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THE TAUPO ERUPTION, NEW ZEALAND
I. GENERAL ASPECTS

By C. J. N. Wilson†[1] and G. P. L. Walker‡[2], F.R.S.
† *Geology Department, Imperial College, London SW7 2BP, U.K.*
‡ *Geology Department, Auckland University, Private Bag, Auckland, New Zealand*

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[Plates 1–6]

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The *ca.* A.D. 186 Taupo eruption was the latest eruption at the Taupo Volcanic Centre, occurring from a vent, at Horomatangi Reefs, now submerged beneath Lake Taupo in the central North Island of New Zealand. Minor initial phreatomagmatic activity was followed by the dry vent 6 km³ Hatepe plinian outburst. Large amounts of water then entered the vent during the 2.5 km³ Hatepe phreatoplinian ash phase, eventually stopping the eruption, though large amounts of water continued to be ejected from the vent area, causing gullying of the ash deposits. After a break of several hours to weeks, phreatoplinian activity resumed, generating the 1.3 km³ Rotongaio ash, notable for its fine grainsize and for containing significant quantities of non- or poorly-vesicular juvenile material. The vent area then became dry again, and

[1] Present address: Geology Department, Auckland University, Private Bag, Auckland, New Zealand.
[2] Present address: Hawaii Institute of Geophysics, 2525 Correa Road, Honolulu, Hawaii 96822, U.S.A.

eruption rates and power markedly increased into the 23 km^3 Taupo 'ultraplinian' phase, which is the most powerful plinian outburst yet documented. Synchronous with this ultraplinian activity, lesser volumes of non- to partially-welded ignimbrite were generated by diversion of ejecta from, or partial collapse of, the eruption column. The rapid rate of magma withdrawal during this phase removed support from the vent area, to trigger local vent collapse and initiate the catastrophic eruption of the *ca.* 30 km^3 Taupo ignimbrite. Finally, after some years, lava was extruded on to the floor of the reformed Lake Taupo, and floating fragments derived from the lava carapace were driven ashore. The known eruption volume is more than 65 km^3, while additional volumes are represented by primary material now beneath Lake Taupo and layer 3 to the ignimbrite phases; a total volume of more than 105 km^3 is likely, equivalent to more than 35 km^3 of magma plus more than 3 km^3 of lithic debris. Airfall deposits more than 10 cm thick blanketed 30000 km^2 of land east of the vent, while ignimbrite covers a near-circular area of *ca.* 20000 km^2. Widespread and locally severe ground shaking occurred during, but mostly after the eruption, associated with subsidence in the Lake Taupo basin. Secondary deposits are abundant above and extending beyond the Taupo ignimbrite, consisting of the products of surface water interacting with the still-hot ignimbrite and subsequent water reworking of the light, pumiceous materials. The complexity and size of this eruption preclude accurate forecasting of the size, nature and return period of the inevitable next eruption from the Taupo Volcanic Centre.

1. Introduction

The Taupo eruption was the latest volcanic event at the Taupo Volcanic Centre in the central North Island of New Zealand (figure 1) (Wilson *et al.* 1984). This eruption is of interest for several reasons:

(*a*) It was one of the largest explosive eruptions in the world within the past 7000 years; it included the most powerful plinian and the most violent ignimbrite-forming events yet documented.

(*b*) It generated a great variety of pyroclastic deposits: two plinian pumice falls, three phreatomagmatic ashes and several ignimbrite flow units (including some of intraplinian type).

(*c*) The vent was located within a large lake, and magma–water interaction determined the style of parts of the eruption.

(*d*) The eruption occurred at an inverse volcano and represents a style of activity which may be considered typical of such volcanoes.

Few rhyolitic eruptions have been documented, but the youth and good preservation of the products enable this one to be examined in some detail. Many of the data and ideas have been previously published and it is intended that the various papers referenced herein be read in conjunction with this account. This paper I provides an overall account of the eruption, presenting brief summaries of previously published data and detailing those parts of the eruption sequence which have not previously been described. A companion paper (Wilson 1985, hereafter referred to as Paper II) presents a detailed study of the nature and emplacement history of the Taupo ignimbrite which marked the eruption climax.

The many ^{14}C dates of the Taupo eruption were averaged by Healy (1964) to give *ca.* A.D. 130, while Wilson *et al.* (1980) have suggested from historical evidence that the calendar date of the eruption was *ca.* A.D. 186.

The Taupo volcano is unusual in being an inverse volcano (Walker 1981*a*) (figure 2). In

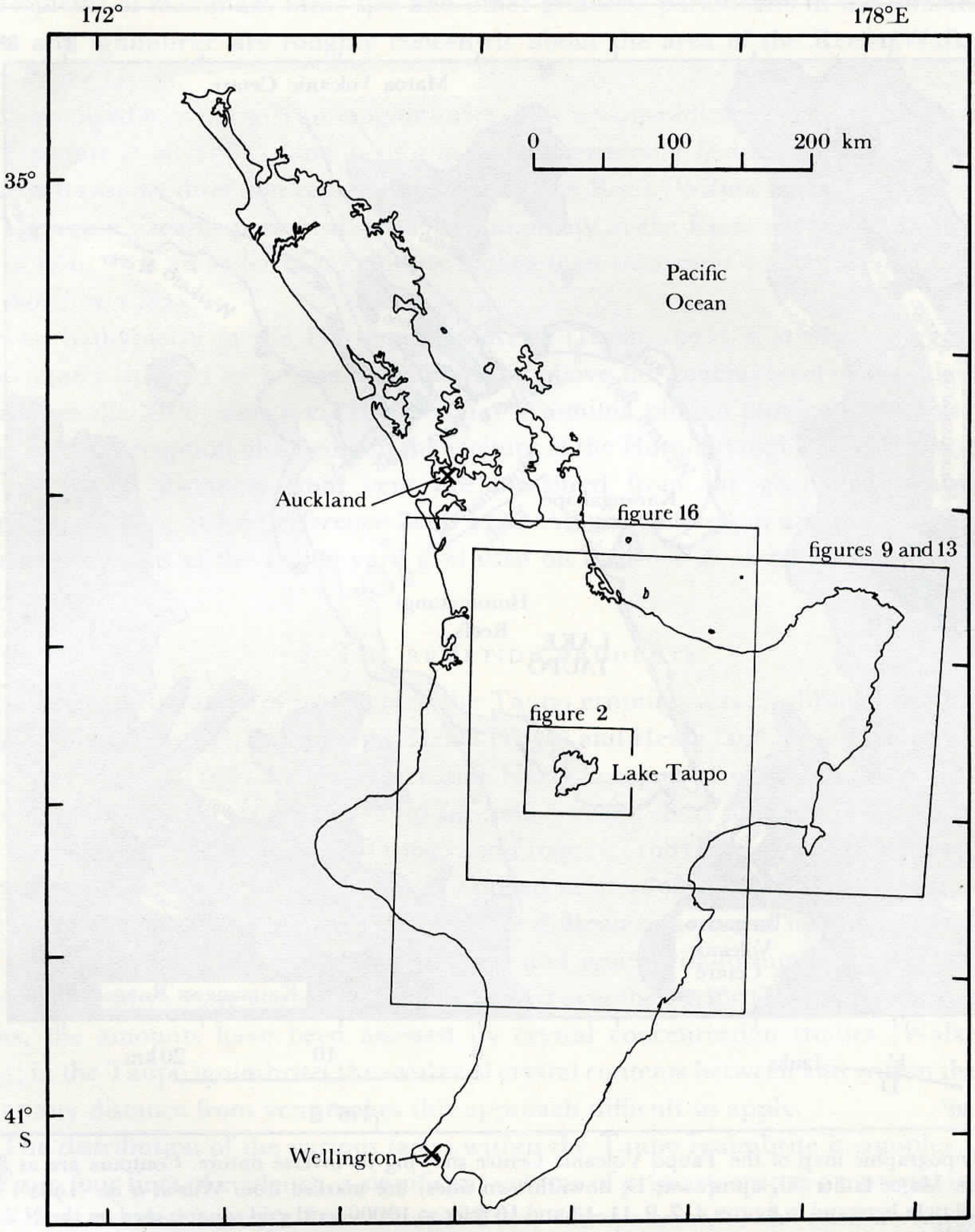

FIGURE 1. Map of the North Island, New Zealand, showing the areas covered by figures 2, 9, 13 and 16.

general, its eruptions have been so powerfully explosive that the accumulation of material about the vent was insufficient to counterbalance the subsidence caused by magma withdrawal. As a result, the vent area for the Taupo eruption is now the lowest point for 40 km in any direction. Available data suggest that a similar situation has persisted for at least the last 20000 years (see, for example, Self 1983) and there is no evidence for any substantial volcanic edifice within the Lake Taupo area during this period.

For descriptive purposes, the vent level for the Taupo eruption is assumed to have been at the same level as the modern lake surface (357 m above sea level (Irwin 1972)). Evidence for the existence of a sizeable Lake Taupo at that time is given by the nature and volume of the

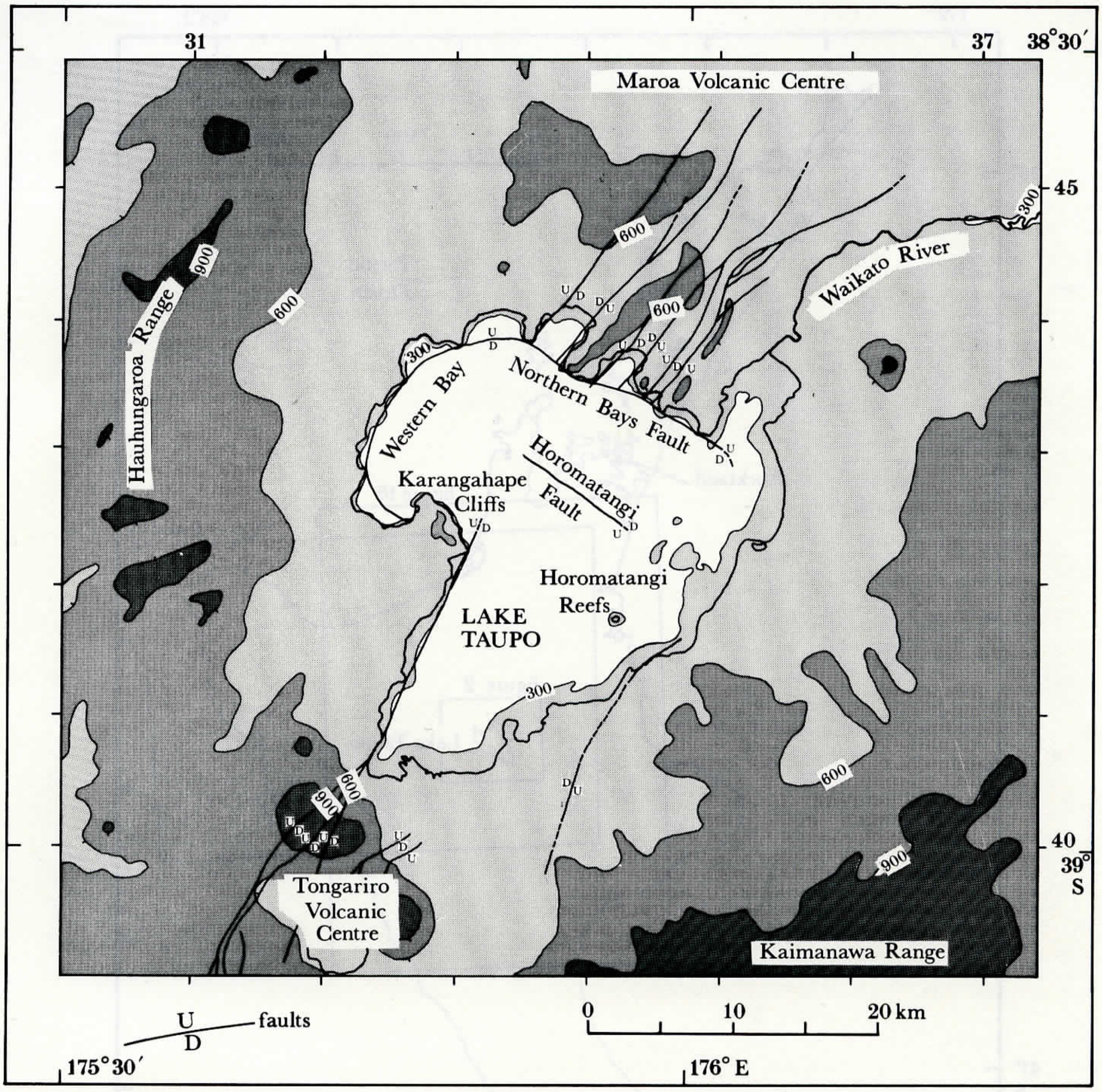

FIGURE 2. Topographic map of the Taupo Volcanic Centre showing its inverse nature. Contours are at 300 m intervals. Major faults (U, upthrown; D, downthrown sides) are marked from Wilson *et al.* (1984). Inner marginal ticks here and in figures 4, 7, 9, 11, 13 and 16 refer to 10000 yard grid squares used on the N.Z.M.S. 1, 1:63360 maps.

phreatomagmatic deposits, and by certain deposits and grainsize anomalies in the Taupo ignimbrite. The lake surface cannot have been significantly higher than at present because subaerial deposits from the Taupo eruption are found to within 5 m of the present lake level.

The vent positions for all the explosive eruptions from 20000 years B.P. onwards now lie within the modern Lake Taupo. Evidence that the vent was situated in the vicinity of Horomatangi Reefs (figure 2) during the Taupo eruption includes:

(*a*) The dispersal axis for each fall deposit passes through the Reefs area, but the lack of ballistic lithics at onshore exposures implies that the vent lay several kilometres offshore (Walker 1980, 1981*b*, *c*).

(*b*) Isopleths of maximum-lithic size and other grainsize parameters in the plinian pumice deposits and ignimbrite are roughly concentric about the area of the Reefs (Walker 1980, 1981 *b*; Paper II).

(*c*) Carbonized logs in the Taupo ignimbrite show a vent-radial orientation about the Reefs area (Froggatt *et al.* 1981), and bedforms in and erosional features below the ignimbrite indicate a transport direction radially away from the Reefs (Wilson 1981).

(*d*) There is a sizeable present-day thermal anomaly at the Reefs where the local heat flow (up to 2 W m^{-2}) is an order of magnitude higher than over most of the lake floor (Calhaem 1973; Northey 1982).

(*e*) The bathymetry of the Horomatangi Reefs (Irwin 1972) is strongly suggestive of a volcanic crater situated on a cone or dome rising above the general level of the lake floor.

Data from the 3400 years B.P. (Healy 1964) Waimihia plinian pumice are consistent with the vent for that eruption also being in the vicinity of the Horomatangi Reefs (Walker 1981 *b*).

In this paper, distances from vent are measured from the geometric centre of the Horomatangi Reefs, at grid reference 3460 4223. All grid references are given to the nearest 100 yards† in terms of the 10000 yard grid used on the New Zealand 1:63360 topographic maps.

