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History of vertical displacement of Kerepehi Fault at Kopouatai bog, Hauraki Lowlands, New Zealand, since c. 10 700 years ago

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Abstract Thirteen tephra layers interbedded with peat, and a basal peat horizon, in four pairs of cores provide radiocarbon-dated reference horizons that indicate vertical displacement on the Kerepehi Fault at Kopouatai bog, Hauraki Lowlands. Progressive offset of the horizons with time shows that vertical fault movement, downthrown to the west, has been occurring for the past c. 10 700 radiocarbon years at an approximately uniform rate of c. 0.13 mm/yr. Step functions indicate faulting events (earthquakes) at c. 1400, c. 5600, c. 6800, and c. 9000 years ago, a mean recurrence interval of c. 2500 years. These findings support geophysical and geological evidence that the Hauraki Depression is an active rift, and show that active faulting occurs along the northern as well as southern extensions of the Kerepehi Fault.

If such earthquakes occur randomly in time, and based on the return period of 2500 years, there are 2%, 18%, and 33% probabilities of a major earthquake affecting the Kerepehi Fault at Kopouatai bog in the next 50, 500, and 1000 years, respectively.

Keywords faults; paleoearthquakes; stratigraphy; tephrochronology; Holocene; Hauraki Rift; Kerepehi Fault; Kopouatai bog

INTRODUCTION

The Hauraki Depression, containing the Hauraki Lowlands, is interpreted as a large rift structure c. 20–30 km wide extending from Matamata to the Hauraki Gulf over a distance of 200 km or more (Fig. 1; Hochstein & Nixon 1979; Hochstein et al. 1986). It is bounded to the west chiefly by Jurassic metagreywackes and Tertiary volcanics (Kiwitahi Volcanics), and to the east by Tertiary and Quaternary volcanics of the Coromandel Group (Healy et al. 1964; Schofield 1967; Hochstein & Nixon 1979; Houghton 1987). Geophysical cross-sections (Hochstein & Nixon 1979) show that the rift, from west to east, consists of a fault-angle depression, a median horst, and a graben. Two major normal faults, the Hauraki and Kerepehi Faults, strike NNW along the eastern boundaries of the graben and the fault-angle depression, respectively; a minor hinge fault, the Firth of Thames (or Miranda) Fault, forms the western boundary of the rift structure (Fig. 1A). Transverse faults cross the Hauraki Lowlands causing horizontal offsets of the Hauraki and Kerepehi Faults of up to 3 km (Hochstein & Nixon 1979). Pillans (1986) reported a subsidence rate along the Firth of Thames Fault of 1.5 mm/yr.

The rift structure is partially infilled with Tertiary and Quaternary terrestrial sediments to a maximum thickness of c. 3 km (Kear & Tolley 1957; Healy et al. 1964; Hochstein & Nixon 1979). The most recent deposits comprise mainly volcaniclastic alluvium of the Hinuera Formation, deltaic and estuarine sediments, and locally reworked sediments (Healy et al. 1964; Hume et al. 1975; Cuthbertson 1981; Houghton & Cuthbertson 1989). Interbedded with and overlying these deposits are extensive peat deposits including the Kopouatai bog which is c. 9000 ha in extent (Fig. 1; de Lange 1989).

The Kerepehi Fault

The Kerepehi Fault, occupying a medial position in the Hauraki Lowlands and upthrown to the east (Fig. 1), is active to the south of Waitoa–Te Aroha, where it is associated with shallow earthquake activity and hot springs, and with multiple displacement of land surfaces (Hochstein & Nixon 1979; Berryman & Hull 1984). Beanland & Berryman (1986) mapped the fault as a series of traces comprising simple or stepped scarps that face to the west and range in height from 1 to 8 m. Most traces offset the upper surface of the Hinuera Formation (aged c. 19 000 years*: Hogg et al. 1987), which provides the only age control for assessment of fault history. The displacement of Holocene tephras at a site near Matamata (Berryman & Hull 1984) indicates that there has been at least one Holocene faulting event, but the number, timing, and size of individual events is unknown (Beanland & Berryman 1986). There may be a component of dextral motion on the Kerepehi Fault, as suggested from a single site east of Matamata (40 km south of Kopouatai bog), but it is uncertain whether such displacement is representative of the fault as a whole (Beanland & Berryman 1986).

