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Extension of the New Zealand kauri (*Agathis australis*) chronology to 1724 BC

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Abstract: Long tree-ring chronologies have been constructed in the Northern Hemisphere for dendroclimatology and palaeoenvironmental studies, radiocarbon calibration and archaeological dating. Numerous tree-ring chronologies have also been built in the Southern Hemisphere, primarily for dendroclimatology, but multimillennial chronologies are rare. Development of long chronologies from the Southern Hemisphere is therefore important to provide a long-term perspective on environmental change at local, regional and global scales. This paper describes the extension of the New Zealand *Agathis australis* (kauri) chronology from AD 911 to 1724 BC. Subfossil (swamp) kauri was collected from 17 swamp sites in the upper North Island. Kauri timbers were also obtained from an early twentieth century house on the University of Auckland campus. Twelve site chronologies and 11 independent tree-sequences were constructed and crossmatched to produce a 3631-yr record, which was calendar dated to 1724 BC–AD 1907 against the modern kauri master chronology. A new long chronology, AGAUc04a, was built by combining the modern kauri data with house timbers and subfossil kauri. This new chronology spans 1724 BC–AD 1998. It is of similar length to chronologies from Tasmania and South America and is the longest tree-ring chronology yet built in New Zealand. The greatest significance of the long kauri chronology lies in its potential as a high-quality palaeoclimate proxy, especially with regard to investigation of the El Niño–Southern Oscillation phenomenon. The chronology also has application to investigation of extreme environmental events, dendroecology, archaeology and radiocarbon calibration.

Key words: Dendrochronology, tree-ring, long chronology, kauri, *Agathis australis*, New Zealand, late Holocene.

Introduction

Long tree-ring chronologies, some spanning almost all of the Holocene, have been constructed in the Northern Hemisphere for dendroclimatology and palaeoenvironmental studies (eg, Briffa and Matthews, 2002), calibration of the radiocarbon curve, and archaeological dating (eg, Baillie, 1995). Numerous tree-ring chronologies have also been developed in the Southern Hemisphere, primarily for dendroclimatology, but multimillennial-length chronologies are rare (Luckman, 1996; Villalba, 2000). Notable records include a 3622-yr *Fitzroya cupressoides* (Alerce) chronology from northern Patagonia (Lara and Villalba, 1993), and a subalpine *Lagarostrobos franklinii* (Huon Pine) chronology from Tasmania, which extends back to 2146 BC (Cook *et al.*, 2000). The extension of existing chronologies and/or development of additional long chronologies from the Southern Hemisphere is therefore important to provide a long-term perspective on local- and regional-scale environmental change, as well as contributing to the global network of tree-ring chronologies used for dendroclimatological and environmental research.

In New Zealand, two chronologies span over 1000 years. These are a *Lagarostrobos colenosii* (Silver pine) chronology from the Oroko Swamp, on the West Coast, South Island developed by Cook *et al.* (2002), which spans AD 816–1998, and a 1088-yr *Agathis australis* D. Don Lindley (kauri) chronology (AD 911–1998) from the upper North Island (Fowler *et al.*, 2004). Kauri has long been recognized as a species from which a multimillennial chronology could be constructed (eg, Dunwiddie, 1979: 260; Ogden, 1982: 102). The trees are long-lived, reaching ages in excess of 1000 years, and there are numerous swamps in the kauri growth region that contain well-preserved stumps and trunks. In addition, kauri was one of the major timber types used in New Zealand during the late nineteenth and early twentieth centuries for buildings and a wide variety of other structures, leaving logging remnants

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in forests and a potential tree-ring resource in colonial-era (and later) buildings.

This paper describes the development of new subfossil (swamp) kauri and house timber chronologies, and the linking of these chronologies to the 1088-yr modern kauri chronology, to create a continuous kauri record extending back to 1724 BC. It assesses the statistical quality of the long chronology as a prelude to palaeoclimate investigations, and considers other palaeoenvironmental and archaeological applications the long kauri chronology may have.

Background

Modern kauri

The recent history of kauri dendrochronology has been described in detail by Fowler *et al.* (2004). The first modern kauri site chronology was constructed in the late 1970s (La Marche *et al.*, 1979). By the mid 1980s there was a network of 15 modern site chronologies distributed throughout the natural growth range of kauri and chronological coverage extended back to the AD 1500s (Ahmed and Ogden, 1985). In the late 1990s four modern site chronologies were updated and extended so that the kauri record spanned AD 1269–1998. The analysis and crossdating of a single logging relic extended the record to AD 911. Statistical analysis of modern chronologies identified a strong common signal between all sites, justifying averaging data into a single master kauri chronology (AD 911–1998) (Fowler *et al.*, 2004).

Subfossil kauri

Holocene-age subfossil kauri was first collected for dendrochronology from sites near Hamilton, Waikato (Figure 1), during the 1970s by researchers from the Laboratory of Tree Ring Research, University of Arizona (Dunwiddie, 1979). To our knowledge, no chronologies were derived from these samples. Two wood assemblages, Furniss Rd (FNSR) and Pukekapia (PUKE), were obtained from sites in the Waikato Lowlands (Figure 1) during the early 1980s by Martin Bridge and John Ogden of the University of Auckland. A single site-chronology was developed for PUKE and radiocarbon dated to *c.* 3500–3000 BP (Bridge and Ogden, 1986) but a site chronology was not developed at that time from the FNSR assemblage.

Sampling of subfossil kauri resumed in the late 1990s. Assessment of the temporal spread of Holocene-age radiocarbon dates from swamp kauri listed by Ogden *et al.* (1992) indicated that whilst dates as old as *c.* 7400 BP had been obtained, most radiocarbon dates from kauri occurred in the past 4000 years. This information, combined with the radiocarbon date span of Bridge and Ogden's (1986) Pukekapia chronology, suggested that construction of long floating subfossil chronologies was a realistic goal. There was, however, some doubt as to whether linking the modern and subfossil record would be possible.

Sample collection

Swamp kauri

To date, 133 samples of Holocene-age kauri have been collected from 17 swamp sites (Table 1). The sites are clustered mainly in the lower Waikato Lowlands and in Northland (predominantly in westerly locations near Dargaville) (Figure 1). Four samples have also been collected from former swamps in South Auckland.

The collection of subfossil kauri from the swamp sites has been opportunistic as the extraction costs preclude targeted sampling. In recent years swamp kauri has become a valuable commodity used for furniture and wood turning. Extraction is often undertaken as a commercial venture by contractors, sawmillers and landowners. Only as a result of their support, has it been possible to obtain significant quantities of swamp kauri for analysis.

