

# A medial to distal volcanoclastic record of an andesite stratovolcano: detailed stratigraphy of the ring-plain succession of south-west Taranaki, New Zealand

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**Abstract** The >25 ka volcanoclastic ring-plain succession in south-west Taranaki has been remapped to establish a much more detailed understanding of the older stratigraphic record of Mt. Taranaki. Coastal cliff exposures show a range of volcanoclastic lithofacies, including debris-avalanche and lahar deposits, and allow a detailed chronological reconstruction of past volcanic and sedimentary events. Five new debris-avalanche deposits were identified, and their distribution in coastal cross-sections mapped. In addition, four previously described units were renamed and their stratigraphic position and lateral extent redefined. Chronostratigraphic control of the younger (<50 ka) sequence was obtained by radiocarbon dating of wood found within, or peat interbedded with, the deposits. Emplacement ages of the older units were estimated from their stratigraphic position and underlying marine wave-cut surfaces. Overall, at least 14 widespread debris-avalanche deposits occur within the <200 ka ring-plain record of Mt. Taranaki, suggesting one major edifice failure on average every 14,000 years, with an increase in frequency since 40 ka. The stratigraphic reconstruction of the ring-plain succession showed that the same pattern of deposition was repeatedly produced throughout the existence of Mt. Taranaki. Depending on their sedimentological characteristics, the different volcanic and sedimentary lithofacies can be related to phases of edifice-construction or collapse events. Based on the identified cyclic sedimentation pattern, we

present a new episodic stratigraphy that integrates existing and new lithostratigraphic units into a coherent chronostratigraphic framework that can be applied to the entire volcanic and volcanoclastic succession at Mt. Taranaki. This model takes into account the complex geological processes that have taken place on the volcano and provides a more uniform stratigraphic terminology that could be applied to repeatedly collapsing stratovolcanoes elsewhere.

**Keywords** Mt. Taranaki · Andesite stratovolcano · Volcanic stratigraphy · Ring-plain succession · Volcanoclastic · Debris-avalanche deposits

## Introduction

Ring-plain successions of stratovolcanoes provide a significant long-term record of past eruptive and sedimentary events that may not be preserved or exposed closer to source (e.g. Neall 1975; Smith 1987, 1988; Cronin and Neall 1997; Lecointre et al. 1998; Belousov et al. 1999; Davidson and De Silva 2000). Deposits recording these events can often be dated by applying the radiocarbon method to intercalated soil/peat layers and ripped-up fragments of wood, as well as by identifying interbedded tephra of known age. This provides the basis for a chronological reconstruction of volcano evolution and a stratigraphic overview of volcanoclastic successions.

Previous studies on and around Mt. Taranaki mainly focused on the younger volcanic history. Deposit sequences that built up the modern edifice and younger landscape-shaping parts of the volcanoclastic apron surrounding the volcano have been the key to understanding the last c. 26,000 years of volcanic activity (Neall 1979; Neall et al. 1986; Alloway et al. 1995, 2005; Procter 2009). Yet, little

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is known about the history prior to this, since older units are buried by tens to hundreds of metres of more recent volcanoclastic deposits. Due to the interplay of coastal erosion and tectonic uplift (Pillans 1990), older parts of the ring-plain succession are exposed in coastal cliffs in south-west and southern Taranaki with sedimentary records extending back to at least 100,000 years (Neall 1979; Palmer and Neall 1991). These were studied as part of a regional mapping project and later examined from a sedimentological perspective (Neall et al. 1986; Palmer and Neall 1991; Zernack et al. 2009), but no detailed stratigraphy was established. However, this information is needed in order to estimate recurrence times of volcanic events and provides the basis for developing more accurate probabilistic hazard forecasts.

In this paper, we present results from more detailed mapping of the coastal sections in south-west Taranaki and the developed stratigraphy of the older ring-plain succession. The detailed study of these sequences has enabled a comprehensive reconstruction of the earlier volcanic history of Mt. Taranaki and the establishment of a new chronostratigraphic framework for the entire volcanic succession.

### Stratigraphy of Mt. Taranaki

Volcanic activity at Mt. Taranaki began more than 130,000 years ago as indicated by some of the earliest identified volcanic products (Motunui Formation) that closely underlie the c. 127 ka NT2/Rapanui wave-cut surface (Alloway et al. 2005). The last known eruptions include the Taurangi eruption of AD1755 (Druce 1966) and emplacement of the summit dome, considered to have occurred around AD1800 (Platz 2007). The volcanic history has been characterised by alternating phases of edifice construction and collapse (Neall et al. 1986; Alloway 1989; Palmer and Neall 1991; Alloway et al. 2005; Zernack et al. 2009), which accumulated a thick volcanoclastic apron around the present stratovolcanic cone. Modern Mt. Taranaki is made up of lavas and pyroclastic deposits mostly younger than 10 ka. This 12-km<sup>3</sup> edifice represents only a small component of the total volume of material erupted compared with the c. 150-km<sup>3</sup> ring plain. The stratigraphy of the volcano has been subdivided into two separate groupings: the edifice-forming deposits and those of the ring-plain succession (Neall 1979; Neall et al. 1986; Alloway et al. 1995, 2005). These are summarised in the following sections.

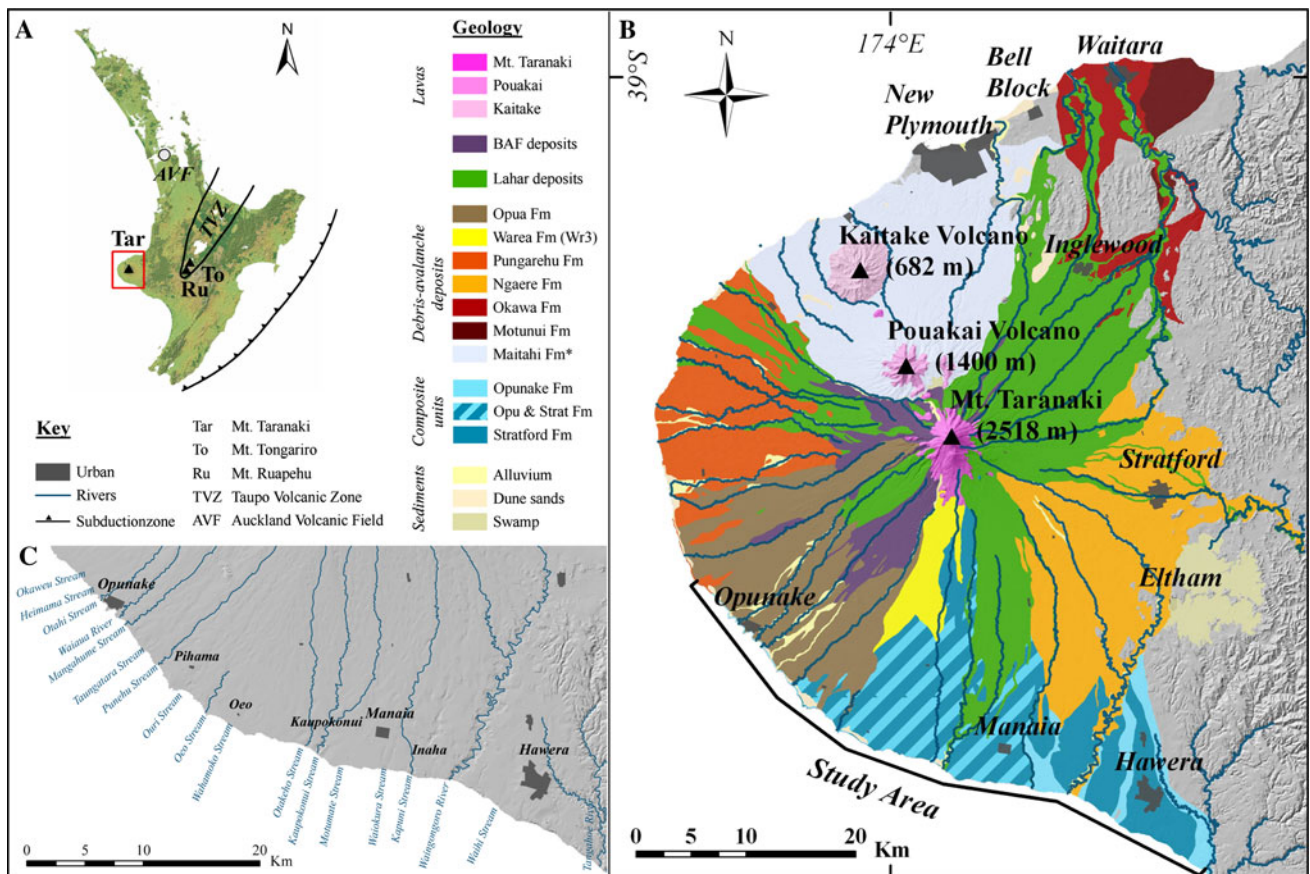
#### Ring-plain stratigraphy

Early studies and geological maps of Taranaki subdivided the apron of volcanoclastic material surrounding the

Taranaki volcanoes into several segments of different ages and origin based on geomorphological features and soil properties (Lensen 1959; Grant-Taylor 1964; Hay 1967; Grant-Taylor and Kear 1970). The formation of these so-called “ring-plains of laharic agglomerate” was thought to coincide with periods of Pleistocene glaciation, while the corresponding warm interglacial periods were marked by cutting of marine benches (Flemming 1953; Grant-Taylor 1964; Hay 1967). The absence of laharic breccias during interglacial intervals, i.e. periods of marine incursion, was explained by diminution of volcanic activity during warm climates (Grant-Taylor 1964). Five “ring-plains” were attributed to Kaitake and Pouakai Volcanoes and two younger ones to Mt. Taranaki; the “Stratford and Opunake lahars” (Hay 1967). No type sections of the Stratford and Opunake Formations were described and their upper and lower boundaries have never been defined. Instead, they were solely distinguished based on weathering differences and ash cover, i.e. >4 m and >1 m of ash, respectively (Grant-Taylor and Kear 1970).

Later mapping projects followed a more modern approach in reconstructing the volcanic history of the Taranaki peninsula. The former laharic “agglomerates” were interpreted as individual debris-avalanche deposits resulting from major collapses of past edifices. Studies by Neall (1979), Neall et al. (1986), Alloway (1989), Gaylord et al. (1993), Neall and Alloway (2004), Alloway et al. (2005) and Procter (2009) recognised and mapped the distribution of five debris-avalanche deposits from Mt. Taranaki (Motunui, Okawa, Ngaere, Pungarehu and Opu Formation) and one from Pouakai Volcano (Maitahi Formation). These re-defined or newly mapped formations mostly replace the older units (Fig. 1). Exceptions are the oldest surfaces of unknown age, which have not been studied in detail, and the volcanoclastic sequence in southwest and southeast Taranaki, where a thick soil and ash cover and the lack of distinct surface characteristics did not allow the detailed mapping of individual units.

Hence, while areas in western and eastern Taranaki previously mapped as Stratford and Opunake Formations have been redefined, these outdated composite units still make up the southern sector of the geological map (Neall and Alloway 2004). The main distribution of the Stratford Formation is to the east of Manaia, while the Opunake Formation covers the coastal areas from Opunake to Manaia. Both comprise similar lithofacies, i.e. laharic, debris-avalanche and alluvial deposits that accumulated between c. 80–50 ka and 38–30 ka, respectively (Grant-Taylor and Kear 1970; Neall 1979). Later studies of the south-western ring-plain described the occurrence of three debris-avalanche deposits within the Stratford Formation and one within the lahar-dominated Opunake Formation (Palmer and



**Fig. 1** a Overview map of the North Island, New Zealand and major late Quaternary volcanic areas, including the Taranaki peninsula. b Quaternary Geological Map of Taranaki showing the distribution of volcanic, volcanoclastic and sedimentary deposits (after Neall and

Alloway 2004) and the location of the study area. c Digital elevation model of the study area illustrating the location of towns, rivers and streams

Neall 1991; Palmer et al. 1991). More recently, Zernack et al. (2009) identified a total of 13 large debris-avalanche deposits within the <130 ka record of Mt. Taranaki as well as a wide spectrum of other volcanic mass-flow, fluvial and aeolian deposits. The existing lithofacies within the Mt. Taranaki ring-plain succession were interpreted to record repeated growth and collapse of the central edifice and used to develop a model for cyclic volcanoclastic sedimentation in the surrounds of long-lived andesitic stratovolcanoes.

#### Tephra and edifice stratigraphy

Mt. Taranaki has experienced frequent explosive pyroclastic eruptions, with most fall units distributed in a broad NNE to SSE sector from the present summit (Neall 1972; Alloway 1989; Alloway et al. 1995; Turner et al. 2009). The oldest tephra are best preserved in peat and carbon-rich sediments exposed along the northern coast, which provide a record of eruptive activity from >130 to 28 ka (Alloway 1989). Ring-plain records near the volcano are

largely buried or have been influenced by post-depositional mixing and weathering, thus only allowing a few of the most prominent tephra beds to be identified. The <28 ka record of eruptive activity is better preserved in the eastern and north-eastern ring plain and contains at least 75 individual tephra >10<sup>7</sup> m<sup>3</sup>, resulting in an average periodicity of one eruption of this magnitude approximately every 300–330 years (Alloway 1989; Alloway et al. 1995; Turner et al. 2009). In the younger past, subplinian eruptions produced several widespread tephra: the c. 4,100 years BP Korito Tephra, the c. 3,600 years BP Inglewood Tephra, the c. 1,400 years BP Kaupokonui Tephra and the Burrell Ash and Lapilli in AD1655 (Neall 1972; Alloway 1989; Neall et al. 1986; Alloway et al. 1995; Cronin et al. 2003; Platz 2007; Turner 2008).

Frequent effusive activity interspersed with dome-building episodes produced lava flows and dome-collapse block-and-ash-flows that built up the present-day edifice (Neall 1979; Neall et al. 1986; Platz 2007). In addition, debris-flow deposits were emplaced on the flanks of the volcano (Neall 1979; Neall et al. 1986; Alloway 1989).

The oldest recognised lava flows are the c. 8,000 years BP Warwicks lavas and the 7–3,300 years BP Peters Lavas (Stewart et al. 1996; Neall 2003). Several lava flows and tephra beds were erupted from the satellite vent “Fanthams Peak” between 3,300 and 2,800 years BP (Neall et al. 1986; Downey et al. 1994; Alloway et al. 1995; Turner et al. 2009), followed by the extrusion of four lava domes from subsidiary vents on the lower flanks of Mt. Taranaki (Neall 1971; Neall et al. 1986). The uppermost part of the modern edifice consists of the 1,700 years BP Staircase lavas and the youngest lava flows of the Skeet and Summit group (McGlone et al. 1988; Downey et al. 1994; Stewart et al. 1996; Neall 2003). The Tahurangi eruption in AD1755 was considered the last known eruptive activity at Mt. Taranaki (Druce 1966), until Platz (2007) suggested a later emplacement of the present summit dome around AD1800.

## Methods

### Stratigraphic correlation

A stratigraphic framework and chronology of debris-avalanche and lahar deposits of the south-western ring plain has been established from detailed field mapping. Radiocarbon ages obtained from wood found within, and peat interbedded with, the deposits, and identification of a rhyolitic tephra marker bed, provided timeframes and chronostratigraphic control of the younger sequence. The age of older units was estimated from their stratigraphic position in relation to mapped marine terraces as well as cover-bed stratigraphy and tephrochronology (cf. Pillans 1983; Neall et al. 1986; Alloway et al. 2005).

Remapping of the Opunake and Stratford Formations has focused on coastal cross-sections, which provide continuous lateral exposure. Field investigation started with the northernmost and youngest units of the exposed volcanoclastic succession north of Opunake and proceeded southwards to the oldest units near the Tangahoe River mouth, south of Hawera, where the volcanoclastic sequence pinches out (cf. Fig. 1).

Lahar (debris-flow to hyperconcentrated flow) deposits in Taranaki are superficially similar in lithology, texture and fabric (Zernack et al. 2009). This lack of individual diagnostic properties makes mapping and correlation of separate flow units difficult. To establish a stratigraphic overview and because of the large number and narrow distribution of single flow units, genetically related series of hyperconcentrated flow and debris-flow deposits were grouped into stratigraphic packages. Mapping was focused on the correlation of these deposit packages enclosed by distinctive marker horizons.

