

Paleoseismicity of the Rotoitipakau Fault Zone, a complex normal fault in the Taupo Volcanic Zone, New Zealand

KELVIN BERRYMAN

SARAH BEANLAND*

Institute of Geological & Nuclear Sciences
P.O. Box 30 368
Lower Hutt, New Zealand

STEVEN WESNOUSKY

Department of Geological Sciences
University of Nevada
Reno, Nevada 89557, USA

Abstract Trenching of 6 of the 10 fault strands that comprise the 5 km long, 1 km wide Rotoitipakau Fault Zone, Taupo Volcanic Zone, New Zealand, shows that surface rupture has occurred at least eight times in the zone during the past 8500 yr. Single-event displacements on each strand vary from a few decimetres to perhaps more than 2.5 m, and there may have been as much as 4.5–5.0 m of cumulative slip on several strands in a single event. Five airfall tephra whose ages span the past 8500 yr provide time lines within which cumulative slip rate has varied by approximately 10 times: from 1–2.5 mm/yr in the period from the AD 1886 Tarawera Tephra to the present, and in the c. 4000 yr period from the 4.8 ka Whakatane Tephra to the 0.65 ka Kaharoa Tephra; to 11 mm/yr in the c. 500 yr period from 0.65 ka to AD 1886. All but one of the fault strands are downthrown to the southeast, suggesting that the fault zone is part of the western margin of the Whakatane Graben. This short fault zone may therefore be a splay of the Braemar Fault Zone, and the very large displacement:length ratios characteristic of fault rupture in this fault zone may be misleading if the fault connects to the southwest with the Braemar Fault. Alternatively, faults in this volcano-tectonic province may exhibit different surface faulting characteristics than normal faults in nonvolcanic regions where most of the fault parameter scaling relationships have been developed. Large displacement:length ratios are a characteristic of fracturing above dike intrusions. Such fracturing is accompanied by well-defined grabens and single-episode (monogenetic) formation. In the Rotoitipakau Fault Zone, the lack of graben development, and polygenetic movement history, indicates the fault zone is a primary tectonic feature.

Keywords normal fault; earthquake geology; paleoseismicity; Taupo Volcanic Zone; Whakatane Graben

INTRODUCTION

The Rotoitipakau Fault Zone comprises a complex suite of fault strands in the northeastern part of the Taupo Volcanic Zone (TVZ) of the North Island, New Zealand. The TVZ is characterised by a chain of arc volcanoes, coalescing backarc caldera volcanoes, and pervasive arc-parallel normal faulting (Fig. 1). We examine this fault zone because there was triggered slip on three of its strands in the 1987 Edgecumbe earthquake (Beanland et al. 1989), and because it became apparent that, in this compact but complex fault zone, no one strand of the fault represents the complete rupture history. Late Quaternary stratigraphy of the region includes sequences of airfall tephra that are, in places, tens of metres thick, the spatial extent and chronology of which have been extensively studied (Vucetich & Pullar 1964, 1969; Vucetich & Howorth 1976; Froggatt & Lowe 1990). These sequences provide age control and a rare opportunity to determine a detailed paleoearthquake history for a normal fault zone characterised by multiple, subparallel strands.

The Rotoitipakau Fault Zone is within the 30 km long and 15 km wide Whakatane Graben at the northeastern onshore part of the TVZ between the Okataina Volcanic Centre and the Bay of Plenty coast (Fig. 1). We define the fault zone as the compact, c. 5 km long and 1 km wide suite of fault strands striking about 055°, and located approximately in the central part of the Whakatane Graben. To the southwest, with a gap of 2–4 km, are more faults that are part of the Braemar Fault Zone. To the northeast, but not directly along strike, are the Otakiri, Onepu, and Edgecumbe scarps that ruptured in the 1987 Edgecumbe earthquake (Fig. 1). Within the Rotoitipakau Fault Zone there are about 10 fault strands (Fig. 2), each of which is less than 3 km long, and some have scarps that are up to 30 m in height. Where streams have cut through the larger scarps, offsets of the younger alluvial valley floors are 1–5 m, indicating repeated movement of the faults through late Quaternary time (Fig. 3).

Trenches were excavated across six strands of the fault zone at sites in young alluvial valleys where scarp heights are in the range of 1–5 m. Trenches averaged c. 15 m long, 4 m wide, and 4 m deep. Trench walls were cleaned, and the wall most clearly showing faulting relationships was marked with a 1 m string grid and logged at 1:20 scale. Trench sites are labelled according to the particular fault strand, A through F, as indicated on Fig. 2. A more detailed description of the stratigraphy shared by the trenches and logs of the individual trench exposures is presented in the next section and followed by a summary and discussion of the results.

GEOLOGY AND STRATIGRAPHY OF THE FAULT ZONE

The late Quaternary geology of the Rotoitipakau Fault Zone is dominated by the accumulation of the unwelded ignimbrite

*Deceased.

G98021

Received 25 June 1998; accepted 3 November 1998

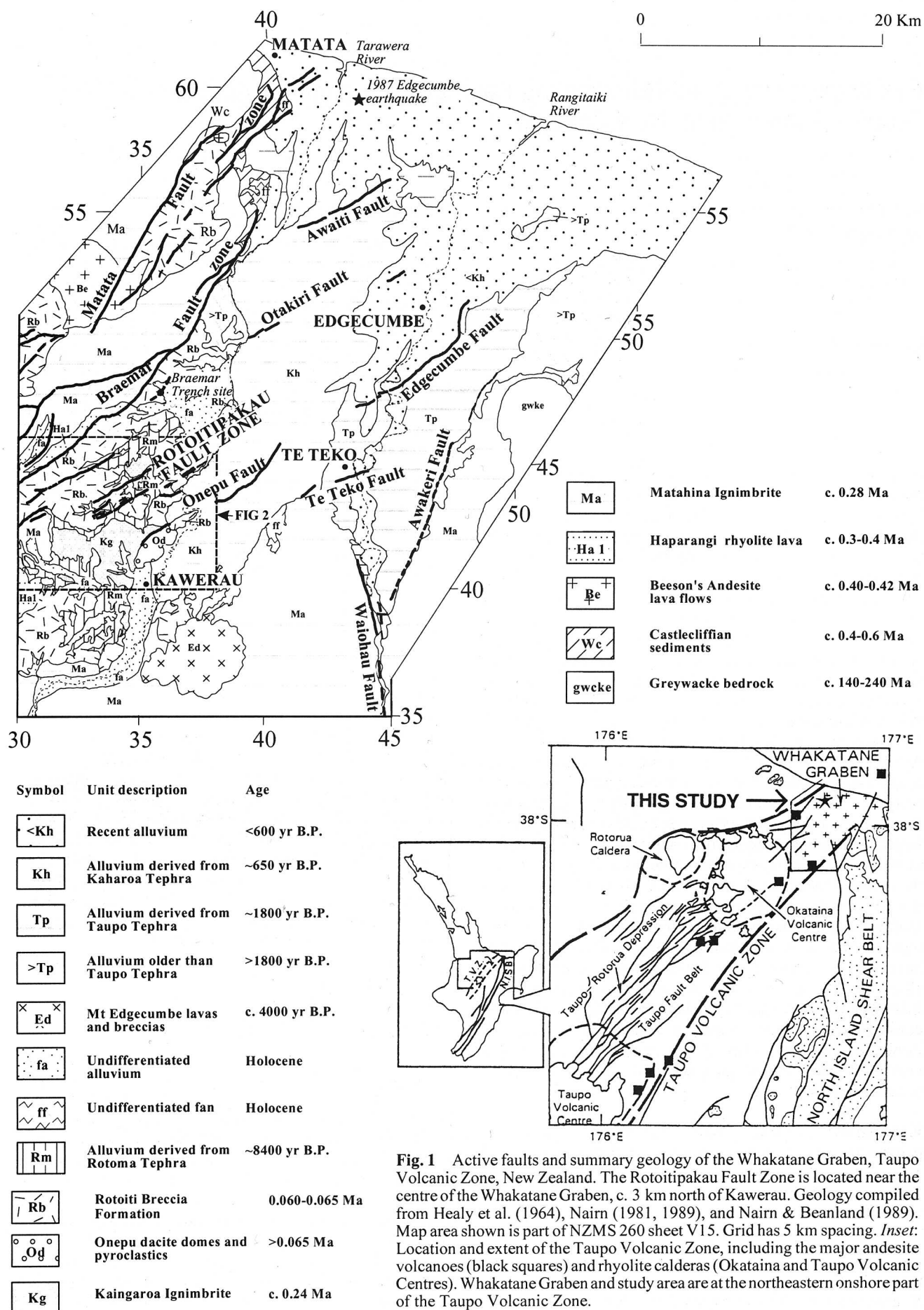


Fig. 1 Active faults and summary geology of the Whakatane Graben, Taupo Volcanic Zone, New Zealand. The Rotoitipakau Fault Zone is located near the centre of the Whakatane Graben, c. 3 km north of Kawerau. Geology compiled from Healy et al. (1964), Nairn (1981, 1989), and Nairn & Beanland (1989). Map area shown is part of NZMS 260 sheet V15. Grid has 5 km spacing. *Inset:* Location and extent of the Taupo Volcanic Zone, including the major andesite volcanoes (black squares) and rhyolite calderas (Okataina and Taupo Volcanic Centres). Whakatane Graben and study area are at the northeastern onshore part of the Taupo Volcanic Zone.

