FIELD TRIP 5

Southern Wairarapa Fault and Wharekauhau Thrust (Palliser Bay)

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Overturned Last Interglacial beach deposits overthrust by Torlesse greywacke along the Wharekauhau thrust, Te Mahonge Stream, Palliser Bay



Frontispiece a: Photograph of the Wairarapa Fault, looking northward across the town of Featherston (photo by Lloyd Homer, GNS Science). Much of this scarp displaces the post-Last Glacial Maximum "Waiohine" terrace surface (green paddocks) in an up-to-the-NW sense. Stop 1 of this field trip is located just to the south of this image.

Field Trip 5: Southern Wairarapa Fault and Wharekauhau Thrust (Palliser Bay)



Frontispiece b: Photograph of the Wharekauhau thrust in Wharekauhau Stream, looking east. A greyweathering "flap" of crushed Torlesse terrane rests structurally above (and in thrust contact with) younger fluvial gravels exposed near stream level. Other fluvial gravels (near the skyline) rest in depositional contact on the Torlesse rocks. This exposure is part of Stop 4 in the field trip.

Trip Summary

This all-day field trip highlights new observations and interpretations on the southern part of the Wairarapa Fault zone. In it, we first examine some very large (15 - 18.5 m) dextral-slip displacements at several sites near Pigeon Bush that have been attributed to the 1855 earthquake. Second, we visit the Cross-Creek pull-apart graben, a recent paleoseismic trenching site on the Wairarapa Fault from which we have been able to infer the occurrence of 5 major surface rupturing earthquakes during the past ~5200 years (this is two more than there are known raised beach ridges of that age at Turakirae Head). Third, we visit a site near Riverslea Station along the Wharekauhau fault system (an eastern strand of the southernmost Wairarapa fault system) where a recent

paleoseismic trench revealed evidence of surface rupturing on a strike-slip fault during 1855. Finally, on the south coast at Palliser Bay we walk up Te Mahonge and Wharekauhau Streams, paying special attention to near-coastal exposures of the Wharekauhau thrust, a conspicuous (albeit inactive) element in the Wharekauhau fault system. The Wharekauhau thrust places Torlesse rocks on top of variably tilted, late Quaternary marine deposits and fluvial gravels. Recent work (structural geology and ¹⁴C and Optically Stimulated Luminescence dating) suggests that the (oblique?) thrust underwent a period of very rapid motion (accruing >220 m of heave) during the period \sim 71-14 ka, corresponding to a horizontal shortening rate of >4 mm/y. Subsequent to this, the thrust became inactive and was in part buried by younger fan sediments. We infer that present-day deformation (including during 1855) at the southern end of the Wairarapa Fault zone is partitioned between slip on: 1) the more western Wairarapa-Muka Muka fault system (dominantly dextral-slip, but also causing local uplift of the coast near Turakirae Head; 2) a series of discontinuously expressed, near-vertical strikeslip faults and linking oblique- reverse faults near the trace of the older Wharekauhau thrust, and perhaps locally reactivating parts of it; and 3) a blind thrust fault between Lake Onoke and the western margin of the Wairarapa Valley.

Introduction

The Pacific-Australia plate boundary in the North Island of New Zealand accommodates oblique subduction of oceanic crust along the Hikurangi margin of the North Island, and oblique continental collision in the South Island (Fig. 1). In the southernmost North Island, the contemporary oblique plate convergence of ~42 mm/yr can be broken down into ~30 mm/yr of margin-orthogonal motion and ~28 mm/yr of margin-parallel motion and (Beavan et al, 2002). The margin-orthogonal component is accommodated by thrust faulting and related folding in the onshore and offshore parts of the Hikurangi Margin's upper plate, including in an offshore accretionary wedge consisting of NE-striking reverse faults and folds, and by contractional slip on the subduction megathrust beneath these faults, which is thought to be strongly "coupled" in the southern part of the North Island (Barnes and Mercier de Lépinay, 1997; Barnes et al., 1998; Barnes and Audru, 1999; Nicol et al., 2002, 2007). The margin-parallel component of plate motion is accommodated by dextral-slip on the NNE-striking faults of the North Island Dextral fault belt (NIDFB), including the Wellington and Wairarapa faults (e.g., Beanland, 1995; Van Dissen and Berryman, 1996; Mouslopoulou et al., 2007), by clockwise vertical-axis rotation of eastern parts of the North Island (e.g., Wallace et al., 2004; Nicol et al., 2007; Rowen and Roberts, 2008), by strike-slip on active ENE-striking structures in Cook Strait (such as the Boo Boo Fault), and by oblique-slip on other, NE-striking offshore faults, including the subduction megathrust (Barnes and Audreu, 1999; Nicol et al., 2007). Seismicity data suggest that faults of the NIDFB, including the Wairarapa fault, intersect the subduction megathrust at depths of 20-30 km beneath the southernmost part of the North Island (e.g., Reyners, 1998). GPS geodetic data suggest that this segment of the subduction interface is currently "locked" and is accumulating elastic strain (Wallace et al., 2004).



Figure 1. a) Tectonic index map showing major active faults and other structures of the southern North Island, New Zealand (largely after Begg & Johnston, 2000; Lee and Begg, 2002; and Barnes, 2005), and location of field trip stops sites along the Central and Southern sections of the Wairarapa fault. Inset on upper left shows contemporary plate tectonic setting of New Zealand (plate motions from Beavan, 2002). b) Schematic cross-section X-X' (position of currently locked part of subduction interface after Wallace et al., 2004).



Figure 2. Fault traces along a southern part of the central Wairarapa Fault, south of Featherston (from Rodgers and Little, 2006), showing locations of Stop 1 (Pigeon Bush area) and Stop 2 (Cross Creek Pull-apart graben).

The Wairarapa fault is interpreted to have been initiated in the Pliocene as a reverse fault and reactivated as a strike slip fault at ~1-2 Ma in response to a clockwise vertical-axis rotation of the forearc relative to the Pacific Plate (Beanland, 1995; Beanland and Haines, 1998; Kelsey et al., 1995). The Wairarapa fault is the easternmost strike-slip fault in the NIDFB; whereas farther to the east, the structural style is dominated by margin-perpendicular shortening (folding and reverse faulting), a combination of which has uplifted the Aorangi Range on the SE coast of the North Island (Formento-Trigilio et al., 2002; Nicol et al., 2002). Dipping steeply to the northwest, the Wairarapa Fault bounds the eastern side of the Rimutaka Range, marked by a topographic step between

the ranges and the subdued alluvial plain of the Wairarapa basin to the east. The central section of the fault is typically complex at the surface, including 250-500 m wide zone of mostly left-stepping *en echelon* traces and/or deformational bulges that have been active in the late Quaternary (Grapes and Wellman, 1988; Rodgers and Little, 2006) (Frontispiece a and Fig. 2). The northern section of the fault is marked by a series of dextral-slip splays (e.g., Carterton Fault) that bifurcate eastward away from the main trace of the Wairarapa fault farther to the west (Fig. 1). This main trace extends northward as far as Mauriceville South of Lake Wairarapa, the southern section of the fault includes a western strand that continues southwestward into the Rimutaka Range; and an eastern strand, that steps eastward ~5-6 km before deflecting back to a NNE-SSW strike and bordering the range front as far as the southern coast (Grapes and Wellman, 1988; Begg and Mazengarb, 1996; Begg and Johnston, 2000) (Fig. 1).

We refer to the faults that comprise eastern strand of the greater (southernmost) Wairarapa fault zone as being the "Wharekauhau fault system". This strand has previously been interpreted to consist chiefly of an active thrust fault termed "the Wharekauhau thrust" that is also inferred to have been a locus of surface rupturing during the 1855 earthquake. For this field trip we will restrict the term "Wharekauhau thrust" to a specific low-angle fault. Well exposed near the Palliser Bay coast, this (oblique?) thrust emplaces Torlesse terrane rocks in its hangingwall over Quaternary sediments in its footwall (Frontispiece b). We infer this major fault to be inactive and not to have ruptured (at least as a thrust) in 1855. While some northern parts of the thrust may locally have been reactivated during the Holocene, other active faults in the Wharekauhau fault system can be shown to be younger than adjacent (inactive) thrust strands. The demonstrably active structures include near-vertical dextral-slip (or oblique-slip) structures, some of which can be shown to have ruptured in 1855, but we do not refer to these as the "Wharekauhau thrust."

The Wharekauhau thrust separates uplifted Mesozoic greywacke on the northwest from Quaternary strata of the Wairarapa basin on the southeast. Quaternary strata in the footwall of the fault chiefly consist of last interglacial marine deposits and alluvial fan gravels derived from the Rimutaka Range. Partly overlapping the fault, and (as we will argue) post-dating its activity, are a sequence of post-Last Glacial Maximum gravels mapped as the "Q2" unit by Begg and Johnston (2000), and informally termed the "Waiohine gravels" by many previous geologists in the Wairarapa Valley. The top surface of this abandoned fan complex (the "Waiohine surface") has been widely mapped along the western side of the Wairarapa Valley, where it dips gently eastward beneath the surface of Lake Wairarapa (Begg and Johnston, 2000; Lee and Begg, 2002). On the western margin of the lake, the age of this surface has recently been bracketed by ¹⁴C dating of samples collected on both sides of its gravel tread at a single site (Cross Creek trenching site- Stop 2 in this field trip). These results constrain fan abandonment to have taken place soon after 12.4 ka. Based on the stratigraphic context of the samples collected in gravel close below the terrace tread, these authors infer an abandonment age of 12-10 ka for the surface at that locality. This age, together with reported lateral offsets of 99-130 m relative to that terrace surface (in particular at Waiohine River, Fig. 1), suggests a Late Quaternary dextral-slip rate for the Wairarapa Fault of 8-15 mm/yr (Wang and Grapes, 2007; Little et al., in press). A slip rate has



never been measured for the Wharekauhau thrust, or for any other faults in the Wharekauhau fault system.

Figure 3. Isoseismal map of 1855 earthquake (from Grapes and Downes, 1997) showing area of ground damage (stippled) and rupture along Wairarapa Fault. W = Wellington. Inset- crosssection along A-B showing inferred shape and extent of Wairarapa Fault rupture at depth during 1855 (after Darby and Beanland, 1992).

