A 2400 yr record of natural events and anthropogenic impacts in intercorrelated terrestrial and marine sediment cores: Waipaoa sedimentary system, New Zealand

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ABSTRACT

The Waipaoa sedimentary system spans ~100 km from terrestrial upland to continental rise. Alluvial buffering has little effect on sediment flux at the outlet of this mesoscale dispersal system, and hinterland-to-margin transport is accomplished rapidly. Because of this synergy, the floodplain and shelf depocenters are sensitive to changes in sediment production in the hinterland, and natural and anthropogenically forced changes in sediment source dynamics that occur at several temporal and spatial scales leave distinctive signals in the stratigraphic record. Manifested as variations in sediment properties, these signals appear in intercorrelated sediment cores from a headwater riparian storage area and the major terrestrial and marine repositories for sediment discharged during the past 2.4 k.y. The signals represent the landscape response to vegetation and land-use change, short-term fluctuations in climate that affect surface properties and processes, and extreme storms and subduction-thrust earthquakes. Extreme storms are the minimum geomorphologically effective event preserved in the sediment records. Lower-magnitude storms that are integral components of the prevailing hydrometeorological regime create high-frequency fluctuations in sediment properties and collectively contribute to event sequences of >100 yr duration. Events and event sequences comprise a hierarchy of temporally sensitive phenomena, the impacts of which are conditioned by frequency and magnitude. By contrast, vegetation disturbance is a spatially sensitive phenomenon that directly impacts sediment source areas and lowers the threshold of landscape sensitivity to erosion. For this reason, the Taupo eruption of 1.718 ka and the piecemeal vegetation changes that occurred after the arrival of Polynesian settlers also generated strong depositional signals. After European colonization, deforestation of the hinterland altered landscape sensitivity and precipitated the transition to an erosional regime that impacted sediment production and dispersal across the entire magnitude-frequency spectrum of events, regulating sediment delivery to and transport in stream channels. No other perturbation had such a profound impact on the Late Holocene depositional record.

Keywords: sediment dispersal, sediment cores, source to sink, depositional signals, environmental change.

INTRODUCTION

Unlike their larger counterparts that discharge to the ocean across passive margins through deltaic depocenters (cf. Nittrouer et al., 1996), the high-yield rivers that discharge onto active continental margins have smaller catchments, and much of their sediment load escapes to the ocean (Milliman and Syvitski, 1992). Dispersal systems traversing active margins thus constitute a traceable continuum from source to sink, wherein the links among terrestrial sediment production, transport, and accumulation in the marine environment may be preserved (e.g., Nittrouer and Sternberg, 1981; Leithold, 1989; Sommerfield et al., 1999). For these reasons, depocenters on active margins have the potential to register variations in sediment discharge that are forced by changes in climate, geology, and land use, as well as oceanographic regime (cf. Wheatcroft et al., 1996; Sommerfield and Nittrouer, 1999; Carter et al., 2002; Gomez et al., 2004a).

The generation, dispersal, and accumulation of riverine particulate matter on active continental margins are relevant to understanding biogeochemical cycling (Leithold and Blair, 2001; Gomez et al., 2003; Komada et al., 2004; Leithold et al., 2006), as well as to the creation of margin stratigraphic records (Nittrouer and Wright, 1994; Wiberg et al., 1996). Investigations undertaken on the river-fed California-Oregon-Washington continental margin highlight the importance of short-duration, large-magnitude storm events to the land-ocean transfer of terrigenous sediment (e.g., Wheatcroft et al., 1996, 1997). Simulations also suggest that changes in the riverine input to the ocean, manifest as variations in particle size, that occur over time scales of decades to centuries may be preserved in shelf sedimentary records (Syvitski and Morehead, 1999; Morehead et al., 2001). To date, however, investigations of flood-dominated marine depositional environments have focused on the dispersal and accumulation of modern sediment (Sommerfield et al., 1999; Sommerfield and Nittrouer, 1999; Mulder et al., 2001).

Here, we examine the cause of variations in particle size and sediment (bio)geochemistry, in three intercorrelated cores from the Waikohu River floodplain, the Poverty Bay Flats, and the adjacent Poverty Shelf depocenter of the Waipaoa sedimentary system, New Zealand (Fig. 1). The first site is representative of

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GSA Bulletin; November/December 2007; v. 119; no. 11/12; p. 1415–1432; doi: 10.1130/B25996.1; 11 figures; 1 table.

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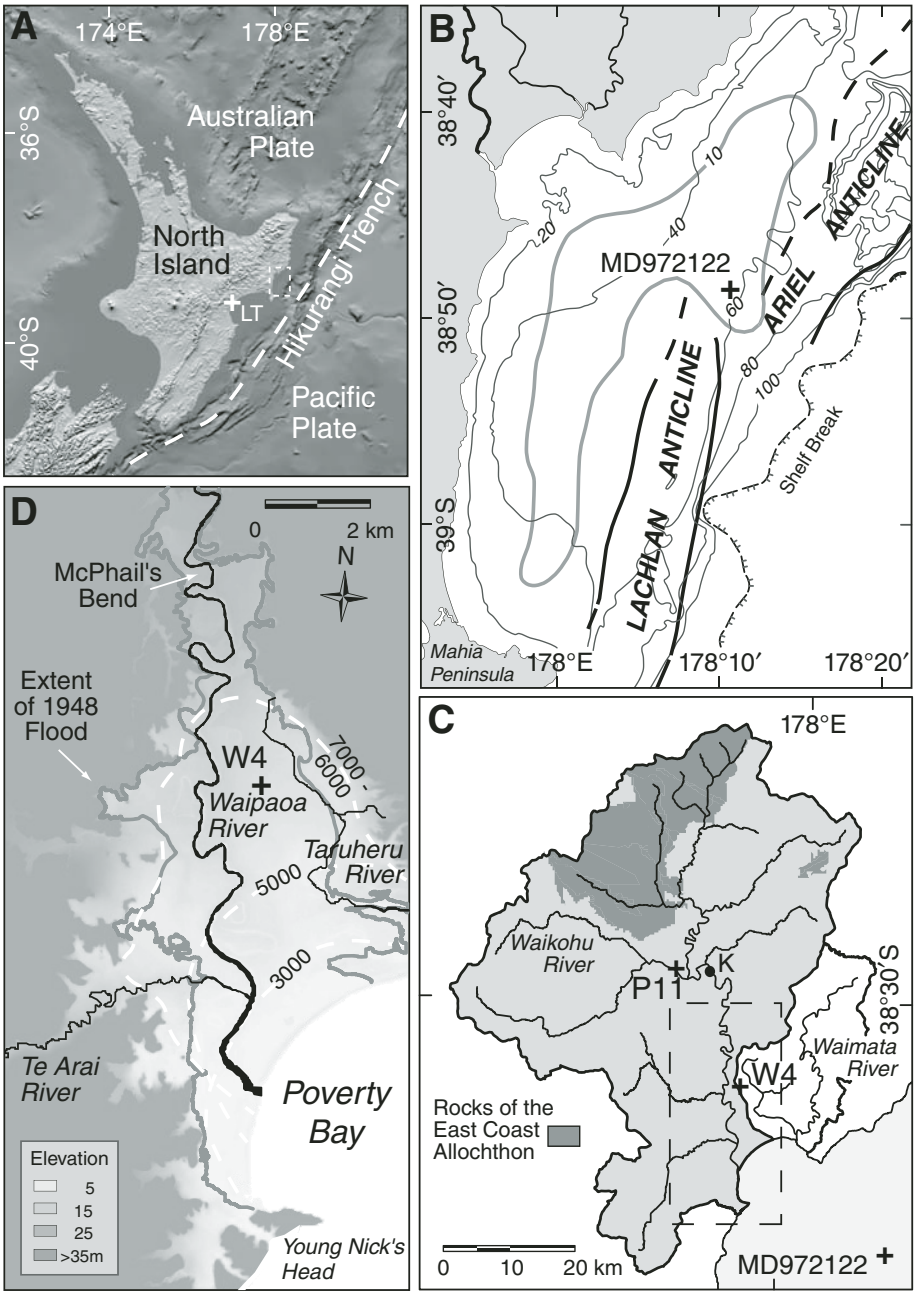


Figure 1. Maps showing sites and localities referred to in the text. (A) Physiography of New Zealand's North Island and the adjacent ocean floor, the location of the Australian-Pacific plate boundary (dashed line), and Lake Tutira (LT). Dashed box indicates the area covered in B, which shows the structure and bathymetry of Poverty Bay and the Poverty Shelf depocenter (after Foster and Carter, 1997), the 10 m isopach to the reflector on the shelf dated at ca. 8000 ^{14}C yr B.P. (solid gray line), and the location of Calypso core MD972122. (C) The Waipaoa and Turanganui basins, showing the distribution of gully-prone terrain underlain by the rocks of the East Coast allochthon (after Mazengarb and Speden, 2000), the location of the gauging station at Kanakanaia (K; solid dot), and the location of drill core P11 in relation to those of cores MD972122 and W4. Dashed box indicates the area covered in D, which shows relief of the Poverty Bay Flats, the maximum inland extent of the Holocene transgression, and the subsequent positions of progradational shorelines (dashed lines; after Brown, 1995), the extent of inundation during the last major flood prior to the construction of the flood-control leveés (solid gray line; after Pullar, 1962), and the location of drill core W4.

riparian storage areas along headwater tributaries, while the latter sites characterize the major repositories of fluvial sediment discharged during the middle and late Holocene (Pullar and Penhale, 1970; Foster and Carter, 1997; Gomez et al., 2004a). Our focus is on the past 2.4 k. y., during which time erosion processes were influenced by a well-documented sequence of natural events and anthropogenic activities, and for which there is a proxy record of storm activity from nearby Lake Tutira (Eden and Page, 1998; Trustrum et al., 1999). First, we identify the sediment sources and sinks and define the parameters used to unravel the history of hillslope erosion in the Waipaoa sedimentary system. We then examine the nature of the signals preserved in the shelf record and correlate them with those in the terrestrial record. Finally, we show how these signals can be linked to changes in sediment source dynamics and how they can be used to determine how stratigraphy records natural events and anthropogenic activity.

STUDY AREA

Along with the adjacent shelf, the 2205 km^2 Waipaoa River and 312 km^2 Turanganui basins are located within the zone of active deformation at the boundary of the Australian and Pacific plates, on the east coast continental margin of New Zealand's North Island (Fig. 1A). The rate of uplift in the hinterland of the Waipaoa sedimentary system is ~4 mm yr^{-1}, but slight subsidence occurs near the coast, and, although two fault-controlled anticlines are growing on the outer shelf (Fig. 1B), the middle shelf is subsiding at a rate of ~2 mm yr^{-1} (Brown, 1995; Berryman et al., 2000; Foster and Carter, 1997; Barnes et al., 2002). Moderate to large earthquakes occur frequently, and there have been four magnitude >7 subduction-thrust earthquakes at the northern end of Ariel anticline in the past 2500 yr (Berryman et al., 1989; Ota et al., 1991; Reyners and McGinty, 1999).

