The Sedimentation and Drainage History of Haroharo Caldera and The Tarawera River System, Taupo Volcanic Zone, New Zealand

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Executive Summary

Haroharo caldera has been formed by the coalescence of multiple collapse structures over the last 350 kyr, the latest major collapse accompanying voluminous rhyolite pyroclastic eruptions at ~50 ka. The caldera has formed a sink for precipitation on surrounding catchments, with overflow via the Tarawera River through the Whakatane graben to the sea at ~30 km to NE. Lakes have probably always occupied at least part of the caldera floor, but the early lacustrine history is largely obscured by younger eruptives. Since 26 ka, the Haroharo, Okareka, Rotoma and Tarawera volcanic complexes have grown within the caldera during eleven eruption episodes, confining ten lakes on the caldera margins. Growth of the volcanic complexes has greatly altered drainage paths and ponding areas within and marginal to the caldera, so that the present ~700 km^2 caldera catchment area is about half the ~1400 km^2 area that drained into the caldera between 26 ka and 9.5 ka. The present Tarawera River flows out of the caldera through a channel modified during that time by larger river flows and catastrophic floods. Down cutting would have been accelerated by last glaciation sea levels that reached 120 m lower than at present. Deposits of two eruption-associated catastrophic floods at ~8 ka and ~0.7 ka, plus a smaller flood at AD1904, are exposed in the Tarawera River valley. An earlier catastrophic flood, at 13.8 ka, is inferred from the breach left in a pyroclastic fan dam formed at that time, but any sediments are buried. The Haroharo eruption at 5.5 ka produced multiple lahars and voluminous sedimentation in the Tarawera River valley, and a 120 m rise in level of lava-dammed Lake Tarawera, but no catastrophic flood occurred at that time. The 5.5 ka dam remained until the lake outlet was blocked during the 0.7 ka Tarawera eruption, forcing the lake to >30 m above present level before dam failure released the latest catastrophic flood. The history of Haroharo caldera demonstrates that future rhyolite eruptions will greatly affect the Tarawera lake and river system, with lahar deposition and catastrophic floods having devastating long-term impacts on the highly productive flood plain between the caldera and the coast.

Contents

Chapter 1: Introduction

Haroharo caldera (Figures 1, 2) is a complex structure formed over the last 350 kyr by multiple collapse events associated with a series of voluminous (~10-100 km^3) rhyolite ignimbrite eruptions (Nairn 2002) from the Okataina Volcanic Centre (OVC) in the Taupo Volcanic Zone (TVZ). The caldera-forming events at OVC have produced a large (30 by 30 km) basin in which precipitation (historically ~1.5 m/yr) on the surrounding catchments (Figure 3) is collected, with overflow draining to the sea via the Tarawera River. The early volcanic and structural history of Haroharo caldera is poorly known, and any associated sediments are mostly buried, so that the early hydrological history is obscured. The post-26.5 ka volcanic and structural history of the caldera is much better understood (Table 1, Figure 2), and although much of the sediment record has been removed or buried, some inferences can be made as to lake history and drainage during this period. The most recent OVC eruption episodes, the Kaharoa at ~AD1315 and the Tarawera at AD1886 (Table 1), both led to damming of the outlet of Lake Tarawera (the largest lake within the caldera), causing lake-outbreak floods that we have previously described (Hodgson and Nairn, 2000; submitted). Here we reconstruct the earlier drainage and sedimentation history of Haroharo caldera by combining the intracaldera eruption history with results of seismic profiling in Lake Tarawera (Davy and Bibby, in press), and our mapping and interpretation of sediments exposed in the Tarawera River system.

Chapter 2: Geologic Setting

The southern part of the present Haroharo caldera and the Puhipuhi basin were largely formed as a result of collapse during the voluminous (~150 km^3) Matahina ignimbrite eruptions at ~280 ka (Figure 2; Table 1). The northern part of the caldera was similarly formed at ~50 ka[1] during the ~100 km^3 Rotoiti ignimbrite eruptions (Nairn 2002). The subsidiary Rotoma caldera and Okareka embayment (Figure 2) both formed as a result of collapse during the Rotoiti eruptions. Some later Haroharo caldera collapse may have occurred at 33 ka (all ^{14}C ages are corrected to calendrical ages), accompanying the >10 km^3 Mangaone ignimbrite and plinian fall eruptions. This was the largest episode of the ~30 km^3 sequence of Mangaone Subgroup (henceforth MSg) intracaldera eruptions between 40 ka and 31 ka (Table 1), but any evidence for collapse is buried beneath younger eruptives.

All rocks now exposed within Haroharo caldera are younger than the TVZ-wide stratigraphic horizon formed by the Oruanui Tephra erupted from Taupo volcanic centre at 26.5 ka (Wilson 1993). The oldest exposed rocks in Haroharo caldera are lavas and pyroclastics of the 25 ka Te Rere eruption episode (Table 1), which marked commencement of growth of the Haroharo and Okareka complexes (Figure 2) in the north and west of Haroharo caldera. Growth of the Tarawera complex in the south of the caldera began with the 21 ka Okareka eruption episode (Table 1, Figure 2). Eleven discrete intracaldera eruption episodes are recognized, with about 85 km^3 of rhyolite and 2 km^3 of basalt erupted from more than 40 vents in the past 25 kyr (Table 1, Nairn 2002). Growth of the Haroharo, Tarawera, Okareka and Rotoma complexes (Figure 2) over the last 25 kyr has progressively infilled the caldera floor, impounding the 10 present lakes on the caldera margins. Lake Tarawera is the largest at 41 km^2 area and 2.3 km^3 volume when surface is at +300 m (above sea level), with maximum depth of 80 m to the flat-floored central basin (Figure 2). The lake overflows at ~7 m^3/s into the Tarawera River via the outlet at the eastern end. The Tarawera River drains the caldera through Puhipuhi basin into the narrow "Kawerau canyon" channel (Figures 1, 2), and thence to the coast across the Rangitaiki Plains formed by Holocene sediments infilling the subsiding Whakatane graben (Pullar 1981, 1985; Nairn and Beanland 1989).

[1] Age of the Rotoiti episode is controversial, with published ages ranging between ~65 and 44 ka. Here we avoid this debate, and use an "average" age of ~50 ka (without prejudice).

Chapter 3: Early Caldera and Lake History

Because large calderas at OVC form deep basins originally extending below sea level in an area of moderate rainfall (where precipitation considerably exceeds evaporation), their natural state is to be filled with water to overflow level. For the syn-Matahina caldera, overflow was originally controlled above +170 m by the near-flat surface of the Matahina ignimbrite sheet that forms the eastern margin to Puhipuhi basin (Figure 2). Overflow from Puhipuhi basin into the subsiding Whakatane graben eventually cut a channel down through the welded ignimbrite, presumably to near sea level at the time. Between ~280 ka and ~250 ka, sea level was well below the present level, at -30 m to -100 m (Chappell and Shackleton 1986), so the channel is very likely to have been cut down to below present sea level. This proto-“Kawerau canyon” was probably a deep narrow gorge, later modified by increased river flows and catastrophic floods (see below), and has remained the outlet to Haroharo caldera. The present Kawerau canyon is filled to ~ +50 m with young sediment, and the depth to which underlying ‘bedrock’ has been excavated is unknown.

The syn-Matahina caldera would have been partially infilled by the Kaingaroa and Mamaku ignimbrites erupted from the adjacent Reporoa and Rotorua calderas (Figure 1) at ~230 ka and ~220 ka respectively, initially displacing any lakes within it. However neither ignimbrite appears to have reached the proto-Kawerau canyon (Nairn 2002) so that drainage from the caldera may have been unimpeded. A ~180 kyr period without known major eruptions at OVC followed the Mamaku Ignimbrite eruption. Small dacite domes within the Puhipuhi basin appear to have grown during this interval, with some dacite lavas intruding lacustrine sediments and forming incipient pillows at ~+150 m (at V16/245309; this and later elevations read from “Tasmap” Tarawera Forest Map with 6 m contours), and showing that a lake existed within the basin to at least this level. Lacustrine sediments are also found at +210 m within the Puhipuhi basin (at V16/247293), but their stratigraphic position is unclear, and they may have been uplifted by the dacite intrusion. Also during this time the lake within the new Rotorua caldera must have risen to overflow, probably to NE through the developing Tikitere graben (Figure 1), i.e. away from the syn-Matahina caldera at OVC.

The period of quiescence was ended at ~50 ka by eruption of the Rotoiti ignimbrite from the northern part of the OVC. The initial Rotoiti eruptions were phreatoplinian and/or produced very fragmented pyroclasts, indicating some magma interaction with water, possibly a lake (Nairn 1981, 2002). Later Rotoiti eruptions were dry, producing voluminous non-welded ignimbrite flows that were accompanied by collapse extending the syn-Matahina caldera to north, to form a much larger composite basin – the present Haroharo caldera (Figures 1, 2). The embayments at Rotoma and Okareka appear to have formed at this time, probably by collapse associated with withdrawal of underlying magma migrating towards the Rotoiti vents within Haroharo caldera (Nairn 2002). The Rotoiti ignimbrite flows were mainly directed north towards the Bay of Plenty coast and east into the Whakatane graben (Figure 1), filling the Puhipuhi basin and Kawerau canyon to a level slightly higher than the rim of (now dissected) Matahina ignimbrite (i.e. to about +200 m). A considerable volume of Rotoiti ignimbrite must have also accumulated within the syn-Rotoiti caldera, but a deep caldera basin remained after the eruption, probably with floor below sea level. This is suggested by large arcuate slump scars around the eastern and northern rims of the syn-Rotoiti caldera (Figures 1, 2) that plunge deep beneath the surfaces of the modern lakes Okataina and Rotoiti, and by the results of seismic profiling in Lake Tarawera (Davy and Bibby in press; and see below).

A lake would have formed in the syn-Rotoiti caldera, rising to overflow the Rotoiti ignimbrite-filled Puhipuhi basin, and to exhume the Kawerau canyon. Erosion by drainage from the caldera lake, and downcutting by the streams flowing from the large catchments (Figures 1, 3) to south of the Puhipuhi basin, had removed much of the Rotoiti ignimbrite filling the basin before the MSg eruptions commenced at ~40 ka (Table 1). The largest of these eruptions, at 33 ka, produced massive ignimbrite deposits (K. Spinks pers comm; Nairn 2002), which infilled the Puhipuhi basin to +170-200 m and again blocked drainage from Haroharo caldera. The post-Mangaone lake within Haroharo caldera must have risen to ~ +200 m before it could again overflow across the Mangaone deposits in the Puhipuhi basin, to re-excavate the Kawerau canyon and cut down across the Puhipuhi basin. The caldera lake would have fallen towards pre-Mangaone levels, probably within a few thousand years after the eruptions.

A major increase in the catchment area contributing to Haroharo caldera occurred during the period between the last of the MSg eruptions at ~31 ka and the first of the present Haroharo intracaldera eruptive sequence – the 25 ka Te Rere eruptions from the Haroharo and Okareka complexes (Figure 2). The level of Lake Rotorua had risen considerably after the Rotoiti eruptions had infilled the Tikitere graben, blocking Rotorua caldera drainage to north. Lake Rotorua rose to overflow at about +380m, before headward erosion working back from the rim of Haroharo caldera broke through the Rotoiti ignimbrite dam in the Tikitere graben and captured the outflow from Lake Rotorua and its 505-km^2 catchment (Figures 3, 4a: Healy 1975; Nairn 1981, 2002; Esler et al., 2002). The ~1 km-wide, >60 m deep valley now occupied by the western arm of Lake Rotoiti (Figure 2) appears to have been excavated by a major flood event, suggesting that the level of Lake Rotorua is likely to have dropped rapidly. Elevation of the submerged valley floor where it crosses the Haroharo caldera rim is ~ +220 m. This is a lower limit below which Lake Rotorua could not have fallen, and an upper limit for any lake in Haroharo caldera at this time. The duration of the interval of Lake Rotorua drainage into Haroharo caldera is uncertain. It may have been terminated by emplacement of the 25 ka Te Rere episode eruptives (Figures 2, 4b) in the northern part of Haroharo caldera, although the history of Lake Rotorua levels (see Appendix 1) suggests that Rotorua drainage via Haroharo continued until the 9.5 ka Rotoma episode. This later termination model is shown in Figures 4b, c, d.

