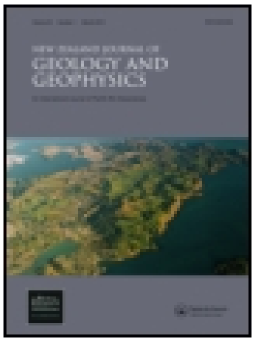

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Late Quaternary movement on the Ohariu Fault, Tongue Point to MacKays Crossing, North Island, New Zealand

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Abstract The Ohariu Fault is one of the major active dextral strike-slip faults in the Wellington region. It extends northeastward from offshore at Tongue Point to Waikanae and beyond, but in the north the fault trace becomes intermittent. Extrapolation of the trend of the Ohariu Fault across Porirua Harbour suggests a 1.5 km right step.

South of Porirua Harbour the fault is characterised by lateral displacement of drainage features of up to 450 m, a single-event lateral displacement of 4–5 m, an average horizontal slip rate of 1–2 mm/yr, and a recurrence interval of 2000–5000 yr. The timing of the last event was between 150 and 1130 cal. BP. North of the harbour the fault is characterised by lateral displacement of drainage features of up to 250 m, a single-event lateral displacement of 2.9 m, a horizontal slip rate of 0.6–1.9 mm/yr, and a recurrence interval of 1530–4830 yr. The timing of the last event was between 1070 and 2310 cal. BP.

Although the possibility exists that Porirua Harbour is a pull-apart basin marking separate rupture segments on the Ohariu Fault, the data suggest there is a single rupture segment from Tongue Point to Waikanae. On this assumption, the last movement on the fault occurred 1070–1130 yr ago. The average horizontal surface displacement for the event was 3.7 m (based on seven sites) and the estimated earthquake magnitude was M_w 7.1–7.5.

Keywords Ohariu Fault; Wellington; Porirua; Makara; Tongue Point; Mackays Crossing; neotectonics; late Quaternary; active fault; strike-slip; dextral; slip rates; NZMS 260 R26, R27

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INTRODUCTION

Geological setting

The present-day boundary between the overriding continental crust of the Australian plate and the subducting oceanic crust of the Pacific plate occurs offshore from the southern North Island of New Zealand (Fig. 1, inset). Oblique subduction occurs at the Hikurangi Trough, and most of the southern North Island occupies an active margin characterised by dextral strike-slip faulting (Walcott 1978). In the Wellington region, most of the strike-slip component of plate motion is taken up on these strike-slip faults (Berryman 1990). Faults in the east generally have higher lateral slip rates than those in the west (Berryman 1990; Van Dissen & Berryman 1991).

The major active faults (Wairarapa, Wellington, Ohariu, Pukerua, and offshore faults; Fig. 1) strike northeast through the Wellington region. At the southern coast, the Ohariu Fault occurs 4 km west of the Wellington Fault. The faults diverge northeastward, and 70 km to the northeast at Waikanae they are 30 km apart. The Ohariu Fault is less topographically pronounced than either the Wellington or Wairarapa Faults. From Makara to MacKays Crossing (Fig. 2), the fault trace is well defined, but to the north, beyond MacKays Crossing, surface traces become intermittent. This may be a function of trace preservation in more active landscape, but could also be related to the way in which plate motion is partitioned between the major faults.

Previous work

McKay (1892) was the first to show an active fault in the Ohariu valley. Hall (1946) named the feature the Ohariu Fault and indicated it may be continuous with the "Quartz Creek Fault" north of Porirua Harbour. Adkin (1954) described Hall's Quartz Creek Fault and other active traces in Kahao* and Horokiri Streams north of Porirua Harbour, naming the features the Kaka, Kakaho, and Mt Wainui Faults. These features were later linked by Lensen (1958) and termed the Owhariu Fault. Macpherson (1948) mapped an active fault trace in the Muaupoko Stream valley and labelled it the Gibbs Fault. On the 1:250 000 geological map, Kingma (1967) extended the Ohariu Fault north to include Macpherson's trace, annotating it the Owhariu-Kakaho-Gibbs Fault. In a popular account of Wellington geology, Stevens (1974) used the name Owhariu Fault when describing features in the Ohariu and Kahao valleys. Detailed mapping of late Quaternary fault traces and landforms in the Porirua

*Kahao Stream is the name given in the "Gazetteer of New Zealand Place Names" (Lands and Survey 1968) and the online New Zealand Geographic Place-names Database (at **http://www.linz.govt.nz**) for this stream. Many topographic maps, including the current NZMS 260 sheet, show the feature as Kakaho Stream, and many publications on faults in this area have used this incorrect spelling.

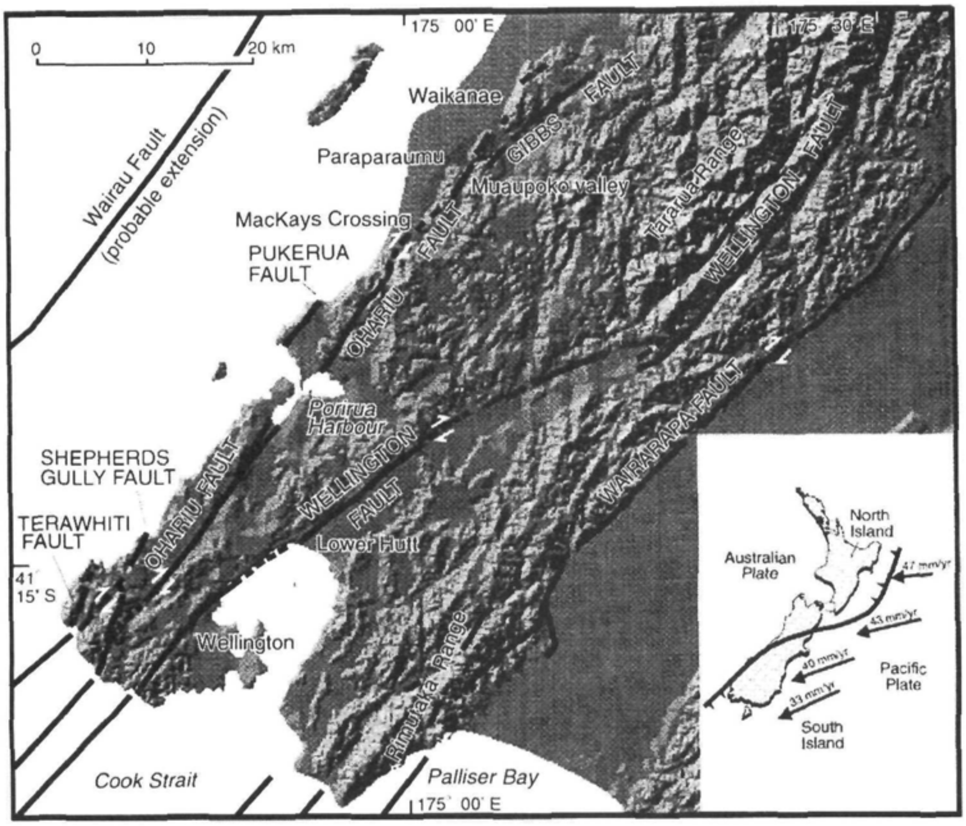

Fig. 1 Location of Ohariu Fault and other active faults in the Wellington region. Offshore data from Carter et al. (1988) and Lewis et al. (1994); onshore South Wairarapa data and probable extension of Shepherds Gully Fault from Begg & Mazengarb (1996). *Inset*: Approximate boundary between the Australian and Pacific plates, and relative plate motion (from DeMets et al. 1990).

area by Williams (1975) was extended south by Ota et al. (1981), who applied the name Ohariu Fault and presented data concerning horizontal and vertical offsets, rates, periodicity, and amount of fault movement. Carter et al. (1988) demonstrated the Ohariu Fault extended some distance offshore. North of Waikanae, a "new" active fault has recently been discovered (Van Dissen et al. 1998). This feature, currently under study, is most likely the northeastern continuation of the Ohariu Fault and extends to within about 10 km of Palmerston North.

This study

In this paper, we use the name Ohariu Fault for the fault that extends from central Cook Strait south of Tongue Point northeastward to Waikanae and beyond (Fig. 2). The name Gibbs Fault is retained for the ENE-trending fault that most probably branches from the Ohariu Fault near MacKays Crossing.

A major motivation for this study was to refine our understanding of the hazard posed by the Ohariu Fault. Large earthquakes on the fault pose a serious threat to the Wellington Region, from both the strong ground shaking that would be generated and localised ground rupture. The Ohariu Fault passes through Porirua City, and a number of major lifelines such as State Highway 1, the North Island Main Trunk Line, gas and electricity distribution lines, and the proposed Transmission gully highway cross the fault. Features resulting from past fault ruptures provide data that allow the size and return period of similar future faulting events to be estimated. This assists planners to select appropriate sites for future development and enables engineers to design structures capable of withstanding the expected hazard.

While the Ohariu Fault is presumed to be a continuous feature, the surface traces are not. Except for the 7 km long section between Waiariki Stream and Makara (Fig. 2), active traces of the Ohariu Fault can be followed through the Ohariu valley, Porirua, Kahao Stream valley, upper Horokiri Stream valley (also referred to as Transmission gully), MacKays Crossing, and Valley Road valley, and these traces are described here. Whereas sharp traces mark the Ohariu Fault from Makara as far north as Waikanae, the traces become more intermittent beyond MacKays Crossing. This paper is restricted to describing the fault south of the MacKays Crossing-Valley Road area. In most areas where no trace is preserved, we suspect that erosion associated with steep topography has modified or obliterated evidence of surface displacement. Where preserved, displaced geomorphic features that were once continuous across the fault provide reference lines and surfaces that allow determination of displacement. Terrace surfaces are examples of reference features suitable for measuring vertical displacements, and terrace risers, stream channels, and ridges are often suitable for determining horizontal displacements.

Work for this study began in 1986 with aerial photograph interpretation of the area from Porirua Harbour to Waikanae (metric topographic map series NZMS 260, R26). Subsequently, all fault traces identified on airphotos were walked out for their entire length. Measurements of displacement were made using a tape measure or, for large lateral displacements, by direct measurement from aerial photographs. Previously unpublished data from 80 localities between Kahao Stream and Valley Road are recorded (Appendix 1) and important localities are referred to in the text (e.g., Loc. 035).

Trenching of the fault in the Ohariu valley (three trenches) and in the Horokiri valley (one trench) was conducted between 1990 and 1992. Detailed logs of trench walls (simplified and presented as Fig. 5, 7, 9 and Appendix 2), together with radiocarbon data (Appendix 3) from deposits exposed in the trench walls, were used to infer a faulting history for each trench. Key to the interpretation is the identification of "colluvial wedges" that form after a faulting event, as the exposed upthrown block sheds material across the fault onto the surface of the downthrown block. Typically, the colluvial wedge unconformably overlies the fault plane, and fines upward and away from the fault plane. Subsequent fault movement tends to truncate the colluvial wedge, the material on the upthrown block being reworked to form another wedge. Other keys to the interpretation of faulting history are fault-disturbed or displaced deposits.

For the purposes of this study, the Ohariu Fault is subdivided into three sections (Tongue Point–Makara, Makara–Porirua Harbour, and Porirua Harbour–MacKays Crossing) defined on trace orientation and continuity (Fig. 1, 2). This paper describes the nature of the fault trace in those three sections and reviews data from previous workers for the southern sections. New data on the location of the fault trace in the Porirua Harbour–MacKays Crossing section is presented, together with details of late Quaternary displacements, slip rates, and timing of the last event determined from mapping and trenching of the fault.

OHARIU FAULT

Tongue Point–Makara

The Ohariu Fault is traced for c. 20 km across the continental shelf from the central Cook Strait to Tongue Point (Carter et al. 1988). The fault comes onshore near Waiariki Stream (NZMS 260 grid ref. R26-27/484847), just west of Tongue Point (Fig. 2), on the Wellington south coast. A pronounced crush zone in Waiariki Stream, in places several tens of metres wide, can not be traced beyond 1.5 km from the coast, and it is not known whether the fault passes up the left or right branch (493865) before presumably crossing into the Makara valley. It is possible that a splay of the fault may also extend towards the Shepherds Gully Fault in Shepherds Gully, as suggested by the orientation of linear drainage in this area.

