Paleogroundwater in the Moutere Gravel Aquifers near Nelson, New Zealand

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ABSTRACT. Radiocarbon, oxygen-18 and chemical concentrations have been used to identify groundwater recharged during the last ice age near Nelson. Moutere Gravel underlies most of the Moutere Depression, a 30 km-wide system of valleys filled with Plio-Pleistocene gravel. The depression extends northwards into Tasman Bay, which was above sea level when the North and South Islands of New Zealand were connected during the last glaciation. The aquifers are tapped by bores up to 500 m deep. Shallow bores (50-100 m) tap "pre-industrial" Holocene water (termed the modern component) with carbon-14 concentrations of 90 ± 10 pmC and $\delta^{18}O$ values of $-6.8 \pm 0.4‰$, as expected for present-day precipitation. Deeper bores discharge water with lower ^{14}C concentrations and more negative $\delta^{18}O$ values resulting from input of much older water from depth. The deep end-member of the mixing trend is identified as paleowater (termed the glacial component) with ^{14}C concentration close to 0 pmC and more negative $\delta^{18}O$ values ($-7.6‰$). Mixing of the modern and glacial components gives rise to the variations observed in the carbon-14, oxygen-18 and chemical concentrations of the waters. Identification of the deep groundwater as glacial water suggests that there may be a large body of such water onshore and offshore at deep levels. More generally, the influence of changing sea levels in the recent past (geologically speaking) on the disposition of groundwaters in coastal areas of New Zealand may have been far greater than we have previously realized.

INTRODUCTION

Groundwater in the Moutere Valley is an important resource for horticulture. Deep bores revealed the hitherto unknown water resource in the early 1980s, after shallow bores were found to provide limited and unreliable supplies. The present work uses isotope and chemical measurements in conjunction with other data (Thomas 1989), to improve understanding of the system (Stewart and Thomas 2002).

The term paleowater refers to groundwater that can be clearly identified by means of its radiocarbon date, and/or by another isotopic or noble gas signature, as originating in the colder climatic conditions of the late Pleistocene (Edmunds 2001). The objectives of this paper are to establish the deep Moutere Gravel groundwater as "paleo" water, and to consider some implications for New Zealand groundwaters.

Hydrogeology

The Moutere Depression is a 30 km-wide system of valleys between the Tasman Mountains and the ranges of east Nelson at the top of the South Island (Figure 1a). Voluminous Plio-Pleistocene gravels (including Moutere Gravel) are preserved in the depression and have been incised by the Motueka, Moutere and Waimea rivers (Rattenbury et al. 1998). Geophysical interpretation of seismic data and petroleum bores indicate that the depression reaches depths of 2500 m on the eastern side (Lihou 1992). The depression formed in the Pliocene-Pleistocene during uplift of the Tasman Mountains and the east Nelson Ranges.

Moutere Gravel is a uniform yellow-brown, clay-bound gravel, with deeply weathered clasts almost entirely of Torlesse-derived sandstone and semi-schist. Well rounded, quartzofeldspathic sandstone clasts in a brown weathered muddy sand matrix comprise the bulk of the gravel.

The Moutere Valley lies south of Motueka (Figure 1b). Most of the Moutere River catchment comprises Moutere Gravel (marked tm). The catchment is underlain by a north-east trending basinal structure in which Moutere Gravel reaches a maximum depth of about 600 m (Figure 2). A basement high running through Ruby Bay forms the southern flank of the basin. Basement granite then descends south of Ruby Bay to the Waimea Fault on the east side of the Waimea Plains reaching 2,500 m. Groundwater in Moutere Gravel south of the Ruby Bay high is largely unexplored.

The floor of the Moutere Valley has a Quaternary infilling (uk), which derives from reworked Moutere Gravel (Figures 1b, 2). Shallow bores (<20m) draw limited and often unreliable supplies of water from the valley infill, showing that permeabilities are low. Shallow bores on the Moutere Hills also tend to have low yields and unreliable supplies. Rainfall is the main recharge source of these supplies, with possibly variable contributions from local streams (Thomas 1989).

The hydrogeology has been described by Thomas 1989, 1991, 1992, 2001. Significant groundwater resources are found in deep Moutere Gravel aquifers. The three aquifers in vertical succession are the Shallow Moutere Aquifer (SMA), Middle Moutere Aquifer (MMA), and Deep Moutere Aquifer (DMA) (Figure 2). Intervening leaky clay layers containing carbonaceous material constrain the aquifers. Groundwater heads are generally higher and yields improve significantly with depth. Many deep bores (>50m) are artesian. The deep bores are cased to 30-50 m depth and then are generally screened or open to the bottom, so that they are likely to draw on water from several depths. Thomas (1989) has identified feed zones in several bores from downhole measurements.

The Moutere groundwater resource north of the Ruby Bay basement high is divided into two zones by a major fault; the western and eastern zones (Figure 1b). Pressure communication between bores is limited across this barrier. These zones are used for management of the resource (Thomas 2001). A third groundwater zone (southern) is defined south of the Ruby Bay high for discussion purposes.

Recharge to the aquifers is believed to occur by infiltration of rainfall where the Moutere Gravels outcrop. Two units have been identified by geological mapping, a lower unit (tm_1) and an upper unit (tm_2). The lower unit outcrops only in the southwest of the area (Figures 1b and 2), dips gently northeast into the Moutere Valley, and correlates with the DMA and MMA. The upper unit correlates with the SMA. Thomas (1989, 1992) proposed a recharge model in which rainfall infiltrated only where the lower unit outcrops in the Rosedale Hills area. This was revised to include recharge from both outcropping units of Moutere Gravel (Figure 2, Stewart and Thomas 2002). However, such recharge only applies to the “modern” component, because conditions would have been very different during recharge of the “glacial” component. And no modern recharge (i.e. tritium or CFC-bearing water) has yet been observed in the bores within the valley, despite groundwater levels generally recovering from their summer drawdown during the subsequent winter and spring.

