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Sequential impacts of Polynesian and European settlement on vegetation and environmental processes recorded in sediments at Whangapoua Estuary, Great Barrier Island, New Zealand

Abstract Whangapoua Estuary, Great Barrier Island, New Zealand, is central to a proposed Marine Reserve, and is currently managed for conservation by the Department of Conservation. This paper describes the sequential impacts of Maori and European people on the process of estuarine vegetation succession in time and space, and the rate of estuarine sedimentation. Multiple cores from one estuary gave confidence in assessing the temporal sequence of vegetation change, but bioturbation and other disturbance factors made it difficult to interpret ^{14}C dates from the estuarine environment. The modern vegetation zonation pattern on the estuary is an active succession, which has been generated by rapid estuary in-filling, probably initiated as a consequence of erosion following Maori burning of the adjacent forest. European forest clearance for agriculture resulted in a further increase in estuarine sedimentation, and may have re-activated earlier sediments trapped in adjacent swamps. The combined effects of two phases of human exploitation have resulted in large-scale loss of nutrients and top-soil from catchments throughout Great Barrier Island. Conservation management of the estuary should take account of the anthropogenic impacts that have driven the plant succession and created the current vegetation zonation pattern. This pattern is neither static nor 'natural', but rather an on-going response to the changing human activities in the surrounding catchment.

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Introduction

The date of arrival and/or settlement of Polynesian (Maori) people in New Zealand is a controversial topic, but most of the evidence favours a recent settlement date of 800–650 cal year BP (1150–1300 AD) (reviewed by Lowe et al. 2000). However, recent radiocarbon dates on rat (*R. exulans*) bones suggest the possible arrival of people c. 2000 BP (Holdaway 1996, 1999). Establishing the date of settlement is crucial to understanding the rates of environmental processes consequent on the presence of people. The impacts of Polynesian people on biotic, environmental and landscape processes have been well-documented (Davison 1984; Lowe 1988; McGlone 1989; Anderson 1991; Spriggs and Anderson 1993; Holdaway 1996; Newnham et al. 1998a; McGlone and Wilmshurst 1999; Lowe et al. 2000; Horrocks et al. 2001a), and can be summarised as follows: (1) extinctions or drastic reductions of the populations of many small bird, vertebrate and invertebrate species, largely as a consequence of the rapid spread of the human commensal *Rattus exulans* (Worthy and Holdaway 2002); (2) extinction of the megafauna by hunting (especially moa, large flightless birds in the genera *Dinornis* and *Anomalopteryx*); (3) direct and indirect impacts on coastal marine mammals, fish and shell-fish; (4) destruction of forest vegetation by fire (McGlone 1978, 1983; Ogden et al. 1998, 2003), and (5) the consequential effects of increased erosion and run-off from hill-slopes and sedimentation in swamps, lakes, estuaries and shallow marine environments (McGlone 1983; Elliot et al. 1997; Wilmshurst 1997; Newnham et al. 1998b; Horrocks et al. 2001a, b, 2002a). Similar events have been recorded following the first arrival of Polynesians on other Pacific Islands (Kirch 1984). Whatever the 'arrival date' or the role of rats in bird extinctions and vegetation change,

there is no doubt that the extinction of the megafauna and the destruction of forest by fire were due to Maori. Forest clearance commenced c. 1300 AD and continued for at least 200 years, by which time the large marine mammals and the moa were largely extinct. Although Maori brought no distinctive pollen-bearing cultigens to New Zealand, their arrival is marked by forest clearance, which left a distinct palynological signature, recognisable in sites throughout New Zealand. This signature comprises: (1) a rapid fall in the pollen of tall forest trees (mainly *Dacrydium* in the North Island and *Nothofagus* in the South); (2) an increase in light-demanding shrubs and herbaceous species, especially the fern *Pteridium esculentum* in the North Island and *Poaceae* in the South; and (3) the appearance (often but not always for the first time) of charcoal in the sediments (Newnham et al. 1998a). These changes in the pollen, spore and charcoal record can clearly be ascribed to forest destruction by fire. Their association with the first unequivocal evidence of people in New Zealand implies that the fires were lit by them. By this process, probably 35% of the forest was destroyed, especially in the drier eastern parts of both islands (McGlone 1983).

Unlike Maori, Europeans introduced a wide range of exotic plants into New Zealand, several of which produced abundant pollen which became trapped in sediments. Increases in Poaceaea, *Taraxacum* and *Plantago* are characteristic, while the presence of *Pinus* pollen is diagnostic for the European period. Although Europeans were present in New Zealand from the late eighteenth century, the generally accepted date for the commencement of European impact on the terrestrial environment is 1840 AD (Wendelken 1976; Newsome 1987). Soon after this date the European population increased rapidly, forested land began to be cleared and swamp-land drained for agriculture. Fire was again used as a tool, or accidentally escaped, to destroy large areas of remaining forest. Many mammals were also introduced, some for husbandry (e.g. sheep and cattle), others for sport (e.g. rabbits, deer) (Wilson 2004). The net effects of forest clearance and a style of land-use ill-suited to the frequently steep, infertile and now unstable hillsides, were widespread erosion and loss of top-soil. This destructive exploitation of the remaining natural resources continued for a century, being terminated or slowed only as a consequence of the reduction in available manpower after two world wars (King 2003). European exploitation of Great Barrier Island followed a similar pattern (Sewell 2001).

Our study was designed to examine the successional sequence of vegetation types on Whangapoua Estuary, Great Barrier Island, using palynological techniques. A serendipitous consequence was to document the impacts of both Maori and European land-use on the vegetation of the estuary and adjacent catchment. Our first aims were to describe the existing vegetation zonation patterns on the estuary in relation to the tidal regime, and demonstrate that this pattern is accurately reflected in the modern pollen rain. These initial results will be briefly summarised as they demonstrate important features required for the interpretation of the pollen sequences (Deng et al. 2004). We then interpret the palynological records in sediment cores from the different vegetation zones, and demonstrate the impacts of people on the rate of vegetation succession and sedimentation. This study thus differs from most palynological studies because it relates temporal processes to current spatial zonation patterns, demonstrating how the latter have spread and colonised new substrate created as a consequence of sequential human impacts on the surrounding catchment. Finally, we stress the importance of this understanding for effective conservation management.

Study area

Great Barrier Island is located in the Hauraki Gulf c. 90 km east of the city of Auckland (Fig. 1a). It is the largest offshore island in the New Zealand archipeligo (c. 28,500 ha). It's rugged forest and scrub covered interior are composed of ancient volcanic rocks (Moore 2001). The New Zealand-wide colonisation events described in the introduction were closely mirrored in the history of Great Barrier Island. Palynological and other data record the Maori impact signature c. 600 BP (c. 1350 AD) (Horrocks et al. 2001a). Archaeological evidence of Maori presence is widespread, in shell middens and Pa (fortified hill-top settlements) (Clough 2001; Nichol et al. 2003). However, due to a combination of intense inter-tribal conflict ('the musket wars') following the acquisition of new weapons, and the spread of European diseases, the Maori population was much reduced in the early nineteenth century. Europeans then used the island as a base for exploiting marine resources (1800–1830 AD), minerals (1840s), and the kauri (*Agathis australis*) forests. Kauri logging (and probably forest fire) was extensive in the catchments a few kilometres to the west of Whangapoua in the 1860s, and was followed by rapid forest clearance for agricultural purposes throughout the Island (Sewell 2001). This clearance peaked early in the twentieth century. By 1940 AD much of the forest was converted to grassland, but after this date cleared land began to revert to native scrub (mainly *Leptospermum scoparium* and *Kunzea ericoides*) with introduced woody weeds such as *Pinus* spp. also increasing. These trends have accelerated since the collapse of the dairy industry in the 1960s.