Identification and nomenclature of marker beds

Key units for correlation were as follows:

### *Widespread debris-avalanche deposits*

Debris avalanches at Mt. Taranaki spread out effectively without confinement on the gently dissected ring-plain, which resulted in the development of 3 lithofacies with distributions that differ from those of valley-confined examples. Axial-A facies is dominated by a hummocky surface expression with closely spaced, large mounds and a brecciated, clast-supported fabric with little sandy matrix. With distance from source, it grades into interclast matrix-rich axial-B facies, characterised by smaller, more widely spaced mounds, an increasing matrix-component, abundant megaclasts, jigsaw-cracked and shattered clasts as well as rip-up clasts (Neall 1979; Palmer and Neall, 1991; Palmer et al. 1991; Alloway et al. 2005; Zernack et al. 2009; Procter 2009). These two facies are attributed to the avalanche phase of the landslide and exhibit distinctive sedimentary and geomorphic features that have been used elsewhere to infer a debris-avalanche origin (e.g. Siebert 1984; Ui et al. 1986; Glicken 1991; Scott et al. 2001). Towards the margins, the deposits grade into thinner, matrix-supported cohesive debris-flow deposits that show a progressive decrease in primary clasts and an increase in secondary components and only scattered low mounds (marginal facies). Longitudinal facies transitions are best displayed by the largest known debris-avalanche deposit from Mt. Taranaki, the Pungarehu Formation, and the youngest example, the Opua Formation (Neall 1979; Ui et al. 1986; Procter 2009). In the studied coastal cross-sections, both units also show gradual, consistent lateral transitions between the thick axial-facies deposits that are interpreted to have been emplaced by debris avalanches and the thinner cohesive debris-flow deposits towards the margins that directly relate to them. While some of the marginal and distal units addressed here have some characteristics more closely associated with cohesive debris-flow deposits (e.g. their high content of clay-rich matrix and average thickness), they also show a clear gradual transition in structure and texture to the debris-avalanche deposits, including coherent lithological components such as megaclasts, jigsaw-cracked clasts and rip-up clasts (cf. Neall 1979; Palmer et al. 1991; Zernack et al. 2009; Procter 2009). Based on these observed field relationships, these units are interpreted to represent the direct distal (runout) and lateral (marginal) facies of a debris avalanche that originated from the failure of a proto-Mt. Taranaki edifice.

The longitudinal and lateral transformation of volcanic debris avalanches into long-runout cohesive debris flows at Mt. Taranaki and elsewhere has been mainly attributed to

the incorporation of water-saturated sediments and soils (e.g. Palmer et al. 1991; Vallance and Scott 1997; Scott et al. 2001). The matrix of Mt. Taranaki debris-avalanche deposits contains amorphous and crystalline clay particles and minerals, in particular allophane, a short-range-order clay mineral that forms by rapid weathering of andesitic ash under the humid-temperate climate conditions of Taranaki (Neall 1976; Parfitt et al. 1981; Alloway et al. 2005; Procter 2009). The dominance of allophane indicates that this matrix component was derived from (a) andic soils interbedded with the original edifice strata that collapsed to form the debris avalanche and (b) thick allophane-rich andic coverbeds on the ring plain that were eroded along the flow path and incorporated into the debris avalanche, rather than representing hydrothermally altered material at source or being the product of post-emplacement diagenesis (Neall 1976; Alloway et al. 2005). The known thixotropic properties of allophane and its high capacity for water storage most likely engendered the extremely high mobility for Mt. Taranaki debris avalanches.

Debris-avalanche deposits occur abundantly in the Taranaki ring-plain succession and are easily recognised due to their distinctive sedimentological characteristics. The considerable thickness (typically between 0.5–6 m) of the deposits in combination with a wide, continuous lateral distribution makes them the most useful and reliable markers for correlation of the volcanoclastic sequences.

#### *Continuous paleosols and peat layers*

Paleosols and peat layers represent long hiatuses in volcanoclastic deposition, are typically thin (5–20 cm), and of limited lateral extent, which makes them inadequate for correlation. Some paleosols of greater thickness can be

traced for several hundreds of metres in lateral exposure and rarely up to several kilometres, thus allowing some correlation of the over- and underlying deposits. Neall (1972, 1979) recognised two distinct tephric soils in the younger succession of western Taranaki that were named after interbedded tephra layers; the 16,100 years BP “Okato Tephra” separating the Pungarehu from the overlying Warea Formation and the 6,970 years BP “Oakura Tephra” interbedded between the Warea and Opuwa Formations. Two thick peat/organic paleosol sequences are relatively widespread in the study area and could easily be identified in numerous locations, despite their variable thickness. The younger peat sequence is thickest in the Opunake area, but a correlative was also recognised in sections near Manaia. It is here named Hihiwera Peat after Hihiwera Stream, and its uppermost layer was dated at c.  $28,824 \pm 237$  years BP (Table 1). Previous workers obtained several radiocarbon dates of this significant deposit at various locations, giving an age range of 30–34,400 years BP (Grant-Taylor and Rafter 1963a, b; Grant-Taylor 1964; McGlone et al. 1984; cf. Table 1). A second prominent organic paleosol represents an important marker within the oldest parts of the succession. It is exposed near the bottom of the cliff sections for c. 6 km near Oeo. It is characterised by the preservation of tree stumps in growth position at its top and hence referred to as Puketapu buried forest. It is here assumed to be of similar age to the “Manaia Lignite”, which occurs over a coastal stretch of 2.5 km near Manaia and is believed to have formed around 80 ka during MISS 5a (McGlone et al. 1984).

#### *Rhyolitic tephra derived from the Taupo Volcanic Zone*

Four prominent rhyolitic tephtras have been found in Taranaki (Wellman 1962; Aitken 1978; Stewart et al. 1977; Geddes

**Table 1** Radiocarbon and amino acid racemisation dates of important peat deposits

| Laboratory number             | $^{14}\text{C}$ age (years BP) | Cal. age (ka)      | Stratigraphic unit     | Sample location <sup>a</sup> |
|-------------------------------|--------------------------------|--------------------|------------------------|------------------------------|
| Wk-19143 <sup>b</sup>         | $28,824 \pm 237$               | $34,227 \pm 283$   | Hihiwera Peat (top)    | 2583809E 6193200N            |
| NZ331 <sup>c</sup>            | $34,400 \pm 1,500$             | $39,735 \pm 1,443$ | Hihiwera Peat          | 2583440E 6193829N            |
| NZ409 <sup>d</sup>            | $31,800 \pm 1,800$             | $37,180 \pm 1,797$ | Hihiwera Peat          | 2583748E 6193347N            |
| BJP-015/ANU-1887 <sup>e</sup> | $33,300 \pm 1,100$             | $38,679 \pm 1,097$ | Hihiwera Peat          | 2610466E 6179350N            |
| BJP-014 <sup>f</sup>          | $30,000 \pm 20,000$            | Out of range       | Hihiwera Peat          | 2610466E 6179350N            |
| Wk-19144 <sup>b</sup>         | Background                     | Out of range       | Puketapu buried forest | 2592199E 6184736N            |
| BJP-010 <sup>f</sup>          | $95,000 \pm 20,000$            | Out of range       | Manaia lignite         | 2610466E 6179350N            |

<sup>14</sup>C ages converted to calendar ages using the Fairbanks et al. (2005) calibration curve

<sup>a</sup> Sample locations grid reference in NZ Map Grid Coordinates; radiocarbon dates

<sup>b</sup> This study ( $t_{1/2} = 5,568$  years)

<sup>c</sup> Grant-Taylor and Rafter (1963a, b)

<sup>d</sup> Grant-Taylor (1964)

<sup>e</sup> McGlone et al. (1984)

<sup>f</sup> Amino acid racemisation dates McGlone et al. (1984)

et al. 1981; Alloway 1989; Alloway et al. 1994, 1995, 2005): the c. 4,000 years BP Stent Tephra, the c. 22,590 years BP Kawakawa Tephra/Aokautere Ash, the c. 45–55,000 years BP Rotoehu Tephra and the c. 350–400 ka Rangitawa Tephra. In this study, only the Kawakawa Tephra was identified at several coastal locations in western Taranaki, where it occurs as discontinuous 1- to 3-cm-thick yellow pods of ash within a prominent laminated soil below the Pungarehu Formation.

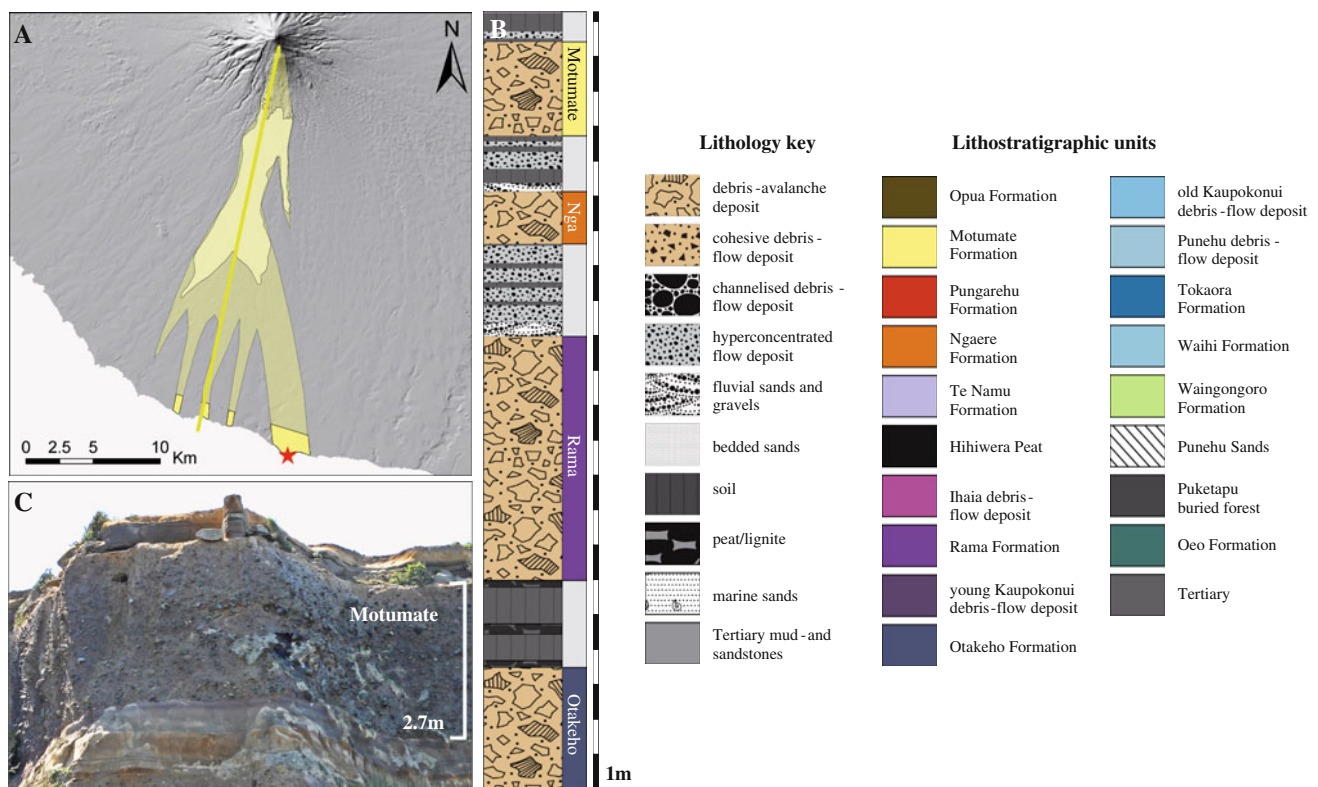
#### Widespread dune sands

A 10-m-thick sequence of well-sorted, cross-stratified dune sands occurs in the older part of the south-western ring-plain succession over a broad stretch of coastline (>15 km). The paleo-dunes typically occur below the Otakeho debris-avalanche deposit to c. 1.4 m below the Puketapu buried forest and are here named Punehu Sands after Punehu Stream. Such an incursion of sand dunes is likely to have been triggered by one of the higher sea-level stands of the post-Rapanui succession. Based on their stratigraphic position, the dune sands are most likely associated with cutting of the c. 80 ka Hauriri marine bench (cf. Pillans 1983), consequently their accumulation age is estimated at c. 60–80 ka.

## New or redefined debris-avalanche deposits

### Motumate Formation (redefined unit)

The Motumate debris-avalanche deposit is named after Motumate Stream in south Taranaki. The unit occurs in discontinuous exposures over a c. 10.8 km stretch of coastline between Oeo and Waiokura Streams (Fig. 2a; cf. Fig. 1b). At its type locality, the deposit forms a prominent c. 3.5-m-thick, massive layer near the top of the cliff section. Here, it is characterised by pebble- to cobble-sized, poly-lithologic clasts and small, rounded rip-up clasts in a clay-rich matrix (Fig. 2c). Its upper and basal contacts are planar with no evidence for erosion. It is bracketed by two thin paleosols and overlain by a thin hyperconcentrated flow deposit and thick soil (Fig. 2b). Two hyperconcentrated flow deposits and fluvial sediment with interbedded paleosols occur directly below the unit. Near the type locality, the Motumate Formation can be traced over c. 1.8 km, but rapidly thins to either side from 3.5 m to c. 0.8 m, suggesting that it was deposited in a relatively deep paleo-channel. The Motumate debris-avalanche deposit was also identified in three channels west of the type section, where it is characterised by fewer, pebble- to small cobble-sized clasts in >90% matrix and ranges in thickness from c. 0.3–1 m.



**Fig. 2** a Coastal extent, extrapolated distribution, dispersal axis and type section (red star) of the Motumate debris-avalanche deposit in comparison to the Wr3 lobe of Neall (1979, 2003) in bright yellow.

**b** Stratigraphy of the Motumate type section, where the deposit is characterised by coarse clasts in a clay-rich matrix (**c**)

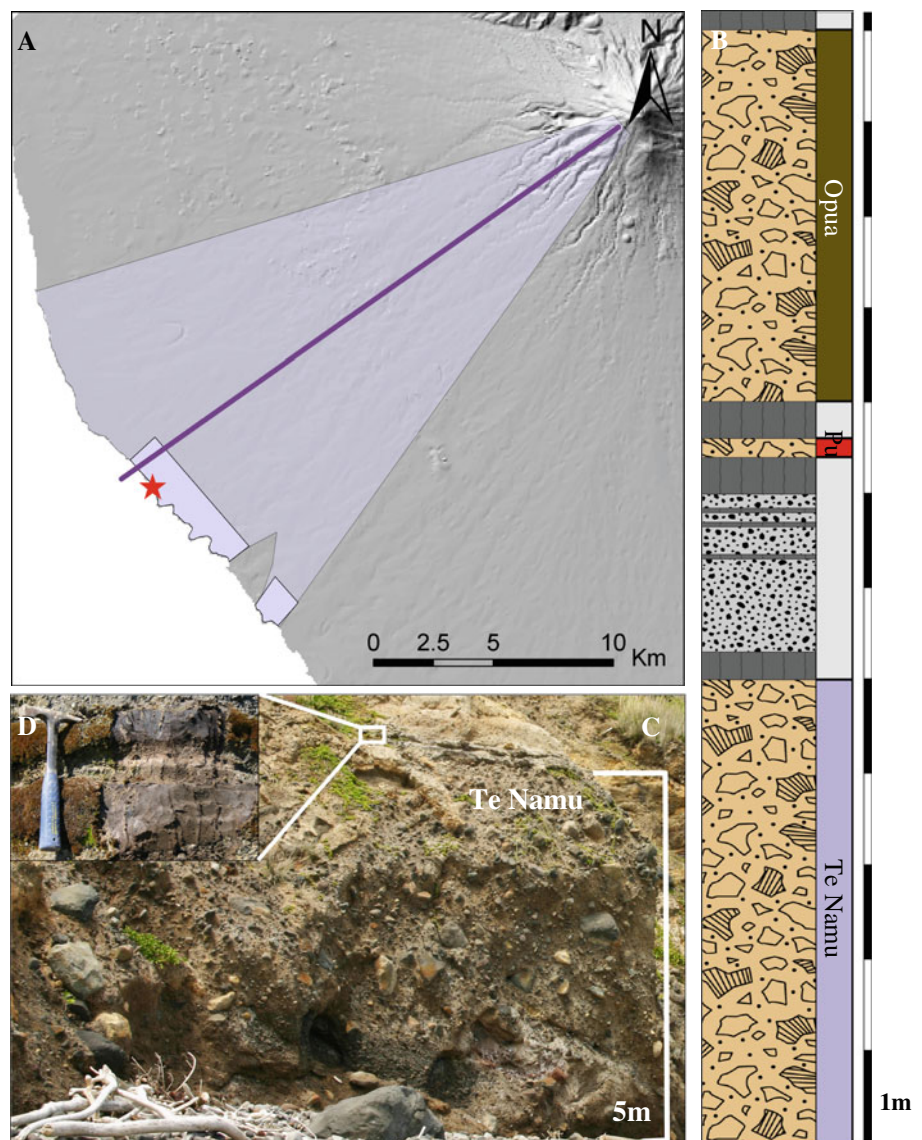
The lenticular deposit geometry, minor thickness and narrow distribution range of the Motumate deposit in coastal locations indicate deposition from a relatively small debris avalanche, which was confined to paleo-channels in these medial areas. Due to its stratigraphic position, distribution and sedimentary characteristics, the Motumate debris-avalanche deposit is here correlated to the southern lobe of the Warea Formation (Wr3) of Neall (1979). The Wr3 unit is c. 5 km wide and >3 m thick at 350 m asl but bifurcates into two <2-m-thick lobes along Oeo and Otakeho Streams below 240 m asl (Neall 1979). Between 450 and 250 m, <5-m-high mounds occur that become progressively smaller to the south along Oeo Stream and are absent where the deposit thins to <2 m. The distribution of the Motumate debris-avalanche deposit in coastal locations is consistent with an inferred origin from the Wr3 lobe (cf. Fig. 2a). The age of the Motumate Formation is

constrained via its correlative, the Warea Formation, which is bracketed between the c. 19.2 ka Okato Tephra and the c. 7.8 ka Oakura Tephra (Neall 1979) and is here estimated to have been emplaced at c. 12–14 ka.

