Volcanic hazards in Auckland, New Zealand: a preliminary assessment of the threat posed by central North Island silicic volcanism based on the Quaternary tephrostratigraphical record

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Abstract: The City of Auckland (population *c.* 1 million), built on a basaltic volcanic field active as recently as *c.* AD 1400, faces an additional volcanic threat: that from several large and productive rhyolitic and andesitic eruptive centres of the central North Island, 140–280 km to the south and southeast. Non-basaltic tephra fallout layers originating from these distal eruptive centres are numerous and widespread in the Auckland region and have primary thicknesses ranging from *c.* 1 mm to $\geqslant$ 0.6 m; ignimbrites up to 9 m thick are also documented but are uncommon. The assessment of volcanic hazards in Auckland is made problematical by the different types of volcanic threat posed by these two spatially distinct source areas, and by the lack of recognition hitherto given to the threat from the distal sources. This paper reviews the Quaternary records of distal volcanism affecting Auckland and outlines current investigations into the assessment of environmental impacts of past eruptions. Our preliminary results indicate that the potential threat to Auckland from the distal volcanic sources has been underestimated and that further research into the impacts of Quaternary volcanism on Auckland's environment and infrastructure is essential. The importance of this threat was underscored in mid-1996 when a small magnitude eruption of Mt Ruapehu necessitated closure of Auckland International Airport for three nights.

Assessments of volcanic hazards for the City of Auckland have focused entirely on the threat from the local volcanic field (Figs 1, 2). The surface geology of the city is dominated by Late Quaternary basaltic volcanism, represented by 49 centres, with the most recent eruption (Rangitoto) about 500 radiocarbon years ago (Brothers & Golson 1959; Nichol 1992; Lowe *et al.* 1999*b*) attesting to continuing activity. (All ages reported in the text are conventional radiocarbon ages based on the old half-life unless otherwise stated.) The field is characterized by low-frequency, low-magnitude

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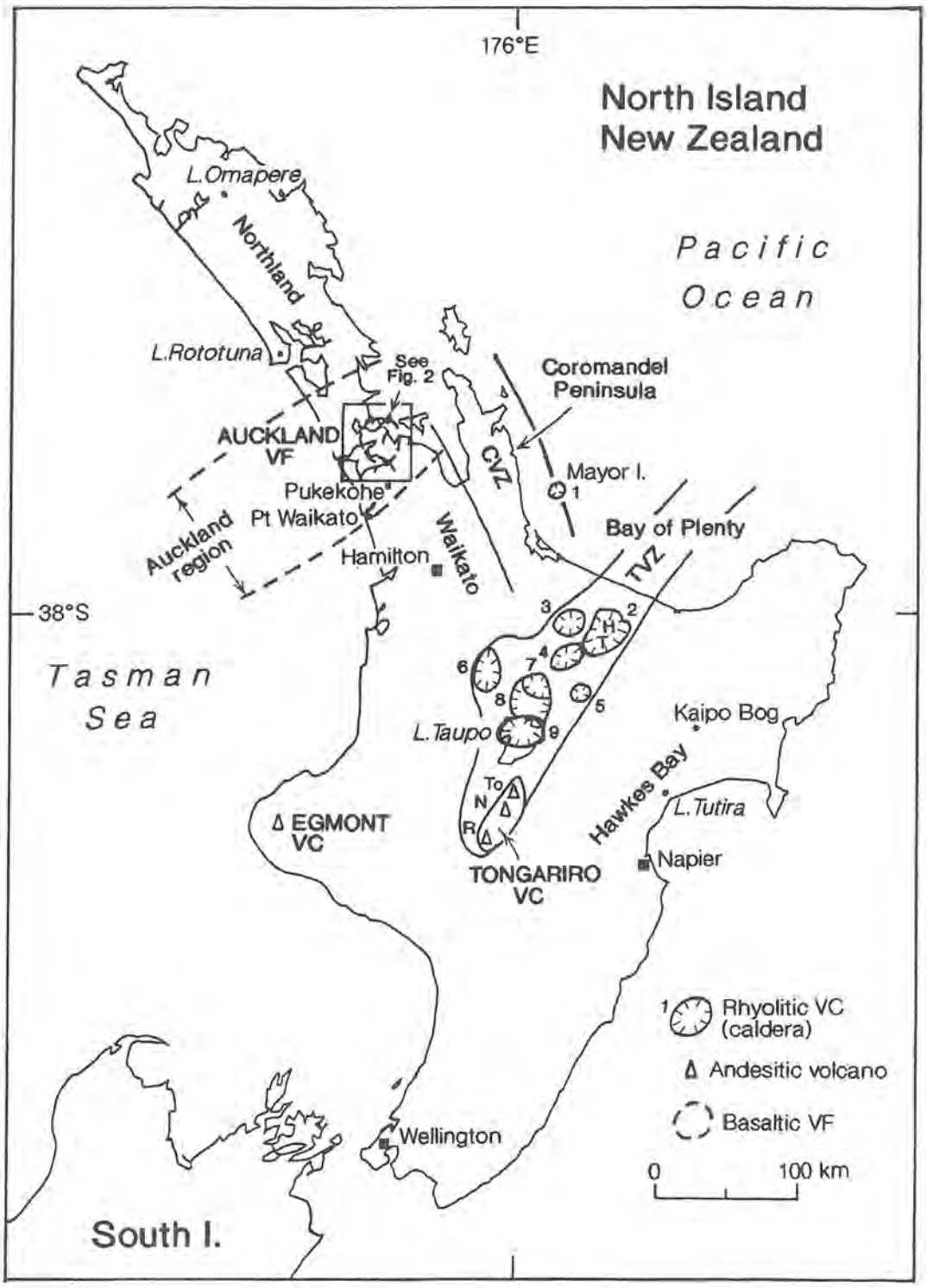

Fig. 1. Locations of the main volcanic centres active in the central North Island during the Quaternary (after Houghton *et al.* 1995; Wilson *et al.* 1995*c*), and other localities mentioned in the text. TVZ, Taupo Volcanic Zone; CVZ, Coromandel Volcanic Zone (Skinner 1986). Rhyolitic volcanic centres: 1, Tuhua; 2, Okataina; 3, Rotorua; 4, Kapenga; 5, Reporoa; 6, Mangakino; 7, Maroa; 8, Whakamaru; 9, Taupo. Named volcanoes: H, Haroharo; T, Tarawera; To, Tongariro; N, Ngauruhoe; R, Ruapehu. VF, volcanic field; VC, volcanic centre.

