Tsunami geomorphology in New Zealand
A new method for exploring the evidence of past tsunamis

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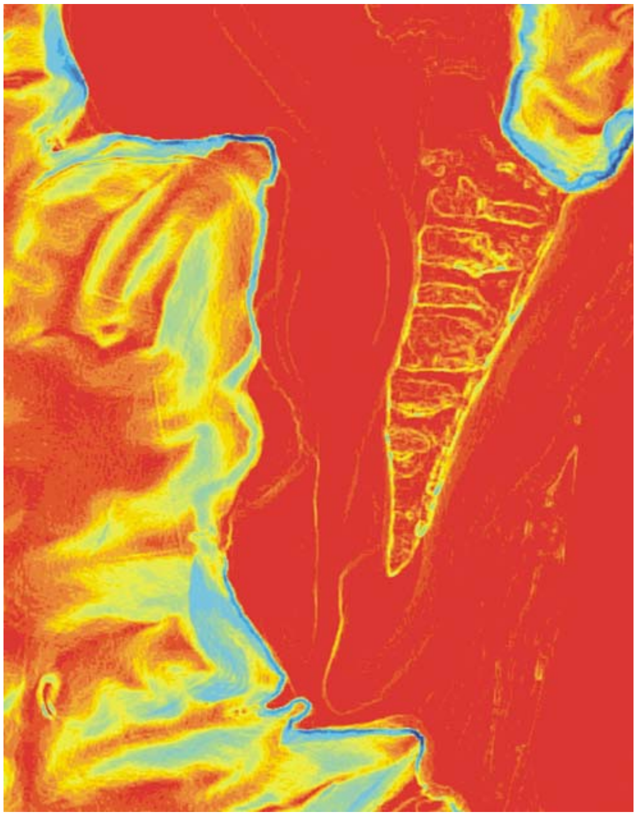

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Cover: Sand spit at the mouth of Pleasant River, Otago - edge detection image derived from LIDAR data.

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Contents

Abstract

A method is developed for using light detecting and ranging (LIDAR) data combined with brief ground surveys to identify past tsunami from their geomorphic signatures on the coast. Analysis of modern and past tsunamigenic features from within New Zealand and around the world identified a suite of tsunami-related geomorphological features, including:

- Pedestals: remnant sections of dune ridge separated by scoured areas
- Hummocky topography or sand sheets that form landward from pedestals (hummocky topography is the old, weathered equivalent of sand sheets)
- Parabolic dune fields, which are remobilised sand sheets landward of pedestals
- Low Profile Sequences: post-tsunami feature indicative of changes to coastal sediment budget.

The type of features formed by a tsunami, and the ability to detect and interpret tsunami geomorphology by LIDAR (and also in the field), hinge on the interaction between five key criteria:

- Availability and type of sediment (e.g. sand/gravel)
- Embayment type
- Prograding/eroding coast
- Small/large accumulation space
- Wet/dry landward environment

An appreciation of the geomorphic setting and history of a coast is therefore of fundamental importance when identifying what to look for and where to look for tsunami evidence.

Using such LIDAR interpretations and iterating with a palaeotsunami database serves two key purposes:

- As a reconnaissance tool, LIDAR data augments point source geological information to provide an indication of the magnitude and frequency of palaeotsunami inundation(s)
- The combined data provides a more comprehensive dataset of runup heights and inundation for comparison with numerical model simulations.

Moderate to small tsunamis (~1.0-5.0 m runup) are unlikely to create regionally significant changes to coastal geomorphology but may be identifiable locally. A regional LIDAR scan would therefore help to identify the relative scale and approximate chronology of large multiple events. As an initial survey, or as part of a larger desktop study incorporating a search for palaeo and historical data, a LIDAR interpretation of tsunami geomorphology can significantly contribute to a more comprehensive understanding of the hazard for a particular region.

When this approach was applied to a pilot study area along the Otago coast, many of the above features and associations were identified, and for the region overall these provided evidence of at least one large,

contemporaneous, regional-scale tsunami within the past 6000 years or so. A critical review of all the available tsunami source data helped us determine the most probable tsunami generation scenario for this event. We propose that groundshaking caused by a 14th century Akatore Fault rupture probably destabilised sediments that had accumulated at the head of one or more submarine canyons along the edge of the continental shelf off Otago Peninsula **-** in a similar fashion to the Kaikoura Canyon where accumulated sediments are believed to be mobilised by a local fault rupture.

For coasts like Otago where there is evidence of at least one large palaeotsunami and an historical database of smaller events, we suggest there is adequate justification for more comprehensive studies such as inundation modelling and a detailed geological survey to better determine the tsunami hazard.

Introduction

New Zealand sits astride the boundary between the Pacific and Australian Plates. To the north in the Tonga-Kermadec-Hikurangi trench, the Pacific Plate is subducting from the east at a rate of 40 mm/yr. To the south in the Puysegur trench, the Australian Plate is being subducted from the west with a convergence rate of 35 mm/yr. In the centre of New Zealand, the plates are locked. This unique tectonic setting provides a wide range of potential tsunamigenic sources (Walters et al. 2006a, 2006b). A key step in managing the tsunami hazard is to identify the occurrence and magnitude of past events around the New Zealand coast.

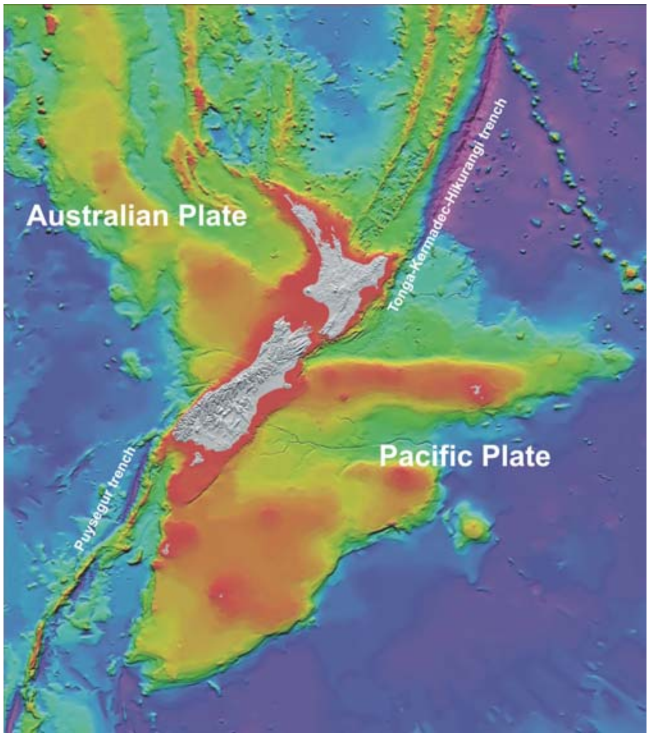

***Figure 1*:** New Zealand – showing key tectonic associations

An historical tsunami database for New Zealand has been compiled by several researchers over the past 25 years or so, with information dating back to the early 1800s. This database now has a record of over 40 tsunamis (Berryman 2005). Localised runup of over 10 m has been reported on occasion, but in general terms the historical record has arguably only one major distant event and no significantly large local ones. Development of a prehistoric database started in the mid-1990s with the discovery of New Zealand's first palaeotsunami deposits (Goff & Chagué-Goff 1999). It has subsequently expanded to include items dating back over two million years. Site records from over 200 sites provide details of more than 30 Holocene palaeotsunamis (Goff 2006). These geological signatures of tsunamis provide clues to a hazard that are poorly understood from historical records alone. Indeed, in northeast Japan, western North America, Norway and Scotland, tsunami deposits serve as warnings of unusually large tsunamis (Nanayama et al., 2000; Atwater et al., 2005a; Bondevik et al., 2005). Tsunami deposits also afford estimates of tsunami recurrence (Pinegina et al., 2003; Cisternas et al., 2005; Kelsey et al., 2005), and can yield constraints on tsunami flow depth and velocity (Jaffe & Gelfenbaum, 2002; Atwater et al., 2005b).

The most common geomorphic signature of a tsunami consists of an onshore sand sheet a few centimetres to decimetres in thickness. Sand sheets normally cover a beach-ridge plain, an estuarine marsh, or a lake bottom. Some researchers have also reported apparent erosional features associated with tsunamis (e.g. Aalto et al., 1999). Few, though, have considered a comprehensive study of possible geomorphological features related to tsunami inundation (Yulianto et al., in prep.; Kitamura et al., 1961).

Recently, workers have been studying a previously reported but little-used tsunami signature called a *tsunami-scour fan*. It forms where a tsunami cuts a breach, or cleans out an existing one, through a beach ridge. Using material scoured from the breach, the tsunami builds a fan as it emerges from the breach. The fan may build on the landward side during inflow, on the seaward side during outflow, or both (Kitamura et al., 1961). Such fans have potential advantages over a sand sheet as a record of tsunami occurrence and characteristics because the fan deposit may attain a thickness of 50 cm or more. Such a great thickness may promote preservation in areas where thinner sand sheets do not endure, so that the breach may be spotted centuries later by remote sensing.

Tsunami-scour fans were previously noted, on opposite sides of the Pacific Ocean, as by-products of the tsunami associated with the giant Chilean earthquake of May 22, 1960. They formed abundantly in northeast Japan by inflow and outflow where the 1960 tsunami cut breaches through roads and levees (Kitamura et al., 1961). They have also been reported from the tsunami's source region. Near the city of Valdivia a fan built by tsunami inflow approaches 1 m in thickness behind an open-coast beach ridge (Bourgeois & Reinhart, 1989). In addition, to the south near Maullín, sandy fans are evident on aerial photos taken in January 1961 (Atwater et al., 1999). Still other examples of tsunami scours have been reported from Kamchatka (MacInnes et al., 2005).

In New Zealand, similar features have been noted but as yet have not been reported in peer-reviewed publications (Goff & McFadgen, 2006). Unlike those reported by researchers in Chile, Japan, and the US, the New Zealand features are part of a geomorphological association purported to have been created by palaeotsunamis. These include:

- Hummocky topography landward of dune systems (Figure 2a).
- Pedestal features – often associated with either hummocky topography or overwash deposits (Figure 2b).

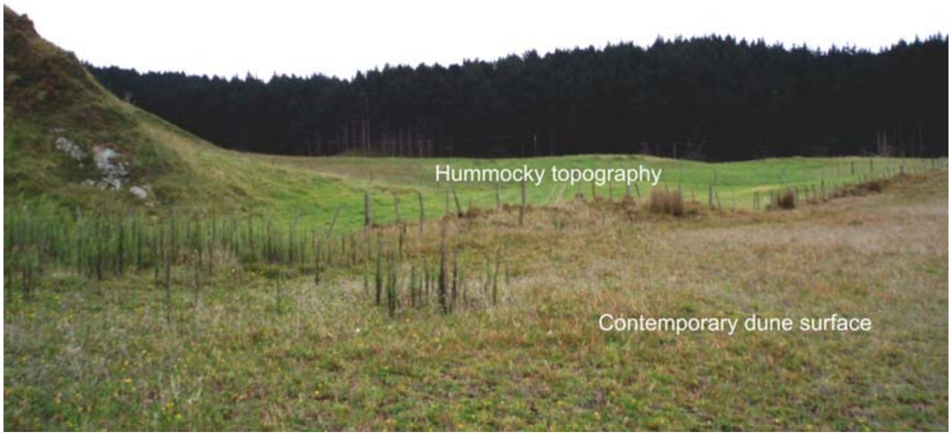

***Figure 2a*:** Whangaruru North – hummocky topography inland of contemporary dune system (Photo: J. Goff).

Figure 2b**:** Great Barrier Island – resistant pedestal surrounded by palaeotsunami deposit (pebbles) – hummocky topography visible in distance (Photo: Scott Nichol, University of Auckland).

If, as Yulianto et al. (in prep.) surmise, tsunami-scour fans can be identified centuries later by remote sensing, they can potentially be used to study the tsunami hazard on coastlines with little or no historic record. A remote sensing technique for identifying past tsunamis would be particularly useful:

- As a broad brush tool to ascertain whether a hazard exists.
- As an alternative and/or complementary technique to geological studies.
- To help determine the magnitude and frequency of major tsunami inundations.
- So that comparisons could be made with storm-related geomorphology for a comprehensive coastal hazard assessment.

In this report, we develop the use of airborne LIDAR as a remote-sensing tool to aid the detection of palaeotsunami deposits. With its high spatial density of data points (typically ~1-2 m) and accurate ground elevation fixes (typically to within a standard error of 0.15 m), LIDAR delivers topographic information that theoretically should be adequate to identify hummocky topography, pedestals, and scour-fan features if they have been preserved within the landscape. To date, several segments of the New Zealand coast have been surveyed with airborne LIDAR (e.g. Otago, Canterbury, southern Hawke's Bay, Bay of Plenty, Auckland area), and more of the remainder of at least the low-lying coastal segments are likely to be surveyed in the near future. While a prime motivation for most of these surveys is to enable accurate prediction of inundation by fresh and salt-water flooding (including flooding by tsunami washover) using numerical hydrodynamic models, they also offer the potential for identifying the signature of past tsunamis.

We first examine the characteristic morphologies expected to be generated by large tsunamis. To a substantial degree, these depend on the local coastal geomorphic setting, particularly the amount of accumulation space available in which to form a deposit (e.g. if there is a broad low-lying backshore behind a beach ridge), whether the beach sediment is sand or gravel, and the abundance of beach sediment. By detailing the range of morphologies possible, and by illustrating them with photographs from recent and ancient examples, we intend that this report will serve as a resource to aid others to identify tsunami features. We also identify how tsunami-generated features may be distinguished from similar features created by large coastal storms. Second, we describe the methods developed for processing LIDAR topography data into imagery suited for tsunami feature identification. Third, we apply these methods to potential localities on the Otago coast. Finally, we draw together the regional picture that emerges regarding the vulnerability of this coast to tsunami.

Features of tsunami and storm deposits

This section examines the characteristic morphologies expected to be generated by tsunami. We begin with a review of the controlling factors, which include the local geomorphic setting and the scale of the event. We also discuss how tsunami features differ from those created by large storm waves, and how these features might weather over time. The geomorphic setting affects the amount and type of sediment the area of accumulation space available (i.e., the space available for sand to accumulate landward of the dunes), and whether the accumulation area is wet (e.g. an estuary) or dry (e.g. a dune field or backshore plain).Conceptually it is important to consider both storm and tsunami features since theoretically either could be responsible for sudden marked changes in coastal geomorphology. Variations in the potential longshore and inland extent of these processes are shown in Figure 3.

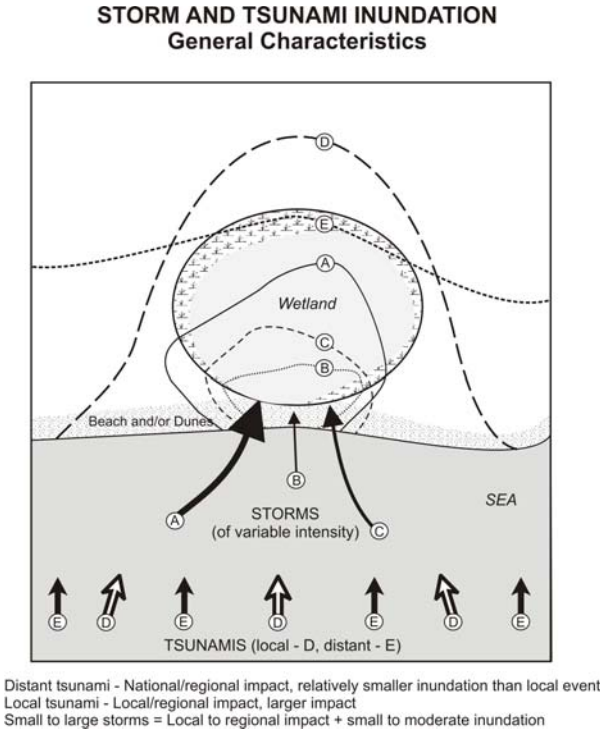

***Figure 3*:** General landward and longshore characteristics of storm and tsunami inundation (after Liu & Fearn, 2000).

The 2004 Indian Ocean tsunami provided clear evidence that a large tsunami is required to leave a marked geomorphological signal in the landscape. The topographic extent of this signal is generally governed by antecedent sand supply (Figures 4 & 5).

***Figure 4*:** Sri Lanka: Top – large scale pedestal formation on sand-rich coast; Bottom – small scale foredune pedestals on sand-poor coast (arrows indicate pedestals). Smaller geomorphological features are produced along coastlines with a reduced sand supply (Photos: J. Goff).

***Figure 5*:** Sri Lanka: Top – thick sand sheet landward of large scale pedestal formation shown in Figure 4 for sand-rich coast; Bottom – thin sand sheet landward of small scale foredune pedestals shown in Figure 4 for sand-poor coast (Photos: J. Goff).

The preservation of geomorphological features is affected by subsequent sand supply. Assuming similar post-tsunami conditions, in sand-rich areas there would be rapid rebuilding of coastal dunes and loss of pedestal topography, only the largest pedestals remain exposed. There are several variables, however:

- Post-tsunami sand supply may be severely reduced if the tsunami entrains all available offshore sand (above and often considerably below storm wave base) and transports it inland. Subject to sub-aerial processes, this probably removes it from the coastal sediment transport cycle for some considerable time. Evidence of sand removed from the system would be preserved inland.

- Post-tsunami sand supply may be severely reduced if the tsunami transports large quantities of sand from the shore and nearshore seaward beyond the normal storm wave base. This effectively removes it from the coastal sediment transport cycle. There would be no terrestrial evidence of the sand removed from the system.

- Post-tsunami sand supply may increase markedly if the tsunami was generated by a large, local earthquake that led to large quantities of new sand being routed into the coastal zone from rivers (a delayed pulse can also occur in arid areas where years may pass between the earthquake and the next major rain event).

- Other factors unrelated to tsunamis may affect sand supply conditions, such as extreme climatic events or anthropogenic land clearance.

Event magnitude and spatial extent are also important controls on tsunami generated morphology. “Large” events would probably be in the region of 10 m runup or greater. This broad brush assumption may well change as further work is carried out, but it is based upon known wave heights from the Indian Ocean tsunami, and from the known effects of palaeotsunamis. We believe that inundation by region-wide large events would cause multiple breaching of dune systems as opposed, for example, to the isolated tsunami-scour fan reported by Yulianto et al. (in prep.) and other researchers (Figure 6). In other words, they would create multiple tsunami-scour fan assemblages during one inundation. The assemblages would include remnant dune ridges, or *pedestals*, between each breach, and the individual overwash fans would coalesce to form *sand sheets* that may or may not be mobile depending upon aeolian and dune swale conditions. This overall concept is not new, and the effects of tsunamis upon a sandy barrier coastline have been modelled through morphological descriptions by Minoura & Nakaya (1991) showing multiple breaches of dune barriers with isolated dune remnants (“pedestals”) (Figure 7).

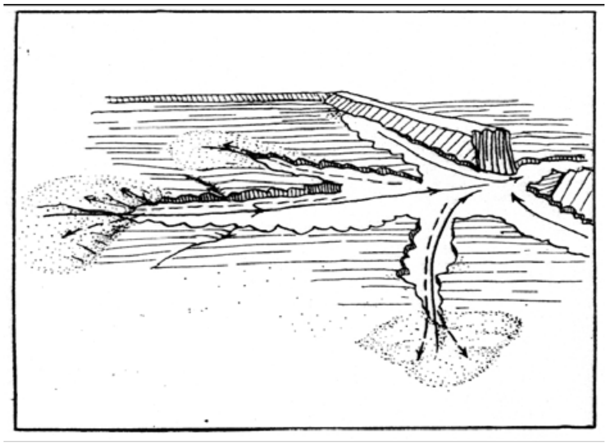

***Figure 6*:** Diagram of Tsunami-scour fan from Yulianto et al. (in prep).

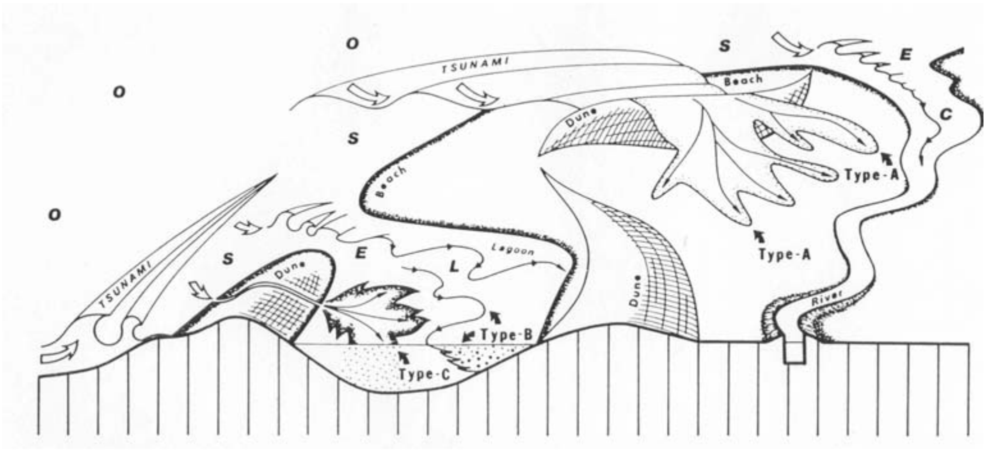

***Figure 7*:** Diagrammatic interpretation of tsunami inundation and formation of multiple tsunami-scour fans. O = offshore; S = shoreface; E = estuary; C = channel; L = lagoon (from Minoura & Nakaya, 1991).

Large tsunamis in shallow water have the potential to carry large amounts of sediment. Tsunami overwash of dune ridges can reduce their height, create multiple breaches, transport eroded sediment into dune slacks (reworked aeolian dune sand and offshore sediments), and deposit a sand sheet across the landward topography – wet or dry. Dunes can also be remobilised by the passage of a tsunami (Bryant, 2001). If the sediment volume carried is large then, according to Bryant (2001, 106-107):

"*a raised back barrier may form from coalescing overwash fans or small lagoons may be completely infilled. If these surfaces are not covered by seawater or quickly vegetated, they may be subject to wind deflation, with the [landward] formation of parabolic dunes (if the prevailing wind is onshore). Alternatively, sub-aerial processes may weather the sand in situ, developing a similar hummocky topography*."

