Paleoenvironmental Analysis of Uplifted Coastal Lake & Wetland Sequences in the Wellington Region

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LAYPERSON'S ABSTRACT

The history of three coastal waterbodies in the Wellington region is determined from sediments accumulated in the last 7000 years at Okupe Lagoon on Kapiti Island, Taupo Swamp north of Plimmerton, and Lake Kohangapiripiri to the east of Pencarrow Head. Each waterbody is located between two major, active faultlines and all have been inlets of the sea at some time in the past. Sediment cores between 2 and 6 metres long were taken from each site and fossils of single-celled algae (diatoms) were removed from the sediment and identified. Environmental preferences of different diatom species were used to determine what past environments were present at the study sites. Diatom species change dramatically from the base of the cores to the top and indicate that each site has been isolated from the sea in the last 7000 years. In some cases the suddenness, amount, direction and completeness of the changes suggest that large earthquakes were the cause of change. Evidence for the penultimate earthquake on the Ohariu Fault is recorded at two sites and occurred between 800 and 380 BC. Effects of known past large earthquakes are also recorded at the study sites. This project extends what is known of the history of earthquakes in the Wellington region and demonstrates the use of fossil diatoms for detecting past earthquakes.

TECHNICAL ABSTRACT

Diatom analysis of sedimentary sequences from three coastal waterbodies in the Wellington region, indicates that uplift and / or isolation from the sea has occurred at each site in the last 7000 years. Past depositional environments are determined using high resolution diatom analysis of cores from Okupe Lagoon on Kapiti Island, Taupo Swamp north of Plimmerton, and Lake Kohangapiripiri to the east of Pencarrow Head. Marked changes in fossil diatom assemblages occur in each sequence in response to decreased paleosalinity and / or paleo water depth. The suddenness, amount, direction, and completeness of some of the changes point towards coseismic uplift as the cause of change. Evidence for the penultimate large, surface-rupture earthquake on the Ohariu Fault is recorded at two sites and occurred between 800 and 380 BC. Another seven events represent effects at the study sites of known large paleoearthquakes. This research extends what is known of Wellington's paleoseismic history and illustrates the use of diatom analysis as a paleoseismic tool at sites where geomorphologic or stratigraphic evidence is inadequate.

OBJECTIVES

1. To provide high-resolution records of change in depositional environment at three uplifted coastal waterbodies in the Wellington region.
2. To document and estimate the magnitude of coseismic uplift events recorded over the last 7000 years in the sedimentary sequences of each site.
3. To place the events in a chronological framework by radiocarbon dating a number of samples from each sequence.
4. To correlate the events with those described in previous studies, to comment on possible sources, and to discuss the implications of the new data for hazard planning.

CONTENTS

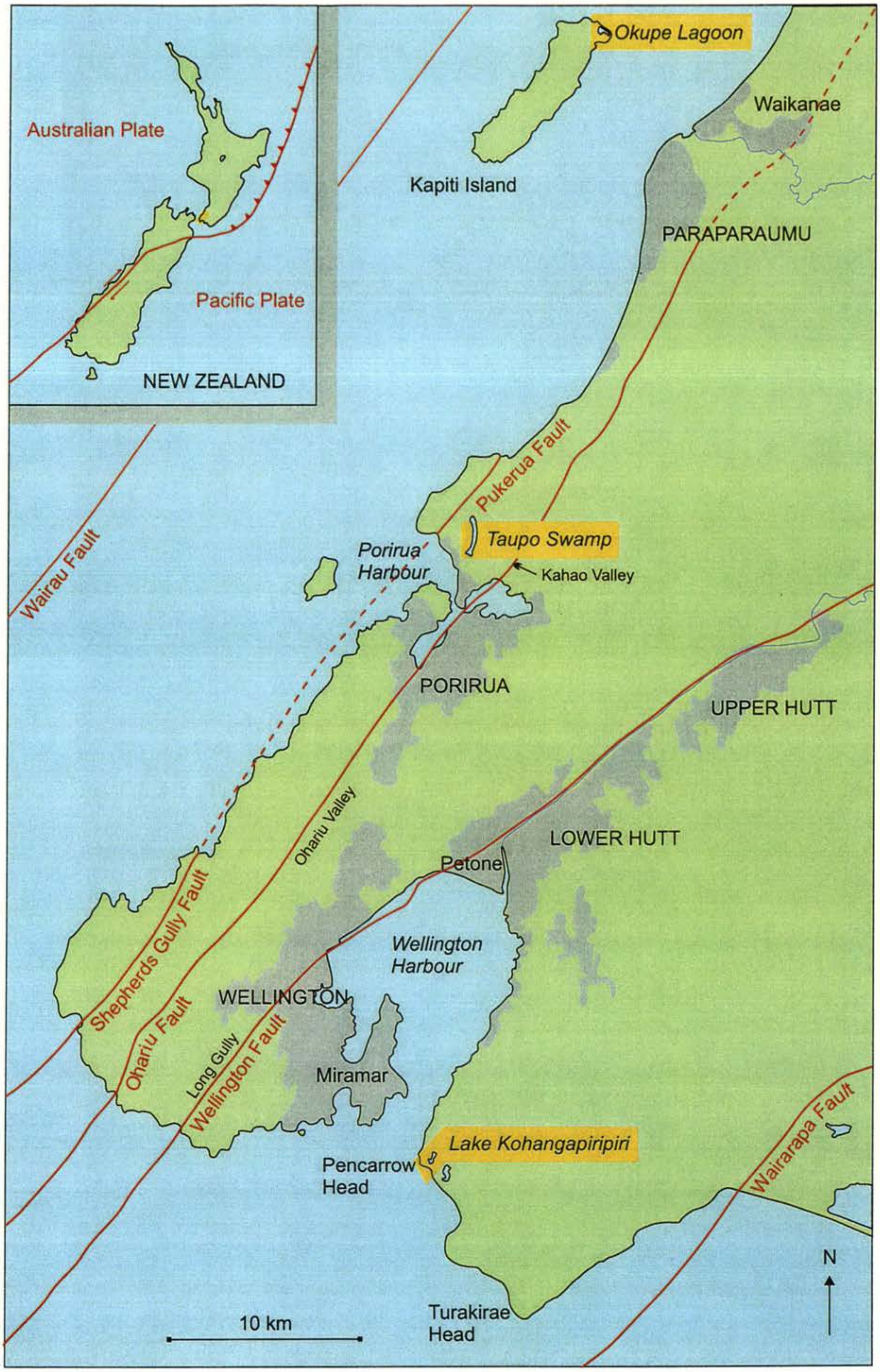


Figure 1.1 Map of the Wellington region showing study sites, major active faults, and localities mentioned in text

1 INTRODUCTION

New Zealand is situated on the boundary between the Australian and Pacific tectonic plates (Fig. 1.1). Beneath the North Island of New Zealand the Pacific plate is subducting obliquely beneath the Australian plate. As a result of this movement the Wellington region is crossed by a number of major active dextral strike-slip faults. The Wairarapa, Wellington, Ohariu, Shepherds Gully - Pukerua and Wairau Faults together accommodate approximately 60-90% of the boundary-parallel movement (Van Dissen & Berryman, 1996). No evidence of fault creep has been found on any of Wellington's faults (Van Dissen & Berryman, 1996), so it is likely that much of the movement is achieved coseismically, ie during earthquakes.

During historic times there has been one large surface rupture earthquake in Wellington, this occurred on the Wairarapa Fault in 1855. The earthquake caused severe damage to central New Zealand and resulted in uplift and tilting of 5000 km^2 of land (Grapes & Downes, 1997). Today, an earthquake of similar magnitude would present a very serious hazard because of the large number of people living in the region. To mitigate the effects of such an event it is useful to have an understanding of the behaviour of individual faults and the type of event Wellington is likely to experience. This information is best obtained from the geologic record, especially because the historic record in New Zealand is so short. Van Dissen and Berryman's (1996) study highlights this need for paleoseismic studies by showing that estimates of earthquake hazard for the Wellington region based solely on the historical record, underestimate the intensity of all events with return times of greater than 50 years.

Paleoseismic studies carried out in Wellington have provided much of what is known of the region's Holocene paleoseismicity (eg, Van Dissen & Berryman, 1996; Hull & McSaveney, 1996; Heron *et al.*, 1998; Pillans & Huber, 1995; Stirling, 1992). However the majority of paleoseismic studies have been of physical features such as terraces, beaches and fault scarps. This project aims to expand the record by investigating paleoearthquakes preserved in sedimentary sequences. Sites were chosen that have not been previously investigated for their seismic history and yet are known to have undergone uplift from historical and geomorphological evidence. These include Okupe Lagoon on Kapiti Island situated between the northern extension of the Wairau Fault and the Pukerua Fault, Taupo Swamp just north of Plimmerton lying between the Pukerua and Ohariu Faults, and Lake Kohangapiripiri on Wellington's south coast almost half way between the Wellington and Wairarapa Faults (Fig.1.1).

The technique chosen to carry out paleoenvironmental interpretation of the sedimentary sequences is diatom analysis. Diatoms are single-celled algae that are a useful tool for a great number of environmental reconstruction applications. In the field of paleoseismology, diatom analysis has been used as independent evidence for coseismic submergence events on the North American west coast and as an aid in identifying tsunami events (Hemphill-Haley, 1995). In New Zealand, although there is much paleoseismic research being conducted, there are few examples of the use of diatom analysis in paleoseismology (eg, Ota *et al.*, 1989 & 1995). This project is a beginning in terms of specifically investigating what contribution diatom analysis can make to paleoseismology in New Zealand. An assessment of the technique is included in the conclusions of this report.

2 TECHNIQUES

Coring and Surveying

Sediment cores were taken using the School of Earth Sciences' Russian-type corer. This was operated by 2 to 4 people working from a wooden platform in shallow water. The corer takes semi-cylindrical sediment samples of 5.5 cm diameter and 50 cm length. Coring proceeds in 50 cm sections until the compactness of the sediment or an increase in grain size prohibits deeper penetration. A piston corer that collects 1 m long cylindrical samples was trialed at the Lake Kohangapiripiri site and used to collect the upper section of the sequence. The Russian-type corer was then used to extend the record to greater depths. Depths penetrated ranged from 200 cm at Okupe Lagoon to 650 cm at Lake Kohangapiripiri. Cores were wrapped in plastic and placed in split pvc downpipe tubing for transport and storage. They are being stored at 2 degrees Celsius in the School of Earth Sciences' cold room.

The determination of heights above mean sea level is crucial when considering the possibility of relative changes in sea level at a particular site. Heights were determined by measuring the elevation difference between the core site and a local point of known height using a SOKKIA Electronic Distance Meter. The points of known height included a trig station at Okupe Lagoon, a benchmark at Taupo Swamp and a lighthouse at Lake Kohangapiripiri.

Sediment Sampling and Processing

Cores were described and photographed in the School of Earth Sciences' sedimentology laboratory soon after collection. Samples were then removed for grain size analysis, diatom analysis and radiocarbon dating. Diatom samples (about 1 gram of sediment) were taken every 10 cm and later at 5 cm intervals when interesting horizons had been located. Grain size samples (about 20 g of sediment) were taken approximately every 50 cm or where there were obvious grain size changes. Initially large pieces of wood and shell were removed for dating. Once events had been identified, sampling of organic sediment was undertaken for dating of specific intervals.

Diatom samples were chemically and physically processed in order to concentrate diatom frustules within the sediment and thereby facilitate the identification and counting of them. Samples were digested in 27% hydrogen peroxide to remove organic matter and heated in 32% hydrochloric acid to remove carbonate. Sand was settled out of suspension and discarded after decanting the remainder of the sample. Clay was removed by washing samples with dilute sodium hexa-metaphosphate and repeated centrifuging at slow speed. Aliquots of the processed samples were diluted with filtered water, poured into Battarbee trays containing coverslips, and left to evaporate. Coverslips were mounted onto microscope slides on a hot plate using Naphrax diatom mountant. These permanent mounts are being stored in the paleontology section of the School of Earth Sciences.

Location & Core Number	Sample Depth (cm)	Sample Material	Dating Technique	$\delta^{13}C$ (‰)	Radiocarbon Age [a] (years BP)	Calibrated Age [b] 1 sigma (cal. years)	Calibrated Age [b] 2 sigma (cal. years)	Lab Number [c]
OKUPE LAGOON								
OL97-5	38	Wood	Standard	-27.6	580 +/- 130	1296 to 1451 AD	1234 to 1644 AD	Wk 5697
OL97-5	80	Wood	Standard	-27.9	1210 +/- 80	775 to 972 AD	670 to 1017 AD	Wk 5698
OL97-5	109-112	Organic Sand	AMS	-28.5	4530 +/- 60	3350 to 3090 BC	3370 to 3010 BC plus 2950 to 2920 BC	Wk 8349 / NZA 11828
OL97-5	128-135	Shell	Standard	-0.3	3360 +/- 140	1436 to 1101 BC	1612 to 902 BC	Wk 6353
OL97-5	180-195	Shell	Standard	1.0	4780 +/- 150	3336 to 2892 BC	3508 to 2741 BC	Wk 5699
OL97-3	25-27	Wood	Standard	-29.3	1100 +/- 80	780 to 790 AD plus 830 to 840 AD plus 880 to 1040 AD	770 to 1160 AD	Wk 6350
OL97-3	145-150	Shell	Standard	-1.8	4010 +/- 100	2235 BC to 1941 BC	2392 to 1816 BC	Wk 6351
OL97-3	167-180	Shell	Standard	-1.5	4510 +/- 140	2907 BC to 2567 BC	3099 to 2407 BC	Wk 6352
OL97-2	166-170	Peat	AMS	-22	1961 +/- 60	36 BC to 89 AD plus 108 to 117 AD	95 BC to 212 AD	NZA 10617
TAUPO SWAMP								
TS97-1	238-240	Organic Mud	Standard	-30.5	2460 +/- 80	770 to 390 BC	800 to 380 BC	Wk 8095
TS97-1	250-258	Wood	Standard	-25.9	1830 +/- 160	20 to 40 AD plus 50 to 420 AD	200 BC to 650 AD	Wk 8096
TS97-1	536-538	Wood	AMS	-26.1	4984 +/- 56	3898 to 3884 BC plus 3800 to 3700 BC	3945 to 3649 BC	NZA 9275
TS98-2	158-162	Wood & peat	Standard	-30.7	1450 +/- 140	430 to 730 AD 740 to 770 AD	250 to 1000 AD	Wk 8351
TS98-2	222.5-227.5	Organic Mud	AMS	-29.5	2470 +/- 60	760 to 680 BC plus 670 to 640 BC plus 590 to 580 BC plus 550 to 400 BC	770 BC to 400 BC	Wk 8352 / NZA 11853
TS98-2	286-294	Organic Sand	Standard	-29.5	3010 +/- 230	1500 to 900 BC	1900 to 500 BC	Wk 8353
TS98-2	493-500	Shell	AMS	-1.4	4940 +/- 60	3452 to 3315 BC	3508 to 3243 BC	NZA 10568
KOHANGAPIRIPIRI								
KP99-1	46-49	Organic Mud	AMS	-25.4	1559 +/- 55	426 AD to 564 AD	397 AD to 628 AD	NZA 11750
KP99-2	450	Wood	AMS	-25.4	4606 +/- 70	3501 to 3436 BC plus 3380 to 3342 BC	3625 to 3592 BC plus 3526 to 3098 BC	NZA 10613
KP99-2	573-577	Organic Mud	Standard	-27.5	5970 +/- 190	5060 to 4580 BC plus 4570 to 4550 BC	5300 to 4350 BC	Wk 8355

Table 2.1 Summary of Radiocarbon Age Results.

[a] Conventional radiocarbon age before present (1950 AD) after Stuiver and Polach, 1977, *Radiocarbon* 19: 355-363.
[b] Calibrated age in calendar years after Stuiver *et al.*, 1998, *Radiocarbon* 40(3): 1041-1083.
1 sigma range (68.2 % probability) and 2 sigma range (95.4 % probability) reported.
[c] Wk: The University of Waikato Radiocarbon Dating Laboratory; NZA: Institute of Geological and Nuclear Sciences Rafter Radiocarbon Laboratory

Grain size analysis was carried out to aid the description of past depositional environments. Analysis involved determining the proportions of organic matter, carbonate, sand and mud of the sediment. Proportions were measured in dry weight so samples were dried and weighed at the beginning and after each stage of the processing. Samples were digested in 27% hydrogen peroxide to remove organic matter and heated in 32% hydrochloric acid to remove carbonate. Sediment was then sieved through a 60 micron mesh to divide it into a fine fraction (proportion of mud) and a coarse fraction (proportion of sand).

Radiocarbon Dating

Radiocarbon dating of organic material was carried out to determine the age of the sedimentary sequences and the events that occur within them. An initial batch of wood and shell samples from near the base of each core was submitted to determine the age of the sequences being analysed. Bulk sediment samples were submitted when it was known which intervals were of particular interest and where no wood or shell material was available. Most samples had a high enough carbon content to be dated by standard methods at the Waikato Radiocarbon Dating Laboratory, the remaining were dated by Accelerator Mass Spectrometry (AMS) at the Rafter Radiocarbon Laboratory, Lower Hutt (Table 2.1). Of the nineteen dates processed, only two were not in chronological order within the sedimentary sequences. Date Wk 8096 was made on a long twig that is subsequently thought to have been carried down the sequence during coring. Date Wk 8349 / NZA 11828 was made on organic sand so is likely to have included some sources of older carbon, it is discounted in favour of the two dates below it made on shell. Although in sequence, date Wk 8353 was also made on organic sand so is treated with some caution. Calibrated calendar years are used in the text and are quoted at the 95 % (2 sigma) confidence level unless otherwise stated.

