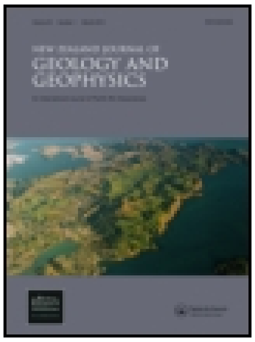

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Paleoseismology of the Waverley Fault Zone and implications for earthquake hazard in South Taranaki, New Zealand

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Abstract The Waverley Fault Zone, c. 40 km northwest of Wanganui, New Zealand, has clearly defined surface fault scarps trending southwest–northeast for a distance of c. 8 km, from Lake Oturi in the south through to the Brunswick Terrace strandline northeast of Waverley. Paleoseismic studies involving trenching were carried out to determine the timing of past earthquakes, the amount of surface displacement associated with them, and an estimation of associated earthquake magnitudes. The Waverley Fault Zone has been the site of several large, surface-rupturing events in the past. Trench excavations across the fault zone revealed that the zone consists of normal faults dipping 50–80°SW, with a minimum of two displacements having occurred since deposition of the Kawakawa Tephra 22 500 yr ago. Single-event fault displacements were measured to be at least 1–2 m vertically. From these values the estimated earthquake magnitudes associated with past earthquake events are calculated, using the Wells & Coppersmith fault regression formula, to range from M 6.6 to 6.7. Calculations using the formula $M_o = \mu\, \grave{u}\, L\, w$ show significantly lower magnitudes, having a maximum value of M 6.5. An average value of M 6.3 was obtained and accepted by this study.

Keywords Waverley Fault Zone; paleoseismic studies; earthquake hazard; normal faulting; Kawakawa Tephra; Taupo Volcanic Zone; Ngarino Terrace; Rapanui Terrace; Brunswick Terrace

INTRODUCTION

Surface fault scarps are usually interpreted as being the evidence of past large-magnitude earthquakes. By studying surface fault scarps, an extension can be made from historical earthquake occurrence to the longer term record of large earthquakes. From these studies it may be possible to characterise future earthquake hazard. The purpose of this paper is to present the results of paleoseismic investigations along the Waverley Fault Zone, South Taranaki, New Zealand.

The Waverley Fault Zone is a southwest–northeast trending zone of active normal faults that passes through the township of Waverley and across a series of strandline marine terraces of the South Taranaki region (Fig. 1). A large surface-rupturing earthquake occurring within this zone would cause major damage to the infrastructure of Waverley and the surrounding region.

This paper outlines the geology of the South Taranaki region, recognising the utility of the marine terrace stratigraphy and chronology for establishing age control of geomorphic surfaces. Trenching studies were used for a paleoseismic investigation to determine the amounts of prehistoric surface displacement on the Waverley Fault, and the timing of past surface-rupturing events, to provide a basis for an estimation of maximum earthquake magnitudes.

GEOLOGICAL SETTING OF THE WAVERLEY AREA

The South Taranaki region lies to the west of the principal zone of deformation in the North Island. Unlike the central part of the plate boundary zone, which has been subjected to major deformation, the South Taranaki region has not been affected by major deformation since the activity on the Taranaki Fault Zone in the Miocene (c. 20 m.y. ago) (King & Thrasher 1992). Quaternary deformation is limited to mild uplift and warping, probably as isostatic uplift on the margin of the Wanganui Basin (Pillans 1990a).

The landscape of the South Taranaki region is dominated by a flight of marine terraces. These marine terraces extend in a northwest–southeast direction roughly parallel to the present coastline for more than 100 km, rise to more than 300 m above present sea level, and extend up to 20 km inland from the coast (Fig. 1). The terraces are the result of Quaternary sea-level fluctuations during mild tectonic uplift and tilting (Pillans 1990a, b). Marine terraces typically consist of a basal wave-cut platform overlain by marine sediments that grade up into nonmarine sediments. Up to 15 m of marine sand (commonly with conglomerate or, more rarely, shell layers at the base) overlies the wave-cut platforms. The marine sediments grade upwards into peat and/or a variety of other littoral and terrestrial deposits, which may include fluvial sediments, tephra, dune sand, loess, and laharic debris. The total thickness of marine and nonmarine sediments overlying a wave-cut platform generally increases with age of the terrace, and exceeds 40 m for some of the older terraces. A terrace riser defines the inland margin of each terrace and represents the location of a fossil seacliff and shoreline at the peak of the marine transgression which cut the platform below it (Pillans 1990b).

