Journal of the Royal Society of New Zealand

ISSN: 0303-6758 (Print) 1175-8899 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzr20

Stratigraphy, age, and correlation of voluminous debris-avalanche events from an ancestral Egmont Volcano: Implications for coastal plain construction and regional hazard assessment

Brent Alloway , Peter McComb , Vince Neall , Colin Vucetich , Jeremy Gibb , Steve Sherburn & Mark Stirling

To cite this article: Brent Alloway , Peter McComb , Vince Neall , Colin Vucetich , Jeremy Gibb , Steve Sherburn & Mark Stirling (2005) Stratigraphy, age, and correlation of voluminous debris-avalanche events from an ancestral Egmont Volcano: Implications for coastal plain construction and regional hazard assessment, Journal of the Royal Society of New Zealand, 35:1-2, 229-267, DOI: 10.1080/03014223.2005.9517782

To link to this article: https://doi.org/10.1080/03014223.2005.9517782

Published online: 30 Mar 2010.

Journal of the Royal Society of New Zealand
Volume 35, Numbers 1 & 2, March/June, 2005, pp 229–267

Stratigraphy, age, and correlation of voluminous debris-avalanche events from an ancestral Egmont Volcano: implications for coastal plain construction and regional hazard assessment

Brent Alloway[1], Peter McComb[2], Vince Neall[3], Colin Vucetich[4], Jeremy Gibb[5], Steve Sherburn[6], and Mark Stirling[1]

Abstract Two previously unrecognised debris-avalanche deposits have been identified on the eastern flanks of Egmont Volcano beneath a thick mantle of tephric and andic soil material that has mostly subdued their topographic expression. The Ngaere Formation is a c. 23 ^{14}C ka large volume (>5.85 km^3) debris-avalanche deposit that is widely distributed over 320–500 km^2 of the north-east, south-east, and south portions of the Egmont ring plain. The second deposit, Okawa Formation, is a c. 105 ka large volume (>3.62 km^3) debris-avalanche deposit that has been mapped over a minimum area of 255 km^2 in northern and north-eastern Taranaki. Both debris-avalanche formations contain axial facies with hummocks composed mainly of block-supported brecciated andesitic debris. A less conspicuous marginal facies, texturally resembling a mudflow, is more extensive. A third debris-avalanche deposit (Motunui Formation) is extensively preserved along the north Taranaki coast where it is truncated by a c. 127 ka wave cut surface (NT2) and closely overlies a c. 210 ka wave cut surface (NT3). The source of this debris-avalanche deposit is unknown.

Side-scan sonar and shallow seismic profiling have been useful in accurately delineating the distribution of combined Okawa and Motunui debris-avalanche deposits in the offshore environment but cannot distinguish between the two deposits or enable onshore spatial and volumetric estimates for each unit to be revised. However, the widespread occurrence of debris-avalanche rock material offshore does emphasise the importance of this lag material altering the orientation of the coast influencing both wave climate and rates of coastal erosion. Similarly, the extensive onshore occurrence of debris-avalanche rock material appears to be a significant factor in widening of the north Taranaki coastal plain and preservation of the NT2 and NT3 uplifted marine terrace surfaces.

Initiation of collapse by magmatically-induced seismicity is apparently common at many stratovolcanoes. Emplacement of Ngaere Formation was immediately preceded

[1]Institute of Geological and Nuclear Sciences (GNS), Gracefield Research Centre, P.O. Box 30 368, Wellington, New Zealand.
[2]Marine Consulting and Research, ASR Ltd, 3/17 Nobs Line, New Plymouth, New Zealand.
[3]Institute of Natural Resources, Massey University, Private Bag 11 222, Palmerston North, New Zealand.
[4]17 Ruru Street, Waikanae, New Zealand.
[5]Coastal Management Consultancy Ltd, 555 Esdaile Road, RD 6, Tauranga, New Zealand.
[6]GNS, Wairakei Research Centre, Private Bag 2000, Taupo, New Zealand.

R04013; Received 13 August 2004; accepted 5 April 2005; Online publication date 27 July 2005

by a magmatic fall unit and is directly overlain by a closely spaced sequence of 13 fall units. In contrast, there is no evidence to indicate that an eruptive event triggered or immediately followed the Okawa debris-avalanche event, but seismically induced gravitational sliding cannot be discounted.

Egmont Volcano has repetitively collapsed over its c. 127 ka history and has generated at least five voluminous landscape-forming debris-avalanche deposits. Probabilistically-based return times are calculated at c. 1967 ^{14}C yr for volumes $\geq$0.15 km^3 and c. 21 000 ^{14}C yr for volumes $\geq$7.5 km^3. Despite lower return times in comparison to tephra emission, Egmont Volcano is an inherently unstable cone because it comprises interbedded lavas and unconsolidated volcaniclastic deposits with a high slope angle overlying a faulted basement of Tertiary sediments. Should eruptive activity recommence and coincide with significant upper cone dilation, then the likelihood of a gravitational cone collapse is expected to increase although critical thresholds remain to be modelled. Fortunately, the Taranaki Regional Volcanic Contingency Plan is based on pre-emptive evacuation which is intended to minimise loss of life in advance of an eruptive and/or cone collapse event occurring.

Keywords Taranaki; Egmont Volcano; debris-avalanche; gravitational collapse; andesitic tephra; late Quaternary

INTRODUCTION

The Taranaki landscape of western North Island, New Zealand is dominated by the 2518 m andesitic Egmont Volcano. Egmont, the youngest and most southerly volcano of the Taranaki Volcanic Succession, is the second highest mountain in the North Island and the largest andesitic stratovolcano in New Zealand. Deposits of fragmental debris at the base of Egmont Volcano display a surface of numerous hills and small mounds. In early geological surveys these "conical hills" were considered to be a series of small independent volcanic vents (de Clarke 1912; Morgan & Gibson 1927). Bossard (1928) later suggested that these hills were blisters on lava flows. It was Grange (1931) who was first to argue that they were remnants of a huge lahar flow based on their similarity to other volcanic mudflow deposits. Neuman van Padang (1939) and van Bemmelen (1949) attributed similar hills at the base of several Indonesian volcanoes to "landsliding or avalanching" of a sector of the volcanic cone, with the resultant deposits described as volcanic breccias. In Japan, research prior to the 1980 Mt St Helens eruption suggested that these deposits differed from lahars. Murai (1961) used the term "dry mudflow" to distinguish debris-avalanches emplaced by "gravitational forces without the agency of water". Mizuno (1964) also distinguished fragmental deposits of "avalanche-type" from those of "flow-type". Then in 1975, Ando & Yamagishi (1975) concluded that many of the mudflow hills at the base of Japanese volcanoes actually formed by either cold or hot avalanches. The 1980 Mt St Helens eruption was the first instance in which details of a large volcanic debris-avalanche were observed and documented at the time of emplacement (e.g., Glicken et al. 1981; Voight et al. 1981, 1983; Glicken 1986) and this event has provided a pivotal model for the interpretation of similar deposits elsewhere (e.g., Soya & Katsui 1981; Mimura et al. 1982; Crandell et al. 1984).

In Taranaki, Neall (1979) mapped three late Quaternary laharic breccia deposits extending west and south-west from Egmont Volcano (Fig. 1). These deposits showing development of mounds or "conical hills" (Morgan & Gibson 1927), were named Opua, Warea, and Pungarehu Formations and later identified as debris-avalanche deposits. The most spectacular of these three deposits is the Pungarehu Formation with an estimated minimum volume of 7.5 km^3. This deposit was mapped between 10 and 27 km from the present summit and covers an area of between 200 and 250 km^2 (Neall 1979; Ui et al. 1986).

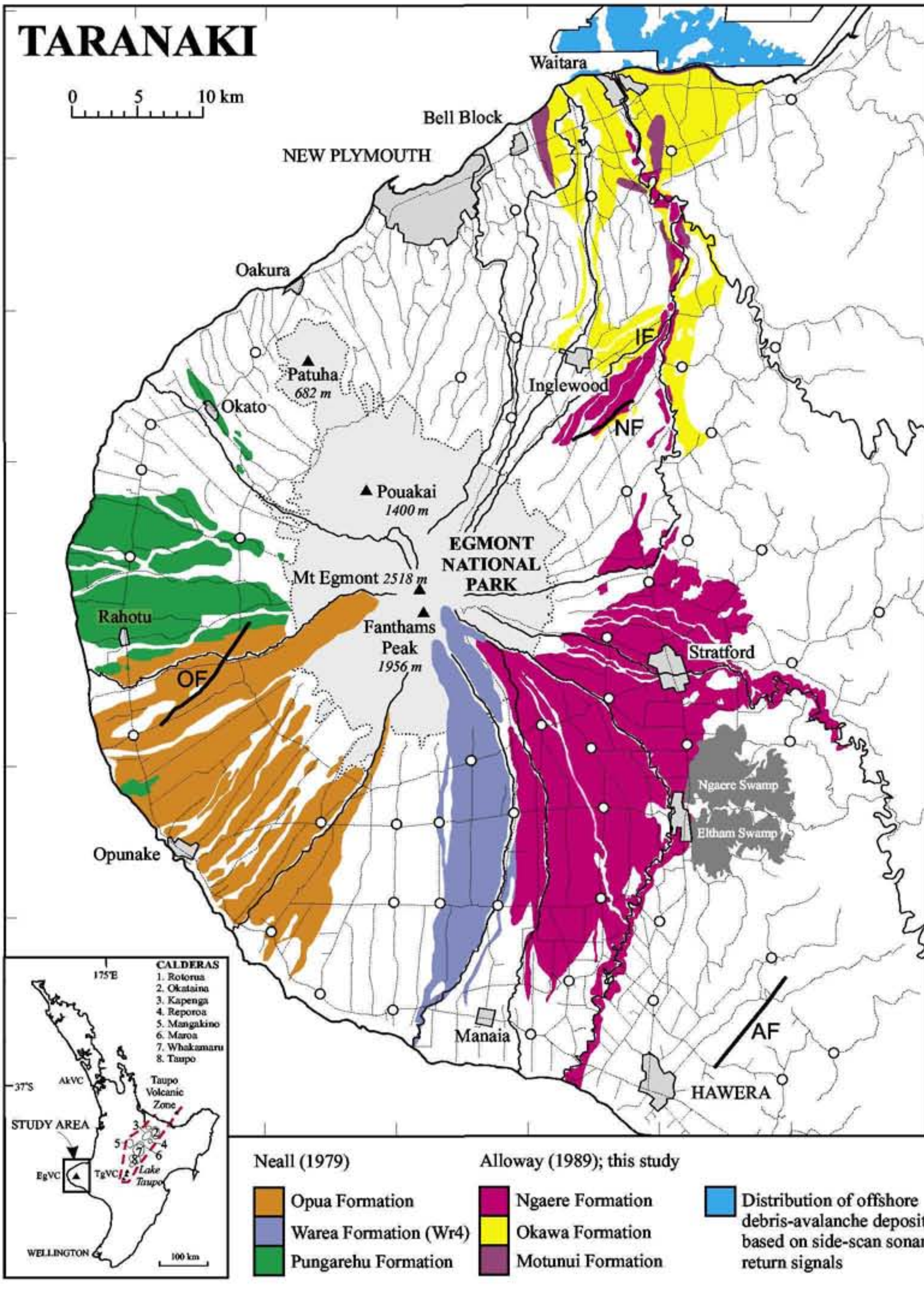


Fig. 1 Distribution of debris-avalanche deposits offshore north Taranaki as determined by side-scan sonar, as well as the location of onshore normal faults. IF, Inglewood Fault; NF, Norfolk Fault; OF, Oaonui Fault; AF, Ararata Fault. Inset shows study area, rhyolitic caldera volcanoes of Taupo Volcanic Zone, Tongariro Volcanic Centre (TgVC), Egmont Volcanic Centre (EgVC), and Auckland Volcanic Field (AkVF).

In this study, two previously unrecognised debris-avalanche deposits have been identified on the eastern flanks of Egmont Volcano beneath a thick mantle of tephric and andic soil material, as well as laharic deposits that have mostly subdued their topographic expression.

Of the three debris-avalanche deposits mapped by Neall (1979), the age of the south-eastern lobe of the Warea Formation (Wr4) is significantly younger than the other lobes. An age of between 3.6 and 4.2 ^{14}C ka is suggested for Wr4 based on recent tephra identification (B. V. Alloway unpubl. data) and this revised age is used in this study to calculate debris-avalanche volume-frequency return times.

Andisols and tephrochronology

In Taranaki, allophane dominated cover-bed (andic) deposits have formed from intermittent accretion and subsequent weathering of aerially transported fine-grained volcaniclastic sediment. Andic deposits in north-eastern Taranaki comprise six reddish beds with moderately to well developed soil structure alternating with five contrasting yellowish loess-like beds with massive to poorly developed soil structure. Reddish beds accumulated during warm climatic episodes, and yellowish units accumulated during cool or cold episodes (Alloway 1992a,b). The age of these reddish and yellowish beds can be established from the presence of multiple Egmont derived andesitic tephras near the ground surface, the occurrence of widespread central North Island rhyolitic tephras found within the succession, and by matching the climatic intervals deduced from the succession of andic beds to the marine oxygen isotope stages (OIS). These andic beds where interbedded with debris-avalanche deposits have also been useful in constraining their approximate emplacement age. For instance, Ngaere Formation occurs within uppermost yellowish bed (Sy1), which is correlated with early and mid OIS 2 because it contains Aokautere Ash, a widespread c. 22.6 ^{14}C ka silicic chronohorizon derived from Taupo Volcano in central North Island (Froggatt & Lowe 1990) and the c. 23.4 ^{14}C ka Tuikonga Tephra derived from Egmont Volcano (Alloway et al. 1995). The older Okawa Formation occurs beneath a prominent reddish bed (Sr5) that is correlated by Alloway (1989) to the global warm period and high sea level transgression of OIS 5c. This correlation is supported by palynological evidence obtained from the highly carbonaceous material enveloping Okawa Formation at Airedale Reef (Alloway 1989; Newnham & Alloway 2001, 2004).

Nomenclature and facies architecture

The main internal structure of debris-avalanche deposits can be subdivided into two major components: (1) fragmental rock clasts (FRCs), and (2) matrix. An FRC is here defined as a fragmented or deformed piece of lava or layered volcaniclastic material commonly preserving stratification and/or intrusive contacts formed within the original volcanic edifice. In Taranaki, the most commonly recognised FRC is andesitic lava that is commonly brecciated forming a diamicton of homogeneous composition. The scheme of Sundell & Fisher (1985) has been used to define the FRC size classes: boulder (0.256–10 m), megaboulder (10–100 m), block (100–1000 m) and megablock (1–10 km). A gravel-sized class of FRCs (0.002–0.256 m) is also used. In this study, the matrix is referred to as inter-clast matrix and is defined as all the material within the deposit surrounding the FRCs and <0.002 m in diameter. It should not be confused with the matrix of an FRC, which is here termed intra-clast matrix.

Inter-clast matrix includes all blended, unsorted, and unstratified parts of the deposit and consists of material ranging in size from clay to very coarse sand. Incorporated with the inter-clast matrix are rip-up clasts of plastically distorted soil, peat and tephra layers, clasts with variable rounding, and wood fragments derived from the terrain beneath. Inter-clast matrix is more abundant in inter-mound areas and is predominant in the distal and lateral margins of the deposit.

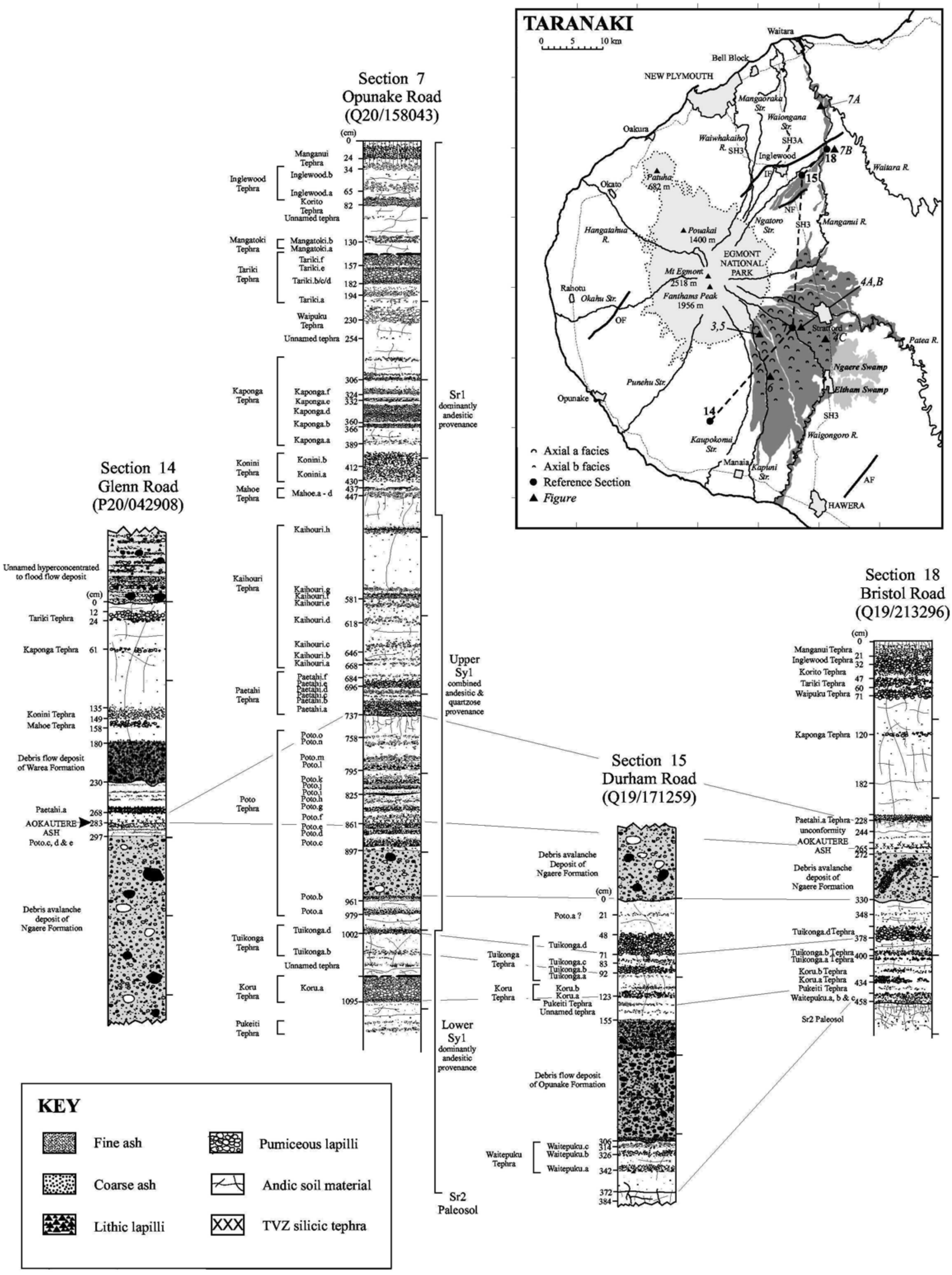


Fig. 2 Stratigraphic columns showing the correlation of Ngaere Formation (dark grey unit in inset map) and enveloping tephra beds from Glenn Road (Section 14), Opunake Road (Section 7), Durham Road (Section 15) and Bristol Road (Section 18).