Diatom Analysis

Diatoms are single-celled algae that live in all types of aquatic environments from the open ocean through to damp soil. They build silica shells (frustules) that often preserve well in the sedimentary record. Although microscopic, these frustules are uniquely structured and can be identified to species level under a microscope. Diatoms are particularly useful because they are sensitive to a wide range of environmental factors including water depth, substrate type, salinity, pH and nutrient concentrations. Preferences of individual species can be determined from modern ecological studies and applied to fossil diatoms. The range of preferences present in a fossil assemblage of diatoms is analysed and used to reconstruct past depositional environment. Certain assumptions are made in this process, for example, unless evidence exists to the contrary, it is assumed that the fossil diatom assemblage is representative of the initial living community. Factors such as preservation of diatom frustules and concentration of diatoms in the sediment can be used to judge whether the assemblage is a fair representation.

Category	Salinity (‰)	Range
Salt intolerant	<0.2	Narrow
Fresh	0.2 to 1.0	Medium
Fresh brackish	0.5 to 2.0	Wide
Brackish	2 to 10	Medium
Brackish marine	10 to 25	Wide
Marine	25 to 35	Medium
Fresh indifferent	0 to 10	Very wide
Brackish indifferent	0.2 to 25	Very wide

Table 2.2 Salinity categories into which diatom species were grouped. Estimated salinity values and ranges are listed to help define the categories and do not correspond to characteristics of individual species.

Category	Habitat
Subaerial	Out of waterbodies on wet, moist or temporarily dry sites
Benthic:	
Benthic attached	Attached to plants, rocks or grains
Epiphytic	Attached to plants
Epipsammic	Attached to sand grains
Epipelic	Sediment surface
Tychoplanktonic	Sediment surface & shallow / turbulent water
Planktonic	Water column

Table 2.3 Habitat categories into which diatom species were grouped.

Diatoms were examined on a Leitz microscope under x1600 magnification and species were identified with reference to standard diatom floras (Krammer & Lange-Bertalot, 1986-1991; Hartley, 1986; Hendey, 1964; Hustedt, 1985; Patrick & Reimer, 1966 and Foged, 1979). At least 400 diatom valves were counted in most samples and 200, or occasionally only 100, valves were counted in samples with low diatom concentration. Environmental preferences for each diatom species were taken from van Dam *et al.*, 1994, Round *et al.*, 1990, Vos and de Wolf, 1993 and the above floras. An estimate of the concentration of diatom valves was calculated using the following equation:

$$\text{Total valves} = \text{valves counted} \times \frac{\text{area of evaporation tray}}{\text{area of slip counted}} \times \frac{\text{sample volume}}{\text{aliquot volume}}$$

Concentrations are expressed as valves per gram of sediment after dividing the total valves by the dry weight of initial sample used. The preservation and diversity of diatom assemblages were estimated qualitatively.

Two main environmental variables were chosen to be of most use to this project, these were salinity and habitat types. Diatoms are known to respond strongly to salinity (Palmer and Abbott, 1986) and in coastal waterbodies salinity is a very useful indicator of connection with the sea. Diatoms were classified according to their salinity preferences into one of eight categories (Table 2.2). Within a waterbody diatom species have favoured habitats. Analysis of the habitat preferences of fossil diatom assemblages is used to provide information about the past water depth and energy regime of the waterbody. Diatoms usually live on the floor of the waterbody (benthic) or in the water column (planktonic), these categories have been divided further to provide more environmental detail (Table 2.3).

Species were grouped into the above categories and proportions were plotted against depth at each site. These plots were used to interpret past depositional environment. Zones were defined by grouping intervals of similar diatom concentration and assemblage composition. Zone boundaries were placed at the mid-point between two samples unless a sediment boundary occurred in this interval in which case it was placed at the sediment boundary.

Recognition of Coseismic Events

Movement along faults in the Wellington region is largely horizontal with a smaller component of vertical movement (Begg and Mazengarb, 1996). This study attempts to detect the vertical component of movement during an earthquake by investigating the relative sea level change that results from such an event. At a coastal waterbody site, a change in relative sea level leads to changes to the connection with the sea, energy regime, sediment supply, water depth and water chemistry (for example salinity and pH). These physical and chemical changes result in large and immediate changes to the flora and fauna of the waterbody. The sensitivity of diatoms to their environment, their ubiquity in such waterbodies, and their potential for preservation makes them ideal markers for identifying such changes in the fossil record.

Relative sea level changes can be caused by aseismic processes as well as coseismic events. Nelson *et al.* (1996) describe five criteria by which to consider changes in depositional environment that may have a coseismic origin:

- suddenness of the change
- amount of change
- lateral extent of the change
- synchroneity of the change
- coincidence with tsunami deposits

The authors state that the more of these criteria that are met at increasing numbers of sites, the greater the likelihood of a coseismic cause for the change. These lines of evidence are adopted in this study with particular emphasis given to the suddenness and amount of change as Shennan *et al.* (1998) found these pieces of evidence to be most definitive. Although only three sites are investigated in this study, the existence of a fault-trench-derived paleoseismic record for the Wellington region, provides additional information with which to assess causes of change.

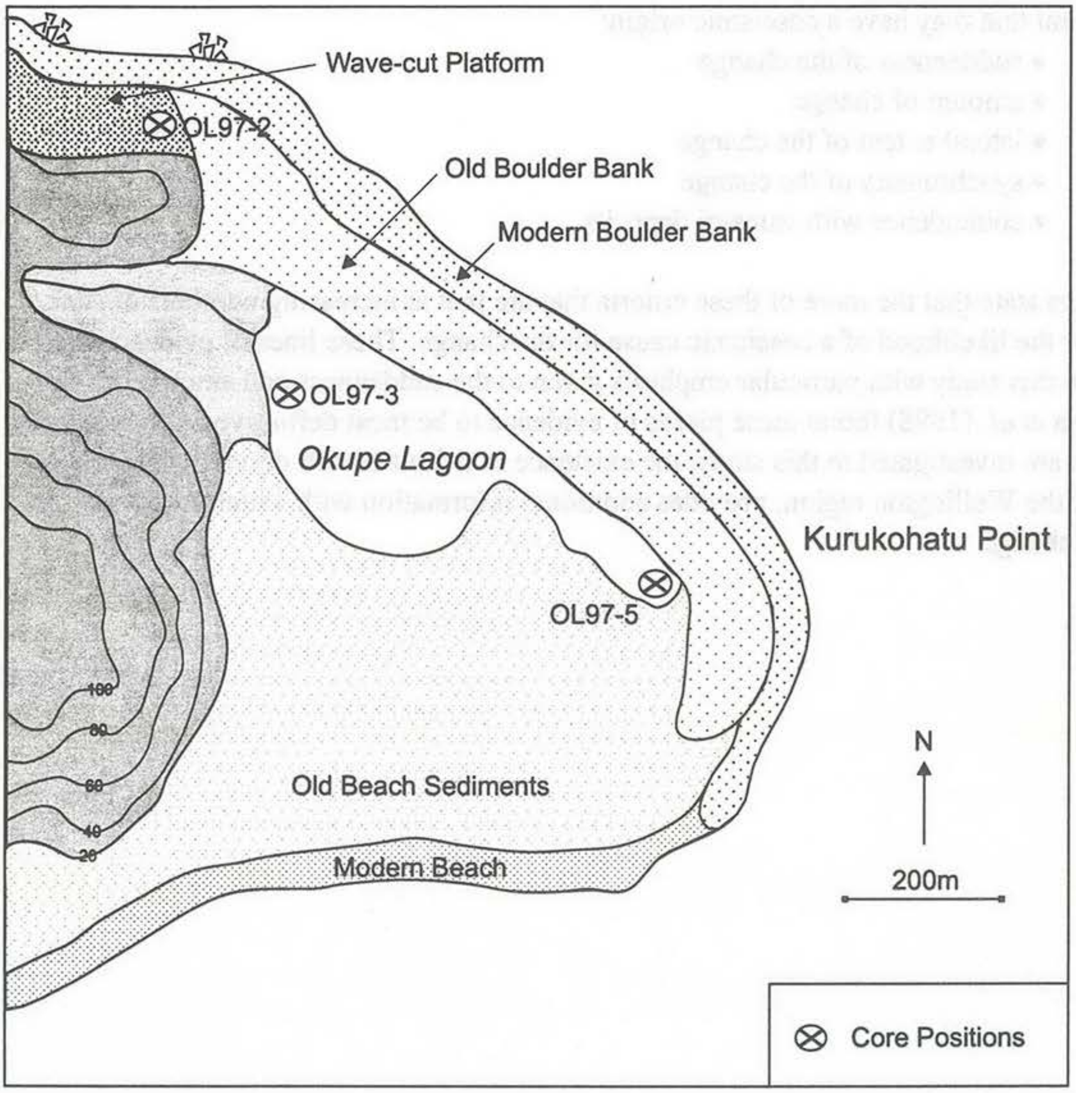


Figure 3.1 Site map of Okupe Lagoon with core positions

3 PALEOENVIRONMENTAL ANALYSIS

SITE 1: OKUPE LAGOON

Introduction

Kapiti Island is a hilly bush- and scrub-covered island that lies 5.5 km off the west coast of the southern North Island. It is composed of Torlesse Supergroup bedrock similar to that of the Wellington region and follows the same structural trend as the mainland (Moore & Francis, 1988). Okupe Lagoon is a small (8 ha) lagoon that exists on a lobe of Holocene sediments at the northeastern end of Kapiti Island (Fig. 3.1). The water surface of the lagoon is only 2 m above mean sea level and water depth is about 50 cm. The lagoon is completely isolated from the sea by two boulder storm ridges. However it probably has groundwater connection with the sea because water in the lagoon is brackish with salinity values of 17-20 parts per thousand. The catchment consists of one small valley (80 ha), the stream bed of which is dry for most of the year. Therefore fresh water input to the lagoon is assumed to be rainfall and some groundwater from the catchment.

Several geological studies of Kapiti Island have been carried out in the past (eg, Ferrar, 1928; Flemming & Hutton, 1949; Moore & Francis, 1988) but this is the first to look specifically at the depositional history of Okupe Lagoon and its surroundings. The two early studies note the presence of raised beaches, boulder-banks and benches indicating recent uplift of the island. Moore and Francis (1988) describe these raised features in more detail. Two distinct storm beach ridges exist at Kurukohatu Point, one is the modern storm beach and the higher one is an older beach thought to have been uplifted by about 2 m. A storm beach ridge also exists at Rangatira point and there are small remnants of old beaches preserved along the east coast of Kapiti Island. Remnants of wave-cut platforms including stacks and corresponding sea caves also occur along this coast. Uplifted features were not directly measured or dated by Moore and Francis but were considered to be a likely result of 1.5 - 2 m of uplift in the "c. 1460 AD earthquake" or the combined effects of a number of late Holocene earthquakes.

The diatom and grain size analysis of the current project was part of a larger study designed to describe the boulder storm ridges at Kurukohatu Point and determine the history of Okupe Lagoon. This wider study included surveying profiles of the boulder storm ridges and analysing fossil foraminifera and pollen in cores from the lagoon. The results of these parts of the work are reported elsewhere (Goff *et al.*, 2000) but some of the details will be used here to support the diatom evidence.

Sedimentary Sequences

Four cores were taken from Okupe Lagoon and one from a rock pool on the raised wave-cut platform to the northwest of the lagoon. Cores OL97-3 and OL97-5 appeared to contain the most detailed sedimentary sequences so these were chosen for further analysis. Core OL97-3 was taken from the western edge of the lagoon and is 180 cm long. Core OL97-5 was

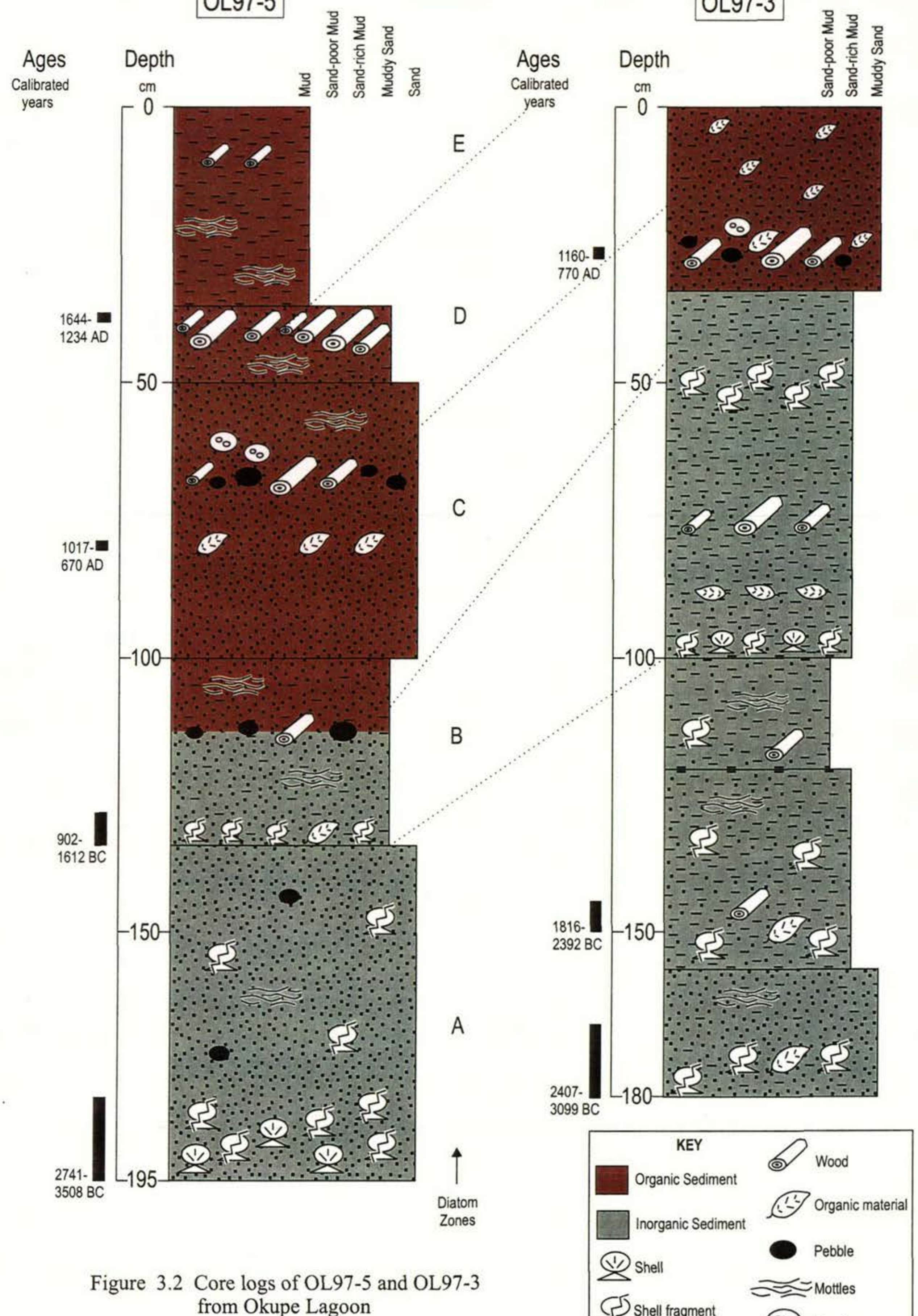


Figure 3.2 Core logs of OL97-5 and OL97-3 from Okupe Lagoon

collected from the far eastern edge and is 195 cm long. Both sequences have an age of about 3000 BC at the base (Fig. 3.2).

The lower half of core OL97-5 consists of grey sand with shell fragments of the estuarine bivalve *Austrovenus stutchburyi* and occasional greywacke pebbles. At 134 cm depth there is the last occurrence of shell fragments and the size of shells is significantly smaller than those at the base of the core. At 113.5 cm there are several rounded greywacke pebbles and pieces of wood and above this point the sediment has a much higher organic content. The interval from this point up to 36 cm is a dark brown organic sand with occasional mottles and layers of organic material. Between 69 and 65 cm there is a concentration of pieces of wood and rounded greywacke pebbles. Two pieces of pumice occur immediately above this layer. Between 38 and 36 cm there is a layer of large wood fragments. From 36 cm to the surface the sequence consists of organic mud. It is brown and heavily mottled between 36 and 20 cm and grey with occasional small pieces of wood above this.

Core OL97-3 is generally finer grained than the sediment of OL97-5. Grey muddy sand and sand-rich mud make up most of the sequence. Shell fragments occur scattered and in layers from the base of the core up to 50 cm depth and layers of organic material and wood occur throughout the core. Above 33 cm the organic content of the sediment is higher giving it an olive black colour. The most distinctive sedimentary feature that can be correlated between cores is the 3-4 cm thick layer of large pebbles and pieces of wood that occurs between 65 and 69 cm in OL97-5 and between 24 and 27 cm in OL97-3. This layer is dated at 770-1160 AD in OL97-3 which is consistent with an estimate of 560-1495 AD in OL97-5 made using accumulation rates and the dates either side of the pebble layer.
Other correlations are made on the basis of diatom assemblages.

