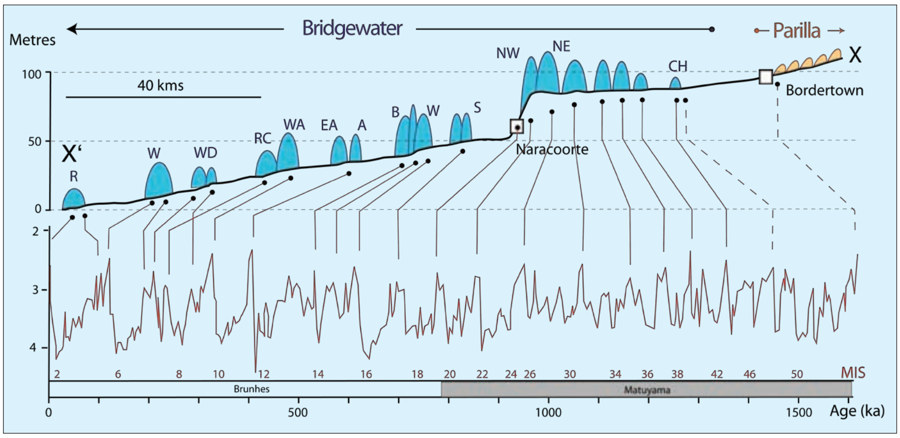

Figure 2: Correlation of the strandline-coastal ridge system (along profile line X'-X in Fig. 1c from near Kingston via Naracoorte to Bordertown) with marine isotopic interglacial peaks based on the chronology of Tian et al., 2002. Ridge sequence and isotope correlation, Naracoorte to coast from Murray-Wallace et al., 2001. The age of the oldest Bridgewater ridge is tentatively correlated with isotope stages 43 or 47, dated to near 1.3-1.4 Myr ago. Beach-ridge names: (CH) Cannonball Hill, (NE) Naracoorte East, (NW) Naracoorte West, (S) Stewart, (W) Woolumbool, (B) Baker, (A) Ardune, (EA) East Avenue, (WA) West Avenue, (RC) Reedy Creek, (WD) West Diary, (W) Woakwine, (R) Robe (Murray-Wallace et al., 2001).

understanding of that role presents new challenges in modeling predictions of future greenhouse responses.

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NZ-Maars: Extracting high resolution paleoclimate records from maar crater lakes, Auckland, New Zealand

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Introduction

An understanding of the mechanics of past climate change is a powerful tool for managing the consequences of present and future climate variability. However, the high-resolution records of climate change needed to determine the forces driving this variability are typically limited to the duration of the instrumental record. The short duration of that record in New Zealand (little more than 100 years) means that we have limited insight into the operation of the climate system under earlier and different climate scenarios, so that we need to use geological data sets to reconstruct past climates (Shulmeister et al., 2006). However, most geological datasets have a resolution of millennia to centuries at best, too coarse for integration with climate systems operating on timescales of months to decades. Hence, the NZ-Maar project was established to exploit the high-resolution paleoclimate records contained in laminated maar lake sediment sequences from Auckland, northern New Zealand (Fig. 1).

The Auckland region has a dense cluster of about 48 basaltic volcanoes, mostly tuff rings and scoriaceous cinder cones, all within Auckland City, New Zealand's largest and most densely populated center (Fig. 1). In addition, there are a number of maar craters, each of which has been a lake some time after its formative eruption, and several of which have been cored to extract records of sedimentation and

