Extension of New Zealand kauri (*Agathis australis*) tree-ring chronologies into Oxygen Isotope Stage (OIS) 3

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Palmer, J., Lorrey, A., Turney, C. S. M., Hogg, A., Baillie, M., Fifield, K. and Ogden, J. 2006. Extension of New Zealand kauri (*Agathis australis*) tree-ring chronologies into Oxygen Isotope Stage (OIS) 3. *J. Quaternary Sci.*, Vol. 21 pp. 779–787. ISSN 0267–8179.

Received 31 January 2006; Revised 24 July 2006; Accepted 25 July 2006

ABSTRACT: New Zealand kauri (*Agathis australis*) is both long-lived and sensitive to climate so during the past two decades an extensive network of sites has been sampled for dendrochronological analyses. The network can be divided into three general groups based on the time period they cover—‘modern’ kauri (MK), late-Holocene kauri (HK) and ‘ancient’ kauri (AK) from before the Last Glacial Maximum (LGM). Although the groups are restricted to northern New Zealand (i.e. having overlapping ranges) they occur at different elevations. Modern kauri sites tend to be along ridges and much higher than the two subfossil groups (i.e. HK and AK sites). We propose the modern kauri situation to be a typical artefact of anthropogenic activities. In contrast, the subfossil groups are the result of a complex process of dune migration, levee formation and water-table rise leading to bog formation driven by rising sea levels. Most of the 16 AK sites have radiocarbon ages clearly within Oxygen Isotope Stage (OIS) 3 and a preliminary group of chronologies have been developed that collectively cover 10 719 yr. Analysis is ongoing, but there is clear potential to span a much greater time period and recover detailed palaeoclimatic information. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: dendrochronology; *Agathis australis*; tree-rings; OIS 3; New Zealand

Journal of Quaternary Science

Introduction

Although loosely termed as ‘warm’ by the isotopic nomenclature, Oxygen Isotope Stage (OIS) 3, spanning the period 25 000 to 60 000 yr ago (25–60 ka), was a period of exceptional climatic variability during the late Quaternary. Within the North Atlantic region, OIS 3 was characterised by a series of rapid ($<10^2$ yr) and severe (10^1 °C) millennial-scale climatic oscillations referred to as Dansgaard–Oeschger (D–O) events that have been identified in oceanic, ice and terrestrial records throughout the Northern Hemisphere (Voelker *et al.*, 2002). These D–O events can be bundled into regular, decreasing amplitude, cooling cycles as asymmetrical ‘sawtooth’ shapes (Bond Cycles; Bond *et al.*, 1993) that culminated in massive discharges of ice into the North Atlantic, of which the most

prominent are the so-called Heinrich events. The exact timing, magnitude and global extent of these events are currently uncertain (Sarthein *et al.*, 2002), limiting our understanding of how rapid, extreme climate shifts are propagated around the world, particularly to Australasia.

A review of centennial-scale records from marine, ice-core and terrestrial sites for OIS 3 by Voelker *et al.* (2002) highlighted the bias in the spatial database towards the Northern Hemisphere. Marine records were also nearly twice as abundant as the ice-core and terrestrial sites combined. Their conclusion was that more records are needed, especially from the Southern Hemisphere. Of the 183 sites listed from the latter, only one was derived using tree-ring widths (with none in the Northern Hemisphere). This key site is located in northern Patagonia, Chile, where 28 *Fitzroya cupressoides* trees produced a 1229-yr floating chronology (Roig *et al.*, 2001) dated at around 50 000 ^{14}C yr BP. The position and orientation of the stumps suggested that the trees in this chronology were overwhelmed by a lahar (i.e. a catastrophic single event). Their discovery was a result of a recent earthquake that subsequently exposed the subfossil

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F. cupressoides stumps, suggesting little chance of developing a continuous record through all of OIS 3 from that region.

