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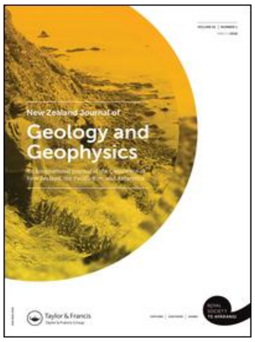

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# Whanganui Basin, an archive of prehistoric earthquakes? Waitapu Shell Conglomerate (c. 0.9 Ma), North Island, New Zealand

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**ABSTRACT**
The Waitapu Shell Conglomerate is an important marker horizon in the eastern Whanganui Basin, occurring within a Pleistocene volcaniclastic record that contains early eruption products from the Taupo Volcanic Zone. The unit comprises a cross-bedded pebbly-shell conglomerate containing the first influx of Kaukatea Pumice (c. 0.9 Ma) within the Rangitikei succession. We document soft sediment deformation structures that occur in close stratigraphic proximity to the Waitapu Shell Conglomerate and other laterally equivalent units within the basins Castlecliffian outcrop belt. Soft sediment deformation structures formed through a combination of liquefaction and fluidisation, triggered by a range of mechanisms, including evidence of high sedimentation rates, loading, slope instability and potential for wave and earthquake-induced seismicity. Lateral changes in depositional style toward the basins eastern margin relate to relative position on the paleo-shelf, reduction of accommodation space, intermittent preservation of low stand deposits and proximity to the uplifting paleo-axial range.

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Pleistocene; Castlecliffian; biostratigraphy; Whanganui Basin; seismicity; liquefaction; fluidisation; submarine landslides; loading

## Introduction

The formation of soft sediment deformation structures (SSDS) is typically associated with rapid sedimentation, where loading of water-saturated sediments results in expulsion of water and deformation of bedding (Bailey and Carr 1994; Manville et al. 2005; Owen and Moretti 2011). These structures have also been attributed to settling, sliding or slumping within an unstable, water-saturated environment (Fleming 1953; Lewis 1971; Collinson 1996; Strachan 2008). Potential paleoseismic origins are indicated by studies in the Bay of Plenty and Waikato (Carr 1984; Bailey and Carr 1994; Kleyburg et al. 2015), including the distal volcaniclastic equivalent of the Matahina Ignimbrite where SSDS are attributed to liquefaction following rupture along the Waiohau Fault (Bailey and Carr 1994).

SSDS in the Plio-Pleistocene succession of the Whanganui Basin (WB) have been recorded during numerous studies (Fleming 1953; Seward 1974; Shane 1991; Abbott 1994; van der Neut 1996; Brackley 1999; Pillans et al. 2005). A majority of this work has focused on the western and central WB where recognition of cyclic sedimentation corresponding to Quaternary climatic events has driven research interest (Carter et al. 1991; Pillans 1994). The east of the basin has received considerably less attention. We address this knowledge gap by formally defining the Waitapu Shell Conglomerate and documenting the SSDS that occur in close stratigraphic proximity. The Waitapu Shell Conglomerate is correlated between sections using tephrostratigraphy and biostratigraphy, enabling recognition of laterally equivalent units and providing some perspective into the nature and extent of SSDS within the WB's Castlecliffian outcrop belt.

Waitapu Shell Conglomerate contains abundant reworked charcoal and pumice, recording a major rhyolitic eruption in the central North Island and resultant first influx of Kaukatea Pumice within the Rangitikei succession at c. 0.9 Ma. Directly beneath and some 25 m above the base of the conglomerate, lie SSDS that can be traced as a zone of deformation. The Waitapu Shell Conglomerate crops out within the steep hill country of the Rangitikei District northeast of Marton (Figure 1). The stratigraphy dips gently south and is locally offset and gently folded about a series of actively growing anticlines that traverse the Manawatu Plains (Te Punga 1957; Melhuish et al. 1996; Jackson et al. 1998).

## *Geological setting*

The study area is located in the WB, positioned c. 200 km west of the convergent margin between the Pacific and Australian plates (Figure 1). Volcanism and extension in the central North Island are related to subduction at the Hikurangi Margin (Houghton et al. 1995; Stratford and Stern 2004). Volcanism has migrated southeast through time, commencing in the

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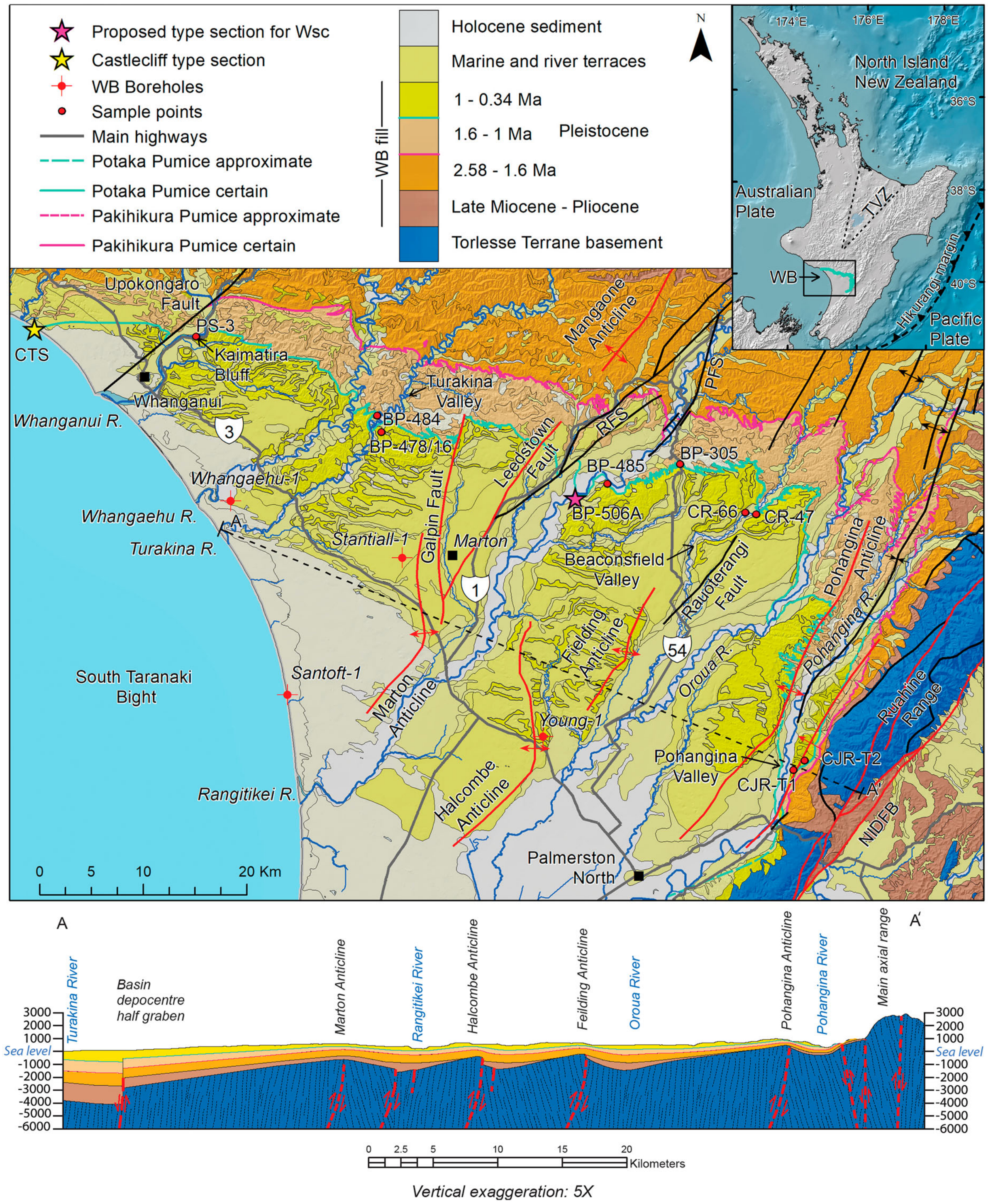


**Figure 1.** Map displaying the on land portion of the Whanganui Basin (WB) relative to the Taupo Volcanic Zone (TVZ) and Hikurangi margin. Sample and section locations are shown, including the proposed type section for the Waitapu Shell Conglomerate (Wsc). The North Island Dextral Fault Belt (NIDFB), Castlecliff type section (CTS), Rangitikei Fault System (RFS) and the Pakihikura Fault System (PFS) are displayed. A simplified cross section A to A′ illustrates the undulating basement surface beneath the Late Miocene -Pleistocene basin fill, constrained by available borehole data. Data sourced from Feldmeyer et al 1943; Te Punga (1952); Fleming (1953); Milne (1968); Seward (1976); Anderton (1981); Melhuish et al. (1996); Pillans et al. (2005), GNS Science and this study.

Taupo Volcanic Zone (TVZ) at c. 2 Ma (Briggs et al. 2005). Subsidence of the western lower North Island has facilitated sedimentary preservation of volcanic and climatic signals spanning the entire Quaternary Period (Stern et al. 1992, 1993; Pillans 2017). Volcanic activity at the Mangakino Volcanic Centre in the western TVZ was initiated during two periods of caldera-forming activity from 1.68 to 1.53 and 1.21 to 0.95 Ma, respectively, providing an important source of sediment to the WB during Castlecliffian time (Briggs et al. 1993; Shane 1993; Houghton et al. 1995; Krippner et al. 1998; Pillans et al. 2005).

Subsidence of the WB approximately kept pace with sedimentation throughout the Plio-Pleistocene, resulting in preservation of a c. 4.5 km-thick sedimentary succession (Carter and Naish 1998). Regional tilting of the basin fill is a result of southward migration of the basin depocentre and simultaneous uplift along the northern and eastern margins. Late Quaternary uplift has been calculated at a rate of 0.3–0.5 m/ka in the location of the modern coastline and c. 1–3 m/ka adjacent to the axial range (Pillans 1986). This tectonic regime has resulted in exposure of gently dipping (2–15°) marine strata along coastal cliffs and river valleys (Fleming 1953; Abbott 1994) and the preservation of extensive flights of marine (Pillans 1990a) and river terraces (Te Punga 1952; Milne 1973). Orbitally driven climatic cycles have been linked to sedimentary deposition of the basin fill, corresponding to fifth (100 ka) and sixth (40 ka) order sequences.

Forty-seven unconformity-bounded cycles are recognised and correlated to oxygen isotope stages 100–3 (Naish and Kamp 1995; Carter and Naish 1998; Abbott and Carter 1999). Each cycle relates to a glacial/interglacial couplet, represented by a transgressive (TST), highstand (HST) and in some cases, regressive (RST) and lowstand (LST) systems tracts. At the Castlecliff type section, near Whanganui City (Figure 1) preservation of TSTs and HSTs occurs with bounding sequence surfaces represented by erosional unconformities, formed during subaerial exposure at sea-level low-stands and subsequent transgressive marine ravinement. During the Pleistocene, particularly towards the eastern margin of the basin, preservation of incised valley fill (Rees et al. 2018b) and coastal plain facies (Te Punga 1952; Milne 1968) occurred during marine regressions and sea-level low-stands, complicating sequence stratigraphic interpretation (Naish et al. 2005; Pillans et al. 2005).

### *Stratigraphy*

The middle Kai Iwi Group sediments surrounding the Waitapu Shell Conglomerate form the focus of this study, encompassing a portion of the Waiomio and Kaimaitra Pumice Sand formations (Table 1). The Kai Iwi Group comprises five cyclothems (WB cycles 34–38) deposited between c. 0.99 and 0.6 Ma (Pillans et al. 2005). The base of the group is defined by the first influx of Potaka Pumice into the sedimentary record, during the transgression of cycle 34 (Pillans et al. 2005; Rees et al. 2018a). We correlate the Waitapu Shell Conglomerate to the early transgression of cycle 36, marking the first influx of Kaukatea Pumice into the Rangitikei succession and positioned one cycle below the first appearance datum of *Pecten novaezelandiae* (Figure 2C). Primary Kaukatea Tephra is intermittently preserved within cycle 35, including at Turakina (van der Neut 1996), Pohangina (Rees et al. 2018b), Whanganui (Kershaw 1989) (Figure 2B,E) and in the Castlecliff-1/1A drillcore (Naish et al. 2005). The first influx of Kaukatea Pumice is recognised in a majority of WB sections (Pillans et al. 2005) highlighting its value as a chronostratigraphic marker horizon. The first influx of a new pumice geochemistry into the WB is not entirely isochronous, given lateral changes in preservation across the basin. Specifically, preservation of low stand deposits, below the ravinement surface (RS) in the far eastern basin predate Type A1 shellbeds (Abbott and Carter, 1994), positioned above the RS in the central and western basin sequences. However, for working purposes, the two are deemed lateral equivalents (Pillans et al. 2005).

Major element glass shard analysis (Figure 3, Supplementary Data File A) and field mapping within the Beaconsfield and Pohangina valleys (Figure 1) allow for the recognition of lateral equivalents of the Waitapu Shell Conglomerate within eastern WB sections (Figure 2D,E). Previous correlations of Kershaw (1989), Abbott (1994), Pillans et al. (1994), van der Neut (1996) and Pillans et al. (2005) are compiled in Figure 2, allowing for the addition of and comparison to the Turakina and Kaimatira Bluff sections.

### *Paleo-liquefaction*

Liquidisation involves the formation of fluidised sediment, whereby sediment experiences a complete loss of shear strength and behaves as a cohesionless, viscous fluid (Allen 1977, 1982; Davenport and Ringrose 1987). The common mechanisms of liquidisation are liquefaction and fluidisation (Alfaro et al. 2002; Onorato et al. 2016). Liquefaction is associated with an increase in pore fluid pressure and a reduction of shear strength (Owen and Moretti 2011; Quigley et al. 2013). Sediment liquefies as excess pore-water pressures exceed the static confining pressure, causing large strains and sediment flow together with a breakdown of the grain fabric (Seed and Lee 1966; Seed and Idriss 1982; Idriss and Boulanger 2008).

Fluidisation is the mechanism where a liquid-like condition is achieved by forcing a fluid from an external source upward through the sediment until the immersed weight of the grains is balanced by the total fluid drag (Molina et al. 1998). A distinction is made in the literature between liquefied systems, in which solids settle downward through the fluid, and fluidised beds in which fluids move upward through the solids, suspending them without net downward movement (Lowe 1976).

Paleo-liquefaction within sediments is commonly recognised by injection structures forming sand dykes or sills and severely distorted or offset bedding (Bastin et al. 2015; Kleyburg et al. 2015). Liquefaction develops through the action of a trigger, including seismic events, waves, rapid deposition/loading of sediment, slope instability or groundwater movement (Owen and Moretti 2011).