Fig. 2 Rotoitipakau Fault Zone showing fault strands and trench sites A–F. The downthrown side of faults is shown by the bar and ball symbol. The upland area in the vicinity of the fault zone are the eroded remnants of the pyroclastic flows of the c. 65 ka Rotoiti Tephra Formation. Valley floors are underlain by reworked material of the c. 8.5 ka Rotoma Tephra Formation. Hot springs and drillholes in the Kawerau geothermal field, where greywacke basement has been intersected at c. 1 km subsurface, are indicated by crosses and filled circles, respectively. Map area and 1 km grid are part of NZMS 260 sheet V15.

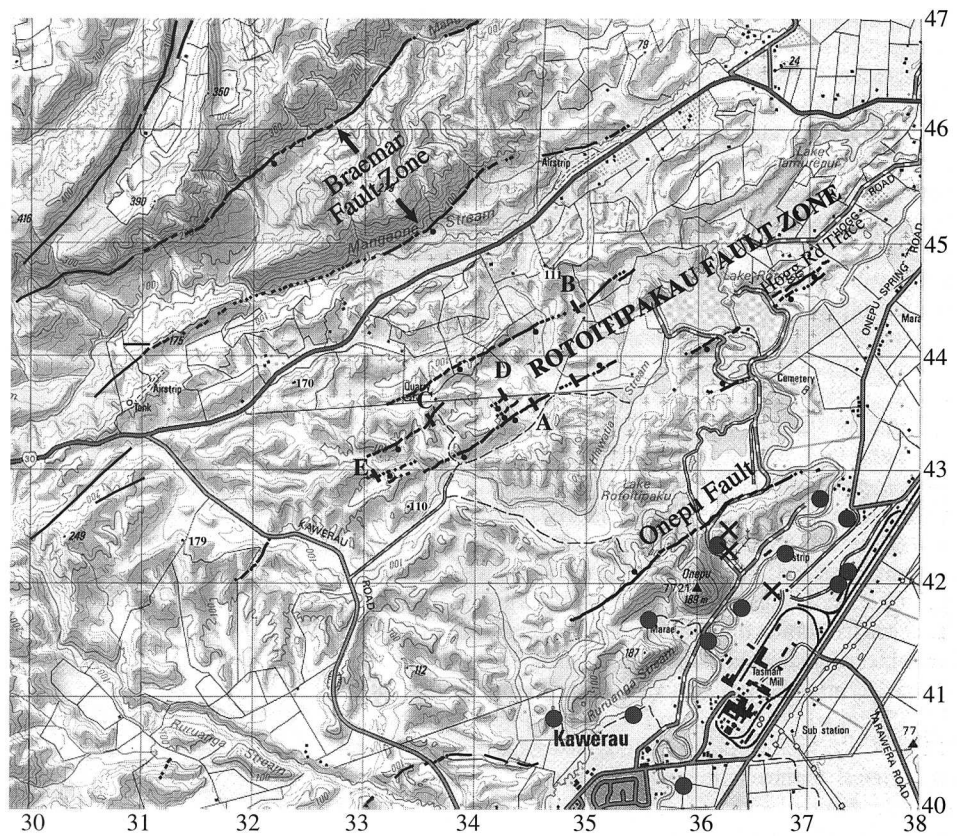
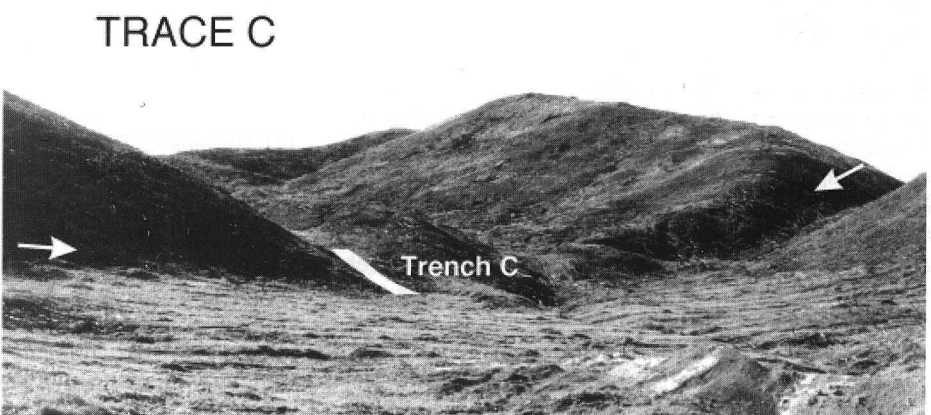


Fig. 3 View of trace C, showing the location of trench C across a c. 6 m high scarp in a steep gully floor. The larger scarp is c. 10 m high in Rotoiti Tephra Formation deposits.



(Rotoiti Breccia) component of the Rotoiti Tephra Formation (Froggatt & Lowe 1990), which was erupted from the Okataina Volcanic Centre (Nairn 1981) (Fig. 1). Ages of the Rotoehu Ash, the plinian airfall component of the eruption, are in the range of 60–65 ka (Ota et al. 1988; Wilson et al. 1992) (Table 1). In the study area, the ignimbrite is c. 80–100 m thick. The upper surface (plus mantling younger airfall tephra deposits) forms the upland at 100–170 m elevation (Fig. 2), into which subsequent streams have cut.

Airfall tephra

Stratigraphically above the Rotoehu Ash are members of the Mangaone Subgroup, comprising up to 10 m of coarse, white, shower-bedded pumice lapilli that have been dated at in the range 28–45 ka (Froggatt & Lowe 1990). The

Mangaone Tephra deposits are preserved only on the upland surface.

The oldest tephra that occurs within the low-level valley system (Fig. 3) is the Rotoma Tephra, which is an c. 2 m thick airfall deposit of ash and lapilli. The top of the Rotoma Tephra is a characteristic dark blue-grey, resulting from incorporation of finely disseminated charcoal. The occurrence of Rotoma Tephra within the low-level valley system indicates that dissection of the Rotoiti Breccia upland mainly predated eruption of the Rotoma Tephra. The Rotoma eruption also triggered significant erosion and deposition, and our trenches and natural exposures in the area reveal several metres of reworked Rotoma ash and lapilli within the low-level valleys above the airfall Rotoma. This widespread erosive and depositional event has resulted in wide, flat valley floors.

The tephra has a weighted mean age of 8530 ± 10 yr BP (Froggatt & Lowe 1990).

Mamaku Tephra, generally c. 1 m thick, overlies Rotoma Tephra. This airfall tephra grades upwards from pebble-sized shower-bedded lapilli to a massive sandy ash. It is increasingly weathered upwards to an orange-brown colour, reflecting soil development before the deposition of the overlying Whakatane Tephra. Mamaku Tephra has a weighted mean age of 7250 ± 20 yr BP (Nairn 1981; Froggatt & Lowe 1990). Whakatane Tephra overlies Mamaku Tephra and is similar in thickness, colour, grain size, and weathering, but the two tephra are separated by a weak, yellow-brown paleosol. Whakatane Tephra has a weighted mean age of 4830 ± 20 yr BP (Froggatt & Lowe 1990).

The upper part of the airfall tephra sequence consists of two young tephra with rather different physical appearance from the early to mid Holocene-age tephra. The older of the two is Kaharoa Tephra, an unweathered, white, pumiceous, shower-bedded unit, commonly with a fine white basal ash, overlain by up to 0.4 m of sandy ash. It has a weighted mean age of 665 ± 15 yr BP (Lowe et al. 1998). The uppermost Tarawera Tephra is up to 0.4 m thick, consisting of basaltic fine black scoria and ash erupted from Mt Tarawera in AD 1886.

Soils and paleosols

Each airfall tephra unit upwardly grades into a paleosol, which is typically characterised by a dark yellow-brown sandy silt loam. Exceptions to the yellow-brown colour of paleosols are the charcoal-rich blue-black colours of the Rotoma paleosol, and the black organic-rich soil developed on the Kaharoa Tephra. The modern topsoil has developed from the AD 1886 Tarawera Tephra and is characterised by an organic-rich black horizon that is up to 0.4 m thick. In places where there has been alluviation on the downthrown side of the scarp, or erosion of the scarp, a soil in the footwall block may be a partial correlative with several soil horizons in the hanging wall. One would expect that the single polygenetic soil of the footwall would be more strongly developed than the partial soils formed on intervening units on the downthrown side. However, soil colour and texture develops very rapidly in the volcanic ash parent materials in the study area, so the visual appearance of the polygenetic soil (often developed within a few hundred years) is not much different to the smaller mongentic soils of the hanging wall. Chemical analysis may demonstrate the maturity of the various types of soils, but that is beyond the scope of this study.

Alluvium and colluvium

In the excavated trenches, and in adjacent exposures, a variety of redeposited and reworked ash and lapilli units

were exposed. They have been distinguished from the primary, airfall-bedded tephra units by bedding, sorting, and mixing characteristics. We also distinguish between alluvium, which has characteristics of being deposited by water, and colluvium, which appears to have been deposited as mass movement or soil creep on steep slopes. Whereas the alluvial units are well stratified and well sorted within beds, the colluvial units tend to be more massive in structure and poorly sorted.

PALEOSEISMOLOGY OF THE ROTOITIPAKAU FAULT ZONE

During the 1987 Edgecumbe earthquake, small, 0.05–0.3 m, normal separation displacements were recorded on two strands of the Rotoitipakau Fault Zone (Beanland et al. 1989). Trenching studies revealed that these ruptures coincided exactly with the positions along faults associated with much larger offsets of the Holocene tephra horizons. We interpret these small displacements as triggered slip events as described by Yeats et al. (1997, p. 286). These ruptures appeared at distances of 2–5 km from the closest primary rupture of the Edgecumbe earthquake.

Criteria for determining paleoseismic events

The criteria for determining prehistoric fault rupture have developed rapidly in the period since fault trenching studies began about 20 yr ago, although Gilbert (1890) recognised many of the essential elements of active normal faults in the Basin and Range province of western United States late last century. In trenches excavated to decipher the history of surface fault rupture on normal faults, some of the key observations are listed below. Several of these criteria relate to the special circumstances that arise in relation to deposition and displacement of airfall tephra units.