Rocks in the Waipaoa sedimentary system include: (1) a structurally complex suite of Cretaceous and early Tertiary sandstone, argillite, mudstone, marl, and limestone; and (2) a cover sequence of poorly consolidated Miocene and Pliocene sandstone, siltstone, mudstone, and limestone (Mazengarb and Speden, 2000). In the north-northwestern sector of the hinterland, Cretaceous and early Tertiary rocks form thrust sheets of the East Coast allochthon (Fig. 1C), which are more indurated but have a lower rock mass strength than the Neogene cover beds that underlie the rest of the Waipaoa sedimentary system. No part of the Waipaoa sedimentary system was glaciated, but many hillslopes have not yet adjusted to the rapid phase of postglacial

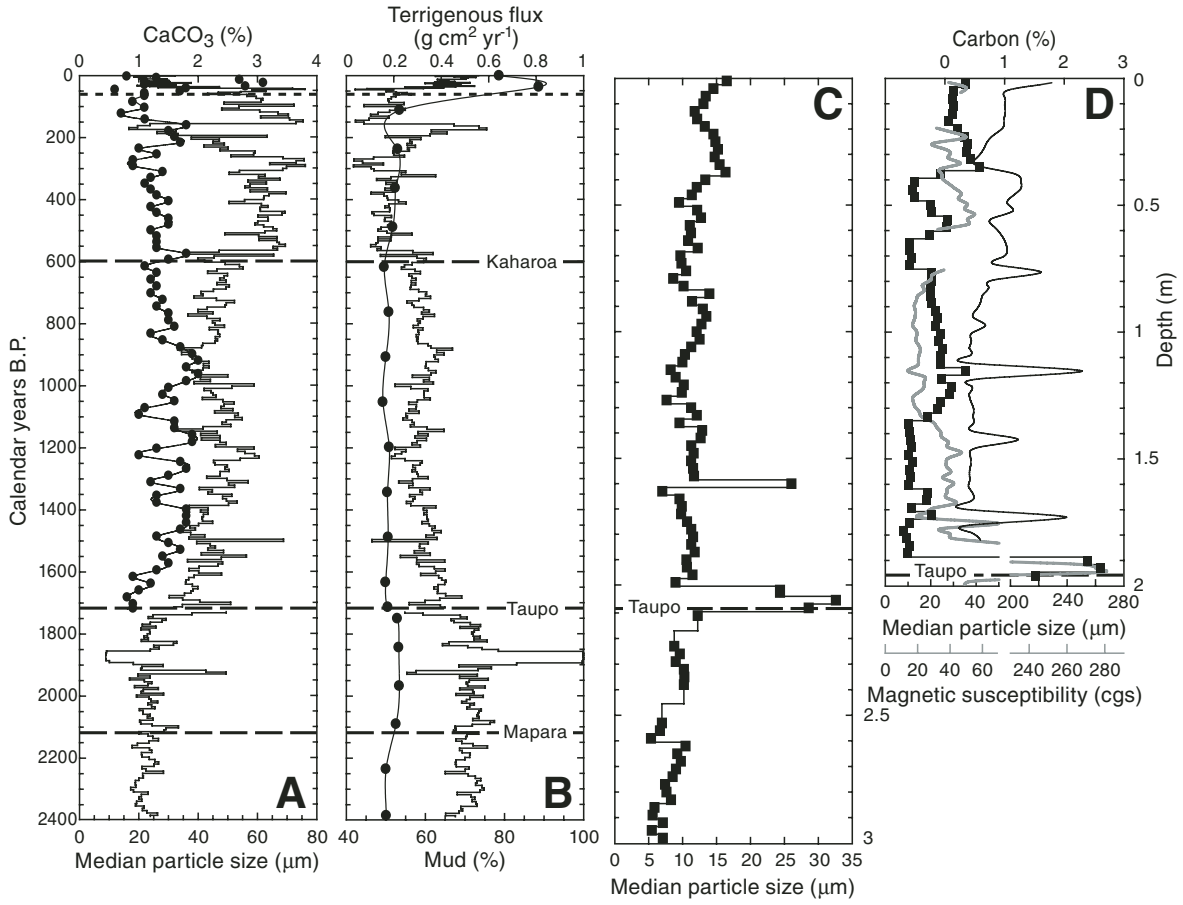


Figure 2. Down-core variations in texture, and associated parameters in sediment samples from MD972122 (A and B), W4 (C), and P11 (D). Solid dots in A and B show the $CaCO_3$ content and terrigenous flux (uncorrected for salt content). Solid black and gray lines in D indicate carbon content and magnetic susceptibility, respectively. Long dashed horizontal lines indicate the position of the macroscopic (Mapara, Taupo, and Kaharoa) tephras used to define the age-depth relation and correlate the cores, and the short dashed horizontal line indicates the position in MD972122 at which the supported ^{210}Pb activity becomes indistinguishable from the background activity.

downcutting that culminated ca. 5.58 ka (unless otherwise designated, ages are calendar years before present) (Gage and Black, 1979; Berryman et al., 2000; Mazengarb and Speden, 2000; Crosby and Whipple, 2006). The lower reaches of the Waipaoa River initially followed the course now occupied by the Taruheru River and drained into the northern sector of Poverty Bay (Figs. 1C and 1D), but after the Taupo eruption, the Waipaoa captured the Te Arai River, and the Turanganui drainage was dissevered as the river mouth migrated southward to its present position (Pullar and Penhale, 1970).

The prevailing climatic regime, which is dominated by the El Niño–Southern Oscillation (ENSO), established by ca. 4 ka, and the climate changed little during the late Holocene (McGlone et al., 1993; Gomez et al., 2004a). Mean annual precipitation is 1590 mm yr^{-1}, and one or two cyclonic storms pass within 100 km of New Zealand every year (Hessell, 1980; Hastings, 1990). The largest storm on record generated a peak discharge ≥4000 m^3 s^{-1} and ~26 Mt of suspended sediment in 50 h (Trustrum et al., 1999). Volcanic eruptions, fire, and severe storms periodically disturbed the primary forests, which were established in the mid-Holocene (Norton et al., 1986; Grant, 1989; Froggatt and Rogers, 1990; McGlone et al., 1993; Wilmshurst et al., 1999). Cultural activities, involving land clearance by fire, impacted the native vegetation from ca. 650 ^{14}C yr B.P., but wholesale destruction of the forest cover did not begin until after the arrival of European colonists in the 1820s (Pullar, 1962; Wilmshurst et al., 1999). Today, only ~2.5% of the basin is covered by old growth forest.

Many hillslopes exhibit soil profiles that have been rejuvenated by erosion processes or are mantled by raw soils that lack topsoil development (Jessen et al., 1999). Air-fall tephras are an important component of soils, alluvium, and marine deposits in the Waipaoa sedimentary system (Pullar, 1962; Vucetich and Pullar, 1964; Gage and Black, 1979; Foster and Carter, 1997; Gomez et al., 2004a), and tephras from the Taupo and Kaharoa eruptions at 1.718 and 0.6 ka provide distinctive stratigraphic markers (Fig. 2).

Different combinations of lithology, structure, and topography yield terrain types with varying degrees of stability (Jessen et al., 1999). Hills underlain by the Miocene–Pliocene cover sequence are prone to shallow landsliding, whereas the deformed rocks in the hinterland are susceptible to gully erosion (Reid and Page, 2003; Marden et al., 2005). About two-thirds of the terrain in the Waipaoa sedimentary system currently is prone to shallow landsliding, which would not have been as prevalent prior to deforestation. However, very large compound failures can occur under native forest, and earth flows and slumps affect hillslopes in the hinterland underlain by rocks of the East Coast allochthon

that were regraded during the early Holocene (Henderson and Ongley, 1920; Gage and Black, 1979; Liébault et al., 2005). Gullies occupy <1% of the land area. Active gullies generate sediment during events of all scales and show no threshold effects (Hicks et al., 2000, 2004), so that frequent runoff events currently are relatively more important than large floods to the mean annual suspended load of the Waipaoa River (15 ± 6.7 Mt yr^{-1}). The mean annual suspended load of the Waimata River, the largest river in the Turanganui basin where a hydroclimatic threshold limits sediment availability, is 0.8 ± 0.7 Mt yr^{-1} (Kettner et al., 2007).

In Poverty Bay, freshwater discharged from the Waipaoa River that flows seaward on the surface is compensated by seawater inflow at depth, and the weak baroclinic circulation generates an anticlockwise gyre that fills the bay (Stephens et al., 2002). Most sand remains in the bay, but it is estimated that >90% of the mud is transported to the shelf (Smith, 1988; Foster and Carter, 1997). Under present conditions, flood discharges may exceed the critical suspended sediment concentration for hyperpycnal plume generation at the Waipaoa River mouth once every ~40 yr, and the critical condition rarely seems to have been exceeded in the period prior to European colonization (Hicks et al., 2004; Kettner et al., 2007). Thus, most of the mud appears to be distributed by hypopycnal plumes, carried out of Poverty Bay by the baroclinic circulation, and dispersed on Poverty Shelf in a direction determined by the shelf circulation and ambient wind field (Foster and Carter, 1997; Stephens et al., 2002). Sea level and the prevailing circulation pattern were established in the mid-Holocene (Gibb, 1986; Carter et al., 2002), and since the early Holocene, ~8 km^3 of mud has accumulated on Poverty Shelf (Fig. 1B). Off-shelf escape of this sediment is restricted by the growing anticlines, but a well-defined sediment lobe extends seaward of the gap between the Lachlan and Ariel anticlines (Orpin, 2004; Orpin et al., 2006).

SEDIMENT CORES, ANALYTICAL METHODS, AND DEPTH-AGE RELATION

Drill core P11 was obtained from the lowest terrace bordering the Waikohu River (38°27.51′S, 177°48.36′E), drill core W4 was obtained from the Waipaoa River floodplain (38°36.88′S, 177°55.97′E), and Calypso core MD972122 was obtained from the middle shelf (38°48.67′S, 178°10.18′E) at 55 m water depth (Figs. 1B, 1C, and 1D). The top of the Calypso core was complemented by a 0.65-m-long box core, in which the sediment-water interface was preserved. All three cores were split into two halves, one of which was archived. The other halves and box core were logged, photographed, X-radiographed, and subdivided into 0.01 m sections. Magnetic susceptibility was measured at 0.02 m intervals down MD972122 and P11 using a manually operated, Bartington Instruments MS2 probe. Environmental magnetic parameters were determined for 1.5-m-long sections of MD972122 at 0.01 m intervals, using the University of Southampton's computer-controlled superconducting rock magnetometer (Gomez et al., 2004a). Dry bulk density (uncorrected for salt content) was determined every 0.2 m, and microprobe and mineralogical analyses were used to identify the macroscopic tephras. The analyses described next were conducted on the top 4, 3, and 2 m of cores MD972111, W4, and P11, respectively.

Pollen analysis was performed on 48 subsamples taken from the box core and the top 3 m of MD972122. Particle-size measurements were performed using a CILAS 1064 laser granulometer, following dispersion by $(NaPO_3)_6$ and ultrasound. The sampling interval within the top 4 m of MD972122, 3 m of W4, and 2 m of P11 was 0.01, 0.03, and 0.03 m, respectively, and the error and reproducibility of mean values were ±0.6 μm and ±0.5%. The clay mineralogy in subsamples taken at 0.03 m intervals from the top 3 m and 2 m of MD972122 and W4, respectively, was determined by X-ray diffraction (D'Ath, 2002). Estimated uncertainties for each identified mineral were ±5%–15%. Geochemical analyses were performed on bulk 0.01 or 0.03 m subsamples from MD972122 and W4. Concentrations of 32 major and trace elements were obtained by neutron activation analysis at Missouri University Research Reactor (Glascock, 1992). Reference standards (SRM-1633a Flyash and SRM-688 Basalt) were irradiated and measured with each batch of samples and used for calibration. The analytical error was between 1% and 2%. Wedepohl's (1995) estimates of crustal composition were used to normalize the element concentrations to the composition of upper continental crust. Pools of phosphorous related to mineral matter, soil oxyhydroxides, and an organic fraction in 0.03 m subsamples from both cores were distinguished using a sequential extraction technique at Indiana University–Purdue University Indianapolis (Filippelli and Delany, 1996; Latimer and Filippelli, 2001), where reducible Fe and Mn also were determined by inductively coupled plasma–emission spectrometry. Total carbon and nitrogen in each 0.03 m subsample, as well as additional 0.01 m infills from the uppermost 1.5 m of MD972122 and 0.03 m subsamples from P11, were determined using a LECO 2000 combustion analyzer. The $CaCO_3$ content was calculated from the C:N ratio and corroborated by weight-loss determinations performed at random on 15% of the subsamples using 1 + 1 HCl to evolve CO_2 from the carbonate (Blakemore et al., 1987). Errors involved in the P and reducible Fe and Mn determinations were ±5%. The measurements of total carbon were reproducible to within ±0.1%, and the discrepancy ratio of measured to calculated $CaCO_3$ values was 1.08 ± 0.46. For comparative purposes, we also sampled and analyzed (using the methods described previously) a representative range of the weathered bedrock, soil, and regolith present on landslide-prone hillslopes in the hinterland, as well as the suspended sediment in transport in the Waipaoa River during low and intermediate flows (see Gomez et al. [2003] for details of the sampling program).

Comparison between the particle size and pollen spectra from the Calypso and box cores revealed that ~0.1 m was missing from the top of MD972122, and the ^{210}Pb activity profile indicated that the top 0.5 m of MD972122 postdated 1890 (F.M. Soster, 1999, personal commun.). The stratigraphy in the top 4 m of MD972122 was further constrained by three tephras (Gomez et al., 2004a), one of which (the Taupo tephra) also was present within W4 and P11 (Fig. 2). Based on established dates for the tephra formations (Froggatt and Lowe, 1990; Sparks et al., 1995; Lowe et al., 1998), we used linear interpolation to determine the age at intermediate depths between the dated levels in MD972122. On this basis, the top 4 m of sediment in MD972122 accumulated over the past ~2.4 k.y. Due to the discontinuous nature of floodplain sedimentation, we made no attempt to determine the age at intermediate depths between tephra layers in W4 or P11.