2. The eruption products

The formal stratigraphy of products of the Taupo eruption was established by the pioneer work of Baumgart (1954), Baumgart & Healy (1956) and Healy (1964), and has recently been revised by Froggatt (1981 *a*). Baumgart and Healy recognized eight members which were considered to have been erupted in rapid succession over a short time span. The stratigraphic names assigned to the units by Healy (1964) and Froggatt (1981 *a*) are retained where practical, but a volcanological terminology has been applied in most cases (table 1).

The volume estimates presented in table 1 are difficult to arrive at for three reasons:

(*a*) The fine ash associated with the plinian- and ignimbrite-forming eruptive phases was widely dispersed by strong westerly winds, much of it over the Pacific Ocean. For the two plinian deposits, the amounts have been assessed by crystal concentration studies (Walker 1980, 1981 *b*); in the Taupo ignimbrite, the scatter of crystal contents between and within the various facies at any distance from vent makes this approach difficult to apply.

(*b*) The distribution of the various facies within the Taupo ignimbrite is complex.

(*c*) From four lines of evidence, a significant volume of primary eruptive material is believed to now be concealed beneath Lake Taupo. First, extrapolation of the onshore outcrop area and thickness of the early ignimbrite flow units (figures 5 and 7) suggests that substantial volumes (of the order of cubic kilometres) of this material may have accumulated around the vent area. Second, extrapolation towards vent of thickness data from various facies in the Taupo ignimbrite (Paper II) implies that significant quantities of the ignimbrite would have been deposited over the area now occupied by the lake. Third, evidence from the Taupo ignimbrite suggests that portions of the Taupo flow were trapped in two areas of a pre-eruption Lake Taupo which now form part of the modern lake (§3). Fourth, evidence from seismic surveys (Northey 1982) shows the presence of substantial volumes of little-consolidated deposits below the lake floor. These seismic studies do not allow delineation of the Taupo eruption products but, from the evidence above, their volume is inferred to be between 20 and 60 km^3.

† 1 yard ≈ 91 cm.

TABLE 1. SUMMARY OF STRATIGRAPHY AND VOLUMES OF THE TAUPO ERUPTION PRODUCTS

(Compiled from data in Walker (1980, 1981 *b*, *c*), this paper and Paper II. Magma volumes assume a density of 2.3 g cm^{-3} and lithic-debris volumes a density of 2.6 g cm^{-3}. The Taupo Ignimbrite of Froggatt (1981) is divided into Lower, Middle and Upper units and a 'lithic lag layer', which correspond with our interpretations thus:

Lower unit	early ignimbrite flow units, plus layer 1 of the Taupo ignimbrite (in part);
lithic lag layer	ground layer (part of layer 1) of the Taupo ignimbrite;
Middle unit	layer 1 (in part) and layer 2 (in part) of the Taupo ignimbrite.
Upper unit	layer 2 (in part) of the Taupo ignimbrite, plus secondary deposits.)

Healy (1964)	Froggatt (1981)	this paper	volume *in situ*/km^3	volume, magma/km^3	volume, lithics/km^3
(Taupo Pumice Alluvium)	—	secondary deposits	—	—	—
	—	floated giant pumices	?	?	—
	Taupo Ignimbrite	secondary deposits	—	—	—
Upper Taupo Pumice Rhyolite Block Bed (members 1 and 2)		Taupo ignimbrite	31	10	2.1
Taupo Lapilli (member 3)	Taupo Lapilli	Taupo plinian pumice + early ignimbrite flow units	23 1.5	5.1 0.5	0.73 0.05
Rotongaio Ash (member 4)	Rotongaio Ash	Rotongaio phreatoplinian ash	1.3	0.7	0.09
'putty-coloured ash' (member 5)	Hatepe Tephra	Hatepe phreatoplinian ash	2.5	1.0	0.12
Hatepe Lapilli (members 6–8)		Hatepe plinian pumice	6	1.4	0.18
		initial phreatomagmatic ash	0.015	0.005	negl.
Paleosol developed on older deposits			*subtotal ca.* 65	18.7	3.27
		layer 3 deposits of ignimbrite phases	up to *ca.* 20	up to *ca.* 7	negl.
		primary material now under Lake Taupo	20–60	8–20	?
			total ⩾105	⩾35	>3.27

The known or inferred volume of the eruption products is 65 km³, equivalent to about 19 km³ of magma plus more than 3 km³ of lithic debris (table 1). To this must be added layer 3 of the Taupo ignimbrite (possibly as much as 20 km³) and the volume of primary eruptive material under Lake Taupo. Our best estimate for the total eruption volume is more than 105 km³, equivalent to more than 35 km³ of magma.

(*a*) *The pre-ignimbrite fall deposits*

The initial ash (figure 3*a*, plate 1) forms the base of the eruption products over a limited area east of Lake Taupo (figure 4). It reaches a maximum observed thickness of only 65 cm and is not found more than 20–25 km from vent. Its volume (*ca.* 0.015 km³) is negligible in comparison to the succeeding units but is comparable to that of historic eruptions such as that at Soufriere, St Vincent in 1979 (Shepherd *et al.* 1979). The deposit is a near-white pumiceous ash and is uniformly fine grained at all but the thickest exposures. It contains few coarse clasts, but commonly coarse pumices and lithics at the base of the Hatepe plinian pumice have impacted into it. At its base, it contains sparse leaf impressions and it has not baked the underlying soil; from this, its fine-grained nature, and its similar appearance to the later Hatepe phreatoplinian ash it is inferred to have been generated by relatively minor phreatomagmatic activity.

The initial ash is sharply overlain by the Hatepe plinian pumice deposit (Walker 1981*b*), which is much coarser, is generally free of fine ash, reaches thicknesses exceeding 2 m near Lake Taupo and can be traced as far as the east coast of the North Island. The thickness and grainsize of the deposit increase steadily towards Lake Taupo, but a lack of ballistic clasts in onshore exposures implies that the vent lay some kilometres within the lake and precludes an onshore vent location (see Baumgart 1954). The Hatepe plinian pumice has a volume estimated from isopach maps of 2.3 km³ (Walker 1981*b*), but the quantities of free crystals found in the deposit imply that a substantial volume of fine vitric ash has been lost downwind, in the Pacific Ocean. If this is allowed for, then the total volume of the deposit is estimated to be 6 km³ (Walker 1981*b*), corresponding to 1.4 km³ of magma plus 0.18 km³ of lithic debris (table 1). This deposit represents a typical plinian outburst (Walker 1981*d*), with a *D*-value of *ca.* 10000 km² (where *D* is the area enclosed by the 0.01 maximum-thickness isopach; Walker 1973), and it has a volume, thickness and dispersal similar to the A.D. 79 Pompei pumice of Somma-Vesuvius (Lirer *et al.* 1973). Healy (1964) recorded two local ashfall members (7 and 8 in table 1; figure 3*b*) at the base of the Hatepe pumice, which thin rapidly away from the area of Taupo township. Recent fieldwork demonstrates that members 7 and 8 are intraplinian ashes within the lower part of the Hatepe pumice and are quite distinct from the initial ash. From their vesicular and poorly sorted nature and their local distribution, the intraplinian ash beds are interpreted as rain-flushed ashes generated by local rainshowers.

The Hatepe plinian pumice is overlain sharply by the informally named 'putty-coloured ash' (Healy 1964), now termed the Hatepe phreatoplinian ash (Walker 1981*c*). This deposit is pale grey, rich in fine ash and shows a poorly developed bedding. It is over 2 m thick in areas close to Lake Taupo and persists to the east coast of the North Island, having a volume, estimated from isopach data, of 2.5 km³ (Walker 1981*c*). The deposit is poorly sorted, containing pumice clasts similar to but slightly denser (by *ca.* 25%) than those in the underlying Hatepe plinian pumice, together with an abundant fine ash matrix which is vesicular and locally contains a fine-scale bedding attributed to the splashing of water falling along with the ash (Walker 1981*c*,

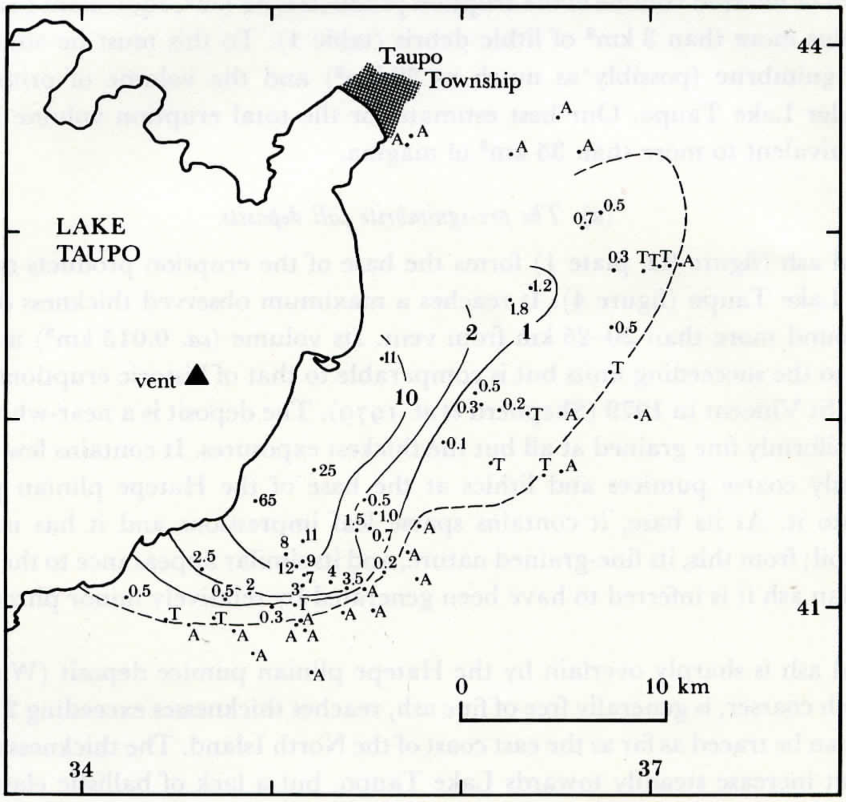

FIGURE 4. Isopach map of the initial phreatomagmatic ash. Values and isopachs in centimetres. T, trace; A, absent.

figure 4). A minor erosion episode, represented by gullying (Walker 1981*c*, figure 6) occurred during this phase, and this deposit is separated from the succeeding unit by a locally prominent erosion surface.

The overlying Rotongaio phreatoplinian ash is dark grey, contrasting thus sharply with the earlier deposit, and usually has a poorly developed fine plane-parallel bedding. It is thicker than the Hatepe ash in near-vent sections, but it thins more rapidly and has a much smaller volume than the Hatepe ash (1.3 km³ from isopach data; Walker 1981*c*). The Rotongaio ash locally rests on slopes steeper than 60°, is often vesicular and contains rounded pellets of accreted

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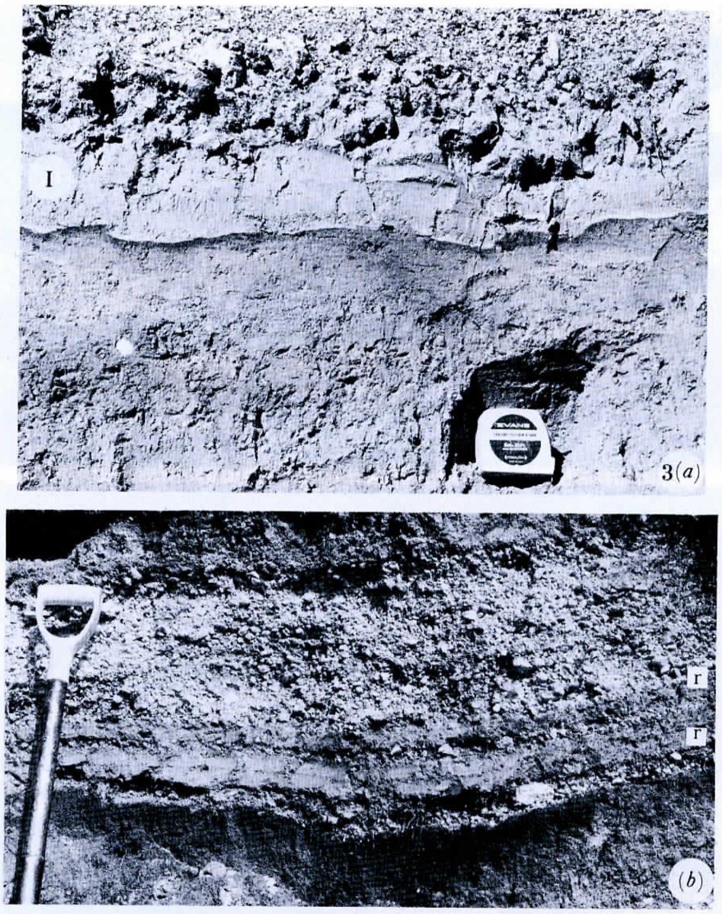
DESCRIPTION OF PLATES 1 AND 2

FIGURE 3. (*a*) The initial phreatomagmatic ash (I) overlying a soil developed on the *ca.* 3400 years B.P. Waimihia eruptives and overlain by the Hatepe plinian pumice. Locality at 3517 4160, 8 km from vent. (*b*) Two rainflushed ash beds (r) within the basal part of the Hatepe plinian pumice. Locality at 3573 4353, 16 km from vent.

FIGURE 6. Photographs of the early ignimbrite flow units. (*a*) Aerial view, looking south, of the thick proximal early flow unit outcrop. Waitahanui township (figure 7) in foreground. (*b*) Sintered proximal early flow units exposed in 'Earthquake Gully' (locality 2 in figure 7) at 3543 4218, 8 km from vent, overlain by the Taupo ignimbrite (I) whose lowest part is the coarse-lithic-rich ground layer. Height of the exposure is *ca.* 30 m. (*c*) Proximal early flow unit material (E) resting on the Rotongaio phreatoplinian ash (R) and enclosing a Taupo plinian pumice layer (P). Locality at 3543 4215, 8 km from vent. (*d*) A distal early flow unit (E) enclosed within the Taupo plinian pumice and overlain by the Taupo ignimbrite (I). Locality at 3613 4208, 14 km from vent.



6(*a*)

FIGURES 3 AND 6 (*a*). For description see opposite.