SAMPLING AND METHODS

Sampling

Groundwater bores were purged of at least three casing volumes before samples were taken. Bottles were flushed with the water to be sampled, emptied, refilled with water and allowed to overflow, then carefully sealed to prevent evaporation. Samples of water were collected in 28 mL glass bottles for ^{18}O, 500 mL bottles for carbon isotopes, and 1.1 L bottles for tritium. The carbon isotope samples were collected air-free. Bore locations are shown in Figure 1b. (More details on the bores are given in Stewart and Thomas 2002).

Rafter Radiocarbon seawater line method.

The 150 ml samples were extracted using the Rafter Radiocarbon standard seawater method. A seawater vessel is prepared before each extraction. 4 ml of ortho-phosphoric acid is added to the side arm of the flask, and a magnetic stirrer and anti-bumping granules added to the bottom of the flask. The flask and contents are "tared" on a 2 decimal place balance. The 150 ml portion of water to be processed was removed using a plastic syringe from each groundwater sample. The water was transferred to the bottom of the glass seawater vessel using the syringe. The water was added carefully so the acid and water did not mix. Care was taken not to expose the water samples to atmospheric air as much as possible, by flushing the vessel with N_2 gas through a thin plastic hose placed into the spout of the vessel during addition of the sample. The sample bottle was sealed and weighed. The sample and acid were shaken together for approximately 1 minute to mix and attached to the seawater vacuum line. Room air was pumped from the connection between the seawater vessel and the vacuum line to a desirable vacuum. Two dry ice ethanol dewars are placed on the first two traps to collect water vapour, and two liquid nitrogen dewars are placed on the following two traps to collect carbon dioxide. The water sample in the seawater vessel is stirred throughout the transfer with a magnetic stirrer to aid transfer of the gas. The water bubbles vigorously during the vacuum transfer and the extraction is carried on until the bubbling has completely ceased and the vacuum line has again reached the baseline vacuum which takes approximately 20 minutes.

The carbon dioxide gas is vacuum distilled twice to further dry and purify it before measurement of the pressure. The amount of CO_2 gas collected is measured in a known volume, and the amount of dissolved inorganic carbon in the sample calculated. The carbon dioxide gas is made into a graphite target for measurement of ^{14}C by AMS. ^{14}C concentration is expressed as percent modern carbon (pmC), where the activity of "modern carbon" is taken as 95% of the activity of the NBS oxalic acid standard in 1950. Errors depend on concentration, ranging from ±0.07 pmC for near zero to ±0.8 pmC for 100 pmC concentrations.

Part of the gas is retained for measurement of ^{13}C by mass spectrometry. ^{13}C concentrations are expressed as δ values with respect to VPDB (Vienna PDB, the international standard). The measurement errors are ±0.1‰.

Oxygen-18 and tritium

For ^{18}O measurement on the waters, 2 mL of the water is isotopically equilibrated with CO_2 gas at $29^{o}C$ for two hours, and then the CO_2 is analysed in a stable isotope mass spectrometer

(Hulston et al. 1981). ^{18}O concentrations are given as δ values with respect to VSMOW (Vienna SMOW, the international standard). Measurement errors are ±0.1‰.

Tritium samples are distilled, enriched in tritium using electrolysis by a factor of about 80 and are then counted in a Quantalus low background liquid scintillation counter for several weeks (Taylor 1994). Tritium concentrations are given as tritium units (TU), where 1 TU is 1×10^{-18}. Detection limits (errors for near zero concentrations) are ±0.003 TU.

Chemical data

Water samples have been collected from groundwater bores in the Moutere Valley by Tasman District Council hydrologists for a number of years. Samples for cations were field filtered and acidified with high-purity nitric acid. Samples for anions were field filtered and kept below 4°C until analysed, and bicarbonate samples were collected unfiltered, kept below 4°C, and analysed within 48 hrs of collection. Samples were analysed by the Cawthron Institute in Nelson. Methods for cation analyses include Atomic Adsorption and ICP-OES, and for anion analyses include auto titrator, auto analyser, and ion chromatography.

RESULTS

Carbon Isotope Compositions

The carbon-13 concentrations in dissolved inorganic carbon (DIC) from Moutere are plotted against the reciprocal of the bicarbonate concentration (1/bicarbonate) in Figure 3a. The δ^{13}C values are remarkably uniform around the values –20 to -24‰ (except for one sample, see below). This range shows that all of the carbon is sourced from organic matter within the soil or aquifers. Waters gain dissolved CO_2 by plant respiration and oxidation of organic matter as they pass through the soil, where CO_2 partial pressures are commonly 10 to 100 times those in the atmosphere. A second source of CO_2 is from carbonaceous matter within the aquifers, in this case from the intervening clay layers between the aquifers. Oxidation of such matter produces CO_2 if chemical and/or microbiological conditions are suitable (bacteria are needed to catalyse redox reactions between water and organic matter). The dissolved CO_2 reacts with rocks to become neutralised to HCO_3^- and CO_3^{2-} ions (Clarke and Fritz 1997). Bicarbonate is the dominant form of carbonate in the present waters.

Only one sample has δ^{13}C outside the range –20 to -24‰, namely 8107 with δ^{13}C of –13.3‰. This sample is likely to have reacted with marine carbonate, which has the effect of moving the sample towards the δ^{13}C value of such carbonate (approximately 0‰). The dotted line in Fig. 3a shows the effect of reaction with marine carbonate. Carbon from carbonate rock would have zero ^{14}C, hence it would have a diluting effect on the ^{14}C concentration. The short dotted line in Fig. 3b shows the effect of reaction with carbonate on this sample.