The development of high-resolution tree-ring chronologies in the mid-latitudes is crucial if we are to test hypotheses of inter-hemispheric synchronicity of climate change during OIS 3. The variation in tree-ring widths from one year to the next is widely recognised as an important source of accurate palaeoclimatic information (Bradley, 1999). Historically, the research focus for dendroclimatology has been in mid- to high-latitudes (e.g. Fritts, 1976; Briffa and Matthews, 2002; Cook *et al.*, 2004) though this is extending towards the tropics (D'Arrigo *et al.*, 2006). In the ocean-dominated Southern Hemisphere, relatively few tree-ring chronologies have even been developed for the Holocene (Jones *et al.*, 2001) though Cook *et al.* (2006) (this issue) describe substantial progress towards providing reliable dendroclimatic records in the Australasian region. Around 100 tree-ring chronologies have been developed from seven native conifer species and three angiosperms in New Zealand since the late 1970s at sites across the country (ITRDB, 2004; Norton and Ogden, 1987). Most tree-ring chronologies from New Zealand, however, span less than 500 yr in length.

Kauri (*Agathis australis*) is both long-lived (over 500 yr; Ogden, 1983) and sensitive to climate (Ogden and Ahmed, 1989; Fowler *et al.*, 2000). *Agathis australis* is an evergreen conifer within the family Araucariaceae which has several tropical species. *Agathis* is spread along the western edge of the Pacific with kauri being the southernmost representative and the only Araucariaceae endemic to New Zealand (Salmon, 1980). It is a large canopy-emergent tree that reaches heights exceeding 30 m with some living specimens having diameters greater than 5 m (Sale, 1978). The dendroclimatic potential of kauri has been recognised since Dunwiddie (1979) first produced a tree-ring chronology. Since then, a network of 17 chronologies from modern kauri sites has gradually been developed (Buckley *et al.*, 2000; Fowler *et al.*, 2000, 2004) and recently linked to late Holocene (subfossil) material extracted from bog sites (Boswijk *et al.*, 2006; see also Cook *et al.*, this issue).

In this paper, we will consider the data under three headings: (1) 'modern kauri' (MK): trees that were living at the time of sample collection (increment cores)—the dimensions of the tree and its location on the landscape are known; (2) 'Holocene kauri' (HK): timber collected from bogs of late Holocene age; and (3) 'ancient kauri' (AK): wood from bogs of before the Last Glacial Maximum age—most belongs to OIS 3, but some probably relates to earlier interstadial or interglacial periods (e.g. OIS 5). Here we report on the development of AK sites from OIS 3 and compare them to modern and late Holocene kauri data already published.

New Zealand kauri collections

Modern kauri (MK) sites (Table 1(a))

Living kauri trees are found predominantly on ridges and north-facing slopes at elevations between sea level and ca. 600 m, from the far north of New Zealand southwards to Kawhia (approximately 34–38° S; Poole and Adams, 1986) (Fig. 1). Modern kauri stands rarely border swamps or bogs, although the present pattern is largely an artefact of Polynesian burning (McGlone, 1983; Ogden *et al.*, 1998) and European logging from the 1870s to the 1930s (Reed, 1964; Halkett and Sale, 1986). The pre-logging distribution is not known in detail, but it was certainly more common in the lowlands than at present. Seventeen modern kauri chronologies are summarised in

Table 1(a). Sites range in altitude between 630 m and 90 m, with a mean of 280 ± 135 m. As expected, the average ring-width of sites at higher elevation is smaller than those at lower elevation. The overall average ring-width (ARW) was 1.66 ± 0.59 mm yr⁻¹. This is similar to the rate of 1.57 ± 0.21 mm yr⁻¹ determined by Ahmed and Ogden (1985). An important point to note is that these growth rates do not include trees unable to be cross-dated. Kauri is not an easy species to cross-date (because it has both false and missing rings) so an initial bias might be towards the faster-growing trees. This is supported by the quoted growth rate by Ahmed and Ogden (1985) for non-cross-dated series from 8 sites being 1.13 ± 0.44 mm yr⁻¹. However, many of the cross-dated sites have been reassessed and updated so that our reported growth rate now includes a much larger number of series (240 compared with 131 trees). The increase is also a benefit of better cross-dating tools being available (e.g. Fowler *et al.*, 2004) and has resulted in representation from the entire MK growing region.