(*Facing p.* **206**)

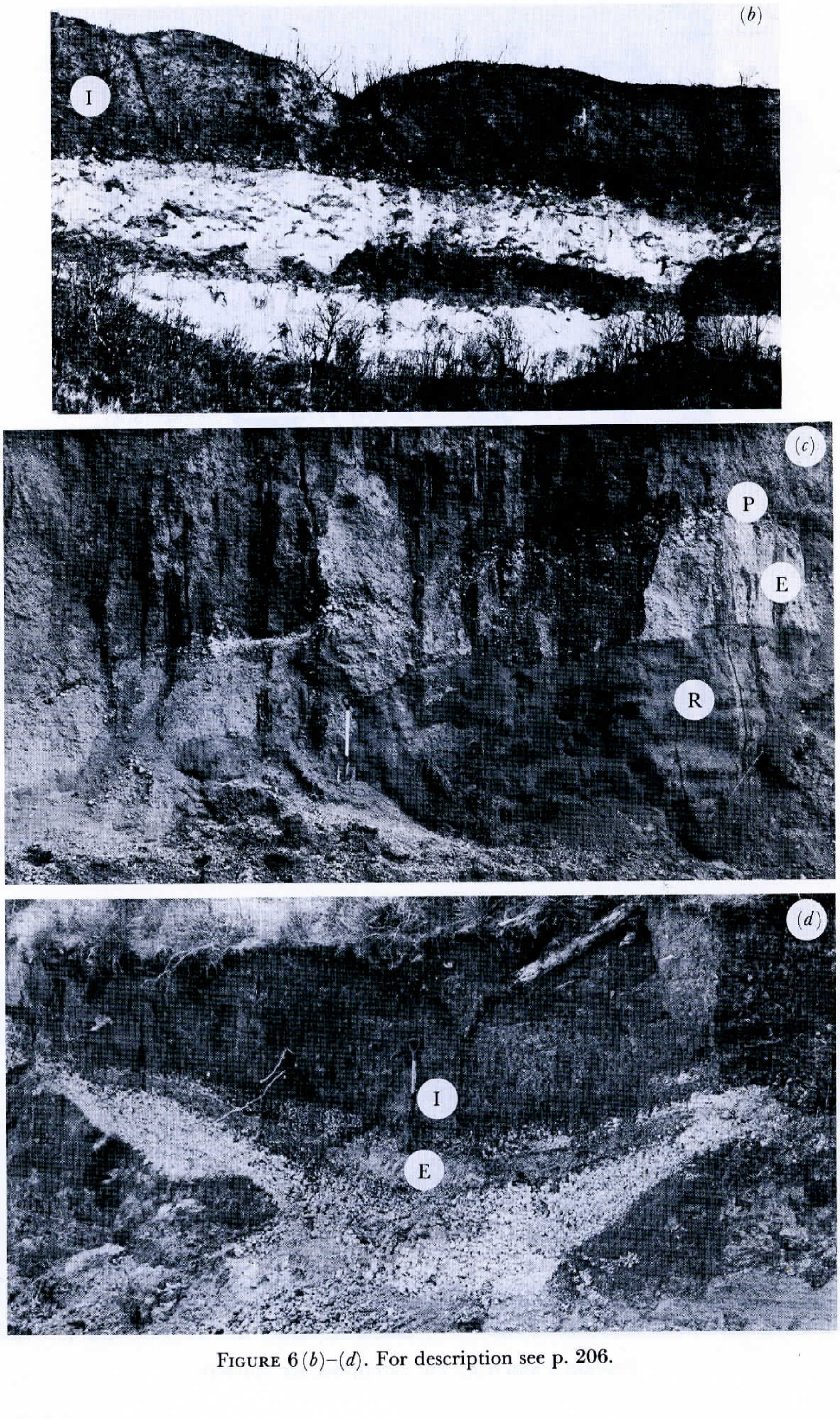


FIGURE 6 (*b*)–(*d*). For description see p. 206.

ash up to a few millimetres across; from this, it is inferred to have fallen as a wet, cohesive mud. Locally the layer has penecontemporaneously slumped into and partially filled the erosion gullies cut into the Hatepe ash, and the contact between the two units sometimes reveals soft-sediment deformation structures. The Rotongaio ash is dominantly composed of dense pumice to obsidian particles, and a very high proportion of the deposit consists of sub-millimetre material (Walker 1981*c*, figure 10).

Both the Hatepe and Rotongaio ashes are interpreted (Self & Sparks 1978; Walker 1981*c*) as phreatoplinian deposits. A number of features, among them the unusually small variations in grainsize with distance from vent, indicate that both ashes were flushed out of the eruptive plume by water, but accretionary lapilli, commonly regarded as a normal indicator of rain flushing (see, for example, Moore & Peck 1962) are scarce. The exponential outward decrease in thickness of both ashes (followed for the Rotongaio out to nearly the 1 mm isopach) indicates that the water which caused the flushing could not have come from a chance local shower (as with the Hatepe intraplinian ashes mentioned earlier). The water may have come from a general and widespread rain, uniformly distributed over the entire ash dispersal area, producing a progressive cleansing of the plume, but it is more likely that the water was erupted from the vent so that there was an exponential outward decay in water precipitation and hence the amount of ash flushed.

The pronounced gullying of the top of the Hatepe ash, which was clearly caused by running water in a brief erosion episode before the Rotongaio ash was erupted, is a significant factor here. The average gully depth and thickness of Hatepe ash eroded are greatest in near-vent exposures and both decrease away from vent. However, many of the gullies only penetrate a short way into the Hatepe plinian pumice. It could be supposed that the gully depth was controlled by the thickness of the impermeable Hatepe ash and that once the highly permeable plinian deposit was reached, the water could drain away freely and erosion ceased. An important point against this is that a few tens of kilometres or more away from vent, the plinian deposit is thinner, so that had water landed in quantities sufficient to cause erosion like that seen nearer vent, then the plinian deposit itself would be expected to show signs of erosion as well; such signs are absent. It seems hard to escape the conclusion that the amount of erosion represented by the gullying decreases markedly away from the lake and thus that the water involved was derived from Lake Taupo by some mechanism. There is insufficient evidence to decide whether the water rose as vapour which then condensed as rain or was ejected directly in liquid form.

Since first working on this problem, our attention has been drawn by R. W. Johnson to a record of a possible volcanogene 'waterspout' during the eruption of Vulcan, Rabaul in 1937 (Stehn & Woolnough 1937; Fisher 1939) when water falling from the eruption column extensively gullied the ash blanket. At Taupo the ejection of water must have been on a huge scale as erosion of the ash blanket extended over about 1500 km^2 and some 0.5 km^3 of ash was eroded. The quantity of water causing this erosion cannot have been less than about 2 km^3, this being in addition to the water which was erupted with the two phreatoplinian ashes and accompanied their deposition (Walker 1981*c*).

An earlier erosion event took place during the Hatepe phreatoplinian phase, although the gullies produced by it are not conspicuous, and plinian conditions were also briefly re-established during the same phase to produce a thin but coarse pumice layer. These variations are interpreted to reflect minor fluctuations in the water or magma fluxes, or both.

The Rotongaio ash is sharply overlain by the Taupo plinian pumice deposit (Walker 1980), which is a remarkably coarse and widely dispersed unit, representing the most powerful plinian outburst yet documented (Walker 1981*d*). This deposit is broadly similar in nature to the Hatepe plinian pumice, but is noticeably coarser (see, for example, Walker 1980, figure 3) and contains a poorly defined stratification defined by several slightly coarser and finer plinian-style layers (Walker 1980, figure 10). The thickest section of the Taupo plinian pumice is only 180 cm thick, and the isopachs close about a point some 20 km east of Lake Taupo, which led to earlier proposals of an on-land vent location (Baumgart 1954; Healy 1964). However, grainsize data clearly indicate that the vent must lie some kilometres out within the lake, and the Horomatangi Reefs were postulated to represent the vent site (Walker 1980). The volume of this unit is estimated as 6.2 km^3 from isopach data but, as with the Hatepe plinian pumice, large quantities of free crystals occur in the on-land deposit, implying that large amounts of fine vitric ash were erupted but were blown out to sea before they could be deposited. By measuring the mass of loose crystals in the deposit, and assuming the magma crystal content to be the same as that in large clasts in the deposit, the mass of 'lost' vitric material can be estimated (Walker 1980). This method yields a volume estimate of 23 km^3 (equivalent to 5.1 km^3 of magma plus 0.73 km^3 of lithic debris); although this is considerably larger than estimates derived from isopach data (Froggatt 1982), the method used is considered to be more reliable. The limited maximum thickness and widespread nature of the Taupo plinian pumice result in its having a *D*-value (Walker 1973) of *ca.* 100000 km^2, a figure about an order of magnitude larger than that for typical plinian deposits, such as the earlier Hatepe plinian pumice (Walker 1981*d*). Its dispersal is so great that the term 'ultraplinian' seemed justified for the deposit (Walker 1980) and the extreme eruption style.

(*b*) *The early ignimbrite flow units*

At many exposures within *ca.* 15 km of vent, the Taupo plinian pumice is interbedded with ignimbrite flow units, the whole assemblage underlying and being clearly distinct from the Taupo ignimbrite proper (figure 5). These intraplinian ignimbrites are here termed the early ignimbrite flow units. Froggatt (1981*a*) defines these early flow units as the Lower unit of the Taupo Ignimbrite (see table 1), but our work shows that they represent events which are temporally and genetically distinct from the Taupo ignimbrite proper, and we treat the two separately.

In distal outcrops, up to three thin early flow units occur which are poorly sorted, rich in fine material and contain carbonized vegetation. Nearer vent, up to at least twelve flow units, totalling more than 40 m, occur, separating the plinian deposit into several thin but coarse pumice layers. Several fine-grained layers are visible within the Taupo plinian pumice beyond 15 km from vent (Walker 1980, figure 10). When traced towards vent these bands become better defined and increase in number to more than ten. The early flow units appear to be their correlatives.

(i) *Proximal exposures of the early flow units*

Twelve early flow units between 0.5 and 5 m thick are exposed in 'Earthquake Gully', the dry valley followed by Highway 1 south of Waitahanui (figures 6*a*, *b*, plates 1 and 2, and 7). They show a wide variety of fluidization grading styles, mostly of weakly to moderately fluidized types 1 and 2 (Wilson 1980). In other thick sections, such as those east and north of Waitahanui,

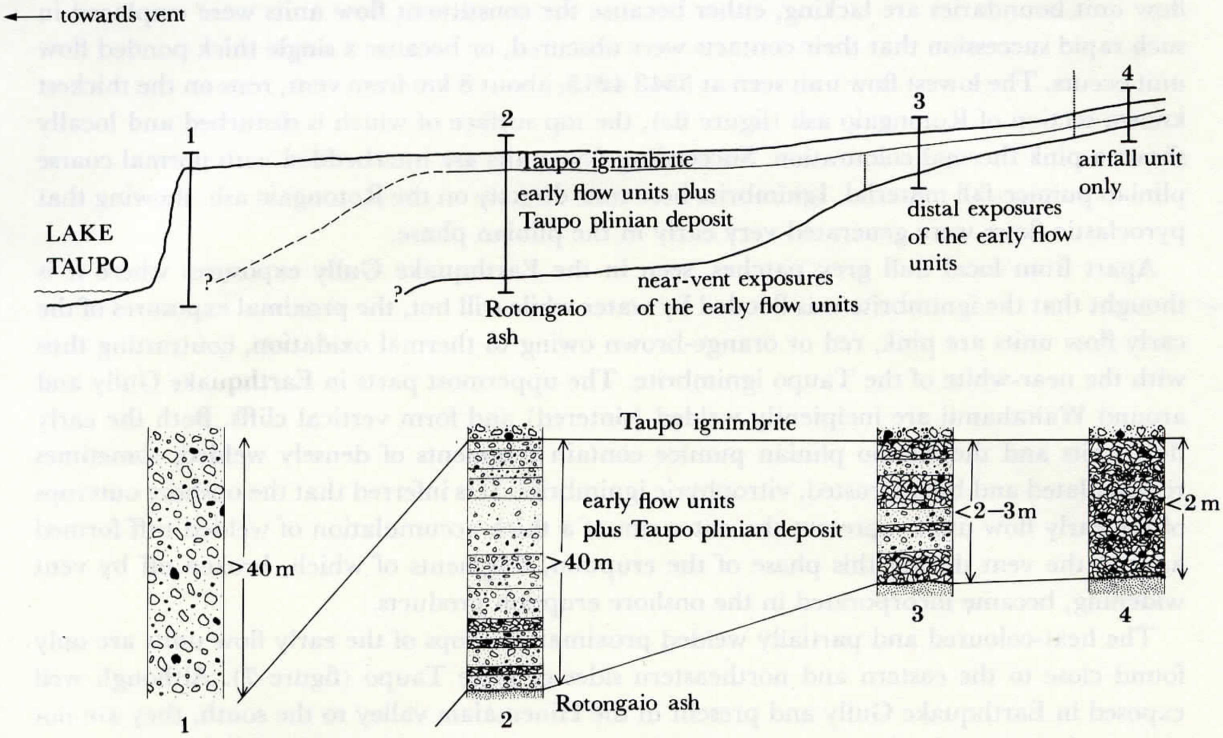


FIGURE 5. Schematic sections showing the stratigraphic relationships of the early ignimbrite flow units. Sections 1–4 are based on measurements made at the localities marked 1–4 on figure 7.

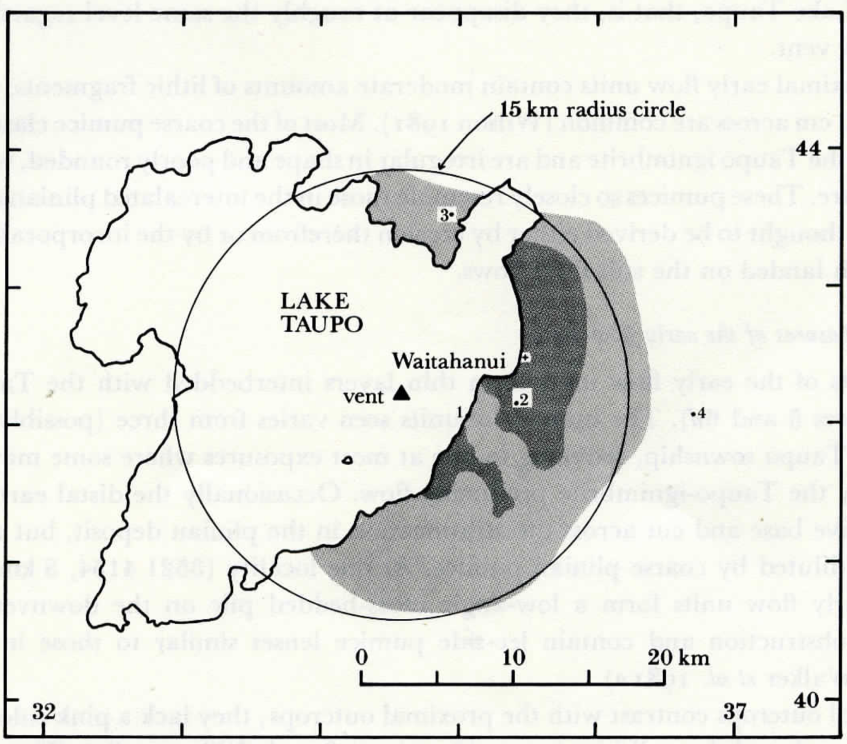


FIGURE 7. Map of outcrop areas of the proximal (darker shading) and distal styles (lighter shading) of the early ignimbrite flow units. Localities marked 1–4 are those of the corresponding sections in figure 5.

flow unit boundaries are lacking, either because the constituent flow units were emplaced in such rapid succession that their contacts were obscured, or because a single thick ponded flow unit occurs. The lowest flow unit seen at 3543 4215, about 8 km from vent, rests on the thickest known section of Rotongaio ash (figure 6*c*), the top surface of which is disturbed and locally shows a pink thermal colouration. Succeeding flow units are interbedded with normal coarse plinian pumice-fall material. Ignimbrite here rests directly on the Rotongaio ash, showing that pyroclastic flows were generated very early in the plinian phase.

