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Coastal dune ridge systems as chronological markers of palaeoseismic activity: a 650-yr record from southwest New Zealand

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Abstract: A study of two shore-parallel dune ridge sequences in southwest New Zealand shows that tectonic activity has been the primary controlling influence in their formation since at least AD 1450. The timing of dune-building episodes at the mouths of the Haast and Okuru Rivers was determined using the ages of colonizing trees. Episodic dune formation was indicated by clear discontinuities in tree ages, with distinct cohorts having colonized successive, newly formed, dune ridge-swale units. At both sites, four dune ridge-swale units have formed since AD 1450, with each unit closely postdating an Alpine fault rupture (*c.* AD 1460, *c.* AD 1615, AD 1717, AD 1826). Colonizing cohorts of trees started growing within 20–46 years after an earthquake at both sites, and all known major regional earthquakes have resulted in a dune-building episode. No other dunes are present at either site. Progradational coastal dune systems have potential as a tool for palaeoseismic studies. In regions with high background levels of sediment delivery to limit erosion/burial of dunes and with little coseismic subsidence, dune systems may preserve a spatially discrete record of major earthquake-induced sedimentation events over the Holocene. Earthquakes are a key driver of palaeoenvironmental change and coastal plain development in this tectonically active region.

Key words: Coastal dunes, palaeoseismic activity, Alpine fault, sediment supply, earthquakes, landslides, river, tree ages, New Zealand, late Holocene.

Introduction

Coastal dune ridge systems occur in close proximity to many large, active fault zones including those of the western USA (Cooper, 1958), eastern Russia (Pinegina and Bourgeois, 2001) and southwest New Zealand (Coates and Nathan, 1993; Dickinson and Mark, 1994). Palaeoseismological research in these areas has traditionally been concerned with identifying geological or geomorphological features associated with the immediate effects of past earthquakes, such as tsunamis, uplift or subsidence, with the aim of estimating earthquake magnitude and/or frequency (eg, Berryman *et al.*, 1989; Meyers *et al.*, 1996; Atwater, 1997; Goff *et al.*, 2000; Pinegina and Bourgeois, 2001). For example, studies of the extensive dune systems of northwestern USA indicate that great subduction earthquakes accompanied by coseismic subsidence have led to cycles of catastrophic erosion followed by progradation and dune ridge formation before the next earthquake (Meyers *et al.*, 1996; Phipps *et al.*, 2001).

However, in tectonic settings where there is little or no subsidence to erode former dunes but where there are high sediment yields, dune ridges themselves may preserve a record of large regional earthquake events. On a catchment-wide basis Goff and McFadgen (2002) have linked proposed post-earthquake changes in a model in which factors such as forest disturbance (Veblen *et al.*, 1992; Wells *et al.*, 1999; Cullen *et al.*, 2003), landslides (Adams, 1981), increased fluvial sediment transport and aggradation (Adams, 1980; Grant, 1985), and rapid coastal dune building (McFadgen, 1985; Moseley *et al.*, 1991) combine to create a sequence of geomorphological responses to an earthquake. In this model large pulses of sediment created by coseismic landsliding are rapidly moved to the coast where they leave a clear signature in the landscape. Researchers have also speculated that the dramatic coastal dune ridge sequences in southwest New Zealand may in part be

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due to the after-effects of large Alpine fault earthquakes (Coates and Nathan, 1993; Berryman and Hull, 2003). Several large earthquakes have occurred on this fault over the past few centuries, with four events already dated to AD 1826, AD 1717, *c.* AD 1615 and *c.* AD 1460 (Wells *et al.*, 1999, 2001; Norris *et al.*, 2001).

Most aspects of Goff and McFadgen's (2002) model have been clearly demonstrated, with large earthquakes causing severe tsunami, landsliding, forest toppling and river aggradation (eg, Adams, 1980, 1981; Veblen *et al.*, 1992; Yetton, 1998; Goff *et al.*, 2000; Cullen *et al.*, 2003). However, the potential flow-on effects of these processes with respect to rapid delivery of sediment to the coast and associated changes in dune systems have received little attention. Without this, formation of dunes in New Zealand, for example, has generally been attributed to eustatic sea-level fluctuations together with recent progradation of the coast (eg, Suggate, 1989), anthropogenic land disturbance (eg, Cowie, 1963) or climatic shifts of alternating stormy and calm periods (eg, McFadgen, 1985; Coates and Nathan, 1993).

Nevertheless, the rapid movement of earthquake-derived material to the coast following historical earthquakes has been recorded. Most work on this subject has been undertaken in the Southern Hemisphere, primarily in South America and New Zealand. In AD 1970, a 7.7 Mw earthquake in northern Peru caused large and extensive landslips (Moseley *et al.*, 1991). During the El Niño of AD 1972–1973, heavy rainfall and floodwaters rapidly transported the sediment in to rivers and downstream to the coast, and within two years dunes moved inland, burying archaeological sites and disrupting human occupation of the coast. Following the AD 1929 Murchison earthquake (Mw 7.8) in New Zealand the majority of sediment had moved to the coast within a decade (Adams, 1981), while in the eastern South Island McFadgen and Goff (2005) have proposed a geomorphological relationship over 4000 years between fault ruptures and consequent river aggradation and coastal dune building.