The South Taranaki–Wanganui terraces were first described by Fleming (1946, 1953), who mapped and named the Rapanui (younger) and Brunswick (older) Terraces. Fleming also recognised terraces older than the Brunswick surface but could find no evidence for their marine origin. These older terraces were collectively named the Kaiatea Terraces, which Fleming regarded as fluvial in origin. Later

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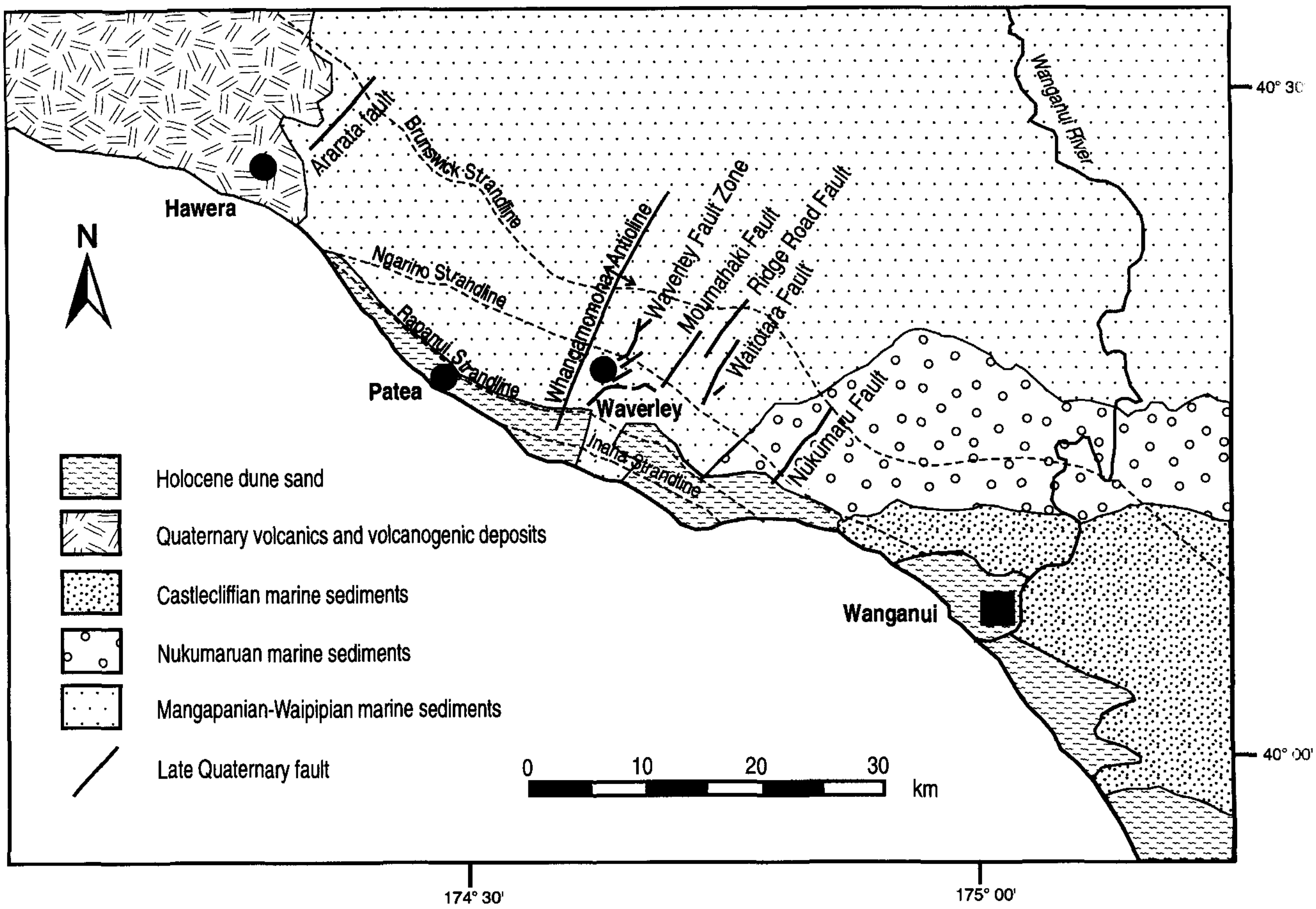

Fig. 1 Geological map of South Taranaki showing onshore active faults and terrace strandlines.

workers (Grant-Taylor 1964, 1978; Dickson et al. 1974; Pillans 1983) recognised further marine terraces and demonstrated that the Kaiatea Terraces were also of marine origin (Pillans 1990b). The marine terraces unconformably overlie 4–5 km thick Pliocene–Pleistocene (6–0.01 Ma) shallow marine sediments of the South Wanganui Basin (Anderton 1981), the centre of which lies some 20 km offshore to the south of Wanganui. The South Wanganui Basin is a broad basin which, from oil well and seismic survey data, appears to have a block-faulted structure (Anderton 1981).

Studies of the geological history of the South Taranaki region (e.g., Fleming 1946, 1953; Pillans 1990a, b) have revealed that a number of southwest–northeast striking faults have accumulated substantial vertical displacements since the last interglacial, equated with oxygen isotope stage 5e (120–130 000 yr) (Fig. 1). Of particular interest for this study is the Waverley Fault Zone, which strikes southwest–northeast across the Rapanui and Ngarino Terraces and intersects the southeastern corner of Waverley township. The fault zone probably continues southwards to the coast, but Recent dune sands deposited close to the coast cover any surface offset.