Although no surface trace is preserved in Waiariki Stream, displacements have been determined from remnants of a marine terrace on either side of the stream at the coast. The marine terrace is vertically offset by 40 m up to the west. The fossil sea cliff that is the front of the terrace shows an apparent right-lateral displacement of at least 100 m. Ota et al. (1981, p. 29) assumed the terrace surface to be 120 000 yr old, and postulated the 100 m offset was a minimum value, with the true lateral displacement being between 120 and 144 m. However, it is difficult to differentiate between tectonic lateral displacement and preferential erosion of the sea cliff, and the above lateral displacement figures should be interpreted with caution.

Makara–Porirua Harbour

In the Makara valley, the Ohariu Fault is preserved as an intermittent trace trending northeast (032–048°) on the eastern side of the valley (Loc. O402–O416*). A Pliocene outlier at Makara was interpreted as lying between strands of the Ohariu Fault (Grant-Taylor & Hornibrook 1964; Kingma 1967), and Ota et al. (1981) and Begg & Mazengarb (1996) mapped an active trace on the northeastern side of the outlier. The fault passes from the Makara valley through the hills to the west of Takarau Gorge (Loc. O411–O020) into the Ohariu valley, where intermittent traces and then a 6 km long, near-continuous trace are preserved to the west of the Ohariu Valley Road (Loc. O028–O062 and beyond). The fault bifurcates before crossing the ridge both west and east of Spicer Trig. Two kilometres farther northeast, two near-parallel fault traces are preserved, one adjacent to Broken Hill Road (Loc. O086) and the other, parallel to the Colonial Knob Walkway (Loc. O088), passes west of Porirua Hospital toward Porirua City (Williams 1975; Ota et al. 1981).

Displacements on the Makara–Porirua section of the Ohariu Fault are dextral and up to the northwest, except at Porirua where both near-parallel traces are up to the southeast. The largest lateral displacement measured by Ota et al. (1981) was c. 450 m on incised drainages south and west of Takarau Gorge (Loc. O416, O411). The largest vertical displacement measured was 5 m (Loc. O402). A terrace riser and stream channel offset at separate localities on the eastern side of the Takarau Gorge Road (Loc. O020, O028) and a stream channel offset on the eastern side of Makara Stream, 750 m northeast of Makara (Loc. O404), indicate displacements of between 4–5 m horizontal and 0.6 m vertical (Ota et al. 1981). Ota et al. (1981) recorded numerous other sites with similar-sized horizontal displacements, and we infer that these sites are indicative of the size of surface rupture resulting from the most recent event. A 5 m single-event horizontal displacement is supported by Williams (1975), who measured offsets of 5, 10, and 17 m on each of several small tributary streams in upper the Ohariu valley.

Near Porirua, Williams (1975) recorded a c. 30 m right-lateral offset of a now-destroyed shoreline, thought to relate to the maximum postglacial transgression (c. 6500 yr ago). Slip rates calculated from Williams' Porirua data are three times larger than those calculated elsewhere on the fault (see Table 1) and led Ota et al. (1981) to question the dating of the shoreline. Van Dissen & Berryman (1991) suggested that vertical offsets of the harbour floor may have contributed to the apparent lateral offset of the shoreline.

Ota et al. (1981) noted that at some sites in the Ohariu valley, large horizontal displacements were accompanied by anomalously small vertical displacements. At their example site (Loc. O062), a 20 m lateral displacement is accompanied by 1.1 m vertical displacement. Given single-event lateral and vertical displacements of 5 and 0.6 m, respectively, the 20 m lateral displacement suggests four events; the expected vertical displacement is therefore 2.4 m. Ota et al. (1981) suggested the small vertical displacement may indicate reversal of throw during postglacial time. Trenching near the site (see Fig. 5) revealed that sedimentation on the downthrown side of the fault has significantly reduced the scarp height, which does not reflect the total accumulated vertical displacement. In addition, the fault plane dips at a low angle (<10°), which has resulted in deformation being spread over a broad zone, making scarp height difficult to determine.

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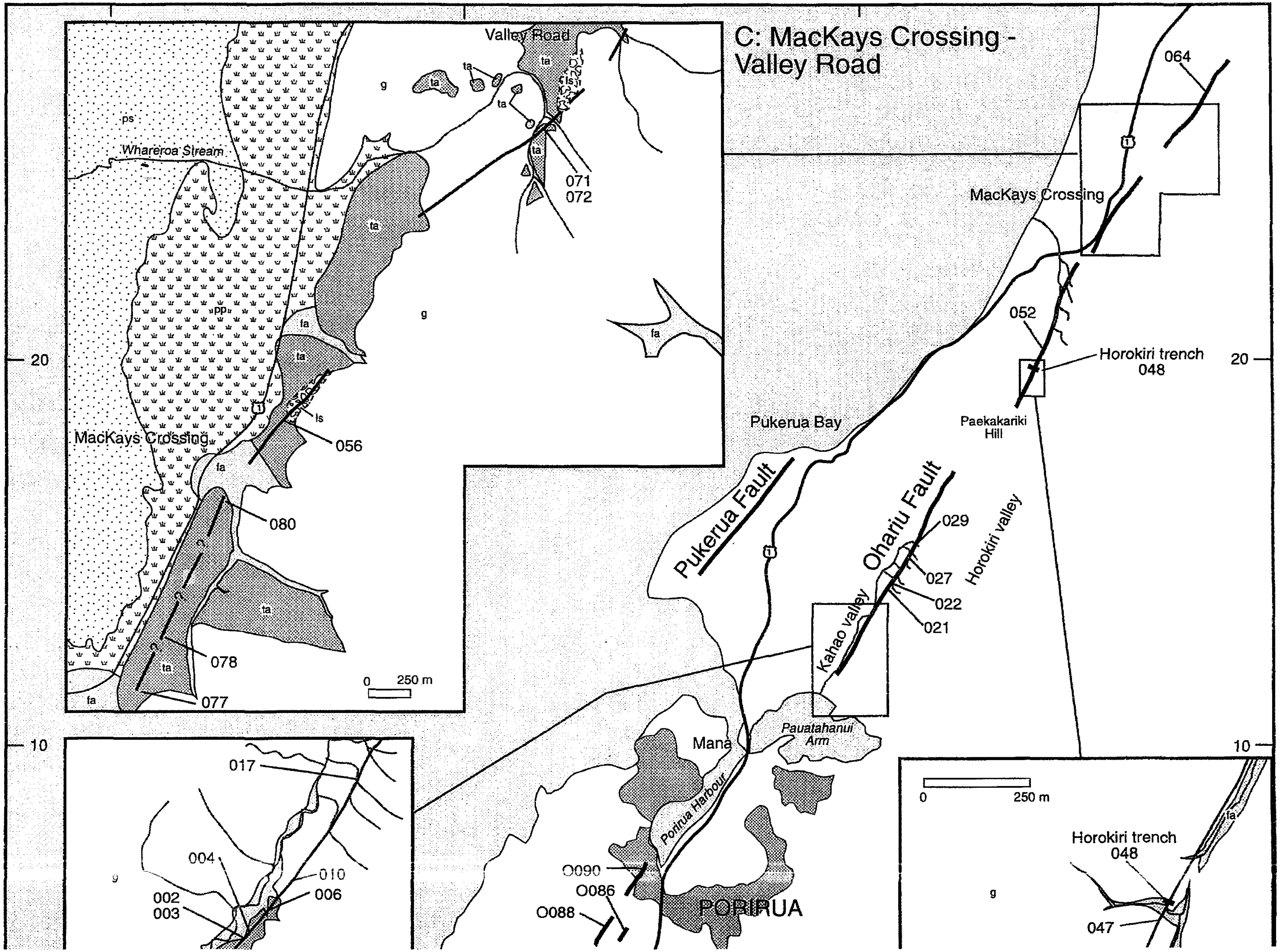
*Locality numbers in this form are from table 8 of Ota et al. (1981) and are depicted in Fig. 2.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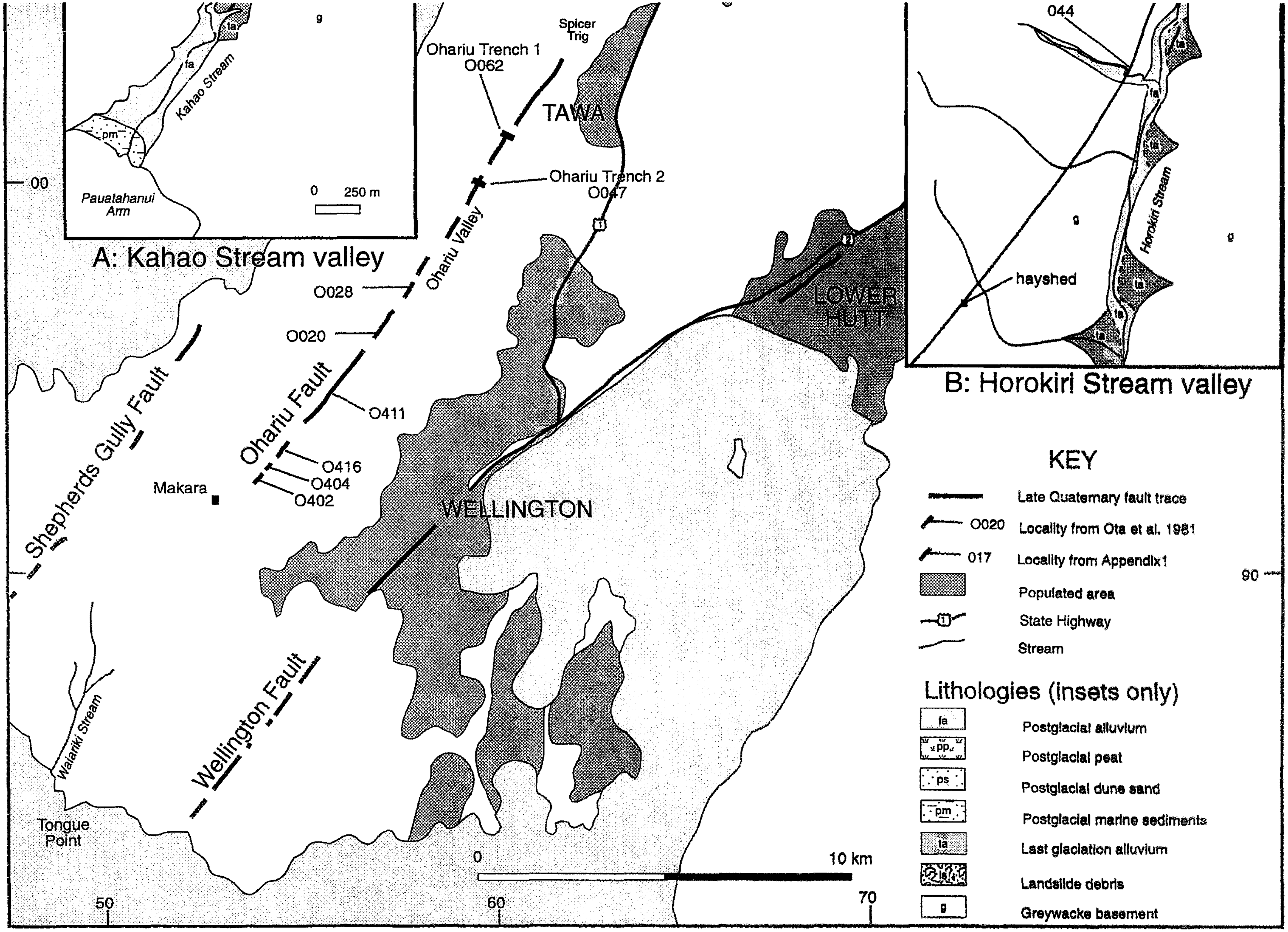

Fig. 2 Active traces of the Ohariu Fault between the Wellington coast and MacKays Crossing, south of Paraparaumu. Data south of Porirua Harbour are from Ota et al. (1981); key locality numbers are of sites referred to here and are from their table 8. Insets of areas north of the harbour show key localities from this study (see Appendix 1).