**Table 1.** Stratigraphic nomenclature and correlations between the Castlecliff type section (Fleming 1953; Abbott and Carter, 1999) and the Rangitikei section in eastern WB (Te Punga 1952; Bussell, 1984; Potter, 1984; Abbott, 1992; and this study).

| Fleming (1953) Abbott and Carter (1999) Castlecliff type section | | Te Punga (1952) Rangitikei | | Potter (1984) Bussell (1984) Rangitikei | | This study Rangitikei | |
|---|---|---|---|---|---|---|---|
| POUAKAI GROUP | Papaiti Alluvium | UPPER RANGITIKEI FORMATION | Mangaone Sandstone | POUAKAI GROUP | Westoe Fm. | POUAKAI GROUP | Westoe Fm. |
| | St Johns Alluvium | | | | | | |
| | Rapanui Fm. | | | | | | |
| | Brunswick Fm. | | Halcombe Conglomerate | | Halcombe Conglomerate Fm. | | Halcombe Conglomerate Fm. |
| | Kaiatea Fm. | | Waituna Conglomerate | | | | |
| SHAKESPEARE GROUP | Landguard Fm. | | | SHAKESPEARE GROUP | *Mingaroa Fossil Bed Mb.* | SHAKESPEARE GROUP | |
| | Putiki Shellbed | | | | *Upper Kakariki Shell Conglomerate Mb.* | | |
| | Mosstown Sand | | | | *Te Hiri Shellbed Mb.* | | |
| | Karaka Siltstone | | Rangitawa Fossil Beds | | *Rangitawa Fossil Bed Mb.* | | Mangatapu Fm. |
| | Upper Castlecliff Shellbed | | | | Mangatapu Fm. | | |
| | | | Kakariki Conglomerate | | *Kakariki Conglomerate Mb.* | | |
| | Shakespeare Cliff Sand | | | | *Pryce Shellbed Mb.* | | |
| | Shakespeare Cliff Siltstone | | Ruamahanga Conglomerate | | *Ruamahanga Conglomerate Mb.* | | *Ruamahanga Conglomerate Mb.* |
| | | | | | *Otapatu Shellbed Mb.* | | |
| | Tainui Shellbed | | Onepuhi Fossil Beds | | *Onepuhi Fossil Beds Mb.* | | |
| | Pinnacle Sand | | | | Tokorangi Fm. | | Tokorangi Fm. |
| | Lower Castlecliff Shellbed | | | | *Toms Shellbeds Mb.* | | |
| | Seafield Sand | | Toms Conglomerate | | *Toms Conglomerate Mb.* | | *Toms Conglomerate Mb.* |
| KAI IWI GROUP | Upper Kai Iwi Siltstone Kupe Fm | | Shell Creek Fossil Beds | | *Shell Creek Fossil Bed Mb.* Reu Reu Fm. Waiomio Fm. (Abbott, 1992) | KAI IWI GROUP | Reu Reu Fm. |
| | Upper Westmere Siltstone | | | | | | *Waiomio Shellbed Mb.* |
| | | | | | | | Waiomio Fm. |
| | Lower Westmere Siltstone | | Waitapu Shell Conglomerate | | | | *Waitapu Shell Conglomerate Mb.* |
| | Omapu Shellbed | | | | | | Kaimatira Pumice Sand Fm. |
| | Lower Kai Iwi Siltstone | | | | | | |
| | Kaimatira Pumice Sand | | Potaka Pumice | | | | *Potaka Pumice Mb.* |
| OKEHU GROUP | Upper Okehu Siltstone | | | | Undifferentiated | OKEHU GROUP | Rewa Fm. |
| | Okehu Shell Grit | | | | | | *Mangapipi Conglomerate Mb.* |
| | Lower Okehu Siltstone | | | | | | |
| | Butlers Shell Conglomerate | | Mangapipi Fossil Beds | | | | *Mangapipi Mb.* |
| | | | | | | | Makirikiri Tuff Fm. |
| | Makirikiri Tuff | | Pakihikura Pumice | | | | *Pakihikura Pumice Mb.* |

Liquefaction associated with recent seismic events has been highlighted in New Zealand (Ward et al. 2011), demonstrating the susceptibility of our environment to this potentially destructive process. Recent seismic events in Canterbury (Cubrinovski et al. 2011), Italy (Alessio et al. 2013) and Japan (Yasuda et al. 2012) have provided case studies, stimulating research into liquefaction susceptibility (Green et al. 2011, 2014) and its relationship to environments of deposition (Giona Bucci et al. 2017, 2018).

Historic evidence of liquefaction in the Whanganui-Manawatu and Horowhenua-Wellington areas has been documented by Eiby (1968) and Fairless and Berrill (1984). These records include evidence of liquefaction within coastal to marginal marine environments where observations have been made of cracking, sand boils and cockles rising to the surface following the 1843 Whanganui, 1848 Marlborough and 1855 Wairarapa earthquakes.

Marine sediments have the potential to liquefy, due to their unconsolidated, water-saturated nature at the seabed (Alfaro et al. 2002). However, reworking of seabed deposits by tides, wave action and surface bioturbation leads to low preservation potential for surficial SSDS and a relative dominance of subsurface SSDS within the geological record (Reid et al. 2012; Giona Bucci et al. 2017). Given the tectonic setting of the WB, it is probable that the basin contains evidence of past earthquakes within its shallow to marginal marine facies, characterised by fine-grained, saturated sediments with high liquefaction potential. However, confidently identifying the trigger mechanism for

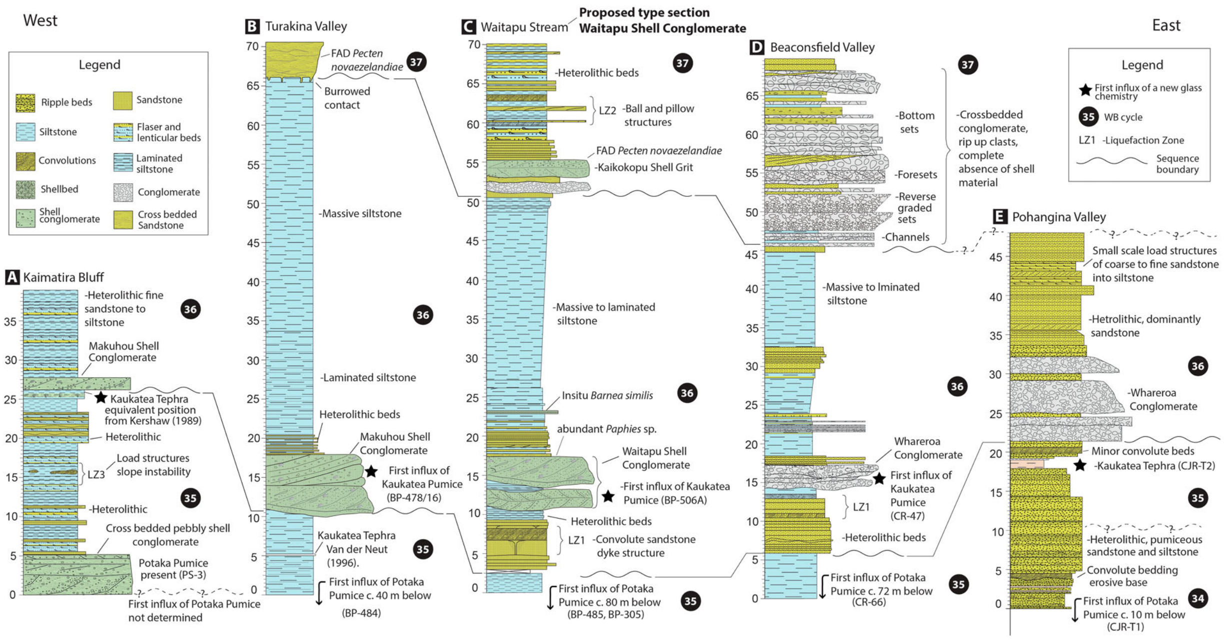


**Figure 2.** Stratigraphic log of the proposed type section for the Waitapu Shell Conglomerate near the mouth of Waitapu Stream, Rangitikei Valley (BL34 1582 6596) and other laterally equivalent sections from across the basin. Data sourced from Kershaw (1989), Abbott (1994), Shane (1994) van der Neut (1996), Pillans et al. (2005), Rees (2018a) and this study.

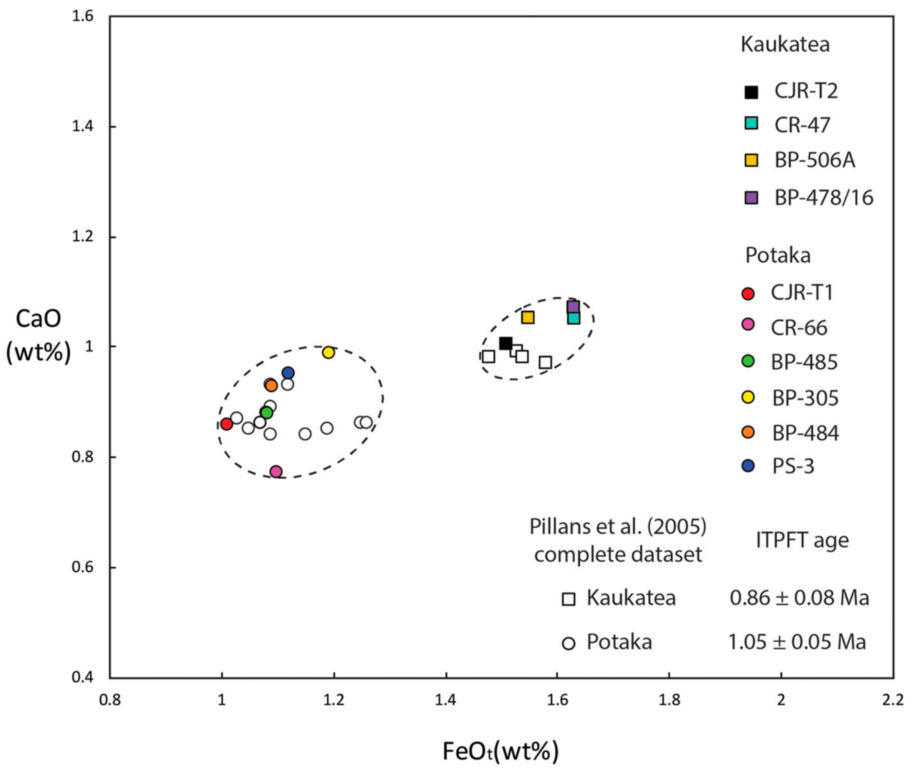


**Figure 3.** Mean CaO versus $FeO_t$ (wt%) composition of glass shards analysed from tephra-fall and/or volcaniclastic samples and correlation to the complete dataset of Pillans et al. (2005). Data sourced from Shane (1994), Pillans et al. (2005) and Rees (2018a).

SSDS can be difficult (Owen and Moretti 2011), presenting a challenge for paleoseismic investigations in the WB.

## Methods

During fieldwork, we identified common SSDS within a particular interval of the WB's Castlecliffian succession (c. 1–0.9 Ma), extending from Pohangina Valley c. 70 km west to Kaimatira Bluff (Figure 1). Recognition and description of the main types of SSDS within this stratigraphic interval (Figure 4) proceeded during geological mapping in the eastern WB (Rees et al. 2018a, 2018c). Mapping involved compilation and revision of local stratigraphic nomenclature (Feldmeyer et al. 1943; Te Punga 1952; Fleming 1953;

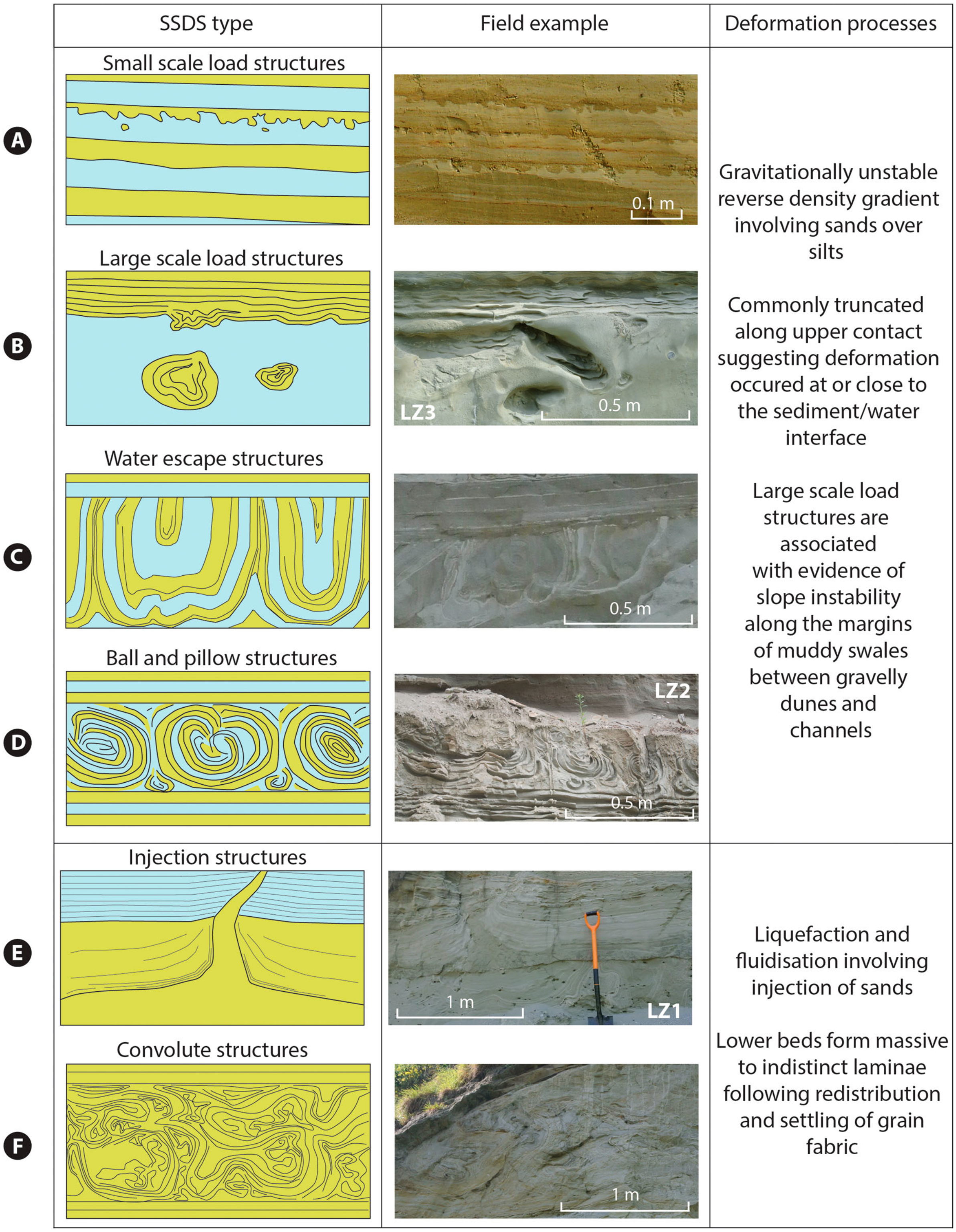


**Figure 4.** The main types of SSDS recognised in the WB and their interpreted processes of deformation.

Seward 1976; Bussell 1984; Potter 1984; Abbott 1992; Naish and Kamp 1995; van der Neut 1996). Table 1 outlines the revised nomenclature and its relationship to the Castlecliff type section (Figure 1) near Whanganui City (Fleming 1953; Abbott and Carter 1999).