Figure 4. Oblique aerial view, looking northeast, of the uplifted beach ridges at Turakirae Head. The ridges have been dated using ¹⁴C (radiocarbon) and Be¹⁰ surface exposure dating techniques (Hull and McSaveney et al. 2006). Here, 2 km SW of the axis of greatest uplift in 1855, BR2 was raised 4.7 m in 1855, BR3 was raised 7.1 m in the event prior to 1855, BR4 was raised 3.7 m in the earthquake before that, and BR5 was raised 3.4 m in the earliest Holocene earthquake recorded here. In the distance, at least two raised marine benches (analogous with the Holocene bench in the foreground) can be seen in the coastal profile. Suggested age correlations for these benches (Ota et al., 1981) were based on high sea level stands of the international sea level curve.



GeoSciences '08 Field Trip Guides Little, Schermer, Van Dissen, Begg & Carne Wairarapa Fault 82

The 1855 Earthquake

The Wairarapa Fault east of Wellington, New Zealand ruptured on January 23, 1855, resulting in ground shaking, landsliding (especially in the Rimutaka Range), regional uplift, tsunamis, and >120 km of ground rupturing (Grapes, 1999; Grapes and Downes, 1997). Historic accounts indicate that the 1855 earthquake ruptured the Wairarapa Fault, Fresh scarps attributed by Grapes (1999) to the 1855 rupture are preserved in the landscape from near the coast to Mauriceville, as much as ~88 km northward (Fig. 1). More recent work suggests that slip in 1855 may also have ruptured a northward continuation of the Wairarapa Fault, the Alfredton Fault: scarps along that fault were rejuvenated sometime after 250 - 330 years BP, implying that the 1855 rupture may have extended to Alfredton, as much as 30 km beyond Mauriceville (Schermer et al., 2004). These data suggest that the onshore part of the 1855 rupture could have been as long as ~120 km. Modern estimates of magnitude based on dislocation modeling of the observed distribution of vertical uplift, and on the felt extent of ground shaking (Fig. 3) suggest a moment magnitude (M_w) of 7.9 to 8.2 (Darby and Beanland, 1992; Dowrick, 1992), whereas revised measurements of surface offset and inferred rupture size suggest an M_w of at least 8.2 to 8.3 (Little and Rodgers, 2005; Rodgers and Little, 2006). This makes the 1855 earthquake by far the largest seismic event in modern New Zealand history (Van Dissen and Berryman, 1996). One goal of this field trip (Stop 1) is to provide participants with a chance see the fault rupture and slip that took place during a recent (in this case, ~150 year old) earthquake. At Stop 1 we will examine a place (Pigeon Bush and environs) where "smallest" strike-slip offsets as high as 15 -18.5 m have been measured and attributed to that historic earthquake (Rodgers and Little, 2006).

The interaction of the subducting plate interface and faults of the NIDFB is poorly understood, although GPS modelling suggests that the megathrust is currently locked and is also loading crustal faults at depth beneath the southern North Island (Darby and Beavan, 2001; Wallace et al., 2004). Rodgers and Little (2006) argued on the basis of the remarkably high co-seismic slip during the 1855 rupture, and especially its unusually large displacement/length ratio, that this earthquake co-ruptured a part of the subduction interface with which it was contiguous down-dip, an inference that is consistent with elastic dislocation modeling of the vertical component of motion during that earthquake, albeit not required by it (Beavan and Darby, 2005). The only way such modeling was able reproduce the large amplitude of uplift at Turakirae Head in combination with the short wavelength of that uplift signal was by imposing a reverseslip motion on a fault nearby to Turakirae Head (e.g., on the Muka Muka Fault, Fig. 9). This large co-seismic uplift (up to a maximum of 6.4 m at the crest of the Rimutaka anticline, Fig. 1) has been inferred from the height of a beach ridge near Turakirae Head (labeled "BR 2" in Fig. 4). Dating of this beach ridge and the three other beach ridges, above it, led McSaveney et al. (2006) to infer the timing the last four earthquakes on the Wairarapa fault, and to infer a mean recurrence interval of ~2200 yrs for Wairarapa Fault earthquakes. More recently, the authors of this field trip guide have undertaken paleoseismic trenching studies to determine the chronology of paleoearthquakes on this fault, and to compare this record of fault rupturing with the geomorphic record of coastal uplifts near Turakirae Head. Visiting these trenching localities and discussing the results derived from the trenching (and their comparison to the age of the uplifted beach ridges) is a second objective of this field trip (at Stops 1, 2, and 3).

Surface Expression of Central Segment of the Wairarapa Fault Zone, South of Featherston

Heading South from Featherston on Western Lake Road, you note the scarp of the Wairarapa fault off your right. Typically it is located near the upper edge of the grazed paddock land, and below the heavily bushed foothills of the Rimutaka Range (Frontispiece a)

Although within a few decades of 1855 the land was largely deforested and converted to grazing land, and despite the passage of 150 years, many of the scarps in the Featherson-Lake Wairarapa region are still remarkably fresh-looking, and are likely to be of 1855 age. These scarps locally retain slopes of $30-70^{\circ}$ – steep enough to expose planar outcrops of the terrace alluvium. Other probable 1855 scarps lack such steep faces, but demonstrably cut and displace small landforms, such as shallow rills. Scarps higher than ~20 m occur on the limbs of the anticlinal bulges. These are typically mantled by landslides. Where the fault is expressed by multiple overlapping segments at the surface, each not necessarily experiencing slip at the same time, recognition of the 1855 increment of slip becomes difficult or impossible.

In the southern Wairarapa Valley, the fault zone strikes ~046° overall but is slightly arcuate in detail (Figs. 2 & 5), and one can define three relatively straight sections that are bounded by Owhanga Stream and Cross Creek. The most prominent scarps of the Wairarapa Fault border the eastern edge of its zone, where they cut Torlesse Terrane bedrock and late Quaternary alluvium, especially the "Waiohine" surface, which is typically displaced vertically by 5-20 m across the fault zone. Because the "Waiohine" surface is an old surface, these scarps represent many Wairarapa Fault ruptures. Most of these scarps are linear, ~1-3 km long, and discontinuous (Fig. 2). The fifteen individual strands that Rodgers & Little (2006) mapped in the area south of Featherston are 1200±700 m long and define a distinct, left-stepping, en echelon pattern. The overlapping parts of the stepovers are typically 400-600 m long and 20-200 m wide. Some of these compressional stopovers coincide with uplifted fault blocks, whereas others bound an active anticline or tectonic bulges, expressed in the landscape by the warping of the alluvial terraces, and by laterally varying scarp heights. Right-stepping en echelon zones are rare but result in small closed depressions and bogs less than a few tens of metres in width. Both situations cause along-strike variations in slip and locally complicate the interpretation of 1855 displacement.

Along the western side of the Wairarapa Fault zone, at higher elevation and closer to the topographic front of the Rimutaka Range, other laterally continuous, and perhaps now inactive fault strands with more subdued or diffuse scarps can be traced using air photographs. This observation suggests faulting may have stepped eastward away from the range front with time.



Figure 5. Geological map of the southern Wairarapa (from Begg & Johnston, 2000). The locations of Stops 1, 2, 3 and 4 are shown. Note location of Turakirae Head (shown in photo of Fig. 4). Some of the splaying of the Wairarapa Fault and the Wharekauhau fault systems can be seen. The Wharekauhau Thrust is exposed near the coast at Stop 4, where it dips gently $(20-30^{\circ})$ to the west, suggesting that the two faults merge at depth.

STOP 1. 1855 Rupture Trace in the Pigeon Bush Area (Pigeon Bush Localities 1, 2, and 3)

Park the vehicles at Pigeon Bush 1 and walk to Pigeon Bush localities 2 and 3. We will return on foot to the vehicles after approximately 1 hour.

Pigeon Bush Locality 1

Pigeon Bush 1 is justifiably the most famous geological site on the Wairarapa Fault. There, Grapes and Wellman (1988) interpreted two well-preserved, beheaded streams as evidence of dextral offset of a small stream gully cross-cutting the Wairarapa Fault during two sequential earthquake events, most recently in 1855. The fault is marked by a SE-facing scarp cut into Waiohine gravel that is ~6 m high. On the northern side of this scarp, the uplifted "Waiohine" terrace is tilted SW, whereas on its southern side it is partly buried beneath a ~1 m-thick layer of silt (and by younger swamp deposits). The silt was incised by the two channels. Wang and Grapes (2007) dated two samples of the silt by OSL methods, obtaining ages of 7.0 \pm 0.5 ka and 4.3 \pm 0.5 ka.

Stop 1: Pigeon Bush Sites 1, 2, and 3



Figure 6. Google Earth Image of Pigeon Bush Localities.

On the uplifted (NW) side of the fault, the "Waiohine" gravels have been back-tilted to the southwest by $\sim 5^{\circ}$ on the limb of an anticlinal bulge that crests to the NE of this site. Over time, this tilting has diverted some of the stream's headwaters southward into an adjacent stream. Thus the gorge on the up-thrown side of the scarp now seems disproportionately deep with respect to the small, low-discharge stream that currently flows within it. This is important because the stream flows through an entrenched gorge that is, in a sense, partially abandoned and thus little modified since its displacement along the fault.

As recognized by Grapes and Wellman (1988), the well-preserved geomorphology of the beheaded streams supports the idea that this younger increment of slip accrued during a single event, rather than as a composite displacement involving one or more intermediate stages. Both beheaded channels on the downstream side of the fault retain a linear morphology all the way up to the fault, where they are orthogonally truncated against the scarp. Similarly, the source gorge on the upstream side does not widen significantly at the fault, but remains narrow, linear, and fault-transverse all the way to



Figure 7. Microtopographic map of the Pigeon Bush 1 site, showing beheaded channels displaced by slip on the Wairarapa Fault. Map is based on a survey data set consisting of >10,000 points (Rodgers & Little, 2006). Trench Logs are from Little et al. (in press). All ¹⁴C ages (including two from the pits dug by Rodgers and Little, 2006) yielded similar ages, suggesting a bush fire that took place at, or soon after, ~546-497 cal yr. BP (1404-1453 cal. yrs, AD), perhaps in response to Maori burning.

the scarp. There is no evidence for a paleo-channel having run along the fault scarp between the modern stream and either of the abandoned channels, as might reflect an intermediate phase of stream dog-legging induced by shutter ridge damming. According to Rodgers and Little 2006, the proximal beheaded channel has been displaced 18.7 ± 1.0 m dextrally and $\geq 1.25\pm0.5$ m vertically relative to the deeply entrenched active channel on the upstream side of the fault. The other channel is displaced 32.7 ± 1.0 m dextrally and $\geq 2.25\pm0.5$ m vertically from its source. This larger offset suggests that the older, distal channel had previously been displaced by 14.0 ± 1.0 m of dextral-slip and ~1.0 m vertical-slip prior to incision of the proximal abandoned channel. The vertical-slip estimates do not account for any post-slip incision of the upstream channel and so are minima. The ~18.5 m dextral-slip of the proximal channel is the largest coseismic displacement documented for any strike-slip earthquake globally. The next-largest is 14.6 m of strike-slip during the 1931 earthquake on the Keketuohai-Ertai fault in Mongolia (Baljinnyam et al., 1993).