Holocene kauri (HK) sites (Table 1(b))

The late-Holocene kauri logs are found in poorly drained lowland sites lying in peat, and scattered over a 200-km stretch of northern New Zealand (Fig. 1). HK sites extend to the current southern limit of kauri in the Waikato (approximately 38° S). Eleven chronologies described in detail by Boswijk *et al.* (2006) are listed by region in Table 1(b). All the sites are situated close to modern sea level (range 5 to 15 m) and the average ring-width is less than those for modern kauri.

OIS 3 'ancient kauri' (AK) sites (Table 1(c))

The OIS 3 (AK) sites show geographical overlap with the Holocene (HK) sites, but are not found towards the southern limit, and extend further north onto the Aupouri Peninsula (i.e. 34° 50'–36° 20' S). Some of the buried trees are of enormous proportions, with diameters greater than 4 m and individual ages of more than 2000 yr. The remarkable preservation state of subfossil kauri (with bark often still intact; Fig. 2), coupled with renowned timber qualities (Clifton, 1994) and living tree protection from logging, has meant buried kauri (i.e. both HK and AK) is a valuable resource. Consequently the wood is currently being 'harvested' for commercial purposes. This has resulted in an increasing rate of extraction although the resource is dwindling. Table 1(c) documents 16 sites from which chronologies have been obtained or which are currently under investigation.

A comparison of the three different collections (i.e. MK, HK and AK) in terms of their elevations and growth rates are summarised in Fig. 3. An intriguing observation is that there is virtually no overlap in the altitudinal range of the different types of sites (Table 1; Fig. 3). The modern sites are spread over a wide elevational range but are rarely near sea level whereas all the Holocene sites are close to sea level and the AK sites are consistently perched around 30 m higher (with the two eastern AK sites—OMA, MNG being the exceptions). Although the AK sites are at higher elevations than the HK sites, they are still in a lowland setting, with almost no altitudinal overlap with MK sites. The very slow average growth rates of some of the AK trees, maintained over several centuries are a notable feature of the data. Overall, however, the AK sites are not significantly different from the HK sites in average growth rates implying that

