Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand

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Abstract

A ca. 2250 year storm history has been identified from a high-resolution lake sediment record from the east coast of the North Island, New Zealand. This event-based chronology identifies 340 storms in the pre-European record. The record is largely one of natural variability without human impacts. Layers of minerogenic sediment representing the products of individual storm events are clearly visible in lake cores. These storm sediment pulses, derived mainly from landslides, record the frequency and magnitude of storms. Clusters of pulses identify six periods of high sedimentation and associated erosion before European settlement (A.D. 1878). At least five of these are interpreted as periods of higher rainfall and probably warmer temperatures, since historic records show that most large storms are derived from the subtropics/tropics. Most of the storm periods correspond to warm climate intervals previously identified from New Zealand and from Southern Hemisphere palaeoclimatic evidence. The Mapara 2 period (ca. 2090–1855 cal. yr B.P.) was the stormiest. Other periods were of shorter duration. The Mapara 2 period occurred at times of sustained warmth in the Tasmanian and Chilean tree-ring records, which might suggest hemispheric warming at this time. One storm period (Burrell), which occurred during the historical ENSO record, was at a time of moderately high ENSO activity. Three earlier periods also appear to show responses to ENSO. Two storm periods correspond to previously proposed New Zealand-wide periods of increased erosion and sedimentation. Estimates of palaeo-storm rainfalls from relationships between storm rainfall and sediment thickness of historical events suggest that storm pulses ca. 12 mm thick represent palaeo-storms of ca. 450 mm rainfall.

Keywords: palaeoclimatology: Holocene: lake sedimentation: New Zealand: storm history: ENSO

1. Introduction

To understand the significance of anthropogenic climate change it is also necessary to understand natural climatic variability (Stocker and Mysak, 1992; Wasson, 1994). Researchers are increasingly turning to palaeoclimatic records to provide an understanding of this variability. Such palaeoclimatic reconstructions rely on a variety of proxy data, including historical records, biological records (e.g., tree rings, corals, pollen, and microorganisms), biochemical indicators (e.g., biochemical varves, fossil pigments), geomorphic and geologic features (e.g., dated glacial moraines, varves, speleothems), and oxygen isotope data from ice cores.

The Past Global Changes (PAGES) core pro-
ject of the International Geosphere-Biosphere Programme (IGBP) contains a major objective, Paleoclimates of the Northern and Southern Hemisphere (PANASH), one focus of which is on the last two thousand years (Bradley et al., 1995). Few high-resolution records of past climatic conditions over this period have been identified from the Southern Hemisphere (Bradley and Jones, 1993; D’Arrigo et al., 1995). Those that have generally record century-scale, decadal or annual variability. This paper reports on a high-resolution late Holocene lake record from the east coast of New Zealand, which is event-based. Lake Tutira, surrounded by steep, landslide-prone hills, acts as a highly efficient sediment trap, with conditions suitable for the formation and preservation of well-defined laminations. Consequently, layers of storm-generated sediment or ‘storm sediment pulses’ can be clearly identified. Page et al. (1994a) have correlated the sedimentation record, for the period since Europeans arrived in 1878, with the storm history derived from a 93-year daily rainfall record. This correlation of sediment layers with storm events has been confirmed by time markers such as $^{137}$Cs peaks from the atmospheric bomb tests of the 1950s and 1960s; volcanic glass from the 1945 Mt. Ruapehu eruption; the formation since 1959 of black gyttja-like deposits associated with eutrophication resulting from washed-in phosphate fertilisers; changing pollen and diatom spectra associated with vegetation changes resulting from European settlement; and disruption of beds by the 1931 Hawke’s Bay earthquake ($M_{7.8}$). This chronology of storm-induced erosion has identified the magnitude, frequency and threshold for erosion-producing storms, and established a relationship between sediment thickness and storm rainfall.

Storm sediment pulses also occur in the pre-European and pre-Polynesian sections of the sediments. New Zealand was not settled by humans until ca. 900–800 $^{14}$C yr B.P. (McGlone et al., 1994), and the onset of Polynesian deforestation in the lake catchment was ca. 490 cal. yr B.P. (Wilmshurst, 1997). A core from Lake Tutira, containing a ca. 2250 cal. year record of sedimentation, provides a palaeoclimate record of storms and of natural climate variability, which is largely without the complication of human impacts. The relationship between annual rainfall, storm events and the Southern Oscillation Index (SOI) during the European period suggests that the pre-European record may also reflect past fluctuations in El Niño-Southern Oscillation (ENSO).

The record is not only one of climatic variability but also one of landscape response. The magnitude and frequency of storm sediment pulses provide a local record of erosion and sedimentation. The record is a continuous, undisturbed one which overcomes the spatial and temporal variability exhibited on the landscape. As such it has advantages over other New Zealand chronologies of Holocene erosion which have been constructed from geographically widespread data.

The purpose of this paper is to establish the storm history at Lake Tutira over the last two millennia from the lake sediment record, to determine whether there have been periods of increased storm frequency, to examine their climatic significance, and to relate these to New Zealand-wide periods of landscape instability/erosion postulated in previous studies.

2. Environmental setting

Lake Tutira is a small lake (1.8 km$^2$) on the east coast of the North Island, New Zealand (Fig. 1). It is surrounded by steep hills 300 to 400 m above sea level, composed mainly of soft Tertiary siltstones and sandstones (interbedded with limestones and conglomerates). The geomorphic features of the catchment are described in Page et al. (1994a,b). The lake was formed as a result of a large landslide (Adams, 1981) about 6500 $^{14}$C yr B.P. (Trustrum and Page, 1992). Before Polynesian settlement the catchment was covered with conifer-broadleaved forest. This was replaced by bracken fern/scrub following a succession of fires beginning ca. 490 cal. yr B.P. (Wilmshurst, 1997). The catchment has been largely transformed into pasture since the arrival of European settlers during the 1870s (Guthrie-Smith, 1953).

The Lake Tutira catchment periodically experiences major rainstorms which cause widespread
landsliding and sediment deposition in the lake. A sediment budget for a major cyclonic storm (Page et al., 1994b) describes the processes of sediment generation, transport, and delivery; quantifies the total sediment generated, the relative contribution of erosion processes, the amount of sediment held in storage on the landscape, and the amount discharged into the lake. A geomorphic analysis of the catchment identifies those landforms which are the main sources of sediment. The lake is
gradually filling with these sediments, its average depth having been reduced by about 1.1 m over a 38 year period (Grant, 1966). Its present mean depth is 21 m with a maximum of 42 m. Studies of lake sediment cores (Page et al., 1994a) show layers of minerogenic sediment which range from thin clay to thicker, graded beds comprising clay with silty or sandy bases. The graded beds represent the inwashing of sediment eroded from the catchment during large rainstorms. Thin clay layers represent smaller storms. These layers or 'storm sediment pulses' are interspersed with darker, organic-rich deposits which represent slow accumulation of biological material and catchment sediment (Fig. 2).