Groundwater dating by ^{14}C is complicated by changes in ^{14}C activity in the atmosphere during the late Pleistocene and Holocene, and by dilution of ^{14}C in groundwater by dead carbon derived from soils and rocks when carbon-bearing solutions penetrate underground. Most of the ^{14}C in groundwater is gained from the soil, where CO_2 accumulates by root respiration and decay of vegetation, as noted above. The ^{14}C in dissolved inorganic carbon (DIC) is susceptible to reaction and dilution with dead carbon from carbonate, other minerals and organic matter in the soil and groundwater zones. A dilution factor q is used to take account of the resulting dilution of ^{14}C (Clarke and Fritz 1997). The age equation is written

$$t = (1/\lambda) \cdot \ln (q \cdot a_o / a_t) \tag{1}$$

where a_o is the initial ^{14}C activity ($q.a_o$ the diluted initial activity in the groundwater), a_t is the ^{14}C activity in groundwater after time t (i.e. when measured) and λ is the carbon-14 decay constant ($1/\lambda = T_{½} / \ln 2 = 8267$ years). The apparent simplicity of this equation is deceptive. Numerous methods have been proposed for estimating q, based on the chemical and ^{13}C composition of the groundwater (a summary of methods is given in Clarke and Fritz 1997).

Figure 3b shows ^{14}C concentrations plotted against $1/HCO_3$. The ^{14}C concentrations show a wide range of values, from almost 0 to 100 pmC. Shallow bores have ^{14}C concentrations in the range 90 ± 10 pmC; this is taken as the initial ^{14}C activity. (None of the waters have concentrations high enough to indicate the presence of carbon-14 from nuclear weapons testing and hence are 'pre-bomb'; i.e. they were all recharged before the early 1950s.)

The low ^{14}C concentrations in the deep bores along with the low $\delta^{13}C$ values (which indicate absence of marine carbonates) show that the waters have had long residence times in the deep aquifer. None of the waters have zero ^{14}C concentration (the lowest are 8.6 pmC (western and eastern zones) and 2.4 pmC (southern zone)), but the waters are mixtures because the bores are open to the aquifer from 50 m down to as much as 500 m depth. This allows water from several depth levels to contribute to the discharges. The ^{14}C, ^{18}O and some chemical constituents show variations consistent with such mixing; Figure 4a shows the mixing line between ^{14}C and $\delta^{18}O$.

The data have been interpreted in terms of mixing between two types of water, a shallow component with ^{14}C concentration of 90 ± 10 pmC and a deep component with 0 pmC. The shallow component is designated "modern", but it has zero tritium and CFC concentrations and therefore is "pre-industrial" water, with age in the hundreds of years (Stewart and Thomas 2002).

The deep component was recharged during the last glaciation and is the "glacial" component. A minimum mean age can be estimated using equation 1. We assume that the ^{14}C activity of the deep water is less than 1 pmC, and that of the shallow water is 90 pmC. The bicarbonate concentrations in the deep and shallow waters are 200 and 60 mg/L respectively (Figure 5a), hence the dilution factor (q) is 60/200. These give a mean age greater than 27,000 years. This is probably an underestimate, but an age within the glacial period is what is important not the precise age.

Oxygen-18 concentrations

$\delta^{18}O$ values give information on the source and conditions of recharge to the groundwater because there is generally a relationship between the location of recharge and its $\delta^{18}O$ value (Stewart and Morgenstern, 2001). ^{18}O concentrations in water are expressed as δ values with respect to VSMOW (Vienna Standard Mean Ocean Water).

The mean $\delta^{18}O$ value of precipitation at Moutere is discussed in Stewart and Thomas (2002). They conclude that precipitation-recharged groundwater in the region under present-day conditions will have mean $\delta^{18}O$ values in the range –6.8 ± 0.4‰. This comes from analysis of monthly samples of precipitation from several nearby sites, and from locally-fed springs and shallow bores.

Estimation of the mean $\delta^{18}O$ value of precipitation during the last glaciation is more problematical. The values will have been affected by at least three competing processes; 1. the sea would have been enriched in ^{18}O because low-^{18}O ice would have been locked up in ice sheets world-wide leading to higher mean $\delta^{18}O$ values, 2. the atmospheric temperature would have been lower leading to greater isotopic fractionation between atmospheric water vapour and precipitation, and therefore to lower mean $\delta^{18}O$ values, and 3. the sea would have been far from its present position (by up to several hundred kilometres for Moutere) leading to a more continental climate and therefore to lower mean $\delta^{18}O$ values. Evidence suggests that glacial age groundwater at Moutere would have been more negative than late Holocene groundwater by about 1‰. (e.g. the $\delta^{18}O$ value of calcite deposited on stalactites near Hamilton, New Zealand, was 0.95‰ lower during the last glacial maximum than present deposits (Hendy and Wilson 1968). This difference would have been mainly due to the $\delta^{18}O$ difference in the waters flowing over the stalactite at these times (Hendy and Wilson 1968).)

The $\delta^{18}O$ values of the groundwaters were found to be in the range –6.4 to –7.5‰, except for one bore in the southern zone with $\delta^{18}O$ of –8.3‰. This is a wider range than expected for Holocene waters in the area. The $\delta^{18}O$ values also show relationships with bore depth (Figure 4b), with lower $\delta^{18}O$ values at depth, and with ^{14}C as seen above. These observations support the idea of two types of water (modern and glacial). The $\delta^{18}O$ of the glacial component is found to be –7.6‰ from the mixing diagrams.

Hence, the favoured explanation is that there are two types of water in the Moutere aquifers. The first is a body of 'fossil' water occupying deeper levels of the Moutere aquifers, which has lower $\delta^{18}O$ values because it was recharged during the last glacial period (in the Pleistocene). Above this is 'modern' water, recharged in the last few hundred years of the Holocene, and with $\delta^{18}O$ values much the same as today. These two end member compositions are shown by the large hollow squares in the figures; the line connecting them shows the effect of mixing of these waters. (Older Holocene water may also be present in the modern component.)

The southern zone bores do not draw on a consistent deep component, unlike the deep bores in the western and eastern zones, and show much more scatter. Part of the reason may be that deep permeabilities are not so high in the south and consequently the southern bores draw more water from higher levels in the aquifers than in the western and eastern zones.