Bryant (2001) makes the point that storms tend to only surge through gaps in dunes, sporadically depositing lobate fans that rarely coalesce or penetrate far inland. This is a key difference generally, but there is room for confusion in areas of low accumulation space (e.g. in a small pocket beach, there may be insufficient accumulation space for more than one lobate fan and two pedestals).

Conceptual models

A series of conceptual models were developed to consider the major variables discussed above – namely sand supply and accumulation space. While sand-rich and sand-poor, gravel-rich and gravel-poor scenarios were considered, not all are shown below. Gravel scenarios were considered because these represent a significant proportion of New Zealand's coastline.

The conceptual models are presented in Figures 8-23 as follows:

Figure	**Tsunami inundation models**
8	National/regional high impact, local extreme impact
9	Subsequent dune/gravel ridge development
10	Coastal plain (large accumulation space) - sand poor scenario, plan view
11	Coastal plain (large accumulation space) - sand poor scenario, in profile
12	Enclosed bay (limited accumulation space) - sand rich scenario, plan view
13	Enclosed bay (limited accumulation space) - sand rich scenario, in profile
14	Gravel scenario - gravel rich, plan view
15	Gravel scenario - gravel rich, in profile
	Storm inundation models
16	Regional high/moderate impact, local high impact
17	Subsequent dune/gravel ridge development
18	Coastal plain (large accumulation space) - sand poor scenario, plan view
19	Coastal plain (large accumulation space) - sand poor scenario, in profile
20	Enclosed bay (limited accumulation space) - sand rich scenario, plan view
21	Enclosed bay (limited accumulation space) - sand rich scenario, in profile
22	Gravel scenario - gravel rich, plan view
23	Gravel scenario - gravel rich, in profile

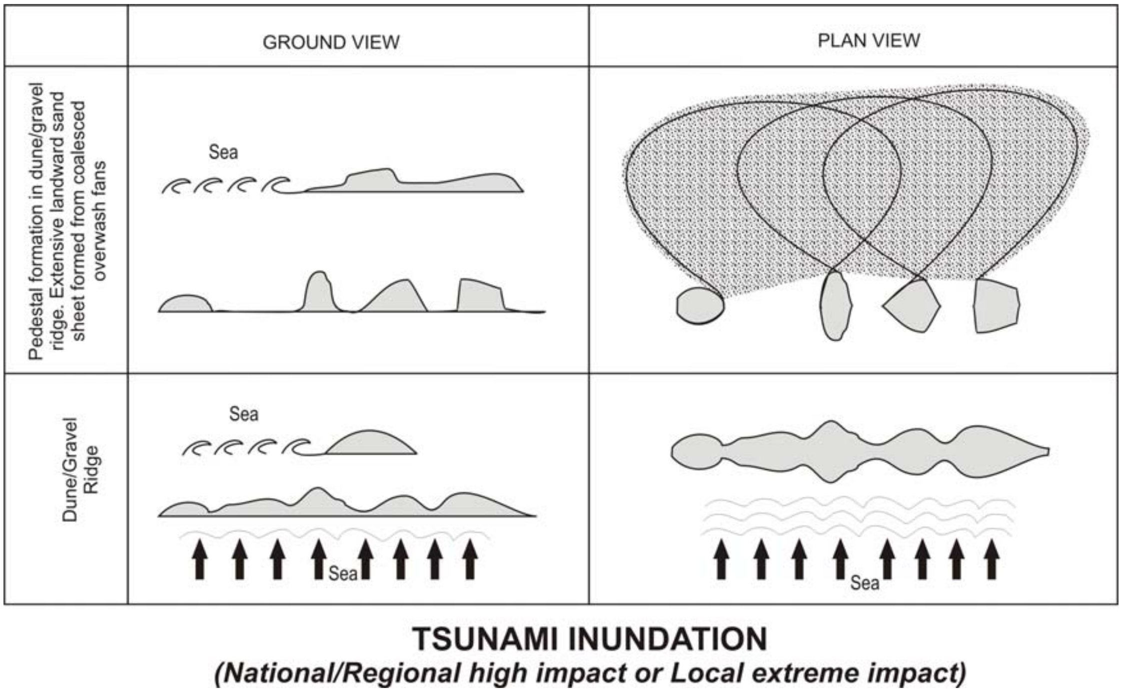

Figure 8**:** Pedestal and overwash fan formation from tsunami inundation – light grey shading = in situ dune sand.

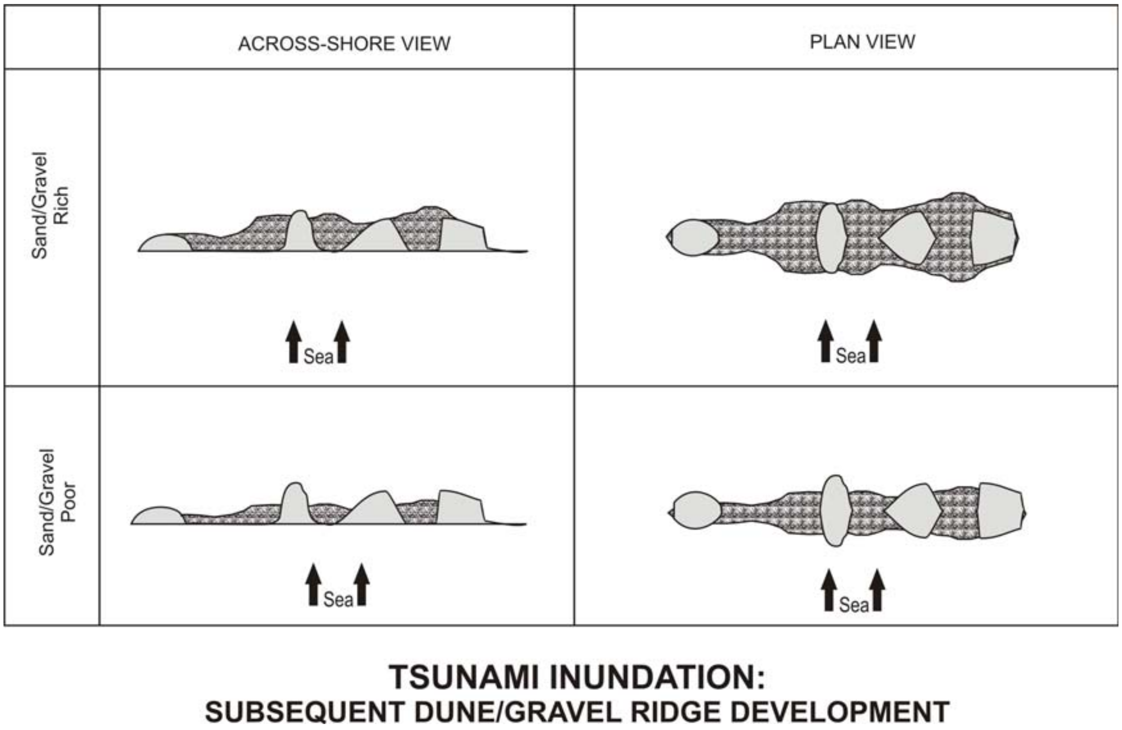

Figure 9**:** Pedestal development over time in different sand supply conditions. Light grey shading = in situ dune sand, dark mottled shading = new sand supplied to the dune system following inundation.

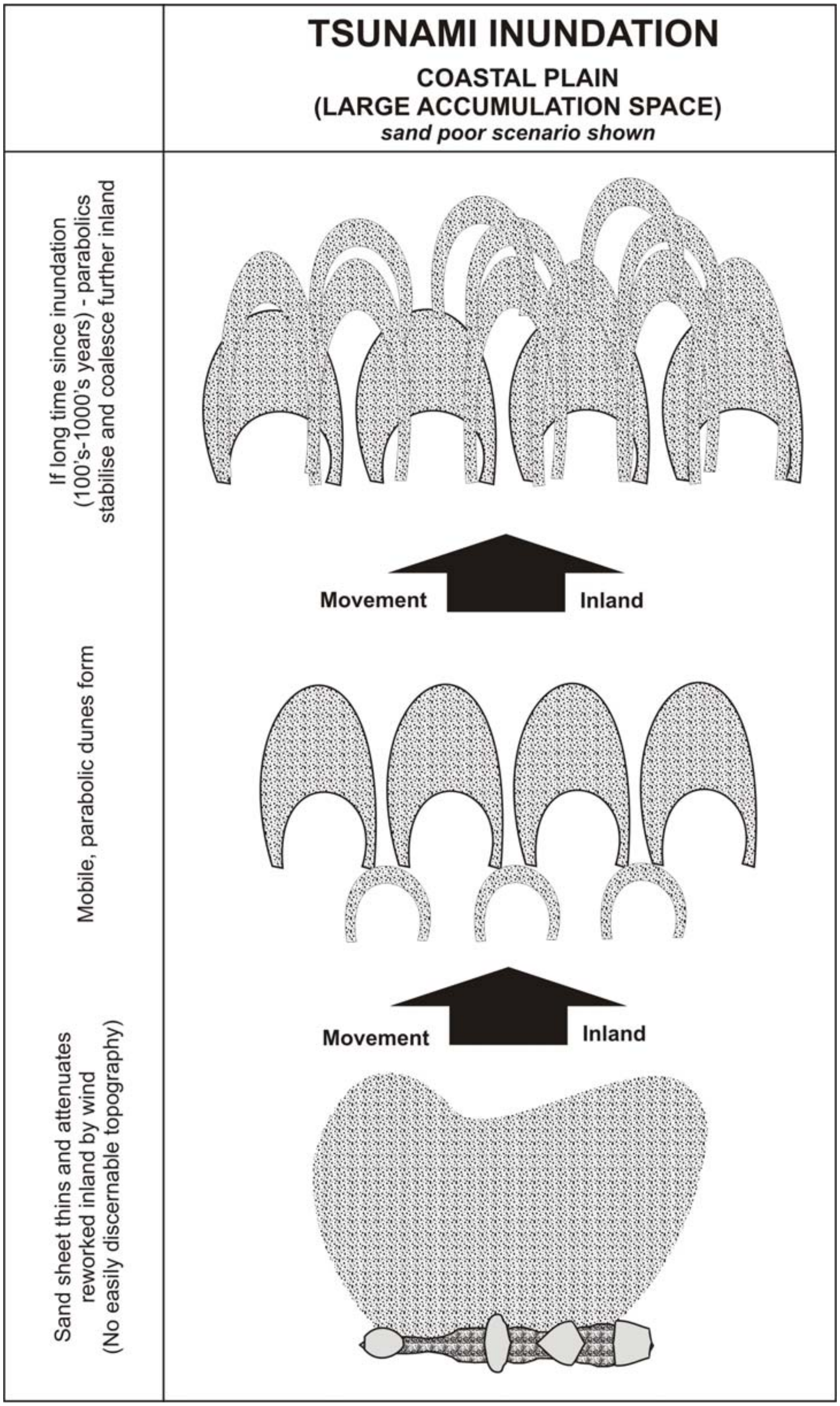

***Figure 10*:** Sand sheet–parabolic dune development (bottom to top of diagram) with large accumulation space AND dry ground conditions (in wet conditions the sand sheet is immobile and weathers). Sand-poor conditions.

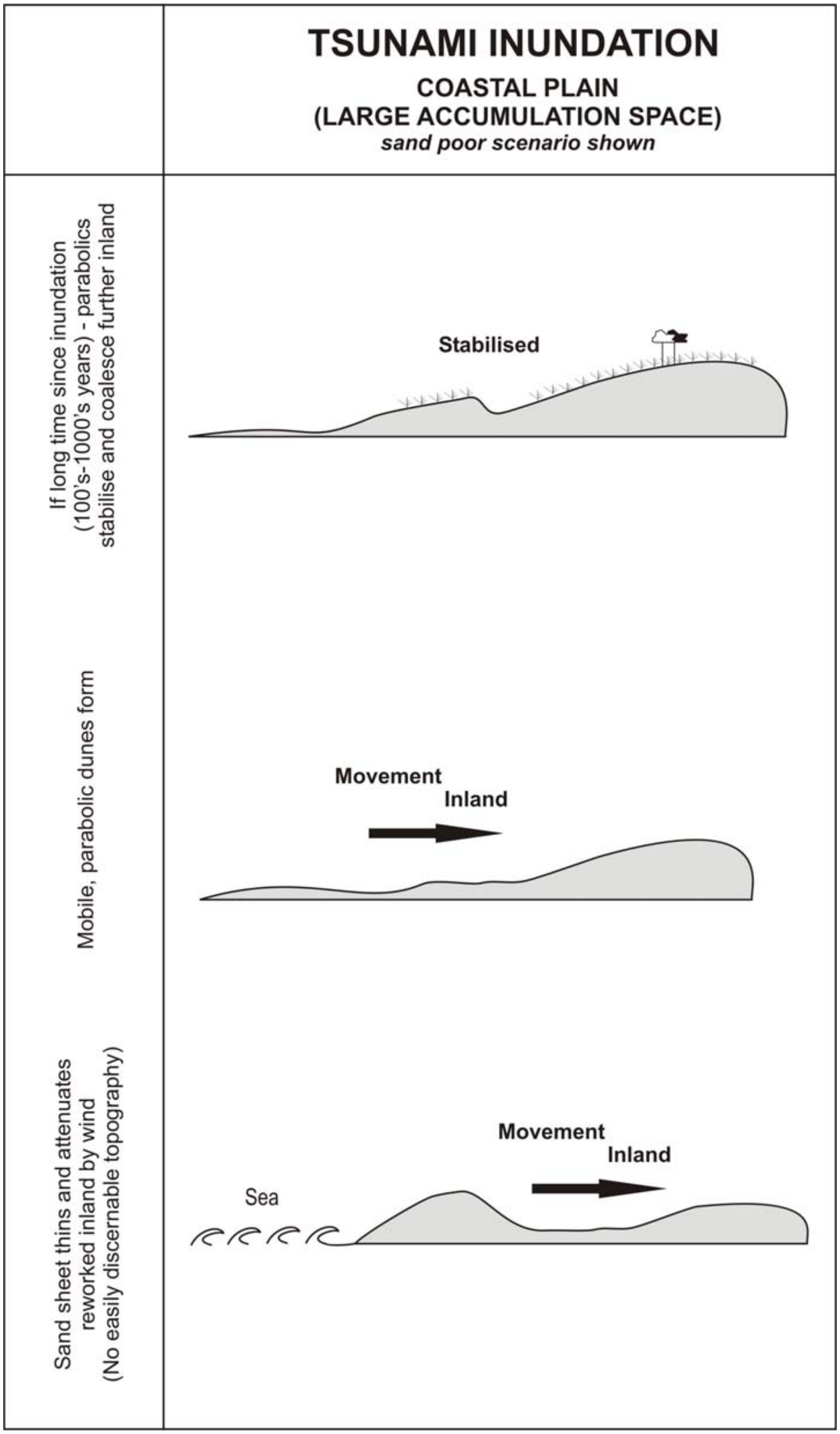

***Figure 11*:** Sand sheet–parabolic dune development in profile with large accumulation space AND dry ground conditions (in wet conditions the sand sheet is immobile and weathers). Sand-poor conditions.

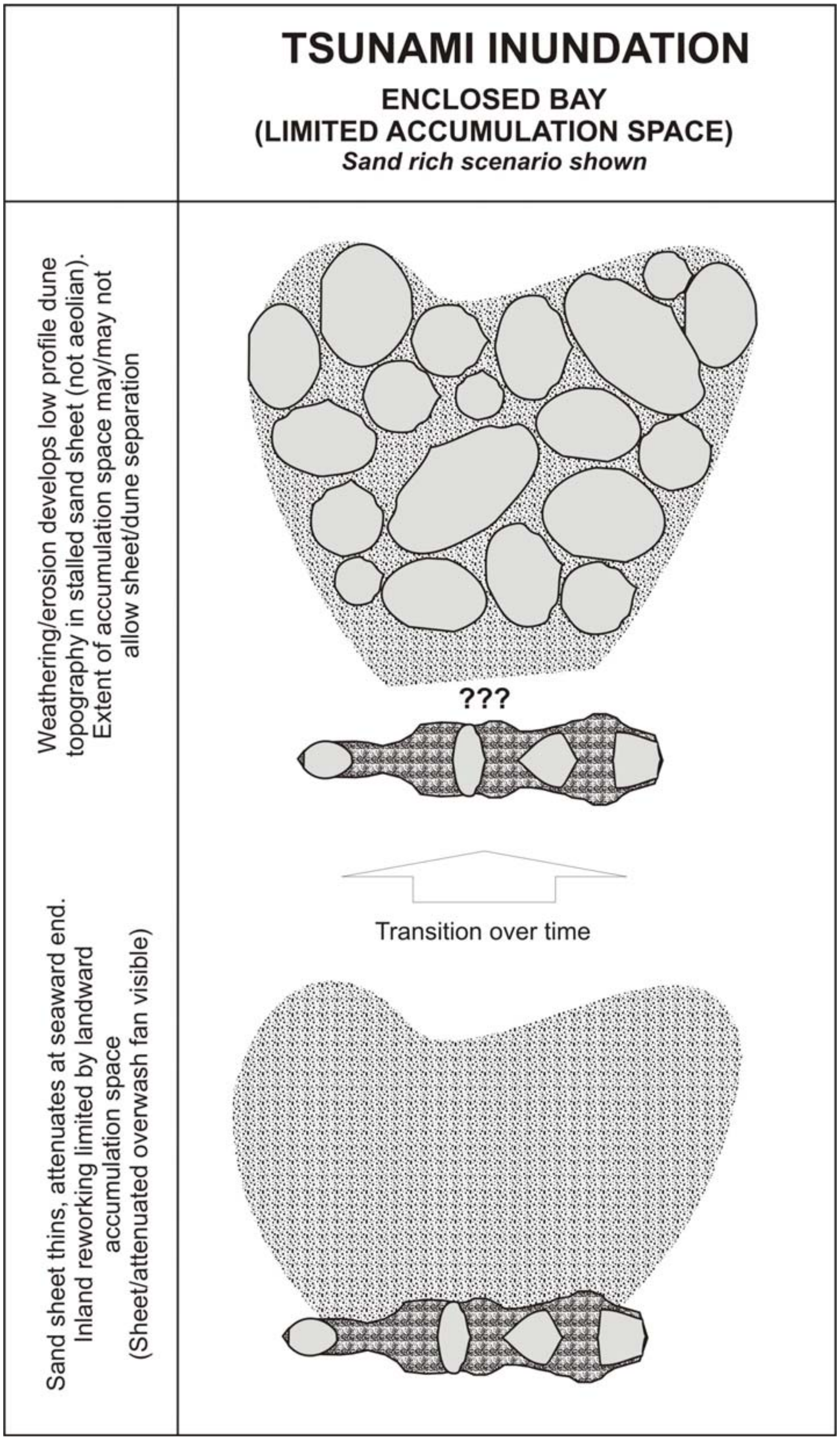

Figure 12: Sand sheet–hummocky topography dune development with limited accumulation space AND wet/dry ground conditions. The upper section of the figure represents the formation of hummocky topography through time – the light grey shaded areas represent remnant small, low-profile dunes

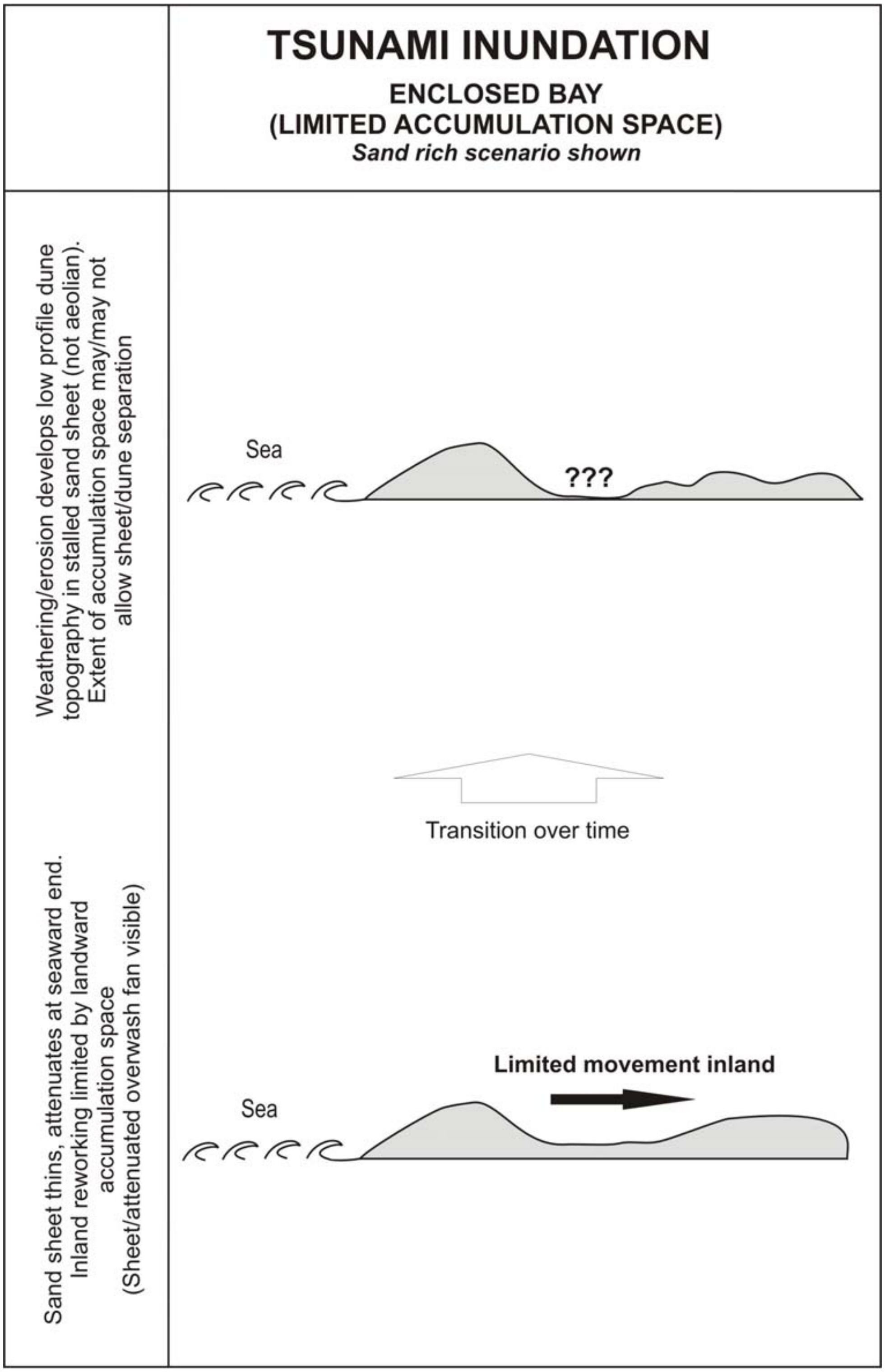

***Figure 13*:** Sand sheet–hummocky topography dune development in profile with limited accumulation space AND wet/dry ground conditions. This is a profile view of Figure 12. In the upper section the question marks indicate the separation zone between existing coastal dunes and hummocky topography – the degree of separation is dependent upon the landward extent of the accumulation space.