3. Climate-landslide relationship

The majority of the allochthonous sediment accumulated since European settlement has been landslide derived (Page et al., 1994a,b). Hillslope morphology indicates that landsliding was also a major process in hillslope development under indigenous forest, although at a lower magnitude (Page and Trustrum, 1997). Landsliding under forest has been recorded in a variety of New Zealand terrains, and is generally recognised as an important hillslope process under forested conditions (Crozier et al., 1992). In order to use these layers as a surrogate for palaeoclimatic conditions it is important to consider other agents that could be responsible for triggering sediment movement. Crozier (1996) discusses the link between climate and landslides, and outlines the problems associated with establishing that link. He lists other potential triggering factors as: seismic activity, fluvial undercutting, human effects and changes in the non-climatic threshold for landsliding due to stress release, weathering or tectonically induced base level changes. Although these factors cannot be discounted as contributing to the sedimentation record, including the undoubted occurrence of earthquakes, the most compelling evidence for the climatic trigger comes from the coincidence of landsliding with storm rainfall in the historic record. In the absence of human influence over much of the record, the number of sediment pulses, and their distribution pattern is consistent with a dominantly climatic signal.

Another factor to consider when using the frequency and magnitude of storm sediment pulses to infer palaeoclimatic conditions is the change in the climatic threshold that occurs following a close succession of storms which removes material from the most susceptible sites without allowing sufficient time for soil recovery. This leads to 'event resistance' or the need for more extreme events to trigger landsliding (Crozier, 1986; Page et al., 1994b). Evidence of this phenomenon is present in the European storm record (Page et al., 1994a).

![Fig. 2. Section of Lake Tutira core 15 showing Mapara 1 period. Pale grey layers represent individual storm sediment pulses interspersed with darker, organic-rich deposits. The 8 mm storm pulse is one of six large individual storm events which fall outside the main storm periods.](image-url)
Although event resistance is also assumed to occur in the pre-European record, without a detailed knowledge of storm rainfall and timing it could not be recognised.

4. Methods

The sedimentation history is largely derived from a single Mackereth core (LT15) 5900 mm long, taken from near the centre of Lake Tutira, but with reference to three other cores from Lake Tutira (LT16) and adjoining Lake Waikopiro (LW3 and LW8) (Figs. 1 and 3). Core LT15 was selected from more than 40 cores extracted from the lake because of the length and detail of the storm sediment record, and its age is well constrained by tephras. Core LT16 was taken close to core LT15. It has a similar but shorter record which is documented by Wilmshurst et al. (1997). The two Lake Waikopiro cores are closer to sediment sources. Consequently, they have more detailed records of sedimentation since European arrival but do not extend back so far in time (Fig. 3). Most other cores also contain shorter records, although a longer core from a swamp at the head of the lake with a less well defined storm sediment record has been used to calculate comparative sedimentation rates for the period 6500–1850 ¹⁴C yr B.P. (Page and Trustrum, 1997).

The sediment layers in core LT15 are outlined in Fig. 4, in which all layers of 3 mm or more are shown individually while thinner layers are shown as numbers on the right hand side of the diagram. The positions of vegetation changes, resulting from Polynesian burning and European settlement, are

![Fig. 3. Correlation of storm sediment layers (shaded) in cores from Lakes Tutira (LT) and Waikopiro (LW).](image-url)
at 2540 and 1390 mm, respectively. These positions were determined using pollen analysis (Wilmshurst et al., 1997), and correlated from core LT16 by their depth relationships to specific storm pulses present in both cores. The presence of four tephra datums (Eden and Froggatt, 1996)—Mapara Tephra 2120 cal. yr B.P. at 5705 mm, Taupo Tephra 1718 cal. yr B.P. at 4575 mm, Tufa Trig Formation member 5 tephra 665 cal. yr B.P. at 2825 mm, and Burrell Tephra 295 cal. yr B.P. at 1920 mm—provide a chronology.

The core has been subdivided into sixteen intervals based on clusters of storm sediment pulses representing deposition from storm events (Table 1). The duration of intervals and their boundaries in time are estimated using the average sedimentation rates between the Mapara, Taupo, Tufa Trig Formation member 5 and Burrell tephra datums. Storm sediment pulses were excluded when estimating time intervals and sedimentation rates because they were deposited rapidly (days to months), although several pulses of fine clay 10–20 mm thick without graded bedding may represent longer time intervals such as a continuously wet season. The Burrell Tephra (Druce, 1966) and Taupo Tephra (Sparks et al., 1995) have been directly dated in calendar years using tree-ring data. The ages of the Tufa Trig Formation member 5 tephra (Donoghue et al., 1995) (hereafter referred to as Tufa Trig 5 tephra) and Mapara Tephra (Froggatt and Lowe, 1990) have been determined by conventional radiocarbon dates. In the case of the Tufa Trig 5 tephra, its age is based on dated peats overlying and underlying the tephra.

Fig. 4. Storm sediment stratigraphy for Lake Tutira core 15 showing tephra datums and storm periods.
Table 1
Temporal distribution of storm periods, durations, numbers of storms and proportions of storm sediment

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Period</th>
<th>Time interval (A.D./B.C.)</th>
<th>Time interval (cal. yr)</th>
<th>Time interval (14C yr)</th>
<th>Duration (cal. yr)</th>
<th>Thickness (mm)</th>
<th>Storms (#)</th>
<th>Storm sediment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1390</td>
<td>European</td>
<td>1985-1878</td>
<td>0-72</td>
<td>0-72</td>
<td>107</td>
<td>1390</td>
<td>25</td>
<td>52</td>
</tr>
<tr>
<td>1390-2016</td>
<td>Burrell</td>
<td>1878-1594</td>
<td>72-356</td>
<td>72-369</td>
<td>284</td>
<td>626</td>
<td>25</td>
<td>18</td>
</tr>
<tr>
<td>2016-2118</td>
<td>Tufta Trig 2</td>
<td>1594-1575</td>
<td>356-375</td>
<td>369-392</td>
<td>19</td>
<td>102</td>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td>2118-2323</td>
<td>Tufta Trig 2</td>
<td>1575-1449</td>
<td>375-501</td>
<td>392-544</td>
<td>126</td>
<td>205</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>2323-2540</td>
<td>Tufta Trig 2</td>
<td>1449-1446</td>
<td>501-504</td>
<td>544-547</td>
<td>&gt;3</td>
<td>217</td>
<td>9</td>
<td>98</td>
</tr>
<tr>
<td>2540-3200</td>
<td>Tufta Trig 2</td>
<td>1446-1014</td>
<td>504-936</td>
<td>547-1025</td>
<td>432</td>
<td>657</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>3200-3565</td>
<td>Tufta Trig 1</td>
<td>1014-864</td>
<td>936-1086</td>
<td>1025-1183</td>
<td>150</td>
<td>365</td>
<td>43</td>
<td>54</td>
</tr>
<tr>
<td>3565-4042</td>
<td>Taupo</td>
<td>864-515</td>
<td>1086-1435</td>
<td>1183-1551</td>
<td>349</td>
<td>477</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>4042-4118</td>
<td>Taupo</td>
<td>515-496</td>
<td>1435-1454</td>
<td>1551-1571</td>
<td>19</td>
<td>76</td>
<td>6</td>
<td>72</td>
</tr>
<tr>
<td>4118-4780</td>
<td>Mapara 2 (c)</td>
<td>496-93</td>
<td>1454-1857</td>
<td>1571-1957</td>
<td>403</td>
<td>546</td>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>4780-4923</td>
<td>Mapara 2 (c)</td>
<td>93-14</td>
<td>1857-1936</td>
<td>1957-2019</td>
<td>79</td>
<td>143</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>4923-5451</td>
<td>Mapara 2 (b)</td>
<td>A.D. 14-B.C. 34</td>
<td>1936-1984</td>
<td>2019-2056</td>
<td>48</td>
<td>528</td>
<td>48</td>
<td>89</td>
</tr>
<tr>
<td>5451-5670</td>
<td>Mapara 2 (a)</td>
<td>34-149</td>
<td>1984-2091</td>
<td>2056-2138</td>
<td>107</td>
<td>219</td>
<td>45</td>
<td>41</td>
</tr>
<tr>
<td>5670-5755</td>
<td>Mapara 2 (a)</td>
<td>141-203</td>
<td>2091-2153</td>
<td>2138-2185</td>
<td>62</td>
<td>85</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>5755-5819</td>
<td>Mapara 1</td>
<td>203-227</td>
<td>2153-2177</td>
<td>2185-2203</td>
<td>24</td>
<td>64</td>
<td>12</td>
<td>55</td>
</tr>
<tr>
<td>5819-5900</td>
<td>Mapara 1</td>
<td>227-282</td>
<td>2177-2232</td>
<td>2203-2246</td>
<td>55</td>
<td>81</td>
<td>6</td>
<td>17</td>
</tr>
</tbody>
</table>