The use of marker horizons was paramount for correlation between the sections. Mid-Pleistocene marker horizons in the Rangitikei District typically comprise a TST; pebbly shell conglomerate containing reworked fossils from estuarine to offshore environments and volcaniclastic sediment that in many cases represents the first influx of a new pumice geochemistry into the basin (Type A1 shellbed of Abbott and Carter, 1994). Many of these units are prominent in the landscape, allowing for ease of mapping.

We chose to document the Waitapu Shell Conglomerate, as it is well constrained by the WB chronostratigraphic framework, is associated with large-scale SSDS and displays interesting lateral variation across relatively short distances (<16 km). The Waitapu Shell Conglomerate is a unit that marks the boundary between the Kaimatira Pumice Sand Formation (Fleming 1953) and newly revised Waiomio Formation in the Rangitikei District (Table 1). In this study we propose a type section for the Waitapu Shell Conglomerate, following the detailed works of Te Punga (1952) and Abbott (1994), specifying an easily accessible outcrop at the entrance to Waitapu Stream, Potaka Station (NZ Topo50 map reference BL34 1582 6599).

We logged sections (Figure 2), collecting fossils and samples from primary tephra-fall and volcaniclastic beds. Sample locations were marked by handheld GPS (Figure 1). Fossil identification and paleoenvironmental interpretation was greatly aided by Dr Alan Beu (GNS Science) (Supplementary Data File B). The Waitapu Shell Conglomerate and its correlatives within each section were assessed for clast shape, size and composition (Supplementary Data File C).

Tephrostratigraphy and field mapping were used to trace the lateral equivalent of the Waitapu Shell Conglomerate eastwards into the Beaconsfield and Pohangina valleys (Figures 1 and 2), documenting facies changes towards the Ruahine Range (Figure 1). Beds composed entirely of glass were targeted when available. Pumice clasts were sampled from conglomerate beds, before being gently crushed during sample preparation. Samples were washed through a 63 µm sieve, discarding silt and clay-sized particles. Following drying, samples were then dry sieved to collect the 125–250 µm fraction for mounting in epoxy plugs. Glass shard major elements were determined using a JEOL JXA-8230 Electron Probe Microanalyser (EPMA) at Victoria University, Wellington. Analyses were determined using an 8 nA beam current, 10 µm beam diameter, and the glass standards ATHO-G from the MPI-DING collection (Jochum et al. 2006) and VG568 (Jarosewich et al. 1980). All analyses presented are weight percent, recalculated to 100% on a water-free basis (Supplementary Data File A). Total Fe ($FeO_t$) was calculated as FeO while $H_2O$ was calculated by the difference from 100%. Bivariate plots were constructed using $FeO_t$ Vs CaO Wt % to aid tephra correlation with published datasets (Figure 3).

## Results

### Section descriptions

#### Waitapu Stream – proposed type section

The Waitapu Shell Conglomerate (Figure 2C) contains a heterolithic mixture of bioclastic and siliciclastic sediments, with clasts typically of pebble size in a matrix of coarse sands and granules. The basal contact is erosive with channels up to 1 m deep carved into the underlying laminated to lenticular bedded siltstone and fine sandstone (Figure 5). Large-scale, low-angle, trough cross-bedded sets 1–2 m thick contain large (up to 400 mm), angular rip-up clasts of the laminated to lenticular bedded siltstone and fine sandstone. Lenses of siltstone, 0.1–0.3 m thick, drape the crossbeds, pinching out laterally. The rip-up clasts contain original laminated to lenticular bedding formed prior to reworking (Figure 6B) and appear to be derived from the heterolithic beds immediately beneath the cross-bedded sets.

Clasts are dominantly pebbles of sub-rounded, disc to blade-shaped, greywacke, pumice, rhyolite and ignimbrite 2–64 mm in diameter, with rare larger clasts >100 mm (Supplementary Data File C). Clasts are typically weakly aligned along the cross-bed sets. Rare charcoal is particularly evident within the lower-most channelled cross-bed sets, occurring as pockets of rounded clasts up to 70 mm in diameter. Variable concentration and composition of clasts occurs throughout the deposit, with particular cross-bedded sets enriched in bioclastic material, greywacke pebbles and pumiceous alluvium. Lenses of distinctive, very coarse to granular quartz- and ferromagnesian-rich sands occur locally, displaying strong sorting and resultant mineral separation by density.

Bioclastic material is highly worn, comprising approximately equal proportions of granule-sized debris and variably preserved fossil Mollusca dominated by *Paphies* sp. Particular lenses of highly enriched bioclastic material occur, in which shell fragments and whole shells comprise up to 80% of the material in a siliciclastic matrix. Similarly, other lenses are enriched in pumiceous sediment containing abundant sub-rounded pumice clasts up to 150 mm in diameter. The largest pumice clasts significantly outsize clasts of any other lithology.

Large-scale convolute, water escape and injection structures (LZ1) occur 1–2 m below the Waitapu Shell Conglomerate (Figures 5 and 6A,D) underlying a locally channelled unit of laminated to lenticular siltstone and fine sandstone. LZ1 SSDS are characterised by an injection structure originating from an area of deformation within fine laminated to massive sandstone 2 m below the main zone of convolute bedding (Figure 5). The 1.5 m-high injection structure is characterised by consolidated medium to fine-grained sandstone at its core, displaying a funnel-shaped contact with the intensely convoluted fine sandstone to coarse siltstone above. The dyke geometry is 0.2 m wide near its base and increases in width to 1 m at the upper funnel shaped contact. The interval of intense convolution overlying the dyke structure contains multiple smaller sites of injection with a majority of the convolute bedding centered in the lowermost portion of fine sandstone, grading upwards into wavy-laminated fine sandstone to coarse siltstone. During repeat visits, the outcrop face was observed to

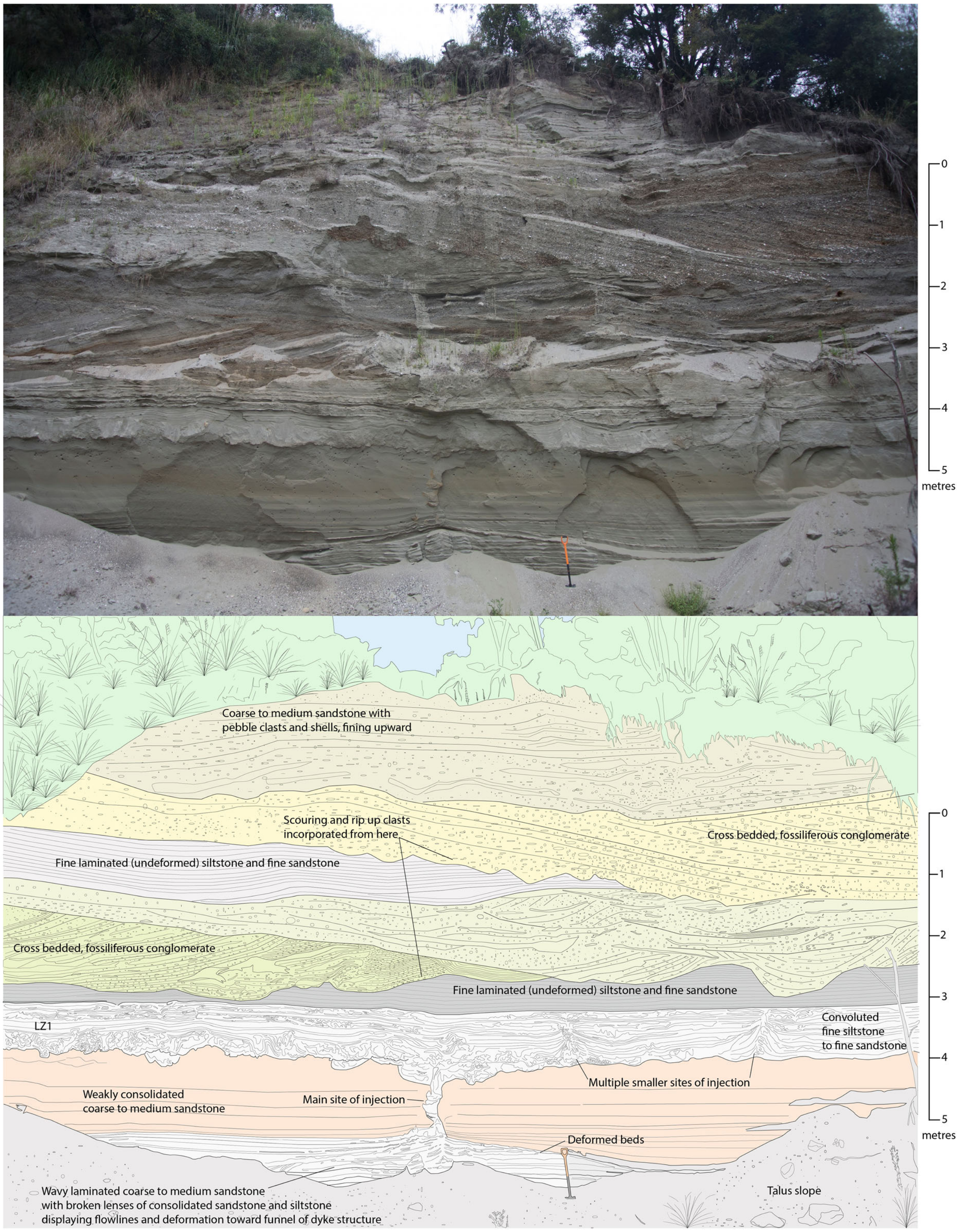


**Figure 5.** Sketch of the proposed Waitapu Shell Conglomerate type section at Waitapu stream (BL34 1584 6597). Spade is 1 m high, note lift in top of laminated sandstone to left of spade grading upwards into a zone of massive fine sandstone. The injection structure starts at the apex of this lift before funnelling into the overlying intensely convolute fine sandstone and siltstone of Liquefaction Zone 1 (LZ1).

be actively eroding, revealing other dyke structures originating from LZ1 located 6–10 m from the dyke sketched in Figure 5.

A gradual fining upward sequence occurs above the Waitapu Shell Conglomerate (Figure 2C), changing from heterolithic sediments with rare shell debris to massive, sparsely fossiliferous siltstone. Overlying the fine-grained massive siltstone is a conglomeratic unit. The base is characterised by a 1 m thick, well sorted, un-fossiliferous, clast-supported greywacke conglomerate overlain by coarse to granule sandstone. A cross-bedded shell conglomerate, locally scours into this greywacke conglomerate-sandstone unit. The first appearance of *P. novaezelandiae* within the shell

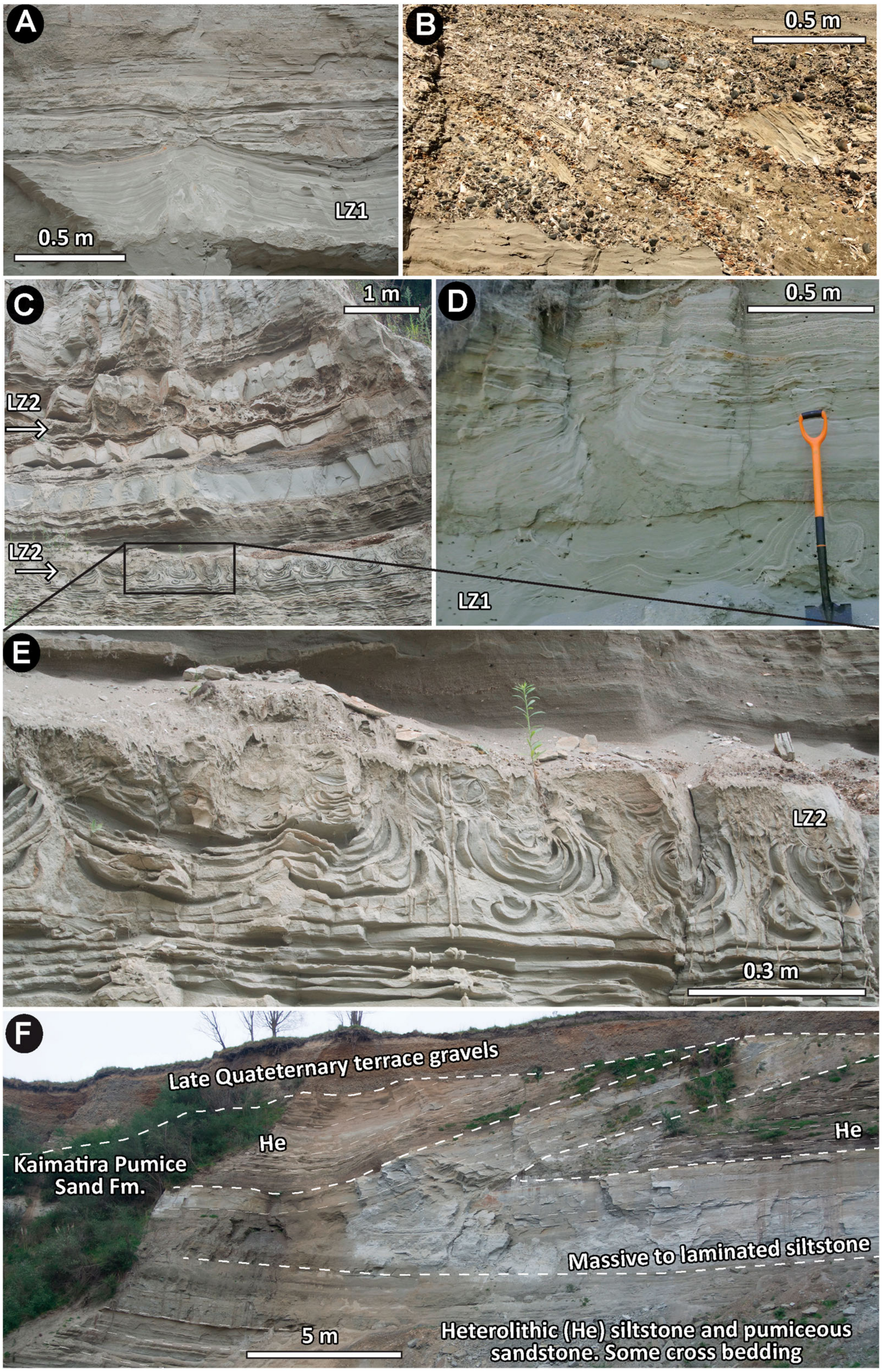


**Figure 6. A,** Close up of Liquefaction Zone 1 (LZ1), displaying a site of injection at the Waitapu Stream section. **B,** Rip up clasts of laminated to wavy lenticular coarse siltstone and fine sandstone within the Waitapu Shell Conglomerate, retaining bedding. **C,** Liquefaction Zone 2 (LZ2), c. 40 m above the base of the Waitapu Shell Conglomerate displaying two beds with ball and pillow structures (BL34 1675 6563). **D,** An injection structure exposed within LZ1. **E,** Close up of photo B, LZ2, showing ball and pillow structures formed in fine sandstone and siltstone. **F,** Interpreted slope instability within Kaimatira Pumice Sand Formation, stratigraphically below Waitapu Shell Conglomerate. This outcrop is located c. 800 m NE of the proposed type section for the Waitapu Shell Conglomerate (BL34 1664 6643).

conglomerate allows correlation to the Kaikokopu Shell Grit (Abbott 1994). The Kaikokopu Shell Grit passes upwards into a complex of heterolithic, interbedded sandstone, siltstone and 0.2–0.5 m thick beds of coarse shell debris and sandstone displaying unidirectional cross-bedding.