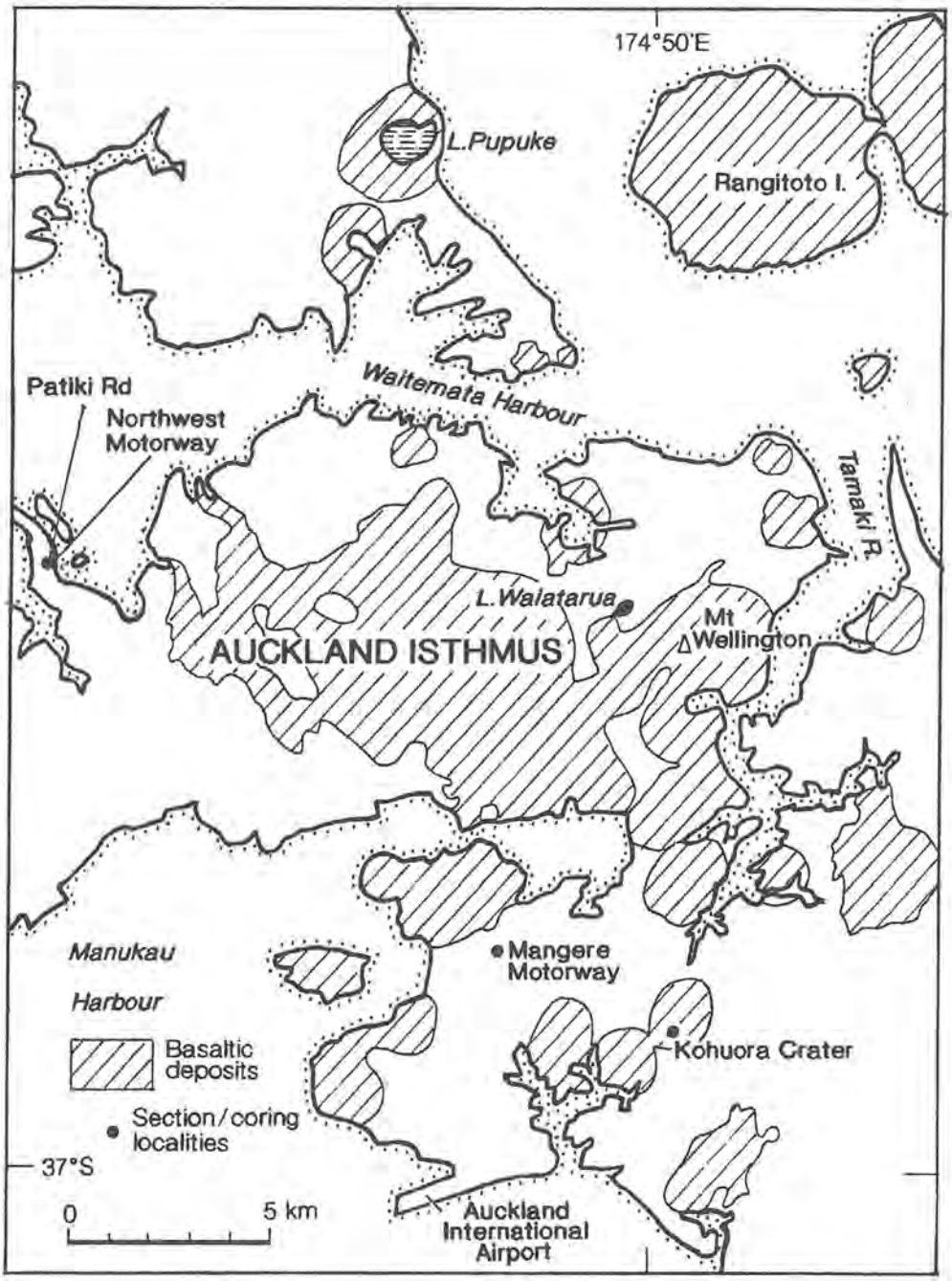

Fig. 2. Auckland Isthmus and basaltic deposits (scoriaceous tephra, tuff, lava) of the Auckland Volcanic Field (after Kermode 1992), and locations of sites referred to in the text. The map encompasses the majority of the Auckland urban area, which has a population of *c.* 1 million.

basaltic eruptions and, although most hazards are probably confined to a radius of 1-4 km, the concentration of population, buildings, transport and communication systems, and economic activity, together with uncertainties in locating the next eruptive centre, mean risk levels are high (Dibble *et al.* 1985; Cassidy *et al.* 1986; Houghton *et al.* 1988; Kermode 1992; Smith & Allen 1993; Allen & Smith 1994; Johnson *et al.* 1997). The main hazard types are destructive pyroclastic surges and small blasts including phreatomagmatic activity, fall of wet or dry tephra (i.e.

unconsolidated ash, lapilli, bombs or blocks), and aa and pahoehoe lava flows (Allen & Smith 1994; Johnson *et al.* 1997). The associated tsunami hazard in the Auckland region is comparatively minor — a recent assessment by de Lange & Hull (1994) concluded that the greatest threats are from earthquake-generated events or far-field volcanogenic tsunami from the west coast of South America.

However, the City of Auckland also faces a quite different volcanic hazard, namely that arising from deposits originating from distant rhyolitic and andesitic volcanic centres in the central North Island (CNI) (Fig. 1). These centres have been active during most of the Quaternary and are characterized by relatively high-magnitude, high-frequency eruptions. In this paper, evidence is presented that demonstrates that CNI volcanism is likely to be hazardous to the City of Auckland, and preliminary work towards an improved assessment of these hazards is described. It is our contention that the threat of tephra fall in particular from these distant volcanic centres has not been adequately assessed, and hence we suggest lines of research that could be undertaken to assist with a re-evaluation of the full spectrum of volcanic hazards that the city and surrounding region faces.