* In text these dates are rounded to the nearest 5 yr.
* Burrell Tephra 1920 mm (<1 mm thick).
* Tufta Trig 2 tephra 2825 mm (3 mm thick).
* Taupo Tephra 4575 mm (116 mm thick).
* Mapara Tephra 5705 mm (<1 mm thick).

at one site (Donoghue et al., 1995), while the Mapara Tephra has six dates, each determined at different localities (Froggatt and Lowe, 1990). The individual radiocarbon dates were converted into calendar year ages using the CALIB v.3.0.3c programme (Stuiver and Reimer, 1993) and calendar year ages were determined for the two tephras based on the midpoint in separation of, or the midpoint in overlap of, the calibrated age ranges at the one standard deviation level. Ages are expressed in both calendar and radiocarbon years (B.P.) (Table 1) to facilitate comparisons with other data. Dates given in Table 1 are rounded to the nearest five years in the text. Using these sedimentation rates Polynesian deforestation began at ca. 505 cal. yr B.P. which corresponds well with the 490 cal. yr date calculated by Wilmshurst et al. (1997) for nearby core LT16.

5. European storm record

The storm history since 1895 was derived from a daily rainfall record at Lake Tutira. Storm sediment pulses in core LT15 were then correlated with this record, aided by the chronology established in three key cores from Lake Tutira (LT16) and Lake Waikopiro (LW3 and LW8) (Fig. 3) using time markers described above (Page et al., 1994a). These three cores contain recognisable sediment layers from all the main storms recorded in the rainfall record (Table 2).

Sediments deposited during the European period total 1390 mm in LT15. There is a detailed record of storms since 1960 in this core as well as most of the large storms before this. A total of 25 layers are present. The 1988 Cyclone Bola storm, which was the largest recorded, is not present due to disturbance of the unconsolidated very fine sediments at the time of sampling. The thickest layer, 235 mm, is from the second largest storm in 1938.

5.1. Storm origins

The tracks of 39 storms which have produced sediment layers in the cores shown in Fig. 3 were traced using meteorological records and newspaper reports to find their origins. Sixty seven percent
Table 2
Characteristics of main sediment-producing storms since European settlement. Superscripts indicate additional significant storms which occurred within six months of a listed storm as outlined below.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall (mm)</th>
<th>Max. two-day rainfall (mm)</th>
<th>Max. one-day rainfall (mm)</th>
<th>Southern Oscillation Index</th>
<th>Storm origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>6–9 March 1988 (b)</td>
<td>754</td>
<td>648</td>
<td>329</td>
<td>+0.1</td>
<td>tropical cyclone 'Bola'</td>
</tr>
<tr>
<td>24–27 July 1985 (c)</td>
<td>388</td>
<td>310</td>
<td>185</td>
<td>-0.3</td>
<td>temperate depression</td>
</tr>
<tr>
<td>8–9 April 1982</td>
<td>219</td>
<td>219</td>
<td>161</td>
<td>-0.2</td>
<td>tropical cyclone 'Bernie'</td>
</tr>
<tr>
<td>22–28 December 1980</td>
<td>338</td>
<td>153</td>
<td>79</td>
<td>-0.3</td>
<td>temperate depression</td>
</tr>
<tr>
<td>17–22 June 1978</td>
<td>257</td>
<td>151</td>
<td>132</td>
<td>+0.3</td>
<td>temperate depression</td>
</tr>
<tr>
<td>15–16 April 1977 (d)</td>
<td>307</td>
<td>307</td>
<td>236</td>
<td>-0.8</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>29 December–1 January 1975</td>
<td>248</td>
<td>189</td>
<td>129</td>
<td>+2.3</td>
<td>temperate depression</td>
</tr>
<tr>
<td>13–16 June 1974</td>
<td>269</td>
<td>204</td>
<td>143</td>
<td>+0.1</td>
<td>temperate depression</td>
</tr>
<tr>
<td>13–14 June 1973</td>
<td>279</td>
<td>279</td>
<td>234</td>
<td>+0.8</td>
<td>temperate depression</td>
</tr>
<tr>
<td>2–3 May 1971</td>
<td>229</td>
<td>229</td>
<td>132</td>
<td>+0.7</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>2–4 June 1963</td>
<td>241</td>
<td>212</td>
<td>123</td>
<td>-1.0</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>16–20 November 1960</td>
<td>321</td>
<td>242</td>
<td>157</td>
<td>+0.5</td>
<td>temperate depression</td>
</tr>
<tr>
<td>13–16 July 1956</td>
<td>250</td>
<td>198</td>
<td>179</td>
<td>+1.1</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>30 July–1 August 1954</td>
<td>243</td>
<td>222</td>
<td>141</td>
<td>+0.3</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>2–7 March 1944</td>
<td>364</td>
<td>189</td>
<td>134</td>
<td>+0.5</td>
<td>tropical depression</td>
</tr>
<tr>
<td>3–7 September 1943</td>
<td>297</td>
<td>223</td>
<td>135</td>
<td>+0.5</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>23–27 April 1938 (e)</td>
<td>705</td>
<td>533</td>
<td>324</td>
<td>+0.3</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>25–28 May 1933</td>
<td>423</td>
<td>364</td>
<td>225</td>
<td>+0.5</td>
<td>tropical depression</td>
</tr>
<tr>
<td>8–16 February 1932</td>
<td>452</td>
<td>272</td>
<td>228</td>
<td>-0.5</td>
<td>tropical depression</td>
</tr>
<tr>
<td>12–16 May 1929</td>
<td>401</td>
<td>293</td>
<td>151</td>
<td>-1.0</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>1–2 July 1927</td>
<td>248</td>
<td>248</td>
<td>131</td>
<td>-0.2</td>
<td>temperate depression</td>
</tr>
<tr>
<td>10–12 March 1924</td>
<td>405</td>
<td>395</td>
<td>344</td>
<td>+0.2</td>
<td>tropical depression</td>
</tr>
<tr>
<td>2–6 March 1918</td>
<td>241</td>
<td>148</td>
<td>80</td>
<td>-0.4</td>
<td>tropical depression</td>
</tr>
<tr>
<td>10–13 June 1917 (f)</td>
<td>511</td>
<td>427</td>
<td>213</td>
<td>+1.6</td>
<td>subtropical depression</td>
</tr>
<tr>
<td>2–3 August 1916 (g)</td>
<td>261</td>
<td>261</td>
<td>141</td>
<td>+1.4</td>
<td>?subtropical depression</td>
</tr>
<tr>
<td>16–18 May 1914</td>
<td>348</td>
<td>253</td>
<td>142</td>
<td>-1.1</td>
<td>temperate depression</td>
</tr>
<tr>
<td>30 Mar–1 April 1910</td>
<td>420</td>
<td>334</td>
<td>212</td>
<td>+1.3</td>
<td>tropical depression</td>
</tr>
<tr>
<td>14–18 July 1906</td>
<td>352</td>
<td>215</td>
<td>110</td>
<td>+0.5</td>
<td>unknown</td>
</tr>
<tr>
<td>17–24 May 1905</td>
<td>427</td>
<td>172</td>
<td>137</td>
<td>-3.0</td>
<td>unknown</td>
</tr>
<tr>
<td>30 January–2 February 1897 (h)</td>
<td>365</td>
<td>203</td>
<td>163</td>
<td>-1.1</td>
<td>unknown</td>
</tr>
<tr>
<td>26–28 April 1895</td>
<td>354</td>
<td>319</td>
<td>184</td>
<td>-1.1</td>
<td>unknown</td>
</tr>
</tbody>
</table>

