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Field Trip 5

TARANAKI

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INTRODUCTION

Mt. Taranaki, which is also referred to as Mt. Egmont or Egmont Volcano, is a 2518 m stratovolcano which has been active for at least the last 115 ka (Alloway *et al*., 1992). It lies 140 km west of Mt. Ruapehu and is volumetrically New Zealand's largest andesitic stratovolcano. Although historically Mt. Taranaki was considered to be dormant, recent work (Turner et al 2005) has shown a much more frequent record of activity, perhaps even more recent than the widely accepted event in 1755, shortly before first European settlement in New Zealand (Druce 1966). Even small eruptions of Mt. Taranaki would cause potential hazards for the population and local industries, for example dairy farming and oil and gas industries. Mt. Taranaki is located in the centre of the Taranaki Peninsula in the western North Island. The Taranaki Peninsula is an onshore component of the Taranaki Basin, a sedimentary basin along the west coast of the North Island. The eastern boundary of the basin is the Taranaki Fault, which is an east‐dipping reverse fault (Fig. 1.3a). The Cape Egmont Fault Zone (CEFZ) subdivides the Taranaki Basin into the Western Stable Platform and the tectonically active Eastern Mobile Belt (King 1991; King and Thrasher 1996,). The Taranaki Basin is filled with a sequence of at least 6 km of Cretaceous to Cenozoic sedimentary rocks. In the Taranaki region, these are overlain by Quaternary volcanic and volcaniclastic rocks. The sediments of the Taranaki Basin contain New Zealand's primary oil and gas reserves and extensive exploration has been done in the area, including numerous drill holes.

Mt. Taranaki is the youngest of 4 volcanic centres in the Taranaki region (Fig. 1). The volcanoes form a northwest‐southeast trending lineament with volcanism becoming progressively younger towards the southeast. The oldest volcanic centre is Paritutu volcano, including the Sugarloaf Islands near New Plymouth, with a K‐Ar age of 1.75 Ma. The remnants of Paritutu volcano are outcrops of volcanic rock in and offshore from New Plymouth and comprise plagioclase‐phyric, strongly porphyritic andesites (Price et al. 1999). The next younger volcano is Kaitake with 0.57 Ma, followed by Pouakai with 0.25 Ma and Mt. Taranaki with a K‐Ar age of less than 0.12 Ma (Neall 1979, Neall et al. 1986). Kaitake volcano has been eroded down to a series of ridges with few outcrops of hornblende andesite dikes and diorites (Neall 1979, Neall et al.1986). Pouakai volcano is 1399 m at its highest point and consists of several lava‐capped ridges and remnants of an eroded ring plain. Volcanic rocks from Pouakai are also hornblende andesites. The volcaniclastic Maitahi Formation (Fig 1) consists of debris flow and avalanche deposits derived from Pouakai volcano.

On the southern flank of the volcano is Fanthams Peak which is a parasitic vent that rises to 1962 m and has been active since at least 7000 years ago (Neall et al. 1986). The volcano can be subdivided into an upper and a lower section. The upper section consists of lava flows from Mt. Taranaki and Fanthams Peak, while the lower section is an extensive ring plain around the volcano. This ring plain consists of laharic, pyroclastic and alluvial volcaniclastics, representing fragments of pre‐existing cones that have been deposited by debris flows and lahars after cone collapses.

Beneath the Taranaki Peninsula, the continental crust is 25 to 35 km thick (Stern et al. 1987). The volcanoes in this region are 180 km above the Wadati‐Benioff zone (Adams and Ware 1977), which is significantly deeper than beneath the TVZ. The volcanoes of the TVZ overlie only 15 km of attenuated crust with an anomalously high heat flow of up to 900 mW/m^2 (Stern et al. 1987, Stern and Davey 1987). On average, heat flow in the Taranaki Basin is 60 mW/m^2 and is close to the continental norm (Studt and Thompson 1969, Pandey 1981). A small high heat flow anomaly with a maximum of 73 mW/m^2 occurs near New Plymouth. This can be explained by either a magmatic intrusion in the crust or magmatic underplating (Allis et al.,1995). Recent seismic studies of the Taranaki region (Sherburn et al. 2005) showed a brittle - ductile transition zone at only 10 km depth beneath Mt. Taranaki. This can be explained by an unusually hot crust beneath the volcano, caused by multiple dike and sill intrusions and possibly partial melting of crustal rocks.

There have been several edifice collapses during the evolution of Mt. Taranaki and the present upper cone is less than 10 ka old (Neall 1979, Neall et al. 1986). The mean period between larger eruptions from Mt. Taranaki is estimated at ~330 a (Alloway et al. 1995). Smaller eruptions have probably occurred more often, but their geological records are not as well preserved. The volcanic rocks of Mt. Taranaki are predominantly high - K andesites and basaltic andesites, with minor dacites and high - alumina basalts. Lavas from Fanthams Peak vent are predominantly basalt and basaltic andesite (Price et al. 1992, Price et al. 1999, Neall et al. 1986, Stewart et al. 1996). The youngest eruptives at the summit of Mt. Taranaki have the highest SiO_2 - content and the lavas have become progressively more K - rich with time (Stewart et al. 1996, Price et al. 1999). The most abundant phenocryst phase in Mt. Taranaki rocks is plagioclase, followed by clinopyroxene, amphibole and titanomagnetite. Orthopyroxene and olivine are less common.

VOLCANICLASTIC PROCESSES

The volcaniclastic apron around Egmont Volcano displays a surface comprising numerous hills and small mounds. In the first geological surveys carried out in Taranaki (de Clarke 1912; Morgan & Gibson 1927) these “conical hills” were thought to be a series of small independent volcanic vents or blisters on lava flows, Bossard (1928). Grange (1931) was the first to argue that they were of lahar flow origin, based on their similarity to other volcanic mudflow deposits. Similar hills at the base of several Indonesian volcanoes were later attributed to “landsliding or avalanching” of a sector of the volcanic cone, with the resultant deposits described as volcanic breccias (Neuman van Padang, 1939; van Bemmelen, 1949). Research in Japan prior to the 1980 Mt. St. Helens eruption had suggested that these deposits differed from lahars, for example, Murai (1961) used the term “dry mudflow” to distinguish debris-avalanches emplaced by “gravitational forces without the agency of water”. Mizuno (1964) was another who distinguished fragmental deposits of “avalanche-type” from those of “flow-type”. Ando and Yamagishi (1975) subsequently 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 occasion when a large volcanic debris-avalanche was observed and documented at the time of emplacement (e.g., Glicken et al. 1981; Voight et al. 1981, 1983; Glicken 1986) providing model for the interpretation of similar deposits elsewhere (e.g. Mimura et al. 1982; Crandell et al. 1984).