Each of the last two earthquakes on the Wairarapa fault at this site resulted in abandonment of a stream channel immediately downstream of the narrow headwater gully and incision of a new channel in downstream continuity with that gully. Hoping to date the last two earthquakes, Little et al. (in press) excavated trenches PB-1 and PB-2 (Fig. 7) at right angles to each of the two channels to date their incision and abandonment. Trench PB-2 was cut orthogonally across the older of the two beheaded channels. Fluvial terrace gravels at the base are scoured beneath a ~ 1 m deep, channelbounding unconformity. The channel is infilled by a massive, matrix-supported pebbly clay interpreted as a debris-flow. No fluvial deposits are present. A single piece of charcoal near the top of the debris flow (PB-22) vielded a ¹⁴C age of 543-495 cal. yrs BP, which suggests that it is another element of the above-described burn population that had become entrained into the debris flow. The only fluvially deposited organic material that we found in either channel (charcoal) occurs as detrital particles within the fluvial deposits that infill the incisional scour beneath the youngest of the two beheaded channels. This channel was cut immediately after the penultimate earthquake. Thus our preferred age of charcoal-producing "burn event" (~546-497 cal yr. BP) provides a minimum age constraint for the penultimate earthquake at this site (event Pb₂). Historical data indicates that the youngest earthquake here (event Pb₁) took place in 1855.

Pigeon Bush Locality 2

This region is located <1 km northeast of Pigeon Bush 1 (Fig. 6). Here the fault is characterized by a scarp that coincides with an abrupt southeast-facing topographic step and two elongate topographic depressions. A second strand marked by a small, southeast-facing topographic step may occur to the southeast of the main one, and a third may be present ~100 m to the northwest, but neither of these coincides with any fresh scarps or has revealed any evidence of recent slip.

Two small streams are incised 1.0 to 4.5 m into the older terrace alluvium and are dextrally displaced across the fault (Fig. 8). Where the streams cross the fault trace they deflect abruptly to the southwest to flow parallel to the fault before deflecting back to the southeast again on the downthrown side of the fault. Linear axes were defined along



Figure. 8. Microtopographic map of the Pigeon Bush 2 site, showing channels displaced by slip on the Wairarapa Fault (from Rodgers and Little, 2006). See Fig. 6 for location.

these incised channels and their dextral offset was restored with the aid of a microtopographic map. A narrow fluvial terrace remnant is preserved on the NW side of the western of the two streams (Stream B). Its 0.75 ± 0.25 m of incision by the modern stream on the NW side of the fault, and the 1.25 ± 0.25 m of vertical-offset of stream channel B across the fault together suggest ~2 m of vertical-slip (interpreted as a minimum, as this sum does not account for any post-1855 deposition that may have partially infilled the channel on the on SE side). Dog-legging of this southwestern stream implies 13.0 ± 1.5 m of dextral-slip, whereas dog-legging of the other active stream to the NE records 27.4 ±1.5 of dextral-slip. Following Grapes and Wellman (1988), we interpret the smaller stream offset to have accumulated in 1855 and the larger one to record a summation of slip during both 1855 and the next-older (penultimate) earthquake. This two-increment model of slip accumulation is strongly

supported by recent discovery of a subtle abandoned stream channel on the downthrown side of the fault to the southwest of the SW active stream. The beheaded stream channel is dextrally offset by 26.3 ± 5.0 m from its incised source: thus both of the small streams preserve evidence for a ~26-27 m horizontal slip, and one of the streams, similar to the nearby Pigeon Bush 1 site, also preserves evidence for a younger and smaller increment of offset.

Pigeon Bush Locality 3

Located about 300 m southwest of Pigeon Bush 1 (see Fig. 6). is site that Rodgers and Little (2006) described featuring a beheaded channel on the southeast side of the fault that has been dextrally offset relative to an active channel segment on the upstream side. At this locality (Pigeon Bush 3), the Wairarapa Fault zone is ~50 m wide, comprising a 2 m high, southeast-facing fault scarp to the southeast and a 2 m high, northwest-facing fault scarp to the northwest (Fig. 9). The southeast strand is characterised by a linear, southeast-facing topographic step, though it is unclear whether this segment slipped in 1855. The northwestern strand is continuous with the main scarp at Pigeon Bush 1, is similarly fresh-looking, and crosses a small stream, and displaces a small river terrace. This stream is now partly dammed by a dextrally displaced shutter ridge.

The small stream that flows across the northwestern fault strand has been diverted northeastward around the shutter ridge. Southwest of this fault strand, a 0.75 to 2.0 m deep wind gap (abandoned channel) is incised into the shutter ridge at an elevation ~ 2 m higher than the current level of the stream. Restoration of the western edge of this inactive, beheaded channel segment on the southeast side of the fault with the (also inactive) terrace riser on the northwest side of the fault indicates a dextral-slip of 15.1 ± 1.0 m and vertical-slip of -1.8 ± 0.5 m (up to southeast) across this strand. Recent incision of the terrace remnant on the upstream part of the fault suggests that despite its downthrown sense of local relative motion, this northwest fault block was uplifted relative to sea level in 1855, similar to other sites on that side of the Wairarapa Fault.

Between the offset (abandoned) channel and the active stream, the uphill-facing free face formed by the 1855 rupture plane is still remarkably well preserved. This near-vertical plane is only locally obscured beneath small fans of colluvial debris derived by the gravitational collapse of that free face during the past ~150 years.



Figure 9. Microtopographic map of the Pigeon Bush 3 site, showing channels displaced by slip on the Wairarapa Fault. See Fig. 6 for location. From Rodgers and Little (2006).

STOP 2: The Cross-Creek Pull-Apart Graben

Park the vehicles on the grass beside the pull-apart graben (depression). We will get out of the vehicles, examine the scarp and trenching sites, and discuss the paleoseismic data collected here (time spent at this stop approximately 30 minutes).

Whereas most of the *en echelon* segments along the central Wairarapa fault are leftstepping, contractional, and marked by bulges (Fig. 2); a stepover between fault strands near Cross-Creek is right-stepping, dilational, and marked by a small pull-apart graben (Figs. 2 and 10). The swampy pull-apart graben is today watered by a small southwardflowing stream that traverses a series of diffuse scarplets on the north side of the main depression before it exits from the western end of the graben (Fig. 10a). The drier eastern end of the graben is abutted by a tilted terrace surface overlain by a small inactive alluvial fan (Fig. 10b). The graben is down-faulted into the regionally extensive, post-Last Glacial Maximum (LGM) "Waiohine" terrace gravels (Begg and Johnston, 2000). Four trenches were excavated across opposite sides of the pull-apart graben (Trenches CC-1, CC-2, CC-3, and CC-4, Fig. 10a).



Figure 10. a) Vertical aerial photograph of Cross-Creek pull-apart graben showing trench sites and fault-trace locations. The photograph by Lloyd Homer (GNS Science) pre-dates track construction that has mostly destroyed the scarplets on the NW side of the graben. b) Microtopographical map of the NE end of the pull-apart graben showing trench locations. Map is based on 1505 points that were surveyed using real-time kinematic differential G.P.S. c) Auger transect and topographic profile across Cross-Creek pull-apart graben showing depth to gravel and location of the ¹⁴C sample "Auger-3." Note that scale of the profile is slightly enlarged relative to Fig. 10b, and that it is vertically exaggerated by 2 : 1.

Hand augering revealed a continuous layer of peat above the graben's down-dropped substrate of terrace gravel. This peat thickens southward to at least \sim 3.8 m near the southern boundary fault (Fig. 10c), where a large piece of wood (sample Auger-3) was intersected at \sim 1 m above the base of the peat (Fig. 10c). This wood was part of a log (others were extracted from the peat by the digger), and yielded a ¹⁴C age of 5580-5300 cal yrs B.P. Two other ¹⁴C samples (a wood and a peat) were collected from a peat that occurs interbedded with alluvial gravels of the "Waiohine" terrace on the southern, uplifted block. The peat (sample CC-1-1a in Fig. 11a) yielded an age of 12.1-12.7 cal kyrs B.P. (95% confidence interval), providing an important maximum constraint on the timing of abandonment of the Waiohine terrace near Lake Wairarapa.

Trenches Across the Southern Bounding Fault of the Cross-Creek Pull-apart Graben

Trenches CC-1 and CC-4 were excavated across the southern bounding fault of the pullapart graben. Fig. 11a shows a log from trench CC-1. Eleven ¹⁴C samples were dated from trench CC-1, and eight from trench CC-4. Of these, three are wood, and sixteen are peat or organic clay-silt.

On the basis of the combined data from trenches CC-1 and CC-4, we interpret five earthquakes to have ruptured the southern bounding fault of the Cross-Creek graben during the past ~5.2 kyr (Fig. 12). Trench CC-4, which exposed older sediments than CC-1, recorded evidence for the oldest event (CC_{S5}) in the form of a large colluvial wedge ("cwA") exposed in the lower part of trench (not shown in Fig. 11a). Radiocarbon samples from below and above this wedge bracket this earthquake to the interval 5450-4620 cal. yrs B. P.

The next-youngest earthquake, CC_{S4} , caused refreshment and collapse of the scarp, leading to emplacement of a colluvial wedge "cwB" in CC-4 (not shown on Fig. 11a) and to development of the upward fault truncations below the "intra-peat unconformity". Combining the age constraints of the colluvial wedge with those of the unconformity yields a composite age range for event CC_{S4} of 3690-3070 cal. yrs. B.P.

