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FIELD TRIP GUIDES

Field Guides

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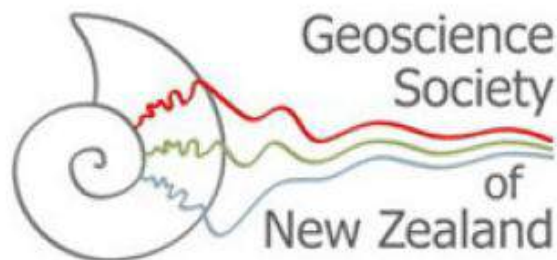
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FIELD TRIP 3

Late Quaternary tectonic deformation at the southern end of the Wairarapa Fault system

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Cover page photograph. Overturned beds in fault slice ("horse") of Last Interglacial beach deposits overthrust by Torlesse along the Wharekauhau thrust, Te Mahonge

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.

Frontispiece b: Photograph of the Wharekauhau thrust in Wharekauhau Stream, looking east. A grey-weathering "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 and are a structural repetition of the fluvial gravel sequence exposed at river level. This exposure is part of Stop 3 in the field trip.

Trip Summary

This all-day field trip highlights 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 are attributed to the 1855 earthquake. Second, we visit the Cross-Creek pull-apart graben, a paleoseismic trenching site on the Wairarapa Fault from which the occurrence of 5 major surface rupturing earthquakes during the past ~5200 years has been inferred. Third, after arriving at the Ocean Beach on the south coast at Palliser Bay, we will walk up and down Wharekauhau and Te Mahonge streams, paying special attention to 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. Structural geology and ^{14}C and Optically Stimulated Luminescence dating suggests that the thrust underwent a period of very rapid motion (accruing >220 m of heave) during the period ~71-14 ka, corresponding to a horizontal shortening rate of >4 mm/yr (Schermer et al., 2009). Subsequent to this slip, the thrust became inactive, and was in part buried by loess and alluvial sediments. Contrary to the suggestions of some (e.g., Sibson, 2006), we do not think that this thrust ruptured during the 1855 earthquake. At the final stop, we will consider the pattern of late Quaternary coastal uplift on the south Wairarapa Fault, while examining new data on the age and elevation of uplifted marine terraces there. Our overall goals are to understand spatial and temporal

changes in slip partitioning at the southern end of the greater Wairarapa fault zone, including a brief (~50 ka) period of rapid slip on the Wharekauhau thrust. We analyze the implications of these data for the kinematic linkage between the Wairarapa, Wharekauhau, and adjacent faults at different times, including with the subduction interface.

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 [Beavan et al., 2002]. At oblique subduction zones, plate motion is commonly partitioned between the subduction megathrust and arrays of strike-slip and reverse faults in the upper plate [e.g., Fitch, 1972; McCaffrey, 1992]. In many locations these upper plate faults may pose a greater hazard to society than the megathrust especially where the relatively shallow hypocenters of these earthquakes occur near populated regions. There is much we do not yet understand about how these faults interact with each other and with the subduction interface, and how these linkages may change over time. For example, how similar is the pattern by which upper plate faults and fault segments interact with one another on short (e.g. 10^2-10^3 yr, seismic cycle) versus on long (10^4-10^6 yr) time scales? How is slip partitioned among oblique, reverse, and strike-slip faults and between the hangingwall and subduction zone faults on different timescales? Active faults in the upper plate of the Hikurangi margin of New Zealand form a complex array of strike-slip, oblique-slip, and reverse faults (Fig. 1). Most of New Zealand's largest historical earthquakes have occurred on these faults, including in 1855 (M~8.2), 1931 (M7.8), and 1934 (M7.6). The Wairarapa fault zone (Figs. 1, 2), one of the major fault zones in the North Island, plays an important role in accommodating upper plate deformation [e.g., Beanland and Haines, 1998]. The 1855 Wairarapa earthquake, was observed to produce surface rupture along the southern part of the Wairapapa Fault zone (Fig. 1) [Grapes and Wellman, 1988; Grapes and Downes, 1997; Ongley, 1943], and resulted in up to 6.4 m of coastal uplift, and up to ~18.5 m of dextral slip, the largest coseismic rupture known for an historical earthquake worldwide [McSaveney et al., 2006; Rodgers and Little, 2006].