- (1) The upper termination of the fault plane, either at the ground surface or buried by young stratigraphic units, provides an important constraint on the time of the last event.
- (2) Normal faults are typically steeply dipping when they reach the ground surface in alluvial deposits, and the exposed surface fault scarp is prone to erosion (Fig. 4). Recognition of this erosion and the resultant formation of colluvial sediments, as scarp-derived colluvial wedge units that taper away from the fault, is based on seminal work of Wallace (1977). Scarp degradation models predict that, as a first approximation, the maximum thickness of the scarp-derived colluvium is half the height of the free face, and that the thickness of the wedge is a limiting minimum scarp height.

Table 1 Tephra formations of the geology of the Rotoitipakau Fault Zone.

Tephra formation	Age (yr BP)	References
Tarawera Tephra	AD 1886	
Kaharoa Tephra	665 ± 15	Lowe et al. 1998
Whakatane Tephra	4830 ± 20	Froggatt & Lowe 1990
Mamaku Tephra	7250 ± 20	Nairn 1981; Froggatt & Lowe 1990
Rotoma Tephra	8530 ± 10	Froggatt & Lowe 1990
Mangaone Tephra	28 000–45 000	Froggatt & Lowe 1990
Rotoiti Tephra	60 000–65 000	Ota et al. 1988; Wilson et al. 1992*

*Fission track, and bracketing Ar-Ar ages, respectively.

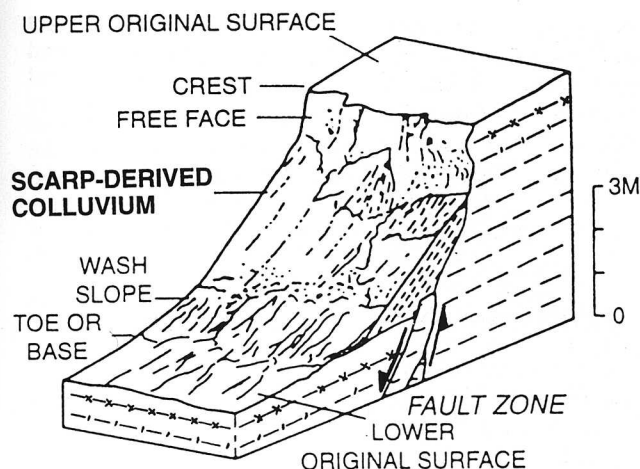


Fig. 4 Conceptual diagram of a degrading normal fault scarp in unconsolidated deposits showing the erosion and burying of a free face and accumulation of a scarp-derived colluvium. Colluvium covers the upper termination of the fault plane. (Adapted from Wallace 1977)

- (3) Thickness variations in alluvium across the fault plane are a good measure of the displacement. Alluvium and, to some extent, airfall tephra tend to flatten the fault topography, so thicker deposits on the downthrow side of the fault suggest burial of an already existing fault scarp.
- (4) Identifying the provenance of the materials making up scarp-derived colluvial wedges provides a means of establishing which stratigraphic units in the footwall have been exposed to erosion, and thus provides some constraint on the size of individual displacements.
- (5) Airfall tephra units can mantle pre-existing scarps, but if the buried scarp is steeper than the angle of repose of the unconsolidated materials (c. $\geq 30^\circ$), then the tephra may be discontinuous across the scarp, and appear to be displaced. On older, degraded fault scarps the tephra are more likely to be attenuated across the fault. If the tephra are not attenuated in close proximity to the fault plane they can be assumed to have been covered by another unit before faulting, and the faulting was not sufficiently large to expose the tephra unit to erosion on the face of the newly created scarp.
- (6) Evidence for progressive displacement is a key criterion to identify multiple displacement events in a trench.
- (7) Vertical accretion of stratigraphic units may occur in some instances due to far-field effects (such as volcanic eruption or alluvial sedimentation), whereas some are generated in the near-field, such as by fault rupture (e.g., scarp-derived colluvial wedges). In all of these situations, the presence of soils (paleosols) between stratigraphic units represents former ground surfaces. Reconstructing the sequence of events by restoring the displacement of former ground surfaces (paleosols) is a powerful tool for differentiating surface faulting events and resulting scarp erosion from far-field accretionary processes.

Trenches in the Rotoitipakau Fault Zone

Logging and interpretation of the timing of paleoseismic events in the six trenches excavated in this study provides a

basis for evaluating the rupture history of each of the strands of the Rotoitipakau Fault Zone. We then integrate the rupture history of each of the strands of the fault zone (see Fig. 12) to establish the characteristics of rupture of this complex normal fault.

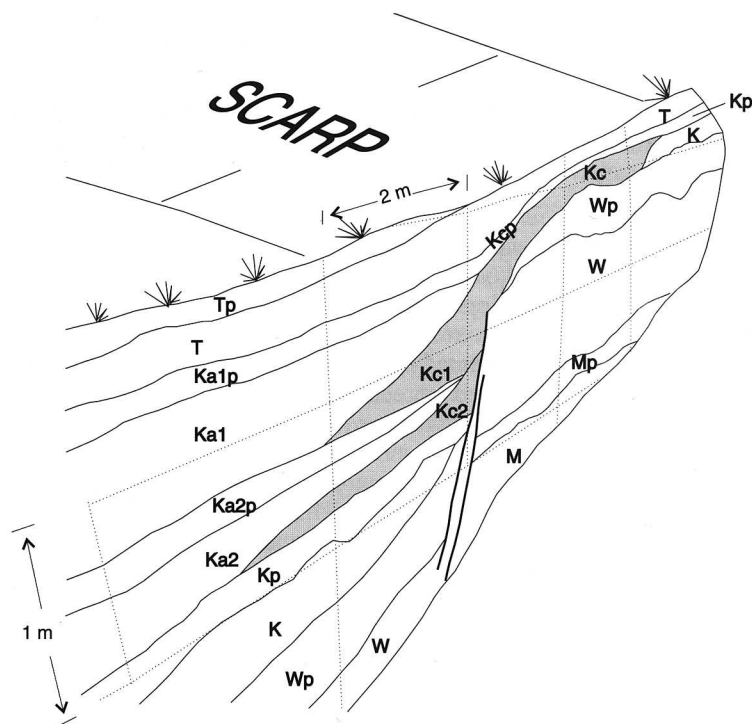
Trace/trench A Trace A is the main, c. 2 km long fault on the southeastern side of the Rotoitipakau Fault Zone (Fig. 2). It forms a southeast-facing scarp up to 30 m high across the c. 65 ka upland composed of Rotoiti Tephra Formation. Trench A was excavated toward the northeastern end of the trace where it crosses a flat-floored valley where the scarp is c. 2 m high. The excavation revealed a southeast-dipping normal fault and a stratigraphic sequence covering the past c. 7000 yr (Fig. 5, 6A). On the upthrown side of the fault the oldest unit exposed is Mamaku Tephra (unit M) in which a weak paleosol (unit Mp) has formed. Above this paleosol, 4.8 ka Whakatane, 0.6 ka Kaharoa, and AD 1886 Tarawera Tephra are in stratigraphic order (Fig. 6A). On the downthrown side of the fault the paleosol on (presumably) Mamaku Tephra was reached in auger holes (Fig. 6A). Exposed in the trench wall on the downthrown side were the upper part of the Whakatane Tephra (unit W) and a sequence of Kaharoa Tephra (unit K), Kaharoa-derived alluvium (unit Ka), two Kaharoa-derived colluvial units (units Kc1, Kc2), and intervening paleosols. The Tarawera Tephra (unit T) and a modern topsoil are well preserved on the downthrown side, but on the upthrown side the topsoil has been stripped and the Tarawera Tephra is exposed at the ground surface.

Three surface-faulting events are interpreted from this trench. The events are recognised as two scarp-derived colluvial units and larger displacement of the paleosol developed on Mamaku Tephra (c. 5–7.2 ka) once the younger events are removed (Fig. 6A–D). The youngest event is represented by colluvial wedge unit Kc1 (Fig. 6A) and occurred more recently than the Kaharoa eruption (665 ± 15 cal. BP) because the colluvium is composed of Kaharoa airfall material. Fault displacement of 0.6 m of dip-slip movement is required to restore the pre-event ground surface (i.e., continuity of soil horizon Ka2p with Kcp of the upthrown side, Fig. 6B). The combined thickness of units Ka1p and Kc1 that formed in response to the faulting is also c. 0.6 m.

The penultimate event, represented by colluvial wedge Kc2, is also younger than Kaharoa Tephra. The wedge is composed of Kaharoa-derived material and the eroded material from the Whakatane paleosol on the upthrown side. The wedge was deposited on top of a soil (Kp) that had formed on Kaharoa airfall (Fig. 6B). Removal of the penultimate event by restoring the paleosol in the Kaharoa airfall unit requires 0.55 m of dip-slip movement (Fig. 6C). Removal of the penultimate event also restores the paleosol on Whakatane airfall (unit Wp), indicating no fault rupture for some time before Kaharoa deposition (0.6–74.0 ka). A third event of up to 0.5 m dip-slip is required to restore the paleosol in Mamaku-derived alluvium (Fig. 6D). This third event appears to be coincident with (immediately before) the eruption of Whakatane Tephra (because there is no evidence of erosion of the paleosol on Mamaku on the upthrown side of the fault and no evidence of a Whakatane-derived colluvium). The Whakatane Tephra thickness (airfall plus paleosol) is c. 0.2 m thicker on the downthrown side, consistent with thicker accumulation in the lee side of a newly formed scarp.