The eastern coastline of Great Barrier includes several former marine embayments, which have been converted into swamps by coastal progradation and natural sedimentation in the late Holocene, and in some cases into pasture by drainage since European colonisation. The vegetation and palynological history of these wetlands have been described (G. N. Rutherford, unpublished; Cameron 1999; Horrocks et al. 2000a, b, c; Ogden 2001; Horrocks et al. 2001a, b). Whangapoua
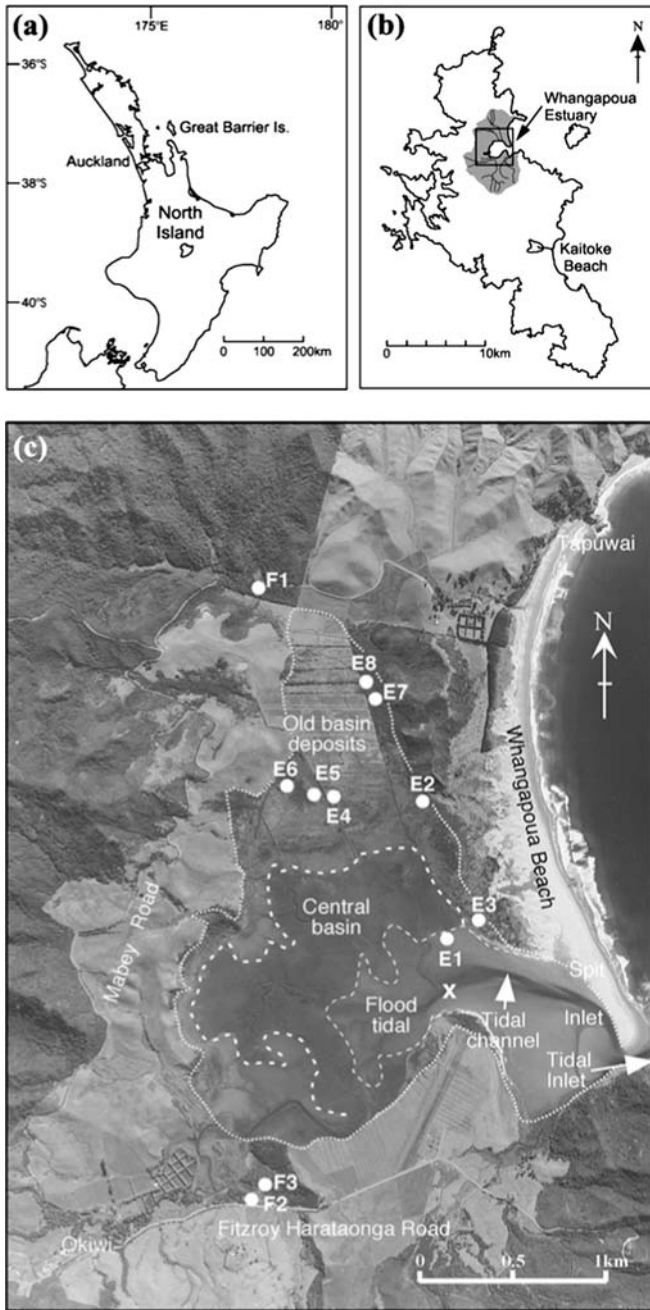
Fig. 1 a North Island, showing location of Great Barrier Island. **b** Great Barrier Island showing location of Whangapoua Estuary. The *shaded area* is the catchment surrounding the estuary. **c** 1999 aerial photograph of Whangapoua Estuary. Core sites are indicated by a *round dot*. *E* Estuarine core site, *F* Freshwater core site, *X* Present estuarine channel 'centre'. The *white dashed lines* represent the boundaries between flood tidal, central basin and old basin deposits which together constitute the estuary. The boundary between the old basin deposits and the surrounding catchment is also indicated by a *white dotted line*

value of its wetlands, which provide habitat for several rare bird species. A management plan will be developed in the near future. The surrounding catchment is relatively small (c. 29 km^2), but extends to the highest point on the Island (621 m). The estuary is bounded to seaward (east) by a sand-spit c. 2 km in length, and comprises a flood tide basin, which is covered and uncovered by tidal action every day and composed of mainly sandy sediments, a central basin including mangroves (*Avicennia marina*) and salt marsh communities, which are also regularly inundated by high tides, and older basin deposits further landwards (Plate). The central basin deposits are generally silty muds, while the older basin deposits are now influenced mainly by periodic freshwater input from the catchment, and have peaty silts at the surface. These older deposits are generally covered by *Leptospermum* scrub communities, but have been partially cleared and drained in 1979–1980 to create rough grazing land (Ogle 1980; Cameron 1999). Most of the coring described in this paper was into these older deposits.

As a consequence of sea-level rise before 6,000 BP, and possibly more recent changes, several streams have formed swamps where their flow is blocked on meeting the older estuarine deposits. These marginal freshwater swamps have distinct vegetation comprising large herbaceous monocots in the genera *Typha, Phormium* and *Cordyline* and some swamp forest tree species (e.g. *Dacrycarpus dacrydioides*).

The nearest weather station to Whangapoua Estuary is c. 4 km to the west at Port Fitzroy. Mean annual rainfall for the period 1961–1997 was 1,893 mm (NIWA 1997), well distributed throughout the year. However, exceptionally heavy rains occur once or twice most years. Mean daily maximum air temperatures are c. 19°C, and minima c. 12°C. The maximum tidal range is c. 3.5 m.

Estuary is the largest and least modified of these systems, and is a good example of a Barrier Enclosed Lagoon (Hume 2003). (Note that the Whangapoua Estuary illustrated by Hume is not the same one described here, although its geomorphology is very similar).

The Whangapoua Estuary is centred on latitude 36° 8′ S and longitude 175° 24′ E (Fig. 1a, b). The estuary is situated near the centre of the recently proposed Aotea (Great Barrier) Marine Reserve, but has been excluded from the proposal due to conflicting views of management associated with Maori customary rights to harvest shellfish (Auckland Conservancy 2004). However, the area is, and will remain, a reserve managed by the Department of Conservation for the high conservation

Methods and materials

Vegetation survey

Methods for the vegetation survey (Deng et al. 2004) are only outlined here, as the results are not presented in detail. Five transects, ranging in length from 160 to 540 m and each covering all or part of the vegetation sequence from the tidal mangroves to the terrestrial

Plate 1 Zonation of vegetation in the Whangapoua Estuary northern New Zealand. Visible are three vegetation zones and the sequence of vegetation succession from sea to landward i.e. from mangrove (*right*) to salt meadow then to swamp forest (*left*). The *grey area* of dead *leptospermum* is visible in the centre of the photograph. This zonation was formed c.700 years ago after the Polynesian settlement. The sandspit enclosing the estuary can be seen behind the saltmarsh. *Photo* Yanbin Deng

Leptospermum communities were studied. On each transect 5×2 m plots were located at 20 m intervals. Plant species frequency was recorded for all species using ten 1 m^2 sub-plots in each plot. An additional three transects were similarly sampled in marginal freshwater swamps. The (127) species × (108) plot frequency matrix was analysed using the software PCORDWIN (McCune and Mefford 1997). The programme TWINSPAN was used to classify plots and species into groups recognised as plant communities (Hill 1979; Van Tongeren 1995). De-trended correspondence analysis (DCA) was used to ordinate the data, illustrating the relationships between the communities and the main environmental gradients (Kent and Coker 1992).

Modern pollen rain

Five surface samples of moss, plant litter or mud were collected in each vegetation plot, homogenised and sub-sampled (Horrocks and Ogden 1994; McGlone and Moar 1997; McGlone and Meurk 2000) to provide 108 samples for pollen analysis. Details of method and results are given in Y. Deng (unpublished). These samples are thought to represent pollen added to the surface over the last few years (< 5 years). Although the addition of re-worked pollen cannot be ruled out in the tidal sites, the results presented relate only to the locally dominant species so that re-working is unlikely to have influenced the pattern obtained. Pollen extraction and analysis followed the standard procedures outlined below.

The pollen and sedimentary record

Eight core sites were selected to represent vegetation types from close to the mangrove edge to the landward *Leptospermum* communities (E1-8). A further three cores were extracted from freshwater swamps (F1-3) (Fig. 1c). Cores were taken either with a hand driven D-section corer, or using a petrol-driven 'vibra' corer. Maximum core depth was 3.5 m. Pollen extraction followed standard acetylation and hydrofluoric acid techniques (Moore et al. 1991). At the beginning of the procedure *Lycopodium* marker spore tablets were added to allow estimation of the efficiency of the process and absolute pollen frequency estimation if required (Stockmarr 1971). Because estuarine sediments tend to have a high inorganic component, large samples (1–1.5 cm^3) were used. Pollen was identified and counted at 400–1,000 × magnification. On most slides, at least 250 dry-land pollen grains were counted. Pollen and spore identification employed a set of reference slides, and standard identification manuals (Cranwell 1953; Pocknall 1981a, b, c; Large and Braggins 1991; Moore et al. 1991). All pollen types were included in the pollen sum. The software packages TILIA. 2, TILIAGRAPH. 2 and TGView 1.6.2 (E. Grimm, Illinois State Museum, IL, USA) were used to construct and zone the pollen diagrams. Only those six pollen diagrams containing Pre-Polynesian, Polynesian and European zones are presented here. Site E1, situated near the estuarine mouth, has been subject to current changes and turbulence, and it contained a hiatus, followed by rapid sand deposition; its palynology is not presented. Sites E3 and E7, both on the eastern edge of the estuary abutting the sand spit, are also not presented because they failed to reach Pre-Polynesian sediments, or in the case of E3 these sediments were non-polleniferous dune sands. Likewise the freshwater swamp cores F1 and F3 failed to sample the Pre-Polynesian sediments and are not considered further, except in the calculation of sedimentation rates. Loss-on-ignition analyses of the sediments were made at one site only (E8) and followed the procedures of Davis (1974). Samples were subjected to low-temperature ignition (430°C.) for 24 h and the resultant loss in sample mass was assumed to be combusted plant organic matter.