Core OL97-2 is a 170 cm long sequence taken from a rockpool on the raised wave-cut platform to the northwest of Okupe Lagoon. It consists entirely of brownish black peat. The initiation of peat formation within the rockpool must have occurred some time after the platform was isolated from the sea. A radiocarbon sample was submitted from the base of this core to provide a minimum age for the time of uplift.

Diatom Assemblages

Diatom samples were analysed at 5 cm intervals in core OL97-5 and at 10 cm intervals in core OL97-3. The assemblages are presented from core OL97-5 because they are better preserved (Fig. 3.3). Seventy four diatom species were identified. The lower part of the sequence has poor preservation and low concentrations which are thought to be a result of the active environment the sediments were deposited in. This section of the sequence was deposited in a shallow marginal marine setting, for which poor or differential preservation of diatoms is well documented (Denys & de Wolf, 1999). Low concentrations probably partially reflect naturally low numbers of diatoms living in the original environment. Much lower levels of primary productivity have been recorded for diatoms living on active beach sands than for assemblages on silt and clay in more sheltered settings (McIntire and Moore, 1977). The upper part of the sequence has good preservation of diatoms with high

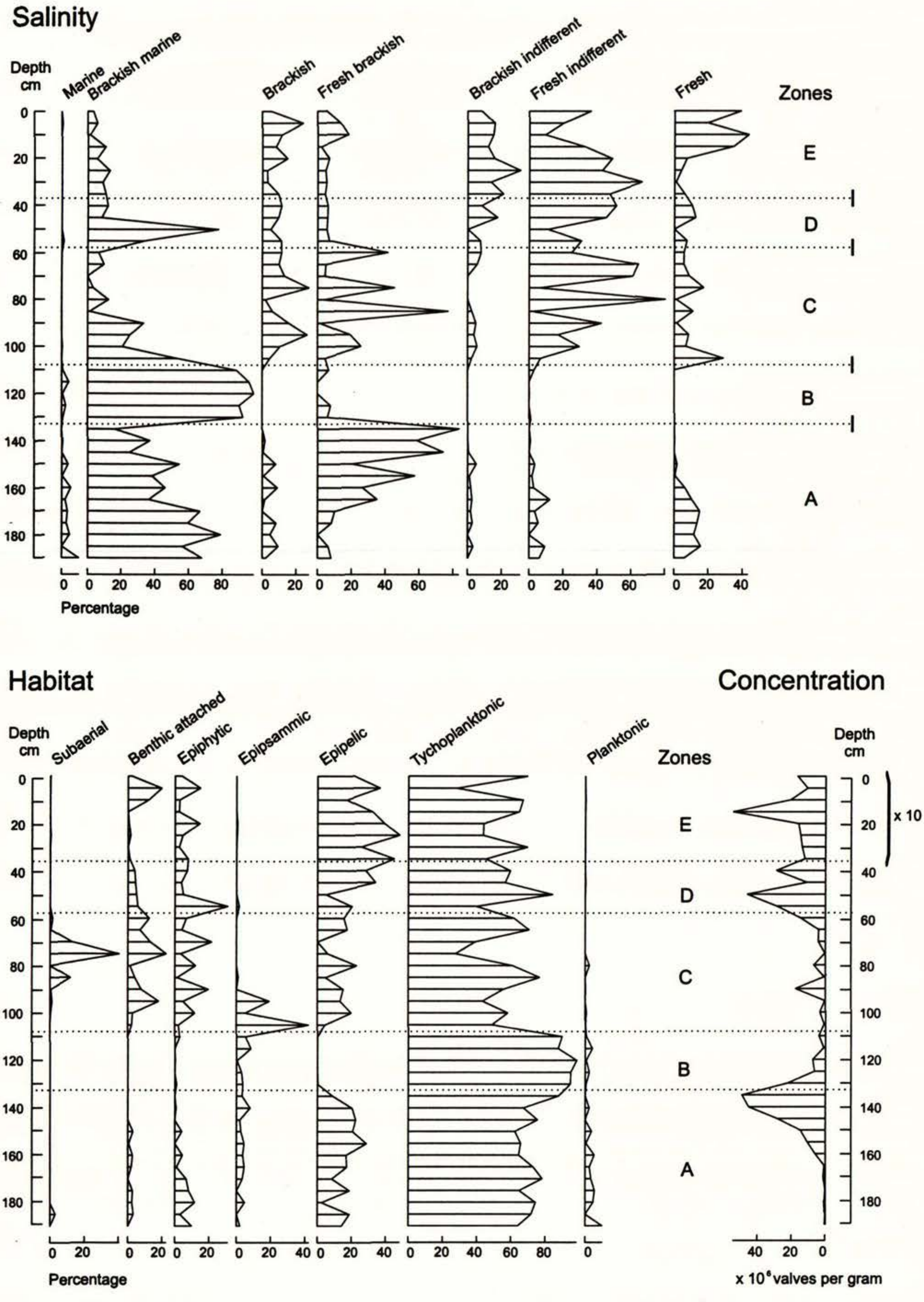


Figure 3.3 Diatom assemblages in core OL97-5 from Okupe Lagoon

concentrations particularly in the upper 36 cm. This part of the sequence is thought to have been deposited in a lagoonal environment isolated from the direct influence of the sea. Diatom assemblages are divided into five zones as summarised in Table 2.1.

Depositional environments

Four main depositional environments are represented by the sedimentary sequence and diatom assemblages in core OL97-5 at Okupe Lagoon (Fig. 3.4). Zone A (195 to 134 cm) was a sheltered marine embayment that shallowed through time from a low tide / lower intertidal environment in the lower part of the zone (below 160 cm) to an intertidal site in the upper part of the zone. Transport to the waterbody from the open sea was less restricted here than in all subsequent environments.

Zone B (134 to 107.5 cm) has low concentrations of diatoms and is dominated almost entirely by the brackish marine tychoplanktonic species *Paralia sulcata*. The low diversity of the assemblage hinders full interpretation of the depositional environment. However *Paralia sulcata* is known to be more competitive than other species under conditions of widely varying salinity, low light, and with substrates of fine-grained, organic-rich sediment (Zong, 1997). Therefore the past environment is likely to have been a predominantly open lagoon at about high tide level. The occasional occurrences of marine species indicate it was open to the sea. This would be unfavourable to other diatoms because of the shallow, turbid waters and factors mentioned above.

Zone C (107.5 to 57.5 cm) is interpreted to represent a predominantly closed brackish lagoon. The environment was isolated from the sea but peaks of single brackish marine diatom species suggest there may have had sporadic influxes of salt water especially during the lower part of the zone. Very low concentrations of diatoms and the only presence of subaerial species in the sequence indicate that the lagoon was ephemeral with extended periods of very shallow water depths or only moist soil conditions present at the site.

The diatom assemblage of zone D (57.5 to 36 cm) represents a brackish lagoonal environment. The higher concentrations of diatoms and lack of subaerial species indicate a permanently ponded, deeper, waterbody than that of zone C.

Zone E (36 to 0 cm) is defined by very high concentrations of well preserved diatoms. Assemblage composition is similar to that of zone D but the high concentrations imply that a more favourable environment was established by this time. This is likely to be due to an improved nutrient supply. The waterbody was a shallow, saline lagoon with macrophytes growing in the vicinity, very similar to the waterbody at the site today.

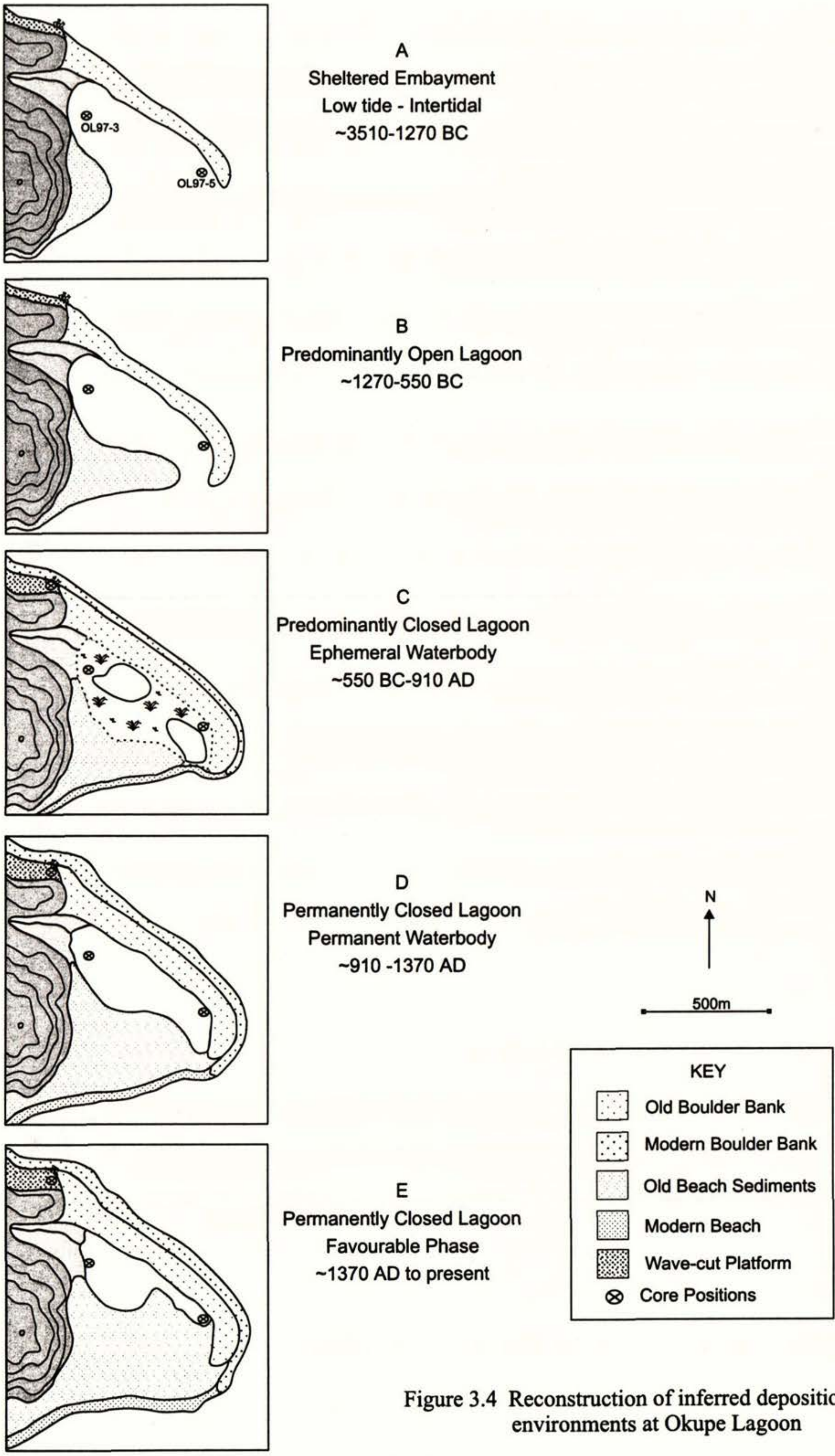


Figure 3.4 Reconstruction of inferred depositional environments at Okupe Lagoon

Zones (cm depth)	Sedimentology	Diatom Assemblages	Other Evidence (Goff, *et al.*, 2000)	Depositional Environment
A 195 to 134	• Inorganic sand • Shell hash at base grading to scattered shell fragments at top • Scattered pebbles	• Low concentration of diatom frustules & many broken • Concentration & preservation increases above 160 cm • Brackish marine tychoplanktonic assemblage • Some open marine species	• Marine low tide or lower intertidal zone foram species present below 160 cm • Marine intertidal forams above this	**Sheltered Embayment** • Shallowing from low tide / low intertidal to intertidal
B 134 to 107.5	• Inorganic muddy sand • Layer of small shell fragments & organic material at base • Wood fragments & mottles • Layer of rounded pebbles & pieces of wood at top	• Low concentration & low diversity • Dominated by brackish marine, tychoplanktonic *Paralia sulcata* • Occasional marine planktonic species	• Marine intertidal foram assemblage in shell layer at base • No forams above this	**Predominantly Open Lagoon** • turbulent waterbody, fluctuating water chemistry
C 107.5 to 57.5	• Organic muddy sand and organic sand above 100 cm • Scattered organic material • Layer of rounded pebbles & wood near top with pieces of pumice	• Very low concentration • Dominated by fresh indifferent & fresh brackish tychoplanktonic species • Fair proportion of benthic species including subaerial forms	• Occasional forams representative of a sheltered environment with lowered salinity above high water	**Permanently Closed Lagoon** • ephemeral waterbody
D 57.5 to 36	• Organic sand • Numerous wood fragments increasing to layer of large pieces at top of unit • Mottles throughout	• Low concentration • Brackish & fresh indifferent tychoplanktonic assemblage • Peak of brackish marine species	• As above	**Permanently Closed Lagoon** • permanent waterbody
E 36 to 0	• Organic mud • Heavily mottled at base, lighter brown with wood fragments at top	• High concentration of well preserved diatom frustules • Fresh & Brackish indifferent epipelic / tychoplanktonic assemblage	• As above	**Permanently Closed Lagoon** • favourable conditions

Table 3.1 Summary of paleoenvironmental evidence for Okupe Lagoon with inferred depositional environments.

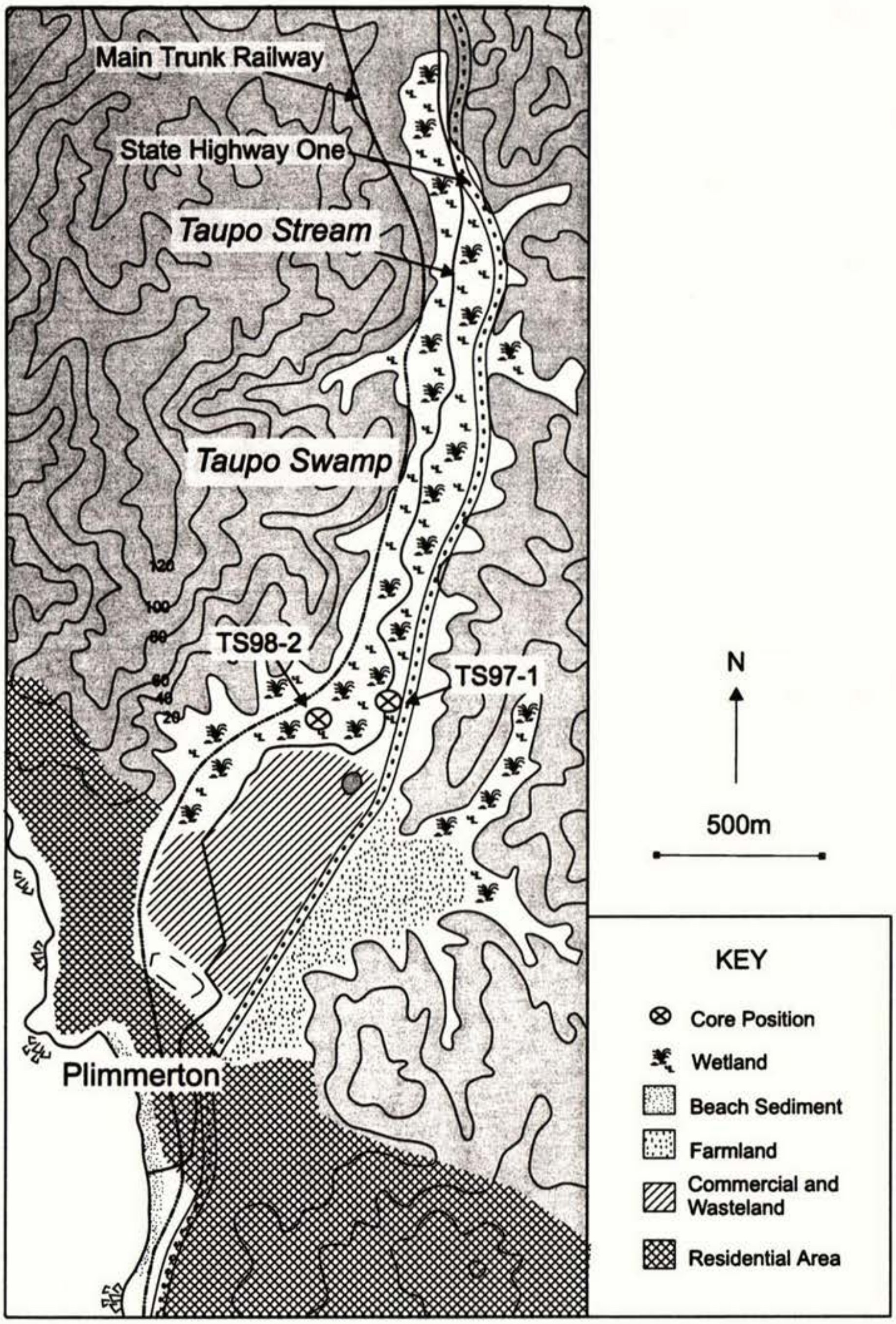


Figure 3.5 Site map of Taupo Swamp with core positions

SITE 2: TAUPO SWAMP

Introduction

Taupo Swamp is a narrow 2 km long fresh water flax swamp that lies between State Highway One and the Main Trunk Railway just north of Plimmerton (Fig. 3.5). The swamp used to rise from 2 m above mean sea level (amsl) behind the beach ridge that Plimmerton now occupies, to 20 m amsl at its northern end. However the southern end of the swamp has been drained and developed for farming and industrial use. The rest of the swamp is protected by the Queen Elizabeth II Trust as one of the few remaining wetlands in the Wellington region. The swamp is fed by Taupo Stream which drains an 820 ha catchment of pasture land. The stream has been channelised through much of the swamp but the water table is generally maintained at the swamp surface (Bagnall & Ogle, 1981).