To the north of Waitoa–Te Aroha, the fault is inferred to pass through the eastern margins of the Kopouatai bog (Fig. 1; Hochstein & Nixon 1979). In this paper we confirm the existence of the Kerepehi Fault as mapped in this area by Hochstein & Nixon (1979) and, based on tephrostratigraphic studies of the Kopouatai bog, examine its history of vertical displacement for the past c. 10 700 years.

*All ages reported and discussed in the text are conventional radiocarbon ages in years B.P. based on the old (Libby) half life of 5568 years (Hogg et al. 1987).

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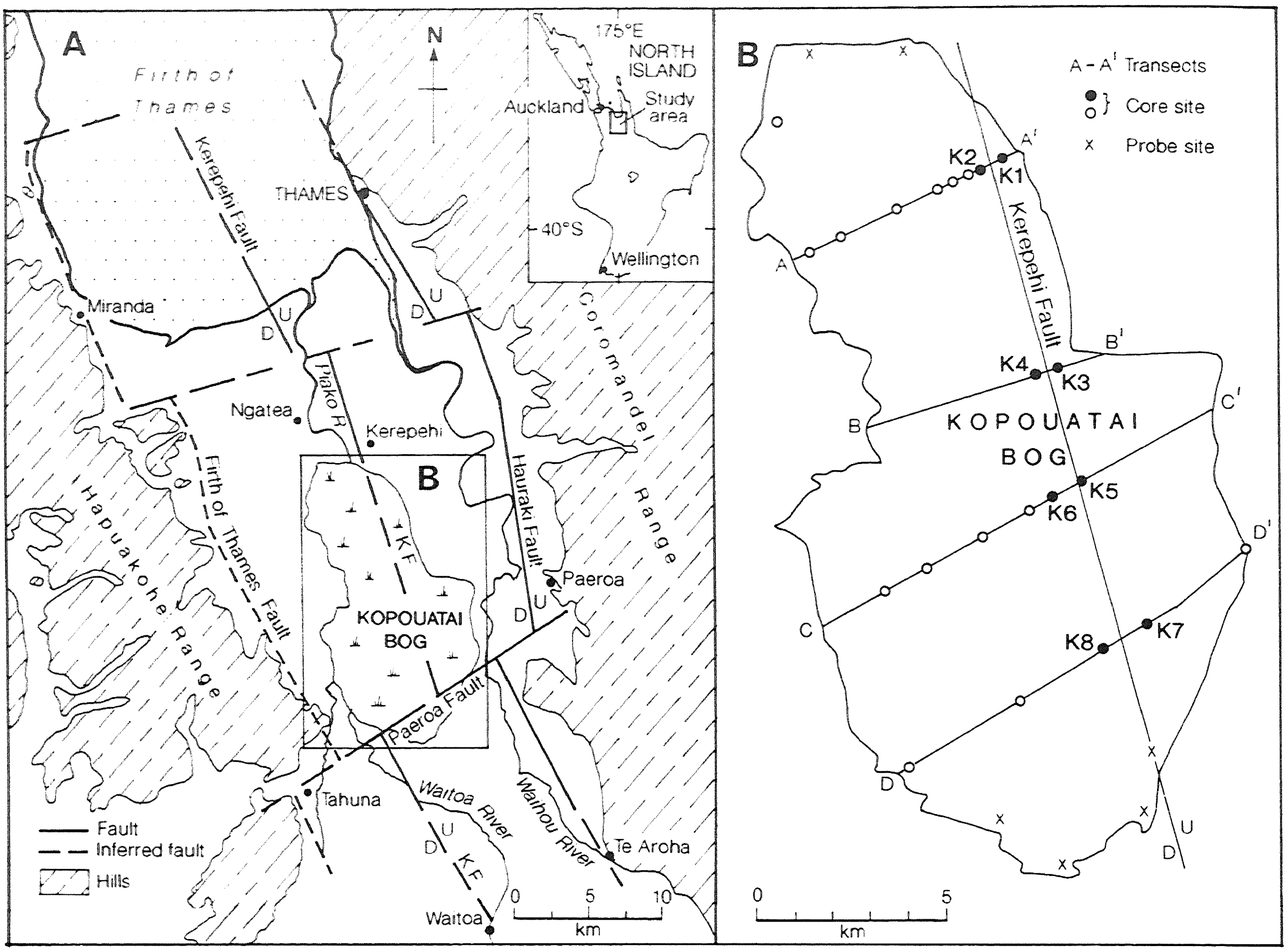