The margin-orthogonal component of plate motion in the southern North Island 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; Lamb, 2011), 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).
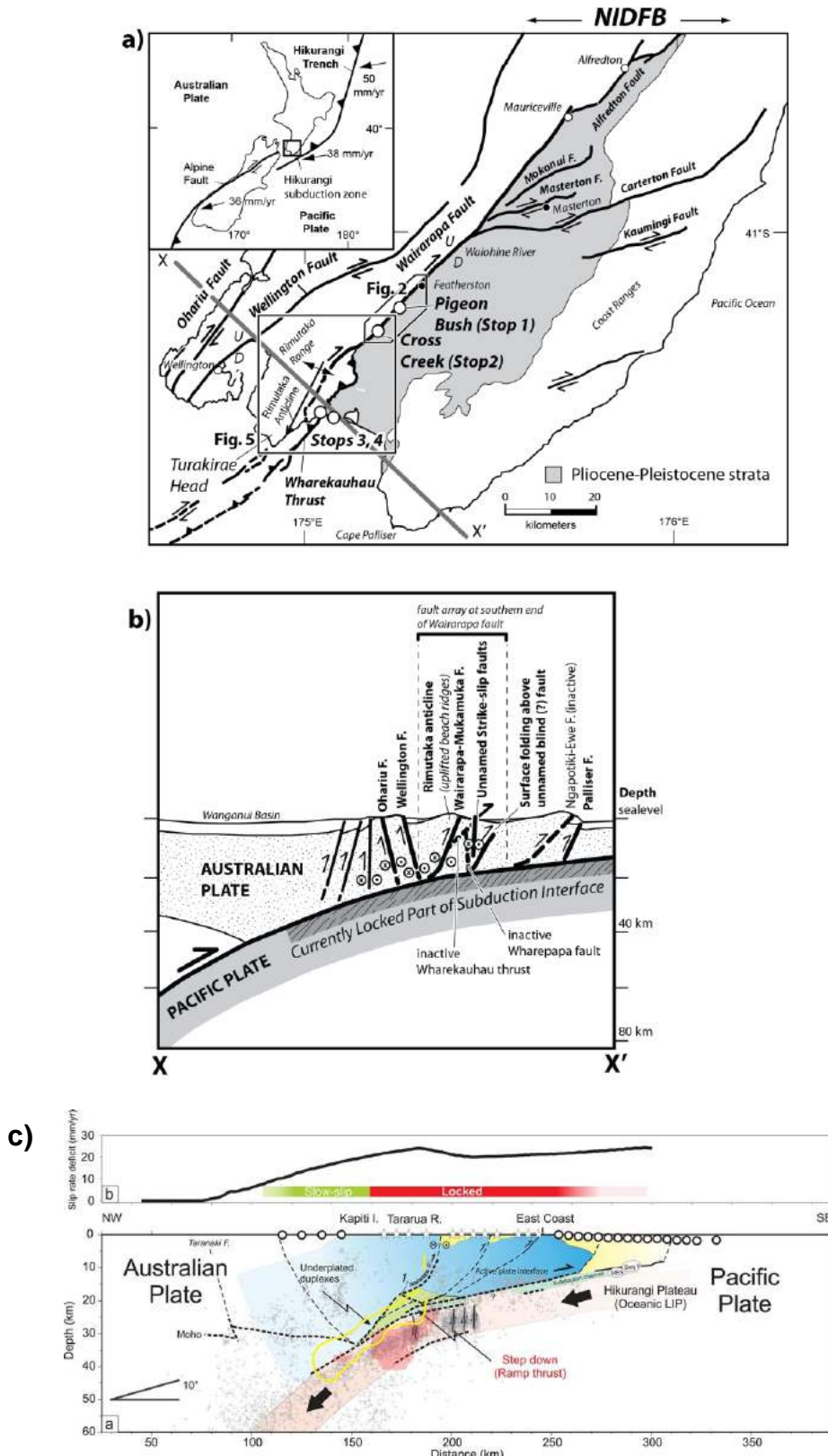
Figure 1. a) Tectonic index map showing major active faults and other structures of the southern North Island, New Zealand (largely after Begg & Johnston, 2000; Lee and Begg, 2002; and Barnes, 2005), and location of field trip stops sites along the Southern Wairarapa fault. Inset on upper left shows contemporary plate tectonic setting of New Zealand (plate motions from Beavan, 2002). b) Schematic cross-section X-X' showing faults and schematic position of currently locked part of subduction interface after Wallace et al., 2004); c) Composite section along the SAHKE seismic transect showing interpreted boundaries and faults, including the Wairarapa Fault (Henrys et al., 2013).
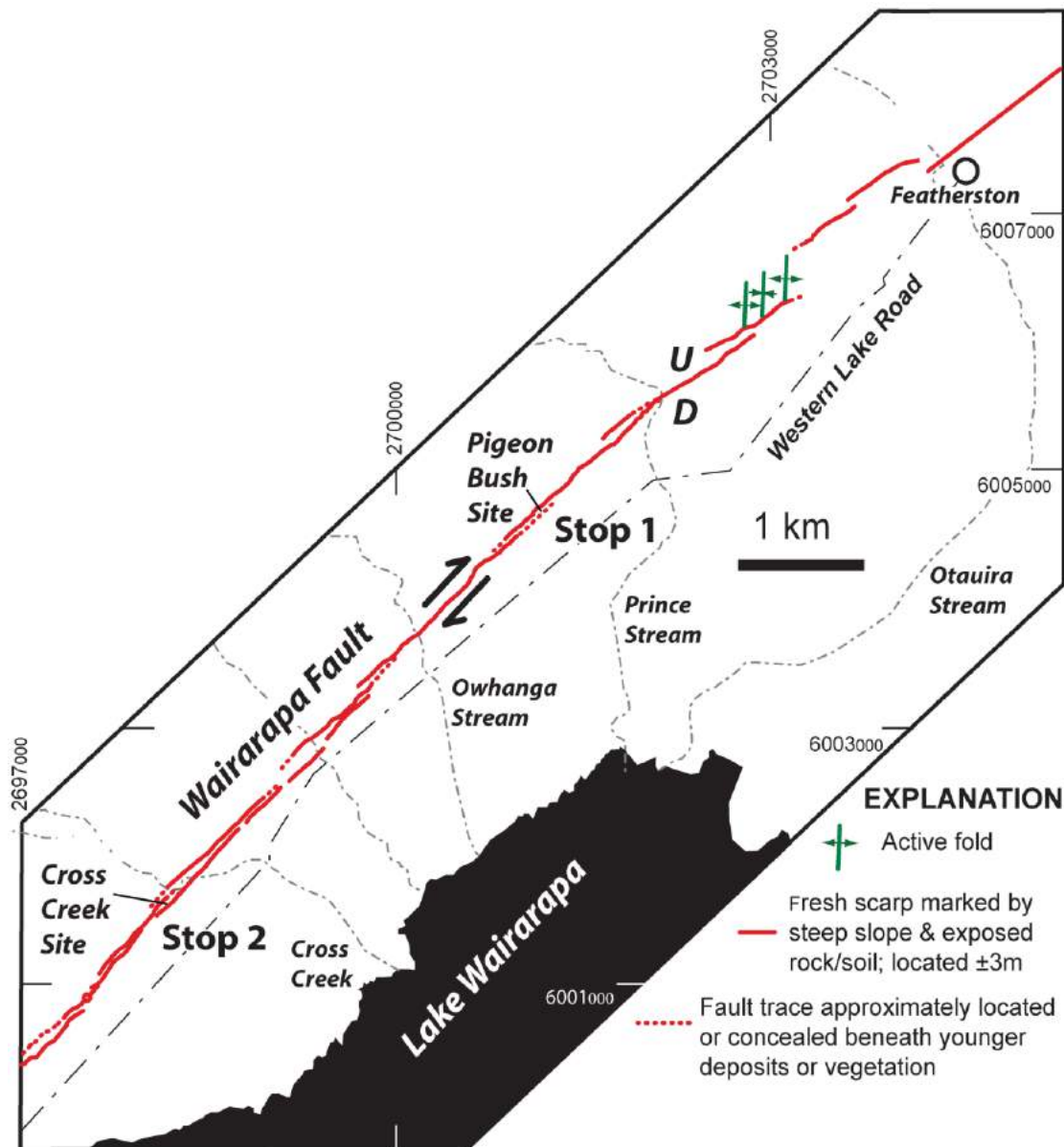
Figure 2. Fault traces along a southern part of the central Wairarapa Fault, south of Featherston (from Rodgers and Little, 2006), showing locations of Stop 1 (Pigeon Bush area) and Stop 2 (Cross Creek Pull-apart graben).