The third-youngest earthquake (event CC_{S3}) rejuvenated the scarp to cause formation of colluvial wedge "cw2" in trench CC-1. The age of this wedge is bracketed by ¹⁴C samples to the interval 2340-740 cal. yrs. B.P., Our preferred age for this earthquake, however, is based on sample CC-1-6 alone; as this age (2340-2110 cal yrs. B.P.) is interpreted to record death of a tree by earthquake-induced toppling immediately prior to emplacement of the wedge.

In trench CC-1, we infer that the penultimate earthquake (event CC_{S2}) caused emplacement of colluvial wedge, "cw3." This wedge draped across the pre-existing (and gouge-laden) trace of fault 1. The age of the wedge is bracketed by ¹⁴C samples to the interval 920-800 cal. yrs. B.P.

Inferred on historical grounds to be the 1855 earthquake, most recent earthquake (CC_{S5}) is expressed in trench CC-1 by the rupturing of fault strand 2 upward from wedge "cw3" to extend into the modern soil profile. A maximum age constraint of 970 cal. yrs. B. P. is provided by sample CC-1-14, from the faulted "om" layer, which is overlain by the wire-bearing layer, "wl" (undated, but assumed modern).

Trenches across the Northern Bounding Fault of the Cross-Creek Pull-apart Graben

Adjacent trenches CC-2 and CC-3 were excavated across the northwestern margin of the pull-apart graben. Figs. 11b and 11c show logs from trench CC-3. None of the fault strands on the northern side of the graben cut to the surface, and the topographic scarp is offset \sim 5-6 m southward relative to the subsurface fault zone. These relationships reflect lateral accretion of the uppermost gravelly layers across the fault scarp during nearby



a) Cross Creek Trench 1 (CC-1), NE Wall : Southern strand, Wairarapa Fault Zone

2 Radiocarbon samples with field number



Figure 11. Selected trench logs across the southern (a) and northern (b, c) boundary faults of the Cross-Creek pullpart graben on the Wairarapa Fault. See facing page for explanation of units.

Explanation for CC-1 (Fig. 11a)



Explanation for CC-3 (Figs. 11b & 11c)

u-col Pebble-cobble gravel in a sand-silt matrix (v. poorly sorted).Clasts are angular-subangular s-col s-col contains wire and both units are interpreted as anthropogenic fill grs :: Coarse gravelly silt to NW of fault zone, grading SW into fine to coarse gravel that contains increasing sand-silt component. op 🔀 Organic rich silt and peat. Pronounced crumb soil structure. Abundant modern roots CPg Pebble gravel (compact). Clasts are well-sorted, subrounded, and imbricated (interpreted as fluvial deposit) Coarse sand (well-sorted) with sparse fine pebbles (fluvial) SS pg Coarse sand to fine pebble gravel, locally including cobbles. Interpreted as fissure-infilling fluvial deposit co-2 Pebble-cobble gravel supported by matrix of silty or clayey sand (poorly sorted). Clasts are subangular-subrounded. co-1 Interpreted as colluvial wedges ogs Mixed unit near tree: Gravelly organic rich silt. Subrounded-subangular clasts cs Mixed unit near tree: Gravelly coarse sand os 🗔 Mixed unit near tree: Organic rich silt with varying gravel component. Subrounded-subangular clasts pt1,pt2 Fibrous, organic-rich clay or peat with abundant wood fragments and some scattered pebbles pt3,pt4 sp1 sp1 Tectonically mixed and sheared peats and gravels (sub-vertical orientation of blade shaped clasts in sp1) gs Gravelly sand in matrix of sandy silt, clast supported (fluvial terrace) ssg 🔀 Organic rich, fine sandy and silty gravel, subrounded-subangular clasts (fluvial terrace deposit) stg Sheared terrace gravel with alignment of clasts parallel to fault (coarse sandy matrix) fg O Faulted cobble terrace gravels tg 🕞 Terrace gravel: boulders and cobbles (subrounded) in a pebble-sand matrix. Clast supported and crudely bedded.

road construction. Seven samples from trench CC-2 and five from CC-3 were ¹⁴C dated. Of these, four are wood and the rest are peat, organic clay, or charcoal.

On the basis of the combined data from trenches CC-2 and CC-3, we recognize at least four earthquakes to have ruptured the northern bounding fault of the graben since \sim 5.2 ka. These events are labeled CC_{N4} (oldest) to CC_{N1} (youngest) on Fig. 12.

We infer that the oldest earthquake CC_{N4} resulted in emplacement of the colluvial wedge, "co-1." on Fig 11c?? Temporal constraints for this earthquake are provided by ¹⁴C samples from peats on both sides of the wedge. These ages bracket the earthquake to the period, 5280-4640 cal. yrs. B.P. This interval overlaps with CC_{S5} on the opposite side of the graben. Our preferred age for event CC_{N4} , 5209-4842 cal. yrs. B.P., is based on the interpretation that six wood samples were derived from a forest that was toppled or damaged by this earthquake. For this preferred age, we use the age of sample CC-2-38, the youngest element of the inferred death assemblage.

The next-youngest earthquake to rupture the northern side of the graben (CC_{N3}), we interpret to have caused emplacement of the colluvial wedge, "co-2." Figs. 11b, 11c?? Age constraints provided by peat samples both above and below the wedge yield an age range for the earthquake of 3080-1991 cal. yrs. B.P.– an interval that overlaps with CC_{S3} on the opposite side of the graben.

The penultimate earthquake (CC_{N2}) to rupture the northern boundary fault of the graben caused opening of a ~1 m-deep fault-fissure (Figs. 11b, c). This cavity was infilled initially by the pebble gravel unit "pg" and later by the sand of the "ss" unit. These well-sorted fluvial sands and pebbles were deposited across the pug-lined faults bounding the fissure (fault strands 1 and 2), with the youngest member of the infill sequence (unit "cpg") locally downlapping southeastward onto peat. We infer that CC_{N2} caused, moreover, some combination of the following: SE-ward tilting of the "co-2" wedge, anticlinal bulging of the peat basin to the SE, and deposition of the colluvial wedge "co-3" on the NE wall of trench CC-2 (not shown in Fig. 11). A maximum age constraint for event CC_{N2} of 2150-1940 cal. yrs. B.P. is provided by sample CC-3-2 beneath the fissure-infilling sequence.

The final rupture at the site, CC_{N1} , caused renewed slip on fault strands 1 and 2, and initiation of fault strands 5, 6, and 7 (Fig. 11b, 11c). Inferred to be the 1855 earthquake, this faulting deformed the fissure-infilling sequence of stream sediments (units "ss," "pg," and "cpg") that was deposited after earthquake CC_{N2} .



Figure 12. Time-space plot of surface-rupturing Wairarapa fault earthquake events inferred from all available types of paleoseismological data (from Little et al., in press). Data for Tea Creek trench (events labelled, *T*) are from Van Dissen and Berryman (1996, and unpub. ¹⁴C data). Diatom-based paleoenvironmental data for coastal uplift events at Lake Kohangapiripiri (events, *K*, shown as solid black bars) are from Cochran et al. (2007). Uplift events near Turakirae Head on Palliser Bay (events, Tk, shown as open to closed blue bars) inferred from raised beach ridges (BR-1 to BR-5) are taken from McSaveney et al. (2006). Small numbers quoted in meters denote inferred single-event uplift magnitudes for a given event. For Palliser Bay data, these refer to the maximum uplifts near Turakirae Head as inferred by McSaveney et al. (2006). Name of key ¹⁴C samples that bracket the timing of rupture events in trenches (this study) are identified at maximum and minimum limits of error bars (95% confidence), and refer to the field sample names listed in Table 1. Colored horizontal bands depict the maximum and minimum age range (at 95% confidence) for each earthquake event as derived from an analysis of the composite set of trench data and ¹⁴C results.

Late Holocene Rupturing History of the Southern Wairarapa Fault and Comparison to the Turakirae Head Beach Ridges

By integrating the key stratigraphic and structural events observed in the eight paleoseismic trenches (2 at Pigeon Bush, 4 at Cross-Creek and 2 at Riverslea, which is Stop 3), and by dating and correlating these using the 40 new ¹⁴C samples, Little et al. (in press) interpreted a composite surface rupturing history that included at least five

earthquakes on the southern part of the Wairarapa fault since ~ 5.2 ka (Fig. 12). McSaveney et al. (2006) identified and dated the uplift and stranding of four late Holocene beach ridges at Turakirae Head. Three of these are younger than ~5.2 ka. Each of these corresponds to one of our independently determined Wairarapa fault rupturing events (Fig. 12). Two of our trench-determined fault rupturing events cannot be matched to a corresponding beach ridge at Turakirae Head. These are the Penultimate Event and Fourth Event. Our comparison between the trench-based earthquake rupturing history of the Wairarapa Fault and the sequence of raised beaches at Turakirae Head leads us to conclude that flights of uplifted gravel beach ridges may provide an incomplete record of paleoearthquakes on adjacent reverse-oblique faults. The paper by Little et al. (in press) suggests several processes, both tectonic and nontectonic, that might result in the geomorphic "omission" of one or more beach ridge from an uplifted sequence. These include: a) variable rupture geometries at the southern end of the Wairarapa-Wharekauhau fault systems (a zone of particularly complex fault splaying and folding in the near-surface, Fig. 1b), with some earthquakes causing only a small uplift at Turakirae Head and no discrete beach ridge being raised; and b) landward retreat of an active storm berm (perhaps during a particularly stormy interseismic periods) to cause its overwhelming of, or amalgamation with, the next highest beach ridge (thus causing an apparent omission of a beach ridge).

STOP 3 (Time Permitting) Riverslea Trenching Site on Wharekauhau Fault System

Park the vehicles on the circular driveway near the milking shed. Walk 10 minutes to scarp of the Wharekauhau fault near Manganui Stream. Discuss the nature of this scarp, the location and context of the two trenches excavated across it, and the significance of the data collected in them. Total time at this stop about 40 minutes

Travelling south from Stop 2 along the edge of Lake Wairarapa, we diverged from the trace of the Wairarapa Fault (*sensu strictu*). Between the Burlings and Wairongomai Rivers the main strand of the Wairarapa strikes SSW, leaving the range-front (which steps eastward), and continuing into the high country of the southern Rimutaka Ranges (Fig. 1). Near this location, the Wharekauhau fault system splays eastward away from the Wairarapa fault for ~5 km, before deflecting back to a SSW strike and continuing along the eastern edge of the Rimutaka Ranges to at least as far south as Palliser Bay.