Te Namu Formation (new unit)

The Te Namu debris-avalanche deposit is a formerly unknown unit named after Te Namu Pa in south-west Taranaki that first crops out east of Okaweu Stream at the bottom of the sequence. It forms a distinct unit from this outcrop to Opunake and was also identified between Waiteika and Ponehu Streams over at least 8.8 km of lateral exposure (Fig. 3a) and inland, c. 0.8 km up Waiaua Stream. Its extent further north is unknown since the sequence dips under the present-day sea level, but the deposit most likely continues for at least the same lateral distance as was observed south-eastwards.

**Fig. 3** **a** Map of the coastal extent, extrapolated distribution, dispersal axis and the location of the type section of the Te Namu Formation. **b** Stratigraphy of the Te Namu type section. **c** Here, the deposit contains coarse clasts as well as abundant rip-up clasts in a clay-rich matrix and is overlain by two distinct organic paleosols interbedded with andesitic tephra beds and a pale pink silt layer (**d**)



At its type locality, the Te Namu Formation is >5-m-thick and characterised by pebble- to boulder-sized clasts and abundant large rip-up clasts up to 1.5 m across (often consisting of an underlying peat/soil layer, possibly the Hihiwera Peat) in a clay-rich matrix (Fig. 3c). It is overlain by a distinct soil sequence consisting of two dark organic paleosols that are separated by two andesitic tephra beds and an interbedded pale pink silt layer (Fig. 3d). Above the soil, four hyperconcentrated flow deposits are exposed, separated by thin paleosols, and the sequence below the Te Namu is not exposed (Fig. 3b). Northwest of the type section, hyperconcentrated flow deposits and cross-bedded fluvial sands separate the Te Namu from the Opuia and Pungarehu Formations and the Kawakawa Tephra in the soil sequence below the Pungarehu.

A minimum emplacement age of  $25,198 \pm 167$  years BP (Wk-16401) was obtained from a sample of the paleosol overlying the Te Namu debris-avalanche deposit (Table 2). Near Opuake, the strata below the Te Namu are exposed and consist of several thin hyperconcentrated flow deposits, cross-bedded fluvial pebbly sands and an intercalated normal to reverse-graded transitional debris-flow/hyperconcentrated flow deposit. A piece of ripped-up wood from within the Te Namu debris-avalanche deposit collected here gave a maximum age of  $29,074 \pm 399$  years BP (Wk-16402), resulting in an emplacement age of c. 30.3–34.5 ka.

#### Ihaia debris-flow deposit (new unit)

A cohesive debris-flow or runout debris-avalanche deposit (Ihaia) is exposed below the Hihiwera Peat, over c. 3.2 km northwest of Opuake (Fig. 4a). At most outcrops, the deposit is c. 1 m thick, and up to 1.6 m at its type locality, where it is characterised by predominantly pebble-sized clasts and abundant pieces of wood in a clay-rich matrix (Fig. 4c). Its base is marked by a thin layer with coarser

cobble-sized clasts. A piece of wood from within the deposit at this location was dated at  $31,522 \pm 381$  BP (Wk-19142; cf. Table 2) equivalent to 36.9 ka calibrated date, which fits well with the age of the directly overlying Hihiwera Peat (c. 34.4 ka). The deposit occurs near the bottom of the section and is underlain by fine-grained pumice-rich hyperconcentrated flow deposits (Fig. 4b).

It was most likely produced by a small debris avalanche that post-dated the Rama event and was roughly confined to the Opuake paleo-river system, which is located between Heimama and Waiau Streams and was active from >34 to c. 14 ka. Though unlikely, it cannot be ruled out that the debris-flow deposit represents a marginal correlative of the Rama debris-avalanche deposit. Hence, it is here only informally named Ihaia debris-flow deposit after Ihaia Road that runs roughly parallel to its interpreted dispersal axis.

#### Rama Formation (redefined unit)

The Rama debris-avalanche deposit represents the most prominent unit within the former Stratford Formation and was described by Neall et al. (1986) and Neall (2003) as a c. 50,000 year-old debris-avalanche deposit with a minimum thickness of 10 m and a minimum volume of  $1.5 \text{ km}^3$ . Later studies by Palmer and Neall (1991) and Palmer et al. (1991) referred to the deposit as Stratford Formation debris avalanche 1 with an inferred age of 48,000 years, a maximum observed thickness of 17 m, volume of  $2.6 \text{ km}^3$  and covering an area of  $510 \text{ km}^2$ . Its described lateral extent of 32.1 km (Palmer et al. 1991) is similar to the data presented here. Redefining this debris-avalanche deposit was necessary to emphasise its distinct and mappable character and to replace the Stratford Formation with a more rigorous stratigraphic subdivision. It was named after Rama Road near Manaia township, which runs roughly parallel to its interpreted dispersal axis.

**Table 2** Radiocarbon analytical data of selected Mt. Taranaki debris-avalanche deposits (DAD)

| Debris-avalanche unit | Laboratory number  | Analysis method <sup>a</sup> | Sample type, stratigraphic position | Sample location <sup>b</sup> | Radiocarbon dates (years BP) | Calibrated ages <sup>c</sup> (cal years BP) |
|-----------------------|--------------------|------------------------------|-------------------------------------|------------------------------|------------------------------|---|
| Pungarehu DAD         | Wk-16398/NZA-22349 | AMS                          | Peat directly below DAD             | 2580818E 6196883N            | $20,776 \pm 170$             | $24,801 \pm 268$                            |
| Te Namu DAD           | Wk-16401           | LSC                          | Organic soil above DAD              | 2580818E 6196883N            | $25,198 \pm 167$             | $30,326 \pm 251$                            |
|                       | Wk-16402/NZA-22895 | AMS                          | Tree log within DAD                 | 2582262E 6195044N            | $29,074 \pm 399$             | $34,484 \pm 434$                            |
| Ihaia DAD             | Wk-19142           | LSC                          | Wood within DAD                     | 2583439E 6193828N            | $31,522 \pm 381$             | $36,896 \pm 417$                            |
| Rama DAD              | Wk-19143           | LSC                          | Thick peat above DAD                | 2583809E 6193200N            | $28,824 \pm 237$             | $34,227 \pm 283$                            |
| Otakeho DAD           | Wk-19140           | LSC                          | Wood within DAD                     | 2602116E 6180599N            | Background                   | >50   |
| Waihi DAD             | Wk-19141           | LSC                          | Large log within DAD                | 2612625E 6179170N            | Background                   | >50   |

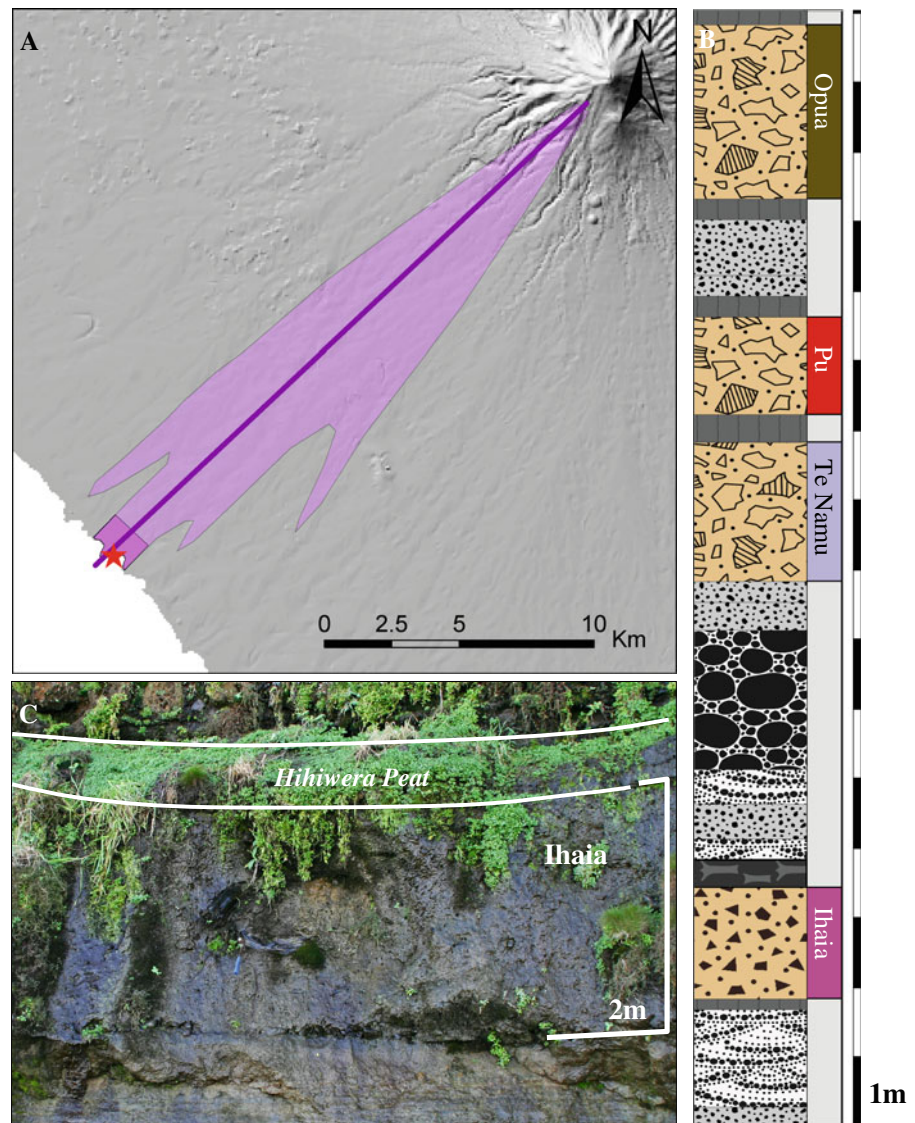
<sup>a</sup> AMS accelerator mass spectrometry, LSC liquid scintillation counting. Dated by the Waikato Radiocarbon Dating Laboratory, based on Libby half-life ( $t_{1/2} = 5,568$  years)

<sup>b</sup> Sample locations grid reference in NZ Map Grid Coordinates

<sup>c</sup> Conversion of radiocarbon ages to calendar ages after Fairbanks et al. (2005)



**Fig. 4** **a** Map displaying the type section and inferred distribution of the Ihaia debris-flow/debris-avalanche deposit along the paleo-Opunake river system. **b** Stratigraphy of the Ihaia type section, where the deposit is directly overlain by the Hihiwera Peat and consists of >90% matrix with few clasts and abundant pieces of wood (**c**)



In this study, the Rama Formation was correlated over a c. 25.5 km long stretch of coastline in southwest Taranaki (Fig. 5a). At its type section, the deposit is c. 5.5 m thick and characterised by pebble- to cobble- and few boulder-sized clasts and rip-up clasts in a clay-rich matrix (Fig. 5c). It also contains large brecciated megaclasts up to 5.5 m across, which are common at several locations. The Rama overlies the Otakeho Formation (Fig. 5b), and the sequence above consists of a series of at least 9 hyperconcentrated flow deposits with interbedded paleosols.

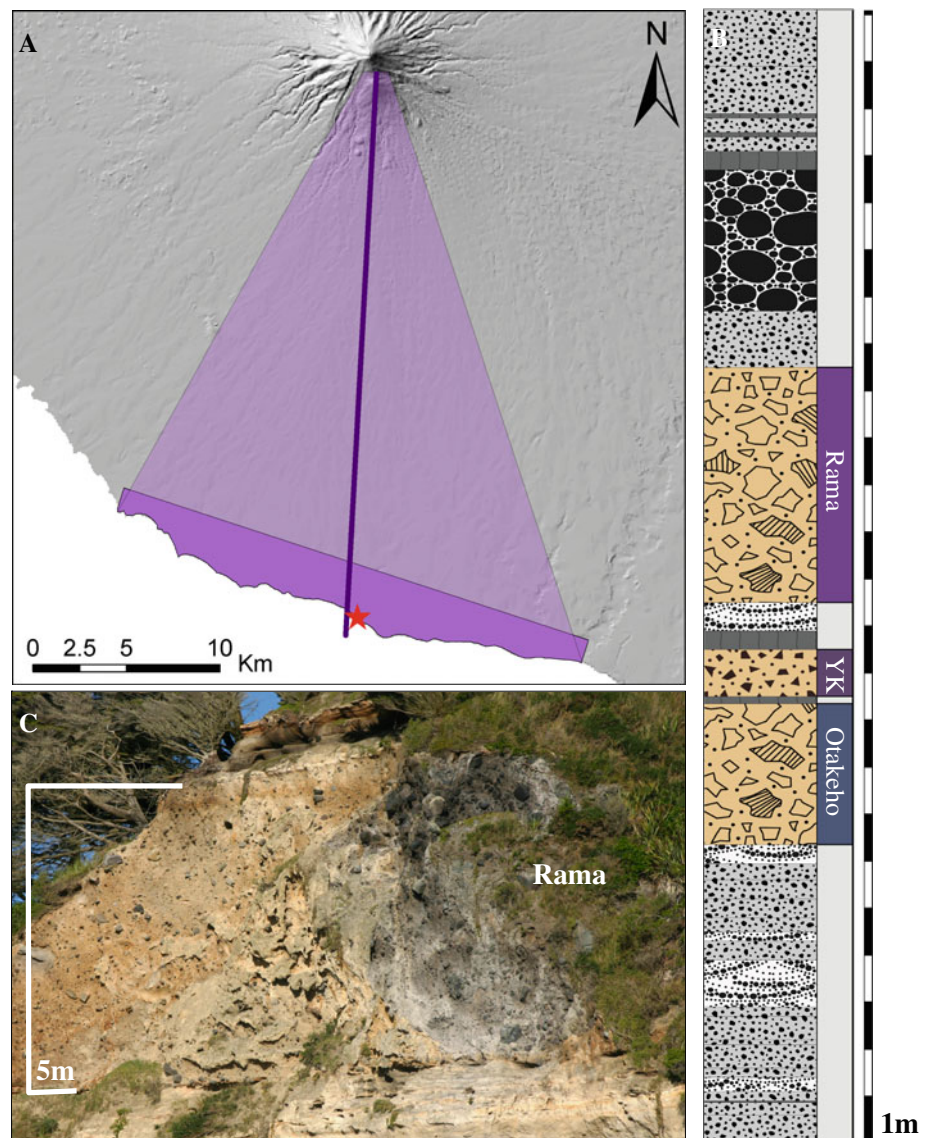
At the Inaha Section of McGlone et al. (1984), near Manaia, the Rama debris-avalanche deposit forms a massive c. 8-m-thick marker unit near the top of the cliff with similar sedimentological characteristics to its type section. Fine-grained hyperconcentrated flow deposits, fluvial sands and interbedded peat layers occur between the Rama Formation and the Inaha marine bench, cut into the Tertiary mudstone sequence at the bottom of the cliff. The Rama is

directly overlain by a prominent c. 0.8- to 1-m thick peat sequence, which is here correlated with the Hihiwera Peat. A radiocarbon date of c. 33,300 years BP (ANU-1887, McGlone et al. 1984; cf. Table 1) gives a minimum age of c. 40 ka for the Rama Formation. Its maximum observed deposit thickness of 12 m suggests that the Rama is one of the most voluminous debris-avalanche deposits of the southern ring-plain succession.

