Environmental changes in Okarito Lagoon, Westland, New Zealand

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ABSTRACT

The ecosystem structure and geomorphology of Okarito Lagoon are largely driven by high-magnitude, low-frequency seismic activity in the following chain of events: fault rupture/earthquake (probably on the Alpine Fault); compaction of the lagoon floor sediments by groundshaking and liquefaction; local subsidence of the Lagoon and surrounding area by about 50 cm or more; tsunami inundation as a result of subsidence/compaction, and other causes; increased sediment supply to the coast in the years following the earthquake; lagoon deepens and freshens due to poor tidal exchange; Okarito River supplies increased silts/fines to the Lagoon; later (in the order of decades), the sediment supply to the coast starts to decrease; Lagoon level falls, allowing forest growth to re-establish on eastern shores; Okarito River incises into its channels in the delta; and finally, a period of quiescence and stability until the next fault rupture.

The present situation is different from previous events in the Holocene in that the course of the Waitangi-taona River is artificially maintained and flows into the Okarito River upstream of the Lagoon. This provides increased sediment load, and probably increased heavy metal and nutrient loading. This may affect all flora and fauna there. It also may have a detrimental effect on mahinga kai values. In addition, there has been, and continues to be, human occupation and use of the coastal area in the vicinity of the Lagoon.

The implication for the future is that ecosystem resilience is reduced, and Okarito Lagoon and its margins are more susceptible to invasion of aggressive pest/weed species in the aftermath of a catastrophic event. The Okarito community and, by analogy, more widespread human population centres of the West Coast are at risk from tsunami and the combined after-effects of large, local fault ruptures.

Keywords: Okarito Lagoon, Waitangi-taona River, New Zealand, river diversion, earthquake risk, tsunami, sediment quality, Harihari Ecological District

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1. Introduction

Okarito Lagoon, Westland (43°11´S, 170°14´E) is one of the largest estuarine inlets on the West Coast of the South Island. It is about 10 km long and 1–2.5 km wide with an overall area of c. 20 km^2 (Figs 1 and 2).

The Lagoon has been the focus of several conflicts in the recent past concerning impacts to its environment from: native logging in the Okarito Forests, the sustained diversion of the Waitangi-taona River into the catchment by engineering works, and proposed tourism development of Okarito village (MacPherson 1981; Griffiths & McSaveney 1986; Boffa Miskell Ltd. 2000). Impacts on the lagoon environment are of particular concern because of the high conservation values of the area. These include, but are not limited to, Okarito Lagoon, Lake Windermere, Waitangiroto River, the surrounding World Heritage Site and National Park, Donovan's Store, the Youth Hostel, parts of the coastal strip, the township wetland and catchment, the white heron colony, and Okarito brown kiwis. Okarito Lagoon is the centrepiece of the area and an application to recommend it as a Ramsar Heritage site is currently under consideration by the Department of Conservation. Furthermore, the Tai Poutini papatipu runanga of Te Runanga o Ngai Tahu have an interest in the area, and both Te Runanga o Makawhio and Te Runanga o Kati Waewae have expressed concern about increased sedimentation in the lagoon and the loss of mahinga kai values.

2. Background

Okarito Lagoon is separated from the sea by a low sand barrier with a maximum elevation of about 4.0 m (Figs 2 and 3). In the recent past, the exit of the lagoon was located towards the northern end of the barrier, about 7 km north of the present village (Brunner 1952). However, the present exit of the lagoon is located at the southern end adjacent to the old wharf and Okarito village. This exit blocks from time to time, although anecdotal evidence suggests that this has become less frequent since AD 1967, following the diversion of the Waitangi-taona River into the catchment (Anon. 1976). However, the exit is known to be relatively unstable; for example, in the past 30 years water has at least once flowed through the seaward side of the village, exiting at the northern end of Kohuamarua Bluffs (I. James, pers. comm., July 2000).

While the lagoon receives freshwater from many sources, most of these are minor creeks draining small catchments in the surrounding glacial moraine (with the exception of the Okarito River) (Fig. 2). In general terms, the inflow of freshwater is derived from three main catchments: the Okarito Forest (9700 ha), Lake Mapourika catchment (c. 9000 ha), and Waitangi-taona River (8300 ha) catchments. The first is drained by a series of small creeks and is underlain by compact, glacially derived material of the Okarito Formation (Warren 1967).

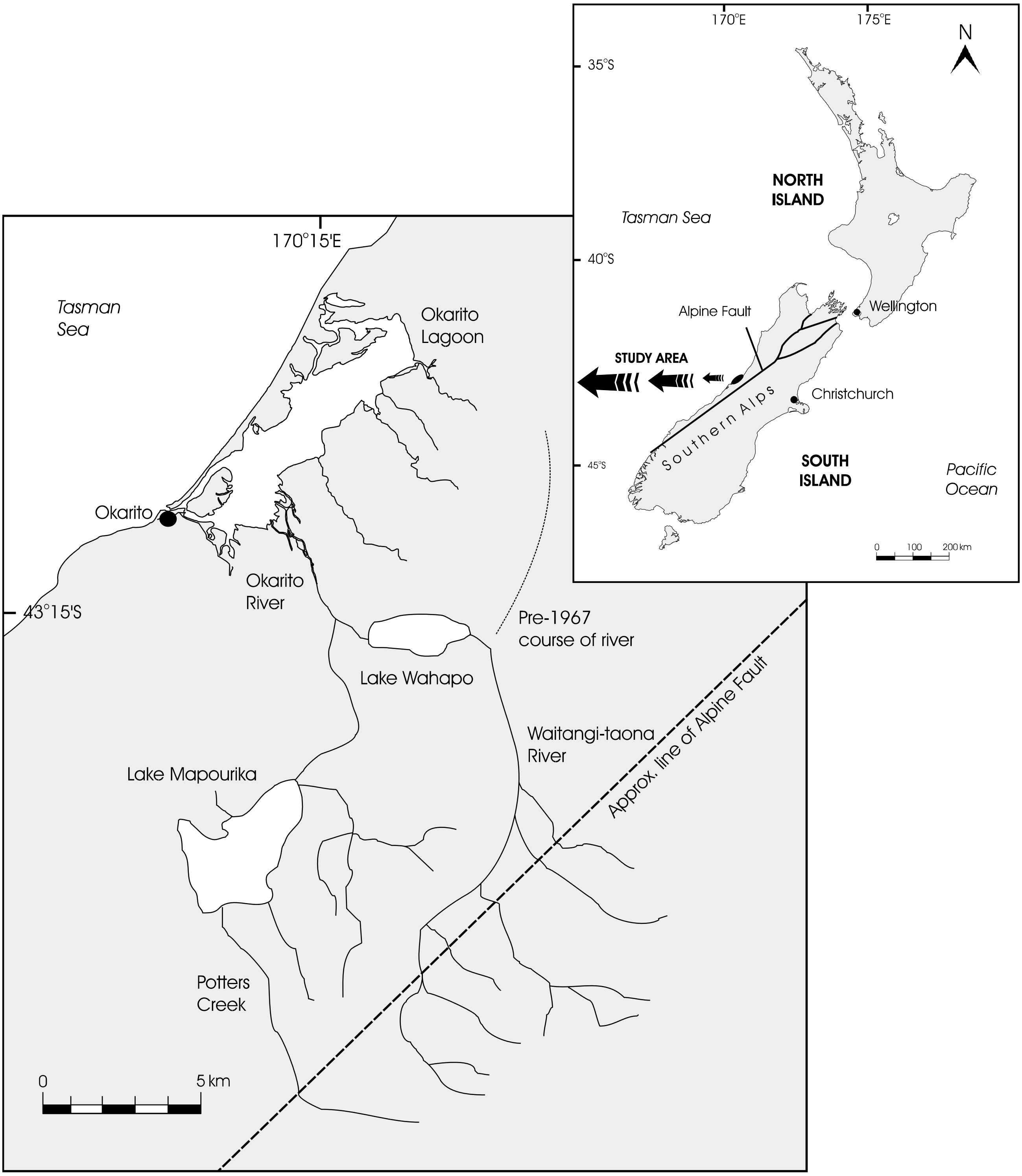

Figure 1. Map of Okarito Lagoon catchment.

Both of the other catchments feed into the Okarito river, the Waitangi-taona River passing through Lake Wahapo before entering the River (Fig. 2). These two catchments have a more complex geology determined to a large extent by the Alpine Fault, which crosses through their upper reaches.