Fig. 5 Oblique photograph and line drawing of trench A. The grid lines are 1 m apart vertically and 2 m apart horizontally. Units are tephra (capital letters), paleosols (p), alluvium (a), and colluvium (c). T, Tarawera Tephra; K, Kaharoa Tephra; W, Whakatane Tephra; M, Mamaku Tephra. For example, Tp = paleosol developed in Tarawera Tephra, Ka = alluvium derived from Kaharoa Tephra, Kap = paleosol developed in Kaharoa-derived alluvium, Kc1 = colluvial unit 1 derived from and stratigraphically above Kaharoa Tephra.



Trace/trench B Trace B is a 2.5 km long, southeast-facing scarp on the western side of the fault zone (Fig. 2). The trace was trenched in a gully floor near the northern end of the fault strand where the scarp was c. 4 m high. A 0.2 m displacement occurred here in the 1987 Edgecumbe earthquake. On the upthrown side, the trench exposed redeposited Rotoma Tephra and a severely truncated and eroded sequence of airfall tephra, colluvium, and intervening paleosols (Fig. 7A). Tarawera Tephra is fairly continuous along the trench exposure, but on the upthrown side the paleosol below this is a composite of the Kaharoa and Whakatane paleosols (units Kp+Wp). The fault comprises one distinct throughgoing plane and a c. 0.3 m wide zone of numerous small fractures and shears. The 1987 rupture clearly occurred on the principal

fault plane and extended through the previously unfaulted Tarawera Tephra (AD 1886). On the downthrown side, the oldest unit exposed is a poorly sorted unit interpreted to be scarp-derived colluvium (Wc). A paleosol (Wcp) has developed in the top of this unit, which in turn is overlain by Kaharoa Tephra (Fig. 7A). We therefore interpret the colluvial unit (Wc) as derived from Whakatane Tephra, equivalent to a similar unit on the upthrown side. Both alluvial and colluvial Kaharoa-derived units occur on the downthrown side, overlain by Tarawera Tephra and the modern topsoil.

Three surface-faulting events are interpreted from the stratigraphic relationships exposed in trench B (Fig. 7B, C). The most recent was a 0.2 m displacement associated with the 1987 Edgecumbe earthquake. Restoring this displacement

Event Horizons

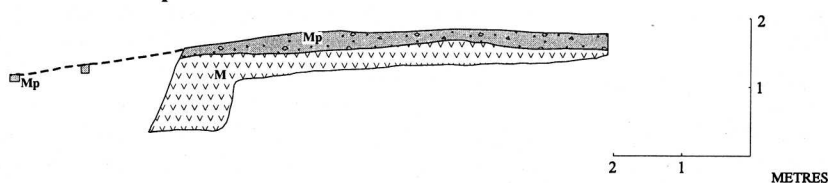
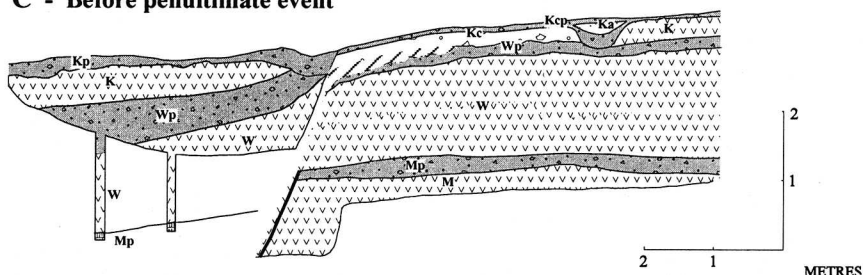
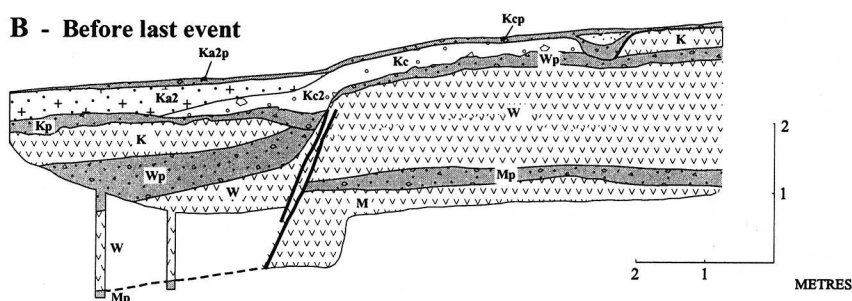
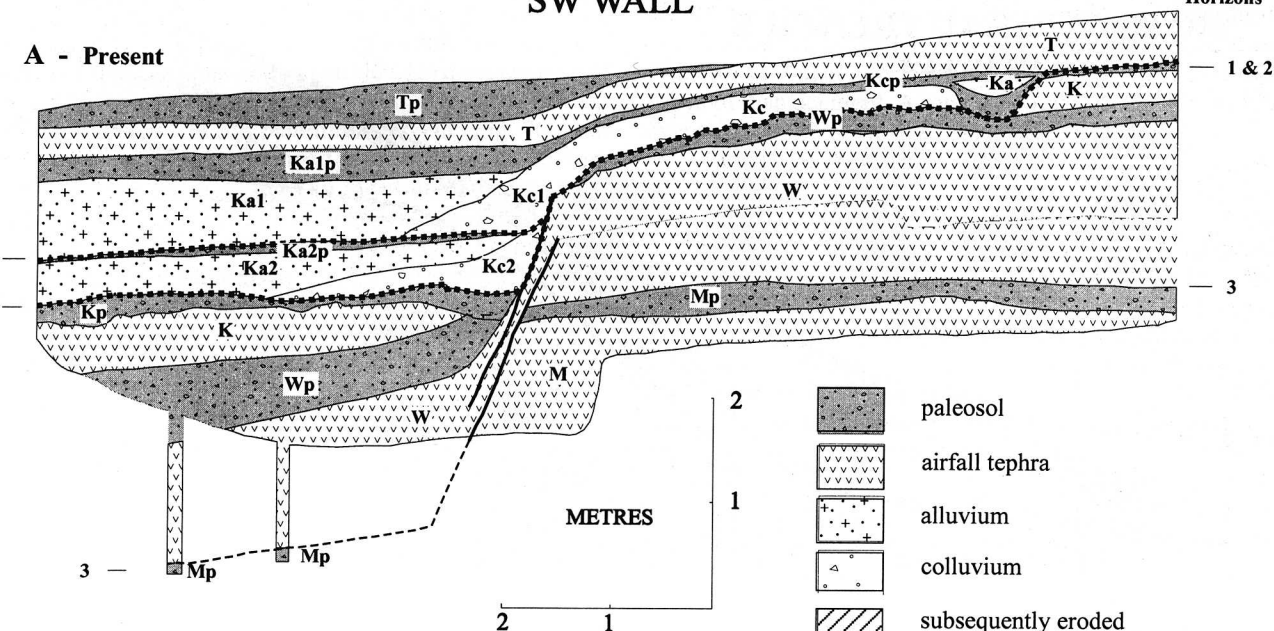


Fig. 6 **A**, Log of trench A showing stratigraphic horizons (tephra, paleosols, alluvial and colluvial units as for Fig. 5), and interpreted event horizons. **B**, Inferred stratigraphic relationships before the most recent event (i.e., event 1 removed). The restoration relies on recognising paleosols as former ground surfaces and restoring these as continuous horizons. **C**, Inferred stratigraphic relationships before the penultimate event (i.e., two events removed). **D**, Inferred stratigraphic relationships before the antepenultimate event (i.e., three events removed).