#### Young Kaupokonui debris-flow deposit (redefined unit)

A clay matrix-rich debris-flow deposit is exposed below the Rama Formation at Kaupokonui Stream. It was referred to as Stratford Formation 2 by Palmer et al. (1991) and described as having a maximum thickness of 1.5 m, a maximum width of 10.7 km, covering an area of 90 km<sup>2</sup> with a volume of 0.1 km<sup>3</sup>. Palmer and Neall (1991) attributed this “muddy diamicton” to a small debris

**Fig. 5** **a** Coastal extent, extrapolated inland distribution, dispersal axis and location of the type section of the Rama Formation. **b** Stratigraphy of the Rama type section, where the deposit is characterised by coarse clasts, few small rip-up clasts and a large brecciated megaclast in a clay-rich matrix **(c)**



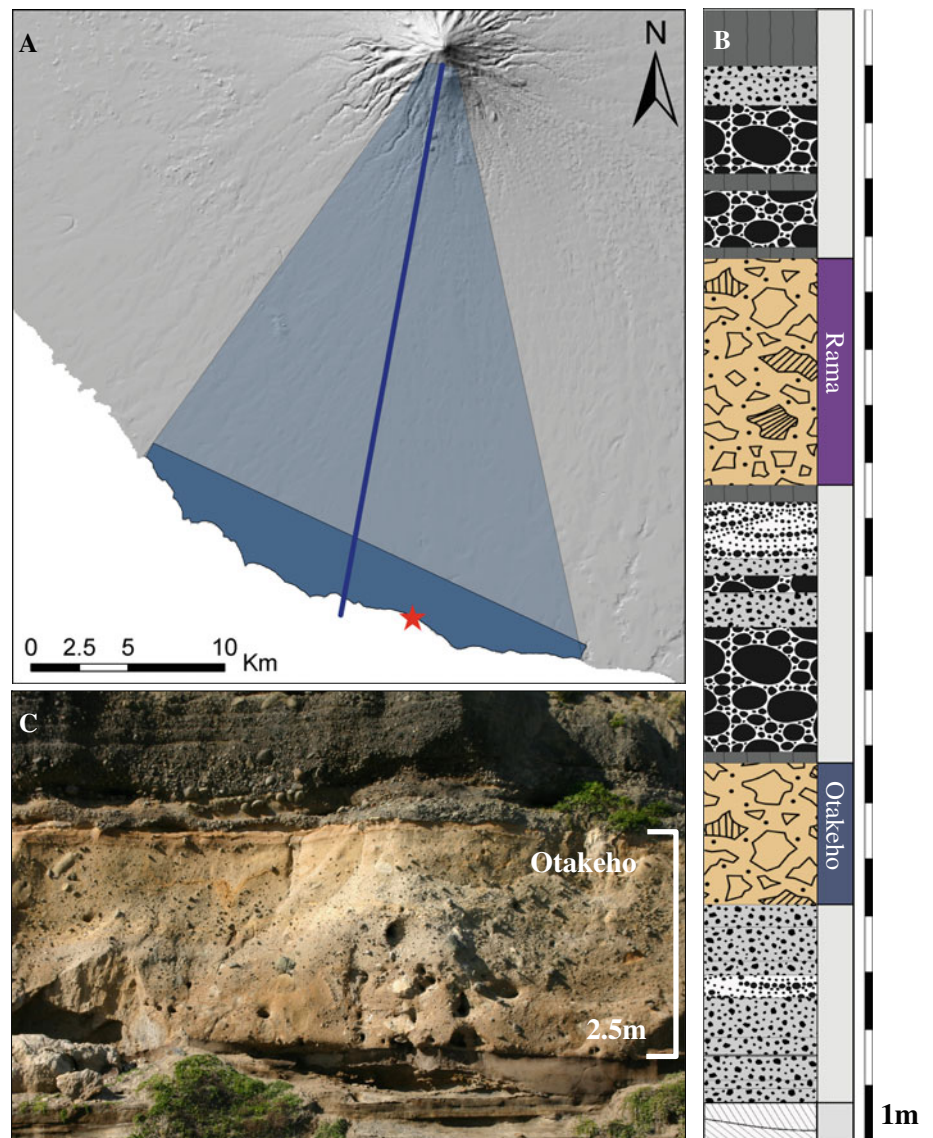
avalanche that was channelled down the Kaupokonui and Waingongoro catchments. In this study, the debris-flow deposit could not be correlated with units that occur along the Waingongoro River but was only mapped over c. 1 km south-east of Kaupokonui Stream.

It is very matrix-rich and contains mainly pebble- and few cobble-sized clasts, which are mostly concentrated near the base of the deposit, giving it a normally graded appearance. It has a maximum thickness of c. 1.3 m but rapidly wedges out. It was most likely deposited from the distal portions of a small debris avalanche or small collapse-generated debris flow that was confined to a paleo-Kaupokonui Stream. Due to its localised distribution and minor importance, the debris-flow deposit has not been formally named. It was emplaced between 40 and 55 ka as indicated by its stratigraphic position between the Rama and Otakeho debris-avalanche deposits.

Otakeho Formation (redefined unit)

A second prominent debris-avalanche deposit was recognised within the Stratford Formation and referred to as Stratford Formation debris avalanche 3 (Palmer and Neall 1991; Palmer et al. 1991). This deposit was described as being c. 80,000 years old, with a maximum thickness of 6 m, 32.1 km lateral width and a volume of  $>1 \text{ km}^3$ , covering an area of  $370 \text{ km}^2$  (Palmer et al. 1991). The unit is here named Otakeho Formation after Otakeho Stream in south Taranaki. It was mapped over c. 24.5 km along the south-western Taranaki coastline (Fig. 6a). At its type section, the Otakeho debris-avalanche deposit is c. 2.5 m thick, massive and contains pebble- to cobble-sized clasts and small rip-up clasts in a clay-rich matrix (Fig. 6c). Coarser clasts are rare and the matrix makes up  $>85\%$  of the deposit (cf. “cohesive-type debris avalanche

**Fig. 6** **a** Mapped coastal extent, inferred distribution and dispersal axis of the Otakeho Formation, similar to the Rama debris-avalanche deposit. **b** Stratigraphy of the type section for the Otakeho Formation. **c** Here, the deposit is characterised by >85% clay-rich matrix with medium-coarse clasts and few small rip-up clasts



deposit”, Zernack et al. 2009). At this locality, abundant large holes represent tree casts, but the deposit contains only small, scattered pieces of wood. The bottom half of the Otakeho has a greenish colour in contrast to the more yellow-brownish top, which probably represents an oxidation/reduction effect and marks the position of the top of the summer groundwater table. A thin soil has developed into the top of the Otakeho, which is separated from the overlying Rama debris-avalanche deposit by a series of thick, coarse, channelised hyperconcentrated flow deposits that grade into finer-grained hyperconcentrated flow deposits and fluvial sediments (Fig. 6b). Here, the sequence below the Otakeho is made up of thin hyperconcentrated flow deposits and intercalated fluvial sands. Cross-bedded dune sands (Punehu Sands) crop out at the very bottom of the section.

Over a wide stretch of coastline, the Otakeho debris-avalanche deposit directly overlies a peat layer rich in large pieces of wood and a thick yellow tephric soil, underlain by a massive stack of dune sands with intercalated peat beds and weakly developed paleosols. Farther south-east, the Punehu Sands are replaced by stacks of hyperconcentrated flow deposits with interbedded fluvial sands. Clearly, these two lithofacies are of similar age and represent two different lateral paleoenvironments. Towards the margins of the deposit, the Otakeho Formation consists almost exclusively of a clay-rich matrix and contains only scattered, pebble-sized clasts mostly <5 cm in diameter. It is characterised by abundant ripped-up fragments of trees including large logs and large stratified rip-up clasts. A wood sample from within the debris-avalanche deposit was collected at a location near to the type section but its age

exceeded the limit of the radiocarbon method (cf. Table 2). Hence, the age of the Otakeho Formation is estimated to be c. 55 ka.

#### Punehu and old Kaupokonui debris-flow deposits (redefined units)

Near Punehu Stream, a thin clay matrix-rich debris-flow deposit occurs below the Otakeho Formation over a c. 0.7-km-long stretch of coastline. The deposit is c. 0.5–1 m thick, matrix-rich (90–95%) and contains small, scattered pebble-sized clasts. It is separated from the overlying Otakeho debris-avalanche deposit by a thin paleosol and underlain by a thick paleosol and stacks of dune sands or peat and pumiceous hyperconcentrated flow deposits. The deposit was most likely emplaced by the run-out of a small cohesive debris flow that was generated by a small collapse and confined to a paleo-Punehu Stream in distal areas.

Another clay-rich debris-flow deposit occurs at this stratigraphic position at Kaupokonui Stream. It is c. 0.8 m thick and separated from the Otakeho Formation by fluvial sediment. It was most likely produced by a similar process to the debris-flow unit at Punehu, i.e. the distal run-out of a small, collapse-related debris flow that was channelised down a paleo-Kaupokonui catchment. Both cohesive debris-flow deposits occur at a similar stratigraphic position to the Tokaora and Waihi debris-avalanche deposits but, due to the lack of correlation and their limited lateral extent, they are interpreted to represent individual smaller events rather than lateral equivalents of the same large debris-avalanche event.

#### Tokaora Formation (new unit)

The Tokaora debris-avalanche deposit has not been described previously and was named after Tokaora township in south Taranaki. It is exposed near Hawera for c. 2 km of coastline east of the Waingongoro River (Fig. 7a). At its type section, the deposit thickens to c. 3 m in a small paleo-channel and wedges out to the east. It is characterised by pebble- to cobble-sized scattered clasts in a dark brownish matrix and a distinct yellowish top, separated from the basal darker part by a sharp and wavy boundary (Fig. 7c). The sharp colour difference of the matrix may have been produced by differential weathering or diagenesis of the deposit rather than due to sedimentological differences. The Tokaora is overlain by bedded grey transitional hyperconcentrated flow/streamflow deposits and separated from the underlying Waihi Formation by a thin layer of rounded fluvial pebbles and sands (Fig. 7b).

The small lateral extent of the Tokaora debris-avalanche deposit suggests that it was produced by the channelised run-out of either a smaller debris avalanche or rather the marginal portion of one that was directed to the east,

similar to the Ngaere event. Its emplacement age can only be roughly estimated from its stratigraphic position below the Otakeho and above the Waihi debris-avalanche deposits, suggesting approximately 60 ka.

#### Waihi Formation (new unit)

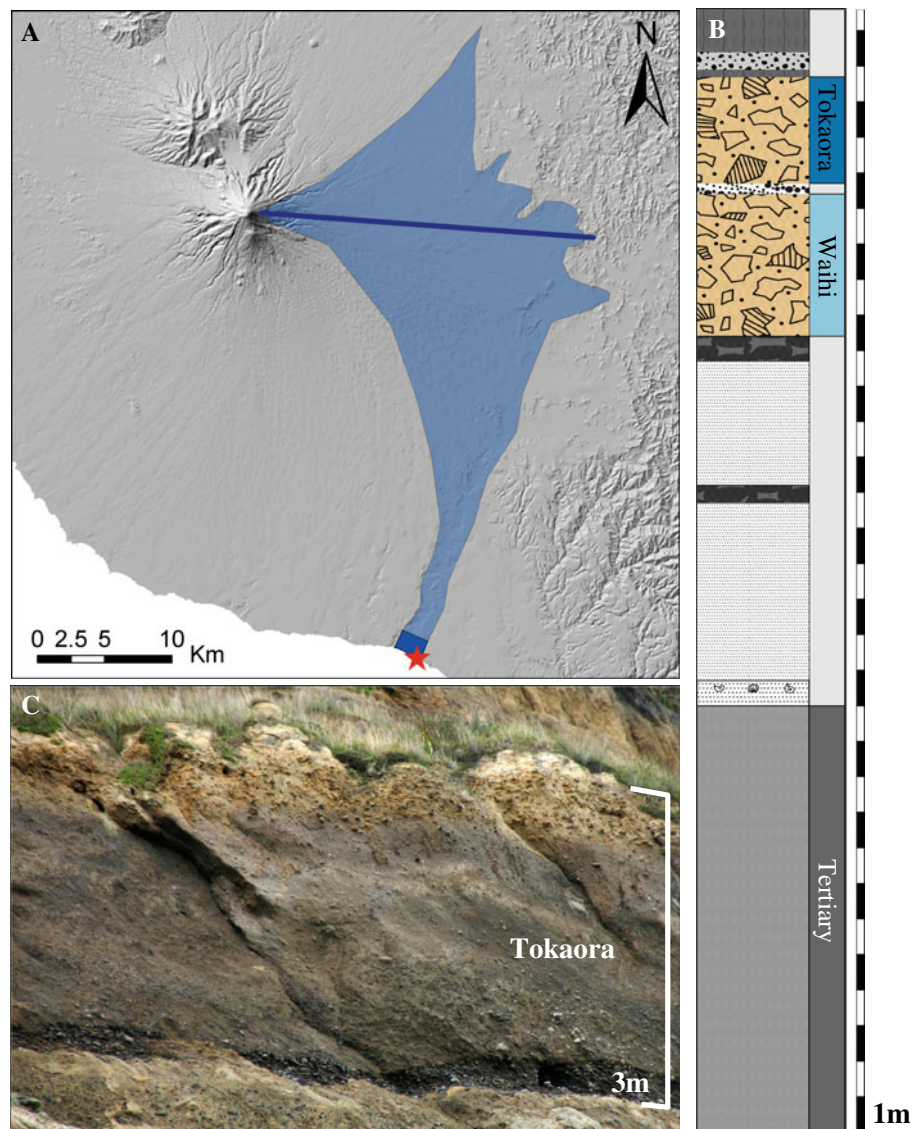
The Waihi debris-avalanche deposit is a formerly unknown unit, named after Waihi beach near Hawera in south Taranaki. It is exposed over 17.8 km, south of Hawera, between Waiokura Stream and Tangahoe River (Fig. 8a), where the volcanoclastic sequence wedges out and the uplifted tertiary mud- and sandstone succession forms the entire cliff section. The Waihi debris-avalanche deposit is c. 4 m thick at its type section and contains pebble- and cobble-sized clasts (typically <10 cm) in a clay-rich matrix (Fig. 8c), with large, rounded megaclasts >5 m across occurring in outcrops nearby (Fig. 8d). The deposit has a high content of pumice clasts and larger clasts are concentrated in a c. 1-m-thick bouldery basal layer. Secondary clasts are abundant, including abundant small (c. 0.2–0.5 m in diameter) to fewer medium-sized (1–1.5 m across) ripped-up fragments of mudstone and pieces of wood. Above the Waihi are fluvial sands and a thin hyperconcentrated flow deposit, capped by a thick soil (Fig. 8b). The Waihi directly overlies the Waingongoro debris-avalanche deposit, which shows similar sedimentological characteristics.

West of the type section, both debris-avalanche deposits thicken in a small channel. Here, the Waihi Formation appears to consist of two gradational units with different sedimentological characteristics, which most likely represent two pulses of a single collapse series. The bottom unit ranges in thickness from 3–5 m and is exceptionally coarse, containing large cobble- to boulder-sized clasts and abundant brecciated megaclasts of the same lithology. In contrast, the 2- to 3-m-thick upper unit is matrix-rich and contains pebble- to cobble-sized clasts as well as small rip-up clasts, typical characteristics of the Waihi Formation elsewhere.

The overall dimensions of the deposit with a maximum thickness of 9 m at a runout distance of c. 45 km and its sedimentological characteristics suggest that the Waihi debris-avalanche deposit is of very large volume. The course of this debris avalanche might have been similar to that of the Ngaere event with the main body of the flow being directed to the east and a marginal portion flowing southward to the current coastline area. This distribution pattern would explain the limited lateral extent and considerable thickness of the deposit.

The emplacement age of the Waihi Formation can only be estimated from its stratigraphic position. It predates the Otakeho and Tokaora events and overlies the Oeo and Waingongoro debris-avalanche deposits, giving an approximate age range of c. 50–80 ka (assumed to be emplaced most likely at 70 ka).