Radiocarbon dating was carried out either by the University of Waikato Radiocarbon Dating Laboratory (Wk), University of Waikato, Hamilton, New Zealand or, in the case of AMS dates on pollen, subcontracted to the Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand (all samples have Wk- reference numbers). The surface of the sediments was assumed to represent present day sediment. Zone boundaries were dated by extrapolation from the ^{14}C dates in each core. These zone boundary dates were used to estimate one set of sedimentation rates within the different zones. Since zone boundaries recognised in different cores are presumably synchronous, additional estimates were made, based on the assumption that the boundaries represented, respectively, 1840 AD (European/Polynesian boundary) and 1300 AD (Polynesian/Pre-Polynesian boundary). The basis for this assumption is provided in the discussion.

Results

Vegetation zonation

The species classification and ordination are presented in Fig. 2, which illustrates environmental gradients and species groupings. The two ordination axes account for c. 77% of the variance. Six major species groupings, characterised by (1) *A. marina*, (2) *Juncus krausii*, (3) *Leptocarpus similis*, (4) *Baumea* spp (mainly *B. juncea*), (5) *L. scoparium* and *Gleichenia microphylla*, and (6) *Typha orientalis* and *D. dacrydioides* can be recognised. The first group is located on the margin of the flood tide basin, groups (2), (3) and (4) occupy the central basin, with progressively less regular tidal inundation, group (5) represents the transition to terrestrial vegetation, while groups (6a) and (6b) represent younger and older freshwater swamp communities, respectively. Groups 6a and 6b are clearly separated in the plot ordination (not presented) and identified as distinct communities elsewhere on Great Barrier Island (G. N. Rutherford, unpublished). The communities defined by the classification and ordination are clearly visible in the field, although, as expected, the boundaries between them become progressively more diffuse as more species enter the sequence through time (in the landward direction).

Pollen representation

With one exception, the percentages of different pollen types in the surface sediments reflect the aboveground vegetation. *J. krausii*, forming a distinctive vegetation zone between the mangroves and *Leptocarpus* salt meadow, is totally absent from the surface sediments. This pollen grain was shown to be readily destroyed during the extraction process (Y. Deng, unpublished), and is probably not preserved in the sediments. Apart from this, the abundance of different pollen types in the surface sediments clearly reflects the successional position of the vegetation zone (Fig. 3).

On the first axis of the DCA, the species 'peaks' for the pollen types present closely follow the vegetation sequence in Fig. 2 (from right to left: *Avicennia* > *Sarcocornia* > *Leptocarpus* > *Baumea* > *Gleichenia* > *Leptospermum* > *Typha* > *Dacrycarpus*). This sequence is also reflected in the sediments. It is this clear representation of the current vegetation zonation in the current pollen rain that provides confidence in the interpretation of the sedimentary sequences illustrated, for example, in Fig. 5a. Other, less common, pollen types also show clear association with the vegetation, increasing confidence in the recognition of the plant community in the sedimentary record. Certain entomophillous pollen types, notably *Avicennia*, are not produced in abundance or transported far (Mildenhall 1987) so that even traces of their pollen indicate local presence of the plant. Widespread (wind dispersed and 'over-represented') pollen types, such as the abundant forest tree *Dacrydium cupressinum*, tend to blur the interpretation, but high % values of these are associated with more open vegetation types. *Baumea* pollen extends in abundance over much of the sequence, reflecting both the wide ecological tolerance of *B. juncea* (which occurs in both saline and freshwater environments) and the presence of additional *Baumea* species in terrestrial and freshwater habitats.

Radiocarbon dates

The radiocarbon dates from the cores are summarised in Table 1. The age–depth relationship, based on the most reliable estuarine cores, is given in Fig. 4 and Table 2. The ages of the zone boundaries were extrapolated from the ^{14}C dates assuming the surface represents 2000 AD and that sedimentation rates are constant between the dates and the horizons. Mid-points of the calibrated ages for the 95% probability range were used as the best approximation to the 'true' date, and because a single date (rather than a range) was required for the estimation of mean sedimentation rates. By this process seven estimated ages (Table 2) were obtained for the (supposedly synchronous) Polynesian/Pre-Polynesian boundary. These dates show much variation between cores, and follow the age–depth trend. For this reason these dates, and the sedimentation rates derived from them, are considered less reliable than those derived from assuming that the PO/PR horizon should be dated c. 1300 AD. The European/Polynesian boundary shows good agreement between sites, but is c. 100 years older than expected. These problems are addressed in the discussion.

Pollen diagrams

Figure 5a–f illustrates the main features of the pollen diagrams presented in full by Y. Deng (unpublished).

Fig. 2 *Two-dimensional graph showing the results of the TWINSPAN species classification overlaid onto the results of the species ordination and the generalised vegetation types. The first four letters for genus and species names are used (large dots). Some species names are not shown to avoid overlap of symbols (small dots). Numbers represent species groupings assigned in the TWINSPAN classification. The three major vegetation zones are identified by circled numbers and general axis interpretations are shown.* 1, *Avicennia marina, Zostera novazelandica*; 2, *Juncus Krausii*; 3, *Leptocarpus similis, Sarcocornia quinqueflora, Plagianthus divaricatus*; 4, *Baumea juncea*; 5, *Leptospermum scoparium, Gleichenia microphylla*; 6a, *Typha orientalis, Baumea rubiginosa, B. articulata, Gleichenia dicarpa, Carex lessoniana*; 6b, *Myrsine australis, Kunzea ericoides, Cordyline australis, Phormium tenax, Dacrycarpus dacrydioides, Carex virgata*
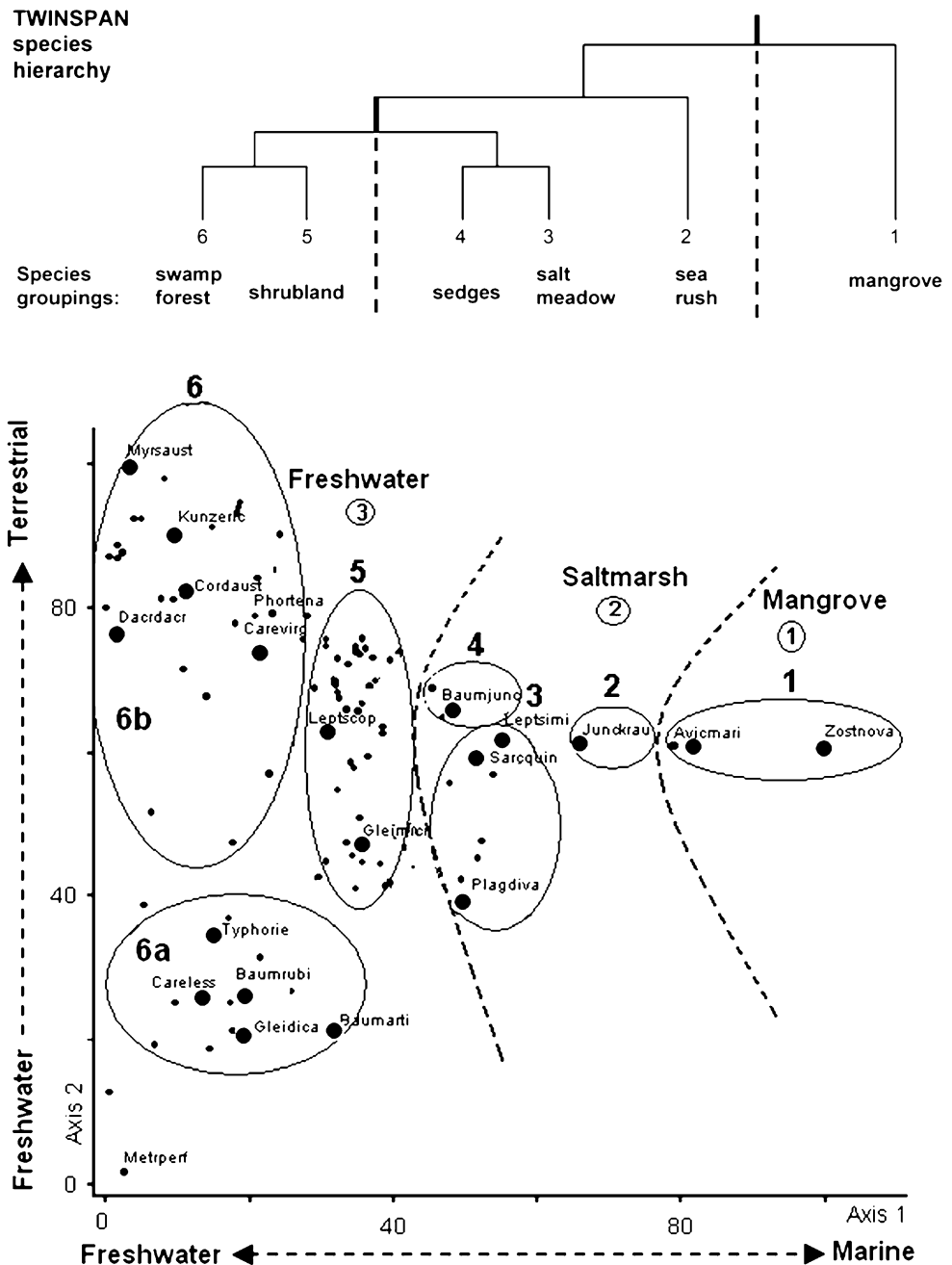
The zonation (EU, European; PO, Polynesian; PR, Pre-Polynesian) is based on independent CONISS classifications of each diagram, using all species, not just those in the Fig. 5.