Despite this, there has been no detailed study investigating the relationship between past seismic activity and coastal dune formation, or assessing the possible use of dune ridge systems as off-fault records of palaeoseismicity. This paper reports on a study carried out on the Haast and Okuru River dune ridge systems in southwest New Zealand. Our aim is to establish the relationship between large earthquakes and coastal dune formation in a tectonically active region, and to assess the potential usefulness of coastal dune systems for palaeoseismic investigations. We test the idea that the dune ridge sequences represent a record of large earthquakes, rather than the gradual accumulation of material or being related primarily to climatic events, by using tree ages to examine the coincidence of timing between dune ridge formation at Haast and Okuru and the four large Alpine fault earthquakes since AD 1450. We show that distinct dune ridges formed at Haast and Okuru following all four of these earthquakes.

Study area

Haast and Okuru dune systems

The Haast and Okuru dune ridge systems are located in south Westland, New Zealand (Figure 1). They extend up to 5 km inland and over 20 km of coast (Dickinson and Mark, 1994). Coastal processes in the region are dynamic and rapid, with frequent fierce seas and high wave energy. Sand transported downriver by the Haast and Okuru/Turnbull Rivers is carried north by longshore drift and supplies material to the rapidly prograding coastline. Progradation of the coast in this area is believed to have been taking place since sea level stabilized some 6000 years ago (Molloy, 1988). The catchments drain over 150 km of the main divide of the Southern Alps. Haast River is the larger of the two catchments, covering an area of approximately 1350 km^2, as opposed to about 750 km^2 for the Okuru/Turnbull catchment. The Haast catchment is distinctive in that its major tributary flows parallel to the coast for many kilometres, so that its catchment drains a large area of country to the north of the river's mouth at the Tasman Sea.

Both catchments drain semi-schistose greywacke and argillite bedrock near the main divide of the Southern Alps, with the bulk of their catchments comprised of well-foliated schists that are prone to slumps and failures (Tonkin and Basher, 1990; Cox and Findlay, 1995). Topography is strongly influenced by the plate boundary at the Alpine fault (Whitehouse, 1988). East of the fault the Southern Alps rise abruptly, resulting in the central and upper reaches of valleys having narrow boulder-choked river beds and steep-sided valley walls. West of the fault the rivers flow across extensive outwash surfaces up to 10 km wide, built up following deglaciation (McEwen, 1987). Precipitation in the region is frequent and heavy throughout the year; mean annual rainfall varies from about 3500 mm at the coast to up to 10 000 mm in the front ranges of the Southern Alps (Griffiths and McSaveney, 1983). The combination of high rainfall, steep topography and weak rocks makes the area very susceptible to erosion. Consequently the Haast River has one of the highest sediment yields in the world, at around 12 736 t/km^2 per year, or 17.2×10^6 t/yr for the catchment (Griffiths, 1979; Griffiths and Glasby, 1985). Flow records are also available for the Haast River, which has a mean flow of 193 m^3/s and a mean annual flood of 3725 m^3/s (Griffiths, 1981). In general terms, the region is characterized by a strongly perhumid and mesothermal climate, such that temperate rainforest dominates vegetation up to the timberline at about 1300 m altitude (Wardle, 1980).

The episodic nature of coastal plain accretion is demonstrated by shore-parallel dune ridges that occur on both coastal plains (Figure 2). These distinctive dune ridges and the rapid progradation in the region have generally been attributed to climatic shifts, in which long periods of stormy weather (which deliver much sediment to the coast and build dunes) alternate with periods of relative quiescence (Coates and Nathan, 1993). Some researchers have speculated that earthquake-derived sedimentation from ruptures of the nearby Alpine fault may also be a possible contributing factor to the development of the dune ridge systems (Coates and Nathan, 1993; Berryman and Hull, 2003). Others, however, have proposed that similar dune ridge sequences 350 km further north near Barrytown resulted from minor eustatic sea-level fluctuations together with recent progradation of the coast (Suggate, 1989).

Dune morphology varies between the two sites, with the larger Haast River catchment being associated with a larger dune ridge system. The Haast system is extensive (*c.* 10 km alongshore × 5 km inland), with dunes 20–100 m wide, rising 1.5–3.5 m above adjacent dune slacks (Dickinson and Mark, 1994), while dunes at the Okuru/Turnbull site (*c.* 5 km × 3 km) are up to 30 m wide and 1.5 m above adjacent dune slacks.