HISTORICAL SEISMICITY

From records of historical seismicity collected since 1840, the Waverley Fault Zone is located within a relatively seismically quiet part of New Zealand, c. 60 km southwest of the western margin of the Taupo Volcanic Zone (Fig. 2). Earthquakes have mainly been of small to moderate magnitudes, with only eight events of M_L (local magnitude) ≥5 within 50 km of Waverley in historic time. Many of the large historical earthquakes have originated in the highly active Taupo Volcanic Zone and offshore to the west of Mt Taranaki. Thus, the historical seismicity pattern of the Taranaki–Wanganui region shows a strong gradation from larger and more frequent earthquake events in the east and west to fewer and smaller earthquakes in the centre of the region near Waverley.

The largest event to occur close to Waverley in historic times was the 1946 magnitude 6.4 event, which produced an estimated shaking of Modified Mercalli (MM) intensity 8 in the township. By the early 1940s the distribution of seismographs in the National Network had developed sufficiently to give reasonable coverage for shallow earthquakes (<33 km depth) of magnitudes ≥4.3, providing all stations were operating. This led to events post-1940 being relatively well located in contrast to those pre-1940, when locations could be in error by up to 50 km in both latitude and longitude. A magnitude 7.5 event is thought to have occurred in 1843 near Wanganui but its precise location is uncertain.

Wanganui also experienced an earthquake swarm in October 1982 with MM intensities of up to 6 being felt in Wanganui, and magnitudes of up to M_L 4.9 being recorded.

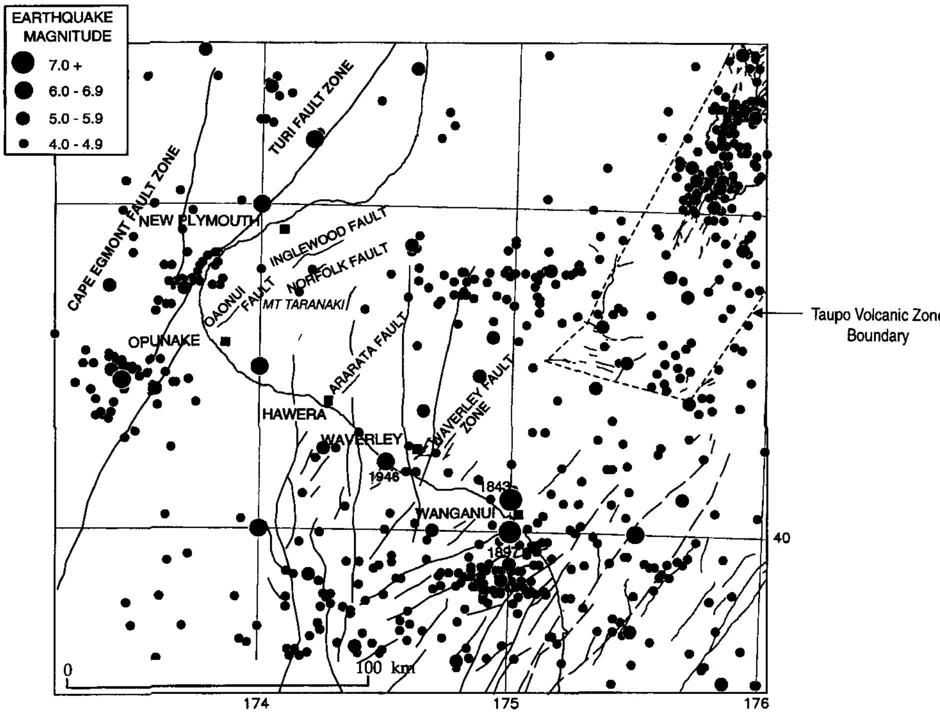

Fig. 2 Historic (1840–present) shallow (<40 km) earthquake epicentres of magnitude 4+ within the Taranaki region.

Some damage was caused by this sequence of events and aftershocks. The sequence coincided with a minor upsurge in the frequency of moderately strong earthquakes in a wider region, extending from Marlborough (500 km south) to Taranaki. Epicentres of the Wanganui shocks were tightly concentrated in an area south of the city and in the part of Wanganui Basin where the sediments are thickest. The epicentral area has for some years been characterised by an unusually high frequency of microearthquakes, although stronger shocks have been no more frequent than in the surrounding areas. Anxiety that this sudden change of behaviour might be a precursor of a bigger earthquake was heightened by the concurrent activity in surrounding areas.

WAVERLEY FAULT ZONE

The Waverley Fault Zone is one of several southwest–northeast trending active zones of faulting in the South Taranaki region that vertically displace middle and late Pleistocene (500 000–10 000 yr) marine terrace surfaces. Other faults within the region include the Ararata, Nukumaru, and Moumahaki Faults, which are all downthrown to the east, and the Ridge Road and Waitotara Faults, which are downthrown to the west. All are normal faults trending southwest–northeast across the South Taranaki region. A series of right stepping, en echelon scarps, up to 4 m high, links the Waverley and Moumahaki Faults. These scarps may represent the westward continuation of Holocene activity on the Moumahaki Fault (Pillans 1990a).