> a Southern Oscillation Index data from standardised Tahiti–Darwin sea level pressure data (NOAA www database).
> b 290 mm 31 August–3 September 1988 (subtropical depression).
> c 265 mm 13–15 March 1985 (temperate depression).
> d 309 mm 23–30 August 1977 (subtropical depression).
> e 306 mm 24–26 January 1938 (temperate depression).
> f 259 mm 12–14 May 1917 (subtropical depression).
> g 214 mm 17–18 April 1897: 201 mm 27–28 March 1897 (unknown origins).

of the storms (Table 2) were from latitudes to the north of New Zealand, i.e., of subtropical or tropical origin. Of the nine storms totalling 400 mm or more rainfall, eight were of subtropical/tropical origins, the ninth, in 1905, was of unknown origin. Furthermore, of the nine storms which produced rainfall intensities exceeding 300 mm over two days, seven were of subtropical/tropical origins, one was of temperate origin, and the other was of unknown origin.

The decadal storm frequency (derived from storms listed in Table 2) indicates that most storms occurred in the 1910s, 1970s and 1980s, with very few storms in the 1940s, 1950s and 1960s. Since
the 1940s, and particularly after 1954, there has been a change in atmospheric circulation over New Zealand with a decrease in the westerly flow pattern and an increase in northeasterly airflows (Trenberth, 1976). This has been accompanied by increased rainfall over northern and eastern North Island, warmer temperatures (Trenberth, 1976), and an increased incidence of cyclonic storms (Grant, 1981). It appears that the increased frequency of storms at Tutira since 1970 may have resulted from this trend, although the response is somewhat lagged. Salinger and Hicks (1990) have suggested that further warming may lead to an increased frequency of extra-tropical cyclones passing near to New Zealand.

5.2. Southern Oscillation Index (SOI)

In New Zealand, the Southern Oscillation is manifested by precipitation variations (Gordon, 1986; McGlone et al., 1992) such that on the east coast of the North Island, lower than average rainfall occurs in SOI negative (El Niño) years and higher than average rainfall occurs in SOI positive (La Niña) years. There are also temperature anomalies associated with SOI; Salinger (1980a) noted that New Zealand is warmer when the SOI is positive, which is associated with frequent northerly winds. Also, it is during La Niña years that tropical cyclones originate further west (Revell and Goulter, 1986) and are more likely to track towards New Zealand. There appear to have been variations in El Niño-Southern Oscillation (ENSO) activity during the 20th century as Allan (1993) has noted that Australian ENSOs were weaker from 1921 to 1941 than from 1963 to 1983. Mean annual rainfall at Lake Tutira over the 88 years for which there are complete records is 1384 mm (M.J. Page, unpubl. data) and 64 of these years (73%) experienced rainfall totals which varied in accordance with SOI (SOI data from standardised Tahiti–Darwin sea level pressures—NOAA www database). For the 42 years that had positive SOI, 30 (71%) had rainfall totals exceeding the mean, and all 11 years in which the SOI was one standard deviation above the mean had higher than average rainfall. The Lake Tutira data clearly show the link between rainfall and SOI.

The SOI for the storms listed in Table 2 shows that 58% occurred during the positive phase. Of the 15 largest storms, 65% occurred during the positive phase, and of the storms totalling 400 mm of rainfall or more, this percentage rises to 67%. These data are consistent with the northerly airflows that are characteristic of the positive phase of the Southern Oscillation in New Zealand (Gordon, 1986) in which warm subtropical air masses reach New Zealand more frequently.

6. Pre-European storm record

Six storm sediment or erosion periods are defined for the pre-European part of the core; each named after the nearest tephra datum. Where there are two storm periods adjacent to a tephra datum, the older period is numbered first, e.g., Mapara 1. The European period is not subdivided but a correlation of storm sediment pulses with those in other cores (Page et al., 1994a) is given in Fig. 3. Storm sediment periods are clearly distinguishable, as they contain >50% storm sediment, while non-stromy periods have between 7 and 18% storm sediment (Table 1).

6.1. Mapara 1 period

Near the base of the 5900 mm core (Fig. 2) is a small cluster of storm sediment pulses which were deposited ca. 2175–2155 cal. yr B.P. There are twelve pulses 1–9 mm thick, five of which have graded beds. This represents a short time interval with frequent, regularly spaced storms of moderate size.

6.2. Mapara 2 period

The largest sequence of pulses in the pre-European record is between Mapara and Taupo Tephras. It has been subdivided into three phases based on the magnitude and frequency of the pulses. The Mapara 2 (a) phase consists of 45 pulses deposited ca. 2090–1985 cal. yr B.P. There are twelve pulses 1–9 mm thick, five of which have graded beds. This represents a short time interval with frequent, regularly spaced storms of moderate size.
are >30 mm and one is 81 mm thick. Deposited ca. 1985–1935 cal. yr B.P., this phase represents a time of remarkable storminess with a high frequency of large magnitude storms totalling 89% storm sediment. The Mapara 2 (c) phase comprises 25 pulses deposited ca. 1935–1855 cal. yr B.P. The pulses are regularly spaced and frequent, although they lack graded beds and are <10 mm thick. The three phases of the Mapara 2 period have a combined total of 68% storm sediment. A core containing lake sediments from a swamp at the head of the lake indicates that the interval between Mapara and Taupo Tephras also has the highest sedimentation rate between 6500 and 1800 14C yr B.P. (Page and Trustrum, 1997).

6.3. Taupo period

Between ca. 1455 and 1435 cal. yr B.P. is a cluster of six pulses, four with graded beds. These pulses are 5–20 mm thick and represent moderate-sized storms occurring over a short time-period.

6.4. Tufa Trig 1 period

The Tufa Trig 1 period represents the second longest period of storm activity in the core, occurring between ca. 1085 and 935 cal. yr B.P. However, it is a period of moderate frequency, moderate to low magnitude storms, with the main activity and largest storms occurring at the end of the period (ca. 950–935 cal. yr B.P.). There are 43 pulses between 1 and 21 mm thick, only three of which show graded bedding. This represents the upper part of the period that Wilmshurst et al. (1997) interpreted as having a more extensive fire episode possibly relating to a prolonged period of drought. By contrast, the interval preceding the Tufa Trig 1 period contains five pulses 8–15 mm thick but not closely spaced (an average of 30 years between pulses).

6.5. Tufa Trig 2 period

At ca. 505–500 cal. yr B.P., and coincident with the onset of Polynesian deforestation in the catchment, there is a sequence of nine pulses with very little non-storm sediment. This represents an erosion response to damage to the vegetation caused by burning (Wilmshurst, 1997) which may or may not have been accompanied by an increase in storm frequency and magnitude. Seven of the pulses have graded beds, the thickest of which is 126 mm, the largest in the pre-European record.