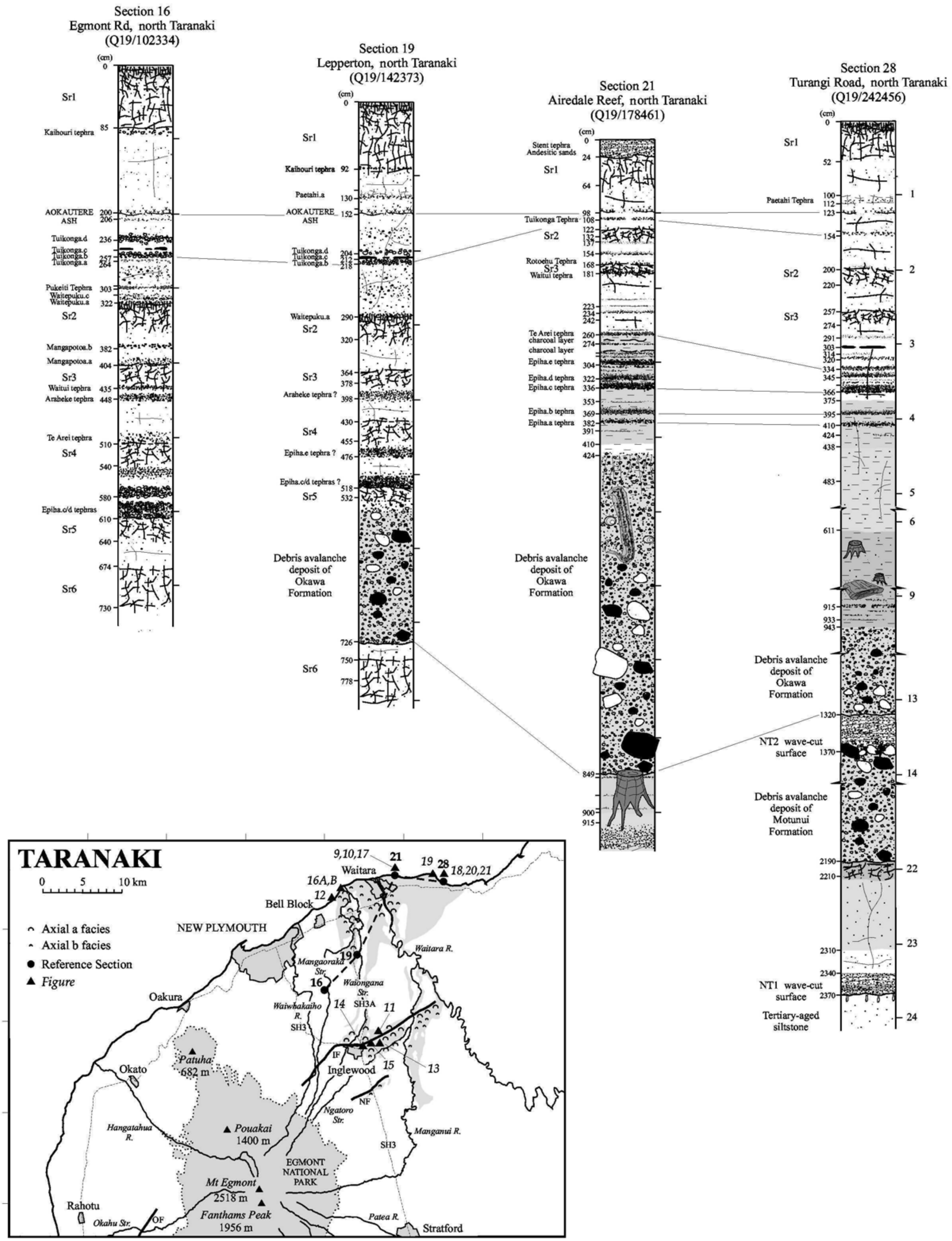


Fig. 8 Stratigraphic columns showing the correlation of Okawa Formation (dark grey area in inset map) and enveloping andic and tephra beds from Egmont Road (Section 16), Lepperton (Section 19), Airedale Reef (Section 21) and Turangi Road (Section 28).

The lithology and relative proportion of inter-clast matrix to the FRCs vary not only throughout each debris-avalanche deposit but also between the deposits. These variations are influenced by the composition of the original volcanic edifice, type and scale of the initial volcanic event, and also the occurrence of nearby ridges, channel systems, and lowlands.

The area of a deposit where FRCs are predominant, and where a hummocky surface develops, was mapped as an axial facies by Neall (1979) and as a block facies by Crandell et al. (1984). In contrast, the area where inter-clast matrix is predominant was mapped as marginal facies by Neall (1979), as matrix facies by Crandell et al. (1984), as main facies by Mimura & Kawachi (1981), and matrix mixture by Ui (1983).

In mapping prehistoric debris-avalanche deposits in eastern Taranaki, an adaptation of axial and marginal facies nomenclature was considered more appropriate since it distinguishes the mapping units from sedimentological descriptions. Three facies are recognised (Alloway 1989; Palmer et al. 1991) and are referred to as axial a, axial b, and marginal facies.

Axial a facies is defined as a mappable area where fragmental rock clasts dominate, with <30% inter-clast matrix, and where the surface topography is dominated by a concentrated area of steep sloping hills and mounds up to 50 m high with basal diameters as much as 500 m.

Axial b facies is defined as an area where the proportion of inter-clast matrix is subdominant to dominant (30–90%) relative to FRCs and where the surface physiography is dominated by sparsely distributed mounds and hills ≤10 m high with basal diameters <25 m. This facies corresponds with the mixed block and matrix facies of Glicken (1986).

Marginal facies is defined as an area where the proportion of inter-clast matrix is dominant (>90%) relative to FRCs and where the surface physiography is without mounds or hills.

NGAERE FORMATION (NEW FORMATION)

The Ngaere Formation is named after the east Taranaki farming community of Ngaere situated on State Highway 3, 4 km south of Stratford. It is a large volume (>5.85 km^3) debris-avalanche deposit that is extensively distributed over the north-east, south-east, and south portions of the Egmont ring plain with an areal extent between 320 and 500 km^2 (Fig. 2). On the south-eastern lower flanks of Egmont Volcano the most conspicuous feature of Ngaere Formation is the extensive hummocky landscape (Fig. 3). However, in the south-eastern sector of Egmont Volcano, a thick succession of weathered tephra fall mantle has reduced the physiographic expression of these hummocks to such an extent that only the largest mounds have surface expression.

Stratigraphy

The stratigraphy associated with Ngaere Formation can be seen in Fig. 2. Ngaere Formation occurs within the uppermost yellowish bed (Sy1). This andic unit is subdivided into a lower Sy1 andic soil unit of dominantly andesitic provenance and an upper Sy1 andic unit of combined andesitic and quartzose provenance. Ngaere Formation occurs near the base of the upper Sy1 and is interbedded between Egmont-sourced ash and lapilli beds (Poto.a and b beds) of Poto Tephra (c. 20.9–22.7 ^{14}C ka) beneath and the c. 22.6 ^{14}C ka Aokautere Ash sourced from Taupo Volcano above. In areas of the south-eastern sector dominated by mounds and hills (axial a facies), the upper contact of Ngaere Formation ranges from sharp to diffuse and usually separates megaboulders and blocks below, from a closely spaced overlying succession comprising Poto.c, d, and e beds of Poto Tephra and Aokautere Ash (Alloway et al. 1995). The lower contact of Ngaere Formation in these areas has not been observed.

In the extensive inter-mound areas of the south-eastern sector (axial b facies) the lower contact is usually sharp and directly overlies Poto.b bed of Poto Tephra and closely overlies coarse ash and lapilli beds of Tuikonga Tephra (Section 7, Fig. 2). In areas of the marginal

Fig. 3 Subdued hummocky surface physiography of Ngaere Formation (axial a facies) on Upper Palmer Road (Q20/107035) in the south-eastern sector of Egmont Volcano. A thick succession of tephra-fall mantle has reduced the physiographic expression of these hummocks to such an extent that only the largest fragmental rock clasts (FRCs) have surface expression.

facies, the upper contact of Ngaere Formation is distinct and separated from Aokautere Ash above by <0.08 m of medial andic material. Here, the lower contact of Ngaere Formation is sharp and separated from Tuikonga.d bed of Tuikonga Tephra below by <c. 0.40 m of medial andic material (Section 18, Fig. 2).

Associated eruptive deposits

At Section 7 (c. 15 km south-east of the present summit) Ngaere Formation is directly underlain by a c. 6 cm thick, very well sorted, reverse graded, dark grey, monolithologic, medium to coarse sandy ash (Poto.b bed of Poto Tephra; Fig. 4A,B). This unit is exposed at two other sites (Q20/218025, Q20/215009) located c. 23 km south-east of the present summit (Fig. 4C). At these localities Poto.b bed comprises <c. 3 cm thick discontinuous ash. It is clear that the texture and sorting (strongly leptokurtic) characteristics of Poto.b bed represent a tephra-fall eruptive that immediately preceded the deposition of the avalanche deposit. This unit does not appear to be associated with any equivalent "pyroclastic density current" deposit.

Ngaere Formation, in the south-east lower flanks of Egmont Volcano, is directly overlain by a sequence of 13, closely spaced, dominantly scoriaceous tephra beds of Poto Tephra (Fig. 5) which represent a post-avalanche phase of high frequency eruptive activity and active reconstruction of a lava dome or central cone. It was during this post-avalanche eruptive phase that another large-volume debris-avalanche deposit (Pungarehu Formation) was initiated from the western side of the reconstructing Egmont Volcano.

Initially, deposits of Ngaere Formation were tentatively correlated with those of Pungarehu Formation (Neall 1979). The andesitic tephra layers most useful in identifying Ngaere Formation in eastern sectors of Egmont Volcano are not well preserved in the west due to their limited westward (dominantly upwind) distribution. Because wood fragments within Pungarehu Formation were dated (NZ1623A) at 22 100 ± 600 ^{14}C yr and closely correspond in age with deposits of Ngaere Formation (closely underlying the c. 22.6 ^{14}C ka Aokautere Ash), provisional correlation was based upon equable age. However, fieldwork in western Taranaki suggests that Pungarehu Formation closely post-dates deposition of Aokautere Ash. From this evidence, it appears that Ngaere and Pungarehu Formations represent two similar but chronologically distinct deposits that relate to the same eruptive episode.

Ngaere Formation is estimated to have an age range of between c. 22.6 and 23.4 ^{14}C ka based on its position with respect to the enveloping Aokautere Ash above and Tuikonga Tephra below (Alloway et al. 1995).

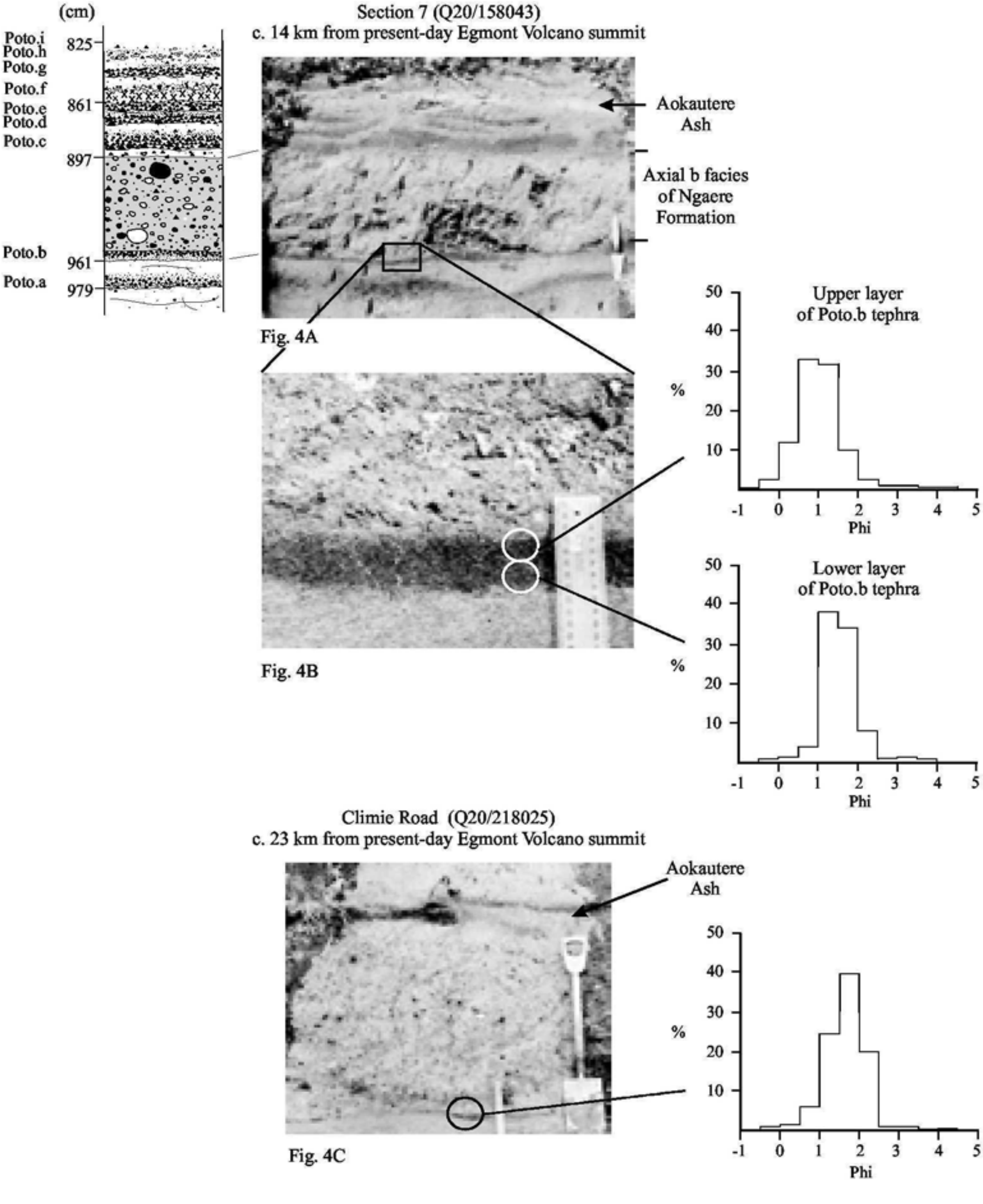


Fig. 4 Ngaere Formation with underlying precursory eruptive (Poto.b tephra) exposed in **A,B**, the vicinity of Cardiff on Opunake Road (Q20/158043) and **C**, Climie Road near Ngaere (Q20/218025). Grain size analysis of Poto.b tephra at these localities exhibiting strong leptokurtic characteristics indicative of a tephra-fall origin.

Lithology

FRCs are the most distinctive component of Ngaere Formation. They most commonly occur as elongate or tabular, grey to very dark grey clasts of andesitic breccia with an intra-clast matrix of identical composition, and may preserve stratification formed within the original volcanic edifice. The contacts between FRCs are often sharp and irregular. With increasing

Fig. 5 Upper contact of Ngaere Formation on Upper Palmer Road (Q20/108037) in the south-eastern sector of Egmont Volcano. Ngaere Formation is overlain by scoriaceous-pumiceous units of Poto Tephra. The position of Aokautere Ash interbedding Poto Tephra is indicated by arrows.

distance from Egmont Volcano, the proportion of FRCs steadily decreases relative to the inter-clast matrix. Similarly, with increasing distance from source, progressive disaggregation and plastic deformation reduces the average diameter of FRCs to gravel size (e.g., Fig. 6). However, some of this size reduction could also be the result of selective deposition of large FRCs as competence of the flow decreased.

The most variable and heterogeneous component of Ngaere Formation is inter-clast matrix (Fig. 7A). This is recognised by lack of bedding and heterolithologic composition. The dominant colour of the inter-clast matrix is yellowish-brown (10YR 5/4 to 5/8), being nearly identical to the medial material underlying Ngaere Formation. Pale brown, yellow, grey and reddish yellow colours predominate in the FRC and pumice fragments. Variations of these colours appear to be influenced by the relative proportions of the original source materials, attrition of FRCs and material incorporated from units underlying the formation. In the north-eastern sector, a wedge of Ngaere Formation is exposed, unconformably overlying an older sequence of tephra beds and andic interbeds along a road cut adjacent to the Manganui River (Section 18; Q19/213296). Here a 0.70 m thick sequence comprising the uppermost tephra bed (Tuikonga Tephra) has been locally incorporated and plastically deformed within the formation (Fig. 7B).