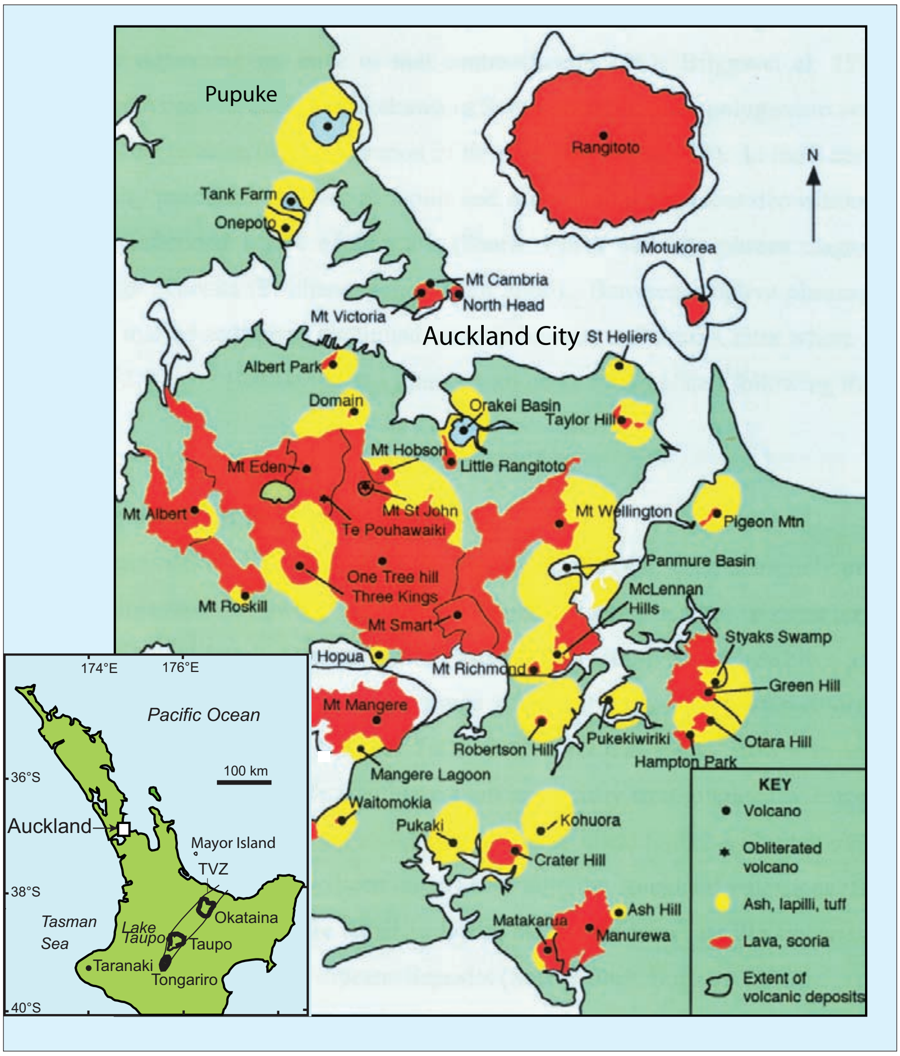

*Figure 1: Location map showing Auckland basaltic cones and maar craters. **Inset** andesitic and rhyolitic tephra sources and volcanic setting of study area (TVZ - Taupo Volcanic Zone) (modified from Alloway et al., 2007).*

paleoenvironments extending back to at least 245 kyr BP. (e.g., Shane and Hoverd, 2002; Horrocks et al., 2005). The Auckland region of northern New Zealand is important in a paleoenvironmental context since it forms an ecological boundary between the far northern North Island and cooler regions to the south.

Aims

The major goal of the NZ-Maar project is to increase our knowledge of the behavior of the New Zealand climate system over the last 50 kyr. This knowledge will be used to contribute to the understanding of climate teleconnections between the northern and southern hemispheres during glaciations, with a focus on abrupt climate change events and long-term variability in global oscillatory climate systems (e.g., El Niño Southern Oscillation: ENSO, and Pacific Decadal Oscillation: PDO). As subsidiary goals, the research is also contributing to the development of paleoclimate proxies and their application to New Zealand data, as well as resolving issues regarding the timing, nature and impacts of volcanic eruptive events in Auckland, the Taupo Volcanic Zone (TVZ) and Mt Taranaki.