SEDIMENT COMPOSITION

A fundamental premise for linking signals preserved in MD972122 to changes in sediment source dynamics is that the Poverty Shelf mud deposit is predominately composed of terrestrial detritus from the Waipaoa sedimentary system. Support for this assumption is provided by the low amount of marine biogenic $CaCO_3$ (1.4% ± 0.5%) present in the post-Taupo segment of MD972122 and the similarity of the element geochemistry and clay mineralogy of source rocks and modern sediments (Figs. 2A and 3; Table 1). The different abundances of Cr probably reflect differences in particle size, and those in Yb and Lu likely are due to a quartz dilution effect (Fig. 3). Ba is an element that bonds to the surface of fluvial sediment and is released when the sediment is mixed with salt water; Na is a sea salt element that enriches hemipelagic mud. Ca is combined in carbonate, and the different abundances in the suspended sediment

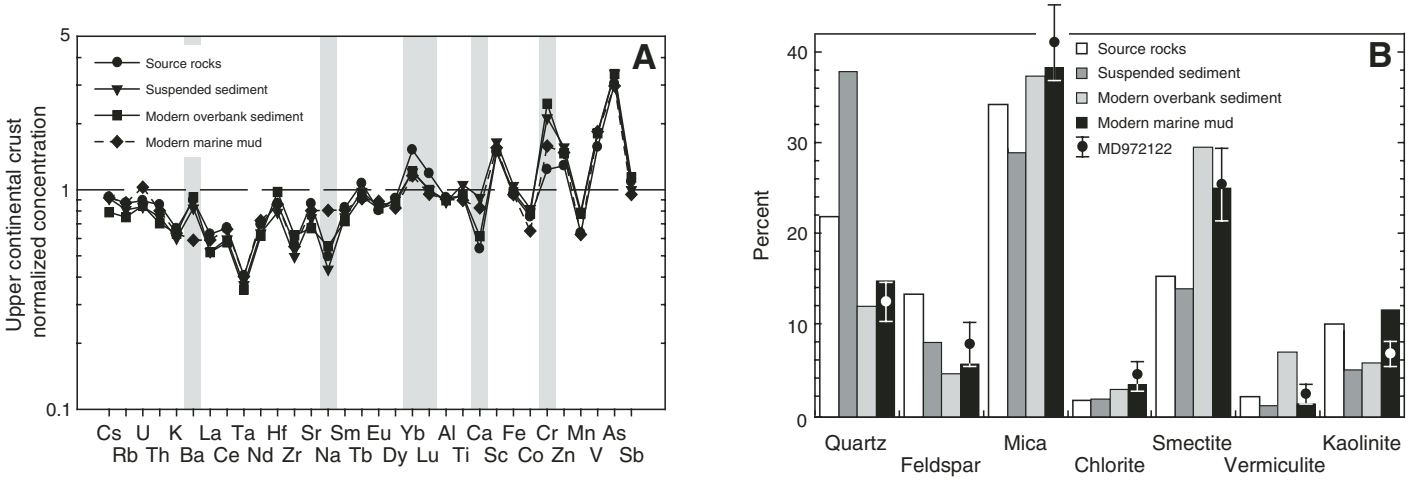


Figure 3. (A) Upper continental crust–normalized diagram of major- and trace-element (averaged) concentrations in source rocks and sediments from the Waipaoa sedimentary system. Elements on the abscissa are ranked according to their compatibility (cf. Gaillardet et al., 1999), and the shading indicates elements (discussed in the text) with different abundances. (B) Clay mineralogy of source rocks and sediments from the Waipaoa sedimentary system. Solid dots and bars indicate the mean and standard deviation of all samples from MD972122, as compared to samples of the modern marine mud obtained from a subsidiary box core.

TABLE 1. SUMMARY MAJOR- AND TRACE-ELEMENT CONCENTRATIONS (PPM) AND UPPER CONTINENTAL CRUST–NORMALIZED CONCENTRATIONS (UCCNC) OF SOURCE ROCKS AND SEDIMENTS FROM THE WAIPAOA SEDIMENTARY SYSTEM

		Cs	Rb	U	Th	K	Ba	La	Ce	Ta	Nd	Hf	Zr	Sr	Na	Sm	Tb
Source	Mean	5.364	95.6	2.227	8.795	19037	597	20.266	44.032	0.608	17.982	5.003	134.3	273	12738	3.89	0.534
Rocks	St dev	1.573	16.9	0.477	1.825	2305	210	3.924	5.214	0.112	3.587	1.045	20	263.1	4648	1.11	0.181
N = 7	UCCNC	0.92	0.87	0.89	0.85	0.66	0.89	0.63	0.67	0.41	0.69	0.86	0.57	0.86	0.5	0.83	1.07
Suspended	Mean	5.302	89.2	2.091	7.738	17221	551	16.863	39.212	0.554	16.454	4.576	117.6	235.3	11155	3.535	0.491
sediment	St dev	0.301	5.1	0.257	0.397	1424	81	0.605	1.889	0.027	1.992	0.156	21.1	62.9	873	0.134	0.061
N = 24	UCCNC	0.91	0.81	0.84	0.75	0.6	0.82	0.52	0.6	0.37	0.64	0.79	0.5	0.74	0.43	0.75	0.98
Overbank sediment	Mean	4.581	82.5	2.116	7.248	18079	616	16.783	37.834	0.527	15.977	5.67	147	211.2	14198	3.38	0.466
post–1927 A.D.	St dev	0.545	5.6	0.298	0.504	1824	83	1.341	2.8	0.042	1.509	0.98	34.3	20.4	1810	0.271	0.038
N = 8	UCCNC	0.79	0.75	0.85	0.7	0.63	0.92	0.52	0.58	0.35	0.62	0.98	0.62	0.67	0.55	0.72	0.93
Marine mud	Mean	5.241	95.1	2.542	8.19	18234	398	19.058	43.306	0.594	18.88	5.095	135.5	255.5	20772	3.774	0.439
post–1927 A.D.	St dev	0.403	3.3	0.311	0.374	1504	41	0.378	1.07	0.042	1.117	0.418	21.7	36.7	507	0.124	0.108
N = 10	UCCNC	0.9	0.86	1.02	0.8	0.64	0.6	0.59	0.66	0.4	0.73	0.88	0.57	0.81	0.81	0.8	0.88

		Eu	Dy	Yb	Lu	Al	Ti	Ca	Sc	Fe	Co	Cr	Zn	Mn	V	As	Sb
Source	Mean	0.764	2.642	2.278	0.32	71260	2914	15866	10.402	29411	8.732	43.3	66.9	335	83	6.091	0.337
Rocks	St dev	0.15	0.57	0.845	0.101	13205	1084	14058	2.403	7100	3.282	18.6	14.5	70	36.5	2.952	0.057
N = 7	UCCNC	0.8	0.91	1.52	1.19	0.92	0.93	0.54	1.49	0.95	0.75	1.24	1.29	0.63	1.57	3.05	1.09
Suspended	Mean	0.792	2.601	1.806	0.269	68314	3290	27158	11.549	32302	9.512	74.4	81.3	420	96.8	6.787	0.31
sediment	St dev	0.034	0.188	0.164	0.018	3895	265	916	0.553	1712	0.396	6.5	6.1	23	7	0.899	0.079
N = 24	UCCNC	0.83	0.9	1.2	1	0.88	1.06	0.92	1.65	1.05	0.82	2.12	1.56	0.8	1.83	3.39	1
Overbank sediment	Mean	0.781	2.502	1.824	0.27	69282	2937	18090	10.483	30098	9.04	86.3	76.2	411	95.9	6.734	0.353
post–1927 A.D.	St dev	0.049	0.281	0.114	0.012	4442	468	2767	0.991	2484	1.219	16.4	10.1	66	10.6	0.725	0.058
N = 8	UCCNC	0.82	0.86	1.22	1	0.89	0.94	0.61	1.5	0.97	0.78	2.47	1.46	0.78	1.81	3.37	1.14
Marine mud	Mean	0.839	2.379	1.72	0.259	70395	2773	24384	10.72	29046	7.432	54.2	74.8	329	96.8	5.905	0.284
post–1927 A.D.	St dev	0.017	0.342	0.121	0.01	2008	415	948	0.697	1492	0.476	5.1	16.7	6	10.3	0.848	0.046
N = 10	UCCNC	0.88	0.82	1.15	0.96	0.91	0.89	0.83	1.53	0.94	0.64	1.55	1.44	0.62	1.83	2.95	0.92

and modern marine mud, on the one hand, and the source rocks and overbank deposits, on the other, likely reflect the greater contribution made by mass wasting of weathered Miocene and Pliocene bedrock by shallow landsliding during large magnitude events, as compared to the contribution made by gully erosion in areas underlain by the rocks of the East Coast allochthon during (the sampled) low and intermediate flows, which currently transport the bulk of the Waipaoa River's suspended sediment load (Claridge, 1960; O'Byrne, 1967; Hicks et al., 2000; Gomez et al., 2004b).

The dominance of smectite in the source rocks, suspended load, modern alluvium, and marine mud (Fig. 3B), compared to vermiculite or kaolinite, to which it is transformed as the weathering profile develops, suggests that the contemporary sediment supply is relatively immature. Differences in the quantities of quartz and feldspar present in source rocks, compared to the alluvial and marine sediments, may result from differential settling of coarser clays where these minerals primarily reside (Claridge, 1960; D'Ath, 2002). The elevated smectite content of the modern marine mud is due either to differential settling or fine inputs from northerly sources (cf. Carter et al., 2002). The remaining differences in the clay mineralogy of the floodplain alluvium probably are more closely related to the slight compositional variations between the rock types affected by gully erosion and shallow landsliding (D'Ath, 2002).

Previous studies have shown that the terrigenous component of mud on the New Zealand continental shelf is derived in a relatively unmodified form from river-borne sediment (Churchman et al., 1988), and the similarities in the clay mineralogy and geochemistry among samples from different parts in the Waipaoa sedimentary system show that the sources and sinks are closely linked. Inputs from other sources cannot be discounted because the same rocks crop out in neighboring river basins (Foster and Carter, 1997), but the volumetric significance of these inputs remains to be established. However, the pattern of sediment dispersal and sediment retention within the mid-shelf basins off the Uawa and Waiapu River mouths, together with the knowledge that the Waipaoa River is the second largest point source in New Zealand, suggest that only minor amounts of exotic sediment reach Poverty Shelf (Hicks and Shankar, 2003; Gomez et al., 2004a). The high measured concentration (mean = 21,611 mg L^{-1}) and low intensity of weathering (Sm/Na = 1.7) conform with the global inverse relation between weathering intensity and sediment concentration (Gaillardet et al., 1999). In the Waipaoa sedimentary system, where both physical and chemical weathering are important and only limited weathering is required to facilitate mass wasting, gully erosion rapidly removes saprolite/regolith, precludes the development of thick soils, and reduces the intensity of weathering reactions. Moreover, hinterland-to-margin transport can be accomplished very rapidly because the flood wave typically takes <24 h to travel between the headwaters and river mouth. Thus, even though the marked mineralogical and geochemical differences that could be used to differentiate sediment source areas in the Waipaoa sedimentary system are lacking and slight differences may be effaced by mixing in transport (Claridge, 1960; D'Ath, 2002), we expect any environmental change in the source area that affects the tempo of the primary erosion processes to be communicated to the depositional record.

CHANGES IN SEDIMENT PROPERTIES WITH TIME

Other than the macroscopic tephras (Fig. 2), neither visual examination nor X-radiography revealed primary physical stratification or bioturbation structures in MD972122, W4, or P11. In the absence of conspicuous depositional fabrics, we used physical and (bio)geochemical parameters to establish a stratigraphy (Figs. 4, 5, and 6).