The Wharekauhau fault system (Fig. 13) has previously been interpreted to consist chiefly of an active thrust (or oblique-reverse fault) termed "the Wharekauhau thrust." For this field trip we will restrict the term "Wharekauhau thrust" to a specific, strongly contractional low-angle fault that is well exposed near the Palliser Bay coast (Stop 4). The thrust emplaces Torlesse terrane rocks in its hangingwall over Quaternary sediments in its footwall, and (as we will see) is interpreted to be an inactive element of Wharekauhau fault system (Schermer et al., in review).

Near High Manganui and Riverslea Station (Stop 3), Begg and Johnston (2000) mapped the top of Manganui Hill (224 m elevation) as being capped by Quaternary gravel, and as being bounded to the east and west by faults (Figs. 14, 15). The western of these, a



Figure 13. Simplified map of Wharekauhau fault system, southern Wairarapa Fault, other tectonic features, and selected geological units (after Begg and Johnston, 2000; as modified by Schermer et al., in review).

west-dipping fault, emplaces Torlesse greywacke eastward over Quaternary sediments. This structure is mantled by several river terraces of unfaulted alluvium and is interpreted by Schermer et al. (in review) to be an inactive thrust.

On the eastern branch of Wharekauhau fault system near Riverslea Station, Schermer et al. (in review) mapped a series of ENE-striking, discontinuous scarps that traverse steep hillslopes underlain by early Quaternary(?) fluvial gravels on both sides of Manganui Stream. In two places, these offset small gullies by 6-8 m dextrally and 1-3 m in an up to the NW sense. Farther to the north, near the Waiorongomai River, where the eastern



Figure 14. Geological map of the Manganui Stream area from Begg and Johnston (2000). The Battery Hill Fault is obscured by late Holocene deposits along much of its length, but offset of the Last Interglacial marine bench at Battery Hill, and folding of the Pounui Anticline indicate the activity of the structures. A folded and abandoned Last Glacial river course of Manganui Stream crosses the axis of the Pounui Anticline. Holocene deposits in the Ruamahanga River area to the east are estuarine to marginal marine in origin. Small red triangles are spot heights, labeled with their elevation in metres. Note that in this field guide (despite the labelling on this figure) we do not refer to this part of the Wharekauhau fault system as being a "thrust."

branch (and rangefront) strikes to the north, Schermer et al. (in review) found scant evidence of terrace deformation or for any active scarp. Thus it is only the ENEstriking, SW part of the eastern branch Wharekauhau fault system near Manganui Stream that appears to be active, and this activity is apparently dominated by dextral slip.

Where the eastern branch crosses the Holocene River terraces at Manganui Stream it is marked by a scarp that is ~ 3 m high. This scarp is the location of Stop 3 (Fig. 16). Begg and Mazengarb (1996) inferred that the 1855 earthquake may have ruptured this part of the Wharekauhau fault system, an inference that is consistent with local tradition in the district, and with downcutting of the Manganui Stream upstream from the scarp (in contrast to the low banks of the same stream below the scarp). More recently, the scarp has been excavated by two trenches. Trench RV-1 was excavated perpendicular to the main ENE-striking, ~ 3 m-high topographic scarp on the terrace. Trench RV-2 was



Figure 15. Oblique elevated image of the Manganui Stream area (by J. Begg). The vertical scale is considerably exaggerated. Note the truncation of the terrace Q5b by the Wharekauhau Thrust (left foreground) and the location of the 1855 trace across Manganui Stream. Note also the Pounui Anticline on the eastern side of the Battery Hill Fault that is bisected by an abandoned Last Glacial Manganui Stream course (Q2a). (Base image by J.M. Lee). Note that in this field guide (despite the labelling on this figure) we do not refer to this part of the Wharekauhau fault system as being a "thrust."



Figure 16. Microtopographical map of the Riverslea fault trenching locality (Little et al., in review). Map is based on 1020 points that were surveyed using real-time kinematic differential G.P.S. methods. GPS survey was tied to an arbitrary local base station and was not corrected against a gazetted geodetic benchmark. Grid marks (in meters) refer to the New Zealand Map Grid Coordinate System.



Figure 17. a) Log of SW wall Riverslea 1 trench (RVL-1) across folded scarp of Wharekauhau thrust near Manganui Stream; b) Photograph of inclined (probably tectonically tilted) laminae in fine to coarse-grained sand layer (unit ss-5 in RVL-1 trench; c) Log of part of the NE wall of the nearby Riverslea 2 trench (RVL-2); d) Photograph of infilled fault fissure in RVL-2 trench. From Little et al. (in press)

placed slightly higher up this slope to intersect a less conspicuous scarplet on the uplifted, NW-side of the main scarp.

The two Riverslea trenches contain evidence for two earthquakes (Events Rv_1 and Rv_2). In trench RVL-2 (Fig. 17 c), the most recent earthquake ruptured to the surface cutting sediments younger than 547-497 cal yrs B.P (sample RVL-2) to create a fissure (Fig. 17d). The fissure was infilled in by soil debris containing "modern" charcoal and is thus consistent with this earthquake being the 1855 rupture. Based on the stratigraphic mismatches across fault strand 1, slip during the fissuring is inferred to have been primarily strike-slip. In the same trench, evidence for an older (penultimate) earthquake includes the depositional overlap of fault 3 (and some splays of fault 2) by undeformed channel gravel ("gvl-18"). A sample of fibrous wood (RVL-4) from the faulted silt (unit "si-9b") below this unconformity to the SE of fault 2 yielded an age of 897-722 cal yrs. B.P.. We are uncertain whether this sample was detrital in origin or a root fragment. If this wood was detrital, then it must pre-date the penultimate earthquake at this site. If a root fragment, then it does not necessarily pre-date that earthquake. Sample RVL-2 must post-date the penultimate earthquake.

In trench RVL-1, near-surface bulging of the terrace sediments is inferred to have raised the main scarp intersected by that trench, at least in part during the 1855 earthquake (Figs. 17a). Six measurements of co-seismic throw on the southern part of the Wairarapa fault's central section during 1855 range up to a maximum of 2.5 m in a NW-up sense (Rodgers and Little, 2006). That the main scarp at Riverslea is ~3 m high suggests its growth in at least two stages. If so, at least two earthquakes must post-date sample RV-1; that is, the penultimate earthquake must be younger than ~1300 cal yrs. B. P.

The lack of a fault in trench RVL-1, and the small offset in RVL-2 suggests that the primary mode of deformation to create the northwest-up scarp on the late Holocene terrace was folding (Fig. 17b). The cause of folding is interpreted to be dip-slip on a northwest-dipping fault, concealed beneath the trenched gravels, that forms the eastern branch of this part of the Wharekauhau fault system. Based on the stratigraphic mismatches across fault strand 2, we infer that a small (several-meter?) strike-slip surface displacement accumulated in 1855 on a steep splay fault in the hangingwall of the blind structure in response to an overall dextral-reverse slip on the main structure at depth. The contrast between demonstrably active tectonics at the trench site on the ENE-striking reach of the eastern strand, and the lack of evidence of Holocene offset on the western strand (and elsewhere along strike) suggests that the eastern branch of the fault zone is a younger structure that is dominated by dextral-slip.

Optional Stop at location of 127 ± 10 ka OSL sample of last-interglacial marine sand on road-cut

On our drive along Western Lake Rd, note how it skirts the edge of the hills and the flat swampy country to the west of Lake Onoke. There is evidence that the road traverses around sandy berms that bounded a former Holocene estuary, the last remnant of which is Lake Onoke itself. The hills to the west are underlain by a several-meter thick Last Interglacial marine deposit (well-sorted and rounded sands and pebble gravels). These beach(?) deposits are overlain a considerable thickness ($\sim 10+$ m) of younger fluvial gravels. This composite origin (marine + fluvial terrace), called unit "Q5a" by Begg and Johnston (2000), can be tracked to the east to beyond Lake Ferry. The terrace surface is folded and reaches a maximum elevation of >150 m (Begg and Johnston, 2000). Lake Pounui, a small lake nestling within these hills is ponded behind an active fault, the Battery Hill Fault. This can best be seen where it displaces the "Q5a" terrace by about 10 m, its eastern side upthrown, and it probably dips to the east (Figs. 13,14). Part of the active Pounui Anticline lies to the east of this fault, and road cuts in the gravel and silt sequences (middle Quaternary Ahiaruhe Formation) within the anticline can be seen on the right hand (eastern) side of the road.

The marine interval is well-exposed on the left-hand side of the road, at an elevation of ~40 m). Near here, Schermer et al. (in review) collected an Optically Stimulated Luminescence sample of sand that yielded an age of 127 ± 10 ka (1 σ), consistent with the marine unit being deposited during Oxygen Isotope Stage 5e.

STOP 4. Wharekauhau Stream Mouth, Palliser Bay (Walking circuit)

Park vehicle at mouth of Wharekauhau Stream (do not attempt to cross it in vehicles). Walk upstream, stopping first to look at stratigraphic relations near the mouth of the stream (Stop 4a). Proceed upstream (about 20 minutes) to an exposure of unit 3 (Stop 4b) and further upstream to a large exposure of the Wharekauhau thrust (Stop 4c). Return downstream and take the farm track up to the ridgetop (large flat paddock) between Te Mahonge and Wharekauhau Streams (Stop 4d). Walk down the track to Te Mahonge stream to see the Wharekauhau thrust exposed on the track (Stop 4e) and the west bank of the stream (Stop 4f). Return along the coast to vehicles. Total time away from vehicles approximately 3 hours.

Travelling west from the optional stop, we drop below the elevated marine surface and cut through early Quaternary fluvial units (Fig. 13). Along the banks of Wharepapa River and the coast, we can see late Quaternary units including marine sands and gravels near the base of the cliffs, overlain by lacustrine silts and alluvial gravels, and the last-glacial "Waiohine" gravels at the top of the sequences. This relationship, late Last Glacial gravels lapping against an older marine bench to the east, the elevation difference of Last Interglacial deposits on each side of the fault, and the presence of a significant negative gravity anomaly near the same contact, points to the presence of a buried fault down Wharepapa Stream (e.g., Kingma, 1967; Rollo 1992; Begg and Mazengarb 1996; McClymont 2000). Figure 19 shows the elevation of the top of the marine unit where it is exposed on the down thrown side. The elevation change, together with incision of the Waiohine surface, is interpreted by Schermer et al., (in review) to reflect deformation in the hangingwall of a thrust further to the east.