Table 1 Summary of kauri (*Agathis australis*) collection sites

(a) Modern kauri (MK) sites								
Region	Site codes	Chronology length (yr)	Elevation (m a.s.l.)	No. trees	Average ring-width (ARW) (mm)	Comments/references (note: only the most recent reference is quoted)		
Northland	PUBL,	359	305	9	1.68 ± 0.42	From Fowler <i>et al.</i> 2004		
	PUKF,	498	290	22	1.54 ± 0.35	From Fowler <i>et al.</i> 2004, updated in Fowler <i>et al.</i> (in prep.)		
	WARA,	339	468	14	1.43 ± 0.48	From Fowler <i>et al.</i> 2004		
	WAID,	275	180	6	2.06 ± 0.34	From Fowler <i>et al.</i> 2004		
	TROU,	473	175	26	1.65 ± 0.39	From Fowler <i>et al.</i> 2004, updated in Fowler <i>et al.</i> (in prep.)		
Auckland	HUPI,	514	90	36	1.47 ± 0.37	From Fowler <i>et al.</i> 2004		
	CASC,	423	180	14	1.26 ± 0.27	From Fowler <i>et al.</i> 2004		
	HUIA,	261	274	7	1.32 ± 0.21	From Fowler <i>et al.</i> 2004		
	WTDM,	274	210	7	1.83 ± 0.53	From Fowler <i>et al.</i> (in prep.)		
	KOND,	206	335	10	1.82 ± 0.41	From Fowler <i>et al.</i> 2004		
Coromandel	MWIL	401	350	6	1.18 ± 0.27	From Fowler <i>et al.</i> 2004		
	LTBR	191	274	11	1.70 ± 0.41	From Fowler <i>et al.</i> 2004		
	HIDV,	306	220	13	1.31 ± 0.12	From Fowler <i>et al.</i> (in prep.)		
	MOEH,	620	630	15	1.29 ± 0.23	From Fowler <i>et al.</i> 2004		
	MASC	729	350	17	0.93 ± 0.30	From Fowler <i>et al.</i> 2004		
Waikato	KAWH	286	80	10	2.54 ± 0.64	From Fowler <i>et al.</i> 2004		
Hawkes Bay	KATI	298	350	17	2.36 ± 0.71	From Fowler <i>et al.</i> 2004		
Total/Average	17 sites	225 ± 87	280 ± 135	240	1.66 ± 0.59			
(b) Holocene kauri (HK) sites								
Region	Site codes	Maximum chronology length	Average elevation (m a.s.l.)	No. trees	Average ring-width (ARW) (mm)	Comments/references		
Northland	MAIT	1003	10	9	0.91 ± 0.19	From Boswijk <i>et al.</i> 2006		
	HOAN,	568	5	1	1.06	From Boswijk <i>et al.</i> 2006		
	YAKK,	970	10	16	1.26 ± 0.78	From Boswijk <i>et al.</i> 2006		
	CHIT,	1319	10	15	1.17 ± 0.32	From Boswijk <i>et al.</i> 2006		
	HARD,	1030	15	13	1.46 ± 0.46	From Boswijk <i>et al.</i> 2006		
	TIKI,	664	5	1	0.87	From Boswijk <i>et al.</i> 2006		
	POUT	575	5	1	1.48	From Boswijk <i>et al.</i> 2006		
Waikato	PUKE,	803	10	15	1.12 ± 0.34	From Boswijk <i>et al.</i> 2006		
	WHAN,	1050	10	34	1.33 ± 0.46	From Boswijk <i>et al.</i> 2006		
	FNSR	1084	10	16	1.11 ± 0.40	From Boswijk <i>et al.</i> 2006		
Total/Average	11 sites	376 ± 106	9 ± 3	121	1.23 ± 0.47			
(c) Subfossil kauri sites older than the Holocene (i.e. ‘ancient kauri’—AK)								
Site	Code	Lat. (South)	Long. (East)	Elevation (m a.s.l.)	No. trees	Average ring-width (ARW)	Radiocarbon age (± 1σ)	Comments/references/ radiocarbon reference number
Northland								
Trig Road	TRIG	34° 47′	173° 04′	30	11	1.05 ± 0.29	>35 000	Wk8442, Ogden <i>et al.</i> , 1992
Wharemaru	WRU	34° 57′	173° 12′	40	2	—	>40 000	Wk13442
Vinac Farm	VIN	34° 59′	173° 11′	40	10	1.41 ± 0.52	60 300 ± 640	Wk14419-14427, Hogg <i>et al.</i> , 2006
Dean Farm	DEAN	35° 01′	173° 11′	40	2	—	>40 000	Wk13337
Lake Ngatu	NGT	35° 02′	173° 11′	30	7	—	>40 000	Wk13443
Stewart sawmill	STE	35° 02′	173° 15′	—	3	1.85	>55 000	Wk16689
							>50 000	Wk 13906
Sweetwater Farm	SWT	35° 04′	173° 11′	30	4	—	>50 000	Wk7075
							>55 000	Wk14689
Duder Farm	DUD	35° 42′	173° 32′	80	24	0.99 ± 0.27	59 700 ± 590	Wk15590-92, 15670-74, 15730-33
							43 800 ± 720	Hogg <i>et al.</i> , 2006, ANUA33016
Bibby Farm	BIB	35° 42′	173° 32′	80	6	1.33 ± 0.38	>55 000	Wk5383
Roe Farm	ROE	35° 48′	173° 38′	70	8	1.16 ± 0.31	>55 000	ANUA33024

(Continues)

Table 1 (Continued)

(c) Subfossil kauri sites older than the Holocene (i.e. 'ancient kauri'—AK)

Site	Code	Lat. (South)	Long. (East)	Elevation (m a.s.l.)	No. trees	Average ring-width (ARW)	Radiocarbon age ($\pm 1\sigma$)	Comments/references/ radiocarbon reference number
Don McLeod Farm	DMC	35° 49'	173° 38'	90	8	1.05 $\pm$ 0.35	>40 000	Wk13444
Finlayson Farm	FIN	35° 50'	173° 39'	80	13	0.99 $\pm$ 0.38	No age available	Adjacent to Roe Farm
							27 796 $\pm$ 182	Wk16711
Coles Farm	COL	36° 06'	173° 56'	30	2	—	46 141 $\pm$ 1398	Wk16712
							No age available	Adjacent to
Randall Farm	RAN	36° 06'	173° 56'	40	3	—	1297 $\pm$ 35	Wk17808,
								Two bog areas.
Mangawhai Heads	MNG	36° 08'	174° 36'	15	9	1.20 $\pm$ 0.45	>50 000	Wk17809
Omaha Flats	OMA	36° 18'	174° 30'	15	55	1.46 $\pm$ 0.46	39 500	Wk17400
							28 518 $\pm$ 221	Wk17551
							>47 330	Wk17550
Total/Average	16			47 $\pm$ 25	167	1.25 $\pm$ 0.45		

the latter may form a useful analogue when considering the ecology of the bogs and the preservation of the wood.