The Alpine Fault is a region of strong compression and rapid shear on the boundary between the Australian and Pacific Plates. Rapid uplift (c. 6–7 mm/yr)

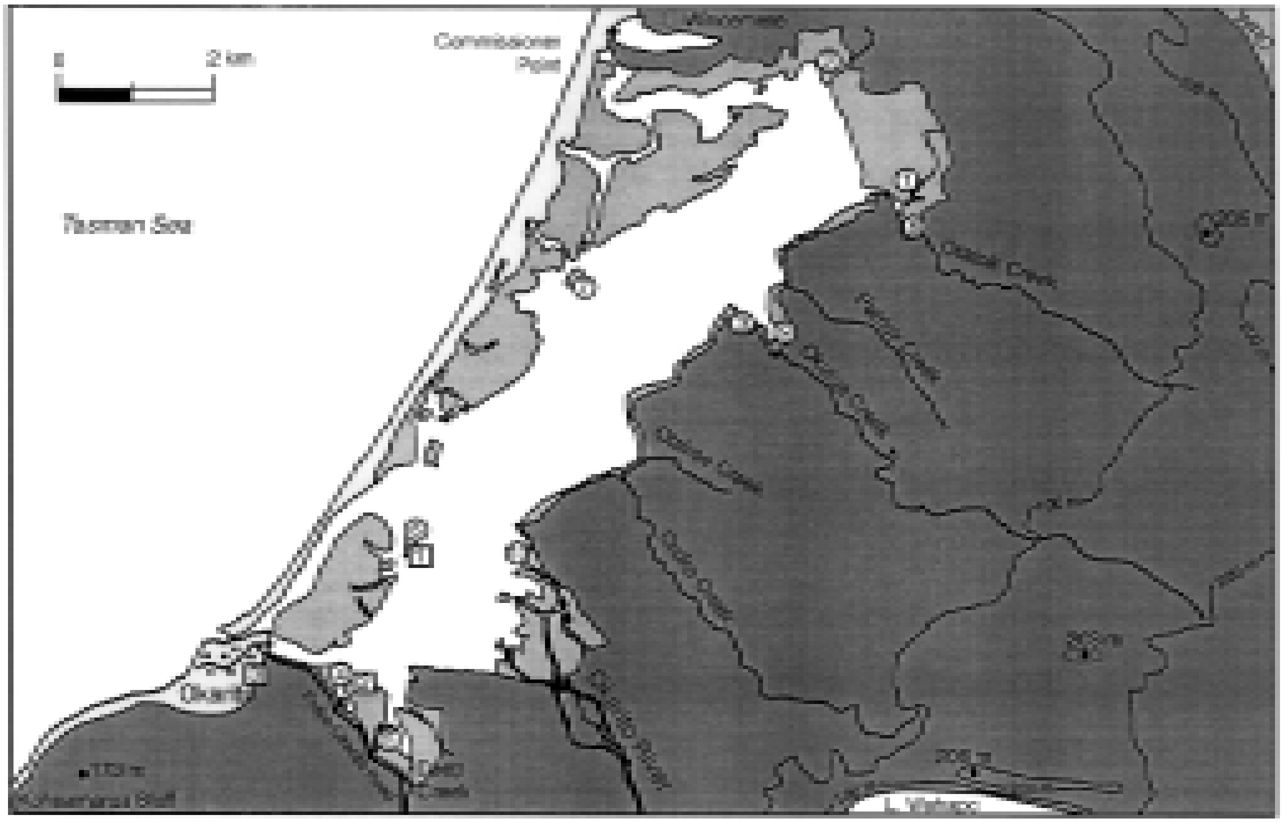

Figure 2. Map of core sites (circles) and trench sites (squares) at the study site, Okarito Lagoon. Shading represents different vegetation types, ranging from dune complexes (light), to lagoonal vegetation, to forest (dark).

and horizontal displacement (c. about 20–30 mm/yr) coupled with heavy rain cause intense erosion of the schists and glacially-derived material to the east of the Fault in the mountains (Berryman et al. 1992; Norris & Cooper 1997). To the west of the Fault, the overprint of late-Quaternary glacial activity is evident in the moraine-dammed lakes of Mapourika and Wahapo, a complex drainage network, and the massive moraines that surround Okarito Lagoon. These recent sediments overlie a basement of Palaeozoic metasediments and granites (Griffiths & McSaveney 1986). The extreme rainfall (in excess of 10 000 mm/yr) and high denudation rates (5–12 mm/yr) of the fractured, easily eroded schists provides large quantities of water and sediment to the flood-prone waterways that empty into Okarito Lagoon. MacPherson (1981) reported one flood event for Easter AD 1978 where 370 mm of rainfall fell in a 24 hour period, generating a combined peak flow for the Mapourika and Waitangi-taona River catchments of about 700 m^3/s, 50 times their mean discharge. In analysing the estimated sediment and water inflow effects, MacPherson concluded that the AD 1967 diversion of the Waitangi-taona River would have a far more significant impact on the environment of Okarito Lagoon than the selective logging of the adjacent Okarito Forest.

If extreme rainfall conditions of the region are seen as the main factor driving delivery of terrestrial sediment to the coast, then large earthquake events, and in particular those of the Alpine Fault, must be viewed as the main generator of material.

Figure 3. Okarito Lagoon, painting by Henry Grant Lloyd 1885. Note the low sand barrier separating the lagoon from the sea (view to the south, with Okarito Lagoon to the left).

The effects of an Alpine Fault rupture have major implications for the Okarito Lagoon catchment. These include landslides, landslide-damming of rivers, forest destruction and tsunami. In the longer term, fault ruptures generate massive river aggradation, channel avulsion, and the increase in sediment supply to the coast (e.g. Yetton et al. 1998; Goff et al. 2000a; Goff & McFadgen 2001). Within the immediate vicinity of the lagoon, the environmental impacts of an Alpine Fault rupture can be hypothesised based upon the early accounts of Brunner (1952), and from evidence obtained from similar locations elsewhere. Brunner (1952) noted in a visit to Okarito in AD 1848 that “to the foot of the mountain range has been recently washed by the sea”. While the mountain range he refers to is probably the encircling moraines, this may well be evidence for tsunami inundation, or at least an elevated lagoon level. Widespread forest destruction as a result of one or more of: ground shaking, river aggradation, channel changing, or tsunami inundation is known to have happened in the region (Wells et al. 1998). Furthermore, the increase in sediment supply to coastal embayments as a result of earthquakes is known to occur in New Zealand (e.g. Goff 1997), and the subsequent decline in water quality causes loss of freshwater and intertidal shellfish sources which is often sustained through smothering by sediment (Grapes & Downes 1997). The compaction of sediments by groundshaking is also widespread and can result in lowering of the lagoon, magnifying the impact of subsequent tsunami inundation (e.g. Atwater 1987).

Two key timeframes are considered in this study because they encompass different types of catastrophic event:

- A period encompassing approximately the last 50 years which primarily addresses the effects of human-induced or managed changes to the environment, such as the sustained diversion of the Waitangi-taona River and selective logging of Okarito Forest.
- A period of several thousand years covering natural environmental changes brought about by catastrophic events, most probably dominated by the overprint of Alpine Fault ruptures as opposed to changes in glacier mass balance. However, the long-term impact of such earthquakes has demonstrable linkages and relevance to the recent past through the natural avulsion (channel change) of the Waitangi-taona River (as it reworks its massive sediment load), and the evidence of saltwater inundation reported by Brunner (1952).

3. Methods

3.1 FIELD SAMPLING AND SAMPLE PREPARATION

In July 2000, fieldwork was undertaken at Okarito Lagoon over a ten-day period. Continuous sediment cores were taken from the lagoon-wetland interface, either just above of just below high water. Ten cores, up to 6 m long, were collected in aluminium tubes using a vibracoring system. Sediment compaction was measured before core retrieval. In the laboratory, the core was split lengthwise, logged and sub-sampled for grain size analysis, organic content, micro- and macro-palaeontological, geochemical, and geo-chronological analyses.

In February 2001, a second visit was made to Okarito Lagoon for the purpose of trenching key sites, as revealed by core samples. Three trenches were dug in tidal flat sediments to confirm the lateral continuity and character of sediment beds observed in cores. In addition, sediment samples were collected from each trench for laboratory analysis.

3.2 ANALYSES OF SEDIMENT SAMPLES

3.2.1 Grain size analysis

The grain size of core samples was measured using a laser particle sizer (Galai^{TM}) that determines particle size based on the time of transition principle, whereby the larger the particle diameter the longer the time of transition across the path of the laser beam. Approximately 1 g of sample was introduced to a solution of filtered water with data collection set to the 99% confidence level. Results reported here are for grain size classes expressed as percent of total particle volume.

3.2.2 Organic content and chemical analysis

Organic content of sediment samples was determined as weight loss on ignition (LOI) by ashing a representative sediment sub-sample at 500°C for 4 hours in a muffle furnace. Results are reported on a dry weight basis.

Major and trace elements (aluminium (Al), barium (Ba), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), sodium (Na), phosphorus (P), lead (Pb), sulphur (S), strontium (Sr), titanium (Ti) and zinc (Zn)) were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES) following a multi-acid 'total' digest (perchloric/nitric/hydrofluoric/hydrochloric). Calibration of these multi-element systems was by means of solution standards that were also used to monitor the systems during the analysis to ensure that stability was maintained. In addition, the same primary rock standard (SY-4), which is an international reference material produced by Canmet in Canada as part of their Canadian Certified Reference Material Project (CCRMP), was run with each set of analyses (only representative data are reported).

The particulate nitrogen (PN) and particulate phosphorus (PP) were determined by acid digestion followed by analysis on a Technicon2 Auto-analyser.