LZ2 occurs c. 25 m above the Waitapu Shell Conglomerate and is interbedded with rare lenses of shell debris and massive siltstone (Figure 6C,E). Here two distinctive beds of soft sediment deformation, 0.3 and 0.6 m thick, occur within a highly variable succession of alternating lenticular fine sandstone and siltstone with rare, thin lenses of shell debris. These beds are characterised by ball and pillow structures (Figure 6E) comprising fine sandstone to siltstone tightly folded into concentric layers with some lateral variation in grain-size and patterns of deformation. LZ2 can be traced for 1 km farther east as the Waitapu Stream cuts across the strike of the gently dipping Pleistocene units (1–3° SSE). Beyond this point, the beds are not exposed, dipping beneath the late Quaternary fill. The heterolithic units gradually fine upward with rare 10–50 mm coarse to granule sandstone layers present, until near the top of the succession where structureless siltstone dominates.

The Waitapu Shell Conglomerate contains a diverse assemblage of fossils (Supplementary Data File B). Shells are often moderately to severely worn. Approximately 50% of fossils occur as fragments with rare lenses containing well-preserved diverse faunal assemblages. Estuarine species are rare and their shells are extremely abraded. The assemblage is dominated by open coast to sandy nearshore species, particularly *Paphies donacina* and *P. delta*.

### Beaconsfield Valley

In Beaconsfield Valley (Figures 1 and 2D), we correlate the Waitapu Shell Conglomerate to an equivalent unit, the Whareroa Conglomerate (Rees et al. 2018a), based on the first occurrence of Kaukatea Pumice (Figures 2D and 3). Whareroa Conglomerate occurs in this section as a clast supported conglomerate displaying 1–2 m thick trough crossbed sets above an erosional lower contact (Figure 7). Clasts are rounded to sub-rounded, comprising a mixture of equant to disc shaped pebbles (13–50 mm). They are dominated by greywacke with locally enriched lenses of pumice. Isolated larger clasts of pumice and charcoal occur up to 60 mm in diameter. No shell material is identified within this interval of the Beaconsfield succession. Crossbed sets often show normal grading with erosive lower contacts and basal lags containing isolated large clasts (45–60 mm). We note 10–60 mm tear shaped load structures consisting of sub-round clasts of granule to

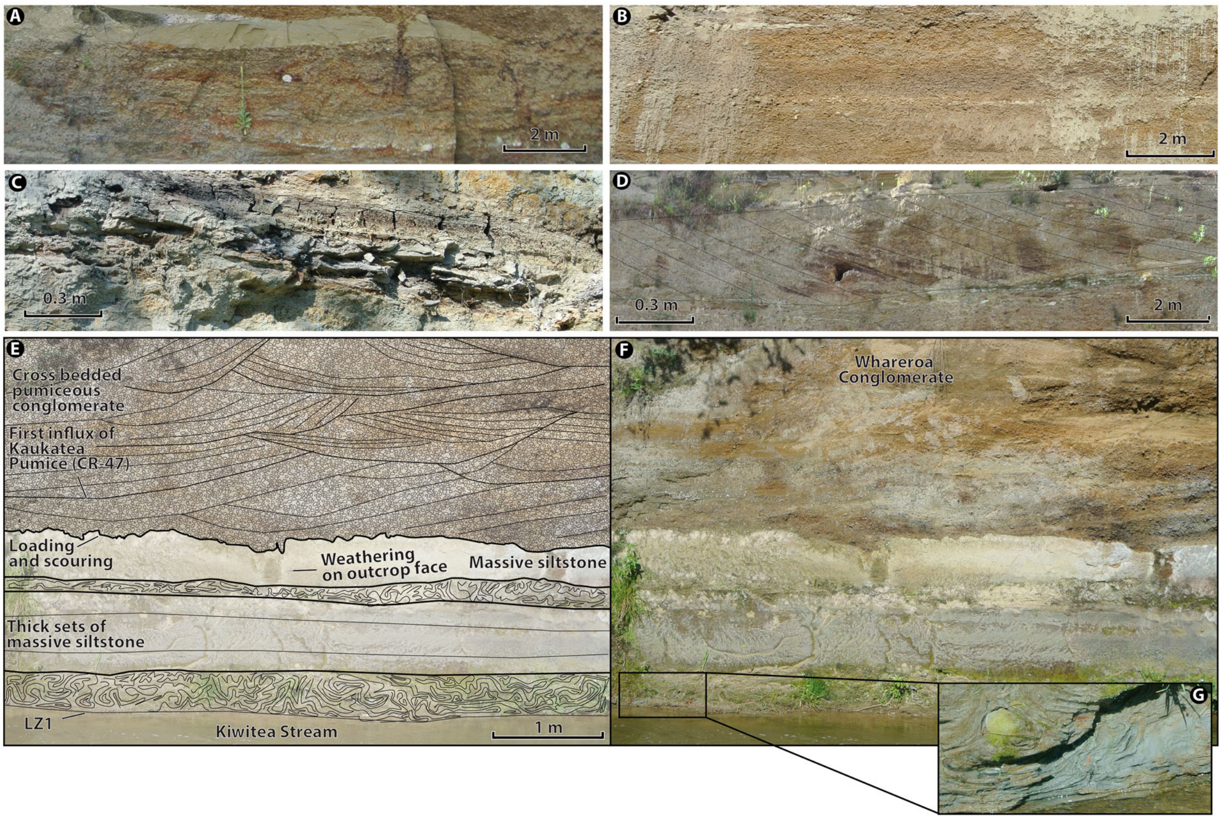


**Figure 7. A,** Channelled conglomerate near the base cycle 37 in Beaconsfield Valley (BL35 3194 6423). **B,** Reverse graded sets located above the channeled conglomerate in A. **C,** A 30 cm thick lignite locally occurring as a cap above the Whareroa Conglomerate in Beaconsfield Valley (BL35 3250 6465). **D,** Foresets overlying the reverse graded sets pictured in B. **E,** Sketch of the Whareroa Conglomerate exposed in Beaconsfield Valley, soft sediment deformation occurs 0.5 and 1.5 m (LZ1) below this lateral equivalent of the Waitapu Shell Conglomerate c. 16 km east of the Waitapu Stream section. Rare load clasts 50–300 mm in diameter occur directly beneath the conglomerate at this outcrop, consisting of coarse conglomerate material sinking and forming balls within the massive siltstone. **F,** Photo used to produce sketch in E. **G,** close up of LZ1 below the Whareroa Conglomerate in Beaconsfield Valley.

small pebbles within a 1 m thick massive siltstone immediately underlying Whareroa Conglomerate. The load clasts penetrate the siltstone to a maximum depth of 90 mm. A 300 mm lignite bed is found locally overlying the Whareroa Conglomerate, pinching and swelling laterally (Figure 7D).

Beneath Whareroa Conglomerate lies c. 8 m of massive to laminated fine sandstone and siltstone with occasional wavy lenses of coarse sand to granule-sized pumice and greywacke clasts. Two beds, 0.3–0.5 m thick, contain convolute structures (LZ1), observed 1 and 3 m below the conglomerate unit, occurring within siltstone and fine sandstone, respectively (Figures 2D and 7). The convolute structures are truncated at their upper contacts by sharp bedding planes.

Fifteen metres of heterolithic beds overlie Whareroa Conglomerate, including five lenses of pebble conglomerate, 0.2–0.15 m thick, interbedded with siltstone and fine sandstone beds. Occasional beds of pumiceous conglomerate 0.5–0.6 m occur, containing abundant reworked pumice, dominated by Potaka geochemistry (determined by EPMA analysis). A 12 m interval of massive to laminated siltstone separates the heterolithic beds from a 25 m thick conglomerate unit interbedded with medium to coarse sandstone and abundant rip up clasts of siltstone. Clasts are rounded to sub-rounded, disc to equant in shape and are largely composed of greywacke with lesser amounts of ignimbrite, pumice and siltstone (25–100 mm in diameter). The conglomerate unit grades from 2.5 m of low angle cross-beds with associated channel cut and fill structures and abundant rip up clasts into 2–2.5 m thick reverse graded sets (Figure 7A,B). Foresets composed of laminated, clast-supported conglomerate beds 100–300 mm thick overlie the reverse graded sets (Figure 7D). The foreset unit is a total of 1–2.5 m thick; the individual beds dip between 16 and 20° S and are truncated along their upper contact by the overlying heterolithic bottom sets. Lenses of siltstone up to 1 m thick become more frequent within the upper part of the conglomerate, interbedded with low angle cross-stratified to laminated pebble conglomerate.

### *Pohangina Valley*

The Pohangina Valley section (Figure 2E) contains a heterolithic succession dominated by fine sandstone. Primary Kaukatea tephra-fall and the first influx of Potaka Pumice has been documented by Rees et al. (2018b), enabling correlation to the other sections. The basal 10 m of this section is characterised by 20–60 mm beds of rippled to laminated, pumiceous sandstone and siltstone. Ripples are commonly highlighted by coarse sand to granule-sized pumice clasts. Basal contacts are often erosional within occasional inclusion of sub-rounded rip up clasts of siltstone 20–35 mm thick. Water escape and convolute structures are apparent within a 0.5–0.8 m thick bed of fine pumiceous sandstone and siltstone located toward the base of section (Figure 2E). The SSDS are truncated by a sharp contact with the overlying sandstone bed.

The heterolithic pumiceous sandstone and siltstone grades upward into 8 m of laminated sandstone with sets between 5 and 150 mm thick. The siliciclastic component in the sandstone increases as volcaniclastic material become less frequent. The beds fine upward into silty fine sandstone with occasional 10–30 mm lenses of carbonaceous siltstone and a 300 mm tephra-fall bed correlated to Kaukatea Tephra (CJR-T2, Figure 3). 0.6 m of fine-laminated sandstone separates Kaukatea Tephra from a 0.5 m bed of minor convolute structures within coarse to fine-grained pumiceous sandstone.

Laminated medium to coarse sandstone, 0.5–0.8 m thick, separates the convolute bed from the overlying Whareroa Conglomerate (Figure 2E). The lower contact of the conglomerate is wavy and erosional. The conglomerate is 10.5 m thick, poorly sorted, consisting of alternating sets of matrix-supported and clast-supported conglomerate with common rip up clasts (20–150 mm in diameter) and discontinuous lenses of siltstone (up to 200 mm thick). Clasts consist of dominantly equant, rounded to sub-rounded greywacke between 3 and 60 mm with rare cobbles up to 68 mm. Low angle cross-bedding grades upward into thick laminated sets 1–2.4 m thick. No shell material is present within this part of the Pohangina succession. The conglomerate displays lateral facies variation between outcrops, changing within 2 km to a moderately well sorted, dominantly clast supported, pebbly conglomerate with little to no inclusion of siltstone lenses, apart from rip up clasts (20–300 mm) occurring along the erosional lower contact. Pumice clasts are typically rare in the described section; however, within laterally equivalent units pumice becomes a very prominent feature.

A 16 m thick, heterolithic succession of coarse to fine siliciclastic sandstone and siltstone occurs above Whareroa Conglomerate. Fine laminae 10–60 mm thick alternate with lenticular sandstone/siltstone couplets and 300–400 mm thick crossbed sets of medium to coarse-grained sandstone. Thirteen metres above the sharp contact with Whareroa Conglomerate, small-scale load structures occur within wavy laminae to lenticular beds (Figure 4A), comprising fine to medium-grained sandstone within massive siltstone.

### *Turakina Valley*

The Turakina Valley section was described by Abbott (1994) and van der Neut (1996). The Makuhou Shell Conglomerate represents the first influx of Kaukatea

Pumice into the Turakina succession (Pillans et al. 2005), laterally equivalent to the Waitapu Shell Conglomerate in the Rangitikei Valley (Figure 2). Primary Kaukatea Tephra occurs within massive to laminated siltstone approximately 5 m below the Makuhou Shell Conglomerate within cycle 35 (Figure 2B). The Makuhou Shell Conglomerate consists of 7 m of cross-bedded, pebbly shell conglomerate. The lower contact is sharp with low relief. Mud drapes occur along the crossbed foresets. Clasts comprise sub-rounded, disk, blade- and roller-shaped pebbles (22–50 mm) with rare larger pebbles up to 60 mm. The clasts are composed of greywacke and pumice that occur together with whole shells within a fine to coarse sand and shell debris matrix. Whole shells comprise approximately 30–40% of the conglomerate, concentrated within bioclastic rich lenses.

The Makuhou Shell Conglomerate contains a mixed assemblage of fossils, similar to the Waitapu Shell Conglomerate (van der Neut, 1996, Supplementary Data File B). The assemblage is dominated by *Paphies sp.* with common Gastropoda including *Maoricolpus sp.*, *Stiracolpus sp.* and *Maoricrypta sp.* There are a range of rocky intertidal species within the assemblage including *Ostrea chilensis*, *Anomia trigonopsis* and *Buccinulum sp.*, however, no estuarine/lagoonal species were identified by van der Neut (1996).