Fault scarps of the Waverley Fault Zone are the result of rupture on a fault, or faults, at depth that has propagated to, and broken, the ground surface. Near Waverley township these scarps extend for a distance of c. 8 km, striking northeast (050°), reaching a maximum height of 5 m, and are downthrown to the southeast. The surface traces of the Waverley zone are generally left-stepping (Pillans 1990a), suggesting a possible dextral component of movement, but with predominantly dip-slip movement. The mapped fault zone displaces the Ngarino and Rapanui Terrace surfaces (210 000 and 120 000 yr in age, respectively), with the apparent absence of horizontal movement at the marine terrace risers probably being the result of the total amount of horizontal offset being less than the topographic irregularities developed on the risers (Pillans 1990b).

The Waverley Fault Zone shows no indication of progressive displacement, with little variation in scarp height observed across the terraces. Nor can the fault be seen to continue as a surface trace trending towards the coast or any farther north than mapped by Pillans (1990b). In the south, mobile young sand dunes have covered any surface indication of faulting as far inland as Lake Oturi (Fig. 3). Farther inland, the fault continues as a series of scarps to the Brunswick strandline (310 000 yr) (Fig. 1).

PALEOSEISMICITY OF THE WAVERLEY FAULT ZONE

Two trenches were excavated across a prominent scarp close to 3 m in height in the southern section of the Waverley Fault Zone (NZMS 260 metric grid ref. Q22/488576), 1.5 km south of Waverley township (Fig. 3). One sample pit was sited away from the fault zone, dug to help determine the stratigraphy of the area. The purpose of the trenches was to determine the age and amount of offset of geological layers that had been displaced by past fault movements. Of the two trenches excavated, only one was able to be safely worked in and logged (Fig. 4).

Stratigraphy

The main sedimentary units exposed in the trench are sands, and these have been deposited by a variety of mechanisms: the oldest were deposited by marine processes, and the

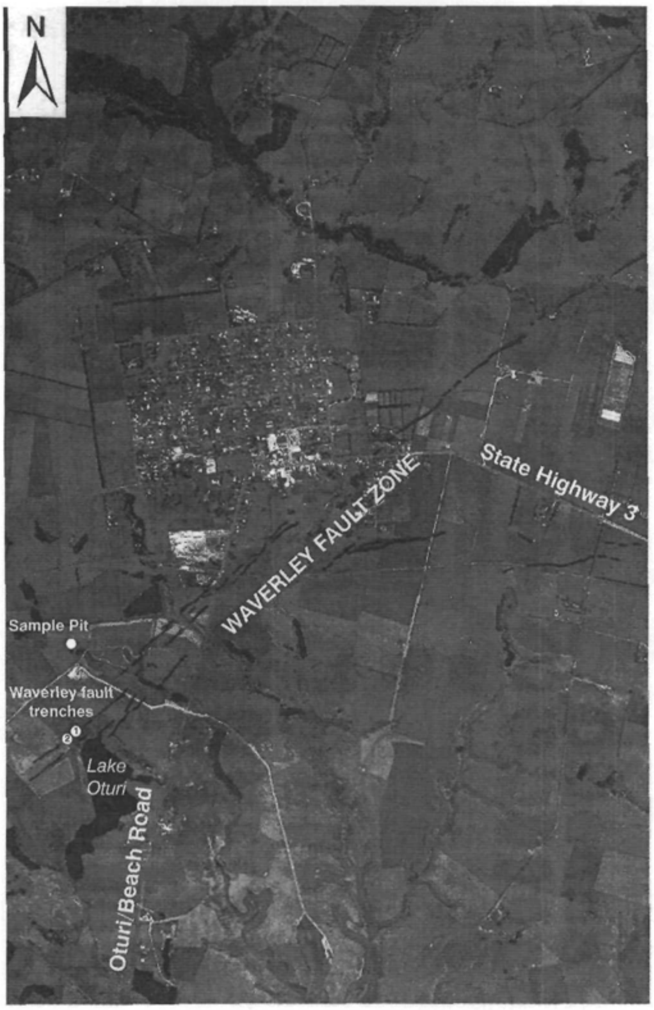

Fig. 3 Aerial photo showing the location of the Waverley Fault Zone and the trenches excavated across the southern end of the zone.

youngest by aeolian or fluvial processes. Prominent ripple structures are visible in the lower part of the section, indicating a marine origin or fluvial process. Similar ripples are not observed in the younger, upper section, therefore aeolian deposition is inferred. Thin iron pans occur above and below interbedded sands where changes of density, texture, and compaction (and hence changes of porosity and hydraulic conductivity) exist between two adjacent beds.

The deposits found within the Waverley fault trench have been accumulating since before 22 500 yr BP until present (see "Faulting history" below), and they have been divided into sedimentary units depending on their mode of deposition and their composition. Below is an outline of the stratigraphy of the trench, the units that have been observed, and the subunits that compose each unit.

Unit 1

The oldest deposits found within the trench were marine in origin. Ripples and water escape structures indicate that the marine environment was evolving during deposition. These laminated, fine-grained sands were located on the upthrown (NW) side of the scarp and were absent from the downthrown (SE) side. An auger hole 3 m in depth failed to intersect these deposits on the downthrown side of the trench. Three horizons of centimetre width "stringers" of tephra deposited in water were found within these marine sands. No age control was obtained.