Fig. 1 **A**, Generalised structure of the Hauraki Depression and the location of Kopouatai peat bog in the Hauraki Lowlands. Hatching represents rocks other than Pliocene–Quaternary sediments and peats (after Hochstein & Nixon 1979). KF, Kerepehi Fault. **B**, Location of transects and coring sites with respect to the Kerepehi Fault in Kopouatai peat bog. Bog boundaries are based on sheet T13 of NZMS 260.

The only evidence for the Kerepehi Fault on the bog's surface is a probable fault trace marked by a narrow line of tall shrub vegetation on the eastern (upthrown) edge that contrasts with low rushes to the west (de Lange 1989). This pattern, best seen in aerial photographs, is especially clear in the northern part of Kopouatai bog, where the tall shrubs are rooted in shallow (2–3 m) peat overlying upthrown sediments.

Cores taken through the peat on both sides of the Kerepehi Fault trace contain preserved tephra layers that have been displaced by its movement. The surface of sediments underlying the peat has also been displaced. We have correlated and dated the tephra layers, and a basal peat horizon, which thus provide dated reference planes enabling us to calculate rates of vertical movement on the fault at Kopouatai bog. Step functions provide an estimate of the number of faulting events and when they occurred. We also assess whether the rates of movement are uniform, as shown in a parallel study at Lake Poukawa, Hawke's Bay (Froggatt & Howorth 1980), and the relationship of the faulting to the development of the Kopouatai bog.

The occurrence of tephra layers in a peat bog with an active fault running through it provides a valuable opportunity to contribute to studies on late Quaternary tectonism in New Zealand using tephrochronology.

STRATIGRAPHY AND CHRONOLOGY OF KOPOUATAI BOG

Cores taken with a D-section manual corer along four west–east transects across the bog (Fig. 1B) contain peat up to 14 m in thickness overlying basal blue-grey muds or, in places, sands or clays. The peat deposits are interspersed with 13 macroscopic airfall tephra layers of ash to lapilli grade, which range from c. 2 to 200 mm in thickness (Table 1). Each tephra has been identified and correlated with named deposits elsewhere in the Waikato–Hauraki region (Lowe et al. 1981; Hogg & McCraw 1983; Lowe 1988) using a combination of stratigraphy, field character, and ferromagnesian silicate mineral assemblage (de Lange 1988, 1989; de Lange & Lowe 1988). The tephras identified are summarised in Table 1 and Fig. 2, in which the nomenclature follows Lowe (1988) and Froggatt & Lowe (1990). An additional "mixed" tephric horizon, comprising material reworked from the adjacent Mamaku and Rotoma Tephras (de Lange 1989), and labelled Un in Fig. 2, was also described.

In many of the cores, 2–5 cm thick slices of peat above or below (or both) the tephra layers, and from at or near the base of the peat deposit, were extracted for radiocarbon dating at the University of Waikato Radiocarbon Dating Laboratory.