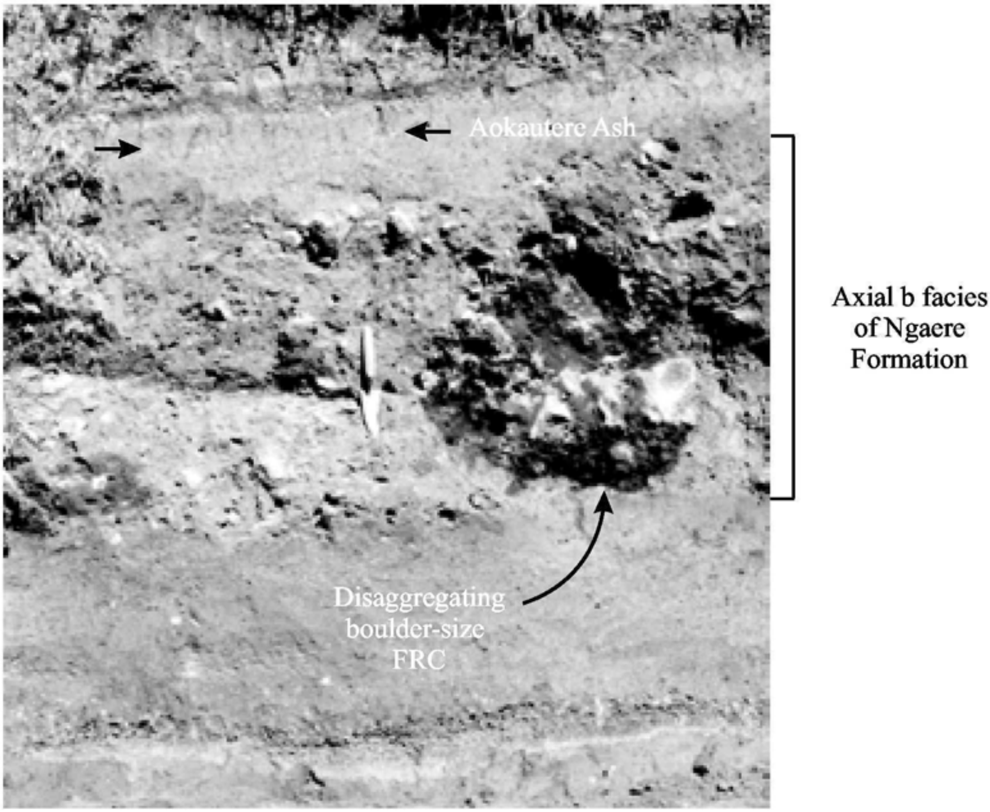


Fig. 6 Ngaere Formation exposed on Eltham Road near Kapuni Stream (Q20/114969). A boulder size fragmental rock clast (FRC) is supported within clay rich inter-clast matrix material of similar thickness. Note the complex interfingering of FRC intra-clast and clay rich inter-clast components.

Physiographic expression

The most conspicuous feature of Ngaere Formation on the south-eastern flank of Egmont Volcano is the extensive hummocky landscape between Manaia and Pembroke Roads (Fig. 3). This landscape can be subdivided into two physiographic types: (a) clustered hummocks with large basal areas and small inter-mound areas (occupied by axial a facies); and (b) scattered hummocks with variable basal diameters and extensive inter-mound areas (occupied by axial b facies). Clustered hummocks (axial a facies) extend eastward from the Egmont National Park Boundary to State Highway 3 in the vicinities of Stratford and Midhirst (c. 18–20 km east of the present Egmont summit). Scattered hummocks (axial b facies) have also been identified along State Highway 3 between Eltham and Stratford, c. 23 km south-east of the present day summit. The most distal mounds correlated with Ngaere Formation are located just north of Matapu c. 25 km south-east from the present summit.

On the eastern lower flanks of Egmont Volcano, north of Pembroke Road, individual mounds and mound clusters of Ngaere Formation protrude beneath surficial fluvio-laharic deposits of Te Popo and Ngatoro Formations that are confined to the flat, tephra-mantled inter-mound areas. Further north, hummocks of Ngaere Formation occur on elevated terrain in the vicinity of Waipuku and Croydon Roads (c. 18 km east of the present Egmont summit).

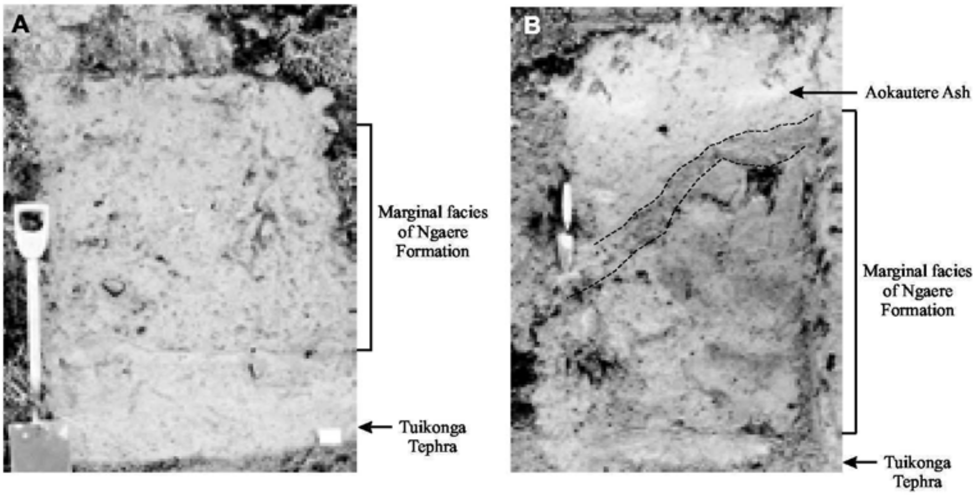


Fig. 7 Ngaere Formation (mapped as marginal facies) exposed **A**, near Manganui Road in the Waitara River valley (Q19/207364) and closely underlain by Tuikonga Tephra and **B**, in a prominent road cut either side of Bristol Road 0.1 km east of the Manganui River Bridge (Q19/213296) and closely overlain by Aokautere Ash. The occurrence of Ngaere Formation within the Manganui/Waitara River valleys, and on the north-eastern portions of the Egmont ring plain suggest a considerably wider distribution than identified in this study.

The density of mounds per square kilometre, as determined from aerial photographs, decreases with increasing distance from Egmont Volcano. Distally in the vicinity of Ngaere, mound density is generally low, not exceeding c. 35 per km^2, but nearer to Egmont Volcano, mound density may exceed 135 per km^2 in small areas between Kaponga and Cardiff.

Distribution

Following initiation of the avalanche the constituent materials were broken up, mixed, and dispersed throughout a minimum area of 320 km^2 on the eastern and south-eastern lower flanks of Egmont Volcano. The occurrence of hummocks east of State Highway 3 and outcrops exposed near the junction of Standish and Ahuroa Roads (Section 21 of Alloway 1989; c. 27 km east from the present summit) suggest that Ngaere Formation extends considerable distances further east towards the Tertiary hill country. An andic-rich diamicton deposit is described within quarried cover-beds of an extensive fluvial terrace directly adjacent to the Patea River in the vicinity of Toko (Simpson 1988). At this locality, the diamicton is closely overlain by Aokautere Ash and is correlated with Ngaere Formation. On this basis, it seems highly probable that the continuous phase of Ngaere debris-avalanche extended a considerable distance down the Patea River valley. Further work is required to accurately determine its distribution here.

Hummocks and debris of Ngaere Formation border the western margins of Ngaere and Eltham Swamps but their extent further east is unknown. These swamps appear to have formed in response to deposits of Ngaere debris-avalanche which blocked drainage tributaries connecting the east Taranaki hill country with the Taranaki coast, and resulted in the formation of two impounded drainages. A narrow ridge of Tertiary-aged mudstone (along Rawhiti Road) separates Ngaere Swamp from Eltham Swamp. On the north side of this narrow ridge, the ground surface of Ngaere Swamp is notably higher in elevation than the surface of Eltham Swamp. This elevation difference is due to differential blockage of the catchment tributaries by Ngaere Formation at two different elevational contours.

The extent of Ngaere Formation north of Waipuku Stream is difficult to ascertain because the formation is infrequently exposed beneath thick deposits of younger fluvio-laharic, tephric, and andic medial-ashy deposits. Ngaere Formation is exposed in the vicinity of Inglewood (Section 15 of Fig. 2) and along the Manganui River (Section 18 of Fig. 2; Fig. 7B). It is also recognised within the confines of the Waitara River valley further north at Q19/207364 (Fig. 7A) and Q19/194390.

In south Taranaki, the extent of Ngaere Formation is difficult to ascertain west of Manaia Road and south of a line extending between Kaponga and Matapu due to inadequate exposure. A >4 m thick andic-diamicton deposit is exposed at the junction of Skeet and Upper Glenn Roads, c. 12 km south-west of Kaponga (Section 14 of Fig. 2), which is here correlated with Ngaere Formation because it closely underlies Aokautere Ash as well as Poto.c to Poto.e beds of Poto Tephra.

From these meagre outcrop data it appears that Ngaere Formation is also extensively distributed to the north-east, south-east, and south portions of the Egmont ring plain. It also appears that Ngaere Formation was channelled down the Manganui/Waitara River valley to the north Taranaki coast. The 320 km^2 areal extent of Ngaere Formation is therefore considered a minimum estimate, and a maximum estimate is 500 km^2. At present, Ngaere Formation is calculated to have a minimum volume of c. 5.85 km^3 (Alloway 1989).

OKAWA FORMATION (NEW FORMATION)

Okawa Formation is named after Okawa Trig. (Q19/199365) located adjacent to the Waitara River valley and c. 8 km to the south-east of Waitara township. Prominent mounds of a voluminous debris-avalanche deposit mapped as Okawa Formation (Alloway 1989) can be clearly observed on the north-eastern margin of the Egmont ring plain (20 km from the present Egmont summit). This debris-avalanche deposit has been mapped over a minimum area of 255 km^2 in northern and north-eastern Taranaki (Fig. 8), and has a calculated minimum volume of c. 3.62 km^3 (Alloway 1989).

Stratigraphy

Stratigraphic correlation columns for Okawa Formation are presented in Fig. 8. The type section of Okawa Formation is here designated as a prominent north-facing cliff exposure at Airedale Reef, 1.4 km east of the Waitara River mouth (Section 21, Fig. 8). The base of the exposed section comprises >0.30 m of massive to cross-bedded, moderately well to well sorted grey andesitic sands which upwardly grade to c. 0.85 m of lignite that contains wood and at least two unnamed andesitic tephras of fine lapilli to coarse sand texture. At low tide, the lignite, with numerous tree stumps in growth position, is exposed on an extensive beach platform which gently descends below present sea level (Fig. 9). Overlying the lignite in the cliff section is a c. 4 m thick laharic diamicton which has been mapped as marginal facies of Okawa Formation (Alloway 1989). Along most of the exposed cliff section, the upper boundary of Okawa Formation is nearly planar. However, in part of the cliff section the Okawa Formation appears to mantle a pre-existing physiographic depression resulting in the development of a shallow concave basin on its upper surface. Within this basin is a c. 1.6 m thick lignite deposit containing wood and units of Epiha Tephra (Alloway 1989). Above this lignite deposit the remainder of the section comprises c. 2.6 m of andic material with proportionately thinner andesitic tephra beds.

Associated eruptive deposits

Closely underlying Okawa Formation at Airedale Reef (Section 21, Fig. 8) is a 1 cm thick dominantly pumiceous coarse ash and fine lapilli bed in lignitic material (Fig. 10A) that

Fig. 9 Okawa Formation at Airedale Reef (Q19/178461) directly overlies highly carbonaceous muds with numerous trees in growth position exposed on an extensive beach platform. The c. 4 m thick Okawa debris-avalanche deposit and overlying upper organic sequence can be observed in the cliff behind.

provides a distal record of pre-avalanche magmatic activity at the ancestral volcano. Closely overlying Okawa Formation is a sequence of seven dominantly pumiceous coarse ash and fine lapilli beds that provide a distal record of post-avalanche eruptive activity (Fig. 10B). At present there is no evidence nearer to source area that indicates an eruptive event either directly triggered the Okawa avalanche or immediately followed from the collapse.

Distribution

Mounds of Okawa Formation are concentrated principally within a c. 2.5 km wide belt that extends north-east from the vicinity of Inglewood (Fig. 11) c. 33 km from the present Egmont summit. Immediately north-east of Inglewood, hummocky mounds are also conspicuous on a small area of elevated and dissected remnant of the Old Surface, previously mapped as Eltham Surface (Grant-Taylor 1964; Hay 1967; Neall 1979) and renamed Old Surface (Neall & Alloway 2004) after Old Trig. (Q19/137345). These mounds suggest that the avalanche had sufficient momentum to partially surmount elevated surfaces on the up-thrown side of the Inglewood Fault.

The major portion of the avalanche was then deflected north-east for c. 7 km along the Inglewood Fault scarp, before the main bulk entered the Manganui River valley and became channelised for a further c. 18 km northwards to the coast. That portion which did not flow down the Manganui River valley continued for a further 4 km along the Inglewood Fault scarp to the present course of the Waitara River.

A subsidiary portion of the avalanche that surmounted the fault scarp at Inglewood became channelised northward along the Waiongana Stream valley. This valley provided a closer and

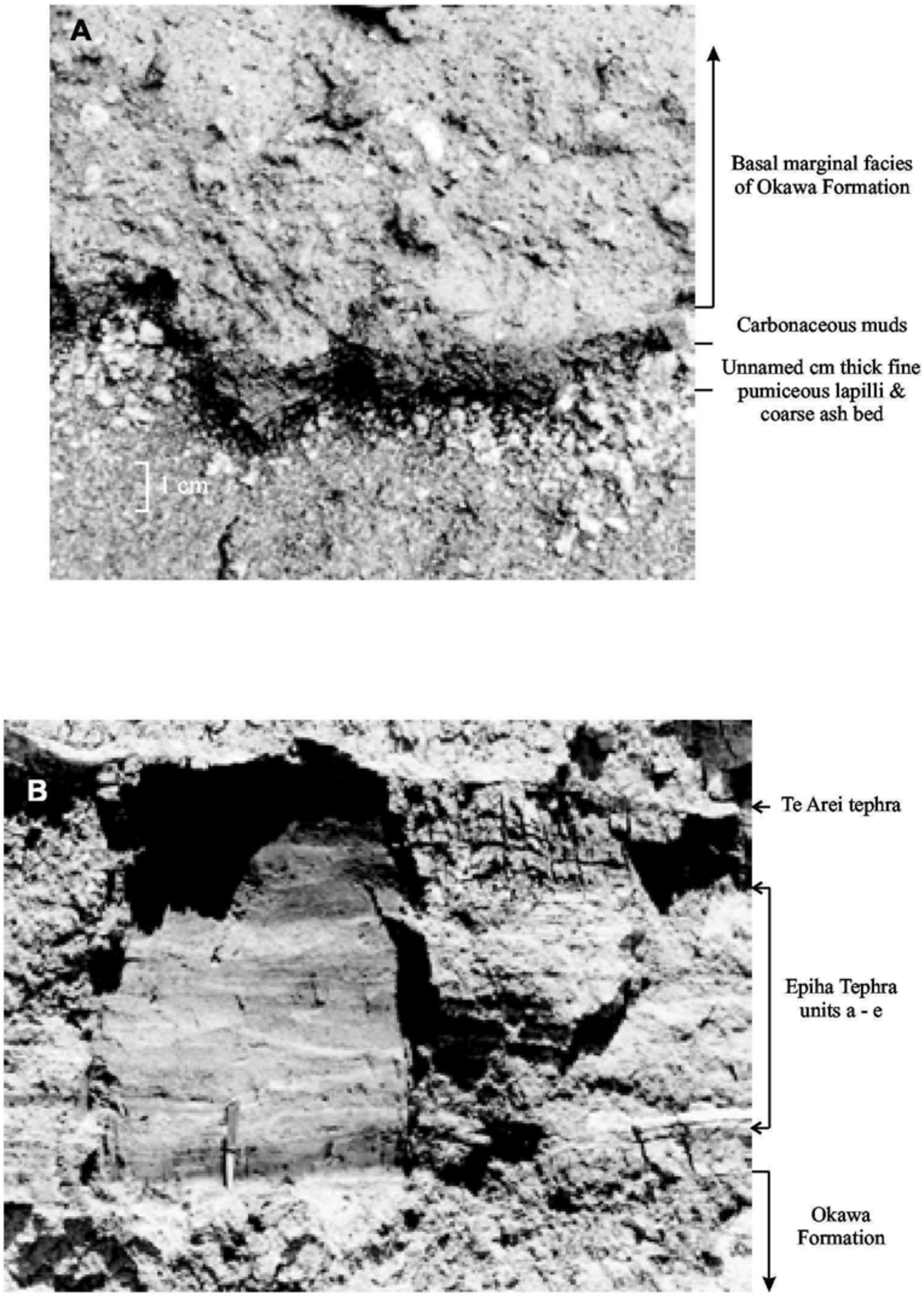


Fig. 10 **A**, Marginal facies of Okawa Formation at Airedale Reef (Section 21, Fig. 8) closely underlain by an unnamed pumiceous fine lapilli bed which provides a distal record of pre-avalanche magmatic activity at the ancestral volcano. **B**, Pumiceous coarse ash and fine lapilli beds of Epiha Tephra closely overlying Okawa Formation provide a distal record of post-avalanche eruptive activity.