Dune ridges are forested, with the conifer species rimu (*Dacrydium cupressinum*), kahikatea (*Dacrycarpus dacrydioides*), totara (*Podocarpus hallii*) and miro (*Prumnopitys ferruginea*) dominant along with the angiosperm species kamahi (*Weinmannia racemosa*) and rata (*Metrosideros umbellata*). The only exception is the youngest dune, which at both sites has been largely cleared of forest and converted to pasture. Interdune hollows vary in wetness and related vegetation cover,

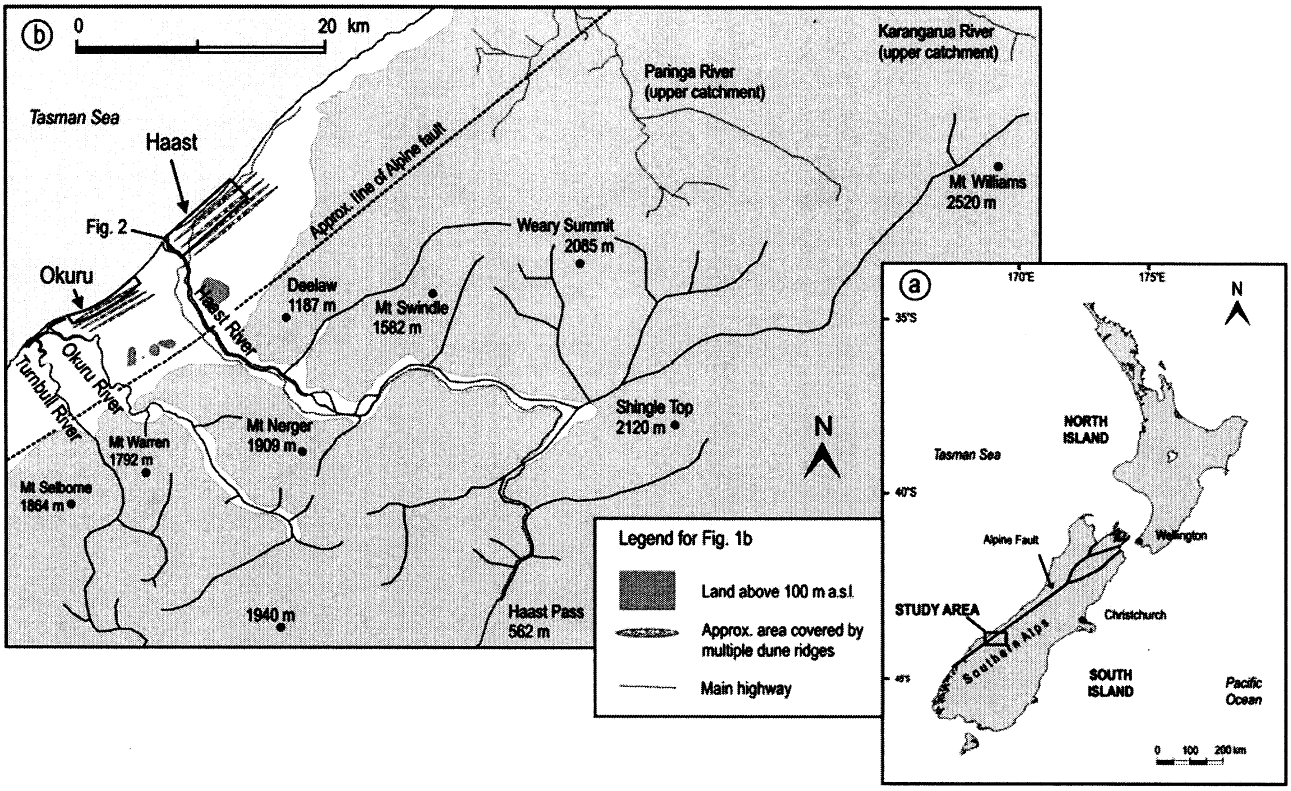

Figure 1 (a) Map of New Zealand, showing the general location of the study area in southwest New Zealand. (b) Map of the Haast and Okuru/Turnbull River catchments. The positions of the Haast and Okuru dune sequences, where sampling of dune ridges was undertaken, are marked at the coast

from open lakes to dense kahikatea forest (Dickinson and Mark, 1994).

Regional earthquake and disturbance chronologies in southwest New Zealand

Four major regional earthquakes in southwest New Zealand since AD 1450 have been well documented, and each triggered an episode of widespread and catastrophic landscape impacts including landsliding, rockfall, river aggradation, floodplain aggradation and toppling of forest (Adams, 1980; Cooper and Norris, 1990; Yetton, 1998; Wells *et al.*, 1999, 2001; Norris *et al.*, 2001; Cullen *et al.*, 2003; W.B. Bull, written communication, 2005). The most recent of these earthquakes, in AD 1826 (McNab, 1907), was centred at least 50 km to the south of the study area but significant landscape impacts extended northwards at least as far as the Karangarua River, *c.* 100 km north of Haast (Wells *et al.*, 2001; Cullen *et al.*, 2003). The exact source of this earthquake is unknown, but it most probably relates to rupture of the southern offshore portion of the Alpine fault (Wright, 2000; Goff *et al.*, 2004). The three earlier earthquakes were the result of ruptures on the Alpine fault in AD 1717, AD 1615±5 and AD 1460±25 (Adams, 1980; Yetton, 1998; Wells *et al.*, 1999, 2001; Norris *et al.*, 2001). The AD 1717 and *c.* AD 1460 events produced the most extensive impacts over the region, with fault rupture and significant landscape damage extending from at least Hokitika (250 km north of the study area) to the Haast/Okuru catchments (Yetton, 1998; Wells *et al.*, 1999; Norris *et al.*, 2001; Cullen *et al.*, 2003). The *c.* AD 1615 event was centred at least 150 km north of the study area, and the fault did not rupture as far south as Haast (Yetton, 1998; Norris *et al.*, 2001). However, significant landscape impacts from this earthquake extended at least as far south as Paringa River and the northern parts of the Haast catchment (Wells *et al.*, 2001; Cullen *et al.*, 2003).