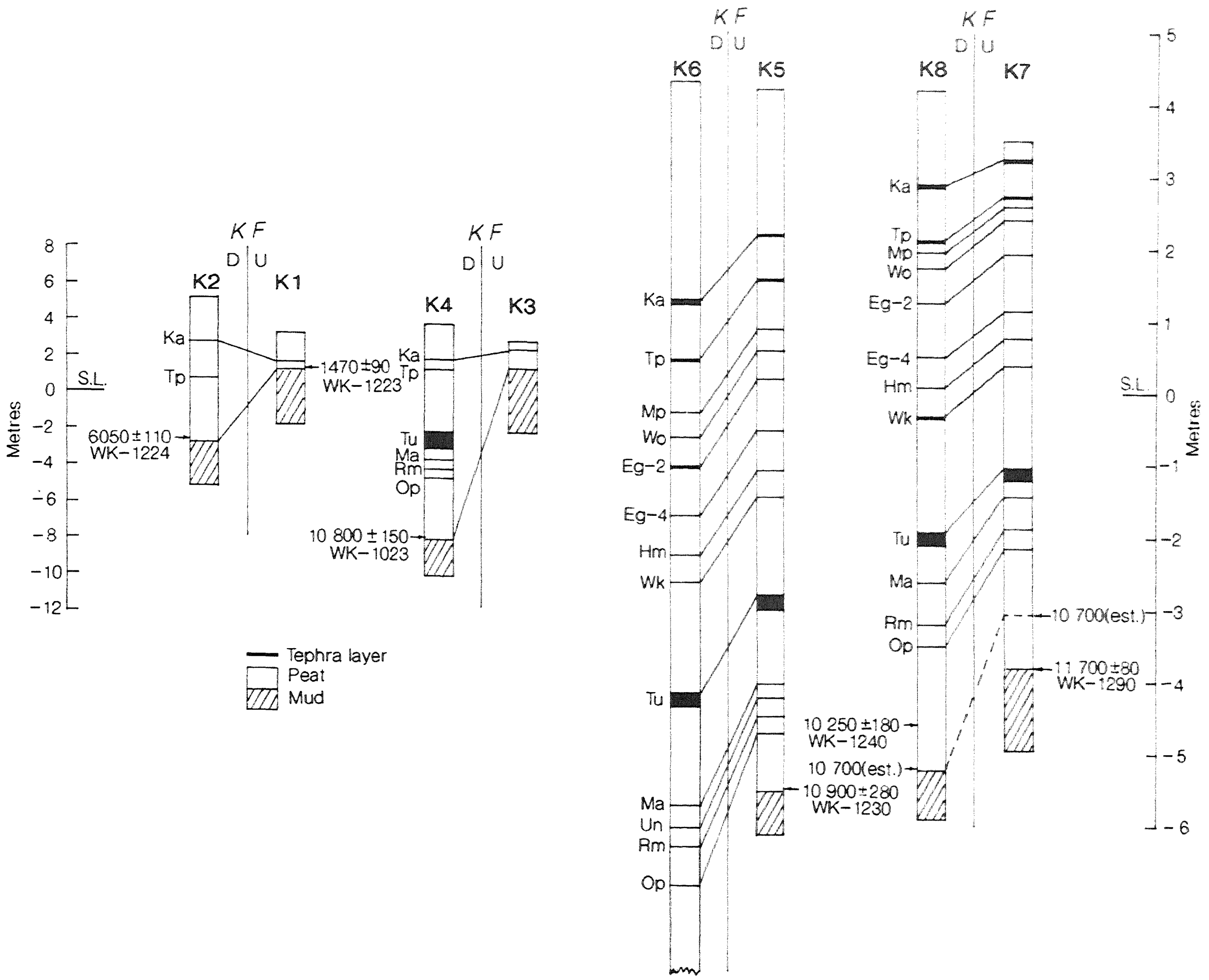

Fig. 2 Stratigraphy of four pairs of cores, K1–K8, which straddle the Kerepehi Fault in Kopouatai bog. Note different scales for cores K1–K4 (left) and K5–K8 (right). *KF*, Kerepehi Fault. Symbols for tephra formations are: Ka, Kaharoa; Tp, Taupo; Mp, Mapara; Wo, Whakaipo; Eg-2, Egmont-2[a]; Eg-4, Egmont-4[a]; Hm, Hinemaiaia; Wk, Whakatane; Tu, Tuhua; Ma, Mamaku; Un, mixed tephra; Rm, Rotoma; Op, Opepe. WK numbers refer to University of Waikato Radiocarbon Dating Laboratory ages (from de Lange 1989).
[a]Egmont-2 and -4 are informal names used by Lowe (1988).

Table 1 Properties of tephra layers identified in Kopouatai bog (after de Lange 1989).