In Taranaki, three late Quaternary laharic breccia deposits extending west and south-west from Egmont Volcano were mapped by Neall, (1979). These deposits with their characteristic mounds or “conical hills” (Morgan & Gibson 1927), were named Opua, Warea and Pungarehu formations; later to be identified as debris-avalanche deposits. The most spectacular of the three is the Pungarehu Formation, which has an estimated minimum volume of 7.5 km^3. This deposit covers an area of 200 - 250 km^2 and extends to between 10 and 27 km distance from the present summit (Neall 1979; Ui et al. 1986). Two previously unrecognised debris-avalanche deposits have recently been identified on the eastern flanks of Egmont Volcano that lie beneath a thick mantle of tephric and andic soil material, as well as laharic deposits that have mostly subdued their topographic expression.

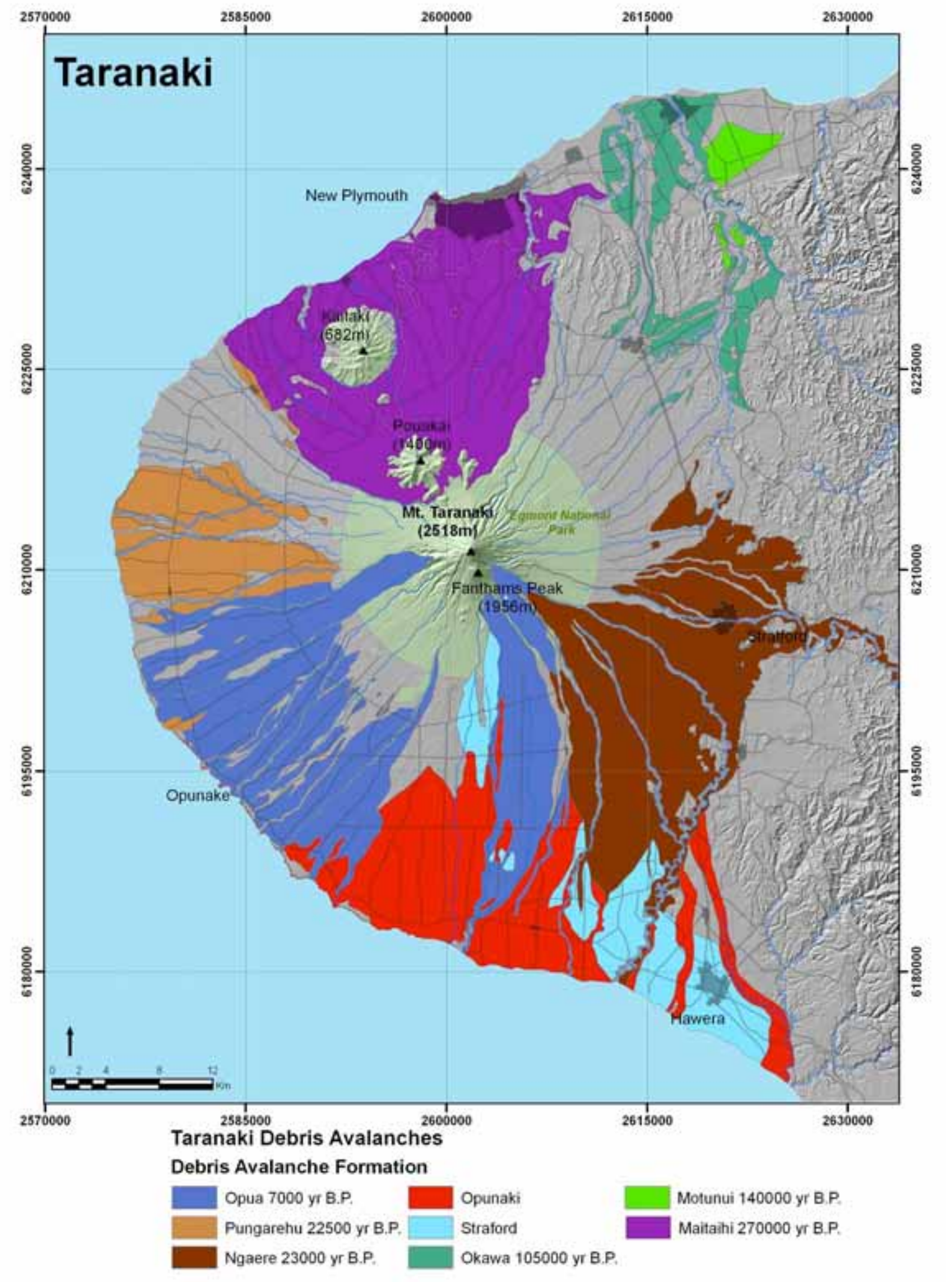

Figure 1: *Distribution and age of Debris Avalanches in Taranaki*

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 – unpublished data).

NOMENCLATURE AND FACIES ARCHITECTURE FOR DEBRIS AVALANCHES

The main internal structure of debris avalanche deposits comprises two major components: 1) fragmental rock clasts (hereafter referred to as "FRCs"), and 2) matrix. A FRC is 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 (Alloway et al., 2005). In Taranaki, the most commonly recognised FRC is andesitic lava that is commonly brecciated forming a diamicton of homogeneous composition. The FRC sizes are classified as: boulder (0.256 - 10 m), megaboulder (10 - 100 m), block (100 - 1000 m) and megablock (1 – 10 km), according to the scheme of Sundell and Fisher (1985), with the addition of a gravel-sized class of FRCs (0.002 - 0.256 m). Matrix is referred to as inter-clast matrix and is defined as all the material within the deposit surrounding the FRCs and less than 0.002 m in diameter. It should not be confused with the matrix of a FRC, which is here termed intra-clast matrix (Alloway et al., 2005).

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. Inter-clast matrix also contains 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.

The lithology and ratio of inter-clast matrix to FRCs varies within each debris-avalanche deposit and between the deposits. These variations are influenced not only by the composition of the original volcanic edifice and type and scale of the initial volcanic event, but also by topographic features such as ridges, channel systems and lowlands.