STOP 4a: Quaternary stratigraphy at Wharekauhau Stream mouth

Time at this stop approximately 20 minutes.

Near the south coast of the Wairarapa Valley, late Quaternary strata and their corresponding landforms, such as wave-cut platforms and fluvial terrace surfaces, record a progression of relative sea level changes, periods of deposition, and pulses of



Wharekauhau fault exposures

Te Mahonge Strm

Wharekauhau Stream

Figure 18. Google Earth map of Stop 4 showing round-trip walking route between Wharehauhau and Te Mahonge Streams and sites visited along the trace of the Wharekauhau thrust near the Palliser Bay coast. See Figure 13 for location of this image.



Figure 19. Geology of Wharekauhau segment, showing Quaternary unit designations as described in text and Figure 20, fault and fold traces, sample locations, and field trip stops. Open star shows sample location from Wang (2001). Surveyed elevation of the top of unit 1 shallow marine deposits is indicated next to triangles; no outcrops of unit 1 occur north of the northermost symbols. Open triangles indicate locations with elevations that are not controlled by detailed surveying. Dashed outline shows area of detailed mapping and laser surveying, two portions of which are detailed in Figures 21, 24. Location of cross sections A-A' and B-B' are indicated. Topographic contours are in meters; grid marks (in meters) refer to the New Zealand Map Grid Coordinate System.



Figure 20. Schematic cross section of stratigraphy in the detailed study area of Figure 19. Squares=location of radiocarbon samples (wood from in-situ roots, stumps); circles=location of OSL samples (silts, fine sands). Age ranges for radiocarbon samples are calibrated age range at 95% confidence. Errors on OSL ages are 2σ . See Figures 19, 21, 24 for detailed sample locations. deformation near the Wairarapa fault since ~125 ka. To the west of the Wharekauhau thrust, the late Quaternary sequence was deposited unconformably above Mesozoic graywacke, whereas to the east of the thrust, the same strata overlie a substrate of Pliocene-Pleistocene marine to non-marine strata (e.g., Begg and Johnston, 2000). The late Quaternary sequence provides a sensitive geological record of landscape evolution and deformation (including both folding and fault slip). In this region (Fig. 19) our stratigraphic work built upon that of earlier studies (Eade, 1995; Grapes and Wellman, 1993; Shulmeister & Grapes, 2000; Shulmeister et al., 2000, Marra, 2003). Unit designations used here (Fig. 20) are newly defined and do not necessarily correspond to the (varied) nomenclature used in the earlier work (most of which is unpublished).

Local exposures of marine sands and gravels (similar to those exposed east of Wharepapa River), herein termed unit 1, occur as a 7-9 m thick sequence in the hangingwall and footwall of the Wharekauhau thrust. In the hangingwall at Te Mahonge Stream, unit 1 overlies greywacke bedrock. In the footwall at the mouth of Wharekauhau Stream (Stop 4a), unit 1 overlies fluvial gravels possibly belonging to the Te Muna Formation (Fig. 20). OSL samples of marine sands collected from unit 1 yielded ages of 106 ± 24 ka (NI48) and 71 ± 8 ka (NI42) (2σ errors). As expected, the three samples of marine sands (including the one at the optional stop east of Wharepapa river, which is not in stratigraphic continuity with the fault-proximal marine unit 1) yield ages that are indicative of the last interglacial sea-level highstand (oxygen isotope stage [OIS] 5). The different locations and the higher elevation and older age of the sample east of Wharepapa River (NI51) relative to NI42 (Figs. 13, 19) suggest their deposition during different sea-level highstands (substages) within OIS 5.

In the footwall of the Wharekauhau thrust, the marine gravels are overlain conformably by ~9 m of organic-rich lacustrine mud, silt, and gravelly silt that locally contains tree stumps in growth position (unit 2a). This unit is interpreted to have been deposited during an interglacial climate in an estuarine lagoon similar to present-day Lake Onoke (Eade, 1995; Marra, 2003; Shulmeister et al., 2000). Unit 2a interfingers northward and westward with, grades laterally into, and is overlain by fluvial gravels containing clasts eroded from the Rimutaka Range (unit 2b). Towards the top of unit 2b, gravels have a distinctive yellowish brown color and contain local thin (<0.5m) silt beds with rooted stumps in growth position. Unit 2 coarsens and thickens towards the trace of the Wharekauhau thrust, where we recognize a locally exposed bouldery facies, unit 2c. These coarse gravels interfinger southeastward with better sorted and stratified gravels typical of unit 2b. We will see unit 2c at stop 4c.

Samples from unit 2 yielded OSL ages that are consistent with deposition near the end of the last interglacial at ~80-70ka (i.e., OIS 5a). Sample NI43 from the lower part of unit 2b yielded an age of 82 ± 34 ka (Figs. 19, 20). This sample is located ~4 m above silts of unit 2b dated by OSL at ~115 ±66 ka (Marra, 2003) and ~16m above a sample of unit 2a dated at 117±60 ka (Marra, 2003)(2 σ errors). A higher sample from unit 2b, ~20m above sample NI43, yielded an age of of 71±18 ka (sample NI52, Figs. 19, 20). We note that our dating accords with the last-interglacial interpretation of these units by Grapes and Wellman (1993) and Shulmeister et al., (2000) and the interpretations of Marra (2003) based on the fossil insect assemblage in unit 2a.

STOP 4b: Upper part of Quaternary stratigraphy at Wharekauhau Stream

Total time at this stop about 20 minutes.

At this stop we will see an exposure of the widespread sandy silt (unit 3) up to $\sim 2 \text{ m}$ thick that caps the unit 2b gravels, and overlying fluvial gravels (unit 4). At this location, the units appear conformable. Grapes and Wellman (1993) reported that this silt contains shards of the Kawakawa tephra (26,500 calib yr B.P; (Wilson et al., 1988) and abundant *in-situ* stumps and roots at its top dated at $12,450 \pm 120$ and $12,760 \pm 110$ 14 C yr BP (Grapes and Wellman, 1993) (these correspond to calibrated ages of ~15 ka). Grapes and Wellman (1993) interpreted the silt as a loess deposited on an abandoned fan surface, but the local presence of poorly sorted fine pebbles in the unit led Shulmeister et al., (2000) to reinterpret the unit as an overbank deposit mixed with loess. Our new OSL ages from samples near the base of the unit are 18.5 ± 2.4 ka and 19.5 ± 3.2 ka (Fig. 20). ¹⁴C samples from the top of unit 3 range from 15 ka to ~9ka, with age decreasing northward and with elevation (Fig. 20). As we will see at later stops, there is a marked angular unconformity beneath unit 3. Furthermore, unit 3 mantles a topographical paleoscarp created by slip on the Wharekauhau thrust, and thus appears to be wind-deposited (a loess). The data suggest that the silt of unit 3 and overlying gravels of unit 4 onlapped northward across the scarp over a period of >5,000 years.

Unit 3 is overlain by alluvial fan gravels (unit 4) that are topped by the terrace tread referred to as the "Waiohine" surface by Grapes and Wellman (1993). Wang (2001) reported a ~5 ka OSL age on a silt lens collected 0.6 m beneath this surface near Stop 4a (sample WK-1; Fig. 19).

STOP 4c: Wharekauhau thrust exposure at Wharekauhau Stream

Discuss the evidence for thrusting and abandonment of the thrust. Total time at this stop about 60 minutes.

At this exposure we can see the imbricate nature of the Wharekauhau thrust as well as key stratigraphic relationships that constrain its timing (Figs. 21, 22). On the right-hand side of the exposure there is evidence of two distinct periods of unit 2b deposition, separated by a soft, red-brown gravelly clay that we interpret as a paleosol. Unit 2c, consisting of disorganized and bouldery, angular gravels, is only found above this clay, and interfingers southward with fluvial gravels of the upper part of unit 2b. Across the length of the exposure, unit 2c occurs in fault contact beneath a lower imbricate of the Wharekauhau thrust, while at the southern end, it is also in discordant depositional contact against steeply dipping (beach) strata of unit 1 in the main hanging wall of the thrust (somewhat obscured by flax bushes). We interpret this discordant contact as a buttress unconformity and unit 2c to represent colluvium derived from the emergent thrust scarp. Older parts of unit 2c were overthrust during fault slip, while younger parts were deposited against the emergent hangingwall, partially burying it. In the upper parts of this exposure, it can be seen that units 3 and 4 overlap the Wharekauhau thrust and units 1 and 2 along an angular unconformity. In the hanging wall of the thrust above the north end of the outcrop, unit 3 occurs as a 5-6 m-thick massive silt that is not



Figure 21. a) Detailed map of Wharekauhau stream area (Stop 4c) derived from surveying topography and geologic contacts with a laser rangefinder. Locations of geochronological samples shown with black dots. b) Cross section B-B', no vertical exaggeration constructed perpendicular to a thrust strike of 210 (N30E) consistent with the structure contours drawn across Wharekauhau stream and the regional trend of the fault. Location shown on Figure 19. Fine dashed lines show bedding traces.



Figure 22. Tracing of a photograph of an outcrop of the thrust at stop 4c. Duplexing in unit 2b is inferred from discontinuities in bedding; duplexing in unit 1 is inferred from extreme thickening of unit in horse relative to undeformed exposures.

capped by any unit 4 gravels. About 20 m to the southeast, unit 3 continues as a <0.5m thick layer that is overlain by unit 4. This fault-proximal part of unit 3 appears to mantle a paleoscarp formed in older units. The angular discordance between unit 3 and older Quaternary strata is typically \sim 30° here (Fig. 21), but disappears to the south (e.g., stop 4b).