Apart from local dull grey patches, seen in the Earthquake Gully exposures where it is thought that the ignimbrite was flooded by water while still hot, the proximal exposures of the early flow units are pink, red or orange-brown owing to thermal oxidation, contrasting thus with the near-white of the Taupo ignimbrite. The uppermost parts in Earthquake Gully and around Waitahanui are incipiently welded (sintered) and form vertical cliffs. Both the early flow units and the Taupo plinian pumice contain fragments of densely welded, sometimes revesiculated and breadcrusted, vitrophyric ignimbrite. It is inferred that the onshore outcrops of the early flow units represent the outer rim of a thick accumulation of welded tuff formed around the vent during this phase of the eruption, fragments of which, broken off by vent widening, became incorporated in the onshore eruption products.

The heat-coloured and partially welded proximal outcrops of the early flow units are only found close to the eastern and northeastern sides of Lake Taupo (figure 7). Although well exposed in Earthquake Gully and present in the Hinemaiaia valley to the south, they are not seen on the intervening plateau and were either never deposited there or were so thin that they were eroded during the emplacement of the Taupo ignimbrite. In the sector from northeast to southeast of vent, these flow units are absent from sections more than about 100 m above the modern Lake Taupo, that is, they disappear at roughly the same level regardless of their distance from vent.

All the proximal early flow units contain moderate amounts of lithic fragments, and pumice clasts up to 20 cm across are common (Wilson 1981). Most of the coarse pumice clasts are denser than those in the Taupo ignimbrite and are irregular in shape and poorly rounded, with a knotty internal texture. These pumices so closely resemble those in the intercalated plinian airfall layers that they are thought to be derived either by erosion therefrom or by the incorporation of airfall pumice which landed on the still-fluid flows.

(ii) *Distal exposures of the early flow units*

Distal parts of the early flow units form thin layers interbedded with the Taupo plinian pumice (figures 5 and 6*d*). The number of units seen varies from three (possibly five) north of vent near Taupo township, reducing to one at most exposures where some may have been eroded off by the Taupo-ignimbrite producing flow. Occasionally the distal early flow units have an erosive base and cut across the stratification in the plinian deposit, but they are not significantly diluted by coarse plinian pumice. At one locality (3521 4154, 8 km from vent) the distal early flow units form a low-angle cross-bedded pile on the downvent side of a pre-existing obstruction and contain lee-side pumice lenses similar to those in the Taupo ignimbrite (Walker *et al.* 1981*a*).

These distal outcrops contrast with the proximal outcrops; they lack a pink colouration and coarse pumice, though large lithics (up to 10 cm) are found (Wilson 1981). They are distinct from the Taupo ignimbrite in that they underlie the lowermost layer 1 deposits of that ignimbrite or, where erosion by the Taupo-ignimbrite producing flow has not been severe, are enclosed within the Taupo plinian pumice. The distal early flow units are more widespread and less constrained by topography than the proximal units, reaching to about 15 km from vent (figure 7), and are accordingly interpreted to have had a higher kinetic energy, so producing thinner and more extensive deposits. In their overall grainsize and morphology these distal early flow units bear the same relationship to the proximal outcrops as does the veneer deposit to the valley ponds in the Taupo ignimbrite (Walker *et al.* 1981*a*).

(iii) *Grainsize characteristics of the early flow units*

Limited grainsize and compositional data were obtained from the early flow units; details are given in Wilson (1981). The early flow units are generally rich in fine material and have relatively high contents of < 10 μm material (between 2.6 and 6.5% by mass) resulting in low (< 63 μm)/(< 10 μm) ratios of 5–10, similar to those in the near-vent Taupo ignimbrite (see Paper II, figure 17). They have moderate contents of crystals (2–6% by mass) and lithics (4–20% by mass), and are only slightly enriched relative to the inferred magmatic crystal content (Paper II, figure 23). In their overall grainsize and compositional characteristics the early flow units are broadly similar to the near-vent Taupo ignimbrite. The proximal and distal varieties only differ in the higher amounts of coarse pumice present in the proximal units.

(*c*) *The Taupo ignimbrite*

The Taupo plinian pumice and its associated early ignimbrite flow units are overlain with a sharp and usually erosive contact by the Taupo ignimbrite, whose emplacement formed the eruption climax. The ignimbrite has a volume of *ca.* 30 km^3 and covers an area of 80 ± 10 km radius centred on Lake Taupo. Its extremely widespread nature, with an aspect ratio of *ca.* 1:100000, makes it representative of deposits termed low-aspect ratio ignimbrites (Walker *et al.* 1980*a*). Instead of ponding around the vent, like the proximal early flow units, to generate a clearly defined ignimbrite surface, the Taupo ignimbrite in large part drapes the pre-existing landscape and in places superficially resembles an airfall deposit (see Healy 1964; Vucetich & Wells 1978).

The ignimbrite can be divided into layers 1 and 2 (Sparks *et al.* 1973; see also Wilson & Walker 1982 and Paper II), which are interpreted to represent material deposited by the flow head and material deposited from the flow body respectively. Layer 1 consists of two main facies, which are of contrasting morphology and composition (Paper II, figure 3; Wilson & Walker 1982, figure 1) and are given the lithological terms of layers 1(P) and 1(H).

Layer 1(P) is rich in pumice and contains locally and regionally variable amounts of fine material. Usually the fines content decreases upwards, often to yield a conspicuous variant termed fines-depleted ignimbrite (FDI; Walker *et al.* 1980*b*), which contains little material finer than $\frac{1}{4}$ mm. Layer 1(P) is interpreted to represent portions of the flow head which were thrown off as a result of the violent expansion of air ingested by the flow and is genetically termed the jetted deposits. Regional variations in the degree of fines depletion show that the fines losses in FDI were induced by extreme gas flow rates generated as the jetted material mixed with surface vegetation; FDI is lacking from areas where vegetation was buried by earlier airfall deposits (Walker *et al.* 1980*b*). Several other jetted deposit variants occur (see Paper II), comprising one found at high altitudes, generated from the upper, more mobile parts of the flow, one found in two areas around Lake Taupo where the flow met substantial bodies of water (see §3), and another which was derived from the pumice-rich flow top.

Layer 1(H) overlies and is thinner than layer 1(P), is very rich in crystals and lithics and is strongly fines-depleted. It is interpreted as material segregated out by strong fluidization within the flow head which has sedimented out to the flow base to form a discrete layer, genetically termed the ground layer (Walker *et al.* 1981*b*).

Layer 2 forms two facies which have different morphologies but very similar compositions, the ignimbrite veneer deposit (IVD) and valley-ponded ignimbrite (VPI) (Walker *et al.* 1980*a*, 1981*a*). These deposits are interpreted as nearly all representing the basal and trailing parts of the flow, left behind because of ground friction. As this basal part slowed further, it became increasingly influenced by the local ground slope, and the upper, more mobile parts drained into the valleys (generating the VPI) leaving behind the thin surface-mantling IVD. Analogous relationships have been observed in some relatively mobile lava flows (see, for example, Tazieff 1977) and rock avalanches (see, for example, Plafker *et al.* 1971). The complex relationships seen between the IVD and VPI are thought to result from variations in the degree of drainage of material into valleys, depending on such factors as the local slope angle (Wilson & Walker 1982). In addition, a volumetrically small proportion of layer 2 consists of pumice-concentration zone material inferred to have been generated on top of the moving flow and stranded by the onward movement of the flow to form coarse-pumice rich drapes over the landscape (Wilson & Walker 1982).

The IVD systematically decreases in thickness with distance from vent and shows various internal structures which reveal aspects of the emplacement history of the flow (Walker *et al.* 1981*a*; Wilson & Walker 1981, 1982; Paper II). The thickness of the VPI is independent of the distance from vent and appears to vary with factors controlling the drainage of material into the valleys and minimizing its subsequent down-valley movement (Wilson & Walker 1982). The VPI contains a wide variety of fluidization-induced grading structures, which are inferred to have been generated on both local and whole-flow scales (Paper II).

The grainsize and composition of layer 2 show great lateral variations, which span almost the entire range of previously documented ignimbrites. Proximal deposits are coarse grained, with lithic clasts often exceeding 50 cm in length, whereas, in contrast, distal deposits are often very fine grained, are almost wholly pumiceous and contain very low-density pumice. These lateral variations are interpreted to be the overall result of two processes within the flow: first, the upward movement of fine and light, dominantly pumiceous, material within the flow in response to strong fluidization and, second, the spreading out of the flow because of its extreme violence so that the upper parts of the flow travelled the furthest (Walker & Wilson 1983; Paper II).

The distant facies of the Taupo ignimbrite replaces and is the lateral equivalent of separate layers 1 and 2 on distal hilly interfluves. It combines features of layer 1(P) and the IVD and is interpreted to be flow-head and -body material that was mixed together and spread over the landscape as the flow ran out of material while still retaining a high velocity (Wilson & Walker 1982; Paper II).

(*d*) *Co-ignimbrite ash*

Few outcrops have been found of a co-ignimbrite ash (layer 3 of Sparks *et al.* (1973)) associated with the Taupo-eruption ignimbrites. Layer 3 of the Taupo ignimbrite proper is preserved above layer 2 only, where it was rapidly buried by, for example, secondary mudflow deposits (see figure 15*c*). A few widely scattered outcrops have also been observed of a fine ash resting on the Taupo plinian pumice beyond the outer limit of the Taupo ignimbrite; this is tentatively interpreted to be a co-ignimbrite ash associated with the latter. No layer 3 deposits have been observed for the early flow units, but it seems likely that any fine ash elutriated from these flows would have been caught up in and dispersed from the major plume associated with the coeval plinian activity.

(*e*) *The floated giant pumice blocks*

Scattered very large pumice blocks are found at exposures on the eastern side of Lake Taupo, mostly associated with the cliff-line of a lake level some 5 m higher than at present and post-dating the pyroclastic phases of the eruption. The pumice blocks measure as much as 12 m, possibly 17 m, in length, but the largest examples have now largely disintegrated *in situ* along prismatic cooling contraction joints. Fragments of the pumice vary between slightly positively and negatively buoyant in water, although field evidence implies that the blocks must have floated into their present positions. One example (figure 8, plate 3) can be seen to have come to rest on and to have slightly compacted and deformed post-Taupo-eruption lake sediments, and then been buried under younger sediments before the lake fell to its modern level.

These examples are similar to the giant pumice blocks found at La Primavera volcano in Mexico (Clough *et al.* 1981), but here they occur stranded on land as the youngest onshore products of the Taupo eruption.

3. Eruption narrative

The eruption began with minor phreatomagmatic activity, which generated the initial ash. From the pumiceous nature of this unit it is thought that vesiculated magma reached the surface to mix with the pre-eruption Lake Taupo. The limited dispersal of the ash suggests that the eruption column was probably no more than 10 km high and the ash was carried onshore by a southwesterly surface wind. The uniform appearance of the ash suggests that the activity was relatively continuous; in comparison with other phreatomagmatic eruptions such as those at Soufriere, St Vincent (Shepherd *et al.* 1979) and Askja (Sparks *et al.* 1981), the thinness and lack of bedding suggest that the duration of this phase was short, perhaps only a few hours.

The presence of blocks of lake sediments in the ground layer of the Taupo ignimbrite in proximal localities south, east and north of the vent suggests that the vent opened within the pre-eruption lake. The volume of the initial ash is small, so it seems likely that the vent was at or just below lake level and was soon cleared of water at the onset of the Hatepe plinian phase. Other blocks found in the Taupo ignimbrite include fragile hydrothermally altered pumice and variously altered rhyolite lavas, indicating that an active hydrothermal system was present at or close to the vent area. There is evidence that the Waimihia eruption took place from a vent at or near the Horomatangi Reefs (Walker 1981 *b*) and the hydrothermal system disrupted by the Taupo eruption therefore dates from at least the time of this event. Similarly, an active hydrothermal area is present at Horomatangi Reefs (Calhaem 1973; Northey 1982) and its products may be incorporated in a future eruption.

The abrupt change from the fine initial ash into the much coarser and more widely dispersed Hatepe plinian pumice suggests that the mass eruption rate jumped rapidly, to clear the vent area of water and begin plinian activity. The Hatepe plinian deposit was produced by a continuous gas blast, with only minor fluctuations, and the magma flux was sufficiently high relative to the water flux that plinian instead of phreatoplinian conditions prevailed. By comparison with similar sized eruptions such as Vesuvius in A.D. 79 (Lirer *et al.* 1973), this plinian phase may have occupied roughly 10–30 hours, which would imply an average magma discharge rate of *ca.* 13000–40000 $m^3 s^{-1}$. Such a discharge rate could maintain an eruption plume of the order of 30 km high (Wilson *et al.* 1978). Accompanying the southwesterly surface winds (indicated from the dispersal of the initial ash) were local showers, which flushed out minor quantities of fine ash during an early stage of the plinian phase over the area around Taupo township. High level winds which dispersed the plinian pumice were from west-southwest to west (figure 9).

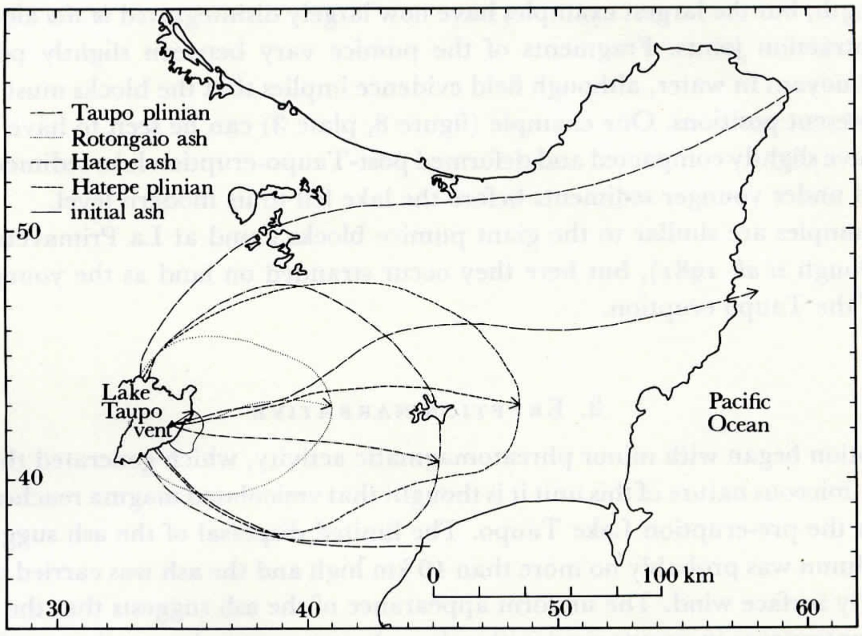


FIGURE 9. Dispersal patterns of airfall deposits from the Taupo eruption. The margin of each deposit is represented by the 3 cm isopach, and the inferred wind direction (arrow) is drawn along each dispersal axis (data from Walker (1980, 1981*b*, *c*) and this paper, figure 4).