Where FRCs predominate, expressed by the development of hummocky surfaces, the debris avalanche was mapped as axial facies by Neall (1979) and as block facies by Crandell et al. (1984). Inter-clast matrix-dominated areas were mapped as marginal facies by Neall (1979), as matrix facies by Crandell et al. (1984), as main facies by Mimura and Kawachi (1981), and matrix mixture by Ui (1983).

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; axial a, axial b, and marginal facies (Alloway 1989; Palmer et al. 1991; Alloway et al., 2005)).

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 and basal diameters as much as 500 m.

Axial b facies is defined as an area where the proportion of inter-clast matrix is sub-dominant 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.

OKAWA FORMATION

Okawa Formation is named after Okawa Trig (Q19/199365) located adjacent 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).

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 lignitic deposit the remainder of the section comprises c. 2.6 m of andic material with proportionately thinner andesitic tephra beds.

Closely underlying Okawa Formation at Airedale Reef (Section 21, Fig. 8) is a 0.01-m-thick dominantly pumiceous coarse ash and fine lapilli bed in lignitic material (Fig. 10A) that 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 provides 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.

Mounds of Okawa Formation are concentrated principally within a c. 2.5-km-wide belt that extends north-east from the vicinity of Inglewood (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 and 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 northwards along the Waiongana Stream valley. This valley provided a closer and 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: NT-2, NT-3 and NT-4). 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 entrance 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. Farther towards 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 asl), 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-sized FRCs of Okawa Formation.

With increasing distance north from 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.

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 appear to be also common in this facies (Fig. 15). Mounds in axial a facies often contain megaboulder to block-sized 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-sized FRC (Figs. 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-sized FRCs are often found in very close proximity to boulder-sized FRCs of identical lithology and similar texture of 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.

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.

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 matching pollen zones identified within enveloping organic sediments to oxygen isotope stages.

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 earlier 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 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).

The Airedale Reef pollen record is chronostratigraphically constrained to lie between the maximum sea level high stand 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).

MOTUNUI 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 which 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. Here, the extensive present-day wave-cut platform, as well as the NT1 and NT2 wave-cut surfaces, is cut into the Motunui debris-avalanche deposit.

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 uncommon constituents within the inter-clast matrix. At one section in the vicinity of Titirangi Stream (Q19/197458), a megaboulder-sized FRC has been wave-cut and unconformably overlain by c. 0.5 m-thick bouldery unit that forms the NT2 wave-cut surface. The occurrence of these FRCs is infrequent, suggesting 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 paleosol 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. 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.

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 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. More recent field work now suggests that there is a second diamicton of similar age which is exposed in the coastal section at Motonui.

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. 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.

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 asl) mean annual rainfall. 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 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 humid-temperate climatic conditions of western North Island, 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 allophane-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 and Scott (1997) suggested that areas covered by clay-rich (cohesive) debris-flow deposits might be up to ten 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 run-out distance of c. 44 km for Ngaere and Okawa formations (see 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

Should there be a resumption of eruptive activity at Egmont Volcano and 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.

TARANAKI LAHARS AND NOMENCLATURE

The Indonesian term "lahar" is commonly used to describe a volcanic mudflow originating from the steep flanks of the volcanic edifice. Usually the event is triggered by volcanic heat melting snow and ice, dam break from a crater lake or rainfall runoff remobilizing or eroding deposited volcaniclastics (Scott, 200?). Smith & Fritz (1989) define the term as "a rapidly flowing mixture of rock debris and water (other than normal streamflow) from a volcano." Peirson & Costa (1987) recognize that lahars consist of water and sediment with the proportions of the two being highly variable in various settings with the rheological characteristics of a lahar being strongly influenced by other factors such as grainsize, velocity, topography and temperature.

The term lahar does however create a broad generalized category of two-phase (water and sediment) volcanic flows. Generally lahars are grouped into two categories, hyper-concentrated flows and debris flows. Beverage and Culbertson (1964) first used the term hyperconcentrated flow to differentiate between normal floods and floods containing a higher sediment concentration between 20-60% sediment. Pierson (2005) generally defines these terms as spectrum from floods (hyperconcentrated flows), that contain 4% by volume or 10% by weight of suspended sediment, to debris flows that contain 60% by volume or 80% by weight of sediment with approximately 50% of rock clasts larger than sand size. However most classifications of lahars (hyperconcentrated flow – debris flow) are rheological classifications based on the flowing sediment/water mass. Rheologically, Peirson and Costa (1987) define the difference between the two end members as hyperconcentrated flows having a yield strength being dominated by fluid flow with constrained sediment moving in a turbulent motion. Debris Flows are described as being more of a plastic mass, with high yield strength with the sediment being more buoyant due to dispersive forces and intergranular collision.

Despite these rheological concepts, classification and definitive description of related deposits are highly variable. In general Pierson (2005) provides a practical description for both;

"*Debris Flow Deposits*

- *Sand and fine gravel grains typically angular to subangular (hillslope source)*
- *Nonstratified, extremely poorly sorted (= massive diamictons)*
- *Normal and/or inverse grading common in vertical sections*
- *Matrix filling all voids except at margins or where washed out*
- *Coherent, semi-indurated consistency; difficult to dig - outcrops break off in small chunks when struck or kicked*
- *Multiple flow units commonly indistinguishable stratigraphically*
- *Coarse clast distribution fairly random in centres of deposit surfaces but more concentrated at deposit margins; deposit surfaces commonly convex upward*
- *Clasts oriented randomly except at flow margins"*

"Hyperconcentrated Flow Deposits (HCFD)

- *Most grains (all sizes) are rounded to subrounded (stream bed source)*
- *Flood deposits sediments usually stratified – distinct laminae and beds, commonly with cross-bedding; HCFDs show faint horizontal to massive bedding with outsized individual gravel clasts and lenses sometimes appear as massive but poorly consolidated diamictons*
- *In flood deposits, abrupt changes in mean grain size in vertical sections; sorting moderate to good within individual bedding units; coarser clasts may be imbricated*
- *In HCFDs, sorting usually poor to very poor; textural changes usually not abrupt*
- *Voids common between larger clasts (openwork texture) in water-flow deposits, not in HCFDs*
- *Flood deposits consistency is loose and friable when dry (easy to dig), although HCFDs slightly more consolidated*
- *Flood deposits surfaces commonly have longitudinal bars (usually armuored with coarse clasts), dunes, and/or ripples; abrupt changes in mean grain size between bars and channel axes are typical"*