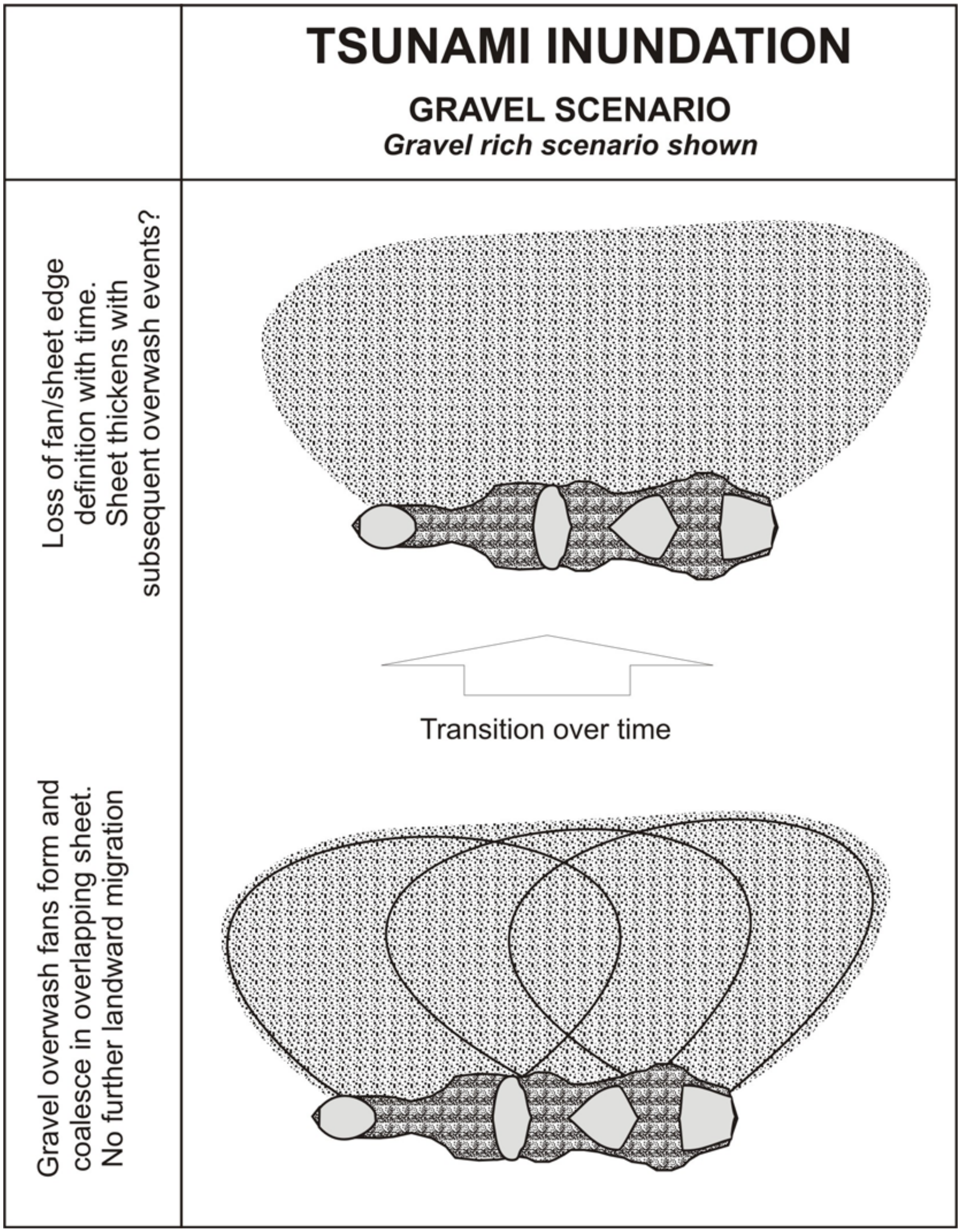

***Figure 14*:** Gravel sheet development.

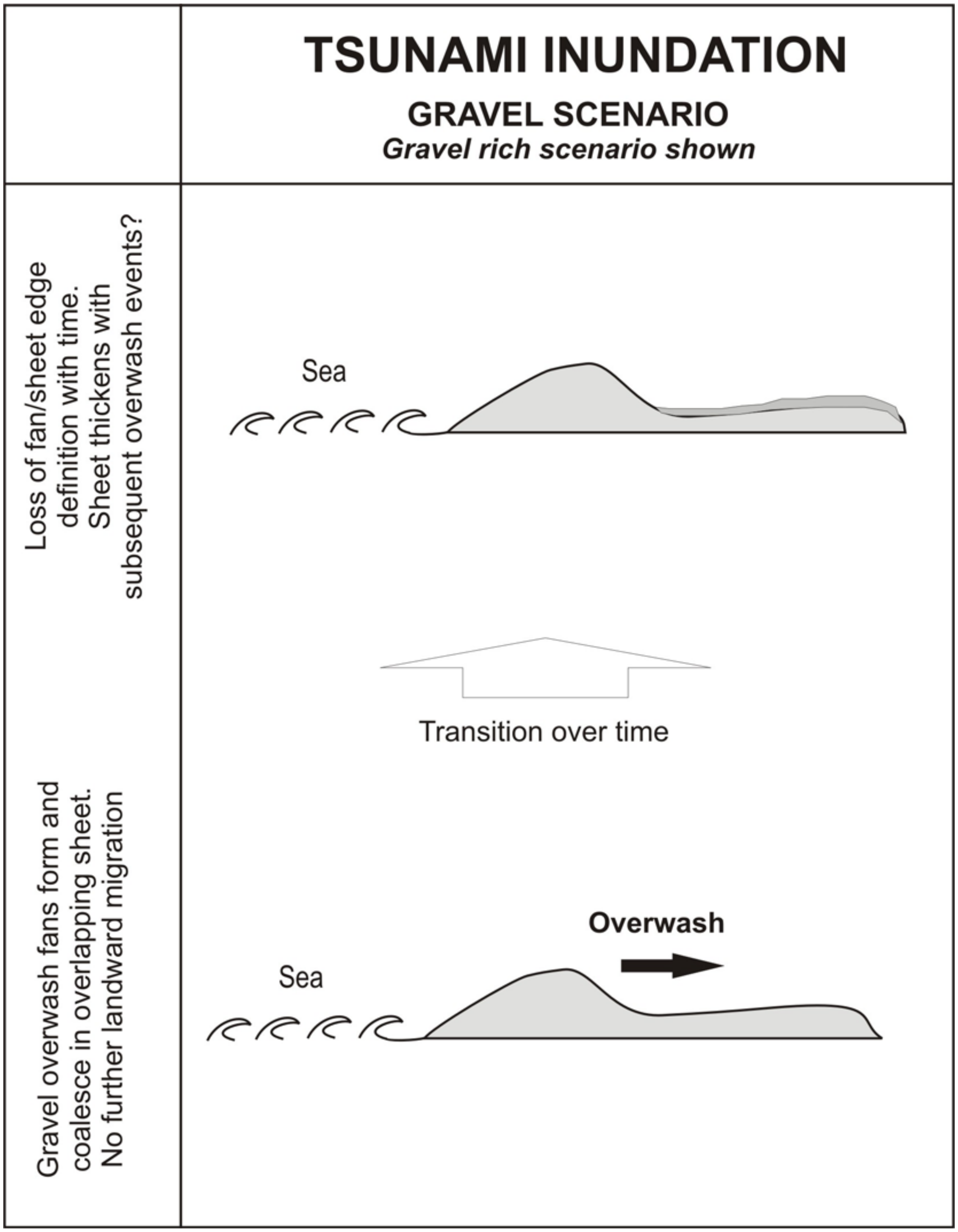

***Figure 15*:** Gravel sheet development in profile.

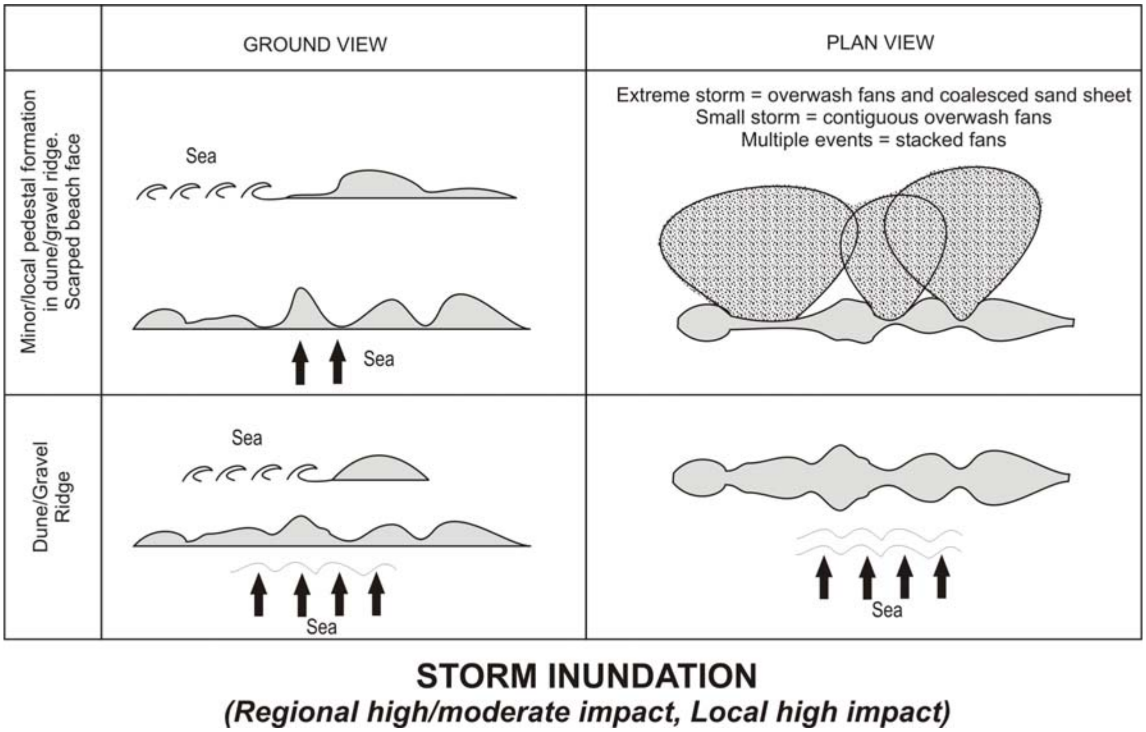

***Figure 16*:** Effects of large storms with stacked overwash fans, local pedestal formation, and seaward scour of dune.

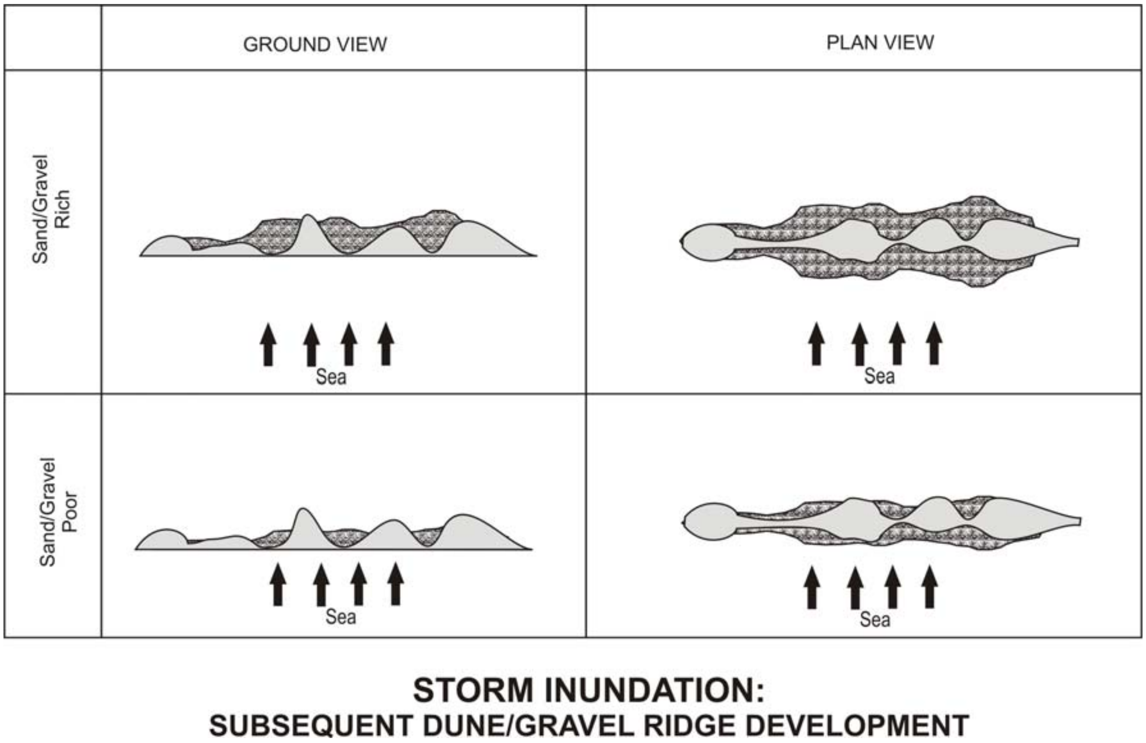

***Figure 17*:** Post-storm dune development in sand-poor and sand-rich environments.

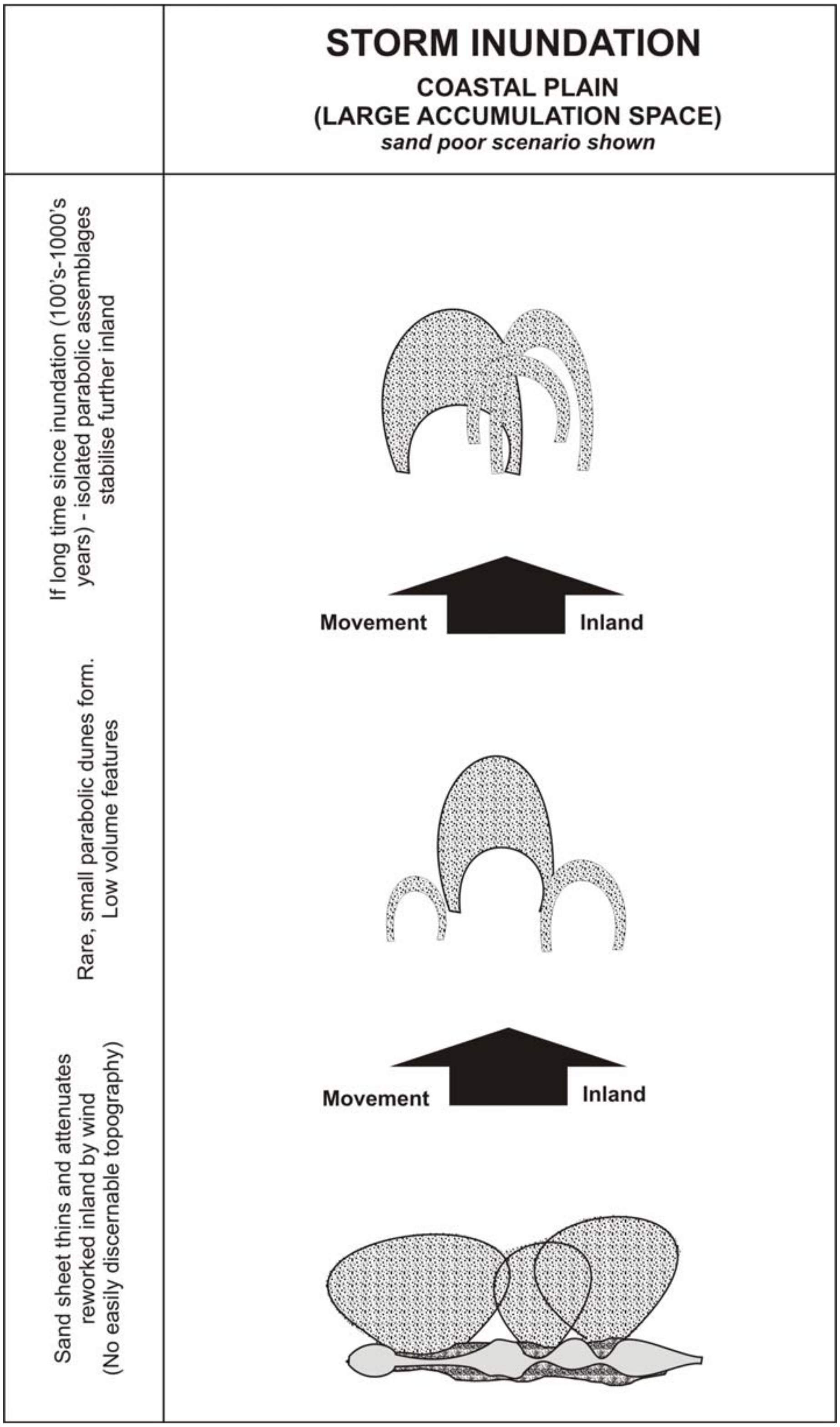

Figure 18: Storm geomorphology develops –discrete parabolic dunes advance inland with large accumulation space AND dry conditions (in wet conditions the sand sheet is immobile, weathers, but does not form hummocky topography because mass is too small).