Geochemical data were normalised for grain size of each sample. Normalisation is a technique which has been used in a number of studies to reduce the effect of grain size and correct for mineralogical variations, and thus can show trends in metal concentrations which are not attributed solely to lithogenic variability. As grain size distribution was determined, the silt content was used as the base for normalisation. Both non-normalised and normalised data are presented.

3.2.3 ^{210}Pb isotope dating

Measurement of the ^{210}Pb isotope, which has a half-life of 22.3 years (Goldberg 1963), is an established method used for the dating of recent sediments (up to c. 120 years). The method is based on the measurement of "excess" ^{210}Pb activity, which is produced by the decay of atmospheric ^{222}Rn and comes down as fallout to be incorporated into accumulating sediments. The total ^{210}Pb activity is the sum of the "excess" activity and "supported" ^{210}Pb, the latter resulting from the decay of ^{226}Ra in the sediment. The amount of "unsupported" ^{210}Pb can be determined by subtracting the "supported" ^{210}Pb from the "total" ^{210}Pb.

Sample preparation and counting based on the general method of Flynn (1968) were carried out at the Australian National Science and Technology Organisation (ANSTO). ^{210}Pb activity was measured by gamma-spectrometry.

3.2.4 Foraminifera

The calcareous remains of microscopic foraminifera are usually preserved in sediments from marine, estuarine and saltmarsh environments. Different foraminifera species are known to have preferential habitats, related to salinity and water depth. Assemblages of foraminifera species can therefore be used as indicators of general salinity levels and approximate water depth. Twelve 10 cm^3 samples of sediment were taken from cores OK 4 and OK 6 for foraminiferal analysis. Samples were washed over a 63 µm sieve to remove the mud. Heavy-liquid flotation was used to concentrate foraminiferal tests (and carbonaceous matter) in samples that had large quantities of sand grains. All or a split of the dried sand fraction was spread over a picking tray and a quantitative census count of all the benthic foraminifera present was made. The presence of other microfossils was also noted.

4. Results and discussion

The primary focus of this report will be on Cores OK 4, OK 6 and OK 10, and Trenches 1, 2 and 3. These are selected with specific objectives in mind:

- Core OK 10 was taken from the Okarito River delta to ascertain the effects of the AD 1967 diversion of the Waitangi-taona River.
- After splitting the cores in the laboratory, the most comprehensive long-term records were found preserved in Cores OK 4 and OK 6. These data are supplemented by information gathered in trenches.

4.1 DIVERSION OF THE WAITANGI-TAONA RIVER

The Waitangi-taona River has been flowing through Lake Wahapo and into Okarito Lagoon since AD 1967. This has probably occurred naturally several times during the past few thousand years, but we find no evidence to this effect one way or the other.

Core OK 10 was taken on the north side of the Okarito River delta and was analysed for a broad suite of nutrients and metals. ^{210}Pb analysis was also carried out to determine the age of the sediment.

Figure 4, which is a summary diagram of the results, indicates that the sediment is primarily coarse grained, varying from very fine sand to gravel. The dating analysis was somewhat difficult given the coarse nature of the sediment, but we have approximated the chronology of events. Sedimentation rates appear to have decreased from about 0.0–3.5 cm/yr around AD 1847–67 to between 0.5 and 1.1 cm/yr in the last 40 years or so. Unfortunately there is no dating control at the base of the core. The decrease would appear to be related to rapid delta growth into the lagoon. The rate has slowed in the vicinity of Core 10 but has increased towards the Lagoon as the delta continues to prograde (I. James pers. comm. July 2000).

Initial geochemical analyses indicated a peak in all metals/nutrients between about 100 and 130 cm depth which coincided with a silt-rich unit. These data were then normalised to correct for variations caused by differences in grain size. A markedly different result was produced.

There are two clear peaks in the metals and nutrients measured in core OK 10, at 50 cm and 15 cm depth (Fig. 4). These peaks are ubiquitous in all the data. It is difficult to explain the lower one without considering the establishment of a gold mining settlement in the area that might have introduced raised metal

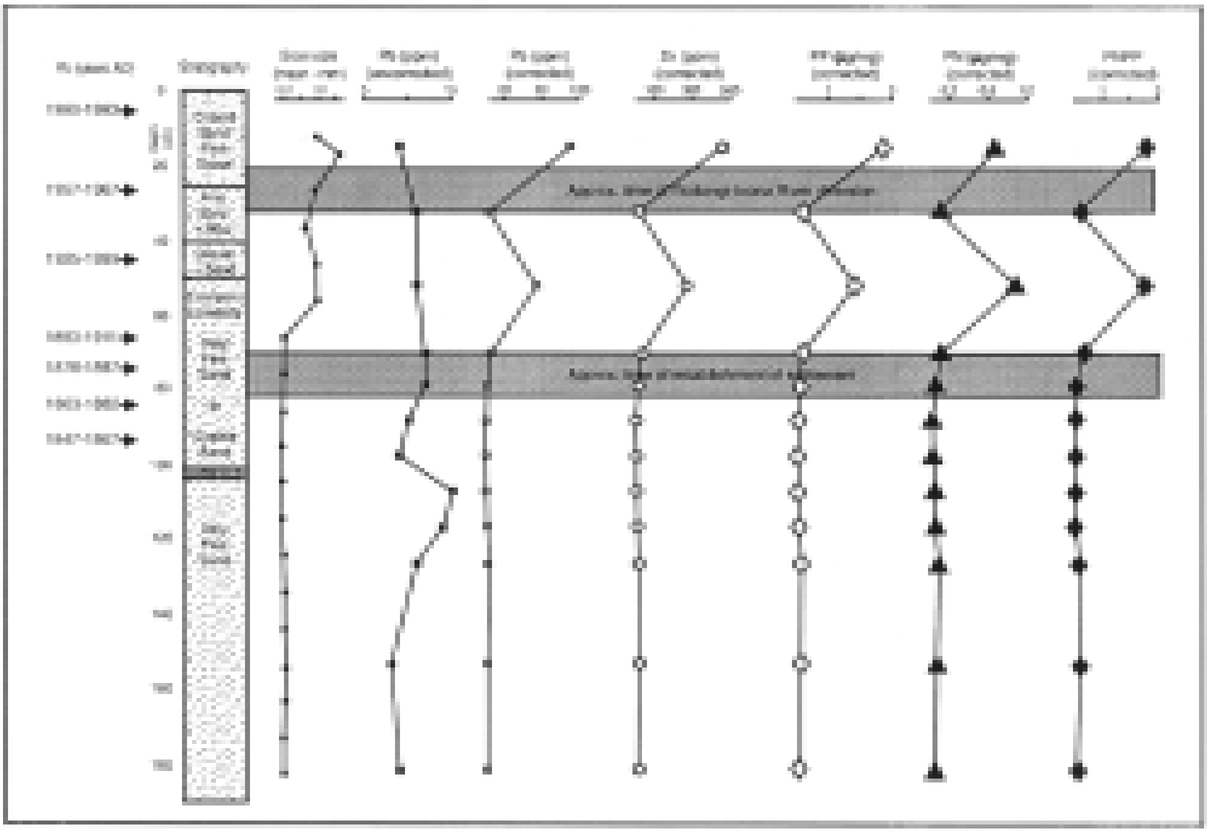

Figure 4. Core OK 10, summary stratigraphy, grain size, and geochemistry. (Because of the generally coarse grain sizes recorded in the core, ^{210}Pb data are considered tentative.)

concentrations into the local waterways. While the effects of settlement appear to have been delayed, this is not unexpected given that much of the activity was peripheral to this area. In the absence of an alternative explanation, we feel that this is the most likely scenario for the lower peak, particularly since there is a marked decline in contaminant/nutrient concentrations toward the mid-20th Century, paralleling the rapid decline in population.

The base of the upper peak in core OK 10 probably dates somewhere between about AD 1957 and AD 1967. While there are insufficient data to ascertain whether this increase has been maintained, it tends to indicate a marked environmental change in the catchment. There has been a small, but steady increase in the local population, but this seems an unlikely cause bearing in mind the rapid turnaround in contaminant concentrations from a low in the earlier part of the 20th Century. This rapid change in contaminant/nutrient concentrations suggests a source that is more proximal to Core OK 10. We consider the most likely explanation for this to be changes in sediment and water input related to the diversion of the Waitangi-taona in AD 1967.

4.2 ENVIRONMENTAL CHANGES AFFECTING THE LAGOON DURING THE HOLOCENE

A Holocene record possibly dating back about 6500 years has been obtained from Okarito Lagoon. Cores OK 4 (at the southern margin of the lagoon) and OK 6 (more seaward) offer the best representation of the past sedimentary environment.