Chemical Compositions

The chemical compositions of the western and eastern zone waters are affected by mixing of the two water types. The glacial water at depth appears to have a nearly uniform composition, whereas the modern water at shallow depths has a more varied composition. This section looks at data for four of the chemical constituents, which show patterns representative of many of the other chemical constituents (Stewart and Thomas 2002).

Bicarbonate and calcium (Figures 5a and b) are readily affected by reaction with soil and rock, and the deep component has higher concentrations of these constituents than the shallow component (the compositions of the end components are indicated by the large squares in the plots). The pattern is of increasing concentration with decreasing $\delta^{18}O$ value, which is indicative of a mixing process. This is consistent with the deep (glacial) component having had much greater interaction with the rock because of its much longer residence time.

Chloride concentrations in groundwater often reflect marine influence on rainfall (i.e. rainout of seasalt particles in the atmosphere) because it is often an unreactive solute underground (Edmunds 2001). For rainfall recharged groundwater, evapotranspiration causes enrichment of chloride while passing through the soil. A third influence is sea water trapped within parts of the aquifer during past higher sea level stands, or present-day intrusion of sea water. The plot of chloride versus $\delta^{18}O$ (Figure 5c) shows glacial water (Cl ~ 5.5 mg/L, $\delta^{18}O$ ~ -7.6‰) mixing with modern water containing a range of chloride values (5.5 to 18 mg/L, $\delta^{18}O$ ~ -6.8‰). The graph has two limbs. Most of the western and eastern bores have chloride near 5.5 mg/L. However, bores on the seaward side of the Moutere Valley (8110, 8423, 8391 and 8089) plot on the upper limb with higher chloride concentrations. This is considered to reflect their location near the sea where they receive rainfall that has higher chloride concentrations from Tasman Bay. If so, this shows that the recharge has occurred locally. The lower limb chloride concentration is very low (5.5 mg/L), and probably reflects a continental effect during both glacial and modern times due to the presence of the high Tasman Mountains west of Moutere which lie at right angles to the prevailing westerlies. Hence it appears that the input of chloride to groundwater in this region might have been much the same in glacial times as it was in pre-industrial (late Holocene) times.

Sodium (Figure 5d) has similarities to chloride, but is more affected by interaction with aquifer rocks. Sea water influence is shown by higher sodium concentrations in 8050 and 8007 (not plotted). The plot with $\delta^{18}O$ shows two limbs as with chloride, but the upper limb values are more scattered (although it still includes two of the same bores, i.e. 8110 and 8089). Most of the samples lie on the lower limb, forming a trend towards higher sodium at depth because of increased water/rock interaction in the deep component.

The southern zone points do not generally conform to the patterns shown by the western and eastern zone points, although they are within the same range of values. As before, this is tentatively attributed to lower permeability at depth in the southern zone leading to more input of waters from higher levels.

Tritium and CFCs

Tritium and CFC concentrations have been measured for a number of the bores (Stewart and Thomas 2002). The results show that the bore waters did not contain detectable tritium or CFC concentrations when first measured (as expected) and continue to show none. (And if anything, carbon-14 concentrations appear to be decreasing rather than increasing since 1988.) On the other hand, groundwater levels, which are drawn down during the summer, generally recover during the subsequent winter and early spring. Thus recharge is occurring, but this new water (which is seen in shallow bores in the hilly Moutere Gravel outcrop areas) must be near the surface in the recharge areas and has not yet found its way to the aquifers tapped by the deep bores, or younger water is slowly penetrating into the deep aquifers, but dilution with old water has been sufficient to keep concentrations at less than detectable levels up to now.

DISCUSSION

^{14}C and ^{18}O concentrations show linear relationships with depth and with each other in the western and eastern zones, showing that two types of water are present. Shallow groundwater has ages of hundreds of years and $\delta^{18}O$ values like present-day rainfall (around –6.8‰). The deep component has low ^{14}C concentration and $\delta^{18}O$ of –7.6‰. These are the modern and glacial water types identified above. The western and eastern bores discharge either modern or mixtures of modern and glacial water, none discharge pure glacial water. The glacial water is believed to have been recharged during part of the last glaciation (20-50,000 years ago).

This is the first time that the $\delta^{18}O$ shift between modern and glacial groundwaters has been reported for a New Zealand system. The measured difference of -0.8‰ can be compared with differences of +0.5‰ (Portugal), -1.3‰ (France), -1.9‰ (England) and -2.5‰ (Poland) measured in coastal regions of Europe (from Figure 7 in Loosli et al. 2001).

The late Quaternary covers a period of strong climatic changes in the New Zealand landscape brought about by the last glaciation. So much ice was locked up in ice sheets that the sea level was about 130 m lower than at present at the last glacial maximum (LGM). This resulted in large increases in the New Zealand land area, during which time new hydrogeological systems were established offshore from the present coastline. Flow within deep aquifers would have been much more active because of the much greater heads due to lower sea level. The warmer climate during the Holocene saw sea level rise rapidly to its present level as the ice sheets melted. This caused water tables in groundwater systems to rise and hydraulic heads to diminish causing profound changes in flow regimes. In particular, flow at deep levels would have become much more sluggish. The present-day configuration of groundwaters in coastal areas is, therefore, to a large extent the result of circulation of freshwater to deeper levels in response to the lower sea level during the last glaciation (Edmunds 2001). The Holocene flow patterns have been superimposed on top of the glacial flow patterns of 10,000 years and more ago.

Figure 6a shows the eustatic sea level curve for the last 140,000 years (Edmunds et al. 2001, after Shackleton 1987). Until 7,000 years ago, the sea had not been at its present level for 100,000 years; it was much lower for most of that time (especially for the last 50,000 years of it). The minimum level was reached about 18,000 years ago (at the LGM). Between 14,000 and 7,000 years ago, the sea level rose rapidly (with fluctuations), and in New Zealand is believed to have reached levels 2-3 m above the present level by 4,000 years ago (Stevens 1990). The level has since declined to the present level.