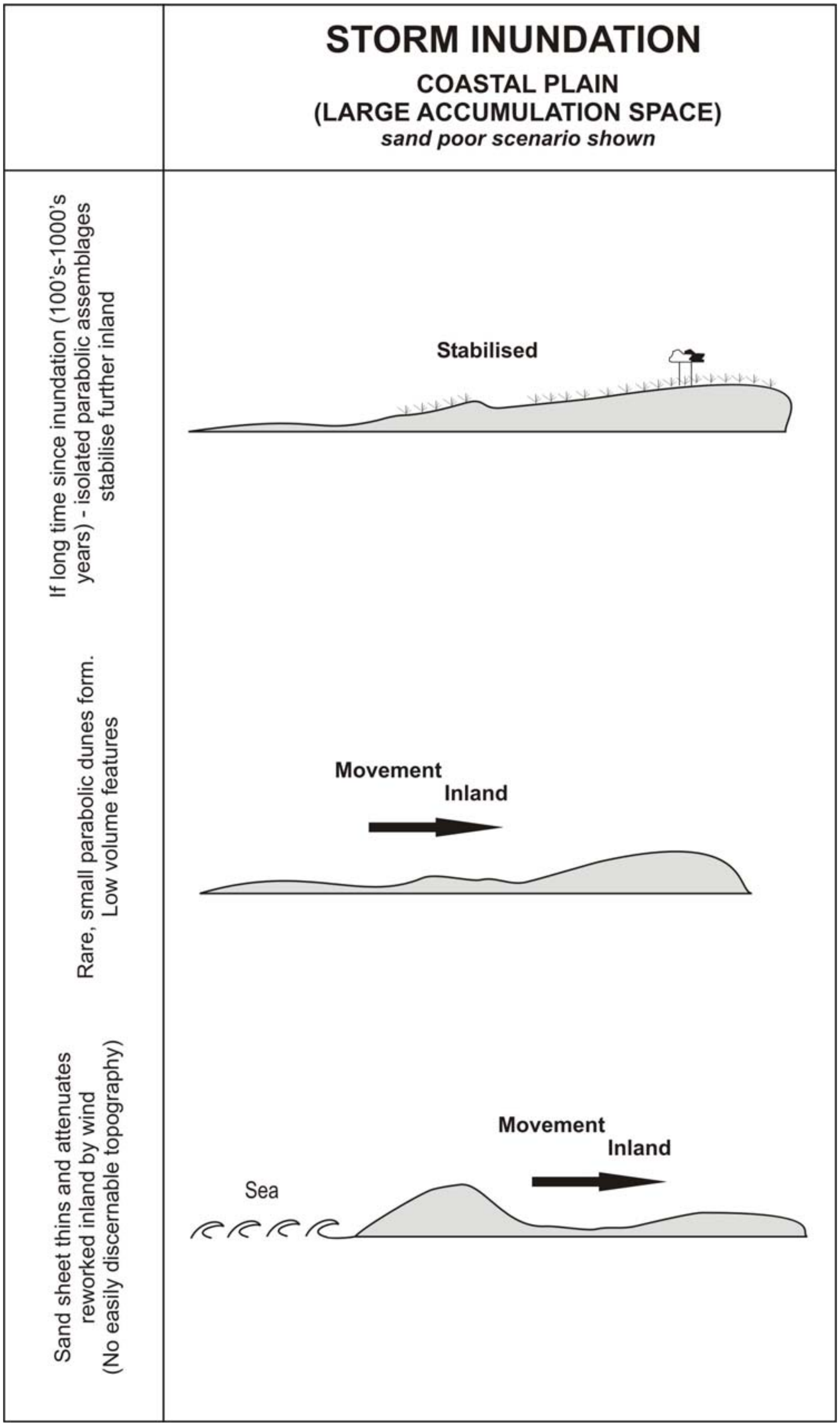

***Figure 19*:** Storm geomorphology develops – in profile.

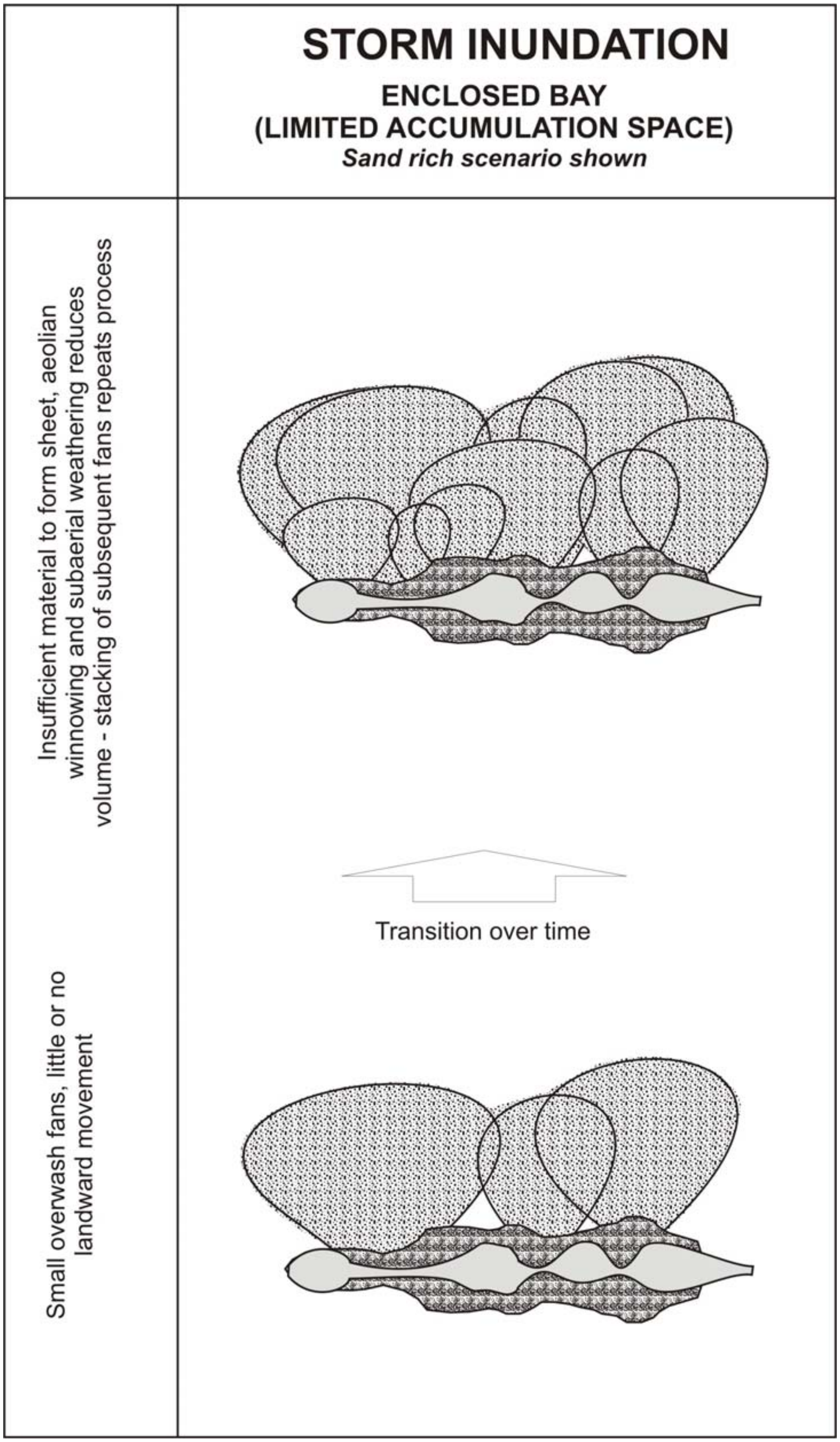

***Figure 20*:** Storm geomorphology develops – with stacked overwash fans in limited accumulation space and wet/dry ground conditions.

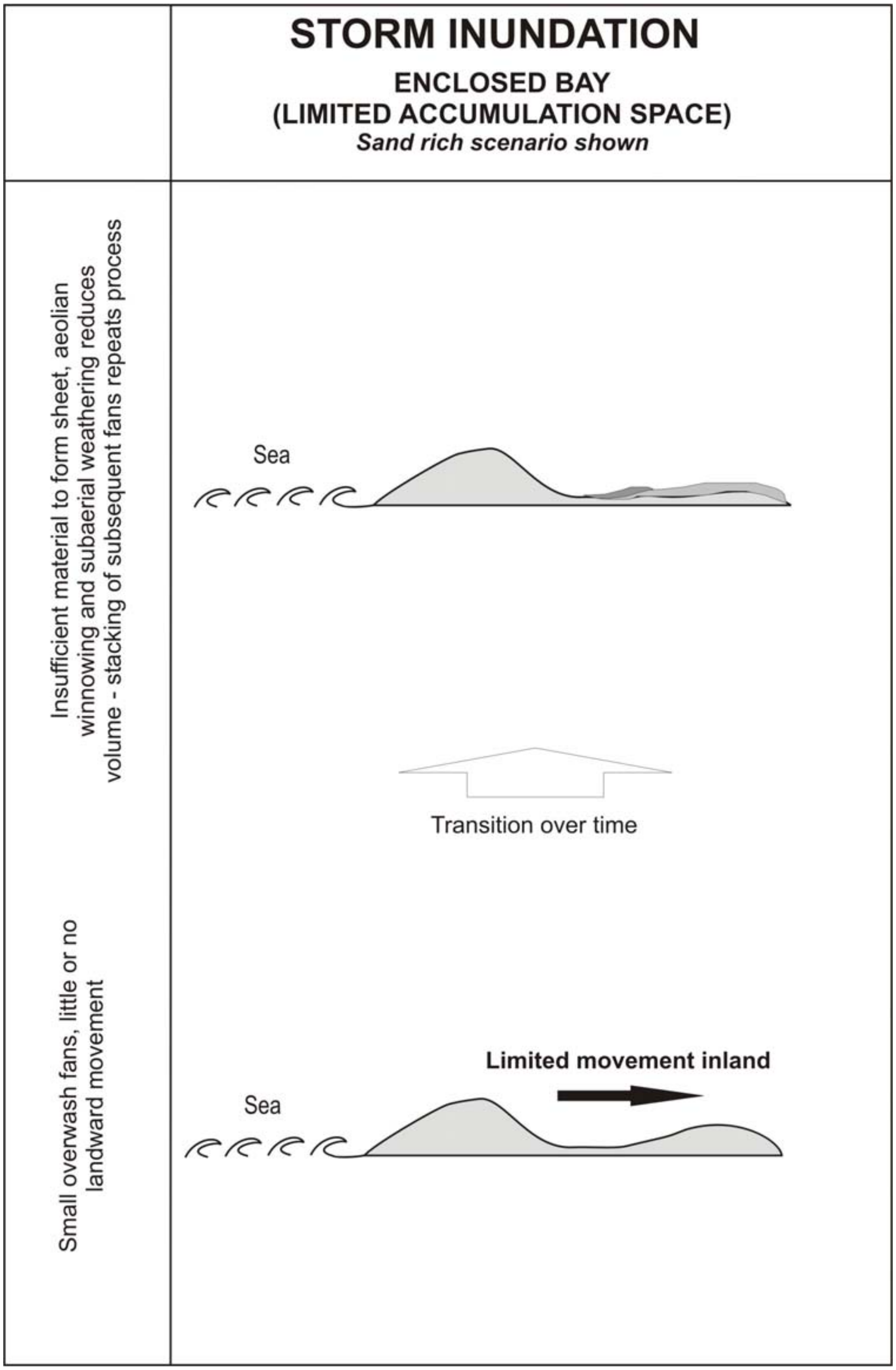

***Figure 21*:** Storm geomorphology develops – with stacked overwash in profile.

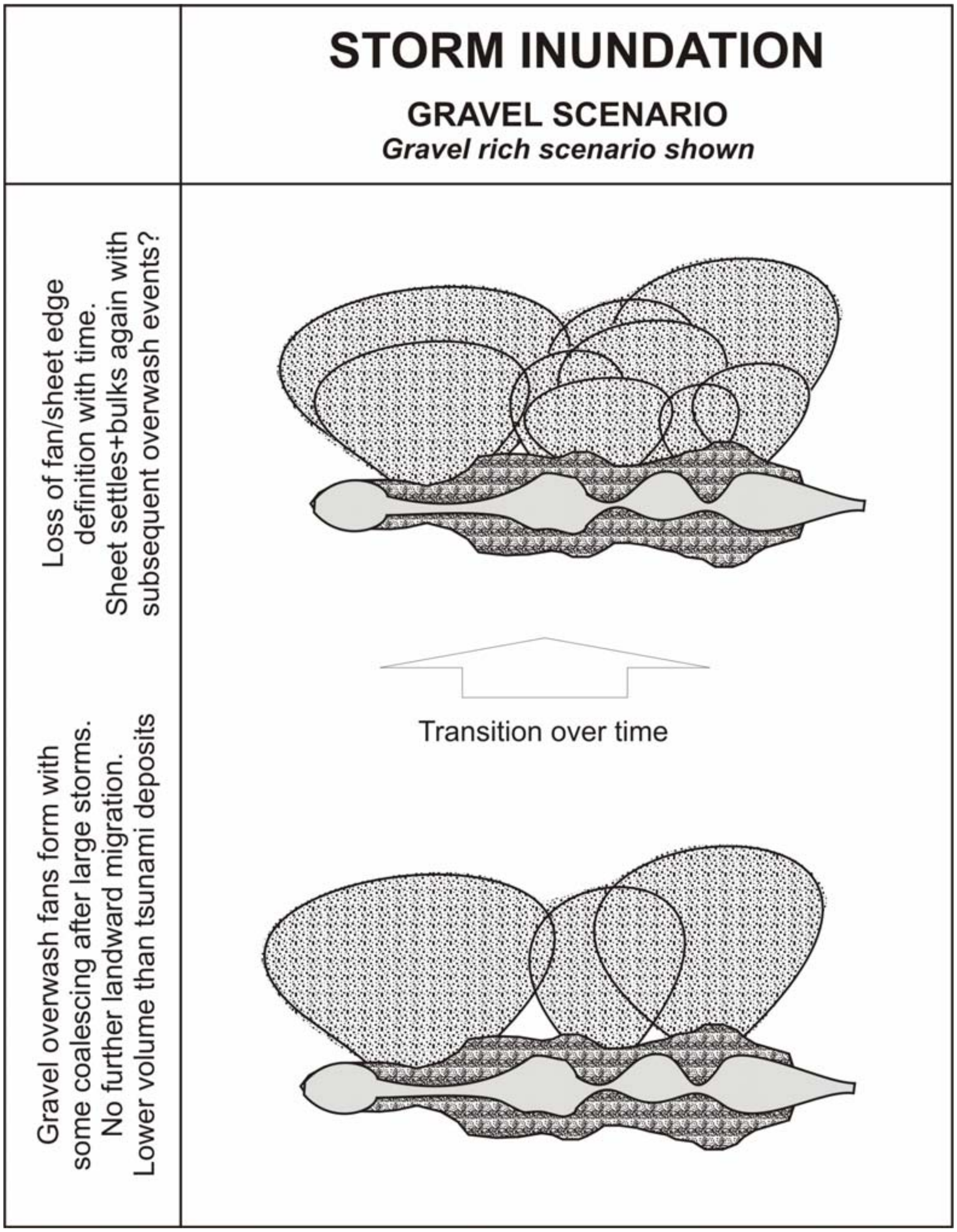

Figure 22**:** Storm geomorphology develops in gravel – with stacked overwash.

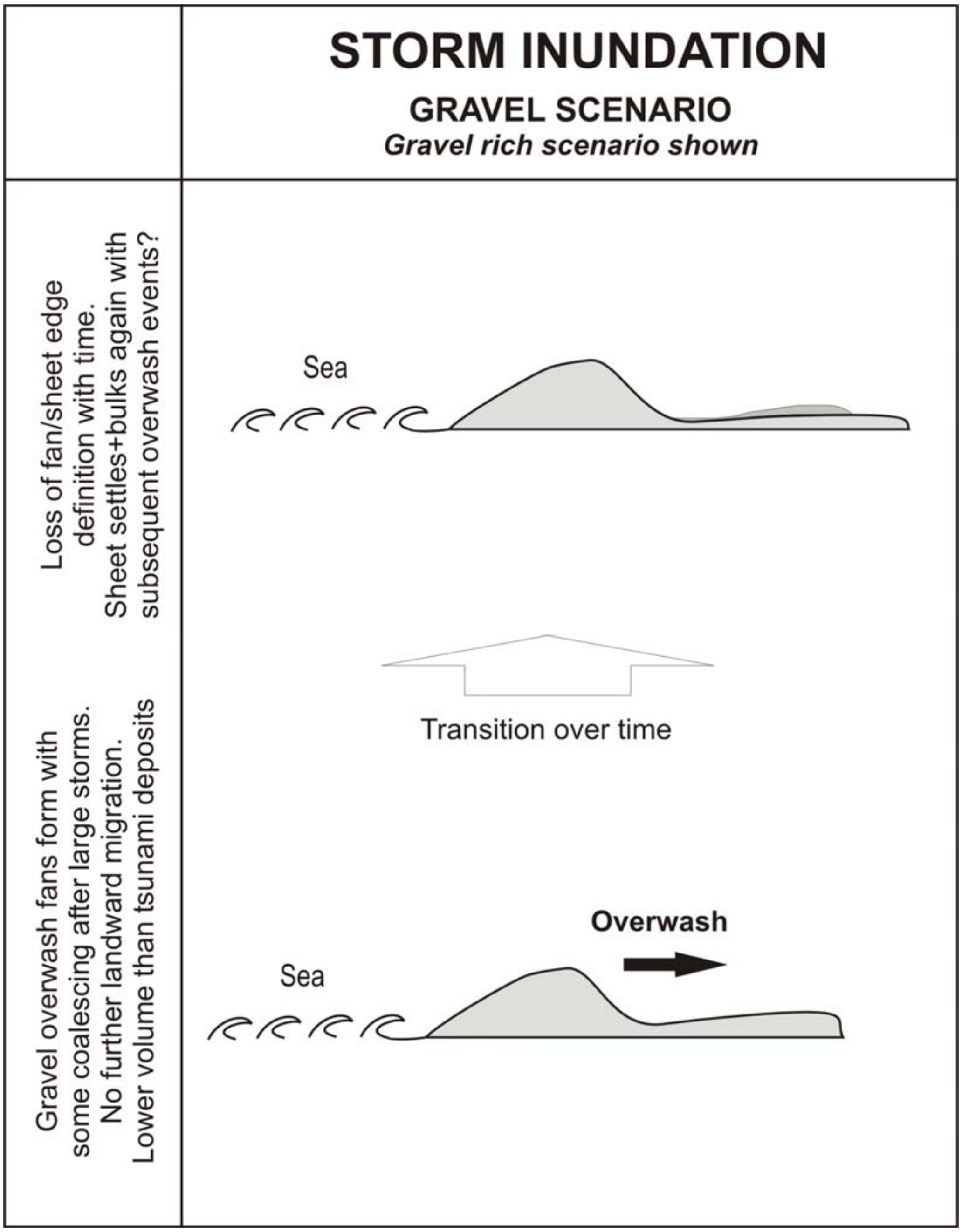

***Figure 23*:** Storm geomorphology develops in gravel – with stacked overwash in profile.

Field examples of tsunami and storm geomorphology

Field examples of pedestal and overwash deposits from contemporary and prehistoric sites are given below for storm and tsunami scenarios. Other rare features are also shown – in most cases, these are poorly preserved in the field, but provide additional geomorphological indicators (e.g. scarping).

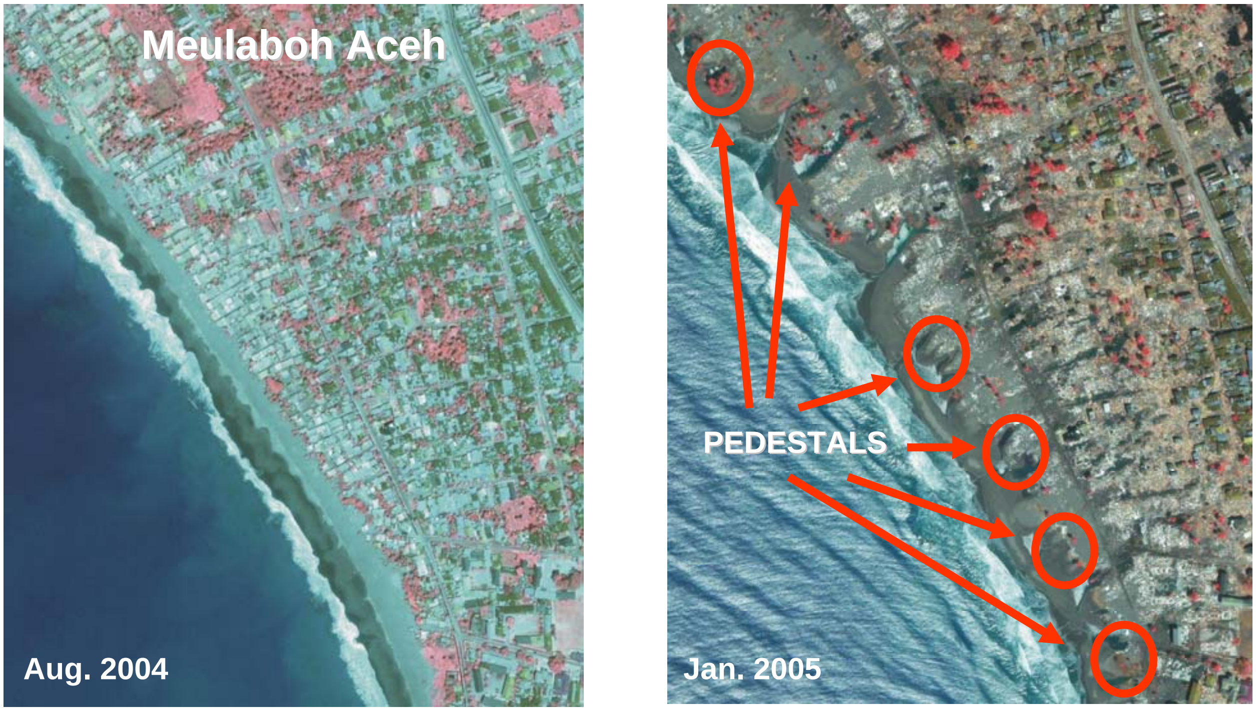

Figure 24**:** Pedestal formation in Aceh Province, December 26th 2004 (Images from http://www.crisp.nus.edu.sg/tsunami/tsunami.html, they were acquired and processed by CRISP, National University of Singapore. IKONOS image © CRISP 2004).

Henderson Bay
(Photo: S. Nichol, University of Auckland).

Chatham Island
(Photo: B. McFadgen, ArchResearch).

Whangapoua, Great Barrier Island
(Photo: S. Nichol, University of Auckland).

Figure 25**:** Pedestal formation in New Zealand – 14/15th century?

Figure 26: Aceh province: overwash and sand sheet formation, 2004 (Images from http://www.crisp.nus.edu.sg/tsunami/tsunami.html, they were acquired and processed by CRISP, National University of Singapore. SPOT image © CNES 2004).

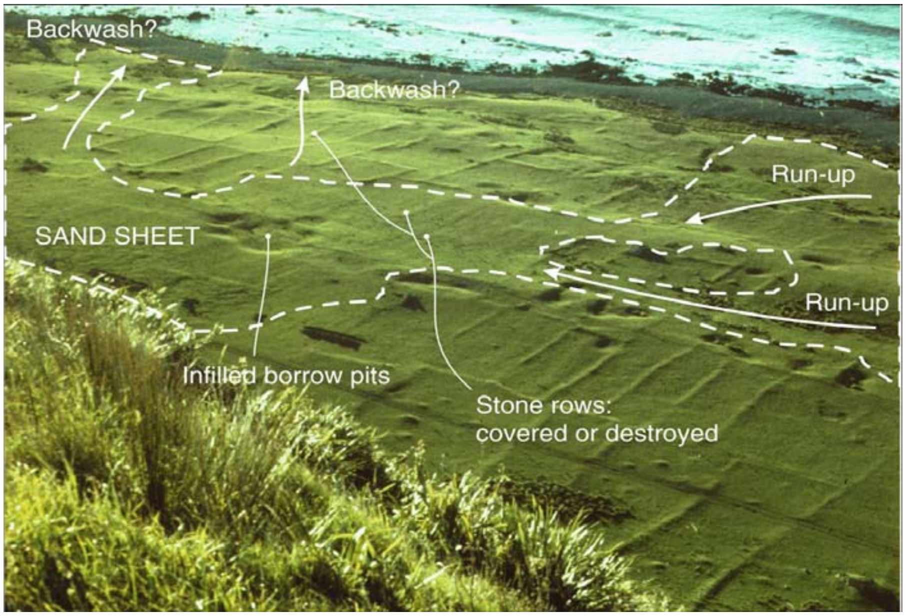

Figure 27: Wairarapa coast: landward sand sheet in limited accumulation space, 15th century (Photo G. Billing, © B. McFadgen).

Figure 28**:** Peru: gravel sheet/overwash fan – 2001 (Photo courtesy of M. Stirling, GNS Science).

Figure 29**:** Sri Lanka: sand sheet and pedestals (Photo: J. Goff – 11 January 2005).

***Figure 30*:** Kapiti coast: remobilised then stabilised dunes, with large accumulation space – 15th century (Photo courtesy of Department of Conservation).

***Figure 31*:** Hawaii: remobilised and stabilised dunes, with large accumulation space – remobilisation date unknown (Photo: J. Goff).

Figure 32**:** Whangapoua, Great Barrier Island: stabilised dunes, larger to west (top picture), with large sand sheet (lower picture) connecting coastal and landward dunes. Large accumulation space but little accommodation space now because of infilling by sand sheet. Bottom circle in top picture is an area of hummocky topography (Photo: K. Parnell, James Cook University).

***Figure 33*:** USA: two examples of storm washover with minor pedestals. These indicate the initiation of single dune remobilisation (Photos courtesy of R. Morton, USGS).