Adkin (1921) in a geomorphological study of Porirua Harbour described Taupo Valley as a drowned valley into which, at some stage, the sea penetrated about 1 km further than the present coastline. Later movement of gravel across the valley mouth caused a lagoon to form and finally the valley to be completely isolated from the sea. Aggradation then filled the waterbody to form the wetland environment present at the site today. Adkin attributes the raised gravel beach ridge and shore platform of the Plimmerton coast to uplift in the 1855 earthquake. Studies of swamp vegetation have been carried out (eg, Bagnall & Ogle, 1981) but this is the first project to look at the sedimentary sequence of the swamp with the intention of describing its depositional and paleoseismic history.

Sedimentary Sequences

Six cores were taken at various sites throughout Taupo Swamp to locate the best sequence. A transition from estuarine sediment to fresh water was only encountered in the lower part of the valley so two cores from this area were studied in detail (Fig. 3.6). TS97-1 is a 550 cm long sequence from the margin of the valley near the present stream course and TS98-2 is a 500 cm sequence from the center of the valley. Wood and shell at the base of the cores have an age of about 3900-3500 BC.

TS97-1 consists predominantly of brownish black, organic-rich, very fine-grained mud. Units of slightly coarser mud and peat alternate throughout the sequence. Contacts between these units are generally gradational. Small pieces of wood and fibrous plant material are scattered throughout the core. The estuarine bivalve *Austrovenus stutchburyi* is common in the lowest 50 cm both as small whole valves and fragments. The small size of the valves (~17 mm length) indicates a brackish environment at the head of an estuary (Beu and Maxwell, 1990). Small brackish and freshwater gastropods, the freshwater mussel *Hyridella menziesi* and fragments of *Austrovenus stutchburyi* occur in several layers between 550 and 324 cm depth. There are no shells in the upper half of the core and sediments are generally finer-grained and more organic.

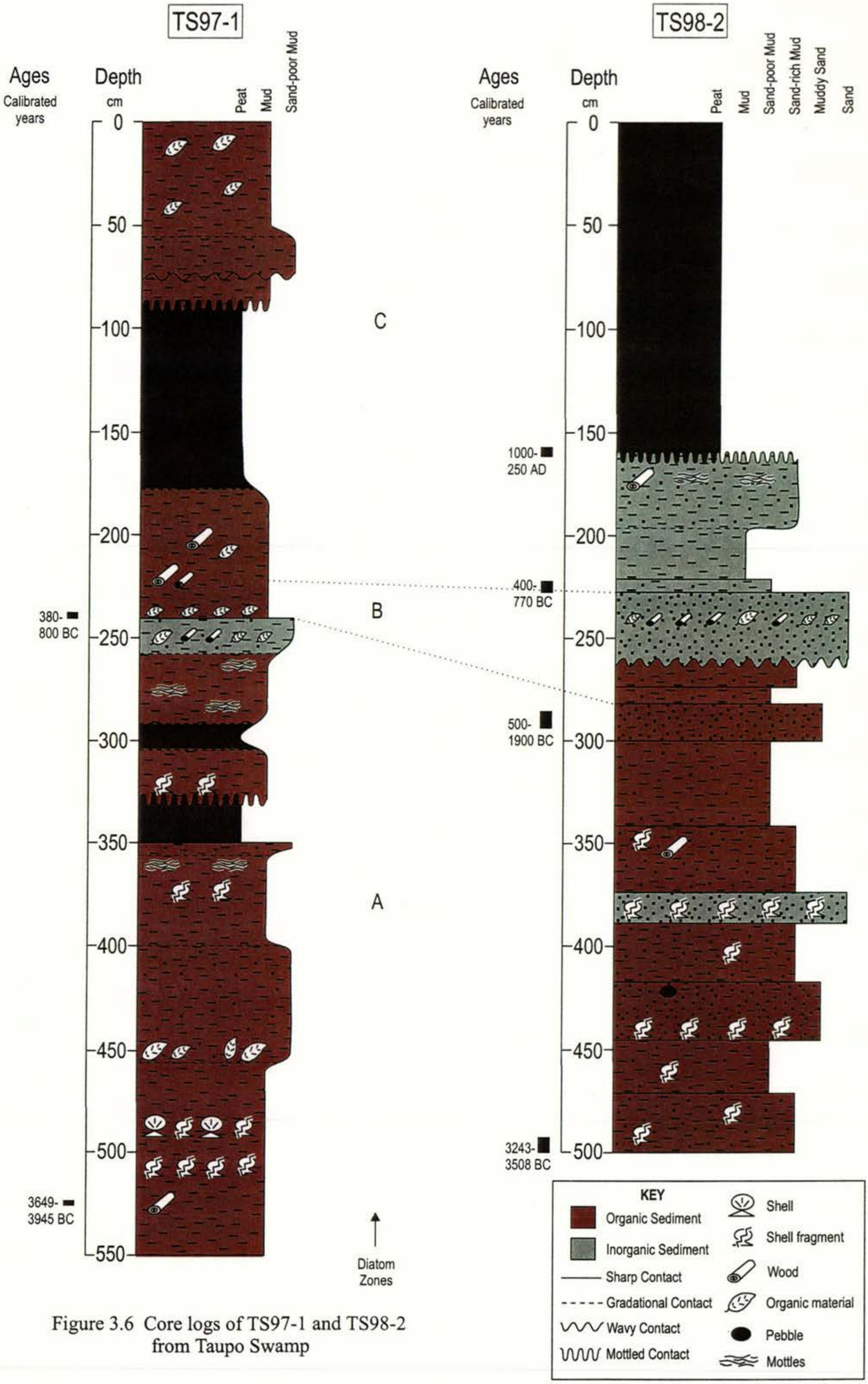


Figure 3.6 Core logs of TS97-1 and TS98-2 from Taupo Swamp

TS98-2 is a coarser-grained sequence than TS97-1, consisting of alternating sands and sandy muds between 500 and 160 cm depth. A thick unit of peat exists from 160 cm to the top of the core. Contacts between these units are generally sharp. Most of the sediment is rich in organic material with pieces of wood and fibrous plant material occurring throughout. An assemblage of shells similar to that found in TS97-1 occurs in distinct layers between 500 and 374 cm depth.

Diatom Assemblages

Diatom samples were generally analysed at 10 cm spacing, with 20 cm spacing used over a stable interval in TS97-1 and 5 cm spacing used over transitional intervals (Figs. 3.7 & 3.8). Over 190 diatom species were identified in TS97-1 and TS98-2. Both cores have very similar diatom assemblages with differences usually reflecting the differing locations of the core sites within the valley. The lower halves of the sequences contain well preserved diatoms that occur in high concentrations in the sediment. The diatom assemblage is very diverse and representative of a brackish lagoonal environment. Diatoms in the upper halves of the sequences are less well preserved and in low concentration. Low concentrations are consistent with the presence of a wetland environment, as exists at the site today, because productivity is generally lower at moist sites especially if peaty acid conditions also exist. A transitional assemblage occurs between the lower and upper parts of the sequence making a total of three diatom assemblage zones defined for Taupo Swamp (Table 3.2).

Depositional environments

Sediment and diatom evidence indicate that three different depositional environments existed at the Taupo Swamp core sites over the last 5000 years (Fig. 3.9). The environment of zone A (TS97-1: 550 to 241 cm, TS98-2: 500 to 282.5 cm depth) had a distal connection with the sea. Salinity was lower than open marine conditions but fairly high and energy regime was certainly much reduced. In effect this could have been the intertidal zone of a small sheltered inlet or a semi-tidal lagoon at the head of such an inlet. The high number of epiphytic diatoms and the high organic content of the sediment are more in line with the sheltered, low energy nature of a lagoon than the tidal flat of an inlet. Fresh water diatoms were probably transported to the waterbody from a fresh water source. The site is unlikely to have been a salt marsh because the complete lack of subaerial species means that the area was permanently ponded. A predominantly open lagoon at the head of an inlet is inferred as the past depositional environment.

Zone B (TS97-1: 241 to 222.5 cm, TS98-2: 282.5 to 227.5 cm depth) is dominated by fresh indifferent, tychoplanktonic *Fragilaria* species. *Fragilaria* species have been termed "isolation indicators" as they are found in high numbers around marine isolation contacts in Norwegian basins and are thought to be associated with rapid changes in water chemistry (Stabell, 1985). In modern sampling in New Zealand high numbers are also associated with very shallow water. Other species present are brackish, fresh brackish, fresh and salt intolerant. The complete lack of marine and brackish marine species indicates that the