The PR zone

The presence of undisturbed forest in the catchment in Pre-Polynesian (PR) times is indicated by high levels for tall coniferous trees (*Dacrydium, Libocedrus* and *Prumnopitys*), tree-ferns (*Cyathea*) and shrubs in the PR zone. A Pre-Polynesian shell layer (or layers) dated c. 3000–3500 BP (Wk-9383 and Wk-10056) indicates a flood tide or marine lagoon environment in the estuary at that time. This shell layer underlies the existing mangrove and salt-marsh communities, and some of the *Leptospermum* shrub-land (Deng et al. 2004). Occasional marine dinoflagellate remains (e.g. Fig. 5b), and the predominantly mineral composition of the sediments (Fig. 6), provide further evidence of a marine environment extending over most of the studied area during the PR period.

Cores F2, E6 and E2 (Fig. 5f, e, c) especially appear to provide evidence of Pre-Polynesian burning, with charcoal and/or *Pteridium* in that zone. However, in view of the clear evidence of downward percolation of exotic pollen when some of the pollen diagrams are
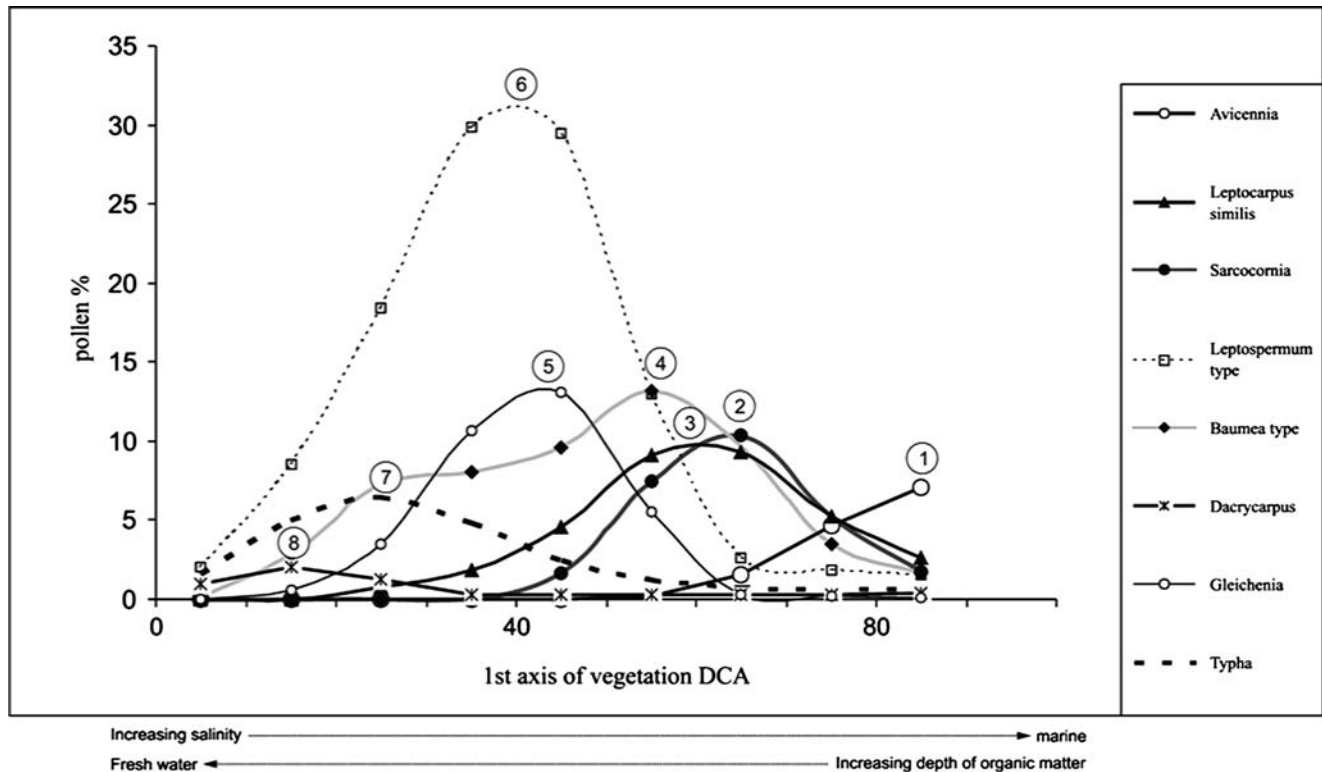
Fig. 3 Smoothed pollen percentage of the diagnostic taxa against the vegetation successional gradient value, showing pollen representation along the first axis of a DCA based on vegetation samples taken across the estuarine gradient. *Numbers 1–8* represent the sequence of species 'peaks'

examined in full, the possibility that this is occurring here also cannot be discounted (see Discussion).

The PO zone

The Polynesian (PO) zone varies from c. 21 to c. 70 cm in thickness. The key features of the PR/PO boundary are a decline in tall tree (mainly *Dacrydium*) pollen and an increase in *Pteridium* spores and charcoal particles. These shifts in composition are regional indicators of vegetation change due to fire, and are clearest at sites E4 and E8 (Fig. 5a, b), though present at all sites. The PO zone encompasses the start of the transition from marine to freshwater dominated sediments in the estuarine sites. This is illustrated in Fig. 5a, in which *Avicennia* gives way to *Leptocarpus* during the zone, which is then followed by *Baumea* and *Leptospermum* communities in European time. The local successional sequence is detectable in full at sites E4, E8, E5 and E2 (Fig. 5a–d) but *Avicennia* is absent from the sequence at E6 (Fig. 5e).

In several of the diagrams in Fig. 5, CONISS splits the PO into two sub-zones. The lower of these (POa) is characterised by a rapid decline in tall tree pollen, associated with an increase in *Pteridium* (which reaches its peak in the PO zone) and charcoal. This is the typical 'Maori burning signature', announcing the arrival of these people in the catchment. Palynologically it is marked by the first CONISS division (the PO/PR

boundary) in five of the six diagrams (Table 2). The upper sub-zone (POb) marks the estuarine transition from the tidal *Leptocarpus* communities, to the more terrestrial *Baumea* zone. In the freshwater swamp (Fig. 5f), the upper POb zone marks the spread of *Typha* and Blechnum (B. capense).

The EU zone

The upper, European, zone is c. 17 cm in depth and is characterised by *Pinus* and an increase in Poaceae pollen. Certain other rare pollen types of definite European origin

(*Betula, Plantago lanceolata*) are also indicative. Although not shown in Fig. 5, some of these pollen types occur in trace amounts in lower (Pre-European) sediments, indicating that some downward percolation has occurred (see also *Pinus* in Fig. 5f). Despite this mixing, the EU/PO zone boundary is clear, being the first or second CONISS division in four of the six diagrams (Table 2). Other features of the EU zone include the prevalence of *Baumea*, *Gleichenia* and *Leptospermum* pollen, indicative of the current vegetation in the vicinity of the core sites. The rise in tall tree pollen in this zone is partly a function of including *Pinus*, but also implies successional changes from scrubland to forest in the wider catchment. The high *Typha* pollen count in the freshwater site at this time is replicated elsewhere on

Table 1 Radiocarbon dates from sites at Whangapoua Estuary

| Site	Wk No[a]	Sample type	Depth (cm)	^{14}C age (year BP)[b]	Calibrated age (year BP) 95%[c]	Calibrated age (year AD) 95%[d]	$\delta^{13}C$ (‰)
E1	Wk-10178	Pollen	165	1400 ± 71	1420–1120	530–830	−25.2
E2	Wk-10056	Cockle	60–80	3356 ± 57	3350–3030		−0.2
E3	Wk-10179	Pollen	190	866 ± 58	920–660	1030–1290	−19.9
E4	Wk-9383	Cockle	110–119	3566 ± 50	3570–3330		1.3
E4	Wk-9545	Soil organics	65–80	853 ± 59	920–660	1030–1290	−26.1
E4	Wk-11292	Pollen and Plant fragments	55	1071 ± 51	1070–880	880–1070	−26.2
E5	Wk-9756	Pollen	109–110	1707 ± 65	1740–1410	210–540	−21.8
E5	Wk-10412	Pollen	85	1444 ± 56	1420–1230	530–720	−26.2
E5	Wk-9316	Peat	30–36	269 ± 66	470–240	1480–1710	−27.6
E6	Wk -9039	Peat	29–34	258 ± 56	460–250	1490–1710	−28.0
E7	Wk-9038	Soil organics	55–60	631 ± 69	670–510	1430–1670	−29.4
E8	Wk-12091	Pollen	70	854 ± 39	800–660	1150–1290	−24.6
F1	Wk-9546	Pollen	170–175	762 ± 58	770–620	1180–1330	−25.5
F2	Wk-10057	Plant fragments	99–100	1077 ± 70	1170–780	780–1170	−28.8
F3	Wk-9100	Twig	180–190	320 ± 60	510–270	1440–1680	−26.6