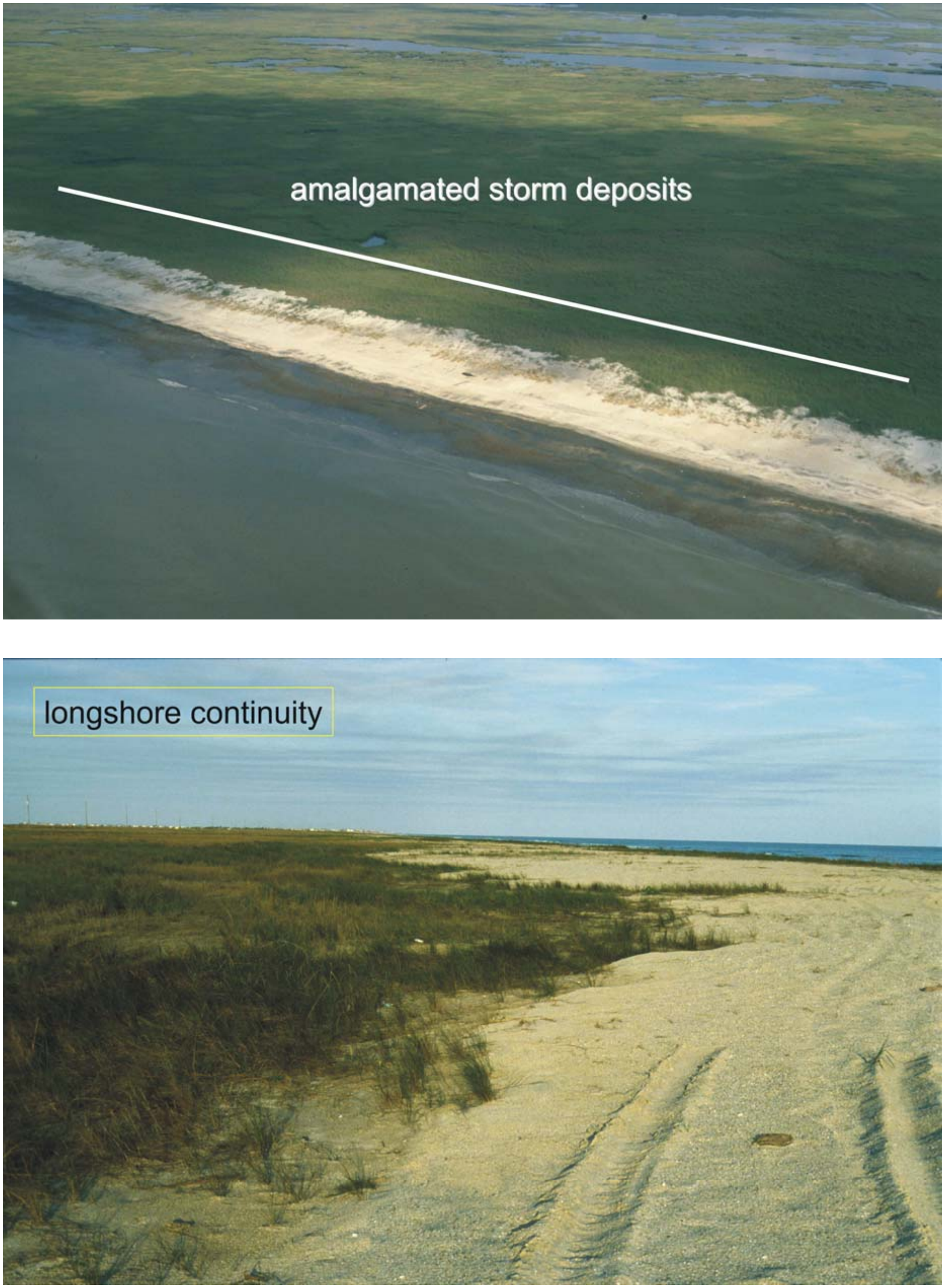

***Figure 34*:** USA: coalesced storm washover fans - note in both photos that fans penetrate a very short distance inland (Photos courtesy of R. Morton, USGS).

Figure 35**:** Scarp carved by tsunami in Sri Lanka, 2005 (Photo: R. Morton, USGS).

Methods

Features such as those developed in the conceptual models described leave a geomorphological imprint that will rarely be recognisable at the resolution of most topographic maps. Aerial photographs and/or LIDAR data are the most convenient mediums for an initial desktop scan. LIDAR data are the preferred medium for this work because the digital information can be manipulated to enhance images of any likely geomorphological features. Stereo pairs of aerial photographs, where available, can be examined as part of the desktop exercise to augment findings.

A general methodology for studying tsunami geomorphology was developed. It included the following steps:

- Identify an appropriate stretch of coastline. In this case, the study was an initial conceptual exercise; however, a similar selection procedure is recommended if the work represents the first time it has been carried out by an organisation or in a country or region. It is advisable to select a stretch of coastline that is believed to have been inundated by large tsunamis in the last 6000 years or so (since sea levels stabilised after deglaciation). The argument may appear circular and only applies in the best case scenarios for coastlines where there is some degree of understanding of past tsunamis. If it is known, or suspected, that only one (or few) large tsunami has inundated a particular stretch of coastline, any related geomorphological imprint should be more unequivocally identifiable. This creates a baseline of data and aids the identification of similar features in other areas. Clearly, if there is little or nothing known about tsunami inundation of the coastline, this convenient first step is bypassed.

- Determine the availability of suitable material – LIDAR is preferred. The degree of pre-processing can be problematic (e.g. topographic detail may be degraded in order to reduce file size) and where possible access to unprocessed or appropriately processed data is recommended. Are there any associated stereo pair aerial photographs available? These are useful at the initial desktop stage to verify features identified using LIDAR. If there is a reasonably long chronological aerial photograph dataset, they can also be used to assist in determining the age of an event. Aerial photograph datasets, however, rarely extend back beyond the 1940s, and as such they are most valuable for confirming that the geomorphological features in question date from prior to this time, or that they were formed by a large historical storm or tsunami.

- An initial scan of small stretches of coastline is selected. The initial scan includes representative stretches of segments of coast that are likely to have retained tsunami features, such as pocket beaches, estuaries, sand and gravel barriers, and so on. If a tsunami geomorphology appears to be present, then the search can be expanded.

- LIDAR images derived from the data are prepared in a GIS. Several images are prepared because geomorphological expression varies between sites as a result of variables such as geology, sand supply, aspect, etc. As a result, a balance needs to be found between shading colours and elevation categories (height gradations) to ensure that, where possible, the presence of features such as low profile (~0.5-1.0m) hummocky topography can be identified.

The files provided by the LIDAR operators, usually in simple text format, include one or more of the following: thinned ground strikes (or last pulse strikes), non-ground strikes (last pulse strikes considered to have been reflected off vegetation rather than the ground), first pulse strikes (which are usually off vegetation if it is present), topography contours and intensity imagery off either first or last pulses. The thinned ground strikes can be used to generate Triangulated Irregular Networks (TINs), which in turn can be used to build grids for visualising the topography (e.g. with shaded relief plots or colour-coded elevations) and for classifying with edge detection techniques.

For our analysis, the text files containing the thinned ground strikes were read into Matlab (similar software may be used), re-formatted, and written out as ESRI shapefiles. Any overlapping shapefiles were merged. The number of points in the merged shapefiles often made it impractical to generate TINs for all the data available, and so topographic maps were used to prioritise areas of study. Bounding coordinates for each area delimited points for extraction from the shapefiles. Point shapefiles were converted to ArcInfo coverage and used to generate TINs in ArcGIS 9.1 (again, other GIS software with similar functionality may be used).

Several edge detection techniques can be used to automatically identify possible features:

- Using the focal standard deviation command (focalstd) in GRID, ArcInfo workstation 9.1.

- Using the focalstd command with the addition of a kernel. The kernel allows for definition of the values and shape of an irregular neighborhood to be used in the edge detection (refer to Filtering method).

- ERDAS Imagine edge detection techniques can also be used. Results from the focal standard deviation tend to be similar to those from ArcInfo tools.

- ConFit tool is an extension to ArcView 3.x and contains convolution-filters. This spatial filter method uses a mask or kernel overlayed on a grid theme. It provides users with a 7x7 mask or kernel. Weights can be applied.

Numerical filtering procedures were used to filter "noise" from the raw edge-detection results. The filtering method chosen was the 'focalstd' command using a kernel. Below are diagrams of the kernels used. Various sizes were tested, but 3x3 was found to provide sharpest results. The frame is placed over every cell in the input grid. The value for the central cell is determined by getting the standard deviation of the cells in the input grid where there is a 1. Further weighting can be applied but was not used in this case.

all

1	1	1
1	1	1
1	1	1

X – cross

0	1	0
1	1	1
0	1	0

D – diagonal

1	0	1
0	1	0
1	0	1

V – vertical

0	1	0
0	1	0
0	1	0

H – horizontal

0	0	0
1	1	1
0	0	0

Further steps in the analysis included:

- A digital catalogue of the selected coastal sites is maintained, and where identified, the above edge detection techniques are applied to better differentiate possible tsunami geomorphology from other features.

- Ground surveys and literature reviews of all available material are undertaken to ascertain the nature of the features identified. Sediment samples, photographs, and other multiple lines of evidence are collated and analysed to determine the origin of the geomorphology.

- If a tsunami origin is confirmed at any of the representative locations (e.g. by reference against information provided in the preceding section or in the literature), then an automated search of the digital data can be undertaken through the GIS to find similar geomorphological features around the coastline. This is a new technique and methodology and as such it is pre-emptive to suggest that all similar LIDAR-distinguished morphology is of tsunami origin. It is suggested that subsequent verification, or ground-truthing, at individual sites is necessary. After some period of repeatedly verifying the automated method, then one could proceed with confidence to other areas without ground-truthing.

- Several options are available at this point – examine the nature and extent of inundation, search for multiple events in the geomorphological record, extend the search to other coasts/stretches of coast, compare with the geological record to determine the magnitude and frequency of tsunami inundation along the coastline, (including the smaller events noted in historical records).

Much of the methodology above is related to an initial conceptual study – searching for the first evidence of tsunami on a coast. Having established that a tsunami record exists in the geomorphology, many of the above steps are unnecessary. For example, we now know that tsunami geomorphology can be identified using LIDAR and that field verification is not necessary. This methodology then incurs considerable cost savings because it becomes a purely desktop study that serves as an initial scan to determine whether a coastline has experienced large tsunamis in the past. If it has, then further field studies, literature reviews, source identification work, and modelling exercises follow.

The study area

Tsunami expectations

For our initial conceptual study, we selected estuarine and pocket beach sites along the coastline of the Otago region. The existing historical database only has a record for one of the chosen sites (Taieri River Mouth) where tsunami wave heights have exceeded 1.0 m. Based upon this database, it has been inferred that there is little or no significant tsunami hazard for the region's coast. The recent Ministry of Civil Defence & Emergency Management report states that the expected "mean estimate wave" for a tsunami with a return period of 2500 years is 3.8 m for Dunedin and between 4-8 m for the Otago region open coast (Berryman, 2005). This estimate is by necessity based on some extrapolation but to date there are no palaeotsunami data to suggest that this is incorrect. Given this lack of information, but a perceived low hazard rating, a comprehensive geological survey is unlikely. However, a recent review of geological and archaeological information for the Otago coastline does suggest that tsunami inundation has occurred since human occupation in the 13th century, but there is little other information (Goff, 2006). If inundation did occur, it would seem likely that this was a rare event over the last 6000 years or so since sea level rose to near its present level. The reasoning behind this assumption is that there are no obvious active local or regional earthquake sources thought to be significant enough to generate a large tsunami. Otago's coastal geomorphology may therefore prove useful for recognising tsunami inundation because only few (perhaps only one) events have occurred in 6000 years or so. If a large enough event occurred it should have created a geomorphology markedly different from other coastal processes. If more than one large tsunami inundation has occurred, it is possible that they would have been infrequent enough to be recognisable as a separate suite of features.

Data source and representative sites

LIDAR data were made available free of charge by Otago Regional Council. Eight sites were chosen, each with geomorphic settings suited to the creation and preservation of tsunami features. Most of these sites also included early (Archaic) prehistoric coastal Maori settlements (Figure 36).

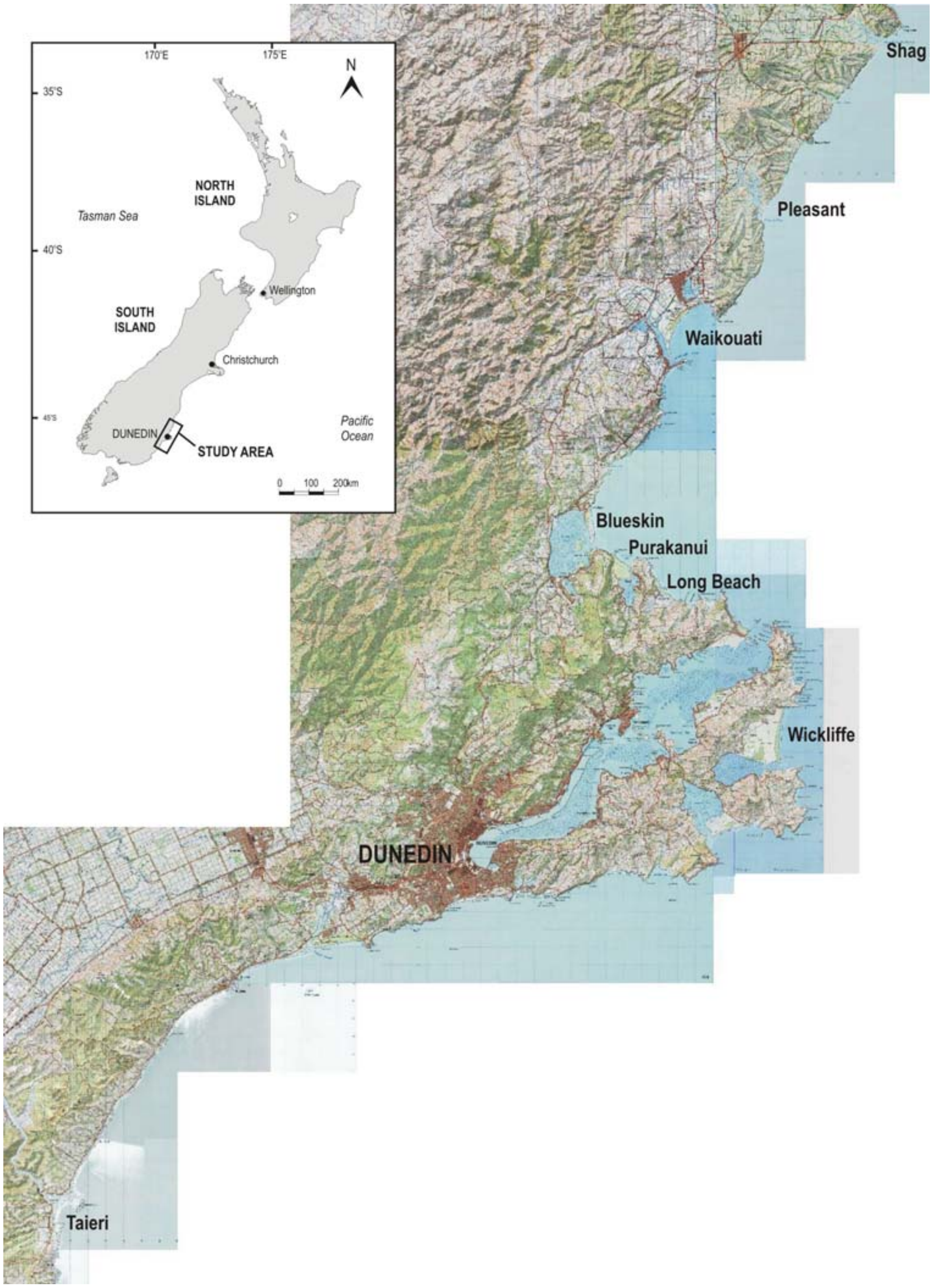

***Figure 36*:** Otago Region coastal locations: Shag River, Pleasant River, Blueskin Bay, Purakanui and Long Beach were the sites of significant early prehistoric coastal Maori settlements.

Results

Visual scans of topographic imagery of the eight sites indicated that one or more of the sites had some degree of pedestal-like structures, overwash/tsunami-scour fans, and potential hummocky topography. These observations were confirmed from the available aerial photograph data.

Some manipulation of the LIDAR data was undertaken to enhance the features, including edge detection (as described in the methodology section). Some of these images are shown below.

Ground-truthing focused on two of the eight sites, Long Beach and Blueskin Bay. These were chosen because they represented distinctly different coastal environments. Long Beach is a small sandy embayment between cliffed headlands. The embayment extends about 1 km inland and has a coastline of approximately 1.5 km. Blueskin Bay is a large (3 km x 3 km) tidal estuary enclosed behind a 500 m wide spit that extends southwards across the mouth of the bay. Both had significant early Maori settlements.

Blueskin Bay

A LIDAR image of Blueskin Bay revealed a series of possible pedestal features along the spit (Figure 37). The data were subsequently manipulated using the image analysis process described above to isolate pedestal-like features on the spit (Figure 38). A ground survey subsequently confirmed the presence of nine pedestals (Figure 39). All were topped with trees and relatively mature vegetation. Pedestals had a core of compact weathered sand and soil markedly older than the overlying unconsolidated, fresh sand. At the southern end of the spit, the scours between the second and third, and fourth and fifth pedestals are currently actively maintained by tidal flows at or near high tide.

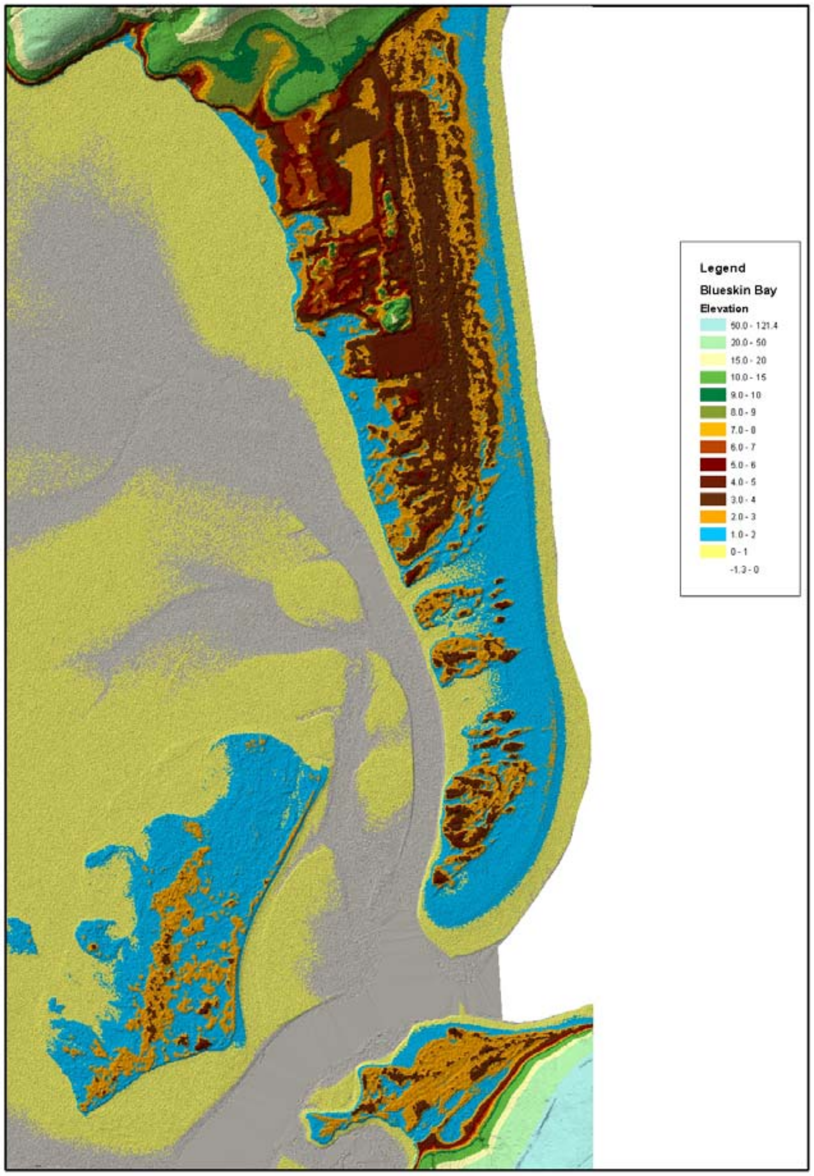

***Figure 37*:** Blueskin Bay: Initial LIDAR image (unfiltered).

Comparison between 1958 and 1990 aerial photographs indicates that the pedestals have largely remained stable over the last 50 years. Variations in pedestal volume have taken place, but the location of the core has not changed (Figure 40). The rapid ground survey did not allow time for a detailed sediment sampling regime, however it was noted that evidence for early Maori occupation was present in less disturbed areas of the weathered soil horizon towards the northern end of the spit. Given that Maori arrival dates back to the 13th century (e.g. Anderson et al., 1996), and the early Maori period ends around the 15th century, it is likely that core material dates to between the 13th to early 15th centuries. Creation of the pedestals is therefore tentatively placed in this timeframe. The relevance of this time period is discussed in more detail on page 61.

The spit is backed by an active estuary. Preservation of a landward sand sheet would seem unlikely since it would be subject to ongoing fluvial and tidal processes. While speculative, it is possible that the rapid deposition of a large volume of sand by tsunami inundation could have exceeded the ability of these processes to remove all the material. The large island assemblage landward of the spit has a morphology consistent with the proposed hummocky topography that would eventuate following long-term sub-aerial weathering (Figures 12, 39, and 40). A more conventional explanation would be that it is a relict tidal delta or spit. In the absence of a more detailed study, however, any interpretation must be considered tentative.