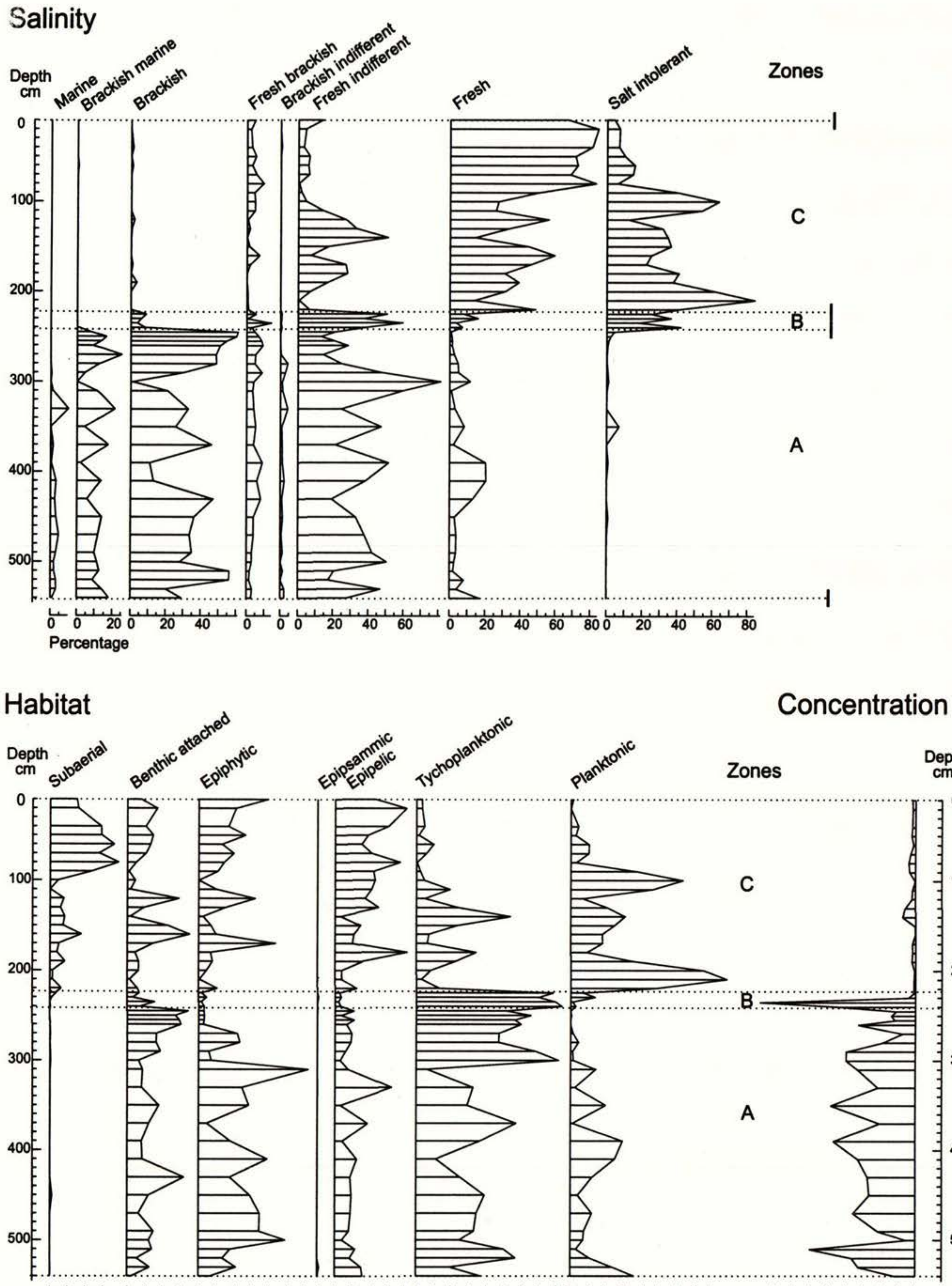


Figure 3.7 Diatom assemblages in core TS97-1 from Taupo Swamp

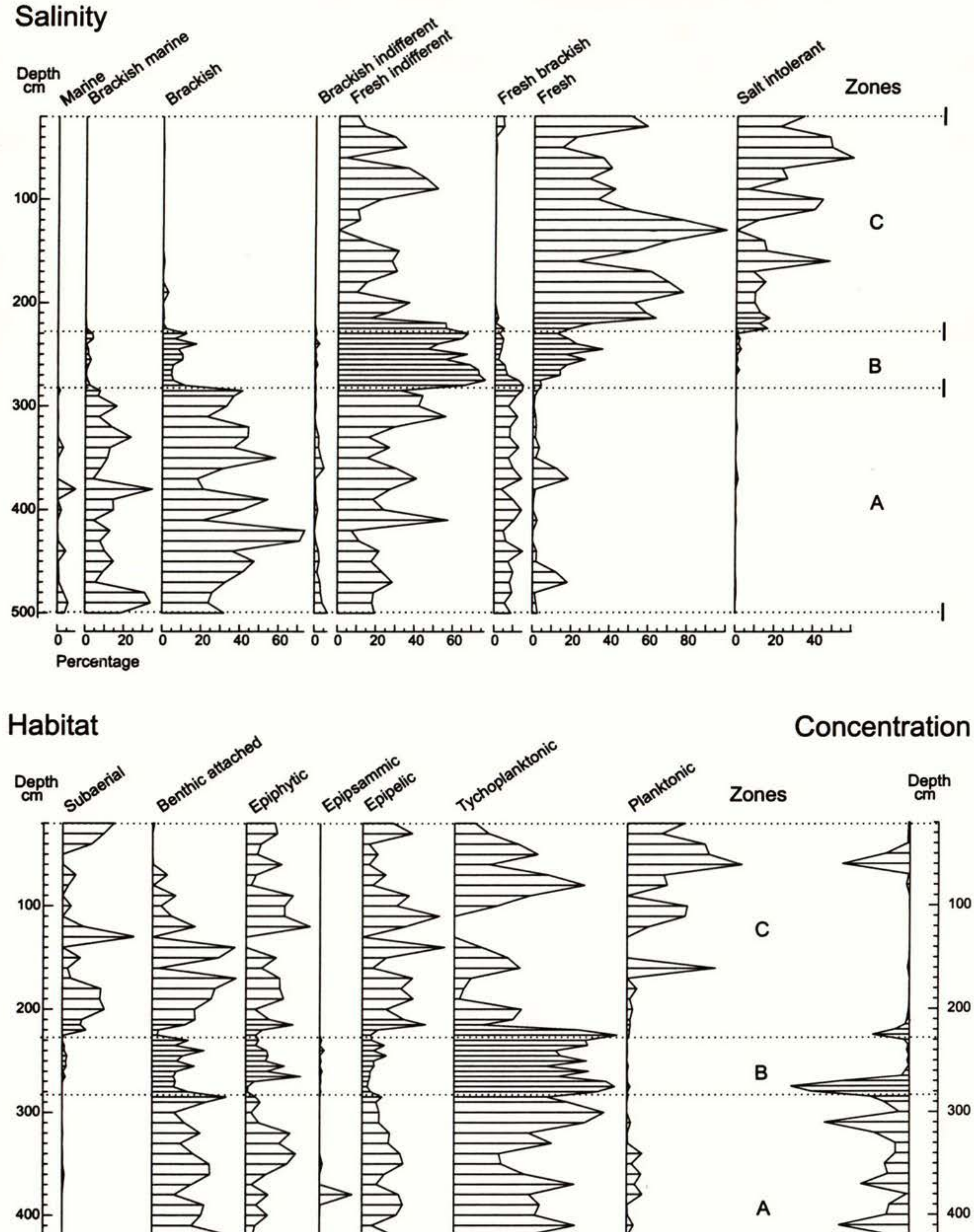


Figure 3.8 Diatom assemblages in core TS98-2 from Taupo Swamp

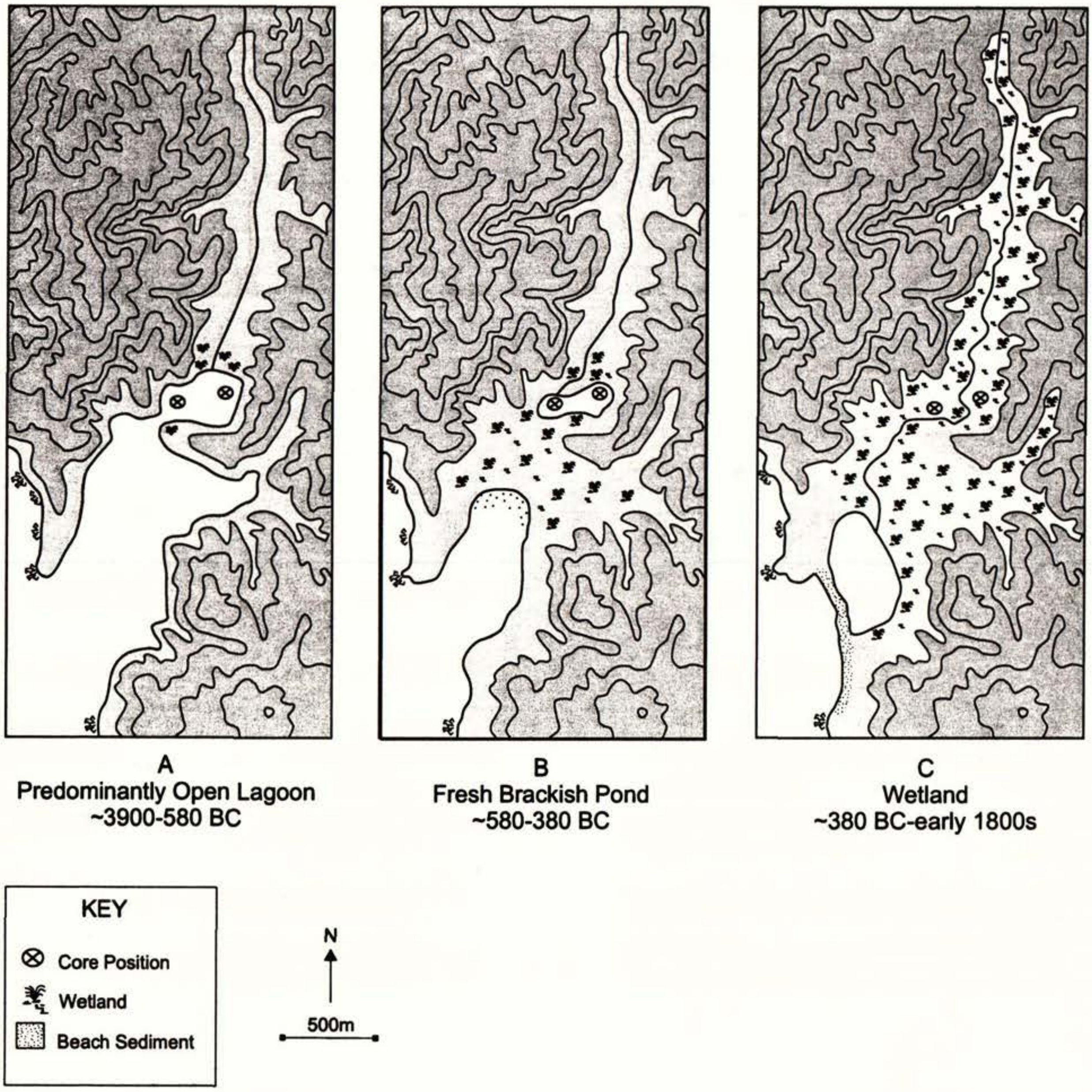


Figure 3.9 Reconstruction of inferred depositional environments at Taupo Swamp

environment was isolated from the sea. The presence of some brackish and fresh brackish species at the central valley site, indicate that the pure fresh water conditions of zone C had not become established. However in TS97-1, salt intolerant wetland species were already inhabiting the site while only a few slightly brackish species continued to live there. Zone B is considered to represent a short-lived, transitional environment between those of zone A and C. The waterbody was a very shallow, fresh brackish pond with fluctuating water chemistry.

The zone is represented in TS97-1 by a thin unit of organic mud. However in TS98-2 the sedimentary sequence consists of a thin unit of mud at the base and a medium grained, well sorted sand above this. The coarseness of the sand is unusual for deposition in a small pond. Therefore the core site is thought to have been located near the fresh water inflow to the pond. In an otherwise low energy setting, the sand unit would have been deposited relatively rapidly by the stream.

Zone C (TS97-1: 222.5 to 0 cm and TS98-2: 227.5 to 0 cm depth) is a wetland environment very similar to the swamp present at the site today. The zone is dominated by fresh and salt intolerant diatoms indicating that a pure fresh water environment existed in the valley throughout this time. Habitat analysis indicates very shallow water depths, with high proportions of subaerial species being consistent with a wetland environment. The greater numbers of the planktonic species *Aulacoseira crenulata* indicate that the wetland had ephemeral pools and was wetter than the sites today.

Zones (cm depth)	Sedimentology & Fossils	Diatom Assemblages	Depositional Environment
A TS97-1: 550 - 241 TS98-2: 500 - 282.5	• Alternating organic muds & sands • *Austrovenus stutchburyi* present below ~300 cm depth • Small brackish & fresh water gastropods • Estuarine foraminifera & ostracods • Pieces of wood and fibrous organic material throughout	• High concentration of well preserved diatom frustules • High diversity assemblage • Dominated by brackish species • Brackish marine & fresh indifferent species co-dominant • High proportion of benthic species especially epiphytes • No subaerial forms	**Predominantly Open Lagoon** • Distal connection with sea • Brackish water • Low energy • Shallow • Macrophytes present
B TS97-1: 241 - 222.5 TS98-2: 282.5 - 227.5	• Organic muds • Unit of medium sand in TS98-2 with bands of black organic material • No shells	• Moderate to low concentration & diversity • Dominated by 'isolation indicator' species • Fresh & brackish forms co-dominant • No marine or brackish marine forms	**Pond** • No connection with sea • Fresh brackish water • Low energy • Very shallow • Stream delta at TS98-2 site
C TS97-1: 222.5 - 0 TS98-2: 227.5 - 0	• Alternating peat & mud • High organic content	• Low concentration of diatoms • Moderate diversity • Dominated by fresh water species • Salt intolerant and fresh indifferent species co-dominant • Reasonable proportions of sub-aerial species	**Wetland** • No connection with sea • Fresh water • Very low energy • Water table at surface or just above producing ephemeral pools • Numerous macrophytes present

Table 3.2 Summary of paleoenvironmental evidence for Taupo Swamp with inferred depositional environments.

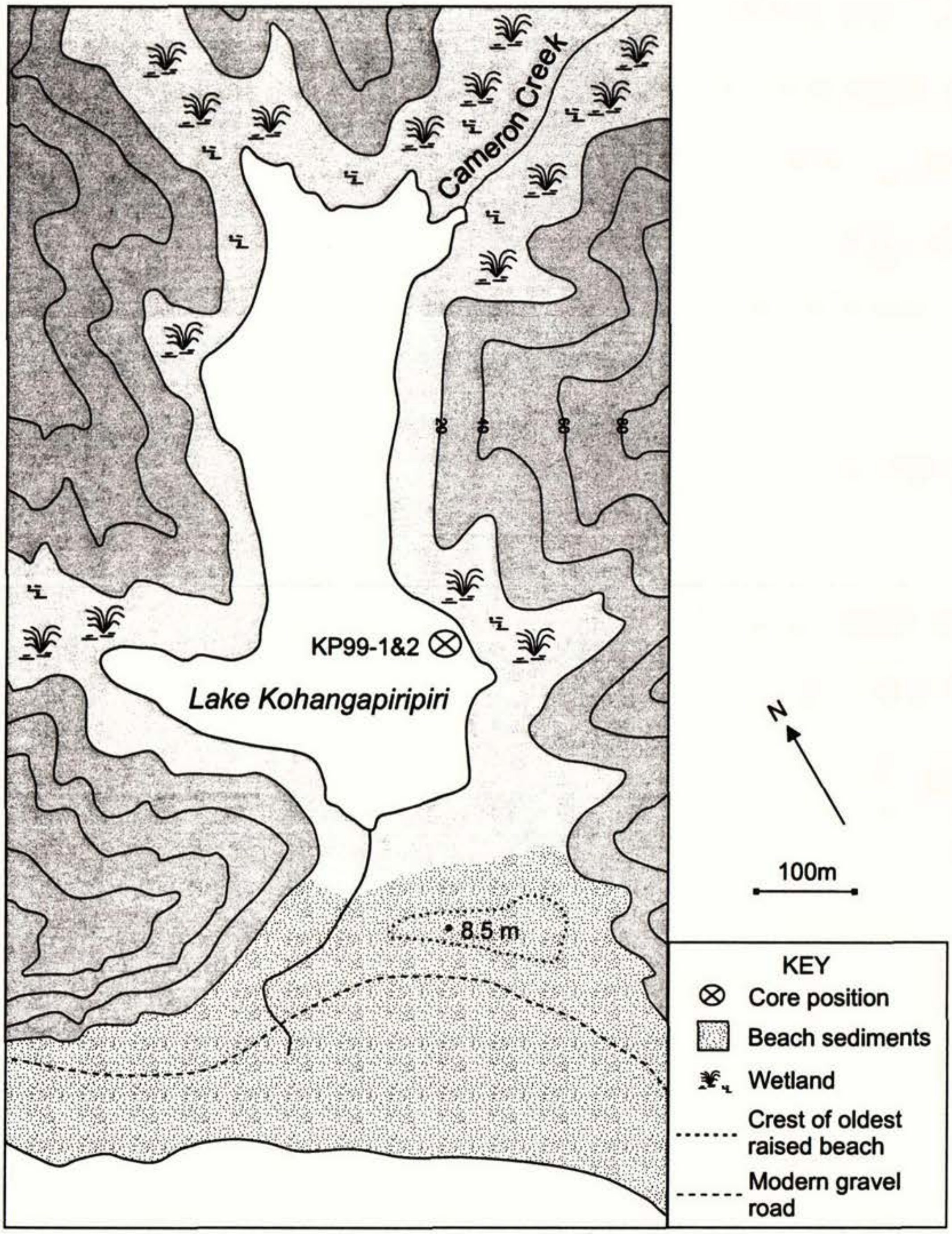


Figure 3.10 Site map of Lake Kohangapiripiri with core position

SITE 3: LAKE KOHANGAPIRIPIRI

Introduction

Lake Kohangapiripiri is one of two freshwater lakes on Wellington's south coast immediately east of Wellington Harbour entrance (Fig. 3.10). The lake surface is only 2 m amsl but is completely isolated from the sea by two raised gravel storm ridges. Cameron Creek drains a 343 ha catchment of scrub and pasture land and runs into the northern end of the lake. At the southern end there is an outlet channel that has breached the highest raised beach but drains into the back of the modern storm beach where it must seep through the gravel at times of high lake level. The lake itself is small (11 ha), has an average depth of 1.6 m and is surrounded by several wetland areas.

Cotton (1921a) described the lakes as drowned valleys. Wave-cut cliffs and truncated spurs are evidence that the valleys were once inlets of the sea and the initial submergence of the valleys is ascribed to the same tilting that formed Wellington Harbour. Cotton (1921b) used the development of the lake margins and delta growth as evidence for stability of the land for thousands of years prior to the 1855 earthquake. In 1955 Adkin surveyed the beach ridges in front of Lake Kohangapiripiri and as a result of finding more than one raised beach ridge, concluded that the 1855 earthquake was not an isolated event. Stevens (1973) also indicates that the gravel barrier was formed by more than one uplift event.

Cochran *et al.* (1999) carried out a paleoenvironmental study of Lake Kohangapiripiri and determined that the lake has been fresh water for at least 7000 years. Although a number of environmental changes were interpreted from the lake record, the stability of the environment was the most interesting result. The present project is an extension of this previous work with the investigation of a core retrieved from an open water, seaward position as opposed to a landward wetland site as studied previously.

Sedimentary Sequence

Core KP99-1 and KP99-2 were collected from the seaward end of Lake Kohangapiripiri off the eastern shore about 150 metres from the barrier. KP99-1 is the piston cored section that penetrated down to 350 cm and KP99-2 was taken with the Russian-type corer down to 650 cm depth. These cores were taken less than 50 cm apart so are considered to represent the same sedimentary sequence and will be used as a composite core (Fig. 3.11).

The sequence consists predominantly of uniform grey organic mud. Throughout this mud there are occasional mottles of organic material, wood fragments and specks of vivianite. In the lowest 40 cm of core angular, weathered, greywacke pebbles are scattered throughout the lake mud and there is a thin layer of similar pebbles between 592 and 589 cm depth. Above this there are several distinct layers of poorly sorted sand and small angular pebbles with specks of vivianite. Between 434 and 418 cm the mud is dark brown due to numerous pieces of organic matter and wood fragments. There are two distinct bands of wood fragments in this interval and a 5 cm thick coarse sand layer at the base. From 60 cm

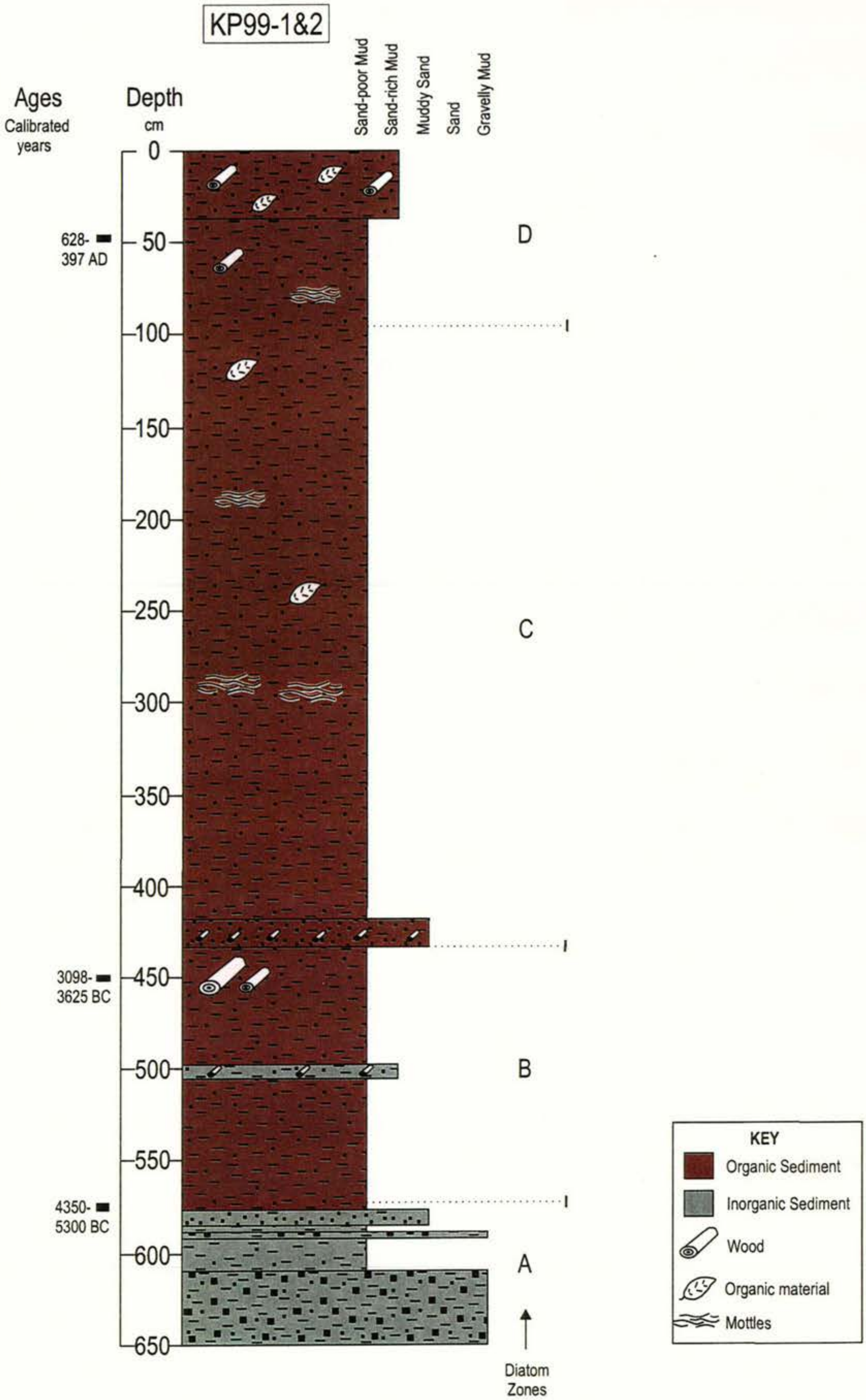


Figure 3.11 Core log of KP99-1&2 from Lake Kohangapiripiri

to the surface there is a gradational increase in organic content and a colour change from yellowish grey to reddy brown. Near the top of the sequence at 38 cm there is a sharp texture change to increased sand content in the mud above.

Diatom Assemblages

Diatom samples were analysed at 20 cm intervals throughout most of the core and at 10 and 5 cm intervals at the base and top of the core where most changes take place (Fig. 3.12). Diatoms are well preserved and occur in reasonable concentrations throughout the middle and upper parts of the sedimentary sequence. Assemblages can be divided into four main zones most of which relate to changes in water depth rather than salinity (Table 3.3). The lower and uppermost parts of the sequence represent shallow water environments and the middle part belongs to a deeper water environment.

Depositional Environments

The sedimentary sequence and diatom assemblages of KP99-1&2 at Lake Kohangapiripiri represent four different depositional environments (Fig. 3.13). During zone A (650 to 577 cm) it is inferred that a predominantly closed lagoon existed on the coast at this site. The marine and brackish marine diatoms indicate that the waterbody was open to the sea, but as the majority of the assemblage indicates only a slightly brackish waterbody, the connection was probably indirect or episodic. Gravel entered the lagoon at this time, probably sourced from small slips off the nearby hillsides.