Methods

The Auckland maar lake sequences contain numerous chemical and biological markers from which a variety of high-resolution ecological and climatological information is being derived. A multi-proxy approach to reconstructing the past environments is being undertaken using: pollen, diatom and chironomid paleoecology; oxygen isotope analysis of diatom silica and sponge spicules and cellulose extracted from lake sediments; carbon and hydrogen isotope analysis of lipid biomarkers; high-resolution elemental geochemistry, and; laminae thickness and facies analysis. Furthermore, the maar lakes received fallout tephra, many of which are well-dated and chemically distinguishable, providing robust age control for the records of climate change they contain (Shane and Hoverd, 2002). In addition, the Auckland maar lakes sometimes demonstrate annual-to-decadal resolution in their laminae and provide a record that details short-duration climate changes as well as long-term trends (Pepper et al., 2004; Shulmeister et al., 2006). The combination of reliable dating tools and proxies of change gives us the ability to determine the exact timing, duration and nature of all of the major climate events to impact northern New Zealand in the past 50 kyr (the limit of reliable tephra and ^{14}C ages).

Results and discussion

Pupuke (the only crater that contains a lake at present), Onepoto, Pukaki, Hopua and Orakei maar craters (Fig. 1) provide excellent late Quaternary tephra and multi-proxy paleoenvironmental records. The rhyolitic and andesitic marker tephra are sourced from the Taupo Volcanic Zone and Mt Taranaki (Fig. 1) and enable stratigraphic correlation between the maar lake sediment sequences, allowing confident identification of coeval changes in the proxies studied at each site. At the younger end of the Pupuke maar lake sequence, ^{210}Pb dating, combined with known-age chemical markers and first appearance of exotic *Pinus* pollen, have provided a well-dated, high-resolution paleoenvironmental record for the past 200 yr covering the entire period of European settlement on the Auckland Isthmus (Augustinus et al., 2006). We have acquired a complete laminated ca. 50 kyr long record from Lake Pupuke (average sedimentation rate 0.35 mm/yr, increasing to 4.5 mm/yr over the past 190 years), which can be correlated directly using marker tephra to the lower resolution Onepoto maar paleolake record (0.13 mm/yr) that extends from 9 cal kyr BP back to ca. 245 kyr BP (Shane and Hoverd, 2002). We recently analyzed another long lake sediment record extending from 14.7 cal kyr BP to ca. 100 kyr from Orakei maar paleolake at a higher resolution of ca. 1 mm/yr.

The Last Glacial Cold Period (LGCP) to early Holocene sequences from Auckland maar lakes provide probably the highest resolution and best-dated terrestrial paleoenvironmental records spanning this period from New Zealand. Selected features of this record as well as one from Pukaki, are shown in Figure 2. There is a close match between the log lowland podocarp grass pollen ratio (LPG), representative of the degree of forest development, from Onepoto and Pukaki maar lakes. These indicate regional LGCP cooling, which commenced ca. 27.5 cal kyr BP, followed by three cool intervals separated by brief milder intervals. δ^{13}C enrichment in the lake sediment organic matter during the LGCP was largely caused by superimposed changes in atmospheric pCO_2 and climatically-induced water stress. This evidence for drier conditions is supported by coeval increased fire frequency (charcoal peaks) and erosion (clastic sediment inwash). The δ^{13}C depletion, together with the expansion of podocarp forest following the commencement of Termination I at ca. 18 cal kyr BP, reflects climatic amelioration, increased water availability and reduced wind stress. δ^{13}C depletion during the Late Glacial-Interglacial Transition mainly reflects increased algal productivity in Onepoto maar lake during the Early Holocene Warm Period, previously identified in several New Zealand paleoclimate records (Fig. 2; Alloway et al., 2007). The Late Glacial Climate Reversal (Fig. 2; Alloway et al., 2007) may be reflected in a brief period of δ^{13}C depletion at ca. 13 cal kyr BP, although the Auckland maar lake pollen record is equivocal in this regard.