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; Henrys et al, 2013—See Figs 1b, 1c). GPS geodetic data suggest that this segment of the subduction interface is currently "locked" and is accumulating elastic strain (Wallace et al., 2004).

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 active and inactive faults that comprise eastern strand of the southernmost part of the 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 that is well exposed near the Palliser Bay coast. This 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.

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 "Q2a" by Begg and Johnston (2000), and informally termed the "Waiohine gravels" by many previous geologists in the Wairarapa Valley (Fig. 5). 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 ^{14}C 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 (Little et al., 2009) 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 11.9 ±2.9 mm/yr (Carne et al., 2011). Prior to the study of Schermer et al., 2009, a slip rate had not been measured for the Wharekauhau thrust, or for any other faults in the Wharekauhau fault system.

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 (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, ~160 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, including the Wairarapa Fault during 1855, 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/rupture 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 reverse-slip motion on a fault nearby to Turakirae Head (e.g., on the Muka Muka Fault, Fig. 5).
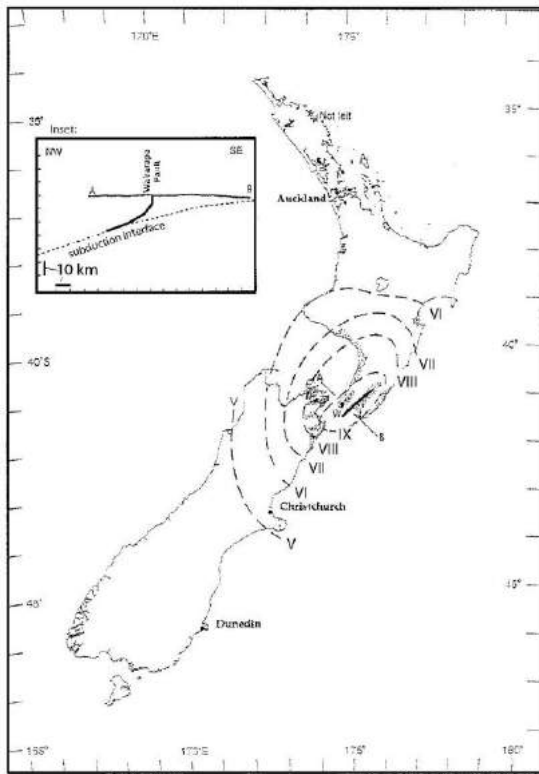
Figure 3. Isoseismal map of 1855 earthquake (from Grapes and Downes, 1997) showing area of ground damage (stippled) and rupture along Wairarapa Fault. W = Wellington. Inset- cross-section along A-B showing inferred shape and extent of Wairarapa Fault rupture at depth during 1855 (after Darby and Beanland, 1992).

Figure 4. Oblique aerial view, looking northeast, of the uplifted beach ridges at Turakirae Head. The ridges have been dated using ^{14}C (radiocarbon) and Be^{10} 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.

The 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, Little et al. (2009) undertook paleoseismic trenching 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. Stop 2 of this field trip will be used to summarize these results.

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 160 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° – 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 (Carne et al., 2012). 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.

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±0.5 ka and 4.3±0.5 ka.
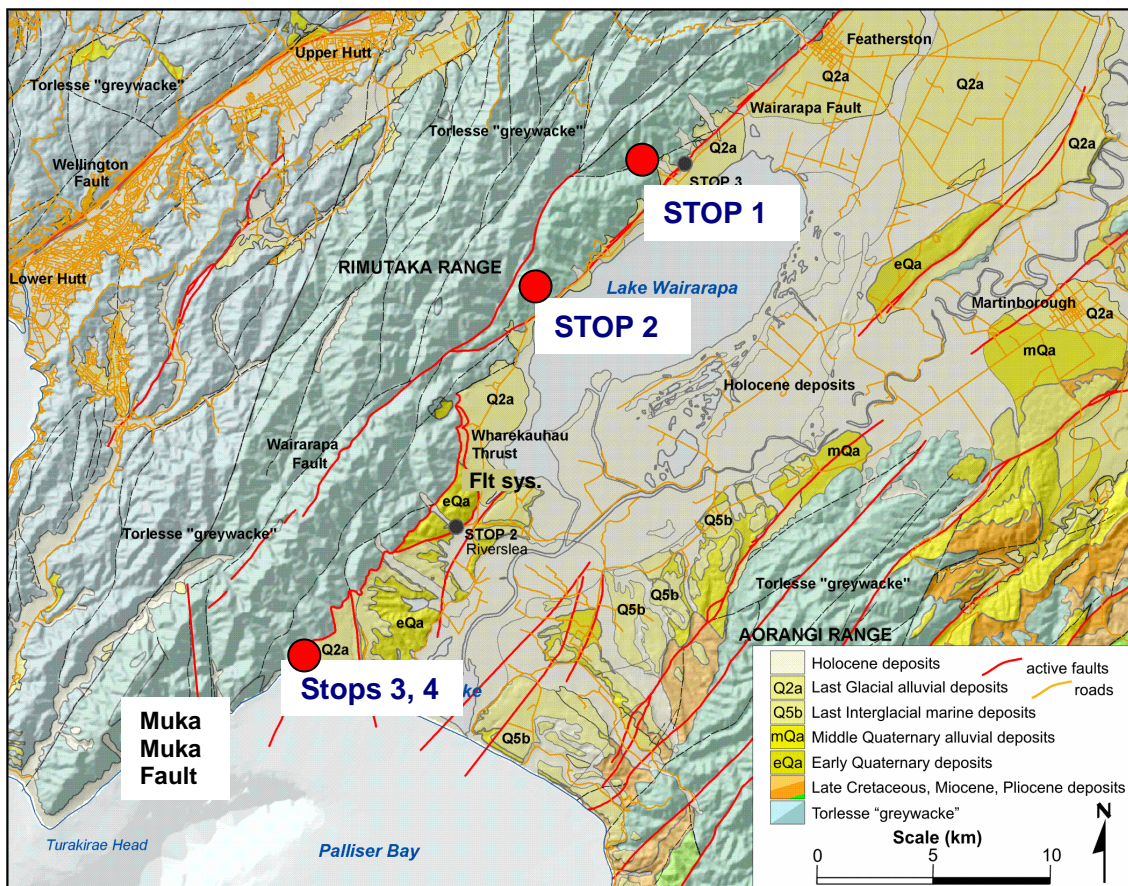