A sharp contact separates the Hatepe plinian pumice from the Hatepe phreatoplinian ash, this implying a sudden increase in the lake water flux into the vent. However, the pumiceous character of the Hatepe ash and the minor intercalated layers of plinian-style material suggest that the vesiculation and fragmentation levels were still at some depth, and that the phreatomagmatic activity was caused by a 'normal' plinian eruption column interacting with large quantities of surface water. The observation that pumice clasts in the Hatepe ash are slightly denser than the equivalent size fractions in the earlier plinian deposit (Walker 1981*b*) is attributed to the quenching interrupting pumice vesiculation and preferentially shattering the weaker, lower-density pumice.

Emission of ash ceased for a time at the close of the Hatepe phreatoplinian phase. Most probably, water penetrated deeply into the vent so that quenching took place at or below the vesiculation level, or alternatively a gas-poor magma fraction arrived in the vent. During this time break the top of the Hatepe phreatoplinian ash was eroded by water derived from the vent area. It is thought that thermal energy was transferred from the magma to the lake water, causing evaporation or the explosive ejection of water from the vent. The time break was possibly as short as a few hours or as long as several weeks (Walker 1981*c*, figure 7). The discharge of material then resumed, generating the Rotongaio ash, some of which is poorly- or non-vesiculated obsidian. It is likely that the obsidian was generated by quiet magma discharge during the break and was merely erupted during the Rotongaio phase.

The wide dispersal of the two phreatoplinian deposits suggests that these were fairly powerful events, sustained by eruption rates comparable to that during the earlier plinian event. However, even given similar eruption rates, the eruption column heights during the phreatoplinian activity would have been lower than during the plinian event owing to the loss of thermal energy in the magma–water interaction (Wilson *et al.* 1978). It is noticeable that the ashes were less strongly dispersed by the westerly airstream than either the initial ash or the Hatepe and Taupo plinian phases (figure 4) (Walker 1980, 1981*b*); for example, minor thicknesses of the phreatoplinian ashes are found west of Lake Taupo (Walker 1981*c*) where plinian material is absent. It is thought that some mechanism inherent in phreatoplinian eruptions causes material to be spread more evenly about the vent. The durations of the Hatepe and Rotongaio phreatoplinian events are difficult to estimate, but comparison with much smaller historical events (see, for example, Shepherd *et al.* 1979; Sparks *et al.* 1981) suggest a few hours to tens of hours each.

At the close of the Rotongaio phreatoplinian phase, the nature of the eruption changed abruptly and the 'wet' vent was transformed to a 'dry' vent again. The erupted material changed from obsidian or dense pumice to very low density pumice, implying that the vent was cleared of water and that both the vesiculation and fragmentation surfaces moved downwards very rapidly. The sequence to the end of the Rotongaio phreatoplinian phase could be interpreted as representing a single magma batch, initially volatile rich (initial ash and Hatepe plinian) and later volatile poor (Rotongaio ash). The abrupt renewal of plinian activity suggests the arrival of a new, more volatile-rich magma batch, which, however, had a similar phenocryst content.

The extreme dispersal and the distances from vent at which particles of a given size are found imply that the Taupo plinian event was exceptionally energetic (Walker 1980, 1981*d*). Various combinations of eruption column height and mean wind velocity can be considered to explain the dispersal characteristics, but a scenario involving a column less than 50 km high requires mean wind velocities that are improbably high (Walker 1980). From the contrasting grainsize characteristics of the coarser and finer bands visible in the deposit, and assuming a constant overall accumulation rate for the deposit, Walker (1980) estimated the duration of this phase to be between 6 and 17 hours. Such a duration would imply magma eruption rates of the order of 8×10^4–2.4×10^5 m^3 s^{-1}, which, from the model of Wilson *et al.* (1978), could sustain an eruption column of the order of 30–40 km high. The discrepancy between this model and Walker's (1980) inference of a greater column height may possibly be explained by the high content of fine material in the erupted material (see the end of this section), which would serve to improve the efficiency of heat transfer in the column and hence boost the power of the eruption (Walker 1980).

The early ignimbrite flow units are undoubtedly intraplinian, and the question then arises as to whether they were generated synchronously with the plinian deposit or in discrete column collapse episodes. One scenario consistent with the field and laboratory evidence is as follows. The vent lay in a basin, and very early in the plinian phase a pool of ignimbrite, of which the early flow units are a part, began to accumulate around it; fragments of this ignimbrite are found as lithics in the Taupo plinian pumice, early flow units and Taupo ignimbrite. The proximal and distal types of early flow unit are interpreted as reflecting the different emplacement velocities of the flows, being lower for the thicker, low energy proximal flow units and highest for the solitary distal flow unit seen at the margin of the outcrop. The proximal units, with their higher temperatures and lower velocities, may have been derived from material diverted at the base of the eruption column, whereas the distal units, from their lower temperatures and hill-climbing abilities, seem more likely to have been generated by column collapse. The most obvious finer bands in the Taupo plinian pumice appear to correlate with individual distal early flow units. Possibly, congestion of the vent, caused by the accumulation of the early flow units, occasionally induced partial column collapse, reducing the column height (to form a finer band in the plinian deposit) and generating a small volume, high velocity pyroclastic flow. The formation of the early flow units as proposed is considered to be directly due to the vent being located within a basin. A very similar relationship appears to have been present during the closing stages of the Waimihia eruption.

The inferred magma eruption rate of 8×10^4–2.4×10^5 $m^3\ s^{-1}$ for the Taupo plinian phase is thought, from the absence of any significant overall normal or reverse grading in the deposit, to have remained relatively uniform. In addition, magma volumes represented by the early ignimbrite flow units may increase this estimate by up to a few tens of percent. However, this rate is still significantly less than the eruption rate inferred for the Taupo ignimbrite of *ca.* 3×10^7 $m^3\ s^{-1}$ (Wilson & Walker 1981). The abrupt switch from fall to flow activity is correlated with this drastic increase in discharge rates and is not, apparently, simply due to the collapse of the Taupo plinian column. A possible explanation (figure 10) is that the high eruption rate during the plinian phase caused the fragmentation level of the magma to drop, this eventually leading to major collapse of the vent region, which greatly widened the vent. The Taupo ignimbrite-producing flow was then formed by column collapse of the erupted material, the inferred discharge rate being much greater than that capable of forming a stable plinian column (Sparks & Wilson 1976; Sparks *et al.* 1978). The lithic contents of the pre-Taupo ignimbrite airfall deposits plus early flow units (*ca.* 1.2 km^3) imply that vent-widening by erosion was important and would possibly have led to column collapse during the course of the eruption. However, the volume (2.1 km^3) and sizes of lithics in, and the extremely high inferred eruption rate of, the Taupo ignimbrite suggest that the transition from fall to flow activity was not simply due to gradual vent widening which initiated column collapse (see, for example, Sparks & Wilson 1976), but was attended by a drastic change in eruption conditions.

Field data have been used to suggest that the parent flow to the Taupo ignimbrite was erupted over roughly 400 s as batches of material which gradually coalesced so that from *ca.* 40 km outwards the flow was a single wave of material (Wilson & Walker 1981). During most of its passage the flow consisted of a head, strongly fluidized by ingested air, which generated layer 1 deposits, and a body plus tail, which generated layer 2; however, in distal hilly areas the whole flow became affected by strong air-ingestion fluidization (Wilson & Walker 1982). The flow moved at high velocities over a locally mountainous landscape at speeds which probably exceeded 250–300 $m\ s^{-1}$ near vent and remained high (locally more than 100 $m\ s^{-1}$) to the outer limits of the flow (Paper II, figure 2). During emplacement, a variety of processes, acting in response to fluidization or the flow kinetics, operated within the flow. They include processes at the flow front to form the jetted deposits and FDI, segregation and sedimentation of material within the flow head to form the ground layer, variable degrees of drainage of flow body material into depressions to delineate the IVD and VPI, fluidization-induced grading

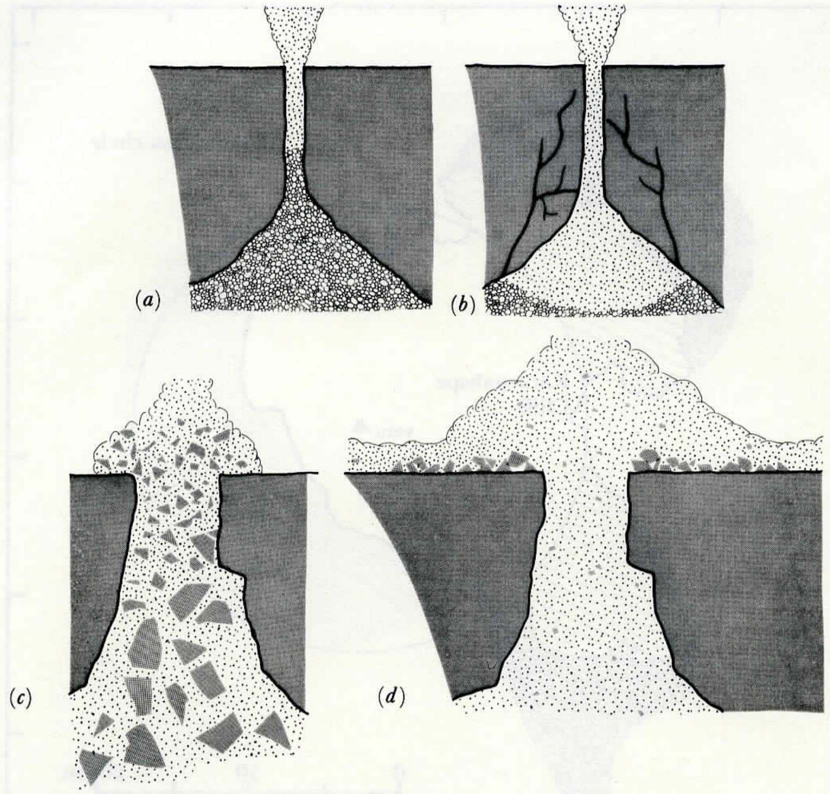


FIGURE 10. Schematic diagrams to show the inferred sequence of events leading to the Taupo ignimbrite eruption. (*a*) During the Taupo plinian phase, the boundary between coherent, vesicular magma (bubble texture) and fragmented material (stipple) moved downward, eventually (*b*) leaving the vent area unsupported. (*c*) The vent area then collapsed, unroofing the magma chamber which then catastrophically erupted, the first material containing large numbers of coarse lithics and (*d*) later material having smaller, and a lower content of, lithics (see Paper II).

within the VPI, and grainsize and compositional segregation within the flow and its reflection in lateral variations in the ignimbrite (Walker *et al.* 1980*b*, 1981*a*, *b*; Wilson & Walker 1982; Walker & Wilson 1983; Paper II).

Variations in the nature of the Taupo ignimbrite provide some clues to the size and form of Lake Taupo at the time when the ignimbrite was erupted. In two areas around Western Bay and the southern part of the lake (figure 11) the ignimbrite shows two anomalous features. First, maximum lithic clast sizes are unusually low in both layers 1 and 2, but especially in layer 1 and around Western Bay (Paper II, figures 11 and 38). Second, jetted layer 1 deposits, and layer 2 deposits very near the lake, lack carbonized vegetation but instead contain open holes interpreted as tree and branch moulds, occasionally coated by a thin layer of fine pumiceous ash in which bark impressions can be seen. Both layers 1 and 2 commonly contain vesicles interpreted to have been steam bubbles trapped in a water-saturated material.

In addition, the ignimbrite is poorly developed downvent from Western Bay in a north-northwesterly direction where, although it reached to 70 km or more, it is unusually thin (see, for example, Grange & Taylor 1932). Our explanation of these anomalies is that part of the Taupo flow met with remnants of Lake Taupo in these two areas, lost its larger lithics and became cold, wet and muddy. It seems possible that the early flow units originally spread radially from vent over a roughly circular outcrop of *ca.* 15 km radius and just reached the

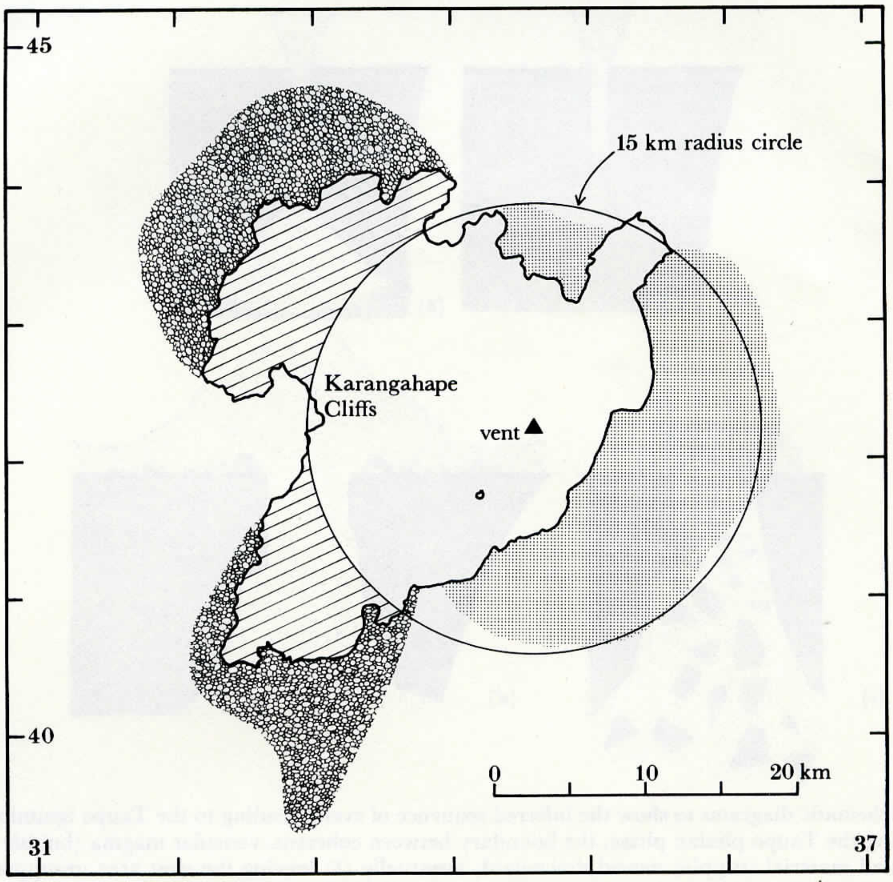


FIGURE 11. Map showing postulated remnants of Lake Taupo at the close of the Taupo plinian phase. If the early flow units (stipple) extended in all directions away from vent to about 15 km they would have isolated two portions of the lake basin (diagonal hatching); the bubble texture marks the outcrop areas of carbon-free, vesicular Taupo ignimbrite (see text for discussion).

western shore of the lake at the foot of the Karangahape Cliffs, isolating two remnants of the lake in the northwestern and southern parts of the basin (figure 11).