Unit 1a

Two and a half metres of aeolian sands comprise unit 1a, which overlies the older marine sequence. These well sorted, fine grained sands are light grey and have megabed structures (large steeply dipping foreset beds), indicating aeolian deposition within the unit. Coarser, well-sorted horizons also exist within the unit.

Both units 1 and 1a were identified only on the upthrown side of the fault scarp.

Unit 2

A unit of very fine grained, bedded sands was identified on the downthrown side of the fault trench. These sands could not be traced across the fault zone to the higher side of the fault. Overthickening on the downthrown side of the fault is thought to have occurred during, or just after, deposition of this unit. The unit showed heavy iron staining throughout, with some areas being cemented.

Unit 3

Overlying unit 2 was the lowest marker bed, the Kawakawa Tephra (22 500 yr BP). Field identification of this tephra was reinforced by a radiocarbon sample (NZA 6236) taken from immediately above the tephra that gave an age of 22 670 ± 250 yr BP. The tephra was mauve to light grey and had a fine-grained basal horizon with coarse layers in it. Charcoal was apparent within the middle, coarser grained layer before the deposit fined upwards. This unit appeared to have been deposited in, and over, an already visible scarp at this site. An iron-stained tephric unit overlying the Kawakawa Tephra is incorporated into unit 3. This unit is composed of reworked Kawakawa Tephra and is itself overlain by a medium grained, orange/brown, sandy paleosol.

Unit 4

A wedge of colluvial material overlying the Kawakawa paleosol comprises unit 4. This unit was light to medium brown, poorly sorted, and of a very fine to fine grain size. A small proportion of silt was identified in the otherwise mainly sand deposit. No bedding was seen within the unit.

Unit 5

This unit was composed of weathered and unweathered ironsands deposited in a shallow water to aeolian environment. Slight ripple bedding is seen lower in the unit, indicating a shallow water means of deposition. These two sand subunits are described individually but comprise the same unit and are separated only by a short time gap—the lower subunit showing evidence of burrowing and voids which have been infilled by the sands of the upper subunit. The upper subunit is a dark grey, fine to medium grained sand, massive in appearance and strongly tephric in composition. The presence of augite/magnetite within the subunit is evident. The lower subunit shows more dominantly the iron-stained colours of weathering. These reddish-brown, fine to very fine grained sands (with a small silt content) are also massive.