[a] *Wk* University of Waikato Radiocarbon Dating Laboratory
[b] Conventional age based on Libby half-life of 5568 year with correction for isotopic fraction applied, ±1 standard deviation due to counting
[c] 95% probability range (year BP)
[d] 95% probability range (year AD)

Fig. 4 Radiocarbon age: depth plot for estuarine sites. E4, E5, E6 and E8. Regression for age maxima (*open squares*): cal year AD = 1993.0-15.738.depth (cm); r^2 0.868. Regression for age minima (*open, triangles*): cal year AD = 2159.0-14.908.depth (cm); r^2 0.855. *Superimposed filled squares* are the estimated age (cal year AD) of the PO/PR boundary at sites (*left to right*) E6, E2, E4. Superimposed (two independent estimates) E8 and E5. *Superimposed open circles* are estimate age (cal year AD) for the EU/PO boundary of the same sites (*points overlap*)
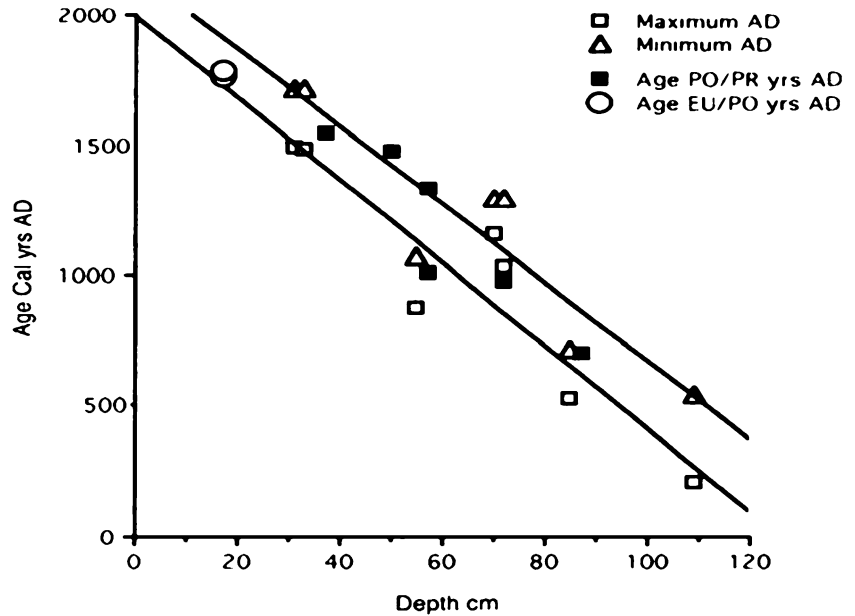
Table 2 Estimates of the human impact boundary dates AD from six cores at Whangapoua Estuary showing both Polynesian and European impacts

Core site	Pre-Polynesian–Polynesian boundary			Polynesian–European boundary		
	CONISS division	Depth (cm)	Date AD mid-point	CONISS division	Depth (cm)	Date AD mid-point
E2	2	50	1474	1	17	_[b]
E4	1	57	1011, 1325[a]	2	17	1758
E5	1	87	705	3	17	1767
E6	1	37	1539	4	17	1755
E8	1	72	975	2	17	1778
F2	1	82	1150	2	22	1735
Mean ± SD	(mode = 1)	63 ± 18	1168 ± 298	(mode = 2)	18 ± 2	1759 ± 16

[a] Independent estimates derived from two dates (Wk-9545, Wk-11292)
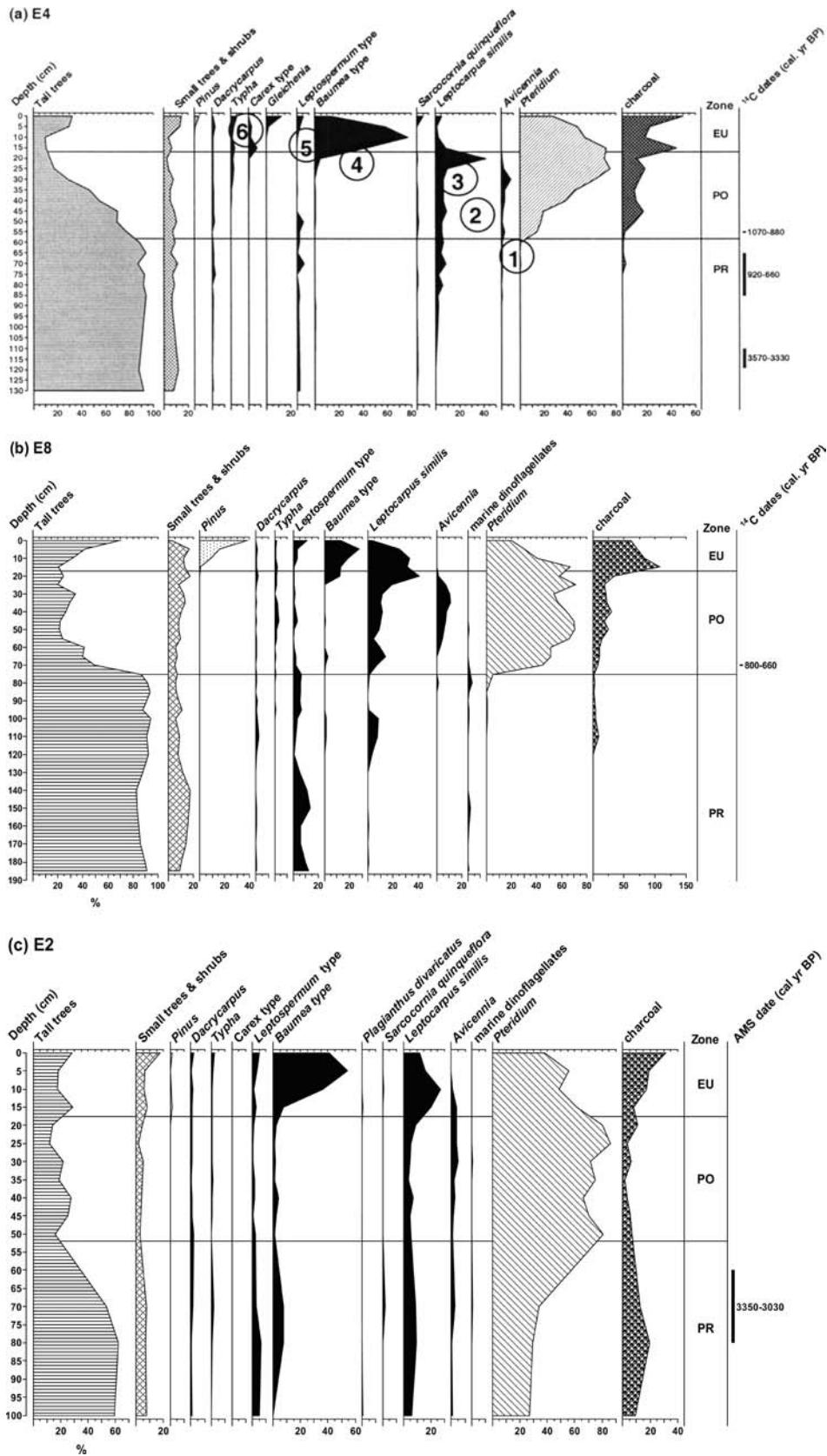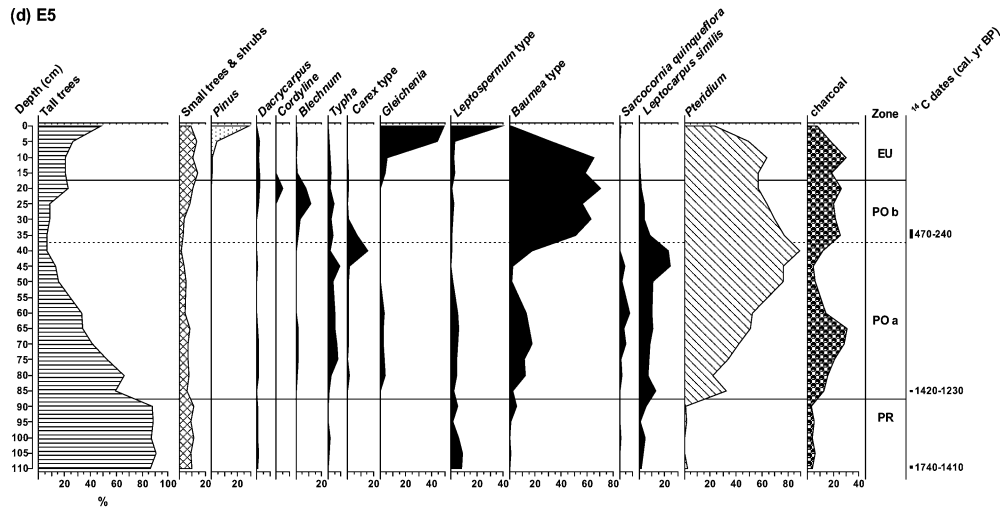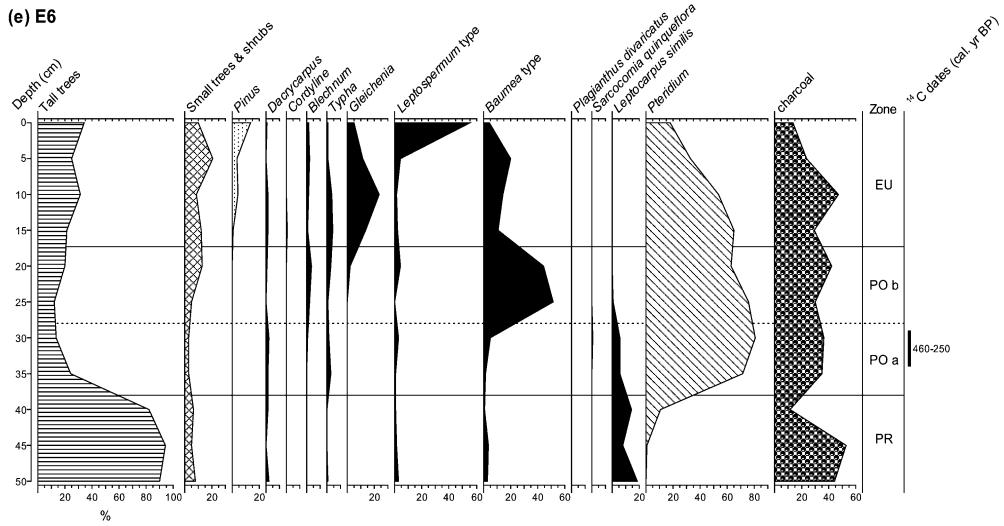[b] No relevant radiocarbon date available