After the explosive eruption, Lake Taupo began to reform and the water level rose to 30 m above its present level. It later fell as the outlet river cut through the ignimbrite to form the present shallow canyon just below Taupo township, leaving wavecut benches at various intermediate levels (Grange 1937). The giant pumice blocks, by analogy with La Primavera (Clough *et al.* 1981), are thought to have spalled off an underwater lava extrusion and then floated to the surface; the Horomatangi Reefs may be the ruins of such an extrusion. The pumices are found only at levels up to *ca.* 10 m above the modern lake surface and are thus inferred to post-date the maximum lake height. Although they could have floated for some time, the predominant southwesterly winds (Maunder 1970) would most likely have blown them ashore, implying that the lava was erupted at least some years later.

In summary, the total time occupied by the explosive phases of the eruption could be as short as a few days or as long as months, largely depending on the time gap represented by erosion between the Hatepe and Rotongaio phreatoplinian events. The generation of the giant pumices may then post-date the rest of the eruption by years. During the eruption, the discharge rate fluctuated over several orders of magnitude, the largest events having the highest eruption rates (figure 12). The total thickness of the airfall deposits amounts to over 5 m in places (figure 13), nearly all the material being blown east of vent by strong southwest to west winds (figure 9). Airfall deposits more than 10 cm thick were deposited over *ca.* 30000 km² of land, while a partially overlapping area of *ca.* 20000 km² was devastated by the Taupo ignimbrite flow (figure 13).

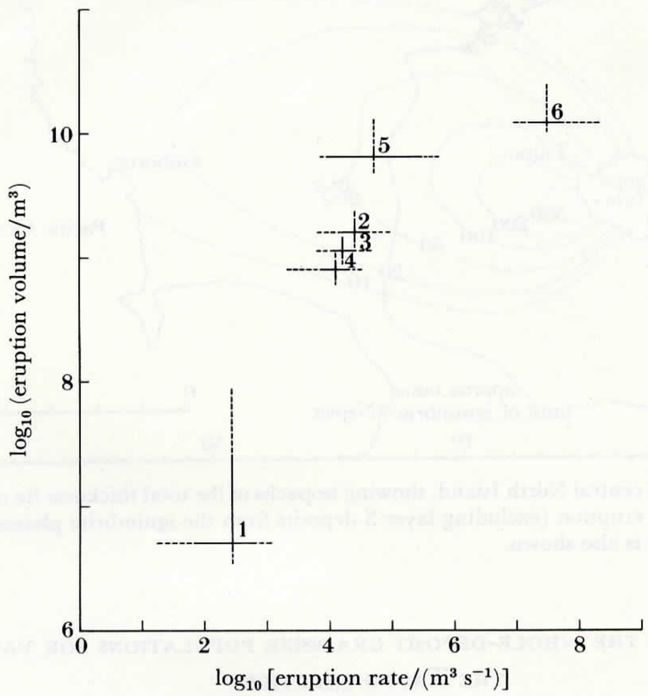


FIGURE 12. Plot of inferred discharge rates against volume (both expressed in terms of magma plus lithics; table 1) for various phases of the Taupo eruption. 1, initial phreatomagmatic ash; 2, Hatepe plinian pumice; 3, Hatepe phreatoplinian ash; 4, Rotongaio phreatoplinian ash; 5, Taupo plinian pumice and early ignimbrite flow units; 6, Taupo ignimbrite. Lengths of lines indicate uncertainties of estimates. Eruption rates for phases 1, 5 and 6, delineated by the horizontal lines, do not take account of material now beneath Lake Taupo, but the vertical lines give estimates of the probable maximum volumes of each unit.

From grainsize studies of the deposits, estimates can be made of the whole-deposit grainsize population of the eruption material at various stages (table 2). These data show that the plinian deposits have relatively high contents of fine material, appreciably more than would be expected from observations of their coarse nature in onshore exposures. The difference in nature between the plinian and phreatoplinian deposits is attributed to their eruptive mechanisms. In the former, the fine ash is thought to remain airborne for long periods and hence to be very widely dispersed (Walker 1980), whereas in the latter, flushing of the eruption plume by water is inferred to have brought down the fine ash much closer to vent (Walker 1981*c*). Minor differences in initial grainsize populations between the Hatepe plinian and phreatoplinian deposits suggest that mixing of vesiculated and fragmented magma in the eruption column with water caused relatively minor additional fragmentation and generation of fine ash. In contrast, note the appreciably finer grainsize population of the Rotongaio ash, believed to have been generated by the direct interaction of magma and water (Walker 1981*c*).

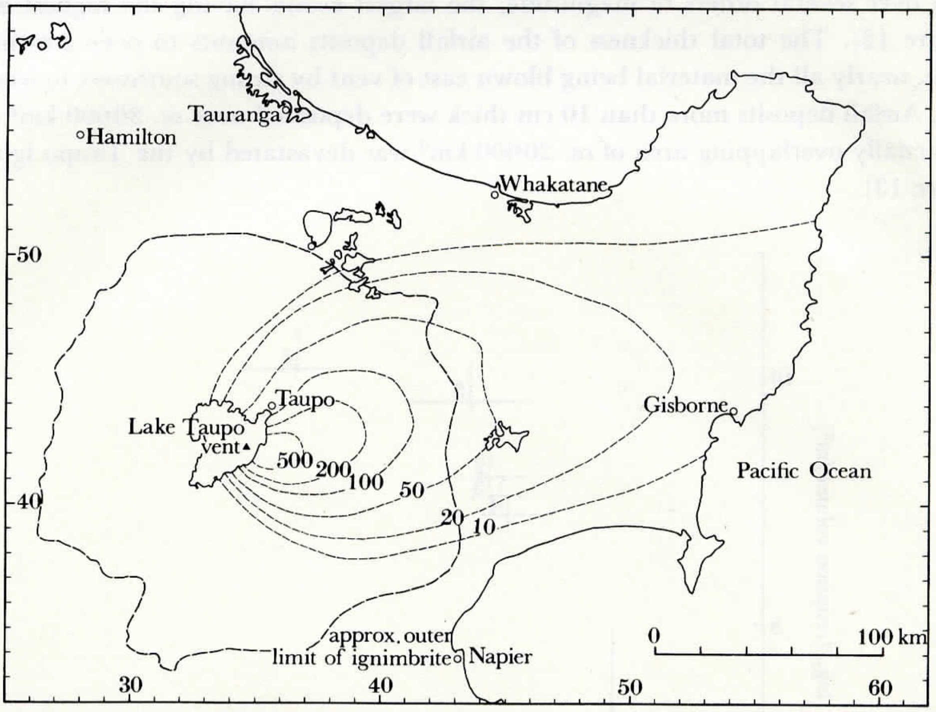


FIGURE 13. Map of the eastern central North Island, showing isopachs of the total thickness (in centimetres) of airfall deposits from the Taupo eruption (excluding layer 3 deposits from the ignimbrite phases). The area covered by the Taupo ignimbrite is also shown.

TABLE 2. ESTIMATES OF THE WHOLE-DEPOSIT GRAINSIZE POPULATIONS FOR VARIOUS PHASES OF THE TAUPO ERUPTION

(The lower limits of each size class are given in linear units (mm or μm) and in terms of ϕ, where $\phi = -\log_2$ (grainsize/mm). Estimates were compiled from Walker (1980, 1981*b, c*) and Paper II.)

size class		Hatepe plinian pumice	Hatepe phreatoplinian ash	Rotongaio phreatoplinian ash	Taupo plinian pumice	Taupo ignimbrite
512 mm	-9ϕ	—	—	—	—	(⩾ 512 mm) 0.2
256 mm	-8ϕ	—	—	—	—	1.1
128 mm	-7ϕ	—	—	—	—	3.0
64 mm	-6ϕ	—	—	—	—	5.4
32 mm	-5ϕ	(⩾ 32 mm) 1.1	—	—	(⩾ 32 mm) 0.7	7.3
16 mm	-4ϕ	1.1	0.6	—	1.4	6.0
8 mm	-3ϕ	2.6	—	0.1	2.3	6.0
4 mm	-2ϕ	3.7	0.9	0.3	3.1	7.0
2 mm	-1ϕ	4.7	2.4	0.7	3.5	7.5
1 mm	0ϕ	5.5	4.2	1.5	3.8	7.5
½ mm	1ϕ	6.2	7.9	2.4	4.4	8.0
¼ mm	2ϕ		15.9	7.1	3.5	7.5
⅛ mm	3ϕ		14.9	14.9		7.0
63 μm	4ϕ		17.2	26.5		6.0
31 μm	5ϕ	75.1	9.0	15.2		5.5
16 μm	6ϕ		17.1	16.6	77.3	6.3
8 μm	7ϕ		5.5	5.4		6.7
4 μm	8ϕ		3.4	5.9		2.6
< 4 μm	—		1.0	3.4		0.3

4. Tectonic activity and the Taupo eruption

As well as volcanism, there is evidence for significant tectonic activity both during and after the Taupo eruption.

Southwest of Lake Taupo, the ground is locally cut by narrow (5–20 cm) subvertical fissures which are lined by a few millimetres of fine pumiceous ash and infilled by the Taupo ignimbrite. The absence of Rotongaio ash suggests that the fissures were opened during the plinian or ignimbrite phases by severe ground shaking causing local downslope movement. At one exposure near Taupo township (figure 14*a*, plate 4), the Taupo airfall deposits show slumping after the Rotongaio ash but before the Taupo ignimbrite, suggesting ground shaking as the cause.

In many places around Lake Taupo and occasionally as far as 70 km from vent, clastic dykes are found which cut the secondary deposits and Taupo ignimbrite and often penetrate underlying deposits. The dykes are subvertical and can be up to a metre wide. Mostly the infilling is a fine vitric ash and it occasionally has a crude vertical or horizontal layering, or both; more rarely it is a poorly sorted mix of pumices up to a few centimetres across in an ash matrix. In one example (figure 14*b*), the fine ash infill is subvertically laminated and the laminae have been folded along vertically plunging axes, the lamination and folding probably being due to repeated opening and closing of the fissure.

In dykes with a fine ash infill, the ash is more than 97 % vitric material, has a median grainsize finer than 100 μm and has the characteristics of a layer 3 deposit (Sparks & Walker 1977). It is thus interpreted to consist of layer 3 material which entered the fissures from above after the ignimbrite had consolidated enough to support an open fissure but before layer 3 had been removed by erosion. The more poorly sorted dyke infills seem to represent portions of the ignimbrite that had slumped into the fissure.

Occasionally, local funnel-shaped bodies of incoherent breccia are found (figure 14*c*) which consist of fragile blocks of Taupo ignimbrite, layer 3 material and reworked ash interspersed with numerous subvertical fluidization segregation pipes. These breccia bodies appear to have formed by the collapse of fissures and the pipes are interpreted as degassing structures initiated by ground shaking.

It is thus inferred that at times during and after the Taupo eruption, severe and widespread ground shaking occurred, some of it presumably related to the collapse of areas of the Lake Taupo basin in response to magma withdrawal. North of the lake, the top surface of the valley ponded Taupo ignimbrite slopes gently towards the lake, from horizontal more than 2–7 km from the lake margin, to about 8° close to the lake, which may be attributable to subsidence. However, in other areas remote from the lake, the tops of the valley ponds slope downvalley at an angle roughly equal to the pre-ignimbrite gradient. On present evidence the increase in the slope of the valley ponds towards the lake could thus be an original depositional feature.

The Lake Taupo area is traversed by several major faults (figure 2), such as that defining the western shore south from Karangahape Cliffs, and some of these probably moved during or after the eruption. Geophysical evidence (Northey 1982) suggests that localized caldera collapse may have occurred in the northern part of the lake between the Horomatangi and Northern Bays Faults, but its magnitude is uncertain. Significant downwarping of large areas in and around the Lake Taupo Basin must have followed the eruption, but at present we lack a suitable datum to tie down relative or absolute movements.

5. Secondary deposits

Many kinds of secondary deposits overlie and extend beyond the Taupo ignimbrite and are interpreted to reflect the interaction of water with the still-hot ignimbrite and water reworking of the low-density pumiceous materials. All significant volumes of secondary material appear to be derived directly or indirectly from the Taupo ignimbrite; the airfall deposits seem to have been little affected by reworking (see, for example, Healy 1967).

In many places, large quantities of water evidently gained access to the still-hot ignimbrite. No rootless explosion craters, such as at Mount St Helens (Rowley *et al.* 1981) have been recognized, but segregation pipes rising from the base of the ignimbrite are common and can occasionally exceed several metres across. Many of the Taupo ignimbrite valley ponds and their adjacent veneer deposits are overlain by fine-ash rich bedded deposits, which often exceed 1 m in thickness (figure 15*a*, plates 5 and 6). These deposits often show a lensoid- or cross-bedding and appear to have been emplaced by laterally moving flows of some kind. Their basal contact is often marked by minor reworking, and segregation structures in the underlying ignimbrite are truncated against the contact (figure 15*b*), implying that the bedded deposits were generated a short time after the ignimbrite was emplaced. Essentially identical relationships are seen at Mount St Helens (authors' own observations) where finer-grained cross-bedded deposits overlie the May 1980 ignimbrite and are especially well developed around rootless explosion craters. At Mount St Helens these deposits clearly represent the products of large phreatic explosions where water flashed to steam and ejected quantities of material on to the surrounding ignimbrite (Rowley *et al.* 1981). A similar origin for the corresponding deposits at Taupo seems likely.

In addition to the cross-bedded deposits, which are inferred to have been deposited by a laterally moving flow or surge, local airfall deposits which are thought to be related to phreatic explosions are recognized at some exposures. One of the most prominent deposits covers several square kilometres in the Reporoa Basin, about 30 km northnortheast of Lake Taupo, and consists of a thin (less than 30 cm) ash layer, with common centimetre-sized accretionary lapilli, which forms a discrete layer above the ignimbrite.

Material interpreted as mudflow deposits is very common, both overlying the ignimbrite (figure 15*c*) and extending downstream beyond the limits of inferred primary ignimbrite. These deposits often superficially closely resemble the ignimbrite, but their matrix is always vesicular and is commonly shot through by pipes in which the clasts are mud coated; localized iron staining is common, and included carbonized vegetation fragments are usually abraded and do not have any fluidization segregation pipes emanating from them (see Paper II). Often the basal contact of the inferred mudflow deposits is churned and mixed, apparently owing to the passage of quantities of steam generated when the wet mudflow overrode the hot ignimbrite. Mudflow and more dilute muddy-flood deposits extend for tens of hundreds of kilometres beyond the known limits of the ignimbrite (see, for example, Fleming 1953; Healy 1967; Kear & Schofield 1978) and their distribution indicates that extensive catastrophic flooding occurred on all rivers draining the central North Island (figure 16). Much pumice was carried to the coast, there to be distributed by shoreline and oceanic currents (see, for example, Wellman 1962).