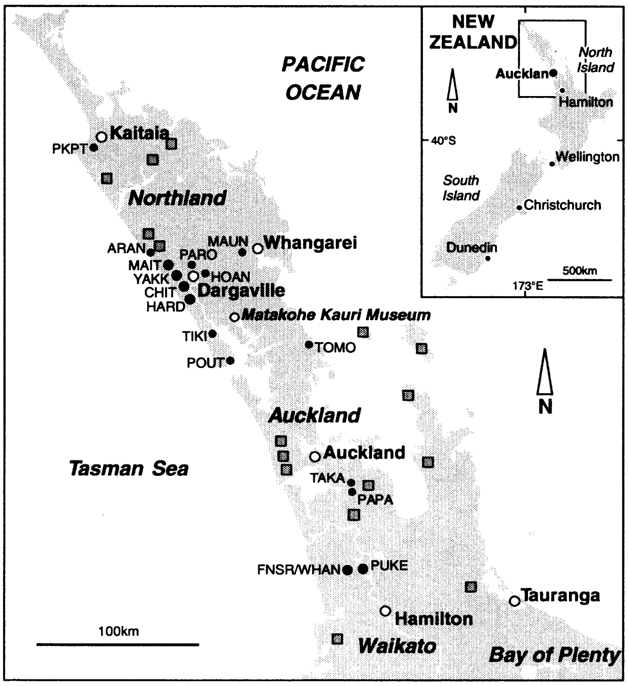

Figure 1 Location of kauri sites in the upper North Island, New Zealand. Full site names are listed in Table 1. Large solid circles indicate subfossil kauri sites where multiple samples were collected. Small solid circles indicate sites with single samples only. Shaded squares (not labelled) mark the position of modern kauri sites. The house at 26/28 Wynyard Street was in the centre of Auckland City

Table 1 Subfossil kauri sites (1983–2004) and Wynard Street House

Site	Code	Latitude	Longitude	NZMS grid reference	Year collected	No. of kauri samples	Comments
Northland							
Chitty	CHIT	35°57′38″S	173°50′32″E	260-PO7 866820	2002	15	Samples cut from stumps and some trunk sections One log was newly extracted
Harding	HARD	36°00′04″S	173°50′06″E	260-P08 850775		13	Samples cut by Nelson Parker, Nelson's Kaihu Kauri The logs were newly extracted
Hoanga	HOAN	35°52′40″S	173°55′23″E	260-PO8 940911	2002	1	From a log at Kaihu Valley Sawmill
Maitahi	MAIT	35°50′55″S	173°45′08″E	260-P07 786945		9	From milled slabs at Kaihu Valley sawmill and remnant sections on the surface at the swamp
Pouto	POUT	36°21′45″S	174°10′51″E	260-Q09 165370		1	From a log at Kaihu Valley Sawmill
Tikinui	TIKI	36°07′27″S	173°58′36″E	260-P08 985637	2001/2002	1	From a log at Nelson's Kaihu Kauri
Yakas	YAKK	35°54′57″S	173°47′27″E	260-P07 820870		16	Slices cut from remnant logs at Korariwhero Flat
Auckland							
Takanini	TAKA	–	–	260-R11 unknown	1980s, 2001	4	One slice from a display slab, two milled slabs and one remnant from the swamp
Waikato							
Furniss Rd	FNSR	37°31′15″S	175°03′22″E	260-S13 920070	1983	15	Cross-sections cut from newly extracted trees
					2004	1	Cross-section from a newly extracted head-log
Pukekapia Rd	PUKE	37°30′54″S	175°07′46″E	260-S13 985075	1983	15	Cross-sections cut from newly extracted trees
Whangape	WHAN	37°31′00″S	175°02′41″E	260-S13 910075	1998	34	31 cross-sections + 3 cores from logs in woodpiles on two farms (Hammond and Langsford)
Matakohe Kauri Museum							
Aranga	ARAN	35°44′46″S	173°36′42″E	260-O07 660060		1	Extracted 1982 from Aranga Swamp, Aranga, (*c*. 7600 BP)
Maungatapere	MAUN	–	–	260-Q07 unknown		1	River sinker, near Whangarei (Maungatapere: Q07 199144)
Papakura	PAPA	–	–	260-R11 unknown		1	Extracted 1983, south Auckland
Parore	PARO	–	–	260-P07 unknown	2004	1	Parore Swamp, Babylon, near Dargaville (Parore: P07 850870)
Pouto	POUT	36°21′45″S	174°10′51″E	260-Q09 165370		1	Southern tip, North Kaipara Peninusla
Pukepoto	PKPT	–	–	260-O04 unknown		1	Near Kaitaia (Pukepoto town: O04 310720)
Tikinui	TIKI	36°07′27″S	173°58′36″E	260-P08 985637		1	North Kaipara Peninsula
Tomorata	TOMO	–	–	260-R08 unknown		1	Tomorato Swamp; could be near Tomorata Lake (260-R08 590550)
Total subfossil kauri						133	
Wynyard St House and shed							
Wynard	WYND	36°51′09″S	174°46″ 18″ E	260-R11 684 817	2003	93	Early twentieth-century house and shed formerly at 28 and 26 Wynard Street, University of Auckland campus

Each site was assigned a four-letter code. Grid references are for the New Zealand Map Service (NZMS) Topo map 260 (1:50 000) series. The exact source locations of Takanini and some of the museum samples are unknown. Grid references for the nearest town are listed for Maungatapere, Parore and Pukepoto, and a possible source location is identified for Tomorata swamp.

The kauri trunks had already been removed from peat and, in most cases, were at a timber mill when sampled, so there is no stratigraphic or other environmental information directly associated with the samples. It is known that all the kauri were recovered from drained and cleared swamps in or adjacent to river valleys mostly less than 20 m above sea level. However, it is not clear whether the kauri were growing directly on peat, or on adjacent Pleistocene sand hills.

Museum samples

Eight longitudinal swamp kauri slabs displayed at The Matakohe Kauri Museum, Northland (Figure 1) were sampled by trimming the top 5 cm from each slab. The slabs were from logs recovered from different sites in Northland. Two slabs were from the same locations as two other swamp kauri samples (POUT and TIKI) collected from sawmillers. Radiocarbon dates for seven slabs, obtained when the trees were extracted, indicated that the timber ranged in age from *c.* 7600 yr BP to 740 yr BP. The eighth slab was described as 'modern' and was cut from a 'sinker' log. Up until the early twentieth century, waterways were used to transport kauri logs to the timber mills (Reed, 1964). Logs were often lost during floods, and some of these logs sank. These 'sinkers' are occasionally recovered today.

House timbers

Kauri timbers were collected from an early twentieth century house (28 Wynyard Street; WYND), and a shed on an adjacent property (26 Wynyard Street) on the University of Auckland campus, which were being demolished. All the timber from the house and shed was in salvage piles on the demolition site. Samples were cut using a chainsaw from a range of timber types, including weatherboards, sarking (wall lining) and joists. In total, 93 kauri samples were obtained from the house and shed.