6.6. Burrell period

The Burrell period comprises eight pulses between ca. 375 and 355 cal. yr B.P. The first six are 2–4 mm thick and the last two are 12 mm and 47 mm thick (graded bed).

6.7. Individual storm pulses

The following large individual graded beds occur in the intervals between erosion periods: an 8 mm pulse at 5730 mm (ca. 2130 cal. yr B.P.) (Fig. 2); a 16 mm pulse immediately after the Taupo Tephra at 4459 mm (ca. 1718 cal. yr B.P.); a 29 mm pulse at 3034 mm (ca. 800 cal. yr B.P.); a 15 mm pulse at 2603 mm (ca. 540 cal. yr B.P.); a 10 mm pulse at 1880 mm (ca. 280 cal. yr B.P.); and a 16 mm pulse at 1636 mm (ca. 175 cal. yr B.P.).

In all, there are 340 storm sediment pulses in the 2160 calendar years before European settlement. This gives an average of a storm every 6.4 years. Storm return periods for each interval are given in Table 3.

7. Sediment thickness–storm rainfall relationship

Core LT15 provides a unique record of the frequency and timing of palaeo-storms. However, in the absence of rainfall records the magnitude of these storms is unknown. The study of the European sedimentation history of the cores by Page et al. (1994a) showed that small storms with rainfalls between 150 and 200 mm deposited <5 mm sediment in the lakes, and that only storms with rainfalls >300 mm produced significant (>12 mm) layers. However, these rainfall totals relate to a pasture landscape, and triggering thresholds would have been higher under the fern/scrub and forested landscapes that prevailed before Europeans arrived. The relationship between sediment thickness and storm rainfall for the European period under pastoral farming was used to estab-
lish an indicative, relative measure of magnitude for palaeo-storms. In order to account for the lower sedimentation rate under forest, the sediment thicknesses for a given rainfall event were reduced by a factor of 6.1 representing the difference in storm sedimentation rate between pasture and forest (bulk density data indicate there is negligible compaction down the core; Page et al., 1994a). Using this relationship, storm sediment pulses of ca. 3 mm were the result of ca. 300 mm storms, and pulses of ca. 12 mm were the result of ca. 450 mm storms. The number of storms is listed according to these sediment thickness categories for each period in Table 3.

The average interval between storms before European settlement is 6.4 years. The Tutira rainfall record for the 93 year period between 1895 and 1988 shows that storms with intervals of 6–7 years have totals of 325–350 mm (assuming European storm frequency is similar to that of the preceding 2177 calendar years).

Analysis of annual rainfall records at Tutira shows that years with large rainstorms tend to have higher than average annual rainfall: 66% of years with rainstorms >300 mm and 85% for rainstorms >400 mm. This would suggest that storm periods represent intervals of higher rainfall and the inter-storm intervals lower rainfall. Hicks (1995), in a study of 167 landslide events throughout New Zealand, has established a relationship between the frequency (return period) of major climatically induced landslide events and mean annual rainfall. Rainfall totals required to induce such events under pasture at Tutira are of the order of 250–300 mm in 2–3 days (Page et al., 1994a; Hicks, 1989). Although the relationship was established for pastoral hill country, the sediment thickness–storm rainfall relationship for forest, derived from the Tutira data, indicates that storms with ca. 300 mm totals are the approximate threshold for the generation of lake sediment. Therefore, applying the return period for storms for each storm period and inter-storm interval (Table 3) to Hicks’ model may give an indication of the mean annual rainfall for the period/interval. On this basis, the Mapara 2 (a) and (c), Taupo, Tufa Trig 1 and Burrell periods had mean annual rainfall of 2000–3000 mm while the Mapara 1 and Mapara 2 (b) periods had mean annual rainfall >3000 mm. Mean annual rainfall for inter-storm intervals was less than present.

8. Climatic significance

Analysis of the European (post-1895) part of the record reveals that most of the sediment-
generating storms originated from subtropical/tropical latitudes. Also, the majority of storms occurred at times when the Southern Oscillation was in its positive (La Niña) phase. The prevalence of northeasterly airflows during Las Niñas, and the subtropical origins of storms, imply overall warmer temperatures at these times. The Tutira storm record provides a measure of past precipitation because the years which experienced storms were likely to have had above average rainfall based on the historic record. Also, precipitation variations may be strongly associated with the frequency of storm tracks and associated trajectories of airflow behind or ahead of storms (Salinger, 1980b). Therefore, the temporal distribution and frequency of storms in the Tutira record provide information on past precipitation, temperatures and Southern Oscillation Index.

The most striking stormy period in the Tutira record is the Mapara 2 period which occurred ca. 2090-1855 cal. yr ago and lasted 235 years. This was a period of frequent storm activity, and the central part of the period, in particular, comprised a succession of major storms, with very few interruptions, which lasted for about 50 years. The period represents a time of above average rainfall. By extrapolation from weather patterns in the European period, it is likely that there were increased northerly airflows and associated trajectories of airflow at this time as subtropical and tropical air masses penetrated to the eastern North Island more frequently. Correspondingly, it is most likely that the Southern Oscillation would have been dominantly in its La Niña phase.

Other stormy periods, e.g., Mapara 1 (ca. 2175-2155 cal. yr B.P.), Taupo (ca. 1455-1435 cal. yr B.P.), and Burrell (ca. 375-355 cal. yr B.P.), were generally of short duration. These, too, probably represented wetter than average periods with increased northerly airflows, frequent incursions of subtropical air masses, and positive SOI. The long Tufa Trig 1 period of moderate frequency, moderate to low magnitude storms from ca. 1085 to 935 cal. yr B.P. probably represents similar climatic conditions but at a lower magnitude. For example, the lower magnitude of the storms may indicate there were proportionally fewer subtropical air masses, which are those most capable of producing high intensity rainfalls. Correlation with changes in the pollen record from adjacent core LT16 (Wilmshurst et al., 1997) relating to a period of forest disturbance and inferred drought suggests that El Niño episodes also may have been more pronounced at this time.

The six large storm sediment pulses recognised outside the storm periods represent single storms which probably originated from subtropical latitudes during Las Niñas. Because they are not part of a sequence of storm events extending over a period of years they are of lesser value in terms of climatic trends. Consequently their relationships have not been analysed in this paper.

8.1. New Zealand palaeoclimatic evidence

Evidence for New Zealand palaeoclimates over the last 2000 years is derived largely from glacial evidence, speleothems, tree rings and pollen (Burrows and Greenland, 1979). Much of the evidence relates to past temperatures and precipitation. The glacial record shows a regular series of South Island valley glacier advances which occurred at 2700-2200, 1800-1700, 1500, 1100, 900, 700-600, and 400-100 14C yr B.P. (Gellatly et al., 1988). Glacial advances are complex responses to mass balance changes, not necessarily related to temperatures (Bradley and Jones, 1993). For example, the recent advances of glaciers in southern South Island have been attributed to more frequent Los Niños since 1980 (Jones, 1996).

The Mapara 1 and 2, Taupo, and Tufa Trig 2 storm periods clearly correspond to intervals between ice expansion episodes while the Tufa Trig 1 and Burrell periods correspond to or overlap with glacial advances (Fig. 5). The latter suggest that the relationship between North Island storm events and inferred warmer periods between glacial advances are not simple systems. Also, it is not possible to interpret their relationships with confidence in view of the inexact dates of the glacial advances.