The 26 ka to 9.5 ka period during which catchment area of Haroharo caldera was at maximum (1400 km^2 – twice the present day 700 km^2 - Nairn 2002) includes the last glacial maxima when sea level fell to about -120 m (Chappell and Shackleton 1986; Bradshaw and Nelson 2004). Sea level was below -50 m and falling at time of the Rotorua drainage capture (Figure 5). A likely catastrophic flood into Haroharo caldera was undoubtedly followed by a doubling of the long term Tarawera River base flow from Haroharo caldera into Puhipuhi basin and Kawerau canyon. The coincidence of increased river flows with the glacial period of low sea levels (assumed to produce a steeper river gradient) implies that excavation of the Kawerau canyon reached its deepest level at this time. We infer this excavation level to be well below present sea level. The stratigraphy found in some geothermal wells at Kawerau (Figure 1), together with elongated subsidence patterns in the geothermal field, is consistent with extension of the Kawerau canyon into the Whakatane graben to north of Kawerau (Nairn 1986; plus unpublished data). Later catastrophic floods in the Tarawera River (Figure 5 and see below) occurred at times when the canyon was likely floored with sediment deposited as a response to rising sea levels. We interpret the present, sediment-floored, Tarawera River channel (at +40 to +50m elevation in the Kawerau canyon) to be approximately graded to present (Holocene) sea levels, from the coast upstream to the Tarawera Falls (Figures 1, 2). Earlier, lower sea levels during the last 26 kyr would have encouraged a steeper river gradient and deepening of the Kawerau canyon (Figure 2), with the only likely hard rock nick point control located within Matahina Ignimbrite beneath the canyon.

Chapter 4: History of the Post-26.5 ka Lakes in Haroharo Caldera

4.1 Present Lakes

The present lakes are all constructs of the post-26.5 ka eruptions in Haroharo caldera (Nairn 1981, 2002). Lakes Okareka, Tikitapu and Rotokakahi are impounded by lavas of the Okareka complex emplaced at 25 ka and 15.7 ka (Figure 2). These lavas blocked valleys previously draining east through the Okareka embayment into Haroharo caldera. Lake Okataina is impounded between the western caldera wall and post-26 ka lavas of the Haroharo complex (Figure 2). It reached its present form when the 5.5 ka Rotoroniu lava was emplaced against the 8 ka Te Horoa dome, separating this caldera-moat basin from Lake Tarawera. Lake Rotoma was formed when extrusion of the 9.5 ka Rotoma lava flow (Figure 2) blocked drainage from Rotoma caldera into Haroharo caldera. Similarly, Lake Rotoehu was formed when extrusion of the 9.5 ka Te Pohue lavas blocked southward drainage from valleys eroded across the caldera rim (Figure 2). The western arm of Lake Rotoiti occupies the drowned valley that carried the post-26.5 ka outflow from the Rotorua basin into Haroharo caldera before the valley was dammed by growth of the Haroharo complex (see above). The eastern arm of Lake Rotoiti occupies the caldera moat. Lake Rerewhakaaitu occupies valleys previously draining north across the southern rim of Haroharo caldera until they were dammed by pyroclastic flows from the Tarawera complex at 13.8 ka and 0.7 ka (Figure 2). Lake Rotomahana also lies across the caldera rim but occupies craters formed during the AD1886 Tarawera-Rotomahana eruption (Nairn 1979). Shallow ponds occupied the Rotomahana basin before AD1886. Lake Tarawera is impounded between 21 ka lavas and the Haroharo caldera rim and to west and south, and post-17.7 ka lavas and pyroclastic flows erupted from Tarawera and Haroharo complexes to north and east (Figure 2). The lake reached essentially its modern form after the 5.5 ka Whakatane eruption episode, and may not have existed before the 8 ka Mamaku episode (see below).

4.2 Lake Impoundment Sequence

The post-26 ka history of caldera-floor lake impoundment is complex but a sequence (Figure 4) can be inferred from the ages of the confining lavas and pyroclastic flow deposits, with some support from the sedimentary record within Lakes Rotoiti and Tarawera, and the Tarawera River valley. By 17 ka the caldera floor had been partly infilled by the 25 ka rhyolite lavas in the Okareka embayment to west, the 25 ka Haroharo complex eruptives to northwest, and the 21 ka and 17.7 ka Tarawera complex eruptives to south, confining any lake towards the centre of the caldera floor (Figure 4b, c). None of these eruption episodes appears likely to have significantly affected drainage from the caldera at low elevation, as no thick eruptives extended into Puhipuhi basin (Figures 2, 4b, c). We infer that a caldera-floor lake was at low elevation at this time, probably well below ~+100 m (Figures 4a-c, 5). A proto-Lake Rotoiti appears to have formed before 13.8 ka (Pickrill 1993), probably overflowing at low elevation (~+260 m – see Figure 4b) around the northern and eastern caldera margins.

The 13.8 ka Waiohau eruption episode (Table 1; Nairn 2002, Speed et al., 2002) was the first post-26 ka event to have a major effect on drainage from Haroharo caldera. Extrusion of the Waikakareao dome lavas (Figure 2) from Tarawera complex was accompanied by a large sector collapse and accompanying pyroclastic eruptions. A fan of Waiohau pyroclastics flowed northeast into the Te Haehaenga and Puhipuhi basins (Figures 2, 4d, 6a), and must have reached the caldera rim (the toe of the fan has since been excavated - see below). The pyroclastic fan was immediately overridden by the Pokohu lava flow (Figure 2) and block-and-ash flows (henceforth b-a-flows) derived by collapse of the advancing lava flow front. The Waiohau pyroclastic fan would have dammed drainage from the caldera, forcing the caldera-floor lake to rise above ~+220 m (the present elevation of the dissected surface of the >2 km-wide fan toe at V16/223334 – Figure 6a) before the lake could overflow. The lake rise may have been particularly rapid (Figure 5) if the Rotorua, Rotoiti, Rotoehu and Rotoma catchments were still draining into Haroharo caldera, producing a catchment size double that at present (see above). Overflow across the Waiohau fan may have initiated the deep but now largely dry and 'headless' (lacking significant catchments) "Titoki stream" gullies in the fan surface (Figure 6a) that lack other plausible explanation. The main Tarawera River channel was eventually excavated through the toe of the Waiohau fan, probably by catastrophic failure during lake outbreak. This post-Waiohau excavation produced a ~1 km wide, 3 km long channel (with trapezoidal cross section) which now terminates the Waiohau pyroclastic fan (Figure 6a), and is partly filled with 8 ka and younger sediment fans (see below). However, no Waiohau-age sediments that could confirm a catastrophic breaching origin are exposed downstream; any pre-Mamaku (>8 ka) sediments in the Tarawera River valley are now buried by younger deposits. The post-Waiohau lake outbreak channel was cut to below +140 m, as ~8 ka (post-Mamaku) gravel outcrops at this elevation in the upper channel (at V16/222344 – site a on Figure 6a), without exposure of the gravel base. It appears that the lake level dropped by >80 m during the post-Waiohau lake outbreak, from c. +220 m to below +140 m (Figure 5). We note that sea level at 13.8 ka was at about –60 m (Bradshaw and Nelson 2004).

Pyroclastic flows from the 9.5 ka Rotoma eruption episode (Table 1; Nairn 2002) must have entered the northern shores of the low elevation (below ~ +140 m) caldera-floor lake that remained after the post-Waiohau dam breach (Figure 5), but this area is now deeply buried beneath younger lavas (Figure 2) and no record remains. We infer no change in lake level at this time (Figure 5). However, the lake was again greatly modified during the 8 ka Mamaku eruption episode, when extrusion of the Te Horoa, Ruakokopu and Te Matae lavas (Figures 2, 4e) advanced the northern shoreline, producing a new lake outlet control point and causing a large rise in lake level (Figure 5). The present Tarawera River flows through a 400 m wide channel between the Te Matae and Pokohu lava flows, about 1 km below the Tarawera Falls (Figures 2, 6a). This channel was significantly enlarged by the ~AD1315 syn-Kaharoa catastrophic flood (Hodgson and Nairn 2000; submitted), destroying evidence of the previous lava flow morphology. We infer that during the Mamaku episode, the Te Matae lava advanced to butt against the Pokohu lava and Waiohau pyroclastic fan around V16/184325 (Figure 6a), forming a lava dam that impounded the caldera floor to southwest. The present dissected Pokohu lava surface in this area is at ~ +300 m (the Te Matae lava flow extends to >+400 m), suggesting that the post-Mamaku lake could have risen towards +300 m (Figure 5). At this level the lake would have extended north past Te Horoa dome into the Okataina caldera moat (Figure 4e), producing a larger surface area than the present lake. Any lacustrine evidence of this high lake level is submerged beneath the present (+300 m) Lake Tarawera, but seismic reflection profiling suggests post-Mamaku episode sedimentation occurred in the lake (see below).

Independent evidence for a syn-Mamaku high dam and lake level comes from post-Mamaku gravel found in fan remnants downstream (Figure 6a, and see below). These gravel deposits are inferred to have originated from a catastrophic dam breach flood that incorporated Te Matae lava and Waiohau episode eruptives. The lake had fallen below +270 m before the 5.5 ka Whakatane eruptive episode, probably to about +210 m (Figure 5, and see below). This return to a low level must have resulted from the post-Mamaku dam failure, after which the Tarawera River would have flowed through a low elevation channel between the Pokohu, Ruakokopu and Te Matae lavas (Figures 2, 4e).

Lavas extruded from Haroharo vents (Figure 2) during the 5.5 ka Whakatane episode (Nairn 2002; Kobayashi et al., submitted) produced the present Lake Tarawera northern shore, and confined the Tarawera River into its present channel. The Rotoroniu lava flowed southwest onto the 8 ka Te Horoa dome (Figures 2, 4f), separating the Lake Okataina basin from the new Lake Tarawera. The Tapahoro lavas flowed southeast over the 8 ka Ruakokopu and Te Matae lavas (Figure 2) to lap onto the 13.8 ka Pokohu lava flow and, along with an associated b-a flow fan, blocked the post-Mamaku lake outlet channel (Figure 4e, f). This caused lake level to rise at least 60 m (from drowned trees), and probably by ~120 m (based on seismic reflection data – see below). Several drowned trees have been found in vertical growth position off the western shore of Lake Tarawera; one located where the lake floor is now at 30 m depth (i.e. at +270 m) is ^{14}C dated (old $T^{1/2}$) at 5090±100 yr BP (Nairn 2002; Hodgson and Nairn 2000; submitted), equivalent within error limits to the 5.5 ka calibrated age of the Whakatane episode. The ^{14}C age records the rise of lake level through +270 m (Figure 5), drowning the trees, after the Tapahoro lavas and b-a-flow fan had blocked the post-Mamaku lake outlet. The lake continued to rise through the present +299 m level until it could overflow onto the Pokohu lava flow at +325-330 m (Hodgson and Nairn, submitted). Extensive post-Whakatane terraces that occur on the western shore of Lake Tarawera (Figure 2) at about 30 m above present lake level (i.e. at +330 m) record this lengthy high stand.

A full account of the post-Whakatane history of Lake Tarawera is given in Hodgson and Nairn (submitted). In summary; we concluded that lake level fell slowly from ~+330 m to ~+315 m during the ~5 kyr between the Whakatane and 0.7 ka Kaharoa eruption episodes (Figure 5), as overflow slowly cut a narrow gorge down through the Tapahoro b-a flow fan dam (Figure 7). There is no coarse sediment evidence in the Tarawera River channel for a major flood event during this time (see below). Unlike the previous Waiohau pyroclastics fan dam (13.8 ka), and the Te Matae-Pokohu lava dam (8 ka), no catastrophic breaching of the 5.5 ka Tapahoro fan dam followed the Whakatane eruptive episode. Instead, failure of the Tapahoro fan dam was delayed until the narrow gorge was dammed during the Kaharoa eruption episode, forcing the lake to again rise to ~+330 m and generating a catastrophic flood when the dam failed. This syn-Kaharoa flood formed the present Tarawera River channel, and is described elsewhere (Hodgson and Nairn 2000; submitted), as is a much smaller post-AD1886 eruption flood that occurred in AD1904 (White et al. 1997).