Fig. 5 Summarised pollen diagrams from key pollen taxa of six sites (**a–f**). *Circled numbers* on (**a**) E4 represents the successional vegetation stages (cf. Fig. 2)
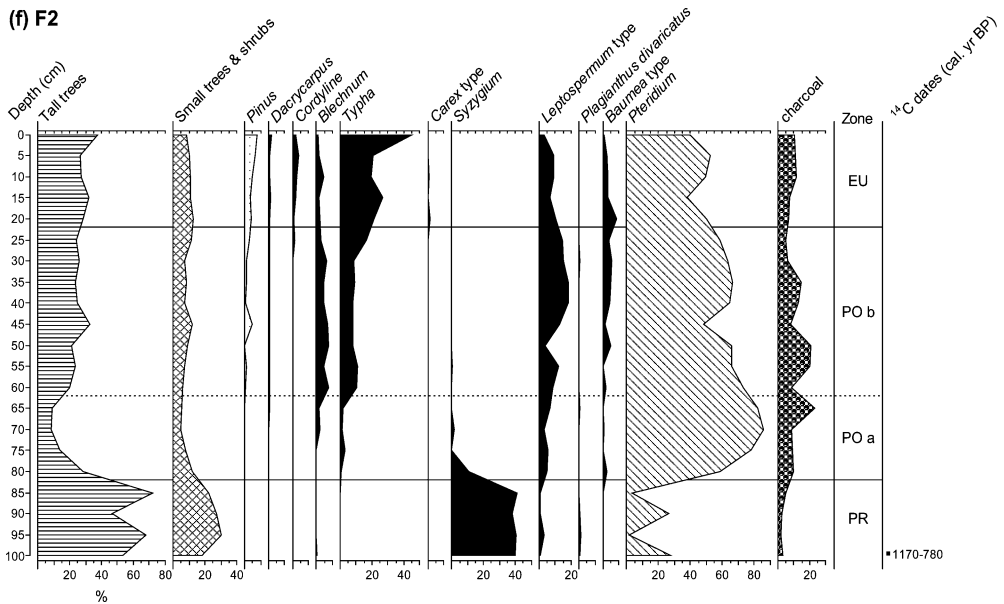
34

Fig. 5 (Contd.)

Great Barrier (e.g. site F1, and Horrocks et al. 1999, 2000b).

Estuarine succession

Sites E4 and E8 both illustrate the switch from open lagoon or flood-tide estuary to mangroves coincident with surrounding forest decline and increased charcoal and *Pteridium*. The successional sequence from mangroves to *Baumea* and *Leptospermum* is indicated (Fig. 5a). Here, and in E2, the *Baumea* zone appears to have been created largely during European times—i.e. in the last two centuries. Sites E5 and E6, situated further from the old tidal margin, show similar patterns, but with *Baumea* peaking earlier, in late Polynesian times. *Avicennia* pollen was not recorded at site (E6), suggested that either this zone was succeeded by *L. similis* earlier in the PR period (below the depth sampled) or mangroves were never present at this site.

Freshwater succession

Site F2 records a switch from a swamp forest (dominated by *Syzygium*—now rare on Great Barrier Island) to a more open swamp with *Typha* and *Leptospermum*. *Cordyline* and *Dacrycarpus* appear to have increased in European times associated with expansion of the *Typha* swamp. The current successional pattern in the mesotrophic freshwater swamps, both here and elsewhere on Great Barrier Island (G. N. Rutherford, unpublished), appears to be from an invasive *Typha* stand to a *Cordyline australis/Phormium tenax* swamp, which is eventually replaced by forest dominated by *D. dacrydioiders*. Most of the *D. dacrydioides* trees around swamp sampled are young trees (< 150 years).

Sedimentation rates

Table 2 gives the estimated ages of the CONISS zone boundaries, based on the ^{14}C dates and assumptions that the surface sediments represent 2000 AD and that there have been constant deposition rates between the dates and the boundaries. The PO/PR boundary is clearly marked in all diagrams, usually being the first CONISS division, However, the extrapolated dates for it vary so widely (705–1539 AD) that it is difficult to estimate the date of Maori impact from them. The European transition is less clearly marked palynologically, but appears to be more precisely dated. However, that date too (1759 ± 16 AD) is earlier than anticipated for European forest clearance on Great Barrier Island. Despite these difficulties, two methods of calculating sedimentation rates give broadly similar results (Table 3).

Both demonstrate a large increase in estuarine sedimentation rates across the PO/PR boundary, and a further (less dramatic) increase in European times. Sedimentation rates in essentially terrestrial sites, gaining sediments only from exceptional floods or as wind-borne dust, are c. 1.0–2.0 mm year^{-1}. In the freshwater swamp site, which today appears to constitute a sediment trap for a stream originating in the hills to the south, rates seem to have been higher in the period of landscape instability caused by Maori fires (PO zone). The results (Fig. 7) are consistent with a hypothesis that the finer sediments trapped in lower catchment swamps in Polynesian times have been re-activated and transported to the estuary as a consequence of increased run-off during European times.

Discussion

The sequence of vegetation zonation on Whangapoua Estuary is reflected in the modern pollen rain, and in the sedimentary record. This provides confidence in the interpretation of the latter as a succession, in which the different vegetation zones replace each other through time at any location as they migrate across the accreting estuarine flats. Successional rate will vary, depending both on the influx of sediments from terrestrial and marine sources, and on the depth profile of the estuary at any location. While these factors are not known, it is evident that the successional process in the

Table 3 Mean sedimentation rates in mm year^{-1} at seven estuarine and three freshwater swamp locations at Whangapoua estuary

Period location	European sedimentation mm year^{-1} ± SD (n)	Polynesian sedimentation mm year^{-1} ± SD (n)	Pre-Polynesian sedimentation Mm year^{-1} (n)
Estuarine[a]	1.23 ± 0.75 (7)	0.93 ± 0.50 (7)	0.39 ± 0.32 (2)
Estuarine[b]	1.31 ± 0.81 (7)	1.10 ± 0.80 (7)	0.18 ± 0.09 (3)[c]
Freshwater[a]	1.64 ± 0.31 (3)	2.89 ± 2.28 (3)	1.02 (1)
Freshwater[b]	1.75 ± 0.33 (3)	2.40 ± 1.14 (3)	0.55 (1)

[a]Estimated using the dates of the period boundaries from Table 2, and relevant ^{14}C dates and depths for the Pre-Polynesian period. Note that the average sedimentation rate for the European period jumps to 2.17 mm year^{-1} if site E1 is included
[b]Estimated on the assumption that the EU/PO boundary represents 1840 AD and the PO/PR boundary represents 1300 AD
[c]Site E1 included here, although there is evidence of large-scale erosion of material from the upper PR zone
n Sample number

inner estuary at Whangapoua commenced after the arrival of Polynesian people, and has progressed from estuarine mangroves to terrestrial *Leptospermum* scrub communities in a few centuries (c. 700 years or less). During this time on average c. 78 cm of sediment have accumulated. More impressively, the linear extension of vegetation from the northern end of the estuary (near Site E8) towards the south has been c.1.6 km, and about 3 km^2 of new semi- terrestrial surface has been created. This represents the infill of c. 77% of the old estuary area, almost certainly as a consequence of first Maori, then European, forest burning, felling and vegetation clearance for agriculture.