Local lacustrine deposits are commonly found where rivers were blocked by debris. Two types are seen: a fines-free assemblage of coarse, very well rounded pumices (see, for example, figure

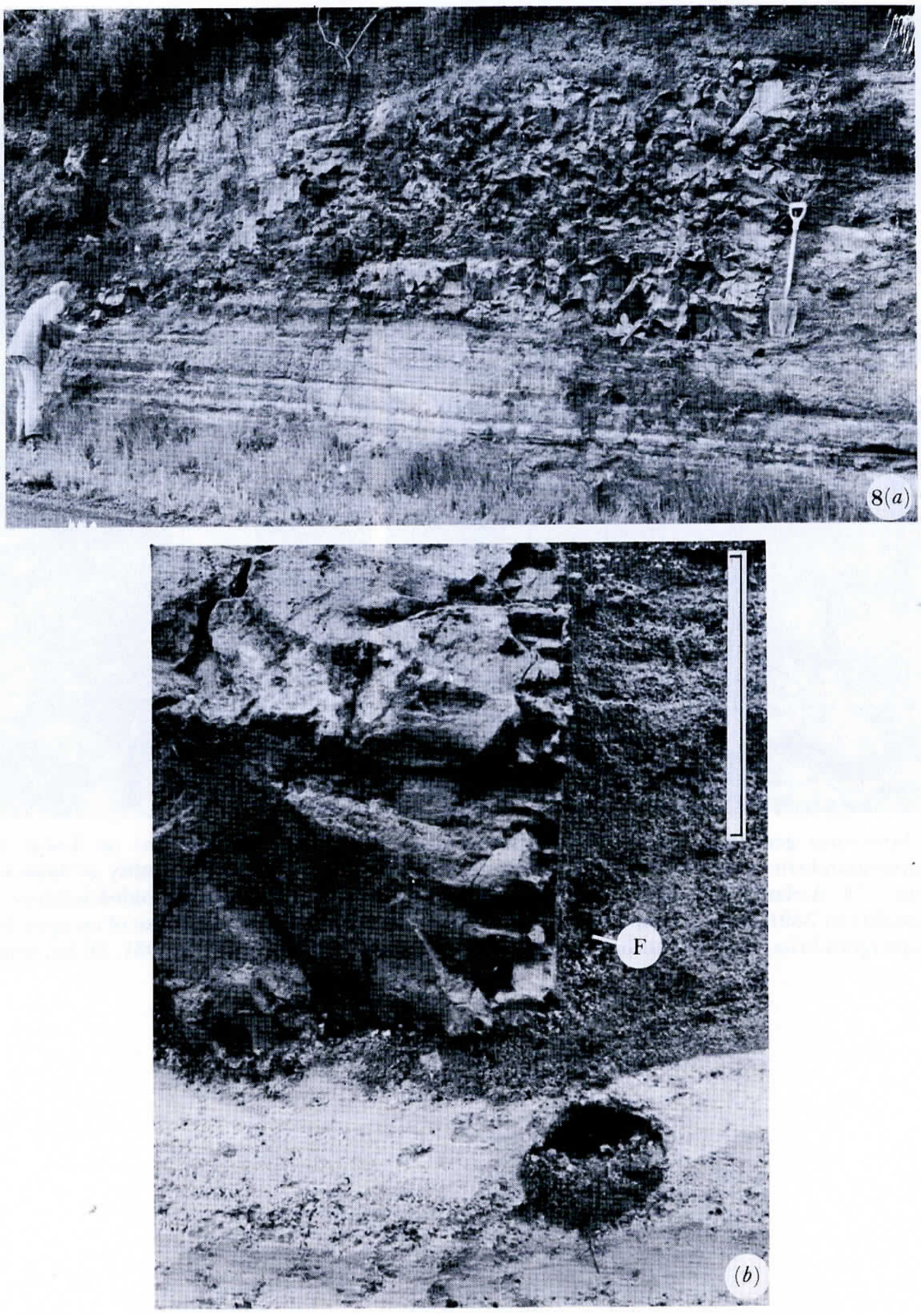


FIGURE 8. (*a*) A single giant pumice block enclosed within subhorizontal lake sediments. Locality at **3441 4136**. (*b*) Detail view of the lower right-hand corner of the pumice block illustrated in (*a*), showing the compaction of the underlying sediments with an attendant fluid-escape segregation structure (F). Note the cooling contraction joints developed normal to the margin of the pumice. Scale bar is 20 cm long.

(*Facing p.* 222)

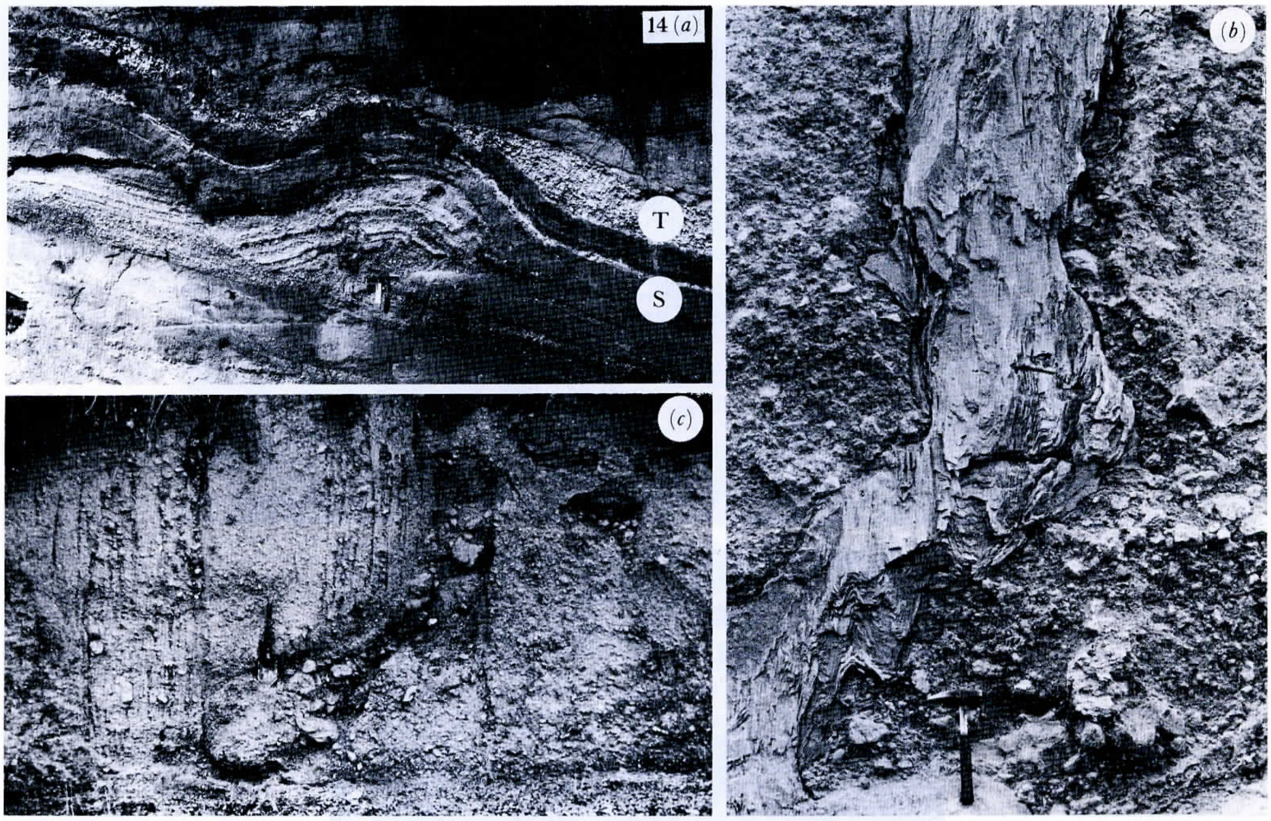


FIGURE 14. Structures generated by tectonic activity related to the Taupo eruption: (*a*) Local slumping of pre-Taupo-ignimbrite airfall deposits (T, Taupo plinian, s, pre-eruption soil). Locality at 3494 4352, 12 km from vent. (*b*) A clastic dyke cutting valley-ponded Taupo ignimbrite. Note the folded laminae in the dyke infill. Locality at 3591 4178, 13 km from vent. (*c*) Breccia produced by the collapse of an open fissue within the Taupo ignimbrite; note the accompanying degassing pipes. Locality at 3439 4051, 16 km from vent.

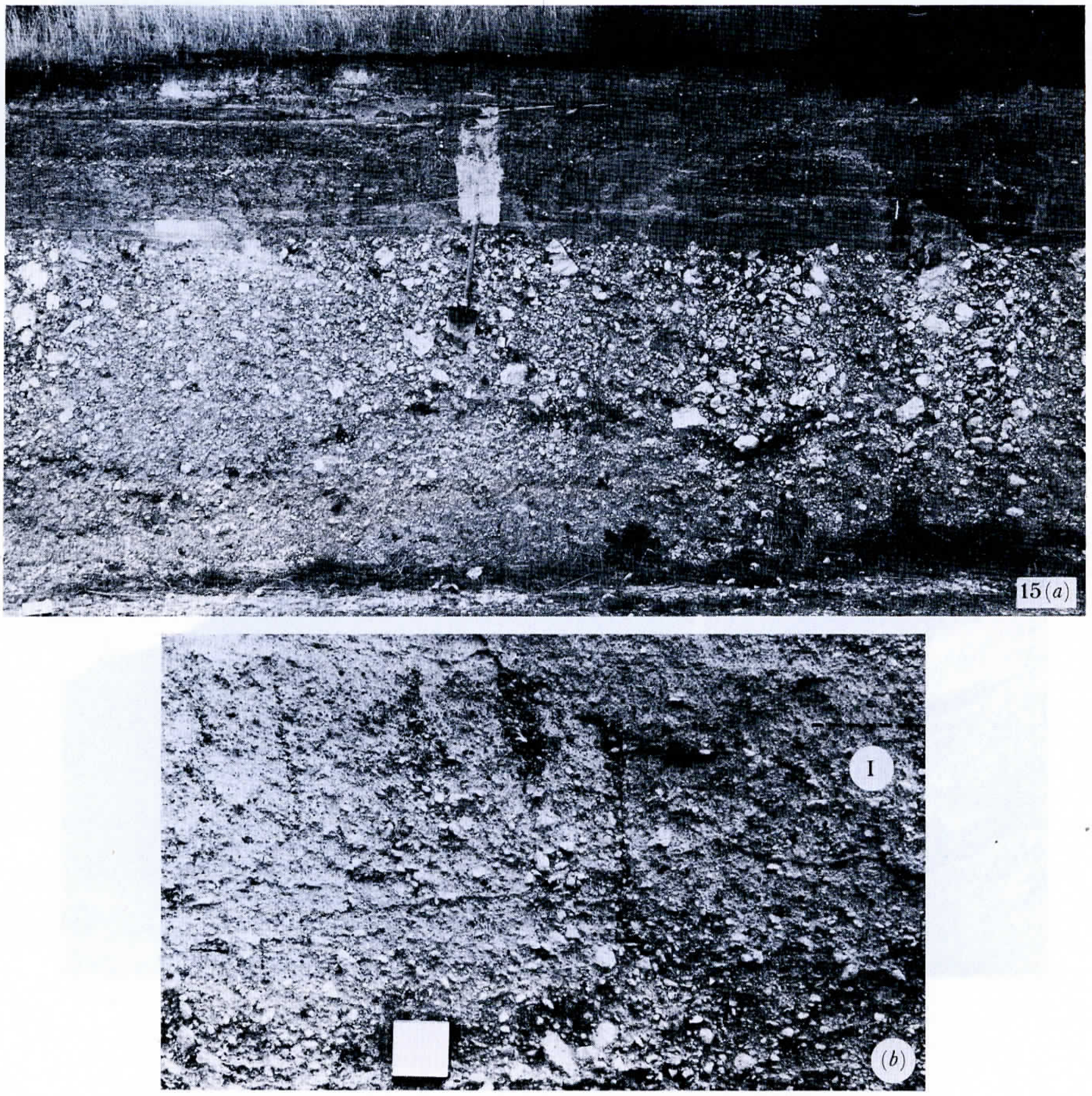


Figure 15. Secondary deposits. (*a*) Typical fine-grained, stratified, cross-bedded secondary deposits overlying the coarser Taupo ignimbrite. These deposits are interpreted to have been ejected by phreatic explosions. Locality at 3531 4426. (*b*) Detail of the contact between the Taupo ignimbrite (I) and some secondary deposits, showing segregation pipes in the former truncated along and defining the contact; note the continuous stratification in the secondary deposits above the pipes. The tape case is 5 cm square. Locality at 3475 4465. (*c*) Secondary deposits over the Taupo ignimbrite. The base of the exposure is in primary ignimbrite (I), overlain by a layer 3 ash (3), which is slumped and faulted into a structure interpreted as a degassing vent produced where water flooded the ignimbrite. Layer 3 is in turn overlain by a massive pumiceous mudflow deposit (m) and finer-grained, stratified material (s) interpreted as phreatic explosion deposits. Locality at 3518 4150. (*d*) Section through deposits of a temporary post-eruption lake. Horizontal stratified pumiceous beds, partly derived from pumices which were floating on the lake surface, butt against *in-situ* Taupo eruption deposits at a fossil shoreline on the left. The cutting face is 3.5 m high. Locality at 3563 4101.