Quaternary volcanism in the central North Island

It has been estimated that *c.* 25% of the world's eruptions in historical or prehistorical times with a volcanic explosivity index of 5 or more were from the CNI of New Zealand; moreover, this region contains the world's strongest concentration of youthful rhyolite volcanoes (Simkin & Siebert 1994). In CNI, andesitic activity started *c.* 2 Ma ago and was joined by voluminous rhyolitic (plus minor basaltic and dacitic) activity from at least *c.* 1.6 Ma (Wilson *et al.* 1995*c*). This silicic volcanism has produced a complex of volcanic centres and covered much of the CNI with extensive plateaux of ignimbrites (deposits from pyroclastic flows) and mantling tephra fall deposits which together have bulk volumes *c.* 15 000-20 000 km^3 (Healy 1992; Houghton *et al.* 1995; Wilson *et al.* 1995*c*). The most extensive pyroclastic deposits are derived from rhyolitic caldera volcanoes of the central Taupo Volcanic Zone (TVZ) (Fig. 1). Smaller volumes have been erupted from the andesitic centres, chiefly Egmont and Tongariro volcanic centres, and from the offshore peralkaline Tuhua Volcanic Centre (Mayor Island). TVZ activity has continued to the present. Beyond these source regions, numerous tephra layers have been identified from their stratigraphic position, field properties, mineralogy, and chemical composition, and the radiometric or geomagnetic ages of many Quaternary units are now known with reasonable certainty (e.g. see Froggatt & Lowe 1990; Shane & Froggatt 1991; Kohn *et al.* 1992; Stokes *et al.* 1992; Alloway *et al.* 1993, 1995; Wilson 1993; Shane 1994; Houghton *et al.* 1995; Donoghue & Neall 1996; Naish *et al.* 1996; Pillans *et al.* 1996; Shane *et al.* 1996).

We focus below on five major eruptive centres of CNI that have been active during the Late Quaternary, these representing the greatest potential threat to the City of Auckland today. The reader is referred to Blong (1984, 1996) and Chester (1993) for comprehensive overviews of the effects of volcanic eruptions, and to Dibble & Neall (1984), Dibble *et al.* (1985), Gregory & Watters (1986), Houghton *et al.* (1988), Ministry of Civil Defence (1995), Johnson *et al.* (1997), and Houghton (1998) for more specific accounts of the principal volcanic hazards of North Island.

Tuhua (Mayor Island)

Situated 30 km from the Coromandel/Bay of Plenty coast and 140 km southeast of Auckland, this isolated, peralkaline rhyolite volcano has a complex history of eruptions dating from *c.* 130 ka (Houghton *et al.* 1992). It exhibits a wide range of eruption styles and intensity, with the largest known event occurring *c.* 6.2 ka ago (Tuhua Tephra). This tephra is widespread on North Island (Hogg & McCraw 1983; Lowe 1988; Newnham & Lowe 1991), but only one other event (Te Paritu Tephra at *c.* 14.5 ka) is recorded on North Island (Lowe 1988; Wilson *et al.* 1995*a*). Three other Mayor Island-derived tephras, all pre-Holocene, have been recorded in sediments in marine cores northeast from the volcano (Pillans & Wright 1992). Activity on Mayor Island since the Tuhua Tephra was deposited seems to be limited to caldera infilling by lavas within the last few thousand years (Houghton *et al.* 1992). The potential hazards for Auckland are confined to ashfall, and are likely to occur only from powerful eruptions taking place during easterlies (Buck 1985).

Okataina

Okataina is the world's second most productive rhyolitic volcanic centre (Wilson 1993; Wilson *et al.* 1995*c*). Situated *c.* 200 km south-southeast of Auckland, it consists of two major volcanoes, Haroharo and Tarawera. Tarawera erupted 10 June AD 1886, producing the biggest and most destructive eruption in New Zealand in historical times (Walker *et al.* 1984). Nine other large eruptive episodes are recognized spanning the last *c.* 21 000 years (Nairn 1989; Froggatt & Lowe 1990; Lowe *et al.* 1998), while a number of earlier events additionally deposited ignimbrites that individually exceeded 100 km^3 in magma volume (Dibble *et al.* 1985; Nairn 1989, 1991). Eight macroscopic tephra fallout layers derived from the Okataina Volcanic Centre, ranging from 1-110 mm in thickness, have been identified in post-18 ka lake sediments and peats near Hamilton in the Waikato region, *c.* 80-130 km south of Auckland (Lowe 1988; Hodder *et al.* 1991; Newnham *et al.* 1995). The principal hazards for Auckland are likely to be tephra fall during southeasterlies and southerlies and, in extreme cases, pyroclastic surge and flow with co-ignimbritic ash.

Taupo

Situated *c.* 230 km south of Auckland, Taupo is the single-most frequently active and productive rhyolitic volcano on Earth (Wilson 1993). The products of 28 eruptions postdating the voluminous 22 600 years BP Kawakawa (Oruanui) eruption (which generated $\geqslant$ 800 km^3 of erupted material) have been described by Wilson (1993). All but seven of these were plinian in dispersal. The latest major eruption was the immensely powerful ultraplinian Taupo Tephra event (equivalent to Unit Y of Wilson 1993) *c.* 1850 years BP. Because there is a wide spectrum of eruptive volumes and repose intervals, the timing and size of any future eruption cannot be predicted easily. Taking a longer-term perspective, Wilson (1993) suggested that in terms of time and erupted volumes, the post-22.6 ka record at Taupo may be considered as eruptive 'noise' superimposed on the more uniform, longer-term activity in the central Taupo Volcanic Zone as a whole, where very large

eruptions such as the Kawakawa occur on the average at more evenly spaced intervals of around one per 40-60 thousand years (see also Houghton *et al.* 1995; Wilson *et al.* 1995*c*). At least five macroscopic tephra fallout layers derived from the Taupo Volcanic Centre, ranging from 2-50 mm in thickness, have been deposited in post-18 ka lake sediments and peats in the Waikato region (Lowe 1988; Hodder *et al.* 1991; Newnham *et al.* 1995). As with Okataina, the principal hazards for distant localities are likely to be tephra fall deposition and, in extreme events, pyroclastic surge and flow with co-ignimbrite ash.