The main difference of zone B (573 to 434 cm depth) from zone A are the higher concentrations of diatoms, the much smaller proportion of brackish species, and the decline of marine and brackish marine species. These factors suggest that the salinity of the waterbody was lower in this zone and the connection with the sea was no longer present. The small numbers of marine diatoms were probably washed over the barrier during storms. A permanently closed lagoon is inferred to have been present at the site.

Zone C (434 to 95 cm depth) makes up most of the sequence of KP99-1&2. Diatom concentration is high but diversity is fairly low because the interval is dominated by three main species. These are the fresh and fresh brackish planktonic species *Cyclotella stelligera, Aulacoseira ambigua* and *Cyclostephanos dubius.* The domination of this interval by planktonic species indicates that the lagoon was fairly deep during this time.

Zone D (95 to 0 cm depth) represents a littoral site in a permanently closed lagoon. The water was shallow and it freshened from fresh brackish to fresh during this time. There were probably an increased number of macrophytes growing in the lagoon and wetland conditions were more proximal. The upper two samples in this zone appear to represent a further shallowing with planktonics decreasing to less than 5% and benthics increasing. Salt intolerant and subaerial species, typical of marginal wetland sites, also increase in these two samples.

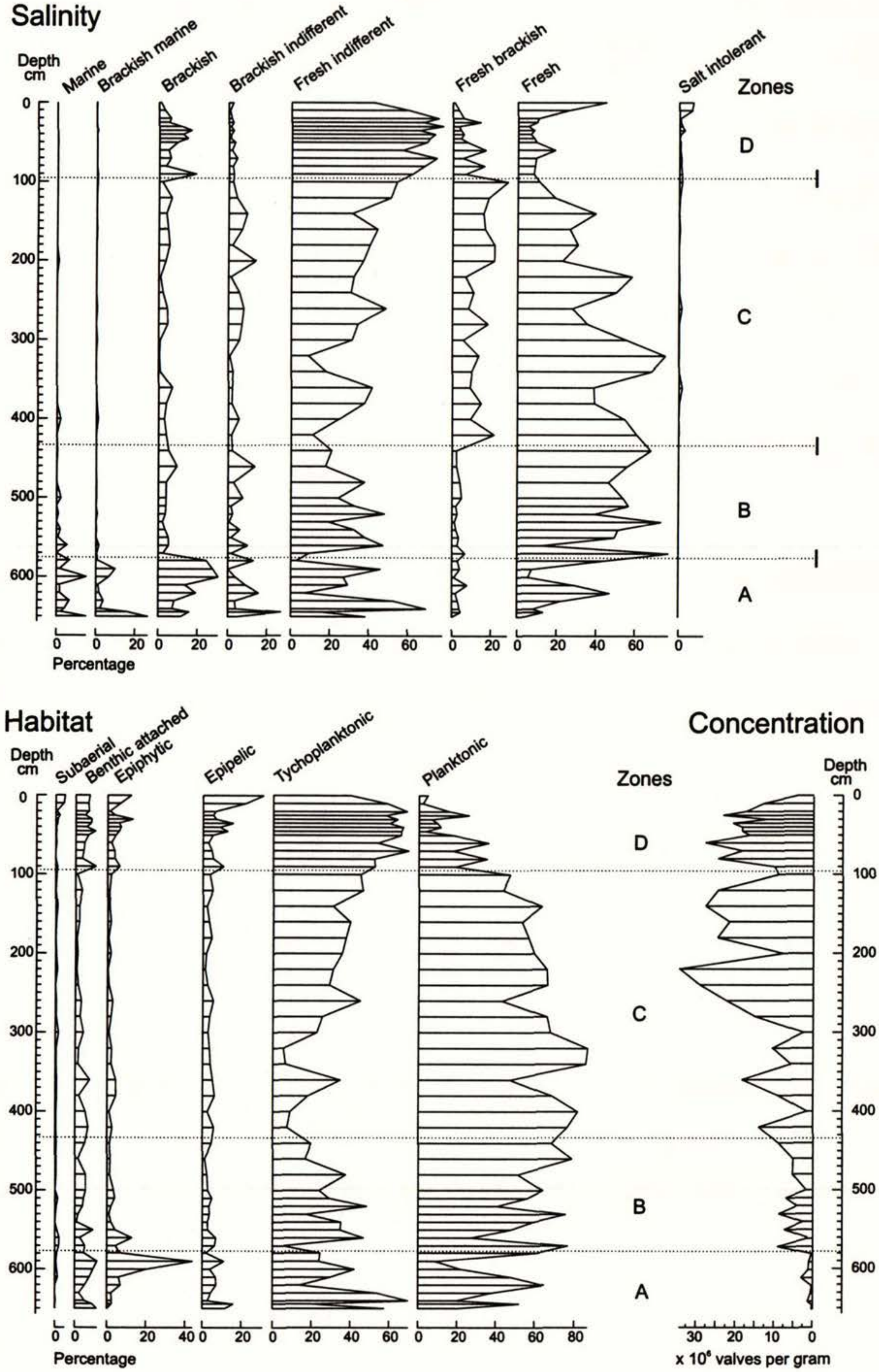


Figure 3.12 Diatom assemblages in core KP99-1&2 from Lake Kohangapiripiri

Zones (cm depth)	Sedimentology & Fossils	Diatom Assemblages	Depositional Environment
A 650 to 577	• Sand-rich mud with angular coarse pebbles & granules • Layer of more concentrated gravel at 590 cm • Layer of coarse, poorly-sorted sand at top with flakes of organic material	• Low concentration of frustules • Moderate diversity assemblage • Dominated by brackish, fresh indifferent & fresh water species • Some marine & brackish marine species • Tychoplanktonic & planktonic habitats preferred with a peak of epiphytes in the gravel layer	**Predominantly Closed Lagoon** • Indirect connection with sea • Slightly brackish water • Moderate to shallow water depth
B 577 to 434	• Uniform organic sand-poor mud • Layer of sand-rich mud at 500 cm • Occasional pieces of wood	• Moderate concentration • Small proportion of brackish species & very few marine & brackish marine occurrences	**Permanently Closed Lagoon** • No connection with sea • Fresh brackish water • Moderate water depth
C 434 to 95	• Layer at base of numerous wood fragments & coarse sand • Uniform organic sand-poor mud • Occasional mottles & pieces of wood	• High concentration, increasing above 280 cm • Low diversity • Dominated by fresh & fresh brackish planktonic species	**Permanently Closed Lagoon** • Deep fresh brackish water
D 95 to 0	• Uniform organic sand-poor mud at base, organic sand-rich mud above 38 cm • Scattered organic material, wood & mottles	• High concentration • Dominated by fresh indifferent tychoplanktonic species • Fair proportion of benthic species	**Lagoon Margin** • Shallow fresh brackish water • Freshens at top

Table 3.3 Summary of paleoenvironmental evidence for Lake Kohangapiripiri with inferred depositional environments.

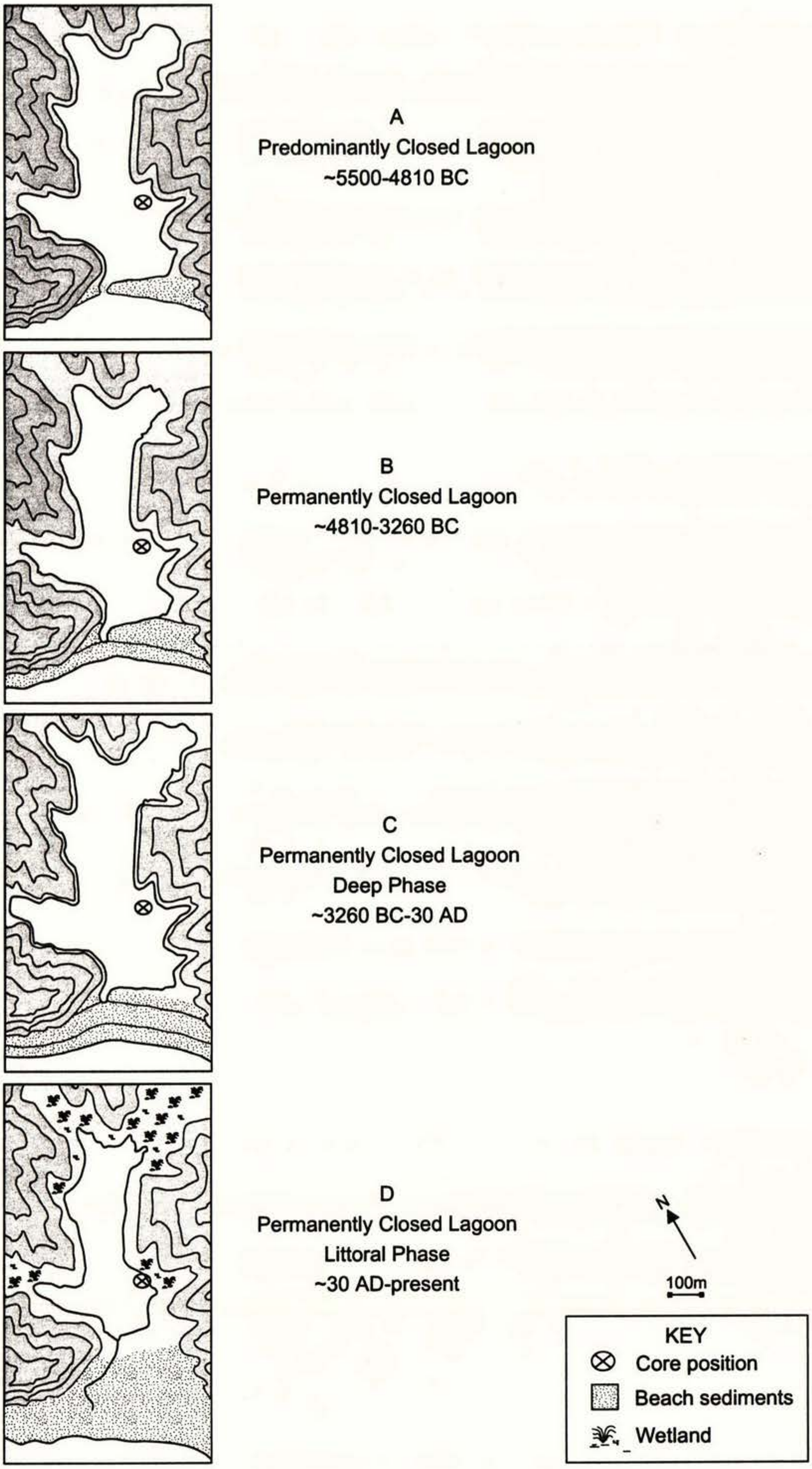


Figure 3.13 Reconstruction of inferred depositional environments at Lake Kohangapiripiri

4 PALEOSEISMIC INTERPRETATION

Sediment and diatom evidence indicate that a number of different depositional environments have been present at Okupe Lagoon, Taupo Swamp and Lake Kohangapiripiri over the last 4000 - 7000 years and each site has been isolated from the sea in this time. Considering the presence of raised beaches and wave-cut platforms near these sites, and the record of earthquake events derived from faults in the Wellington region, it is likely that some of these changes were caused by earthquake events. The first part of this section is a site by site discussion of the transitions and a coseismic vs aseismic assessment of their cause. There is a brief section on estimating earthquake magnitude, then the timing of each transition is compared with the timing of previously recognised earthquake events. Implications of the findings for hazard planning are summarised.

Three types of transition are identified below.
Those that are:

1. Independent diatom-based evidence for coseismic uplift
    - transitions comply with at least four of Nelson's (1996) criteria
    - cannot be easily explained by an aseismic cause
2. Consistent with the effects of an earthquake event
    - require external evidence at the site or age correlation with a previously recognised event to be associated with an earthquake
    - these are then termed earthquake signatures
3. More simply explained by an aseismic cause

SITE 1: OKUPE LAGOON

Of the four major transitions in depositional environment that have occurred at Okupe Lagoon in the last 4000 years, one is thought to be direct evidence of a coseismic uplift event, the other three are consistent with coseismic causes but require correlation with other evidence to be validated as earthquake signatures (Fig. 4.1).

Transition A-B at 134 cm depth consists of a sharp contact from sand to muddy sand. Immediately above this is a thin layer containing the last occurrence of intertidal shells and foraminifera. The transition occurs as a grain size change and layer of small shells in OL97-3 at 100 cm depth. The depositional environment changes from the intertidal zone of a sheltered embayment to a predominantly open lagoon. It involves a change in relative sea level but the magnitude of change is uncertain because of the lack of detail available regarding the environment of zone B. The change occurs suddenly at 134 cm. Although there is evidence of gradual shallowing throughout zone A from low tide to intertidal depths, there is no prior evidence of the site becoming restricted. Constriction of the connection with the sea happened suddenly. Continued sediment accumulation was probably the cause of gradual shallowing, and barrier growth the cause of restriction, but barrier growth seems to have been accelerated by a single event such as a large storm or coseismic uplift event at this time.

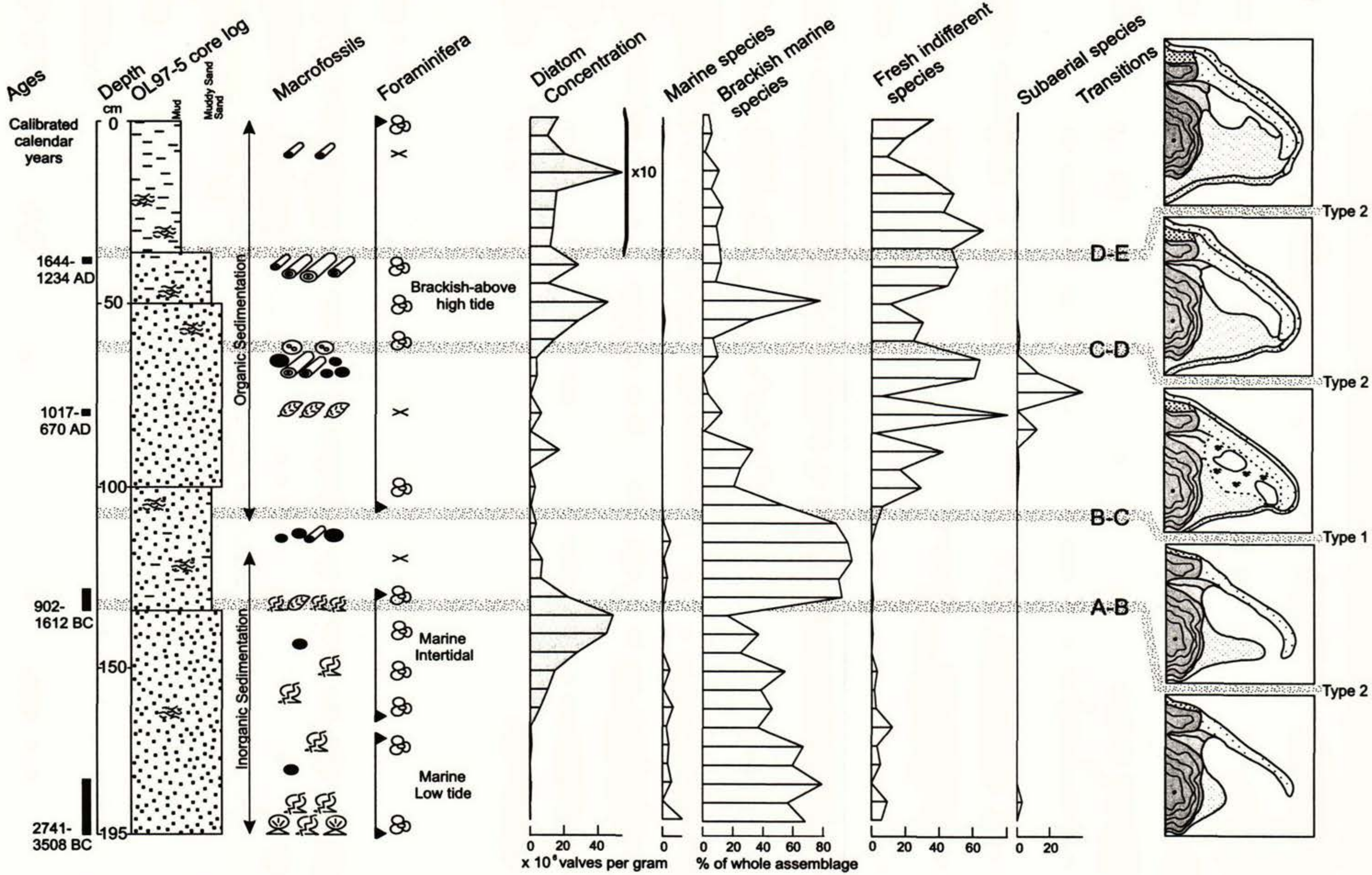


Figure 4.1 Composite plot showing summary evidence for changes in depositional environment at Okupe Lagoon

It is possible that the layer of small shells and foraminifera that occur in both cores was transported into the new environment by a salt water inundation related to the above event, but the small size of shells suggest it was a last attempt by these organisms to live in an unfavourable environment.