Sampling of house timbers was undertaken to determine if such material could be a useful tree-ring resource. Because quite large trees (> 1 m diameter) were being converted into small timbers (eg, weatherboard which measures 150 mm × 22 mm in cross-section), the ring sequences are likely to be short compared with those derived from living tree cores or swamp kauri samples. However, Erne Adams (1986: 10) reports that trees reputed to be up to 4000 years old were being felled. Therefore, although the houses were constructed in the late nineteenth and early twentieth centuries, the age of kauri being logged and milled means that temporally 'old' material could have been used in a structure.

Tree-ring analysis

Slices (or 'biscuits') were cut from recovered swamp kauri logs (Figure 2) which were reduced to radii. Between one and six radii were cut per sample, depending on the shape of the sample. The subfossil, museum and house timbers samples were trimmed to *c.* 2–6 cm height to fit on a measuring stage and sanded to a fine finish to reveal the rings clearly. Short series length was not an issue with subfossil kauri, where some series had over 1000 rings, but 20 house-timber samples had less than 50 rings, so were discarded.

Ring widths were measured to an accuracy of 0.01 mm using a measuring stage linked to a computer. Same-tree radii from the subfossil samples were crossmatched and then averaged together into a tree-sequence, which was subsequently used for intertree crossmatching and chronology development. Because of the small size of the house timbers, one radius was measured from each sample. Single series were crossmatched to develop a site chronology. Site chronologies were produced by averaging raw ring width measurements from each crossmatched tree-sequence or radii. These were used for comparison between different sites. The standardization of data after chronology building was complete is described below.

The CROS programs (Baillie and Pilcher, 1973; Munro, 1984) included within the Dendro for Windows suite (Tyers, 2004) were used to aid crossmatching. The CROS programs measure the correlation coefficient between samples at every position of overlap. Significant matches are reported as a Students *t* value, to take account of the length of overlap. Pilcher *et al.* (1995) report that for Scots Pine (*Pinus sylvestris*) *t* values over 4.00 may be considered significant, and *t* values over 6.00 are likely to be very significant. This criterion was applied to kauri. When searching for overlaps, a minimum acceptable length of 50 years was applied.

All statistically suggested matches were checked visually using line plots. It was found that significant *t* values could be reported, particularly with multicentury-length series, even if there was a ring error towards the end of the series. Kauri can produce false rings, where the annual ring is divided by an apparent boundary, or locally absent rings, where the annual ring is not complete around the entire circumference of the tree. Rigorous crossmatching within and between trees can usually resolve individual problems. However, clusters of locally absent rings occasionally occurred on some of the swamp kauri, affecting the suitability of the sample for crossmatching. In these cases, series were truncated to span only the reliable section(s), or excluded from further analysis.

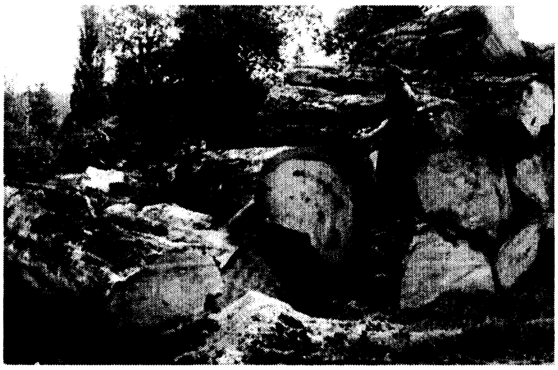

Figure 2 Nelson Parker cutting subfossil kauri samples from Hardings (HARD) at his timber mill. The logs had only recently been extracted and transported to the timber yard. Photo: A. Lorrey, 2002

Results

Crossmatching between subfossil kauri

From 133 swamp kauri samples, 98 were crossmatched against other kauri samples (discussed below). Duplicate samples were identified in the Furniss (FNSR) and Whangape (WHAN) groups, Maitahi (MAIT) and Yakas (YAKK) reducing the total number of crossmatched tree-sequences to 86 (Table 2). Tree-sequences were built from 17 samples, but none of these could be crossmatched to any other kauri samples. In this case, the tree-sequences may have had undetected ring problems preventing crossmatching or were not contemporary with any other kauri. Radii from five samples were measured, but these series had such a disturbed growth pattern that intratree crossmatching was not possible. Eleven samples were unsuitable for analysis as the rings were quite wide and complacent, or had extreme wedging and suppression.

Subfossil chronologies

Between 2001 and 2004, ten subfossil kauri site chronologies were constructed (Table 2). Three well-replicated site chronologies were established from the Waikato assemblages. These include a new version of the Pukekapia (PUKE) chronology (Fowler *et al.,* 2001). Compared with Bridge and Ogden's original 1986 chronology, sample depth was increased from five trees (9 radii) to ten trees (41 radii), and the chronology was extended from 491 to 803 years. The improvements in sample depth and length are likely due to advances in computerized crossmatching techniques. The chronologies *Whangape* and *Furniss1* were built from samples collected in the 1980s and late 1990s from the same swamp site. In the course of crossmatching, three almost identical tree-sequences were identified from the FNSR and WHAN assemblages, indicating that the same kauri logs had been sampled twice. It should be noted that when *Whangape* was built it was known to have a weak period of 5 years when one sample had an ambiguous ring, and all other samples had at least one locally absent ring. Every care was taken with crossmatching, but independent replication of the time period was thought necessary to resolve this issue.

Seven site chronologies were constructed from assemblages collected near Dargaville (Table 2). The Chitty (CHIT), Harding (HARD) and YAKK assemblages produced two site chronologies each and one chronology was created from the MAIT assemblage. Compared with the Waikato groups, sample depth in each Dargaville site-chronology is low (three to five trees only).