Porirua Harbour

No information exists on the location of the fault (or faults) within Porirua Harbour. Extrapolation of the trend of the Porirua traces northward and the Kahao valley trace southward indicates the possibility of a 1.5 km right step in the vicinity of Mana. Such a geometry on a right-lateral fault would result in a pull-apart basin (Burchfeil & Stewart 1966; Mann et al. 1983) and an area of relative subsidence. Surveys of marine terraces in the area by Ota et al. (1981) indicate those west of Porirua Harbour decrease in height towards the harbour, and those surrounding the harbour were "relatively depressed", with the last interglacial terrace being at c. 5 m above sea level (Ota et al. 1981; J. Begg. pers. comm.) The last glaciation aggradation terrace is 13 m below present-day sea level in the Pauatahanui Arm of the harbour (Grant-Taylor 1980), although the base level at that time, which was lower than that of the present day, would probably have been controlled by the height of the outlet in the Mana area. The available evidence is, however, consistent with relative subsidence associated with an active pull-apart or releasing bend on the Ohariu Fault.

Porirua Harbour–MacKays Crossing

The Ohariu Fault (Fig. 2), extends up the northeastern side of Kahao valley to the Paekakariki Hill Road, parallels the road for c. 1.5 km, then strikes northeast toward Horokiri valley. It crosses the slopes west of Horokiri Stream and passes through the saddle at the head of the stream into an unnamed stream that drops towards State Highway 1. The fault crosses this stream before trending northeast through low saddles towards MacKays Crossing. To the north of MacKays Crossing, the fault is mapped through several saddles east of State Highway 1 to east of Valley Road. North of Valley Road, sections of trace up to 2 km long are separated by up to 3.5 km gaps.

Kahao Stream

The trace of the Ohariu Fault in the vicinity of Kahao Stream trends northeast along the eastern margin of the valley (Fig. 2, inset A) and is marked by intermittent small scarps (Kaka Fault of Adkin 1954) in the lower valley (Loc. 002–006*) and by a striking set of displaced ridges and guided streams (Kakaho Fault of Adkin 1954) in the upper valley (Loc. 010–029 and beyond).

The fault is not seen in the postglacial alluvium (fa) of the floor of Kahao valley, but on the eastern side of the lower valley the trace displaces remnants of last glaciation alluvial fans and fluvial terraces (ta). The trace side-steps to the left (e.g., Loc. 002), and the strike swings from northeast (047°) towards NNE (038°) in the upvalley direction (see Adkin 1954, fig. 3). Displacements are dextral and west side up. Vertical displacement on the terraces reaches 1.2 m (Loc. 003), but an offset ridge (Loc. 010) farther up the valley indicates 1.8 m vertical displacement. An incised channel within a younger last glaciation lower valley terrace indicates a maximum dextral displacement of 14.5 m (Loc. 006). Horizontal displacements generally increase up the valley. Offset streams in the upper valley suggest up to 250 m cumulative dextral displacement (Loc. 027, 029).

*Locality numbers in this form are from Appendix 1 and are depicted in the insets in Fig. 2.

The smallest lateral offset measured in Kahao valley is 2.9 m (Loc. 004, 017, 021, 022), and is inferred to indicate the size of the most recent surface rupture event. At one of these localities (Loc. 004), the related vertical displacement is 0.95 m, and similar small vertical displacements are measured elsewhere (Loc. 001, 003, 007, 012).

The fault passes through a saddle at the head of Kahao Stream into a tributary of Horokiri Stream. The valley is steep sided, and no traces are seen, but crush zones in greywacke exposed in the stream and an adjacent track, and notched spurs to the east of Paekakariki Hill Road, define the fault.

Horokiri Stream

Within the Horokiri Stream valley (Fig. 2, inset B; Fig. 3) the Ohariu Fault trends NNE (020–040°). From the gas pipeline on the saddle above Paekakariki Hill Road (741190), the fault is marked by crush zones in greywacke (g) and several low saddles. A small scarp visible on old aerial photographs in this vicinity has been partially destroyed by construction of a farm track and a hayshed. The fault trends towards Horokiri Stream, crossing the hillslope to the west where it is expressed as a subdued scarp, or a bench where slopewash (colluvium) has accumulated behind the scarp, and several small streams are ponded by offset topography (Fig. 3). From the saddle at the top of Horokiri Stream (near Loc. 048), the fault follows a NNE-draining stream before swinging northeast though fault-guided streams toward MacKays Crossing.

Along the Horokiri Stream section of the fault, displacements are dextral and up to the southeast, although in some localities apparent vertical displacements are the result of lateral offsets of topography. The largest horizontal displacement measured from surface features is 36 m (Loc. 047; see Fig. 8). Scarps across tributaries of Horokiri Stream (Loc. 044, 048) are up to 2.2 m high, but are the result of lateral displacement of high ground rather than vertical displacement across the fault. A small degradation terrace remnant in the NNE-draining stream (Loc. 052) is displaced by a 1.3 m vertical scarp. An exposure in the stream immediately to the south showed slope debris faulted against greywacke, and a fault plane orientation of 045/55° NW.

Trenching in Horokiri Stream near the saddle (Loc. 048) indicates that the cumulative lateral displacement may be as much as 76 m in the last 40 000 yr (see Fig. 8 and associated discussion).

MacKays Crossing

Immediately south of MacKays Crossing, a broad 2 m high step (Loc. 077–080) trends NNE (022–037°) across a large last glaciation alluvial fan (ta) and may mark the Ohariu Fault (Fig. 2, inset C). North of MacKays Crossing the fault trends northeast (055–070°) and is marked by a series of low saddles and traces across hillslopes (g) and fan surfaces (ta) to south of Whareroa Stream, near Valley Road (Loc. 071). The fault crosses remnants of a last glaciation surface (ta) adjacent to Whareroa Stream, and has formed a small graben 6–10 m wide and 43 m long (Loc. 072).

Dextral displacements are in the order of 10 m as judged from a poorly defined offset stream channel cut in the fan surface (Loc. 056) immediately north of MacKays Crossing, and at Whareroa Stream, where the largest horizontal displacement, measured from an offset drainage, is 7 m (Loc. 071). Vertical displacements are generally small

Fig. 3 Looking south down the Horokiri valley toward Porirua Harbour (right distance). The Ohariu Fault (solid arrows) is preserved as a bench crossing the hillslope to the west (right) of Horokiri Stream from the right foreground to the gas pipeline on the ridge in the middle distance. Augering behind the scarp on the bench indicated peat impounded behind greywacke/colluvial debris. The small stream in the right foreground is ponded by offset topography and was the site for the Horokiri valley trench (see Fig. 8). The Horokiri valley is fault controlled, with crush zones exposed at a number of localities. Features that may be active traces have been reported in the lower valley (Hancox 1969) and middle valley (M. Stirling pers. comm.), but have not been examined by us; a possible active trace is noted on the photo (dashed arrows). *Photo*: *D. L. Homer, Institute of Geological & Nuclear Sciences Ltd.*

(c. 0.7 m) and are predominantly east side up, although accumulated vertical displacement on the possible trace south of the MacKays Crossing could exceed 2 m (Loc. 078). A single locality indicates a dextral displacement of 3.8 m (Loc. 064) and may reflect the size of the horizontal displacement resulting from the most recent surface rupture event.

TRENCHES

Four trenches were excavated across the Ohariu Fault in the area of this study, three in the Ohariu valley, at two separate sites (596001, c. Loc. O047; 605013, c. Loc. O062), and the fourth in the Horokiri valley, east of Paekakariki Hill Road (747199, Loc. 048).

Ohariu valley 1 site

In the upper Ohariu valley, the Ohariu Fault separates alluvial fans from a flat-topped, central valley ridge. To the east of the fault, at least three surfaces of differing relative elevation slope down toward it. Rangitawa Tephra (Mildenhall et al. 1977; Pillans 1992; Kohn et al. 1992) occurs within deposits on one of the older surfaces in this area, indicating some of these features are at least 350 000 yr old.

At the Ohariu valley 1 trench site (Loc. O062), the central valley ridge shows marked dissection (Fig. 4). A minor tributary of the Ohariu Stream flows from a deeply dissected area against the foothills, across a little dissected fan surface adjacent to the fault, and then through a 60 m wide valley in the dissected ridge. It seems unlikely that the present stream dissected the ridge which rises to over 20 m above the present valley. A stream to the south of the trench site (Fig. 4) is deeply incised in a fan, and may have been responsible for the dissection of the ridge, the ridge subsequently being displaced 225 m by fault movement (A–A' of Fig. 4 inset). The widths of the valleys at both localities are similar. Numerous displaced drainages with similar horizontal offsets occur along the fault to the south. The ages of these displaced features are not known.

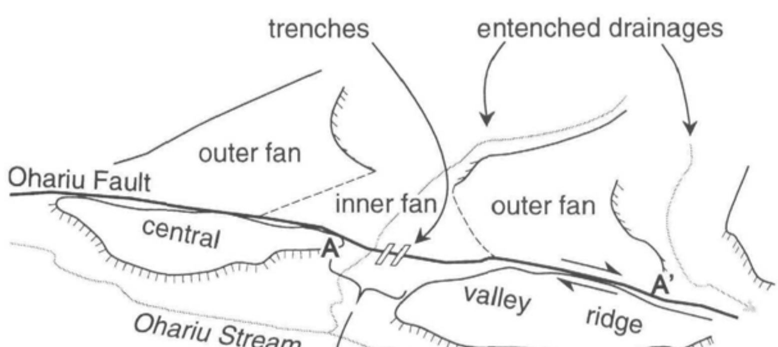

Fig. 4 Looking southeast over the site of Ohariu valley trenches 1a,b adjacent to upper Ohariu Valley Road. The dissected central valley ridge is east of the Ohariu Stream (foreground), with the Ohariu Fault at the ridge's eastern margin (see sketch). A tributary of the Ohariu Stream (centre) passes from a deeply dissected outer fan region against the foothills, across a little dissected inner fan, across the Ohariu Fault, and through the dissected ridge. We infer that the central valley ridge was dissected by the tributary to the south (A matching with A'), the ridge being subsequently moved north 225 m by displacement along the fault. *Photo: D. L. Homer, Institute of Geological & Nuclear Sciences Ltd.*

Differences in dissection of the surface to the west of the fault at the trench site suggest that the area is a composite feature comprising an older outer fan and a younger inner fan (Fig. 4). Drainage is entrenched at the upslope end of the surface, and this dissection is in the older fan and is similar to that seen immediately to the south. This dissection once extended across the entire surface of the older fan, but the lower portion has since been infilled by the younger inner fan alluvium, which overtopped the outer fan adjacent to the road. We infer that infilling occurred at a time when the drainage was blocked by movement on the Ohariu Fault, probably as an undissected portion of the central valley ridge was moved adjacent to the trench site. Later, as the dissected portion of the ridge was moved adjacent to the trench site, the scarp was overtopped and drainage resumed through the pre-existing valley.