Structural features are also well displayed at this outcrop, where the Wharekauhau thrust consists of two subparallel thrust planes that are spaced ~1-1.5 m apart, and that flatten from ~30°NW dip to horizontal towards the south (Fig. 22). The higher thrust juxtaposes highly fractured Cretaceous Torlesse greywacke (foliated cataclasite) in its hangingwall to the northwest above steeply dipping unit 1 strata to the southeast. The lower thrust juxtaposes unit 1 beach gravels above gently dipping strata of unit 2 (subunits 2b and 2c). Between the two fault planes, the slice of steeply dipping strata of unit 1 occurs as a "horse" that is internally folded. The structural thickness of unit 1 in this horse (up to ~100m) is > 10 times greater than the observed maximum stratigraphic thickness of unit 1 away from the fault (7-9 m). Although the discontinuity of exposure prevents us from verifying the inference, this relationship suggests that unit 1 in the horse is repeated several times by thrust duplexing or distributed deformation. Imbricate thrusts may also occur within unit 2 beneath the lower thrust.

The geometric and stratigraphic relationships suggest initial formation of a faultpropagation fold, followed by the fault tip propagating upward to the surface, and cutting off the steep forelimb. The subvertical dips in the imbricate fault slice of unit 1 and locally in unit 2 immediately below the lower thrust and in unit 1 above the upper thrust indicate that the strata were folded prior to thrusting. The eastward shallowing of the thrust planes, and the coincidence of the flat thrust surface with the paleosol within unit 2b (Fig. 22) suggests that the thrust ramped upward to the contemporary free surface before collapsing gravitationally.

In Wharekauhau Stream, corresponding hangingwall and footwall cutoffs are not exposed so there is little control on total shortening. Cross section B-B' can be used, however, to calculate a minimum heave of $65 \pm 2m$ on the upper thrust of the imbricate system from the amount of overlap of the greywacke and the fragment of unit 1 in the hangingwall, assuming a thrust strike of N30E (Fig. 21b). Doubling that to account for the similar overlap of unit 1 on the lower fault (and without accounting for any duplexing) gives a minimum of 130 m shortening across both thrusts. Varying the strike of the thrust to account for poor exposure of the surface results in <15m difference in the heave.

STOP 4d: Deformation (?) of the Waiohine surface at Te Mahonge Stream

Return downstream and take the track up to the paddock between Te Mahonge and Wharekauhau Streams. View and discuss the (lack of) evidence for 1855 surface rupture on the paddock surface, and the stratigraphy exposed in the slip face. Total time at this stop about 40 minutes (including the walk).

"Te Mangonge" Stream is an historic locality, described by Rodney Grapes in his book, "*Magnitude 8 Plus*" as the location where, immediately after the 1855 earthquake, Edward Roberts, a surveyor for the *Royal Engineers and Clerk for Works*, observed a break along the creek, across which "the range of hills [Rimutaka Range] have gone up alone forming a perpendicular precipice." As a consequence of this uplift of the coastal rock platform, a coastal route negotiable by foot or ox-cart (or mountain bike) was opened up for the first time between the Wairarapa and Wellington. Charles Lyell met Roberts in England a year later, and included the surveyor's account of 1855 co-seismic deformation into his book, "*Principals of Geology*" (Lyell, 1868), along with a crosssection of the "fault and fissure" in "Te Mangonge" Stream (Fig. 23a). The maximum coastal uplift in 1855 occurred ~4 km to the northeast of Turakirae Head, where the 1855 beach ridge was elevated vertically by 6.4 m on the upper block of the Wharekauhau Thrust (Hull and McSaveney, 1996; McSaveney et al., 2006).

A review of the historical record (Downes and Grapes, 1999; Ongley, 1943) indicates that there was no definitive report on the nature of any earthquake rupture at the coast in 1855 at either Te Mahonge or Wharekauhau streams. The report that Edward Roberts gave to Lyell does not describe the location of the "precipice". Later interviews of Roberts by Lyell state that Roberts found "raised nullipores" 9 feet above the tide line the morning after the 1855 earthquake near Muka Muka rocks (Lyell, 1868). Although the exact location of his observation is uncertain, Muka Muka rocks is west of the NW corner of Palliser Bay and ~3 km west of Te Mahonge stream. This is evidence of coseismic coastal uplift relative to sea level, but it is not evidence for a rupture plane in Te Mahonge stream.

The diagram published by Lyell (1868) (Fig. 24a) showing the fault that he inferred to have slipped in 1855 actually came from a description provided by Walter Mantell, a geologist who was in New Zealand at the time of the earthquake:

"According to Mr. Mantell the risen mass consists of old stratified argillites, with the normal composition of argillaceous schists, but without schistosity. This mass forms a several hundred foot high cliff towards the sea, whereas the tertiary marine strata, which are exposed to the east, next to the shore, form another relatively low cliff which would not be higher than eighty feet. These tertiary strata did not rise." (Lyell, 1856), as translated in Downes and Grapes, 1999)

The juxtaposition of "old argillite" (greywacke) against "Tertiary strata" (Quaternary silts and gravels) describes the relationships near the mouth of Te Mahonge stream (stops 4e, 4f) but is not, however, the same place as where Roberts measured the "raised nullipores", nor is it a description of a coseismic rupture or scarp.

In 1934-35 M. Ongley (1943) mapped scarps along the 1855 rupture from Alfredton to the coast. He disagreed with Lyell on several points, noting that the fault that Mantell described was not at the NW corner of Palliser bay as originally described, but was further east (at Te Mahonge stream). He also noted the fault is not a vertical fissure as reported in Lyell (1868), but a gently dipping thrust. Furthermore, Ongley (1943) did not find a surface scarp on either side of Wharekauhau stream, and stated that the southernmost scarp was located ~1mile (1.6 km) north of the coast (on the SE flank of Wharekauhau Mountain). The scarps that he illustrates (Figs 1, 2 in Ongley, 1943) trend more easterly than the thrust contact and may be some of the strike-slip features or landslide scarps mapped by Schermer et al. (in review). Ongley (1943) stated that "*the line of it [the 1855 scarp] runs to the coast well west of the fault between the two formations*". Furthermore, although Ongley (1943) shows a dashed line of surface



Figure 23. Previous interpretations of the Wharekauhau thrust as exposed in Te Mahonge and Wharekauhau Streams near the Palliser Bay coast. a) diagram of Te Mahonge Stream exposure of the fault (illustration in Lyell, 1868; note the steep dip of the fault); b) diagram after Grapes and Wellman (1993) who interpreted the Waiohine Terrace surface as being deformed and tilted across the fault at the location of photograph (c), Note that the top of Grapes and Wellman's "agB" unit is equivalent to the unit "Q2a" of Begg and Johnston (2000), and to the top of "unit 4" of Schermer et al. (in review, as used in this guide).

ruptures on his map south of Lake Wairarapa, none of the area traversed for the present study has definite fault scarps that are as steep or fresh-looking as the area to the north from Hinaburn to Alfredton (e.g. Grapes and Wellman, 1988; Rodgers and Little, 2006; Schermer et al., 2004). Although Ongley (1943) stated clearly that Lyell's diagram did not represent the 1855 rupture, the error has persisted through recent publications (Grapes and Downes, 1997; Grapes and Wellman, 1993; Sibson, 2006).

The location of Roberts' coastal uplift observation on Palliser Bay is constrained by the beach profiles of Hull and McSaveney, (1996); McSaveney et al., (2006) who show that the easternmost preserved uplifted beach ridge is <1km east of Muka Muka stream (Fig 13) and interpret this to be approximately the location of Roberts' observation in 1855. Given the evidence for lack of recent rupture of the Wharekauhau thrust, we suggest that the fault, if indeed it ruptured the surface at the coast, did so closer to Muka Muka

stream. McSaveny et al (2006) reach a similar conclusion from their detailed analysis of the Turakirae head data.

At this stop (Fig. 23c), vertically above the exposures of the thrust in Te Mahonge Stream, the Waiohine terrace surface was interpreted by Grapes and Wellman (1993) to be warped upward during rupture of the Wharekauhau thrust in 1855 and prior earthquakes. Our new mapping shows that the Waiohine gravels (unit 4) do not show the same dip as the terrace surface, which is mantled by a younger layer of colluvium derived from the hilly topography northwest of the inactive thrust trace. The strata in unit 4 everywhere dip <15° and onlap depositionally against the more steeply dipping strata in the thrust hangingwall (Fig. 24). From these relationships we infer that the Waiohine surface at the top of unit 4 is undeformed and that the local increase in surface slope of the hillside adjacent to the paleoscarp is a primary depositional feature of the landscape (slope colluvium) and not the result of tectonic deformation in 1855 or at any earlier time.

Looking back towards stop 4c, the Waiohine surface is visible in both the hangingwall and footwall of the thrust as the cleared paddocks, but it is not continuous across Wharekauhau stream (Fig. 21b). Grapes and Wellman (1993) inferred that ~ 20 m of height difference between these two parts of the surface was due to deformation along the thrust. A laser-surveyed topographic profile along the Waiohine surface across the trace of the thrust from NW to SE across the stream shows the surface is 15 m lower on the SE side of the stream, but the dips are low (2.5-5°) and it is not clear if there is a change in dip that can be associated with the trace of the thrust (Fig. 21b). We interpret the dips as primary features of the fan surface. If the change in slope is indeed due to thrusting, the active fault must lie below the surface, and can not have the same nearsurface expression as the (inactive) Wharekauhau thrust.

STOP 4e: Wharekauhau thrust at Te Mahonge Stream

Walk down the farm track to the exposure of the thrust at the base of the track (true left bank of the stream). Total time at this stop about 40 minutes (including the walk).

At this location we can see the two thrusts enclosing the horse of unit 1, and higher on the slope, the unconformity between unit 2, which dips $25-90^{\circ}$, and units 3 and 4, which dip $\sim 10^{\circ}$ (Figs. 24d, 25). If there is time to walk upstream to view a large exposure in the slip face, we will see unit 4 onlapping the paleoscarp (Figs. 24a, b).

The two thrusts flatten in an eastward direction from NW dipping to subhorizontal (Fig. 24b). On the west bank of Te Mahonge Stream (stop 4f), both thrusts are steeply dipping. Here, the upper thrust is subhorizontal and the lower thrust is oriented 358/16E. Cataclasite fabric in the hangingwall greywacke also flattens upward, from 68°NW to 23°NW, with the hinge direction of this antiform trending 026 (Fig. 24c). Within the horse, unit 1 is folded by "drag" on the upper thrust (Fig. 25).

Above the thrust, a hangingwall anticline deforms the greywacke and the unconformably overlying units 1 and 2. Near the crest of the anticline (near the top of the track, and a few meters up from the base of the track), several steeply SE- and NW-dipping faults with <0.5m normal separation cut unit 2, perhaps to accommodate

localized extension above the fold crest. Units 3 and 4 onlap, pinch out against, and partially bury, a paleoscarp defined by the older, more strongly deformed hangingwall units (Fig. 25).