**Fig. 7** **a** Coastal extent and location of the type section of the Tokaora Formation as well as its extrapolated inland distribution based on the dispersal of the Ngaere Formation. **b** Stratigraphy of the Tokapra type section, where the deposit thickens in a small channel and is characterised by small clasts in a dark brownish matrix and a distinctive yellowish weathered top (c)



#### Waingongoro Formation (new unit)

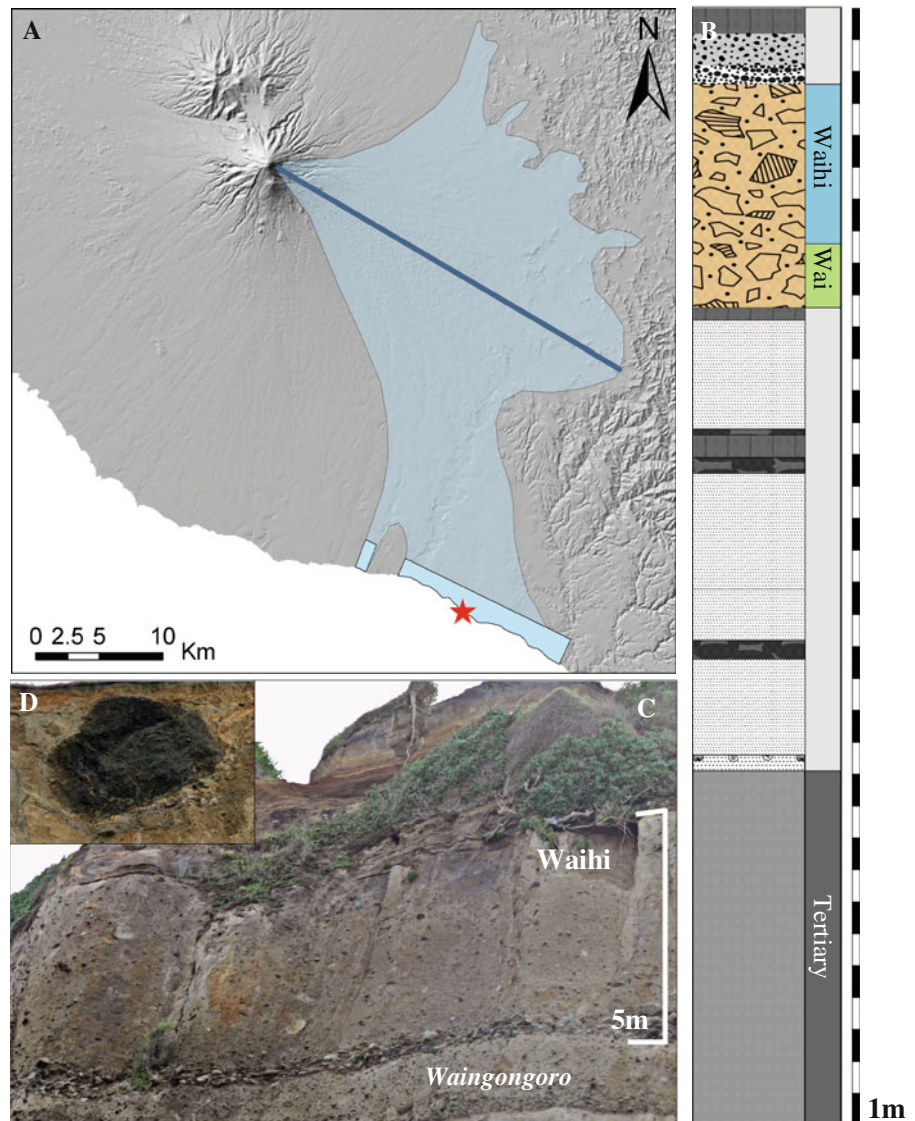
The Waingongoro debris-avalanche deposit is named after Waingongoro River and has not been described elsewhere. It shows similar distribution and deposit characteristics to the overlying Waihi Formation but is of smaller volume, probably smoothing the terrain and hence allowing the subsequent Waihi debris avalanche to spread over a larger area. The Waingongoro debris-avalanche deposit was mapped over a distance of 16.6 km, south of Hawera, between Waiokura Stream and Tangahoe River (Fig. 9a). At its type locality, the deposit is 5 m thick and contains pebble- to cobble-sized clasts, including a high content of pumice clasts, a few larger boulder-sized clasts, as well as small rounded rip-up clasts in a clay-rich matrix (Fig. 9c). Rip-up clasts become more abundant a few hundred metres east. In several locations, the Waingongoro debris-avalanche deposit

is characterised by a coarse basal layer similar to the Waihi. This zone of subrounded to subangular cobble- to boulder-sized clasts is often very distinct and can be up to 0.5 m thick, while the upper part of the deposit is typically characterised by smaller clasts.

The deposit is underlain by a thick laminated soil and bedded sands that are interbedded with thick soil and peat layers (Fig. 9b). Here, a thin but distinct paleosol separates it from the overlying Waihi Formation and an overlying thick series of bedded sands with intercalated thin peat beds. The sands above the Waihi are interpreted as being emplaced from thin, laminar-bedded transitional hyper-concentrated flows/dilute stream flow with interbedded fluvial sands, while the sands below the debris-avalanche deposits more likely represent dune and beach sands.

Similar to the Waihi, the age of the Waingongoro Formation could only be estimated based on its stratigraphic

**Fig. 8** **a** Map displaying the coastal extent of the Waihi Formation, its extraplated distribution inland based on the dispersal of the Ngaere Formation, dispersal axis and type section. **b** Stratigraphy of the Waihi type section. **c** The deposit typically shows a distinct coarse basal layer similar to the underlying Waingongoro Formation and is characterised by abundant small to large rip-up clasts and large (here c. 5 m in diameter) brecciated megaclasts (**d**)



position below the Otakeho and Tokaora and above the Oeo debris-avalanche deposits. It is thought to have been emplaced around 75 ka, with respect to the possible age of the Waihi. The paleosol between the Waihi and Waingongoro is thin and often missing, indicating that the deposits were most likely emplaced within a relatively short period of time. However, it is impossible to precisely determine the age of these two units without further dating.

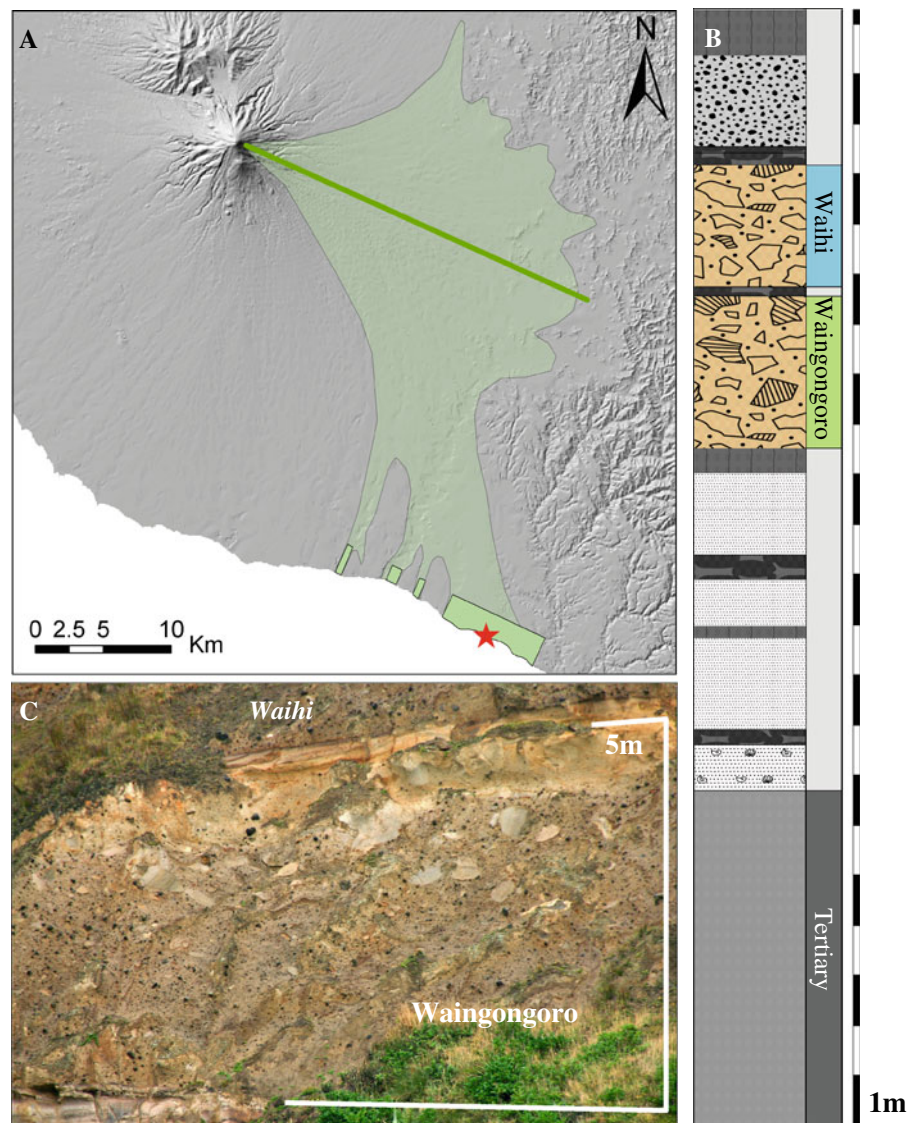
#### Oeo Formation (new unit)

The Oeo debris-avalanche deposit is a previously unrecognised unit, which was named after Oeo Stream in south-west Taranaki. It crops out at the very bottom of the cliff section in two locations (Fig. 10a). At its coastal type section near Oeo township, the deposit forms a c. 4.5-m-high and c. 20-m-wide mound at the bottom of the sequence (Fig. 10c). It is characterised by a brecciated, almost clast-supported

fabric with little matrix. Clasts range in size from a few cm to c. 1 m in diameter. The largest lava blocks are fractured and show characteristic jigsaw cracks. The deposit appears to consist of several monolithologic domains, which are even more obvious within the second exposed mound described below (Fig. 10d). The Oeo debris-avalanche deposit is directly overlain by a sequence of bedded Punehu dune sands with intercalated paleosols and peat beds, including the Puketapu buried forest, that wedges against the mound and is not exposed on its top. The mound and the sand wedges either side are overlain by the Otakeho Formation followed by a thick series of hyperconcentrated flow deposits with interbedded paleosols and the intercalated Rama Formation (Fig. 10b).

A second, larger debris-avalanche mound with a height of c. 5–6 m and a width of c. 40 m is exposed at a location to the north-west. The deposits wedging on either side of this mound consist of Punehu sands with intercalated soil/peat beds and the prominent Puketapu buried forest, which is

**Fig. 9** **a** Mapped coastal extent and location of the type section for the Waingongoro Formation with an extrapolated inland distribution and interpreted dispersal axis similar to the Waihi debris-avalanche deposit. **b** Stratigraphy of the Waingongoro type section. **c** Here, the deposit is characterised by abundant small rip-up clasts of the underlying bedded sands and a similar appearance to the overlying Waihi Formation



here characterised by a soil with a tree stump in growth position. The Oeo debris-avalanche deposit is characterised by several monolithologic domains that represent individual megaclasts with different sedimentological characteristics (Fig. 10d). The top of the mound is clast-supported and consists exclusively of brecciated, strongly altered andesite. The shattered clasts range in size from a few cm to >1 m across. In contrast, a small megaclast and the domain below are characterised by a fine-grained matrix and angular–subangular clasts of various sizes. The bottom layer is matrix-rich and contains predominantly subrounded–rounded clasts. The base of the deposit is not exposed.

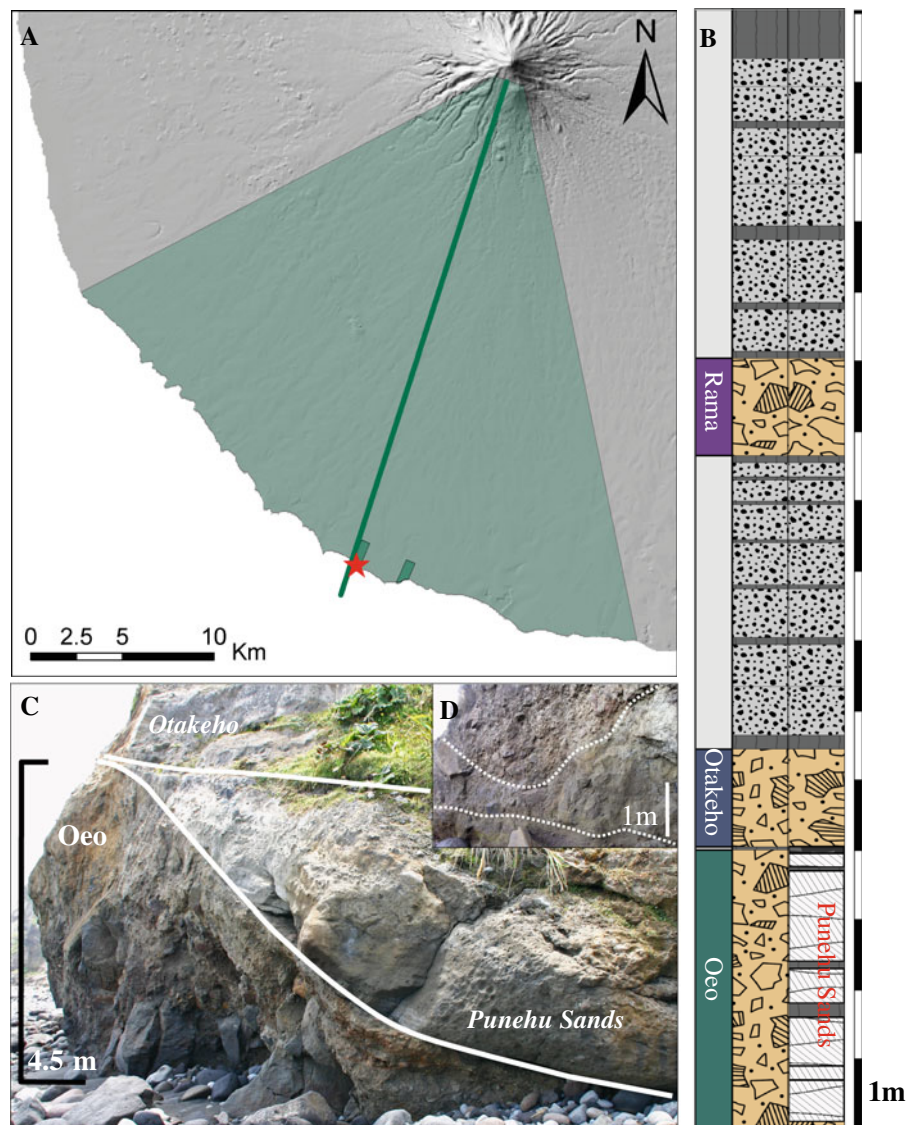
Due to its stratigraphic position and the thick overlying sequence, the uplift rates in South Taranaki were not sufficient to excavate the Oeo debris-avalanche deposit above the present-day sea level. Exposure of the top of the deposit is limited to two locations where it forms thick mounds that

protrude out of the paleo-landscape. Such debris-avalanche mounds typically occur near the main axis of dispersal, suggesting a south-westerly distribution for the Oeo. The dispersal limit of the deposit is indicated by its absence in exposed sequences of assumed similar age above the tertiary mudstones east of Kapuni Stream. The age range of the Oeo Formation is given by the closely overlying c. 80 ka Puketapu buried forest and the cutting of the Inaha marine bench into the underlying Tertiary mudstone sequence at c. 105 ka. Its emplacement age is here estimated at c. 85–90 ka since it closely predates the formation of the Puketapu buried forest.

Mangati Formation (redefined unit in north Taranaki)

A formerly unnamed debris-avalanche deposit is exposed in coastal cliffs near Bell Block (Alloway 1989) and is here named Mangati debris-avalanche deposit after its

**Fig. 10** **a** Map showing the location of the two coastal outcrops of the Oeo Formation and its extrapolated distribution inland, based on the inundation area of the volumetrically and sedimentologically similar Pungarehu Formation. **b** Stratigraphy of the type section, where the otherwise buried Oeo debris-avalanche deposit forms a c. 4.5-m-thick mound (**c**) that consists of several monolithologic megaclasts or domains (**d**, marked by white dotted lines)



occurrence east of Mangati Stream. The unit is characterised by a maximum thickness of 6 m and coarse clasts in a clay-rich matrix. Over most of its exposure along the coast north-east of Bell Block, its base is marked by a distinct layer of cobble- to boulder-sized rounded to subangular clasts (Fig. 11). In some locations, large logs are found within this basal layer, which protrude from the deposit at a c. 90° angle, roughly parallel to flow direction. It is underlain by cemented, iron-stained, high-angle cross-bedded sands with occasional large tree stumps in growth position. These sands are part of the covered sequence of the c. 210 ka NT3/Ngarino marine bench (Pillans 1983, 1990; Alloway 1989). The Mangati debris-avalanche deposit is separated from the overlying Motunui Formation by a thick peat with interbedded andesitic tephra layers. Based on its stratigraphic position, the emplacement age of the Mangati Formation is estimated at c. 200 ka. The unit is included here because

geochemical evidence confirms its origin from Mt. Taranaki (Zernack 2008), making it the oldest known deposit from this volcano and hence requiring revision of estimates for inception of volcanic activity from >130 ka to sometime before 200 ka.