A 0.6 m high uphill-facing scarp is preserved across the mouth of the 60 m wide valley cut in the central valley ridge. Two trenches (1a, 1b), 10 m apart across the scarp, revealed greywacke overlain by gravel and gravelly silt to the west of the Ohariu Fault, and fan, stream, and swamp deposits to the east (Fig. 5). The presence of fine-grained

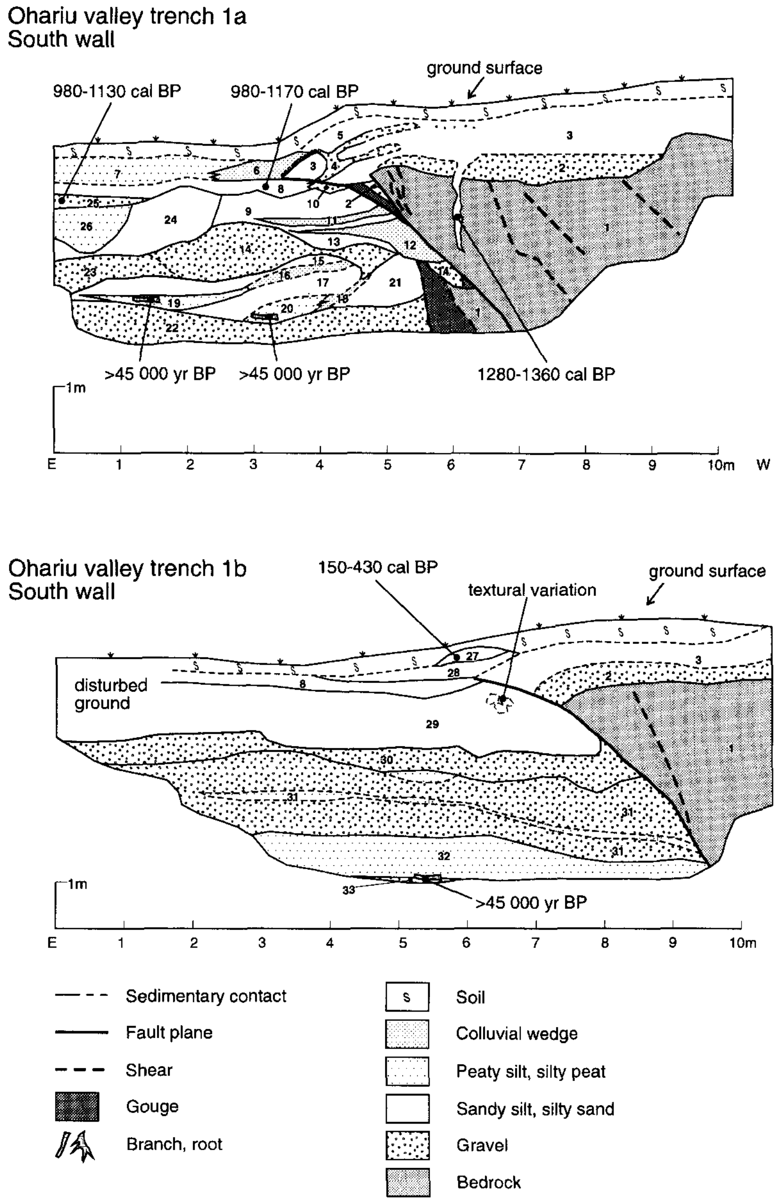

Fig. 5 Logs of southern walls of two trenches (situated 10 m apart; see Fig. 4) at site 1 in the Ohariu valley. The key gives generalised description of the units (detailed descriptions are given in Appendix 2). Five scarp-derived colluvial wedge deposits are identified in trench 1a, each representing individual faulting events; a sixth event may be indicated by the faulted gravel unit 14. The first two faulting events formed colluvial wedges (units 18, 16) within finer deposits at the base of the trench; the third formed the third colluvial wedge (unit 12) and may have formed a graben dragging in the orange gravels (unit 14); the fourth (?fifth) event truncated the third wedge (unit 12) and produced the fourth colluvial wedge (unit 11); the last movement truncated the fourth wedge, thrust the hanging wall over a silty soil (unit 8), and produced the youngest colluvial wedge (unit 6). Deposits associated with a number of other faulting events may have been removed by erosion associated with deposition of gravel unit 14. Other events may not have created deposits. The differences seen in the deposits at the two trench sites are attributed to increased fluvial activity and consequent channelling in the area of trench 1a. Details of dated materials are given in Appendix 3.

organic-rich sediments at the base of the trench indicates deposition in a quiet environment. These deposits are part of the alluvium comprising the inner fan and have infilled the dissected portion of the older fan (not exposed in either trench). They indicate ponding before 45 000 yr BP (Wk-1786, 1787, 1791 – University of Waikato Radiocarbon Dating Laboratory numbers). An oxidised orange gravel (units 2, 30 – see Appendix 2 for detailed descriptions of units) in the southern wall of trench 1b also appears in trench 1a (units 2, 14), although channelling and deformation on the downthrown side of the fault partly obscures stratigraphic relationships. The gravel appears to be laterally extensive and relatively horizontal, and indicates a 1.4 m vertical displacement across the fault. These deposits are thought to have been deposited after overtopping of the scarp as drainage was re-established through the central valley high.

Several planes of movement were present in both trenches. The predominant fault plane was reverse, dipping 45° at depth, but decreasing to 10° within 1 m of the surface (Fig. 5). Models of simple thrust fault scarp morphology (Carver & McCalpin 1996, pp. 192–193) suggest the low angle of thrusting makes the formation of a free-standing face capable of shedding debris to form a colluvial wedge unlikely. Whilst uplift on this part of the Ohariu Fault is probably small in a single event, the actual scarp height would be significantly higher if the dextral component of faulting displaced relatively higher ground into the area on the upthrown side of the fault. In addition, the strength of the greywacke basement and relatively high angle of the fault plane below 1 m depth suggests that a free-standing face capable of forming colluvial wedges could be formed during some faulting events. However, it is probable that during other faulting events a pressure ridge was formed as the upthrown block thrust over the downthrown block, sliding on the ground surface, and bulldozing material from that surface in front of itself.

In the Ohariu valley 1a trench, scarp-derived colluvial wedges (units 6, 11, 12, 16, 18; Fig. 5) are inferred to be the result of five faulting events. A possible sixth event is

Fig. 6 Looking southeast over the site of Ohariu valley trench 2 adjacent to upper Ohariu Valley Road. A remnant of the dissected central valley ridge is in the left foreground. Ohariu Fault (arrowed) crosses its northeastern margin, parallel to the road, and displaces a low-level fan. *Photo*: *D. L. Homer, Institute of Geological & Nuclear Sciences Ltd.*

indicated by the faulted gravel (unit 14) against the fault plane. The two oldest faulting events produced wedges of fine–medium angular gravel (units 18, 16). The wedges interfinger with organic silts to the east, but do not extend westward to the fault scarp due to subsequent channelling associated with unit 14. The third faulting event produced a wedge of silty sandy, fine to coarse, very angular to flaky gravel (unit 12). It overlies the easternmost plane of movement. This faulting event may also have deformed an underlying gravel (unit 14). Alternatively, this deformation may have been the result of a separate event. The fourth (?fifth) faulting event truncated unit 12 and produced a thin wedge of silty fine–medium angular gravel (unit 11). The last faulting event truncated wedge 11 and produced the youngest identified fault-derived deposits, comprising silt with sparse small cobbles (unit 6). The low angle of the fault plane and position and lithology of units 2, 3 and 4 suggest that during this event a pressure ridge may have formed and pushed out over the ground surface (unit 8). Unit 6 probably represents a colluvial wedge formed in front of the pressure ridge from material shed from the ridge, but may be part of the pressure ridge.

Textural variation within unit 29 in trench 1b adjacent to the fault plane suggested the presence of chaotic blocks of similar material, possibly fallen from unit 3 during the faulting event that created unit 11 in trench 1a.

Dating of the above events is poorly constrained. Twigs from a silty paleosol (unit 8) truncated by the fault plane provided a radiocarbon date of 980–1170 cal. BP (Wk-1788). This date is stratigraphically consistent with the 980–1130 cal. BP (Wk-1789) date obtained from unit 25. Charcoal from a silt (unit 27) overlying the fault plane in Ohariu Valley 1b trench was dated at 150–430 cal. BP (Wk-1790). The data indicate the most recent movement occurred between 150 and 1130 cal. BP.

Twigs or roots from an infilled fissure in the upthrown block were dated at 1280–1360 cal. BP (Wk-1937). The fissure is inferred to have formed as a result of a faulting event, through collapse of the upthrown block, and indicates an event sometime before 1280 cal. BP. It would seem

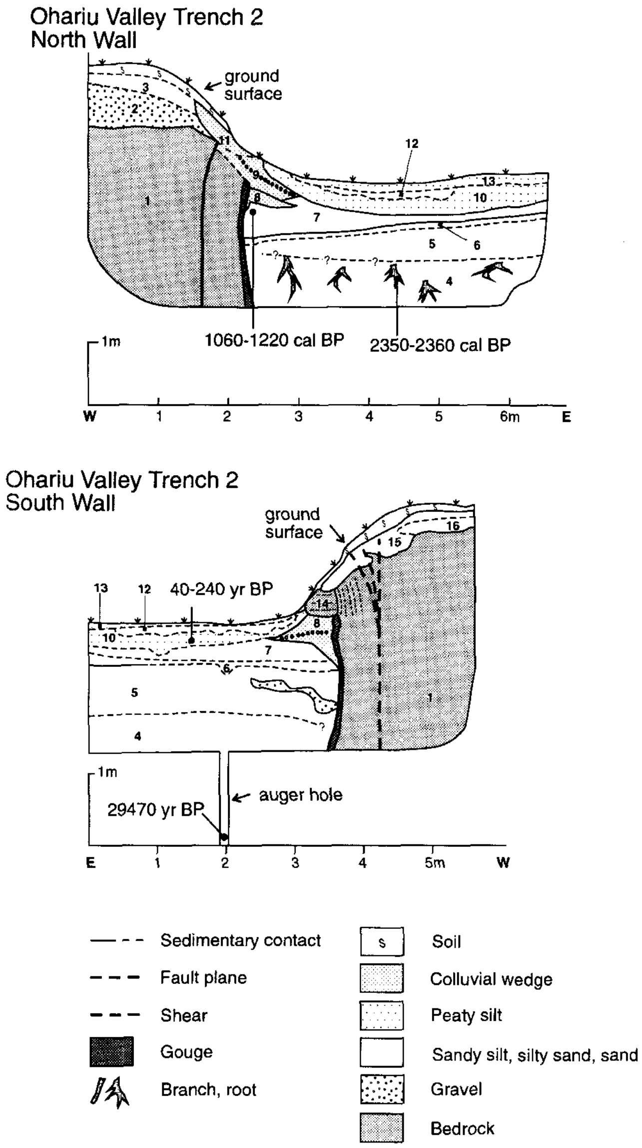

Fig. 7 Logs of both walls of trench at site 2 in the Ohariu valley. Four faulting events have been recognised, the latest three events each forming a scarp-derived colluvial wedge deposit identified in the northern wall. The earliest event was on the easternmost fault plane and deformed the base and a gravel within unit 5 in the southern wall. The oldest colluvial wedge (unit 8) was formed by the next event. The third event, also on the easternmost plane of movement, truncated unit 8 and resulted in the formation of a second wedge (unit 9). The most recent event occurred on the western fault plane truncating the second wedge, and created the youngest wedge (unit 11). Descriptions of units are given in Appendix 2. Details of dated materials are given in Appendix 3.

unlikely that such a fissure would remain open for any great length of time. If the material was twigs, it would be the same age as the fissure fill and date a faulting event at that time*. However, some uncertainty exists as to the nature of the dated material. If the dated material was roots, it could be considerably younger than the fissure fill. The fissure would therefore be related to the penultimate faulting event.

The oldest events recorded in the trench (represented by wedges 16, 18) are >45 000 yr old (Wk-1786, 1787). The events represented by wedges 11 and 12 could not be dated. An erosional unconformity at the base of gravel unit 14 separates the faulting events represented by unit 12 and units 16 and 18. The amount of time represented by this unconformity, and the number of faulting events that may have occurred within this time break, is not known. In addition, the low angle of the fault plane in the upper portion of the trench suggests that some ruptures may not produce a free-standing face and associated wedge to record the event (Carver & McCalpin 1996). As a consequence, these trenches do not record all the faulting events that occurred over the time interval exposed in them.