Tephra (source)[a]	Range in thickness (mm)	Description	Ferromagnesian minerals[b]
Kaharoa Tephra *(O)*	10– 50	White, hard, "sugar-like", coarse to fine ash.	Hyp>>Hbe>Aug[c]
Taupo Tephra *(T)*	10– 30	Cream, soft, fine-medium pumice lapilli.	Hyp>>Aug>Hbe
Mapara Tephra *(T)*	2– 3	White, fine ash[d].	nd[e]
Whakaipo Tephra *(T)*	3– 5	White, coarse ash & rare hard, fine lapilli[d].	Aug>Hyp>Hbe[f]
Egmont-2 tephra *(E)*	3– 5	Brown, coarse ash & fine pumice lapilli[d].	Aug>Hyp>Hbe[f]
Egmont-4 tephra *(E)*	2– 3	Dark brown, "peppery" medium lapilli & fine ash.	Aug>>Hbe>Hyp
Hinemaiaia Tephra *(T)*	5– 7	White, fine ash[d].	Hyp>>Aug=Hyp
Whakatane Tephra *(O)*	5– 10	White, fine ash.	Hyp>Cgt=Hbe>Aug
Tuhua Tephra *(TU)*	140–200	Olive grey to reddish, coarse to medium ash .	Aeg>>Aen>Rie>Hbe
Mamaku Tephra *(O)*	12– 20	Yellow, compact fine ash.	Hyp>>Hbe>Aug
Mixed tephra bed	15– 20	White-pink medium to fine ash & rare fine lapilli.	Hbe
Rotoma Tephra *(O)*	6– 10	Cream, coarse to medium ash & hard, fine lapilli.	Cgt>>Hbe>Hyp=Aug
Opepe Tephra *(T)*	5– 10	Greyish, medium to fine ash & rare fine lapilli.	Hyp>>Aug>Hbe

[a]Volcanic centre: *O*, Okataina; *T*, Taupo; *E*, Egmont; *TU*, Tuhua [Mayor Island] (Froggatt & Lowe 1990).
[b]Based on point-counts of 2–4ø size fraction of heavy mineral assemblages: Hyp, hypersthene; Aug, augite; Hbe, calcic hornblende; Cgt, cummingtonite; Aeg, aegirine; Aen, aenigmatite; Rie, riebeckite.
[c]Biotite, normally characteristic of this tephra (Froggatt & Lowe 1990), is absent here.
[d]Discernible in the field only by its gritty texture.
[e]Not determined.
[f]Samples of these two tephras, which occur close together in the cores, are probably contaminated by each other.

The ^{14}C ages obtained helped to confirm the tephra correlations and provided a stratigraphically consistent chronology for calculating rates of displacement (de Lange 1989).

Stratigraphy of cores straddling Kerepehi Fault

Four pairs of cores (K1–K8) taken from both sides of the Kerepehi Fault on the four transects (Fig. 1B) were examined in detail. The stratigraphy of these cores is shown in Fig. 2; ages of the tephra layers are in Table 2 (see below).

The cores on transects A–A′ and B–B′ show major displacement of the subpeat sediments, but the thin deposits of peat eastward of the fault contain only a single tephra layer. However, cores K5 & K6 and K7 & K8 on transects C–C′ and D–D′, all in thick peat deposits, contain many tephra layers and, consequently, provide the most comprehensive record for estimating the history of vertical displacement on the Kerepehi Fault.

The length of the record is constrained by the oldest horizon present in each of the two pairs of cores. In K5 & K6 the oldest dated horizon common to both cores is Opepe Tephra (aged c. 9050 years)—underlying sediments were not reached in K6. For K7 & K8 we have used the two dates on peat at or near the base of the cores (WK1240, 1290; Fig. 2) to estimate rates of peat accumulation (assumed to be constant) and hence calculate the age and position of the oldest peat "horizon" common to both cores. This horizon, aged c. 10 700 years, occurs at the base of peat in K8, 36 cm below WK1240. In K7, it is 75 cm above WK1290 at the base of the peat (Fig. 2). The age of deposition of the muddy subpeat sediments, which probably represent the Hinuera Formation, is uncertain but predates c. 12 000 years ago.