Heterolithic beds of laminated to lenticular fine sandstone and siltstone occur above the Makuhou Shell Conglomerate, grading into c. 40 m of massive siltstone. Cross-bedded fossiliferous sandstone rests above the massive siltstone, separated by a burrowed, wavy contact. The FAD of *P. novaezelandiae* within the fossiliferous sandstone facilitates correlation to the Kaikokopu Shell Grit, defined at the Castlecliff type section (Abbott 1994). No SSDS are noted at this stratigraphic interval within the Turakina Section, although convolute beds are present within the middle Kaimatira Pumice Sand Formation (van der Neut 1996).

### *Kaimatira Bluff*

Well exposed strata at Kaimatira Bluff (Figure 1) and the surrounding area have been well described by Kershaw (1989) and Abbott (1994) and compiled within Figure 2A. At the base of the section, 5 m of cross-bedded, pebbly shell conglomerate contains clasts of Potaka Pumice (Shane 1994), enabling correlation to the Kaimatira Pumice Sand Formation. However, the first occurrence of Potaka Pumice at this section has not been established due to limited exposure. The shell conglomerate contains disarticulated, often broken and fragmented *P. sp and Cyclomactra tristis.* Clasts consist of sub-rounded, disc, blade and roller shaped granules to pebbles of greywacke 1-60 mm in diameter. Rare larger cobbles upto 67 mm are present.

Heterolithic siltstone to coarse sandstone beds with lenses of granule greywacke and shell debris occur as lenticular to laminae sets 20–60 mm thick above the basal conglomerate. These beds truncate the underlying conglomerate cross-beds at an undulating, erosive lower contact. A massive to laminated bed of siltstone (Figure 8) occurs as a broad 11 m wide swale structure above the heterolithic beds, pinching and swelling from 0.1 to 1.2 m in height. A highly deformed 300 mm lens of ball and pillow structures occurs at the southern edge of this structure, swelling from 50 to 300 mm and becoming progressively more deformed down dip (Figure 8). The SSDS are composed of circular convolutions of interbedded siltstone and fine to coarse sandstone with thin seams of shell debris and pebbles. The outer layer is composed of consolidated siltstone, forming an erosion resistant rind that accentuates the structures at outcrop.

Above the massive siltstone lies 3.5 m of heterolithic, cross-bedded siltstone with fine to coarse sandstone and lenses of shell debris and pebbles. These beds are similar in lithology to the SSDS present within the underlying massive siltstone. The lower contact surface contains convolute bedding and load structures, ranging from 50 to 400 mm in size, typically tear shaped or horizontally elongated.

Massive to laminated siltstone separates the heterolithic beds from a 2.5 m thick fossiliferous unit, containing a lower condensed shellbed dominated by *O. chilensis* and *Talochlamys gemmulata* (Figure 8E) and overlying cross-bedded shell conglomerate (Figure 8D) with abundant *P. sp*. The approximate stratigraphic position of the Kaukatea Tephra is located between the condensed shellbed and the erosive base of the overlying cross-bedded shell conglomerate (Kershaw 1989; Abbott 1994). This allows for correlation of the shell conglomerate to the Makuhou Shell Conglomerate of Abbott (1994) and van der Neut (1996).

The Makuhou Shell Conglomerate at Kaimatira Bluff displays mud draped crossbeds 0.5–1 m thick, merging into lenticular to flaser bedded siltstone bottom sets. Clasts are sub-rounded, dominantly disc shaped pebbles of greywacke, 19–64 mm in diameter with rare cobbles up to 120 mm. The matrix is composed of equal portions crushed shell debris and coarse to granule sands. Isolated large clasts of pumice occur, up to 100 mm in diameter. Shells are often abraded and worn with rare lenses of well-preserved diverse assemblages including *P. sp.*, *Xymene expansus*, *T. gemmulata*, *Barbatia novaezelandiae*, *Zethalia zelandica*, *Trochus taratus*, *Nucula nitidula*, *Alcithoe fusus* and *Alcithoe arabica*.

Heterolithic, siltstone and fine- to medium-grained sandstone, 12 m thick, occurs above the Makuhou Shell Conglomerate. Beds contain rippled to laminae sets 20–60 mm thick.

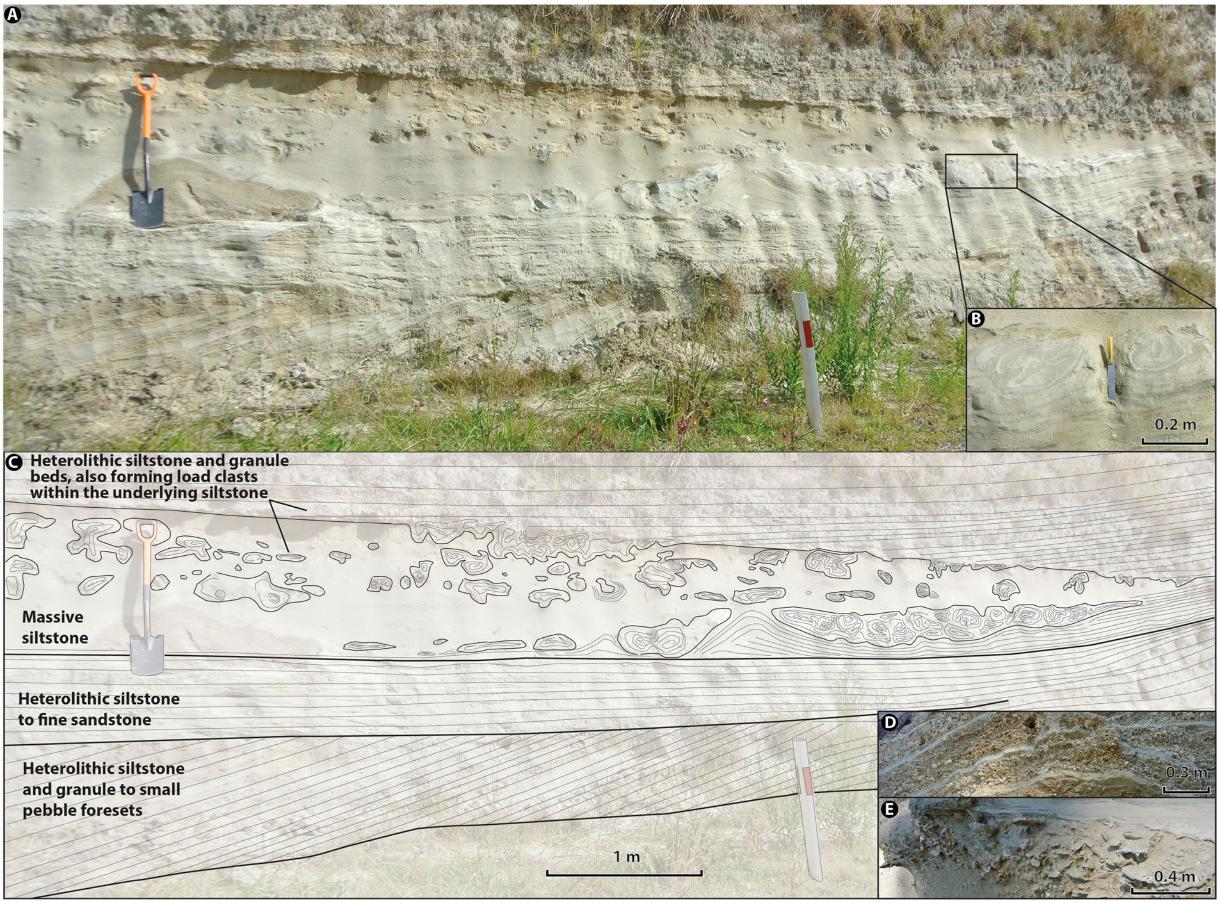


**Figure 8. A,** Base of the Kaimatira Bluff section displaying load and ball and pillow structures composed of convolute siltstone, sandstone and granule clasts within massive siltstone. Massive siltstone occupies swales between dunes composed of cross-bedded pebbly shell conglomerate, Kaimatira Pumice Sand Formation (BL32 7887 8156). Progressive downslope deformation of the heterolithic bed within the siltstone swale is interpreted as evidence of slope instability. **B,** A close up photo of a deformed bed of heterolithic siltstone to granule clasts within laminated to massive siltstone. **C,** A sketch of Photo A. **D,** The Makuhou Shell Conglomerate exposed in the hillslope beside Kaimatira Bluff (BL32 7934 8150). **E,** The basal condensed shellbed at the base of Makuhou Shell Conglomerate within the Kaimatira Bluff section. Intense bioturbation and burrowing occurs in the siltstone below this shellbed.

## Discussion

### *Stratigraphy and sedimentology*

#### *Waitapu Shell Conglomerate*

The Waitapu Shell Conglomerate contains fossils representative of a wide variety of depositional environments (Supplementary Data File B). Shells are well mixed, broken and abraded, typical of reworking by waves and tidal currents. Trough cross-bedding indicates dune bed forms produced by strong unidirectional currents (Harms et al. 1982; Duke et al. 1991). Set thicknesses of up to 2 m implies the influence of strong tidal and/or storm-driven currents (Abbott 1998; Le Bot and Trentsaux 2004). Mud draped crossbed foresets (Figure 5) indicate fluctuating energy conditions, including slack water/quiescent periods where finer particles settled from suspension. The channelled erosion surface below the crossbed sets was likely formed by strong storm/tidal action, possibly related to a reduction in the mean wave base and localised scour and fill of sediments (Dott and Bourgeois 1982).

The Waitapu Shell Conglomerate is analogous to the basal TST shell conglomerates described at the Castlecliff section (Abbott 1998), interpreted to represent deposition on a storm-dominated, muddy innermost shelf (Abbott and Carter 1994). We infer the presence of a fluvial outlet in close proximity to the depositional site, with headwaters located in the present-day central North Island, supplying abundant greywacke and volcaniclastic detritus to the coast. This is consistent with the lateral changes observed within the Waitapu Shell Conglomerate, as it grades into an eastern margin conglomerate facies, characterised by a lack of marine fossils, rare lignite and equant greywacke clasts, suggesting closer proximity to and influence from fluvial systems draining the uplifting paleo-axial range (Figures 9 and 10).

At the WBs eastern margin, we envision braid plains, delta fronts and gravelly beaches to have developed during sea level low stand, locally incising through the previous HST, as evidenced by delta type architecture above undulating surfaces of erosion within eastern margin conglomerate deposits (Figure 7A,B,D). Nearby land was likely deforested

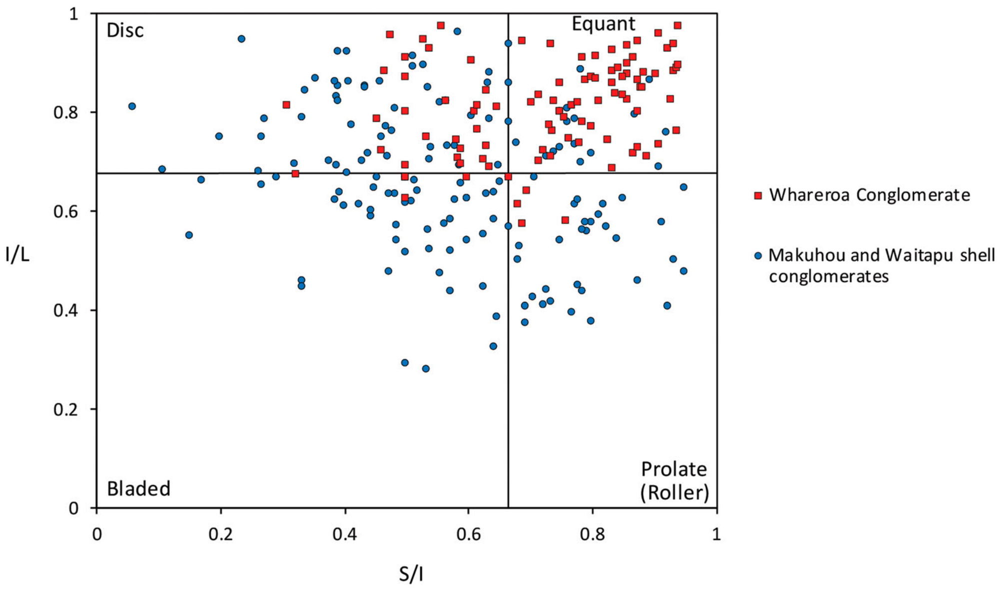


**Figure 9.** Zingg diagram showing clast shape measurements from the Whareroa Conglomerate (Pohangina and Beaconsfield valley sections) and the Makuhou and Waitapu shell conglomerates (Kaimatira Bluff, Turakina and Waitapu Stream sections).

and sediment input particularly high (Beu et al. 1981; Lewis et al. 1994). Low stand deposits were later scoured and eroded during transgressive ravinement, reworked into shelly gravel dunes at inner-most shelf depths (Abbott 1998). Local preservation of low stand deposits in eastern WB (Abbott 1992), suggests