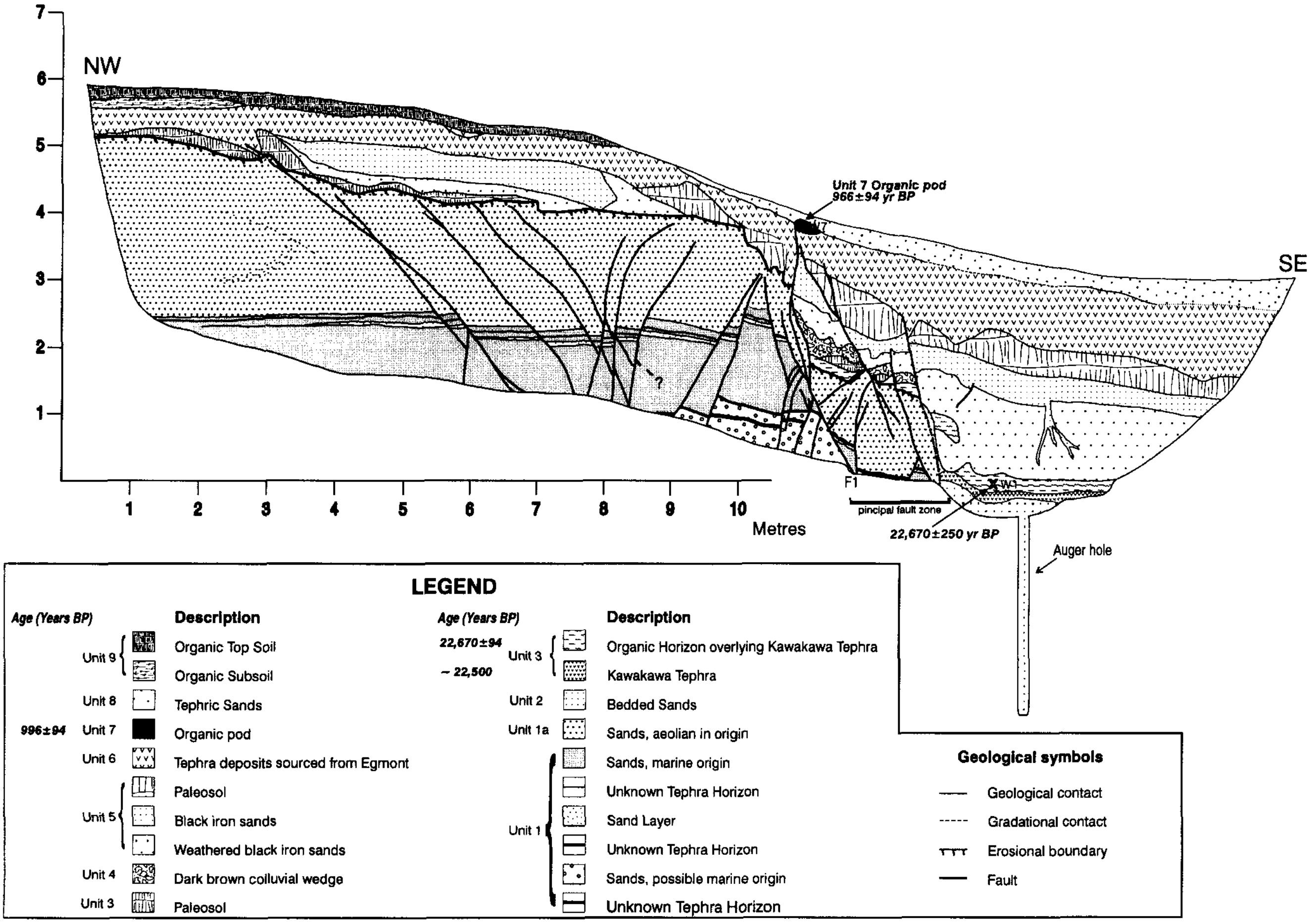

Fig. 4 Log of the Waverley fault trench.

Overlying the upper subunit there is a distinct paleosol, light brown, and of a silty, fine sand texture.

Unit 6

This unit is composed of a series of tephra deposits sourced mainly from Mt Taranaki. Due to the location of this study within the Taranaki region, and the prominent wind direction, Mt Taranaki is the only realistic source for these tephras. The tephras, due to their distal accumulation, are not distinct event horizons. Mixing has taken place, with deposits occurring relatively close to each other in time. The unit is composed of light grey-brown, silty, fine to medium grained sands overlain by a grey/black soil horizon.

Unit 7

This unit—a pod of organic material—is located abutting the fault and being truncated by it. This is a very fine grained, medium brown/grey, sandy soil. Charcoal was apparent within the unit.

Unit 8

This is a layer, or unit, of tephric-rich, light tan, very fine to medium grained sands. It was deposited interspersed with tephra from Mt Taranaki causing mixing of the two deposits (units 7 and 8). Deposition of this unit continued after the input from Mt Taranaki had ceased, allowing a distinctive unit to be formed.

Unit 9

The topsoil and subsoil horizons have formed above, and into, the tephric sands. Both horizons are tephra rich, dark grey/black, and friable.

Faulting history

Two sets of planar faults are exposed within the trench (Fig. 4). Both sets trend northeast (022–057°), with one set dipping 60–88° NW, the other set dipping 51–74° SE. Most faults can be followed across the floor of the trench between the two walls, indicating some continuity to the features. The main faults within the trench have normal separation.

The fault with the greatest measurable throw is F1 (Fig. 4), a southeast-dipping normal fault (c. 2 m of dip-slip separation). This fault displaces the entire stratigraphic sequence through to the upper tephric sands (unit 8) which overlie the Mt Taranaki (Egmont) tephra. Other faults within the trench indicate dip-slip displacements of up to 2 m.

The age of faulting within the Waverley trench was constrained by two dateable horizons. Radiocarbon dates taken from charcoal-rich horizons within this trench give some time control, but samples were scarce. The Kawakawa Tephra was located at the base of the downthrown side of the trench, giving a maximum age of 22 500 yr for several events. The organic horizon overlying the tephra (unit 3) was dated and provided a radiocarbon age of 22 670 ± 250 yr BP (NZA 6236). A soil pod near the surface of the trench (unit 7) provided a radiocarbon age of 966 ± 94 yr BP (NZA 6237). From the stratigraphy within the trench, a minimum of two or possibly three surface faulting events are interpreted to have occurred since the deposition of the Kawakawa Tephra and before development of the soil pod.

The earliest recorded event offset the organic horizon overlying the Kawakawa Tephra and its associated paleosol. A cumulative normal displacement across this southern segment of the fault zone, of at least 1.5 m, is represented by these offsets. A colluvial wedge (unit 4) deposited by scarp erosion after this event is seen in the trench stratigraphy.

A younger surface-rupturing event is represented by displacement on the black dune sands (unit 5) and the displacement recorded on the colluvial wedge material (unit 4). This movement represents a cumulative displacement of at least 0.9 m.

The last event to occur along the investigated segment of the Waverley Fault Zone is poorly represented, with the tephra deposits from Mt Taranaki (unit 6) being offset by only c. 100 mm. This offset may be due to settlement during an earthquake, not an actual surface-rupturing event, or could be related to movement on one of the other strands of the Waverley Fault Zone. Therefore, this event is not classified as a proven surface offset.

From the stratigraphy seen in the trench there is no evidence for any further surface-rupturing events. If further events had occurred, colluvial wedges would have been deposited within the fault zone, originating from the upthrown side of the fault. Events before 22 500 yr BP had significant offsets: the marine sands (unit 1) identified on the upthrown side of the fault were not identified on the downthrown side. These sands, the oldest deposit within the trench, must have been significantly displaced for them to be where they are today.

From this investigation, the timing of the two, or possibly three, events seen within the trench can be bracketed as occurring between 22 500 yr BP and c. 1000 yr BP. From this assumption it is possible to calculate a recurrence interval of 7000–11 000 yr for similar magnitude events. These values bracket the possible time range for the recurrence of surface-rupturing events along the southern section of the Waverley Fault Zone. If the last (of three) event was c. 1000 yr ago, with a mean recurrence interval of c. 7000 yr, then the combination of a long recurrence interval and a relatively recent event would suggest low hazard.