Chapter 5: Intracaldera Geomorphology and Sediments

5.1 Sediment Beneath the Present Lake Tarawera

Marine seismic reflection techniques used in the ~80 m deep Lake Tarawera (Figure 2) have defined major caldera structures displacing Mamaku Ignimbrite at depth beneath the lake floor, and revealed details of the overlying sedimentary/volcanic sequence (Davy and Bibby, in press). High-resolution, shallow penetration imaging to ~30 m below the lake floor was obtained using a high-frequency 'Uniboom' sound source. This work revealed two well-defined, near-continuous reflection horizons in lacustrine sediment at ~10 m and ~30 m below the central basin lake floor; the upper horizon "A" was correlated with the Whakatane eruption episode, the lower "B" with the Mamaku eruption episode (Davy and Bibby, in press). Horizon A was interpreted as resulting from the sinking of initially floating pumice, during, or soon after, a period of shallow (<5 m depth water) deposition in the central lake area. Horizon A is about 1-2 m thick, and lies at 10-15 m depth below the near flat central lake floor, i.e. at ~ +210 m. If this interpretation is correct, horizon A represents the early plinian phase of the Whakatane episode (Kobayashi et al., submitted), when pumice falls and flows entered a shallow post-Mamaku lake at ~+210 m (Figure 5). This phase was followed by extrusion of the Tapahoro lava flows to dam the lake outlet and cause the lake to rise to ~+330 m (see above). Horizon B is at ~ +190 m, and may represent the plinian pumice fall phase of the Mamaku episode, which was followed by extrusion of the Te Horoa, Ruakokopu and Te Matae lavas (Figure 2) and subsequent rise in lake level to ?+300 m (Figure 5). No estimate is available for lake depth (or existence) during deposition of horizon B. Horizon B is underlain by >600 m of layered deposits, but the seismic reflection data cannot determine if these are either pre-Mamaku primary eruption deposits or lacustrine sediments (B. Davy, pers comm., 2004).

5.2 Sediment in the Tarawera River Valley and Tributary Valleys

Surface evidence for sedimentary responses to the four latest (8 ka, 5.5 ka, 0.7 ka and AD1886) volcanic eruptions at OVC is preserved in valleys on the floors of Haroharo caldera, Puhipuhi basin and Kawerau canyon, and on the Rangitaiki Plains. Deposits of earlier sedimentation episodes are mostly not exposed due to burial or removal by erosion. Below the lava-controlled Tarawera Falls (Hodgson and Nairn, submitted; Figure 2) the present Tarawera River flows through Te Haehaenga basin, occupying the caldera floor between the Haroharo and Tarawera complexes, before entering the Puhipuhi basin at ~+100m. The Waiaute Stream valley (Figure 6) is a major tributary, which drains north from the Tarawera volcanic complex within Haroharo caldera, into Puhipuhi basin. The lower reaches of the Waiwhakapa, Mangawhio and Mangate streams (Figure 6) within Puhipuhi basin occupy tributary valleys perched above the Tarawera River. Sediment in these basins and valleys, and the Kawerau canyon, is preserved as gravel terraces, benches and fans, and basin-filling silts. We have mapped landforms and sediment in the Tarawera River system above Kawerau, using interbedded tephras for dating (Figures 6, 8, 9; Table 2). Sedimentation on the Rangitaiki Plains below Kawerau has been described by Pullar (1985; and see below). The syn-Kaharoa catastrophic flood produced the most extensive sedimentation and erosion visible today and is described in detail elsewhere (Hodgson and Nairn 2000; submitted). Sediment resulting from the preceding Whakatane and Mamaku eruption episodes is also exposed in the Tarawera River system, but all older deposits are buried. Here we describe the pre-Kaharoa sedimentary record.

5.3 8 ka Mamaku Episode Sedimentation

Gravel deposited between the 8 ka Mamaku and the 5.5 ka Whakatane episodes is found only at three sites in the Tarawera River valley (Figure 6a). Whakatane Tephra overlies a weathered surface on the gravel, but base of the gravel deposit is nowhere exposed. Mamaku Tephra is presumed to underlie the gravel.

The most upstream outcrop of post-Mamaku sediment is at V16/222344 (site a on Figure 6a), at ~+140 m within the Tarawera River channel cut through the 13.8 ka Waiohau pyroclastic fan. Whakatane Tephra overlies weathered coarse gravel (Figure 8) exposed in a cliff face cut into the highest terrace within the Waiohau fan channel. This high bench was cut back by the syn-Kaharoa flood (to produce the cliff exposure), leaving a ~1-km long, ~0.5 km wide terrace remnant at the mouth of the 13.8 ka channel. The surface of the high bench is distinctly scoured, presumably by waning flow after the gravel deposition. The post-Mamaku gravel is weathered and orange-stained, very poorly sorted, unconsolidated, fines-poor and weakly-bedded (Figure 8). Clasts are dominantly glassy to lithoidal rhyolite, derived from the Te Matae and Pokohu lavas (as shown by crystal contents, and EMP glass analyses – P. Shane pers comm. 2004), with minor pumice. Maximum clast sizes are 0.4-0.5 m in intermediate diameter. Base of the gravel is not exposed. We infer the high bench is constructed from the gravel exposed in the cliff face.

At the downstream end of the Waiohau fan channel, post-Mamaku gravel is exposed at V16/244333 (site b on Figure 6a) in the face of a small (~0.5 km long, ~0.5 km wide) fan remnant that was deposited in the mouth of the Waiaute Stream valley. The eastern end of this fan is also scoured. The fan has been cut back by the syn-Kaharoa flood to expose weathered, orange-stained, very poorly sorted, weakly consolidated and weakly bedded gravel beneath Whakatane Tephra. Clasts are lavas and pumices. Similar but finer-grained post-Mamaku sediment is also exposed at V16/247333 and V16/251327 (sites c and d on Figure 6a; Figure 8), where this fan remnant extends south into the mouth of the Waiaute Stream valley. At site D exposure furthest from the Tarawera River (i.e. at V16/251327), ~2 m of horizontal and low-angle cross-bedded, unconsolidated pebbly sand, containing a single 0.6 m intermediate diameter boulder, is overlain by ~4 m of Whakatane Tephra (Figure 8). Because this post-Mamaku gravel fan slopes down into the Waiaute valley mouth, away from the Tarawera River, it records a major sedimentation event in the Tarawera River channel that backfilled the mouth of the tributary Waiaute Valley.

Post-Mamaku gravels also form the lowermost sediment unit exposed further downstream in the Tarawera River channel, within truncated high level terraces to south of the river between the Mangawhio and Mangate streams, i.e. at V16/296333 and V16/305343 (sites e and f on Figure 6a). The lithic gravels are typically >1 m-thick (base not exposed), weathered, weakly-bedded and weakly imbricated deposits (Figure 8, V16/305343), which are overlain by Whakatane Tephra.

The post-Mamaku gravel deposits exposed within Haroharo caldera and Puhipuhi basin record a major flood event (see below) that deposited a gravel bench through the Tarawera River valley from the Te Haehaenga basin to at least the entrance of the Kawerau canyon. Much of this bench was later excavated by the syn-Kaharoa flood, so that only remnants are now left.

5.4 5.5 ka Whakatane Episode Sediment in the Tarawera River Channel

Sediment deposited during and after the ~5.5 ka Whakatane eruption episode is widely distributed through the Tarawera River and its tributary valleys (Figures 6b, 8). A large ~4-km wide, >4-km long pumiceous pyroclastic flow fan (here denoted the “Pukemaire fan” - Figure 6b) accumulated in the Te Haehaenga basin below the main Whakatane pyroclastic eruption vents at Makatiti (Figure 2; Kobayashi et al., submitted). Although since truncated by syn-Kaharoa flood erosion, the Pukemaire fan must have filled the post-Mamaku Tarawera River valley across to the Waiohau pyroclastics fan (Figure 6b). The Pukemaire fan is dominated by primary pyroclastic flow deposits, with some overlying lahar deposits. The eastern part of the fan, between the Mangakotukutuku and Kaipara streams, is dominated by redeposited Whakatane ash and pumice forming the “Kaipara” lahar fan built by outwash from the Kaipara Stream gully (Figure 6b). Kaipara fan sediment >20m thick is well exposed on Rotoiti Road at V16/218350 and Kaipara Road at V16/223351 (sites a and b on Figure 6b; Figure 8). No Whakatane episode pyroclastic flow deposits are found in the Kaipara Stream catchment (Kobayashi et al., submitted), so the Kaipara part of the Pukemaire fan must have been built from redeposited airfall tephra.

A thick, high (~ +120 m) fan remnant at V16/244341 (site c on Figure 6b; Figure 8) on the north side of the Tarawera River valley, within the Waiohau fan channel, was truncated by the syn-Kaharoa flood (Hodgson and Nairn submitted). The cut face exposes a >20-m thick sequence of Whakatane Tephra fall and multiple metres-thick, massive, pumiceous sand and gravel (Figure 8). On the opposite side of the Tarawera River, 0.8 km to south and at ~ +110 m, a ~2.5 m thick Whakatane fall sequence at V16/ 244333 (site d on Figure 6b) is interbedded with two thin (~0.1 m) beds of massive pumiceous sandy gravel. Hollows on the surface of the massive beds are filled with laminated silt and cross-bedded sand. These thin beds are the only Whakatane episode sediment on the south side of the Waiohau fan channel. The thick high fan to north of the river is not present to south, suggesting it was built (like the Kaipara fan) by washing of airfall tephra from the steep slopes of the caldera rim to north.

A low terrace formed in the Tarawera River channel by lahar outwash from the Pukemaire fan may be represented by Whakatane sediment exposed at c. +100 m on Fenton’s Mill Road (V16/261338; site e on Figure 6b) on the north bank of the Tarawera River. This low terrace forms part of the sediment-infilled valley to north (Figure 6b), and may have extended >12 km downstream to V16/305344 (f on Figure 6b; Figure 8). Here pumiceous, massive gravel is interbedded with pumiceous, weakly bedded gravel and laminated silty sand (Figure 8) to form a ~2-m high terrace adjacent to the Tarawera River. The terrace deposits are overlain by syn-Kaharoa lithic gravel and we infer they are post-Whakatane sediments. Further downstream, in the Kawerau canyon, the river is flanked by terraces that at V16/314361 (site g on Figure 6b) comprise 1.0 - 3.0 m thick, poorly sorted, cross-bedded, pumiceous sand with gradational contact on 0.5 – 1.0 m thick, poorly bedded Whakatane Tephra (Figure 8). Here the post-Whakatane sands are overlain by Kaharoa Tephra fall beds. At Kawerau, the Tarawera River floodplain terrace at V15/360405 is exposed in the riverbank as ~1 m thick poorly bedded Whakatane pyroclastic fall interbedded with pumiceous silt and sand, and overlain by ~2.5 m of poorly structured, unconsolidated, orange-stained pumiceous gravel

(Figure 8). The post-Whakatane sediment is overlain sequentially upwards by Kaharoa pyroclastic fall, syn-Kaharoa gravel (Hodgson and Nairn, submitted) and laminated silt (Figure 8).

5.5 5.5 ka Whakatane Episode Sediment in Tributary Valleys

Valleys in Puhipuhi basin tributary to the Tarawera River have steep sides above wide flat floors formed by recent sedimentary infilling of a topography previously eroded much deeper into the Mangaone and Rotoiti ignimbrites that had filled the basin (Nairn 1981, 2002). This erosion occurred when the Tarawera River channel was considerably deeper than at present (see above). No exposures through the recent sediment infill to bedrock are available, but post-Whakatane sediment is exposed in the southern tributary Waiwhakapa and Mangawhio streams. Metres-thick, horizontally bedded and cross-bedded pumiceous sand and gravel form <7 m high terraces at V16/257324 (site i on Figure 6b; Figure 8) in the Waiwhakapa Stream valley. Bedding is occasionally marked by iron-staining. The base of the post-Whakatane sediment is nowhere exposed, but the upper contact is marked by a yellow-brown paleosol beneath Taupo Tephra fall (Table 1) and, at V16/271308 (j on Figure 6b), 4 m-thick fine-grained Taupo Ignimbrite that has carbonized several thick (0.3 m diameter) tree trunks in growth position. This is the northernmost known exposure of Taupo Ignimbrite, which must have flowed down the Waiwhakapa Stream valley from the Rerewhakaaitu basin 11 km to south.

In the Mangawhio Stream valley at V16/294319 (site k on Figure 6b; Figures 8, 9), >3.0 m thick weathered pumiceous gravel is horizontally bedded, grading upwards into low angle cross bedding, and is overlain by 2.0 m of Taupo and younger tephras to form a ~10-m high terrace. Base of the pumiceous gravel is obscured by fans of loose gravel and vegetation and Whakatane Tephra is not exposed.

The post-Whakatane sediment filling the Waiwhakapa and Mangawhio valleys is perched at slightly higher elevation than the post-Whakatane sediments within the main Tarawera River channel, and can only have been deposited as outwash from higher in the tributary valley catchments. Both catchments extend ~12-15 km to south, directly under the axis of the Whakatane Tephra main dispersal plume (Figure 4f), and the thick (>1 m) tephra would have been eroded from steep slopes during intense rainfall, to be redeposited in the lower valleys. The same sedimentation process probably produced the flat-floored valleys in Puhipuhi basin to north of the Tarawera River (Figure 6b), but exposures through this infill are not available.