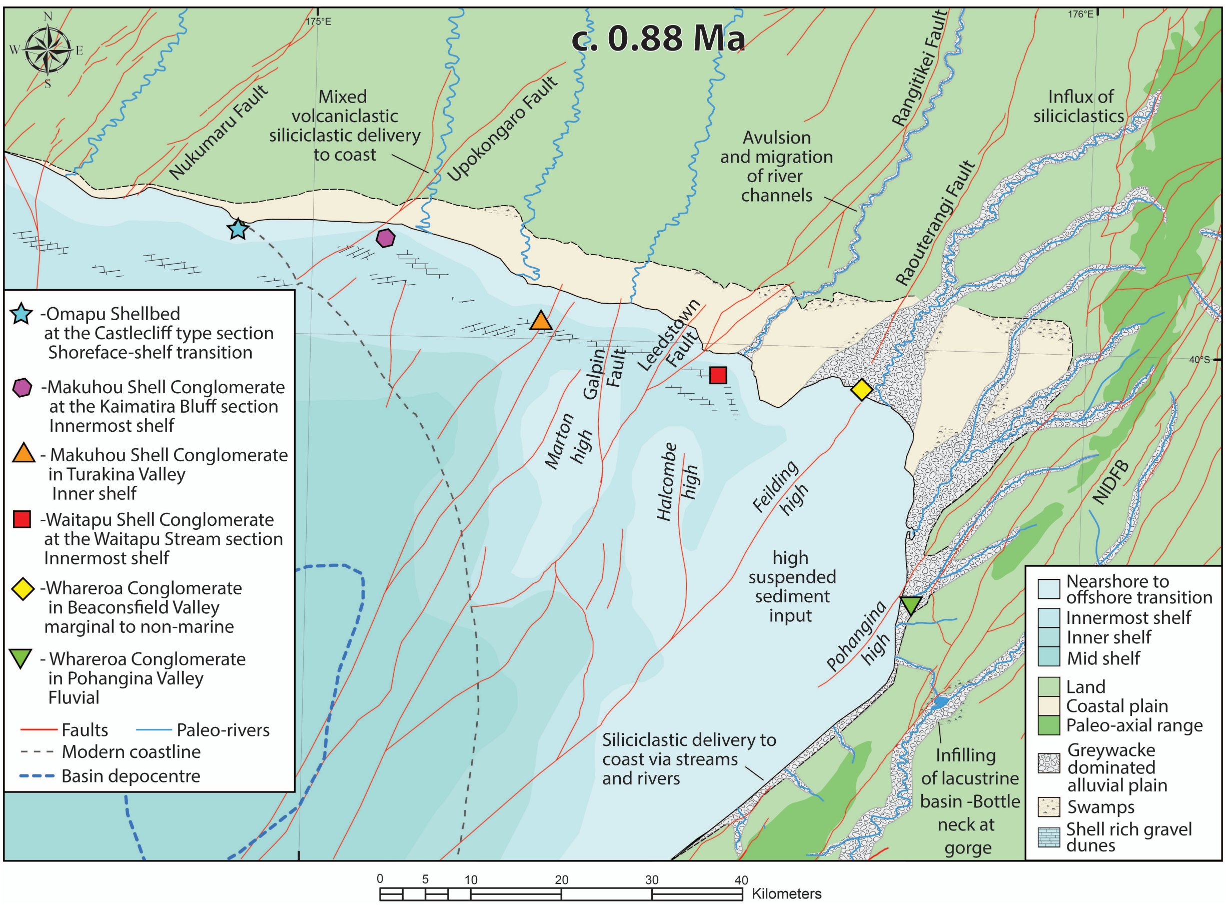


**Figure 10.** Schematic cartoon of the WB during the marine transgression of WB cycle 36 (MIS 22) at c. 0.88 Ma (Bowen et al. 1998; Lisiecki and Raymo 2005). The location of time equivalent strata are displayed across the basin to demonstrate the approximate position of the paleo-shoreline and transition into greywacke dominated conglomerate toward the paleo-axial range. Data from Feldmeyer (1943), Piyasin (1966), Milne, (1968), Seward (1974), Anderton (1981), Abbott (1994), van der Neut (1996), Brackley (1999) and GNS Science.

transgressive ravinement was either not as destructive or that low stand incision was more pervasive along the eastern basin margin.

Marine transgression and associated shoreface retreat triggered sedimentary infilling of the valleys incised during the previous low stand (Rees et al. 2018b). Estuarine systems developed, hosting a wide range of species, including *Cyclomactra tristis, Austrovenus stutchburyi, Paphies australis* and *Cominella adspersa* (Supplementary Data File B), the shells of which were transported into the marine environment by rivers (Hayward and Stilwell 1995) or became entrained during transgressive ravinement and sedimentary reworking (Abbott 1998).

The abundant unweathered pumice within the Waitapu Shell conglomerate is typically of a much larger clast size than the accompanying clasts of greywacke, suggesting that a phase of important eruptions in the TVZ preceded and perhaps accompanied its deposition (Te Punga 1952). This is consistent with the incorporation of clasts of charcoal within the lowest beds of the Waitapu Shell Conglomerate. In the Pohangina, Turakina and Whanganui valleys (Figure 1), Kaukatea Tephra is preserved within marginal to shallow marine deposits just below the stratigraphic position of the Waitapu Shell Conglomerate, suggesting that volcanic activity closely preceded deposition of Waitapu Shell Conglomerate, occurring within cycle 35 (Naish et al. 2005; Pillans et al. 2005).

### *Whareroa Conglomerate*

We correlate the Whareroa Conglomerate west from Pohangina Valley to Beaconsfield Valley (Figures 1 and 2D). The name introduced in Rees et al. (2018a) is adopted in Beaconsfield Valley to describe a similar eastern margin conglomerate facies occupying the same stratigraphic position and to negate the unnecessary introduction of further nomenclature.

The most notable change within the Kai Iwi Group from the Waitapu Stream to Beaconsfield Valley (Rangitikei and Oroua catchments, Figure 1) is a total absence of marine Mollusca. The last shellbed noted in the succession is below the Rewa Pumice (c. 1.19 Ma), and marine fossils are not encountered again until the Onepuhi Fossil Beds (c. 570 ka). This change is mirrored in the Pohangina Valley succession where the last shellbed containing marine Mollusca occurs below the Rewa Pumice.

The absence of fossils within the Whareroa Conglomerate occurs together with a change in clast shape, characterised by a greater proportion of equant clasts (Figure 9). We interpret the Whareroa Conglomerate in the Beaconsfield section to occupy a more landward position relative to the Waitapu Shell Conglomerate, with more of a direct influence from a paleo-fluvial outlet. The lignite bed, locally capping the Whareroa Conglomerate (Figure 7C), suggests a marginal to non-marine setting, where organic matter preservation occurred in coastal wetlands developing on an outer alluvial floodplain or coastal plain (Figure 10).

### *Makuhou Shell Conglomerate*

The Makuhou Shell Conglomerate and overlying heterolithic to massive siltstone beds in Turakina Valley represent an ideal WB sequence as defined by Abbott (1998), recording progressively deeper water deposition above a transgressive ravinement surface. The basal cross-bedded shell conglomerate is considered to have formed seaward of the transgressive shoreface (Abbott 1994). Shell material was derived from contemporary shoreface to marginal marine/estuarine environments together with a reworked component from the underlying rocks. Siliciclastic and volcaniclastic pebbles derived from paleo-rivers draining the central North Island and paleo-axial range were incorporated during reworking of LST coastal plain and alluvial facies and were supplied contemporaneously by rivers feeding the coast. Seaward of the reworked gravel deposits heterolithic silt and sands were deposited on a storm-dominated, muddy, inner shelf (Abbott 2000). During sea level high stand, massive to laminated siltstone accumulated at inner- to mid-shelf depths (Abbott 1997).

## Soft sediment deformation structures

### *LZ1*

The soft sediment deformation of LZ1 (Figure 2C) originates from a fine sandstone bed displaying water escape structures and a related sand dyke. We interpret paleo-liquefaction as having occurred within this fine sandstone, resulting in subsequent settling and the formation of indistinct to massive bedding, associated with re-distribution of grain-to-grain contacts. No evidence of bioturbation is present within this unit. Subsequent fluidisation above this basal sand is apparent within the overlying intensely convolute beds where multiple smaller sites of injection occur (Figure 6A). The overlying sandstone typically contains a higher proportion of coarse silt, a greater level of consolidation and displays wavy laminae to convolute bedding in contrast to the underlying massive, unconsolidated sandstone. Evidence of fluidisation includes multiple sites of injection, resulting from pore fluid expulsion from the underlying sandstone. As the pore-fluid has travelled up through the sediment, it has entrained particles resulting in convolute bedding displaying a moderate degree of sorting and separation of grains by density (Figures 5 and 6A).

Large (400 mm) sub-angular, rip-up clasts of laminated to lenticular siltstone and sandstone display original bedding structures, demonstrating that the sediments were already moderately consolidated, prior to subsequent scouring and erosion (Figure 6B). These clasts appear to be derived from the heterolithic facies directly beneath the cross-bed sets. We do not observe any loading structures along the contact between the Waitapu Shell Conglomerate and underlying heterolithic beds. Therefore, the storm/tidal activity involved in the deposition of Waitapu Shell Conglomerate is unlikely to have caused the LZ1 soft-sediment deformation, as the sediment would be required to be in a soft, unconsolidated and water-saturated state for wave-induced liquefaction to occur (Mory et al. 2007). Loading during deposition does not appear to have caused the LZ1 SSDS at the Waitapu Stream section. Rare load structures are preserved directly below the Whareroa Conglomerate in Beaconsfield Valley (Figure 7). These structures occur in massive siltstone stratigraphically above LZ1. We suggest the silt that Whareroa Conglomerate was deposited onto at the Beaconsfield section, was in an unconsolidated, water-saturated state, prone to deformation during loading, conditions that do not appear to have existed during deposition of the Waitapu Shell Conglomerate c. 16 km farther west.

### LZ2

The base of cycle 37 at the Waitapu Stream section (Figure 2C) is marked by the Kaikokopu Shell Grit, grading upward into a heterolithic succession with interbedded SSDS (LZ2). We interpret this heterolithic succession as having been deposited on a storm-dominated, muddy innermost shelf with strong tidal currents, evidenced by unidirectional cross-bedding and the occurrence of abundant laminated coarse siltstone and fine sandstone. The ball and pillow structures of LZ2 are truncated along their upper contacts, suggesting they formed at or close to the sediment/water interface. They are separated by undeformed beds, 0.4–1 m thick, including 0.2 m beds of broken shells (shell debris), characteristic of a high rate of sediment supply and a high-energy environment (Figueiredo et al. 1982). The interpreted environment of deposition is well within the known range of the mean storm wave base on the modern Manawatu coast (c. 40 m, Dunbar and Barrett, 2005). Wave energy has been shown through experimental work (Okusa 1985; Lindenberg et al. 1989; Sassa and Sekiguchi 2001) and field studies to be capable of producing similar structures (Seed & Rahman 1977; Dalrymple 1979; Alfaro et al. 2002). Therefore, we cannot conclusively rule out the possibility of loading from rapid deposition (Kerr and Eyles 1991; Hildebrandt and Egenhoff 2007) or storm wave-induced liquefaction (Molina et al. 1998; Alfaro et al. 2002; Mory et al. 2007) during formation of LZ2.

### LZ3

Toward the western basin margin at Kaimatira Bluff, we observe a prominent change in SSDS, associated with heterolithic facies of the Kaimatira Pumice Sand Formation. Cross-bedded, pebbly shell conglomerates occur as a series of gravel dunes or waves with intervening swale and interdune silts and muds (Figure 8). Seafloor instability is indicated by the SSDS, where progressive down slope deformation occurs along the margins of the swales (Figure 8). This suggests the interdune sediments behaved as fluid mud into which coarse-grained sands and granule material were able to sink, forming load and ball and pillow structures. Down slope, flow is indicated within the SSDS gradually decreasing toward the centre of the swale where the siltstone becomes structureless. We suggest paleoslope instability is related to and perhaps a control on the formation of LZ3.

We observe similar relationships within Kai Iwi Group strata exposed in the Rangitikei and Beaconsfield valleys where evidence of slope instability occurs together with load structures, convolute bedding and channels (Figure 6F). Slope instability appears to be particularly common within Kaimatira Pumice Sand Formation, suggesting increased sediment delivery to the coast following ignimbrite emplacement led to rapid deposition, loading and instability within the nearshore shelf environments of the WB.

### Seismicity

We examined our SSDS data against the widely accepted criteria for identifying a seismic trigger presented by Seilacher (1969), Sims (1973, 1975), Obermeier et al. (1990) and Obermeier (1996). Here, we review the criteria and examine our observations in relation to each criterion.

(1) SSDS occur within a seismically active area, including known faults distributed throughout the WB Castlecliffian outcrop belt (Beu et al. 1981; Pillans 1986, 1990b; Begg et al. 2005). Active faults include the Leedstown (Pillans 1990b), Galpin (Hellstrom 1993) and faults underlying the Halcombe Anticline (Melhuish et al. 1996). Major reverse faults, the Rangitikei and Rauoterangi faults (Figure 10) displace Plio-Pleistocene strata by up to 293 m (Feldmeyer et al. 1943; Naish and Kamp 1995). These faults are suggested to have been active through the Plio-Pleistocene, with a renewed phase of uplift occurring at c. 1 Ma, coinciding with a phase of volcanic activity within TVZ from 1.21 to 0.95 Ma (Briggs et al. 1993; Houghton et al. 1995; Krippner et al. 1998).

(2) The SSDS we describe are restricted to specific stratigraphic horizons and are interbedded between units that remain undeformed.

(3) SSDS can be traced over a wide lateral extent. In this paper, we present evidence of liquefaction that can be traced beneath correlatives of the Waitapu Shell Conglomerate for 16 km from Beaconsfield Valley to the Rangitikei Valley (Figure 1). Furthermore, the occurrence of SSDS can be traced more loosely within an intermittent zone from Pohangina Valley to Kaimatira Bluff in the Whanganui Valley, a distance of c. 70 km.

(4) The structures described here are similar to those produced experimentally under conditions of earthquake-induced shaking (Nichols et al. 1994; Owen 1996). They are also comparable to SSDS reported in the literature within areas of known seismic activity (Obermeier et al. 1987; Blanc et al. 1998; Matsuda 2000; Perucca et al. 2014) and modern-day features of liquefaction documented following seismic events in New Zealand (Reid et al. 2012; Villamor et al. 2016), Japan (Lin 1997; Ishihara et al. 2014) and Italy (Ninfo et al. 2012; Rodriguez-Pascua et al. 2015).

(5) There is evidence of an upward-directed strong hydraulic force that acted suddenly within LZ1, including multiple sites of injection. This sudden hydraulic force is also interpreted as having been brief, as it only affects a particular horizon, with overlying laminated to lenticular siltstone and sandstone remaining undisturbed.

(6) There is no evidence of artesian springs or groundwater movement within the succession. The rise and fall in sea level associated with mid-Pleistocene 100 ka cycles following the mid-Pleistocene transition (c. 950 ka) (Medina-Elizalde and Lea 2005) occur on a longer timescale and are unlikely to initiate soft sediment deformation. The SSDS described in this paper are considered to have formed almost instantaneously.

Given the evidence stated above, combined with records of coastal liquefaction from relatively recent earthquakes (1848 Marlborough, 1855 Wairarapa earthquake) within the Whanganui-Manawatu Region (Fairless and Berrill 1984), we suggest that LZ1 has been induced by seismic events associated with tectonic and volcanic activity within the central and lower North Island.

### *Loading, rapid deposition and slope failure*

There is evidence of slope failure within the Kai Iwi Group strata (Figures 6F and 8). The failures are particularly common toward the base of the group, likely related to an increased sedimentation rate following emplacement of the Cape Kidnappers and Rocky Hill ignimbrite sheets (c. 1 Ma) (Cooper et al. 2017). Sedimentary response to ignimbrite emplacement involves inundation of river and coastal settings, causing valley aggradation, river avulsion, infilling of coastal embayment's and coastal progradation (Manville and Wilson 2004; Kataoka 2011). A dramatic flood of volcaniclastic sediment entered the WB at c. 0.99 Ma (Potaka Pumice of Te Punga, 1952). This influx of volcaniclastic sediment forms one of the thickest TSTs documented within the WB (Pillans et al. 2005) and resulted in coastal progradation (Lewis 2007). We correlate the instability associated with LZ3 to this episode of increased sedimentation (Figures 2A and 3), characterised by an abundance of unstable, water-saturated sediment entering the WB, creating a hydraulically active seafloor environment (Abbott and Carter 1999).