Ohariu valley 2 site

At the Ohariu valley 2 trench site (Loc. O047), c. 1.5 km south of Ohariu valley 1 site, drainage from an alluvial fan is dammed behind an uphill-facing scarp 1.5 m high, forming a swamp (Fig. 6). Trenching across the scarp and swamp revealed loess and gravel overlying greywacke to the west of the Ohariu Fault and fan, aeolian, and swamp deposits to the east (Fig. 7). Two distinct planes of movement were identified, both were near-vertical at depth but became reverse near the surface.

Three colluvial wedges are identified. The oldest (unit 8) is truncated by the easternmost fault plane. This unit comprises white fine–medium sand that is similar to unit 16 found on the western side of the fault in the trench's southern wall. A thin bed of weathered clasts occurs within unit 8 in the southern wall. The second wedge (unit 9) is a sandy gravelly silt. Within it, a stone line separates finer material in the upper part from coarser debris beneath. The wedge overlies the easternmost fault plane, but is truncated by the westernmost fault plane. The youngest wedge (unit 11), a silt to sandy silt with subangular to subrounded clasts, overlies the westernmost fault plane.

An auger hole in the base of the trench indicated the sandy silt exposed in the lower part of the trench (unit 4) was 2.5 m thick and passed through 0.5 m of silty sand and gritty sand to a gravelly sand.

At least four faulting events are recorded in the trench: the earliest event was on the easternmost fault plane and deformed the base of the sandy silt (unit 5) along with a gravel channel-fill within it (Fig. 7, southern wall). This deformation predates the relatively undeformed unit 6. The next event, seen in both walls of the trench, was also on the easternmost plane. The rupture formed a void adjacent to the fault plane without deforming units 6 and 7, the void being filled with the oldest colluvial wedge (unit 8). The third event, seen most clearly in the northern wall, occurred on the same plane, truncating the oldest wedge and formed a second wedge (unit 9). The most recent event occurred on the western fault plane, truncating the second wedge and creating the youngest wedge (unit 11). In the southern wall, shearing associated with this event penetrated unit 15.

Dating of the events is uncertain. Silt (unit 7) beneath the oldest colluvial wedge (unit 8) provided a radiocarbon date of 1060–1220 cal. BP (NZA3531), but the sample comprised numerous roots. There is no evidence from elsewhere on the Ohariu Fault to suggest three faulting events in 1200 yr, and we assume that some of the roots were from trees significantly younger than unit 8. A sample from a root within fine sandy

*The 2σ range for the dated material (1190–1420) and for the faulting event (0–1180) are closely spaced in time, but suggest the last faulting event occurred after fissure formation.

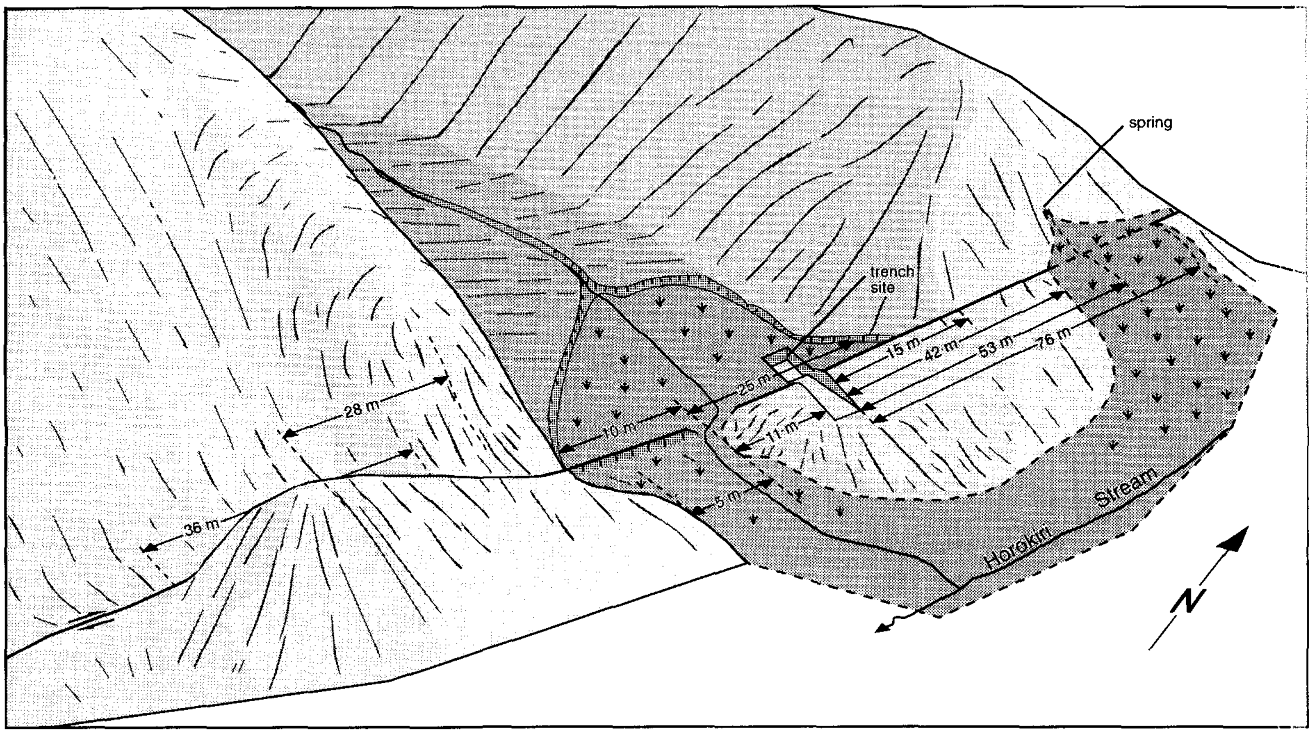

Fig. 8 Sketch of the Horokiri trench site (not to scale; see also Fig. 3) indicating displacements measured from topography and trench. Offsets of 28–36 m can be measured from the ridge crest and change in slope south of the trench site. An organic silt overlying basement in the trench (see Fig. 9) is inferred to have been formed when the site was adjacent to the spring north of the trench, and indicates an offset of between 42 and 76 m. Other measurements shown in this diagram are referred to in the discussion on slip rate.

silt (unit 4) was radiocarbon dated at 2350–2360 cal. BP (NZ8056). The contact between units 4 and 5 may represent a former ground surface, with the roots in unit 4 being from trees growing on that surface. However, it is considered more likely that the contact is a grain-size change from silt and fine sandy silt to sandy silt, above which the roots have been preferentially removed by weathering. Thus, the dated root may have been from a tree growing at a surface considerably higher than unit 4, and does not therefore adequately constrain the age of unit 4. However, the roots may date a faulting event. Drainage at this locality is poor as it passes from the downthrown block to the upthrown block, and it is probable that any faulting event would cause a rise in the water table and changes in sediment deposition. Such changes could kill trees, and the roots may therefore date an event at 2350–2360 cal. BP. Charcoal from the base of unit 4 in the auger hole was dated at 29 470 ± 380 yr BP (NZ3413).

Horokiri valley

At the Horokiri valley trench site (Loc. 048), movement on the Ohariu Fault has partially dammed a 35 m wide stream valley (Fig. 3, 8). The natural dam comprises a broad ridge up to 2.5 m high, upstream of which impeded drainage has formed a swamp. In the vicinity of the trench site, displaced topography such as ridges and changes in slope indicate dextral offsets of between 28 and 36 m.

Trenching across the ridge and swamp revealed greywacke overlain by organic silt, colluvial debris, and loess to the east of the Ohariu Fault, and alluvial and swamp deposits to the west (Fig. 9). The dip of the greywacke surface and of the overlying deposits in the northern wall of the trench east of the fault indicates deposition on an eastward-facing slope. These colluvial deposits could be derived only from the hillslopes to the north of the trench site on the western side of the fault. The presence of the organic silt (unit 2), which is up to 350 mm thick immediately overlying a sloping greywacke surface, would be difficult to explain in the inferred hillslope environment, dominated by coarse-grained deposition, were it not for a present-day analogue at the site. A spring 50 m north of the trench site is currently forming a swamp across the fault (Fig. 8). We infer that the organic silt represents a similar swamp deposit that was subsequently buried by colluvium (units 3–7) derived from the hillslope between the spring and the trench site as lateral displacement juxtaposed the swamp on the eastern side of the fault with the hillslope on the western side. Shearing of the greywacke in the northern wall appears to be dragged over to the east, and the presence of fault gouge along the contact between the greywacke and overlying sediments in that direction suggests the surficial deposits have slid down the greywacke contact. Loess (unit 8) occurs within the upper part of the colluvial deposits in the northern wall. To the west of the fault plane, a series of alluvial and peaty deposits is channelled into loess (unit 11). The fault plane is truncated by slip debris (unit 10). An undulating contact between very soft peat (unit 15) and an overlying soft organic silt (unit 16) may indicate soft sediment deformation resulting from strong shaking, but could also be related to compaction of the basal peat during accumulation of the overlying silt.

In the southern wall, channelling was stronger, but instability of the trench wall prevented logging of the lower part. A single peat (unit 18) was truncated and deformed by the faulting. A younger peat (unit 17) passes laterally into a silt containing subangular clasts (unit 19), the transition

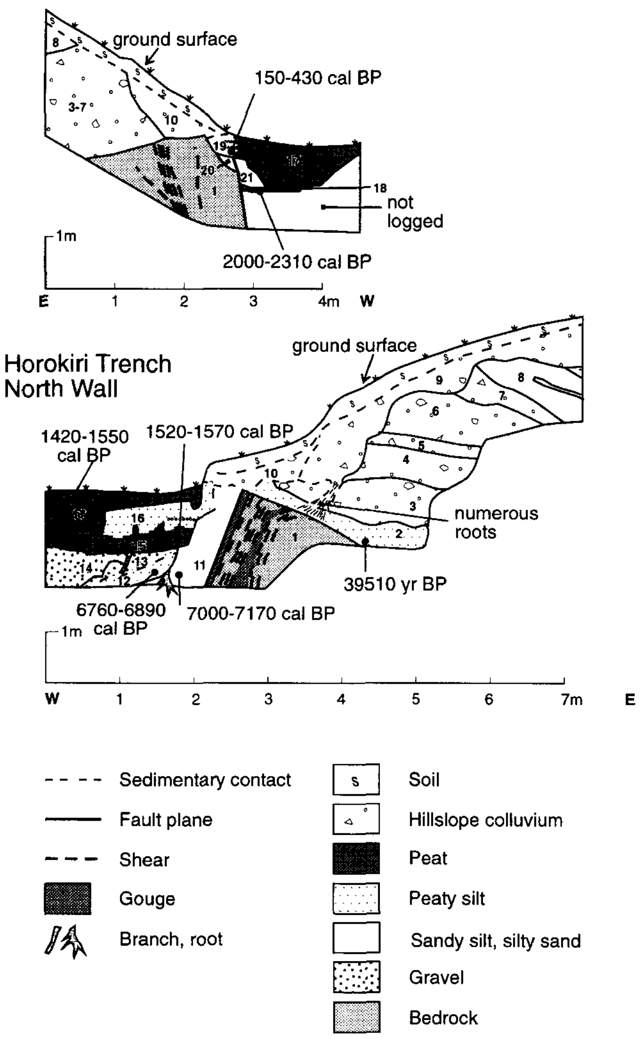

Fig. 9 Logs of both walls of trench in the Horokiri valley. Organic silt (unit 2) sitting on basement is overlain by hillslope-derived colluvium (units 3–7) in the northern wall, indicating high ground to the west. At least 42 m of lateral displacement (see Fig. 8) is required to explain the deposits. The log of the southern wall is incomplete due to wall collapse. A deformed peat (unit 18) indicates a faulting event since 2000–2310 cal. BP, and the overlying unfaulted deposits (units 17 and 19) provide an upper limit of 150–430 cal. BP. Detailed descriptions of units are given in Appendix 2. Details of dated materials are given in Appendix 3.

being immediately above the fault plane. These deposits shown no evidence of faulting.