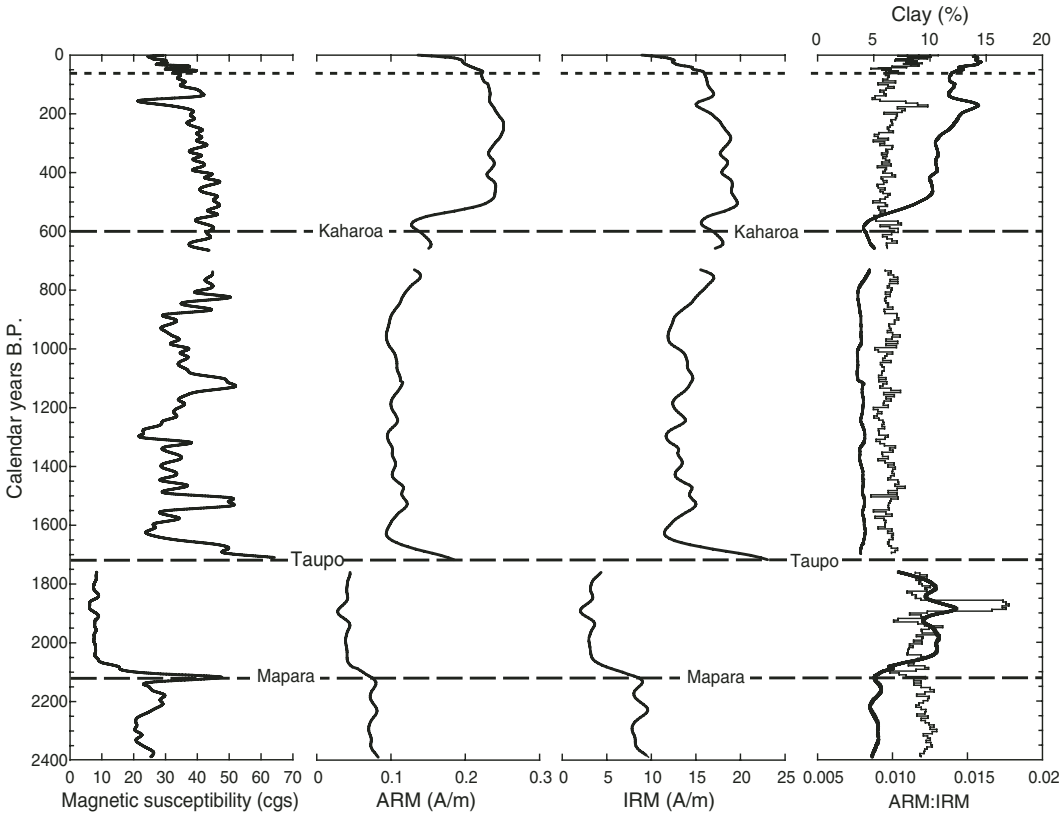


Figure 4. Down-core variations in environmental magnetic parameters and clay content in sediment samples from MD972122. The dashed horizontal lines are as defined in Figure 2. ARM—anhysteretic remanent magnetization; IRM—isothermal remanent magnetization.

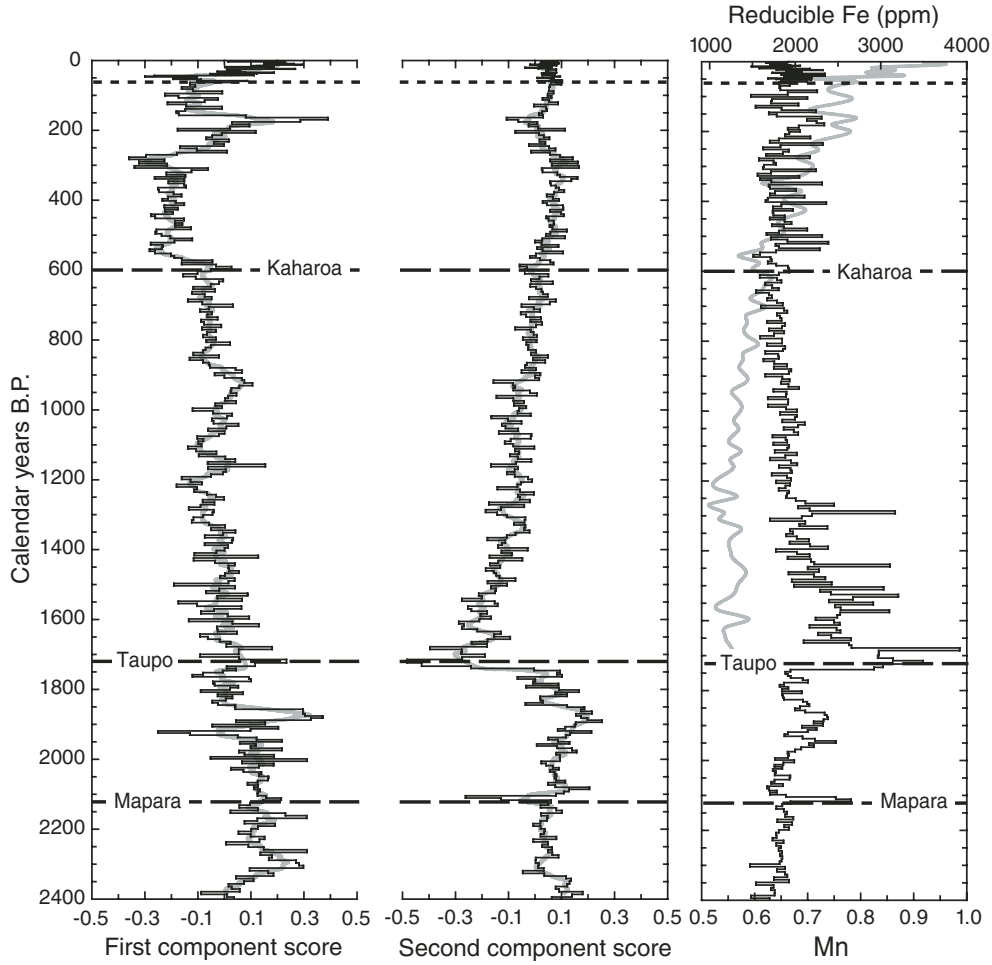


Figure 5. Down-core variations in the first two component scores for upper continental crust–normalized major- and trace-element concentrations (gray line is a five-point moving average), Mn (upper continental crust–normalized concentration, UCCNC), and reducible Fe in sediment samples from MD972122. The dashed horizontal lines are as defined in Figure 2.

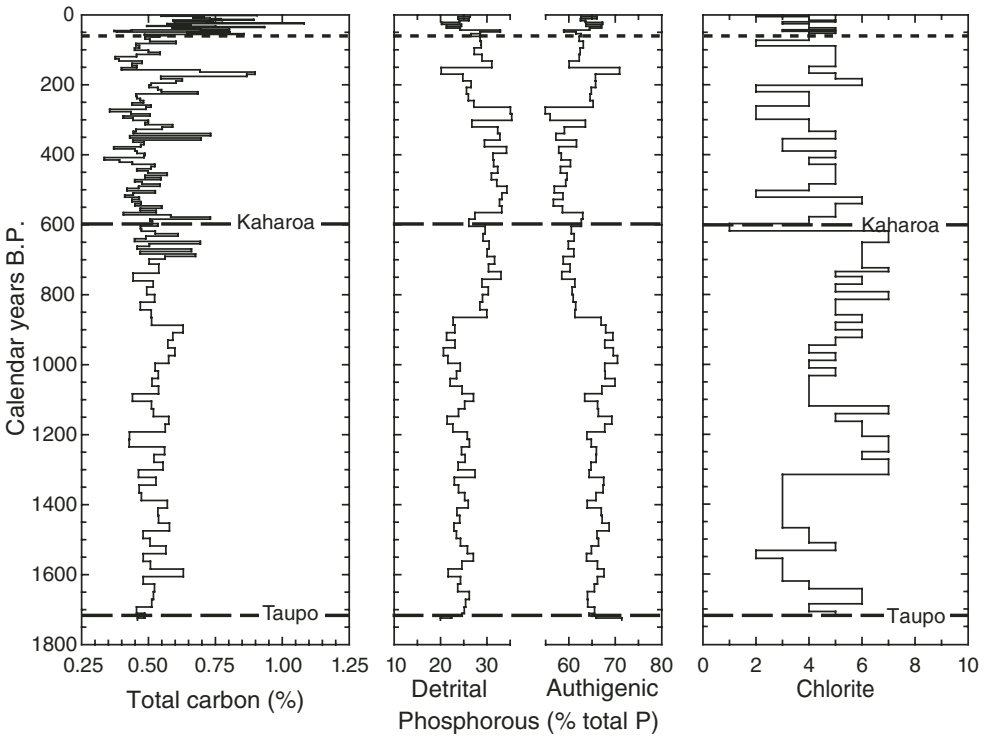


Figure 6. Down-core variations in total carbon, detrital and authigenic phosphorous, and chlorite (upper continental crust–normalized concentration, UCCNC) in sediment samples from MD972122. The dashed horizontal lines are as defined in Figure 2.

As indicated by the generally low values for the oxide-bound P fraction (mean = 0.6 ± 0.21 μmol/g) in MD972122 and sediment color, oxic conditions were maintained in all three cores during deposition. We also found no evidence for postdepositional modification in MD972122 (Gomez et al., 2004a). Accordingly, we relate changes in magnetic susceptibility, anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) to variations in sediment supply (cf. Turner, 1997). Magnetic susceptibility is directly proportional to the concentration and size of magnetic minerals in a sample. ARM and IRM indicate variations in the concentration of magnetic minerals, where ARM is more sensitive to fine magnetic particles, and IRM, to coarse magnetic particles (Verosub and Roberts, 1995). The ARM:IRM ratio is a proxy for overall variations in particle size; higher and lower values are indicative of greater concentrations of fine- and coarse-grained magnetic minerals, respectively. Throughout the top 4 m of MD972122, variations in magnetic susceptibility, ARM, and IRM are in phase with one another, reflecting changes in the overall concentration of detrital magnetic minerals, and variations in the ARM:IRM ratio occur concomitantly with variations in clay content (Fig. 4).

We employed principal components analysis to synthesize element attributes and differentiate variations in concentration (Fig. 5). The first component explains 29% of the cumulative variance in the element concentrations. Metals (e.g., Sc, Cs, and Fe) that exhibit increasing concentrations with decreasing particle size are the largest contributors to this component, which is itself loosely (R^2 = 0.74) associated with median particle size. An additional 16% of the cumulative variance in the element concentrations is explained by the second component. Rare earth elements and metals that are soluble during weathering (e.g., Co, Yb, Lu, Mn, and Eu) make the largest contributions to this component. Reducible Mn accounts for 10.8% ± 1.8% of total Mn, suggesting that most Mn reaches Poverty Shelf as a constituent of mineral particles. We use Mn, which often is enriched in the upper soil horizons relative to the underlying parent material (cf. Korobova et al., 1997), to help characterize the nature of changes in sediment influx. Variations in reducible Fe occur concomitantly with variations in total Fe. Thus, the reducible Fe likely is related to authigenic soil oxides (e.g., goethite, hematite, limonite) present in the B-horizon, and is indicative of the intensification of soil erosion in the catchment rather than sedimentary redox conditions. In MD972122, we employ chlorite, which transforms rapidly to vermiculite as soils form and is more common in the landslide-prone Miocene and Pliocene cover beds than in the rocks of the East Coast allochthon, as a proxy for weathering intensity because Na is present in sea salt.

The small amount of organic matter in the marine sediment core is very refractory. Total C increases and is more variable toward the top of MD972122 (Fig. 6), and there is a weak (R^2 = 0.50) inverse correlation between total C and median particle size. Organic P content also exhibits little variability (mean = 0.83 ± 0.15 μmol/g). Offshore, organic P typically displays a down-core decrease that is related to the progressive decay of labile organic matter, and the lack of a diagenetic signal is more characteristic of terrestrial records where the P supply is dependent on weathering (Filippelli and Delaney, 1996; Filippelli and Souch, 1999). Detrital P content exhibits a weak correlation with median particle size (R^2 = 0.53). Detrital and authigenic P are both indicators of terrestrial inputs derived from the soil profile (Walker and Sayers, 1976). Collectively, both mineral P fractions account for >85% of total P content. Throughout the Waipaoa sedimentary system, soils developed on hillslopes mantled by tephra have a high natural glass content (cf. Jessen et al., 1999), and we use the volcanic glass content of the sand fraction to indicate the intensity of soil loss from hillslopes. The disturbance of forest by air-fall ash from volcanic eruptions, fire, and cultural activities encourages the growth of seral taxa that colonize open land (Wilmshurst et al., 1997), and we use the amount of *Pteridium esculentum* (bracken) spores present in a sample as an indicator of the level of disturbance to the natural forest cover (Fig. 7A).