Large-scale load structures (LZ3) and convolute bedding, in particular, are common along the margins of slope failures. Slope failure appears to exert a control on these structures and perhaps provide a triggering mechanism. Failure itself could be related to rapid deposition and resultant instability within a shallow marine environment. Indeed evidence of loading, associated with LZ3 would corroborate this. Initiation of slope failure by wave or earthquake-induced seismic activity is a possibility (Stigall and Dugan 2010), however, attribution of SSDS to seismicity relies on elimination of all other possible trigger mechanisms (Moretti and van Loon 2014) and is therefore unviable for LZ3.

## Conclusion

The Waitapu Shell Conglomerate is an important chronostratigraphic marker horizon in the eastern WB. We formally designate a type section at Waitapu Stream, Rangitikei Valley. The fossil assemblage contains a mixture of estuarine to offshore species including a component derived from underlying rocks. Deposition took place seaward of a transgressive shoreline on a storm-dominated, muddy, innermost shelf, characterised by migrating gravel dunes interfingering with deeper water heterolithic facies. The abundance of fresh pumice and charcoal indicates deposition closely followed a major TVZ eruption within a phase of renewed volcanic activity from the Mangakino Volcanic Centre at c. 0.9 Ma.

We infer the presence of a fluvial outlet in close proximity to the depositional site, with headwaters located in the present-day central North Island and paleo-axial range, supplying abundant greywacke and volcaniclastic detritus to the coast. This is consistent with lateral changes observed within the Waitapu Shell Conglomerate, as it grades into an eastern margin conglomerate facies, suggesting closer proximity to and influence from fluvial systems draining the uplifting paleo-axial range.

We interpret liquefaction to have occurred within LZ1 beneath the Waitapu Shell Conglomerate, resulting in settling and the occurrence of indistinct to massive bedding following re-distribution of grain-to-grain contacts. The overlying intensely convolute beds contain multiple injection sites attributed to successive fluidisation above the basal sandstone. We trace LZ1 east into Beaconsfield Valley and relate formation to earthquake-triggered seismicity, given an absence of load structures or signs of slope instability.

LZ2 occurs within a heterolithic succession typical of a high rate of sediment supply. The SSDS are truncated along their upper contact, suggesting they formed close to the sediment/water interface. The interpreted environment of deposition is within the known range of the mean storm wave base. A variety of possible trigger mechanisms are proposed, including rapid deposition, loading and storm wave-induced liquefaction.

The basal Kai Iwi Group contains common evidence for seafloor instability and associated soft sediment deformation (LZ3). We relate LZ3 to an increased sedimentation rate following emplacement of the Cape Kidnappers and Rocky Hill ignimbrite sheets (c. 1 Ma). Sedimentary response to ignimbrite emplacement involved inundation of river and coastal settings, causing valley aggradation, river avulsion, infilling and loading of the Whanganui coastal embayment and formation of a hydraulically active seafloor.

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## References

Abbott ST. 1992. The Mid Pleistocene Waiomio Shellbed New Zealand The Mid Pleistocene Waiomio Shellbed (Castleclif- fian, c . 550-600 ky), Wanganui Basin, New Zealand. Alcheringa: An Australasian Journal of Palaeontology. 16(2):171–180.

Abbott ST. 1994. Sequence Stratigraphy, Sedimentology and Paleoecology of Pleistocene Cyclothems in the Castlecliff Section, Wanganui Basin, New Zealand [unpublished PhD thesis]. Queensland: James Cook University of Northern Queensland. 297 p.

Abbott ST. 1997. Foraminiferal paleobathymetry and mid-cycle architecture of mid-pleistocene depositional sequences, Wanganui Basin, New Zealand. Palaios. 12 (3):267–281.

Abbott ST. 1998. Transgressive systems tracts and onlap shellbeds from mid-Pleistocene sequences, Wanganui Basin, New Zealand. Journal of Sedimentary Research. 68:253–268.

Abbott ST. 2000. Detached mud prism origin of highstand systems tracts from mid-Pleistocene sequences, Wanganui Basin, New Zealand. Sedimentology. 47 (1):15–29.

Abbott ST, Carter RM 1994. The sequence architecture of mid-Pleistocene (c. 1.1-0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea-level cyclicity. In: De Boer PL, Smith DG, editors. Orbital forcing and cyclic sequences, special publication of the International Association of Sedimentologists. Oxford: John Wiley & Sons; p. 367–394.

Abbott ST, Carter RM. 1999. Stratigraphy of the Castlecliffian type section: 10 mid-pleistocene sequences from the Wanganui coast, New Zealand. New Zealand Journal of Geology and Geophysics. 42(1):91–111.

Alessio G, Alfonsi L, Brunori CA, Burrato P, Casula G, Cinti FR, Civico R, Colini L, Cucci L, De Martini PM, et al. 2013. Liquefaction phenomena associated with the Emilia earthquake sequence of May-June 2012 (Northern Italy). Natural Hazards and Earth System Sciences 13: 935-947.

Alfaro P, Delgado J, Estevez A, Molina JM, Moretti M, Soria JM. 2002. Liquefaction and fluidization structures in Messinian storm deposits (Bajo Segura Basin. Betic Cordillera, southern Spain). Internation Journal of Earth Sciences. 91(3):505–513.

Allen JRL. 1977. The possible mechanics of convolute lamination in graded sand beds. Journal of the Geological Society, London. 134(1):19–31.

Allen JRL 1982. Sedimentary structures: their character and physical basis. New York: Elsevier.

Anderton PW. 1981. Structure and evolution of the South Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics. 24(1):39–63.

Bailey RA, Carr RG. 1994. Physical geology and eruptive history of the Matahina ignimbrite, Taupo volcanic Zone, North Island, New Zealand. New Zealand Journal of Geology and Geophysics. 37(3):319–344.

Bastin SH, Quigley MC, Bassett K. 2015. Paleoliquifaction in Christchurch. New Zealand Geological Society of America Bulletin. 127(9/10):1348–1365.

Begg JG, Palmer A, Gyopari M 2005. Geological synopsis of the Manawatu-Horowhenua area for a review of the region's hydrogeology. Institute of Geological and Nuclear Sciences Client Report 2005/172. 22 p.

Beu AG, Browne GH, Grant-Taylor TL. 1981. New *Chlamys delicatula* localities in the central North Island and uplift of the Ruahine range. New Zealand Journal of Geology and Geophysics. 24(1):127–132.

Blanc EJP, Blanc-Aletru MC, Mojon PO. 1998. Soft-sediment deformation structures interpreted as seismites in the uppermost Aptian to lowermost Albian transgressive deposits of the Chihuahua basin (Mexico). Geologische Rundschau. 86:875–883.

Bowen DQ, Pillans B, Sykes GA, Beu AG, Edwards AR, Kamp PJJ, Hull AG. 1998. Amino acid geochronology of Pleistocene marine sediments in the Wanganui Basin: a New Zealand framework for correlation and dating. Journal of the Geological Society. 155(3):439–446.

Brackley H. 1999. The Stratigraphy and Environments of Deposition of Early-Mid Pleistocene Sediments of the Pohangina Region, Eastern Wanganui Basin, New Zealand [unpublished MSc thesis]. Palmerston North: Massey University. 113 p.

Briggs RM, Houghton BF, McWilliams M, Wilson CJN. 2005. $^{40}Ar/^{39}Ar$ ages of silicic volcanic rocks in the Tauranga Kaimai area. New Zealand: Dating the transition between volcanism in the Coromandel Arc and the Taupo volcanic Zone. New Zealand Journal of Geology and Geophysics. 48(3):459–469.

Briggs RM, Gifford MG, Moyle AR, Taylor SR, Norman MD, Houghton BF, Wilson CJN. 1993. Geochemical zoning and eruptive mixing in ignimbrites from Mangakino volcano, Taupo volcanic zone, New Zealand. Journal of Volcanology and Geothermal Research. 56:175–203.

Bussell MR. 1984. Geology and Paleobotany of the Rangitawa Stream area, Southeast Wanganui Basin [unpublished thesis]. Wellington: Victoria University of Wellington. 181 p.

Carr RG 1984. The Matahina Ignimbrite: its evolution including its eruption and post depositional changes [unpublished PhD thesis]. Auckland: University of Auckland. 1–254 p.

Carter RM, Naish TR. 1998. A review of Wanganui Basin, New Zealand: Global reference section for shallow marine, Plio-Pleistocene (2.5-0 Ma) cyclostratigraphy. Sedimentary Geology 122(1–4): 37–52.

Carter RM, Abbott ST, Fulthorpe CS, Haywick DW, Henderson RA. 1991. Application of Global Sea - Level and Sequence - Stratigraphic Models in Southern Hemisphere Neogene Strata from New Zealand. Special Publication of the International Association of Sedimentologists (12): 41–65.

Collinson JD. 1996. Alluvial sediments. In: Reading HG, editor. Sedimentary environments: processes, facies and stratigraphy. Oxford: Blackwell; p. 37–82.

Cooper GF, Morgan DJ, Wilson CJN 2017. Rapid assembly and rejuvenation of a large silicic magmatic system: Insights from mineral diffusive profiles in the Kidnappers and Rocky Hill deposits, New Zealand. Earth and Planetary Science Letters 473: 1–13.

Cubrinovski M, Bray JD, Taylor M, Giorgini S, Bradley B, Wotherspoon L, Zupan J. 2011. Soil liquefaction Effects in the central Business District during the February 2011 Christchurch earthquake. Seismological Research Letters. 82(6):893–904.

Dalrymple RW. 1979. Wave-induced liquefaction: a modern example from the Bay of Fundy. Sedimentology. 26:835–844.

Davenport CA, Ringrose PS. 1987. Deformation of Sediments and Sedimentary Rocks. Geological Society, London, Special Publications 29: 299–314.

Dott RH, Bourgeois J. 1982. Hummocky stratification: Significance of its variable bedding sequences. Geological Society of America Bulletin. 93:663–680.

Duke WL, Arnott RWC, Cheel RJ. 1991. Shelf sandstones and hummocky cross-stratification: new insights on a stormy debate. Geology. 19:625–628.

Dunbar GB, Barrett PJ. 2005. Estimating palaeobathymetry of wave-graded continental shelves from sediment texture. Sedimentology. 52:253–269.

Eiby GA. 1968. A descriptive catalogue of New Zealand earthquakes. New Zealand Journal of Geology and Geophysics. 11(1):16–40.

Fairless GJ, Berrill JB. 1984. Liquefaction during historic earthquakes in New Zealand. Earthquake Engineering. 17(4):280–291.

Feldmeyer AE, Jones BC, Firth CW, Knight J. 1943. The geology of the Palmerston- Wanganui Basin, 'West side', North Island, New Zealand. Unpublished Report of the Superior Oil Company of New Zealand, Petroleum Report Series 171. Wellington: Ministry of Economic Development. 46 p.

Figueiredo AG, Sanders JE, Swift DJP. 1982. Storm-graded layers on inner continental shelves: Examples from southern Brazil and the Atlantic coast of the central United States. Sedimentary Geology. 31:171–190.

Fleming CA 1953. The geology of Wanganui subdivision. New Zealand Geological Survey Bulletin 52. 362 p.

Giona Bucci M, Villamor P, Almond P, Tuttle M, Stringer M, Ries W, Smith C, Hodge M, Watson M. 2018. Associations between sediment architecture and liquefaction suceptibility in fluvial settings: The 2010-2011 Canterbury earthquake sequence, New Zealand. Engineering Geology. 237:181–197.

Giona Bucci M, Almond P, Villamor P, Tuttle M, Stringer M, Smith C, Ries W, Bourgeois J, Loame R, Howarth J, et al. 2017. Which sedimentary environment best preserves paleoliquefaction features? PATA DAYS. 2017. 8th International Workshop on Paleoseismology, Active Tectonics and Archeoseismology, 13th – 16th November, Blenheim, New Zealand. p. 1–4.

Green RA, Cubrinovski M, Cox B, Wood C, Wotherspoon L, Bradley B, Maurer B. 2014. Select liquefaction case histories from the 2010-2011 Canterbury earthquake sequence. Earthquake Spectra. 30(1):131–153.

Green RA, Wood C, Cox B, Cubrinovski M, Wotherspoon L, Bradley B, Algie T, Allen J, Bradshaw A, Rix G. 2011. Use of DCP and SASW tests to evaluate liquefaction potential: predictions vs. observations during the recent New Zealand earthquakes. Seismological Research Letters. 82 (6):927–938.

Harms JC, Southard JB, Walker RG 1982. Structures and sequences in clastic rocks. Society of Economic Paleontologists and Mineralogists, Short Course No. 9: 1-249.

Hayward BW, Stilwell JD. 1995. Floating cockle shells (*Austrovenus stutchburyi*) – their significance to paleoenvironmental assessments. Tane. 35:143–148.

Hellstrom JC. 1993. An investigation of the Galpin Fault, Marton, Rangitikei [unpublished BSc (Hons) thesis]. Victoria University of Wellington. p. 89–89.

Hildebrandt C, Egenhoff S. 2007. Shallow-marine massive sandstone sheets as indicators of palaeoseismic liquefaction – an example from the Ordovician shelf of central Bolivia. Sedimentary Geology. 202:581–595.

Houghton BF, Wilson CJN, McWilliams MO, Lanphere MA, Weaver SD, Briggs RM, Pringles MS. 1995. Chronology and dynamics of a large silicic magmatic system: central Taupo volcanic Zone, New Zealand. Geology. 23(1): 13–16.

Idriss IM, Boulanger RW. 2008. Soil Liquefaction during Earthquakes. Monograph Series: Oakland, California. Earthquake Engineering Research Institute. 1–261.

Ishihara K, Araki K, Toshiyuki K 2014. Liquefaction in Tokyo bay and Kanto regions in the 2011 great east Japan earthquake. The 2011 Great East Japan Earthquake. Earthquake Geotechnical Engineering Design, Springer International Publishing. p. 93–140.

Jackson J, van Dissen R, Berryman KR. 1998. Tilting of active folds and faults in the Manawatu region, New Zealand: evidence from surface drainage patterns. New Zealand Journal of Geology and Geophysics. 41(4): 377–385.

Jarosewich E, Nelen JA, Norberg JA. 1980. Reference samples for electron microprobe analysis. Geostandards Newsletter. 4(1):43–47.

Jochum KP, Stoll B, Herwig K, Willbold M, Hofmann AW, Amini M, Aarburg S, Abouchami W, Hellebrand E, Mocek B, et al. 2006. MPI-DING reference glasses for in situ microanalysis: New reference values for element concentrations and isotope ratios. Geochemistry, Geophysics, Geosystems. 7(2):1–44.