### Distribution of known Formations in the study area

#### Opu Formation

The Opu debris-avalanche deposit makes up the top of the cliff sections over a c. 14.6-km-wide stretch of coastline in the north-western part of the study area (Fig. 12a), with a small marginal lobe being confined to Ouri Stream. This observation matches the coastal distribution of the Opu Formation as marked on the geological map of Taranaki by





**Fig. 11** Photograph of the Mangati debris-avalanche deposit in north Taranaki, showing the typical distinct basal zone of coarse clasts and large protruding tree logs

Neall and Alloway (2004; cf. Fig. 1). The deposit is thickest (5–8 m) north-west of Opunake, between Heima and Otahi Streams, along its main dispersal axis. Here, it is characterised by abundant pebble- to boulder-sized clasts and large megaclasts in a clay-rich matrix and several small mounds <2 m in height in coastal cross-sections. Towards the margins, size and number of original clasts decrease while the number of rip-up clasts increases. The deposit is covered by a thick soil that makes up the present-day surface. The Opu typically overlies the distinct Oakura Tephra (cf. Neall 1979).

#### Pungarehu Formation

The Pungarehu debris-avalanche deposit occurs in coastal cliff sections in the north-western part of the study area over c. 11.5 km (Fig. 12b), showing a continuous exposure over most parts and preservation in several small channels in the Opunake area. The mapped extent of the Pungarehu Formation in the study area complements the geological map of Neall and Alloway (2004) since the earlier work displays only the distribution of surficial units. The Pungarehu is thickest at the northern limit of the study area (4–8 m) and rapidly thins to c. 1 m near Opunake. The deposit is characterised by abundant cobble- to boulder-sized clasts, shattered clasts and megaclasts that become less abundant and smaller with decreasing deposit thickness, while the matrix content and the number of small rip-up clasts increase. The second main lobe southeast of Opunake is characterised by a matrix-rich deposit of orange-reddish colour with scattered small clasts and a varying thickness of c 0.8–2 m. The Pungarehu is separated from the overlying Opu Formation by the Okato Tephra, one or several thin, fine-grained hyperconcentrated flow deposits of Warea age and the Oakura Tephra (cf. Neall

1979). It typically directly overlies a laminated soil that contains the Kawakawa Tephra.

#### Ngaere Formation

The Ngaere debris-avalanche deposit crops out in the southern part of the study area and was correlated over c. 10.7 km laterally (Fig. 12c). It is exposed continuously south of Manaia, between Kaupokonui and Waiokura Streams, and occurs as a thin, matrix-rich, lenticular deposit in several channels near Hawera. Previously, the Ngaere Formation was only mapped over a short stretch of coastline east of the Waingongoro River (Neall and Alloway 2004) but was here found to extend further to the west. The distribution pattern suggests that the marginal parts of the debris avalanche were channelled down and reached the present-day coast along one larger (Waiokura Stream) and several small paleo-valleys.

The deposit is thickest (c. 4.5–5 m) south-east of Manaia, where it is characterised by pebble- to cobble- as well as boulder-sized clasts in a clay-rich matrix, and thins rapidly to 1.5 m towards the margins of this distal lobe. It is overlain by fluvial and hyperconcentrated flow deposits with intercalated paleosols/peat beds and in the westernmost locations by the Motumate Formation. Below, it is typically separated from the Rama debris-avalanche deposit by a series of hyperconcentrated flow deposits with interbedded paleosols.

Near the mouth of the Waingongoro River, the deposit is confined to a fluvial channel within the paleo-Waingongoro valley that was cut into the underlying Waihi Formation. The debris-avalanche deposits are interbedded with a thick sequence of cross-bedded fluvial sand and gravel confirming the long-lasting existence of this deeply cut river valley. A large unconformity between the Ngaere and Waihi Formations (see Fig. 13) reflects filling of the paleo-valley since the Waihi collapse, with subsequent erosion leading to incision of a new fluvial channel, which became filled by the Ngaere debris-avalanche deposit. Fluvial and volcanoclastic sediments that were deposited in the valley afterwards have been gradually eroded until present day.

#### Correlations

A schematic overview of debris-avalanche marker beds, prominent peat layers and mappable sedimentary units is presented in Fig. 13. Hyperconcentrated flow deposits and channelised debris-flow deposits are common in all parts of the studied volcanoclastic sequences in west, south-west and south Taranaki but could not be illustrated on this large scale because of their limited extent. The large number of identified events implies that lahars occurred frequently throughout the entire volcanic history of Mt. Taranaki.

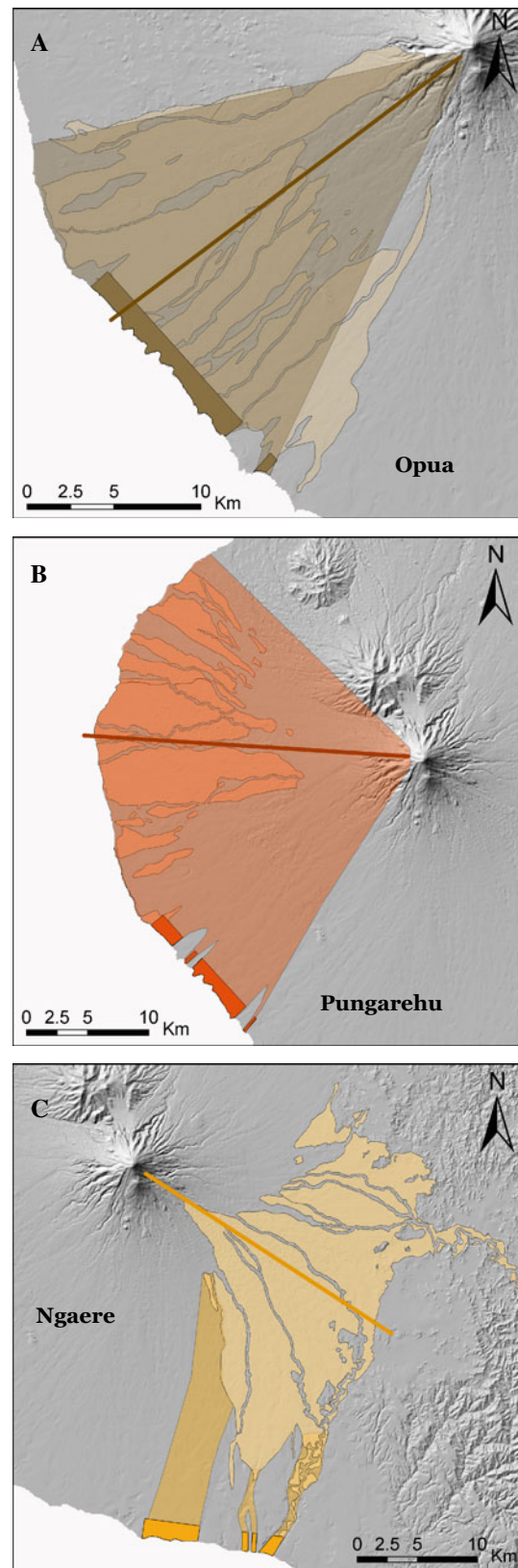
**Fig. 12** Observed coastal extent and inferred distribution inland of the Opua (a), Pungarehu (b) and Ngaere (c) Formations, complementing their mapped surface distribution by Neall and Alloway (2004). This comparison demonstrates that the extrapolated inland dispersal of the units studied in coastal cross-sections can only be regarded as a minimum

### Distribution, volume and frequency of volcanic mass flows

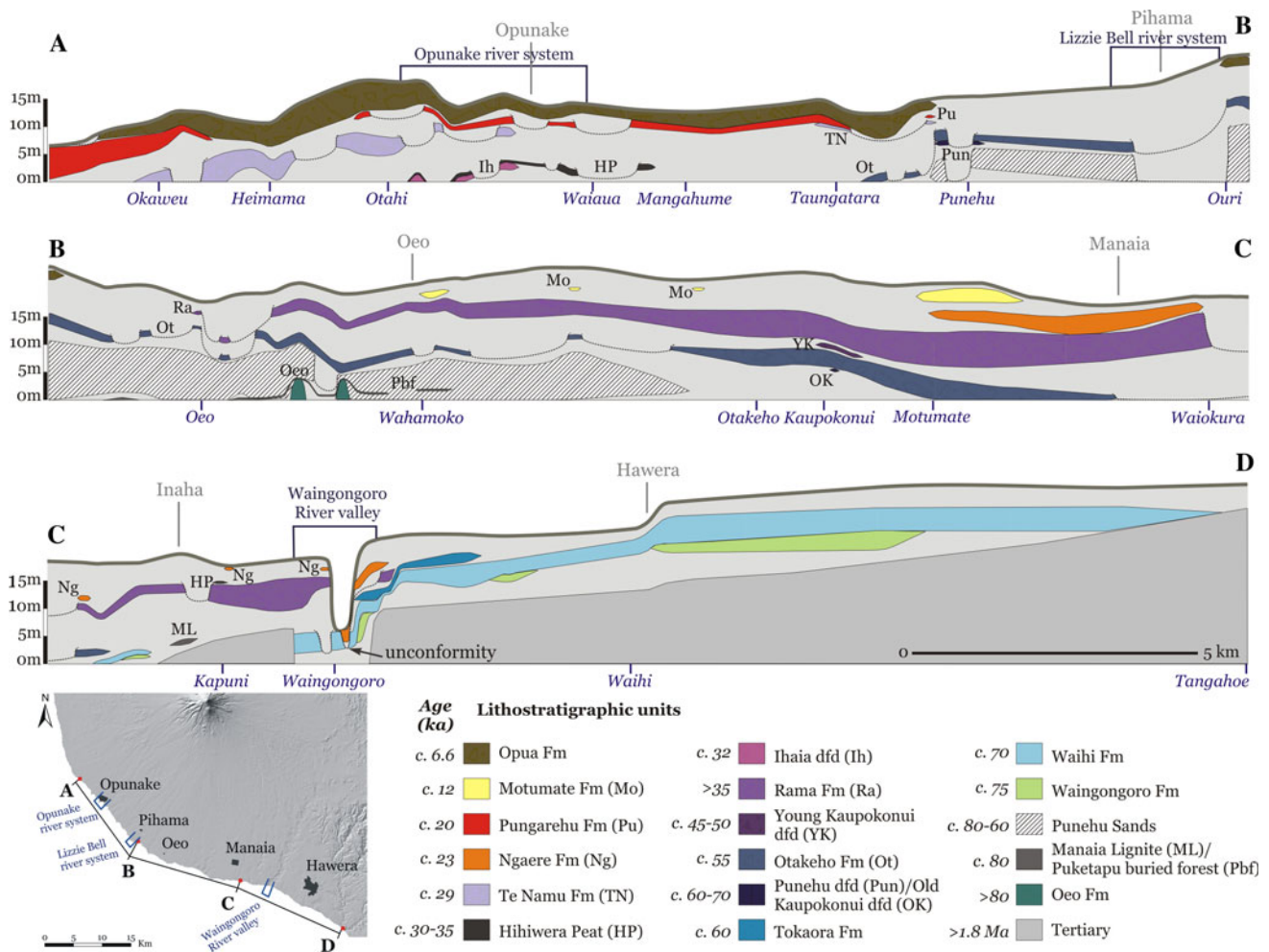
#### Volcanic debris avalanches

The distribution of Mt. Taranaki debris-avalanche deposits was mainly controlled by the direction of collapse. Failures occurred on similar sectors of the edifice during certain periods (Table 3), indicating that different parts of the edifice were more unstable and thus vulnerable to collapse at different times throughout the volcanic history (cf. Zernack et al. 2009). The apparent distribution pattern of debris-avalanche deposits may reflect preservation and exposure of specific time packages of the succession or could indicate that the direction of collapse was influenced by internal and/or external processes, such as local stress regimes within the volcano resulting from its internal structure, a dominant direction of dike emplacement, the regional tectonic stress field, the slope of the subvolcanic basement, and for multiple failures of the same sector, weak horizons developed on the floors of preceding collapse amphitheatres, and the orientation of the amphitheatres (cf. Siebert 1984; Vallance et al. 1995; van Wyk de Vries and Borgia 1996; Lagmay et al. 2000).

Minimum volumes of the studied debris-avalanche and cohesive debris-flow units were calculated using their extrapolated inundation area and an average deposit thickness, which was estimated based on their maximum observed thickness in coastal outcrops as well as deposit characteristics (Table 3). Calculated volumes range from  $<0.1 \text{ km}^3$  for the smallest, channelised debris-flow deposits up to c.  $7.5 \text{ km}^3$  for the largest debris-avalanche deposits that were produced by catastrophic edifice collapses. The cohesive Pungarehu and old Kaupokonui debris flows as well as the young Kaupokonui and Ihaia flows were of very small volume,  $<0.1$  and  $0.1\text{--}0.2 \text{ km}^3$ , respectively. The flows were hence restricted to small channels when reaching a travel distance equivalent to the present-day coastline, resulting in thin matrix-rich deposits of limited lateral extent. The Motumate Formation was produced by a debris avalanche that was confined to major paleo-channels in distal areas. Its calculated deposit volume of  $0.5\text{--}1 \text{ km}^3$  is significantly smaller than that of the more widespread debris-avalanche units but larger than the clay-rich debris-flow deposits. In contrast, the Te Namu, Otakeho and Tokaora debris-avalanche units show similar deposit characteristics and maximum medial thicknesses to



the Opua Formation, indicating that the collapse events were of similar size, although the Te Namu has a smaller lateral extent and extrapolated inundation area. Previous



**Fig. 13** Cross-section of the medial Mt. Taranaki ring-plain succession showing the correlated key horizons exposed in coastal cliff sections of the western to southern Taranaki peninsula. Also displayed are the locations of paleo-river systems as described in the text as well as streams and townships of Fig. 1C for orientation.

*Dotted lines* connecting individual units represent areas where these were eroded during subsequent channel formation and replaced by channel fills. In contrast, the absence of these unconformity lines indicates that the deposits were not emplaced in these areas but were restricted to paleo-channels

volume estimates for the Opua Formation of c. 0.35 km<sup>3</sup> (Neall 1979) have been revised upwards based on new calculations by Procter et al. (in review), who suggested a minimum of 1.98 km<sup>3</sup> and a maximum volume of 2.38 km<sup>3</sup>. This fits in well with the minimum volumes of c. 1.5–2 km<sup>3</sup> for the Te Namu and 2–2.5 km<sup>3</sup> for the Otakeho and Tokaora Formations calculated here. Deposit characteristics and thickness of the Rama debris-avalanche deposit indicate that it is of much larger volume than the Opua but considerably smaller than the Ngaere and Pungarehu Formations. Its calculated minimum volume of 4.5–5 km<sup>3</sup> significantly exceeds an earlier suggested deposit volume of >2.6 km<sup>3</sup> (Palmer et al. 1991).