Chronology length across all subfossil sites ranges from 582 years (*Chitty2*) to 1319 years (*Chitty1*). Six chronologies span more than 1000 years. The development of millennial-length site-chronologies was aided in part by inclusion of long individual series. The average length of crossdated subfossil sequences was 403 years. Seven samples had more than 800 rings and two exceeded 1000 rings. Interestingly, almost all of the long samples were from the Dargaville assemblages. The majority of Waikato ring sequences were between 200 and

Table 2 Details of the subfossil kauri and house-timber site chronologies and tree-sequences

Site	Code	Chronology/ tree-sequence	Length (years)	Trees/ radii	Average growth rate (mm)	Sensitivity[a]	Date span	References[b]
Waikato								
Furniss Rd	FNSR	*Furniss1*	1084[c]	10/42	1.18	0.42	315 BC–AD 769	1
Pukekapia Rd	PUKE	*Pukekapia*	803	10/41	1.11	0.32	1724 BC–922 BC	2
		PUK001	231	1/4	0.63	0.43	39 BC–AD 192	
Whangape	WHAN	*Whangape*	1050	27/65	1.17	0.31	1180 BC–131 BC	3
Dargaville								
Chitty	CHIT	*Chitty1*	1319	5/13	1.18	0.37	477 BC–AD 842	4
		Chitty2	582	3/7	1.32	0.35	1257 BC–676 BC	
		CHI008	208	1/3	1.33	0.43	1718 BC–1511 BC	
Harding	HARD	*Harding1*	1029	5/17	1.40	0.30	AD 124–AD 1152	5
		Harding2	1030	3/13	1.16	0.33	1466 BC–437 BC	
Hoanga	HOAN	*HOA001*	568	1/3	1.06	0.38	AD 1093–AD 1660	6
Maitahi	MAIT	*MAI005*	419	1/3	0.90	0.34	1362 BC–944 BC	7
		MAITAHI	1003	3/16	0.71	0.29	576 BC–AD 427	
Pouto	POUT	*POU001*	575	1/5	1.48	0.52	1315 BC–741 BC	6
Tikinui	TIKI	*TIK001*	664	1/7	0.88	0.31	AD 67–AD 730	8
Yakkas	YAKK	*Yakkas1*	970	5/13	0.63	0.33	AD 304–AD 1273	9
		YAK008	245	1/2	1.26	0.35	128 BC–AD 117	
		Yakkas2	587	4/7	1.61	0.31	1547 BC–961 BC	
Museum								
Matakohe Museum	MAUN	*MAU401*	230	1/2	1.80	0.40	AD 888–AD 1117	TRL unpublished data
	POUT	*POU401*	97	1/2	2.02	0.35	AD 702–AD 792	
	TIKI	*TIK401*	527	1/1	1.31	0.28	38 BC–AD 489	
	TOMO	*TOM401*	374	1/1	1.32	0.36	AD 800–AD 1173	
House								
26/28 Wynyard St	WYND	*WYND28A*	444	–/13	0.84	0.27	AD 940–AD 1383	10
		WYND28B	442	–/18	1.00	0.23	AD 1466–AD 1907	10
Subfossil/houses				86/298			1724 BC–AD 1907	

[a] The sensitivity statistic is based on that of Fritts (1976)

[b] 1, Boswijk *et al.* (2001); 2, Fowler *et al.* (2001); 3, Boswijk and Palmer (2003); 4–8, Boswijk (2004a,b), Boswijk (2005a,b,c); 9, Boswijk and Palmer (2004); 10, Lorrey *et al.* (2004).

[c] * *Furniss1* originally spanned 724 years, but was extended to 1084 years by the addition of a new sample in 2004.

400 years long and only one tree-sequence had more than 800 rings. The majority of Dargaville ring sequences were between 400 and 700 years long. Further comparison of age and size classes may indicate whether this is an artefact of preservation or if there are real differences in age and size between the Waikato and Dargaville trees.

On average, the Waikato and Dargaville chronologies have similar growth rates: 1.15 mm/yr for Waikato, 1.16 mm/yr for Dargaville. The Waikato chronologies have similar mean ring width values (1.11–1.18 mm) whilst the Dargaville site chronologies have a greater range of variability (0.63–1.61 mm), reflecting differences in the age-structure of the chronology groups. Comparison with modern site chronologies suggests that on average the subfossil trees tend to be slower growing than crossdated kauri from the modern sites (1.58 mm). The subfossil kauri also appear to be more sensitive than kauri from modern sites. Although these results are similar to findings by Bridge and Ogden (1986) and Ogden *et al.* (1993) for Holocene and ancient (*c.* 40 000 yr BP) kauri, such comparison should be approached with caution as the influence of sampling bias has yet to be determined.

Intersite crossmatching of subfossil chronologies

All the chronologies and unmatched tree-sequences were compared against each other to identify contemporary series. Within the Waikato group, overlaps were identified between *Pukekapia* and *Whangape* (258 years) and *Whangape* and *Furniss1* (185 years) (Figure 3). The crossmatching was statistically significant (Table 3) and visually acceptable.

The Dargaville chronologies cluster in two groups, linked by *Maitahi* (Figure 3). In addition, six single tree-sequences from the Dargaville assemblages and four museum samples were independently crossmatched against other site chronologies and tree-sequences (Figure 3). Despite low sample depth, the crossmatching statistics are consistently good within each group with very high values obtained between long site chronologies, especially *Harding1* and *Yakas1* (Table 3). The strength of the cross-correlations, and good visual agreement between sites, indicates that there is a strong common signal between the sites.

The Dargaville record replicates 2487 years of Waikato, confirming the periods of overlap between the three Waikato chronologies. Significantly, three Dargaville chronologies spanned the weak period where the Whangape chronology had a problematic ring, at which time the chronologies went out of sequence by one year. Crossmatching between all tree-sequences (and radii) from Waikato and Dargaville crossing the year in question was reviewed within and between sites, and all the wood samples were rechecked. This determined that a false ring had been included in the Waikato record. The Whangape series were amended and the site chronology rebuilt.

House timber chronologies

Two chronologies were built from the Wynyard Street house and shed, which were crossmatched against the modern kauri master (Table 3; Lorrey *et al.*, 2004). *WYND28A* and *WYND28B* were calendar dated to AD 940–1383, and AD 1466–1907, respectively (Table 3; Figure 4). Although only 38% of samples collected were dendrochronologically dated, the analysis indicated that house timbers have good potential for chronology building. The length of crossdated series ranged from 53 years to 222 years. Finding that series of a few hundred years could be obtained from house timbers, such as weatherboard, and that long site chronologies could be constructed was a pleasant surprise.

Calendar dating the subfossil chronologies

As the subfossil data base developed, the approximate temporal position of the chronologies was established by radiocarbon dates (discussed below). It became increasingly clear from these that the Waikato and Dargaville records extended across the first millennium AD and into the second millennium AD. This was confirmed by crossmatching of the subfossil sample *HOA001*, which was younger than anticipated (AD 1093–1660), to the modern kauri master and *WYND28A* (Table 3; Figure 4). *HOA001* and *WYND28a* also crossmatched to *Yakas1*. The period of overlap between the subfossil, house and modern chronologies was further replicated by two museum samples, *MAU401* and *TOM401*. The weaker crossmatch between *Yakas1*, *Harding1* and the modern master probably relates to low sample depth – between AD 911 and 1269 the modern master is based on one tree-sequence only – and perhaps comparison of records derived from old trees (> 1000 years in the case of *Yakas1*) with the inner (young) rings of a single tree.