Earthquake magnitude

In the absence of surface rupture along the Waverley Fault Zone during historical time, when instrumental measurements of earthquake magnitude could be made, the magnitude of past earthquakes can be estimated only from measurements of the fault length and amount of fault displacement. In this study, the amount of surface displacement occurring during the last two earthquakes has been determined from trench exposure.

Earthquake moment magnitudes (*M*) have been calculated using the dip-slip displacement values measured in the trench. These measurements show the dip-slip separation of layers, and only represent the dip-slip component of movement at each trench site. Horizontal offsets of topography are absent along the Waverley Fault Zone. Therefore, I assume that the fault is normal, dips 60–88°SE, and the measured dip-slip separations represent the total slip on the fault segment during each earthquake at that site.

For the two events that have caused significant offset within the trench it is possible to calculate magnitudes. The formula of Wells & Coppersmith (1994) was developed from a regression between displacement and surface-rupture length:

$$M = a + b \log (MD) \qquad \text{(Eqn 1)}$$

where M = moment magnitude; MD = maximum displacement; a = 6.61 and b = 0.71, both are constants.

The primary purpose of developing regression relationships among various earthquake source parameters is to predict an expected value for a dependent parameter from an observed independent parameter (Wells & Coppersmith 1994). For the Waverley Fault Zone, we wish to determine the expected magnitude event that would cause a known surface displacement and length of surface rupture. The younger event within the trench offset the weathered black sand unit (unit 5) by a minimum of 0.9 m, and a magnitude of 6.6 has been calculated for this event. The earlier event displaced the Kawakawa Tephra (unit 3) by at least 1.5 m, giving a calculated magnitude of at least 6.7.

DISCUSSION

There are a number of views regarding the occurrence of active faults within South Taranaki. Stern & Davey (1988), Pillans (1990a), and Stern et al. (1992) have invoked flexural uplift around the edge of the Wanganui Basin to explain these faults. Stern & Davey (1988) likened the Wanganui Basin to the wedge-flexure type of back arc basin, a basin controlled by the development of a broad flexural downwarp. The description of the Wanganui Basin as a flexurally controlled compressional basin incorporates the concept that the driving load for downward flexure is the vertical component of the shear coupling between the Australian and the underlying, subducting Pacific plate. The model is consistent with the high-angle reverse faulting evident in seismic sections, as well as the pattern of crustal earthquakes beneath the southeastern part of the basin (Pillans 1990a). Compressional and extensional stresses related to plate bending are generated within the basin and are of sufficient magnitude to cause surface faulting of both normal and reverse sense. A partial match between the observed distribution of reverse and normal faults with that predicted by the three-dimensional flexural model is observed (Stern et al. 1992). Surface faulting caused by episodic rupture could produce several metres of displacement. A purely flexural origin might suggest shallow or "rootless" faulting extending to only a few kilometres depth. However, the storing of enough energy to break with several metres of displacement might suggest that the faults originate at greater depth. To quantify this statement it is possible to calculate the seismic moment for a surface rupture event, and from this determine the down-dip extent of the fault zone.

$$M = 2/3 \log (1.5M_o + 10.7) \qquad \text{(Eqn 2)}$$

$$M_o = 10^{\,1.5(M+10.7)}$$
$$= 10^{\,1.5(6.7+10.7)}$$
$$= 1.26 \times 10^{26} \text{ dyne cm}$$

$$M_o = \mu \, \dot{u} \, L \, w \qquad \text{(Eqn 3)}$$
$$= (3 \times 10^{11})\ 150\ (800\ 000)\ w$$
$$w = \frac{1.26 \times 10^{26}}{(3 \times 10^{11})\ 150\ (800\ 000)}$$
$$= 3\ 500\ 000 \text{ cm}$$
$$= 35 \text{ km}$$

$$d = w \sin(\text{dip}) \qquad \text{(Eqn 4)}$$
$$= 35 \sin 70°$$
$$= 31 \text{ km}$$

where M = moment magnitude; M_o = seismic moment; μ = shear modulus or rigidity (3×10^{11} dyne cm^{-2}); $\dot{u}$ = displacement (cm); L = length of fault (cm); w = width of fault; d = depth of fault.

From existing data, a depth of 31 km is considered to be deeper than expected. Either the magnitude calculated from Wells & Coppersmith (1994) is incorrect or the Waverley Fault Zone may not be of seismogenic origin. Flexural bending due to downwarping of the Wanganui Basin may have contributed to fault zone formation. In this instance the expected magnitude for surface-rupturing events, as those seen in the Waverley fault trench, can be calculated from Wells & Coppersmith (1994). Using a preferred dip value of 70°, a displacement per event of 1.5 m, and a fault length of 8 km, I obtained the results in Table 1a. Table 1b uses a preferred dip value of 70°, a displacement per event of 1.5 m, and a fault depth of 12 km.