4.2.1 Core OK 6 (comparison with OK 4)

Core OK 6, like most of the cores taken from the lagoon, is dominated by a very fine sand matrix. However, the other marked characteristic of the core is that it has a series of fining-upward beds, some of which are associated with an underlying buried soil and/or an erosional contact (Fig. 5). Looking in more detail at the composition of these beds, it is apparent that they share many similar attributes. The bed that commences at 1.10 m depth in Fig. 5 (marked by an arrow on the right-hand side) is used to identify these attributes:

- The fining-upward bed overlies a buried soil containing roots, in situ organic remains and shell. This is marked by an erosional contact that truncates the soil.
- Grain size data indicate that the bed fines upwards to a point defined by the shaded box, where silt content increases from 5 to 45%. Above this point, the silt content declines while a very fine sand matrix is maintained (this is discussed below).
- Magnetic susceptibility (a measure of iron sand content) shows a marked increase at the base of the bed.
- Iron, sulphur, and titanium show similar peaks at the base of the bed.
- Loss on ignition (a measure of organic content) is low at the base, increasing as the sediment fines upwards.
- Foraminiferal data from above (1.01–1.03 m) and below (1.15–1.17 m) the contact indicate a change in salinity and a subsidence of about 0.50 m (see Appendix I).

This is the only fining-upward bed that displays this particular suite of signatures, but others are worth noting:

- 3.20 m: Erosional contact, fining-upwards, magnetic susceptibility peak, sulphur peak.
- 2.50 m: Gradational contact, fining-upwards, magnetic susceptibility peak, iron, sulphur, and titanium peaks, slight decrease in organic content.
- 2.10 m: Gradational contact, fining-upwards, magnetic susceptibility peak. Weak signal in trace elements.
- 1.90 m: Gradational contact, fining-upwards, magnetic susceptibility peak, sulphur peak? Increased organic content? Foraminiferal data from below the contact and within the bed indicate a change in salinity and a subsidence possibly as high as 1.00 m (see Appendix 1 – it is recorded as two events, but since the foraminifera samples do not bracket the whole deposit they may represent only one event).

- 0.78 m: Buried soil, erosional contact, fining-upwards, magnetic susceptibility peak? low sulphur? Decrease in organic content. Foraminiferal data from above and below the contact indicate a change in salinity and a subsidence of about 0.50 m (see Appendix 1).
- 0.30 m: Gradational contact, fining-upwards, geochemistry unclear, decrease in organic content.

A total of seven possible sequences can be identified, although only the five most recognisable have been shaded in Fig. 5.

4.2.2 Interpretation of attributes

This suite of attributes is diagnostic of marked changes in the palaeoenvironment of the lagoon and most, if not all, indicate catastrophic inundation by saltwater. This interpretation, and the reasons for a lack of the full range of diagnostic criteria at any one level in the core, are discussed below.

First, a buried soil is indicative of subsidence. If this is overlain by an erosional contact then a high-energy event has most probably removed part of the soil (Atwater 1987; Goff et al. 1998).

A fining-upward sediment trend is indicative of a high-energy event that initially deposits coarse, heavy material, but as the energy wanes, finer material falls out of suspension. In the case of the example given at 1.10 m (this also applies to other sequences in the core), the fining-upward sequence reaches a point at around 0.90 m where less silt is deposited, but a very fine sand matrix is retained. This may well represent winnowing of fine material by the backwash of a tsunami, or by tidal currents following deposition. We acknowledge that a tsunami is not the only mechanism that could produce upward-fining trends in estuarine sediments. For example, sedimentary processes related to migration of tidal channels in the lagoon could also cause sand bars and shoals to fine upward as they are abandoned.

Tsunami deposits generally fine inland and upwards (Goff et al. 1998), and the same trend found at 1.10 m in OK 6 is also recorded at 0.55 cm in OK 4 as a fining-upwards bed overlying a buried soil (Fig. 6). In this case, the fining-upward trend is from a fine sand to a very fine sand, suggesting that the overall deposit has fined inland. A similar association is found at Trench 3 behind the village, suggesting that the saltwater spread out to cover all low-lying parts of the area following a subsidence event (Fig. 7). This interpretation is tentative and further work is required to assess the extent of the deposit, and establish a robust chronology. Correlation of similar sediment cycles between cores at this stage is also tentative and requires further dating of sediments to validate the synchronicity of depositional episodes, and also further lateral correlation across the lagoon to establish the continuity of these events.

Magnetic susceptibility (a measure of ironsand content) shows a marked increase at the base of the fining-upward cycle. Ironsands are denser and heavier than sands of a similar grain size and therefore require higher energy to transport them. Concentrations of heavy minerals such as ironsands are often produced by wave swash on beaches where the concentrate represents a lag deposit. Within an estuary such as Okarito Lagoon, sorting of sands according to density is unlikely to be achieved by tidal currents, particularly at a relatively distant location as represented by core OK 6. In this core, the peak in magnetic susceptibility lies immediately above the buried soil. This suggests that wave swash (tsunami?) may have sorted the sands across the soil surface in addition to eroding the soil.

Iron, sulphur, and titanium show similar peaks at the base of the sequence. Titanium is another indicator of ironsand enrichment, while iron and sulphur are key chemical indicators of saltwater inundation into freshwater environments (Chagué-Goff & Goff 1999).

Organic content decreases at the base, increasing as the sediment fines upwards. A decrease in organic content at the base of a deposit would be expected in the case of a high-energy event, as the less dense organics are often removed. In the case of a tsunami, higher levels of organics are often found in the upper part of a fining-upward sequence as the less dense material settles out (this is recorded in the 1.10 m example).

Microfossil analysis proves useful in determining not only the seaward or landward source of an event, but also other environmental changes. In the case of foraminifera, these are indicators of saline conditions. While some can survive in fairly low saline concentrations (high intertidal), others need subtidal conditions. While their presence indicates saltwater, an examination of the relative percentage of each species gives a strong indication of water depth (Hayward et al. 1999). Subsidence is indicated in at least two and possibly four cases. Examination of additional data such as grain size and stratigraphy suggests that subsidence has probably occurred in at least three cases (1.90 m depth: at least 0.50 m subsidence?, 1.10 m depth: at least 0.50 m subsidence?, and at 0.78 m depth: possibly as much as 1.0 m subsidence?).

Macrofossil analysis can also useful but in this instance was only carried out in Trench 1 (Figs 2 and 7) in sediments immediately overlying the buried soil. Intertidal species were recorded, including: *Mactra ovata*, *Austrovenus stutchburyi*, and *Amphibola crenata*. In addition, several macro algae, most probably seaweed, were identified. Articulated and broken shells were recorded, indicative of reworking by higher energies than would be expected within the lagoon.

The lack of certain attributes in any one fining-upward bed does not discount the validity of the interpretation that these are related to high-energy events from the sea. In most cases the lack of a signal is a function of the slightly different depths at which samples were taken for different analyses. In other cases the geochemical signal can be difficult to identify in sandy sediments and can be a factor of preferential preservation where it is found. The importance of using a suite of diagnostic criteria to interpret palaeo-environmental changes cannot be overstated, and this coupled with a comparison between each sequence in individual cores, provides a robust interpretation of past events.

In the cases where subsidence has been identified by either buried soils and/or foraminiferal data (0.78 m, 1.10 m, 1.90 m) the accommodation space (the gap between the tide level and the new water level created when the land subsided) would have been rapidly filled by seawater – a tsunami. It is highly likely therefore that other sequences with similar diagnostic criteria are comparable events, although not necessarily tsunami. In the absence of unequivocal evidence, these other sequences can be termed ‘catastrophic saltwater inundations’ (CSIs), most probably caused by either tsunami, cyclone,