Tongariro

The principal sources of local (CNI) volcanic risk today are the subduction-related andesitic volcanoes of the Tongariro Volcanic Centre (Dibble *et al.* 1985), situated 260-280 km south of Auckland. Contemporary activity at Mt Ruapehu (2797 m above sea-level (asl)), a large stratovolcano, has resulted in tephra fall at distances >100 km away in recent decades. The AD 1995 and 1996 eruptions of Ruapehu produced a cumulative volume of 0.06 km^3 of tephra that was deposited >300 km from source over an area >30 000 km^2 (Houghton *et al.* 1996), and resulted in the temporary closure of eleven airports throughout the North Island. At Auckland, the International Airport was closed overnight on three occasions for *c.* 12 hours in mid-1996 (19 June; 8 & 9 July), whilst an associated deterioration in air quality was recorded (G. Fisher, pers. comm. 1996). Mt Ngauruhoe (2290 m asl) is essentially a parasitic cone on Mt Tongariro (1968 m asl) that has erupted, on the average, every second year since AD 1839, the latest major event being in AD 1974-5 (Nairn & Self 1978). These recent eruptions of Ruapehu and Ngauruhoe have been on a relatively minor scale in comparison with much of their previous activity. The Late Quaternary history of the centre has been described by Hackett & Houghton (1986), Donoghue *et al.* (1995, 1997), Donoghue & Neall (1996), Cronin *et al.* (1996) and Nairn *et al.* (1998). Eleven post-12 ka tephra fallout layers from the Tongariro Volcanic Centre have so far been identified as medium-coarse ash layers 1–20 mm thick in lake sediments in the Waikato region (Lowe 1988). Thin macroscopic and microscopic ash layers from Tongariro are also recorded in sediments of both Lake Tutira and Kaipo peat bog, respectively *c.* 120 km to the east and 150 km northeast of source (Lowe & Hogg 1986; Eden *et al.* 1993; Eden & Froggatt 1996; Lowe *et al.* 1999*a*). The potential impacts for Auckland are likely to be limited to ash fall deposition during southerlies.

Egmont (Taranaki)

The Taranaki landscape of western North Island is dominated by the 2518 m-high subduction-related andesitic Mt Egmont volcano (also known as Mt Taranaki), situated 280 km south of Auckland. The youngest and most southerly volcano of the Taranaki volcanic succession, Egmont is the second highest mountain in the North Island and the largest andesitic stratovolcano in New Zealand. The post-130 000 year stratigraphic record indicates that ash eruption and lahar inundation are typical recurring features of Egmont volcano. Since 28 ka, at least 76 tephras (with volumes >10^7 m^3) have been erupted intermittently (Alloway *et al.* 1995), with the latest definitive eruption of the volcano at *c.* AD 1755 or possibly later, near *c.*

Table 1. *Some effects of the accumulation of critical thicknesses of tephra*

Thickness	Effects on humans and livestock[a]	Effects on property and vegetation
1 mm	Little or none. Minor short-lived respiratory problems. Rapid recovery.	Airports closed. Minor disruption of some water supplies. Electronic and magnetic media affected
1 cm	Fish and insects killed. Little or no visibility. Infections of respiratory tract, asthma. Inflamed eyes.	Rusting of exposed metal. Transport immobilized. Electrical shorting and transformer fires. Stormwater and sewage systems may become inoperative. Food crops will require protection or post-harvest cleaning.
10 cm	Serious respiratory problems. Some human deaths possible. Bird life killed. Livestock will require imported feed.	Power blackouts. Crops destroyed or severely damaged. Trees stripped and branches broken. Roof collapse may occur.
1 m	Deaths and injuries due to building collapse. Livestock need to be moved or protected.	Building collapse. Vegetation fires. Trees destroyed. Total failure of all lifelines. Emergency services inoperative. Severe siltation of drainageways, ports and harbours.
10 m	Enormous loss of human life through building collapse and burns. Total loss of livestock.	Long-term loss of land use. Widespread building collapse. Some drainage ways, ports and harbours permanently altered.

[a] The effects are probably conservative especially at the 1 and 10 m levels [after Houghton *et al.* (1988) and Blong (1996)].

AD 1860 (Druce 1966; Neall 1972, 1992; Neall & Alloway 1986; Lees & Neall 1993; Price *et al.* 1999; Lowe *et al.* 1999*b*). Though not as voluminous as their more silicic counterparts, Egmont-sourced tephra beds are now recognized as more frequently erupted and more widely distributed across the North Island than first envisaged. Twelve post-12 ka tephra fall beds have so far been identified as medium-coarse ash layers 1-5 mm thick in lake sediments and peats of the Waikato region, *c.* 150-200 km north-northeast from source (Lowe 1988; Hodder *et al.* 1991; Newnham *et al.* 1995). Macroscopically visible Egmont tephras have also been identified in sediments of Lake Tutira (Eden *et al.* 1993; Eden & Froggatt 1996) and Kaipo bog (Lowe *et al.* 1999*a*). The principal threat to Auckland is ash-fall during southerlies and southwesterlies.

What are the likely threats for Auckland?

For the Auckland region, most of the volcanic hazards associated with these CNI centres do not pose a major threat. The most obvious hazards include ignimbrites, co-ignimbrite ash fall, lahars, and seismic activity. While devastating close to source, most of these hazards will have negligible physical impact on the Auckland region except for perhaps deposition from extreme but very infrequent ignimbritic events. The main volcanic hazards considered likely to have a direct physical impact upon Auckland on a relatively frequent basis would be fallout of silicic tephras and associated aerosols. The nature and extent of impact of tephra fall will be related to the primary thickness of the deposit (Table 1).

In turn, the thickness, as well as particle size and composition of tephric material deposited distally, and the distances and directions that tephras are transported, will be influenced by a number of volcanological and meteorological factors. Volcanological factors include the style of eruption, direction of blast and orientation of vent, physical and chemical properties of the source magma and the degree of magma–water interaction, height of eruption column, volume of erupted material, and whether or not pyroclastic flows are generated (Cas & Wright 1987). The efficacy of tephra fall dispersal will also depend upon wind direction, especially that of the jet stream in the stratosphere, as well as the dispersal characteristics of the fall deposits and synoptic meteorological conditions prevailing between the volcanic centre and the extremes of the tephra dispersal range. Duration of the eruptive episode and whether this is continuous or interrupted will also be important (Wilson 1993). Distal tephra thicknesses may be increased by co-ignimbritic ash fall due to elutriation from pyroclastic flows (Sparks & Walker 1977; Froggatt 1982; Fisher & Schmincke 1984) or by premature fallout due to particle aggregation or scavenging (Cas & Wright 1987). Overthickening of tephras in stratigraphic sequence may also occur because of reworking or by the addition of contemporaneous non-tephric material to the tephra unit. Remobilization of tephra-fall deposits following severe rainstorms also may lead to substantial overthickening in drainage channels adjacent to large catchments.