Figure 5. Geological map of the southern Wairarapa (from Begg & Johnston, 2000). The locations of Stops 1, 2, 3 and 4 are shown. Note location of Turakirae Head (shown in photo of Fig. 4). Some of the splaying between (and within) the Wairarapa Fault and the Wharekauhau fault system can be seen. The Wharekauhau Thrust *(sensu stricto)* is exposed near the coast at Stop 3, where it dips gently (20-30°) to the west. It probably merges with the steeper-dipping Wairarapa Fault at depth (See Fig. 1b).

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 ~5° 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 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.
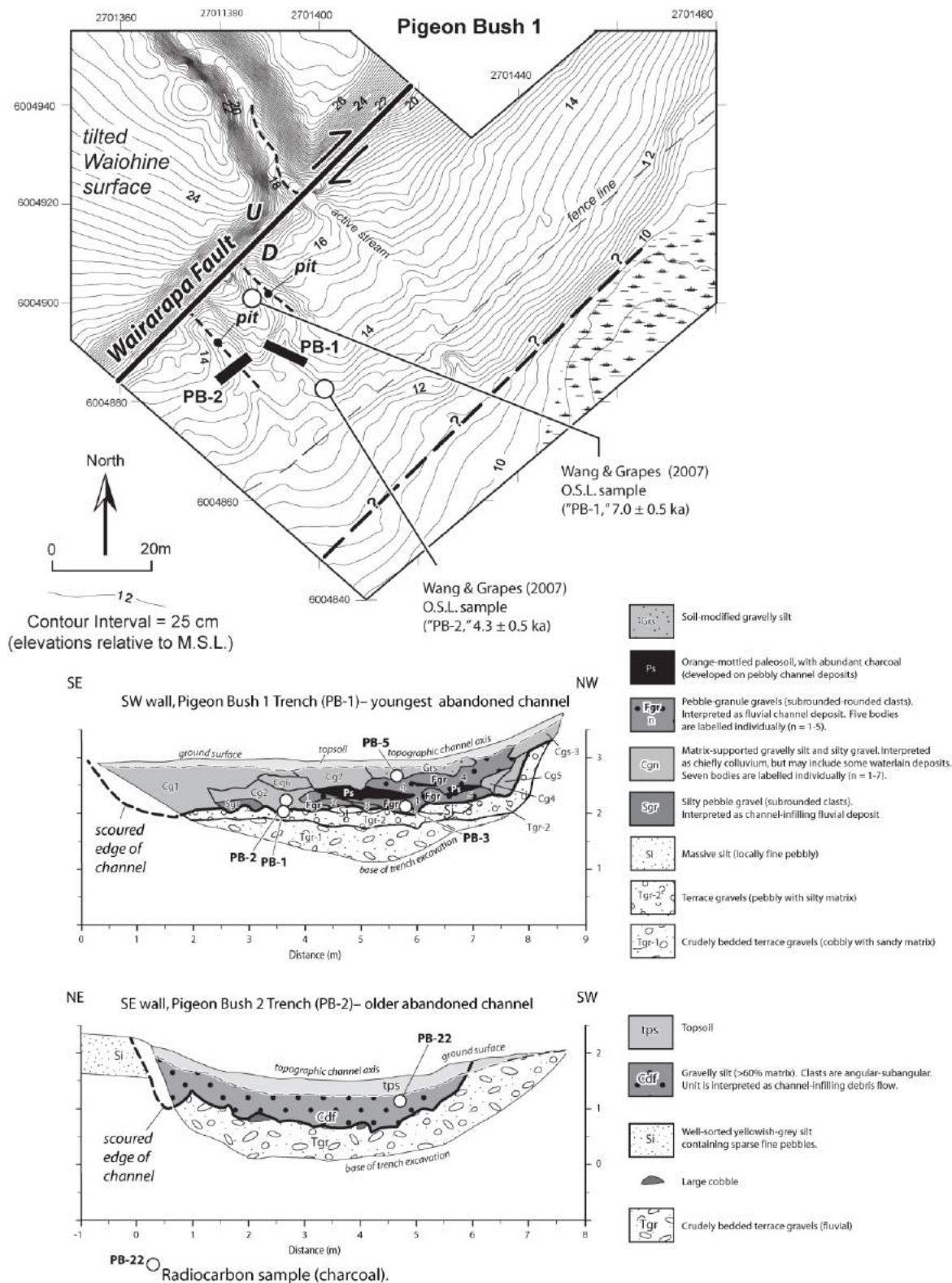
Figure 7. Topographic map of the Pigeon Bush 1 site, showing beheaded channels displaced by slip on the Wairarapa Fault. Map is based on a survey data set consisting of >10,000 points (Rodgers & Little, 2006). Trench Logs are from Little et al. (2009). All ^{14}C ages (including two from the pits dug 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.