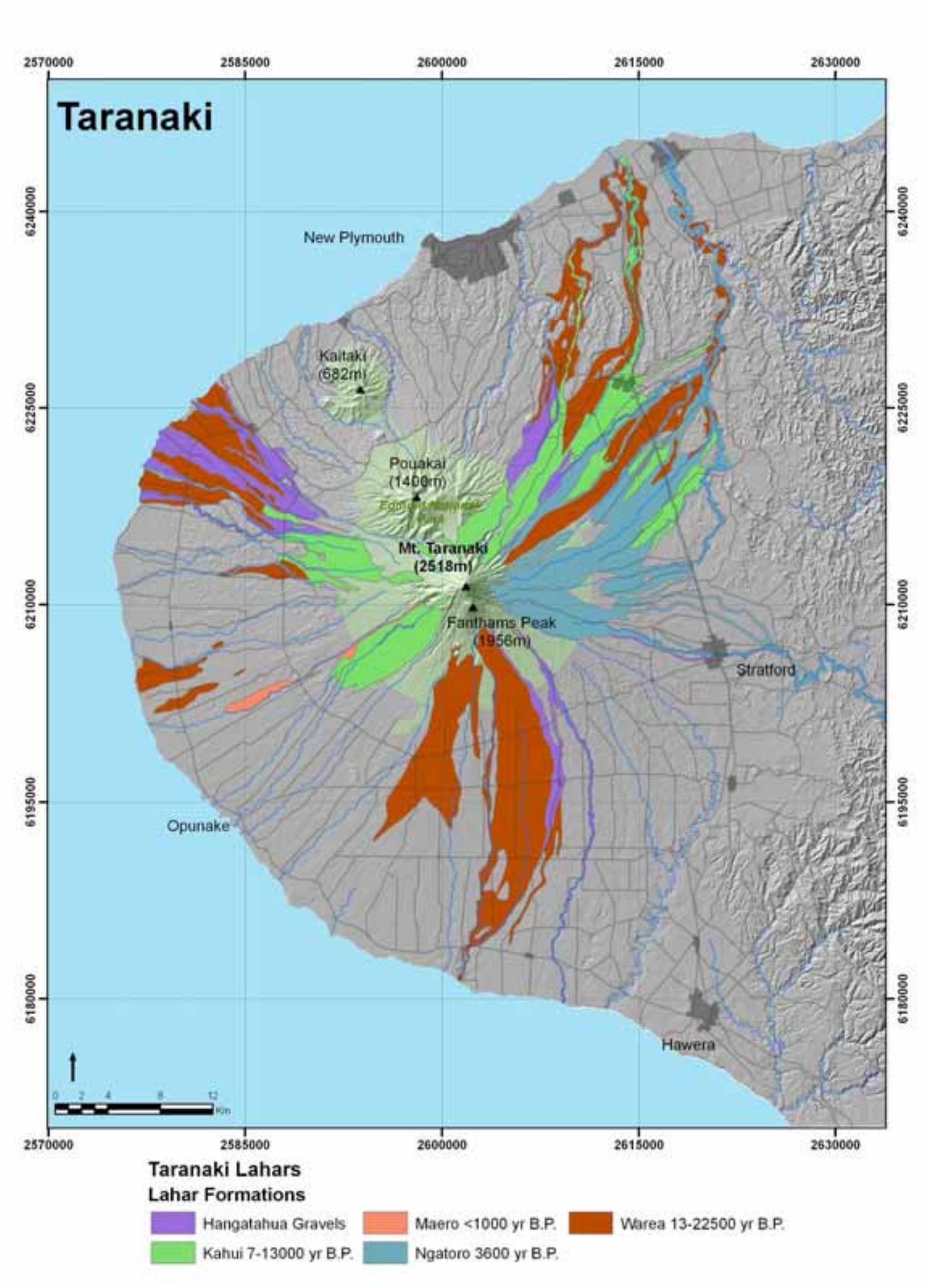

Figure 2: *Distribution and age of Lahar Formations in Taranaki*

Changes in channel morphology, flow discharge and inclusion of water can dramatically and rapidly change mechanisms required for deposition (Pierson, 2003), therefore changing the characteristics and textures of the related deposits. These transitions can be seen in a variety of stratigraphically equivalent lateral and longitudinal sections in the Taranaki ring-plain with the most common changes resulting in textures of either clast-rich/-supported or matrix-rich/-supported deposits. These changes can be seen clearly as overbank, Hyperconcentrated flow deposits directly grading out from the paleochannel or grading directly from the central debris flow facies of the flow. Transitions from debris flow to hyper-concentrated flow can also be seen in longitudinal or downstream change in grain size. The most obvious change is the deposit becoming thinner and inundating a wider area with clasts being deposited and grain size becoming finer.

Mt Taranaki and the surrounding ring-plain have not been inundated by lahars in historic times and no lahars have been witnessed by the surrounding community; yet the stratigraphic record shows re-occurring periods of frequent large lahar events. The most recognisable lahar deposits on the ring-plain are those of the 13-22500 yr B.P Warea Fm. (Neall, 1979). Other identified lahar deposits are the Kahui Debris Flows (7000-12000 yr B.P.) and the Maero Debris Flows (<1000 yr B.P.) (Neall, 1979). However, these formations are not single events but represent time periods of activity and are more recognised as chrono-stratigraphic units. Further volcaniclastic diamictons on the Taranaki ring plain that may be related to laharic or flood activities are the Holocene Hangatuhua Gravels and sections of the Opunake Fm (30000-38000 yr B.P).

WAREA FM.

The Warea Fm. can be found in the field between the township of Warea and the Stony River in western Taranaki. The deposit is recognised on the landscape as large flat areas between and around the debris avalanche mounds of older deposits. Neall and Alloway (2004) identified a number of lobes originating from the cone in several directions and grouped all lahar deposits as one chrono-stratigraphic unit.

In general the Warea Fm. is described as being a laharic conglomerate, breccia and sandstone that spans a large time period from 13000-22500 years B.P., the age being primarily derived from ove- and underlying tephra and soil layers. The type locality of this deposit shows a coarse sandy matrix containing poorly sorted, dense, sub-angular, black andesitic clasts which range in size from 1cm to 10cm. The unique characteristic of this deposit is its strong lithification and the abundance of large (~30cm) radial fractured, breadcrusted volcanic bombs. This deposit was interpreted to be a warm lahar generated from eruptive processes or possibly the distal parts or run-out phase of a pyroclastic flow that has interacted with snow or water.