Transition B-C at 107.5 cm depth represents isolation of the waterbody from the sea and shallowing of the environment. There is a layer of pebbles and wood at 113.5 cm depth and organic sedimentation occurs from this point on. The transition occurs in core OL97-3 at 50 cm depth where a layer of large shell fragments is preserved. Many changes occur to the diatom assemblage including a switch from dominantly brackish marine to dominantly fresh indifferent and fresh brackish species. This indicates that a large magnitude change in salinity took place at the transition. There was also a large change in water depth from a shallow water lagoon to a moist soil with ephemeral pools of very shallow water. The change occurs suddenly in the diatom record with no indication of freshening or shallowing in zone B.

The sedimentary features at the transition in each core suggest that some type of depositional event occurred at this time. The wood and pebbles in core OL97-5 were probably derived from the catchment and barrier and could have been deposited by a storm. However the large shell fragments of core OL97-3 must have been derived from a seaward source because the waterbody of zone B did not support any kind of mollusc. This presents the possibility of a tsunami or a storm of large enough proportions to transport shells either over the barrier or through the opening for a distance of about 500 metres. Peaks of brackish marine diatoms in the base of zone C support the occurrence of a marine influx at this time.

The cause of isolation of the waterbody from the sea at transition B-C is most likely due to the final closing of the gravel barrier. Continued sediment transport and deposition could have led to such a closure. However the evidence for substantial shallowing of the waterbody occurring concurrently with isolation indicates that coseismic uplift was the likely trigger for barrier closure.

At transition C-D (57.5 cm depth) there is a distinct 4 cm thick layer of large rounded pebbles and wood fragments with pieces of pumice near the top of the layer. A very similar layer occurs synchronously in core OL97-3. The transition involves a change from an ephemeral lagoon to a permanent waterbody. An influx of salt water is suggested by the large peak in brackish marine species in the middle of zone D and this may well have made the site more favourable to micro-organisms. However a single influx is unlikely to be responsible for development of a long term lagoonal environment without some lowering of base level. Therefore it is suggested that subsidence, or compaction of the sediments through liquefaction, led to lowering of the floor of the lagoon below the water table enabling a more permanent waterbody to exist at the site. A large storm event causing movement of material off the boulder bank into the lagoon, and some overtopping of the barrier by waves, could explain the deposition of the pebble layer and brackish marine diatoms. However this explanation does not provide a mechanism for creating a permanent waterbody. Lack of an indication as to the magnitude of change prohibits interpretation of this transition as a coseismic uplift event. However all pieces of evidence could be explained by this one

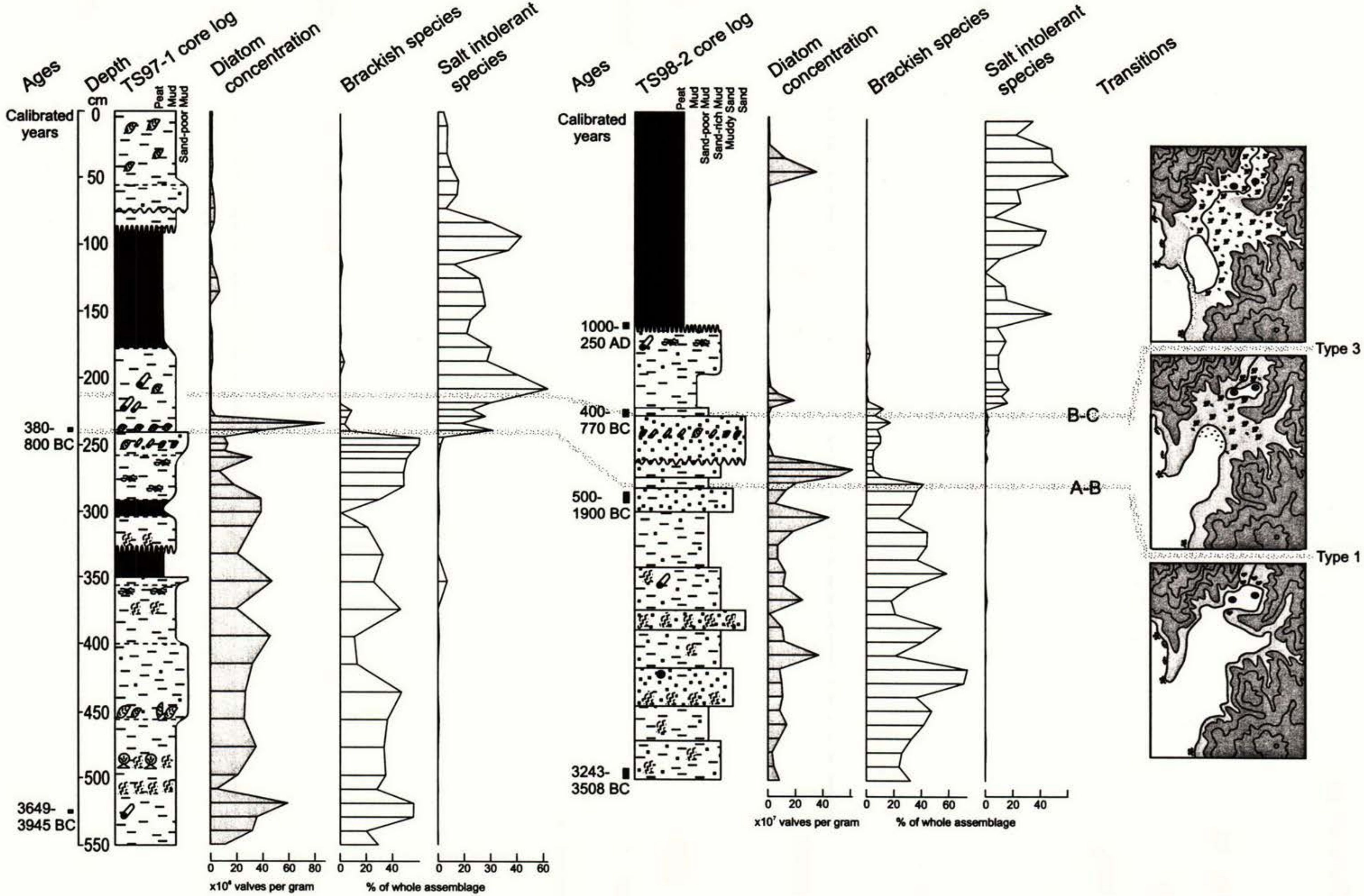


Figure 4.2 Composite plot showing summary evidence for changes in depositional environment at Taupo Swamp

occurrence, for example through the shaking, liquefaction and / or subsidence, and saltwater influx that an earthquake would cause.

A sharp transition from organic sand to organic mud occurs at the boundary between zone D and E at 36 cm depth. This is accompanied by a concentration of large wood fragments in the core, and a dramatic increase in diatom concentration. There was obviously some disturbance of the catchment at this time causing a large influx of wood into the lagoon. This could also bring about a renewed source of nutrients causing diatoms to flourish. The cause of catchment disturbance is consistent with the effects of shaking from an earthquake event but could equally be explained by flooding, landsliding, or even early land clearance as human habitation on Kapiti began almost 1000 years ago (Maclean, 1999). The transition to a waterbody with a finer-grained substrate implies that a long term change to water depth or sediment supply also took place at this time.

SITE 2: TAUPO SWAMP

There are two main changes in depositional environment at Taupo Swamp. The first is considered to be the direct result of a coseismic uplift event. The second occurs not long after the first and is thought to represent the establishment of a stable environment following the existance of a short-lived, unstable, earthquake-generated environment (Fig. 4.2).

Transition A-B consists of a change in depositional environment from an open brackish lagoon at the head of an inlet to a predominantly freshwater, very shallow pond. There is a sharp contact in both sedimentary sequences to finer-grained, more organic sediment. In TS97-1 a 2 cm thick rootlet layer was deposited immediately above the transition. A large scale environmental change is inferred to have occurred across the transition because salinity decreases by at least one order of magnitude and only six diatom species overlap into zone B out of an assemblage of at least 80 species in zone A. The change is inferred to have happened suddenly because diatom assemblages change completely over a 3 mm interval in the sedimentary sequence. Considering the likely occurrence of some bioturbation this is a very rapid transition. The event is thought to have occurred synchronously in both cores because the date at the base of zone B in TS97-1 and at the top of zone B in TS98-2 are essentially the same and zone B is considered to represent a short-lived environment of no more than 200 years.

Aside from evidence for a tsunami event, transition A-B at Taupo Swamp complies with all of Nelson's criteria for a coseismic cause. A barrier closing across the valley mouth could cause a large change in salinity quite suddenly but this mechanism would not account for the shallowing and draining of the site that occurs in this case. The contacts are unlikely to be erosional from channel cutting, flood or storm events because they represent a unidirectional environmental change to a low energy, freshwater environment that persists for thousands of years.

Transition B-C consists of a change from a fresh brackish shallow pond to a completely fresh water wetland environment. The change is not distinguishable in the sedimentary sequence

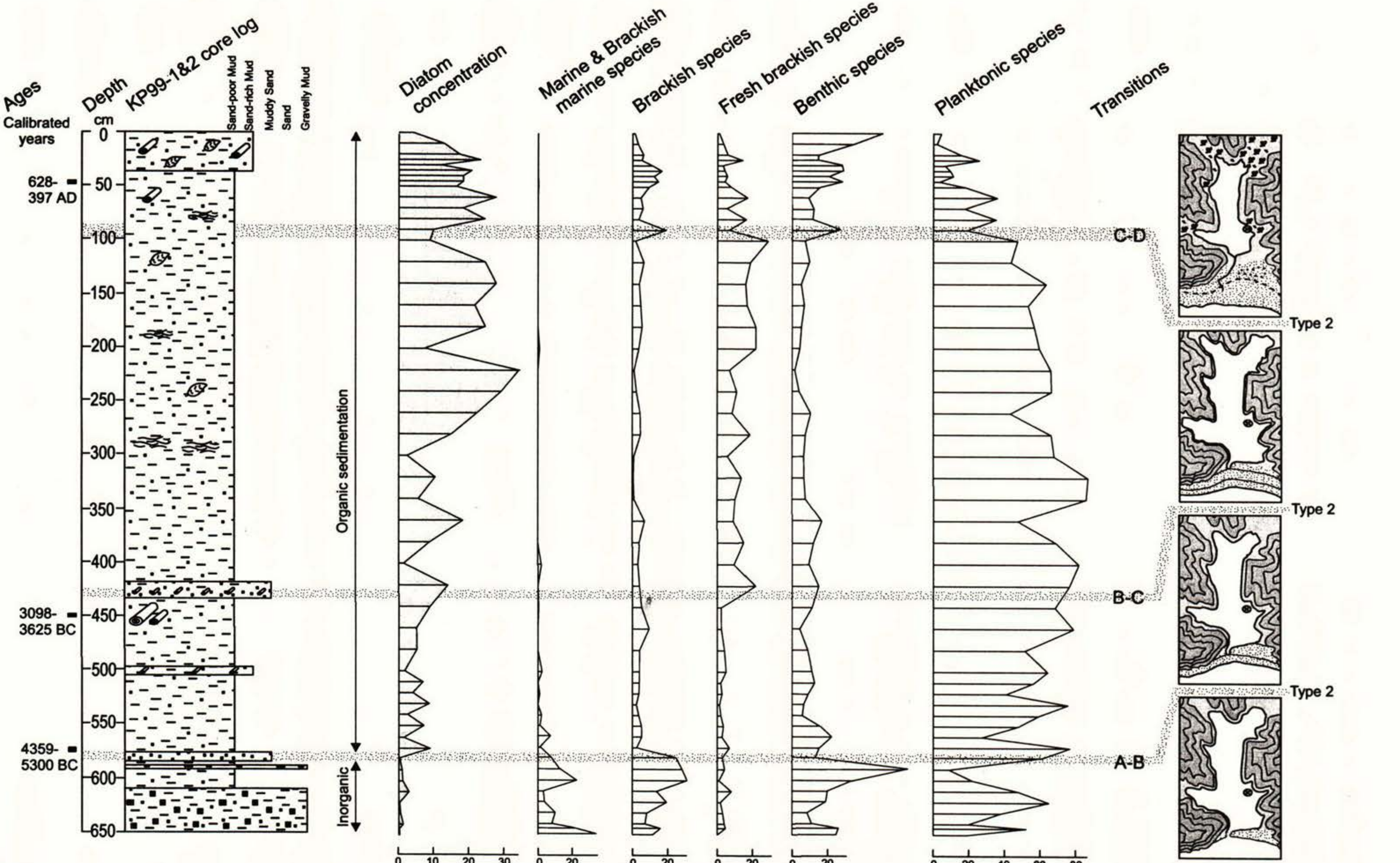


Figure 4.3 Composite plot showing summary evidence for changes in depositional environment at Lake Kohangapiripiri

of TS97-1 but involves a sharp contact to finer grained sediment in TS98-2 (relating to movement of the stream channel away from the site). The transition was probably caused by continued drainage at the site as a result of longer term adjustment of the water table to uplift.

SITE 3: LAKE KOHANGAPIRIPIRI

At Lake Kohangapiripiri there are three distinct changes in the diatom assemblage through time and the basal two changes are accompanied by layers of coarser sediment in the sedimentary sequence. Although none of these changes provide enough information to directly infer a coseismic cause, the nature of each change is consistent with a coseismic origin (Fig. 4.3).

Transition A-B at 577 cm depth involves deposition of a layer of sand and completion of the final stage of isolation of the waterbody from the sea. The cause of change was not necessarily of great magnitude considering the waterbody was already predominantly closed. The shift in diatom assemblage occurs moderately suddenly at this point but without the earlier part of the record it is hard to put this shift in context. The transition appears to occur near the base of the sedimentary sequence from the northeastern wetland of Lake Kohangapiripiri (Cochran *et al.*, 1999) but synchroneity is hard to establish because part of the record is missing near this point. It is likely that the transition was caused by closing of the gravel barrier that was in place between the lake and the sea at this time. This could have occurred gradually through sediment accumulation or rapidly in a storm event or earthquake uplift. The layer of sand deposited at this time consists of angular, poorly sorted greywacke clasts consistent with the fine toe of a landslide off the nearby hillside. The concurrence of this deposit with the change in diatom assemblage favours a catastrophic cause rather than continuation of sedimentary processes.

Transition B-C at 434 cm depth involves deposition of a unit composed of layers of sand and wood fragments and the initiation of a relatively deep water phase in the lake's history. This change is of moderate magnitude as it is estimated to involve a minimum of one metre increase in water depth. It is also moderately sudden because the three planktonic species that dominate zone C all increase dramatically at this depth. The transition is a lake-wide event that occurs synchronously in the wetland core (Cochran *et al.*, 1999). A sudden deepening of the lake basin could be caused by coseismic subsidence, compaction due to liquefaction of the lake sediments or increased ponding behind a higher or less permeable barrier. The incorporation of layers of sand and wood into the record indicates that some disturbance of the catchment occurred concurrently.

Transition C-D is not represented in the sedimentary sequence but involves a shallowing of the lake as inferred from the diatom flora. A very similar shallowing signal is found in the sedimentary sequence of the wetland. The ages for this transition at each site, estimated using accumulation rates, just overlap but because of apparent sediment loss at the top of the sequences, ages of the most recent changes in the lake's history may not be accurate. This transition could be the result of sediment accumulation and infilling of the lake basin.

A moderately sudden change in the diatom flora may occur when accumulation reaches a point where light levels on the lake floor make habitation of the sediments favourable to diatoms. However this would result in an assemblage change in a fairly localised area. Transition C-D occurs at both ends of the lake at a similar time suggesting that a lake-wide cause of shallowing is required.