Dating of faulting events is poorly constrained, as most datable material is confined to channel deposits that are not in direct contact with the fault. Loess (unit 11) faulted against greywacke (unit 1) in the northern wall is older than 7000–7170 cal. BP (NZ8035). The faulted peat (unit 18) in the southern wall indicates an event since 2000–2310 cal. BP (NZ8034). Unfaulted peat from the transition zone between units 17 and 19 indicates the last faulting event is older than 150–430 cal. BP (NZ8544). Branches from a stratigraphically lower position in the same peat (unit 17) in the northern wall of the trench were dated at 1420–1550 cal. BP (NZ8036).

TIMING OF SURFACE RUPTURE EVENTS

South of Porirua Harbour

Williams (1975) used a radiocarbon date on a displaced charcoal-bearing layer in a fanglomerate some 200 m west of the nearest trace of the Ohariu Fault in the Porirua area to infer the most recent movement at about 200 yr ago. The nature of the offset is not known but could be related to rupture on another fault or to some other event (e.g., slope failure). In the Ohariu 1a trench, the most recent faulting event disrupted a soil dated at 980–1170 cal. BP (Wk-1788). The soil overlies a gravel dated at 980–1130 cal. BP (Wk-1789). An unfaulted silt overlying the fault plane was dated at 150–430 cal. BP (Wk-1790). These data constrain the most recent faulting event in the area south of Porirua Harbour to between 150 and 1130 cal. BP (Fig. 10).

If the roots preserved in unit 4 in the Ohariu 2 trench are the result of tree death related to change in groundwater and/or sedimentation, then they date an earlier event at 2350–2360 cal. BP (NZ8056).

Four faulting events were seen in Ohariu 2 trench (Fig. 7); we do not know how many faulting events, if any, occurred in the time represented in the auger hole at the base of the trench. These faulting events are younger than the charcoal collected from unit 4, at the base of the auger hole, and dated at about 29 500 yr BP. This indicates a maximum mean recurrence interval for surface rupture events of 7870 yr (max. range 5900–9833) on this part of the fault.

North of Porirua Harbour

Augering at several localities (e.g., Loc. 044) in Horokiri valley south of the trench site indicates ponding and peat accumulation behind the fault scarp (Fig. 3). Minor colluvial debris in the auger holes suggests no significant disturbance of the hillslopes since scarp formation. A branch at the base of the peat was dated at 1060–1230 cal. BP (NZ7423) and is inferred to indicate formation of the scarp before that time. A similar date was obtained from wood at the base of a swamp behind the scarp in Kahao Stream, indicating a maximum age for ponding of 980–1160 cal. BP (NZ7427). At Waikanae, a stump buried in an unfaulted terrace along the strike of the Ohariu Fault and below a faulted terrace yielded an age of 1070–1270 cal. BP (NZ7428), and provides a minimum age for the most recent event. The only faulting event recorded from the Horokiri trench is dated at younger than 2000–2310 cal. BP (NZ8034) but older than 150–430 cal. BP (NZ8544). These data constrain the most recent faulting event in the area north of Porirua Habour to between 1070 and 2310 cal. BP (Fig. 10). The timing of older events has yet to be established.

Summary

Figure 10 summarises the constraints on the timing of the last faulting event as detailed above. The possibility exists that the sections of the Ohariu Fault south of Porirua (Makara–Porirua) and north of Porirua (Porirua–Waikanae) represent separate rupture segments of 24 and 31 km long, respectively, on which the most recent ruptures were closely spaced in time. However, the simplest interpretation is of a single segment totalling 55 km or more. Regressions of total rupture length and single-event displacement published by Wells & Coppersmith (1994) yield a total rupture length exceeding 100 km for an average single-event displacement of 3.2 m or

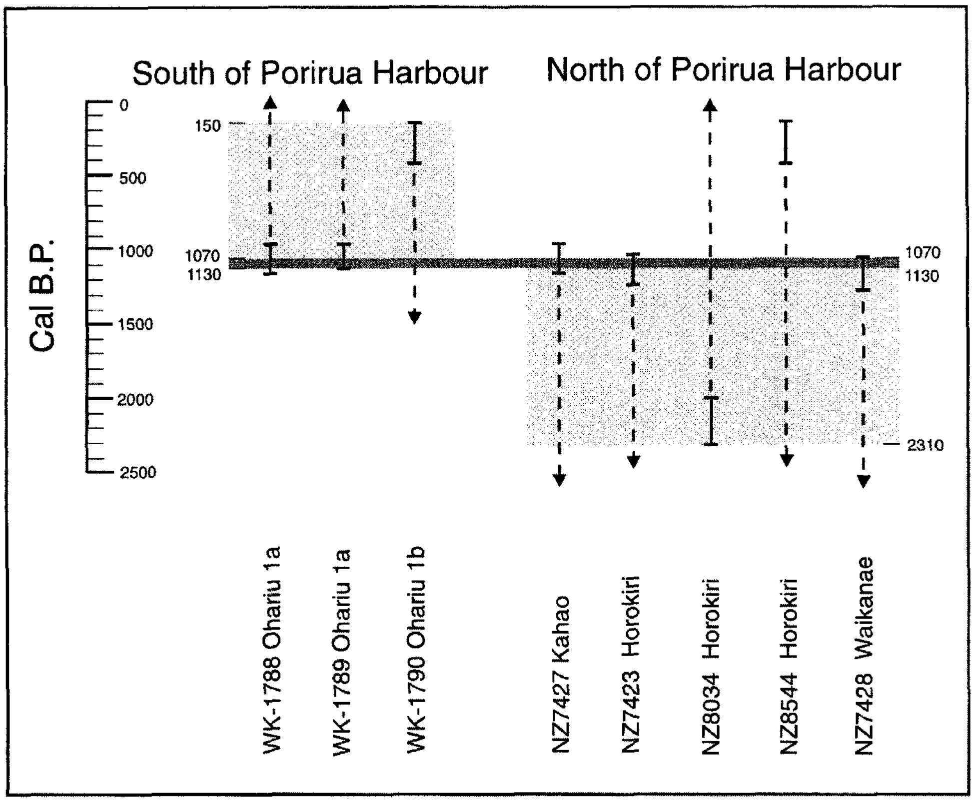

Fig. 10 Constraints on timing of the last event on the Ohariu Fault. Treated as separate segments with individual rupture histories north and south of Porirua Harbour, the timing of the last event is loosely constrained (light shaded boxes) in each segment. Treated as a single segment from Makara to Waikanae, the preferred interpretation, the timing of the last event is more tightly constrained (darker shaded box).

greater. Geomorphic estimates of lateral displacements of 3–5 m on the Ohariu Fault favour the single segment interpretation. Accepting the single segment interpretation, the timing can be more closely constrained to 1070–1130 cal. BP.

LATE QUATERNARY SLIP RATE ON THE OHARIU FAULT

Based on the measured displacements presented in earlier sections of this paper, and dates obtained from the trenching studies and earlier fieldwork, the slip rate of the Ohariu Fault can be estimated (Table 1). Ota et al. (1981) used an apparent 120–140 m dextral offset of an assumed 120 000 yr old shoreline at Waiariki Stream to indicate a horizontal slip rate of 1.0–1.2 mm/yr. Vertical offset of a marine terrace above that shoreline at the coast adjacent to Waiariki Stream indicates vertical rates of displacement of 0.3 mm/yr up to the northwest. Due to the difficulty of differentiating between tectonic lateral displacement and preferential erosion of the sea cliff, and uncertainties associated with the age of the displaced features, these estimates must be regarded as tentative.

In the upper Ohariu valley, displaced drainage features of unknown age indicate a dextral offset in the order of 220 m. Surfaces to the southwest contain the Rangitawa Tephra (Mildenhall et al. 1977; Pillans 1992; Kohn et al. 1992), indicating some of these features are at least 350 000 yr old. Detailed mapping may constrain the ages of the various surfaces, and allow a slip rate to be calculated. As discussed previously, a drainage in the vicinity of the Ohariu 1 trenches indicates a 225 m displacement (Fig. 4). Fine-grained

Table 1 Summary of slip rate data for Ohariu Fault.

Location name	Loc. no.	Measured offset: Horizontal (m)	Measured offset: Vertical upthrow (m)	Age of offset feature (yr)	Slip rate: Horizontal (mm/yr)	Slip rate: Vertical (mm/yr)	Reference
Waiariki Stream		120–140	40 NW	120 000*	? 1.0–1.2	? 0.3	Ota et al. 1981
Ohariu valley	T1	225		> 45 000*	< 5		this study
	T1		1.4 NW	< 22 590*		> 0.06	this study
		5†		9833†	> 0.5		
Porirua	0090	30		? 6500*	<4.6		Williams 1975
Kahao Stream	006	14.5		< 22 590*	> 0.6		this study
valley	003		1.2 W	< 22 590*		> 0.05	this study
Horokiri	049	42–76		> 39 500	< 1.1–1.9		this study
trench site		c. 15		> 10 000*	1.5		this study
		< 16		6900	< 2.3		this study
Valley Road	071	7		10 000*	> 0.7		this study

*Age is inferred rather than directly determined.
†Displacement is average displacement per faulting event; age is maximum recurrence interval for faulting event.

sediments at the base of trenches 1a and 1b in Ohariu valley indicate ponding before 45 000 yr ago as a result of the juxtaposition of the central valley ridge with the drainage through the trench site. This indicates that 225 m offset is older than 45 000 yr, and provides a maximum lateral rate of displacement of 5 mm/yr.

At the same site, the orange gravel (units 2 and 14 in trench 1a; units 2 and 30 in trench 1b) is vertically displaced 1.4 m. The overlying grey silt, interpreted as loess, lacks Kawakawa Tephra (Wilson et al. 1988), suggesting it is younger than 22 590 yr. This indicates a minimum vertical rate of displacement of 0.06 mm/yr.

Williams (1975) recorded a 30 m dextral offset of an assumed postglacial (c. 6500 yr old) shoreline at Porirua (Loc. O090), indicating a slip rate of 4.6 mm/yr. Ota et al. (1981) indicated there was some uncertainty as to the age of the feature, and Van Dissen & Berryman (1991) suggested that vertical offset of the harbour floor may have contributed to the apparent lateral offset of the shoreline. Despite the uncertainty, the slip rate has been used as a poorly constrained maximum for the Ohariu Fault south of Porirua (Van Dissen & Berryman 1991).

North of Porirua Harbour, offset channels in terraces above Kahao Stream indicate up to 14.5 m dextral displacement (Loc. 006). Loess capping the terraces lacks Kawakawa Tephra (Wilson et al. 1988), indicating they are <22 590 yr old. This suggests a minimum rate of lateral displacement of 0.6 mm/yr. Vertical offset of the same terrace farther south (Loc. 003) reaches 1.2 m, indicating a minimum vertical rate of displacement of 0.05 mm/yr.

In the Horokiri trench (Fig. 9), the organic silt (unit 2) in the northern wall has been displaced c. 50 m from its source, a spring on the hillslope to the north. The spring is currently forming a swamp 34 m wide on the upthrown side of the fault. A radiocarbon date of 39 509 + 2420 −1800 provides a minimum age for the organic silt (only a small amount of modern carbon contamination would be required for a sample beyond the range of radiocarbon dating to yield this result). Using the present-day extent of the swamp to estimate its former extent, the minimum and maximum offset of the organic silt is calculated to be 42 and 76 m, respectively. This indicates a maximum horizontal slip rate of between 1.1 and 1.9 mm/yr for the last 40 000 yr.