However, recent field mapping of the Warea Fm shows a complex system of landscape re-adjustment and reaction after deposition of the Pungarehu debris avalanche that inundated vast areas of the ring-plain. This complex system shows areas of braided river channels with flood deposits redistributing already erupted material, the transport of freshly erupted material and large confined debris flows that fill channels.

The Warea Fm. can then be divided into 6 very different spatial groups (fig. 2) defined by stratigraphy and distribution along specific river catchments; (1) Stony River. – >16ka <22.5 ka, (2) Matanehunehu Stream – 14826 +/- 77 B.P., (3) Waiweranui Stream – <22.5 ka, (4) Kapoaiaia Stream – <22.5 ka, (5) Oanui Stream – 17 702 +/-82 B.P., and (6) Mangawhero Stream – >1.8 ka <7 ka.

All areas show a maximum of three individual episodes separated by time represented by soil development. Within each major episode there are a number of pulses of different flows shown by changes in grainsize, sorting, bedding features and occasionally a thin silt layer which represents a period of ponding or settling of water on the top of the flow. All deposits typically show features characteristic of debris flows such as poor sorting, matrix support, angular clasts or fragments and lateral/longitudinal transition into hyperconcentrated flows which display better sorting and smaller clast size.

CYCLIC VOLCANICLASTIC SEDIMENTATION AT MT. TARANAKI: A HISTORY OF GROWTH AND DESTRUCTION

The last 150,000 years of volcanic activity at Mt. Taranaki/Egmont-Volcano were marked by alternating phases of edifice construction and large edifice collapse events, the latter producing catastrophic debris avalanches. These have contributed a substantial volumetric component to the ring-plain around the cone.

Previous work (Palmer & Neall, 1991) had split the volcaniclastic succession into an inferred edifice-construction sequence (Opunake Fm; 48-20 ka BP) and a sequence representing destruction (Stratford Fm; 80-48 ka BP). However, more detailed mapping now reveals a greater complexity of packages of deposits representing higher frequency cycles of growth and destruction, including several unrecognised debris avalanche events (Table 1).

Years BP (ka)	Debris avalanche event
7	Opua
20	Pungarehu
< 23	Motumate
23	Ngaere
23-33	Stratford
29	Te Namu
33	Otakeho
> 50	Oeo
105	Okawa
130	Motunui
190	Motunui 2
270	Maitahi (Pouakai)

Table 1: *Overview and age of debris avalanche events from Mt. Taranaki and Pouakai Volcano (Maitahi).*

Repeated debris avalanche events from unstable volcanic edifices have been inferred from a number of long-lived stratovolcanoes, e.g. Mt Rainier (Vallance & Scott, 1997), Colima (Stoopes & Sheridan, 1992), Shiveluch (Belousov et al. 1999), and St. Augustine (Beget & Kienle, 1992). However, in many of these locations it is impossible to access the oldest units because they are deeply buried by more-recent volcaniclastic deposits. Unusually, at Mt Taranaki an almost complete stratigraphic record of distal ring-plain successions is exposed due to continuous coastal erosion of the tectonically uplifted areas of southern Taranaki. This allows a detailed analysis of the processes that are behind Mt Taranaki's evolution and apparent cycles in behaviour (Zernack et al. 2005). They are interpreted to represent a natural frequency in the growth dynamics of stratovolcanoes that may be globally applicable.

The volcaniclastic sequences along the Southern Taranaki coast represent a cross-section through diverse sedimentological settings and volcaniclastic lithofacies. This unique record of distal ring-plain deposits displays a wide range in sedimentary characteristics between stratigraphic layers and strong contrasts within individual units over lateral and longitudinal distances. These differences in sedimentology can be used to interpret their diverse origins as well as varying emplacement mechanisms and depositional conditions. At least six volcaniclastic flow facies were recognised, as well as variants that are transitional between them. They are interpreted as:

- Debris-avalanche deposits (DA).
- Unconfined debris-flow deposits related to DA (DF).
- Hyperconcentrated-flow deposits (HF).
- Channelised debris-flow deposits (CH).
- Floodplain / overbank deposits related to CH and HF (FP).
- Localised stream deposits (SF).

These facies appear to be related to specific periods within a repeating pattern of deposition, which can be used to develop a model of cyclic volcaniclastic sedimentation in distal areas of stratovolcanoes (Zernack et al 2006).

A generalised volcanic cycle at Taranaki begins after the destruction of large portions of the edifice by collapse. The subsequent edifice re-growth is characterised by small-scale pyroclastic eruptions and localised lava flows with no long-runout mass-flows being produced. Distal areas accumulate thick paleosols of medial ash and/or lignite with interbedded tephra layers reflecting the proximal activity.

Ring-plain locations show three types of sequences: (1) Areas where DA deposition is followed by a period of distal quiescence, marked by the onset of paleosol or lignite formation and their preservation. (2) Areas which are repeatedly buried by DAs with little (preserved) accumulation between collapse events. (3) Areas that are frequently inundated by DF, HF and CH deposits. Erosive and transitional contacts to the underlying DA deposit imply that its surface was rapidly reworked.

Once the cone has grown to a size at which pyroclastic activity starts generating long-runout mass-flows, distal accumulation is characterised by massive sequences of pebbly sand-dominated, mainly monolithologic, DF and HF deposits that intercalate with tephra beds, paleosols, dune sands, and local fluvial sediments. Monolithologic DF and HF units can be pumice/scoria-rich flows, possibly generated from pyroclastic tephra fans, or may contain dense clasts, representing runout of dome-collapse block-and-ash-flows. The coarse body of these flows seems to be confined to pre-existing channels forming CH deposits which grade into more wide-spread, unconfined overbank-type (FP) deposits.

Edifice growth appears ultimately limited to a critical point at which it fails. The cycle is closed with a major sector or cone collapse, in distal areas represented by coarse, very poorly sorted, polylithologic DF and DA deposits. These clay- and sand-rich matrix-supported units commonly contain cracked and shattered clasts as well as intact megaclasts, typically up to 20 m in diameter, and rarely up to 100 m. Major DAs bury extensive areas of the ring plain and reshape the landscape, in contrast to those of earlier parts of the cycle which tend to be confined to channels.

Although large sector collapses and the generation of debris avalanches represent the greatest hazard at this stratovolcano, they are far less frequent than other mass-flow events. The seemingly quiet construction phases between DAs also produce frequent long-runout HFs and DFs extending >30 km from source. Hence, in order to forecast future hazards from these types of volcanoes, it is extremely important to understand their cyclic nature as well as the point of the cycle which they are currently in. Forecasting models can be refined by considering not just return periods of debris avalanches but also the preconditioning of the edifice to failure, and the type and nature of other hazards at different parts of the cycle.