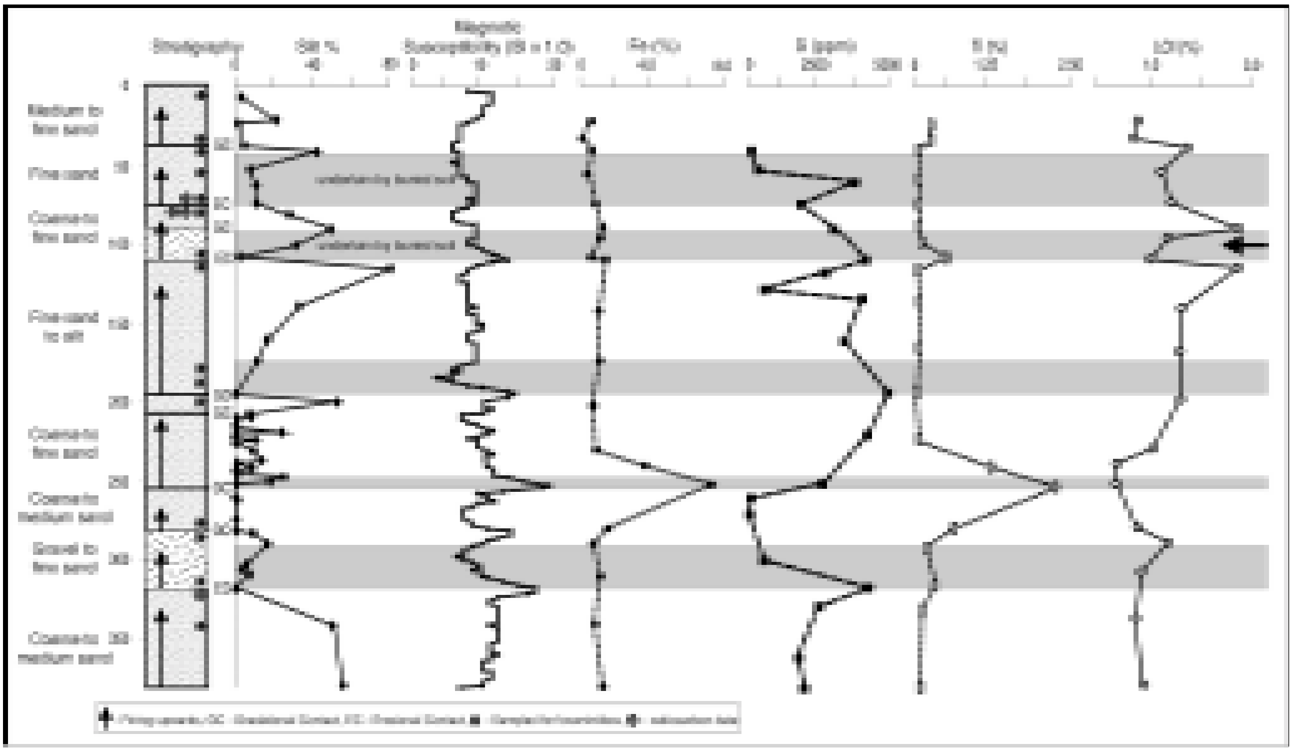

Figure 5. Core OK 6, grain size, magnetic susceptibility, and geochemical data. Arrow at the right indicates the fining upwards sequence discussed in the text.

breaching of a new lagoon entrance, or channel changes (adjacent to Core OK 6).

Interestingly, the benthic foraminifera identified contain no species that live in open-water, normal-salinity conditions. All recognised species present require slightly to strongly reduced salinity conditions in a sheltered inlet, harbour or estuary environment. Thus there is no indication, in the samples studied, of any open-coast, pre-lagoon environments nor of any tests being swept into the lagoon by tidal surges, storms or tsunami. However, it is clear that where subsidence has been involved, tsunami inundation is inevitable.

As a rule of thumb, researchers in New Zealand have operated in the belief that to preserve a recognisable signal of tsunami inundation, wave height must be at least 5.0 m (Lowe & de Lange 2000). Initially this scenario seems unlikely, but with a small lagoon entrance it is improbable that any single catastrophic inundation will pass completely through this gap, and some, if not most, will overtop the 4.0 m high sand barrier between the lagoon and the sea. Given this possibility, tsunami inundation of Okarito Lagoon may have taken the form of a rapid rise in water level, rather than as a catastrophic wave form. Even so, strong currents would have been generated as the water was forced into the estuary allowing the transport of coarse sediments to normally low-energy sites such as core OK 6.

The fact that subsidence has taken place suggests a generating mechanism, most likely associated with fault rupture. The closest active fault is the Alpine Fault approximately 10 km east of the lagoon. The Alpine Fault has a recurrence interval of a Magnitude 8.0+ event about once every 260 years (Bull 1996; Yetton et al. 1998; Goff et al. 2000a) with the last recognised rupture occurring in AD 1717, although there is evidence to suggest that a rupture which affected

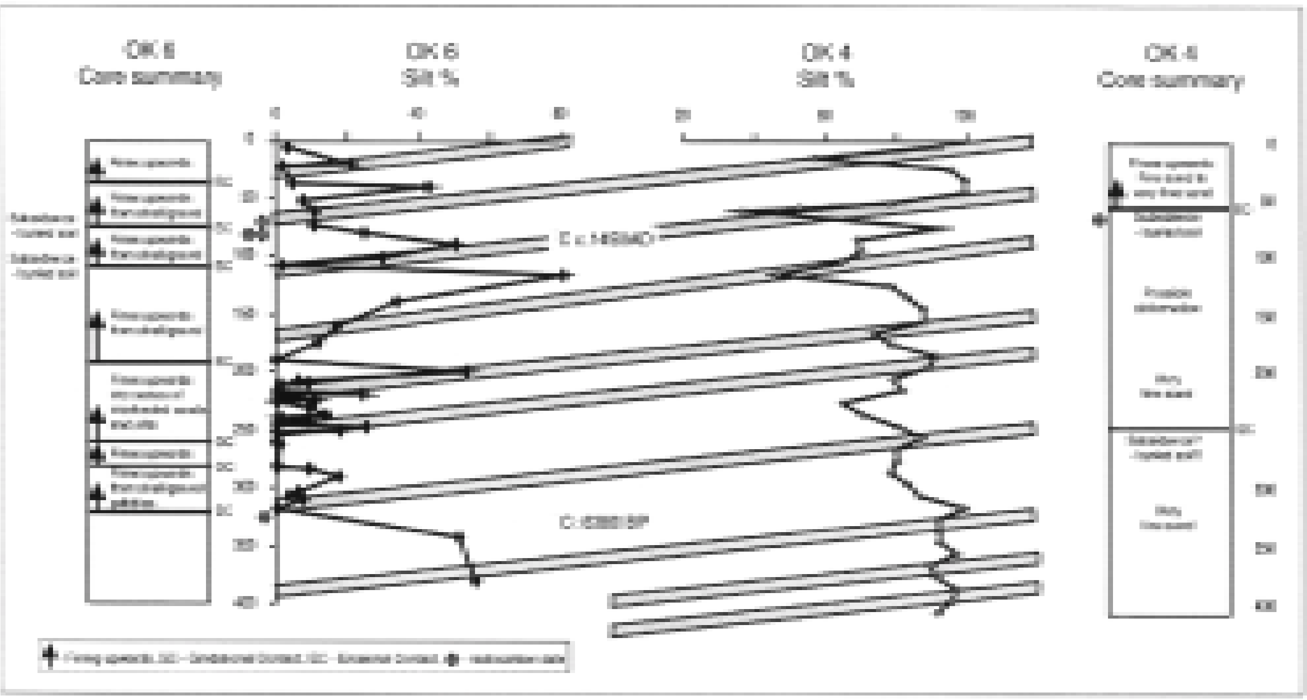

Figure 6. Comparison between cores OK 4 and OK 6, interpretation of grain size and core log data. Details of radiocarbon dates are given in Table 1. Similar key palaeoenvironmental changes are shaded. (Note that the full extent of each sequence has not been shaded, so some depths may not correspond exactly to those discussed in the text.)

Okarito Lagoon might have occurred in the mid-1820s (Brunner 1952). Considerable effort has been expended in attempts to ascertain the recurrence of Alpine Fault ruptures with both on-fault and off-fault data being used (e.g. Bull 1996; Yetton et al. 1998). Acknowledging that these ruptures are large, it is surprising that no previous work has been carried out on the possible off-fault signatures recorded in Okarito and other adjacent lagoons. It seems highly likely that the subsidence reported in this study is linked directly to Alpine Fault ruptures, either as the result of compaction caused by groundshaking or by structurally controlled, local subsidence. Inter-pretation of the core data suggests that the former is unlikely to represent more than 10–20 cm, which leads to the conclusion that there may well be a connection between Alpine Fault ruptures and subsidence of the Lagoon.

It is worth noting that it is extremely difficult to identify subsidence events from the sedimentary record, but we have been fortunate in some instances here where a buried soil has been preserved. Acknowledging that several large subsidence events have occurred, it is quite likely that many smaller < 0.50 m ones may have also taken place. It is also worth reiterating that fining-upward beds do not have to represent a tsunami; they may also represent the breaching of a new lagoon entrance, a storm or cyclonic event, or even channel changes. However, the sedimentary records of storm and cyclonic events are usually more chaotic and easily differentiated from tsunami deposits (e.g. Nanayama et al. 2000). Furthermore, the breaching of a new entrance and/or or channel changes are likely to be represented as locally significant high energy events, as opposed to being recorded as fining-upward beds in more than one core.