FAULT MOVEMENT

The ages, depths, and offset of each of the 13 tephra layers, and of the oldest dated peat horizon, in core pairs K5 & K6 and K7 & K8 are given in Table 2.

The ages attributed to all but three tephra layers are pooled mean ages of numerous radiocarbon dates (including those obtained from Kopouatai) published in Froggatt & Lowe (1990). The ages applied to the two Egmont-derived tephras and the mixed tephra bed are mean ages of dates obtained from Kopouatai bog. Errors on the tephra ages are ± one standard deviation. Based on the 1 SD error for WK1240 (180 years), we have arbitrarily applied an error of ±200 years to the c. 10 700 year old peat horizon in cores K7 & K8.

Elevations of the bog's surface at K5 & K6 coring sites are 4.2 and 4.3 m above sea level, respectively; at K7 & K8 they are 3.5 and 4.2 m. These elevations are based on survey data in Harris (1978) and have estimated minimum errors of ±0.1 m. The depths, and hence offsets, of the marker horizons in each pair of cores have been corrected to account for the different surface elevations: 0.7 m and 0.1 m were subtracted from depths measured in K8 and K6, respectively. We have assigned errors of ±0.1 m for the offsets (cf. ±0.05 m used by Froggatt & Howorth 1980). We assume that the amount of vertical offset between the tephra layers in the four cores is due wholly to vertical fault movement, and that any peat compaction near the Kerepehi Fault has been horizontally uniform. The peat in this part of Kopouatai bog has been largely unaffected by modern drainage.

The amount of offset between the two pairs of cores increases with depth (Table 2). The apparently greater offset of the older tephras, and of the basal peat horizon in K7 & K8, indicates repeated movement on the fault.

Step function analysis and offset rates

The offsets of each tephra layer and the basal peat horizon are plotted against age for core pairs K5 & K6 (Fig. 3A) and K7 & K8 (Fig. 3B). In order to examine the age and history of fault movements, a series of step functions, based on the three general forms described by Froggatt & Howorth (1980, pp. 495–6) (see also Wellman 1969 and Moore 1987), have been fitted to the age versus offset data. The functions that best fit the Kopouatai data for both pairs of cores appear to contain elements of all three forms.

Four vertical steps, representing (paleo)earthquakes, have been drawn in both Fig. 3A and Fig. 3B. These functions show generally irregular patterns with step displacements c. 1400 years ago (0.3 m offset), c. 5600 years ago (0.2 m), c. 6800 years ago (0.4 m), and c. 9000 years ago (0.4–0.9 m; mean 0.7 m). Two additional small steps of c. 0.1 m (at c. 2100 and

Table 2 Age, depth, and offset of tephra layers and basal peat horizon in core pairs K5 & K6 and K7 & K8 from Kopouatai bog.

Horizon	Age (yr B.P.)	Depth (m) K8	Depth (m) K7	Offset (m)[a]	Depth (m) K6	Depth (m) K5	Offset (m)[a]
Kaharoa Tephra	770 ± 20[b]	0.6	0.3	0.3	2.9	2.0	0.9
Taupo Tephra	1850 ± 10[b]	1.3	0.8	0.5	3.7	2.6	1.1
Mapara Tephra	2140 ± 30[b]	1.5	0.9	0.6	4.5	3.3	1.2
Whakaipo Tephra	2690 ± 20[b]	1.7	1.1	0.6	4.8	3.6	1.2
Egmont-2 tephra	3400 ± 60[c]	2.2	1.6	0.6	5.2	4.0	1.2
Egmont-4 tephra	4140 ± 130[c]	2.9	2.3	0.6	5.9	4.7	1.2
Hinemaiaia Tephra	4530 ± 20[b]	3.3	2.7	0.6	6.4	5.2	1.2
Whakatane Tephra	4830 ± 20[b]	3.7	3.1	0.6	6.8	5.6	1.2
Tuhua Tephra	6130 ± 30[b]	5.3	4.5	0.8	8.4	7.0	1.4
Mamaku Tephra	7250 ± 20[b]	5.8	4.7	1.1	9.7	8.0	1.7
Mixed tephra bed	7711 ± 95[d]	–	–	–	10.0	8.2	1.8
Rotoma Tephra	8530 ± 10[b]	6.4	5.2	1.2	10.3	8.5	1.8
Opepe Tephra	9050 ± 40[b]	6.7	5.5	1.2	10.8	8.7	2.1
Basal peat	10 700 ± 200[e]	8.7	6.6	2.1	–	–	–