The sequential impacts of people at Whangapoua are palynologically replicated between many cores. The same horizons can be objectively identified and the zonation readily interpreted in terms of the successional spread of vegetation zones as the estuary in-fills. This repeatability gives confidence in interpreting the results, but might suggest that eleven cores were more than required. However, the wide range of estimated dates (1168 ± 298 AD) for the supposedly synchronous PO/PR horizon illustrates the problem of relying on one or few cores for the dating of events in turbulent sedimentary environments (cf. Byrami et al. 2002). Bioturbation and water movement in the profile might be expected as a consequence of nearby tidal fluctuations, but a net downward movement is implied by the presence of occasional exotic pollen deeper than expected in several of the profiles.

The different estimates of the PO/PR boundary vary systematically with depth (Fig. 4). This suggests the contamination of the dated pollen samples by older carbon, increasing with depth. This could arise if the initial burning was predominantly old-growth forest. Trees in such forest in New Zealand are frequently > 600 years old (Lusk and Ogden 1992). Old carbon from ancient forest (and forest soils) could thus contaminate the earliest PO levels, but decrease upwards as catchment erosion declined (McGlone and Wilmshurst 1999). The small size of AMS pollen samples renders them particularly vulnerable to contamination by microscopic charcoal. Fortunately the horizons are clear, and alternative approaches to dating them are available.

The PO/PR boundary has been identified in other sedimentary sequences on Great Barrier Island (Horrocks et al. 2001a: nine profiles) and elsewhere in the North Island (Newnham et al. 1998a: ten profiles). In almost all cases the boundary is immediately after the deposition of the Kaharoa tephra, which has been 'wiggle-match' dated to 1314 ± 12 AD (Hogg et al. 2003). This tephra forms a distinctive thin white 'silt' horizon (c. 0.5–2 cm) in all the studied coastal swamps of Great Barrier, *except* the Whangapoua Estuary. Its absence is surprising, because most of the ^{14}C dates on pollen (Table 1) are significantly older than 1300 AD. If these dates are correct, Kaharoa tephra should be present in the profiles. Only at the freshwater site F1

did we find traces of it. This site was re-cored several times and the Kaharoa layer was shown to be absent from most cores, and diffuse where present, strongly indicating that it was a secondary deposit. The absence of macroscopic representation of the Kaharoa tephra in all except one peripheral profile is significant, indicating that most of estuary was seawater or tidal at the time of the deposition so that the tephra layer was not preserved. Thus, we can argue that most of the ^{14}C dates based on pollen in Table 1 are too old (contaminated with older carbon) because if they were correct, primary Kaharoa tephra would be present in at least some of the profiles. Consequently, the PO/PR horizon must be post-Kaharoa. Supporting archaeological evidence comes from four recent ^{14}C dates from shell middens on the nearby Whangapoua spit, which average out to 1551 ± 92 cal year AD, but with one of them possibly as early as 1390 AD (Nichol et al. 2003). The possibility of an earlier Maori arrival date cannot be excluded. If the ^{14}C dates (Table 1) are accepted at face value, then the PO/PR at Site E5 (Wk 10412) would be over 1,000 years old. However, on the same basis this horizon would have different ages at other sites, which seems implausible. These considerations suggest that the PO/PR boundary is synchronous between sites and represents post-Kaharoa forest clearance by fire soon after. c. 1300 AD. This date (which falls within one standard deviation of the estimated date: Table 2) was used to estimate a second set of sedimentation rates. Likewise, new sedimentation rates were estimated using 1840 AD in preference to 1759 AD for the impact of Europeans (EU/PO) (Newsome 1987; Sewell 2001).

The estimated sedimentation rates derived by the two approaches (Table 3) are similar in magnitude, in broad agreement with rates measured in other estuaries (Hume 2003) and show similar patterns over time and between freshwater and estuarine environments. As in other studies (e.g. Hume and McGlone 1986; Hume and Dahm 1991; Wilmshurst 1997) sedimentation increased markedly across the PO/PR boundary, presumably as a consequence of forest clearance by fires set by Maori causing increased soil erosion in the catchment. Initially, the effects were most pronounced in the marginal freshwater swamps. However, increased fine silt input into the estuary appears to have initiated and driven the plant succession from mangroves, through saltmarsh, to more or less terrestrial scrub communities in the inner parts of the estuary. In this context it is noteworthy that part of the landward (drained) swamp is *wahi tapu* (sacred) to local Maori, because a *waka* (war canoe) supposedly rests beneath the soil there. The implication is that this area, close to core site E8, was indeed open water during an earlier Maori period. Core E8 (Fig. 5b) has marine dinoflagelates in the PR zone (< 72 cm depth) and a shell layer at c. 1 m depth, indicating that it was certainly a marine environment before 1150–1290 AD (Wk-12091; 70 cm depth). About this time mangroves appeared

and became abundant at the site during the subsequent Polynesian period.

Although on average, sedimentation rates in the estuary increased slightly in European times, the difference between European and Polynesian rates is not statistically significant. At Site E8 peak organic accretion was greatest during the PO period, but average organic input was greatest in the EU period (Fig. 6). If the %LOI figures are applied to all sites the overall pattern is not changed, but the differences between periods, shown in Fig. 7a, are reduced. Approximately, 54 and 48%, respectively, of the European and Polynesian period deposits are due to organic matter, which has presumably accumulated mainly from the growth of successional vegetation in situ. At the six sites discussed in detail here, sediment accumulation appears to have been continuous. However, two sites nearer the present estuary entrance (E1 and E3) contain hiatuses and evidence of periods of sediment disturbance. The sand spit may have been breached once by a tsunami surge during the Polynesian period (Nichol et al. 2003). Such events would probably have caused changes in sediment accumulation patterns and successional processes, but there is no evidence that the infilling process has been affected at sites in the upper estuary. For example, although a storm surge in 1997 spread seawater into the freshwater

LOI (%)

Fig. 6 Loss-on-ignition against depth at site E8

phase of the system, causing death of large areas of 30-year-old *L. scoparium*, regeneration was immediate and a fresh stand of this species over 2 m tall, and flowering, now covers the area (Plate 1). However, this event would be palynologically invisible at the sampling resolution used. Single intense rain–storm events in the surrounding catchment have likely added sediment pulses in some areas and removed material in others, and may be the main mechanism whereby old sediments are moved from peripheral freshwater swamps into the estuary. Our data are insufficient to address this further, but there is no suggestion, either from sediment composition or palynology that such events have confounded the clear anthropogenic signal in the latter.

The possibility that some other event, coincident with Maori burning, was responsible for the increased siltation rate and rapid seaward migration of plant communities must also be considered. The 'Little Ice Age' commenced c. 1300 AD, and may have been marked by a rapid sea-level fall of c. 75 cm (Nunn 1998, 2000a, b). Temperature is also thought to have fallen c. 1.5°C and precipitation increased as a consequence of increased frequency of El Nino events. A drop in sea level at the proposed rate (14 mm year^{-1}) would almost certainly drive a centripetal succession on the estuary, and could conceivably have caused the present zonation pattern. Moreover, if it was associated with temperature decline and increased rainfall it would also result in more sediment input. Shifts from saltwater embayments to brackish lagoons, and the infilling of the landward margins of saline lagoons by terrigenous sediments to form coastal freshwater wetlands have been reported for this time in Hawaii and elsewhere in the Pacific (Nunn 2000a), where people had presumably made their first impact much earlier (Athens et al. 2002).

However, as yet we have no independent evidence for this dramatic sea-level fluctuation on Great Barrier, while evidence for forest clearance, demonstrably linked to soil erosion and sedimentation increases in lakes (Wilmshurst 1997) and swamps (McGlone and Wilmshurst 1999), is widespread in both coastal and inland situations throughout New Zealand. Consequently, we favour a largely anthropogenic interpretation of our results, while acknowledging the possibility that the effects of people could have been exacerbated by a coincident sea-level fall and climate change.