Figure 6b shows the inferred New Zealand shoreline during the LGM (Stevens, 1990). The New Zealand land mass was doubled and the main islands of New Zealand were joined by a large plain. Moutere was an inland location, hundreds of kilometres from the nearest sea. A considerable amount of the former Pleistocene freshwater body (detected in this work) could now be present extending under Tasman Bay. It is probable that there is very little natural flow through the deep aquifer (i.e. little natural flow towards outlets under the sea). The lack of ^{14}C indicates that no substantial Holocene recharge has taken place into this water body. Some of the water is evidently now being extracted by the deep Moutere bores, causing marked drawdowns in water levels during the late summer. However, levels recover during the winter. Hence recharge is occurring, and there must be a tendency for shallow water to penetrate deeper as the deep water is extracted.

Where repeated measurements have been made (bores 8404 and 8407), there appears to be a trend towards ages becoming older due to exploitation. This suggests that more of the deep water is being extracted because permeabilities at depth allow more efficient recovery (i.e. water flows more rapidly in the deep aquifer).

Ice age groundwaters have been observed in deep aquifers in other parts of New Zealand. Two of them are in basins in the North Island bordering Cook Strait (see Figure 7). Taylor and Evans (1999) reported a ^{14}C age of 31,000 years for groundwater at a depth of 238.4-

241.4 m in the Whenuakura Formation near Hawera. Another deep groundwater at Shannon was reported as having a ^{14}C age of 40,000 years (pers. comm. CB. Taylor, see also Taylor et al. 2001). Both bores are in sedimentary formations.

These observations again suggest circulation of freshwater to deeper levels in response to the lower sea level during the last glaciation. The influence of changing sea levels in the recent past (geologically speaking) on the disposition of groundwaters in coastal areas of New Zealand may have been far greater than we have previously realized. And New Zealand may be surrounded by a "skirt" of pristine paleo groundwaters at deep levels.

CONCLUSIONS

Radiocarbon, oxygen-18 and chemical concentrations have been used to identify groundwater in the Moutere Gravel aquifers that was recharged during the last ice age. The aquifers are tapped by bores up to 500 m deep. Shallow bores (50-100 m) tap pre-industrial Holocene water (termed the "modern" component") with carbon-14 concentrations of 90 ± 10 pmC and $\delta^{18}O$ values of –6.8 ± 0.4‰, as expected for present-day precipitation. Deeper bores discharge water with lower ^{14}C concentrations and more negative $\delta^{18}O$ values resulting from input of much older water from depth. The deep end-member of the mixing trend is identified as paleowater (termed the "glacial" component) with ^{14}C concentration close to 0 pmC and more negative $\delta^{18}O$ values (–7.6‰). Mixing of the modern and glacial components gives rise to the variations observed in the carbon-14, oxygen-18 and chemical concentrations of the waters.

Identification of the deep groundwater as glacial water suggests that there may be a large body of such water onshore and offshore at deep levels. This water would have been caught by rising sea levels that greatly reduced the rate of flow in the aquifer. More generally, the influence of changing sea levels in the recent past (geologically speaking) on the disposition of groundwaters in coastal areas of New Zealand may have been far greater than we have previously realized.

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Figure captions

Figure 1: (a) Geology of the Moutere Depression, Northwest Nelson. The contact with Separation Point Granite (ks) defines the western boundary, while the eastern boundary is against the upward-faulted east Nelson Ranges. (b) Geological setting of the Moutere Valley showing bore locations. Fine lines show the surface geology comprising Separation Point Granite (ks) to the northwest and Moutere Gravel (units tm_1 and tm_2) to the southeast. The valley floor contains reworked Moutere Gravel (uk_3).

Figure 2: Cross-section showing the structure of the basin underlying the Moutere Catchment. The trace of the cross section is parallel to the fault in Figure 1b. Inferred recharge patterns for the Moutere aquifers are shown (Stewart and Thomas 2002).

Figure 3: (a) $\delta^{13}C$ values versus $(HCO_3)^{-1}$ for bore waters. (b) ^{14}C values versus $(HCO_3)^{-1}$ for bore waters. The line connects the glacial (zero ^{14}C, 200 mg/L bicarbonate) and modern (90 pmC ^{14}C, 125 mg/L bicarbonate) end-members.

Figure 4: (a) $\delta^{18}O$ versus ^{14}C for bore waters; the older waters (low ^{14}C) have more negative $\delta^{18}O$ values. (b) $\delta^{18}O$ values versus bore depths. A line is fitted to the points and connects deep (-7.6‰, 600m) and shallow (-6.8‰, 0m) end-members.

Figure 5(a-d): $\delta^{18}O$ versus HCO_3, Ca, Cl and Na concentrations. Lines connect end-members at $\delta^{18}O$ values of –7.6‰ (glacial water) and –6.8‰ (modern water).

Figure 6: (a) Eustatic sea level curve for the past 140,000 years. (b) New Zealand shoreline in the last glacial maximum (about 18,000 years ago).

Figure 7: Shoreline in the Cook Strait region during the last glacial maximum and ^{14}C ages of some deep groundwaters.