Fig. 11 View of hummocky surface topography of Okawa Formation (mapped as axial a facies) on Lincoln Road (Q19/171288) north-east of Inglewood. The mounds of Okawa Formation are concentrated principally within a c. 2.5 km wide belt that extends north-east from Inglewood (middle-right), parallel with Bristol Road along the southern downthrown side of the Inglewood Fault to just west of the Waitara River. Mt Taranaki (Egmont Volcano) in distance.

more direct route to the northern coastline than the main flow path down the Manganui/Waitara River valleys. When the avalanche emerged from the confines of the Waiongana valley, it spread laterally as a broad lobe across three extensive uplifted marine terraces (named youngest to oldest: NT2, NT3, and NT4). The two fossil cliffs separating these terraces were buried, subduing their topographic expression. The axis of the avalanche remained parallel to the Waiongana Stream valley and is defined by a hummocky belt of prominent mounds that extend to near the Waiongana Stream mouth. A cross-section of this distal portion of the avalanche from axis to margin is continuously exposed in the coastal cliffs for c. 2 km south-west from the Waiongana Stream mouth (Fig. 12). In this vicinity, Okawa Formation drapes over a fossil cliff bounded at the inner edge of NT2 terrace, and partially surmounts last interglacial sand dunes on the NT3 terrace. Here the avalanche deposit is mostly enveloped by peaty and carbonaceous clayey materials with numerous interfingering tephra beds.

The other lobe of the avalanche confined within the Manganui/Waitara river valley appears to have only partially surmounted the higher marine terraces on the coastal plain. As it emerged from the confines of the valley it spread laterally to form an area of scattered debris mounds, just seaward of the fossil cliff cut by the NT2 marine transgression. This portion of the avalanche does not appear to extend further east than the Onaero River on the NT2 terrace.

Mounds are also present on either side of the Waiongana Stream valley immediately to the north of Inglewood. South-east of Inglewood, scattered mounds protrude from beneath thick surficial deposits of younger debris-flow and debris-avalanche deposits. Closer towards

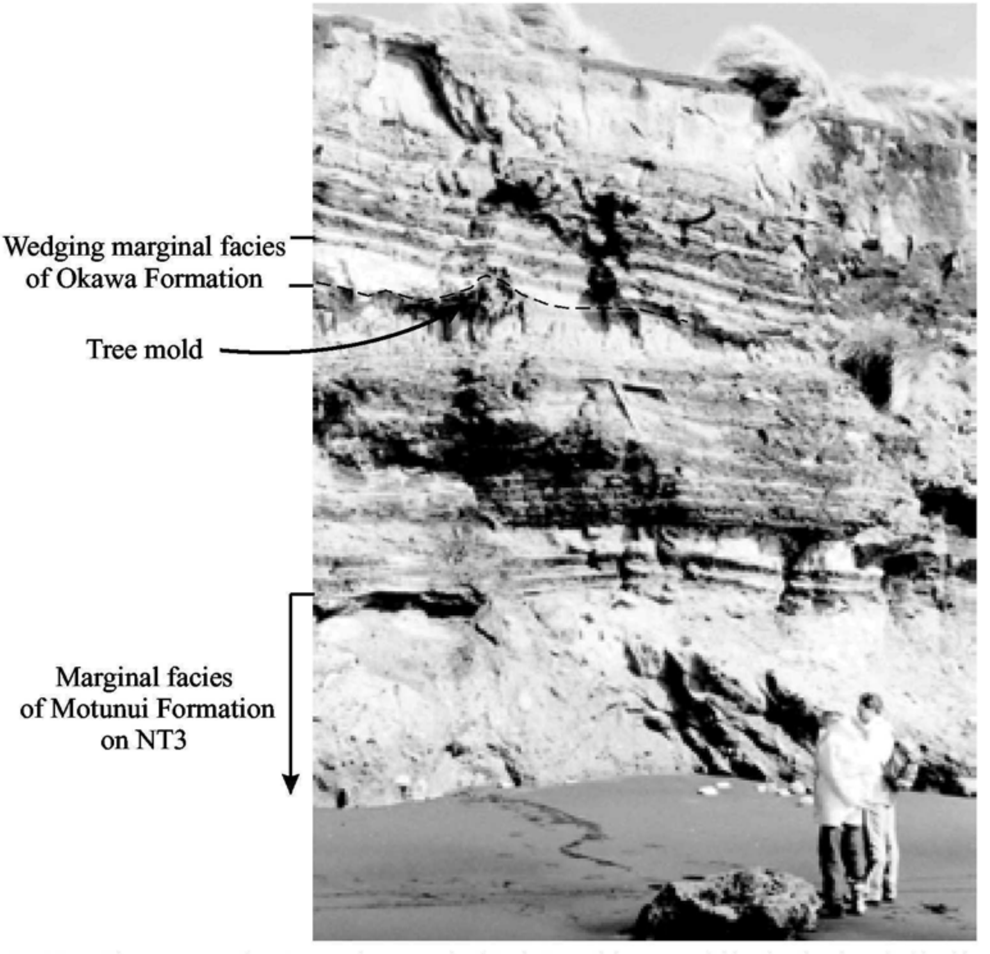


Fig. 12 Okawa Formation (mapped as marginal facies) wedging out within the dominantly lignitic cover-beds of NT3 terrace mid way between the Waiongana Stream mouth and Bell Block beach along the north Taranaki coast. Motunui debris-avalanche deposit can be observed at the base of the section.

Egmont Volcano, mounds do not protrude because they have been buried beneath a thickening succession of younger volcaniclastic material. Accurate estimates of mound dimensions are extremely difficult to ascertain. On the ring plain, irregular and elongate mounds of Okawa Formation are usually mantled by a >8 m thick sequence of cover beds comprising dominantly tephra and associated interfingering andic soil beds. Mound heights and basal diameters may be further accentuated by aeolian wedges of either andesitic sands (Katikara Formation) or locally over-thickened yellowish-brown (Sy-) andic beds. At two sites near Inglewood (c. 200 m elevation above sea level (a.s.l.)), Last Glacial Maximum (LGM) erosion of mound cover-beds is evident by the occurrence of the c. 23.5 ^{14}C ka Tuikonga Tephra unconformably overlying boulder to block size FRCs of Okawa Formation.

With increasing distance north on the ring plain, the mounds gradually become equidimensional in shape, are mantled by a progressively thinner sequence of cover beds, and progressively decrease in basal diameter and height. In the vicinity of Inglewood, some mounds were measured with basal diameters as much as 200 m across and heights of >20 m (e.g., Fig. 13), whereas at the north coast, most mounds have basal diameters <25 m and heights <8 m.

Fig. 13 Large mounds of Okawa Formation in the vicinity of Bristol Road (Q19/176275) near Inglewood.

Lithology

Okawa Formation is exposed predominantly in farm quarry sites located in areas mapped mostly as axial a facies. At these sites the most conspicuous component of the deposit are FRCs. Inter-clast matrix is usually subordinate and seldom observed. The most frequently exposed FRCs are tabular or elongate blocks and megaboulders composed of indurated, grey to very dark grey andesitic breccia. Occasional conjugate fractured lava FRCs are observed (Fig. 14) as well as elongate and sometimes plastically deformed megaboulders and boulders of intensely altered hydrothermal and solfataric debris. Slightly deformed, unconsolidated, stratified blocks that retain their primary bedding are also common in this facies (Fig. 15). Mounds in axial a facies often contain megaboulder to block size FRCs which are usually in sharp and irregular contact with each other. However, in the same facies near the north Taranaki coast, many mounds appear to be cored by a single intensely brecciated boulder size FRC (Fig. 16A,B). Smaller FRCs of gravel and boulder size, retaining primary bedding, are sometimes exposed, suspended in the inter-clast matrix as far north as the present day coast. The primary stratification of these unconsolidated and layered FRCs is sometimes offset along small planes normal to bedding. This deformation is interpreted to have resulted from local compressional stresses exerted upon the clast during transport. In the axial b facies, gravel size FRCs are often found in very close proximity to boulder size FRCs of identical lithology and of similar texture to intra-clast matrix (Fig. 17A). This suggests that the FRCs were continually disaggregating and plastically deforming until all the intra-clast matrix constituents were dispersed as discrete clasts within the inter-clast matrix.

In areas of axial b and marginal facies, fractured and partially offset gravel clasts (Fig. 17B), as well as "rock flour" rims enclosing larger clasts, were noted within the intra-clast matrix of FRCs. These features suggest that grinding and fracturing of intra-clast constituents took place as the FRCs were plastically deforming during transportation.

Fig. 14 Single megaboulder size FRC with two sets of conjugate fractures (indicated by arrows).

Fig. 15 Block size FRCs in sharp and irregular contact with each other at Fredrickson's Quarry adjacent to Bristol Road (Q19/193293) near Inglewood. Note the deformed tephra inter-beds (indicated by arrows).

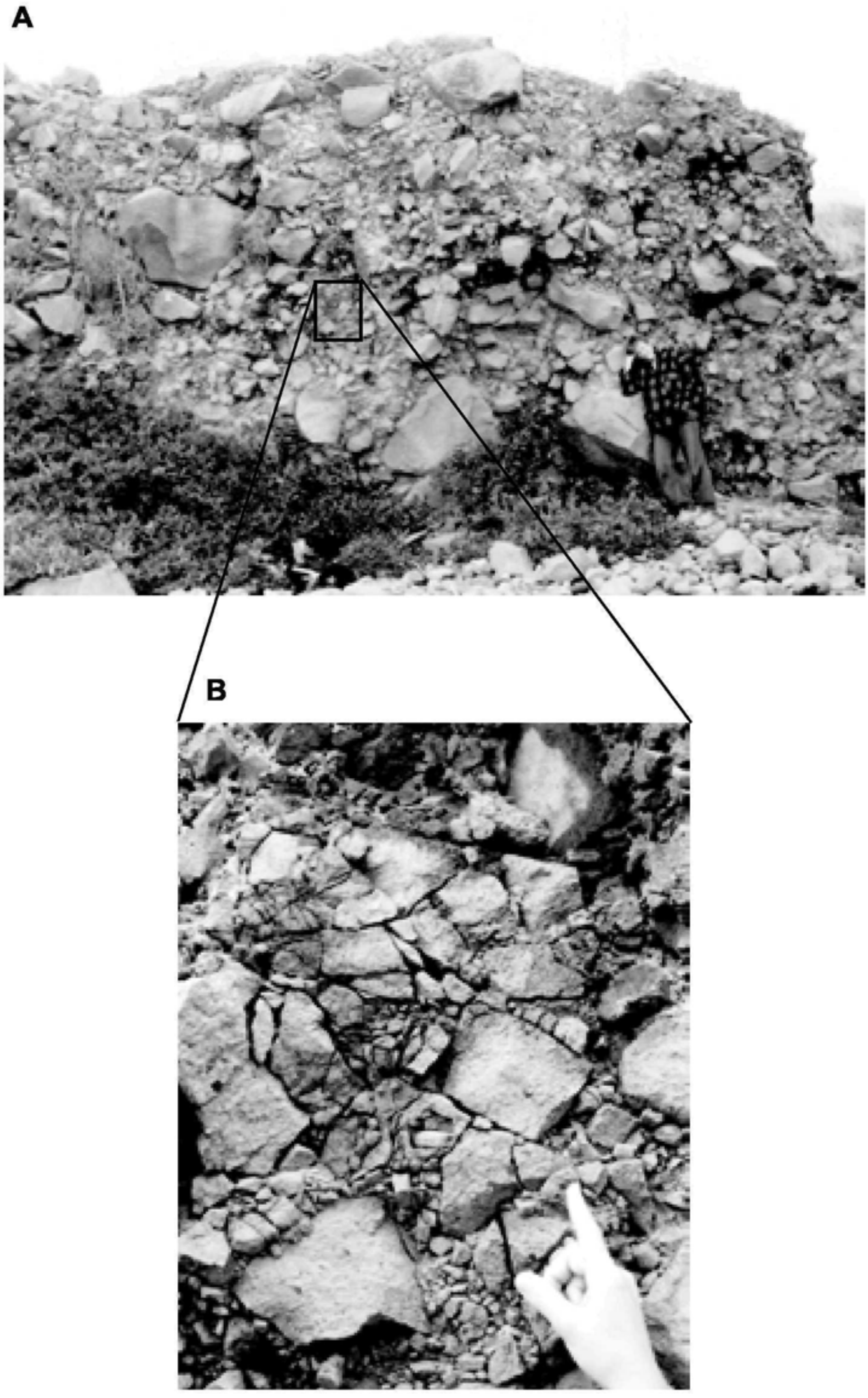


Fig. 16 **A**, Mound of Okawa Formation cored by a single megaboulder size FRC near the Waiongana Stream mouth at Q19/125448. **B**, Distinctive "jig-saw" brecciation forming intra-clast matrix of the megaboulder size FRC.

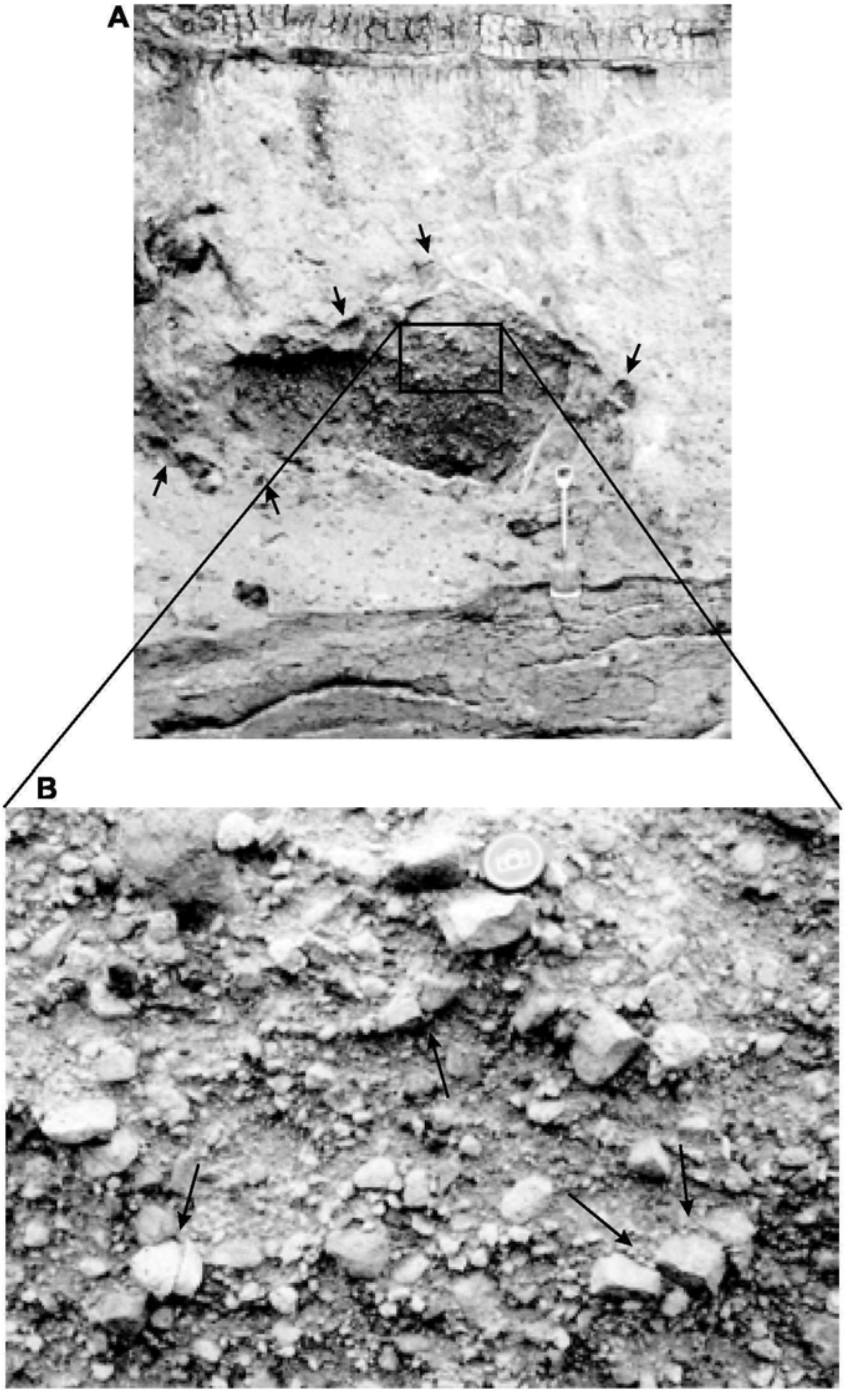


Fig. 17 **A**, Gravel size FRC in close proximity to a boulder size FRC of identical lithology and similar texture of intra-clast matrix. This suggests the FRCs were continually disaggregating and plastically deforming until all the intra-clast matrix constituents were dispersed as discrete clasts within the clay rich inter-clast matrix. **B**, Offset clasts (indicated by arrows) within intra-clast matrix of a boulder size FRC.

Okawa Formation, in areas mapped as the marginal facies, generally contains abundant angular to well rounded rock clasts, many plastically deformed rip-up clasts of peaty and medial material and scattered wood fragments. Coarse grained pumiceous fragments are relatively uncommon. Stratified clasts of Tertiary-aged siltstone are occasionally observed and exhibit features indicative of plastic deformation.

Age

Although not directly dated, the Okawa Formation is chronologically constrained by the underlying NT2 marine terrace, the overlying 2.6 m thick andic succession and by the matching of pollen zones, identified within enveloping organic sediments, to oxygen isotope stages (OIS).