According to Rodgers and Little 2006, the proximal beheaded channel has been displaced 18.7±1.0 m dextrally and ≥1.25±0.5 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 ≥2.25±0.5 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. (2009) 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, channel-bounding 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) yielded a ^{14}C 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 Pb_2). Historical data indicates that the youngest earthquake here (event Pb_1) 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 these incised channels and their dextral offset was restored with the aid of a detailed topographic 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).
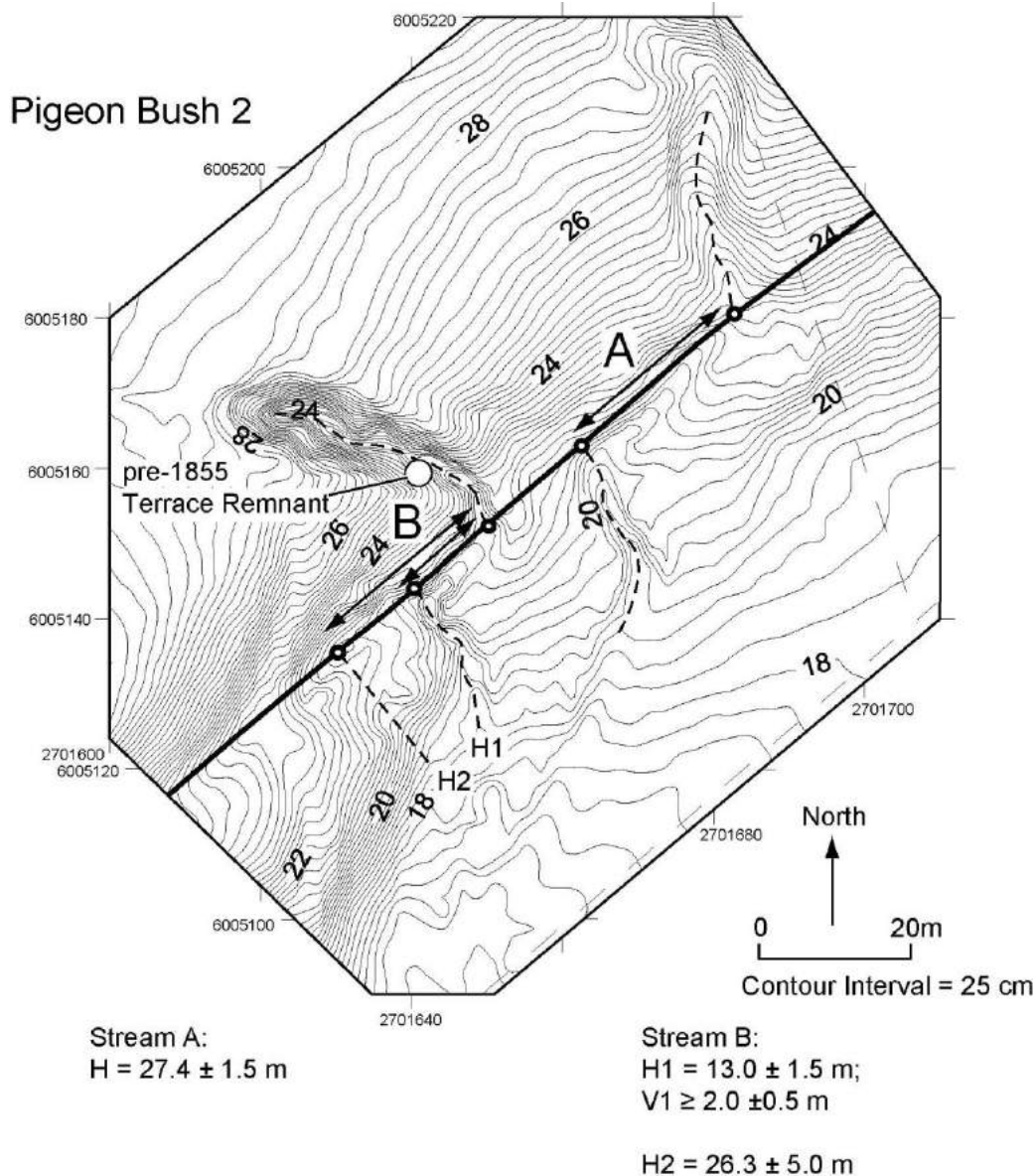
Figure. 8. Topographic map of the Pigeon Bush 2 site, showing channels displaced (and in one case beheaded, channel H2) by slip on the Wairarapa Fault (from Rodgers and Little, 2006). See Fig. 6 for location.