The timing of large earthquakes in the region prior to AD 1450 is not well documented, although evidence suggests there may have been a cluster of large earthquakes in the fifteenth century (Wright, 1998; Goff and McFadgen, 2002; W.B. Bull, written communication, 2005). More specifically, possible Alpine fault earthquake events have been speculatively proposed for central Westland in *c.* AD 1490±5 and *c.* AD 1440±5, based on unusual growth patterns in a few trees near the fault scarp and pulses of rockfalls well to the east of the fault dated by lichenometry (Wright, 1998; W.B. Bull, written communication, 2005).

Methods

Ages of dune ridges at the Haast and Okuru systems

We dated trees on transects located across the youngest portions of the central parts of both the Haast and Okuru dune systems. Wherever possible we aimed to obtain at least 20 trees from each separate dune ridge-swale unit identified. Increment cores were taken from trees at a height of *c.* 1 m above the ground. A range of tree sizes was sampled, but included the largest trees because these are most likely to be the oldest trees on new surfaces (ie, the most rapid colonizers of the new dune). Trees were sampled on all dune positions where possible (so as to be able to identify any variations in age across a dune unit), ie, dune front, top, back and interdune hollow. We sampled inland until trees became consistently too large in diameter to core to the pith with available tree coring equipment. This corresponded to the fourth dune ridge at both Haast and Okuru. Species sampled comprised the conifers rimu, totara, kahikatea and miro. Individuals of rata and kamahi were present on the dunes but were not sampled, because of probable difficulties in coring (rata) and in ring clarity (kamahi).

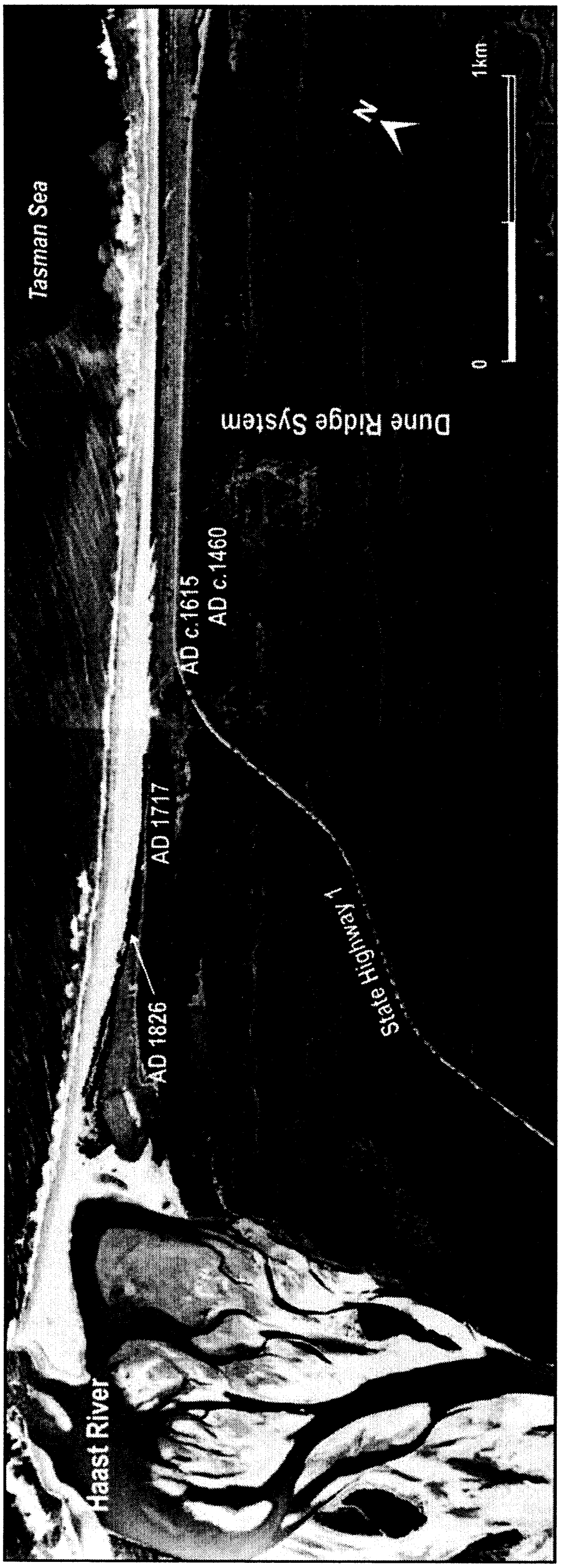

Figure 2 Aerial photograph of part of the Haast River coastal dune ridge system. Successive shore-parallel ridges have built up immediately north of Haast River. Sampling was undertaken on the four youngest dune ridges, and these are marked with the dates of the earthquake events that are inferred to have initiated the sediment pulses leading to dune formation. The Okuru dune ridge sequence (south of Haast River) is similar in appearance. Photograph courtesy of Land Information New Zealand. Crown copyright reserved