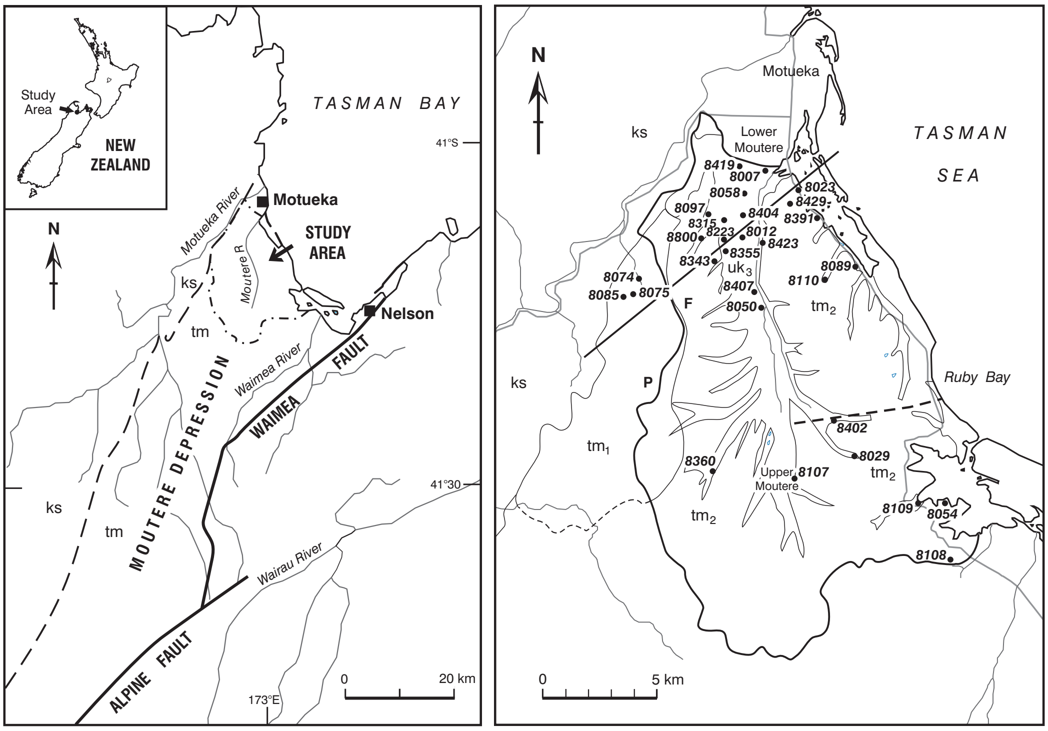

Study Area
NEW ZEALAND
N
TASMAN BAY
41°S
Motueka
STUDY AREA
Motueka River
Moutere R.
ks
tm
Nelson
Waimea River
MOUTERE DEPRESSION
WAIMEA FAULT
41°30
ks
tm
Wairau River
ALPINE FAULT
173°E
0
20 km
N
Motueka
ks
Lower Moutere
TASMAN SEA
8419
8007
8058
8023
8429
8097
8315
8404
8391
8800
8223
8012
8423
8343
8355
8089
uk$_3$
8074
8110
8085
8075
8407
F
8050
tm$_2$
ks
P
Ruby Bay
8402
tm$_1$
8360
Upper Moutere
8107
8029
tm$_2$
tm$_2$
8109
8054
8108
0
5 km

Figure 1

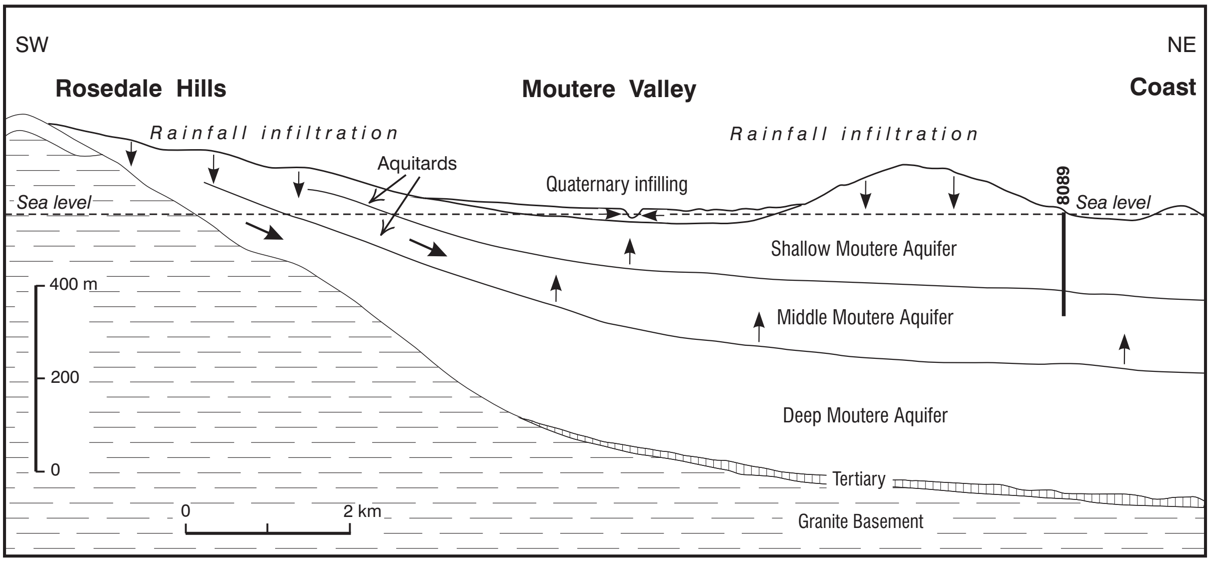
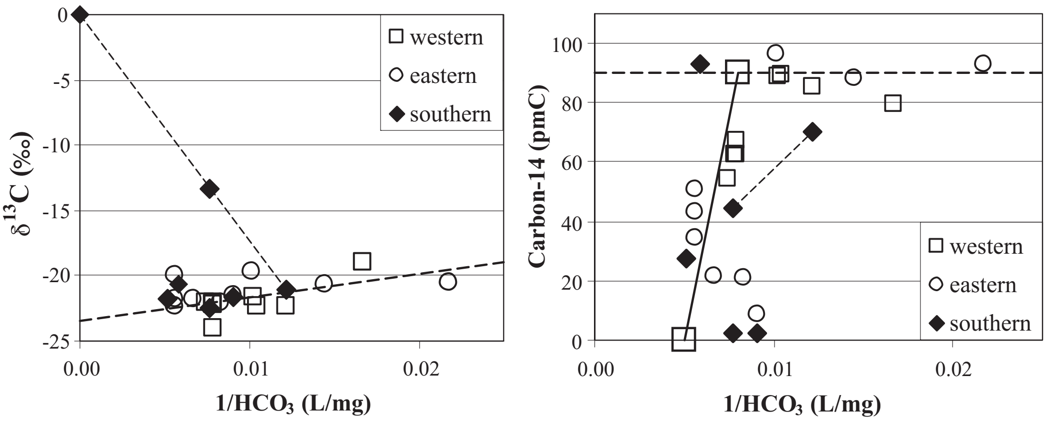