ROTOITIPAKAU TRENCH B SW WALL

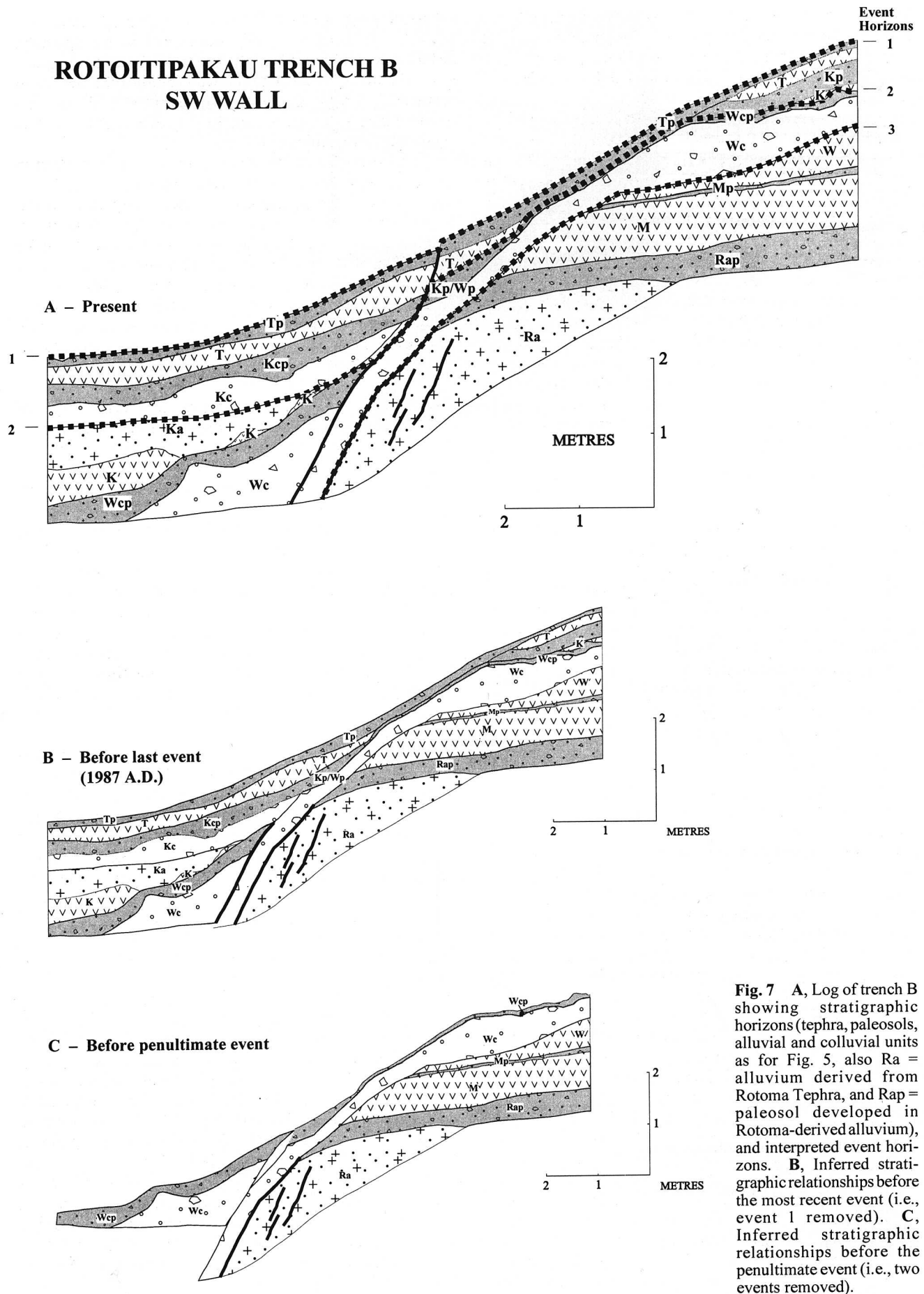


Fig. 7 A, Log of trench B showing stratigraphic horizons (tephra, paleosols, alluvial and colluvial units as for Fig. 5, also Ra = alluvium derived from Rotoma Tephra, and Rap = paleosol developed in Rotoma-derived alluvium), and interpreted event horizons. B, Inferred stratigraphic relationships before the most recent event (i.e., event 1 removed). C, Inferred stratigraphic relationships before the penultimate event (i.e., two events removed).

brings the paleosols developed in Tarawera airfall and Kaharoa colluvium into juxtaposition. The penultimate event is recognised by three observations: (1) the presence of a colluvial wedge (Kc) above Kaharoa airfall; (2) erosion of Kaharoa Tephra from the upthrown side; (3) displacement of the paleosol in the Whakatane-derived colluvium (Wcp). Removing unit Kc in the penultimate event (Fig. 7C) and restoring the paleosol developed in Whakatane colluvium (Wcp) requires 1.5 m of dip-slip movement. The event is thus post-Kaharoa in age. A third event is recognised by the presence of a thick colluvial wedge derived from Whakatane Tephra (unit Wc). Judging by the thickness of the paleosol developed in the Whakatane colluvium (Wc) on the downthrown side of the fault, it seems likely that the faulting event occurred soon after deposition of the Whakatane Tephra. The amount of displacement in this event cannot be accurately reconstructed, but assuming that the Whakatane colluvium overlies Whakatane airfall on the downthrown side, and this in turn was deposited on a Mamaku paleosol (as the stratigraphy of the upthrown side suggests), then the minimum displacement in this post-Whakatane event is ≥ 2.4 m, determined by juxtaposing the lowest, exposed part of the Wc unit with the Mamaku paleosol.

Trace/trench C Trace C has a throw of c. 10 m in the Rotoiti Breccia Formation surface (Fig. 2). The trench was excavated across a 6 m high scarp in a steep, V-shaped gully floor. The trench could not be excavated to the crest of the scarp, and it is possible that other faults occur higher in the footwall. A complex of airfall units, separated by paleosols and several colluvial units, was exposed in the trench (Fig. 8A). The Rotoma airfall unit is severely disrupted by fissuring on the upthrown side. The fault is expressed as one clear principal plane, although there is also a probable older plane that displaces the Rotoma paleosol (Rp) and forms a free face in Mamaku airfall (M). There are also small faults in the hanging wall with both normal and reverse separation.

Three faulting events in the past c. 8500 yr are interpreted from this trench. This conclusion is reached by backstripping successive events as with other trenches. This conclusion is perhaps surprising in that three colluvial units were exposed in the trench, but only two of the colluvial units (Kc and Mc) appear to have been deposited as scarp-derived units in the lee of a newly formed scarp, whereas one of the units (Wc) occurs as a substantial unit on both sides of the fault. The widespread nature of unit Wc suggests widespread slope erosion processes were triggered at this site by deposition of Whakatane Tephra, or that the colluvium is generated by another fault farther back in the footwall.

The most recent event is represented by the colluvial unit Kc that is younger than Kaharoa Tephra. Removal of this unit and restoration of the Whakatane paleosol (Fig. 8B) by 1.5 m of dip-slip movement brings the paleosol (Rp) in Rotoma Tephra into juxtaposition also, indicating no further fault displacement on this fault plane in the interval from Kaharoa to some time in the Rotoma/Mamaku interval (c. 660 to <c. 8400 yr).

The penultimate event was on the second fault plane and is represented by the colluvial unit Mc and the free-face scarp in airfall Mamaku Tephra. Removal of unit Mc and restoration of the paleosol Rp indicates c. 0.4 m of dip-slip motion in this event, which was younger than Mamaku Tephra, but

substantially older than Whakatane Tephra, because the Mamaku paleosol is equally developed in the Mamaku airfall and colluvium (Fig. 8C). The small faults that displace airfall Mamaku in the hanging wall, but not the overlying sequence, probably formed in this event as well and had 0.3 m of displacement. A total dip-slip displacement in this event was of the order of 0.7 m.

At least one prior event is recognised by disruption in Rotoma Tephra of the airfall bedding on the footwall. The fissuring does not extend up into the overlying Mamaku Tephra, and we therefore infer this represents a third event, some time in the interval between Rotoma and Mamaku Tephra (Fig. 8D), probably soon after Rotoma Tephra because the paleosol developed in disturbed Rotoma (Rd) is well developed. The fault rupture responsible for the disruption and fissuring in airfall Rotoma is not exposed in our trench, and thus we can make no estimate of the displacement in this event.

Trace/trench D Trace D is mapped for a strike length of only 200 m or so but has a scarp that is c. 3 m high across the flat floor of a wide gully (Fig. 2). The trench was sited at the break in slope at the edge of the gully because of a fence (property boundary) and limited access in the gully floor. Trace D is approximately along-strike of trace E.

At this site, thick, unfaulted Tarawera Tephra (T) and post-Kaharoa colluvium (Kc) overlie the fault plane (Fig. 9A). Kaharoa and Whakatane Tephra are discontinuous, and Mamaku Tephra has been deposited on eroded airfall Rotoma. The sharp angular unconformity between horizontal airfall bedding in Rotoma Tephra (R), and inclined airfall bedding in Mamaku Tephra (M) is striking. A further key feature in determining the timing of past faulting events is the recognition of the paleosol developed in Rotoma (unit Rp) that is preserved across the truncated Rotoma airfall.

Two faulting events are recognised, one in the interval between Whakatane and Kaharoa deposition (c. 660–4800 yr), and the second between Rotoma and Mamaku deposition (7200–8400 yr). It is possible that unit Kc represents a scarp-derived colluvium from a fault farther back in the footwall, and this would be consistent with the timing of a fault rupture on the co-linear trace E. However, it is also possible that unit Kc represents a blanket colluvium resulting from landscape instability after the deposition of Kaharoa Tephra. The most recent certain event is seen as the small scale fault displacements that extend up through Whakatane Tephra. Other ruptures do not extend to the same level but are sympathetic to the principal normal fault plane and only appear to rupture upwards to a level to accommodate space requirements. Restoring the normal displacement on the principal fault and the sympathetic ruptures in the hanging wall indicates 0.35 m dip-slip displacement, and this brings into juxtaposition the paleosols (Mp and Rp) developed in Mamaku and Rotoma Tephra (Fig. 9B). The displacement in the second event cannot be determined from our trench because we did not expose the fault plane. However, the event must have occurred soon after deposition of Rotoma airfall at c. 8500 yr BP, because this unit is severely eroded, but a well-developed paleosol was then able to develop across the whole of the degraded scarp. This paleosol's development was terminated by the Mamaku Tephra (M) that mantled the degraded scarp.