Modern kauri sites were from higher elevations and faster-growing than the other two types of collections. Normally, the expectation would be that lower-elevation sites are faster-growing than those at higher elevations. Clearly this is not the case and there are several possible causes including temporal

differences in climate, the difference in the segment length of the tree-ring series or habitat type (e.g. well-drained ridges compared with bog margins; Ogden *et al.*, 1992). A difference in growth habitat would raise a uniformitarian issue if multi-millennial climate reconstruction were attempted on the basis of MK trees and applied to the cross-dated HK sites (Fowler *et al.*, 2004; Boswijk *et al.*, 2006).

Figure 1 Location of kauri (*Agathis australis*) sites. Lettering represents sample site codes referred to in Table 1

Figure 2 Preserved bark edge subfossil kauri from Robert Harding's farm, near Dargaville

Holocene and OIS 3 kauri site geography

The majority of ancient kauri sites are located within the dune complex referred to as the North Kaipara Harbour (Sherwood and Schofield, 1985), west of Dargaville on the west coast, and in similar dunes on the Aupouri Peninsula in far Northland (Fig. 1). These dune belts average 8 km in width and comprise a complex of modern and ancient dunes, fluvial, lacustrine and estuarine sediments. There appears to have been a number of separate periods of sedimentation during the Quaternary related to changes in sea level and indicated by at least three seams of lignite visible in cliffs along parts of the coastline. Ancient kauri is also located in low-lying coastal areas in close association with long, arcuate sand barrier systems anchored by rocky headlands along the east coast north of Auckland (DSIR, 1973). Low hills under 300 m elevation with moderate slopes (10–35°) typically back these sites, which are characterised by moist, lowland flats that have commonly been converted to pastureland. On the east coast, the modern barriers fronting OIS 3 kauri sites receive limited sediment from local river catchments primarily from reworked sand (offshore and muddy) and calc-gravelly sand deposits (Carter and Eade, 1980). Local unconsolidated sediment is primarily derived from alluvium and dune sand (Thompson, 1961). The much greater area of AK on the west coast is due to volcanic sediment derived from Mount Taranaki and the Taupo Volcanic Zone via the Waikato River that empties into the Tasman Sea southwest of Auckland, as well as from local sediment sources reworked on

shore (Richardson, 1975). The sediment from these sources are moved along the coast by north-moving longshore drift and incorporated into modern west coast barrier systems that front ancient kauri sites.

The late Holocene sites (HK) in the Waikato, and those situated along the eastern edge of the North Kaipara Barrier, are related to aggradational fluvial systems as sea levels rose during the early-mid-Holocene. Where ages are available, the non-marine sediments at these sites are all post-6.5 ka BP, following local sea-level stabilisation (Gibb, 1986). Although recognising some important differences (see later) we regard these late-Holocene sites as analogues for the earlier preservation of kauri at various times during OIS 3.

The connection between drowned fluvial–estuarine systems and preservation of HK in linked tributary valleys was first recognised close to the Kaihu River near Dargaville (Ogden, pers. comm.). At the Yakkas site (site code YAKK in Fig. 1), stratigraphic studies indicate that estuarine sedimentation in the palaeo-Kaipara Harbour was extensive and rapid, and was subsequently replaced by organic, fresh water sedimentation close to 6 ka BP. Aggradational fluvial features such as palaeo-river terraces observed near the Maitahi site, and relict levees observed up the Kaihu Valley probably resulted from sea-level rise and stabilisation at around the same time in the mid-Holocene (Ogden *et al.*, 1993). At the time of stabilisation, organic fresh water or sub-aerial sedimentation superseded estuarine sedimentation. Subsequently, any kauri communities that were located on nearby hills were then capable of

Figure 3 Relative difference between the three collections of kauri sites (i.e. MK, HK and AK) in terms of elevation against average ring-width (ARW)

colonising lower areas after 6 ka (Ogden *et al.*, 1993), but these areas were probably still prone to periodic flooding. This may help explain suppression and release patterns observed in some associated tree-ring series.