The dispersal direction of the Waihi and Waingongoro debris-avalanche deposits is assumed to be similar to the Ngaere Formation. The deposit thickness and lateral extent of the Waingongoro unit implies that it may have been of a

comparable dimension, which matches its calculated minimum volume of 5–5.5 km<sup>3</sup>. In contrast, the characteristics of the Waihi Formation, in particular its large inundation area, indicate that it was produced by a much larger edifice collapse event, similar to the Oeo and Pungarehu Formations. This is reflected in a minimum calculated deposit volume of 7–7.5 km<sup>3</sup>. The maximum medial thickness and lateral distribution of the Oeo debris-avalanche deposit are unknown since it only crops out at two locations at the bottom of the sequence. Its dominantly clast-supported fabric with large jigsaw-cracked lava blocks and only few matrix-containing megaclast domains are characteristics similar to the Pungarehu Formation close to its dispersal axis. This suggests that the Oeo event was of a comparable size, which is also reflected in a minimum calculated volume of 7–7.5 km<sup>3</sup>. The oldest debris-avalanche deposits along the northern coast show a similar distribution, with

**Table 3** Some aspects of Mt. Taranaki debris-avalanche and cohesive debris-flow deposits

| Debris-avalanche/<br>debris-flow unit | Calibrated<br>age (ka) | Direction<br>of edifice<br>collapse | Maximum<br>observed<br>thickness (m) | Maximum<br>medial<br>width (km) | Minimum<br>runout<br>distance (km) | Calculated<br>extrapolated<br>area (km <sup>2</sup> ) | Calculated<br>minimum<br>volume (km <sup>3</sup> ) |
|---------------------------------------|------------------------|-------------------------------------|--------------------------------------|---------------------------------|------------------------------------|---|--|
| Opuā                                  | 7.5 <sup>a</sup>       | SW                                  | 8                                    | 25 <sup>c</sup>                 | 27                                 | 340   | 1.98–2.38 <sup>f</sup>                             |
| Motumate                              | 14 <sup>b</sup>        | S                                   | 3.5                                  | 10.8                            | 31                                 | 130   | 0.5–1  |
| Pungarehu                             | 24.8 <sup>c</sup>      | W                                   | >16 <sup>a</sup>                     | 35 <sup>c</sup>                 | 26                                 | 570   | >7.5 <sup>a</sup>                                  |
| Ngaere                                | 27.1–28 <sup>d</sup>   | SE                                  | 5                                    | 40 <sup>e</sup>                 | 34                                 | 520   | 5.85 <sup>d</sup>                                  |
| Te Namu                               | 34 <sup>c</sup>        | SW                                  | >5                                   | >8.8                            | 26                                 | 230   | 1.5–2  |
| Ihaia                                 | 36.9 <sup>c</sup>      | SW                                  | 1.6                                  | 3.2                             | 25                                 | 80  | 0.1–0.2  |
| Rama                                  | >40 <sup>c</sup>       | S                                   | 12                                   | 25.5                            | 34                                 | 405<br>510 <sup>g</sup>                               | 4.5–5<br>>2.6 <sup>g</sup>                         |
| <i>Young Kaup.</i>                    | c. 40–55 <sup>b</sup>  | S                                   | 1.3                                  | 1                               | 30                                 | 80  | 0.1–0.2  |
| Otakeho                               | c. 55 <sup>c</sup>     | S                                   | >4                                   | 24.5                            | 32                                 | 375<br>370 <sup>g</sup>                               | 2–2.5<br>>1.0 <sup>g</sup>                         |
| <i>Punehu</i>                         | c. 55–70 <sup>b</sup>  | SW                                  | 1                                    | 0.7                             | 26                                 | 45  | <0.1   |
| <i>Old Kaup.</i>                      | c. 55–70 <sup>b</sup>  | S                                   | 0.8                                  | 0.1                             | 30                                 | 50  | <0.1   |
| Tokaora                               | c. 60 <sup>b</sup>     | E                                   | 2.5                                  | 2                               | 35                                 | 370   | 2–2.5  |
| Waihi                                 | c. 70 <sup>b</sup>     | SE                                  | 8                                    | 17.8                            | 45                                 | 600   | 7–7.5  |
| Waingongoro                           | c. 75 <sup>b</sup>     | SE                                  | 5                                    | 16.6                            | 44                                 | 480   | 5–5.5  |
| Oeo                                   | c. 85–90 <sup>b</sup>  | S                                   | >6                                   | >21                             | 34                                 | 510   | 7–7.5  |
| Okawa                                 | c. 105 <sup>d</sup>    | NE                                  | 4                                    | 9 <sup>e</sup>                  | 39                                 | 255 <sup>d</sup>                                      | 3.62 <sup>d</sup>                                  |
| Motunui                               | >130 <sup>d</sup>      | NE                                  | 6                                    | 17 <sup>e</sup>                 | 41                                 | n/a   | >Okawa   |
| Mangati                               | c. 200 <sup>d</sup>    | NE                                  | 6                                    | n/a                             | 39                                 | n/a   | ~Okawa   |

<sup>a</sup> Neall (1979)<sup>b</sup> Chronostratigraphy this study<sup>c</sup> Radiocarbon dating this study (cf. Table 2)<sup>d</sup> Alloway et al. (2005)<sup>e</sup> Neall and Alloway (2004)<sup>f</sup> Procter (2009)<sup>g</sup> Palmer and Neall (1991), and Palmer et al. (1991)

the Motunui being thicker and laterally more extensive. This indicates that the Motunui is more voluminous than the c. 3.62 km<sup>3</sup> Okawa Formation (Alloway et al. 2005), while the Mangati debris-avalanche deposit is of comparable volume.

At least 14 large and several smaller debris-avalanche deposits have been recognised in this and previous studies of the c. 200,000-year record of volcanic activity at Mt. Taranaki (Table 3). This implies that major slope failures take place on average every 10–14,000 years. However, collapse events are not evenly spaced over time and appear to have become more frequent, with 6 having occurred since 35 ka. The number of debris-avalanche events shown here is considered a minimum and does not represent a true estimate of frequency. Other units might be buried in the ring-plain sediments, in particular to the east of the volcano where outcrops are rare, and to the west where no significant uplift has occurred to expose older parts of the succession.

Apparent gaps in the reconstructed volcanic history may therefore simply reflect absence of preservation of units, or burial, rather than changes in volcanic behaviour.

The distribution of the pre-Ngaere debris-avalanche deposits in south-western and southern Taranaki was determined from correlation of deposits exposed in coastal cross-sections. Due to lack of longitudinal exposure towards the edifice and in some cases incomplete lateral exposure where the strata dip below the surface, or the sequence is eroded by fluvial and lahar channels, the estimated distributions do not necessarily represent maximum extent. Also, it was not possible to determine the true run-out distances of the Taranaki debris avalanches. Their deposits are known to continue onshore for at least 25–45 km from source (Table 3), and a minimum of a further 6 km offshore to the north (Alloway et al. 2005) and >8 km to the west (McDougall and Gibb 1970; Neall 1979). This prevented contouring the complete deposit

thickness and only allowed extrapolation of the likely inundation area onshore. Hence, the calculated deposit volumes were based on comparison to known distributions, maximum recorded thicknesses and deposit characteristics of the better exposed surficial deposits in medial coastal exposures and only represent minimum estimates that do not include offshore components.

### Lahars

Hyperconcentrated flow deposits and channelised debris-flow deposits are common in all parts of the studied volcanoclastic sequences in west, south-west and south Taranaki (cf. Procter et al. 2009; Zernack et al. 2009). The large number of identified events implies that lahars occurred frequently throughout the entire volcanic history of Mt. Taranaki. Here, the deposits were grouped into stratigraphic intervals, because they lack individual diagnostic properties, are numerous, and the narrow distribution of single flow units did not allow distinction of individual events. These deposit packages were correlated by distinct marker horizons interbedded with them, including debris-avalanche deposits, continuous paleosols, and peat layers but these were not sufficient to allow lateral correlation between catchments. Instead, it appears more likely that the grouped deposits were produced by separate episodes of lahars, representing longer periods of sedimentation. In some cases, prominent lithological characteristics allowed the distinction of different series of hyperconcentrated flow deposits, i.e. pumice-rich versus dense andesite-rich units, at individual outcrops.

At any one location, the ring-plain succession contains similar types of deposits, i.e. debris-avalanche and cohesive debris-flow deposits, hyperconcentrated flow and non-cohesive debris-flow deposits with intercalated paleosols and peat layers, channelised coarse non-cohesive debris-flow deposits, localised fluvial sediments, and dune sands, reflecting a repeating pattern of deposition (cf. Zernack et al. 2009). Hence, even though the studied coastal cross-sections represent only restricted insights into the lahar history at Mt. Taranaki, they provide an overview of recurring types of flows and can be regarded as a window into the likely composition of buried parts of the succession.

The occurrence of lahar deposits within the Taranaki ring-plain succession, however, appears unevenly distributed through time and space (cf. Scott 1989). The majority of volcanic mass flows in Taranaki are related to eruptive activity, as indicated by monolithologic clast assemblages within the deposits. The lack of significant soil development or sediment redistribution between stacks of debris- and hyperconcentrated flow deposits suggests that they were rapidly emplaced over relative short periods of time. The clusters of flow units correspond to individual eruptive

episodes, which are separated from each other by longer intervals of quiescence, represented by occasional poly lithologic lahar deposits, fluvial and aeolian redeposition as well as paleosols or peat layers. Furthermore, the distribution of lahar deposits varies according to the geomorphology of the ring plain and the edifice as well as the nature of the drainage network. Debris-flow deposits are restricted to the sites of deeper river channels, while hyperconcentrated flow units are more widespread and occur at any of the coastal locations. They were emplaced on the shallower, broad floodplains, which represent the most active areas of the ring-plain depositional system.

It was not possible to correlate individual flow units or time-equivalents over the entire cross-sectional exposure due to their large number and relatively limited lateral extent, a lack of individual diagnostic properties and significant marker horizons, as well as disturbance of the succession by complex, erosive channel systems. The studied medial ring-plain sequences also only represent part of the volcanic history of Mt. Taranaki and thus cannot include a complete record of lahar events.

Hence, the simplified frequency presented here can only be considered a minimum estimate of recurrence. Calculations were carried out for a limited number of locations, where dated marker beds provided an age range for the recurring debris- and hyperconcentrated flow deposits. The approximate frequency is based on the maximum number of flows over this specific time interval. The ring-plain record suggests that large channelised debris flows occur at least once every c. 2,000 years, while sheet-like hyperconcentrated flows are more frequent events with a minimum recurrence of one event in 500 years.

### Revised stratigraphy of the Mt. Taranaki ring-plain succession

The detailed stratigraphy of volcanic and volcanoclastic deposits at Mt. Taranaki has been established by several workers over the past 80 years, during which time the understanding of volcanic successions has changed significantly. This is reflected in a patchwork of general to more specific details on the developing geologic map. Early geological maps of the Taranaki peninsula date back to the 1920s and were based on the prevailing concept that ring-plain aggradation was limited to glacial periods, while warm climates resulted in the cutting of marine benches. Mapping units such as the “Stratford and Opunake Lahars” were defined mainly based on their geomorphological properties and soil cover and contained a range of different types of deposits that were believed to have formed different “ring-plains” (Hay 1967; Grant-Taylor 1964; Grant-Taylor and Kear 1970). In contrast, later studies distinguished

individual flow units according to their sedimentological characteristics, although also often grouping deposits of similar origin and age (Neall 1979; Alloway 1989; Neall and Alloway 2004; Alloway et al. 2005). This added more detail to the geological map and mostly replaced the older units except for remnants in south-west Taranaki that are still referred to as the Opunake and Stratford Formations.

The different concepts resulted in a complex stratigraphic terminology for the ring-plain succession at Mt. Taranaki with a wide range of deposits being encompassed in the existing lithostratigraphic Formations, i.e.:

- Single debris-avalanche deposits (Motunui, Okawa, Ngaere, Pungarehu and Opuia Formations).
- Packages of deposits of the same or similar origin and thus with similar characteristics that were confined to different catchments, such as debris-flow and hyper-concentrated flow deposits (Warea, Kahui, Ngatoro and Te Popo Formations).
- Groupings of different types of deposits that accumulated over a defined period of time (so-called ring-plains of laharic agglomerate), distinguished by the geomorphology of the landscape (Opunake and Stratford Formations).

Other terms used to define deposit packages within the stratigraphic succession are based on origin, sedimentological or geomorphic characteristics, such as:

- Pyroclastic-flow deposits (e.g. Maero block-and-ash-flow deposits)
- Volcanic mass-flow deposits (e.g. Kahui debris-flow deposits)
- Flood deposits (Hangatahua gravels and sands)
- Tephra beds (e.g. Inglewood Tephra, Burrell Lapilli, Saunders Ash, Newall Ash and Lapilli)
- Lava flows (e.g. Summit Group, Staircase Lavas, Warwicks Castle, The Turtle)

Each of these units refers to widely different lithologies with complex inter-relationships. Furthermore, remapping the former Opunake and Stratford Formations has shown a greater complexity of volcanoclastic lithofacies and allowed a more detailed reconstruction of the past volcanic activity at Mt. Taranaki prior to 25 ka that needs to be added to the previously established stratigraphy (Table 4).

Five new debris-avalanche deposits (Te Namu, Tokaora, Waihi, Waingongoro, and Oeo Formations) have been identified in this study, as well as a wide variety of volcanic mass-flow and reworked deposits. The different lithofacies show a repeating pattern of deposition and can be related to phases of edifice-construction or collapse events, depending on their sedimentological characteristics (cf. Palmer et al. 1991; Zernack et al. 2009). This study illustrates that debris-avalanche deposits were produced frequently and regularly and that the volcanic history of Mt. Taranaki was

**Table 4** Previous lithostratigraphy compared to new/redefined debris-avalanche units

| Formation                           | Previous work                  |                        | This study  |          |
|-------------------------------------|--------------------------------|------------------------|---|----------|
|                                     | Debris-avalanche deposit (DAD) | Age (ka)               | New or redefined DAD & debris-flow deposits (DFD) | Age (ka) |
| Opua Fm.                            | Opua DAD                       | c. 7.5 <sup>a</sup>    | As before   | c. 7.5   |
| Warea Fm.                           | Wr3 lobe                       | 12–14 <sup>a</sup>     | Motumate DAD                                      | c. 14    |
| Pungarehu Fm.                       | Pungarehu DAD                  | 26.5 <sup>a</sup>      | As before, younger age                            | c. 24.8  |
| Ngaere Fm.                          | Ngaere DAD                     | 27.1–28 <sup>c,d</sup> | As before   | c. 27.3  |
| Opunake Fm. 38–30 ka <sup>e</sup>   | Unnamed DAD                    | 33 <sup>b</sup>        | Te Namu DAD                                       | c. 34    |
| Stratford Fm. 80–50 ka <sup>e</sup> | Unnamed DAD                    | c. 50 <sup>f</sup>     | Ihaia DFD   | 36.9     |
|                                     |                                | c. 48 <sup>a</sup>     | Rama DAD  | >40      |
|                                     | Stratford Fm. DAD 1            |                        | Young Kaupokonui DFD                              | 40–55    |
|                                     | Stratford Fm. DAD 2            |                        | Otakeho DAD                                       | c. 55    |
|                                     | Stratford Fm. DAD 3            | c. 80 <sup>b</sup>     | Punehu DFD  | 55–70    |
| Okawa Fm.                           | Unnamed DAD                    |                        | Old Kaupokonui DFD                                | 55–70    |
|                                     |                                |                        | Tokaora DAD                                       | c. 65    |
|                                     |                                |                        | Waihi DAD   | c. 70    |
|                                     |                                |                        | Waingongoro DAD                                   | c. 75    |
|                                     |                                |                        | Oeo DAD   | c. 85–90 |
| Motunui Fm.                         |                                | >105 <sup>c,d</sup>    | As before   | c. 105   |
|                                     |                                | >130 <sup>c,d</sup>    | As before   | >130     |
|                                     |                                | 190–210 <sup>c</sup>   | Mangati DAD                                       | c. 200   |

<sup>a</sup> Neall (1979)

<sup>b</sup> Palmer et al. (1991)

<sup>c</sup> Alloway (1989)

<sup>d</sup> Alloway et al. (2005)

<sup>e</sup> Grant-Taylor and Kear (1970)

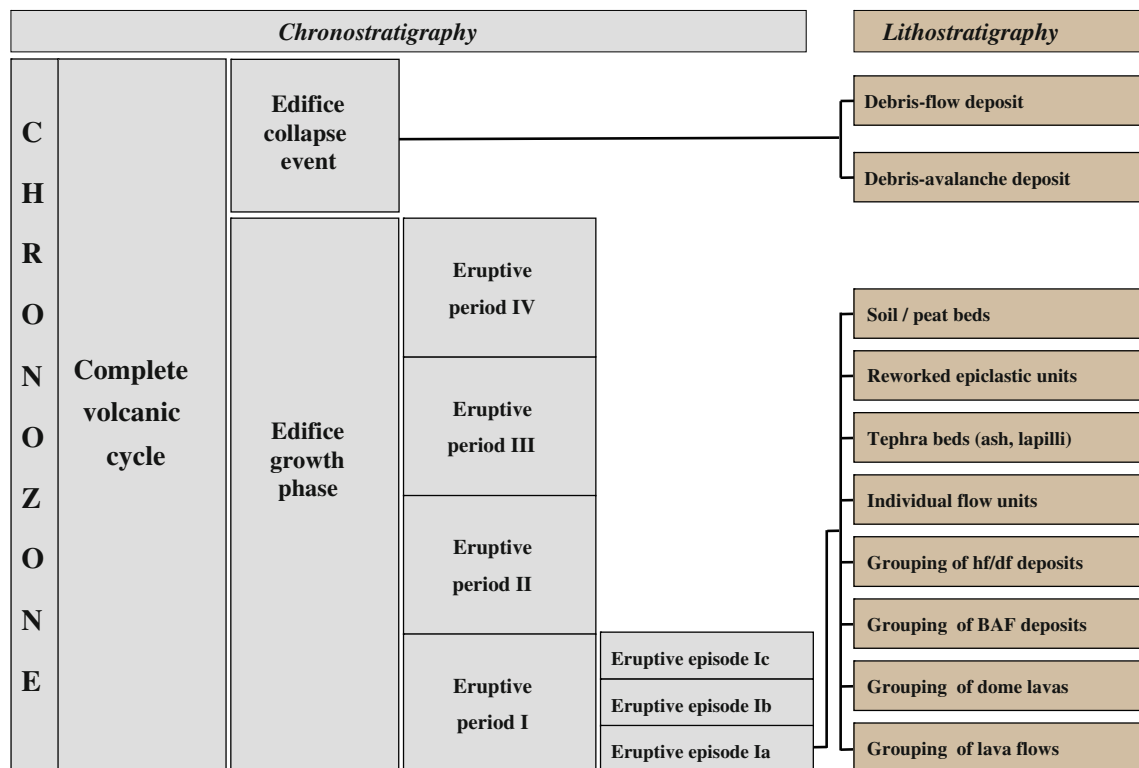
<sup>f</sup> Neall et al. (1986)

characterised by repeated edifice growth and collapse. Hence, creating chronostratigraphic time frames for the volcanic (and volcanoclastic) succession at Mt. Taranaki based on the interpretation of the apparent cyclic volcanic behaviour would provide a more uniform structure and clearer overview of past volcanic and sedimentary events.