REFERENCES

Adams, R.D. and Ware, D.E. (1977). Subcrustal earthquakes beneath New Zealand: locations determined with a laterally inhomogeneous velocity model. New Zealand Journal of Geology and Geophysics, 20: 59 – 83.

Allis, R.G., Armstrong, P.A. and Funnel, R.H. (1995). Implications of a high heat flow anomaly around New Plymouth, North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 38: 121 – 130.

Alloway, B. V. 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, B. V.; McGlone, M. S.; Neall, V. E.; Vucetich, C.G. 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, B. V.; Neall, V. E.; Vucetich, C. G. 1995: Late Quaternary tephrostratigraphy of northeast and central Taranaki, New Zealand. *Journal 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.

Beget JE, Kienle J (1992). Cyclic formation of debris avalanches at Mount St Augustine volcano. Nature 356: 701-704.

Belousov A, Belousova M, Voight B (1999). Multiple edifice failures, debris avalanches and associated eruptions in the Holocene history of Shiveluch volcano, Kamchatka, Russia. Bull Volcanol 61: 324-342.

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

Beverage J.P, Culbertson J.K. (1964). Hyperconcentrations of suspended sediment. J*ournal of the Hydraulics Division, American Society of Civil Engineers* 90: 117-126.

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, R. M. 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, D. R.; Miller, D. D.; Glicken, H. X.; Christiansen, R. L.; Newhall, C. G. 1984: Catastrophic debris-avalanche from ancestral Mount Shasta Volcano, California. *Geology 12*: 143-146.

Dickson M, Fleming, C. A., Grant-Taylor T. L. 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.

Druce, A.P. (1966). Tree ring dating of recent volcanic ash and lapilli, Mt. Egmont. New Zealand Journal of Botany, 4: 2 – 41.

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

Glicken, H. X.; Voight, B.; Janda, R. J. 1981: Rockslide-debris-avalanche of May 18, 1980, Mount St. Helens volcano (abstr.) IAVCEI Symposium Arc Volcanism, Tokyo and Hakone, 109-110.

Grange, L. I. 1931: Volcanic ash showers. *New Zealand Journal of Science and Technology 12*: 228-240.

King, P.R. (1991). Physiographic maps of the Taranaki Basin – Late Cretaceous to Recent. New Zealand Geological Survey report, G155.

King, P.R. and Thrasher, G.P. (Eds) (1996). Cretaceous – Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. Institute of Geological and Nuclear Sciences Monographs, 13, Lower Hutt, 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 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, P. G.; Gibson, W. 1927: The geology of the Egmont subdivision, Taranaki. *New Zealand Geological Bulletin 29*: 92p.

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

Neall V.E. (1979). Sheets P19, P20 and P2l. New Plymouth, Egmont and Manaia (1st ed), Geological Map of New Zealand 1 :5O,OOO. N. Z. Dep. Sci. Ind. Res.. Wellington.

Neall V.E., Alloway B.E. (2004). Quaternary Geological Map of Taranaki. INR, Massey Uni. Dep. Soil Sci. Occ. Pub No.4.

Neall, V.E., Stewart, R.B. and Smith, I.E.M. (1986). History and Petrology of the Taranaki Volcanoes. In: I.E.M. Smith (Ed), Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin, pp. 251 ‐ 263.

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, R. M.; Alloway, B. V. 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.

Palmer, B. A.; Alloway, B. V.; Neall, V. E. 1991: Volcanic debris-avalanche deposits in New Zealand - lithofacies organisation in unconfined, wet avalanche flows In: Sedimentation in Volcanic Settings. SEPM Special Publication No. 45. Edited by R. V. Fisher and G. A. Smith. Tulsa, Oklahoma, U.S.A.

Palmer B.A., Neall V.E. (1991). Contrasting lithofacies architecture in ring-plain deposits related to edifice construction and destruction, the Quaternary Stratford and Opunake Formations, Egmont Volcano, New Zealand. Sedimentary Geology 74: 71-88.

Pandey, O.P. (1981). Terrestrial heat flow in New Zealand. Unpublished Ph.D. Thesis, Victoria University of Wellington, New Zealand.

Parfitt, R. L., 1990: Allophane in New Zealand – a review. Australian Journal of Soil Research 28: 343-360.

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

Pillans, B. J. 1986: A Late Quaternary uplift map for North Island, New Zealand. Royal Society of New Zealand Bulletin 24: 409-418.
Pierson T.C., Costa J.E. (1987). A rheologic classification of subaerial sediment-water flows. Geological Society of America, reviews in engineering geology VII: 1-12.

Pierson T.C. (2005). Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds U.S. Geological Survey Fact Sheet 2004-3142.

Pierson T.C. (2005). Hyper-concentrated flow – transitional process between water flow and debris flow. In Jakob M., and Hungr O., (eds) (2005). Debris-flow Hazards and Related Phenoma. Praxis. Springer Berlin Heidelberg.

Price, R.C., McCulloch, M.T., Smith, I.E.M. and Stewart, R.B. (1992). Pb ‐ Nd ‐ Sr isotopic compositions and trace element characteristics of young volcanic rocks from Egmont Volcano and comparisons with basalts and andesites from the Taupo Volcanic Zone, New Zealand. Geochimica et Cosmochimica Acta, 56: 941 ‐ 953.

Price, R.C., Stewart, R.B., Woodhead, J.D. and Smith, I.E.M. (1999). Petrogenesis of High ‐ K Arc Magmas: evidence from Egmont Volcano, North Island, New Zealand Journal of Petrology, 40(1): 167 ‐ 197.

Russell, M.; Parfitt, R. L.; Claridge, G. G. C. 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.

Scott K.M., Macías J.L., Naranjo JA, Rodriguez S, McGeehin JP (2001). Catastrophic Debris Flows Transformed from Landslides in Volcanic Terrains: Mobility, Hazard Assessment and Mitigation Strategies: U.S. Geological Survey Professional Paper 1630.

Smith G.A., Fritz WJ (1989). Volcanic influences on terrestrial sedimentation. Geology 17: 375-376.

Stern, T.A. and Davey, F.J. (1987). A seismic investigation of the crustal and upper mantle structure within the Central Volcanic Region of New Zealand. New Zealand Journal of Geology and Geophysics, 30(217 ‐ 231).