[a]± 0.1 m error.
[b]Mean age after Froggatt & Lowe (1990).
[c]Mean age of two dates from de Lange (1989).
[d]Mean age of three dates from de Lange (1989).
[e]Estimated from sedimentation rates (see text).
–Not present in core.

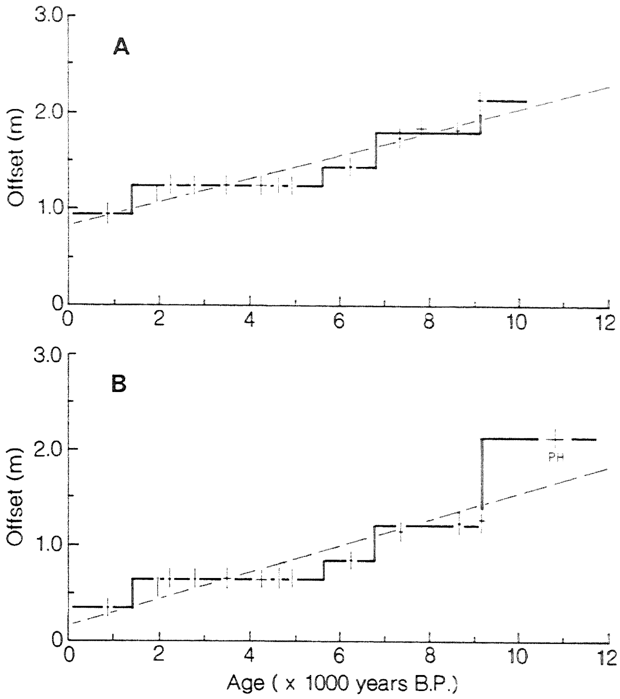

Fig. 3 Offset plotted against radiocarbon age for tephra reference horizons and dated basal peat horizon (PH) in core pairs at Kopouatai. Data points and errors are from Table 2. Step functions have been fitted to the data points; dashed lines are linear functions (see text). **A**, Cores K5 & K6. **B**, Cores K7 & K8.

c. 7500 years ago) are possible but unwarranted given the errors on the offset data.

The mean rate of vertical offset is calculated from the slope of the linear regressions (Froggatt & Howorth 1980), which are shown as dashed lines in Fig. 3. The regression shown in Fig. 3A has the formula $y = 0.00012x + 0.79$ (r = 0.94); in Fig. 3B it is $y = 0.00014x + 0.12$ (r = 0.91). These indicate offset rates of 0.12 mm/yr for K5 & K6 and 0.14 mm/yr for K7 & K8 (i.e., c. 0.13 mm/yr on the average). Beanland & Berryman (1986) estimated an offset rate of 0.4 mm/yr for the Kerepehi Fault near Matamata based on an 8 m displacement of the surface of the Hinuera Formation.

These regressions show that the mean rate of vertical fault movement since c. 10 700 years ago is approximately uniform with time, as demonstrated for the Wairarapa Fault by Froggatt & Howorth (1980). However, the step function patterns suggest that the rate of fault movement may be decreasing slightly, and exponential regressions (not plotted) also fit closely to the data points: for cores K5 & K6 (Fig. 3A) $y = 0.89 \times 10^{0.000037x}$ (r = 0.95); for cores K7 & K8 (Fig. 3B) $y = 0.34 \times 10^{0.000067x}$ (r = 0.95).

Recurrence intervals and earthquake probability

Based on four faulting events with displacements >c. 0.1 m, the mean recurrence interval for the K5 & K6 data (covering c. 9050 years) is c. 2300 years, whereas that for the K7 & K8 data (covering c. 10 700 years) is c. 2700 years. On the average, this gives one major earthquake every c. 2500 years.