Speleothem evidence of palaeotemperatures from northwest Nelson, South Island (Fig. 5; Wilson et al., 1973) which spans the last 800 years, indicates that the Tufa Trig 2 period corresponds to a cold interval in the mid-1400s while the Burrell
period corresponds in part with a warm interval in the mid-1500s.

Tree palaeotemperatures extending back to A.D. 950 determined from cellulose $\delta^{13}C$ variations in *Agathis australis* from northern New Zealand (Grinsted and Wilson, 1979) show that there was a warm interval at around A.D. 1000 which corresponds to the Tufa Trig 1 period (Fig. 5).

Tree ring data on palaeoclimates, from information on silver pine (*Lagarostrobos colensoi*) from the South Island west coast, extends back to the mid-1300s (D’Arrigo et al., 1995). Both the Tufa Trig 2 and Burrell periods occurred during warm intervals in the tree ring record (Fig. 5). Other tree ring records based on *Nothofagus* and *Phyllocladus* (Norton and Palmer, 1992) and *Halocarpus biformis* (D’Arrigo et al., 1995) do not extend far enough back in time to encompass any of the Tutira storm periods.

Pollen evidence for the last 3000 years (McGlone et al., 1992) indicates that vegetation was tolerant of climatic extremes such as droughts and disturbance by fires, but at the same time numerous bogs and swamps were being initiated, suggesting that winters may have been wetter. McGlone et al. attributed these changes to an increased amplitude Southern Oscillation. At this stage no studies appear to have reported vegetation responses over shorter (e.g., century-scale) climatic oscillations.

Of the limited New Zealand palaeoclimatic evidence for the last two millennia only the glacial evidence covers the whole period; the greatest opportunities to make comparisons are in the last 500–1000 years. However, the patterns in Fig. 5 show only a partial agreement as to the timing of warm/cold periods. This may be due to the various proxy data responding in different ways to climate change. The tree-ring data provide the best chronologies since they are annually resolved, while other records have a coarser resolution. From tree-ring evidence, it appears that both the Tufa Trig 2 and Burrell periods occurred during warm periods which supports the idea that stormy periods relate to times when the climate was warmer overall.

### 8.2. Southern Hemisphere and global palaeoclimates

New Zealand evidence for climatic fluctuations over the last two millennia is scanty, and there are few detailed palaeoclimate records for the Southern Hemisphere as a whole (Bradley and Jones, 1993). The best of these are the oxygen isotope studies of ice cores from Antarctica (Mosley-Thompson et al., 1993), and Peru (Thompson et al., 1986), together with tree-ring data from Chile (Lara and Villalba, 1993), Argentina (Villalba, 1990), and Tasmania (Cook et al., 1991, 1992, 1996). They provide data to an annual resolution on regional climates over much of the period.

The last millennium in Europe has been described as comprising two periods of contrasting climate, the Medieval Warm Period, from about...
the ninth to the fourteenth centuries (Hughes and Diaz, 1994), and the Little Ice Age, from about the sixteenth to the nineteenth centuries (Jones and Bradley, 1992). In their review of the Medieval Warm Period, Hughes and Diaz (1994) conclude that there is no compelling evidence for a global warm period at this time although there is evidence to suggest that some regions were warmer than in succeeding centuries.

Some authors find evidence for colder conditions in the Little Ice Age: e.g., Stuiver et al. (1995) using δ^{18}O values from ice core GISP2 in Greenland inferred mean summer temperatures were about 1.7°C colder in the Little Ice Age compared with the Medieval Warm Period, while Thompson et al. (1986) found δ^{18}O values from the Queleccaya ice cap in Peru implied a sustained cold interval between A.D. 1530 and 1900. By contrast, in reviewing the global data over this time interval, Jones and Bradley (1992) find that there is no evidence for a global Little Ice Age and that the interval comprised cold and warm episodes.

Overall, it would seem that the last millennium has had a complex climate history with frequent short-lived temperature fluctuations and marked differences in the climatic conditions experienced in different regions but with little evidence for globally synchronous episodes.

Of interest here is whether the Tutira storm record shows any similarities with regional and Southern Hemisphere climatic patterns. The longest high resolution record relatively close to New Zealand is the 2792 yr Huon pine (*Lagarostrobus franklinii*) tree-ring record from Tasmania (Cook et al., 1991, 1992, 1996). This record represents one of the few proxy records of climate change in the Southern Hemisphere long enough to be compared with the Tutira storm record. Also, the Tasmanian record probably has been influenced by similar climatic factors since New Zealand and Tasmania both occupy oceanic positions at similar latitudes within the circumpolar westerlies. This record (Fig. 6) shows warm intervals at the times of all the Tutira storm periods except for the Tufa Trig 2 period (which is elsewhere shown to represent a deforestation signal). However, since temperatures were above average half the time it is possible that some of the correspondence may be fortuitous. Nevertheless, the warm intervals corresponding to the Mapara 1, Mapara 2 and Tufa Trig 1 periods appear to have had sustained temperatures above the average (Cook et al., 1991, 1996). The *Lagarostrobus franklinii* warm intervals at A.D. 940–1000 (matching the Tufa Trig 1 period) and A.D. 1100–1190 both occurred during the Medieval Warm Period. They also correspond to the ca. 1000 yr B.P. warm interval that is the subject of investigation under the PANASH programme (Bradley et al., 1995). The *Lagarostrobus franklinii* tree-ring record shows both warm and cold episodes over the duration of the Little Ice Age. The Burrell period also occurred during this time.

Other long records are the alerce (*Fitzroya cupressoides*) tree-ring chronologies from southern Chile (Lara and Villalba, 1993) and Patagonia (Villalba, 1990) which extend up to 3620 years. The climatic forcing factors influencing these chronologies are determined by the strength of the prevailing westerlies and their relationship to the southeastern Pacific high pressure cell and the position of the Antarctic pack-ice border (Villalba, 1990). The temporal distribution of above average temperatures (Fig. 6) shows close similarities to the Tasmanian record for the early part of the record up to A.D. 1000. The longest period with temperatures above average was from 80 B.C. to A.D. 160 (Lara and Villalba, 1993) which corresponds closely to the Mapara 2 period (140 B.C. to A.D. 95). The Mapara 2, Taupo, Tufa Trig 1 and Tufa Trig 2 periods all correspond, at least in part, to warm intervals in the *Fitzroya cupressoides* record. The Tufa Trig 2 period occurred at a time when there was a major oscillation from cold to warm temperatures.

A shorter *Fitzroya cupressoides* tree-ring record from northern Patagonia (Villalba, 1990) shows some variations comparable to the Chilean record (Fig. 6). In particular, Villalba finds that the period A.D. 1080–1250 was warm and dry, and correlates this with the Medieval Warm Period. He also recognises a short, generally warm interval from A.D. 1380 to 1520 which occurred at the
time of Tufa Trig 2 period. The Tufa Trig 1 period (A.D. 864–1014) occurred when there were at least nine cold/warm climate oscillations representing departures of 1°C from average in Villalba’s tree-ring record. This was also the time that Wilmshurst et al. (1997) recognised an intense fire episode at Lake Tutira which they considered represented a prolonged period of drought.