The cores were mounted and sanded and the number of rings counted using a microscope (ring widths were not measured, as we required tree age data only). When cores did not intercept the pith, the number of missing rings was estimated using the inner arcs where present (Duncan, 1989), or from the tree's diameter and the growth rate of the innermost 20 rings where no arcs were present. A few trees were cored twice (because the first core missed the pith by a wide margin), and in these instances we used the core with the smallest missing radius to estimate tree age. We excluded from our final data all tree ages that had additions for missing parts of the core of >50 years.

Reconstructing dune formation history

We examined the distribution of tree ages across the sampled dune sequences, and identified cohorts of even-aged trees. These cohorts signify the initial trees that colonized newly formed and stabilized portions of the dune system over time. The oldest tree in each cohort was used to estimate the date of initial colonization of the newly formed dune surfaces. This age will underestimate the actual date of dune formation because of the variable delay in colonization and growth to tree coring height for the first trees at the site.

Comparison of timing of dune formation with regional earthquake history

The ages of each dune unit identified were compared with the chronology of great regional earthquakes for Westland to assess the role of earthquakes in coastal progradation and dune building. Dunes that owed their formation to the earthquakes would be expected to have colonizing forest cohorts with oldest trees that postdated the earthquakes within 50 years.

Results and discussion

Dune formation and ages of dunes

The dune systems clearly recorded a history of episodic formation over the past 650 years. A repeating sequence was present in which a dune-building episode was followed by the establishment of a cohort of colonizing trees (Figure 3). Differentiation (both spatial and temporal) between adjoining cohorts/dune ridge-swale units was sharp and distinct. Cohorts spanned from the top of the former seaward dune to the back (landward side) of the newly deposited dune. Colonization of the seaward side and top of a new dune is thus presumably inhibited by the close proximity to the sea until further dune building takes place.

Trees in the oldest age class of each cohort were spread across the entire dune ridge-swale unit, with no age gradations present. The forest cohorts thus represent colonization of bare sand immediately following dune formation. There is no evidence of gradual incremental build-up of dune sand, for example through abundant sand supply interacting with binding of sand by shoreline vegetation as reported in western USA (Phipps *et al.*, 2001). Rather, tree ages indicate episodic colonization of entire dune units. Initial colonization of the fronts and tops of former dunes at the same time as the backs and swales of the new dunes also demonstrates this – trees could presumably colonize the dune fronts and tops as soon as at least some new dune material formed seaward of them to moderate the influences of salt laden winds, so colonization synchronous with the entire new dune ridge-swale unit indicates rapid building of new dunes.

The forest cohorts on the second to fourth dune ridges at Okuru have bimodal age class distributions, and the timing of the younger mode on each dune coincides with the timing of