Kataoka KS. 2011. Geomorphic and sedimentary evidence of a gigantic outburst flood from Towada caldera after the 15 ka Towada-Hachinohe ignimbrite eruption, northeast Japan. Geomorphology. 125:11–26.

Kerr M, Eyles N. 1991. Storm-deposited sandstones (tempestites) and related ichnofossils of the late Ordovician Georgian Bay formation, southern Ontario, Canada. Canadian Journal of Earth Science. 28:266–282.

Kershaw C. 1989. The geology of the area around Kaimatira Bluff, Wanganui, New Zealand [unpublished BSc (Hons) thesis]. Victoria University of Wellington.

Kleyburg MA, Moon VG, Lowe DJ, Nelson CS. 2015. Paleoliquefaction in Late Pleistocene alluvial sediments in Hauraki and Hamilton basins, and implications for paleoseismicity Proceedings of the 12th Australia New Zealand Conference on Geomechanics (ANZ 2015), 22-25 February 2015, Wellington. p. 524–531.

Krippner SJP, Briggs RM, Wilson CJN, Cole JW. 1998. Petrography and geochemistry of lithic fragments in ignimbrites from the Mangakino volcanic centre: implications for the composition of subvolcanic crust in western Taupo volcanic Zone, New Zealand. New Zealand Journal of Geology and Geophysics. 41(2):187–199.

Le Bot S, Trentsaux A. 2004. Types of internal structure and external morphology of submarine dunes under the influence of tide- and wind-driven processes (Dover Strait, northern France). Marine Geology. 211:143–168.

Lewis B. 2007. Eruptive Source and Depositional Characteristics of the Potaka Tephra, Wanganui Basin, New Zealand [unpublished thesis]. Dunedin: University of Otago. 304 p.

Lewis KB. 1971. Slumping on a continental slope inclined at 1°-4°. Sedimentology. 16:97–110.

Lewis KB, Carter L, Davey FJ. 1994. The opening of Cook Strait: interglacial tidal scour and aligning basins at a subduction to transform plate edge. Marine Geology. 116:293–312.

Lisiecki LE, Raymo ME. 2005. A Pliocene-pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography. 20(PA1003):1–17.

Lin A. 1997. Instantaneous-shaking liquefaction induced by the M7.2 1995 southern Hyogo Prefecture earthquake, Japan. Geology. 25(5):435–438.

Lindenberg J, van Rijn LC, Winterwerp JC. 1989. Some experiments on wave-induced liquefaction of soft cohesive soils. Journal of Coastal Research. 5 (Special Issue no (5): 127–137.

Lowe DR. 1976. Subaqueous liquefied and fluidized sediment flows and their deposits. Sedimentology. 23:285–308.

Manville V, Wilson CJN. 2004. The 26.5 ka Oruanui eruption, New Zealand: A review of the roles of volcanism and climate in the post-eruptive sedimentary response. New Zealand Journal of Geology and Geophysics. 47 (3):525–547.

Manville V, Newton EH, White JDL. 2005. Fluvial responses to volcanisim: resedimentation of the 1800a Taupo ignimbrite eruption in the Rangitaiki river catchment, North Island, New Zealand. Geomorphology. 65:49–70.

Matsuda J. 2000. Seismic deformation structures of the post-2300 a BP muddy sediments in Kawachi lowland plain, Osaka, Japan. Sedimentary Geology. 135:99–116.

Medina-Elizalde M, Lea DW. 2005. The mid-pleistocene transition in the tropical pacific. Science. 310:1009–1012.

Melhuish A, van Dissen R, Berryman KR. 1996. Mount Stewart-Halcombe Anticline: A look inside a growing fold in the Manawatu region, New Zealand. New Zealand Journal of Geology and Geophysics. 39:123–133.

Milne JDG. 1968. The geology and soils of the Apiti District [unpublished MSc thesis]. Wellington: Victoria Universtiy of Wellington. p. 1–122.

Milne JDG. 1973. Upper Quaternary geology of the Rangitikei drainage basin, North Island, New Zealand [unpublished PhD thesis]. Wellington: Victoria University of Wellington. p. 472–472.

Molina JM, Alfaro P, Moretti M, Soria JM. 1998. Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir Basin. Spain). Terra Nova. 10:145–150.

Moretti M, van Loon AJ. 2014. Restrictions to the application of 'diagnostic' criteria for recognizing ancient seismites. Journal of Palaeogeography. 3(2):162–173.

Mory M, Michallet H, Bonjean D, Piedra-Cueva I, Barnoud JM, Foray PB P. 2007. A field study of momentary liquefaction caused by waves around a coastal structure. Journal of Waterway, Port, Coastal, and Ocean Engineering. 133(1):28–38.

Naish TR, Kamp PJJ. 1995. Pliocene-Pleistocene marine cyclothems, Wanganui Basin, New Zealand: a lithostratigraphic framework. New Zealand Journal of Geology and Geophysics. 38:223–243.

Naish TR, Field BD, Zhu H, Melhuish A, Carter RM, Abbott ST, Edwards S, Alloway BV, Wilson GS, Niessen F, et al. 2005. Integrated outcrop, drill core, borehole and seismic stratigraphic architecture of a cyclothemic, shallow marine depositional system, Wanganui Basin, New Zealand. Journal of the Royal Society of New Zealand. 35(1–2):91–122.

Nichols RJ, Sparks RSJ, Wilson CJN. 1994. Experimental studies of the fluidization of layered sediments and the formation of fluid escape structures. Sedimentology. 41:233–253.

Ninfo A, Zizioli D, Meisina C, Castaldini D, Zucca F, Luzi L, De Amicis M. 2012. The survey and mapping of sand-boil landforms related to the Emilia 2012 earthquakes: preliminary results. Annals of Geophysics. 55(4): 735–742.

Obermeier SF. 1996. Use of liquefaction-induced features for paleoseismic analysis – an overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology. 44:1–76.

Obermeier SF, Weems RE, Jacobson RB. 1987. Earthquake-induced liquefaction features in the coastal South Carolina region. Department of the Interior. US Geological Survey Open File Report. 87–504. p. 480–493.

Obermeier SF, Jacobson RB, Smoot JP, Weems RE, Gohn GS, Monroe JE, Powars DS. 1990. Earthquake-induced liquefaction features in the coastal setting of South Carolina and in the fluvial setting of the New Madrid seismic zone. United States Geological Survey Professional Paper. 1504. pp. 1–44.

Okusa S. 1985. Wave-induced stresses in unsaturated submarine sediments. Geotechnique. 35(4):517–532.

Onorato MR, Perucca L, Coronato A, Rabassa J, Lopez R. 2016. Seismically-induced soft-sediment deformation structures associated with the Magallanes-Fagnano Fault System (Isla Grande de Tierra del Fugeo, Argentina). Sedimentary Geology. 344:135–144.

Owen G. 1996. Experimental soft-sediment deformation: structures formed by the liquefaction of unconsolidated sands and some ancient examples. Sedimentology. 43:279–293.

Owen G, Moretti M. 2011. Identifying triggers for liquefaction-induced soft-sediment deformation in sands. Sedimentary Geology. 235:141–147.

Perucca LP, Godoy E, Pantano A. 2014. Late Pleistocene-Holocene earthquake-induced slumps and soft-sediment deformation structures in the Acequion river valley, Central Precordillera, Argentina. Geologos. 20(2):147–156.

Pillans BJ. 1986. A late Quaternary uplift map for North Island, New Zealand. Royal Society of New Zealand Bulletin. 24:409–417.

Pillans BJ. 1990a. Pleistocene marine terraces in New Zealand: a review. New Zealand Journal of Geology and Geophysics. 33(2):219–231.

Pillans BJ 1990b. Vertical displacement rates on Quaternary faults, Wanganui basin. New Zealand Journal of Geology and Geophysics. 33(April 2015): 271–275.

Pillans BJ. 1994. Direct marine-terrestrial correlations, Wanganui Basin, New Zealand: The last 1 million years. Quaternary Science Reviews. 13(3):189–200.

Pillans BJ. 2017. Quaternary stratigraphy of Whanganui Basin – a globally significant archive. In: Schulmeister J, editor. Landscape and quaternary environmental change in New Zealand. Brisbane: Atlantis Press; p. 141–170.

Pillans BJ, Roberts AP, Wilson GS, Abbott ST, Alloway BV 1994. Mangnetostratigraphic, lithostratigraphic and tephrostratigraphic constraints on lower and middle pleistocene sea-level changes, Wanganui Basin, New Zealand. Earth and Planetary Science Letters 121:81–98.

Pillans BJ, Alloway B, Naish TR, Westgate J, Abbott S, Palmer AS. 2005. Silicic tephras in Pleistocene shallow-marine sediments of Wanganui Basin, New Zealand. Journal of the Royal Society of New Zealand. 35(1–2):43–90.

Piyasin S. 1966. Plio-pleistocene geology of the Woodville area [unpublished thesis]. Wellington: Victoria University of Wellington. 145 p.

Potter WD. 1984. Upper Quaternary Geology of part of the lower Rangitikei Valley. [unpublished thesis]. Wellington: Victoria University of Wellington. 84 p.

Quigley MC, Bastin SH, Bradley BA. 2013. Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. Geology. 41(4):419–422.

Rees CJ, Palmer JA, Palmer AS. 2018a. Plio-Pleistocene geology of the lower Pohangina Valley, New Zealand. New Zealand Journal of Geology and Geophysics. 61(1):44–63.

Rees CJ, Palmer JA, Palmer AS. 2018b. Quaternary sedimentology and tephrostratigraphy of the lower Pohangina Valley, New Zealand. New Zealand Journal of Geology and Geophysics. doi:10.1080/00288306.2018.1547321.

Rees CJ, Palmer JA, Palmer AS, Singh R. 2018c. Landscape evolution and hydrogeochemical characteristics of the Pourewa stream catchment, lower North Island, New Zealand. New Zealand Journal of Geology and Geophysics. doi:10.1080/00288306.2018.1541812.

Reid CM, Thompson NK, Irvine JRM, Laird TE. 2012. Sand volcanoes in the Avon-Heathcote Estuary produced by the 2010-2011 Christchurch earthquakes: implications for geological preservation and expression. New Zealand Journal of Geology and Geophysics. 55(3):249–254.

Rodriguez-Pascua MA, Silva PG, Lopez RP, Giner-Robles JL, Martin-Gonzalez F, Moral BD. 2015. Polygenetic sand volcanoes: On the features of liquefaction processes generated by a single event (2012 Emilia Romagna 5.9 Mw earthquake, Italy). Quaternary International. 357:329–335.

Sassa S, Sekiguchi H. 2001. Analysis of wave-induced liquefaction of sand beds. Geotechnique. 51(2):115–126.

Seed HB, Lee KL. 1966. Liquefaction of saturated sands during cyclic loading. Journal of the Soil Mechanics and Foundations Divsion. 92(6):105–134.

Seed HB, Rahman MS. 1977. Wave-induced pore pressure in relation to ocean floor stability of cohesionless soils. Marine Geotechnology. 3:123–150.

Seed HB, Idriss IM. 1982. Ground motions and soil liquefaction during earthquakes, monograph series: Berkeley, California. Earthquake Engineering Research Institute. 1–134.

Seilacher A. 1969. Fault-graded beds interpreted as seismites. Sedimentology. 13:15–159.

Seward D 1974. Some Aspects of Sedimentology of the Wanganui Basin, North Island, New Zealand [unpublished PhD thesis]. Wellington: Victoria University of Wellington. 285 p.

Seward D. 1976. Tephrostratigraphy of the marine sediments in the Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics. 19(1):9–20.

Shane PAR. 1991. Remobilised silicic tuffs in middle Pleistocene fluvial sediments, southern North Island, New Zealand. New Zealand Journal of Geology and Geophysics. 34(4):489–499.

Shane PAR. 1993. Tephrostratigraphy, magnetostratigraphy and geochronology of some early and middle Pleistocene deposits in New Zealand [unpublished thesis]. Victoria University of Wellington. 136 p.

Shane PAR. 1994. A widespread, early Pleistocene tephra (Potaka tephra, 1 Ma) in New Zealand: Character, distribution, and implications. New Zealand Journal of Geology and Geophysics. 37(1):25–35.

Sims JD. 1973. Earthquake-induced structures in sediments of Van Norman Lake, San Fernando, California. Science. 182(4108):161–163.

Sims JD. 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. Tectonophysics. 29:141–152.

Stern TA, Quinlan GM, Holt WE. 1992. Basin formation behind an active subduction zone: Three dimensional flexural modelling of Wanganui Basin, New Zealand. Basin Research. 4(3–4):197–214.

Stern TA, Quinlan GM, Holt WE. 1993. Crustal dynamics associated with the formation of Wanganui basin, New Zealand. In: Ballance PF, editor. South Pacific sedimentary basins. Sedimentary basins of the world 2. Amsterdam: Elsevier; p. 213–223.

Stigall J, Dugan B. 2010. Overpressure and earthquake initiated slope failure in the Ursa region, northern Gulf of Mexico. Journal of Geophysical Research. 115:1–11.

Strachan LJ. 2008. Flow transformations in slumps: a case study from the Waitemata basin, New Zealand. Sedimentology. 55:1311–1332.

Stratford WR, Stern TA. 2004. Strong seismic reflections and melts in the mantle of a continental back-arc basin. Geophysical Research Letters. 31(6):1–5.

Te Punga MT. 1952. The geology of Rangitikei Valley. New Zealand Geological Survey Memoir 8, Wellington, New Zealand. 46 p.

Te Punga MT 1957. Live anticlines in western Wellington. New Zealand Journal of Science and Technology 38: 43–466.

van der Neut M. 1996. Sequence stratigraphy of plio-pleistocene sediments in lower Turakina Valley, Wanganui Basin, New Zealand [unpublished MSc thesis]. p. 149–149.
Villamor P, Almond P, Tuttle MP, Giona-Bucci M, Langridge RM, Clark K, Ries W, Bastin SH, Eger A, Vandergoes M, et al. 2016. Liquefaction features produced by the 2010-2011 Canterbury earthquake sequence in Southwest Christchurch, New Zealand, and preliminary assessment of Paleoliquefaction features. Bulletin of the Seismological Society of America 106(4): 1–25.
Ward SD, Brown MKH, Brown IR, Larkin TJ. 2011. Geological engineering study of liquefaction after the 2010 Darfield earthquake in an area of complex fluvial geology. Proceedings of the Ninth Pacific Conference on Earthquake Engineering: Building an Earthquake-Resilient Society, Auckland, New Zealand 14-16 April 2011, Paper Number 053: p. 1–8.
Yasuda S, Harada K, Ishikawa K, Kanemaru Y. 2012. Characteristics of liquefaction in Tokyo Bay area by the 2011 Great East Japan earthquake. Soils and Foundations. 52(5):793–810.