Termination I occurred ca. 18 cal kyr BP in the multi-proxy Auckland maar lake sequences, as well as many other New Zealand and Antarctic ice core proxy records (Fig. 2; Alloway et al., 2007). Furthermore,

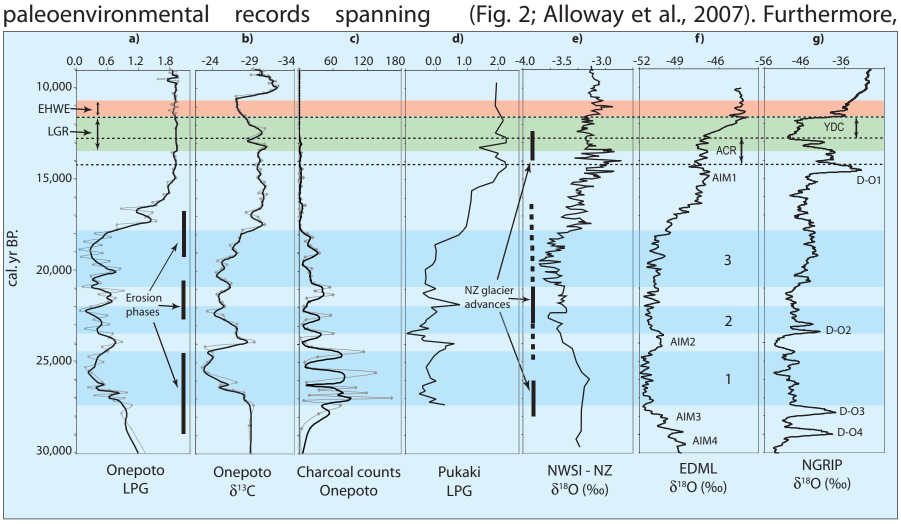

*Figure 2: Comparison of trends in Onepoto maar lake proxies with other proxy paleoclimate data from New Zealand and from Antarctica and Greenland spanning ca. 30 - 9 cal. kyr BP.; **a,b**) Log podocarp/grass pollen ratio (LPG) and organic matter δ^{13}C records from Onepoto maar lake. Erosion phases inferred in the Onepoto maar record from grain size and elemental geochemistry (Augustinus, unpub data); **c**) Charcoal counts from Onepoto maar lake; **d**) LPG record from Pukaki maar lake (Alloway et al., 2007); **e**) New Zealand speleothem composite record from the northwest of the South Island (NWSI) (Alloway et al., 2007); **f**) EPICA Dronning Maud Land δ^{18}O record showing the Antarctic Cold Reversal (ACR) and Antarctic Isotope Maxima (AIM) 1 to 4 (EPICA Community Members, 2006); **g**) NGRIP δ^{18}O record showing the Younger Dryas Chronozone (YDC) and Dansgaard-Oeschger Events (D-O) 1 to 4 (NGRIP Members, 2004). Horizontal blue bars labelled 1 to 3 indicate inferred cool phases during the LGCP. Horizontal green and red bars represent the timing of the Lateglacial Reversal (LGR) and Early Holocene Warm Event (EHWE) respectively in New Zealand (Alloway et al., 2007).*

the apparent phase relationship between the Auckland maar lake and Antarctic Isotope Maxima (AIM) warming intervals during the LGCP and their out-of-phase relationship with Greenland ice core Dansgaard-Oeschger events (Fig. 2) provides further support for interhemispheric asynchrony in rapid climate change.

Members of NZ-Maar:

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Five centuries of ENSO history recorded in *Agathis australis* (kauri) tree rings

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Kauri (*Agathis australis* (D. Don) Lindley) is a canopy-emergent conifer endemic to northern New Zealand (north of latitude 38°S). Mature adults can achieve heights of 30 m and trunk diameters over 2 m are not uncommon. Trees often live for more than 600 years, and ages in excess of 1000 years are known (but rare). This longevity, strategic location in the data-deficient southern hemisphere, and an abundance of source material (living trees, logging relics, colonial-era buildings, sub-fossil wood preserved in swamps; Fig. 1), gives kauri considerable potential for paleoclimate applications. All four sources of material have been successfully exploited and an extensive kauri tree-ring database has been developed. This includes data from 17 modern (living tree) sites, collected in the 1980's, late 1990's and early 2000's (Fowler et al., 2004); 16 colonial-era structures and a logging relic, collected since 2001; and numerous sub-fossil assemblages, collected in the 1980's, late 1990's and early 2000's. The combined tree-ring data provide continuous coverage of the past 3700 years (Boswijk et al., 2006) with "floating" sequences of mid-Holocene date indicating the potential to extend the calendar-dated record back further in time. Large quantities of sub-fossil pre-Holocene wood (Palmer et al., 2006) will also enable paleoclimatic analyses for millennial-length windows over much longer time scales.