The new concept presented here offers a more holistic nomenclature for the entire volcanoclastic succession that focuses on understanding the repeated sequence of events that have made up the geological history of Mt. Taranaki (Fig. 14). It integrates the wide array of mapped volcanic and volcanoclastic lithostratigraphic units into a coherent chronostratigraphic framework (cf. Salvador 1994). Here, we define each of the observed volcanic cycles as chronozones, which can be subdivided into a phase of edifice construction and a subsequent major edifice collapse event. The cone growth phase includes individual eruptive periods, which again consist of eruptive episodes. During the periods of edifice growth and collapse, a wide range of volcanic, volcanoclastic and other sedimentary deposits are produced, which can be mapped and distinguished based on their lithological properties. These lithostratigraphic units comprise formations, members and single mappable units of different origin that can be fitted into the proposed chronostratigraphic framework. Application of this approach

to the known (cf., Neall 1979; Neall et al. 1986; Alloway 1989; Alloway et al. 1995, 2005; Neall 2003; Platz 2007) and newly identified volcanic and volcanoclastic deposits at Mt. Taranaki results in an integrated stratigraphy for the entire known volcanic succession. In Table 5, these units are classed as primary volcanic (edifice-building lava flows, pyroclastic-flow deposits and tephra as well as satellite lava domes), secondary volcanoclastic (lahar, i.e. hyperconcentrated flow and debris-flow, and debris-avalanche deposits) and non-volcanic sediments (including aeolian sand dunes, flood deposits, fluvial and marine sediments as well as peat layers and tephric soils) based on their origin and emplacement mechanisms. In addition, to better represent contemporaneous events, the secondary volcanoclastic units are presented according to their dispersal within the northeastern, southeastern and southwestern sectors of the ring plain.

This new volcanic chronozone concept provides a coherent chronostratigraphic framework for volcanic successions that allows a more consistent overview of past volcanic and sedimentary events and, based on this, a better understanding of the recurrence of and relationships between primary and secondary processes around volcanoes. Hence, its application might help identify and/or emphasise cyclic behaviour at long-lived stratovolcanoes elsewhere.



**Fig. 14** Proposed new stratigraphic conceptual scheme for the Mt. Taranaki volcanic succession, which combines a chronostratigraphic framework and lithostratigraphically defined units

**Table 5** Composite stratigraphic overview of the Mt. Taranaki volcanic succession based on the proposed chronozone concept

| CZ       | EP | EE                    | Primary volcanics |  |   | Secondary volcanics SW sector |     | Secondary volcanics SE sector |     | Secondary volcanics NE sector |     | Non-volcanic sediments | Cal. age (ka)   |
|----------|----|-----------------------|-------------------|--|---|-------------------------------|-----|-------------------------------|-----|-------------------------------|-----|------------------------|---|
|          |    |                       | Lavas             | PF deposits  | Tephrae   | LD                            | DAD | LD                            | DAD | LD                            | DAD |                        |   |
| OAONUIAN | GP | Maero eruptive period | Pyramid           |  |   |                               |     |                               |     |                               |     |                        | AD1839–66   |
|          |    |                       | Tahurangi         | Summit dome  | Pyramid Lapilli   |                               |     |                               |     |                               |     |                        | c. AD1800<br>AD1755<br>AD1664 0.23<br>AD1465–1583                 |
|          |    |                       | Mangahume         | T. BAFs & surges                                       | Tahurangi Ash<br>Tahurangi B<br>Mangahume L<br>Burrell Lapilli<br>Burrell Breccia |                               |     |                               |     |                               |     |                        |   |
|          |    |                       | Burrell           | B. pumice flows<br>B. BAF & surges                     |   |                               |     |                               |     |                               |     |                        |   |
|          |    |                       | Puniho            | P. pumice flow   | Puniho Ash<br>Puniho Breccia  |                               |     |                               |     |                               |     |                        |   |
|          |    |                       | Waieranui         | P. BAF & surges  | Waieranui A<br>Waieranui B  |                               |     |                               |     |                               |     |                        | AD1483–1583<br>AD1390–1520<br>AD1438–45                           |
|          |    |                       | Newall            | W. BAF & surges  | Newall Ash<br>Newall Breccia  |                               |     |                               |     |                               |     |                        |   |
|          |    |                       | Waingongoro       | N. BAF & surges  | Waingongoro A   |                               |     |                               |     |                               |     |                        | AD1325–1472   |
|          |    |                       | Te Popo           | Summit lavas 0.8–0.4                                   | Te Popo Ash<br>Te Popo B.   |                               |     |                               |     |                               |     |                        | AD1438  |
|          |    |                       | Hooker            | TP BAF & surges  | Hooker Lapilli  |                               |     |                               |     |                               |     |                        | AD1173  |
|          |    |                       | Kaupokonui        | Skeet lavas<br>Staircase lavas                         | Kaupokonui T  |                               |     |                               |     |                               |     |                        | c. 1.3<br>< 1.6<br>c. 1.6<br>c. 1.9<br>3<br>3.4–2.9               |
|          |    |                       | Maketawa          | BAFs, E-flank  | Maketawa T  |                               |     |                               |     |                               |     |                        |   |
|          |    |                       | Manganui          | Beehives The Dome Skinner Hill<br>Fantham's Peak lavas | Manganui T  |                               |     |                               |     |                               |     |                        | Te Popo DFD 3.1–2.9<br>Ngatoro DFD                                |
|          |    |                       |                   | Peters lavas 7–3.3                                     | Inglewood T<br>Korito Tephra<br>Mangatoki T<br>Tariki Tephra<br>Waipuku T         |                               |     |                               |     |                               |     |                        | 3.5–2.9<br>3.9–3.7<br>4–3.9<br>4.6–4.4<br>5<br>5.4–5.3<br>6.1–5.7 |
|          |    |                       |                   | At least 3 PFDs  | Warea 4 DF/HFDs   |                               |     |                               |     |                               |     |                        | DFD/HFD   |



Table 5 continued

| CZ          | EP | EE    | Primary volcanics    |                              | Secondary volcanics SW sector   |   | Secondary volcanics SE sector     |                | Secondary volcanics NE sector |        | Non-volcanic sediments   | Cal. age (ka)  |
|-------------|----|-------|----------------------|------------------------------|---------------------------------|---|-----------------------------------|----------------|-------------------------------|--------|--|--|
|             |    |       | Lavas                | PF deposits                  | Tephtras                        | LD                                      | DAD                               | LD             | DAD                           | LD     |  |  |
| OPUAN       | C  |       |                      |                              |                                 |   |                                   |                |                               |        |  | c. 7.5   |
|             | GP | Kahui | Warwick Castle lavas | Kahui BAFs E- & W-flank 13–7 | Oakura Tephra                   | Kahui DFD 13–7                          | Pum. HFD<br>Local channelised DFD | Kahui DFD 13–7 |                               |        | Fluvial deposits<br>Medial ash accum.<br>Soil formation                                | c. 7.8<br>c. 8.9<br>12.3–6.1<br>12.5–11.7<br>13.2–12.9 |
| MOTUMATEAN  | C  |       |                      |                              |                                 |   |                                   |                |                               |        |  | c. 14  |
|             | GP |       |                      |                              | Ahuahu Lapilli<br>Okato Tephra  |   |                                   |                |                               |        | Peat & ash accum.<br>Soil formation  | 18.1<br>c. 19.2  |
| PUNGAREHUAN | C  |       |                      |                              |                                 |   |                                   |                |                               |        |  | 22.4–15  |
|             | GP |       | Puketii dome         |                              | Kaihouru T<br>Paetahi Tephra    | Warea DFD/HFD 20–12.5                   | Warea DFD/HFD 20–12.5             |                |                               |        | Fluvial deposits<br>Opunake RS<br>Katikara Sands                                       | 24.1–23.1<br>c. 24.8–15.1<br>24.8–15.1                 |
| NGAREAN     | C  |       |                      |                              |                                 |   |                                   |                |                               |        |  | c. 24.8  |
|             | GP |       |                      |                              | Poto T c-o<br><i>Kawakawa T</i> | HFD, some pum.<br>Local channelised DFD |                                   |                |                               |        | Medial ash accum<br>Soil formation<br>Fluvial deposits<br>Opunake RS<br>Katikara Sands | 27.3–25<br>27.1<br>c. 27.3–24.8<br>c. 27.3–24.7        |
|             | C  |       |                      |                              |                                 |   |                                   |                |                               | Ngaere |  | 27.3   |

Table 5 continued

| CZ        | EP | EE | Primary volcanics |             | Secondary volcanics SW sector |    | Secondary volcanics SE sector |    | Secondary volcanics NE sector |    | Non-volcanic sediments | Cal. age (ka) |
|-----------|----|----|-------------------|-------------|-------------------------------|----|-------------------------------|----|-------------------------------|----|------------------------|---------------|
|           |    |    | Lavas             | PF deposits | Tephtras                      | LD | DAD                           | LD | DAD                           | LD |                        |               |
|           | GP |    |                   |             |                               |    |                               |    |                               |    |                        |               |
|           |    |    |                   |             |                               |    |                               |    |                               |    |                        |               |
| TE NAMUAN | C  |    |                   |             |                               |    |                               |    |                               |    |                        |               |
|           | GP |    |                   |             |                               |    |                               |    |                               |    |                        |               |
| RAMAN     | C  |    |                   |             |                               |    |                               |    |                               |    |                        |               |
|           | GP |    |                   |             |                               |    |                               |    |                               |    |                        |               |
| OTAKEHOAN | C  |    |                   |             |                               |    |                               |    |                               |    |                        |               |
|           | GP |    |                   |             |                               |    |                               |    |                               |    |                        |               |
| TOKAORAN  | C  |    |                   |             |                               |    |                               |    |                               |    |                        |               |
|           | GP |    |                   |             |                               |    |                               |    |                               |    |                        |               |

Table 5 continued

| CZ           | EP | EE | Primary volcanics |                      | Secondary volcanics SW sector          |    | Secondary volcanics SE sector |    | Secondary volcanics NE sector |    | Non-volcanic sediments   | Cal. age (ka)                |
|--------------|----|----|-------------------|----------------------|--|----|-------------------------------|----|-------------------------------|----|--|------------------------------|
|              |    |    | Lavas             | PF deposits          | Tephtras                               | LD | DAD                           | LD | DAD                           | LD |  |                              |
| WAIHIAN      | C  |    |                   |                      | Tephtras                               |    |                               |    |                               |    | Sediments  | c. 70                        |
|              | GP |    |                   | Te Arei Tephtra      | HFD, local channelised DFD             |    | Runout HFD                    |    | Waïhi                         |    | Fluvial deposits<br>Soil formation<br>Peat accum.<br>Punehu Sands  | c. 75<br>c. 75–70<br>c. 75   |
| WAIWINGOROAN | C  |    |                   |                      |  |    |                               |    | Waingongoro                   |    | Fluvial deposits   | c. 80–75                     |
|              | GP |    |                   |                      | Pumiceous HFD<br>Local channelised DFD |    | Runout HFD                    |    |                               |    | Punehu Sands<br>Puketapu buried forest<br>Manaia Lignite<br>Hauriri Terrace cover-beds<br>Hauriri Marine Bench | <80<br><80<br><80<br>c. 80   |
| OEOAN        | C  |    |                   |                      |  |    | Oeo                           |    |                               |    | Thick peat accum.  | c. 90–85                     |
|              | GP |    |                   | Epüha Tephtra        |  |    | Runout HFD                    |    |                               |    | Inaha Terrace cover-beds<br>Inaha Marine Bench   | 100–80<br><100<br>c. 100     |
| OKAWAN       | C  |    |                   |                      |  |    |                               |    | Okawa                         |    | Thick peat accum.  | c. 105                       |
|              | GP |    |                   | Ninia Tephtra        |  |    | Runout HFD                    |    |                               |    | Rapanui Terrace cover-beds<br>Rapanui Marine Bench   | c. 115–105<br><127<br>c. 127 |
| MOTUNUIAN    | C  |    |                   |                      |  |    |                               |    | Motunui                       |    | Fluvial deposits<br>Soil formation<br>Thick peat accumulation.   | >130                         |
|              | GP |    |                   | Interbedded tephtras |  |    |                               |    |                               |    | Bedded sands   |                              |
| MANGATIAN    | C  |    |                   |                      |  |    |                               |    | Mangati                       |    | Cemented iron-stained sands<br>Ngarino Terrace cover-beds<br>Ngarino Marine Bench                              | c. 200<br><210<br>c. 210     |
|              | GP |    |                   |                      |  |    |                               |    |                               |    |  |                              |

Lithostratigraphic units from Neall (1979, 2003), Neall et al. (1986), Alloway (1989), Alloway et al. (1995, 2005), Platz (2007) and this study

Radiocarbon ages converted to calendar years using the calibration curve from Fairbanks et al. (2005)

CZ chronozone, C collapse, GP growth phase, EP eruptive period, EE eruption episode, PF pyroclastic flow, BAF block-and-ash-flow deposit, B Breccia, L Lapilli, A Ash, T Tephtra, LD lahar deposits, DAD debris-avalanche deposits, HFD hyperconcentrated flow deposits, DFD debris-flow deposits, pum. pumiceous, RS river system

## Conclusions

Remapping of the Opunake and Stratford Formations in coastal cliff exposures of the Mt. Taranaki ring-plain succession revealed a great complexity of volcanoclastic lithofacies and a larger number of debris-avalanche deposits than previously described. These represent distinct units that could be easily recognised and correlated laterally. Overall, five new debris-avalanche deposits were identified and named Te Namu, Tokaora, Waihi, Waingongoro and Oeo Formations. Four previously described units were renamed (Motumate, Rama, Otakeho and Mangati Formations), their stratigraphic position redefined and their lateral distribution mapped in more detail (except for the Mangati in north Taranaki). A number of cohesive debris-flow deposits were recognised, which most likely represent the distal runout of smaller, confined debris avalanches. Correlation of the known Opuā, Pungarehu and Ngaere Formations showed a greater lateral extent in coastal cliff sections than displayed on the geological map by Neall and Alloway (2004).

Overall, a minimum of 14 large debris-avalanche deposits occur within the volcanoclastic ring-plain record of Mt. Taranaki, indicating one major slope failure on average every 10–14,000 years. The deposits reflect a range in volume from small  $<0.1 \text{ km}^3$  debris flows to rare, exceptionally large  $>7.5 \text{ km}^3$  debris avalanches. The exact run-out distance of Taranaki debris avalanches could not be determined, but the deposits extend c. 26–45 km onshore and at least another 6–8 km offshore. Their lateral width in medial coastal cross-sections ranges from c. 9–35 km with a deposit thickness of 2.5 to  $>16 \text{ m}$ .

Hyperconcentrated flow and non-cohesive debris-flow deposits are other common elements of the studied volcanoclastic sequences, indicating that lahars occurred frequently at Mt. Taranaki. Lahar deposits were grouped into stratigraphic intervals since their large number and similar characteristics did not allow mapping of individual units. A stratigraphic overview of the Pleistocene ring-plain succession was based on the correlation of directly and indirectly dated debris-avalanche marker beds and interbedded packages of lahar deposits. This chronological reconstruction of events showed that the same pattern of deposition was repeatedly produced throughout the history of Mt. Taranaki.

The complex and non-uniform lithostratigraphy in Taranaki is integrated into a new volcanic chronozone concept that is based on the identified cyclic pattern of deposition. The developed scheme provides a coherent chronostratigraphic framework that can be applied to the entire volcanic and volcanoclastic succession at Mt. Taranaki but also represents a stratigraphic concept that could be relevant for repeatedly collapsing stratovolcanoes elsewhere.

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