ROTOITIPAKAU TRENCH C
SW WALL

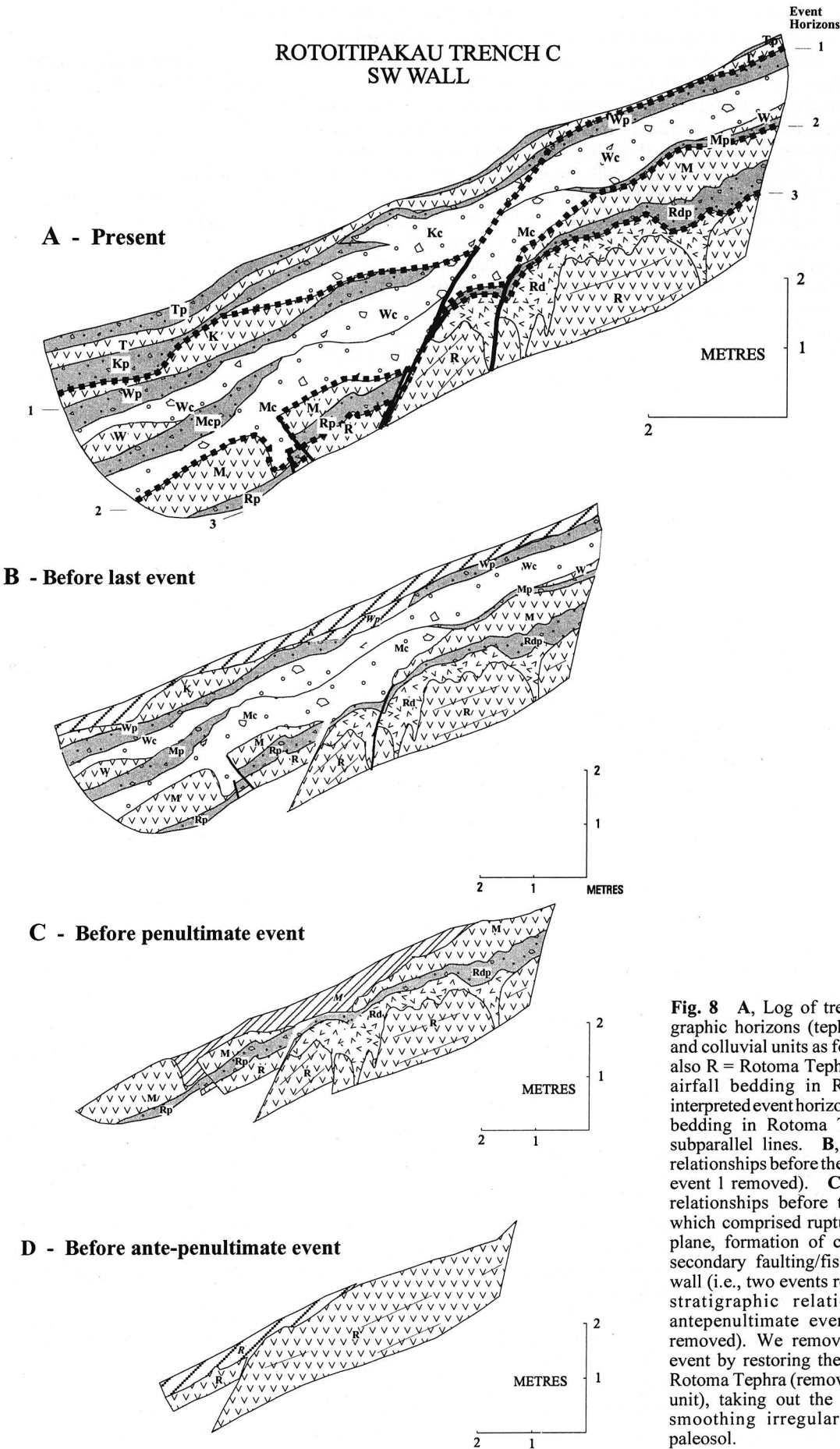
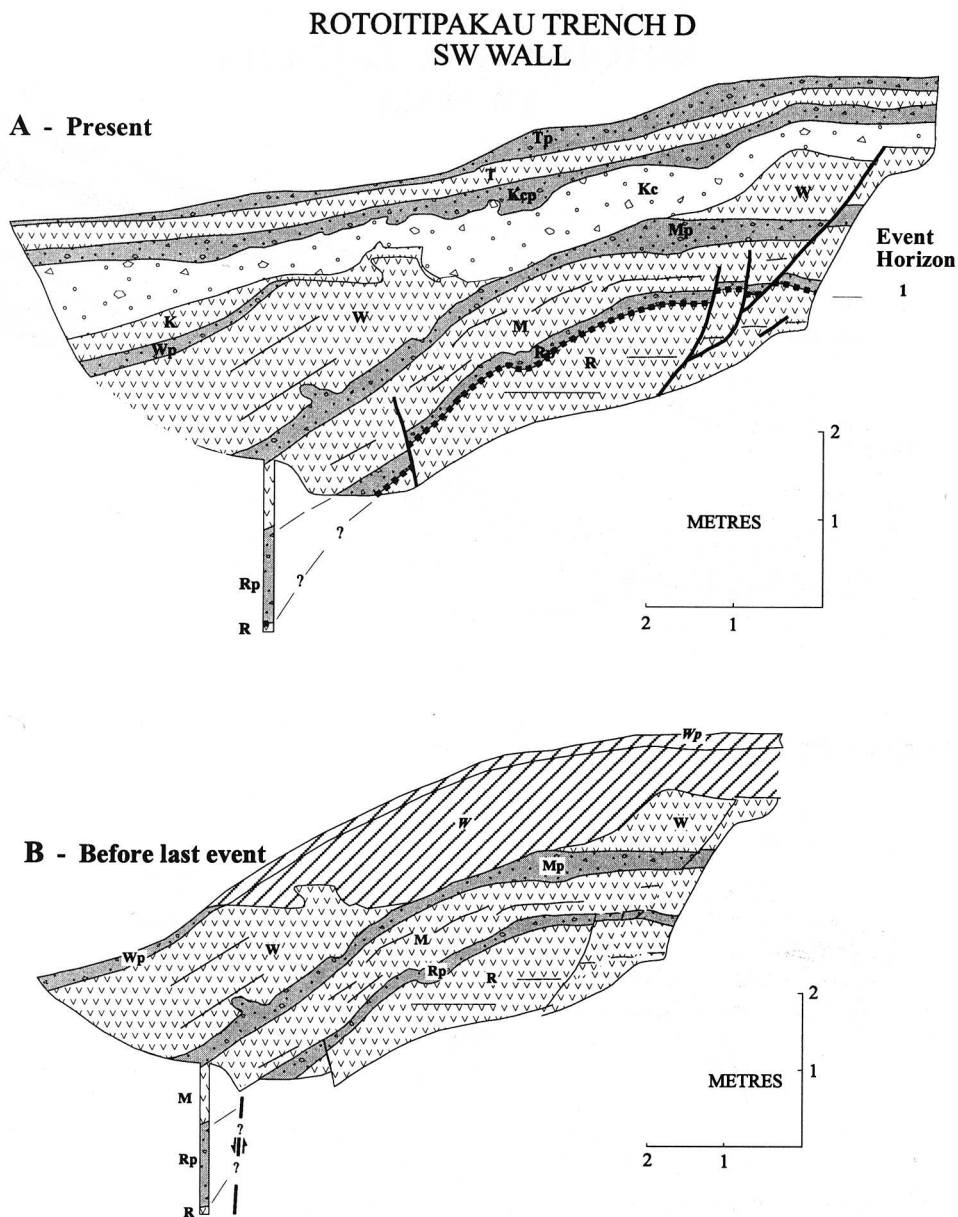


Fig. 8 A, Log of trench C showing stratigraphic horizons (tephra, paleosols, alluvial and colluvial units as for Fig. 5 and following, also R = Rotoma Tephra, and Rd = disturbed airfall bedding in Rotoma Tephra), and interpreted event horizons. Indications of airfall bedding in Rotoma Tephra are shown by subparallel lines. B, Inferred stratigraphic relationships before the most recent event (i.e., event 1 removed). C, Inferred stratigraphic relationships before the penultimate event which comprised rupture of the second fault plane, formation of colluvial unit Mc, and secondary faulting/fissuring in the hanging wall (i.e., two events removed). D, Inferred stratigraphic relationships before the antepenultimate event (i.e., three events removed). We remove the antepenultimate event by restoring the airfall stratigraphy in Rotoma Tephra (removing or restoring the Rd unit), taking out the tilting of blocks, and smoothing irregularities in the Rotoma paleosol.

Fig. 9 **A**, Log of trench D, showing stratigraphic horizons (tephra, paleosols, alluvial and colluvial units as for Fig. 5 and following), and an interpreted event horizon. Indications of airfall bedding in Rotoma, Mamaku, and Whakatane Tephra are shown by subparallel lines within units. **B**, Inferred stratigraphic relationships before the most recent event (i.e., event I removed). At least a second event is indicated by the eroded nature of the Rotoma Tephra and the mantling nature of Mamaku and Whakatane Tephra. Restoration of secondary faulting in the hanging wall implies older faulting as indicated.



Trace/trench E Trace E is a 0.5 km long fault in the southwestern part of the fault zone (Fig. 2). The trench was sited across a 4 m high scarp in a steep gully, either side of which the scarp increases to c. 10 m high. The trench exposed a sequence of airfall tephra, colluvial units, and intervening paleosols that extend down to Rotoma Tephra on the footwall and into the Mamaku paleosol on the hanging wall (Fig. 10A). A narrow zone of faulting extends up-section into Kaharoa-age deposits. The Tarawera Tephra extends across the top of the fault without disruption.