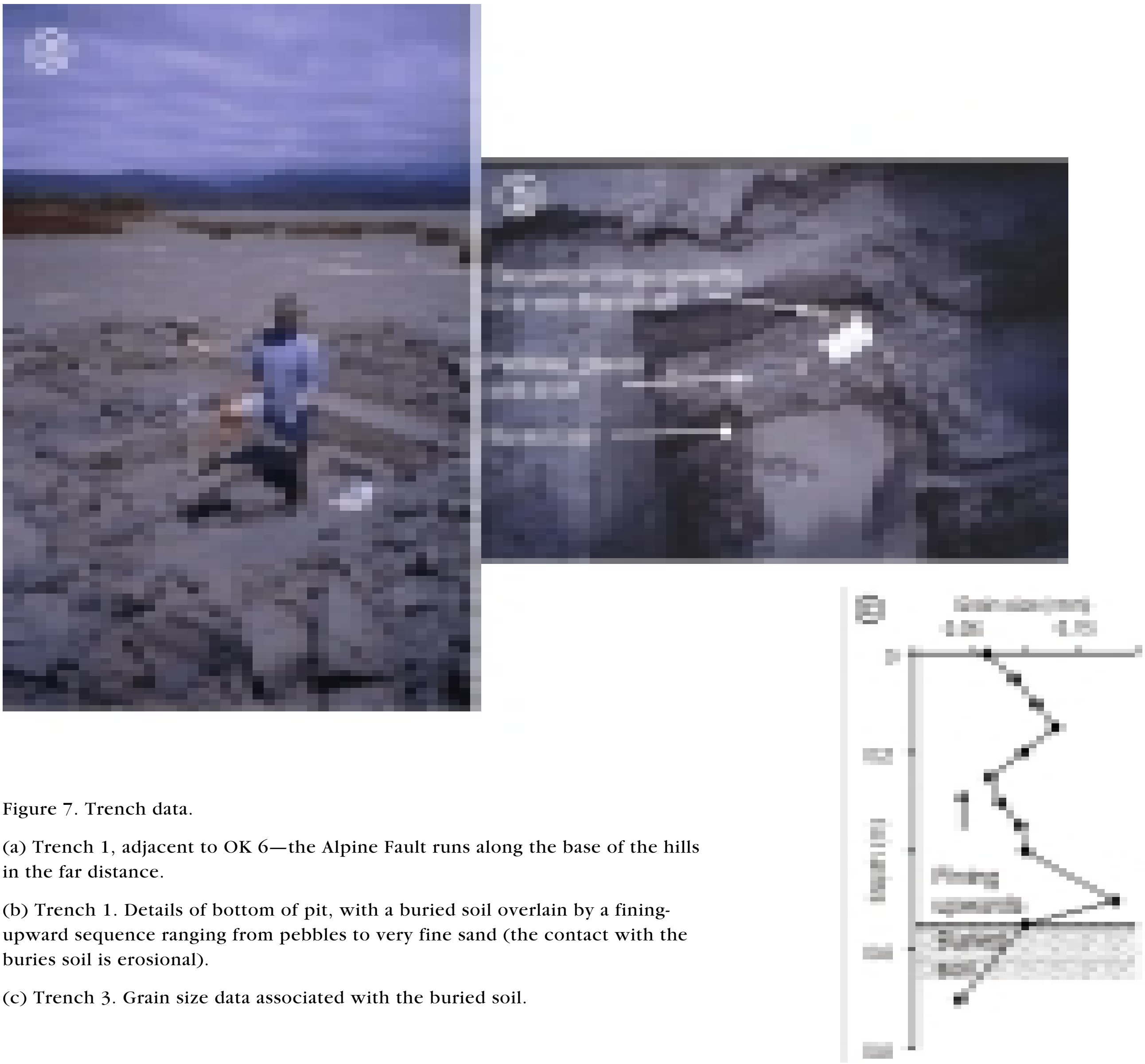

Figure 7. Trench data.

(a) Trench 1, adjacent to OK 6—the Alpine Fault runs along the base of the hills in the far distance.

(b) Trench 1. Details of bottom of pit, with a buried soil overlain by a fining-upward sequence ranging from pebbles to very fine sand (the contact with the buries soil is erosional).

(c) Trench 3. Grain size data associated with the buried soil.

TABLE 1. RADIOCARBON DATA FOR OKARITO LAGOON (CALIBRATIONS BY B.G.McFADGEN, BASED ON STUIVER ET AL. 1998).

LAB NO.	CORE NO.	DEPTH (m)	dC13	^{14}C AGE BP	CALIBRATED AGE (2 s i/v)	MATERIAL SAMPLED
Wk8989	OK 4	0.65	– 26.3 ± 0.2	1800 ± 60	AD 78–391	Root from buried soil
Wk8987	OK 6	0.78	– 21.5 ± 0.2	2170 ± 70	2–393 BC	Bulk soil/organics - buried soil
Wk8618	OK 6	0.82	1.1 ± 0.2	10580 ± 60	10262–10328 BC	Articulated shell - *Austrovenus stutchburyi*
Wk8986	OK 6	0.82	– 0.6 ± 0.2	900 ± 60	AD 1318–1495	Articulated shell - *Austrovenus stutchburyi*
Wk8988	OK 6	3.26	0.1 ± 0.2	6380 ± 60	4774–5071 BC	Articulated shell - *Austrovenus stutchburyi*

4.2.3 Chronology (Figure 6, Table 1)

In attempting to provide a chronology of these events we found that we had insufficient data. The dates of c. AD 1450 (1318–1495) and 6380 BP (4774–5071) are simplifications of calibrated radiocarbon dates reported in Table 1.

Three additional results all relate to attempts to date the buried soil at 0.78 m in core OK 6 and 0.65 m in core OK 4. Radiocarbon ages range from 10 580 ± 60 to 1800 ± 60 ^{14}C years BP. Two dates were taken from either roots or a bulk soil sample and indicate the problems associated with reworked organic material that has been reported from numerous New Zealand locations (e.g. Goff 1997). The most reliable organic material for radiocarbon dating in lakes and coastal lagoons is shell. Shells used for dating should preferably be articulated as opposed to being single or broken, because they are less likely to have been reworked. However, in the case of sample WK8618, an articulated shell has a radiocarbon age of 10 580 ± 60 ^{14}C years BP. Examination of the shell prior to analysis indicated that it did not appear to have been reworked and was unweathered. A subsequent shell date from the same layer produced an age of 900 ± 60 ^{14}C years BP, or about AD 1450, a minimum age for the deposit.

These results offer further support for the tsunami inundation interpretation. The preservation of articulated shells is extremely rare with storm and cyclone deposits, but are a feature of tsunami (e.g. Goldsmith et al. 1999). In this instance, assuming that the shell had not been previously reworked (a reasonable assumption bearing in mind the preservation of the shell) it must have come from offshore Okarito Lagoon in a water depth of about 30–35 m (this water depth is based upon the Holocene sea level curve of Gibb (1986)). The only realistic process that would access this depth of seabed without destroying the shell would be tsunami, given that tsunami are of very short duration.

Regrettably, the expense required to address this problem meant that we were only able to analyse one further sample for radiocarbon and this yielded an age of 6380 ± 60 ^{14}C years BP. Bearing in mind the problems associated with the uppermost buried soil, this must be considered to be a maximum age.

Using estimated Alpine Fault rupture dates based on the work of Yetton et al. (1998) it becomes apparent that there must either be a hiatus somewhere in the core (probably represented by one of the buried soils) or that we are losing the records of older events down the core. The latter has been found to occur at other sites around the country (e.g. Goff et al. 2000b).

While a chronology is difficult to establish, the sedimentological correlation with core OK 4 is remarkable (Fig. 6). Furthermore, it adds more detail. Firstly, it shows that the uppermost event (possibly AD 1826) was too small to be recorded on the landward side of the lagoon (it may simply represent channel changes in the lagoon). Secondly, at the base of OK 4 there appear to be two events that are not recorded in OK 6 (either because core penetration for OK 6 was not deep enough or because these represent local events such as channel changes).

The following comments can be made:

- A combined sedimentary record from cores OK 4 and OK 6 indicates at least 10 fining-upward beds, of which at least two have buried soils and an associated record of subsidence. The two fining-upward beds associated with buried soils provide the most convincing evidence of tsunami inundation, although elements of diagnostic criteria are present for most of the others.

- As a rule of thumb, waves over 5 m in height are needed to leave a recognisable deposit. These are a reasonably high-magnitude, low-frequency event, and will have been interspersed with smaller, more frequent events. This clearly has significant implications for any future development of the Okarito area. Brunner (1952) noted in a visit to Okarito in AD 1848 that 'to the foot of the mountain range has been recently washed by the sea'. This may be related to an event that took place in AD 1826 (McNabb 1907), in which case the after-effects were still noticeable 20 years later. Brunner (1952) also noted the remains of a drowned Maori village on the barrier of Saltwater Lagoon a few km north of Okarito. The nature and location of this observation suggest that it might have occurred in the recent past.
- Wells et al. (1998; 1999) identified two periods of synchronous, widespread disturbance-initiated forest establishment in Westland and assigned these to two previous ruptures of the Alpine Fault: c. AD 1450 and AD 1717 (e.g. Yetton et al.1998). Similar widespread coastal forest destruction has also been reported elsewhere in the Pacific as a result of tsunami inundation and seawater infiltration into soil (Minoura et al. 1996). The c. AD 1450 Alpine Fault rupture coincides with the uppermost buried soil in OK 6 and a similar feature in OK 4.
- It is quite probable that the ecosystem structure and geomorphology of the lagoon is largely driven by high-magnitude, low-frequency events. From a Holocene and human perspective the main 'driver' of environmental change is not climate (indirectly linked to the fluctuations of the mass balance of local glaciers), but rather seismic activity. Earthquakes, groundshaking, saltwater inundation, and increased sediment supply, river aggradation, rapid coastal dune building, and channel avulsion are all related to the same driving mechanism, that of fault rupture. Past ecosystems have probably established a form of quasi-equilibrium with the periodicity of these events, but the resilience of our contemporary ecosystem to change has been severely compromised by human intervention. Therefore, human use of the area has reduced the effectiveness of the environmental buffer, and these catastrophic events are likely to be more damaging in the future.