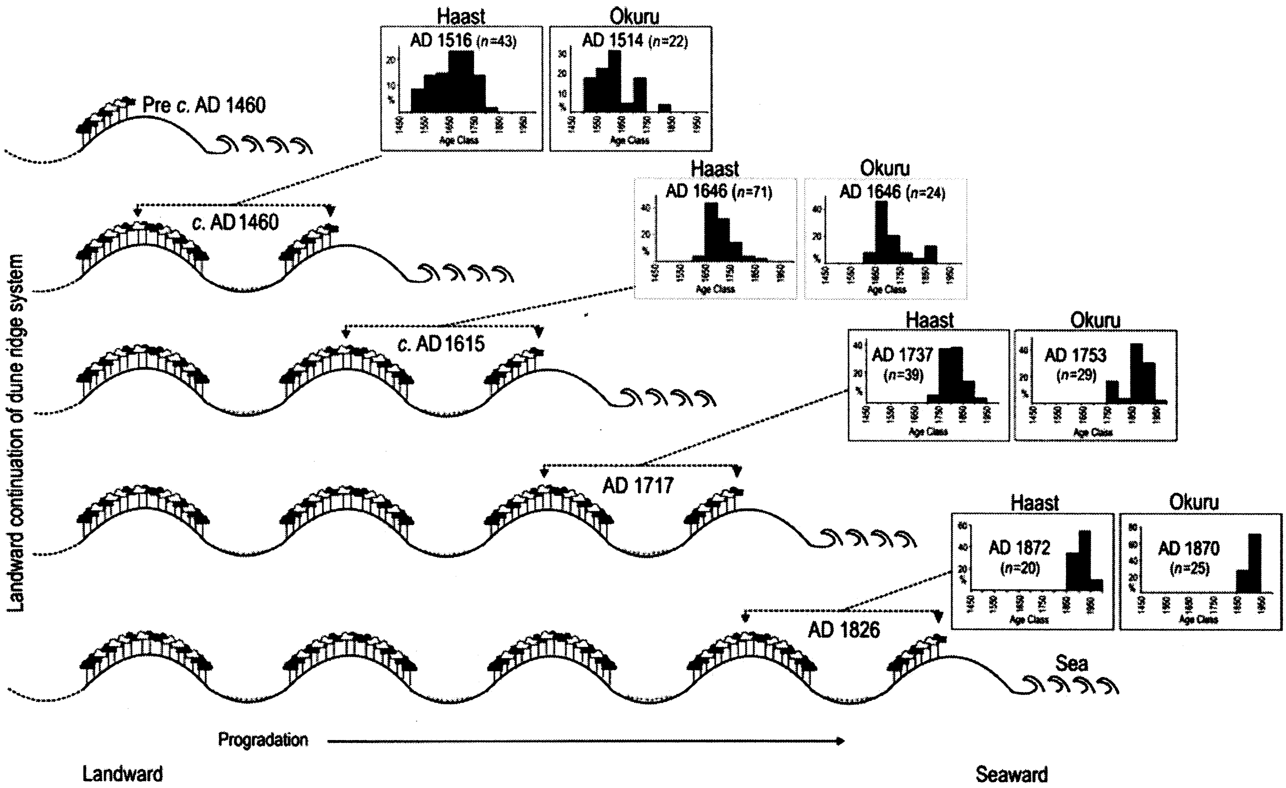

Figure 3 Schematic representation of the chronology of dune building at Haast and Okuru since AD 1450. Following earthquake events, dune ridges rapidly formed and were colonized by new cohorts of trees. These cohorts spanned from the seaward side of the previously unvegetated foredune to the landward side of the newly formed dune. Histograms show age class distributions for tree cohorts on each dune-swale unit, for the Haast and Okuru sites. The y axis gives percent of trees in each age class. Histogram class interval is 50 years, and the number of sampled trees on each dune unit is given by *n*. The calendric date within each histogram gives the age of the oldest sampled tree on the dune unit. Tree ages are not adjusted for colonization delays, but represent ages of trees at 1 m height

the next dune ridge formation event (Figure 3). This represents delayed colonization of parts of each dune ridge-swale unit (rather than gradual or sporadic formation), and probably reflects the relatively low dune ridges at Okuru. Presumably dune ridges here are not high enough to provide full protection from coastal influences across the dune ridge-swale unit, and so complete colonization by trees of the entire dune surface is delayed until the following dune-building episode further removes these coastal influences. In contrast, the generally unimodal age class distributions at Haast imply that the higher dunes provide adequate shelter that enables near complete tree colonization of the dune surface before the next dune-building episode occurs.

The temporal patterns of dune formation on the four sampled dune ridge-swale units were very similar at Haast and Okuru. Oldest trees on dunes show that colonization began at around AD 1870 on the youngest dune at both sites, and at around AD 1750, AD 1650 and AD 1515 on the next three oldest dunes, respectively (Figure 3). The ages of trees are remarkably similar between the Haast and Okuru sequences, suggesting responses to the same causal events.

The dates of the events initiating dune-formation episodes will predate the oldest colonizing trees, and based on observed colonization rates of conifer tree species in the region this is most likely to be less than 50 years and somewhere near 28 years (Wells *et al.*, 1999). On this basis the events initiating dune formation occurred no earlier than, and most probably within the periods of, *c.* AD 1820–1850, *c.* AD 1700–1730, *c.* AD 1600–1630 and *c.* AD 1465–1495, respectively, for the four dune ridges at Haast and Okuru.

The role of earthquakes in dune formation

Cohorts of colonizing trees on all four sampled dune ridges at Haast and Okuru commenced establishment at times coinciding with the region-wide landscape and forest disturbance events associated with the most recent four Alpine fault earthquakes (Wells *et al.*, 1999, 2001; Cullen *et al.*, 2003). The possible date ranges for the events initiating dune formation also fall within the dates of these four earthquakes (AD 1826, AD 1717, *c.* AD 1615±5 and AD 1460±25), and these earthquakes were therefore almost certainly the causal mechanism of dune formation. Thus at both Haast and Okuru, the entire known regional earthquake record over the past 650 years is recorded in the dune-building sequences, and furthermore there are no other events recorded in either sequence over this time. We can conclude that all known great regional earthquakes over this time (ie, those strong enough to produce major landscape impacts) have resulted in dune formation at the coast at Haast and Okuru, and that no other dunes have been preserved resulting from climatically or anthropogenically induced events. The climatic shifts proposed as an explanation for the dune sequences are unlikely to have been an important driver of dune system development, at least over the past 650 years.