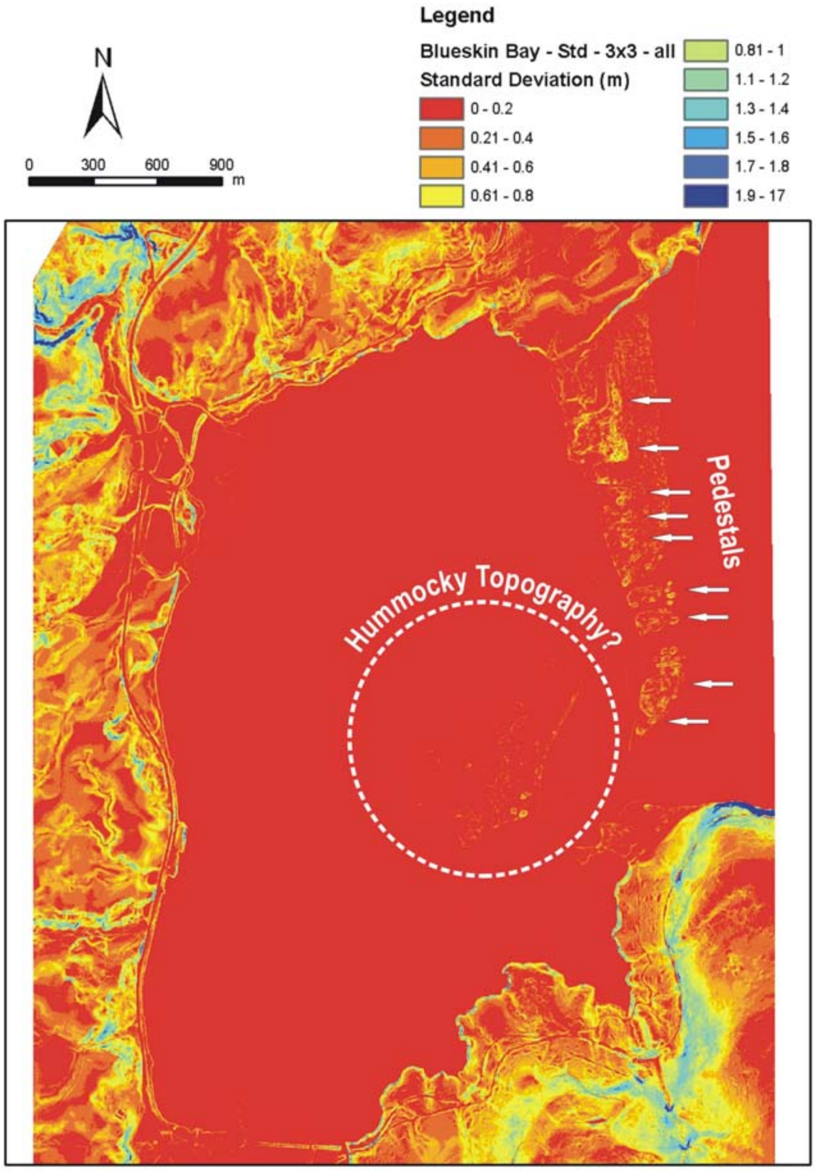

***Figure 38*:** Blueskin Bay: Data manipulation ('all' filtering method) to enhance pedestal-like features. White arrows indicate possible pedestals.

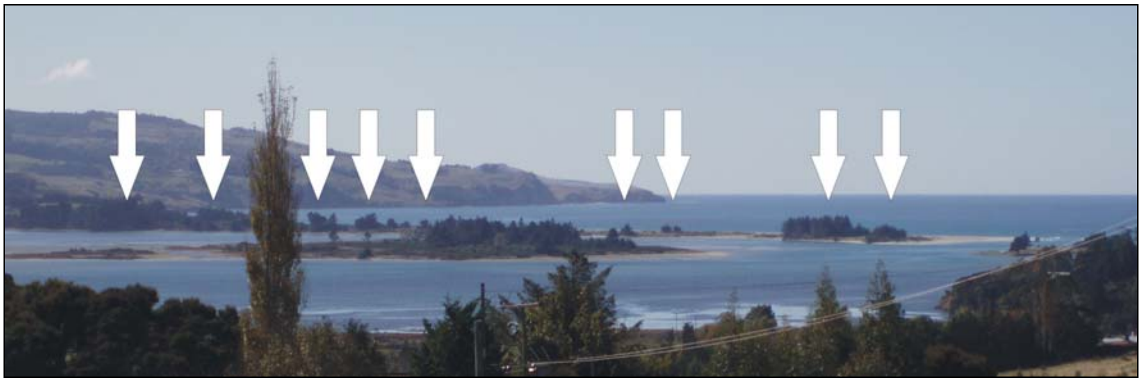

Figure 39: Blueskin Bay viewed from the SW. White arrows indicate remnant pedestals on the spit. An island is visible landward of the spit – this is possibly remnant hummocky topography (Photo: J. Goff).

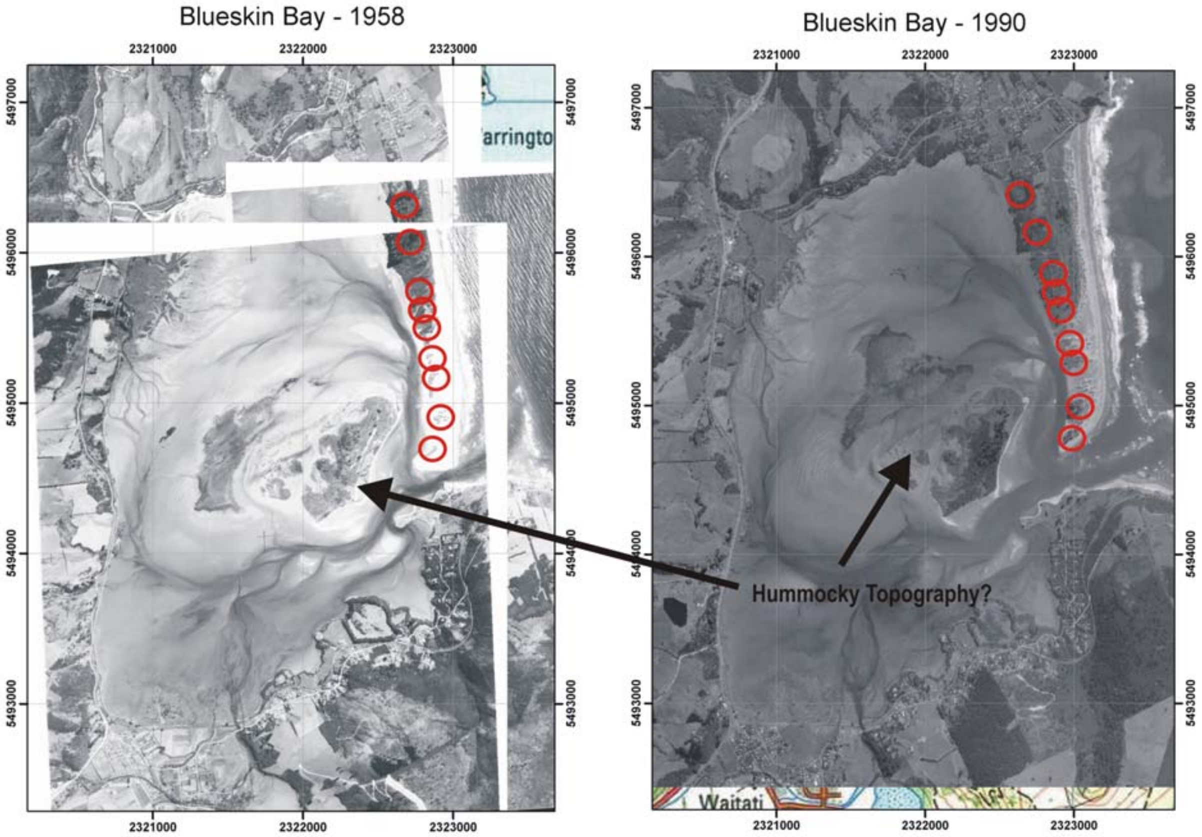

Figure 40: Blueskin Bay: comparison between the 1958 and 1990 aerial photograph mosaics. Pedestal locations are marked by red circles – volumetric changes are visible but the locations have remained stable (Photos courtesy of Otago Regional Council).

Long Beach

The LIDAR image for Long Beach initially revealed a small embayment with two distinct sets of dunes. A fragmented landward set of higher elevation dunes, and an intact seaward group of lower elevation dunes, are separated by a wide, low-profile swath of sand (Figure 41). The seaward dune system started to form around 1863 (Anderson, 1981).

Our initial interpretation of the LIDAR image is shown in Figure 42. There is a section of well-defined hummocky topography landward of the higher elevation dunes. The fan of hummocky topography splays into a small wetland formed where a stream ponded behind the dunes. This pedestal-hummocky topography association is interpreted as tsunami geomorphology. If the speculative interpretation of the chronology of Blueskin Bay is correct, and inundation was more regional than local, this event would most likely have been contemporaneous, occurring around the 13th-15th centuries. Long Beach contains an important archaeological site that shows evidence of having been "washed by the sea" (Leach & Hamel, 1981). Occupation at about this time has been radiocarbon dated to about AD 1460+/-58 years (Leach & Hamel, 1981).

During our reconnaissance survey, the section of the site having been "washed by the sea" was found to be represented by a layer of pebbles and sand approximately 20 cm thick. In similar geomorphological associations elsewhere in the country, this type of sedimentary unit has been defined as a tsunami deposit (e.g. Nichol et al., 2004). Perhaps the important point to make here is that there is no other process capable of depositing such a sedimentary sequence - it is not diagnostic of a storm deposit (e.g. Goff et al., 2004). Since the unit overlays the early Maori site, and extends inland as a coherent unit as a sand sheet/hummocky topography (Figure 43), it seems reasonable to conclude that this relates to a tsunami inundation that occurred around the late 14th to mid-15th centuries.

Comparison between ground survey and the Long Beach LIDAR images indicates that the pedestals are separated from the post-1863 dune sequence by a broad low profile sand plain. The feature, which must have post dated the dune pedestals, was termed a Low Profile Sequence. Its relevance is discussed later.

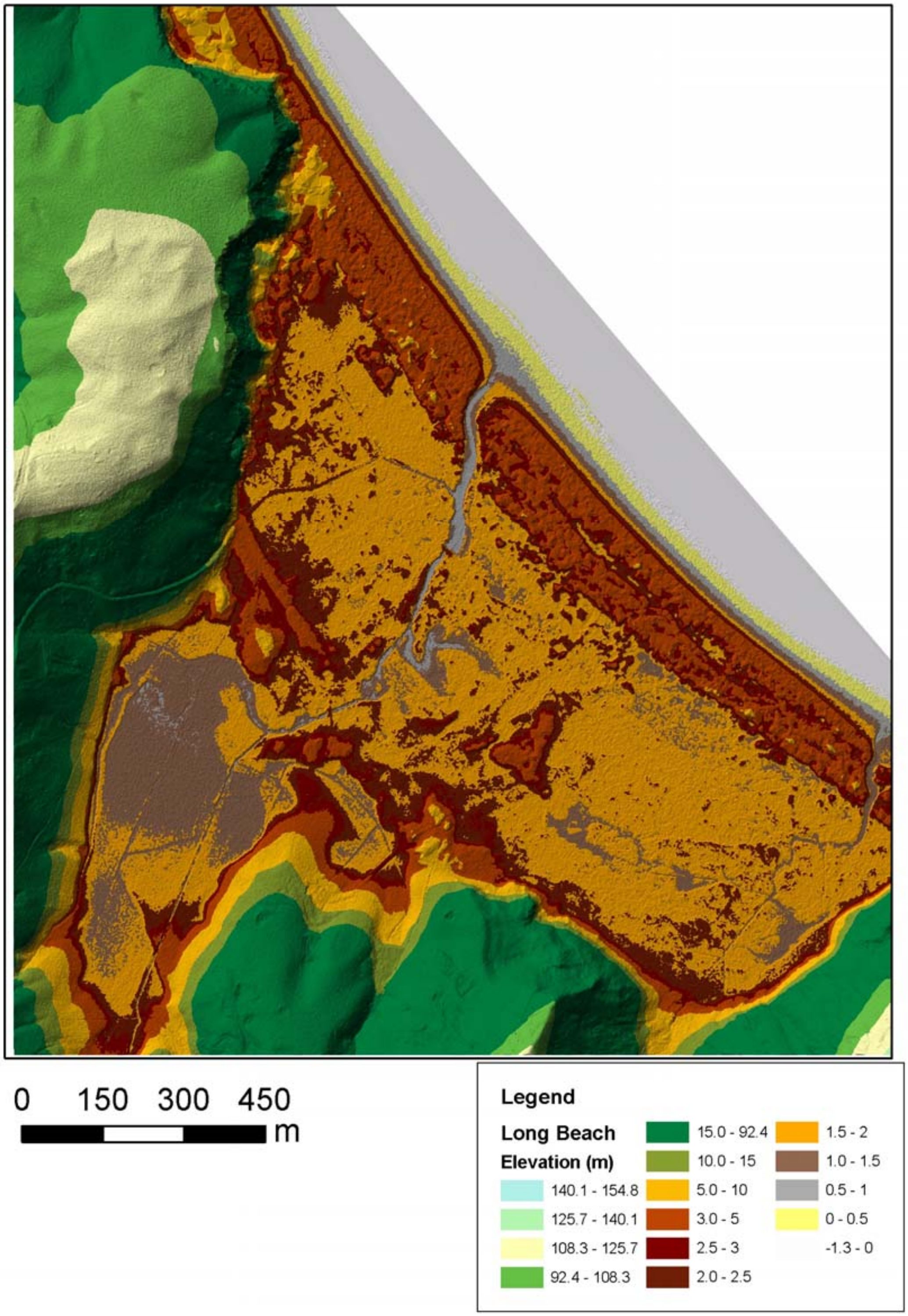

Figure 41**:** Long Beach: Initial LIDAR image (unfiltered).

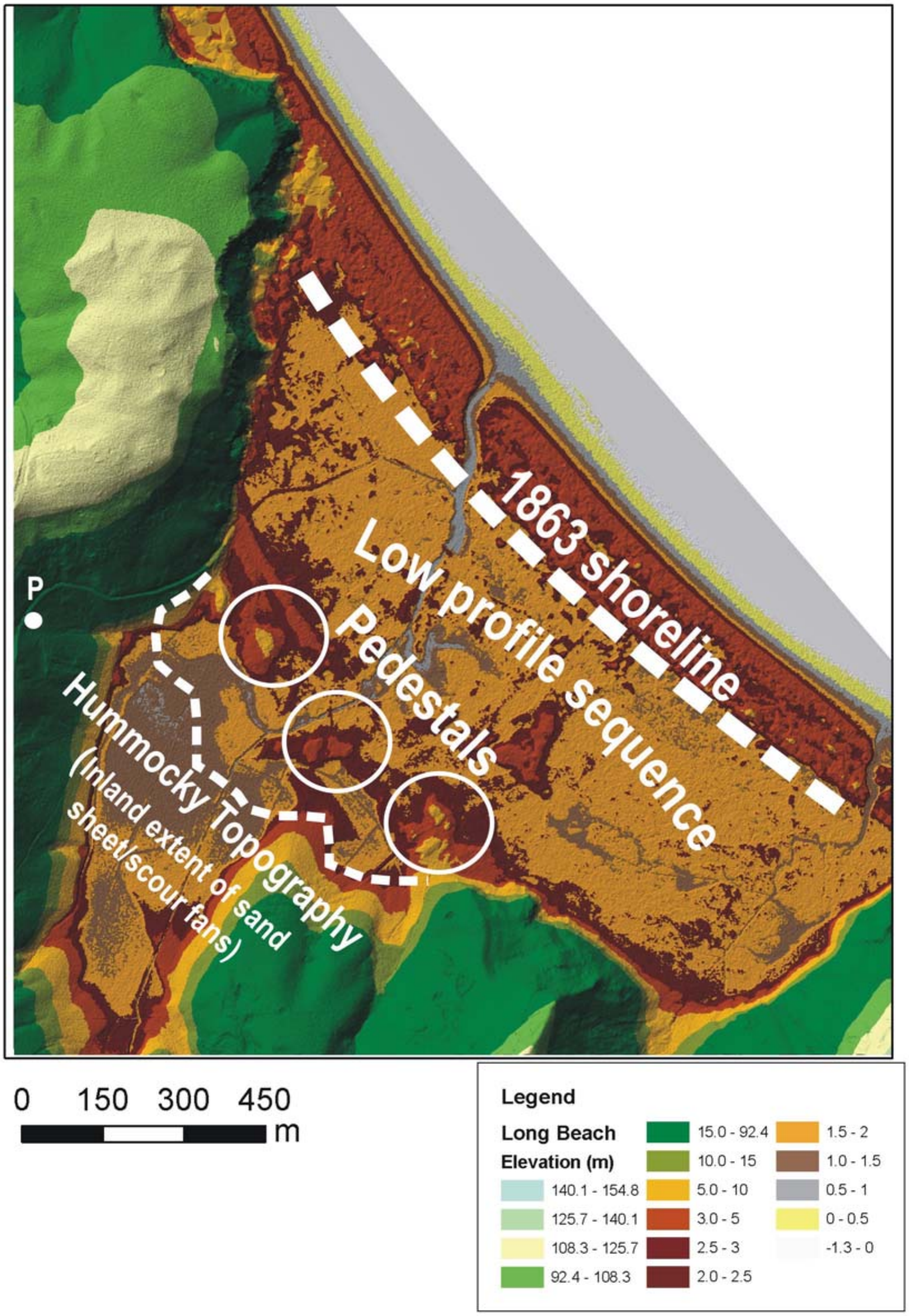

***Figure 42*:** Long Beach: Interpretation. P = Site where the photograph in the next figure was taken from – looking SE.

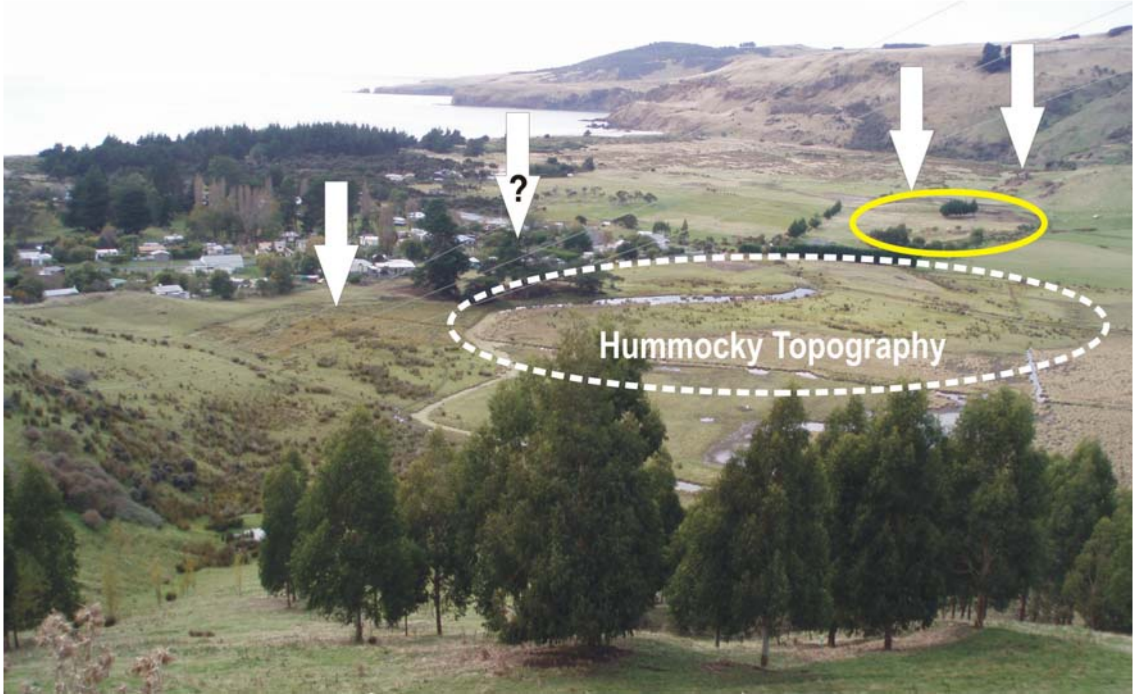

***Figure 43*:** Long Beach viewed from the NW. White arrows indicate remnant pedestals on the spit. The yellow ellipse is the archaeological site. The sand sheet/fan can be seen in the centre of the photo extending into the wetland (Photo: J. Goff).

Shag River

Archaeological site information indicates that the early Maori settlement at Shag River mouth is overlain by a sand sheet. The lateral extent of the sand sheet is shown from the exposure along the south bank of the Shag River where erosion has created a fresh section (Anderson et al., 1996). Pedestals and the landward extent of the sand sheet/hummocky topography have been identified in the LIDAR image (Figure 44). Erosion of the true right bank of Shag River is evident in the LIDAR image at the point where archaeological data have identified a sand sheet separating the early and late (Classic) Maori occupations (Anderson et al., 1996). This could place the event around a period covering the 14th to early 15th centuries. A storm ridge is visible on the seaward side of the pedestals. Small storm overwash deposits can be found between the pedestals but they do not extend landward of them. These storm deposits can be clearly differentiated from the discrete sand sheet/hummocky topography unit that represents deposition by a single event (as opposed to the overlapping storm sediments laid down by multiple events).