Ice core δ¹⁸O chronologies from Quelccaya, Peru and South Pole, Antarctica (Mosley-Thompson et al., 1993) show mostly similar patterns even though the climatic forcing factors are different. The Quelccaya precipitation is driven by convection over the Amazon which is related to seasonal shifts in the Inter-Tropical Convergence Zone while South Pole precipitation arises from winter accumulation of ice crystals under clear sky conditions (Mosley-Thompson et al., 1993). Perhaps not surprisingly these do not resemble the tree-ring patterns very closely (Fig. 6). While the Tufa Trig 2 period corresponds to inferred warm intervals from the δ¹⁸O chronologies, the Burrell period does not.

It was expected that the Tutira storm periods would match best with areas that have comparable climatic forcing factors, e.g., Tasmania and Chile which are within the belt of circumpolar westerlies. This is borne out for at least the older part of the record before about A.D. 1000 (Fig. 6). Nevertheless, the comparisons in Fig. 6 show that all Tutira storm periods correspond to some of the warm intervals in the various chronologies. The Mapara 2, Taupo, Tufa Trig 1, and Tufa Trig 2 have the best matches. Some of these matches may be fortuitous. However, the correspondence of the Mapara 2 period with sustained warm intervals in both Tasmania and Chile suggests that the Tutira record here is reflecting a hemispheric signal. The Tufa Trig 1 period appears to support evidence from Tasmania and Chile for short warm climate intervals at about the time of the Medieval Warm Period. By contrast, the Burrell period occurred during the Little Ice Age which is consistent with Bradley and Jones (1993) evidence that this was a time of fluctuating climates.

8.3. El Niño-Southern Oscillation (ENSO)

The historical rainfall record from Tutira shows relationships between storm events, wet years and SOI. It is therefore likely that most of the storm sediment layers in the pre-European part of the core were deposited during SOI-positive phases. The clusters of storm layers which constitute storm periods may indicate times when the Southern Oscillation was mostly in its positive phase.
The magnitude and frequency of past ENSO events are well established for the last 400 or so years for which there have been historical records with which to verify sequences. There have been some attempts to extend the record further back in time, e.g., Quinn (1992). Tree rings have provided one of the best proxy records of ENSO to date and have been used to determine past frequencies of ENSO (Michaelsen, 1989). He established that ENSO fluctuated in amplitude and frequency over 80–100 year scales and noted that high-frequency periods occurred in the early parts of the 1600s, 1700s, 1800s, and 1900s and low-frequency periods in the later parts of the 1600s, 1700s, and 1800s. Using oxygen isotope ratios of corals, Dunbar et al. (1994) found that ENSO events occurred in higher frequencies from early to mid-1700s and from the mid to late 1800s. The high-frequency periods also contained more moderate to strong events. Over this century, Anderson (1992) has noted a decrease in the frequency and amplitude of El Niño between the 1920s and 1960s, and Allan (1993) noted that the SOI teleconnections were weakened between 1921 and 1941. Overall, however, Enfield and Cid (1991) find no long term increases or decreases in the frequency of ENSO over the last 400 years—which includes the duration of the Little Ice Age.

The Burrell is the only storm period which can be related to the historical ENSO record. This period (A.D. 1575–1595) occurred at a time of medium to high overall El Niño activity (Enfield and Cid, 1991) in which three significant Los Niños occurred (Orthlieb and Macharé, 1993) and a time of generally high growth rates in Galápagos corals (Dunbar et al., 1994). Other Tutira storm periods may have occurred at times of increased ENSO activity, e.g., Wilmhurst et al. (1997) pollen studies for Lake Tutira (core LT16) which show vegetation disturbance resulting from fires and inferred drought at the time of the Tufa Trig 1 storm period. These could suggest that the climate regularly fluctuated from La Niña (storms) to El Niño (drought and fires) at this time. Major temperature fluctuations associated with the Mapara 1 and 2 periods may also reflect increased ENSO activity at these times, although there are no data with which to verify this at present.

### 9. Other evidence for periods of erosion within New Zealand

The six pre-European storm sediment clusters in the Tutira lake record represent periods of increased erosion within the catchment. Although it is a local record, contemporary observations indicate that large storms are often widespread (e.g., Cyclone Bola in 1988 affected most of the North Island), and so we consider the Tutira record to have regional significance.

#### 9.1. New Zealand-wide erosion periods

Grant (1985) proposed eight New Zealand-wide erosion periods based on alluvial sedimentation, and McFadgen (1985) proposed three depositional episodes (two with unstable and stable phases), based on coastal deposits. Both cover the interval since the eruption of Taupo Tephra (1718 cal. yr B.P.) and are based on the dating of deposits from a wide range of sites throughout New Zealand. Concerns exist over aspects of both studies: Grant’s over the validity of establishing a New Zealand-wide erosion chronology based on limited data, especially for northern and southern New Zealand, and whether national patterns of erosion activity are likely to exist in a country which extends over 12° of latitude, and which has marked regional contrasts in climate; McFadgen’s for the use of Loisels Pumice, a sea-rafted pumice, which is now known to be time transgressive in coastal deposits (Osborne et al., 1991), as an isochronous marker layer between sites. Both studies are affected by the uncertainties introduced into the alluvial and coastal records by differences in the 14C age of the charcoal and the date of deposition of the surrounding mineral sediment.

Grant’s periods were at ca. 1718 years (using the current calendar age for the Taupo eruption), 1600–1500, 1300–900, 680–600, 450–330, 180–150, 80–50 cal. yr B.P. and since A.D. 1950. He considered the periods were due to an increased frequency of major rainstorms resulting from increased northerly airflows. McFadgen’s three depositional episodes were the Tamatean 1718–600 (unstable) 600–450 (stable), Ohuan 450–400 (unstable) 400–150 (stable), and Hoatan 150 cal. yr
B.P. present (unstable). He suggested a relationship to changes in the frequency of tropical and extratropical cyclones that parallels Grant’s suggestion.

The Tutira erosion chronology, derived as it is from a single stratigraphy, is compared with the erosion periods of Grant and McFadgen in Fig. 7. The Mapara 1 and Mapara 2 erosion periods identified in the Tutira record are not present in Grant’s and McFadgen’s chronologies which extend only as far back as Taupo Tephra (1718 cal. yr B.P.). The erosion periods identified in the Tutira record are of shorter duration than those of Grant and McFadgen. This is not surprising given that the Tutira record is a local, high resolution one, in contrast to the geographically widespread data used in the other chronologies.

Wilmshurst et al. (1997) have identified the impacts of volcanic activity, natural fires, storms, and Polynesian burning on the vegetation of the Tutira catchment in a palaeoecological investigation of core LT16. In an analysis of erosion pulses they do not identify clusters of storm sediment pulses and conclude that there is no correlation between the timing of pulses and the erosion and deposition periods of Grant (1985) and McFadgen (1985). Their conclusion differs from evidence presented in this paper which is based on core LT15, only 30 m from LT16, at a similar depth and in a similar depositional environment in the lake. Wilmshurst et al. (1997) analysed only those pulses 10 mm or thicker which had graded bedding (smaller pulses were taken to represent low-intensity autumn/winter rainfall events and were not included). In this paper we analysed all visible storm sediment pulses on the basis that under a forest or scrub cover even 1 mm pulses represent significant storms.

We consider that the Tutira record and Grant’s chronology have two periods in common. They are the Tufa Trig 1 with Grant’s Pre-Kaharoa, and the Burrell with Grant’s Matawhero.

It is difficult to assess the significance of the match between the Tutira record and Grant’s erosion periods since the 14C dates used to define Grant’s erosion intervals could have been interpreted differently, and also that as his erosion periods span 43% of the time since the Taupo eruption some matches could be fortuitous. No correlation can be seen between the Tutira chronology and that of McFadgen. Nevertheless, the Tutira record does support the concept of climatically driven periods of increased erosion, at least on a regional scale.