Assessment of volcanic hazards at distal localities should also consider the possible impacts of acid aerosols generated by volcanoes. For example, fluorine-rich gas and ash associated with the Laki fissure eruption of AD 1773 destroyed crops and livestock throughout Iceland and killed 24% of the human population by starvation (Simkin, 1994); social, ecological and meteorological impacts of volcanogenic gases and aerosols associated with this eruption elsewhere in northern Europe have been reported (Grattan *et al.* 1998; Brayshay & Grattan 1999). It has been suggested that the concentration of acid volatiles adsorbed on the surface of tephra particles in an eruption cloud may increase with time spent in transport and distance travelled (Oskarsson 1980; J. Grattan, pers. comm. 1995). Clearly, the possibility of volcanogenic 'acid rain' from CNI eruptions exacerbating Auckland's urban air pollution levels in certain meteorological conditions needs to be considered.

New Zealand's comparatively brief historical and documented era means that evaluation of these potential hazards requires an examination of Quaternary tephrostratigraphical records in the Auckland region. Although urban development across the Auckland Isthmus (Fig. 2) has destroyed or obscured much of the Quaternary geology, much valuable work can still be undertaken there to assist with assessment of the tephra hazard for Auckland from CNI eruptions. Three types of investigation could be pursued profitably:

1. extrapolation from tephra isopachs determined for localities intermediate between Auckland and the CNI volcanoes;
2. review of CNI tephras previously reported in the Auckland and Northland areas, coupled with field observations at new sites;
3. investigation of the impact of past CNI tephra deposition on the Auckland environment using appropriate palaeoecological techniques.

The results of preliminary work that demonstrates the potential of such investigations are reported here.

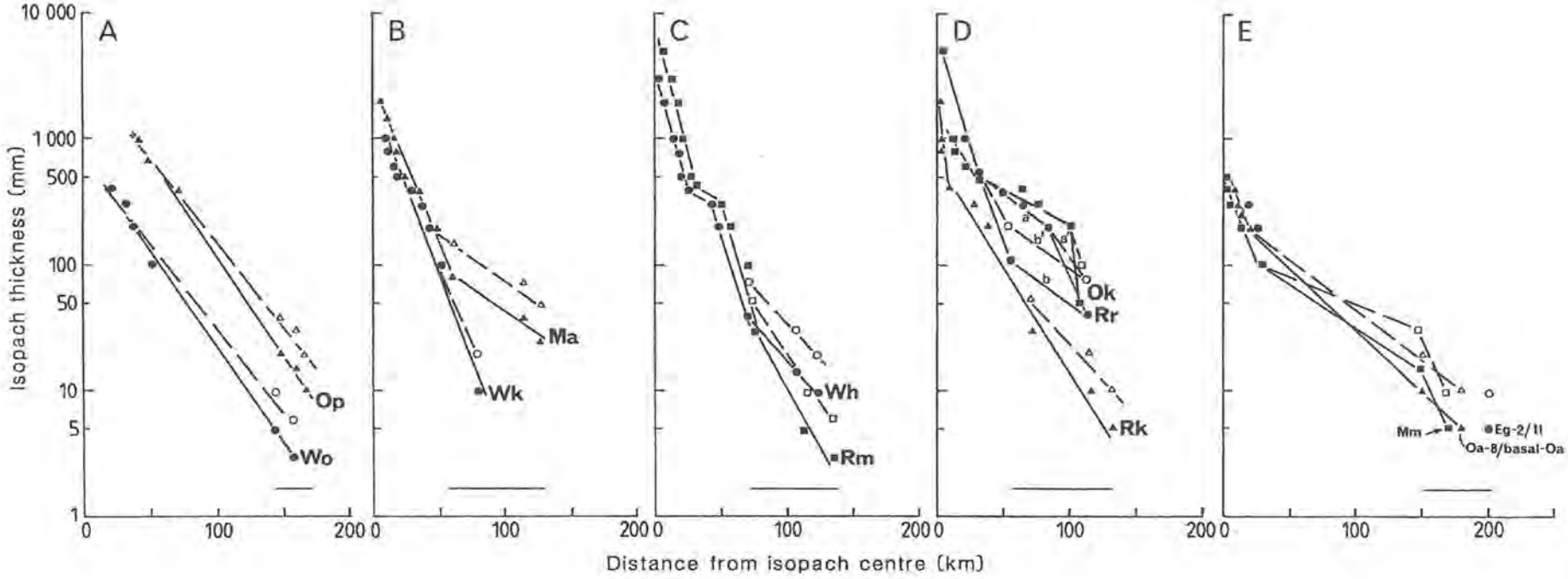

Fig. 3. Plots of tephra isopach thickness against distance from source for twelve post-18 ka CNI-derived tephras based on their distribution in the Waikato region (reprinted from Lowe 1988, fig. 13, p.157, with permission from SIR Publishing). Dashed curves join compaction-adjusted thicknesses (open symbols) for tephras recorded in Waikato lakes. Horizontal bars indicate region of Waikato lake core thickness measurements. Symbols for tephras: Wo, Whakaipo (Unit V of Wilson 1993); Op, Opepe (Unit E); Wk, Whakatane; Ma, Mamaku; Rm, Rotoma; Wh, Waiohau; Rr, Rotorua; Rk, Rerewhakaaitu; Ok, Okareka; Mm, Mangamate (?Waihohonu Lapilli: Donoghue *et al.* 1991); Oa-8/basal-Oa, Okupata; Eg-2/II, Englewood (Alloway *et al.* 1995).

Extrapolation from tephra isopachs

Lowe (1988) constructed provisional isopach maps for eleven post-15 ka CNI tephras recorded in lake sediment cores at 14 sites in the central Waikato region, near Hamilton, *c.* 100–200 km from the CNI volcanic centres and approximately midway between most of these and the City of Auckland (Fig. 1). Andesitic tephras (from Tongariro and Egmont) are more common in the south with their thicknesses decreasing markedly to the north and east. Lowe (1988) argued that the recorded tephra thicknesses probably underestimate equivalent dry-land thicknesses because of compaction or dissemination in the lake sediments and suggested that most of the 41 macroscopic tephras found in the Waikato lakes, erupted between *c.* 18 000 years BP and 1850 years BP, should also occur well beyond the Waikato area. Graphs showing isopach thicknesses plotted against distance from isopach centre suggest a near-linear semilog relationship indicating an exponential decrease in tephra thickness with increasing distance from source (Fig. 3). The change of slope or 'fine tail' in tephra distribution evident in some plots, due perhaps to co-ignimbritic ashfall or premature fallout as discussed above, or to the effects of strong winds, complicates attempts to extrapolate to greater distances using these plots. Nevertheless, they provide a basis for approximate estimates of the frequency with which CNI tephras have reached Auckland during the past *c.* 15 000 years and their possible local thicknesses.