5. Implications of future environmental changes

As mentioned above, by combining the findings of researchers such as Wells et al. (1998; 1999), Yetton et al. (1998) and others, it becomes apparent that the ecosystem structure and geomorphology of the lagoon are largely driven by high magnitude, low frequency seismic events. While we have been unable to produce a detailed chronology of events, there is sufficient information to show that seismic events are key drivers of environmental change in and around the Okarito area. The implications of this for future environmental change are best considered by examining each stage of the chain of events:

- Fault rupture/earthquake (probably on the Alpine Fault).
- Some compaction of the lagoon floor sediments by groundshaking and liquifaction – max. 20 cm?
- Local subsidence of the lagoon and surrounding area probably by about 50 cm or more. Tsunami inundation as a result of subsidence/compaction, but also other possible tsunamigenic mechanisms such as submarine fault rupture (the southern part of the Alpine Fault is submarine) and/or submarine landslides.
- Increased sediment supply to the coast in the years/decades following the earthquake. Earthquake-generated landslides would deliver substantial amounts of sediment to local rivers causing aggradation, channel avulsion, and rapid coastal dune building at the coast.
- The barrier of Okarito Lagoon becomes higher and wider. Probably enough to close outlet/inlet and make it ephemeral. New higher drainage point established, and increased seepage through sand.
- Lagoon deepens and freshens due to poor tidal exchange. Increased growth of freshwater vegetation such as raupo.
- Raised shoreline established (as per I. James, pers. observations). Wave cut notches and caves form along the shore in surrounding moraines.
- Okarito River supplies silts/fines to lagoon. This buries the tsunami deposit and subsided soil. The Okarito River delta progrades into the lagoon. Possible diversion of rivers such as Waitangi-taona into the Okarito River exacerbating the situation.
- Later (in the order of decades) the overall sediment supply to the coast starts to decrease. The barrier is more prone to breaching, longshore and cross-shore sediment movement helps to breach the barrier. Lagoon more open than closed.
- Lagoon level falls to new shoreline allowing forest growth to re-establish on eastern shores. Scarp from former lake level preserved.
- The Okarito River incises into its channels in the delta in response to lowered base level (I. James, pers. observation).
- Period of quiescence and stability until next fault rupture.

The present situation appears to differ from that in the Holocene in that:

- The course of the Waitangi-taona River is artificially maintained and flows into the Okarito River upstream of the lagoon. As discussed above, this provides increased sediment load, and increased heavy metal and nutrient loading. This may affect all flora and fauna in the lagoon. It also may have a detrimental effect on mahinga kai values.
- There has been, and continues to be, human occupation and use of the coastal area in the vicinity of the lagoon.

The implications for the future are that:

- Ecosystem resilience is reduced. Okarito Lagoon and its margins are more susceptible to invasion of aggressive pest/weed species in the aftermath of a catastrophic event.
- The Okarito community and, by analogy, the coastal population centres of the West Coast (bearing in mind that the AD 1826 event appears to have affected an area from at least Invercargill to Okarito Lagoon) are at risk from tsunami and the combined after effects of large, local fault ruptures. Brunner (1952) in

AD 1848 observed the remains of a drowned Maori village a few km to the north on the spit of Saltwater Lagoon. This would appear to be adequate proof of the risk posed by catastrophic events to both past and present communities.

- Following the next large, local fault rupture there will be a sustained degradation of the environment. It is probable that the gradual recovery of Okarito Lagoon and its margins will be marked by significant and irreversible changes in ecosystem structure. The community will face numerous problems, namely groundshaking, tsunami inundation, flooding by higher lagoon/lake levels, increased amounts of windblown sand, and probably numerous aftershocks.

  The broader regional context acknowledges that these catastrophic events are not merely local, but affect a considerable length of coastline such as the AD 1826 event. Therefore it is not just the local ecosystem that is affected, but also those of Southland, Fiordland, and Westland. Many unique ecosystems that are now oases surrounded by a fundamentally altered environment. Similarly, it is not just the contemporary communities that are at risk, but the records of past communities—the historical resources—that are threatened. There needs to be a clear understanding of the future problems posed by such catastrophes.

6. Future research

In Okarito Lagoon additional trenching, and possibly coring at sites in the northern part of the Lagoon would help to ascertain the lateral extent of the uppermost buried soil, and to improve chronological control (including a possible investigation of the drowned Maori village to the north).

The regional analysis could be extended by carrying out similar work at Shearers Swamp to the north, about midway between Okarito and Hokitika.

An analysis of the broader situation in the West Coast could be done by examining wetlands to the north of Westport, and posssibly further south towards Haast.

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awkward questions. Bruce McFadgen is thanked for providing calibrations of radiocarbon ages.

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Appendix 1

FORAMINIFERAL EVIDENCE FOR PALAEO-ENVIRONMENTS OF OKARITO LAGOON CORE HOLES

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Methods

Twelve 10 cm^3 samples of sediment were taken using a short PVC tube corer from cores OK 4 and OK 6) that had been vibracored by James Goff, Scott Nichol and Catherine Chagué-Goff in 2000. Samples were washed over a 63 μm sieve to remove the mud. Heavy liquid floatation was used to concentrate foraminiferal tests (and carbonaceous matter) in samples that had large quantities of sand grains. All or a split of the dried sand fraction was spread over a picking tray and a quantitative census count of all the benthic foraminifera present made. The presence of other microfossils was noted.

Modern analogue technique (MAT)

Estimates of the tidal height or subtidal depth (elevation) at which each foraminiferal fauna from the cores was deposited were made using the modern analogue technique (MAT). This technique utilised a set of relative abundance data on 250 benthic foraminiferal faunas from modern estuaries and coastal lagoons from around New Zealand (data from Hayward et al. (1999) supplemented by relative abundance census data from our current Ahuriri Lagoon entrance transect).

This computer technique generates the dissimilarity coefficients using the chord measure of dissimilarity between the sample faunas and all analogue faunas based on their faunal composition. We chose to use as our estimate of tidal level or depth, the mean value of the five analogue faunas with the most similar composition to our sample (lowest dissimilarity coefficients).

The reliability of these estimates depends on a number of factors, including the range of tidal levels, depths and environments represented by five or more of the analogue samples; and the breadth of the tidal and depth ranges of the major taxa. Previous studies (e.g. Hayward et al. 1999) have shown that the most precise tidal ranges can be obtained near high tide level from marsh faunas, with far broader ranges observed in intertidal mud and sand flats and in subtidal environments. Some taxa with restricted high tidal ranges in near normal salinity situations (e.g. *Haplophragmoides wilberti, Trochamminita salsa, Miliammina fusca*) are known to live in abundance through the entire tidal range and also subtidally in more brackish environments (e.g. Hayward et al. 1999). Thus an assessment of the setting and probable salinity of the lagoon or estuary at the time is important in estimating tidal level.

In graphing the past elevation for core OK 6 based on the MAT estimates, we have assumed that the site shallows at a rate close to that of sediment accumulation with little compaction of the underlying sediment.

Results

Foraminiferal census and other sample data are given in Table A1. Preservation of tests varied between good and poor, with obvious stages in the taphonomic loss of some agglutinated tests. No reworking of older tests was recognised and seems unlikely. Shell material (indeterminate broken bivalve) was present in only one sample (OK 6–79 cm). There are no obvious trends (Table A1) in the abundance distribution of carbonaceous material, fern sporangia, diatoms, thecamoebians, ostracods or planktic foraminifera.

OK 4

Three samples were processed from this core. The lowest sample (380–382 cm) contains no foraminifera nor any other obvious evidence of either a marine or freshwater environment. The other two samples contain sparse foraminiferal faunas. The lower sample (76–78 cm) contains four species that co-occur in modern salt marsh environments around and just below MHW level. The most abundant species (*Ammobaculites exiguus*) is most abundant today in subtidal estuarine channels, but sporadically occurs up to MHW. MAT estimate of elevation for this sample gives a wide range of possibilities between 1.9 m (MHW) and –2 m (subtidal), with a mean of 0.7 m (MLW).

The highest sample (54–56 cm) contains seven specimens of just one species (*Miliammina fusca*). This species dominates low-salinity tidal marshes and both shallow subtidal and intertidal mud banks of upper estuaries. No confident estimate of palaeoheight is possible. The salinity index, SI (1–10 scale) value calculated for this fauna is 6 (corresponding to a salinity range of about 15–25). **No vertical displacement is necessary above 78 cm to explain the faunas present, but neither can it be ruled out**.

OK 6

Nine samples were processed from this core. Only the lowest sample (340–342 cm) lacks foraminiferal tests. The two next samples upcore (199–201, 174–176 cm) are low-diversity faunas co-dominated by *Haplophragmoides wilberti* and *Ammotium fragile.* These faunas indicate lowered salinity (SI = 5) and an elevation between MSL and MHW (mean MAT elevation estimates 1.9 and 1.5 m; range 0.2–2.1 m), possibly in a salt marsh setting.