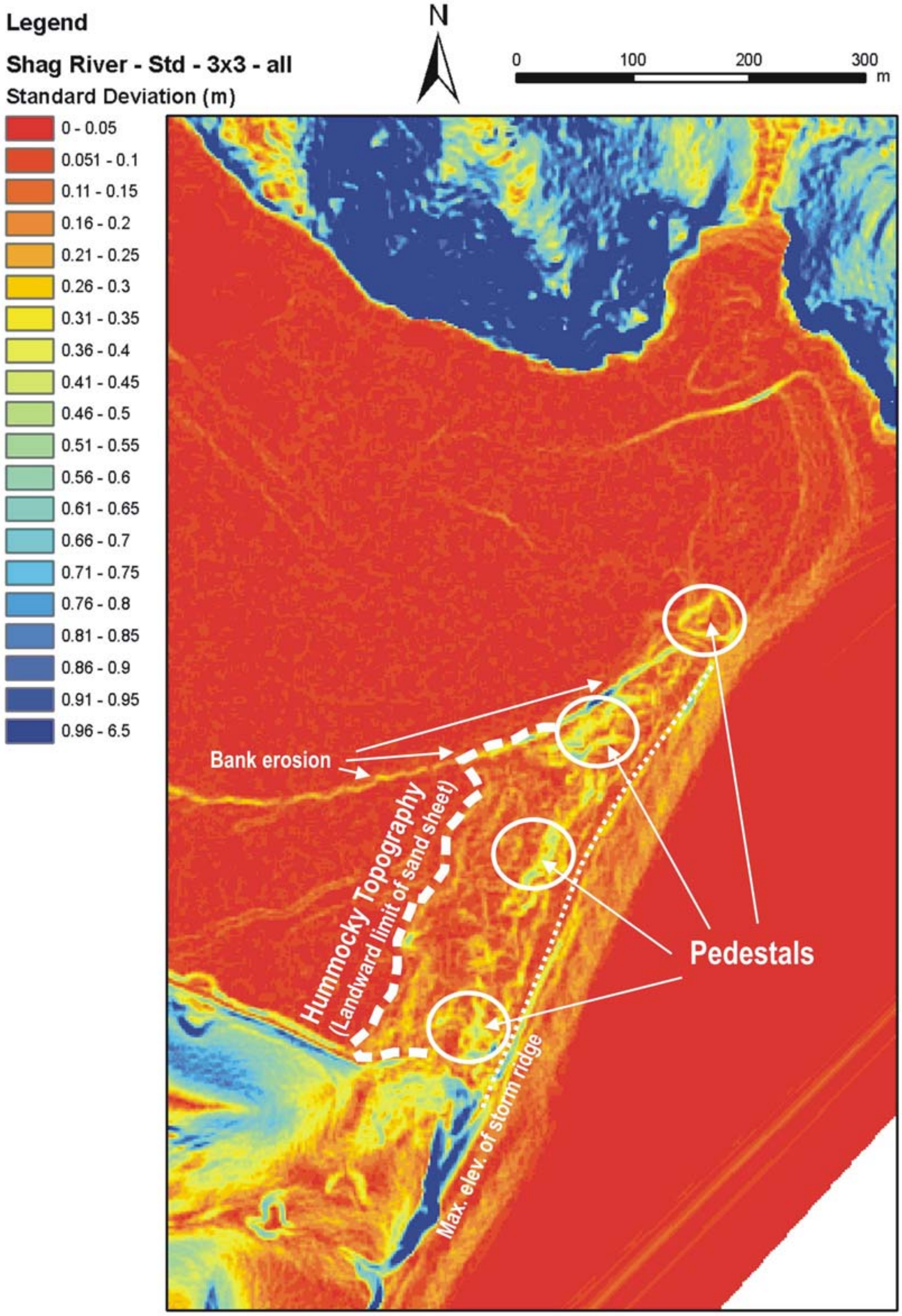

***Figure 44*:** Processed Shag River LIDAR image ('all' filtering method).

Pleasant River

Large pedestals separated by scour channels are visible along the Pleasant River spit on the 1976 aerial photography (Figure 45). These are also well defined on the 2005 LIDAR image (Figure 46). Figure 45 also shows that storm deposits reach a similar elevation on the seaward side of the pedestals but form a linear feature as opposed to a more complex morphology. Variations in storm deposit morphology are evident by comparison between the 1976 aerial photograph and 2005 LIDAR image (Figures 45 and 46). The relative stability of the pedestals is also evident, although considerable erosion has taken place along the southern end of the spit. Information from an early Maori archaeological site to the north of the spit indicates the presence of rare pedestals and a pebble lag deposit incorporated within a remnant hummocky topography (Smith, 1999). The latter is consistent with tsunami deposits reported elsewhere in New Zealand (e.g. Great Barrier Island: Nichol et al., 2003). Active erosion by Pleasant River may have removed evidence of a more extensive landward sand sheet. Sand accumulations to the western side of the river mouth appear to be modern but have not been studied.

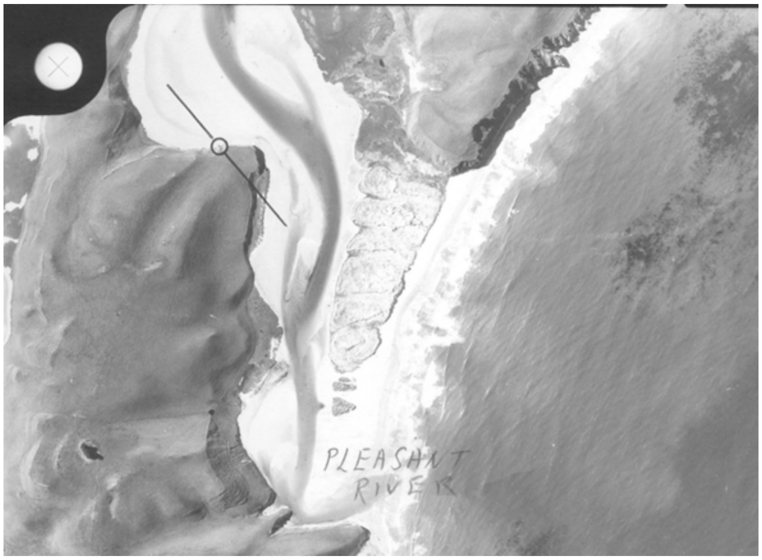

Figure 45**:** 1976 aerial photograph of Pleasant River mouth (Photo courtesy of Otago Regional Council).

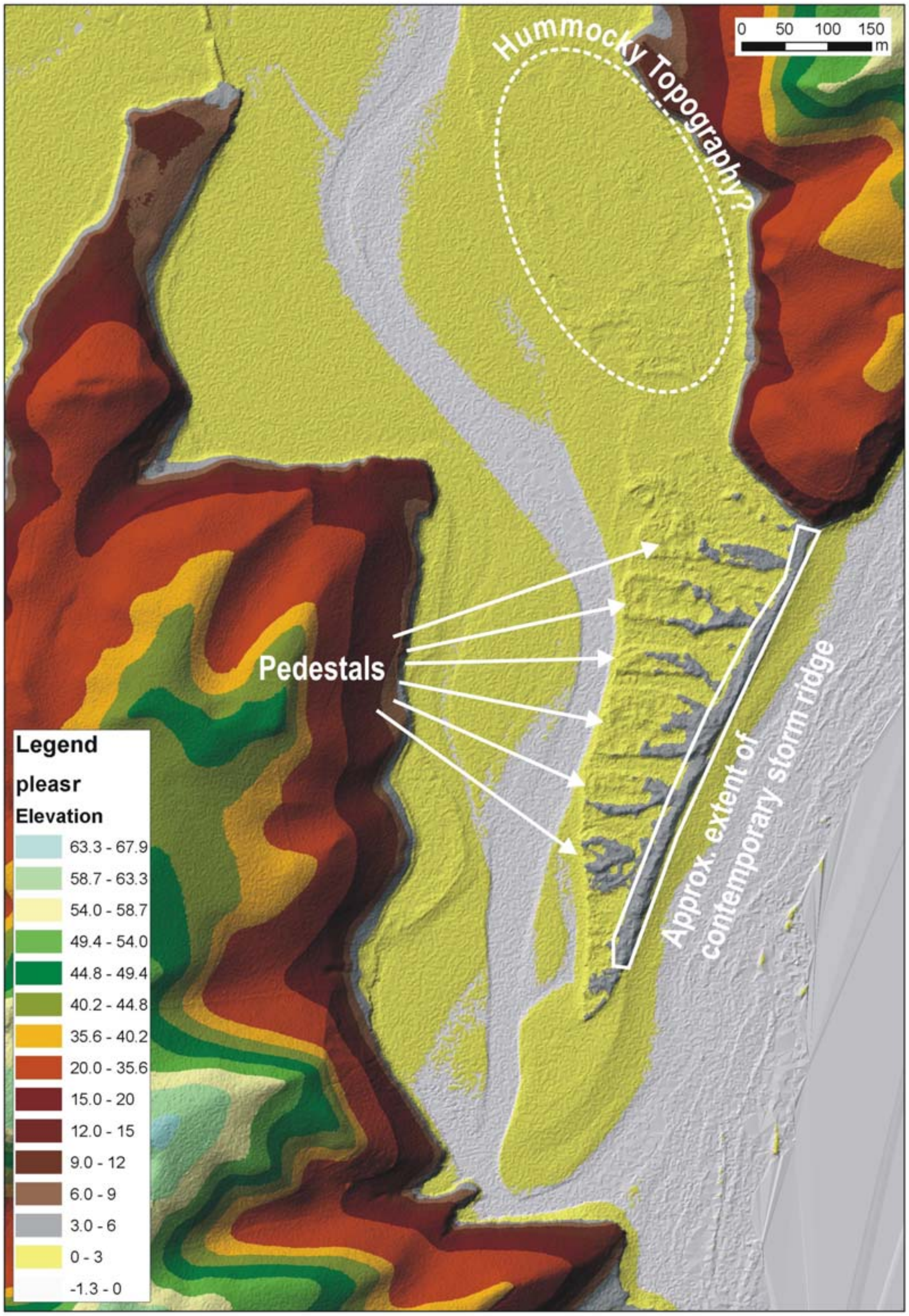

***Figure 46*:** 2005 Pleasant River LIDAR image (unfiltered). Tsunami and storm geomorphology is discussed in the text.

Waikouati

Interpretations based upon a brief reconnaissance survey and image analysis show a distinct pedestal and hummocky topography assemblage at Waikouati Beach (Figure 47). This is less clear, however, from a ground survey because of limited site access and afforestation of the dune sequence. An additional survey of the area being eroded on the true left bank may help define the area designated as hummocky topography. This was outside the scope of the study, but we have tentatively interpreted this as tsunami geomorphology.

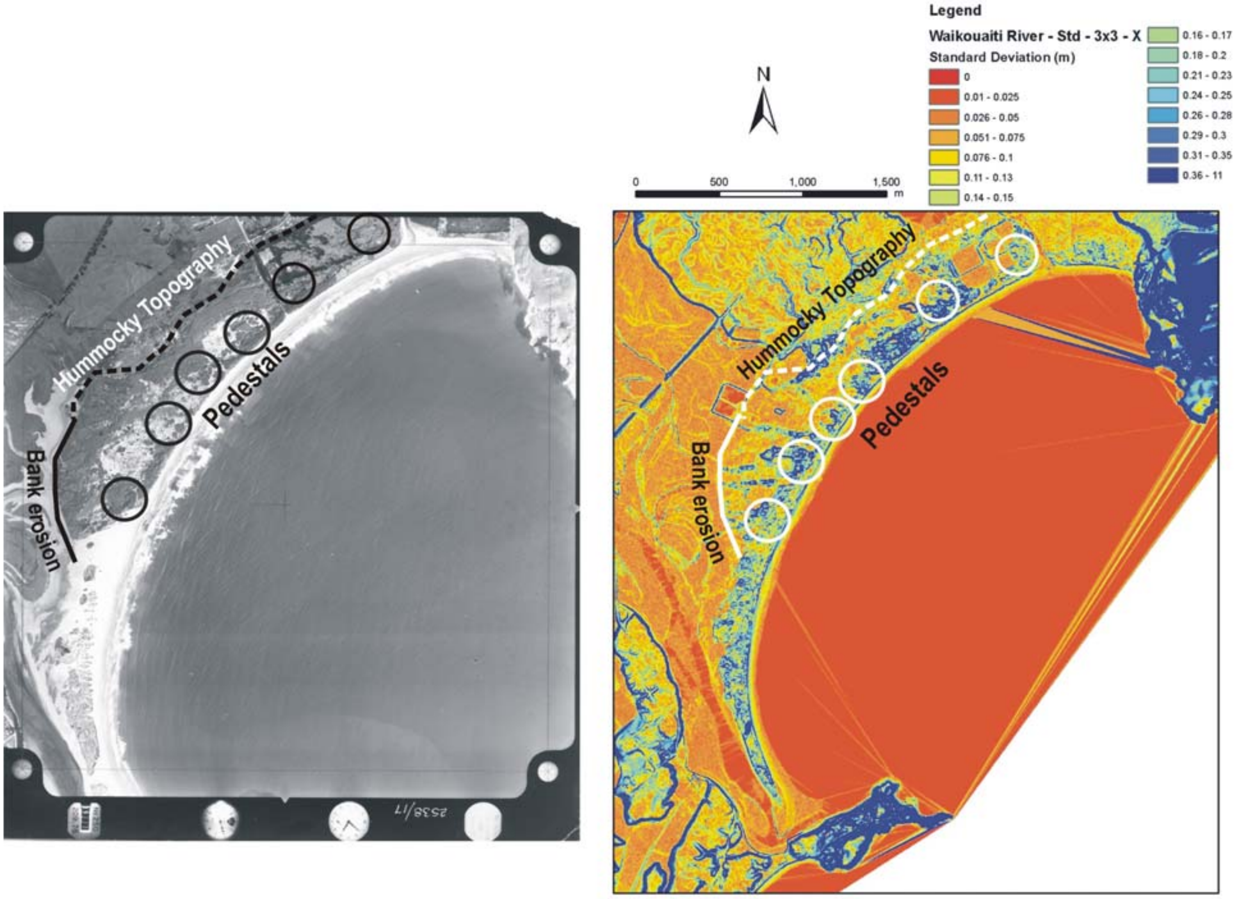

Figure 47**:** Annotated images of the Waikouiti coastline: A 1958 aerial photograph on the left and 2005 LIDAR image ('X-cross' filtering method) on the right (Photo courtesy of Otago Regional Council).

Purakanui

At Purakanui there is an archaeological occupation site immediately landward of the 1863 shoreline captured on cadastral maps (Figure 48). This has suffered erosion from ongoing fluvial activity, but three periods of occupation have been suggested from early to late Maori (Anderson, 1981). A pebble lag deposit apparently eroded out of the dunes is equivocal – it may represent reworked pebbles from a unit underlying the occupation site or a poorly defined unit separating occupation layers. The dunes reach elevations of up to 9 m and do not appear to have been significantly breached (there is also no landward sand sheet). Breaching seems unlikely given that dune heights are consistent across the landward sequence. Some form of tsunami geomorphology - a sand sheet, hummocky topography, or parabolic dune sequence - would be expected if breaching had occurred. Two large pedestal-like features were identified along what approximates a possible 15th century shoreline (based upon radiocarbon-dated material - Anderson, 1981). It is possible that tsunami inundation occurred but failed to overtop the dunes, merely eroding the shoreline at that time. It is also possible that there is no evidence of tsunami inundation. The preservation of tsunamigenic morphology may not be ubiquitous owing to local antecedent morphology. An important point to note here however is the presence of a narrow Low Profile Sequence seaward of the pedestals. This was also noted at Long Beach and may be indicative of the effects of tsunami inundation on the coastal sand budget, as will be discussed later. Interpretations here are speculative.

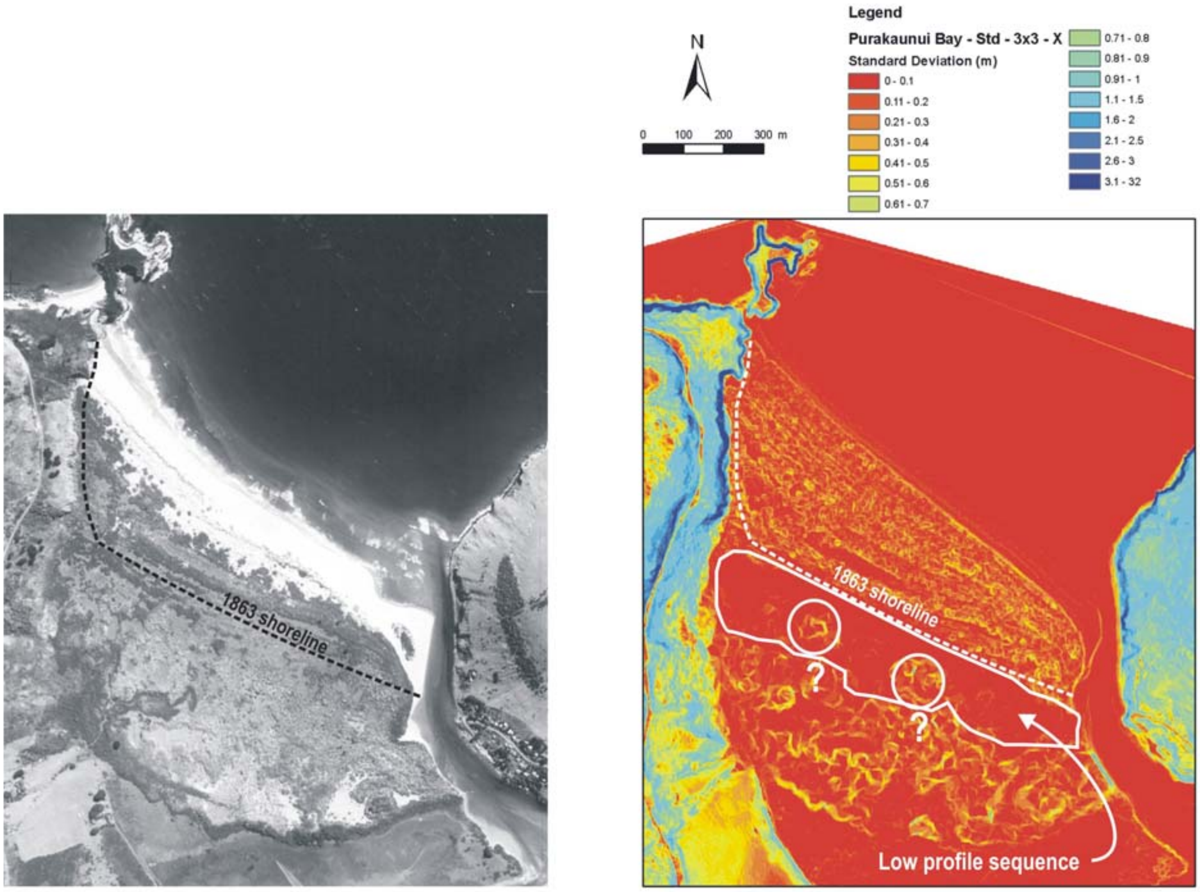

***Figure 48*:** Annotated images of the Purakanui coastline: A 1975 aerial photograph on the left and 2005 LIDAR image (‘X-cross’ filtering method’) on the right (Photo courtesy of Otago Regional Council).

Wickliffe

The ages of various dune systems at Wickliffe are poorly constrained, but it seems likely that by comparison with similar dune systems at Purakanui and Long Beach, the landward edge of the seaward half of the dunes represents an 1863 shoreline (Figure 49). Given this, the landward component of the dune system would be the most likely to preserve any significant indication of tsunami inundation since the historical record extends back to the early 1800's and no significant tsunami has been recorded in the region in that period. Not surprisingly, the landward dunes appear more heavily weathered and possess many pedestal-like features. No further work has been carried out at this site. However, it is noted that the landward and seaward dunes are again separated by a Low Profile Sequence that matches well with those recorded at other sites along the Otago coast.

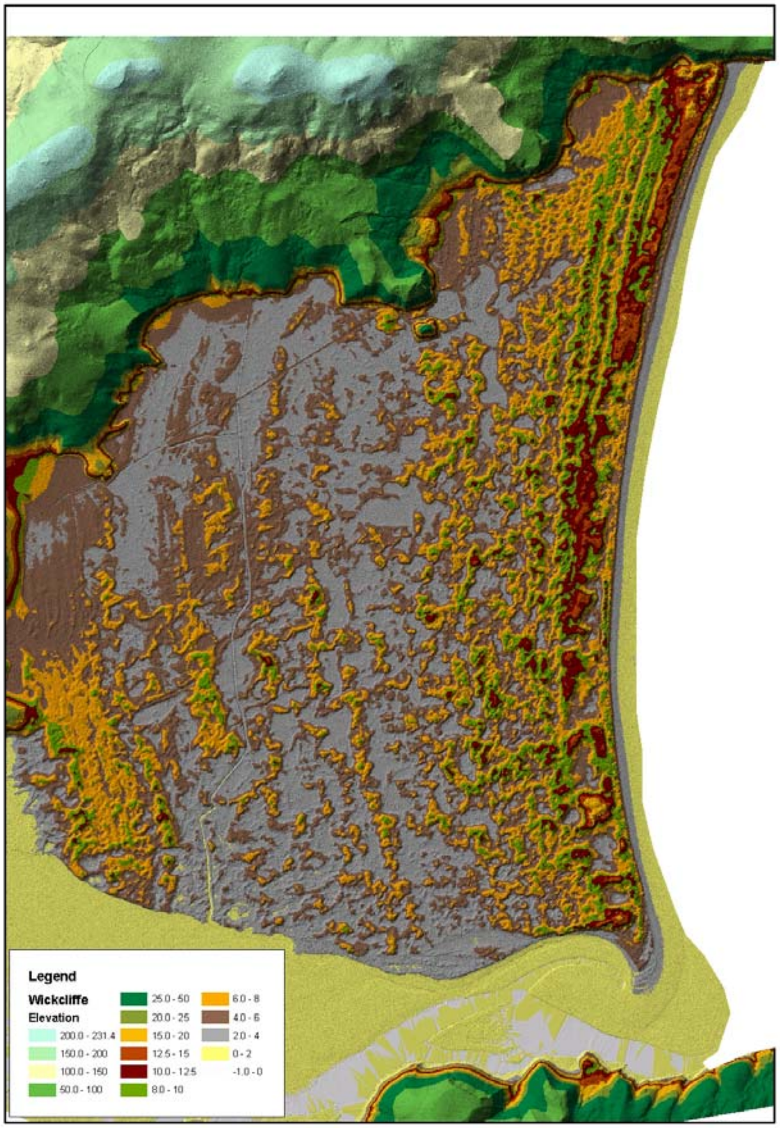

***Figure 49*:** 2005 Wickliffe LIDAR image (unfiltered). See text for discussion of features.

Taieri River

At Taieri River mouth there is a confined accumulation space on the coastal plain landward of the beach and this may be the reason why it is harder to differentiate significant pedestal formation, or simply that they are not present. There are however, several pedestal-like features that have been viewed in the field and a sand sheet that extends up at least two coastal river valleys. A brief reconnaissance survey indicated an extensive sand sheet/hummocky topography consistent with the pedestal morphology identified in the LIDAR image (Figure 50).