In the post-Taupo segment of W4 (Figs. 8 and 9), the generally fine-grained (mean size = 12.5 ± 4.3 μm) nature of the alluvium obviates correlations with particle size, and the largest contributors to the first component (e.g., Hf, Cr, Na, Zr, Sb, and Mn), which explains 44% of the cumulative variance in the element concentrations, are associated with residual weathering products that accumulate in the soil profile. The largest contributors to the second component, which explains an additional 13% of the cumulative variance, are mobile metals (e.g., Na, Ca, and Ba) that reflect weathering intensity (Gaillardet et al., 1999), as does Mn concentration and the Sm/Na ratio. In the post-Taupo segment of P11, we show down-core trends in median particle size, magnetic susceptibility, and total carbon (Fig. 2C).

DELINEATING EVENT HORIZONS

In most cases, we presently are unable to identify the cause of the high-frequency fluctuations in sediment texture and the other parameters we measured (Figs. 2, 4, and 5). In large part, this is because, with six prominent exceptions, reliance on linear interpolation of ages between dated tephras prevented us from dating individual events with confidence. Other "event strata" in MD972122 may also have been effaced by shelf mixing processes or subsumed by the sampling interval. Nevertheless, events that cause a persistent change in the catchment environment may generate a strong enough signal to be preserved in the shelf depositional record (Gomez et al., 2004a). Accordingly, the stratigraphy we outline hinges on the identification of transition points, or "event horizons," delimited by a change in the physical and chemical characteristics of the sediment. The events we distinguish fall into three categories, depending on the strength of the signal preserved in the depositional record and the continuity of the response, which, with the exception of singular events and in accordance with the limitations imposed by the sampling interval and age model, typically is $\geq 10^2$ yr. Category 1 (C1) events are major, long-term responses of several centuries duration that represent the landscape response to the Taupo eruption, Polynesian arrival, European settlement, and subsequent deforestation of the hinterland. Category 2 (C2) events represent the response of surface properties and processes to short-term fluctuations in climate, such as a delayed Southern Hemisphere counterpart to the Medieval Warm Period (MWP). Category 3 (C3) events encompass the response to singular phenomena, such as very large floods and magnitude >7 subduction-thrust earthquakes.

C1 Events—Forest Disturbance

The timing of all four C1 events is well constrained. Each profoundly affected terrestrial conditions and generated a strong depositional response on the middle shelf, manifested in MD972122 by changes in sediment texture, environmental magnetic parameters, geochemistry, and clay mineralogy at 1.718, and ca. 0.56, 0.15, and 0.04 ka, respectively (Figs. 2, 4, 5, and 6). The five resulting textural units are differentiated on a bivariate plot of ARM versus magnetic susceptibility (Figs. 10A and 11). Samples from the pre-Taupo and pre-Polynesian periods plot in a linear band, indicating that the overall changes in magnetic mineral concentration occurred without concomitant changes in either mineralogy or particle size. Samples from the remaining units, where an anthropogenic signal is preserved, plot above this line.

In the pre-Taupo period, the landscape and vegetation cover of the Waipaoa River basin were relatively stable and subject only to occasional perturbations by natural events such as

fire, storms, minor volcanic eruptions, and seismic activity (Froggatt and Lowe, 1990; Berryman et al., 1989; McGlone and Wilmshurst, 1999; Carter et al., 2002). The presence of a well-developed canopy and root network would also have inhibited soil loss from the landscape as a whole. Thus, except during large events that locally disrupted the vegetation cover and lowered the erosion threshold in primary source areas (cf. Kelsey, 1980; Liébault et al., 2005), much of the sediment routinely either would have been derived from hillslopes that were closely coupled to stream channels or riparian storage. Sediment accumulates in the riparian zone during large storms and subsequently is reworked and flushed from storage by more frequent, low-magnitude events (Trustrum et al., 1999).

The Taupo eruption ranks as one of the largest volcanic events of the last 5 k.y. (Wilson and Walker, 1985). It blanketed the east-central North Island, including the Waipaoa sedimentary system, with >0.1 m of air-fall tephra (Vucetich and Pullar, 1964), which occurs as discrete 0.08 and 0.1 m layers in MD972122 and P11, and a diffuse 0.24 m layer in W4 (Fig. 2). The eruptions of 2.12 and 0.6 ka generated far less ash, and the more subdued response to these events is consistent with a lower level of disturbance to the vegetation cover (Figs. 2, 4, and 5). After the Taupo eruption, tall forest taxa declined overall and seral taxa increased, but pollen spectra suggest that the wetland forests of the Poverty Bay Flats and the beech-dominated forests in the hinterland were less vulnerable than the podocarp/hardwood forest cover on the drier lowland hills (Wilmshurst and McGlone, 1996; Wilmshurst et al., 1999). Disruption of the vegetation cover increases the susceptibility of the landscape as a whole to erosion, while fresh volcanic debris is removed rapidly through extension of the drainage network (Rosenfeld and Beach, 1983; Leavesley et al., 1989; Collins and Dunne, 1986). The intensity of surface erosion declines as the tephra-mantled hillslopes stabilize, the mosaic of clearings is revegetated, and the posteruption vegetation reverts to its pre-eruption composition (Lehre et al., 1983; Collins and Dunne, 1986). The latter process took nearly 200 yr to accomplish (Fig. 7; Wilmshurst and McGlone, 1996), and periodic influxes of coarse sediment to the shelf and spikes in the Mn profile are indicative of landsliding and accelerated soil loss during the regeneration period (Figs. 2A, 2B, and 5C). Sediment production in the posteruption period also is tied to the rate of river recovery (Hayes et al., 2002; Major, 2004; Gran and Montgomery, 2005). Sheet and bank erosion gradually releases sediment from riparian storage during the recovery period, starting with tephra and the finer size fractions (Figs. 2, 4, 5, and 7A). Thus, natural perturbations to the vegetation cover engender both primary and secondary erosional responses. The latter may be more persistent, because it requires time for the landscape to recover to predisturbance conditions and sediment to propagate through disturbed catchments (cf. McGlone and Wilmshurst, 1999; Major et al., 2000; Moody and Martin, 2001).

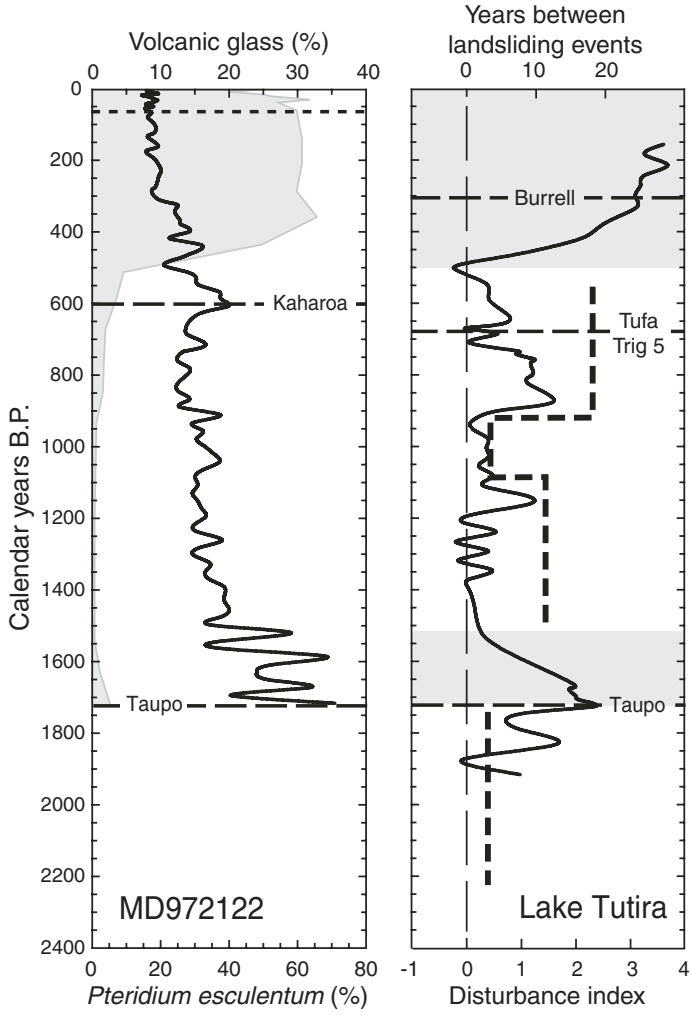


Figure 7. Disturbance to the natural environment in the Waipaoa sedimentary system indexed by the volcanic glass content of the sand fraction and the amount of bracken (*Pteridium esculentum*) in MD972122, and in Lake Tutira indexed by abundance of seral taxa in sediment samples from core LT15 (after Wilmshurst et al., 1997). The shaded portions of the graph indicate disturbance following the Taupo eruption and the arrival of humans in the Lake Tutira watershed, respectively, and the stepped dashed line shows variations in storminess, indexed by changes in the frequency with which the terrigenous sediment in core LT16 was released to Lake Tutira by landsliding (after Eden and Page, 1998). Long dashed horizontal lines indicate the position of the macroscopic (Taupo, Tufa Trig 5, Kaharoa, and Burrell) tephras used to define the age-depth relations and correlate the cores, and the short dashed line indicates the position in MD972122 at which the supported ^{210}Pb activity becomes indistinguishable from the background activity.

The transition from a natural environment to one affected by anthropogenic activities occurred ca. 0.56 ka (Fig. 10A). Maori habitually utilized fire to clear ground and encourage the growth of bracken (Cameron, 1961; McGlone, 1989; McGlone et al., 2005). As is evidenced by the dramatic increase in *Pteridium esculentum* (Fig. 7A), their activities impacted the lowland forests (Wilmshurst et al., 1999; M.B. Elliot, 1999, personal commun.). However, the wetter headwater forests remained intact until after European colonization (Murton, 1968; McGlone and Wilmshurst, 1999; K. Butler, 2003, personal

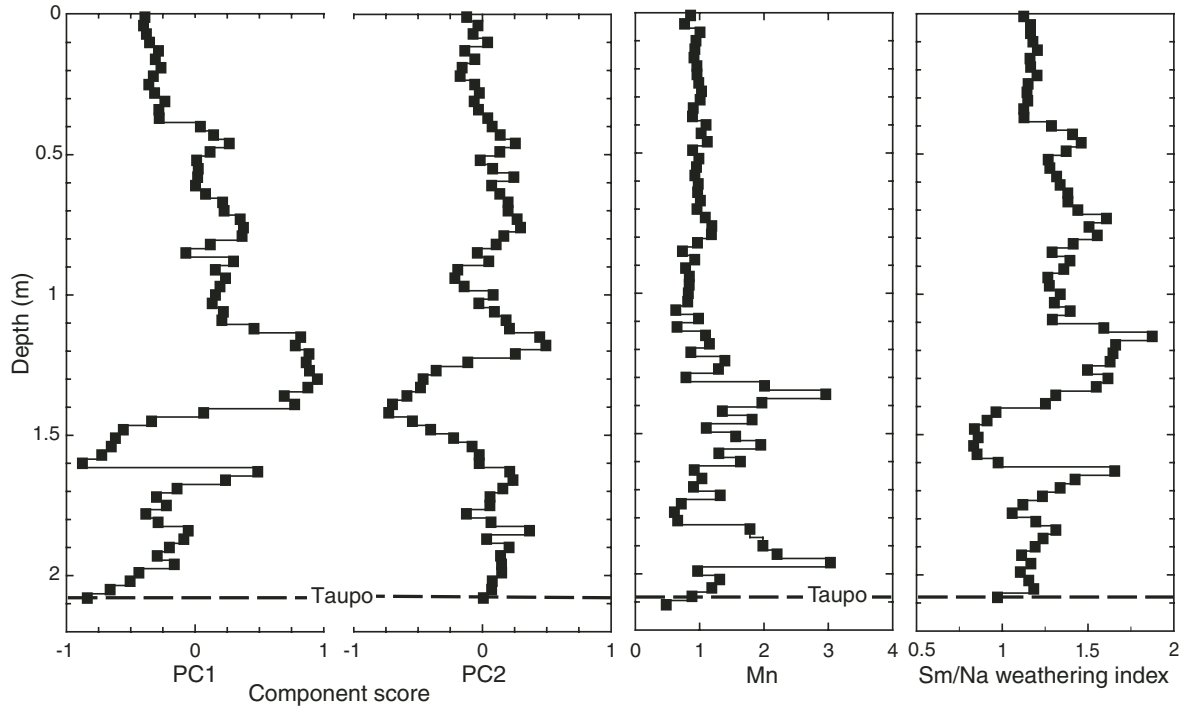


Figure 8. Down-core variations in the first two component scores for (upper continental crust–normalized) major- and trace-element concentrations, Mn (upper continental crust–normalized concentration, UCCNC), and the element ratio Sm/Na (upper continental crust normalized concentrations) in sediment samples from core W4. Horizontal dashed line indicates the position of the macroscopic tephra associated with the Taupo eruption of 1.718 ka.