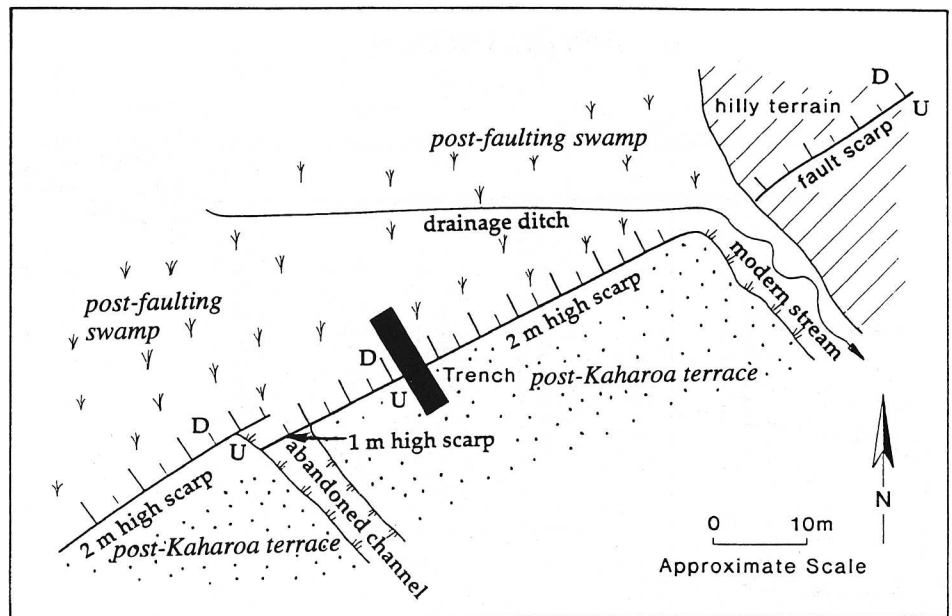
Two faulting events are interpreted in this trench. The most recent is recognised by the presence of a Kaharoa colluvium (Kc) that mantles a buried free face, and by displacement of Whakatane paleosol (Wp). Removal of this post-Kaharoa, pre-Tarawera event by removing the Kaharoa colluvium (Kc) and restoring the Whakatane paleosol requires 0.35 m of dip-slip motion (Fig. 10B). The older event is a post-Whakatane, pre-Kaharoa event, demonstrated by the occurrence of a post-Whakatane colluvium (Wc), and the

need for 1.5 m of dip-slip displacement to restore the paleosol in Mamaku Tephra (Fig. 10C). The erosion of the Whakatane airfall (unit W), and the underlying Mamaku paleosol (unit Mp) from the footwall in close proximity to the scarp, supports the interpretation of a major post-Whakatane event that probably occurred soon after deposition of Whakatane Tephra because the paleosol has developed above the Wc colluvial unit.

Trace/trench F Trace F is 0.5 km long, approximately along-strike of trace A, but with opposite throw, on the southeastern side of the Rotoitipakau Fault Zone (Fig. 2). It is one of the few northwest-facing traces in the Rotoitipakau Fault Zone. Near the middle of the trace it crosses low-lying topography as a 2 m high scarp that forms a barrier to drainage, such that a substantial swamp has developed on the downthrown side (Fig. 11).

Three faulting events on trace F within the past c. 660 yr are interpreted from a shallow trench and the geomorphology

Fig. 11 Sketch of the faulted terrace and trench site on trace F. Trench site location shown in Fig. 2.



at that locality. The terrace that is offset by the 2 m high fault scarp with a small right step-over is younger than c. 660 yr, because Kaharoa Tephra is not present in the trench or in pits or auger holes excavated in the terrace on both the upthrown and downthrown sides. A modern channel, and an abandoned channel that is stranded above the swamp by a 1 m high scarp, crosses the terrace on the upthrown side of the fault (Fig. 11). We infer two fault ruptures in addition to the 1987 rupture, each of c. 1 m vertical displacement, have formed the 2 m high scarp. Displacement of up to 0.05 m was also mapped along this trace after the Edgecumbe earthquake (Beanland et al. 1989), and this was still visible 2.5 yr after the earthquake. The 1987 displacement was also observed in the trench as offset of the Tarawera Tephra, but because of the high water table no older displacements could be defined.

DISCUSSION

The principal objective of this study has been to investigate the interrelationships of the rupture history of a normal fault zone comprising many strands. We trenched six strands of the faults and found evidence for at least seven fault rupture events in the past c. 8500 yr (Fig. 12).

Evaluation of temporal and spatial pattern of paleoearthquakes

Small ruptures (0.05–0.3 m) occurred during the 1987 Edgecumbe earthquake on two of the fault strands that we trenched (traces B, F) and on the Hogg Road strand northeast of traces D and E (Fig. 2). These small displacements are consistent with the longer term fault history of throw on these traces. In all but one of the ruptures, this is opposite to the focal mechanism of the Edgecumbe earthquake and the sense of throw on the Edgecumbe Fault. Therefore, we infer these small displacements to be triggered or secondary slip. We have not been able to decipher other episodes of triggered slip in our data, perhaps because events of this size are below the resolution of detection when buried deeper in the stratigraphy.

Before the 1987 rupture we have evidence for two events in the c. 500 yr period between Kaharoa and Tarawera Tephra deposition (665 yr BP to AD 1886). Two events are observed on the co-linear traces A and F, and single events are observed on traces B, C and E (Fig. 12). It is also possible that there was rupture on trace D, which is co-linear with trace E, in the Kaharoa to Tarawera interval. In the c. 4000 yr interval between Whakatane and Kaharoa deposition, we have data for all but trace F, and therefore regard the record as reasonably complete. We infer a 0.35 m displacement on trace D fairly late in this period. As well, there was a large displacement of >2.4 m on trace B and a 1.5 displacement on trace E in this interval. A displacement of <0.5 m, perhaps coincident with or just before the Whakatane eruption, was inferred from trace A. Thus, in the 4000 yr interval there has been at least one major event affecting traces B and E, another late event on trace D, and a co-Whakatane event on trace A.

Before the Whakatane Tephra deposition the paleoseismic history is unclear because no data are available from traces A, F, B and E (Fig. 12). No rupture occurred in the c. 2500 yr interval on traces C and D, but large events on both of the traces are observed in the c. 1300 yr interval between Mamaku and Rotoma deposition. In developing the most simple picture of fault activity, we infer these to be a single large earthquake event.

In summary, it appears that co-linear traces often (usually) have a similar rupture history, even when the sense of throw is opposite, such as it is from trace A to trace F. Therefore, the gaps between short traces are probably not significant, and fault strands almost certainly have more continuity at depth. Although a large number of earthquakes have been identified in the fault zone, not all traces rupture in every event. For example, the post-Whakatane rupture event occurred on traces B and E, but not on traces C and D (Fig. 12). Our data are insufficient to decipher a detailed pattern of rupture associations, but it does appear that traces A, B and E, on each side and in the centre of the zone, usually rupture together, and that only once in eight events (in the large post-Rotoma event)

northeast would be across an extensive surface underlain by Kaharoa alluvium. Several strands of the fault zone have sustained multiple surface rupture since Kaharoa Tephra deposition, therefore, we would expect to see the fault scarp across the Kaharoa alluvium surface, but none is evident. A direct south-western extension of the fault zone also seems unlikely. The fault strands appear to die-out within the Rotoiti Tephra Formation, and deposits of c. 280 ka Matahina Ignimbrite occur along-strike to the southwest and would be expected to reveal the extension of the fault zone (Fig. 1).

Most of the strands of the Rotoitipakau Fault Zone are downthrown to the southeast, and thus have the same sense of motion as the Braemar and Matata Fault Zones that define the western margin of the Whakatane Graben. The Rotoitipakau Fault Zone may be a more easterly trending branch of the Braemar Fault Zone (055° strike compared with c. 040° strike for the general trend of the Braemar and Matata Fault Zones) that does not extend very much farther to the northeast. Beanland (1989) presented some data on past movement of a subsidiary strand of the Braemar Fault c. 3 km north of the Rotoitipakau Fault Zone (see Fig. 1 for location) and found evidence for two faulting events in the past c. 8000 yr, each of 1–2 m vertical slip. One of the events was bracketed between Whakatane and Kaharoa, and the other was an earlier pre-Whakatane event. While the size of events appears to be similar to those within the Rotoitipakau Fault Zone, the timing of the most recent event is older, and we may infer therefore that not all parts of the Braemar and Rotoitipakau Fault Zones rupture simultaneously.

Because of the large displacements and short fault length, we assume the Rotoitipakau Fault Zone is part of a longer structure, but we should also consider the possibility that unusual rupture dimensions may be possible in this fault zone that is located within an active volcanic and geothermal region (hot springs and geothermal wells are shown on Fig. 2). Similar ratios of displacement to fault length have been noted by Page et al. (1987) and Muffler et al. (1994) from extensional volcanic areas of northeast California. Hackett et al. (1996) discussed the class of faults and fissures related to volcanic intrusion, and used the terminology “dike-induced normal faults”. Several of the characteristics of such faulting is reminiscent of the faulting observed in the Rotoitipakau Fault Zone. Notably, the faults are short, with unusually short length:displacement ratios compared with normal faults in nonvolcanic terrains. Hackett et al. (1996) implied that the 1987 Edgecumbe earthquake and faulting was in response to intrusion, but there was no indication of a magma intrusion signal in the seismological records, there was no increase in volcanic activity at the time of the earthquake, and the earthquake ruptured from c. 8 km depth (Anderson & Webb 1989; Darby 1989), considerably deeper than the depth proposed for faulting associated with dike intrusion. Modelling of dike intrusion (e.g., Mastin & Pollard 1988) is usually related to the formation of a graben. In this respect, both the Edgecumbe Fault and the Rotoitipakau Fault Zone are different: one is a simple normal fault and the other is a fault zone with all but one of the strands with the same sense of slip. Hackett et al. (1996) made the point that dike-induced normal faults are commonly monogenetic, related to a single episode of dike emplacement at a particular locality. We have shown the Rotoitipakau Fault Zone to have had recurrent activity, with up to three rupture events on a single strand in the past 5000 yr (Fig. 12). We therefore

conclude the faulting in the Rotoitipakau Fault Zone reflects primary tectonic rupture which may, in a general way, be related to changes in the state of stress in the vicinity of a large rhyolite caldera, but not directly related to local magma intrusion.