9.2. Regional erosion periods

Pullar and Penhale (1970) identified five periods of infilling on the Gisborne Plains (110 km north-east of Tutira) using buried soils and tephra marker beds. Two of these records have relevance to this study. Period 1 (Kaiti Formation), defined as the
period between Waimihia Tephra (3280 $^{14}$C yr B.P.) and Taupo Tephra (1850 $^{14}$C yr B.P.), was a period of rapid erosion and infilling. At about 2100 $^{14}$C yr B.P. intense sedimentation buried and killed forest on the floodplain at Matawhero (Pullar and Patel, 1972), and rapid erosion in the Ngatapa Valley, west of Patutahi, led to the development of a large fan which ceased after the Taupo eruption (Pullar and Penhale, 1970). Pullar and Penhale relate this period of erosion and sedimentation to earthquakes on the evidence of tilting before the Taupo eruption at a nearby site and the suggested formation of Lake Waikaremoana by a large landslide at the time. Pullar and Patel also point to submerged dune sediment in the Bay of Plenty with a 2100 $^{14}$C yr B.P. tephra overlying it, 1.8 m below sea level, which they suggest may have resulted from earth movements.

The date of 2100 $^{14}$C yr B.P. corresponds to the Mapara 2 period, which stands out as containing the thickest and most numerous sediment pulses, and raises the question of whether earthquakes were the trigger for these periods of increased sedimentation in the Tutira record.

The second period, Pullar and Penhale’s Period 3 (Early Matawhero Formation), began around A.D. 1650 with rapid erosion and infilling. Evidence for the date and cause comes from Grant (1963) who reported catastrophic storm damage to forests in the Huiaarau Range, 60 km north of Tutira (and 75 km west of Gisborne), a ‘few decades before A.D. 1650’. This is close to the end of the Burrell period in the Tutira record.

10. Role of Earthquakes

Seven faults occur within 100 km of Lake Tutira with one only 15 km from the lake. Berryman et al. (1989), in an analysis of Holocene marine terraces on the east coast of the North Island, identify at least 21 paleoseismic events in the last 2500 years. Episodes of activity occurred 300, 500–600, 900–1000, 1500–1600, 2000–2100, and 2300–2400 $^{14}$C yr B.P. along different parts of the east coast. At Mahia Peninsula, 100 km to the northeast of Tutira, uplift occurred at ca. 1900 $^{14}$C yr B.P. This is near the latter part of the Mapara 2 (c) phase.

Hull (1987) reports a marine terrace from the Kidnappers coast, 50 km to the south of Lake Tutira, probably due to a large earthquake ca. 2300 $^{14}$C yr B.P. and the possibility of one or more post-2300 $^{14}$C yr B.P. uplift events. Cutten et al. (1988) in a study of the Rangiora Fault, only 15 km from Lake Tutira, using offsets and ages of river terraces, identify one faulting event between 3300 and 1900 $^{14}$C yr B.P. and two after 1900 $^{14}$C yr B.P., and, based on road-cut exposures, two events between 3300 and 1900 $^{14}$C yr B.P. and two after 1900 $^{14}$C yr B.P.

These studies show that the east coast of the North Island has experienced regular seismicity in the last 2500 years. Earthquakes between 2000 and 2300 $^{14}$C yr B.P. may have contributed to the magnitude if not the frequency of some storm sediment pulses in the Mapara 2 period. This would have been accomplished through ground-shaking and disturbance thereby increasing the susceptibility of soils to later storm erosion.

However, the pattern of sediment pulses in the Mapara 2 period shows no evidence to suggest sudden earthquake initiation, with the largest pulses occurring towards the end of the (b) phase and a sudden reduction in pulse thickness at the onset of the (c) phase. Nevertheless, evidence of earthquake activity may be recorded during the period. Between 5210 and 5245 mm [Mapara 2 (b) phase], four sediment pulses which formed the lake bed surface at that time have a disrupted, wavy appearance. A similar record of the 1931 Hawke’s Bay earthquake is preserved in core LW3 from adjacent Lake Waikopiro (Page et al., 1994a). As a shallow (ca. 15 m), rapidly accumulating site it may be more suited than the site of LT15 (37 m) for recording earthquake tremors, and thus explain the paucity of such evidence in LT15.

11. Conclusions

Sediments from Lake Tutira on the east coast of New Zealand provide a high resolution record
of storms for the last ca. 2250 years. Without human influence for much of this time it is a record of natural climatic variability and landscape response. It provides the most detailed evidence of late Holocene storm magnitude and frequency yet identified for New Zealand.

Three hundred and sixty five storm sediment pulses were identified at an average of one storm every ca. 6 years. Six periods of increased sedimentation, five of which are related to increased storm frequency, were recognised in the pre-European record. Their dates are as follows: 2175–2155, 2090–1855, 1455–1435, 1085–935, 505–500, and 375–355 cal. yr B.P.

Of the six storm periods, the Mapara 2 period (2090–1855 cal. yr B.P.) had the highest frequency and magnitude storms and lasted more than 200 yr, while the other periods generally were of much shorter duration.

The historical rainfall record has been used to infer likely climatic conditions before European arrival. It is inferred that most large storms were of subtropical/tropical origin. A majority of storms probably occurred during ENSO La Niña phases when northeasterly airflows would have been more frequent and temperatures warmer. The storm record is a precipitation record with at least five of the storm periods representing periods of above average rainfall.

Due to the paucity of detailed records, difficulties exist in correlating with New Zealand and Southern Hemisphere palaeoclimatic records, particularly before 1000 yr B.P. Nevertheless, the Mapara 2 period corresponds to sustained warm temperatures in the Tasmanian and Chilean tree-ring records which might indicate that the period represents a Southern Hemisphere-wide climate anomaly.

The Tutira record provides data relevant to several PANASH programme objectives, e.g., increased precipitation was likely to have occurred over the eastern North Island during five of the storm periods; the Tufa Trig 1 period corresponds to the early part of the Medieval Warm Period suggesting warmer temperatures occurred in New Zealand at this time; and the Burrell period occurred during the Little Ice Age, confirming the fluctuating climates over this interval.

Only the Burrell storm period can be directly compared with the historical ENSO record and it appears to have occurred at a time of moderately high El Niño activity. Temperature and precipitation fluctuations implicit in the Tufa Trig 1 period may signal increased ENSO activity at this time, while the wetter and warmer conditions inferred for the Mapara 2, and possibly Mapara 1, periods suggest that La Niña events were either more frequent or more pronounced at these times.

Some periods show similarity with New Zealand-wide periods of increased erosion and sedimentation proposed by Grant (1985). Although the storm sediment pulses are dominantly a climatic signal, in some instances the possibility of earthquakes accentuating the effects of storms cannot be discounted.

Relationships between sediment thickness and storm rainfall and between storm frequency and mean annual rainfall have provided an indication of the magnitude of storms in the pre-European record. Under the forested or fern/scrub covered landscape, sediment pulses ca. 3 mm thick represent storm rainfalls of ca. 300 mm, and pulses ca. 12 mm thick represent storm rainfalls of ca. 450 mm.

This paper has demonstrated the potential of Lake Tutira sediments to provide a high resolution record of palaeoclimatic conditions. It provides a framework for a more detailed analysis of ENSO and precipitation fluctuations over the last two millennia, and by further coring to extend the record to lake formation 6500 years ago.

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