Subfossil kauri sites in the Lake Whangape catchment are connected to the Waikato River system. These subfossil sites were also probably affected by sea-level rise in the late Holocene. Evidence of lake inundation and lake-inlet switching for the Waikato lakes is clear in aerial surveys from the presence of palaeoinlets connected to abandoned bird-foot deltas. Fluvial aggradation and increased sedimentation due to sea-level rise is a likely cause of changing hydrologic conditions within the Lake Whangape catchment, and was probably also enhanced by increased sediment from the Taupo Volcanic Zone (G. Boswijk, pers. comm.). It is possible that hydrologic changes resulting from changes in the Waikato River system may have been imprinted in the kauri tree-rings at these sites.

Methods for collection and analysis of subfossil kauri

Typically, subfossil kauri logs are extracted from bogs that have been converted to pastureland. Much of the original vegetation was cleared prior to the early 20th century. Many of the bogs have been partially drained and often fires have repeatedly passed over them (McGlone, 1983; Ogden *et al.*, 1998). Site disturbance from kauri gum digging operations in the late 1800s, as well as shrinkage of peat following drainage, resulted in the exposure of buried wood. Despite subaerial erosion as a result of prolonged exposure, many well-preserved logs are still discovered. An example is the Awanui 'staircase' tree that is 3.8 m in diameter and radiocarbon-dated at greater than 55 ka (Fig. 4).

Our practice has been to work alongside milling companies who use large earth-moving machinery to extract the buried logs. As the logs are extracted, we cut cross-sections or biscuits from the base of the bole but above the root plate to avoid tree-ring distortion because of buttressing and flaring. Subsampling of the cross-sections is needed in order for the rings to be examined and measured under a binocular microscope. Tree-ring samples are prepared and analysed following

well-documented dendrochronological techniques for ring-width measurement and cross-dating (Stokes and Smiley, 1968; Fritts, 1976; Baillie, 1982; Schweingruber, 1988). Fortunately, kauri is relatively long-lived, with most subfossil trees having hundreds of rings. To date, we have collected 167 cross-sections from 16 different bog sites and 145 have been measured (Fig. 1, Table 1(c)). At almost every site, at least one cross-section was radiocarbon dated.

Discussion and conclusions

Dendrochronological and palaeoecological research at ancient kauri sites in Northland was initially undertaken in the early 1980s. Ogden *et al.* (1992) reviewed 107 radiocarbon-dated subfossil wood samples of Holocene or earlier age. Subsequently, Ogden *et al.* (1993) used average ring-width data of subfossil kauri in their reconstruction of the general patterns of temperature and rainfall in northern New Zealand, but at that time only one chronology from subfossil kauri wood had been published (Bridge and Ogden, 1986).

As with many palaeoecological studies, radiocarbon dating has been critical to understanding the relative time periods covered by the different tree-ring series. Unfortunately, in this case our samples are close to and sometimes beyond the limits of the radiocarbon-dating technique. Originally it was considered that the rangefinder ages prepared using the traditional acid–base–acid pretreatment method was suitable for all samples. However, it was soon discovered that this was not the case and that in some instances, significant modern contamination remained (in extreme examples, finite radiocarbon ages of 30 ka BP were found to be beyond the limits of the method when the alpha-cellulose component was extracted; Hogg *et al.*, 2006). Shifts of this magnitude in wood had previously not been recognised before and led to the research team having to shift to the more time-expensive alpha-cellulose extraction and revise their research accordingly. As a result, significant effort has been invested in fully quantifying the radiocarbon backgrounds of alpha-cellulose kauri samples so that precise, finite ages could be obtained (Hogg *et al.*, 2006; Turney *et al.*, 2006). The discovery that traditional pretreatment methods do not remove all contamination in the wood means

Figure 4 The 'staircase tree' at Ancient Kauri Kingdom, Awanui, Northland, New Zealand