Stern, T.A., Smith, E.G.C., Davey, F.J. and Muirhead, K.J. (1987). Crustal and upper mantle structure of the northwestern North Island, New Zealand, from seismic refraction data. Geophysical Journal of the Royal Astronomical Society, 91: 913 ‐ 936.

Stewart, R.B., Price, R.C. and Smith, I.E.M. (1996). Evolution of high K arc magma, Egmont volcano, Taranaki, New Zealand: evidence from mineral chemistry. Journal of Volcanology and Geothermal Research, 74: 275 295.

Stoopes G.R., Sheridan M.F. (1992). Giant debris avalanches from the Colima Volcanic Complex, Mexico: Implication for long-runout landslides (>100 km). Geology 20: 299-302.

Studt, F.E. and Thompson, G.E.K. (1969). Geothermal heat flow in the North Island of New Zealand. New Zealand Journal of Geology and Geophysics, 12(4): 673 ‐ 683.

Sundell, K.; Fisher, R. V. 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 Regional Council 2000: Taranaki Regional Volcanic Contingency Plan. Taranaki Regional Council, Stratford. 56 p.

Turner, M, Cronin, S J, Bebbington, M, Stewart, B, Neall, V E and Smith, I (2005). Working toward a high-precision record of Mt Taranaki eruptions and ash falls, New Zealand. *In* Pettinga, J R and Wandres, A M (eds). Programme and Abstracts, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Misc. Publ. 119A: 90

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, V. E. 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 J.W., Scott K.M. (1997). The Osceola Mudflow from Mount Rainier; sedimentology and hazard implications of a huge clay-rich debris flow. *GSA Bulletin* 109: 143-163.

Voight, B.; Glicken, H.; Janda, R. J.; Douglass, P. M.; 1981: Catastrophic rockslide avalanche of May 18. In Lipman, P.W. and Mullineaux, D.R., editors, The 1980 eruptions of Mt. St. Helens, Washington: *U.S. Geological Survey Professional Paper 1250*: 347-378.

Voight, B.; Glicken, H.; Janda, R. J.; Douglass, P. M.; 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 Soils with Variable Charge (ed. B.K.G. Theng), Soil Bureau, Department of Scientific and Industrial Research Lower Hutt. p. 87-104.

Zernack A.V, Procter J.N., Cronin S.J. (2005). Cyclic growth and destruction of stratovolcanoes. In: Geological Society of New Zealand Miscellaneous Publication 119A, pp 99-100.

Zernack A.V., Procter J.N., Cronin S.J. (2006). Sedimentary signatures of cyclic growth and destruction of stratovolcanoes: a case study at Mt. Taranaki, NZ. In: Yamada T (ed.), Sediments of Japanese Islands. Abstract, 17th International Sedimentological Congress, Fukuoka, Japan, O-141.

DAY 1

STOP 1.1: KAUPOKONUI BEACH

The coastal cliff at Kaupokonui Beach is one of the best locations to study the wide range of volcaniclastic flow deposits that build up the Taranaki ring-plain. The section also shows the contrasting styles of sedimentation during different periods within the volcanic cycle.

The bottom part of the sequence is made up of a series of hyperconcentrated flow deposits which were generated during the growth phase of an ancestral Mt. Taranaki edifice. They represent the distal run-out of pyroclastic and/or debris flows. Several flows are rich in pumice clasts and seem to be related to periods of explosive volcanic activity. Some hyperconcentrated flows are only separated from each other by a thin silty layer; others show flame structures which suggests that they were emplaced rapidly after each other. The more sediment-rich flows show a characteristic fine-grained basal layer, overlain by the coarser, normally graded main part of the deposit.

Hyperconcentrated flow deposits alternate with cross-bedded, well-sorted sand and pebble beds which contain rounded mainly volcanic clasts. These localised stream deposits represent phases of fluvial reworking during intervals of quiescence throughout the constructional phase of the volcano.

Growth of the edifice was limited to a critical height at which it failed. A major sector or cone collapse generated the overlying Otakeho debris avalanche which closes this volcanic cycle.

The next cycle is represented by a debris flow, a series of thin hyperconcentrated flow deposits and the massive Stratford debris avalanche.

Figure 3: *Stratford and Otakeho debris avalanches and underlying hyperconcentrated flow and fluvial deposits*

Figure 4: *Series of hyperconcentrated flow deposits*

Figure 5: *Periods of reworking represented by fluvial deposits*

STOP 1.2: PUNEHU STREAM

This stop is a good example for the transition of channelised debris flow to overbank hyperconcentrated flood flow deposits. The coarse body of the flow was confined to a pre-existing river channel which cut into the volcaniclastic sequence. The more diluted and thus more mobile part of the flow overbanked the channel and inundated a wider area. Fluvial deposits below and above the channel show that the river/stream system was active before and after the debris flow event.

Periods of quiescence that separate eruptive phases during cone growth are marked by the accumulation of thick soil/peat layers, fluvial reworking and the formation of dune sands as can be seen at this location.

Figure 6: *Transition of channelised debris flow into overbank-type hyperconcentrated flow*

Figure 7: *Massive sequence of dune sands overlain by Otakeho debris avalanche*

STOP 1.3: OPUNAKE BEACH

The cliff section at Opunake Beach provides a good overview of different types of accumulation following a major edifice collapse and the generation of a debris avalanche.

Deposition of the Otakeho debris avalanche at the bottom of the sequence was followed by a period of quiescence at this distal location, marked by the formation of a thick lignite and its preservation. Later on during the regrowth of the volcano, a series of coarse debris flows were channelised down a broad river system around the Opunake area.

Only a thin soil layer is (partly) preserved between the overlying Te Namu and Pungarehu debris avalanche deposits which shows that the region was repeatedly buried by debris avalanches with little accumulation between edifice failures.

After the Pungarehu collapse, the area was repeatedly inundated by debris flows and hyperconcentrated flows which rapidly reworked the surface of the debris avalanche. The flows cut deeply into and eroded the underlying strata. The Opua was the last debris avalanche event at Mt. Taranaki and forms the cliff top.

Figure 8: *A series of four debris avalanche deposits exposed at Opunake Beach*

STOP 1.4 (optional): MIDDLETON BAY

This stop is located within a large paleo-river system which was established after (or possibly before) the Otakeho collapse and was active until deposition of the Opua debris avalanche.