Although the prospects of finding these tephras in the Auckland urban environment are comparatively limited (see below), it may also be useful to look for their occurrence beyond Auckland in the Northland region (Fig. 1). For example, the *c.* 665 years BP Kaharoa Tephra (from Okataina Volcanic Centre; Lowe *et al.* 1998), although not recorded in the western Waikato region (Lowe 1988; Hodder *et al.* 1991), occurs in Northland (Pullar *et al.* 1977; Newnham *et al.* 1998). Other CNI-derived rhyolitic tephras are recorded in Northland, including Taupo Tephra (1850 years BP) (Pullar *et al.* 1977), possibly Mamaku Tephra (7250 years BP), and four thin, uncorrelated ash-grade tephras older than *c.* 65 000 years BP (Lowe 1987). Kawakawa Tephra (22.6 ka) may also be present (Rankin 1973; Self 1983). Further, an Okataina-sourced tephra, the Rotoehu Ash (Froggatt & Lowe 1990), dated at 64 ± 4 ka (Wilson *et al.* 1992; Lowe & Hogg 1995), has been recorded as a *c.* 8-10 cm thick unit in lacustrine sediments at Lake Omapere *c.* 200 km north of Auckland (Fig. 1; Lowe 1987; Newnham 1999). On the basis of glass-shard major element chemistry and its distinctive cummingtonite-rich mineralogy (Froggatt & Lowe 1990), Rotoehu Ash has also been identified by the authors at Lake Rototuna *c.* 90 km northwest of Auckland. It also occurs as a discrete layer *c.* 14 cm thick in a motorway cutting just south of Auckland, and intermixed with other tephra materials in soil profiles near Pukekohe. Using isopach distributions mapped by previous workers, Lowe (1987) found a near linear log-normal relationship between Rotoehu Ash thickness and distance from source, which, together with the above evidence, indicated that this tephra must have been widely distributed across the Auckland Isthmus; however, it is only rarely observed as a definitive layer in Late Quaternary cover bed deposits.

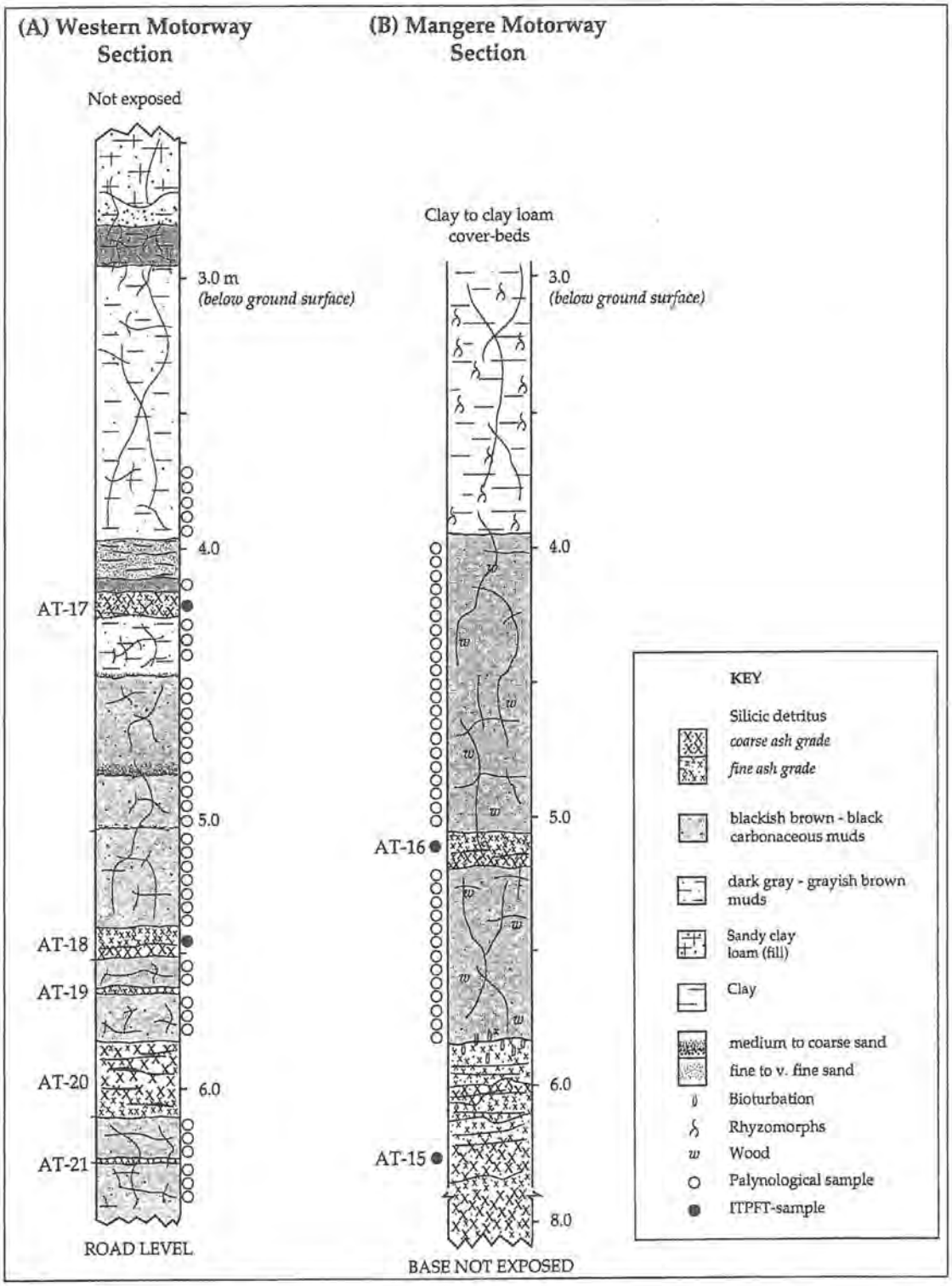

Fig. 4. Stratigraphic columns from (**a**) Northwestern Motorway (R11/595800 – 1 : 50 000 topographical map series grid reference of New Zealand Map Series 260), and (**b**) Mangere Motorway (R11/712689) sections showing uncorrelated silicic tephras and pollen and ITPFT (fission track) sampling positions.