Chapter 6: Sedimentation on the Rangitaiki Plains

The Whakatane graben (Figure 1) is actively subsiding at about 2 ± 1 mm/yr (Pullar 1981; Nairn and Beanland 1989), and is floored by Holocene sediment forming the Rangitaiki Plains. This sediment was carried down the Tarawera, Rangitaiki and Whakatane rivers, to overlie Rotoiti and older ignimbrites found in drill holes (Nairn and Beanland 1989). Soil mapping by Pullar (1985) showed that sediment associated with the Whakatane (5.5 ka), Taupo (1.8 ka), Kaharoa (0.7 ka) and AD1886 eruption episodes formed the main surfical units in the graben; older sediments are buried. The present land surface reflects the rise of sea level to its modern elevation at ~7 ka (Gibb 1986; Carter et al., 2002), when coastal cliffs were cut at Awakeri (Figure 1). Since then the shoreline in the graben has advanced by ~10 km, with about 4 km progradation between the Whakatane and Taupo eruptions (Pullar and Selby 1971; Kear 2003). Taupo eruption sediment was carried down the Rangitaiki River; the Kaharoa and post-AD1886 sediment was transported by the Tarawera River, mostly in the floods described by Hodgson and Nairn (submitted). Post-Whakatane sediment would have been carried down both the Tarawera and Rangitaiki Rivers, so that the progradation that occurred at this time will not be solely due to sedimentation in the Tarawera River system. Deeper sediments, deposited from Tarawera River floods associated with the Mamaku, Waiohau and older events in Haroharo caldera (as described above), must also be buried in the graben but can only be sampled by drilling.

Chapter 7: Discussion and Conclusions

7.1 Post-Mamaku Erosion and Sedimentation

The post-Mamaku gravel deposits in the Tarawera Valley indicate deposition from a highly competent flow with abundant supply of coarse sediment. The present Tarawera River within Haroharo caldera has a near-constant flow, moderated by the storage capacity of Lake Tarawera. Long-term mean river discharge across the lake outlet is ~7 m^3/s, increasing to 20 m^3/s at Kawerau, 25 km downstream. These normal river flows are not capable of transporting voluminous gravel-cobble sized sediment. The coarse, poorly structured and bench-forming post-Mamaku gravel are similar to those deposited by the catastrophic syn-Kaharoa lake breakout flood from Lake Tarawera (Hodgson and Nairn, submitted). We infer the post-Mamaku gravel to have been emplaced by a similar, if rather smaller, peak flood discharge after a lava dam failure released a large volume of water into the Tarawera River valley.

The Te Matae and Pokohu lava flow morphologies, and clast compositions in the post-Mamaku gravel, indicate that the Mamaku episode dam was located where these lavas were in contact (see above). The effects of later eruptions and floods obscure the exact site of this dam, and the level (+300 m?) to which the lake rose behind it. The Waiohau pyroclastic fan below the Pokohu lava flow is now dissected by deep, somewhat sinuous, steep-sided gullies, with very small catchments and only ephemeral stream flows. These gullies could not be formed by the present flow regimes. Whakatane pyroclastic fall deposits found in one gully (not all gullies have suitable exposures), show that gully formation occurred before the Whakatane eruptions. It seems likely that these gullies were formed by overflow from the Mamaku episode dam, occurring across the Waiohau pyroclastic fan before the dam failed.

7.2 Syn- and Post-Whakatane Sedimentation Processes

Evidence as to effects of Pukemaire and Kaipara fan building on Tarawera River flows has been destroyed by syn-Kaharoa flood erosion (Hodgson and Nairn, submitted). However, some effects can be inferred from the known sequence of the Whakatane eruption episode (Kobayashi et al., submitted). The Pukemaire pyroclastic flow fan was emplaced before extrusion of the Tapahoro lava flows (Figures 2, 4f) had begun. The pyroclastic flows and at least some of the lahars that built the Pukemaire/Kaipara fans entered the post-Mamaku Tarawera River channel before Lake Tarawera outflow was blocked by the Tapahoro lavas (see above). Temporary pyroclastic dams would have been repeatedly formed in the main river channel while Lake Tarawera was still overflowing, leading to local ponding in the Pukemaire area. We infer that this continuing syn-eruption interaction of river and pyroclastic flows and lahars would have caused repeated failures of pyroclastic dams, leading to extensive, but not catastrophic, lahar sedimentation downstream. After the Pukemaire pyroclastic flow fan was constructed, there was a period of at least a few years of "normal" flow in the Tarawera River before the Tapahoro lavas and b-a flows reached and blocked the post-Mamaku outlet to Lake Tarawera. [A 3-6 year duration is based on the ~2 km^3 volume of the Tapahoro lava flows between vent and lake outlet, and the ~10-20 m^3/s lava extrusion rates estimated by

Kobayashi et al. (submitted)]. The lake then rose by ~120 m (Figure 5) before overflow across the Tapahoro fan dam was possible; this would have taken ~20 years based on the ~6-7 m/yr rise rate for a dammed Lake Tarawera calculated from the 41 km^2 lake area and the 7 m^3/s lake discharge (Hodgson and Nairn, submitted). During this “no lake overflow” interval, sheet and gully erosion on the Pukemaire/Kaipara fans would have been limited to times of intense rainfall on the local catchments of the Makatiti, Mangakotukutuku and Kaipara streams (Figure 6b), plus the small catchments on the Pokohu/Waiohau eruptives to south of the river. No large ponds are likely to have been developed, and no large dam failure-induced catastrophic flooding seems to have occurred. At this time, the major contribution of sediment to the Tarawera River valley was probably erosion of the thick (>1 m) Whakatane Tephra mantling the catchments tributary to the river (see below).

When Lake Tarawera rose to overtop the Tapahoro fan dam (Figures 5, 6b, 7), overflow occurred into the shallow Hunts Road basin on the Pokohu lava surface, where ponding formed lacustrine deposits at top of the subaerial Whakatane pyroclastic falls mantling the basin floor (Hodgson and Nairn submitted). Overflow from the basin then occurred at multiple points (Figure 6b), into both the Tarawera River valley and the Waiaute valley, increasing dissection of the Waiohau pyroclastic fan below the Pokohu lava flow rim. Some of these overflow channels were later used by the syn-Kaharoa flood, which destroyed any evidence of Whakatane episode erosion or sedimentation. However, massive coarse gravel derived from Waiohau pyroclastics overlies Whakatane pyroclastic fall beds at V16/199329 (h on Figure 6b), in a gully cut into the Waiohau pyroclastic fan. This is evidence of early post-Whakatane overflow to north from the Hunts Road basin before all Lake Tarawera overflow was eventually captured by the more western channel (Figure 6b), now occupied by the present river.

Thick (>1 m) Whakatane Tephra fell across the Tarawera River tributary catchments (Figure 4f). Erosion of tephra fall deposits from steep slopes occurred during intense rainfalls after the rather similar Pinatubo and Rabaul eruptions in 1991 and 1994 (Nairn, personal observations 1991, 1995; Rodolfo et al., 1996; Scott et al., 1996), to generate relatively small lahars in catchments distant from the main ignimbrite deposits. Whakatane Tephra pumice and ash fall deposits will have become saturated by rainfall, triggering failure on steep slopes and creating temporary dams in streams, leading to flash-flooding and debris flows when the dams fail. These processes are likely to have provided the coarser sediments that infilled the lower reaches of the tributary stream valleys in the Puhipuhi basin. Silt that accumulated in these valleys record temporary local ponding consequent on damming of the tributary stream outlets by sediments infilling the main Tarawera River valley.

7.3 Significance of the Lake and Sedimentation History

Historic observations of similar pyroclastic eruptions around the world (i.e. Pinatubo 1991 – Newhall and Punongbayan 1996) suggest that every past eruption episode within Haroharo caldera would have produced major effects on drainage and sedimentation within the caldera and downstream. However, evidence of the hydrological effects of early caldera eruptions on the Tarawera River system is sparse to non-existent; being either buried under younger sediments or removed by later floods.

Very large volumes of Rotoiti and Mangaone ignimbrites were removed from Puhipuhi basin after each of these ignimbrites was deposited; this erosion probably reaching greatest depths at around 20 ka. At this time Lake Rotorua was draining into Haroharo caldera (Figure 4a, b, c), increasing the Tarawera River base flow, and the river channel was likely actively downcutting in response to low sea levels (down to -120 m) during the last glaciation (Figure 5). Eroded material was carried through the Kawerau canyon to be deposited in the subsiding Whakatane graben. Since then, we infer that a major flood occurred in the Tarawera River valley at about 13 ka, after a dam formed across the outlet to Haroharo caldera by the Waiohau pyroclastic fan was breached by the (Rotorua-augmented?) caldera outflow. No sediments from this flood (or earlier floods) are exposed anywhere, and confirming evidence could only be obtained by drilling on the Rangitaiki Plains. The Waiohau-age lake in Haroharo caldera was probably larger in area than the present Lake Tarawera, and was apparently drawn down by ~60 m during the lake outbreak, so that the volume of water released may have exceeded the 1.7 km^3 released by ~40 m drawdown in the syn-Kaharoa flood (Hodgson and Nairn submitted).

The 9.5 ka Rotoma eruption episode seems to have had little effect on the Tarawera River system above Kawerau, although thick tephra falls had major effects on other catchments to north and east of the Lake Rotoma vents. The earliest flood event in the Tarawera River for which sediment is now exposed is associated with the 8 ka Mamaku eruption episode, when failure of a new lava dam released a flood that deposited coarse gravel found as bench and fan remnants downstream into the Puhipuhi basin (Figure 6a). By this time, Lake Rotorua drainage had been excluded from Haroharo caldera (Figure 4e) but Lake Tarawera had risen to an overflow level close to +300 m behind the Mamaku-age lava dam, with an areal extent and volume significantly greater than the present lake. Dam failure appears to have caused lake level to fall by ~90 m to +210 m (from the seismic reflection profiling), so the volume of lake water released also seems to have greatly exceeded that of the syn-Kaharoa flood. However, the post-Mamaku dam was formed by lavas, in contrast to the b-a-flows that were eroded during the syn-Kaharoa failure of the Tapahoro fan dam. The lava construction may have led to much slower breach development in the post-Mamaku dam, and thus a lower peak discharge than the 10^5 m^3/s estimated for the syn-Kaharoa flood (Hodgson and Nairn submitted). The coarseness (most clasts <1 m intermediate diameter) and extent of the post-Mamaku gravel, when compared with the syn-Kaharoa flood gravel (many clasts >10 m), is consistent with a smaller peak discharge for the post-Mamaku event.

The 5.5 ka Whakatane eruption episode led to major sedimentation downstream to the Bay of Plenty coastline, which advanced by 4 km as a result (Pullar 1985). However, no single major flood is associated with the Whakatane episode, and sedimentation was apparently incremental, with infilling of the Tarawera River channel by repetition of relatively small-scale lahars formed by erosion of the growing Pukemaire and Kaipara fans. Tributary valleys were infilled by ash and pumice washed by intense rainfalls from the thick Whakatane Tephra mantle on steep catchment slopes, and these sediment flows were a major contribution to the Tarawera River bed load. However, Whakatane eruptives emplaced at Lake Tarawera outlet formed the dam that failed in the ~AD1315 syn-Kaharoa catastrophic flood – the event with the largest peak discharge of any known flood in New Zealand during the last 20 kyr (Hodgson and Nairn, submitted).

The volcanic and sedimentation history inferred here, together with the better known syn-Kaharoa and post-AD1886 floods (Hodgson and Nairn, submitted), shows that future rhyolite eruptions within Haroharo caldera will have major effects on the whole Tarawera River system, from Lake Tarawera across the Rangitaiki Plains to the coast. Recent experience at Pinatubo and Rabaul demonstrates that post-eruption sedimentation on the Rangitaiki Plains is likely to be the most devastating and long-term impact of a future Haroharo rhyolite eruption episode, with lahars continuing for decades after eruptive activity has ceased.