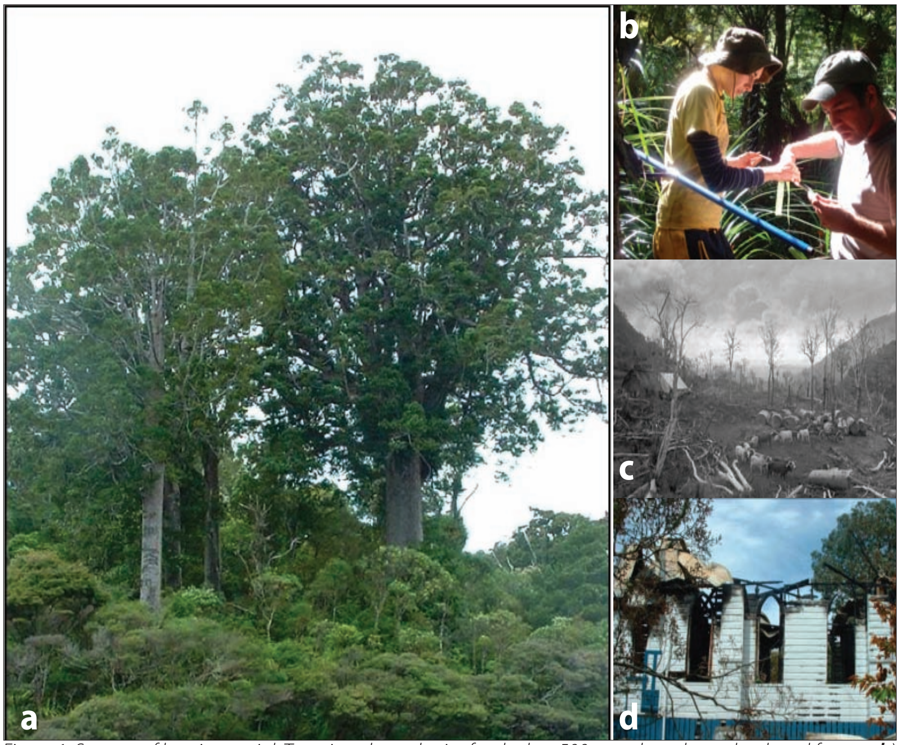

*Figure 1: Sources of kauri material. Tree-ring chronologies for the last 500 years have been developed from: **a,b**) living trees; **c**) a few logging relics (picture courtesy of Auckland Museum Collection); and **d,e**) from colonial-era building timbers.*

In the growing season, Kauri growth is enhanced by cool-dry conditions, yet suppressed by warm-wet conditions, particularly in the austral spring (Sep-Oct–Nov; SON). This relationship to climate is fortuitous in terms of El Niño Southern Oscillation (ENSO) reconstruction potential, because such conditions are associated with El Niño and La Niña events, respectively, in the far north of New Zealand. Moreover, the strongest relationships between kauri growth and climate occur during SON, coincident with the peak strength of the teleconnection between ENSO and New Zealand climate. Recognition of these juxtapositions led to the identification of kauri's potential as an ENSO proxy in the 1990's (Fowler et al., 2000) and has been the primary impetus for research undertaken by the University of Auckland Tree-Ring Laboratory ever since. Fowler et al., (2007) summarized the current understanding, derived from that research. They suggest there is a significant regional-scale forcing signal in the width of kauri tree rings and ENSO is the dominant contributor to that forcing. ENSO's influence on kauri growth is predominantly via the western pole of the Southern Oscillation. Wide kauri tree rings tend to be associated with El Niño events (narrow with La Niña), with similar event registration strength. Strongest statistical relationships are for a five-season window from March, prior to growth initiation (in September), through to the following May. Growing season relationships are stronger when ENSO is most active (e.g., early and late 20th century), but otherwise