Marine terraces

The north Taranaki coastal plain is dominated by a sequence of uplifted marine terraces. Two terraces, informally named NT2 and NT3, were originally mapped (Chappell 1975) below 50 m elevation. These were correlated to the Rapanui and Ngarino terraces of Wanganui described by Dickson et al. (1974) and subsequently dated at c. 125 and 210 ka, respectively, by Pillans (1986). The Airedale Reef section exposes NT2 terrace cover-beds (Alloway 1989), including the Okawa Formation (see below), which is absent from a younger terrace (NT1) that occurs immediately north-east of the Airedale Reef section and correlated by Alloway (1989) with the 81 ka Hauriri Marine Terrace of Wanganui (Pillans 1983).

Andic materials and tephrochronology

At Airedale Reef, 2.6 m of andic material with interfingering andesitic tephra beds overlies carbonaceous sediments enveloping marginal facies of Okawa Formation. Three reddish (Sr-) andic beds and two intervening yellowish (Sy-) andic beds are identified. The uppermost reddish bed (Sr1), occurring near the present ground surface, is dominated by andic soil material, but at sites more proximal to source there are numerous radiocarbon-dated andesitic ash and lapilli beds of late Last Glacial to late post-glacial age (late OIS 2 to 1). Stent Tephra (Alloway et al. 1994), a c. 4.0 ^{14}C ka silicic tephra marker bed from Taupo Volcano, is observed within dune sands overlying Sr1 in coastal sections adjacent to Airedale Reef. At Airedale Reef, the uppermost yellowish bed (Sy1) contains the c. 22.6 ^{14}C ka Aokautere Ash and the c. 23.4 ^{14}C ka Tuikonga Tephra derived from Egmont Volcano (Alloway et al. 1995). Rotoehu Ash, derived from Okataina Volcanic Centre and containing the diagnostic mineral cummingtonite as well as distinctive glass chemistry, is dispersed within the uppermost part of Sr3. At present, the precise age of the Rotoehu Ash is not known, but appears, from several radiocarbon dates (e.g., NZ-877A and NZ-1126A) of wood, charcoal, and peat, to be at about the limit of radiocarbon dating. An age of 47 ^{14}C ka (ANU-5642), estimated to be the equivalent of up to c. 55 cal ka, was reported by Newnham et al. (2004). The occurrence of Rotoehu Ash in marine cores off north-eastern New Zealand indicates likely deposition during early OIS 3 (Wright et al. 1995; Newnham et al. 1999, 2004), consistent with an age of c. 50–55 ka.

Palynological evidence

The Airedale Reef pollen record is chronostratigraphically constrained to lie between the maximum sea level highstand of OIS 5e and the deposition of Rotoehu Ash early in OIS 3. An amino acid racemisation date of 80 ± 20 ka on the Epiha Tephra series (Bussell 1988), overlying Okawa Formation, provides further coarse chronological constraint. Based on matching pollen zones to marine isotope stages with the precise zone/stage boundaries designated by cluster analysis, the Okawa debris-avalanche was emplaced during the OIS 5c/5d transition (Newnham & Alloway 2004).

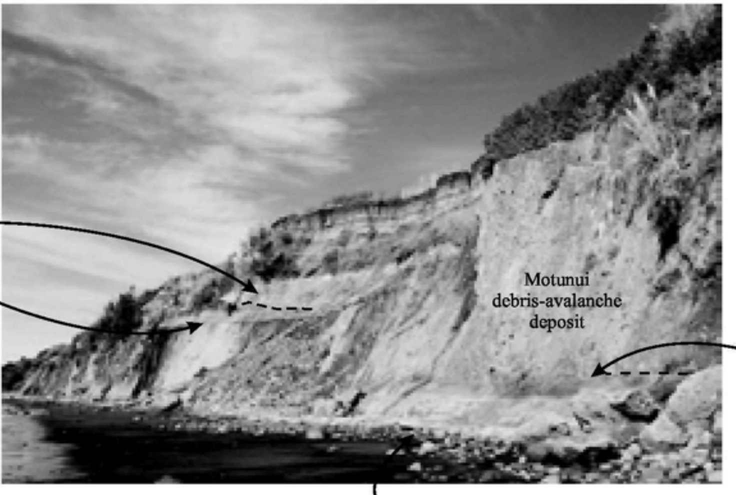


Fig. 18 Motunui Formation exposed in coastal cliffs c. 0.8 km east of Turangi Road (Q19/244455). The upper contact of Motunui Formation is truncated by marine sands and boulders that form the NT2 wave cut surface. Okawa Formation closely overlies these sands and is in turn overlain by c. 5.5 m of woody carbonaceous muds.

MOTUNUI FORMATION (NEW FORMATION)

Motunui Formation is named after the north Taranaki farming community of Motunui located on State Highway 3, c. 5 km east of Waitara. Motunui Formation comprises a single c. 4.25 m thick dominantly unstratified, heterolithologic clay rich diamicton that is near continuously exposed at the base of coastal cliffs that extend from Bell Block eastwards to the vicinity of Waiau Stream. The type section of Motunui Formation is here designated as a prominent north-facing cliff exposure in the vicinity of Turangi Road (Section 28 of Fig. 8, 18). Here, the extensive present day wave cut platform, as well as the NT1 and NT2 wave cut surfaces, are cut into the Motunui debris-avalanche deposit (Fig. 19).

The diamicton comprises abundant angular to well rounded rock clasts and common plastically deformed soil and tephra rip-up clasts dispersed in the clay rich, inter-clast matrix. FRCs are not common constituents within the inter-clast matrix. At one section in the vicinity of Titirangi Stream (Q19/197458), a megaboulder size FRC has been wave cut and unconformably overlain by a c. 0.5 m thick bouldery unit that forms the NT2 wave cut surface (Fig. 20). Based on the infrequent occurrence of these FRCs it is possible to say that the clay rich diamicton deposit resulted from the lateral transformation of a large volume debris-avalanche deposit.

In a cliff section 0.8 km south-east of Turangi Road (Section 28, Fig. 8) an older wave cut platform is exposed beneath the Motunui Formation and the NT2 wave cut surface that truncates its top. Here, the Motunui Formation is underlain by a prominent c. 0.2 m thick carbonaceous palaeosol and is separated from the older wave cut platform below by c. 1.0 m of massive, brown-grey to grey tephric mud that downwardly grades to c. 0.3 m of massive, bluish-grey sands (Fig. 21). These sands at mean sea level directly overlie a bioturbated wave cut platform (NT3?) comprising Tertiary-aged siltstone. Further westwards this older cut surface is not exposed in coastal cliffs but unpublished exploratory well data (Bechtel 1981) from the Motunui Gas-to-Gasoline Plant suggests that this wave cut platform occurs at mean sea level along this portion of the coast.

Fig. 19 Three wave cut surfaces truncating Motunui Formation are exposed c. 0.1 km east of the coastal end of Turangi Road. These are: the present day beach platform, NT1 (lower) and NT2 (upper) surfaces. The strandline of the NT1 surface can be observed just to the left of the person.

Fig. 20 In the vicinity of Titirangi Stream (Q19/197458) a megaboulder size FRC has been wave cut and is unconformably overlain by a 0.5 m thick bouldery unit that forms the NT2 wave cut surface. Okawa Formation can be observed in the top right of the photo.

The Motunui Formation appears to have been emplaced sometime between c. 127–210 ka since it is truncated by the NT2 wave cut surface above and closely overlies the NT3 wave cut surface below.

Based on the extensive distribution of the Motunui Formation on NT3 in the vicinity of Bell Block and its truncation by NT2 east of Airedale Reef, it is evident that this debris-avalanche deposit is likely to have been transported to the coastal plain via an ancestral Waiwhakaiho

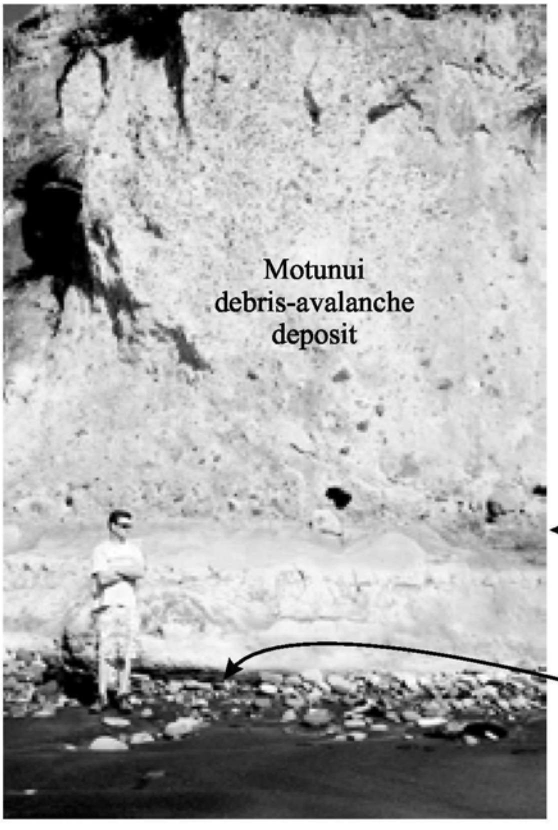


Fig. 21 Motunui debris-avalanche deposit is underlain by a prominent c. 0.2 m thick carbonaceous palaeosol and is separated from the older cut platform below by c. 1.0 m of massive, brown-grey to grey tephric mud that downwardly grades to c. 0.3 m of massive, bluish-grey sands. These sands at mean sea level directly overlie a bioturbated wave cut platform (NT3?) comprising Tertiary-aged siltstone.

River valley (now occupied by the present day Mangaoraka Stream) and the Manganui/Waitara River valleys. The debris-avalanche hummocks evident in the vicinity of New Plymouth crematorium may correlate with Motunui Formation but this has yet to be confirmed because the andic cover-bed stratigraphy has been significantly eroded making correlation difficult. It therefore remains unclear whether this debris-avalanche deposit originated from a youthful ancestral Egmont Volcano or an actively degrading Pouakai Volcano. Due to meagre outcrop data, it is not possible to map this deposit further inland or even to estimate minimum volume.

OFFSHORE DEBRIS-AVALANCHE RECORD

As part of the ongoing development of the Pohokura Gas Field for Shell Todd Oil Services Ltd, seabed surveys have been conducted along the north Taranaki coast (McComb et al. 2003) utilising side-scan sonar, sub-bottom profiling and hydrographic sounding techniques. These data have been useful in delineating the present day offshore distribution of Okawa and

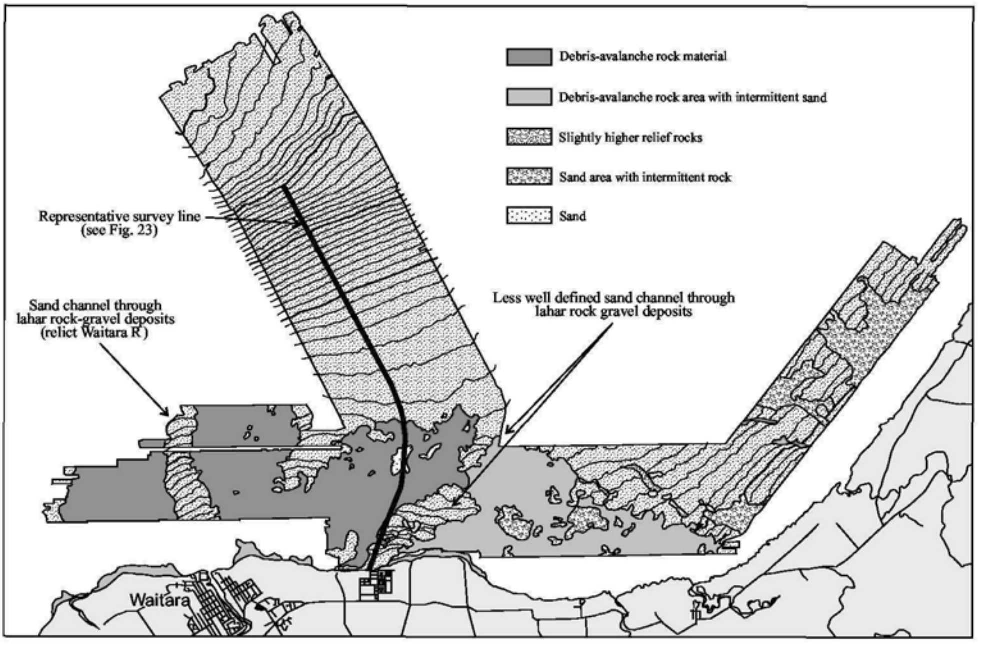


Fig. 22 Distribution of the interpolated seabed-types based on the side-scan sonar return signal. The offshore sandy channel associated with the Waitara River is easily discernible and indicated by an arrow on the far left of the figure.

Motunui debris-avalanche deposits. The offshore survey region (Fig. 1) extended from the Waiongana Stream to Pariokariwa Point (north of Wai-iti beach), mostly between the 10 and 20 m isobaths. In the vicinity of Motunui (Fig. 22), the coverage extends from the shore to the 60 m isobath. Seaward of the beach between Waitara and Motunui, the seabed comprises predominantly bouldery, gravel deposits with occasional high relief. The spatial distribution of these deposits is clearly consistent with the adjacent onshore occurrence of Okawa and Motunui debris-avalanche deposits in coastal cliff exposures.

A representative shallow seismic line is presented in Fig. 23 and extends 16 km offshore from Motunui. The youngest (top) layer is an almost seismically transparent prism of Holocene-aged mud that reaches a maximum thickness of 11 m mid way along the survey corridor. Except at its inner edge the Holocene mud overlies truncated, undulating beds that may be interpreted as sediments deposited during successive highstand and transgressive sea-level fluctuations prior to OIS 5. Emerging from the inner edge of these beds is a strong, irregular reflector that crops out at the sea bed within 4 km of the shore. This coincides with the bouldery gravel deposits mapped from side-scan sonographs. The outer limit of the buried bouldery, gravel deposits is typically 1–2 km seaward of where bouldery gravels are exposed on the inner shelf and 10–12 m below the sea bed. The basal reflector, up to 10 m beneath the exposed nearshore bouldery, gravel deposits, is tentatively identified as the top of Tertiary sedimentary rocks, which generally dip at 2–3° from near the shore to the outer part of the survey corridor, and which are tentatively correlated with Pliocene Urenui Siltstone that outcrop along the coast to the east of Motunui (King et al. 1993).

Within this offshore zone of bouldery gravel, several areas of smooth featureless sand have been identified. These features are typically associated with drowned and now infilled fluvial channel features that existed during low sea-level conditions of the LGM (e.g., the relict Waitara

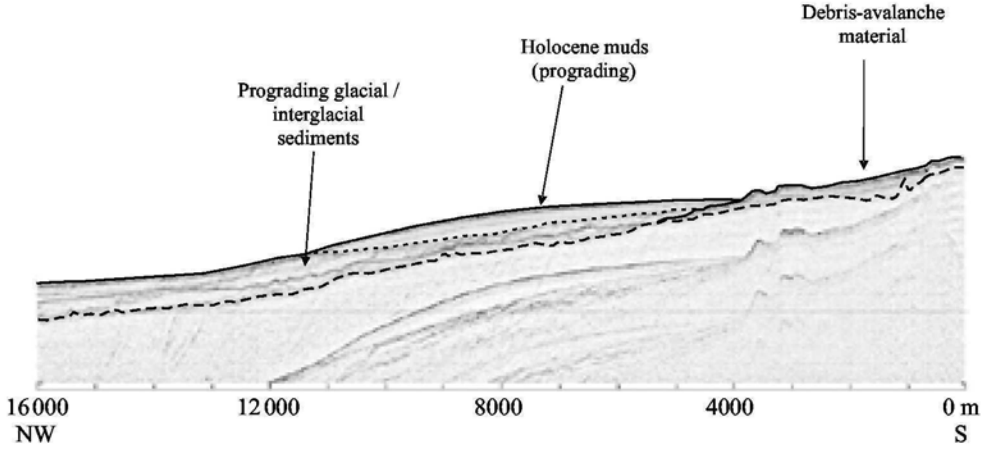


Fig. 23 Stratigraphy as defined by sub-bottom (boomer) survey along a cross-shore line extending 4 km from shore. Holocene muds, prograding glacial/interglacial marine sediments and debris-avalanche material of Okawa and Motunui Formations are indicated. Miocene mudstone basement is defined by the lower black dashed line.

River channel in Fig. 22), or seabed depressions and large scale bathymetric ridges (Storlazzi & Field 2000; McComb 2001). Indeed, the ridge and channel morphology that extends from Motunui beach may represent the differential inundation by lobes of debris-avalanche being emplaced on the coastal plain when it was exposed. The orientation of the dominant ridge features (Fig. 22) is broadly consistent with a debris-avalanche inundation. Interpretation of the hydrographic and shallow seismic data suggest that the large tongue of nearshore sand and mud that extends in a north-easterly direction offshore of Motunui beach is underlain by bouldery gravel and occurs due to preferential fine sediment deposition in a slight bathymetric depression between adjacent debris-avalanche lobes.

The occurrence of metre thick debris-avalanche deposits constituting or covering the uplifted marine terrace has also had a strong influence upon present day orientation of the north Taranaki coastline and this in turn has influenced local wave climate. For instance, most wave energy that approaches the North Island's west coast is from prevailing western and south-western quadrants. Consequently, the orientation of the north Taranaki coastline causes dominant waves to refract by approximately 80–100° in order to arrive at the coastline (McComb 2001). Refraction shadowing also means that a wave height gradient is evident along the north Taranaki coast, with wave heights decreasing to the east. Directly offshore, north Taranaki is a complex reef comprising debris-avalanche lag material and channelised sea bed. Reefs act to focus the wave energy, creating zones of wave height convergence and divergence that vary according to tide and wave period. Waves are often observed breaking on shallow offshore reefs even at high tides. Ultimately, this reduces the amount of wave energy reaching the shore and may be responsible for lessened rates of coastal erosion along these zones armoured by the debris-avalanche. The stable, heavily vegetated cliffs near Motunui may be contrasted with the bare and evidently eroding cliffs that are ubiquitous from Urenui to Mokau.