This is consistent with findings of the role of earthquakes in landsliding and sedimentation over this time period in the nearby upper Karangarua catchment (Wells *et al.*, 2001). Here, the four regional earthquakes triggered episodes of major landslipping and sedimentation, but no other major periods of disturbance were preserved over this time. Climatic events disturbed *c.* 5% of the land surface studied per century, while earthquakes disturbed at least 14–20% and included more large rock avalanches and landslides. At a regional scale, large earthquakes also appear to have been the dominant factor contributing to major and widespread forest toppling, landsliding and aggradation (Yetton, 1998; Cullen *et al.*, 2003; Korup, 2005), despite the occurrence of regular severe storms in the region and associated localized (sometimes severe) impacts (eg, Korup, 2004).

These conclusions do not exclude the possibility that large regional climatic events have also caused large sediment pulses and dune ridge formation in the study area over the Holocene. Such events could include intense El Niño's similar to that inferred in the mid-fifteenth century (Couper-Johnston, 2000), and these events may supplement the record of earthquake-derived sedimentation recorded in the dune ridges. Likewise the possibility of sediment pulses resulting from the combined effects of near-synchronous climatic and earthquake events cannot be ruled out (Goff and McFadgen, 2002). Nevertheless, our results do suggest that in this region seismic driving of dune formation is a dominant agent, and climatically induced sediment pulses have probably not often been sufficiently large to result in enduring dune formation at the coast.

Environmental changes following earthquakes

The ages of trees on the dunes in this study suggest that movement of sediment through the Haast and Okuru River systems to the coast and deposition as dune ridges was relatively rapid following the most recent four earthquakes. Oldest trees on the dunes were no more than 20–46 years younger than the earthquake events for the most recent three events, and this difference will include the time for dune building as well as for tree colonization and growth to coring height; based on probable delays for colonization and growth of trees to core height of between 5 and 40 years (Wells *et al.*, 1999), we can therefore infer that dune formation and stabilization took place in no more than about 5–30 years following each earthquake. This rapid response is consistent with Adam's (1979) contention that most of the 'abnormal' postseismic sediment load in the Southern Alps could be carried to sea in suspension in less than five years. It is also consistent with observations of sediment movement following the AD 1929 Murchison and AD 1968 Inangahua earthquakes on the West Coast of New Zealand – most of the earthquake-derived river aggradation material following the AD 1929 earthquake had reached the sea within a decade, while about half of the earthquake-derived material following the AD 1968 earthquake had reached the sea within 19 months (Adams, 1981).

These rapid movements of sediment reflect the high rainfall and relatively short, steep river catchments in the region. Another probable factor is the nature of the earthquake-derived sediment itself. Adams (1981) noted that earthquake material could be divided into suspended load, which rapidly moves to the sea and comprises the greatest proportion of earthquake-derived material, and bed load, which takes longer to reach the sea. As dunes tend to be composed of the finer material, transportation to the coast could be rapid. In contrast the coarse aggradational load could potentially still be working through the system a century after the earthquake (Yetton, 1998; Korup, 2005).

At a regional scale we could expect these differences in rates of geomorphological processes to be broadly reflected in the ages of stabilized post-earthquake surfaces. We can investigate this by comparing the oldest trees in forest cohorts that were initiated on different surface types in southwest New Zealand following the earthquakes. The regional data set includes over 100 cohorts that regenerated on disturbed surfaces formed by a range of disturbance types, including landslides and river aggradation surfaces, which allows us to test this (Figure 4).