Appendices

Appendix 1 - Implications of Lake Rotorua Level History for Drainage Paths in Haroharo Caldera

Kennedy et al. (1978) and Esler et al. (2002) have used tephra deposits as marker beds to study lake level changes in Lake Rotorua basin since the Rotoiti ignimbrite eruptions. Pickrill (1993) identified seven subsurface reflectors beneath the floor of Lake Rotoiti, correlated these with tephra fall deposits down to the Waiohau Tephra, and recognised that the lake must have existed at that time. These earlier results, modified by new radiometric ages and converted to calendrical dates, are summarized here. Lake Rotorua had fallen from ~+380 m to below +270 m (Esler et al., 2002) just before 26.5 ka, when distal Oruanui ignimbrite was emplaced in the Rotorua basin. Lake Rotorua remained below +280 m (the present level) at time of the Okareka (~21 ka), Rerewhakaaitu (17.7 ka) and Rotorua (15.7 ka) tephra eruptions, was at or below +277 m immediately prior to the Rotoma Tephra eruption (9.5 ka), and had risen to c. +290 m after the Mamaku Tephra eruption (8 ka). This post-26 ka lake history has been explained (Nairn 1981, 2002) by drainage from Lake Rotorua flowing into Haroharo caldera and then being progressively dammed to higher overflow elevations by extrusion of the Haroharo complex lavas and pyroclastics at and after 25 ka (see Figure 4). A proto-Lake Rotoiti at ~+260 m (?) was initially formed by emplacement of the 25 ka Te Rere episode eruptives (Figures 2, 4b), with overflow through northern Haroharo caldera probably continuing around the caldera rim (Figure 4b). This channel was dammed by lavas and pyroclastics of the 9.5 ka Rotoma episode (Table 1; Figure 4e), causing the Lake Rotorua – Rotoiti system to rise to overflow north into the present Kaituna River channel (Figure 1) via the Okere Falls outlet to Lake Rotoiti. Lake Rotorua was probably falling from >+290 m at time of the 8 ka Mamaku episode. Continued downcutting at Okere Falls has since lowered both lakes to their present levels around +280m.

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Figures

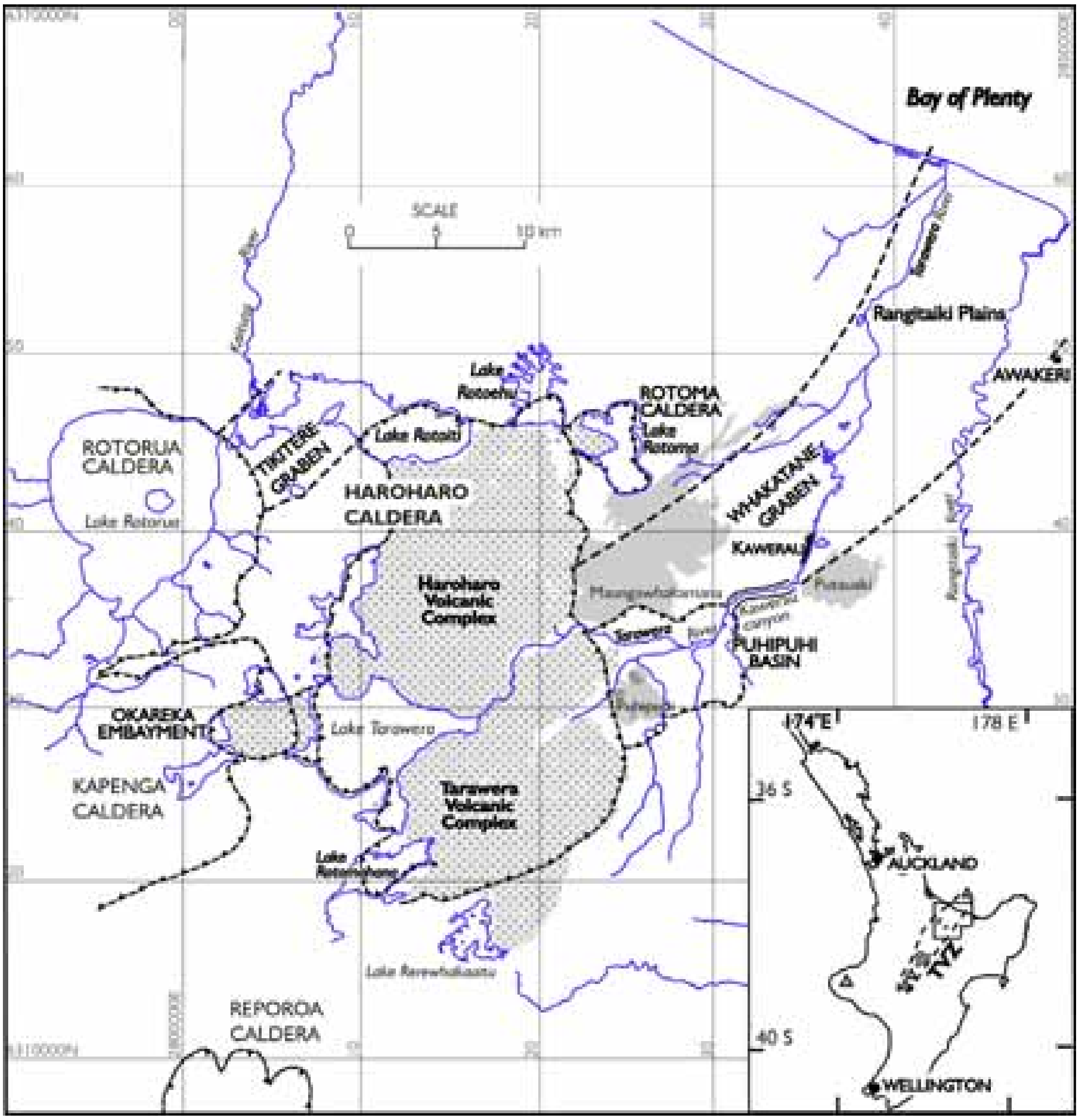

Figure 1 *Map of Haroharo caldera and surrounding region. Inset shows location of the map area in the Taupo Volcanic Zone (TVZ), of the North Island.*

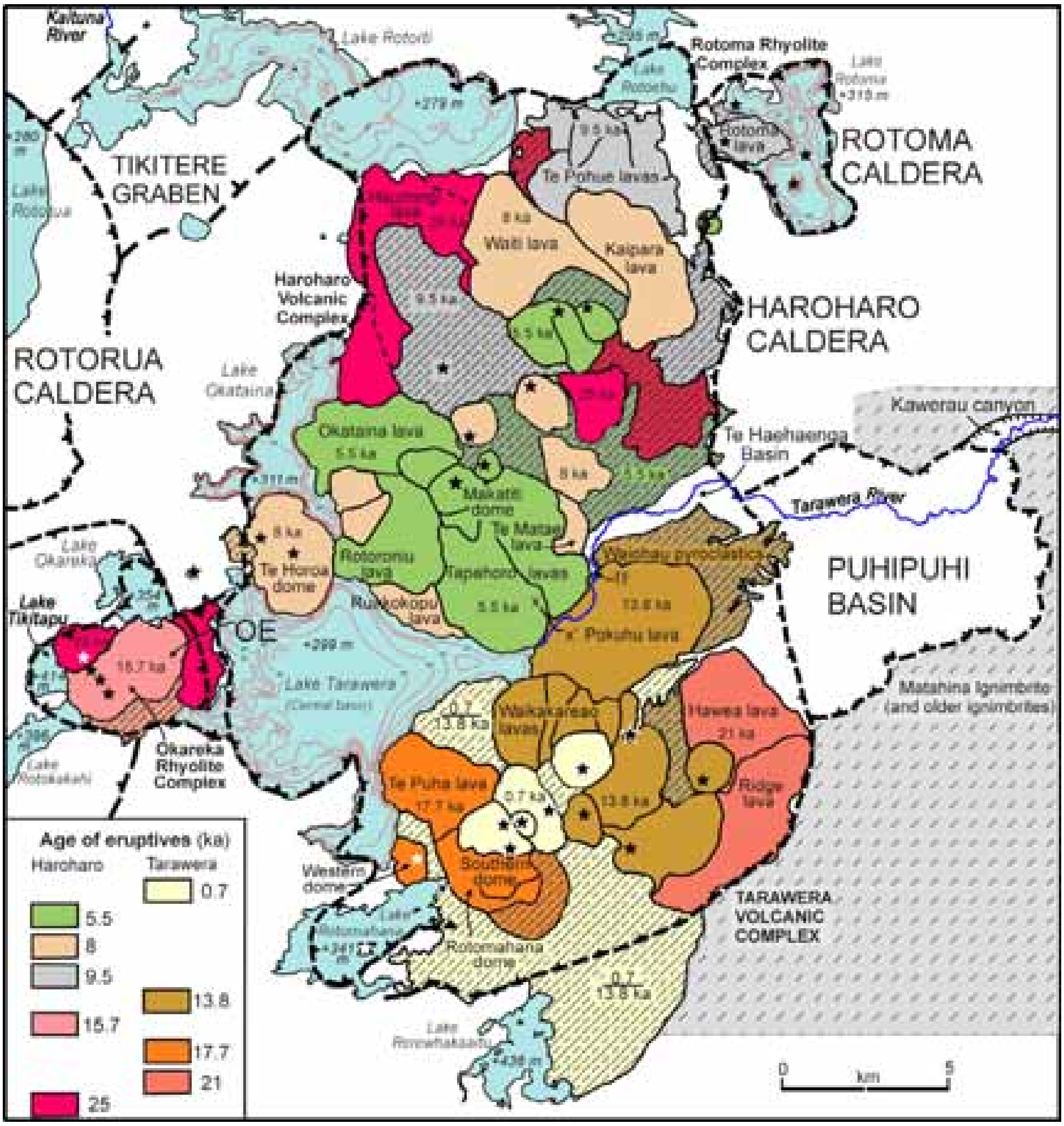

Figure 2 *Post-26.5 ka eruptives within present day Haroharo caldera. Lavas are solid colour; pyroclastic deposits are hatched; stars mark vent locations; bathymetric contours are at 20 m spacing. TF is Tarawera Falls; OE is Okareka embayment. X-X' is line of cross section shown in Figure 7. See Nairn (2002) for a complete listing of eruptive names.*

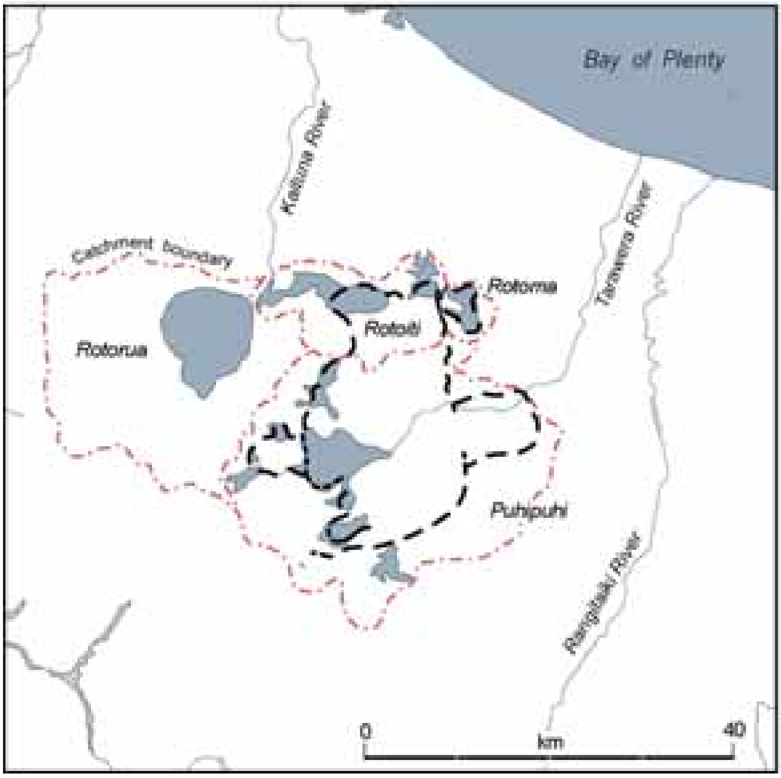

Figure 3 *Map of present day catchment areas for Haroharo caldera and Puhipuhi basin draining to the Tarawera River, and the Rotorua and Rotoiti catchments draining into the Kaituna River. At 26 ka all these catchments drained via Haroharo caldera into Puhipuhi basin.*

Figure 4(a)
At 26 ka, after the capture of Lake Rotorua discharge. A large (?) lake at low level (?<<+100 m) occupies much of the post-Mangaone (31 ka) Haroharo caldera floor.