In all locations strata at the top of unit 2 have a similar dip to those at the bottom of that unit and to beds in unit 1 (Fig. 24d). This concordance indicates no measurable tilting during sedimentation of units 1 and 2, although the variability of dips, the sparsity of data near the top of the unit, and the difficulty of measuring bedding in coarse fan gravels could allow for some minor ($<5^\circ$) shallowing upsection.

The map pattern and thickness variations of units 3 and 4 seen here and in Wharekauhau stream indicate that deposition of these units was strongly influenced by an earlier scarp generated along the Wharekauhau thrust. The angular unconformity beneath these two units, their overlapping of the thrust, and their subhorizontal attitude indicates the thrust was not active at the time of deposition (or subsequently).

Structural evidence exists for steeply dipping faults that post-date motion on the Wharekauhau thrust. Although we have not found a continous, throughgoing fault, several map- and outcrop-scale observations support the hypothesis of late strike-slip faulting that occurs in the vicinity of the inactive thrust traces. The most compelling evidence comes from our detailed mapping. Structure contours drawn parallel to strike from surveyed elevations on the fault surface indicate that the thrust surfaces in Te Mahonge and Wharekauhau stream are not coplanar, and further show that the outcrop in Te Mahonge Stream has been folded or faulted to lower elevation than that in Wharekauhau Stream. However, since the thrust at both locations shows the same flattening-upward geometry (Figs. 21b, 24b), and similar strike and dip of the thrust, fault displacement appears more likely than folding.

In outcrop, exposures in Te Mahonge Stream suggest that following erosion of the thrust and deposition of unit 3, several steeply dipping strike-slip(?) faults cut through the Quaternary units (Figs. 24, 25). Just south of the thrust exposure on the east side of the stream, a fault oriented $\sim 075/80$ SE causes ~ 3 m of down to the southeast vertical separation of the contact between units 2 and 3. Cross section relations implied by the fold geometry in unit 2 suggest that the separation on the unit 1-unit 2 contact is up to the southeast (Fig. 24b). Because the two contacts are not parallel, the opposite vertical separations can be most simply explained by dextral slip. We also interpret this fault to extend across the stream to the west, where the lower "thrust" has been reoriented to a vertical dip. This fault does not cut up to the Waiohine surface. Several steep faults are also observed cutting hanging wall strata in the slip face exposure to the north of this stop, but most are too small to show on the map (Fig. 24a). These faults are NEstriking, steeply dipping faults with at most a few meters of vertical and horizontal separation (Fig. 24e). The exposed faults locally cut up into the upper part of unit 4 but do not cut the Waiohine surface. The presence of both reverse and normal separations suggests strike-slip faulting, but subhorizontal slickenlines were found only on one fault.



Figure 24. a) Detailed map of Te Mahonge stream area (stops 4d, 4e, 4f) derived from surveying topography and geologic contacts with a laser rangefinder. Contour interval is 5m. b) Cross section A-A' (location on Fig. 19), no vertical exaggeration, constructed perpendicular to the average cataclasite strike of 218 (N38E). Fine dashed lines show bedding traces. c) Equal-area stereoplot of structures related to Wharekauhau thrust. Black great circles are cataclasized greywacke planes, with poles shown as dots; black dashed line is minor thrust plane (60 cm separation); grey dotted line is mean plane, with mean pole and cone of confidence shown in open square and circle, respectively. Calculated fold axis assumes scatter of planes is due to upward flattening of the thrust. d) Equal-area stereoplot of poles to bedding: triangles-unit 1; filled-unit 2; open circles units 3, 4. Fold axis of all unit 1 and 2 data shown in black square (13/076) and best-fit great circle, other black square is small-scale fold in duplex. Excluding steep beds in duplex and adjacent to thrust (smaller symbols), average orientations were calculated for bedding in hanging wall and footwall: Mean vector and plane for units 1 and 2 shown by grey cone of confidence and dashed great circle; mean vector and plane for units 3 and 4 shown by black cone of confidence and dashed great circle. e) Stereoplot of small-scale faults adjacent to thrust. Solid great circles are normal faults cutting units 1 and 2 at crest of hangingwall anticline, dashed great circles are inferred strike-slip faults that cut up into units 3 and 4.

STOP 4e: Wharekauhau thrust at Te Mahonge Stream

Walk across the stream to the true right bank. Total time at this stop about 20 minutes.

At this location we can see the steeper portions of the two thrusts enclosing the horse of unit 1, the unit 1-unit 2 contact within the horse, and the steeply dipping bedding in the

footwall of the lower thrust (Fig. 24). Greywacke cataclasite is also well exposed. Relations at Te Mahonge stream provide constraints on the geometry of the thrustrelated deformation, and minimum shortening and slip rates along the thrust. We will summarise these relations at this stop.





Figure 25. a) Tracing of a photograph of an outcrop of the thrust at stop 4e. b) Interpretation of fold and thrust geometry in Te Mahonge stream, including data from area to north of stop 4e.

Summary of magnitude and timing of thrusting on the Wharekauhau thrust

No slickenlines were observed on the thrust plane, so we assume purely dip-slip displacement to calculate a minimum amount of horizontal shortening required by the cross sections. The cross section in Te Mahonge Stream provides a better estimate of slip magnitude because the hangingwall cutoffs of the contacts between greywacke, unit 1, and unit 2 are exposed on the east side of the stream and and the cutoff of the stratigraphic contact between units 1 and 2 within the horse is exposed on the west side of the stream (Fig. 24a), so both could be accurately mapped. Reconstruction of cross sections from Te Mahonge stream (e.g., A-A', Fig. 24b) using the observed range of strikes of contacts and faults yielded a minimum shortening estimate (folding + faulting) of 280±60m.

The vertical component of thrusting (throw) is constrained by the elevation difference between the hangingwall and footwall strata. The throw on the unit 1/unit 2 contact is constrained to 97-102 m. This is a minimum value because the contact is likely folded to lower elevations in the footwall and higher elevations in the hangingwall than the present exposures.

The structural and stratigraphic relationships lead us to infer that the major period of shortening on the Wharekauhau thrust began at ~70 ka. Evidence for the age of initiation of the thrust comes from the observation that bedding in units 1 and 2 is parallel at all locations where we could measure it (Fig. 24d). Although there may have been thrust activity prior to the deposition of unit 1, and/or during the deposition of unit 2b, to cause some (unrecognized) minor fanning of dips within that unit, we infer that deformation of the conformable unit 1-unit 2a contact did not begin until after deposition of the latter. The age of this contact, based on the OSL data described above, is constrained to the interval 106 ± 24 to 71 ± 8 ka. If we are correct in our inference that thrusting began during deposition of the syntectonic unit 2b, then the OSL data would indicate a thrust initiation age of no older than 71 ± 8 ka.

The evidence further suggests the abandonment of thrusting by ~ 20 ka. Onlap of the paleoscarp by units 3 and 4 and the angular unconformity at the base of unit 3 suggest that the thrust was inactive at this time. The recognition of a buttress unconformity within unit 2b suggests deposition of that unit took place during the waning stages of thrust activity. Above the angular unconformity, dates on unit 3 nearest the thrust suggest abandonment occurred after 19.5±3.2 to 9.1-9.5 ka (Fig. 20). Two locations at the base of unit 3 are dated by OSL at ~18-20 ka (samples NI54, NI47, Fig. 20), but these occur at sites where there is no clear angular relationship between unit 2 and unit 3. At the place where the angular unconformity is best documented, where unit 3 lies above deformed unit 2b strata in the footwall, wood at the top of unit 3 (Sample NI41) yielded a ¹⁴C age of 11.2-11.6 ka; however, the base of the unit is not dated at that location. At the only location where the sampled unit 3 overlaps the thrust (NI26), the top of the unit is 9.1-9.5 ka (Fig. 6). The sedimentological characteristics of unit 3 (i.e., very fine-grained, and of uniform thickness to within ~20 m southeast of the thrust) suggest that the thrust was not active during any part of its deposition (e.g., in stark contrast to units 2b, 2c). From these data we infer that the thrust was certainly abandoned by ~ 9 ka, and more likely was abandoned prior to ~ 20 ka.

Vertical and horizontal components of slip rate

Our new structural and geochronological data provide estimates of the late Quaternary slip rate of the Wharekauhau thrust. These rates are minima because the amount of heave and throw are minimum values and because the age of the top of unit 2b could be younger than our youngest dated sample. From the range of horizontal shortening estimates at Te Mahonge Stream (280 ± 60 m) on the unit 1/unit 2 contact, and given the conservative estimate of the duration of thrusting (106 ± 18 ka to 9.1-9.5 ka), the minimum shortening rate is 1.8-4.7 mm/yr. Using our preferred duration estimate of 71±8 ka to 19.5±3.2 ka results in rate of 3.5-8.4 mm/yr. The vertical component of slip rate (throw rate) due to the Wharekauhau thrust can also be constrained using the

minimum throw of 92-102m. Using the conservative estimate of thrusting duration, we estimate a minimum vertical throw rate on the Wharekauhau thrust of 0.8-1.4 mm/yr. Using the preferred timing constraints, the minimum throw rate is 1.5-2.7 mm/yr.

The inferred shortening rate during its activity, 3.5-8.4 mm/yr, exceeds that of all other active thrusts and oblique thrusts in the Hikurangi margin and may have accounted for 11-30% of the margin-normal component of plate motion. After abandonment, deformation at shallow levels has occurred primarily on a segmented fault system that accommodates little to no shortening (<1mm/yr). We infer that present-day deformation (including during 1855) at the southern end of the Wairarapa Fault zone is partitioned between slip on: 1) the more western Wairarapa-Muka Muka fault system (dominantly dextral-slip, but also causing local uplift of the coast near Turakirae Head; 2) a series of discontinuously expressed, near-vertical strike-slip faults and linking blind oblique-reverse thrusts near the trace of the older (inactive) Wharekauhau thrust; and 3) a possible blind thrust fault between Lake Onoke and the western margin of the Wairarapa Valley. The spatial and temporal complexity of the Wharekauhau fault system and the importance it has had in accommodating upper plate deformation argue for an unsteady linkage between upper plate faults and between these faults and the plate interface.

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