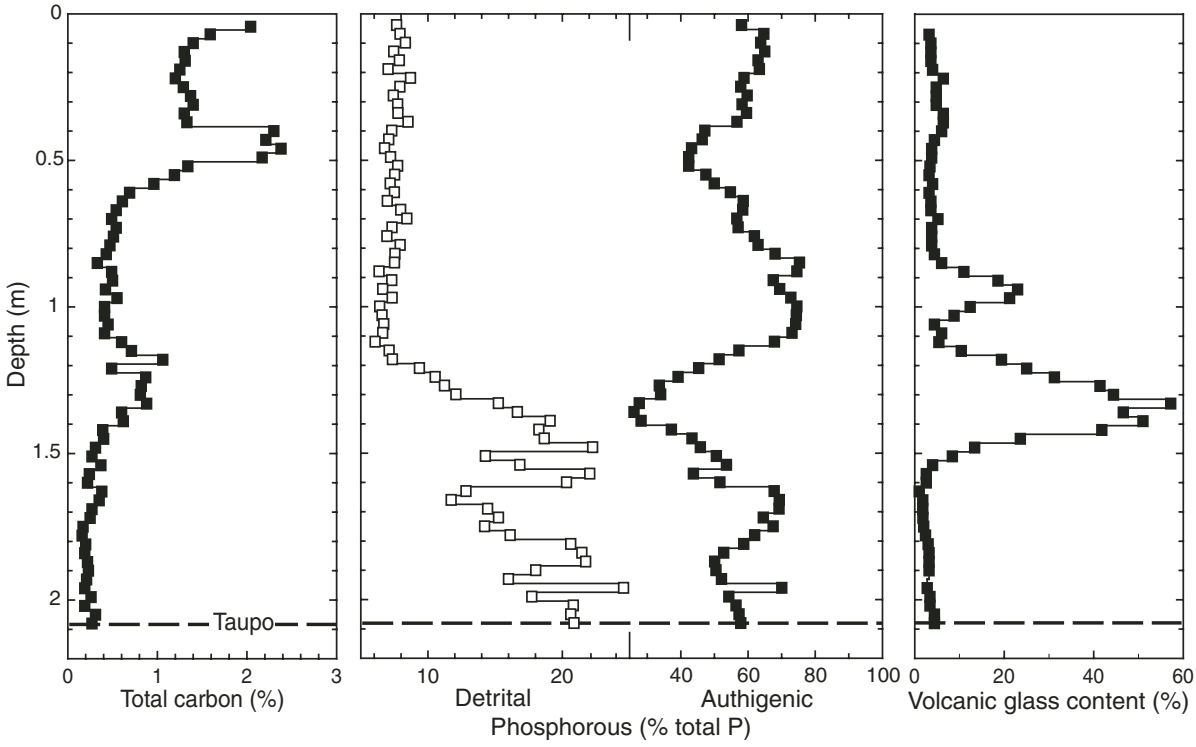


Figure 9. Down-core variations in total carbon, detrital and authigenic phosphorous, and the volcanic glass content of the sand fraction in sediment samples from core W4. Horizontal dashed line indicates the position of the macroscopic tephra associated with the Taupo eruption of 1.718 ka.

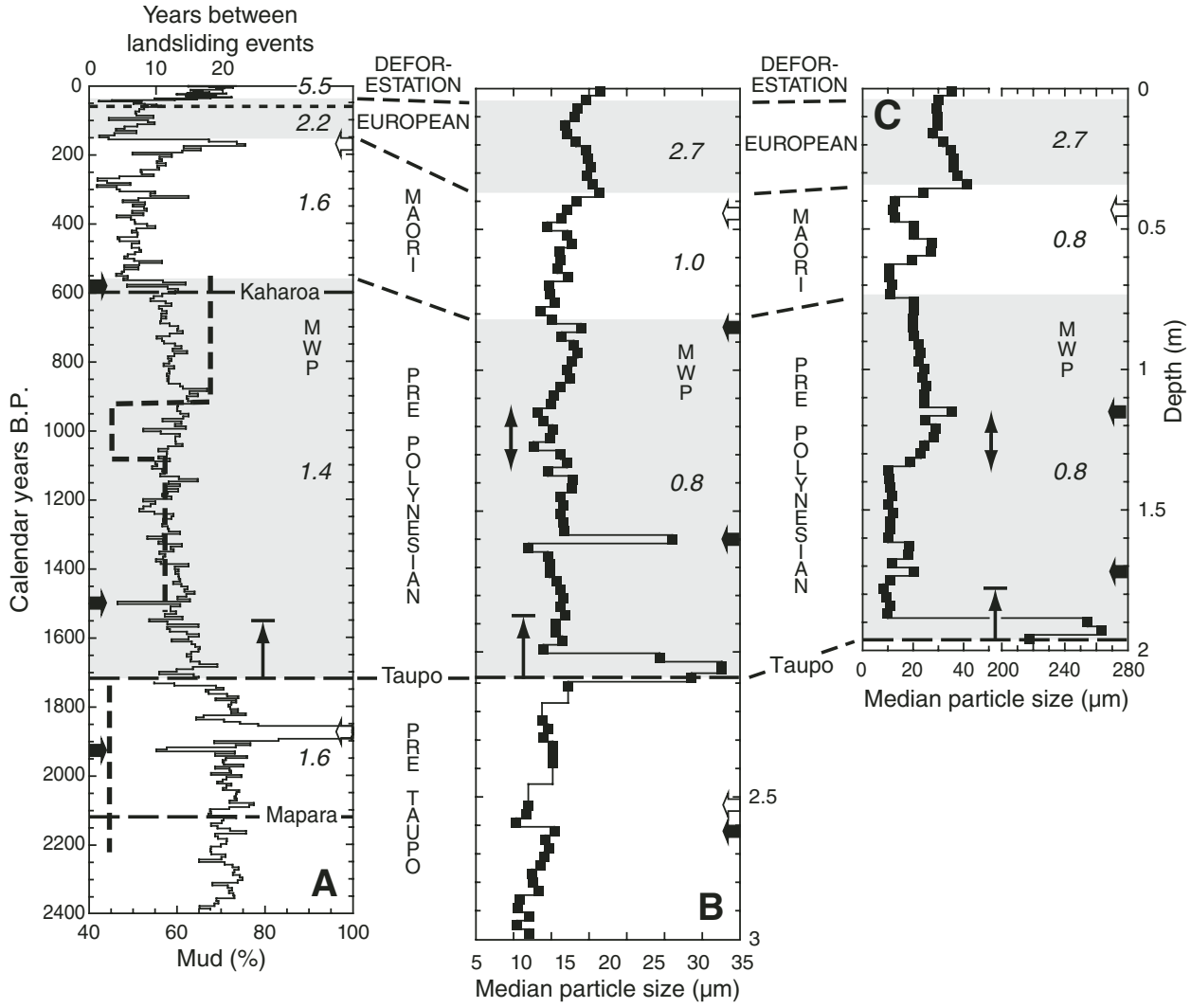


Figure 10. Correlation of C1, C2, and C3 (solid and open block arrows) events preserved in the textural profiles of (A) MD972122, (B) W4, and (C) P11 (see Figure 1 for core locations and text for discussion). C1 event horizons are delimited by shading, and C3 events are indicated by open (large floods) and closed (magnitude >7 subduction-thrust earthquakes) block arrows. The bars and arrows indicate the duration of the recovery period after the Taupo eruption, and the dashed horizontal lines are as defined in Figure 2. C2 events that are a response to centennial-scale fluctuations in climate (stepped dashed line), such as a Southern Hemisphere counterpart to the Medieval Warm Period (MWP), and periods when large storm events occurred more frequently are defined in A with reference to changes in the frequency with which terrigenous sediment was released to Lake Tutira by landsliding (cf. Fig. 7). In B and C, the duration of the period of increased storminess in the pre-Polynesian period is indicated by double-headed arrows. Figures in italics denote the sedimentation rate (mm yr^{-1}) for the indicated time period.

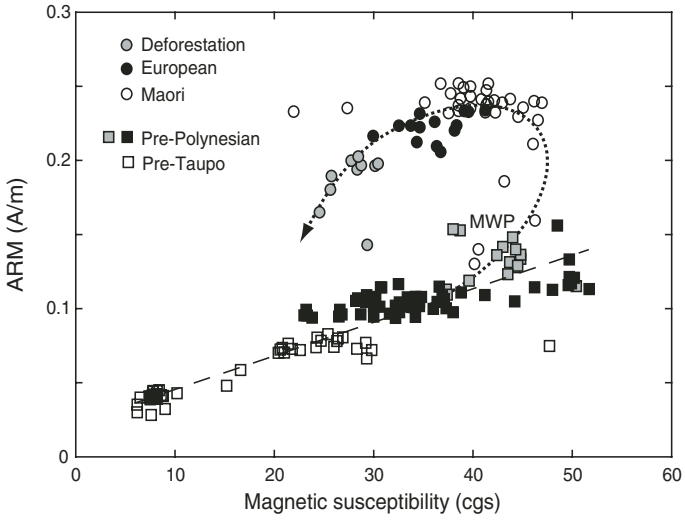


Figure 11. Plot of anhysteretic remnant magnetization (ARM) versus magnetic susceptibility for sediment samples from MD972122. The dashed (regression) line was drawn for samples from the pre-Taupo and pre-Polynesian periods (as defined in Fig. 10), including those associated with a Southern Hemisphere counterpart to the Medieval Warm Period (MWP), and the (dotted) loop indicates the temporal trend in the samples in which an anthropogenic signal is preserved.

commun.). Recurrent spikes in the Mn profile, a concurrent decrease in the amount of chlorite, and increase in reducible Fe suggest that soil loss intensified in the period after Polynesian arrival (Figs. 5C and 6C). By contrast, the piecemeal clearances in the drier lowland regions would have had little impact on the timing and magnitude of runoff and, hence, on bank erosion. In the absence of vegetation, soil erodibility increases in the immediate postfire period, but during rainstorms, erosion processes typically are transport-limited because neither surface wash nor rill erosion removes all of the available soil and ash (Cerdà, 1998; Moody and Martin, 2001). Thus, we associate the production of increased amounts of relatively coarse, weathered material after Polynesian arrival with soil loss from open ground (Figs. 2A, 2B, 4, 5, and 6). Sustained by the piecemeal pattern of individual burns and an increasing human population (Jones, 1988), the signal persists throughout the prehistoric period (Figs. 2A and 7A), by the end of which time much of the forest on and around the Poverty Bay Flats could have been impacted by anthropogenic fires (cf. McGlone, 1989; Ogden et al., 1998).

Indigenous land use intensified after the introduction of metal tools (Cameron, 1961). Wholesale clearance of the forests on the Poverty Bay Flats began in 1835, after the arrival of European colonists, who began to clear the surrounding hills in the 1850s (Pullar, 1962; Mackay, 1982). Removing the native vegetation exacerbated soil loss by enhancing runoff and permanently lowering the erosion threshold on pastoral hillslopes, which became prone to shallow landsliding (Trustrum et al., 1999). The persistent fire-induced changes to the vegetation cover also offset any constraints imposed on sediment availability by the rates of regolith stripping and soil and vegetation recovery on newly exposed hillslopes (cf. Smale et al., 1997), and after European colonization, the flux of terrigenous mud to the middle shelf increased by 150% (Fig. 2).

By 1880 most of the Poverty Bay Flats and surrounding hills had been cleared, and conversions to pasture in the hinterland were under way (Murton, 1968). This phase of land use change continued until ca. 1920, and by the end of that decade, the effects of accelerated erosion in the hinterland were visible in the sedimentary record (Pullar, 1962; Gomez et al., 2004b). As root strength declined and the amount of surface moisture increased, hillslopes in the hinterland responded to deforestation in two ways. First, the incidence of shallow landsliding increased, and it became a pervasive erosional process during the 1920s (Henderson and Ongley, 1920). Second, soon after the end of the most intensive period of land-use change (1890–1910), gullies were initiated in terrain underlain by rocks of the East Coast allochthon (Fig. 1C; Hamilton and Kelman, 1952). Gully development precipitated the well-documented change in process dominance, from an erosional regime dominated by landsliding and other diffusive processes, to one where incisive processes generated most of the sediment transported by the Waipaoa River (Hicks et al., 2000; Gomez et al., 2004a). The corresponding signal appears in the depositional record ca. 0.04 ka (Figs. 2, 4, 5, and 6), and once the limitation on sediment supply during frequent events below the threshold for landsliding was removed, the flux of terrigenous mud to the middle shelf increased by an additional ~300%.