Such a recurrence interval of earthquakes is relatively long in comparison to that associated with tectonically active areas in eastern North Island. For example, recurrence intervals of 800–900 years at Lake Poukawa were reported by Froggatt & Howorth (1980), and Berryman et al. (1987) recorded recurrence intervals ranging from 400 to 2000 years for the uplift of terraces along the eastern coastline. Beanland et al. (1989) suggested a recurrence interval for movement on the Edgecumbe Fault in the Bay of Plenty of the order of 800 to >1000 years.

The latest displacement episode(s) recorded at Kopouatai appears to have been some time after the deposition of Kaharoa Tephra (c. 770 years ago), the youngest reference horizon at Kopouatai. Shallow earthquakes with magnitudes 4.0 and 5.1 occurred near Te Aroha on 1964 July 30, and 1972 January 9, respectively (Adams et al. 1972). The latter event attained an intensity of *MM* VII. Most recently, a local farmer observed that the Edgecumbe earthquake of 1987 March 2 resulted in cracking of the ground surface in the vicinity of the Kerepehi Fault at Kopouatai (M. Bacchus pers. comm. 1988). However, this movement may have been a nontectonic rupture owing to, for example, subsidence or liquefaction effects (cf. Beanland et al. 1989).

If earthquakes occur randomly in time, then the probability of a faulting event resulting in displacement at Kopouatai may be estimated from the expression

$$p({}^{t}E < 1) = 1 - e^{-t/n}$$

where ${}^{t}E$ = time to next earthquake and n = return period. Based on a return period of 2500 years, the probability that a major earthquake will affect the Kerepehi Fault in the next 500 years is 18%, and for the next 1000 years, 33%.

On a shorter time scale, the probability of such an earthquake occurring within 50 years is 2%. In comparison, Smith & Berryman (1986), using mainly historical data, estimated that earthquakes with intensities of *MM* VIII have a 5% probability of occurrence in the Hauraki region within 50 years.

RELATIONSHIP OF FAULTING TO BOG DEVELOPMENT

Offset on the Kerepehi Fault produced the fault-angle depression that enabled peat to accumulate and form the Kopouatai bog c. 12 000 years ago (de Lange 1989). Since then, uplift on the Kerepehi Fault at the mean rate of c. 0.13 mm/yr has been exceeded by peat accumulation rates of c. 0.9 and 1.3 mm/yr in the southern and northern parts of the bog, respectively (de Lange 1989). Thus, the rate of development of the Kopouatai bog has not been constrained by uplift on the Kerepehi Fault. Rather, the growth of the bog, and its water-rich, self-levelling nature, have effectively masked most surface expression of the fault apart from that shown by vegetation patterns.

CONCLUSION

Our data confirm that the Kerepehi Fault is an active fault in its northern (onland) extension and thus support the contention of Hochstein & Nixon (1979) that the Hauraki Depression represents an active, north–south-trending continental rift. The Kerepehi Fault is the only major active fault in the South Auckland–Waikato region (cf. Officers of N.Z. Geological Survey 1983).

SUMMARY

1. Thirteen tephra layers interbedded with peat, and a basal peat horizon, provide dated reference planes that indicate vertical displacement (downthrown to the west) on the Kerepehi Fault at Kopouatai bog.
2. Progressive offset of some marker horizons with time shows that vertical fault movement has been occurring for the past c. 10 700 years at an approximately uniform rate of c. 0.13 mm/yr.
3. Step functions fitted to the data indicate four displacement events (paleoearthquakes) in c. 10 700 years, a recurrence time of c. 2500 years. The steps occur at c. 1400 years (0.3 m offset), c. 5600 years (0.2 m), c. 6800 years (0.4 m), and c. 9000 years (0.7 m) ago.
4. If earthquakes occur randomly in time, and based on the recurrence interval of 2500 years, there are 18% and 33% probabilities that a major earthquake will affect the Kerepehi Fault at Kopouati bog in the next 500 and 1000 years, respectively. The probability of such an earthquake in the next 50 years is 2%.
5. Our findings support the conclusions of Hochstein & Nixon (1979) that the Hauraki Depression is an active continental rift.

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