Colluvial debris occurs within loess (unit 8) in the northern wall of the Horokiri trench. The eastern side of the trench site must have been adjacent to the hill, some 15 m to the north (Fig. 8) at that time, for both loess and colluvium to accumulate at the same time. The source of the loess is inferred to have been the exposed seafloor between Pukerua Bay and Paraparaumu. The postglacial maximum sea level was attained at c. 6500 yr ago, with loess supply to the area being shut off at c. 10 000 yr (Milne & Smalley 1979; Marden et al. 1986); thus, the minimum age inferred for the loess (unit 8) at the trench site is 10 000 yr. Due to uncertainties concerning age and total slip, the calculated slip rate of 1.5 mm/yr should be treated with caution.

The oldest channel (unit 12) exposed in the northern wall of the Horokiri trench formed between 6760–6890 and 7000–7170 yr ago (Fig. 9). The channel parallels the fault, indicating that c. 6900 yr ago the stream was being deflected south by high ground that existed to the east of the fault. There is no topographic or geologic evidence to suggest the stream exited the valley farther north than the trench site. The present-day stream crosses through the high ground 11 m south of the trench, but the present drainage may have removed up to 5 m from the nose during cutting of the present channel. The maximum possible displacement of the channel exit in the last 6900 yr is therefore 16 m. This indicates a maximum slip rate of 2.3 mm/yr.

Near Valley Road, displaced terraces are devoid of loess, suggesting alluvial activity until the end of the last glaciation some 10 000 yr ago (Milne & Smalley 1979; Marden et al. 1986). A 7 m dextral offset of a stream channel cut into these terraces suggests a minimum slip rate of 0.7 mm/yr.

Determining slip rates from young features (those offset by a small number of events) may be imprudent as the effect of another event in the near future will significantly increase the calculated slip rate. However, treated as minimum slip rates, these data help constrain the lateral slip rate on the Ohariu Fault (Table 1) to 1–2 mm/yr, and the vertical slip rate to >0.06 mm/yr. The data do not allow any assessment of possible along-strike variation in slip rate.

EXPECTED EARTHQUAKE MAGNITUDE

Estimates of expected earthquake magnitude can be made from source parameters of historic earthquakes. Independent observable parameters include surface rupture length, maximum surface displacement, and average surface displacement (Wells & Coppersmith 1994). Estimates of maximum and average surface displacements are more difficult to determine for prehistoric earthquakes as there may be uncertainty whether larger displacements are the result of more than one event.

The total surface rupture length for the Ohariu Fault, including the discontinuous surface ruptures north of Paraparaumu, is of the order of 55 km. Based on the assumption that the fault is a single segment, the regression for surface rupture length on strike-slip faults published by Wells & Coppersmith (1994) yields an expected earthquake magnitude of M_w 7.1 ± 0.3.

If the sections of the Ohariu Fault south of Porirua (Makara–Porirua) and north of Porirua (Porirua–Waikanae) represent separate rupture segments of 24 and 31 km, respectively, the regression yields expected earthquake magnitudes of M_w 6.7 ± 0.3 and M_w 6.8 ± 0.3, respectively.

Although it is difficult to determine the maximum single-event lateral displacement on the Ohariu Fault, the large number of surface displacements measuring 3–7 m indicate that the average displacement is probably of this order. Consistent with this is that, within the study area, seven sites considered to represent single-event lateral displacements yield an average displacement of 3.7 m. Using the regression for average surface displacement yields an expected earthquake magnitude of M_w 7.5 ± 0.1.

CONCLUSIONS

The above data provide detail on the recent movement history of the Ohariu Fault. The most recent faulting event in the area south of Porirua Harbour occurred between 150 and 1130 cal. BP, whereas north of the harbour it is constrained between 1070 and 2310 cal. BP.

A mean recurrence interval of faulting determined from the Ohariu trench 2 was 7870 yr (range 5900–9833). Given a single-event displacement of 4–5 m and a slip rate of 1–

2 mm/yr for the Ohariu Fault south of Porirua, the recurrence interval is estimated at 2000–5000 yr. This is similar to the recurrence interval of 1530–4830 yr calculated from a slip-rate of 0.6–1.9 mm/yr and a single-event displacement of 2.9 m for the area north of Porirua Harbour. However, substantial uncertainties remain.

Extrapolation of the trend of the traces into Porirua Harbour from the north and south indicates the possibility of a 1.5 km right step in the vicinity. Such a geometry on a right-lateral fault would result in a pull-apart basin (Burchfeil & Stewart 1966; Mann et al. 1983) and an area of relative subsidence. Pull-apart basins may represent ends of rupture segments on faults (Sibson 1989) and, as such, a change in the character of the fault could be expected. However, the slip rate data (excluding the anomalously high rate calculated for immediately south of Porirua Harbour by Williams 1975) and recurrence interval estimates indicate no major change across the harbour. Data on the timing of the last event is not sufficiently well constrained to allow any conclusions to be drawn on fault segmentation. However, the size of a single-event lateral displacement in the south in the Ohariu valley appears to be twice that in the north.

Until more precise data on the timing of rupture events north and south of the harbour are available, it remains possible that these are two separate rupture segments. However, given the comparison of the single-event displacement to total rupture length (Wells & Coppersmith 1994), it is probable that the Ohariu Fault is a single rupture segment from Makara to Waikanae that is characterised by a horizontal slip rate of 1–2 mm/yr, has an average horizontal surface rupture displacement of 3.7 m, last moved 1070–1130 yr ago, and is capable of generating M_w 7.1–7.5 earthquakes.

An earthquake of M_w 7.1–7.5 on the Ohariu Fault will generate strong ground shaking over the Kapiti coast and much of the wider Wellington area. The associated lateral and vertical displacements along the fault will destroy any structure built across the fault.

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(Appendicies 1–3 follow)

APPENDIX 1 Late Quaternary faulting data for the Ohariu Fault in Sheet R26 Paraparaumu.

Field no.	NZMS 260	Grid reference	Airphoto no.	Feature: Tectonic feature	Feature: Geomorphic feature	Feature: Length (m)	Feature: Height (m)	Trace strike (true)	Fault plane	Vertical: Up	Vertical: Amount (m)	Horizontal: Sense	Horizontal: Amount (m)	Remarks
001	R26	696123	5497 F4	scarp	1st glac surf	30	040			W	0.8-1.0			
002		697123												fault steps 5m west
003		697123		?scarp	?1st glac surf	30	1.7	040		W	0.8			modified by channel
				trench	?1st glac surf					W	1.2			depth 1.7 west, 0.5 east
004		697124		scarp	?1st glac surf	11				W	0.95	R	2.9	channel offset R5.5m; C^{14} NZ 7384, 7427
005		698124		?trace	fan	40				W				modified by drainage
006		699125		trace	channel	14.5		040				R	14.5	offset drainage
007		699126		?trace	fan	17.5		040		W	<0.8			bulge to east 5x1m
008		699126		trace	channel							R		guided stream
009		700127		?trace	slope	30				W				tunnel gully on strike
010		700127		scarp	ridge	14				W	<1.8	R		
011		701128		trace	channel							R		guided stream
012		701129		scarp	ridge	18				W	0.6	R	6.7	
013		702130		trace	ridge	15				W				
014		702131		trace	channel							R	?200	guided stream
015		703131		trace	ridge									
016		703132		trace	channel							R	150	guided stream
017		704133		scarp	ridge	3						R	2.9	gouge in channel
018		704134		trace	saddle					W				
019		704134		trace	channel							R	?40	guided stream
020		705135		trace	saddle									
021		705136		trace	saddle							R	2.9	
022		706137		trace	channel							R	3.0	crushed greywacke
023		707138		trace	saddle									
024		708140		trace	saddle									
025		708141		trace	channel							R	?60	guided stream
026		709143		trace	saddle									
027		710144		trace	channel							R	250	guided stream
028		711146		trace	saddle									
029		712147		trace	channel							R	250	guided stream
030		714150		?trace	saddle									
031		714151		trace	saddle									
032		714152		trace	channel							R	200	guided stream
033		715153		trace	saddle									
034		716154		trace	channel							R	150	guided stream
035		717156		trace	channel									guided stream
036		718158		trace	saddle									
037		720162		trace	saddle									
038		743191	5497 G6	scarp	slope	16		040		E				modified by track
039		745193		scarp	slope	46				E				crush zone on track
040		745194		trace										spring and crush zone
041		745195		scarp	ridge			040		E				^{14}C NZ 7731, 7732
042		746195		scarp	slope	226	2.4			E				^{14}C NZ 7389

(continued)

Field no.	NZMS 260	Grid reference	Airphoto no.	Feature				Trace strike (true)	Fault plane	Vertical		Horizontal		Remarks
				Tectonic feature	Geomorphic feature	Length (m)	Height (m)			Up	Amount (m)	Sense	Amount (m)	
043		746195		scarp	saddle									
044		746196		scarp	ridge					E		R	14.1	change in strike to 020
045		746196		scarp	slope	20		020		E				springs; C^{14} NZ 7423
046		747197		scarp	slope	140	2.4			E		R	?15	?offset slip
047		747198		scarp	ridge							R	25	ridge line
												R	26	break in slope
048		747199		scarp	ridge	64	2.2			E		R	25	swamp behind scarp
049		748199		scarp	slope	70								swamp
050		748200		trace	saddle							R	16.6	beheaded stream
051		748200		?trace	slope									guided stream
052		751206		scarp	lst glac deg surf	26		050	045°/W55° 000°/E70° (minor)	E	1.3			fault planes
053		756222		trace	guided stream							R		
054		757224		trace	guided stream							R		
055		771245	5497 H6	trace	fan					W		R		
056		772246		trace	fan					W		R	?10	
057		772246		trace	fan					W				
058		772246		trace	channel							R	6-7	
059		774248		trace	saddle	15								
060		774249		trace	saddle	45								
061		775249		trace	saddle	20								
062		794270		scarp	fan	20				E	0.6			
063		794270		?trace	fan	31		055						
064		794270		trace	ridge	29		055				R	3.8	offset ridge
065		793269		trace	fan	c.25		060						3.5m wide
066		793269		trace	fan	10		060						intermittent
067		792269		trace	ridge	9	1	060		W	0.7			1.8m wide
068		792269		trace	saddle									
069		789267		?trace	saddle									
070		788264		trace	slope	17		060		SE				
071		787263		?trace	channel							R	7	offset channel
072		787263		scarp	lst glac surf	15		063		SE	0.7			
073		786263		graben	lst glac surf	43.5		063,070		SE				
074		785262		trace	saddle									
075		784261		scarp	ridge	12		060		?NW		R		
076		782260		trace	saddle									
077		763232		?scarp	terrace	30	0.5	037						
078		766237		?scarp	terrace	100	<2	022						
079		768240		?scarp	terrace	150	2	022						
080		769242		?scarp	terrace	100	2	025						

APPENDIX 2 Trench log descriptions.

Ohariu valley 1a trench (Fig. 5)

1. Grey-black to blue-black greywacke, sheared and pulverised, weathered in upper part.
2. Orange silty to sandy, fine to coarse, subangular to subrounded, clast-supported gravel.
3. Mottled silt with some fine sand and rare subangular to subrounded clasts.
4. Brown silty, fine to medium, subangular to subrounded, clast-supported gravel.
5. Light brown, slightly mottled silt with rare sand and fine gravel.
6. Olive brown, slightly mottled silt with very rare fine clasts.
7. Brown organic silt with some modern rootlets.
8. Brown silt with rare, fine to medium cobbles and twigs/roots.
9. Light bluish to grey-green (oxidised orange) clayey silt with fine sand and fine to medium, angular to subangular gravel.
10. Light brown, silty to sandy, fine to medium, subangular to subrounded, clast-supported gravel.
11. Light orangy brown, silty, fine to medium, subangular to subrounded, clast-supported gravel; fining to the east.
12. Silty to sandy fine to coarse, very angular (in places flaky) to subrounded gravel; fining upward and to the east.
13. Orange-stained, light greenish grey, silty sand with medium sand above and below.
14. Orange-stained, light greenish grey, silty to sandy, subangular to subrounded, fine to coarse gravel.
15. Brown, organic-rich silty clay with rare fine weathered gravel.
16. Organic-rich silty clay with abundant fine to medium, angular weathered gravel; gradational into unit 19.
17. Grey, organic-rich silty clay with rare fine weathered gravel.
18. Organic-rich silty clay with abundant fine to medium, angular, matrix-supported, weathered gravel; gradational into unit 20.
19. Dark brown organic silt with wood, and gritty to fine angular basal gravel; gradational into unit 16.
20. Dark brown organic silt with wood, and fine angular basal gravel; gradational into unit 18.
21. Grey, organic-rich silty clay with fine weathered gravel.
22. Organic-rich silty clay with sand and fine gravel in east passing to clayey gravel in west.
23. Greenish to blue-grey, medium, matrix-supported, subangular to subrounded (rare angular) gravel.
24. Massive brown silt with some fine to coarse gravel.
25. Grey, fine subrounded gravel with fibrous peat.
26. Massive brown silty peat, fibrous at base; some sandy beds.