Field surveys of silicic tephras in the Auckland region

Sequences of Quaternary rhyolitic tephra deposits, mostly reworked into estuarine deposits, and exposed at coastal localities in the Auckland region, have been described by Moore (1991). Some primary tephra fall deposits, up to 0.6 m thick, as well as rhyolitic ignimbrite units up to 9 m thick (e.g. distal ignimbrites at Port Waikato: Nelson *et al.* 1989; Kidnappers Ignimbrite, Auckland City: Wilson *et al.* 1995*b*), have been recorded. Deposits of reworked silicic detritus, up to 15 m thick, form a major component of the Quaternary subsurface deposits of the Auckland region. Major element glass compositions of these deposits suggest probable source areas in the Taupo Volcanic Zone, although the Coromandel Volcanic Zone, and potentially a much older age, cannot be ruled out (Nelson *et al.* 1989; Newnham & Grant-Mackie 1993). Clearly, more work needs to be done on the geochemical fingerprinting of these pyroclastic deposits, their stratigraphic relationships, and the impact their deposition might have had on the local environment. Despite the urban environment (and sometimes because of it) there are still opportunities to undertake this work.

For example, sections of rhyolitic tephras interbedded with organic carbonaceous sediments, possibly of Early to Mid-Quaternary age, have recently been exposed by road excavations and in coastal exposures at numerous localities in Auckland including the Northwest Motorway and Mangere Motorway sections (Figs 2, 4; Alloway & Newnham 1995). Investigations in progress at these sites include geochemical characterization using the electron microprobe and isothermal plateau fission-track (ITPFT) dating of the tephras to facilitate their correlation and to date surface and subsurface Quaternary deposits throughout the Auckland region. The study of these surface sections has been augmented recently by the acquisition of two long sedimentary cores extracted from a near sea-level locality at Patiki Road in west Auckland (Fig. 2). The *c.* 55 m-long cores comprise pollen-rich carbonaceous and laminated sediments interbedded with 19 discrete silicic tephra layers, some up to 0.9 m thick. Preliminary ITPFT dating and geochemical analysis of some of these tephras indicate that the sequence extends back more than 1.2 Ma. Because of the near-continuous deposition, and the abundance of discrete tephra beds, the Patiki Road cores can be used as a stratigraphic reference sequence to which deposits at the Northwest and Mangere motorway sections, and at other exposures and cores in the Auckland region and beyond, can be correlated. In this way, a more comprehensive record of the nature and distribution of CNI tephra deposits can be developed.

Other tephra-preserving sites (e.g. Lake Waiatarua and Kohuora Crater, described below) provide further potential to document the record of more recent tephra deposition in the Auckland region, as well as allowing assessment of the environmental impacts of such deposits.

Investigating the environmental impact of past central North Island-derived tephra deposition

Geomorphic processes associated with local volcanic activity have also provided opportunities to investigate the impacts of Late Quaternary CNI volcanism in Auckland. Lava flows have in places blocked drainage routes resulting in the

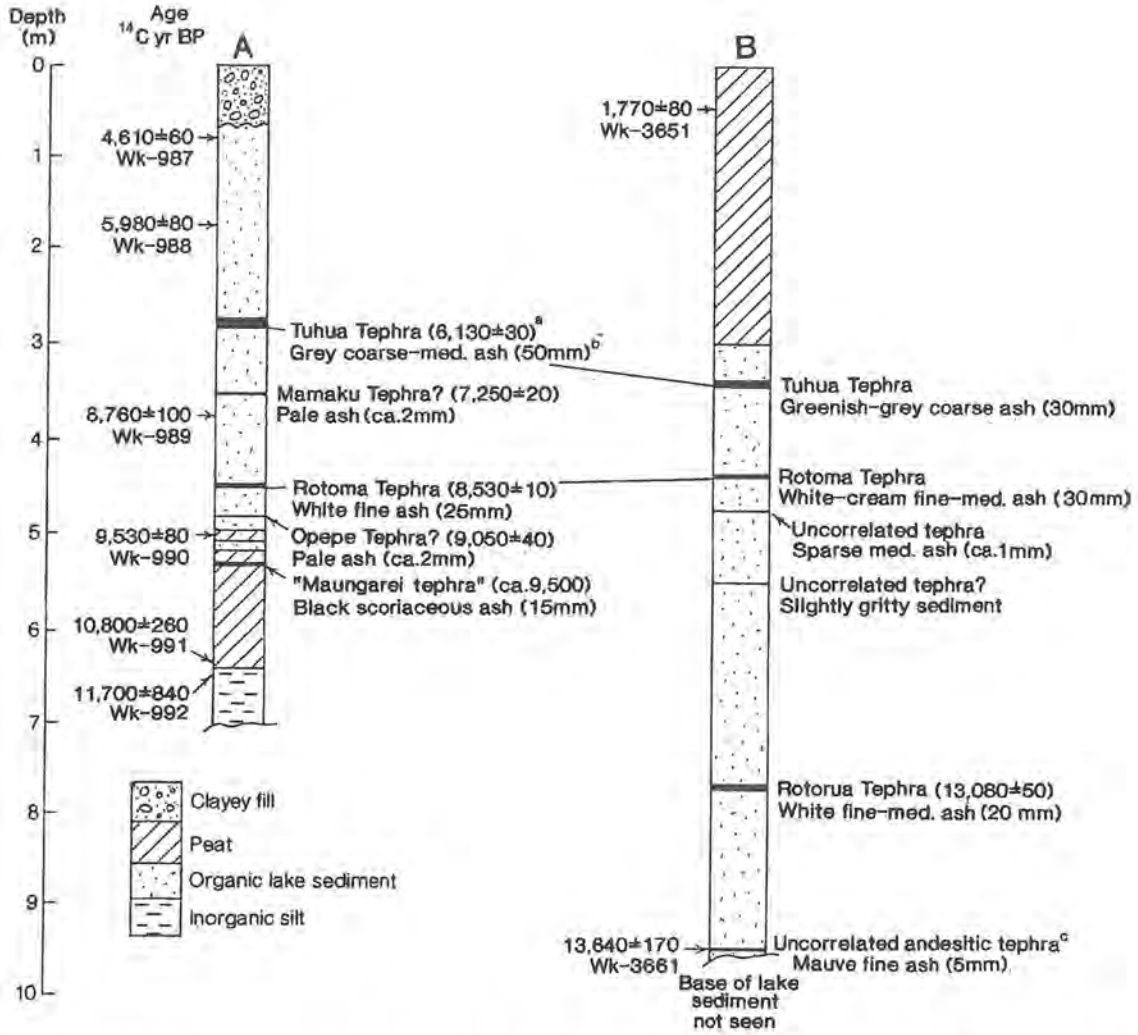

Fig. 5. Stratigraphic columns from (**a**) Lake Waiatarua (R11/732781) and (**b**) Kohuora Crater (R11/744675) showing CNI-derived tephras and radiocarbon dates. Wk- prefixes refer to the University of Waikato Radiocarbon Dating Laboratory number. The Kohuora core has been sampled for pollen analysis at 5 mm intervals above and below the tephra layers, and at *c.* 10 cm intervals for the rest of the sequence. Lake Waiatarua data after Newnham & Lowe (1991). [a] Tephra ages from Froggatt & Lowe (1990); [b] approximate thickness in parentheses; [c] possibly correlates with Rotoaira Lapilli, erupted from Mt Tongariro *c.* 13 700 years BP (Lowe 1988; Donoghue *et al.* 1995).