The link between the subfossil and modern records is considered to be robust, permitting calendar dating of the subfossil kauri. The subfossil record spans 3384 years, between 1724 BC and AD 1660. The entire kauri record, including swamp kauri, house timbers and modern sites, now extends from 1724 BC to AD 1998.

Quality assessment of AGAUc04a

After crossmatching was complete, the raw kauri data were standardized and a long chronology, *AGAUc04a*, was con-

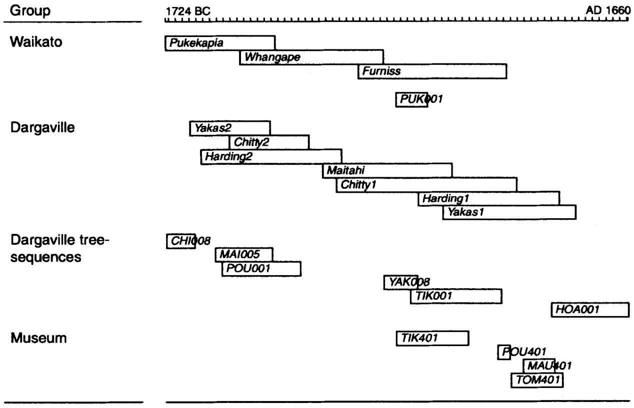

Figure 3 Crossmatched position of the Waikato and Dargaville site chronologies and independent tree sequences. The scale is calendar years BC/AD. The bars represent the entire length of the chronology/tree-sequence. Bars with full names, eg, *Whangape*, are site chronologies. Bars with short names, eg, *CHI008*, are independent tree-sequences

Table 3 Cross correlation and *t*-value matrix for subfossil site chronologies and tree-sequences, house timbers and a modern kauri master, AGAUm04a. Listed *t*-values (top part) and r values (lower part) are from CROS (Baillie and Pilcher, 1973; Tyers, 2004)

Sites	Pukekapia 1724 BC 922 BC	Whangape 1180 BC 131 BC	Furniss1 315 BC AD 769	CHI008 1718 BC 1511 BC	Yakkas2 1547 BC 961 BC	Harding2 1466 BC 437 BC	MAI005 1362 BC 944 BC	POU001 1315 BC 741 BC	Chitty2 1257 BC 676 BC	Maitahi 576 BC AD 370	Chitty1 477 BC AD 842	YAK008 128 BC AD 117	TIK001 AD 67 AD 730	Harding1 AD 124 AD 1152	Yakkas1 AD 304 AD 1273	HAO001 AD 1093 AD 1660	TIK401 38 BC AD 489	POU401 AD 702 AD 792	MAU401 AD 888 AD 1117	TOM401 AD 800 AD 1173	WYND28A AD 940 AD 1383	WYND28B AD1466 AD1907	AGAUm04a AD 911 AD 1998
Pukekapia	*	*8.51*	*	*6.61*	*8.89*	*9.16*	*8.06*	*6.52*	*9.40*	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Whangape	0.47	*	*8.06*	\	*4.35*	*11.49*	*4.26*	*7.12*	*7.02*	*7.18*	*7.98*	\	\	\	\	\	\	\	\	\	\	\	\
Furniss1	\	0.52	*	\	\	\	\	\	\	*11.03*	*12.29*	*5.74*	*9.53*	*7.77*	*11.61*	\	*9.12*	–	\	\	\	\	\
CHI008	0.42	\	\	*	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Yakkas2	0.35	0.29	\	\	*	*16.92*	*10.01*	*6.58*	*11.47*	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Harding2	0.37	0.39	\	\	0.60	*	*8.84*	*14.88*	*18.93*	*7.05*	\	\	\	\	\	\	\	\	\	\	\	\	\
MAI005	0.37	0.27	\	\	0.45	0.40	*	*7.54*	*8.22*	\	\	\	\	\	\	\	\	\	\	\	\	\	\
POU001	0.31	0.32	\	\	0.33	0.53	0.37	*	*10.98*	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Chitty2	0.46	0.30	\	\	0.56	0.62	0.42	0.44	*	\	\	\	\	\	\	\	\	\	\	\	\	\	\
Maitahi	\	0.32	0.39	\	\	0.52	\	\	\	*	*20.81*	*9.87*	*10.93*	*9.37*	*5.93*	\	*11.35*	\	\	\	\	\	\
Chitty1	\	0.40	0.35	\	\	\	\	\	\	0.58	*	*7.82*	*16.75*	*17.20*	*15.04*	\	*14.69*	*4.16*	\	\	\	\	\
YAK008	\	\	0.35	\	\	\	\	\	\	0.54	0.45	*	\	\	\	\	*6.86*	\	\	\	\	\	\
Tik001	\	\	0.35	\	\	\	\	\	\	0.53	0.55	\	*	*16.59*	*13.65*	\	*14.48*	\	\	\	\	\	\
Harding1	\	\	0.29	\	\	\	\	\	\	0.52	0.54	\	0.56	*	*23.09*	–	*12.24*	*7.02*	*6.81*	*7.81*	–	\	*3.23*
Yakkas1	\	\	0.48	\	\	\	\	\	\	0.60	0.55	\	0.55	0.62	*	*7.50*	*8.62*	*6.65*	*8.34*	*10.17*	*7.26*	\	*4.60*
HOA001	\	\	\	\	\	\	\	\	\	\	\	\	\	–	0.49	*	\	\	\	*5.02*	*5.57*	*4.30*	*7.09*
TIK401	\	\	0.37	\	\	\	\	\	\	0.49	0.54	0.49	0.58	0.54	0.54	\	*	\	\	\	\	\	\
POU401	\	\	\	\	\	\	\	\	\	\	0.41	\	\	0.61	0.59	\	\	*	\	\	\	\	\
MAU401	\	\	\	\	\	\	\	\	\	\	\	\	\	0.41	0.49	\	\	\	*	*6.33*	*4.05*	\	*3.84*
TOM401	\	\	\	\	\	\	\	\	\	\	\	\	\	0.39	0.47	0.50	\	\	0.39	*	*4.75*	\	*4.84*
WYND28A	\	\	\	\	\	\	\	\	\	\	\	\	\	–	0.37	0.31	\	\	0.29	0.30	*	\	*8.67*
WYND28B	\	\	\	\	\	\	\	\	\	\	\	\	\	\	\	0.30	\	\	\	\	\	*	10.68
AGAUm04a	\	\		\	\	\	\	\	\	\	\	\	\	0.21	0.24	0.29	\	\	0.26	0.29	0.38	0.46	*

–, overlap $< t = 3.00$; \, no overlap.