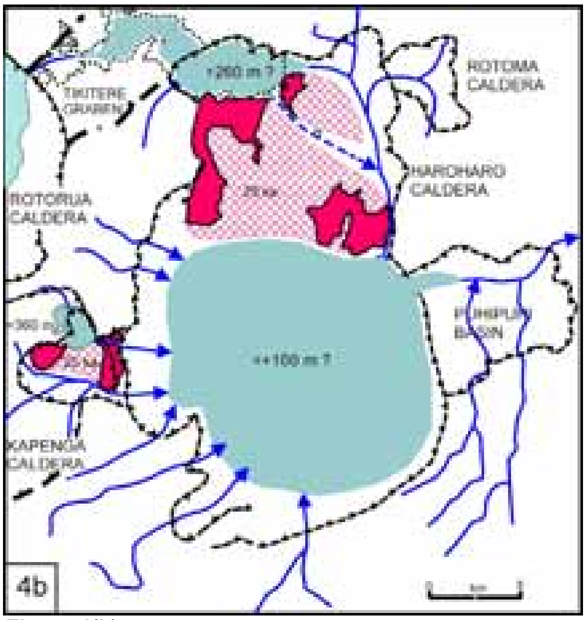

Figure 4(b)
At 25 ka, after the Te Rere eruption episode. Lake Okareka has formed (to ~10 m higher than present elevation); outflow from the Rotorua catchment has formed proto-Lake Rotoiti (to ~+260 m ?). Rotoiti is overflowing through Haroharo caldera to Puhipuhi basin and the Tarawera River. The caldera floor lake is confined to southern part of Haroharo caldera.

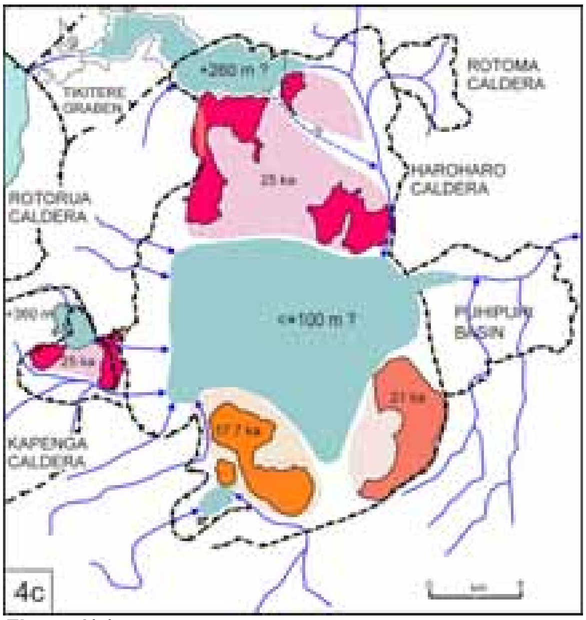

***Figure* 4(c)**
At 17 ka, after emplacement of the initial eruptives of the Tarawera complex. Shallow ponding occurs in the Rotomahana area; the caldera-floor lake is further confined, but no significant change to lake level has occurred.

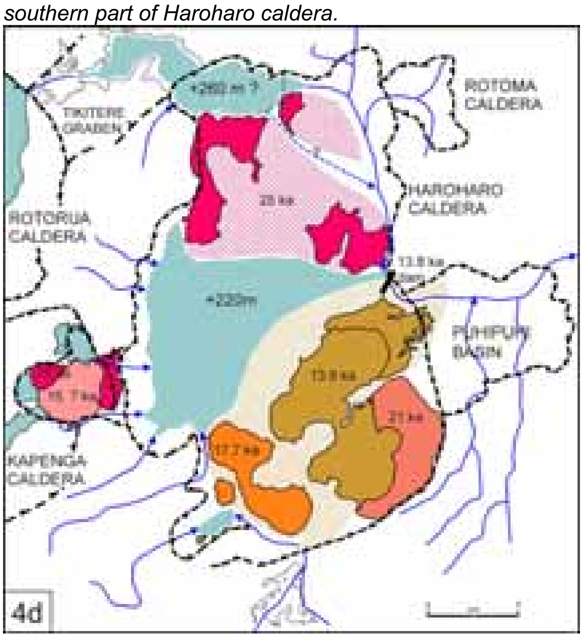

Figure 4(d)
Immediately after the 13.8 ka Waiohau eruption episode. Lakes Tikitapu and Rotokakahi are now dammed behind 15.7 ka lavas in the Okareka embayment; outflow from the caldera-floor lake has been dammed by the Waiohau pyroclastic flow fan and the lake has risen to overflow at ~+220 m. A proto-Lake Rerewhakaaitu has been formed by damming of outflow from a caldera rim valley by 13.8 ka pyroclastic flows.

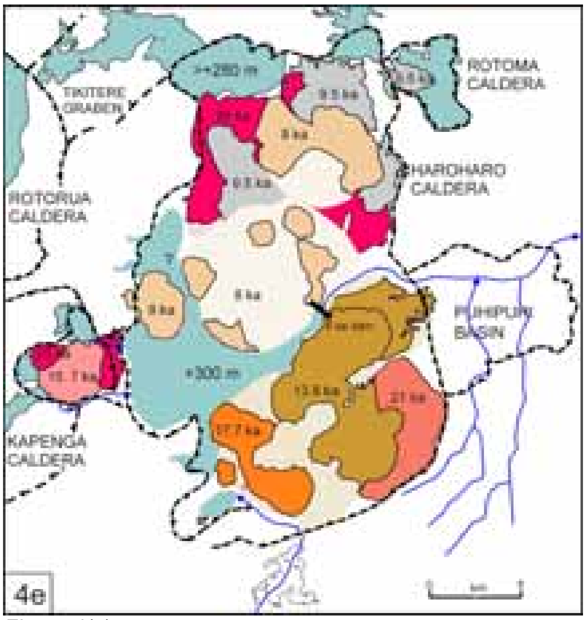

Figure 4(e)

Immediately after the 8 ka Mamaku eruption episode. Emplacement of the 9.5 ka Rotoma eruptives in northern Haroharo caldera has blocked any southward drainage, forming Lakes Rotoma, Rotoehu, and forcing lakes Rotoiti and Rotorua above present levels (~+280 m). Emplacement of the 8 ka Mamaku episode eruptives against 13.8 ka Pokohu lavas has formed a lava dam confining a proto-Lake Tarawera, which rises to ~+300m and may extend north past 8 ka Te Horoa dome (Figure 2) into the Okataina basin. The 13.8 ka pyroclastic fan dam at entrance to Puhipuhi basin (see Figure 4d) had been previously excavated by a catastrophic dam failure flood (probably shortly after the 13.8 ka eruption – see Figure 5) to produce the present channel in this area.

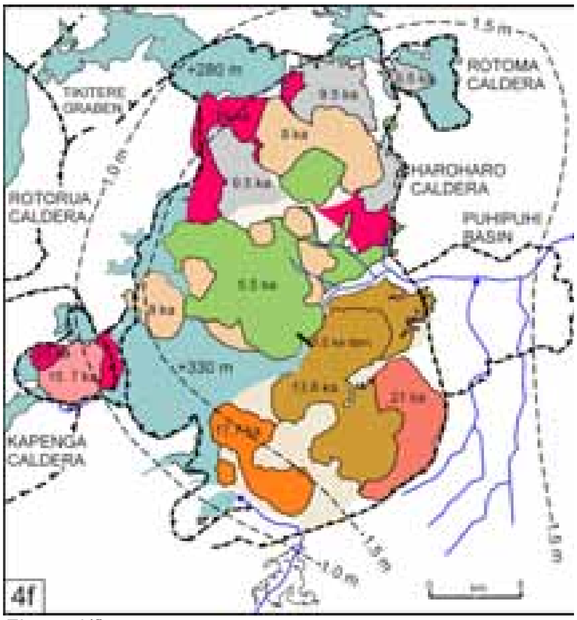

Figure 4(f)

Immediately after the 5.5 ka Whakatane eruptive episode. Emplacement of Rotoroniu lava (see Figure 2) has impounded the Lake Okataina basin. Emplacement of the Tapahoro lavas and b-a-flows has formed the Tapahoro dam, impounding Lake Tarawera, which rises to ~+330 m (i.e. 30 m above present level). Emplacement of a 5.5 ka pyroclastic flow fan (the Pukemaire fan, see Fig 6b) has filled the Te Haehaenga basin across to the 13.8 ka Waiohau pyroclastic fan, infilling the Tarawera River channel earlier excavated by the post-8 ka lake breakout flood (see Figure 5). Dashed lines are the 1.0 and 1.5 m isopachs of the Whakatane Tephra fall deposit (from Kobayashi et al., submitted).

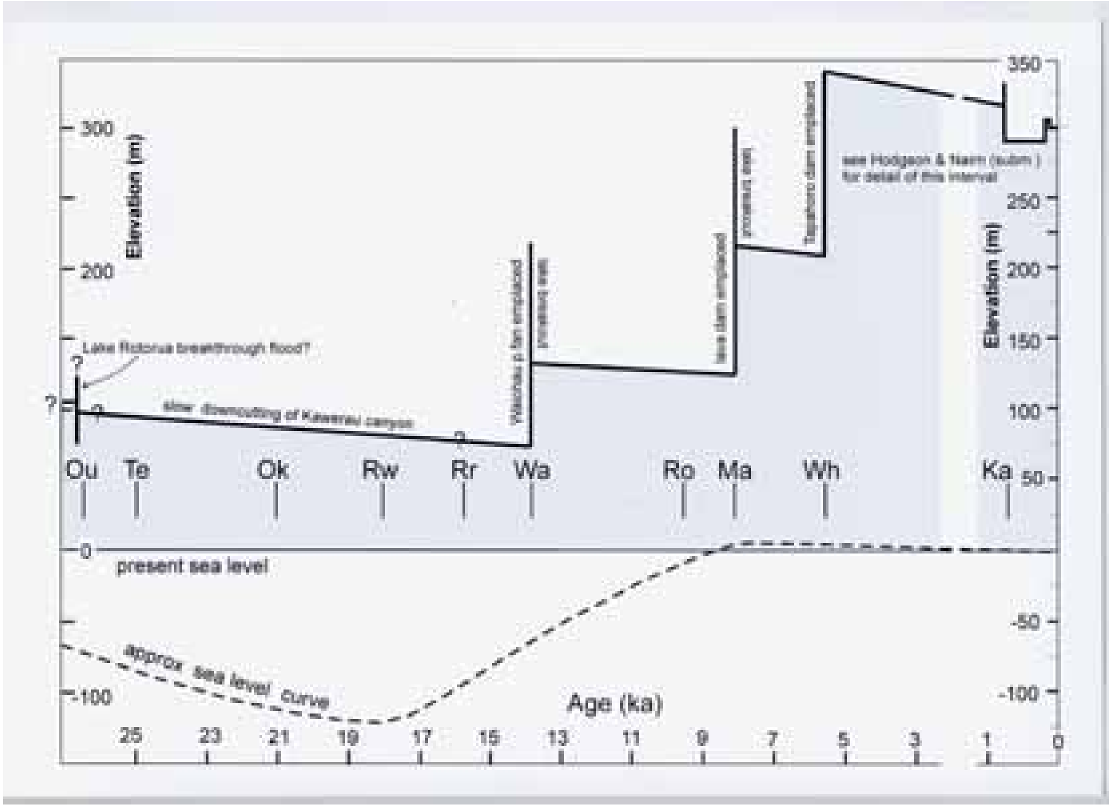

Figure 5 *Schematic summary of the level history inferred for the caldera-floor lake and Lake Tarawera. Ou, Te, Ok, etc are eruption episodes (see Table 1) with ages calibrated from ^{14}C ages (see text); lake level spikes represent short-lived (on this time scale) rises following emplacement of eruptive dams, most of which failed shortly after emplacement, with sudden falls in lake level. Note the hiatus and change in time scale between 1 and 3 ka.*