Wave action and the effects of weathering (wetting and drying) on the Tertiary mudstone tend to erode the cliffs in an episodic fashion, while the erosion of a dissipative shoreline is often more regular. Recent (i.e., post-1840 AD) coastal erosion rates between Mokau to the north and Waitara to the south are about 0.3–0.4 m/yr, with isolated sections showing higher rates (TCC 1987).

DISCUSSION

Debris-avalanche lateral transformation

Both Ngaere and Okawa Formations appear to have originated from ancestral edifices of Egmont Volcano as large volume avalanches which developed at distal sites into clay rich, debris-flow deposits at c. 23 ^{14}C ka (OIS 2) and 105 ka (OIS 5c/d transition), respectively (Fig. 24). In each instance, initial sliding of the ancestral cone appears to have been by rapid *en masse* movement. The avalanche that emplaced the Okawa Formation was probably slowed by the physiographic barrier of the Old Surface, causing the mass to bifurcate and become channelised northwards to the coastal plain. Ngaere Formation, on the other hand, was emplaced virtually unconstrained on the ring plain.

As sections of the ancestral cone initially slid, they broke into many rigid, heterogeneous large fragmental rock clasts. Many of these are relatively undeformed and appear to have rotated only slightly. Indurated andesite lavas and volcaniclastics remained as large FRCs supported by other FRCs and contain minor clay rich inter-clast matrix. Others were surrounded by a mobile inter-clast matrix enabling them to fracture, deform, and disintegrate into smaller FRCs.

As the mass flowed seawards, additional inter-clast matrix was generated by the progressive deformation and disaggregation of FRCs and by the incorporation of medial-ashy material and other poorly consolidated sediments from beneath the moving body of the avalanche. The dominant mode of transport probably changed from slide to flow as the ratio of inter-clast matrix to FRCs increased. The clay rich inter-clast matrix behaved as a high yield strength material supporting and hence transporting the FRCs away from source.

Role of water

Wet debris-avalanches and clay rich (cohesive) debris flows are typically associated with the collapse of fluid saturated portions of a volcanic edifice (Vallance & Scott 1997). Water saturation and weakness of the pre-avalanche mass favour the rapid transformation from debris-avalanche to clay rich debris flow.

Because Ngaere and Okawa debris-avalanche deposits both have minimum volumes in excess of 3.62 km^3, a large volume of water is required to saturate them. Water present in the mass flow may have had two different sources: (a) water that was already available in the volcanic edifice, or (b) water that had been incorporated by the mass flow during transportation, or both (a) and (b).

At Egmont Volcano there is a strong gradient of rainfall with altitude, ranging between 8000 mm (summit area) and 2400 mm (lower flanks c. 300 m a.s.l.) mean annual rainfall (Thompson 1981). Most streams have their headwaters on the upper slopes with no streams having flows within their channels above c. 1060 m (Taranaki Catchment Commission 1984). The mean discharge of all the rivers draining Egmont Volcano to within a 12 km radius of the summit has been calculated at 28 million m^3 per week (Palmer et al. 1991). This discharge rate indicates that there is a large groundwater reservoir present in the volcanic pile which discharges water to surface streams and which will also be a primary component in the event of a collapse.

The incorporation of allophane and ferrihydrite (andic material) as inter-clast matrix constituents is also considered a significant factor in promoting the development and mobility of clay rich debris flows. Under the humid temperate climatic conditions of western North Island,

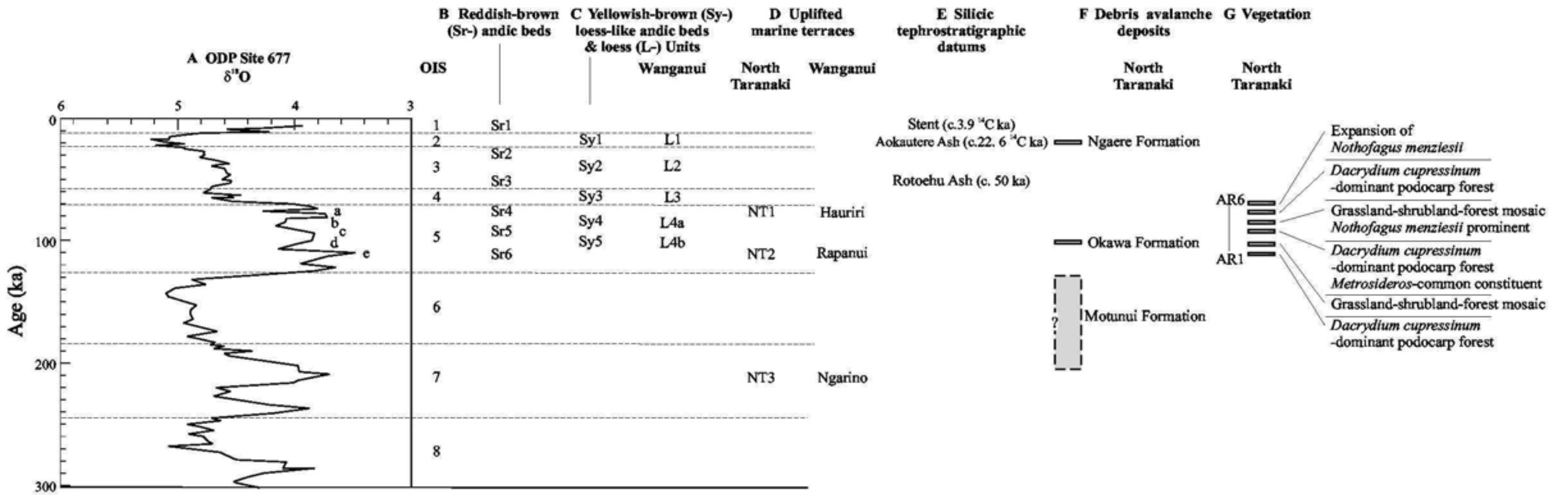


Fig. 24 Correlation diagram showing: **A**, $\delta^{18}O$ stratigraphy from ODP Site 677 (Shackleton et al. 1990); **B**, periods of reddish-brown (Sr-) andic formation; **C**, periods of yellowish-brown (Sy-) andic and loess accumulation in north Taranaki (Alloway et al. 1988, 1992) and Wanganui (Pillans 1988; Palmer & Pillans 1996); **D**, timing of marine terrace cutting in north Taranaki (Chappell 1975; Alloway 1989) and Wanganui (Pillans 1990); **E**, major silicic tephra layers associated with andic cover-beds in Taranaki (Alloway et al. 1992b, 1994, 1995); **F**, timing of debris-avalanche inundation in north Taranaki (Alloway 1989, this study); **G**, palaeovegetation record of north Taranaki (Newnham & Alloway 2001, 2004).

abundant andesitic ash rapidly weathers to short-range-order clay materials such as allophane (Neall 1976; Russell et al. 1981). Allophane consists of hollow spherules with diameters of 3.5–5 nm (Parfitt 1990). Allophane therefore has high specific surface area and correspondingly high capacity for water retention (up to 300% of the weight of dry soil) (Wada 1980).

Thick (>10 m) successions of fine grained andic material dominated by allophane occur on interfluve surfaces of the cone and adjacent ring plain. During a collapse event, cover-bed deposits will directly contribute allophone rich, fine grained material as a primary component. Allophane and ferrihydrite derived from eroded andic cover-bed successions on the ring plain will also enhance the mobility of the marginal lithofacies which spreads as a thin veneer across low gradient surfaces. Certainly, the presence of large volumes of water stored within a cone as well as allophanic material on, and adjacent to, an erupting volcano greatly enhances the risk from clay rich (cohesive) lahars.

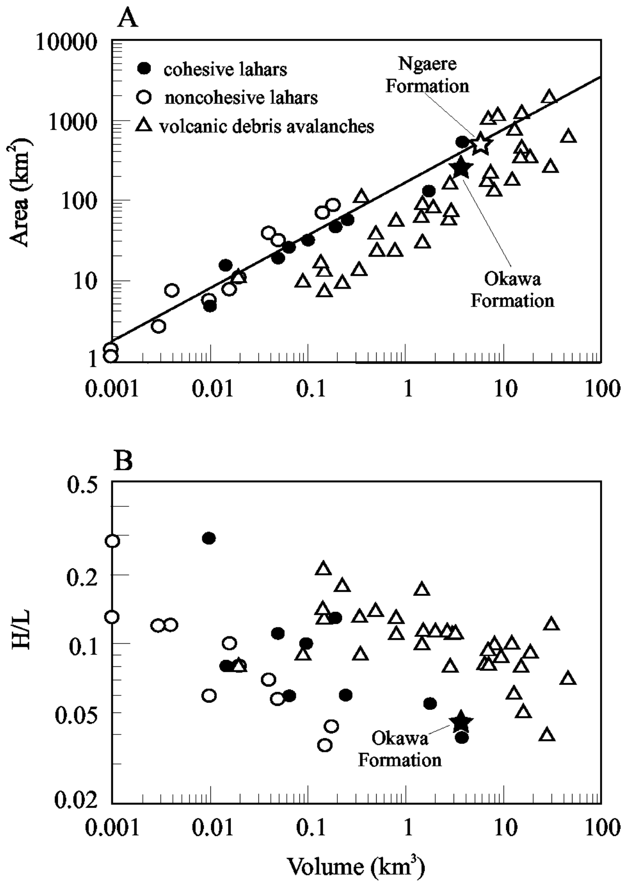
Vallance & Scott (1997) suggested that areas covered by clay rich (cohesive) debris-flow deposits might be up to 10 times those covered by volcanic debris-avalanches. This exceptional mobility is supported in this study and can be illustrated by area versus volume and the ratio H/L (fall height/runout) versus volume. Area-volume plots for both Ngaere and Okawa Formations (Fig. 25A) are comparable to the Osceola Mudflow deposit sourced from Mt Rainier (Vallance & Scott 1997). Assuming a maximum fall height of c. 2500 m (comparable to the height of the present day cone at its maximum slope angle) and a runout distance of c. 44 km for Ngaere and Okawa Formations (Fig. 1), the H/L ratio is calculated at c. 0.0568, similar to Osceola Mudflow deposit and other clay rich (cohesive), debris-flow deposits (Vallance & Scott 1997) (Fig. 25B).

Construction of the north Taranaki coastal plain

The construction of the north Taranaki coastal plain during the Late Quaternary is shown in Fig. 26. The oldest landform remnants observable in north Taranaki are prominent gently seaward-dipping, highly dissected inter-fluves situated to the north of Inglewood. Previously mapped as Eltham Lahars (Grant-Taylor 1964; Hay 1967; Neall 1979), these inter-fluves are renamed Old Surface (Neall & Alloway 2004). Old Surface comprises a wave cut surface truncating Tertiary-aged siltstone closely overlain by marine sands and volcaniclastic deposits sourced from Kaitake Volcano that were deposited around c. 0.5 Ma (Event 1 of Fig. 26). An isothermal plateau glass-fission track (FT) age of 0.40 ± 0.05 Ma obtained from a Rangitawa Tephra correlative (Naish et al. 1995) occurring within the andic cover-beds establishes a minimum age for this surface. The seaward edge of Old Surface was subsequently truncated by the NT5 high sea-level transgression (Event 2 of Fig. 26). A minimum age of 0.43 ± 0.07 Ma for NT5 terrace is established from a zircon-FT age obtained from Rangitawa Tephra similarly occurring within its cover (D. Seward unpubl. data). The NT5 terrace was later truncated during the culmination of the NT4 high sea-level transgression (Event 3 of Fig. 26). NT4 terrace, west of Bell Block, was then extensively inundated by Maitahi Lahars which relate to a debris-avalanche collapse of Pouakai Volcano (Event 4 of Fig. 26). The seaward edge of the surface mapped by Neall (1979), which grades eastward into the NT4 terrace, was then cliffed during the culmination of the NT3 high sea-level transgression (Event 5 of Fig. 26). A single amino acid racemisation date of wood obtained from lignite closely overlying the NT3 wave cut surface yielded a D:L ratio similar to that of wood samples from the cover of the Ngarino Terrace in Wanganui (B. J. Pillans unpubl. data). In the absence of any direct evidence as to the exact timing of this sea-level transgression, an age of c. 210 ka (OIS7) is postulated.

Closely following the emergence of NT3 terrace, Motunui debris-avalanche containing megaboulder size FRCs, inundated the coastal plain between Bell Block in the west to the vicinity of Waiau Stream in the east (Event 6 of Fig. 26). It appears from this widespread

Fig. 25 Graphs of **A**, area versus volume, and **B**, H/L (fall height: runout) versus volume, for cohesive lahars, non-cohesive lahars, and volcanic debris-avalanche deposits. Modified from Vallance & Scott (1997).



occurrence that, in addition to travelling down ancestral Waiongana Stream and Waitara River valleys, it may have also been channelled down an ancestral Waihakaiho River valley, which was then oriented in a north-easterly direction and which is now occupied by the northern part of the present day Mangaoraka Stream course. The NT3 terrace and Motunui Formation was later cliffed during the culmination of the NT2 high sea-level event at c. 127 ka (Event 7 of Fig. 26). Eastward of Waiau Stream, Tertiary-aged marine siltstone was wave cut by the NT2 high sea-level event, whereas westward of Waiau Stream, the NT2 high sea level similarly truncates the Motunui Formation that preserves the NT3 wave cut surface closely beneath its base. The occurrence of the NT2 wave cut surface continuously exposed and cutting across Tertiary (east) and debris-avalanche material (west) at the same elevation in the vicinity of Waiau Stream, suggests the occurrence of a significant normal fault downthrown to the west which topographically constrained the Motunui debris-avalanche. This fault feature has remained inactive since being cut by the NT2 high sea level. The NT2 wave cut surface is overlain by marine gravels and sands, small dunes, and thin lignite. During this NT2 high sea level, a prominent, well developed and distinctively coloured purplish-brown soil (Sr6; Fig. 24) was forming on the ground surface of older uplifted marine terraces.

Following the emergence of NT2 terrace, the north Taranaki coastal plain was extensively inundated by the Okawa debris-avalanche during a cool to warm transitional period at c. 105 ka when the coastal plain was occupied by a grassland-shrubland-forest mosaic (Event 8 of

Fig. 26). The Okawa debris-avalanche was channelised down the Waiongana Stream and Waitara River valleys, laterally spreading onto the coastal plain and extended west to the vicinity of Bell Block and north-eastwards to almost as far as the Onaero River. Except for a small remnant located south-east of Waitara, the debris-avalanche mostly inundated and subdued the surface expression of the NT2 fossil cliff. This event probably represents the first unequivocal evidence of volcanic activity centred at Egmont Volcano. However, the extent and volume of this laharic event suggests that Egmont Volcano must have been a prominent physiographic feature of the central Taranaki landscape.

After deposition of the Okawa debris-avalanche, climatic conditions became warmer and wetter as indicated by the expansion of *Dacrydium cupressinum*-dominant podocarp forest with *Metrosideros* as a common constituent. This warming was coincident with a period of intense eruptive activity depositing Epiha Tephra and marked the beginning of a major cone reconstruction phase. As the cone rebuilt, climatic conditions again became cooler and drier. This change is evident by the reversing of coastal vegetation from forest to a grassland-shrubland-forest mosaic with *Nothofagus menziesii* being particularly prominent (Newnham & Alloway 2004). Epiha Tephra continued to be deposited as climatic conditions became wetter and warmer, and as the *Dacrydium cupressinum*-dominant podocarp forest recolonised the coastal plain. This warming culminated in a marine transgression which cut the NT1 wave cut surface and truncated the seaward edge of NT2 terrace at c. 80 ka (Event 9 of Fig. 26).

The ensuing period between 78 and 60 ka was characterised by intermittent tephra emission from Egmont Volcano that included Te Arei tephra as well as Araheke and Waitui tephras (Alloway 1989). This period was also characterised by cold and dry climatic conditions of OIS4 as indicated by the addition of an inter-regional aeolian quartz component to the Taranaki andic cover-beds (Alloway 1992b) and localised over-thickening of yellow-brown andic beds. The episode following this cold period was characterised by mild climate and reduced activity at Egmont Volcano between c. 60 and 48 ka. It was during this episode that Sr3 formed. At c. 50 ka, Rotoehu Ash was deposited in uppermost Sr3.

Following the deposition of Rotoehu Ash in Taranaki, climatic conditions between 48 and 40 ka became cooler. Sporadic small magnitude eruptions of ash and lapilli beds (Mangapotoa tephra; Section 16, Fig. 8) during this period were locally redeposited. The formation of Sr2 and the apparent absence of interfingering coarse ash and lapilli within, suggests that minor volcanic activity centred at Egmont Volcano occurred during a mild climate interval between 40 and 28 ^{14}C ka. At about 28 ^{14}C ka, activity at Egmont Volcano intensified with frequent, moderate to large magnitude tephra emitting eruptions. This activity resulted in a sequence of 13 tephras being deposited in north-east Taranaki. Debris flows (Opunake Formation) were also generated from this activity, and inundated north-eastern portions of the Egmont ring plain (Alloway 1989; Alloway et al. 1995). Larger debris flows were channelised within the Waiwhakaiho, Mangaoraka, Waiongana, and Waitara catchments and carried to the coastal plain (Event 10 of Fig. 26).