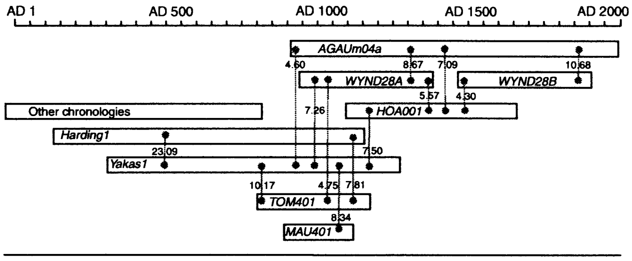

Figure 4 Overlap between the modern kauri master, house timber chronologies, museum tree-sequences and the subfossil chronologies. *t*-values are listed for the key links. Scale is calendar years AD

structed. Standardization followed the techniques applied to modern sites by Fowler *et al.* (2004). The program ARSTAN (Holmes *et al.*, 1986) was used to fit a spline with 50% variance cut-off at 20 years (spline20) to all series. The chronology *AGAUc04a* (Figure 5) was constructed by averaging standardized tree-sequences from all subfossil sites, the house timbers and the same modern series used by Fowler *et al.* (2004) to build the modern kauri master. Such

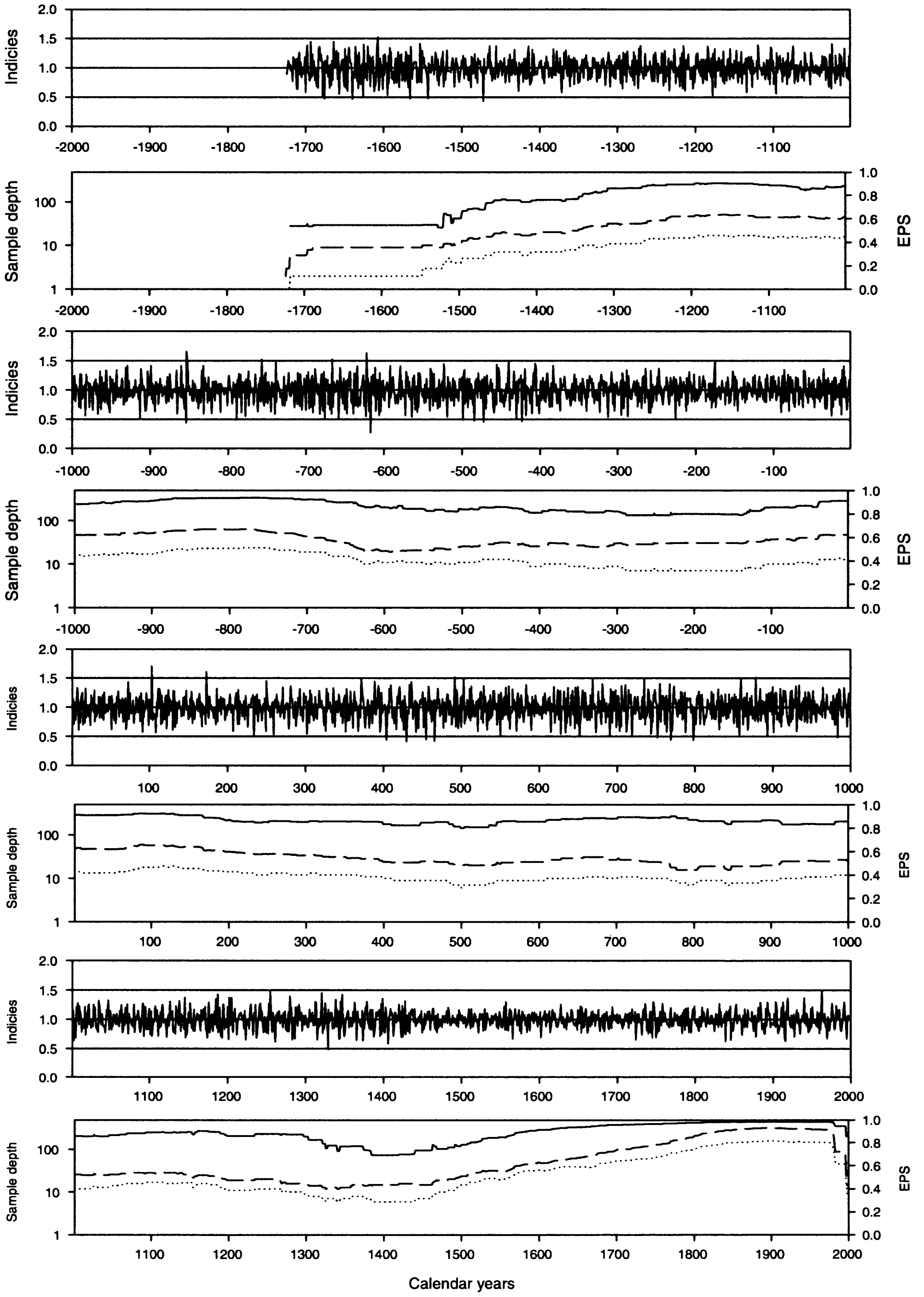

Figure 5 The upper diagram in each pair shows the standardized (Spline 20) chronology, *AGAUc04a*. The lower diagram illustrates the running EPS statistic (upper solid line) and sample depth (radii, dotted line; and tree-sequences, dashed line) for the same time period

chronologies are considered suitable for crossmatching purposes and high-frequency climate applications (Fowler *et al.*, 2004).

The statistical quality of *AGAUc04a* was assessed using the Expressed Population Signal statistic (Briffa and Jones, 1990). EPS is derived from correlations within and between trees, and sample depth, and has a possible range from 0 to 1. Fowler *et al.* (2004) suggest that for kauri, approximately ten trees are required to produce a high quality site-chronology, although this varies depending on the standardization applied to the data. Based on analysis of the evolving quality of the modern kauri master, they also suggested that a relatively small number of trees from multiple sites may be more valuable for constructing a master chronology than a few high quality sites that include numerous trees. In this respect, low sample depth in the Dargaville site chronologies (which do not meet the *c.* ten-tree per site criteria) is compensated for by pooling subfossil data from all sites. This also supports inclusion of independent tree-sequences in a master chronology.

Overall, *AGAUc04a* is a high quality record with an EPS of 0.991. However, calculation of evolving EPS (following Fowler *et al.*, 2004) indicates that signal quality varies over time (Figure 5). The period of highest and consistently high, statistical quality occurs between AD 1583 and AD 1996 (modern and house timbers), when EPS is over 0.900. Between AD 1511 and 1321 EPS drops below 0.800. At this time the chronology is based on few modern sites and archaeological material. Improvement in EPS prior to AD 1300 coincides with the transition to a record dominated by subfossil chronologies and there are three high quality periods during the subfossil record when EPS attains levels approaching those of the modern trees. Separate calculation of the EPS statistic for the Waikato record and the Dargaville record (not shown) suggests that the subfossil signal is dominated by the Waikato chronologies, as expected from the greater number of samples from the Waikato. Assessment of changing signal strength over time indicates that further work is required to boost sample depth to yield a consistently high quality long chronology. In particular, additional samples are required between AD 1300 and AD 1500, 137 BC and 288 BC and prior to 1341 BC.