The first phase of forest clearance by Maori fires was probably followed by the depletion of marine food resources and population decline. That forest regeneration followed the early Maori inflagrations is suggested by the extensive stands of kauri (*A. australis*) present on the Island at the time of European settlement. Such stands are likely to have been composed of one or a few cohorts arising after these fires (Ogden and Steward 1995), and comprised a valuable timber resource, which was rapidly exploited. Logging involved clearing the forest followed by log-extraction using dams, which were released to flush out the logs to the coast. There is evidence of these activities in the headwaters of the stream draining into
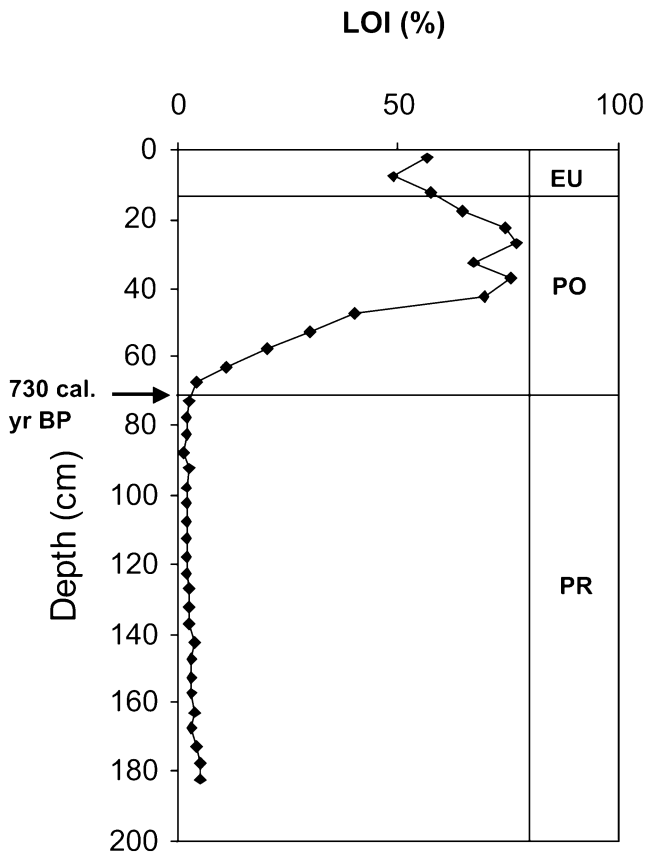
Fig. 7 Mean sedimentation rates expressed as mm/year, plotted for each period. *Error bars* represent mean ± SE. **a** Estuarine core sites, **b** Freshwater core sites. There is no standard error bar on Pre-Impact sedimentation rate in **b** because only one sample (F2) extends to the Pre-Impact period. *Open bars* Estimated using the dates of the period boundaries from Table 2, and relevant depths. *Filled bars* Estimated on the assumption that EU/PO boundary represents 1840 AD and PO/PR boundary represents 1300 AD
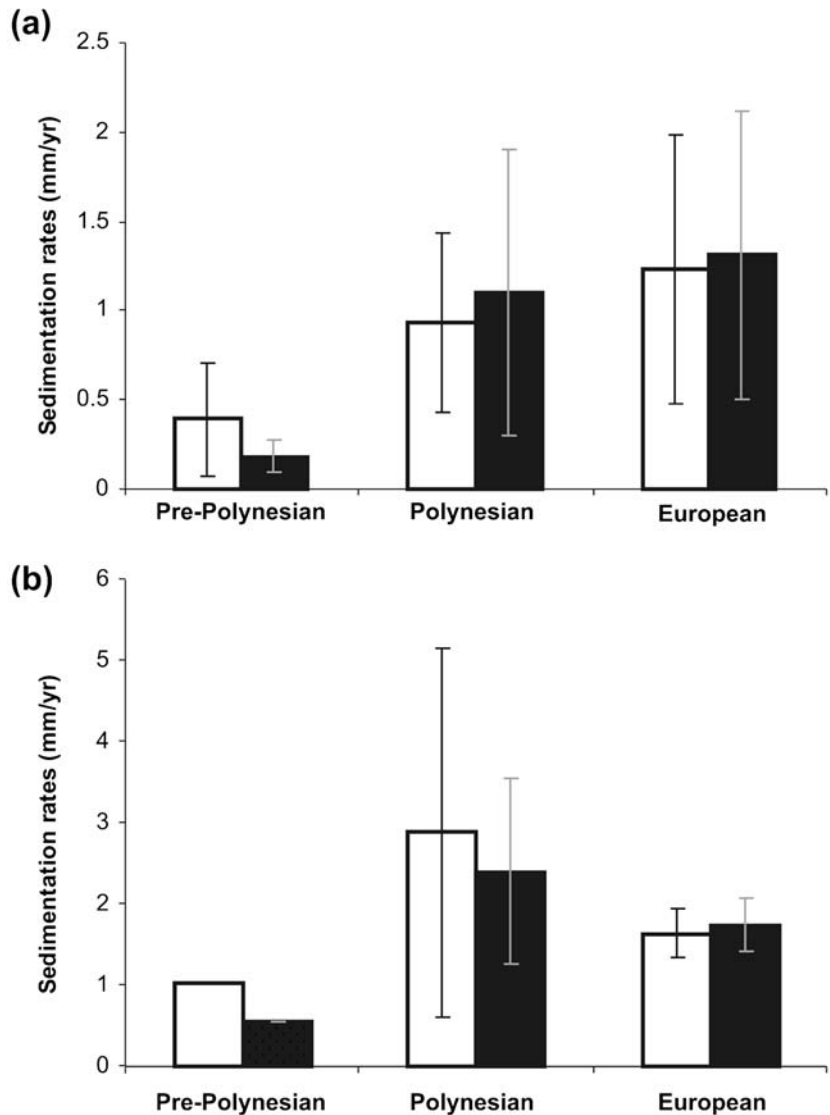
the Whangapoua Estuary via the freshwater swamp from which F2 was obtained. Kauri gum, present in the soil, was subsequently harvested, often requiring further clearance by fire. Conversion to pasture would certainly increase run-off, especially during storm events, when large quantities of sediment are transported from pastures into sediment traps such as swamps, lakes and estuaries (Page et al. 1994; Trustrum et al. 1999). Consequently, increased sediment input after the arrival of Europeans is to be expected (Wilmshurst 1997; Page and Trustrum 1997; Eden and Page 1998). The estimated sedimentation rates did increase slightly in the estuary, although the difference was not statistically significant. The rate in the surrounding freshwater swamps may have declined, although it remained higher than the estuarine rate. After the second (European) phase of forest clearance much of the eastern side of Great Barrier Island was repeatedly burned to prevent scrub growth, and provide an annual flush of new grass on the

farms. This is registered at site F1 and elsewhere in freshwater swamps by the spread of *Typha*, which implies increased eutrophication.

As a consequence of forest fires during early Maori times, subsequent European logging and fires, and the use of fire in pasture management until c. 1940, the soils over extensive hillsides are now skeletal. They have little profile development and thin litter layers overlying bedrock or remnant nutrient-depleted B horizons. Ridge crests frequently have bare soil patches. Regeneration to forest is now slow as a consequence; most slopes carry *L. scoparium/K. ericoides* scrub forest (Land Unit 8, Ogden 2001) and most ridges an open scrub of low-stature *Leptospermum* and invasive woody weeds (e.g. *Hakea* spp., *Erica* spp., *Pinus* spp.); Land Unit 9, Ogden 2001. The soil and nutrients missing from these terrestrial systems are now either lost to the marine environment or stored in the coastal swamps, alluvial flats and estuaries, in which the story of their past is mirrored.

An important lesson from this study is that the present condition of the Whangapoua Estuary is not 'natural' in the sense of approximating the pre-human condition. Rather, the whole of the current vegetation pattern has arisen as a direct consequence of human activities in the surrounding catchment. As soil horizons have been depleted in the latter, so has new land subsequently been created in the estuary. However, the first attempts to utilise this new land for grazing by drainage (1979–1980) resulted in part in increased ingress by saline water, causing a reversal of the successional process in the areas affected (Deng et al. 2004). Current management is primarily for conservation of the indigenous biota, but some shellfish may be harvested by traditional methods. It will be important to research the historical population sizes of the harvested species and to recognise the potential impact of rapid successional processes and sedimentation rates on shellfish population dynamics. Any attempt to change sediment and nutrient input must address surrounding land use, especially grazing animal effects on the inflow streams and peripheral swamps, and aerial top-dressing of fertilisers on the surrounding pastureland. The estuarine ecosystem is the product of factors influencing the vegetation of the catchment and operating over time. Whangapoua Estuary exemplifies this and emphasises the rapidity and extent of these changes under human influence.

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