These results indicate a lower magnitude event than that calculated by Wells & Coppersmith (1994), which would be more in keeping with similar faults investigated within New Zealand (Berryman pers. comm.).

During the development of a flexure-type basin, the Waverley Fault Zone could have formed as a bending moment fault, a side effect of the anticlinal bulge formed itself by downwarping of the Wanganui Basin in association with a northwest–southeast compressional regime. Bending moment faults related to folding are of a small scale and are unlikely to be of major seismogenic significance. At shallow depths (<2–3 km) the low strength of the rocks coupled with the low stress state restricts the elastic strain energy available to generate large earthquakes. Accordingly, they are classified as low-shake faults: they may produce earthquakes, but not large damaging ones (Yeats 1986). However, folds, including those formed by flexural-slip, may themselves be side-effects of deeper, seismogenic faulting. The faults are themselves not the source of major earthquakes, but the folds of which they are a part may be formed by stick-slip on a deeply buried major fault which cuts stronger crustal rocks. All known historic examples of flexural-slip or bending-moment faults are coseismic; none are known to have formed by aseismic creep (Yeats 1986).

Uplift on the margins of a roughly circular basin is thought to produce extensional faulting orientated parallel with the basin margins. In the South Taranaki region this appears to be so. This could indicate that the faults are of purely flexural origin, bending moment faults, and not deep seated as first thought. As the depocentre of the basin has moved over time, fault activity would have increased or ceased, depending on its location in relation to the basin margin. The close association between the Waverley Fault Zone and the Whangamomona Anticline gives added support to the theory that the Waverley Fault Zone is related to basin formation and downwarping. The fault zone is within 5 km of the anticlinal crest, sufficiently close to have been influenced by the formation of the anticlinal structure (Fig. 1).

Alternatively, the Waverley Fault Zone may have formed, like most other normal faults, in a regional zone of extension in response to tension in the backarc region of the Hikirangi subduction zone, and is responding to the same strain as occurs in the Taupo Volcanic Zone along-strike to the northeast. If so, the Waverley Fault Zone can be classed as a seismogenic fault, capable of producing large magnitude earthquakes.

However, it is more likely that the Waverley Fault Zone has been formed as a result of flexural uplift around the margins of the South Wanganui Basin. This is mainly due to the 1–2 m displacements occurring per event being parallel to the basin margins, the segmentation of the fault zone, and the close association between the zone and the Whangamomona Anticline. Further investigations of the northern segments of the fault zone may indicate a similar means of origin for the zone.

Table 1a, b Expected magnitudes (uncertainty ± 0.3) for earthquake events occurring on the Waverley Fault Zone. The method for these calculations is outlined in the accompanying text.

(a)

Shear modulus (μ)	Depth (km) 4	8	12
3.0	6.1	6.3	6.4

(1b)

Shear modulus (μ)	Length (km) 8	12	16
3.0	6.3	6.4	6.5

Faults similar in style to the Waverley Fault Zone have been shown to be of shallow depth. Therefore, it is assumed that the Waverley faults will be consistent with this theory. Depths ranging from 4 to 12 m were chosen to cover a range of depths that could be expected. A selection of lengths for the fault zone were also used to allow for miscalculation of the surface fault rupture length due to recent sediment movement covering the surface trace. A shear modulus of 3×10^{11} dyne cm^{-2} is usually applied to crustal faults (Hanks & Kanamori 1979).

CONCLUSIONS

1. The Waverley Fault Zone is described as a zone of active faults, having experienced repetitive surface rupture during the Quaternary (1.63 Ma to present). The Waverley Fault Zone displays normal extensional faulting over a length of c. 8 km.
2. The historical earthquake catalogue shows that:
   (i) historical earthquake activity has been relatively quiet during the past 150 yr for the Waverley area;
   (ii) eight events of $M_L \geq 5$ have occurred within 50 km of Waverley township in historic time.
3. Trenching studies carried out on the Waverley Fault Zone have determined the following information.
   (i) Surface rupture has occurred on the southern section of the Waverley Fault Zone at least twice during the last 22 500 yr.
   (ii) The deposits cut/truncated by these faulting movements are composed mainly of sands of marine and aeolian origin.

(iii) Earthquake moment magnitudes have been calculated for the two events displacing deposits within the trench, using the regression formula of Wells & Coppersmith (1994). The latest event to have caused significant displacement can be assigned a minimum magnitude of 6.6. The earlier event has a calculated minimum magnitude of 6.7. Both events can be expected to cause shaking of intensity MM9–10 in Waverley township. Additional calculations using the formula of Hanks & Kanamori (1979) resulted in a significantly lower value for the expected magnitude event, this being at maximum *M* 6.5. An average value of *M* 6.3 is obtained and accepted by this study.

(iv) An average recurrence interval for major events along the southern section of the fault zone has been calculated as 7000–11 000 yr. From field studies, surface fault rupture has not occurred for at least 1000 yr.

(v) The earthquake hazard in South Taranaki from future large earthquakes generated along the Waverley Fault Zone is considered to be low.

(vi) The Waverley Fault Zone is inferred to be a result of flexural uplift around the margins of the South Wanganui Basin. Future investigation of the northern segments of the fault zone is recommended to further test this conclusion.

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