Figure 5 Age-class distribution of OIS 3 kauri tree-ring samples

Table 2 Summary of OIS 3 tree-ring chronologies

Chronology name	Span of years	Number of trees	ARW (mm)	Radiocarbon age (years BP)	External cross-matched series
OMAHA1	2129	22	1.34	ca. 50 ka	Finlayson04 $t = 8.35/r = 0.41$
OMAHA2	1524	16	1.66	ca. 33 ka	
OMAHA3	853	5	1.54	ca. 28.5 ka	
OMAHA4	1061	5	0.93	>47 ka	Finlayson09 $t = 13.67/r = 0.45$
MANG1	1410	4	1.16	ca. 39 ka	
TRIG/VINAC1	1342	5	1.22	>35 ka	
TRIG/VINAC2	1230	5	1.19	ca. 36 ka	
TRIG/VINAC3	1170	4	1.28	Undated	
Floating temporal coverage	10 719				

that earlier age measurements are open to reinterpretation (e.g. Ogden *et al.*, 1993).

The age structure of the OIS 3 trees from the different sites is shown in Fig. 5 and demonstrates that a wide range of age classes for kauri has been preserved. Mortality was therefore not age-dependent. Possible scenarios for the age range of individuals found at each site could be a circle of encroaching forest trees growing densely around the bog margins (i.e. a successional hydrosere) that were periodically toppled during storm events as a result of enhanced wind-flow (Lorrey and Martin, 2005).

An example of the multi-millennial length tree-ring chronology construction potential for ancient kauri can be gleaned

from results of floating chronologies constructed (Table 2, Fig. 6). To date, up to 10 719 yr of floating chronology has been replicated. A new site developed at Finlayson's Farm (FIN) has shown that inter-site cross-matching of OIS 3 kauri has great potential for floating kauri site chronologies (Table 2). The inter-site cross-matching is impressive because the OIS 3 chronologies are separated by over a hundred kilometres (e.g. MNG and FIN; Table 2). This is consistent with results obtained from modern kauri sites where high inter-site correlations over large separation distances have been described (Ahmed and Ogden, 1985). In the example shown in Fig. 6, five trees from Trig Road (TRIG) and Vinac Farm (VIN) show high t -test values and together encompass 1342 yr. Furthermore, the spread in the

Figure 6 OIS 3 tree-ring chronology and cross-matching between trees from the sites Trig Road and Vinac Farm

radiocarbon ages obtained from within and between sites indicates that preservation did not take place during one specific period of time. There is therefore considerable potential to develop a continuous tree-ring chronology encompassing all of OIS 3.

The relationship between kauri tree-rings and the SOI (Fowler *et al.*, 2000), and the strong connection to the western pole of the El Niño–Southern Oscillation (ENSO; Fowler, 2005), means there is considerable scope that climatic indices can be successfully reconstructed from OIS 3 kauri at annual resolution over millennial timescales. As a result, records of the atmospheric and ocean circulation interplay between the Australasian and Antarctic sectors could be integrated over tens of thousands of years, and provide important data for global climate models.

The complete lack of any reported OIS 3 tree-ring material from the Northern Hemisphere, and only one published site from the Southern Hemisphere means ancient kauri tree-ring chronologies are some of the oldest, highest-resolution records reported to date. Because the advances in ancient kauri research have primarily been made in the last three years, we consider a continuous kauri chronology spanning tens of thousands of years for OIS 3 is possible within the next decade.

Acknowledgements We would like to acknowledge the support of the local millers and contractors—Dave Stewart, Nelson Parker, Milton Randall, Galvin Frost and Murray Ferris, as well as Albert Lovell and Betty Nelly from the The Kauri Museum (Matakohe). The extensive collection of samples from the Omaha Flats was due to the permission of Tony Gibbs. Technical assistance was provided by Peter Crossley. Anthony Fowler and Gretel Boswijk kindly gave permission to use their data for the comparisons. Funding assistance was provided for various aspects of the research by UK National Environment Research Council Grant # NER/A/S/2001/01037, New Zealand Marsden Award # 03-UOW-057 and UOA-108, Australian Research Council Grant # DP0451152 and FRST Grant UOAX0213.

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