SW
NE
Rosedale Hills
Moutere Valley
Coast
Rainfall infiltration
Rainfall infiltration
Aquitards
Quaternary infilling
8089
Sea level
Sea level
Shallow Moutere Aquifer
Middle Moutere Aquifer
Deep Moutere Aquifer
400 m
200
0
Tertiary
0
2 km
Granite Basement

Figure 2



δ^{13}C (‰)
0
-5
-10
-15
-20
-25
0.00
0.01
0.02
1/HCO$_3$ (L/mg)
□ western
○ eastern
◆ southern
Carbon-14 (pmC)
100
80
60
40
20
0
0.00
0.01
0.02
1/HCO$_3$ (L/mg)
□ western
○ eastern
◆ southern

Figure 3

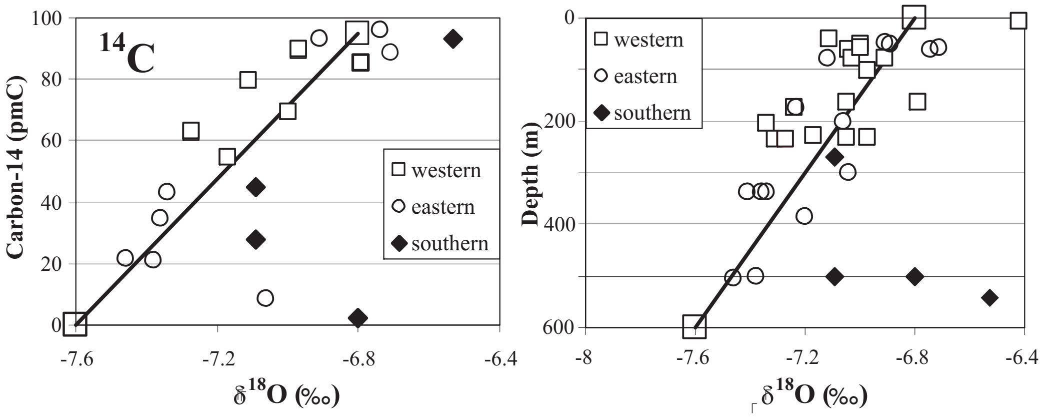

14C
Carbon-14 (pmC)
100
80
60
40
20
0
-7.6
-7.2
-6.8
-6.4
δ18O (‰)
western
eastern
southern
Depth (m)
0
200
400
600
-8
-7.6
-7.2
-6.8
-6.4
δ18O (‰)
western
eastern
southern