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 (labelled as "H2" in Fig. 8). 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 dextrallyoffset 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, an 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 ~160 years.
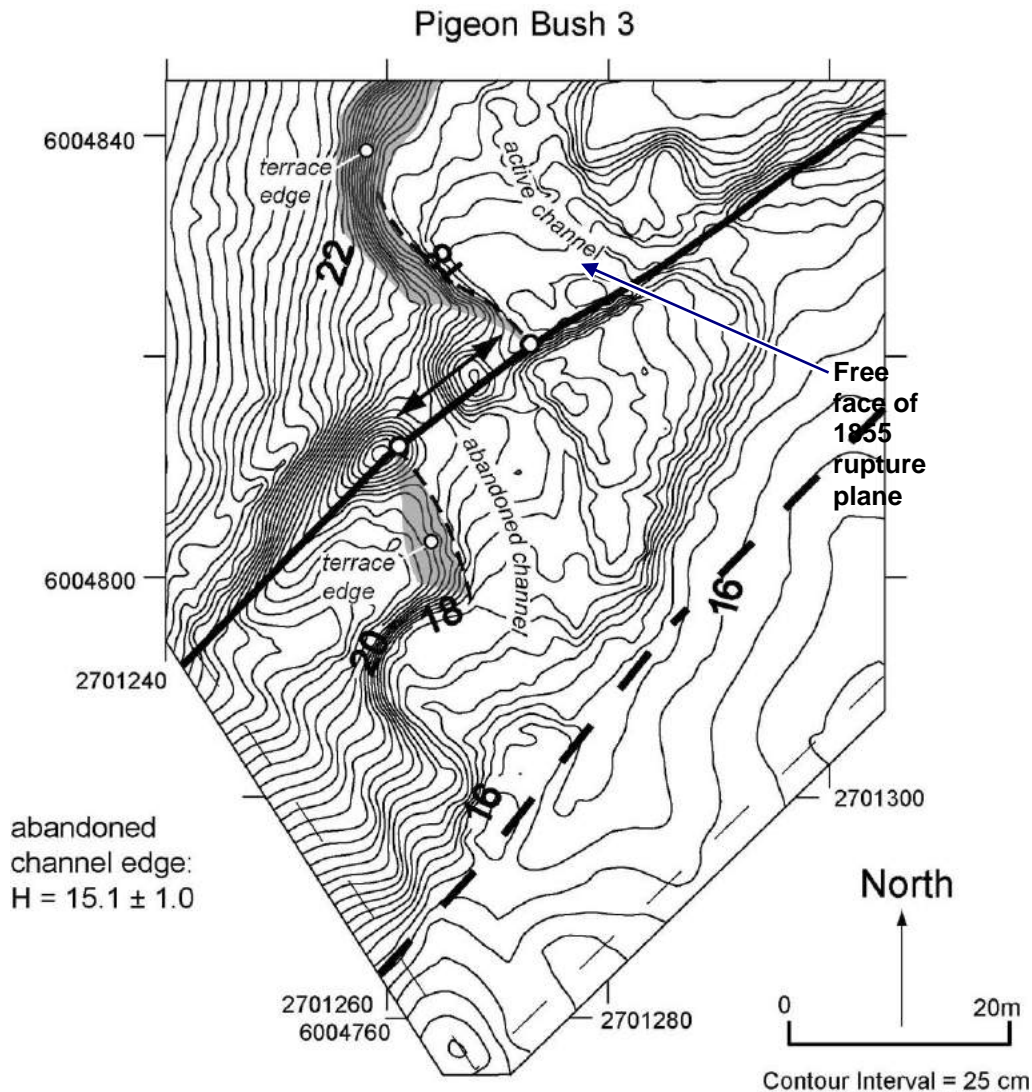
Figure 9. Topographic map of the Pigeon Bush 3 site, showing channels displaced by slip on the Wairarapa Fault. See Fig. 6 for location. From Rodgers and Little (2006).