The cliffs display a cross-section through this complicated system and show a range of fluvial and volcaniclastic lithofacies with transition between them. Exposed are channelised and sheet-like hyperconcentrated and debris flow deposits which alternate with sandy and pebbly fluvial sediments.
The Kawakawa tephra/Aokautere ash which was erupted from Taupo volcano 22.5 ka BP is preserved in a thick soil sequence here.

Figure 9: *Series of debris avalanche, hyperconcentrated flow and fluvial deposits at Middleton Bay*

STOP 1.5: MATENEHUNEHU STREAM SH 45

Debris Flow to Hyperconcentrated flow – Warea Fm

The State Highway 45 and the road cuttings from the Stony River to Warea show a cross-section through the Warea Fm. The outcrops display the typical pumiceous, sand-dominated matrix-rich laharic/hyperconcentrated flow deposit. The deposit shows weak laminar bedding and some internal structure represented by grading of coarser (<2cm sub-rounded) clasts. Some localities exhibit zones of large clasts, cobble- to boulder-rich zones or dense angular andesitic clasts, supported in a sandy matrix. Rare breadcrusted and radially jointed bombs can be found. This lead to the conclusion that this deposit was the result of a hot or warm lahar generated from eruptive activity. Complete sections of this deposit where the base or lower contact is exposed are rare.

The Matenehunehu Stream outcrop represents one of the most important, more complete lateral and vertical sections of the deposit. It displays the Warea Fm. lahar deposits with a central channel, debris flow facies grading laterally into an edge overbank deposit. An underlying peat layer was radiocarbon dated at 14.7 ka.

The centre of the flow shows a very coarse (up to metre-sized sub-rounded boulders in a coarse sandy matrix that makes up approximately 20% of the deposited volume) channel fill. The debris flow rapidly transforms into hyperconcentrated flow which deposited material with a similar grain size distribution as other hyperconcentrated flow deposits. The debris flow is channel-confined and does not have the same run-out length as the associated hyper-concentrated flow. The overbank facies shows greater variation in grading with distinct time breaks of the sediment settling (recognised by a weak laminar and dish and pillar structure of fine mud) and examples of reworking.

This deposit is interpreted to have a rheology with a very confined coarse flow where the flow front and centre are most likely dominated by inter-granular contact and forces of clasts bouncing and rolling along and on each other. The fluid and plastic components and finer material within the flow is pushed to the front and sides being rapidly deposited on the edge of the defined channel.

Figure 10: *Matanehunehu Stream outcrop. Exposure of transition from channel (debris flow) to overbank (hyper-concentrated flow) facies of lahar.*

STOP 1.6 (Optional): KOMENE RD/BEACH STONY RIVER

Hyperconcentrated Flow – Warea Fm.

The Warea hyperconcentrated flow deposits exposed at the coast or outlet of the Stony River differ strongly from the type section.

At this location the Warea Fm. consists of the run-out phase of the three main individual events and related deposits that are found in the Stony River catchment. At distance from source these clay- and pumice-rich deposits have transformed from debris flow to a hyper-concentrated flood flow.

The characteristic hyperconcentrated flow deposit displays a typical longitudinal or downstream change in grain size. The grain size analysis shows that the mean phi size is approximately 0.5-1 incorporating finer material downstream to develop a more poly- or bi-modal distribution. Clast type also changes downstream with only low density, scoriaceous, sub-rounded clasts remaining. However small changes in grain size and clast morphology occur rapidly over small distances with material being constantly eroded and deposited. Yet over longer distances and time period the flow is consistently losing material to transform from a hyperconcentrated flow to a flood.

The rheology of this flood flow is similar to hyperconcentrated flow with a buoyant high sediment load and some large clasts being transported suspended in the flow. This slow moving slurry-like flow spreads across the landscape flowing around barriers such as trees which leave moulds in the deposit. The most obvious change is the deposit becoming thinner and inundating a wider area.

Figure 11: *Komene Rd/Stony River beach outcrop with run-out facies of the Warea Fm found in the north-western section of the Taranaki ring-plain.*

DAY 2

STOP 2.1: OKAWA AND MOTUNUI FORMATIONS

This stop at the end of Mangati Road, Bell Block, takes us to a beach section 3-4 km in length which exposes the stratigraphic relationships of the Okawa and Motunui Formations. We will take about 1½ hours to walk part way along the section. This will take us through the older and younger Motunui diamictons and up into the Okawa Formation. The diamictons are largely clay-rich, marginal facies and features observed are logs swept along by the avalanches (Figure 12), rip up clasts and the stratigraphic relationships to interbedded tephric, dune sand and lignitic material. Channel fill and overbank behaviour are also displayed in the cross section provided by coastal erosion.

Figure 12: *Logs in the base of the Motunui Fm, Bell Block*

Figure 13: *Interglacial Dunes with onlapping Okawa Fm, Bell Block*

STOP 2.2: MAITAHI FORMATION

This formation was originally defined by Neall (1979) for a debris avalanche exposed in coastal sections near Oakura. It comprises both matrix-rich and matrix-poor facies and large megablocks of volcaniclastic origin as well as large rip-up clasts of sedimentary origin. The megaclasts comprise a range of lithologies which include lava flow material and also intact sequences of tephra. The sedimentary rocks are mudstones and sandstones from the underlying Tertiary units of the area. The interclast matrix is often rich in up to cm-sized hornblende crystals.

The Maitahi debris avalanche is thought to have been derived from an edifice collapse of nearby c. 250 ka old Pouakai volcano, based on field studies and lithostratigraphic relationships (Neall, 1979). Subsequent detailed field work has shown that the Maitahi deposits have resulted from debris avalanches that have transformed laterally into debris flows, or lahars. Ar/Ar dates on hornblendes cluster are 670 ka, close to the assumed age of Kaitake Volcano at 580 ka, while two other dates are c. 270 ka and 360 ka (Gaylord et al., 1997).

Three scenarios suggested by this data are;

1. a source from Pouakai volcano
2. a source from Kaitake volcano
3. sequential accumulation from both volcanoes

Stratigraphic continuity with the former Pouakai vent and lack of stratigraphic continuities led Gaylord et al., (1997) to conclude that the most likely source was Pouakai and that the megaclasts were derived from older parts of the edifice or scoured from the terrain over which the debris avalanche passed.

This stop at Oakura Beach is a superb example of the axial facies of a large debris avalanche. As we progress north along the cliffs, we pass into what was a channel down which megaclasts were concentrated. Note the range of megaclast fabrics, including intricate deformation within bedded sedimentary clasts that reflects the deforming forces they were subjected to.

Figure 14: *Maitahi Fm, axial a facies*