Radiocarbon dates

Radiometric radiocarbon dates were obtained from the Waikato Radiocarbon Dating Laboratory for six crossmatched Waikato kauri and three crossmatched Dargaville kauri, while the subfossil chronologies were being developed (Table 4). The radiocarbon dates provided a guide to the temporal position of the floating subfossil chronologies relative to the modern kauri master, prior to the subfossil kauri being calendar dated.

The linking of the modern and subfossil records by dendrochronological dating established precisely the calendar date of each ^{14}C sample from a crossdated kauri. Because the exact length of gap between the nine samples is known, we 'wiggle-matched' the ^{14}C dates to the new Southern Hemisphere calibration curve, SHCal04 (McCormac *et al.*, 2004), to (a) refine the calibrated age ranges for the nine dates listed in Table 4 and (b) compare how well the ^{14}C dates agree with the actual calendar date for each sample.

SHCal04 is comprised of calibration data from the Southern Hemisphere to AD 950 (McCormac *et al.*, 2002) and, before AD 950, the internationally agreed calibration curve (IntCal04) adjusted with a modelled offset, which varies from 55 to 58 years (McCormac *et al.*, 2004). Therefore only one ^{14}C date from a kauri sample falls within the period spanned by calibration data from the Southern Hemisphere. All nine ^{14}C dates have very good fit to the calibration curve. The calibrated date spans for each wiggle-matched ^{14}C date at 95% confidence levels also agree very closely with the actual calendar date of each kauri sample (Table 4). For example, the mid-points for calibrated and actual calendar date ranges for the eight decadal samples are within 1 year of each other. From this, we can infer that very accurate calibrated age ranges can be obtained by wiggle-matching radiocarbon dates (spaced at known intervals) to SHCal04, over the last *c.* 3700 years at least.

Radiocarbon dates were also obtained for five samples that were not dendrochronologically dated in order to determine if the samples were contemporary with or older than the long chronology (Table 4). All were older than 1724 BC. The dates ranged between 2470 – 2205 cal. BC (*CHI006*; WK 15530; 3933±39 BP) and 5468 – 5206 cal. BC (*CHI015*; WK 15532; 6397±47 BP). The temporal position of the ^{14}C sample from the latter series, and that from *HAR009*, suggests that these

Table 4 Radiocarbon dates from subfossil kauri in date order (youngest to oldest) for dendrochronologically dated and floating series

Site code	Sample	Year submitted	Waikato code	^{14}C date (BP)	Calibrated date (2σ)	Dendro-calendar date
Crossdated series						
HARD	HAR010	2004	WK15535	1034±35	988–1042 cal. AD	AD 1011–1020
TIKI	TIK001	2003	WK13489	1365±44	669–723 cal. AD	AD 692–721
FNSR	Waik006	2003	WK13901	1707±38	337–391 cal. AD	AD 360–369
FNSR	Waik005	2003	WK13900	2073±38	73–20 cal. BC	51–42 BC
WHAN	Waik004	2003	WK13899	2443±38	483–430 cal. BC	461–452 BC
WHAN	Waik003	2003	WK13898	2738±40	893–840 cal. BC	870–861 BC
PUKE	Waik002	2003	WK13897	3119±40	1303–1250 cal. BC	1280–1271 BC
CHIT	CHI008	2004	WK15531	3390±38	1558–1505 cal. BC	1535–1526 BC
PUKE	Waik001	2003	WK13896	3441±41	1713–1660 cal. BC	1690–1681 BC
Floating series						
CHIT	CHI006	2004	WK15530	3933±39	2470–2205 cal. BC	
HARD	HAR008	2004	WK15533	4582±43	3368–3033 cal. BC	
HARD	HAR011	2004	WK15536	5006±37	3906–3644 cal. BC	
HARD	HAR009	2004	WK15534	6286±50	5316–5042 cal. BC	
CHIT	CHI015	2004	WK15532	6369±47	5468–5206 cal. BC	

Ten-year blocks of rings were submitted to the Waikato Radiocarbon Dating Laboratory for all samples except TIK001, which was a 30-yr block. All calibrated date ranges were produced using Southern Hemisphere atmospheric data from McCormac *et al.* (2004) and OxCal v3.10 (Bronk Ramsey, 1995, 2001). Radiocarbon dates for crossdated series with known time intervals were wiggle-matched to constrain the age ranges. Standard calibrated date-ranges are presented for the floating series.

two sequences could overlap. However, *HAR009* has a quite disturbed growth pattern and intratree crossmatching was problematic. Therefore no crossmatching has been identified between these two kauri samples.

Discussion

Different applications of a long kauri chronology have been identified since the early days of kauri tree-ring research in the late 1970s (Dunwiddie, 1979; Ogden, 1982; Bridge and Ogden, 1986). Potential applications include dendroclimatology, dendroecological and environmental studies, archaeology and calibration of the Southern Hemisphere radiocarbon curve.

Dendroclimatology

The principal reason for development of subfossil kauri chronologies was to produce long, annually resolved records for dendroclimatology. Recent dendroclimatological investigation of the modern kauri site-chronologies using response function analysis and frequency analysis has identified a strong climate signal common to all sites (Buckley *et al.*, 2000; Fowler *et al.*, 2004). Analyses by Buckley *et al.* (2000) established that kauri growth over the last 150 years tends to be enhanced by cool-dry conditions during the growing season, particularly in spring/early summer, and suppressed during warm-wet conditions. Fowler *et al.* (2000) observed that (based on Mullan, 1995) in northern New Zealand, cool-dry conditions are characteristic of El Niño, and warm-wet characteristic of La Niña, and that ENSO teleconnections had been identified as strongest in September–November by Mullan (1995). The identification of a consistent relationship between kauri growth and ENSO led Fowler *et al.* (2000) to conclude that kauri is a potentially useful proxy for investigation of past ENSO events, particularly in the context of multiproxy reconstructions.

Current research is focused on furthering understanding of the connection between kauri growth and ENSO and developing reconstructions. The long kauri chronology has significantly extended temporal coverage by about an order of magnitude, which has implications with respect to investigation of millennial-scale climate change. As described above, *AGAUc04a* has high overall statistical quality, but there are periods where sample depth should be increased. The level of replication also varies through time as sites and independent tree-sequences start and end (Figure 5). The long kauri record also changes from being based on widely distributed modern sites, located between 80 m and 480 m above sea level and with a predominantly northerly aspect, to archaeological material of unknown origin, and finally, to swamp kauri where the growth environment is unknown and where the low-altitude sites have a predominantly western distribution (Figure 1). The latter group account for approximately three-quarters of the length of the long chronology. The uniformitarianism issues related to the changing composition of the long chronology are currently being investigated.