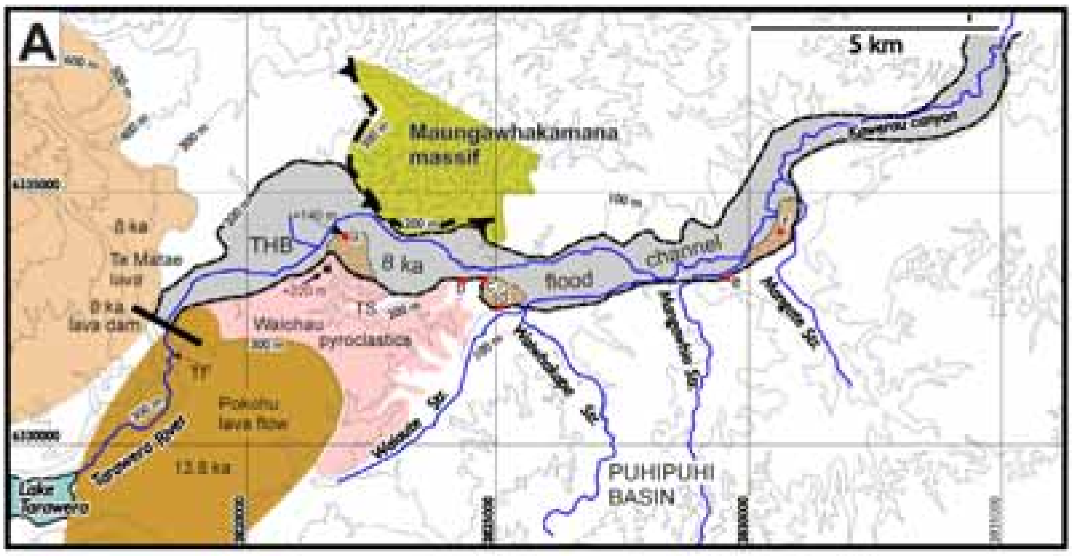

Figure 6(a) *Map showing locations of exposed Mamaku episode sediments (black/brown stipple). Letters indicate sites referred to in text. THB is Te Haehaenga basin; TS is “Titoki stream”; TF is present day Tarawera Falls.*

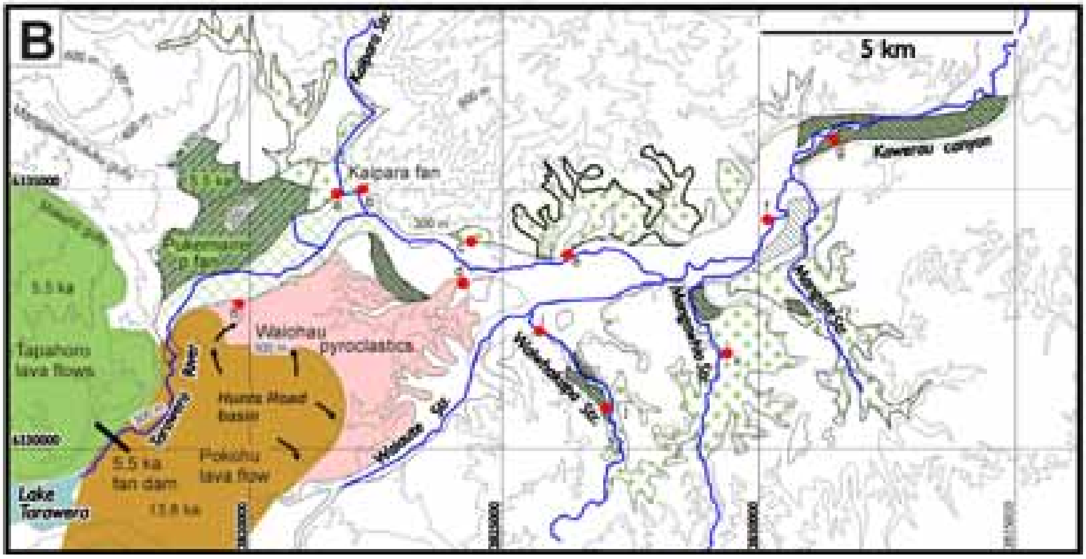

Figure 6(b) *Map of Whakatane episode sediments as lahar remnants (green hatched) in the Tarawera River channel after truncation by the syn-Kaharoa flood (which formed the channel as shown), and as reworked fall deposits filling tributary valleys (+ stipple). Letters indicate sites referred to in text. Arrows show overflows from the post-Whakatane pond in Hunts Road basin.*

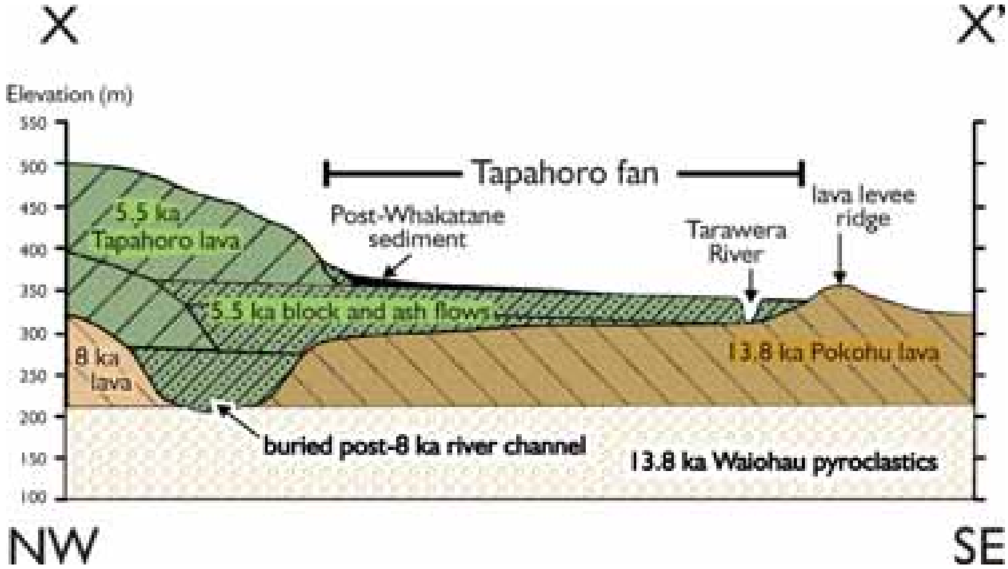

Figure 7 *Tapahoro dam x-section on line X-X' on Fig 2. The x-section (based on Hodgson and Nairn submitted) presents our interpretation of the damming of the post-Mamaku (post-8 ka) Tarawera River channel by the 5.5 ka Tapahoro lavas and block-and-ash flows, and subsequent down cutting of a narrow river gorge before the 0.7 ka Kaharoa episode.*

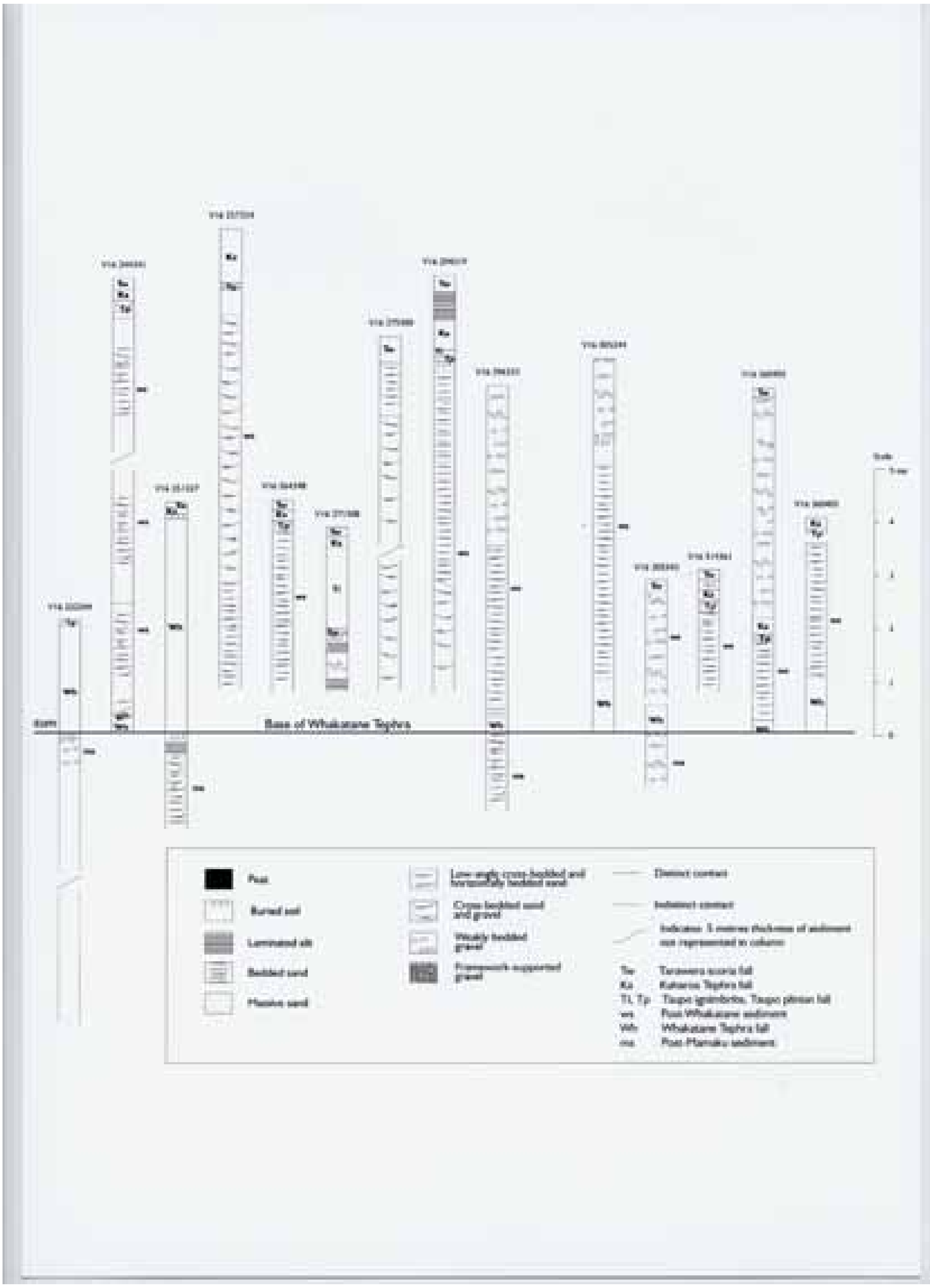

Figure 8 Stratigraphic summary sections showing tephras and sediments at sites described in text.

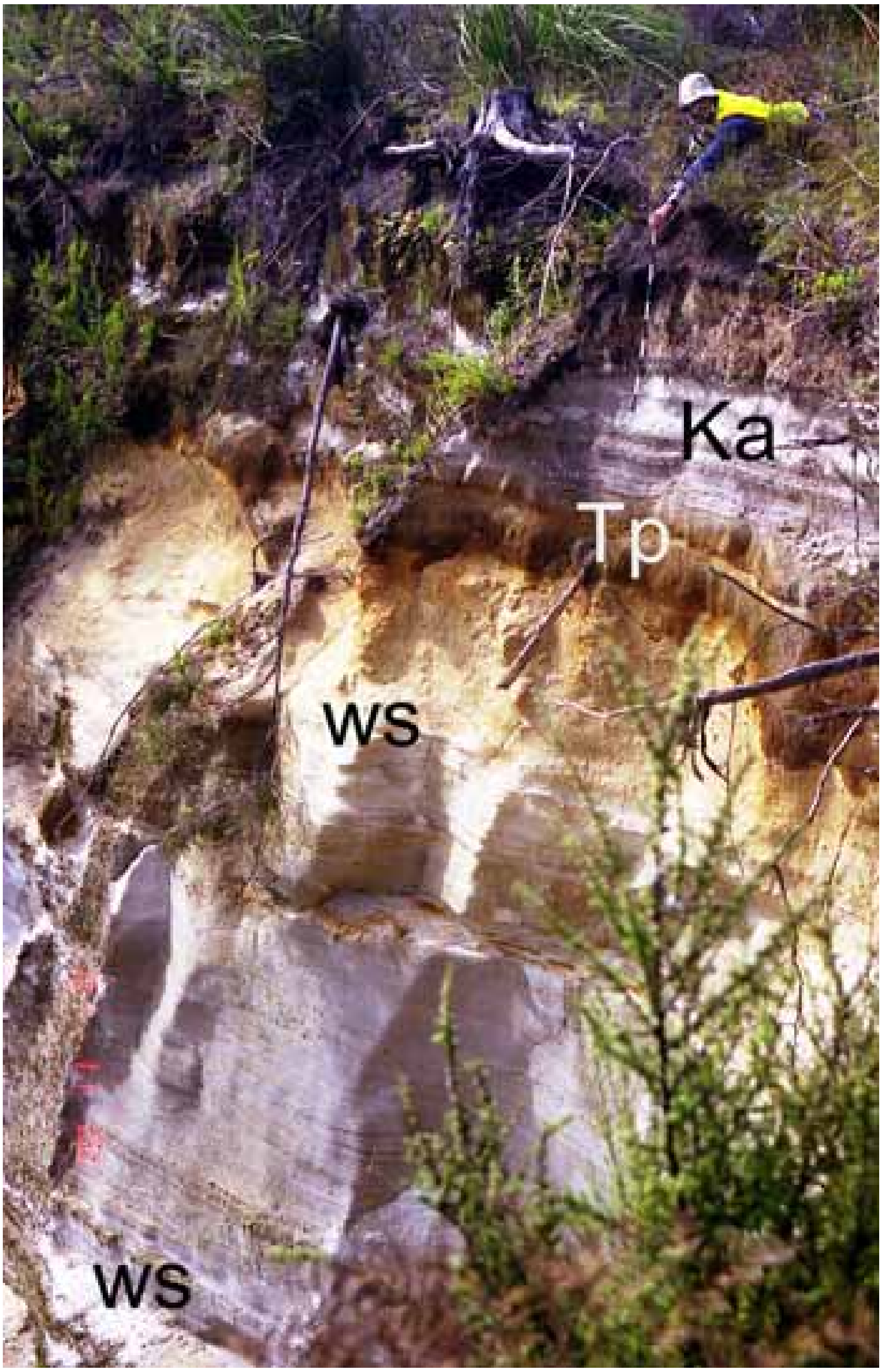

Figure 9 *Post-Whakatane sediment (ws) in the Mangawhio Stream valley at V16/294319 (site k on Figure 6b). Ka is Kaharoa Tephra fall; Tp is Taupo plinian fall; base of the ws is not exposed here. Scale is 1 m long.*

Tables

Table 1 Eruption episodes and effects on Okataina Volcanic Centre drainage. See Figures 1 and 2 for locations of named features, and Figure 5 for a summary of eruption effects on the caldera-floor lake and Lake Tarawera after 26 ka.