formation of lakes or swamps (Searle 1981; Newnham 1990; Newnham & Lowe 1991; Kermode 1992), while many craters have also been infilled with lake sediments and peat deposits. Where such sites have not been destroyed by urban development, they potentially provide continuous records of the local and regional environment since the originating eruptive episode and also may preserve tephra layers derived from subsequent CNI volcanic activity. Palynology has demonstrated the sensitivity of vegetation in northern New Zealand to climate change (e.g. Newnham & Lowe, 1991; Newnham *et al.* 1989, 1993), and so detailed palynological studies of the organic sediments to determine the local paleoenvironment, and any environmental impacts following tephra fall, are also being undertaken (see Giles *et al.* 1999).

Lake Waiatarua (Fig. 2), formed by blockage of drainage in a valley by lava flows, contains four macroscopic silicic tephra layers, between 2–50 mm in thickness and

derived from three CNI sources (Fig. 5). These overlie the *c.* 9500 years BP basaltic Maungarei tephra erupted from nearby Mt Wellington (Newnham & Lowe 1991). The local environmental impact of the Mt Wellington eruption was significant, altering the local hydrology and geomorphology, modifying local vegetation during the eruptive episodes, and in controlling subsequent successional vegetation development. Possible impacts of CNI tephra deposition were not investigated at a fine scale at this site. However, a longer and potentially more detailed record is preserved in lacustrine and peaty sediments infilling Kohuora Crater, a tuff ring at Papatoetoe in South Auckland (Fig. 2). Six macroscopic silicic tephra layers (including at least one andesitic tephra tentatively attributed to the Tongariro Volcanic Centre) have so far been provisionally identified in a 9.5 m-long core from Kohuora (Fig. 5). Work in progress at this site involves further coring, radiocarbon dating, fine-resolution analysis of pollen, and geochemical analyses to determine the likely environmental impacts of the CNI tephra fall deposits. Preliminary results from radiocarbon dating indicate that the top of this sequence is younger than *c.* 1800 years BP and that the base is around 13 700 years BP. However, because the organic sediments at Kohuora Crater extend below 9.5 m depth, this site also presents an opportunity to reconstruct a detailed and continuous environmental history of Auckland extending from near present to well before the last glacial maximum. The chronology to be established at this site will provide a minimum age for the Kohuora eruption. Two radiocarbon dates, $29\,700 \pm 2000$ (NZ488) and $29\,000 \pm 700$ (NZ540) [laboratory number of the New Zealand Radiocarbon (now Rafter) Dating Laboratory, Lower Hutt], both on wood buried in tuff at this volcano (Grant-Taylor & Rafter 1971), require verification in view of the unknown 'inbuilt' age of the wood, the large standard deviations, and the known difficulties of contamination and age reliability towards the upper limits of the method's range.

At the Patiki Road site, preliminary pollen analysis of the long cores indicates that these have good potential for the palynological reconstruction of past climate change. Similar potential is evident at the adjunct Northwest and Mangere motorway sections. This palaeoenvironmental work, together with that on the younger deposits at Kohuora Crater and other sites, will be incorporated into a detailed interlocking and precise time-stratigraphic framework using tephrochronology in conjunction with ITPFT and radiocarbon dating and magnetostratigraphic techniques.

Conclusions

The latest eruption of Mt Ruapehu, commencing 17 June 1996, demonstrated that the assessment of Auckland's volcanic hazards must consider not just the threat from local basaltic volcanism, but also that from tephras erupted and dispersed from the distant CNI volcanoes. Although this recent activity is minor in comparison with earlier eruptions from the central North Island, there are significant risks to the City of Auckland because of its concentration of population, infrastructure and economic activity.

Preliminary research indicates that numerous silicic tephras have been deposited in the Auckland region during the Quaternary. Thicknesses of these primary tephra fall deposits, both rhyolitic and andesitic, range from *c.* 1 mm to $\geqslant$ 0.6 m. Potential effects of tephra deposition of this scale range from short-lived respiratory

problems, closure of airspace, disruption of electronic and magnetic media, and possible disruption of water supplies and sewage and stormwater systems to serious respiratory problems, widespread injuries and death due to building collapse, power blackouts, fires, immobilization of transport and all emergency services, and likely destruction of trees, crops and livestock. Rhyolitic ignimbrites up to 9 m thick are also present in the Auckland region — they pose a very infrequent but extreme hazard that would result in enormous loss of human life through building collapse and burns. Volcanogenic 'acid rain' accompanying CNI eruptions is likely to be an additional hazard that would exacerbate Auckland's urban air pollution levels, and hence possible respiratory and other problems, in certain meteorological conditions.

Further research by the authors aims to geochemically characterize and radiometrically date tephra units from key sections and cores so that they may be more readily correlated to other tephra units occurring throughout the Auckland region and elsewhere. In addition, many of the silicic tephras are associated with organic muds and peats which provide opportunities to undertake palaeoecological and sedimentological investigations into vegetation and landscape response to tephra deposition during the Quaternary.

This research demonstrates the necessity to reappraise the volcanic hazard assessments for the Auckland region because the threat of inundation by tephras and aerosols from distal CNI sources has not yet been considered in any regional or local authority plan. Together with complementary work on the local Auckland Volcanic Field (e.g. Johnson *et al.* 1997), these investigations will lead to better understanding of the evolution of the Auckland landscape, its natural history, and the impacts of Quaternary volcanism.

Lessons from the Auckland study may be applicable to many large cities elsewhere that are not currently considered at risk from volcanism. Our approach recognizes the need to integrate risk and volcanic hazards' assessments, and to develop mitigation strategies for specific localities that may be vulnerable to a variety of hazards either from proximal or distant volcanic sources.

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