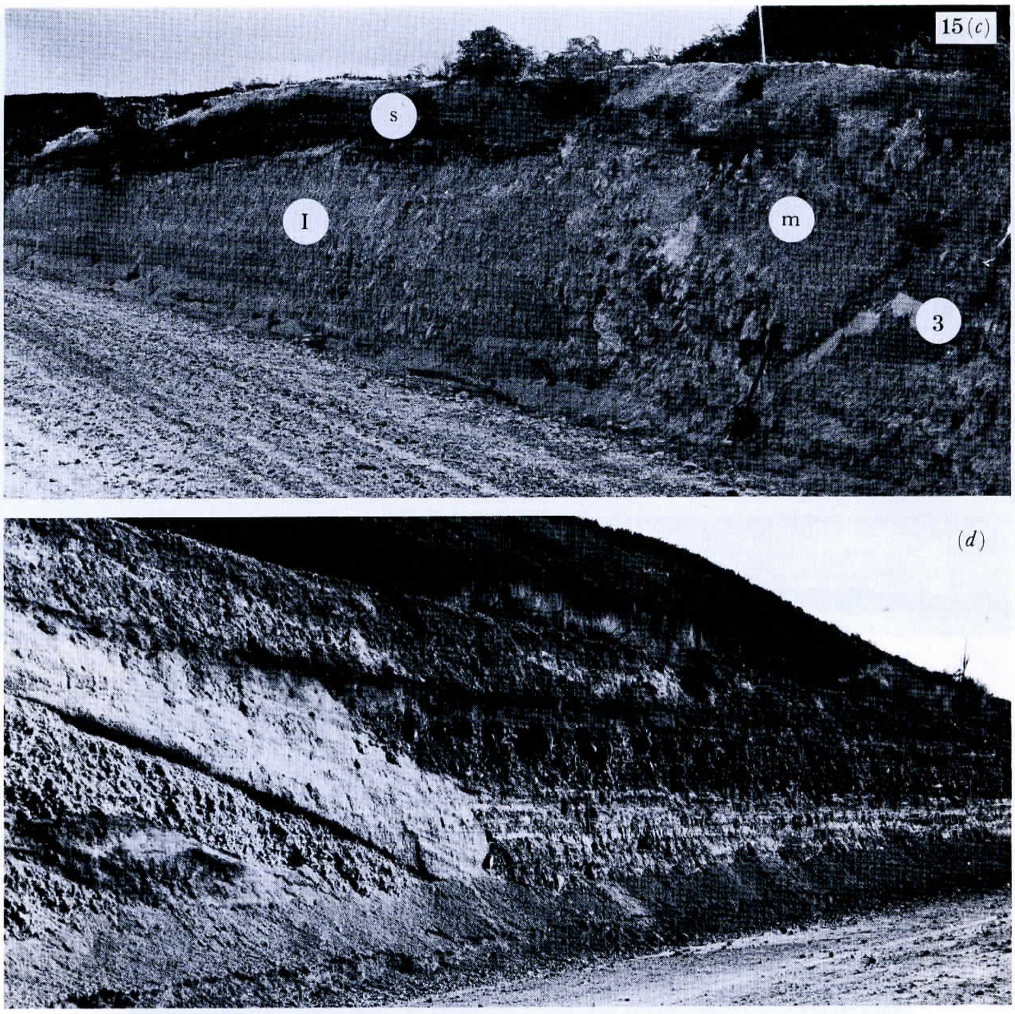


FIGURE 15 (*c*)–(*d*). For description see plate 5.

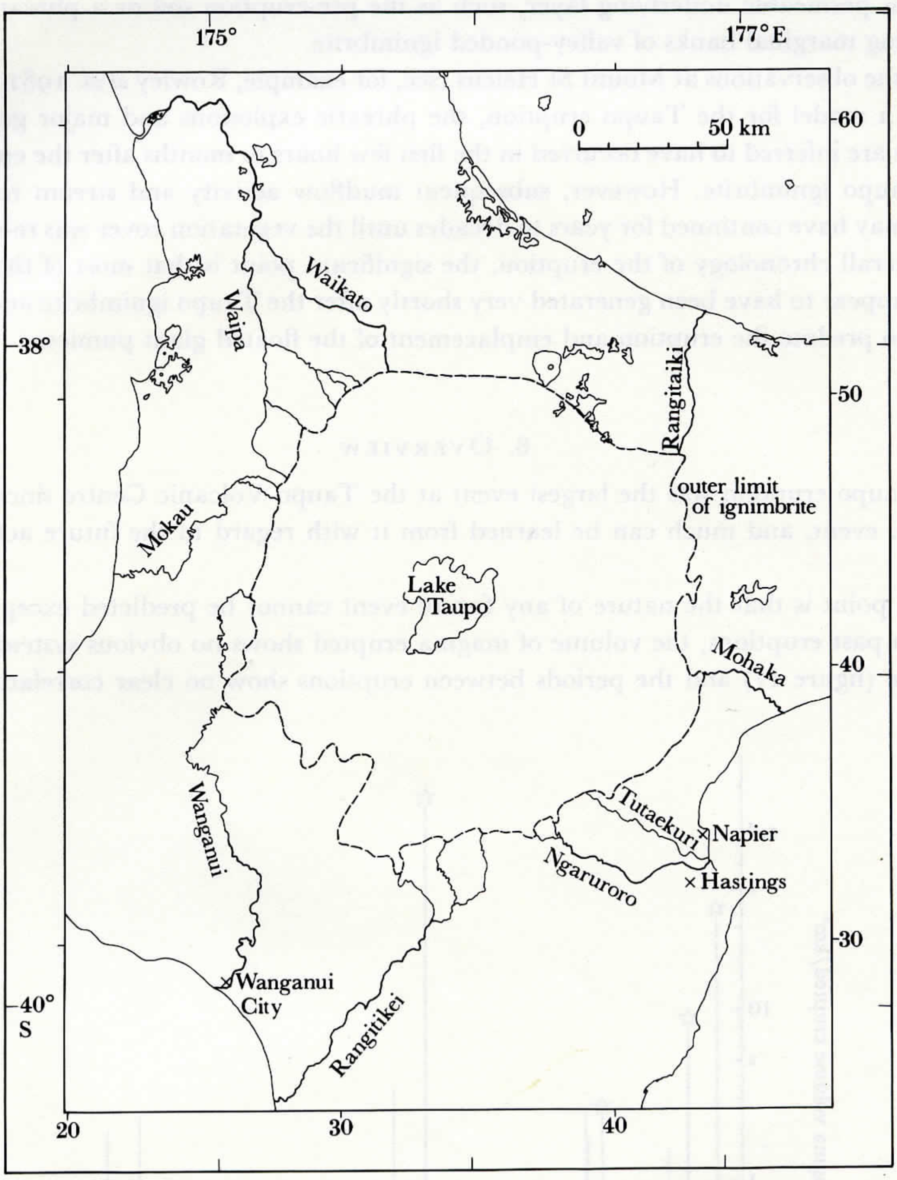


FIGURE 16. Map of the central North Island, showing the rivers which acted as major pathways for mudflows and flooding after the Taupo eruption.

15*d*), which evidently once formed a floating layer on the lake surface, and fine to very fine pumiceous ashes showing millimetre to decimetre thick normally graded beds, each bed representing the input from one discrete erosion and deposition episode.

Streams have extensively reworked the ignimbrite and secondary mudflow deposits. The commonest lithofacies in the resulting sediments is a crystal- and lithic-rich cross-bedded fine sand to coarse gravel with minor amounts of pumice. Favourable sections show channel bedding suggestive of braided stream deposition. Less commonly, well downstream from source, almost-pure pumiceous gravels occur (see, for example, Kear & Schofield 1978). Most streams have reoccupied essentially their pre-eruption courses, usually by sapping along the contact with a less permeable underlying layer, such as the pre-eruption soil or a phreatomagmatic ash, leaving marginal banks of valley-ponded ignimbrite.

Using the observations at Mount St Helens (see, for example, Rowley *et al.* 1981; Cummans 1981) as a model for the Taupo eruption, the phreatic explosions and major generation of mudflows are inferred to have occurred in the first few hours to months after the emplacement of the Taupo ignimbrite. However, subsequent mudflow activity and stream reworking of deposits may have continued for years to decades until the vegetation cover was re-established. In the overall chronology of the eruption, the significant point is that most of the secondary deposits appear to have been generated very shortly after the Taupo ignimbrite and hence are inferred to predate the eruption and emplacement of the floated giant pumices.

6. Overview

The Taupo eruption was the largest event at the Taupo Volcanic Centre since the 20000 years B.P. event, and much can be learned from it with regard to the future activity of the volcano.

A first point is that the nature of any future event cannot be predicted except in general terms. In past eruptions, the volume of magma erupted shows no obvious systematic change with time (figure 17) and the periods between eruptions show no clear correlation with the

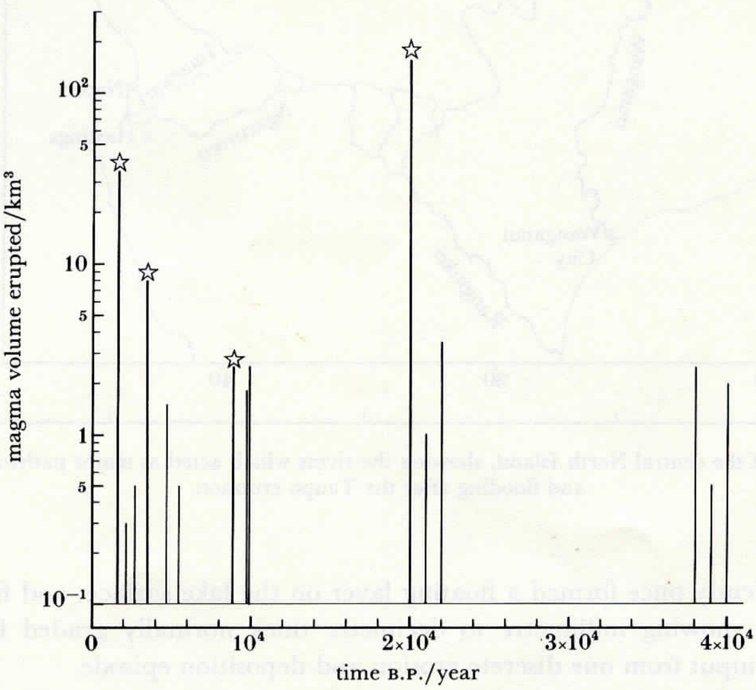


FIGURE 17. Explosive activity at the Taupo Volcanic Centre from *ca.* 40000 years B.P. (^{14}C ages) to the present, showing approximate magma volumes erupted. Magma volumes for eruptions other than those at 1800 years (this paper), 3400 years (Walker 1981*b*) and 20000 years B.P. (Self 1983) are estimated by using the relationships between magma volumes derived from crystal concentration studies (see, for example, Walker 1980) and bulk volumes for the deposits derived from isopach data presented in Vucetich & Pullar (1973) and Vucetich & Howorth (1976). Stars mark eruptions where significant quantities of ignimbrite were generated. (N.B. At least one other post-20000 years B.P. ignimbrite has been found by us, but it has not yet been tied down to a particular eruption.)

size of either the preceding or the following eruptions (figure 18). Thus neither the time to the next eruption, nor the volume that will be erupted can be predicted with any confidence.

The style of any future eruption can be considered in part. As the vents for all the major explosive eruptions of the last 20000 years now lie in Lake Taupo, it seems likely that phreatomagmatic activity will play some role in the next eruption. Ignimbrite has been

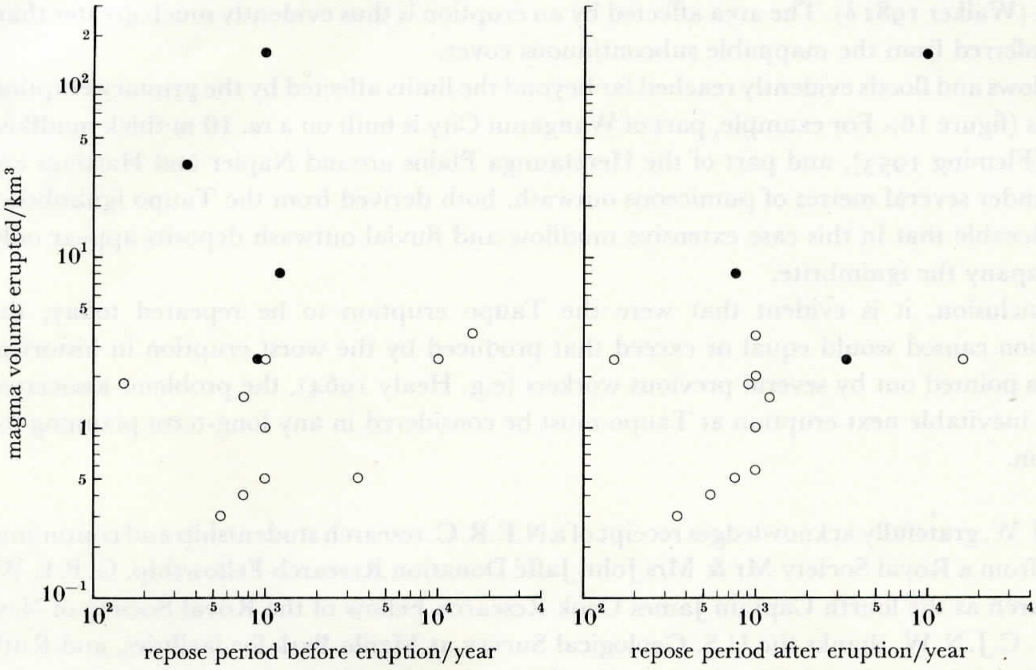


FIGURE 18. Magma volume erupted against repose period before or after the relevant eruption, for explosive activity during the past *ca.* 40000 years at the Taupo Volcanic Centre (data from figure 17). Filled symbols denote eruptions which generated significant quantities of ignimbrite.

produced in at least five of the ten explosive eruptions from 20000 years B.P. to date (authors' unpublished data), and four of the ignimbrites formed during the four largest eruptions (figure 17). Minor dome-building activity could occur on land as occurred at Acacia Bay, just southwest of Taupo township, about 9900 years B.P. Froggatt (1981 *b*) has proposed that the Acacia Bay dome marks the vent location for the moderate volume Karapiti plinian eruption, but our unpublished grainsize data from the plinian fall deposit clearly demonstrate that it was erupted from an unrelated vent now within the modern Lake Taupo.

The duration of any eruption cannot be predicted. Several of the smaller sub-plinian eruptions may have occupied only a few hours, whereas others, such as the Taupo and 20000 years B.P. events, may have lasted for months.

The intensity of eruptions may vary widely. During the Taupo eruption, the inferred eruption rate varied over more than four orders of magnitude (figure 12), some of the changes being very abrupt. Like the eruption volume, there seems to be no *a priori* means by which the eruption rate, with its strong control on the nature and distribution of the eruption products (Sparks & Wilson 1976; Walker 1980; Wilson & Walker 1981) can be predicted. To illustrate this, probably all of the airfall phases of the Taupo eruption could have been watched in safety from atop the Karangahape Cliffs (figure 2), only about 15 km west of the event, but the climactic pyroclastic flow then swept over the area at a velocity which, to judge by the sizes of hills climbed by the flow in that direction, probably exceeded 200 m s^{-1} (Paper II, figure 2).

Sporadic outcrops of thin pyroclastic deposits occur far beyond the limit of subcontinuous cover. Ash from the Taupo eruption has thus been recorded from deposits tens to hundreds of kilometres beyond the area of the mapped eruption products (see, for example, Elder 1965; Pullar 1970; Hubbard & Neall 1980; Lowe *et al.* 1980), and similarly for ash from the Waimihia eruption (Walker 1981 *b*). The area affected by an eruption is thus evidently much greater than can be inferred from the mappable subcontinuous cover.

Mudflows and floods evidently reached far beyond the limits affected by the primary eruption materials (figure 16). For example, part of Wanganui City is built on a *ca.* 10 m thick mudflow terrace (Fleming 1953), and part of the Heretaunga Plains around Napier and Hastings are buried under several metres of pumiceous outwash, both derived from the Taupo ignimbrite. It is noticeable that in this case extensive mudflow and fluvial outwash deposits appear only to accompany the ignimbrite.

In conclusion, it is evident that were the Taupo eruption to be repeated today, the devastation caused would equal or exceed that produced by the worst eruption in historical times. As pointed out by several previous workers (e.g. Healy 1964), the problems associated with the inevitable next eruption at Taupo must be considered in any long-term planning for the region.

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