Episode, Age and (symbol)	Eruptions	Significant Effects on Regional Drainage
Tarawera AD1886 (Tw)	Basaltic scoria eruptions from Tarawera Rift craters, plus phreatic/hydrothermal explosions at Rotomahana and Waimangu.	Rotomahana crater excavated. Scoria >1-m thick mantles slopes on southeast Haroharo complex. Fan building from Tapahoro gully dams Tarawera River near Lake Tarawera outlet; lake rises by 13 m; dam fails in AD1904; lake level falls by ~4 m (to ~+300 m) with flooding in Tarawera River valley.
Kaharoa 0.7 ka (Ka)	Rhyolite pyroclastic eruptions from multiple vents across Tarawera, followed by multiple lava dome extrusion.	Block-and-ash flows from collapse of summit lava domes fill Waiaute Valley and upper Waiwhakapa Valley. Canyon through Tapahoro fan dam is filled causing Lake Tarawera to rise to ~+330 m. Dam fails, lake level falls 40 m to generate catastrophic flood in Tarawera River valley.
Whakatane 5.5 ka (Wh)	Pyroclastic and lava eruptions from multiple vents across Haroharo volcanic complex.	Thick pyroclastic flow deposits accumulate on floor of Haroharo caldera, interacting with Tarawera River to produce lahars. Thick fall deposits are reworked to produce lahars in tributary catchments. Emplacement of Tapahoro lavas and Tapahoro fan blocks outlet to Lake Tarawera which rises 120 m to overflow at ~+330 m. Slow downcutting cuts canyon through fandam over next 4.9 kyr, as lake falls to ~+315 m (?).
Mamaku 8 ka (Ma)	Pyroclastic and lava eruptions from multiple events across Haroharo complex	Ruakokopu and Te Matae lava flows abut western edge of Pokohu lava flow to dam western caldera basin at ~+300 m and create proto-Lake Tarawera. Dam failure generates flood in Tarawera river valley as lake falls to +210 m.
Rotoma 9.5 ka (Ro)	Pyroclastic and lava eruptions from multiple vents within Haroharo Caldera and Rotoma Caldera	Emplacement of Te Pohue lavas terminally obstructs any remaining Lake Rotoiti drainage into Haroharo Caldera, and forces Rotorua/Rotoiti lake system to >+280 m. Lake Rotoehu is formed. Emplacement of Rotoma lava forms Lake Rotoma.
Waiohau 13.8 ka (Wa)	Pyroclastic and lava eruptions from multiple vents across northern Tarawera complex. Widespread plinian fall. Extrusion of Pokohu lava flow.	Emplacement of Waiohau pyroclastic fans; south to create proto-Lake Rerewhakaaitu; north to dam the outlet from Haroharo caldera. Caldera-floor lake rises to overflow at >+220 m. Apparent catastrophic dam failure creates ~1 km-wide breach through the pyroclastic fan; lake falls to <+140 m.
Rotorua 15.7 ka (Rr)	Pyroclastic and lava eruptions from Okareka rhyolite complex vents in Okareka embayment.	Emplacement of 15.7 ka lavas dammed Tikitapu and Rotokakahi valleys to form present lakes, and restrict drainage from west onto the caldera floor.
Rerewhakaaitu 17.7 ka (Rw)	Pyroclastic and lava eruptions from southern Tarawera vents. Widespread plinian fall	Rotomahana dome, Western dome, Southern dome and Te Puha lava emplaced, confining caldera floor lake. No significant impact on drainage from the caldera.
Okareka 21 ka (Ok)	Pyroclastic and lava eruptions from initial Tarawera vents	Hawea and Ridge lavas emplaced. No significant impact on drainage from caldera

Episode, Age and (symbol)	**Eruptions**	**Significant Effects on Regional Drainage**
Te Rere 25ka (Te)	Rhyolite pyroclastic and lava eruptions from multiple vents in the northern part of Haroharo caldera, and Okareka embayment	Emplacement of Haumingi and adjacent 25 ka eruptives diverts to east the river draining Rotorua into Haroharo Caldera. Lake Rotoiti is partially formed, but may continue to drain through Haroharo caldera at ~+260 m elevation. Emplacement of 25 ka lavas partially closed the Okareka embayment to create Lake Okareka.
[Oruanui] 26.5 ka (Ou)	Pyroclastic eruptions at Taupo produce widespread tephra marker layer across North Island	[Important age marker at OVC] No significant effect on drainage from Haroharo caldera.
		Breakthrough of Lake Rotorua into Haroharo Caldera, doubling present catchment area above Kawerau canyon and river discharge within the canyon.
Mangaone Subgroup ~40-31 ka (MSg)	Pyroclastic eruptions with possible lavas? (buried in caldera). Possible caldera collapse at 33 ka.	Filling of Puhipuhi basin and Kawerau canyon by Mangaone ignimbrite raises caldera-floor lake to overflow at ~+200 m. Exhumation of Kawerau canyon and Puhipuhi basin valleys returns lake towards former levels.
Rotoiti ~50 ka (ri)	Pyroclastic eruptions and major caldera collapse in north OVC.	Filling of Puhipuhi basin and Kawerau canyon by Rotoiti ignimbrite must raise caldera-floor lake to overflow at ~+200 m. Exhumation of Kawerau canyon and Puhipuhi basin valleys returns lake towards former levels.
Mamaku Ignimbrite 220 ka (mk)	Major pyroclastic eruptions forming large caldera to west of OVC.	Unknown, probably partial infilling of the syn-Matahina caldera by ignimbrite deposits.
Kaingaroa Ignimbrite 230 ka. (kg)	Major pyroclastic eruptions forming large caldera to south of OVC	Unknown, probably partial infilling of the syn-Matahina caldera by ignimbrite deposits
Matahina Ignimbrite 280 ka (ma)	Major pyroclastic eruptions form large caldera in south of OVC, including Puhipuhi basin	Formation of major drainage basin, with ponded lake water overflowing into subsiding Whakatane graben, cutting the proto-Kawerau canyon

Table 2 Summary of sediment stratigraphy exposed in the Tarawera River valley.

Sediment and Age	**Sediment Description**	**Geomorphology**	**Explanation**
Post AD1886 alluvium	(a) <1 m thick, cm-cross-bedded, mixed pumice and scoria	(a) Fans and terraces	(a) Reworking of pyroclastic fall deposits during heavy rain
AD1904 and younger	(b) < 1 m thick cm-bedded mixed scoria and pumice gravel in fans and terraces; < 1 m thick massive scoria and pumice gravel	(b) Fans and terraces in Tarawera River valley	(b) Traction deposits from high sediment concentration braided stream. The AD1904 flood rejuvenated erosion in gullies on Pukemaire Fan leading to rapid aggradation of Tarawera River bed
Kaharoa pumice alluvium ~AD1315 and younger	(a) < 1 m thick. cm-cross-bedded pumiceous gravel	(a) Fans and low terraces in Tarawera River and Waiaute Stream valleys	(a) Thick fall deposits reworked by hyper concentrated flow and stream flow; concentration of runoff from heavy rainfall in gullies on steep slopes in Tarawera River valley triggering slope failure and erosion
Kaharoa pyro- and lava clasts and older sediments	(b) Abundant Kaharoa pyroclasts, 1 m – 10 m thick cm-horizontal- and low angle cross-bedded pumiceous gravel	(b) Terraces in Waiwhakapa and Mangawhio Stream valleys	(b) Reworking of valley-filling block and ash deposits by hyper concentrated flow immediately following eruption; rapid runoff of rainfall on bare surfaces causing accelerated erosion
	(c) Silt- and clay-sized sediment: <1 m-thick massive and ripple laminated silt; occasional granule-sized pumice floaters	(c) Basin-filling predominantly in Mangate and Mangawhio streams	(c) Deposition from silt and clay-rich slurries entering still water, e.g. temporary pond on tephra surface
	(d) Fine sand- and silt-sized sediment: mm-thick planar-laminated beds	(d) Terrace edge	(d) Fine sediment deposited from flood wave at maximum flow level where it inundated high level terrace surfaces; indicates maximum level of flood water inundation
	(e) Minor Kaharoa pyroclasts and abundant earlier sediment: dominantly < 10 m-thick cm-horizontal- and low angle cross-bedded gravel; minor massive gravel; common boulders	(e) Bars and benches in Tarawera valley and extensive fan on Rangitaiki Plain	(e) Coarse sediment deposited from hyper concentrated flow and high sediment concentration stream flow: deposited from high peak discharge, highly erosive syn-eruption catastrophic lake-breakout flood

Sediment and Age	Sediment Description	Geomorphology	Explanation
Whakatane pumice alluvium 5.5 ka and younger	(a) Whakatane pyroclasts: ~7 m - > 1 m, cm- bedded pumiceous gravel	(a) Fans and terraces in Waiwhakapa and Mangawhio streams	(a) Reworking of thick Whakatane pyroclastic fall deposits to form hyper concentrated flow and sheet flow; rapid runoff of rainfall on steep bare slopes triggering erosion and/or slope failure of over thickened, unconsolidated and rainfall-saturated tephra on steep gullied slopes of Puhipuhi and other hills
Whakatane pyro and lava clasts and older sediment	(b) 0.05 – 0.1 m thick laminated silt interbedded with massive gravel ((c), below) and primary pyroclastics	(b) Shallow depressions in Whakatane pyroclastic fall and flow sequence on terraces in Tarawera River valley; Pokohu lava flow surface.	(b) Local ponding on uneven and/or scoured surface of pyroclastic flow and lahar deposits; rapid runoff of rainfall from bare hill slopes during the eruption and entrainment of fine ash from unconsolidated pyroclastic deposits
	(c) Whakatane pyroclasts: stacked m-thick deposits of massive, pumiceous, sandy gravel interbedded with cm-thick cross-bedded pumiceous silt and sand; occasional boulders; interbedded pyroclastic fall and flow deposits	(c) Fans and terraces in Tarawera River valley; localized deposits perched on hill slopes in gullies on Waiohau Pyroclastics fan	(c) Reworking/transformation of pyroclastic flow and thick pyroclastic fall to debris flows and hyper concentrated flows contemporaneous with eruption; rapid runoff from bare hill slopes and concentrated in relatively small, steep catchments to create erosive flows in areas of thick pyroclastic deposits
Mamaku pumice alluvium 8 ka and younger	(a) 0.2 – 2.0 m thick horizontal laminated silt and sand; occasional pumice clasts rare lithic cobbles	(a) Terrace edge, Tarawera River valley; valley-floor filling, Waiaute Stream valley	(a) Fine sediment from flood wave(s) deposited in over bank situations and/or local ponding?
	(b) Mamaku pyroclasts and lavas and earlier sediment: > 15 m - 1 m thick weakly bedded pumiceous and lithic gravel; few – common boulders	(b) Fans and terraces in Tarawera valley	(b) Coarse sediment deposited from highly erosive and competent river flows; catastrophic flood? braided river?
Rotoma 9.5 ka and younger	No sediment observed in Tarawera River Valley within OVC Thick pumiceous gravel deposited in Ruruanga Stream		