C2 Events—Short-Term Fluctuations in Climate

In addition to vegetation, climate controls hillslope stability by determining the amount, though not necessarily the character, of runoff (Melton, 1957). Paleoclimate reconstructions for the Waipaoa sedimentary system are lacking. However, proxy records of storm activity and vegetation disturbance have been obtained from a lake ~125 km southeast of the area (Fig. 1A). Geomorphologically effective storm activity in the Lake Tutira catchment is linked to landsliding and clastic sediment interposed between organic-rich lacustrine deposits, and the disturbance history has been elucidated from the abundance of seral taxa (Wilmshurst et al., 1997; Eden and Page, 1998; Gomez et al., 2002). Disturbances related to the Taupo eruption and Polynesian arrival occur within similar time frames in the record from Lake Tutira to those observed in MD972122 (Fig. 7). Thus, despite the obvious differences in the scale and setting of the two dispersal systems, the records correlate well with one another. Correlation with MD972122 was accomplished using a linear age model (based on the Taupo and two other tephras) to determine the rate of organic lacustrine deposition between sediment layers attributed to landsliding, and by linear interpolation between levels for which calendar ages were derived in the core used for pollen analysis. Prior to Polynesian arrival, the average interval between large storms extracted from the lacustrine sediments ranged between 3 and 18 yr (Fig. 7B). There are several reasons why the interval between geomorphologically effective storms might depart from the ~4 yr periodicity of the contemporary ENSO-dominated climate (Quinn and Neal, 1992; Diaz and Pulwarty, 1994). They include lengthening of the period between ENSO events when solar activity is strong, periodic strengthening of the zonal westerly airflow, and alterations to the regional pattern of atmospheric circulation (Anderson, 1992; Salinger and Mullan, 1999; Shulmeister et al., 2004).

There is evidence for increased disturbance in the Waipaoa sedimentary system and the Lake Tutira catchment once the forests had regenerated after the Taupo eruption, and in the period

ca. 0.9–0.55 ka, when the interval between large storms increased (Fig. 7). The cause of the former perturbation in climate is uncertain, but the more pronounced latter perturbation may reflect the occurrence of a delayed counterpart to the Medieval Warm Period of 1000–1300 A.D. in the Southern Hemisphere. Evidence for anomalous warming at this time is provided by tree-ring and speleothem records from New Zealand and proxy climatic records from elsewhere in the Southern Hemisphere (Diaz and Pulwarty, 1994; Tyson et al., 2000; Cook et al., 2002; Goosse et al., 2004; Williams et al., 2004). The periodic disturbances in the Lake Tutira catchment may be related to fires ignited by lightning strikes, the incidence of which increased in drier than normal conditions (Wilmshurst et al., 1997). Fire-forced sedimentation related to climatic episodes of hemispheric significance, such as the Medieval Warm Period, also has been observed in Northern Hemisphere river basins (e.g., Meyer et al., 1995). In the Waipaoa sedimentary system, the relationship between climate and fire likely impacted the signal preserved in the depositional record by increasing the frequency with which localized destruction of the forest cover enhanced sediment losses from open ground. Thus, we suggest that the transition to a climatic regime characterized by lengthy periods between large storms (and, perhaps, drier conditions overall) may have prevented the erosional regime from relaxing to its pre-eruption status (Figs. 2, 4, 5, and 6).

Conditions may have been wetter during the previous period (ca. 1.1–0.9 ka), when large storms occurred with a frequency characteristic of the contemporary ENSO-dominated climate. Fire-related disturbances would have been suppressed at this time, although earth-flow activity may have increased. However, concomitant changes in Mn and reducible Fe, a progressive decline in median particle size, and increase in total C are indicative of a transition to a more focused erosional regime, where soil loss makes a larger contribution to sediment yield. The subsequent change in mineral P geochemistry suggests that the trend was reinforced by the onset of the Medieval Warm Period. This is because the podocarp/hardwood forest cover on the lowland hills was more susceptible to fire than forests in wetter locales elsewhere in the Waipaoa River basin (Wilmshurst et al., 1999). For this reason, the environs of the Poverty Bay Flats probably would have been most severely impacted by Maori society (and were the first to be cleared by European colonists). The emergence of a more focused erosional regime not only accounts for the changed nature of the depositional record (Figs. 5 and 6), but also helps explain the continuity of the signal from the period before Polynesian arrival until the hinterland was deforested (Figs. 2, 4, 5, and 6). The shift is well expressed in the plot of magnetic susceptibility versus ARM (Fig. 11), where samples from ca. 0.9 to 0.55 ka are clustered, and there is a progressive change to sediment with more variable susceptibility and an almost constant ARM. Guided by changes in sediment texture and geochemistry (Figs. 2, 4, and 5), we suggest that the variations in susceptibility reflect changes in the supply of (less weathered) minerogenic material from hillslopes, specifically in large multidomain grains that contribute to susceptibility but not to ARM, which is more sensitive to the concentration of fine magnetic particles (cf. Turner, 1997). We presume that evidence of a reaction to the cooler, wetter conditions that likely prevailed during the ensuing Little Ice Age was subsumed by the response to anthropogenic fire.

C3 Events—Large-Magnitude, Low-Frequency Catastrophes

Major storms generate large amounts of sediment in a short time and can imprint a recognizable signal on the depositional record (Kelsey, 1980; Wheatcroft et al., 1997; Johnson et al., 2001; Mulder et al., 2001). Bearing in mind the limitations of our age model, the timing of these events and the duration of the response are difficult to define; however, the imprints of five large-magnitude, low-frequency C3 events clearly are present in MD972122 (Fig. 10A). Two of these events are linked to large floods, and the remaining three, to subduction-thrust earthquakes.

Although there is no obvious attendant deposit in MD972122, the largest historic storm deposited 0.5–1.5 m of sediment on the Waipaoa River floodplain (Gomez et al., 1999). Two other periods of rapid sedimentation occurred on the Poverty Bay Flats ca. 1.875 and 0.175 ka (Fig. 10A), which Brown (1995) associated with more severe floods than any recorded in historic time. There is evidence for the earlier event in Lake Tutira (M.J. Page, 2003, personal commun.), and for the latter in the alluvium on the Uawa River floodplain (Pullar and Rijkse, 1977). Both are recorded in MD972122 by a two-unit sequence composed of ~0.01 m of coarse silt capped by ~0.05 m of fine mud that has similar environmental magnetic properties to sediment deposited after the hinterland was deforested (Figs. 2, 4, and 10A). The implication is that these extreme events were large enough to destabilize hillslopes in the hinterland and initiate gully erosion in terrain covered by native vegetation (cf. Liébault et al., 2005). This is consistent with Grant's (1985) description of the Wakarara alluvium, and with Pullar and Penhale's (1970) observation that the clay mineralogy of buried soils in the Kaiti Formation is indicative of material derived from the East Coast allochthon (and terrain prone to gully erosion). The two-unit sequences also are reminiscent of modern, flood-related marine deposits (cf. Mulder et al., 2001), and their presence in the sediment record perhaps affords the best evidence that the Waipaoa River plume occasionally is driven to depth by very large concentrations of suspended sediment (Hicks et al., 2004).

Earthquakes initiate landslides and mobilize large quantities of coarse debris (cf. Pearce and Watson, 1986; Hovius et al., 2000; Dadson et al., 2004; Goff, 1997), some of which is flushed directly into stream channels during ensuing rainstorms (Campbell, 1966). Much larger amounts of sediment are released when temporary, landslide-dammed lakes fail (Adams, 1981; Costa and Schuster, 1988), though their life span is quite variable. Some lakes fill rapidly and wash out the dam soon after it has been created; other dams remain in place for several years, and a few large landslide-dammed lakes, such as Tutira, have persisted for millennia (Guthrie-Smith, 1969; Read et al., 1992; Eden and Froggatt, 1996). The signal of coseismic landslide activity, manifested as coarse spikes in particle size (Figs. 2 and 10A), is imprinted on the depositional record ca. 1.925, 1.5, and 0.575 ka. The earlier coseismic landsliding event also is recorded in Lake Tutira (Eden and Page, 1998) and in alluvium and emergent beach ridges on the Poverty Bay Flats (Pullar and Penhale, 1970; Pullar and Warren, 1968). All three events are associated with coseismic uplift of marine terraces at the northern end of Ariel anticline, and there is good agreement between our age estimates and the youngest age (1.525 and 0.575 ka) for two of the terraces (Berryman et al., 1989; Ota et al., 1991).

LINKING THE TERRESTRIAL AND MARINE RECORDS

Different stratigraphy is created in proximal and distal depocenters because alluvial systems respond to environmental change in a complex and diachronous manner (cf. Schumm, 1973; Paola et al., 2001). Floodplains also contain a highly censored record of low-frequency, high-magnitude events, whereas a wider range of flows discharge sediment into the ocean. Intercorrelation of MD972122, W4, and P11 is confounded by the aforementioned factors and by inherent uncertainties in the age model. However, the Taupo tephra is a conspicuous time line in all three cores (Figs. 2 and 10), and robust connections between sources and sinks help to preserve the continuity of the depositional response.

On the Waikohu and Waipaoa River floodplains, the response to the Taupo eruption is manifested by a change in Mn content and magnetic susceptibility in W4 and P11, respectively (Figs. 2D, 8, and 10). In W4, distinct changes in the Mn content, the Sm/Na ratio, authigenic P and volcanic glass content, and sediment texture at 0.82 and 0.37 m reflect the piecemeal disturbances to the forest cover after Polynesian arrival and broader-scale European clearances (Figs. 2, 8, 9, and 10B), and corresponding changes in median particle size occur at 0.73 and 0.34 m in P11 (Fig. 10C). The change in sediment properties at 0.82 m in W4 is consistent with an increase in the amount of mass wasting on riparian hillslopes that have a thin, skeletal soil cover and are strongly coupled to river channels (cf. Gomez et al., 2004b). Commensurate with the increased susceptibility of hillslopes to landsliding, there was a 20% increase in the sedimentation rate on the Waipaoa River floodplain following Polynesian arrival, and an ~300% increase after European colonization (Fig. 10B). Sedimentation rates on the Waikohu River floodplain exhibit a similar trend (Fig. 10C), and the presence of a signal in P11 that equates with the period of Polynesian settlement is consistent with archaeological evidence for widespread prehistoric agricultural activity along tributaries in the Waikohu catchment (Jones, 1988).

In W4, the volcanic glass content of the sand fraction increased following the transition to drier conditions that promoted fire-related disturbances and accelerated sediment losses from open ground. The subsequent decline coincides with the period of increased storminess (ca. 1.1–0.9 ka), and the smaller peak, with the delayed Southern Hemisphere counterpart to the Medieval Warm Period (Figs. 9 and 10B). As noted already, mineral P geochemistry also changed at this time (Fig. 9). In P11, both C2 events are associated with a decrease in magnetic susceptibility, but the deposit coarsens as storminess increases (Fig. 10C). The different response is consistent with the erosional regime of the Waikohu catchment, where the terrain is more stable, most sediment is generated by sheet (not gully) erosion, and slope failures typically occur in weathered bedrock on steep riparian (not soil-mantled) hillslopes (Griffiths, 1982; Reid and Page, 2003; Gomez et al., 2004b).

The ca. 0.175 ka flood is represented by an ~0.1-m-thick unit in W4 that can be differentiated in the particle size, organic C, authigenic P, and the Na weathering index profiles, and the ca. 1.875 ka flood can be differentiated by fine-grained sediment at ~2.55 m (Figs. 2C, 8, 9, and 10B). The depositional response to earthquakes is more variable because the impact landsliding has on sediment delivery is spatially heterogeneous (Figs. 2, 8, and 10). We associate the coarse spike in median particle size at 1.6 m with the ca. 1.5 ka earthquake (Fig. 10B). Less prominent spikes occur at 0.85 and 2.62 m, which, on the basis of their position relative to sediment attributed to the pre-Taupo flood and the physical and chemical changes that occurred after Polynesian arrival, represent the ca. 0.575 and 1.925 ka events. In P11, the ca. 0.175 ka flood is represented by fine-grained sediment with an elevated organic C content at ~0.45 m (Figs. 2D and 10C). Coarse sediment with an elevated organic C content and decreased magnetic susceptibility occurs at 1.15 and 1.71 m (Fig. 2D). Relative to the location of the Taupo tephra, the latter signal likely represents the ca. 1.5 ka magnitude >7 earthquake. There is no comparable signal to that at 1.15 m in either MD972122 or W4 (Fig. 10), but its appearance toward the end of the period of increased storminess (ca. 1.1–0.9 ka) is indicative of the subduction-thrust earthquake that occurred at ca. 0.895 ka (Berryman et al., 1989). The origin of the two other peaks in organic C content, which occur at 0.76 and 1.42 m (Fig. 2D), is unclear because the high concentrations of decomposed organic matter do not occur in concert with variations in particle size and magnetic susceptibility.