Coinciding with this increase in eruptive activity was a steadily increasing influx of inter-regional aeolian quartz to the andic cover bed succession (Alloway et al. 1992b) indicating progressively colder and drier climatic conditions. At 23 ^{14}C ka, climatic conditions in Taranaki had deteriorated to such an extent that andesitic sand dunes of Katikara Formation started to develop from pedospheric stripping of tephra and from aeolian redeposition of sub-aerially exposed fluvial deposits within and adjacent to the major catchments. A tephra eruption (Poto. b) representing a renewed cycle of activity at c. 23 ^{14}C ka appears to have initiated a partial collapse of Egmont Volcano and generated Ngaere debris-avalanche that spread principally east and south-eastwards. The resulting deposit is recognised at the south Taranaki coast and within the Waitara River on the north Taranaki coastal plain (Event 11 of Fig. 26).

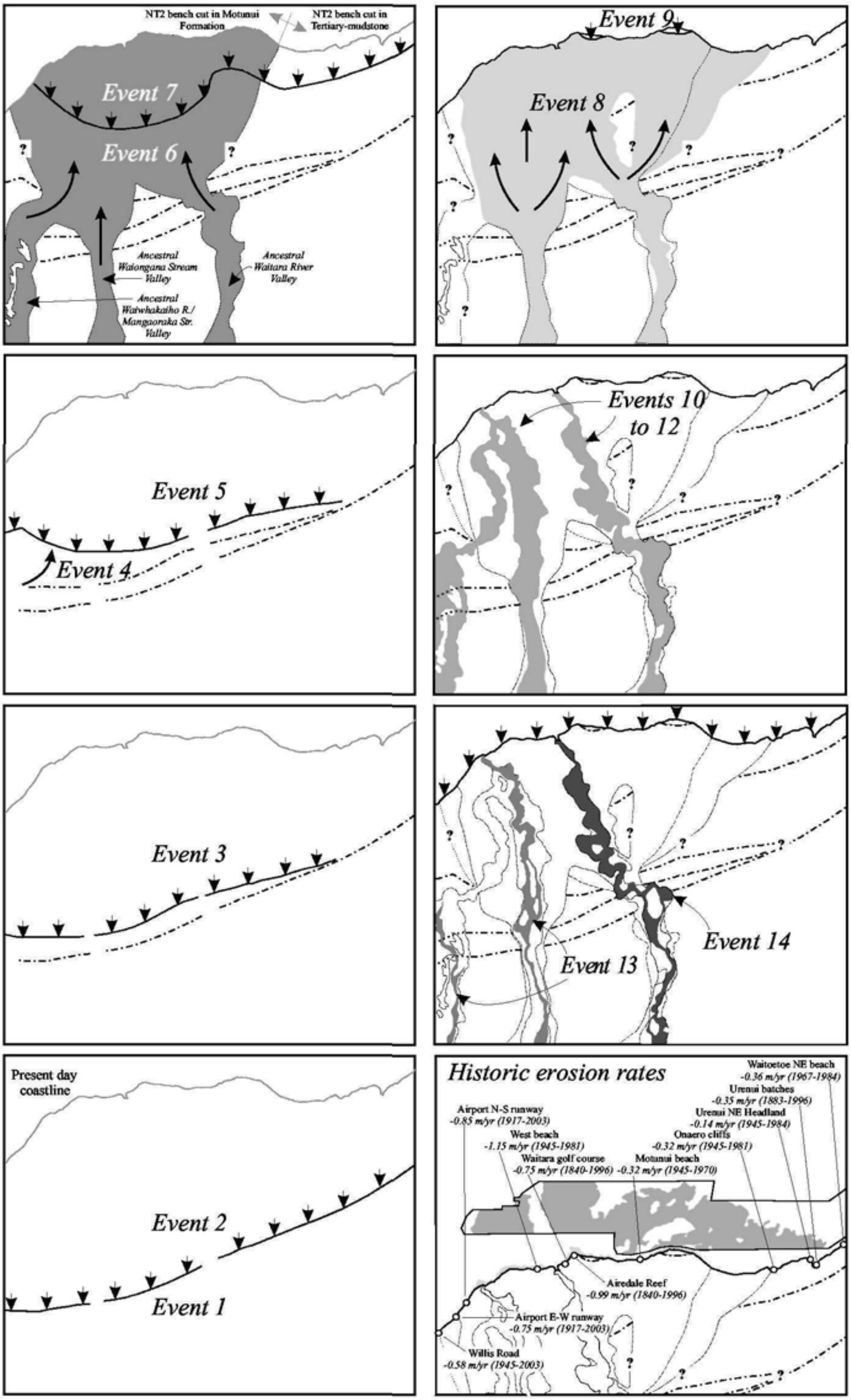


Fig. 26 Progressive (Events 1–14) construction of the north Taranaki coastal plain over the last c. 0.5 Ma. Historic coastal erosion rate data are from McComb (2001, unpubl. data), Gibb (1979, 1996a,b, 2003), and Taranaki Regional Council (1987). For detailed explanation of events see Discussion.

Immediately overlying Ngaere Formation is a sequence of 13 units of Poto Tephra that represent a post-avalanche phase of high frequency eruptive activity and active reconstruction of a lava dome or central cone. The eruptive products originating from this intense activity were principally directed east and south-eastwards (Alloway et al. 1995). The initial phase of this intense activity was coincident with the deposition of Aokautere Ash at c. 22.6 ^{14}C ka.

A subsequent collapse of Egmont Volcano generated another debris-avalanche that spread principally westwards, occurring during the latter stages of the post-Ngaere avalanche phase of cone reconstruction. The resulting deposit (Pungarehu Formation) is characterised by an extensive area of mounds between Okato and Opunake (Neall 1979).

Closely after deposition of Poto Tephra, a renewed cycle of activity between c. 20 and 19 ^{14}C ka resulted in fresh tephra eruptions (Paetahi Tephra) that were principally directed east and south-eastwards (Alloway et al. 1994). A culmination in the influx of inter-regional aeolian quartz to the region closely coincided with the deposition of Paetahi Tephra (Alloway et al. 1992b). A period of sporadic eruptions followed, depositing Kaihouri Tephra between 18.5 and 13 ^{14}C ka. Levels of inter-regional aerosolic quartz flux over this time progressively declined, indicating climatic amelioration. At least five debris flows (Warea Formation), generated from activity between 22.6 and 13 ^{14}C ka extensively inundated the north-eastern portions of the Egmont ring plain (Alloway 1989) and spread down the Mangaoraka, Waiongana, and Manganui/Waitara catchments onto the north Taranaki coastal plain (Event 12 of Fig. 26). Some Warea debris flows laterally transformed into hyperconcentrated flows.

Sporadic activity between c. 12 and 10 ^{14}C ka resulted in the deposition of Mahoe and Konini Tephra over a large area of central and south-eastern Taranaki at 11.4 and 10.1 ^{14}C ka, respectively (Alloway et al. 1994). Activity then intensified between 10 and 8 ^{14}C ka which resulted in eight units of Kaponga Tephra being deposited over central and south-eastern Taranaki. At least three debris flows (Kahui Formation), also generated from this activity, inundated north-eastern portions of the ring plain and became largely confined within the channels of the Mangaoraka and Waiongana Streams (Event 13 of Fig. 26). One Kahui debris flow confined within the Waiongana catchment extended north to the coast.

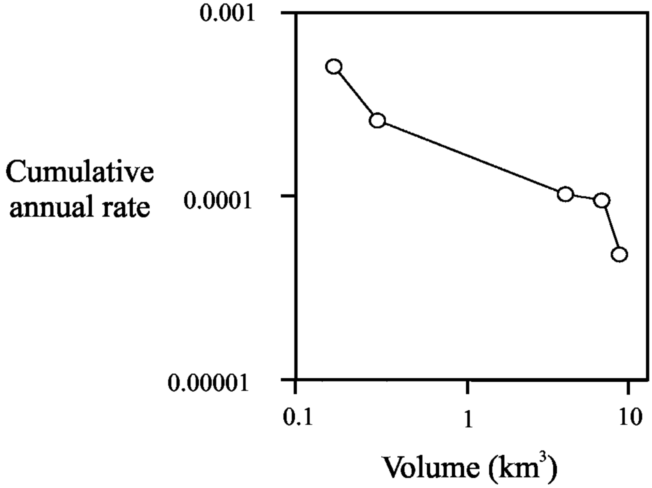
The latest laharic event to inundate the north Taranaki coastal plain closely followed the eruption of Inglewood Tephra at c. 3.6 ^{14}C ka. This laharic event (Ngatoro Formation) extensively inundated the north-eastern and central portions of the ring plain and reached the north Taranaki coast (Event 14 of Fig. 26) down the Waitara River valley after it became confined within the channels of Ngatoro, Waitepuku, and Mangamawhete Stream tributaries and the Manganui River.

Table 1 Probabilistically-based cumulative annual rates and return times for debris-avalanche events from Egmont Volcano.

Debris-avalanche event	Minimum volume (km^3)	Minimum recurrence interval (^{14}C yr BP)	Discrete rate	Cumulative annual rate	Minimum return time ($\geq^{14}C$ yr BP)
Warea[1] (Wr4)	0.15	3900[3]	2.5641-e04	5.0828e-04	1967
Opua[1]	0.3	6600	1.5152e-04	2.5187e-04	3970
Okawa[2]	3.62	10 5000*	9.2593e-06	1.0036e-04	9964*
Ngaere[2]	5.85	23 000	4.3478e-05	9.1097e-05	10 977
Pungarehu[1]	7.5	21 000	4.7619e-05	4.7619e-05	21 000

[1]Neall (1979); [2]this study; [3]Alloway (unpubl. data).
*Not calculated on a ^{14}C yr basis.

Fig. 27 Volume-frequency distribution for Taranaki debris-avalanche events (based on methodology of Stirling & Wilson 2002).



Repetitive collapse history and hazard implication

Egmont Volcano has repetitively collapsed over its c. 127 ka history and generated at least five voluminous landscape forming debris-avalanche deposits (the Warea Wr4 lobe, Opua, Pungarehu, Ngaere, and Okawa) with probabilistically based return times (using methodology of Stirling & Wilson 2002) of c. 1967 ^{14}C yr for volumes ≥0.15 km^3 and c. 21 000 ^{14}C yr for volumes ≥7.5 km^3 (Table 1; Fig. 27). The volume-frequency distribution (Fig. 27) exhibits a typical power law distribution (i.e., decreasing frequency with increasing volume on a log-log scale), except there is an indication of a disproportionately greater frequency of the largest volume debris-avalanche events (the shallowing of the distribution near the maximum volume). This disproportionate frequency appears analogous to a characteristic earthquake frequency distribution (Schwartz & Coppersmith 1984), which is typical of the vast majority of earthquake distributions for active faults (Wesnousky 1994; Stirling et al. 1996). Egmont Volcano is an inherently unstable cone since it comprises unconsolidated volcaniclastics with interbedded lavas, has a high slope angle (vertical to horizontal ratio of 1:11 from sea level at Cape Egmont over a horizontal distance of 27 km) and overlies a basement of Tertiary sediments cut by active faults.

Initiation of collapse by magmatically-induced seismicity is apparently common at many stratovolcanoes (e.g., Mt St Helens). Although Ngaere Formation was immediately preceded by a magmatic fall unit and is directly overlain by a closed spaced sequence of 13 fall units, there is no evidence to indicate that an eruptive event triggered or immediately followed the Okawa or Motunui debris-avalanche events.

The possibility of gravitational collapse events being triggered non-volcanically either by tectonic seismicity or by sedimentary loading also cannot be discounted. Over the last decade, overseas earthquake studies have provided considerable information on the types of landslide caused by earthquakes and the different shaking (*MM*) levels at which they occur (e.g., Keefer 1984; Jibson 1996). Rock and soil avalanches require the strongest shaking (*MM* > 7–8) and are more prone to triggering by the longer duration, lower frequency shaking associated with larger earthquakes (M_w 6–6.5) mainly on slopes >25° and higher than 150 m. In Taranaki, moderate to large magnitude ($M_L \geq 5$) earthquakes have been historically recorded though none has originated in close proximity to Egmont Volcano (Fig. 28A). Nevertheless, a series of faults

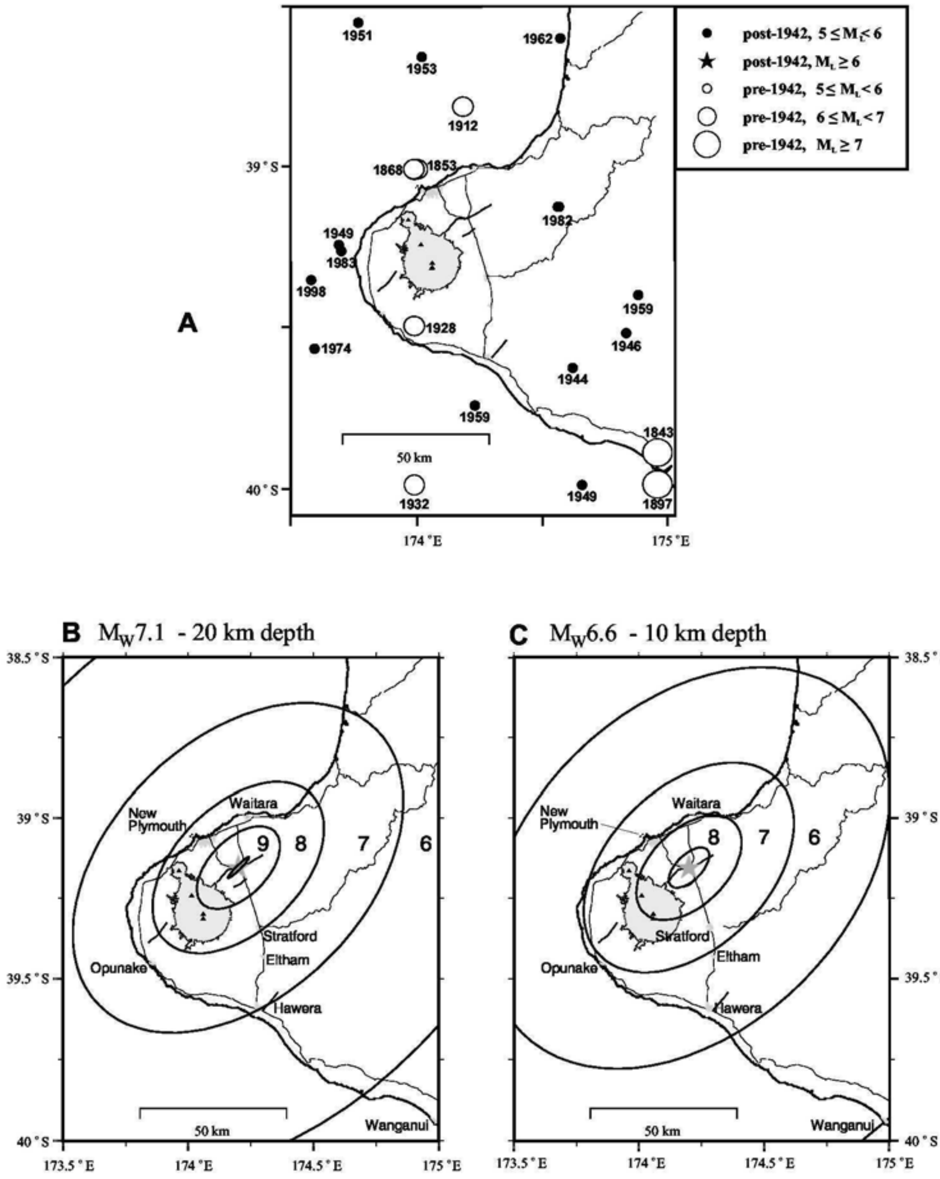


Fig. 28 **A**, Historically recorded earthquakes ($\geq M_L 5$) in Taranaki. *MM* intensity maps modelled for two earthquakes generated from the prehistorically active Inglewood Fault. **B**, M_w 7.1 earthquake at 20 km depth. **C**, M_w 6.6 earthquake at 10 km depth. Isoseismals are calculated from a program written by J. Cousins (GNS, Gracefield) based on Dowrick & Rhoades (1999). Both modelled events result in *MM* intensities ≥8 occurring on the cone.

and lineations has been traced in a dominantly north-east and south-west direction, extending through the present Egmont Volcano (Neall 1971; Alloway 1989), and evidence of past fault activity on some faults has been documented (Alloway 1989). Subsurface investigations have confirmed that movements on some of these faults has occurred during Holocene time with estimated earthquake magnitudes ranging from M_w 6.7–7.2, and average recurrence interval of c. 4 ^{14}C ka (Hull & Dellow 1993). Shaking (*MM*) intensities have been determined for two earthquake events (M_w 6.6 and 7.1 occurring at 10 and 20 km depths, respectively) generated along the Inglewood Fault (Fig. 28B,C). Both modelled events result in *MM* intensities ≥8 on the cone. It is therefore conceivable that a large magnitude seismic event could occur along any number of faults situated in close proximity to Egmont Volcano, triggering a gravitational collapse either by intense ground shaking, or surface rupturing, displacing portions of the stratovolcano edifice itself. In these cases, gravitational collapse would occur without prior warning or precursory activity.

CONCLUSIONS

This study describes the stratigraphy, age, and correlation of three previously unrecognised voluminous debris-avalanche deposits that have inundated the eastern flanks of Egmont Volcano and extended at least as far as the present day north and south Taranaki coastlines. Two debris-avalanche deposits (Ngaere and Okawa Formations) appear to have originated from ancestral edifices of Egmont Volcano as voluminous debris-avalanches which developed at distal sites into clay rich, debris-flow deposits at c. 23 (OIS 2) and 105 ^{14}C ka (OIS 5c/d transition), respectively. While both debris-avalanche deposits are enveloped by tephra fall beds, only Ngaere Formation can be directly related to a triggering eruptive event. Should there be a resumption of eruptive activity at Egmont Volcano with high level magma intrusion resulting in significant upper cone dilation, then the structural integrity of the upper cone will require close monitoring using differential GPS. Fortunately, the Taranaki Regional Volcanic Contingency Plan (Taranaki Regional Council 2000) is based on pre-emptive evacuation which is intended to minimise loss of life should a collapse occur. The possibility of gravitational collapse events being triggered non-volcanically either by tectonic seismicity or by sedimentary loading also cannot be discounted. Certainly, there is now an opportunity to model for volcanic and non-volcanic cone collapse events and determine critical threshold conditions.