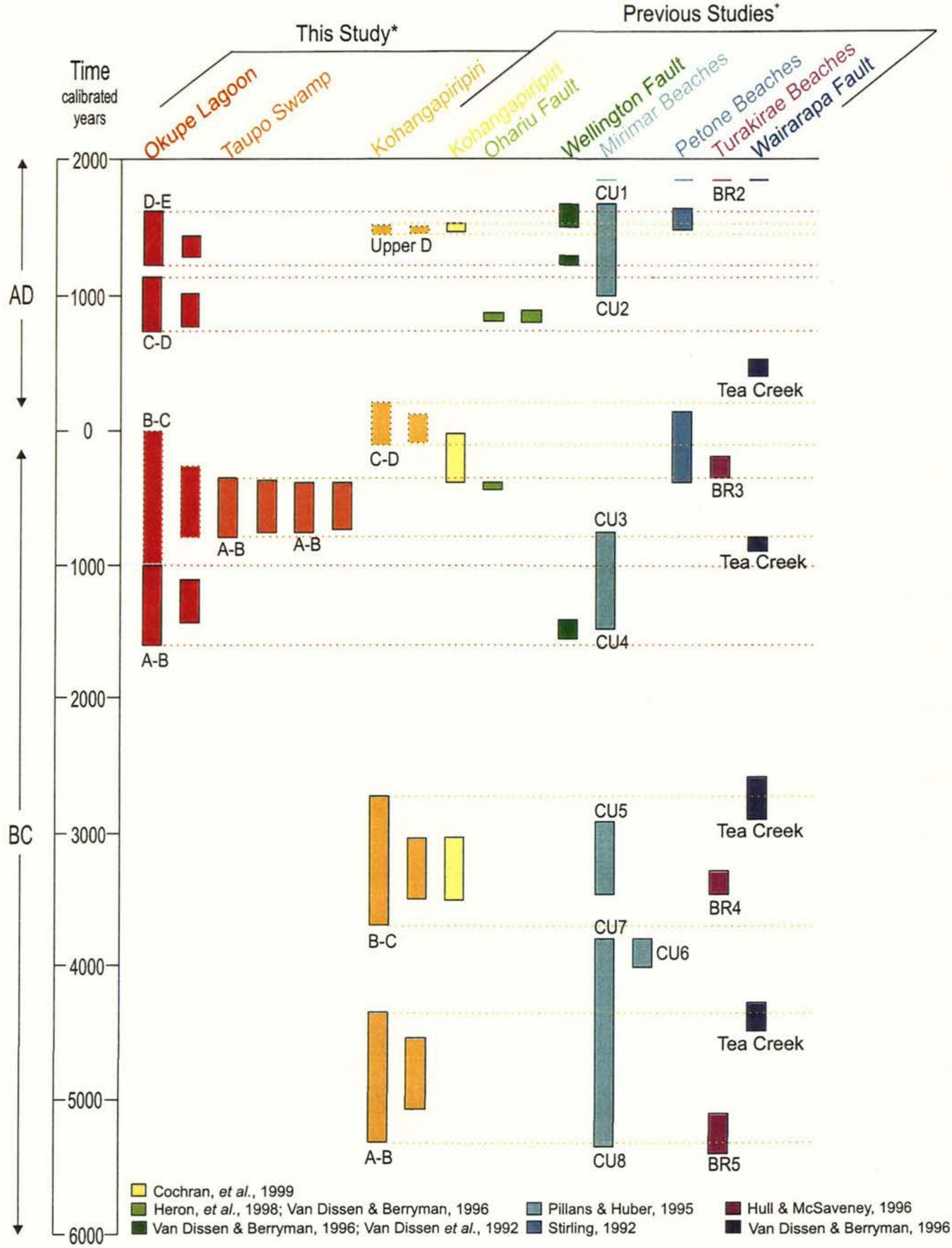
A more sudden shallowing appears to be represented by the top two samples within zone D. This involves a fairly large change in species and the exact signal occurs synchronously in the wetland core. Because it is only represented by the top few samples in each core, further investigation is needed to confirm the nature of this change. A sudden shallowing of lake-wide extent would be consistent with an earthquake-induced change in water table level.

Estimates of Earthquake Magnitude

In the study of paleoearthquakes in the sedimentary record, rough estimates of earthquake magnitude can be gained by determining the amount of vertical displacement with respect to sea level that occurred in the earthquake. This involves knowing the height of the paleoenvironment in relation to sea level when it was deposited and measuring its present height above sea level. There are a number of assumptions made in this process and it is particularly complicated in the Wellington region where uplift may be cancelled by subsidence as each site is on the predominantly upthrown block of one fault and the relatively downthrown block of another fault. Another limitation at present is the lack of information regarding the distribution of diatom species in relation to sea level in New Zealand. This paucity of ecological information, along with the differing role played by barriers at each site, makes it difficult to estimate the past height above sea level of each depositional environment. Future work on modern diatom distribution aims to improve such estimates.

Heights presented below are only an initial, rough attempt to estimate vertical displacement and need to be interpreted in association with evidence for amount of environmental change (connection with the sea, salinity, water depth) and external evidence for uplift at the sites. At Okupe Lagoon the amount of vertical uplift interpreted from diatom assemblages and elevation data could be anywhere between 0 and 1 metre. However external evidence for uplift exists at the site in the form of a raised boulder bank and shore platform. The boulder bank is on average 3.6 m above its modern equivalent and a large rockpool on the shore platform is about 5 m above mean sea level. These elevations indicate that, in contrast with the estimates of Moore and Francis (1988), uplift in the order of 3-4 m has occurred at the site. The age of peat at the base of the raised rockpool gives a minimum age for uplift of the rock platform at 95 BC -212 AD. This implies that the uplift inferred at transition B-C (1005 BC – 2AD) could well have been responsible for uplift of the platform and associated boulder bank.

At Taupo Swamp minimum amounts of uplift of 0.7 m in TS97-1 and 1.7 m in TS98-2 can be inferred from diatom assemblages and present elevations of the cores. The only external evidence for uplift at the site is a raised shore platform which Adkin (1921) attributes to



* 1 & 2 sigma levels of dates presented, those with dotted outlines are estimated from accumulation rates.

⁺ 1 or 2 sigma levels of dates presented following those quoted in publication.

Figure 4.4 Plot of ages of environmental transitions recognised in this study compared with ages of earthquake events in the Wellington region identified in previous studies uplift in the 1855 AD Wairarapa earthquake. However the occurrence of uplift in the Porirua area as a result of the 1855 earthquake is controversial (see Eiby, 1990).

At Lake Kohangapiripiri core elevations and diatom assemblages suggest substantial subsidence over the last 7000 years because the only evidence of marine conditions at the site is over 4 m below present sea level. However this is probably a result of the existence of a large barrier at the mouth of the valley throughout this time (Cochran *et al.*, 1999). The height of the oldest raised beach at Lake Kohangapiripiri is 8.5 m amsl, about 5 m above the modern storm beach. It has been documented that Pencarrow Head was uplifted by 2.1 m in the 1855 earthquake (Grapes and Downes, 1997) so a minimum of 3 m uplift occurred prior to this.

Correlation with Existing Record

Figure 4.4. is a plot of calibrated radiocarbon ages of earthquake events recognised in previous studies plotted alongside the ages of environmental transitions recognised in this study.

Two examples of independent, diatom-based evidence for coseismic uplift were described in the preceding section. These are transition B-C at Okupe Lagoon and transition A-B at Taupo Swamp. As can be seen from figure 4.4, these transitions occurred synchronously at some time between 800 and 380 BC. This is conclusive evidence that the transitions are the result of a regional event rather than local sedimentary processes. For example, it is highly improbable that two barriers on different coasts and in different wind and wave climates would close at the same time without external forcing.

The only date that this event coincides with is a tentative estimate for the penultimate earthquake on the Ohariu Fault put forward by Heron *et al.* (1998). Their date of 410-400 BC comes from a root collected from a trench across the Ohariu Fault in the Ohariu Valley. They suggest a faulting event could have been responsible for death of trees through a change in groundwater or sedimentation. An earthquake on the Ohariu Fault at this time is consistent with the evidence at Taupo Swamp and Okupe Lagoon because the large magnitude of environmental change at these sites indicates a proximal source. Taupo Swamp is about 2 km northwest of the fault in Kahao Valley and Okupe Lagoon about 12 km northwest of the fault at Waikanae. The sense of movement implied by the transitions, that of uplift to the northwest, is conformable with geomorphic observations on the Tongue Point-Makara, Makara-Porirua, Kahao Stream and MacKays Crossing sections of the fault (Heron *et al.*, 1998).

The remaining transitions at Okupe Lagoon, A-B, C-D and D-E, are potentially signatures of previously recognised earthquakes. Transition A-B occurred between 1612 and 902 BC and coincides with the timing of uplift of beaches on the Miramar Peninsula (CU 3 & 4). However it is likely that different earthquakes were responsible for effects at Miramar and Okupe Lagoon. A date of 1590-1430 BC from a trench in Long Gully provides an estimate for the oldest known event on the Wellington Fault (Van Dissen *et al.*, 1992). Considering that uplift along the Wellington Fault is predominantly to the northwest, this event is more likely to have resulted in uplift at Kapiti than at Miramar. An estimate for an event on the Wairarapa Fault may have been the source for uplift at Miramar.

Transition C-D at Okupe Lagoon coincides with estimates for the timing of the last earthquake on the Ohariu Fault. Van Dissen and Berryman's (1996) estimate is the overlap of four dates of the most recent event as represented at four different sites along the fault. Heron *et al.*'s (1998) estimate is the overlap of eight dates made under the assumption that the fault segments north and south of Porirua Harbour ruptured together. The date from Okupe Lagoon made on the distinct layer of wood, pebbles and pumice in core OL97-3 (770-1160 AD), correlates well with these estimates. This indicates that transition C-D at Okupe Lagoon is very likely to be a signature of the last surface rupture earthquake on the Ohariu Fault. Evidence from the lagoon, as described above, suggests the area experienced strong shaking causing catchment disturbance and liquefaction of soft sediments, as well as inundation by a tsunami at this time.

The age of transition D-E at the 95 % confidence level, coincides with the ages of both the last two earthquake events on the Wellington Fault. At the 68 % confidence level the age of the transition falls exactly between the last and penultimate Wellington Fault events. As noted above, this transition was not necessarily caused by an earthquake event. However it is likely that small pieces of wood brought down from the catchment by landslides caused by shaking would be already dead. They would give an older radiocarbon age than the event itself so, if the result of an earthquake, this transition is more likely to be a signature of the last event on the Wellington Fault than the penunltimate event.

The transitions at Lake Kohangapiripiri are thought to be signatures of earthquake events on the Wairarapa Fault. Records of the timing of these earthquakes come from raised beaches at Turakirae Head, offset features and a trench across the fault near Tea Creek Road. It is generally accepted that the age of uplifted beaches at Turakirae Head should coincide with timing of lateral movement along the Wairarapa Fault (Grapes, 1999). However dating of these two components does not closely agree, for example note Hull and McSaveney's (1996) ages for uplift of Turakirae beach ridges and Van Dissen and Berryman's (1996) estimates of event timing from the Tea Creek trench. It is possible that the disparity is a function of the type of deposits being dated in each case, but until the timing is more closely constrained, correlation of earthquake signatures is difficult. Both transition A-B and B-C at Lake Kohangapiripiri coincide with uplift events of Pillans and Huber (1995) at Miramar Peninsula and appear to bracket dates at Turakirae Head and Tea Creek on the Wairarapa Fault. This clustering of ages seems to indicate that dates in each cluster represent one earthquake event, one occurring at some time between 5400 and 4250 BC and the other between 3625 and 2580 BC. Transition C-D at 103 BC-215 AD partially overlaps with uplift timing of a beach at Petone and again occurs between an uplift at Turakirae Head and an event recorded at Tea Creek.

An estimated age for the tentative shallowing event at Lake Kohangapiripiri suggests it was caused by one of the last two events on the Wellington Fault. However, as the dating of recent events in Lake Kohangapiripiri is problematic, and considering this change occurs in the top 20 cm of core, it is possible that this is a signature of the 1855 AD surface rupture earthquake on the Wairarapa Fault, or even caused by man-made drainage at the site.

Implications for hazard planning

This study illustrates what a dominant role large magnitude earthquakes have played in the history of coastal waterbodies in the Wellington region over the last 7000 years. Within this timeframe they are a frequent occurrence and their effects are recorded at widely spaced sites on different fault-bounded blocks. For example there is evidence to suggest that strong shaking occurs as far away as Kapiti Island during earthquakes on the Wellington Fault (over 30 km northwest of the fault in the Tararua Ranges). The last earthquake on the Ohariu Fault caused strong shaking at Kapiti and triggered a tsunami that inundated Okupe Lagoon. The penultimate earthquake on the Ohariu Fault caused substantial uplift at Taupo Swamp and Okupe Lagoon and triggered a tsunami, the effects of which are only recorded at Okupe Lagoon. Earthquakes on the Wairarapa Fault have caused water-level changes and landsliding in the catchment at Lake Kohangapiripiri.

This study confirms the tentative estimate of Heron *et al.*, (1998) for timing of the penultimate earthquake on the Ohariu Fault. Using estimates of slip rates and single-event displacements, Van Dissen and Berryman (1996) calculate a recurrence interval of 1500-5000 years for large, surface-rupture earthquakes on the Ohariu Fault. The time between the penultimate and last events is now able to be estimated at 1290-1220 years indicating that the recurrence interval for these recent events is at the smaller end of the estimated range. Time elapsed since the last event is between 1120 and 1180 years (Heron *et al.*, 1998). Therefore, the available data suggests that the Ohariu Fault could be the source of a major, surface-rupture earthquake within the time frame of human interest. The Ohariu Fault should be considered a major hazard to Porirua City and the Kapiti Coast but also, as it is capable of generating magnitude 7.1-7.3 earthquakes (Heron *et al.*, 1998), to the wider Wellington region.

5 CONCLUSIONS

Objective 1:

High resolution records of change in depositional environment at Okupe Lagoon, Taupo Swamp and Lake Kohangapiripiri indicate that these waterbodies were initially inlets of the sea. A combination of sediment accumulation and tectonic uplift at each site has resulted in isolation from the sea in the last few thousand years. At 3500 BC Okupe Lagoon was an embayment sheltered in the lee of Kapiti Island. Strong wind and wave action led to the growth of a large boulder bank to the north and accumulation of beach sediments to the south. Coseismic uplift enhanced these processes and led to enclosure of the waterbody by about 400 BC resulting in a brackish lagoon. At Taupo Swamp there is little evidence at the site today that the area was originally an estuary. Brackish water diatoms and estuarine shells 3 metres below the swamp surface demonstrate the existence of such an estuary between 4000 and 400 BC. Coseismic uplift and growth of the beach ridge that Plimmerton now occupies, led to isolation of the valley. Tilting may have hindered drainage causing a wetland to form. At Lake Kohangapiripiri only the very base of the sedimentary sequence indicates that the site was once a lagoon open to the sea. A relatively fresh water lake, separated from the sea by a large gravel barrier, has existed at the site since about 5000 BC.

Objectives 2, 3 and 4:

In this study one coseismic uplift event is independently documented from the sedimentary sequences of Okupe Lagoon and Taupo Swamp. The estimated amount of vertical displacement caused by the earthquake is between 0.7 and 4 m of uplift at the sites. These figures, although only rough estimates, suggest a large magnitude, surface-rupture earthquake was responsible for the movement. The event occurred at some time between 800 and 380 BC and can be correlated with an estimate for the penultimate event on the Ohariu Fault (Heron *et al.*, 1998).

Transition:	Age	Indication of Magnitude	Correlation
Okupe Lagoon B-C	1005 BC-2 AD	3-4 m max. uplift	Penultimate Ohariu Fault
Taupo Swamp A-B	800-380 BC	0.7-1.7 m min. uplift	Penultimate Ohariu Fault

The identification and dating of this earthquake event enables Heron *et al.*'s (1998) estimate to be confirmed. This strengthens previous indications regarding the seismic hazard of the Ohariu Fault, ie that it could be the source of a major surface rupture earthquake within the time frame of human interest.

Seven earthquake signatures are documented from the sequences of Okupe Lagoon and Lake Kohangapiripiri. Estimates of earthquake magnitude can not be determined from these signatures but they provide additional information about the lateral extent and type of effects of past large earthquakes. Dating of earthquake signatures also provides additional opportunities for constraining the timing of earthquakes where records do not closely coincide, for example on the Wairarapa Fault.

Transition:	Age	Inferred Effects	Correlation
Okupe Lagoon A-B	1612-902 BC	uplift	Oldest Wellington Fault
Okupe Lagoon C-D	770-1160 AD	shaking, liquefaction & tsunami	Last Ohariu Fault
Okupe Lagoon D-E	1234-1644 AD	shaking	Last Wellington Fault
Kohangapiripiri A-B	5300-4350 BC	uplift & shaking	Oldest Wairarapa Fault
Kohangapiripiri B-C	3671-2733 BC	shaking & uplift / liquefaction	2nd oldest Wairarapa Fault
Kohangapiripiri C-D	103 BC-215 AD	uplift	Penult. Wairarapa Fault
Kohangapiripiri upper D	1466-1533 AD /	uplift	Last Wellington Fault /
	1855 AD	uplift	Last Wairarapa Fault

This record of earthquake signatures illustrates the impact that earthquakes have had in the Wellington region over the last 7000 years. Catchment disturbance and changes to base level are a regular occurrence in the history of these coastal waterbodies. The distance of study sites from the ruptured fault implies, as demonstrated by the historical record of the 1855 earthquake (Grapes and Downes, 1997), that effects of large, surface rupture earthquakes in Wellington are widespread over the region and beyond.

Assessment of the technique

The research reported here provides an example of the contribution diatom analysis of sedimentary sequences can make to paleoseismic studies. This technique can directly detect evidence of earthquake events and also identify signatures of earthquake events. The main advantage of the technique is that it enables new sites to be investigated, including those without physical or stratigraphic evidence of coseismic activity. Diatom analysis can provide high resolution reconstructions of past depositional environments. It is particularly useful in the coastal zone because diatoms are one of the few microfossil groups that live in waters of any salinity - from marine through to fresh water.

Limitations of the technique include:

- Determination of earthquake magnitude relies on approximate estimates of vertical displacement. Information on the distribution of diatoms in relation to elevation above mean sea level and water depth in New Zealand is required before such estimates can be refined.
- The earthquake record derived from this technique is not related to specific faults as trench studies are. Therefore determination of earthquake source relies on correlation with a pre-existing record.
- Sites need to be chosen carefully because not all coastal waterbodies preserve evidence of paleoearthquakes. For example small, low energy waterbodies with small catchments were chosen for this study because they are more likely to contain a complete record than large, high energy sites such as estuaries.

Taking these limitations into account, there remains a distinct potential for the use of diatom analysis in the field of paleoseismology. The paleoenvironmental approach can be strengthened by the use of additional reconstruction tools such as foraminifera, spores and pollen, and sediment analysis, and the contribution of such studies to the paleoseismic record can be improved with increasing numbers of sites investigated.

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