Sample 115–117 cm is co-dominated by *Ammotium fragile* and *Miliammina fusca*, with subdominant *Haplophragmoides wilberti.* This increased presence of *Miliammina* suggests a palaeoelevation slightly lower than the two samples below (201–174 cm). Again a lowered salinity is indicated (SI = 5) and a MAT palaeoelevation estimate in the range 0.9–1.5 m (mean 1.3 m). The rich foraminiferal fauna in sample 101–103 cm is co-dominated by *Ammonia* and *Haplophragmoides* with subdominant *Ammotium.* This association is unusual and not well represented in our modern analogue set. The MAT estimate of elevation is within the broad range of 0.9 (mid to low tidal) to –2.5 m (subtidal).

TABLE A1: CORE HOLE STATION DATA.

OK 4 AU *Leptocarpus similis* salt marsh, MHW

OK 6 AU edge of *Leptocarpus similis* salt marsh, MHWN

OKARITO	OK 4			OK 6								
Interval top (cm)	54	76	380	5	50	71	79	101	115	174	199	340
Interval bottom (cm)	56	78	382	7	52	73	81	103	117	176	201	342
Weight washed (g)	17.6	16.6	12.6	17.3	18.5	16.9	15.0	16.5	18.0	16.1	20.7	17.9
Sand weight (g)	0.1	0.1	0.1	10.5	8.4	6.9	1.1	4.8	0.1	5.1	3.1	3.3
Floated (Y/N)	n	n	n	y	y	y	n	y	n	y	y	y
Fraction counted	1	1	1	1	1	1	1/4	1	1/2	1	1/4	1
Raw counts												
Ammobaculites exiguus		5										
Ammonia aoteana						126	1	88				
Ammotium fragile		2		13	107	8	30	48	42	3	80	
Elphidium exc. clavatum						1		9				
Elphidium exc. excavatum						2						
Glomospira fijiensis												
Haplophragmoides wilberti		2		67	91	23	27	86	13	11	44	
Jadammina macrescens				1								
Miliammina fusca	7	2		22	3	3	13	19	33		4	
Pseudothurammina limnetis								19		2		
Schlerochorella moniliforme												
Trochamina inflata				1								
Trochamminita salsa												
Total specimens	7	11	0	104	201	163	90	250	90	14	128	0
Diversity	1	4	0	5	3	6	5	5	4	2	3	0
Relative abundance												
Ammobaculites exiguus	0	45		0	0	0	0	0	0	0	0	
Ammonia aoteana	0	0		0	0	77	1	35	0	0	0	
Ammotium fragile	0	18		13	53	5	33	19	47	21	63	
Elphidium exc. clavatum	0	0		0	0	1	0	4	0	0	0	
Elphidium exc. excavatum	0	0		0	0	1	0	0	0	0	0	
Glomospira fijiensis	0	0		0	0	0	0	0	0	0	0	
Haplophragmoides wilberti	0	18		64	45	14	30	34	14	79	34	
Jadammina macrescens	0	0		1	0	0	0	0	0	0	0	
Miliammina fusca	100	18		21	1	2	14	8	37	0	3	
Pseudothurammina limnetis		0	0		0	0	0	21	0	2	0	0
Schlerochorella moniliforme	0	0		0	0	0	0	0	0	0	0	
Trochamina inflata	0	0		1	0	0	0	0	0	0	0	
Trochamminita salsa	0	0		0	0	0	0	0	0	0	0	
State of tests	m-p	m-p		g-p	m	m	g-m	g-p	m-p	p	g-p	
(g = good, m = moderate, p = poor)												
Others												
Planktics									1			
Thecamoebians				3	2					4		
Ostracods					1							2
Bivalves	n	n	n	n	n	n	r	n	n	n	n	n
Gastropods	n	n	n	n	n	n	n	n	n	n	n	n
Fern sporangia	r	n	n	o	n	r	n	c	n	n	r	r
Carbonaceous	o	c	n	a	a	a	c	a	a	c	a	a
Diatoms	r	n	n	o	a	c	c	c	c	n	r	r
(a = abundant, c = common, r = rare, n = non-existant)												

The abundance of *Haplophragmoides* is more suggestive of an intertidal elevation than subtidal. A slightly higher salinity is indicated (SI = 6).

The next sample (79–81 cm) is again co-dominated by *Ammotium fragile* and *Haplophragmoides wilberti* with subdominant *Pseudothurammina limnetis* and *Miliammina fusca.* The MAT estimate of elevation is within the narrow range 1.4–1.6 m (mean 1.5 m), midway between mid and high tide level, possibly salt marsh, with a lowered salinity again (SI = 5). Slightly higher (71–73 cm) the fauna switches again and is dominated by *Ammonia aoteana* (77%). This fauna usually indicates a slight increase in salinity (SI = 7) with a broad MAT elevation estimate in the range 1.3 (mid tide) to –2.5 m (subtidal). The additional presence of 14% *Haplophragmoides* indicates a probable higher (i.e. mid tidal) rather than lower elevation. The two highest samples (50–52, 5–7 m) are co-dominated by *Haplophragmoides wilberti* and *Ammotium fragile* again. They indicate the same reduced salinity (SI = 5) with a MAT estimate of elevation within a narrow range of 1.4–1.6 m (mean 1.5 m), midway between mid and high tide level, probably in a salt marsh.

The two faunas dominated by the calcareous species *Ammonia aoteana* may indicate a lower elevation and/or a slightly increased salinity than the agglutinated faunas that surround them. The foraminiferal fauna at 2 m downcore indicates a near high tidal elevation similar to that at the surface. Thus there has been c. 2 m of subsidence and/or compaction during accumulation of the overlying sediment. **MAT elevation estimates based on the intervening faunas could indicate that this subsidence occurred in at least two and possibly four subsidence events (Fig. A1). The most clearly defined subsidence event is between 73 and 79 cm and corresponds to a displacement of about 0.5 m.**

Discussion

Okarito Lagoon provides a challenge for palaeoenvironment determinations based on the preserved foraminiferal faunas. It is impossible to sort out the effects of possible selective taphonomic loss. We do not yet understand the conditions that promote the breakdown of agglutinated tests. Previous studies

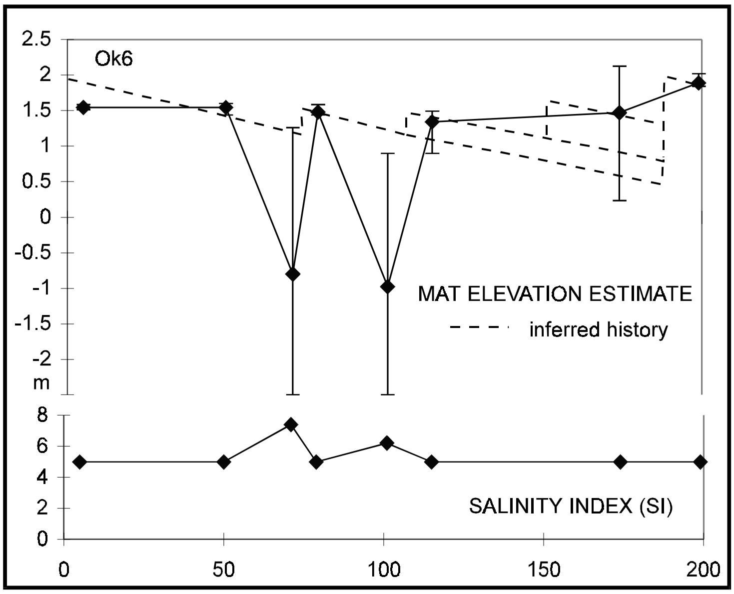

Figure A1. Core OK 6, modern analogue technique estimate of mean and range of elevation and calculated salinity index (1–10 scale) for the upper two cm of the core.

have suggested that *Miliammina* tests breakdown more quickly than most other brackish agglutinated tests, yet many of these tests are present in core samples at depths down to 2 m. The question we are unable to answer is whether the unfossiliferous samples once contained agglutinated foraminifera that have disaggregated or whether these samples accumulated in non-marine environments. Studies elsewhere have shown that a lowering of pH conditions may result in solution of calcareous tests in near-surface sediment or buried sediment. Runoff from New Zealand beech forest is often high in tea-coloured tannins and may be more acidic. Do the rich calcareous faunas reflect drier periods with higher pH or are they an indication of lower tidal elevation, as in many other places around New Zealand?

The foraminiferal faunas in these cores identify one definite and several possible subsidence events. No definite uplift events are identified. The faunas identify a definite subsidence of 2 m within the top 2 m of OK 6 (in 2 to 4 stages). A small subsidence event could be indicated in OK 4.

The benthic foraminiferal faunas contain no tests of species that live in open water, normal salinity conditions. All recognised species present require slightly to strongly reduced salinity conditions in a sheltered inlet, harbour or estuary environment. Thus there is no indication, in the samples studied, of any open coast, pre-lagoon environments nor of any tests being swept into the lagoon by tidal surges, storms or tsunami. Several small planktic foraminiferal tests are present, but this is frequently encountered in modern tidal inlets, where these have been carried in suspension into the inlet on the incoming tide.