Figure 4

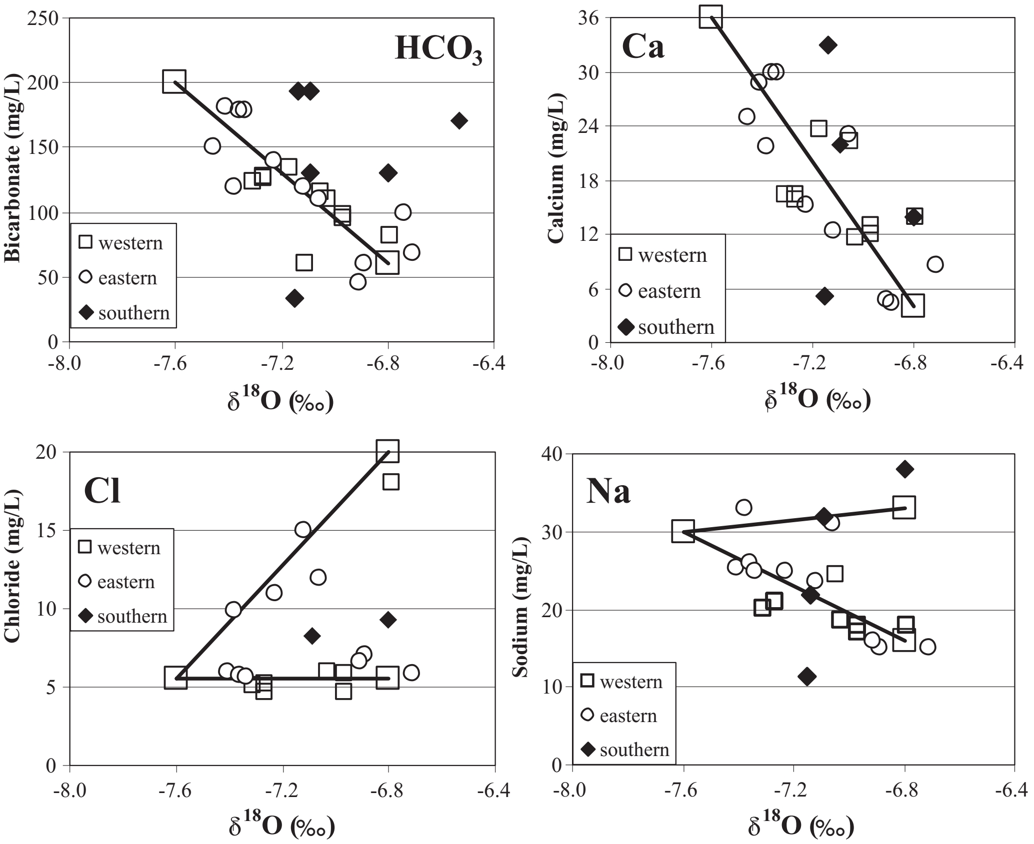

HCO$_3$
Bicarbonate (mg/L)
250
200
150
100
50
0
□ western
○ eastern
◆ southern
-8.0
-7.6
-7.2
-6.8
-6.4
δ^{18}O (‰)
Ca
Calcium (mg/L)
36
30
24
18
12
6
0
□ western
○ eastern
◆ southern
-8.0
-7.6
-7.2
-6.8
-6.4
δ^{18}O (‰)
Cl
Chloride (mg/L)
20
15
10
5
0
□ western
○ eastern
◆ southern
-8.0
-7.6
-7.2
-6.8
-6.4
δ^{18}O (‰)
Na
Sodium (mg/L)
40
30
20
10
0
□ western
○ eastern
◆ southern
-8.0
-7.6
-7.2
-6.8
-6.4
δ^{18}O (‰)

Figure 5

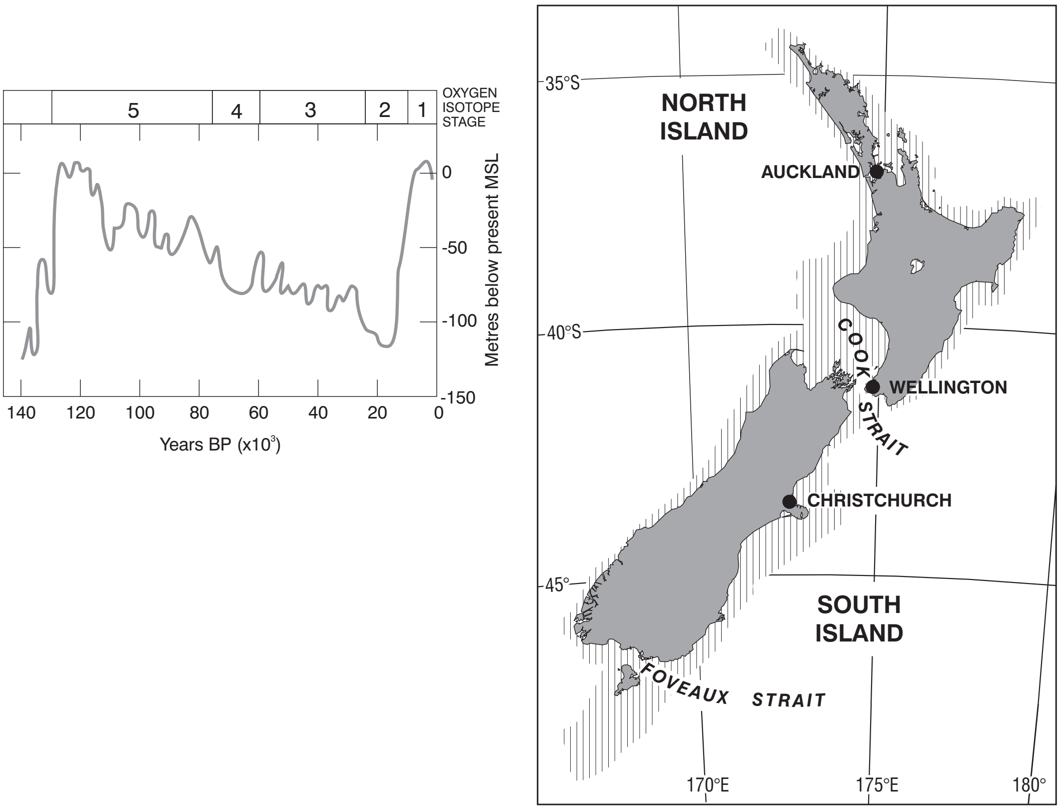

OXYGEN ISOTOPE STAGE
5
4
3
2
1
0
-50
-100
-150
Metres below present MSL
140
120
100
80
60
40
20
0
Years BP (x10³)
35°S
40°S
45°
170°E
175°E
180°
NORTH ISLAND
AUCKLAND
WELLINGTON
COOK STRAIT
CHRISTCHURCH
SOUTH ISLAND
FOVEAUX STRAIT

Figure 6

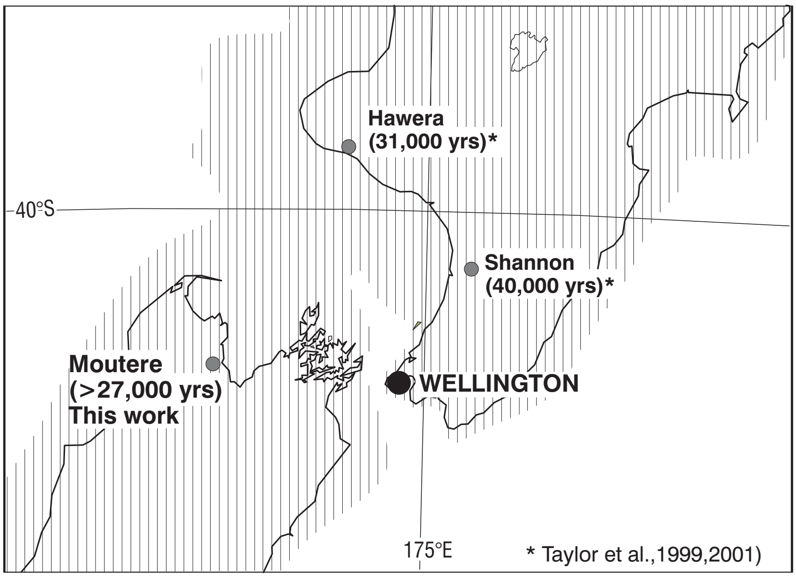

Hawera
(31,000 yrs)*
40°S
Shannon
(40,000 yrs)*
Moutere
(>27,000 yrs)
This work
WELLINGTON
175°E
* Taylor et al.,1999,2001)

Figure 7