Maximum magnitude of earthquakes associated with rupture of the Rotoitipakau Fault Zone

We conclude that the observed faulting in the Rotoitipakau Fault Zone is primary tectonic rupture associated with extension in the Whakatane Graben. Earlier we note that the regressions of Wells & Coppersmith (1994) would suggest a rupture length of 30–35 km in association with the typical 1–1.5 m single-event displacement. The regression of displacement on magnitude from Wells & Coppersmith for normal faults (but noting the scarcity of normal faults in active volcanic environments in the dataset) suggests a maximum earthquake magnitude of M_w 6.8–6.9. If we consider the 1987 rupture on the Edgecumbe Fault as a direct analogue (average dip-slip displacement of 1.7 m on a 13 km long surface rupture, and M_w 6.6 earthquake; Beanland et al. 1989; Darby 1989) then we might infer a smaller earthquake if only the Rotoitipakau Fault Zone were to rupture, or somewhat larger if single-event displacements of 4.5–5 m are realistic. Another approach to thinking about maximum earthquake magnitude for the fault zone is to consider possible or likely rupture dimensions and from this calculate seismic moment and moment magnitude by the equation of Hanks & Kanamori (1979). We have data on single-event displacement and can assess a magnitude based on the 5 km length of the fault zone. The likely seismogenic thickness is a more difficult parameter to estimate. There could be an argument to assume a very thin brittle crust in this high heat flow region close to the Kawerau geothermal field, but drilling there shows that basement greywacke is c. 1 km deep c. 1 km southeast of the Rotoitipakau Fault Zone, and much of the production from that field is from heat sources in the greywacke basement (Nairn & Beanland 1989). The 1987 Edgecumbe earthquake ruptured from c. 8 km (Anderson & Webb 1989). Thus, we estimate several possible moment magnitudes in the range 6.0–7.0 using these parameters (Table 3). We have no grounds for preference of one estimate over another, but we suggest that the large displacement:length ratio may not be unacceptable in active volcano-tectonic regions.

CONCLUSIONS

Trenching of many of the strands in the Rotoitipakau Fault Zone has shown that several fault strands commonly rupture in each event, but that not all strands rupture together or have a common rupture history. Fault strands that are along-strike of one another tend to have a similar, but not coincident, rupture history. Trenches have revealed normal faults with single-event displacements on individual strands that range from a few decimetres to perhaps >2.5 m, at time intervals that have been quite variable. The faults do not therefore have any self-similar spatial or temporal rupture characteristics, and the fault behaviour is apparently random. The faults may be controlled primarily by backarc extensional forces, but these forces may be modified at shallow structural levels by stress changes at this location at the margin of the

Table 3 Possible moment magnitude earthquakes in the Rotoitipakau Fault Zone.

Options	Dip (degrees)*	Length (km)	Single-event displacement (m)	Crustal depth (km)	Seismic moment (N/m ²)†	Moment magnitude (M _w)
1	50	5	1.5	5	1.30E + 18	6.0
2	50	5	4.5‡	5	3.90E + 18	6.4
3	50	30#	4.5‡	8	3.74E + 19	7.0

*Accepting average of dip determinations of the 1987 Edgecumbe earthquake (Beanland et al. 1989; Anderson & Webb 1989).

†Assuming modulus of rigidity of 3×10^{10} N/m².

‡Summation of slip on several fault strands in a single event.

#Assuming the Rotoitipakau Fault ruptures with part of the Braemar Fault Zone to the southwest.

Okataina caldera. Stratigraphic relationships in the trenches indicate that faulting has often occurred close in time to major volcanic eruptions from Okataina caldera. Faulting appears to have occurred immediately before some eruptions and soon after some other eruptions. Thus, faulting or eruption may induce sufficient stress variation to be the trigger for nearby volcanic or fault activity.

We conclude that the faulting in the Rotoitipakau Fault Zone is primary tectonic rupture rather than associated with dike-induced extensional processes as proposed by Hackett et al. (1996) for some faulting in volcanic terrains in Iceland, western United States, and on the flanks of the Hawaiian volcanoes.

The characteristics of the surface faulting observed in the Rotoitipakau Fault Zone present many problems in determining maximum magnitudes associated with the faulting. We suggest that relationships between fault length, single-event displacement, and earthquake magnitude, which have been developed for normal faults in nonvolcanic extensional environments, may not be appropriate to use for the Rotoitipakau Fault Zone and other faults of similar genesis.

ACKNOWLEDGMENTS

We are grateful to the property owners Tasman Forest Ltd and Mr Booker for access to the trench sites and forbearance with some disturbance in the young pine plantation. We thank Ian Nairn for assistance in the field, in particular for tephra identification, and Russ Van Dissen, Ian Nairn, Brent Alloway, David Barrell, Michael Machette, and Alan Nelson for helpful comments on early drafts of the manuscript. We thank Pilar Villamor who prepared the retrodeformed figures of the trench logs. Journal reviews by Jim McCalpin and Mark Hemphill-Haley were particularly valuable and we thank them for their thorough and helpful comments. NSF Grant #INT-8800040 provided travel support for Wesnousky. Research partly funded by the Foundation for Research, Science and Technology contract CO5403. University of Nevada at Reno, Center for Neotectonic Studies contribution number 33. Institute of Geological and Nuclear Sciences contribution number 1526.

REFERENCES

- Anderson, H.; Webb, T. 1989: The rupture process of the Edgecumbe earthquake, New Zealand. *New Zealand journal of geology and geophysics* 32: 43–52.
- Beanland, S. 1989: Detailed fault mapping in the Matahina Dam region. New Zealand Geological Survey client report 89/8. 45 p.
- Beanland, S.; Berryman, K. R.; Blick, G. H. 1989: Geological investigations of the 1987 Edgecumbe earthquake, New Zealand. *New Zealand journal of geology and geophysics* 32: 73–91.
- Darby, D. J. 1989: Dislocation modelling of the 1987 Edgecumbe earthquake, New Zealand. *New Zealand journal of geology and geophysics* 32: 115–122.
- Froggatt, P. C.; Lowe, D. J. 1990: A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand journal of geology and geophysics* 33: 89–109.
- Gilbert, G. K. 1890: Lake Bonneville. *U.S. Geological Survey monograph* 1. 572 p.
- Hackett, W. R.; Jackson, S. M.; Smith, R. P. 1996: Paleoseismology of volcanic environments. Chapter 4 in: McCalpin, J. P. ed. *Paleoseismology*. San Diego, Academic Press. Pp. 147–181.
- Hanks, T. C.; Kanamori, H. 1979: A moment magnitude scale. *Journal of geophysical research* 84: 2348–2350.
- Healy, J.; Schofield, J. C.; Thompson, B. N. 1964: Sheet 5—Rotorua. Geological map of New Zealand 1:250,000. New Zealand Department of Scientific and Industrial Research.
- Lowe, D. J.; McFadgen, B. G.; Higham, T. F. G.; Hogg, A. G.; Froggatt, P. C.; Nairn, I. A. 1998: Radiocarbon age of the Kaharoa Tephra, a key marker for late Holocene stratigraphy and archaeology in New Zealand. *The Holocene* 8: 487–495.
- Mastin, L. G.; Pollard, D. D. 1988: Surface deformation and shallow dike intrusion processes at Inyo Craters, Long Valley, California. *Journal of geophysical research* 93 B11: 13221–13235.
- Muffler, P. L. J.; Clynne, M. A.; Champion, D. E. 1994: Late Quaternary normal faulting of the Hat Creek Basalt, northern California. *Geological Society of America bulletin* 106: 195–200.
- Nairn, I. A. 1981: Some studies of the geology, volcanic history, and geothermal resources of the Okataina volcanic centre, Taupo volcanic zone, New Zealand. Unpublished PhD thesis, lodged in the Library, Victoria University of Wellington, Wellington. 371 p.
- Nairn, I. A. 1989: Sheet V16AC—Mount Tarawera. Geological map of New Zealand 1:50,000. Wellington, New Zealand. Department of Scientific and Industrial Research.
- Nairn, I. A.; Beanland, S. 1989: Geological setting of the 1987 Edgecumbe earthquake, New Zealand. *New Zealand journal of geology and geophysics* 32: 1–13.
- Nairn, I. A.; Kobayashi, T.; Nakagawa, M. in press: The ~10 ka multiple vent pyroclastic eruption sequence at Tongariro Volcanic Centre, Taupo Volcanic Zone, New Zealand: Part 1. Eruptive processes during regional extension. *Journal of volcanology and geothermal research*.
- Ota, Y.; Beanland, S.; Berryman, K. R.; Nairn, I. A. 1988: The Matata Fault: active faulting at the north-western margin of the Whakatane graben, eastern Bay of Plenty. *New Zealand Geological Survey record* 35: 6–13.

- Page, W. D.; Hemphill-Haley, M. A.; Wong, I. G. 1987: Exaggerated fault scarps in the Modoc Plateau, northeastern California [abs]. *Geological Society of America abstracts with programs* 19: 797.
- Vucetich, C. G.; Howorth, R. 1976: Late Pleistocene tephrostratigraphy in the Taupo district, New Zealand. *New Zealand journal of geology and geophysics* 19: 43–50.
- Vucetich, C. G.; Pullar, W. A. 1964: Stratigraphy of Holocene ash in the Rotorua and Gisborne districts. Part 2. *New Zealand Geological Survey bulletin* 73: 43–63.
- Vucetich, C. G.; Pullar, W. A. 1969: Stratigraphy and chronology of late Pleistocene volcanic ash beds in central North Island, New Zealand. *New Zealand journal of geology and geophysics* 12: 784–837.
- Wallace, R. E. 1977: Profiles and ages of young fault scarps, north-central Nevada. *Geological Society of America bulletin* 88: 1267–1281.
- Wells, D. L.; Coppersmith, K. J. 1994: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84: 974–1002.
- Wilson, C. J. N.; Houghton, B. F.; Lanphere, M. A.; Weaver, S. D. 1992: A new radiometric age estimate for the Rotoehu Ash from Mayor Island volcano, New Zealand. *New Zealand journal of geology and geophysics* 35: 371–374.
- Yeats, R. S.; Sieh, K.; Allen, C. R. 1997: The geology of earthquakes. New York, Oxford University Press. 569 p.