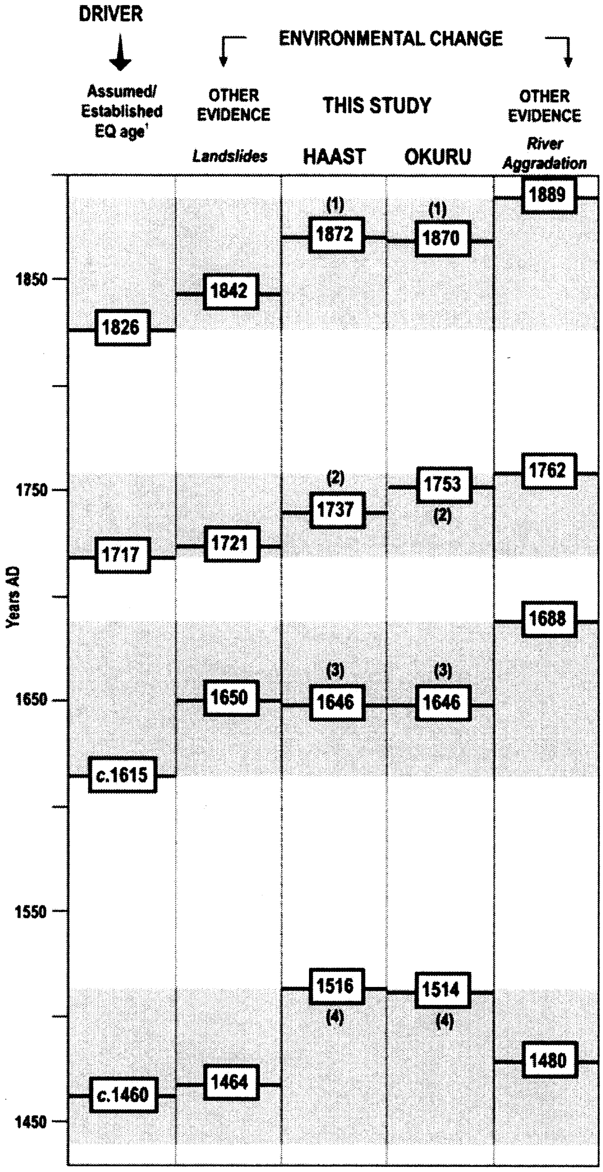

Figure 4 Diagram of the chronology of Alpine fault earthquakes and three related environmental outcomes (landslides, dune building, river aggradation) in southwest New Zealand since AD 1450. All ages are in years AD. Ages for environmental changes give the age of the single oldest tree in all the post-earthquake forest cohorts sampled on the respective landforms following each earthquake. Information on dunes is from this study. Dunes are numbered sequentially, representing successive dunes inland from the sea. Ages for landslides and river aggradation are based on previous studies (Wells *et al.*, 1999, 2001; Cullen *et al.*, 2003). Environmental changes are ordered in a sequence according to expected rapidity of geomorphic process, from fastest to slowest (Goff and McFadgen, 2002). Earthquake events and ages are from combined palaeoseismic evidence in the southwest New Zealand region (Adams, 1980; Cooper and Norris, 1990; Yetton, 1998; Wells *et al.*, 1999, 2001; Norris *et al.*, 2001; Cullen *et al.*, 2003)

There are obviously limitations in this analysis, related to accuracy of dating. These include variable numbers of sampled cohorts on surface types, variable times for trees to colonize stable surfaces and grow to core height, missing rings, estimations of tree age when cores do not intercept the pith and failure to sample the oldest colonizing tree on a surface. These potential errors are likely to be greater the older the surface/cohort is. Nevertheless, we could still expect any marked consistent differences across the surface types to be identified in maximum tree ages. It should also be noted that Figure 4 gives data on the single most rapid example of colonization of each surface type following the earthquakes. Thus, factors such as continued reactivation of surfaces or very slow colonization are not considered.

There is a clear trend in colonization rates on different surface types following the most recent three earthquakes (Figure 4). Colonization of aggradation surfaces in main river valleys generally lags about 40 years behind colonization of landslides, while colonization of dunes may occur as rapidly as on landslides but is generally slightly slower (by one or two decades). These results correspond with the post-earthquake sequence of geomorphological changes proposed by Goff and McFadgen (2002).

This pattern is not evident following the *c.* AD 1460 earthquake, however, with oldest trees on landslide and aggradation surfaces predating those on the dune ridges by several decades. We see two possible explanations for this. First, it could be the result of the increased sampling errors associated with dating increasingly old trees (arising from missing rings, incomplete cores, large inner arcs and/or because the oldest colonizing trees may have already died), so that the relative temporal patterns of colonization are obscured. The second possibility is that the regional record of landsliding and aggradation events from around this time includes not only the surfaces that were formed by the *c.* AD 1460 earthquake, but also surfaces disturbed by an event(s) in the few decades prior to this earthquake. These earlier events could include the large El Niño of around AD 1450 (Couper-Johnston, 2000) or a possible Alpine fault earthquake in *c.* AD 1440 (Wright, 1998; W.B. Bull, written communication, 2005). Further work is needed to resolve this, and the age of the next dune ridge inland from those sampled at the Haast and Okuru sequences could provide useful information in this respect. If these dune ridges had oldest trees dating from about AD 1450 to 1475, then this would provide evidence in support of a major disturbance event just prior to AD 1460.

Palaeoseismic implications

As an off-fault indirect palaeoseismic marker, coastal sand-dune systems hold considerable potential for earthquake studies in New Zealand and in other tectonically active, mountainous regions. The dunes at Haast, for example, may offer the potential to extend regional earthquake records back several thousand years. Many indirect palaeoseismic methods have difficulty in gaining long-term records because the signature of an earthquake in the landscape is often rapidly destroyed, because of the dynamic nature of the landscape and high rates of process. For example landslide and rockfall evidence is often removed by subsequent erosion or buried by further deposition and, on floodplains, thick sedimentary sequences make the record difficult to investigate unless there has been a lowering of base level and subsequent exposure. The dune ridges in this present study may have an advantage over many other off-fault palaeoseismic methods in that they appear to provide a conformable, spatially discrete record of sedimentation events in which the problem of erosion and burial of dunes is limited by the high background levels of sediment delivery of rivers in the region (Griffiths, 1981; Coates and Nathan, 1993; Berryman and Hull, 2003), such that a near-complete record of successive events may be preserved. This is demonstrated by the preservation of spatially distinct dune ridges dating from all four of the most recent Alpine fault earthquakes at both Haast and Okuru.

The relative rapidity of dune building may also be important if major earthquakes are closely spaced in time, because seismic-related pulses of increased sedimentation could more likely be differentiated at the coast as separate dune ridges as opposed to probable overlapping periods of river aggradation. Based on this study, we consider that dunes may be able to differentiate earthquake events as closely spaced as 20–30 years, and that dating of dunes using tree colonization may allow the timing of earthquakes to be estimated with a precision of about ±15 years.

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