Ohariu valley 1b trench (Fig. 5)

1. Dark blue-grey greywacke, sheared and pulverised, weathered in upper part.
2. Light grey-brown, mottled and orange-stained, sandy, fine to coarse, subangular to subrounded gravel.
3. Light reddish brown, mottled silt with some fine sand and rare fine to coarse gravel.
8. Massive, light brownish grey silt.
27. Massive yellow-brown silt with rare cobbles.
28. Brown silt with some clay, rare pebbles, and disseminated charcoal and twigs.
29. Grey, mottled silt with fine gravel beds. Textural variation abundant close to fault plane.
30. Massive, orange-stained, sandy, subangular to subrounded, fine to coarse, clast-supported gravel.
31. Greenish blue, clayey to sandy, fine to medium, angular to subrounded gravel, with organic mud, silt, and sand beds; upper part fining towards east, basal part coarsening to east.
32. Massive, brown, organic-rich silt with abundant wood.
33. Brown organic muddy to sandy fine gravel.

Ohariu valley trench 2, north wall (Fig. 7)

1. Dark grey greywacke, sheared and pulverised; many subvertical shears.
2. Massive, sandy, subangular to subrounded, fine to coarse gravel.
3. Massive, mottled, yellow to pale brown, fine sandy silt.
4. Massive, greenish grey very fine sandy silt and silt.
5. Massive, pale brown, mottled (orange and grey) sandy silt.
6. Massive, light grey fine to medium sand.
7. Massive, light brownish grey to grey sandy silt.
8. Massive, light grey, fine to medium sand with rare weathered subrounded clasts.
9. Pale brown to light yellow sandy and gravelly silt; fines towards the east and upwards; stone line.
10. Dark brown organic silt with charcoal and wood.
11. Pale brown to light yellow silt to sandy silt with subangular to subrounded gravel.
12. Massive, grey brown sandy silt with rare subrounded clasts.
13. Dark grey-brown to grey-brown organic silt with some sand; many modern roots.

Ohariu valley trench 2, south wall (Fig. 7)

1. Dark grey greywacke, sheared and pulverised; many subvertical shears.
4. Massive, greenish grey very fine sandy silt and silt.
5. Massive, pale brown, mottled (orange and grey) sandy silt, with weathered, subrounded gravel.
6. Massive, light grey, fine to medium sand.
7. Massive, light brownish grey to grey sandy silt.
8. Massive, light grey, fine to medium sand with scattered and single bed of weathered subangular to subrounded clasts.
10. Dark brown organic silt with charcoal and wood.
12. Massive, grey brown sandy silt with rare subrounded clasts.
13. Dark grey-brown to grey-brown organic silt with some sand; many modern roots.
14. Orange-stained greywacke; numerous shears.
15. Yellow to brownish silt to fine sand.
16. Massive, white, fine to medium sand.

Horokiri valley trench, north wall (Fig. 9)

1. Blue grey greywacke, sheared and pulverised.
2. Olive brown organic silt with fine to coarse, angular, moderately weathered, very fine to medium gravel; some wood (? in growth position) and a few rich carbonaceous zones; less organic material to west.
3. Light olive brown, slightly sandy to silty, fine to coarse, angular, moderately weathered, gravel; iron staining at base parallel to contact; disturbed zone (root zone) cuts unit.
4. Pale brown to light grey, sandy to silty, angular, moderately weathered, fine to coarse gravel.
5. Crudely bedded to massive, pale brown to light grey, sandy silty, angular, moderately weathered, fine gravel.
6. Crudely bedded, pale yellow, silty, angular, moderately weathered gravel.
7. Pale yellow, silty, angular, slightly weathered fine gravel.
8. Light brownish grey silt with interbedded yellow to olive brown sandy silt with angular, slightly weathered fine gravel.
9. Light yellow brown silt with angular fine to medium clasts; becomes finer upwards.
10. Brownish yellow silt with rare angular fine clasts; becomes finer and more burrowed upwards.
11. Light olive brown to greyish brown mottled silt to fine gravelly silt.
12. Dark greyish brown organic silt with a few fine, angular, moderately weathered clasts along basal contact.
13. Dark greyish brown, fine gravelly sand; clasts are angular to subangular, unweathered.
14. Grey to light yellow, sandy, medium, angular to subangular, mainly clast-supported gravel; wood present.
15. Fibrous peat with small coarse sandy horizon and scattered angular, moderately weathered clasts concentrated at the base.
16. Brown grey to grey brown organic silt with rare fine, angular, moderately weathered clasts; clasts more abundant toward fault plane; contains single stone line.
17. Fibrous peat with sand and granule horizons and rare medium gravel; wood common.

Horokiri valley trench, south wall (Fig. 9)

1. Blue grey greywacke, sheared and pulverised.

3–7. Brownish yellow silty to sandy, fine angular gravel.

8. Brownish yellow silt with rare angular greywacke clasts.
10. Brownish yellow gravelly silt; clasts are fine to medium and subangular.
17. Brown silty peat with several thin fibrous beds.
18. Dark brown silty peat.
19. Grey silt with some fine to medium subangular clasts; thin fibrous peat passes laterally into unit 17.
20. Greenish grey to light greenish grey sandy to gravelly silt; angular clasts scattered throughout and concentrated at base.
21. Massive light grey to pale green gravelly silt; clasts are fine to medium, subangular, and moderately to highly weathered.

APPENDIX 3 Radiocarbon data for the Ohariu Fault.

Lab number	Grid reference	Radiocarbon age (yr BP)	Calibrated age (cal BP) 1 σ range	2 σ range	δ13 C‰	Material, significance, comments
Ohariu valley 1a trench						
Wk-1785	R27 605013 s	1420 ± 60	1280 – 1350	1250 – 1410	-26.1	Twigs from gravel overlying unit 23 in east end of trench.
Wk-1786	R27 605013 s	>45000			-26.1	Wood from silt (unit 20) near base of trench.
Wk-1787	R27 605013 s	>45000			-24.5	Branch in silt (unit 19) near base of trench.
Wk-1788	R27 605013 s	1170 ± 70	980 – 1170	940 – 1270	-27.0	Twigs from faulted soil (unit 8); most recent faulting event younger than 1170 cal BP.
Wk-1789	R27 605013 s	1160 ± 50	980 – 1130	950 – 1180	-26.7	Detrital bark from unit 25 beneath youngest faulted deposit; faulting since 1130 cal BP.
Wk-1937	R27 605013 s	1430 ± 70	1280 – 1360	1190 – 1420	-29.6	Twigs/roots from fissure in hanging wall; penultimate faulting event older than 1280 cal BP.
Ohariu valley 1b trench						
Wk-1790	R27 605013 s	260 ± 70	150 – 430	0 – 480	-27.3	Charcoal in buried soil (unit 27) overlying fault.
Wk-1791	R27 605013 s	>45000			-25.3	Log from muddy gravel (unit 33) near base of trench.
Ohariu valley 2 trench						
NZA 3531	R27 596001 n	1206 ± 65	1060 – 1220	960 – 1280	-27.7	Charcoal and roots from sandy silt (unit 7) beneath colluvial wedge; ?contaminated
NZ 8056	R27 596001 n	2379 ± 33	2350 – 2360	2340 – 2470	-25.2	Root from sandy silt (unit 4).
NZA 3413	R27 596001 b	29474 ± 380			-24.3	Charcoal from sandy silt (unit 4) in auger hole at base of trench.
NZA 3541	R27 596001 s	50 ± 60	40 – 240	10 – 270	-27.3	Charcoal from organic silt (unit 10).
Horokiri trench						
NZ 8010	R26 748199 n	39509 + 2420 -1800			-25.0	Wood from organic silt (unit 2); minimum slip rate over last 40 000 yr.
NZ 8019	R26 748199 n	6000 ± 60	6760 – 6890	6720 – 7000	-26.5	Roots from organic silt (unit 12); minimum age for oldest channel deflected by scarp.
NZ 8020	R26 748199 n	1658 ± 41	1520 – 1570	1420 – 1690	-28.6	Detrital twigs from sandy peat (unit15); ?deformation and faulting since 1570 cal BP.
NZ 8034	R26 748199 s	2146 ± 83	2000 – 2310	1900 – 2340	-26.8	Wood from silty peat deformed against fault (unit 18); faulting since 2310 cal BP.
NZ 8035	R26 748199 n	6181 ± 55	7000 – 7170	6890 – 7200	-25.3	Root from silt (unit 11) truncated by channel; max.age of oldest channel deflected by scarp.
NZ 8036	R26 748199 n	1633 ± 48	1420 – 1550	1400 – 1680	-28.3	Detrital branches from organic silt (unit17).
NZ 8544	R26 748199 n	268 ± 77	150 – 430	0 – 500	-29.6	Peat from gradational (unfaulted) contact between silty peat (unit 17) and gravelly silt (unit 19); faulting before 150 cal BP.
Other						
NZ 7384	R26 697124	481 ± 60	500 – 540	330 – 620	-29.3	Peat from base of swamp behind scarp in Kakaho valley; faulting before 540 cal BP.
NZ 7389	R26 746195	<250			-28.1	Peat from base of swamp behind scarp in Horokiri valley: ?contaminated.
NZ 7423	R26 746196	1215 ± 65	1060 – 1230	970 – 1280	-25.2	Branch at base of swamp behind scarp in Horokiri valley; faulting before 1230 cal BP.
NZ 7427	R26 697124	1160 ± 60	980 – 1160	940 – 1230	-26.4	Branch at base of swamp behind scarp in Kakaho valley; faulting before 1160 cal BP.
NZ 7428	R26 842342	1250 ± 60	1070 – 1270	990 – 1290	-28.2	Stump in terrace near Waikanae undisplaced by fault; last faulting event before 1070 cal BP.
NZ 7731	R26 745195	726 ± 69	650 – 690	550 – 740	-27.8	Branch at base of swamp behind scarp in Horokiri valley; faulting before 690 cal BP.
NZ 7732	R26 745195	860 ± 30	720 – 780	690 – 890	-28.8	Peat from base of swamp behind scarp in Horokiri valley; faulting before 780 cal BP.

Lab number: Wk: University of Waikato; NZ: Institute of Geological & Nuclear Sciences Rafter Radiocarbon Laboratory.

Grid reference: Given on NZMS 260 sheets R26 and R27; n = north wall of trench, s = south wall, b = auger hole in base of trench.

Radiocarbon age: This is the conventional radiocarbon age before present (AD 1950) calculated using Libby half-life of 5568 yr, and corrected to δ^{13} of -25‰. Errors quoted at ± 1σ.

Calibrated age: This is calendar years before present (AD 1950) based on Stuvier & Reimer (1993), but does not incorporate a Southern Hemisphere correction. Age range listed is minimum and maximum for values of the calibrated age range based on a radiocarbon error of 1σ and 2σ rounded to the nearest 10.