The reconnaissance survey continued south and recorded numerous pedestal and hummocky topography features. An area adjacent to the Tokomairiro River was not covered by this report but has excellent possible tsunami geomorphology. This is also the site of an interesting Maori oral tradition noted by Beattie (1915):

> *"The Takitimu canoe had run down the east coast till just below the Otago Peninsula, when she ran off a great wave which the legend says is represented by the Mauka-atua (now called Maungatua) range. The canoe ran off this sea and broached-to and dropped her tata (bailer) which turned into rock, and now is the Hokanui hill near Gore. Then the other wave (represented by the Okaka ridge west of the Waiau River) struck her and she upset, and there she lies as the Takitimu Mountains. When the first wave struck her one of the crew named Aonui was washed overboard, and being turned into stone, still stands on the Tokomairaro beach as the tall basaltic pillar known as Cook's Head."*

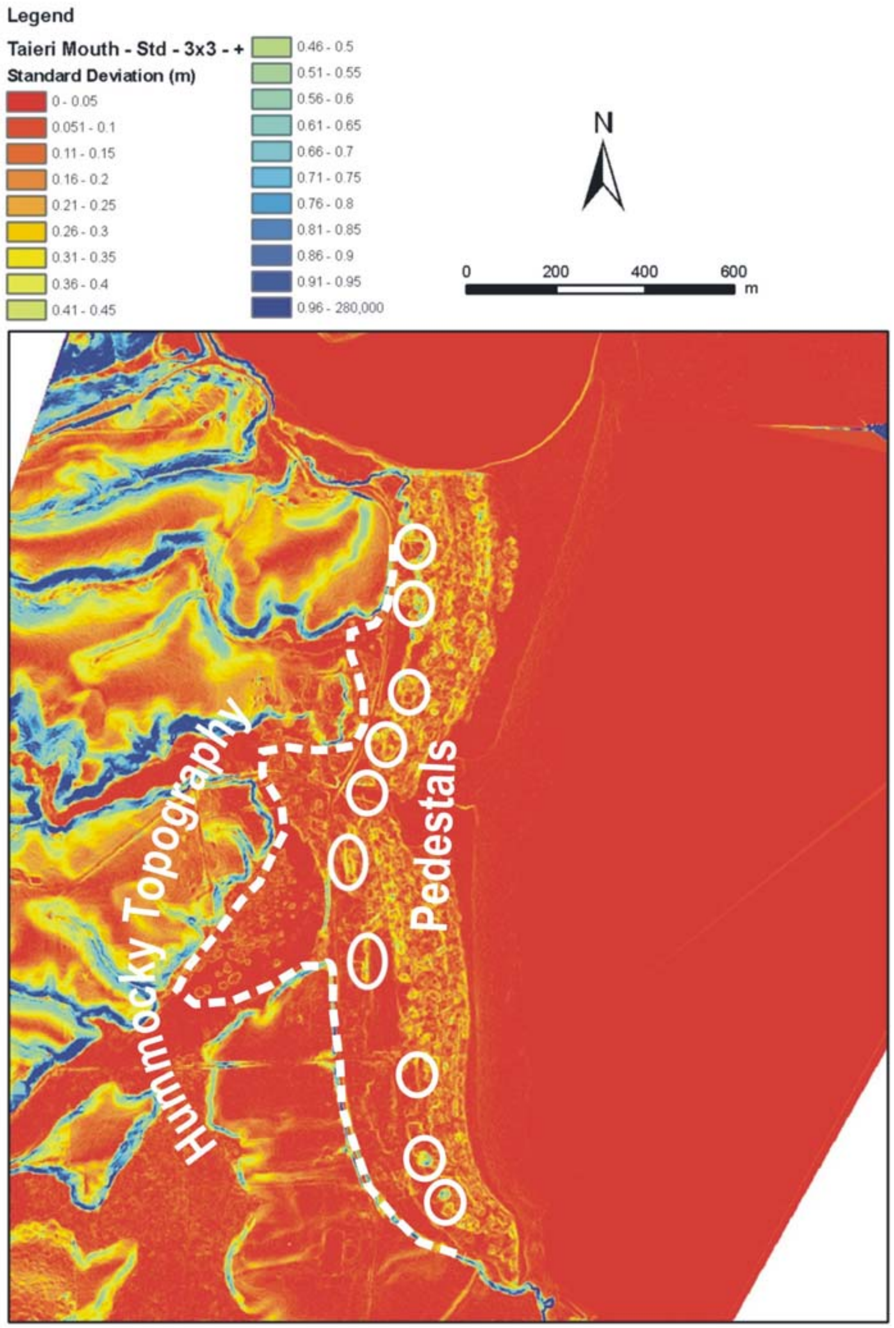

***Figure 50*:** Annotated LIDAR image ('D – diagonal' filtering method) of the Taieri River mouth area.

Discussion on approach

What to look for and where to look

Allowing that a coast has been subject to tsunami in the recent geological past, the ability to detect and interpret their geomorphic signature from LIDAR data, and also in the field, hinges on the interaction between five key criteria.

- Availability and type of sediment (sand/gravel)

  The spectrum of sediment availability ranges from sediment-rich to sediment-poor. In sediment-rich environments, tsunami geomorphology is more likely to be rapidly buried by incoming post-event material (tens of years). This is particularly pertinent for pedestals. In a sediment-poor system, geomorphology is more likely to be preserved for a much longer period (hundreds to thousands of years). Blueskin Bay shows the effects of a sediment-moderate regime, where there have been substantial volumetric changes in pedestal morphology where sand has periodically accumulated then has subsequently been eroded during storms.

- Embayment type

  Embayment types vary in a range from enclosed/semi-enclosed embayments through to gravel/dune pocket beaches. In this study, the closest to the former end member was Blueskin Bay. This semi-enclosed embayment has hummocky topography/sand sheets that have been subject to erosion by tidal and fluvial processes. Smaller estuaries such as the Pleasant and Shag Rivers are dominated by fluvial processes that erode the landward side of remnant pedestals and hummocky topography/sand sheets. Smaller pocket beach type embayments, such as Long Beach, which often have small streams and/or wetlands ponded behind coastal dunes, are more likely to preserve the features of tsunami geomorphology. This is because neither their coastal nor fluvial processes are sufficiently energetic to rework tsunami-emplaced geomorphology.

  (N.B. Cliffed coasts were not a focus of this study).

- Prograding/eroding coast

  An eroding coast is unlikely to preserve the complete geomorphological record of past tsunamis. Over time, the record will become degraded or lost. This is not evident on the Otago coast but has been noted on the Kerikeri Peninsula, Northland. An apparent tsunami geomorphology was recorded by Wellman (1962a), but a recent reconnaissance indicated that the beach and dune system had been completely reworked to the base of the cliff (Chagué-Goff & Goff, 2006). A prograding coast is more likely to preserve the geomorphology.

- Small/large accumulation space

  A restricted landward accumulation space limits the development of tsunami geomorphology. On the other hand, there is less likelihood of post-tsunami remobilisation of the sand sheet, for example by wind and estuarine currents, thus hummocky topography is more likely to develop and be preserved (e.g. Measly Beach, south of the Tokomairiro River mouth). Differentiation of hummocky topography from conventional dune ridge formation will be complicated if multiple tsunami inundations add fresh sand volumes. Large accumulation spaces provide the potential for the development of tsunami geomorphology and the creation of remobilised sand dune phases as landward parabolic dune systems (e.g. Kapiti-Horowhenua coast – the conventional genesis of these dune systems is considered to be as a result of remobilisation caused by land clearance, although dune ages do not coincide – refer to Hawke & McConchie (2006) and Goff & McFadgen (2006) for opposing views). Where there is abundant space, sand sheets will most likely spread further and be thinner.

- Wet/dry landward environment

  A wet landward environment (e.g. backshore swamp/pond) will cause sand to more readily stabilise, whence it is most likely to weather (in situ) over time to form low profile hummocky topography. Dune systems are often associated with some form of ponded or blocked landward drainage system. Low profile hummocky topography closely linked to a pedestal landscape is therefore the most likely geomorphological association for tsunami inundation (Figures 12, 12, 31, 32, and 43). This is not always the case however, and dry landward environments would enable remobilisation of sand with the possible formation of a parabolic dune field (Figure 30) or hummocky topography landward from the original dune source.

Thus a key conclusion from this study is that an appreciation of the geomorphic setting and understanding of the geomorphic history of a region's coast is of great advantage when selecting sites to search for tsunami evidence and in knowing what to look for.

Usefulness of regional LIDAR-derived evidence of past large tsunamis

The importance of using the interpretation of LIDAR images to investigate a regional picture cannot be overstated. A regional tsunami inundation can be compared with the existing draft palaeotsunami database (Goff, 2006). The database can be used to determine whether any events have been recognised in the regional geological record and also to identify possible candidates for a large event based upon a nationwide record. Iteration between the database and LIDAR interpretations serves two key purposes:

- As a reconnaissance tool, LIDAR data augments point-source geological information to provide an indication of the magnitude and frequency of palaeotsunami inundation. The geomorphological record may extend the chronology of past events further back in time than the geological data.

- The combined data provides a more comprehensive dataset of runup heights and inundation extent for comparison with numerical model simulations.

In New Zealand, locally/regionally sourced tsunamis are probably the only ones large enough (~5.0-10.0 m runup or more) to significantly alter coastal geomorphology (with the exception of bolide impacts). The historical tsunami database is dominated by small to moderate events from distant sources, none of which have significantly affected coastal geomorphology (Fraser 1998). The palaeotsunami database on the other hand is dominated by locally and regionally sourced tsunamis. A review of geological and archaeological data indicates that tsunami inundation, dune remobilisation, and archaeological site abandonment are most probably causally linked (e.g. Northland: Hicks, 1975; Coster, 1989; Brook, 1999a; 1999b; Nichol et al., 2004).

Moderate to small events (~1.0-5.0 m runup) are unlikely to create regionally significant changes to coastal geomorphology but may be identifiable locally (e.g. sand-poor sites with low elevation dunes). A regional LIDAR scan would help to identify the relative scale and approximate chronology of multiple events. At this stage however, in the absence of more complete palaeo and historical tsunami databases, some ground-truthing would be necessary to fine-tune event chronologies.

Post tsunami geomorphic signatures

It became evident during this research that additional tsunami-related signatures were present in the coastal geomorphology. More specifically, this relates to the impact of tsunami-created sand transfers on the post tsunami coastal sand supplies. These are more likely to appear in a normally prograding coastal system, where the tsunami may be marked by a perturbation in the rate of progradation. This may take two forms:

- Material is transported offshore, temporarily removing it from the coastal sediment budget (in addition material is removed by landward transport – we generally view this as permanent removal from the coastal sediment budget, although in some cases such as Pleasant River, a substantial amount of this material has been returned over time). The subsequent onshore transport of this material is marked by a distinct period of dune ridge formation. The time lag between tsunami inundation (creation of the tsunami geomorphology) and the formation of a new dune ridge sequence will be recorded as a section of low topography in the prograding sequence. Assuming that the tsunami deposits lie at depths less than the wave base (and so can be reworked landward again), the section of low topography is unlikely to be extensive.

- Material is transported inland and far offshore permanently, removing it altogether from the coastal sediment budget. Such a significant decrease in sediment supply at the coast might be represented by a Low Profile Sequence (LPS, Figure 42) of progradation pending re-supply from longshore sources. This is likely to be an extensive plain given the high magnitude and low frequency of large tsunami inundations.

In the latter case, the seaward extent of the LPS (marking the partial recovery of the sediment supply) may be governed by several factors, some linked to tsunamigenic events, others not:

- An anomalous sediment pulse associated with European colonisation. In some localities at least, a pulse of sand supply along the Otago coastline seems to have occurred in conjunction with major land clearance associated with European colonisation in the mid 1800's (Figures 42 and 48), perhaps assisted by sand generated in the Clutha catchment from gold sluicing.

- A large local/regional earthquake which:
  - Could cause significant groundshaking and would likely introduce large quantities of sediment into river systems. Assuming a moderately unobstructed transport pathway to the sea, sediment pulses in New Zealand rivers can take between 5 and 50 years to enter the coastal sediment budget (e.g. Goff & McFadgen, 2002; McFadgen & Goff, 2005; Wells & Goff, 2006).

  - Could cause subsidence and/or compaction. Subsidence is unlikely on a prograding coast but compaction would slow progradation, reducing the width of the LPS.

  - Could cause uplift which would isolate (and preserve) the tsunami geomorphology from subsequent coastal processes producing a wider LPS.

- A large local/regional sub-aerial or submarine landslide. If this was not generated by a local/regional earthquake then there is unlikely to be any immediate sediment supply response. A gradual return to pre-existing coastal sediment budget conditions would be expected over a period of decades.

- A distantly sourced tsunami may create a tsunami geomorphology in local sand-poor areas of moderately low topography. The most likely post-tsunami recovery in the coastal sediment budget would be similar to the previous point.

Tsunami inundation of the Otago Region coast

The results reported and discussed above provide a valuable expansion of existing knowledge about tsunami inundation on the Otago coast. However, this has not explicitly addressed the issues of tsunami source, timing and hazard for the region.

Most of the limited chronological evidence for tsunami inundation along this stretch of coast comes from archaeological studies. Chronological control is poor, but we infer that one large event probably occurred around the 14th to early 15th centuries. While not discussed in any detail, it appears that this may have been the only large tsunami to have inundated the coastline since sea level rose to the approximate point we experience today about 6000 years or so ago. Some LIDAR images (such as Figure 48 from Purakanui) show possible evidence of an earlier event. If such an event did occur, it must have been at or near the time sea level stabilised (~6000 years BP) but the geomorphology has degraded sufficiently to make such a suggestion speculative at best. This observation is important for two reasons. Firstly, it shows that there is a deterioration of geomorphological signatures with time. This mirrors a similar problem with geological evidence, a process recently termed the “taphonomy” of tsunami deposits. This does not negate the use of LIDAR data but merely indicates the need for caution when interpreting past geomorphology. Secondly, it raises the question of a possible earlier event and reinforces the need for on-site geological investigations.

The most significant problem with interpreting a large, regional tsunami around the 14th to early 15th centuries is that there are no obvious sources for such event along the Otago coast, either over the period in question or at any other time. The only recently active fault that could be a possible source is the Akatore Fault, which runs offshore from just south of the Taieri River mouth towards Waldronville just south of Dunedin city (Figure 36). Norris et al. (1994) estimated that the last movement of this fault dated to about 1200 cal. yr BP and had an approximate vertical slip of about 2.0 m with a maximum magnitude of 6.8-7.3. More recently, Litchfield & Norris (2000) have amended this to about 3.0 m of uplift occurring around about 1150-1000 yr BP. Both scenarios are too small to have generated anything more than a small local tsunami, and they are too old (Schallenberg & Burns, 2004).

A recent reassessment of the radiocarbon dates for the Akatore Fault rupture however, suggests an age range for the rupture between about AD 990 and AD 1450 (B. McFadgen, pers. comm., 2006). This range overlaps with the period of human settlement (beginning about AD 1250). McFadgen (pers. comm., 2006) indicates that some archaeological sites along the Otago Coast dating from the early part of the prehistoric period show a compaction event during or following occupation. The Shag River and Pleasant River mouth sites are examples, and as we have shown in this study, both of these have what are possibly contemporaneous geomorphic records of tsunami inundation. Changes in the shell midden content at the Shag River site are consistent with an event which enlarged the estuary and extended the wetlands around its periphery (Anderson et al., 1996). Dating of the Shag River site indicates the event probably occurred sometime between AD 1330 and AD 1410. This information is soon to be published and will also offer a more regional perspective than is discussed here.

In summary, combining the best data available from the archaeological sites (Shag River mouth) with the recent dating of the Akatore Fault movement refines the age of the contemporaneous event to between AD 1330 and AD 1410. The most realistic scenario appears to have been a moderately large Akatore Fault rupture (Magnitude 7.3) causing compaction (by groundshaking) in several embayments along the Otago coast. Such an event would not, however, generate a large enough tsunami to cause all of the geomorphological evidence we identify. Perhaps more relevant to this issue are earthquake induced effects other than tsunamis. A Magnitude 7.3 tsunami would undoubtedly have caused groundshaking that continued for a reasonable length of time, causing the type of compaction reported at the Shag River and Pleasant River mouths. This groundshaking would also have been felt across the continental shelf. Thus, we hypothesize that groundshaking caused by a mid 14th/early 15th century Akatore Fault rupture may have destabilised sediments that had accumulated at the head of one or more of the submarine canyons along the edge of the continental shelf off Otago Peninsula (Figures 51 and 52). These are known to be active sediment conduits (e.g. Carter & Carter, 1996), but the extent to which sediments accumulate at their heads as opposed to moving continuously down the canyon is unknown. It is possible that the system operates in a similar fashion to the Kaikoura Canyon, where accumulated sediments are believed to be mobilised by a local fault rupture trigger (Lewis & Barnes, 1999; Walters et al., 2006).

At the time of this report, we were advised that a comprehensive analysis of the archaeological information for the Otago coast would soon be published (B. McFadgen, pers. comm., 2006). This geoarchaeological assessment incorporates sites discussed above and concludes that an event most likely occurred between AD 1350 and AD 1370.

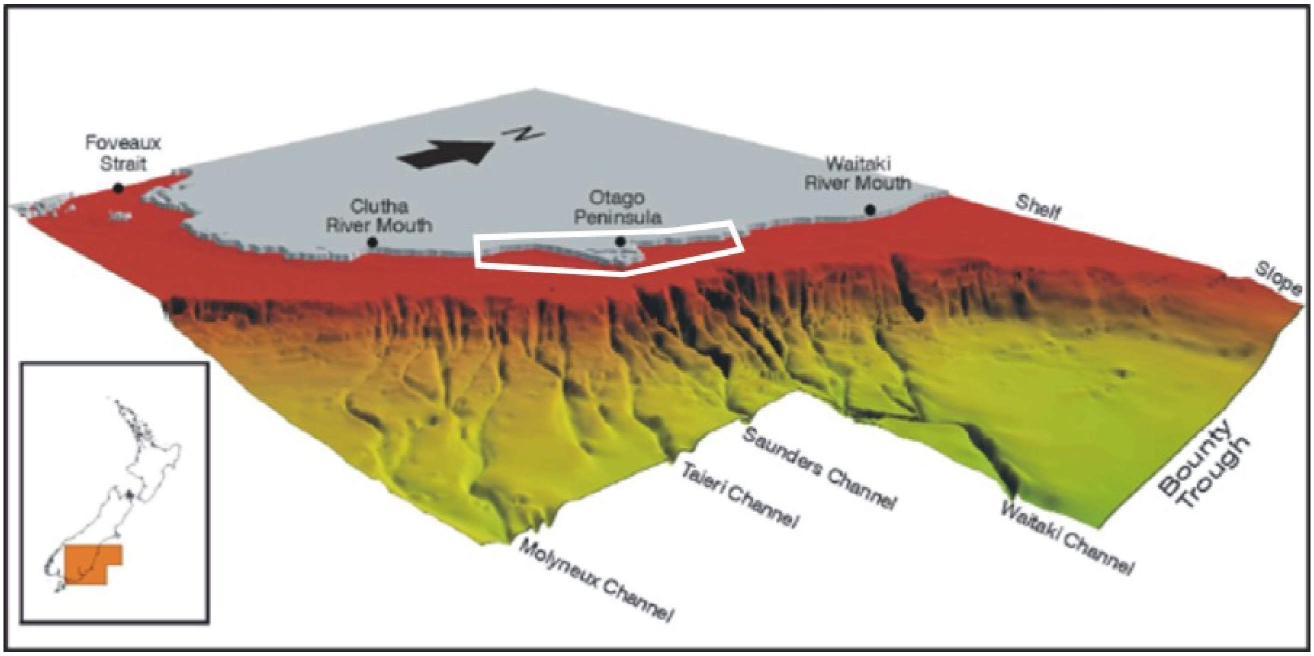

Figure 51: Oblique view of the physiography of the marine sector of the Eastern South Island Sedimentary System continental margin outlining the main submarine canyon conduits to the Bounty Trough. Source: http://baby.indstate.edu/gomez/margins.html.

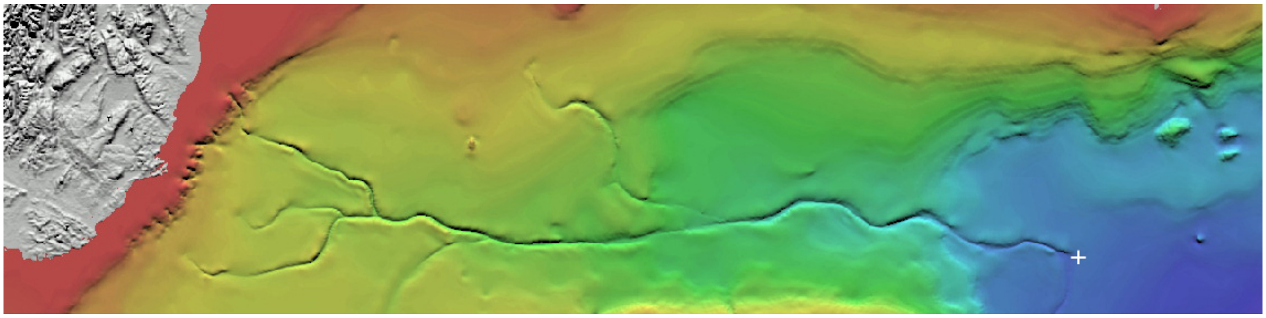

Figure 52**:** Vertical view of the physiography of the marine sector of the Eastern South Island Sedimentary System continental margin outlining the main submarine canyon conduits to the Bounty Trough. Source: http://baby.indstate.edu/gomez/margins.html.

Based on what we regard as firm geomorphic evidence for at least one large (~10.0 m runup or greater) tsunami inundation over the last 6000 years on the Otago coast we feel comfortable with recommending further work be undertaken along the region's coastline - inundation modelling and a geological survey would be justified in this case to better determine the tsunami hazard along the coast. A detailed geological survey would be able to verify whether any ~4.0-10.0 m events have occurred. Supplementing this information, any existing historical data could be used to give an indication of the smaller events that are unlikely to leave any geological or geomorphological record.

Conclusions

The main conclusions of this study are:

- LIDAR data analysis supplemented with brief ground surveys can identify the geomorphic signature of past large tsunami

- The type of tsunami feature, and the chance of finding them, depends on the geomorphic setting, thus this should be appreciated when planning the initial survey of a region. In other words, it is needed to know what to look for and to indicate where to look

- Our initial concept study of the Otago coast provided details of what appears to be a proven suite of tsunami-related geomorphological features relating to a regional-scale event dating from the 15th century, and possibly other events over the past 6000 or so years

- The evidence of at least one large tsunami and an historical database of smaller events in this region provide the justification for a more comprehensive study.

This report represents the first attempt at a comprehensive study of tsunami geomorphology. It is hoped that further work will improve and enhance the information presented.

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