Dendroecology

Bridge and Ogden (1986) considered that subfossil kauri chronologies would be of value for palaeoecological studies. Although kauri is widely preserved in (and recovered from) swamps, little is known about the age and population structure of the buried kauri stands (Ogden *et al.*, 1992). The development of site chronologies from the Waikato Lowlands and Dargaville region enables investigation of age, germination and mortality trends within, and between, sites, set within a precise chronological framework. This will assist in refining our understanding of the late Holocene history and ecology of kauri. The information can also be applied in conjunction with other palaeoenvironmental evidence, such as palynology, to further understanding of environmental change in the late Holocene, especially development of the swamps.

Initial observations are that at least two generations of kauri have been preserved at most sites (Figure 3). At CHIT and HARD, kauri has been present since 5000–6000 BC and continued to be preserved in the swamps until as recently as the twelfth century AD. Kauri was also being preserved at the Waikato site, WHAN/FNSR, until at least late in the first millennium AD. There, the kauri are contemporary with a rise in kauri pollen observed at other sites in the wider Waikato region, which has been suggested as indicating expansion of kauri on to marginal ground near lakes, and on, or adjacent to, swamps and oliogotrophic raised bogs (McGlone *et al.*, 1984; Newnham *et al.*, 1989).

Extreme events

Palaeoenvironmental reconstruction also extends into investigation of regional- and global-scale extreme environmental events that have left a signal in the tree-ring record. For example, contemporaneous periods of suppressed growth and narrowest ring events, anomalous rings and frost rings, have been identified in long tree-ring chronologies predominantly from the Northern Hemisphere (eg, La Marche and Hirschboeck, 1984; Baillie, 1994; D'Arrigo *et al.*, 2001). These events have been associated with climatic cooling after major volcanic eruptions (Stothers, 1999). An alternative hypothesis is that the trees contain a signal of environmental impacts associated with close encounters with comets (Baillie, 1999). Construction of the long kauri chronology provides an opportunity to investigate whether trees in the southwestern Pacific also contain significant signals at, or around the same time, which would lend weight to the contention that some of these events had a global impact.

Archaeology

Since the early days of dendrochronology, tree-ring analysis has been a valuable archaeological dating technique. In New Zealand, archaeologists also became interested in the potential of tree-rings for dating archaeological sites (Lockerbie, 1950; Golson, 1955). Early efforts applied dendrochronological techniques in an attempt to crossmatch wood from Maori sites, such as palisade posts (Scott, 1964) or used tree-ring counts to date the deliberate removal of bark from totara (*Podocarpus totara*) trees, used for containers (Batley, 1956). However, these and other attempts at crossmatching were unsuccessful (eg, Cameron, 1960) and since then tree-ring research in New Zealand has been focused on dendroclimatology and ecology. The new subfossil kauri chronologies have increased the number of reference curves available, improving prospects for dating kauri of unknown age, either from natural deposits such as other swamp sites, or archaeological timbers.

Late nineteenth- and early twentieth-century buildings (built predominantly of kauri) are unlikely candidates for dendroarchaeology as the buildings may be less than 100 years old and usually have known construction dates. However, as demonstrated by the Wynyard Street assemblage, long site chronologies can be constructed from house timbers. These chronologies have value for improving sample depth of the long chronology, particularly in the early second millennium AD. *WYND28b* also included samples that retained the final growth ring below bark edge, unexpectedly providing felling dates for the trees (Lorrey *et al.*, 2004). As a consequence of this work, analysis of timbers from a larger set of kauri buildings is now being undertaken to establish whether dendrochronology can be applied to aid interpretation of such buildings; to identify what information can be derived from timbers, apart from dates, such as tree age and timber conversion; and to investigate whether provenancing of the timber is possible.

Radiocarbon calibration

Dunwiddie (1979), Ogden (1982) and Bridge and Ogden (1986) highlighted the potential of a very long kauri chronology in the calibration of a Southern Hemisphere radiocarbon curve. At the time, studies on the temporal variation in ^{14}C using dendrochronologically dated material had not been carried out extensively in the Southern Hemisphere (Dunwiddie, 1979). Because of the longevity of kauri, and extensive swamp kauri deposits, it was seen to have the potential to generate a calibration curve for the Southern Hemisphere covering a time span similar to the Northern Hemisphere (Ogden, 1982).

Southern Hemisphere calibration data for the past 1000 years have now been produced using dendrochronologically dated wood from other New Zealand species (*Libocedrus bidwilliei* (cedar) and Silver pine (Hogg *et al.*, 2002), as well as data from Chile and South Africa (McCormac *et al.* 2002, 2004). Calibration of radiocarbon dates older than 1000 BP is dependent on comparison with Northern Hemisphere data, adjusted with an offset (McCormac *et al.*, 2004). Based on the results presented above, accurate calibrated age ranges are produced when wiggle-matching ^{14}C dates to SHCal04. However, McCormac *et al.* (2004) point out that 'calibration of Southern Hemisphere measurements is best achieved using securely dendrochronologically dated wood'. In this respect, the construction of the long kauri chronology could have application to extension of the Southern Hemisphere calibration back further in time.

Conclusion

The development of the long kauri chronology exceeded initial expectations in that not only were numerous long subfossil chronologies constructed, but they were also linked to the modern, calendar-dated record. This produced a continuous kauri chronology (*AGAUc04a*) over 3700 years long. Previously, only one kauri radiocarbon date of *c.* 5790 BP from the Dargaville region had been reported by Ogden *et al.* (1992). The ^{14}C dates for currently unmatched kauri samples from the Dargaville region suggest that it may be possible to develop new floating subfossil chronologies, or even extend the long chronology, provided more wood of a similar age can be found.

The kauri record is the longest tree-ring chronology yet produced in New Zealand. It is similar in length to the long chronologies from Tasmania (Cook *et al.*, 2000) and South America (Lara and Villalba, 1993), and is a new contribution to the global network of chronologies greater than 1500 years long (Luckman, 1996). The greatest significance of the long chronology probably lies in its potential as a high quality palaeoclimate proxy, especially in the context of reconstruction of past ENSO events. However, several other applications are also evident including: (a) extending understanding of kauri ecology; (b) assisting reconstruction of palaeoenvironmental change in New Zealand during the late Holocene; (c) seeking specific short-term environmental events that are recorded predominantly in northern Hemisphere chronologies; (d) archaeology, with particular reference to late nineteenth- and early twentieth century buildings; (e) radiocarbon calibration. It is clear from the above that the development of the long kauri chronology represents an important advance for New Zealand tree-ring research and will be a valuable contribution to the Southern Hemisphere and global tree-ring network.

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