Motunui Formation, the oldest of the three described debris-avalanche deposits, is only observed along the north Taranaki coastline. Here, it is truncated by the NT2 wave cut surface (c. 127 ka) and closely overlies the NT3 wave cut surface (c. 210 ka). It is unclear whether this debris-avalanche deposit originated from a youthful ancestral Egmont Volcano or an actively degrading Pouakai Volcano. Exactly when activity at Egmont Volcano first commenced is presently unknown though there is scope for conducting comparative geochemistry and $^{40}Ar/^{39}Ar$ dating on mineral phases within brecciated lava FRCs to identify source and ancestral edifice age.

Repetitive inundation of the north Taranaki coastal plain by voluminous debris-avalanche deposits appears to be a significant factor in the widening of the uplifted marine terraces by armouring, although their effect on altering coastal orientation and influencing wave climate is expected, but difficult to measure. The NT2 and NT3 terraces are narrow (<c. 1.0 and 0.7 km wide, respectively) north of Onaero where the coast is dominated by Tertiary-aged sediments, whereas, between Onaero and Waitara the same terraces broaden to maximum widths of c. 4.5 and 2.5 km, respectively. This broadening is clearly coincident with the occurrence of the Motunui and Okawa debris-avalanche deposits constituting or covering the uplifted terrace surfaces.

ACKNOWLEDGMENTS

This paper is dedicated to the memory of Harry X. Glicken, friend and fellow debris-avalanche researcher. Bev Raine and Shane Bayley of Taranaki Regional Council Civil Defence are thanked for their ongoing support and assistance. Dave Rogers, Matt Cook (now located in Whakatane) and other Taranaki-based Department of Conservation (DOC) staff are also thanked for their support and cooperation. We thank Ron

Wilson of Waitara (formerly of Whangamomoana) and other farmers of Taranaki, who always cheerfully allowed access over their properties and who were always interested in knowing a little more about their land. We thank Taranaki Regional Council staff for providing access to coastal erosion and ground water reports. We also thank Harry X. Glicken (deceased), Matt McGlone, and Paul Froggatt for field assistance and advice in the early PhD days. We appreciate the assistance of Dougal Townsend (GNS, Gracefield) for manuscript editing and Dave Heron (GNS, Gracefield) who more recently provided GIS expertise. Finally, the manuscript benefited from reviews by David Lowe (Department of Earth Sciences, Waikato University) and Anthony Walton (Department of Geology, University of Kansas), as well as scientific editorial input from John Clemens (School of Biological Sciences, University of Canterbury).

REFERENCES

Alloway BV 1989. Late Quaternary cover-bed stratigraphy and tephrochronology of north-eastern and central Taranaki Region, New Zealand. Unpublished PhD thesis, Massey University, Palmerston North, New Zealand.

Alloway BV, Neall VE, Vucetich CG 1988. Localised volcanic loess deposits in North Taranaki, North Island, New Zealand. In: Loess: its distribution, geology and soils. Eden DN, Furkert RJ ed. Rotterdam, Netherlands, A. A. Balkema. Pp. 1–6.

Alloway BV, McGlone MS, Neall VE, Vucetich CG 1992a. The role of Egmont-sourced tephra in evaluating the paleoclimatic correspondence between the bio- and soil-stratigraphic records of central Taranaki, New Zealand. Quaternary International 13/14: 187–194.

Alloway BV, Stewart RB, Neall VE, Vucetich CG 1992b. Climate of the last glaciation in New Zealand, based on aerosolic quartz influx in an andesitic terrain. Quaternary Research 38: 170–179.

Alloway BV, Lowe DJ, Chan RPK, Eden DN, Froggatt PC 1994. Stratigraphy and chronology of a c. 4000 year old distal silicic tephra from Taupo Volcanic Centre, New Zealand. New Zealand Journal of Geology and Geophysics 37: 37–47.

Alloway BV, Neall VE, Vucetich CG 1995. Late Quaternary tephrostratigraphy of north-east and central Taranaki, New Zealand. Journal of the Royal Society of New Zealand 25: 385–458.

Ando S, Yamagishi H 1975. Hill topography on the nuee-ardente deposits on the Shikaribetsu Volcano. Bulletin of the Volcanological Society of Japan 20: 31–36.

Bechtel Corporation, 1981. Investigations for site improvement. Gas-to-gasoline plant, Motunui. Unpublished report held at Taranaki Regional Council, Stratford.

Bemmelen RW van 1949. The geology of Indonesia. General geology of Indonesia and adjacent archipelagos 1A. The Hague, Government Printing Office. 732 p.

Bossard L 1928. Origin of the conical hills in the neighbourhood of Mt Egmont. New Zealand Journal of Science and Technology 10: 119–125.

Bussell RM 1988. Quaternary vegetational and climatic changes recorded in cover beds of the South Wanganui Basin marine terraces, North Island, New Zealand. Unpublished PhD thesis, Australian National University, Canberra, Australia.

Chappell J 1975. Upper Quaternary warping and uplift rates in the Bay of Plenty and West Coast, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 18: 129–155.

Clarke E de 1912. The geology of the New Plymouth Subdivision. New Zealand Geological Survey Bulletin 14: 58 p.

Crandell DR, Miller DD, Glicken HX, Christiansen RL, Newhall CG 1984. Catastrophic debris-avalanche from ancestral Mount Shasta Volcano, California. Geology 12: 143–146.

Cotton CA 1969. Volcanoes as landscape forms. 2nd ed. New York, New York. Hafner, 416 p.

Dickson M, Fleming CA, Grant-Taylor TL 1974. Ngarino Terrace: an addition to the Late Pleistocene standard sequence in the Wanganui-Taranaki District. New Zealand Journal of Geology and Geophysics 17: 789–798.

Dowrick D, Rhoades D 1999. Attenuation of modified Mercalli intensity in New Zealand earthquakes. Bulletin of the New Zealand Society of Earthquake Engineers 32: 55–89.

Froggatt PC, Lowe DJ 1990. A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume and age. New Zealand Journal of Geology and Geophysics 33: 89–109.

Gibb JG 1979. Late Quaternary shoreline movements in New Zealand. Unpublished PhD thesis, Victoria University of Wellington, Wellington, New Zealand.

Gibb JG 1996a. Strategic options for the sustainable management of coastal erosion along Urenui beach, New Plymouth District. Report prepared for New Plymouth District Council by Coastal Management Consultancy Limited. C.R. 96/7, 48 p.

Gibb JG 1996b. Strategic options for the training moles at the Waitara River mouth, Tai Hauauru, New Plymouth District. Report prepared for New Plymouth District Council by Coastal Management Consultancy Limited. C.R. 96/8, 40 p.

Gibb JG 2003. The hazard of sea-cliff retreat to New Plymouth Airport. Report prepared for New Plymouth District Council by Coastal Management Consultancy Limited. C.R. 2003/4, 16 p.

Glicken HX 1986. Rockslide avalanche of May 18 1980, Mt. St. Helens volcano. Unpublished PhD thesis, University of California, Santa Barbara, California.

Glicken HX, Voight B, Janda RJ 1981. Rockslide-debris-avalanche of May 18, 1980, Mount St. Helens volcano (abstr.) IAVCEI Symposium Arc Volcanism, Tokyo and Hakone. Pp. 109–110.

Grange LI. 1931. Volcanic ash showers. New Zealand Journal of Science and Technology 12: 228–240.

Grant-Taylor TL 1964. Volcanic history of western Taranaki. New Zealand Journal of Geology and Geophysics 7: 78–86.

Hay RF 1967. Sheet 7 Taranaki. 1st ed. Geological map of New Zealand 1:250 000. Wellington, New Zealand, DSIR.

Hull AG, Dellow GD 1994. Earthquake hazards in the Taranaki region. Geological and Nuclear Sciences Ltd. Client Report prepared for Taranaki Regional Council, 1993/03. 22 p.

Jibson RW 1996. Use of landslides in paleoseismic analysis. Engineering Geology 43: 291–323.

Keefer DK 1984. Landslides caused by earthquakes. Geological Society of America Bulletin 95: 406–421.

King PR, Scott GH, Robinson PH 1983. Description, correlation and depositional history of Miocene sediments outcropping along the North Taranaki Coast. Institute of Geological and Nuclear Sciences Monograph 5. 199 p.

McComb PJ 2001. Coastal and sediment dynamics in a high-energy, rocky environment. PhD thesis, University of Waikato, Hamilton, New Zealand.

McComb PJ, Beamsley B, Lewis K 2003. Surficial seabed and shallow subsurface geological features of the Pohokura gas field and adjacent regions, North Taranaki, New Zealand. Paper 86, Proceedings of the Coasts and Ports Conference 9–12 September 2003, Hyatt Regency, Auckland, New Zealand.

Mimura K, Kawachi S 1981. Nirasaki debris-avalanche, a catastrophic event at the Yatsugatake volcanic chain, central Japan. Abstracts, 1981 International Association of Volcanology and Chemistry of the Earth's Interior, Symposium on Arc Volcanism. P. 237.

Mimura K, Kawachi S, Fijimoto U, Taneichi M, Hyuga T, Ichikawa S, Koizumi M 1982. Debris-avalanche hills and their natural remnant magnetisation—Nirasaki debris-avalanche, central Japan. Journal of the Geological Society of Japan 88: 653–663.

Mizuno Y 1964. Landforms associated with volcanic debris flows at the foot of Zao Volcano. Hirosaki University Faculty Bulletin 13: 23–32.

Morgan PG, Gibson W 1927. The geology of the Egmont subdivision, Taranaki. New Zealand Geological Bulletin 29: 92 p.

Murai I 1961. A study of the textural characteristics of pyroclastic flow deposits in Japan. Bulletin of the Earthquake Research Institute, Toyko University 39: 133–248.

Naish TR, Kamp PJJ, Alloway BV, Pillans BJ, Wilson GS, Westgate JA 1995. Tephrostratigraphy and integrated chronology for Pliocene-Pleistocene marine cyclothemic strata, Wanganui Basin: implications for the Pliocene-Pleistocene boundary in New Zealand. Quaternary International 34–36: 29–49.

Neall VE 1971. Volcanic domes and lineations in Egmont National Park. New Zealand Journal of Geology and Geophysics 14: 71–81.

Neall VE 1976. Genesis and weathering of Andosols in Taranaki, New Zealand. Soil Science 123: 400–408.

Neall VE 1979. Sheets P19, P20 and P21—New Plymouth, Egmont and Manaia. 1st ed. Geological map of New Zealand 1:50 000. Three maps and notes (36 p.), New Zealand Department of Scientific and Industrial Research, Wellington.

Neall VE, Alloway BV 2004. Quaternary geological map of Taranaki, New Zealand, 1:100 000. Institute of Natural Resources, Massey University, Soil and Earth Sciences Occasional Publication 4. (in press).

Neuman van Padang M 1939. Uber die vielen tausend Hugel in westlichen Vorlande des Raoeng-Vulkans (Ostjava). Ing. Ned. Indies 6(4): 35–41.

Newnham RM, Alloway BV 2001. The Last interglacial/glacial cycle in Taranaki, Western North Island: a palynostratigraphic model. In: Goodman DK, Clarke RT ed. Proceedings of the IX International Palynological Congress, Houston, Texas, USA, 1996. American Association of Stratigraphic Palynologists Foundation. Pp. 411–422.

Newnham RM, Alloway BV 2004. A terrestrial record of interglacial climate preserved by voluminous debris-avalanche inundation in Taranaki, Western North Island, New Zealand. Journal of Quaternary Science 19: 299–314.

Newnham RM, Lowe DJ, Williams PW 1999. Quaternary environmental change in New Zealand: a review. Progress in Physical Geography 23: 567–610.

Newnham RM, Lowe DJ, Green JD, Turner GM, Harper MA, McGlone MS, Stout SL, Morie S, Froggatt PC 2004. A discontinuous ca. 80 ka record of Late Quaternary environmental change from Lake Omapere, Northland, New Zealand. Palaeogeography, Palaeoclimatology, Palaeoecology 207: 165–198.

Palmer AS, Pillans, BJ 1996. Record of climatic fluctuations from ca. 500 ka loess deposits and paleosols near Wanganui, New Zealand. Quaternary International 34–36: 155–162.

Palmer BA, Alloway BV, Neall VE 1991. Volcanic debris-avalanche deposits in New Zealand—lithofacies organisation in unconfined, wet avalanche flows. In: Fisher RV, Smith GA ed. Sedimentation in volcanic settings. SEPM Special Publication No. 45. Oklahoma, USA, Tulsa GA.

Parfitt RL 1990. Allophane in New Zealand—a review. Australian Journal of Soil Research 28: 343–360.

Pillans BJ 1983. Upper Quaternary marine terrace chronology and deformation, South Taranaki, New Zealand. Geology 11: 292–297.

Pillans BJ 1986. A Late Quaternary uplift map for North Island, New Zealand. Royal Society of New Zealand Bulletin 24: 409–418.

Pillans BJ 1988. Loess chronology in Wanganui Basin, New Zealand. In: Eden DN, Furkert RJ ed. Loess: its distribution, geology and soils. Rotterdam, Netherlands, A. A. Balkema. Pp. 175–191.

Pillans BJ 1990. Late Quaternary marine terraces, south Taranaki-Wanganui (Sheet Q22 and parts Q20, Q21, R21, & R22). Scale 1:100 000. Miscellaneous series map/New Zealand Geological Survey 18. 1 map and booklet. Lower Hutt, New Zealand Geological Survey. 47 p.

Russell M, Parfitt RL, Claridge GGC 1981. Estimation of the amounts of allophone and other materials in the clay fraction of an Egmont loam profile and other volcanic ash soils, New Zealand. Australian Journal of Soil Research 19: 185–195.

Schwartz DP, Coppersmith KJ 1984. Fault behaviour and characteristic earthquakes: examples from the Wasatch and San Andreas fault zones. Journal of Geophysical Research 89: 5681–5698.

Shackleton NJ, Berger A, Peltier WR 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. Transactions of the Royal Society of Edinburgh Earth Sciences 81: 251–261.

Simpson JO 1988. Late Quaternary stratigraphy of an area east of Stratford. Unpublished BSc honours thesis, Department of Soil Science, Massey University, Palmerston North, New Zealand.

Stirling MW, Wesnousky SG, Shimazaki K 1996. Fault trace complexity, cumulative slip and the shape of the magnitude-frequency distribution for strike-slip faults: a global survey. Geophysical Journal International 124: 833–868.

Stirling MW, Wilson CJN 2002. Development of a volcanic hazard model for New Zealand: first approaches from the methods of probabilistic seismic hazard analysis. Bulletin of the New Zealand Society for Earthquake Engineering 35: 266–277.

Storlazzi CD, Field ME 2000. Sediment distribution and transport along a rocky embayed coast: Monteray Peninsula and Carmel Bay, California. Marine Geology 170: 289–316.

Sundell K, Fisher RV 1985. Very coarse grained fragmental rocks: a proposed size classification. Geology 13: 692–695.

Taranaki Catchment Commission 1984. Groundwater hydrology, Taranaki Ring Plain Water Resources Survey, Taranaki Catchment Commission, Stratford. 123 p.

Taranaki Catchment Commission 1987. Coastal erosion hazard assessment for Clifton County. Taranaki Catchment Commission, Stratford, Taranaki.

Taranaki Regional Council 2000. Taranaki regional volcanic contingency plan. Taranaki Regional Council, Stratford. 56 p.

Ui T 1983. Volcanic debris-avalanche deposits—identification and comparison with non-volcanic debris stream deposits. Journal of Volcanology and Geothermal Research 18: 135–150.

Ui T, Kawachi S, Neall VE 1986. Fragmentation of debris-avalanche material during flowage—evidence from the Pungarehu Formation, Mount Egmont, New Zealand. Journal of Volcanology and Geothermal Research 27: 255–264.

Vallance JW, Scott KM 1997. The Osceola mudflow from Mt. Ranier: sedimentology and hazard implications of a huge clay-rich debris flow. Geological Society of America Bulletin 109: 143–163.

Voight B, Glicken H, Janda RJ, Douglass PM 1981. Catastrophic rockslide avalanche of May 18. In: Lipman, PW, Mullineaux DR ed. The 1980 eruptions of Mt. St. Helens. Washington, US Geological Survey Professional Paper 1250: 347–378.
Voight B, Glicken H, Janda RJ, Douglass PM 1983. Nature and mechanics of the Mt. St. Helens rockslide avalanche of 18 May, 1980. Geotechnique 33: 243–273.
Wada K. 1980. Mineralogical characteristics of Andisols. In: Theng, BKG ed. Soils with variable charge. Lower Hutt, Wellington, Soil Bureau, Department of Scientific and Industrial Research. Pp. 87–104.
Wesnousky SG 1994. The Gutenberg-Richter or characteristic earthquake distribution, which is it? Bulletin of the Seismological Society of America 84: 1940–1959.
Win G, McComb P, Lewis K, Beamsley B 2002. Pohokura seabed survey. Unpublished Client Report (01243-01) prepared for Shell Todd Oil Services Ltd, New Plymouth, New Zealand.
Wright IC, McGlone MS, Nelson CS, Pillans BJ 1995. An integrated latest Quaternary (Stage 3 to present) paleoclimatic and paleooceanographic record from offshore northern New Zealand. Quaternary Research 44: 283–293.