PATTERNS OF CHANGE AND RESPONSE

In the Waipaoa sedimentary system, strong signals of environmental change are preserved because even though relief provides the critical first-order control on denudation, in the short term, sediment production is sensitive to changes in climate, vegetation, and land use (Kettner et al., 2007). Rapid dispersal times ensure the landscape response to erosional events is translated directly to the depositional record and alluvial buffering has little effect on sediment flux at the basin outlet (Phillips et al., 2007). Offshore, rapid subsidence of the middle shelf and the growth of the Lachlan and Ariel anticlines help to maintain signal clarity (Foster and Carter, 1997). However, events of similar magnitude and frequency generate different amounts of sediment, and so event deposit thickness usually is unrelated to event magnitude (cf. Gomez et al., 1995). In such circumstances, assuming they are not effaced by physical and biological processes, the recognition potential of event deposits hinges on the extent to which they exhibit characteristics that differentiate them from the "normal" sedimentary record (cf. Collins et al., 1997; Mulder et al., 2001).

Against a relatively constant background of erosion, transport, and deposition, infrequent events may generate step-function changes in material fluxes (Trustrum et al., 1999), and subduction-thrust earthquakes and extreme storms both generate distinctive signals in the floodplain and shelf depocenters (Fig. 10). Earthquakes influence the role that storms of a given magnitude play in the production and dispersal of sediment by locally reducing the threshold of landscape sensitivity to rainfall events. However, because the supply of sediment from hillslopes destabilized by seismic activity is transport-limited and contingent upon rainfall events to mobilize or cause it to be released from storage, the signal takes an indeterminate amount of time to enter the depositional record (cf. Hovius et al., 2000; Dadson et al., 2004). Extreme storms, by contrast, have the potential to mobilize and simultaneously transport prodigious amounts of sediment and create event deposits distinguishable both by their caliber and composition (Figs. 4, 5, and 10). Sediment contributed by lower-magnitude storms that are a component of the prevailing hydrometeorological regime forms "event sequences" or packages (cf. Grant, 1985; Eden and Page, 1998; Sommerfield et al., 2002), which have distinctive physical and chemical characteristics that are the product of an aggregated response to erosional events that exceed a hydroclimatic threshold (Figs. 4, 6, 8, and 10). Geomorphologically effective storms thus comprise a hierarchy of temporally sensitive phenomena, the impacts of which are conditioned by frequency and magnitude.

By directly impacting sediment source areas, other events generate a strong depositional signal by lowering the threshold of landscape sensitivity to erosion. For example, singular events such as volcanic eruptions can generate large quantities of air-fall tephra that disturbs vegetation over a wide area (Wilmshurst et al., 1999). The signal decays incrementally as forests revert to their pre-eruption state (Figs. 5, 7, and 10). Recovery may be impeded if a disturbance endures and precluded if, after a change in the vegetation cover (or land-use patterns and practices), an erosional threshold is crossed (Knox, 2000). Maori effected piecemeal vegetation changes that lowered the threshold for hillslope erosion by landsliding and scour by surface runoff, modified the source and caliber of sediment supplied to stream channels, and created a significant discontinuity in the depositional record (Figs. 2, 4, 5, 10, and 11). The legacy of Maori land-use conditioned landscape sensitivity and the response to the lowland forest clearances that began after the arrival of European colonists. But conversion of the hinterland to pasture in the late nineteenth and early twentieth centuries redefined the sensitivity of the landscape, and, by changing the boundary conditions of the erosional, but not the hydrological, regime (Kettner et al., 2007), deforestation

had an appreciable effect on sediment supply to streams and the characteristics of the floodplain and shelf sediments (Figs. 2, 4, 5, and 10).

Viewed against the background of late Holocene environmental change, subduction-thrust earthquakes and extreme storms engender textural variations in the depositional record that match or exceed the strength (amplitude) of the deforestation signal (Fig. 10). But once gullies were initiated, both the sedimentation rate on the floodplain and middle shelf increased by ~300% (Pullar and Penhale, 1970; Fig. 10). No other perturbation had a comparable overall impact on the depositional record. This is because deforestation of the hinterland precipitated the transition to an erosional regime that did not involve a threshold limitation on sediment supply and that impacted sediment production and dispersal across the entire magnitude-frequency spectrum of events that regulated sediment delivery to and transport in stream channels. This shift in process dominance is the reverse of what occurred ca. 4.0 ka, prior to which time the sedimentation rate on the shelf (~4 mm yr^{-1}) was more akin to the contemporary rate (5.5 mm yr^{-1}) than the rate (~1.6 mm yr^{-1}) in the period before European colonists arrived (Gomez et al., 2004a; Fig. 10). This suggests that, although historical data indicate that anthropogenic activity altered drainage basin sediment dynamics (cf. Macklin et al., 1992), if an erosional threshold is crossed, the change can initiate a normal process-response function to natural events that may have an equally profound impact on sediment fluxes and the depositional record.

Finally, the signals preserved in depocenters throughout the Waipaoa sedimentary system have a bearing on the ongoing discussion about the implications of vegetation and land-use change in New Zealand prehistory. Establishing the time of settlement has proved controversial, because the populations that first reached New Zealand were small and did not have a large impact on the environment. The first evidence of settlements appears in the thirteenth century (Anderson, 1991; McGlone and Wilmshurst, 1999; Wilmshurst and Higham, 2004), although earlier dates for human occupation have been proposed on the basis of the frequency of vegetation disturbance in pollen records. However, there are compelling natural explanations for these disturbances (Wilmshurst et al., 1997; Ogden et al., 1998; McGlone et al., 2005), and we contribute to this discussion by noting that catastrophic (C3) events that initiate landslides are an important natural element in soil and vegetation dynamics on steep soil-mantled hillslopes (Blaschke et al., 2000). Strong signals of landsliding activity emanate from high-order catchments (Gomez et al., 2002), and our data show that if sources and sinks are closely coupled, these signals can be transmitted throughout larger dispersal systems (Fig. 10). Moreover, because the stabilization and regeneration of forest on landslide scars is a protracted process, sediment may be generated long after the formative event (Smale et al., 1997; Liébault et al., 2005). Thus, we suggest there is the potential for seral taxa (colonizing landslide scars) to produce a signal of vegetation disturbance in the hinterland of comparable strength to that caused by disturbances to lowland forests in coastal locations where the earliest Polynesian settlers landed.

CONCLUSION

Three high-resolution sediment cores from the Waipaoa sedimentary system record the landscape response to both profound and relatively modest natural and anthropogenically induced environment change over the past 2.4 k.y. Similarities in the clay mineralogy and geochemistry between weathered bedrock from the hinterland in the Waipaoa sedimentary system, fluvial suspended sediment, alluvium, and marine mud confirm that modern sources and sinks are closely linked. Variations in sediment properties record periods of landscape instability and intensified hillslope erosion, and changing sediment source dynamics, and they are related to three categories of events. Category 1 (C1) events include the long-term landscape response to the Taupo eruption, Polynesian arrival, European colonization, and the subsequent deforestation of the hinterland, and in MD972122, the corresponding "event horizons" occur at 1.718, and ca. 0.56, 0.15, and 0.04 ka, respectively (Fig. 10A). Category 2 (C2) events represent the response of surface properties and processes to short-term fluctuations in climate, and are superimposed on the conditions that C1 events create (Figs. 7 and 10A). After the forests had regenerated following the Taupo eruption, the transition to a (drier) less stormy climate may have helped to prevent the erosional regime from relaxing to its pre-eruption status by increasing the incidence of disturbance caused by lightning-strike fires. Storm activity also decreased ca. 0.90–0.55 ka, and anomalous warming at this time may be indicative of a delayed counterpart to the Medieval Warm Period in the Southern Hemisphere (Cook et al., 2002; Williams et al., 2004). Fire-related disturbances would have been suppressed in the previous (wetter) period ca. 1.1–0.9 ka, when large storms occurred with a frequency more characteristic of the contemporary ENSO-dominated climate. Category 3 (C3) events are singular, high-magnitude events, such as subduction-thrust earthquakes and very large floods, that probably were more powerful than those experienced in historic time. These events generate a recognizable signal, and the "event deposits" have distinctive physical and geochemical sediment properties (Figs. 4, 5, and 10A). In MD972122, for example, deposits at ca. 1.875 and 0.175 ka that consist of a two-unit sequence of coarse silt capped by fine mud resemble flood-related deposits found on other continental margins (cf. Mulder et al., 2001). Earthquakes initiate landslides and mobilize large quantities of debris that may be flushed directly into stream channels during ensuing rainstorms or released when landslide-dammed lakes fail. In MD972122, they are represented by prominent coarse spikes in particle size at ca. 1.925, 1.5, and 0.575 ka (Figs. 2 and 10A).

All three categories of events that generate a strong enough signal to be preserved in the depositional record on the Poverty Shelf also appear in terrestrial cores W4 and P11 (Fig. 10). This clearly demonstrates that natural and anthropogenic forcing of sediment source dynamics, at a variety of temporal and spatial scales, can leave distinctive signals in the stratigraphic record at disparate locations within a dispersal system. In the Waipaoa sedimentary system, transfer of these signals is facilitated because climate, vegetation, and land use exert the primary influence on sediment production, the amount of floodplain storage is small relative to downstream transport, and hinterland-to-margin transport can be accomplished rapidly. The signals of extreme storms are indicative of the minimum geomorphologically effective event that can be discerned in terrestrial and marine depocenters (Fig. 10). The signals that extreme storms and large coseismic events generate occur against the background of sediment production and dispersal accomplished by lower-magnitude storms that are a component of the prevailing hydrometeorological regime. These smaller storms generate the high-frequency fluctuations in sediment properties that collectively form "event sequences" (Figs. 2, 4, 5, and 10). Events and event sequences comprise a hierarchy of temporally sensitive hydrometeorological phenomena, the impacts of which are conditioned by frequency and magnitude. By contrast, vegetation disturbance is a spatially sensitive phenomenon that directly impacts sediment source areas and lowers the threshold of landscape sensitivity to erosion. The Taupo eruption of 1.718 ka and Maori settlement of the Poverty Bay Flats both disrupted the vegetation cover and produced strong depositional signals. In the former case, the signal decayed as the posteruption vegetation reverted to its pre-eruption state, but in the latter case, recovery was impeded because the disturbance endured. Subsequent deforestation

of the hinterland redefined landscape sensitivity by precipitating the transition to an erosional regime that impacted sediment production and dispersal across the entire magnitude-frequency spectrum of natural events. In the past 2.4 k.y., no other perturbation in the Waipaoa sedimentary system had such a profound impact on the sediment record.

ACKNOWLEDGMENTS

Our research was supported by the U.S. National Science Foundation (grants SBR-9807195 and BCS-0317570 to Gomez), and by the New Zealand Foundation for Science and Technology (contracts C01X0203 to the National Institute for Water and Atmospheric Research, and C09X0013 to Landcare Research). Funding to obtain core MD972122 also was provided by the Department of Conservation, Eastland Energy Community Trust, Gisborne District Council, Indiana Sate University, the Institute of Geological and Nuclear Sciences, Landcare Research, the National Institute for Water and Atmospheric Research, Port Gisborne Ltd., and the J.N. Williams Memorial Trust. Special thanks are due to Hannah Brackley, Kevin Butler, Michele D'Ath, Kelvin Berryman, Brian Daly, Dennis Eden, Mike Elliot, Gabe Filippelli, Mike Glascock, Barbara Manighetti, Mike Marden, Hector Neff, Mike Page, Alan Palmer, Dave Peacock, Ted Pinkney, Andrew Roberts, Brenda Rosser, Yuko Siguta, Fred Soster, Joe Whitton, and the captain and crew of the *Marion Dufresne* for their assistance in the field or for performing laboratory analyses. Commentary provided by James Shulmeister and an anonymous reviewer helped focus our discussion.

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Manuscript Received 6 March 2006
Revised Manuscript Received 31 October 2006
Manuscript Accepted 31 January 2007

Printed in the USA

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