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 left-stepping, 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 southward-flowing 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).
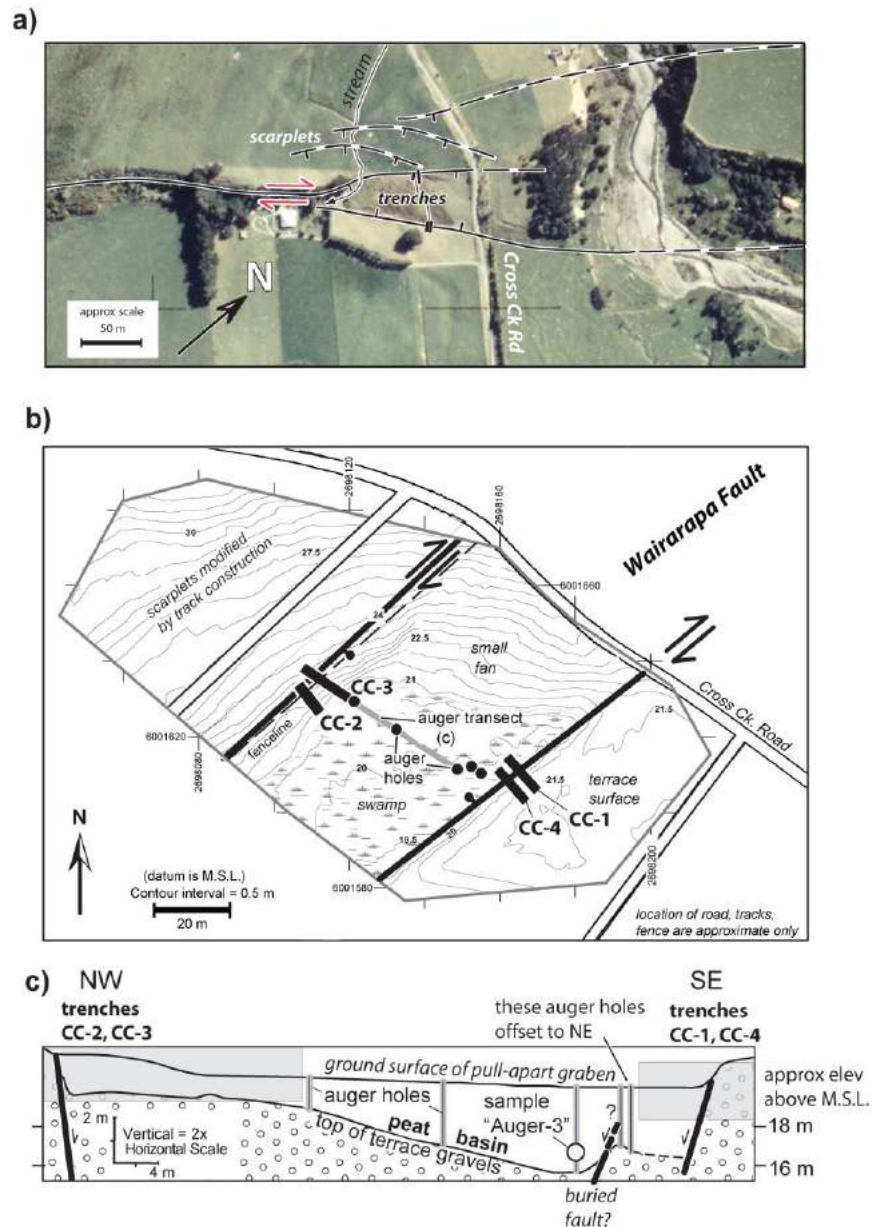
Figure 10. a) Vertical aerial photograph of Cross-Creek pull-apart graben showing trench sites and fault-trace locations. The photograph by Lloyd Homer (GNS Science) pre-dates track construction that has mostly destroyed the scarplets on the NW side of the graben. b) Topographical map of the NE end of 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 ^{14}C 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. From Little et al., 2009.

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 ~3.8 m near the southern boundary fault (Fig. 10c), where a large piece of wood (sample Auger-3) was intersected at ~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 ^{14}C age of 5580-5300 cal yrs B.P. Two other ^{14}C 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.

Paleoseismic Trenches
Trenches CC-1 and CC-4 were excavated across the southern bounding fault of the pull-apart graben. Fig. 11a shows a log from trench CC-1. Eleven ^{14}C 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 ^{14}C 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 ^{14}C 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).
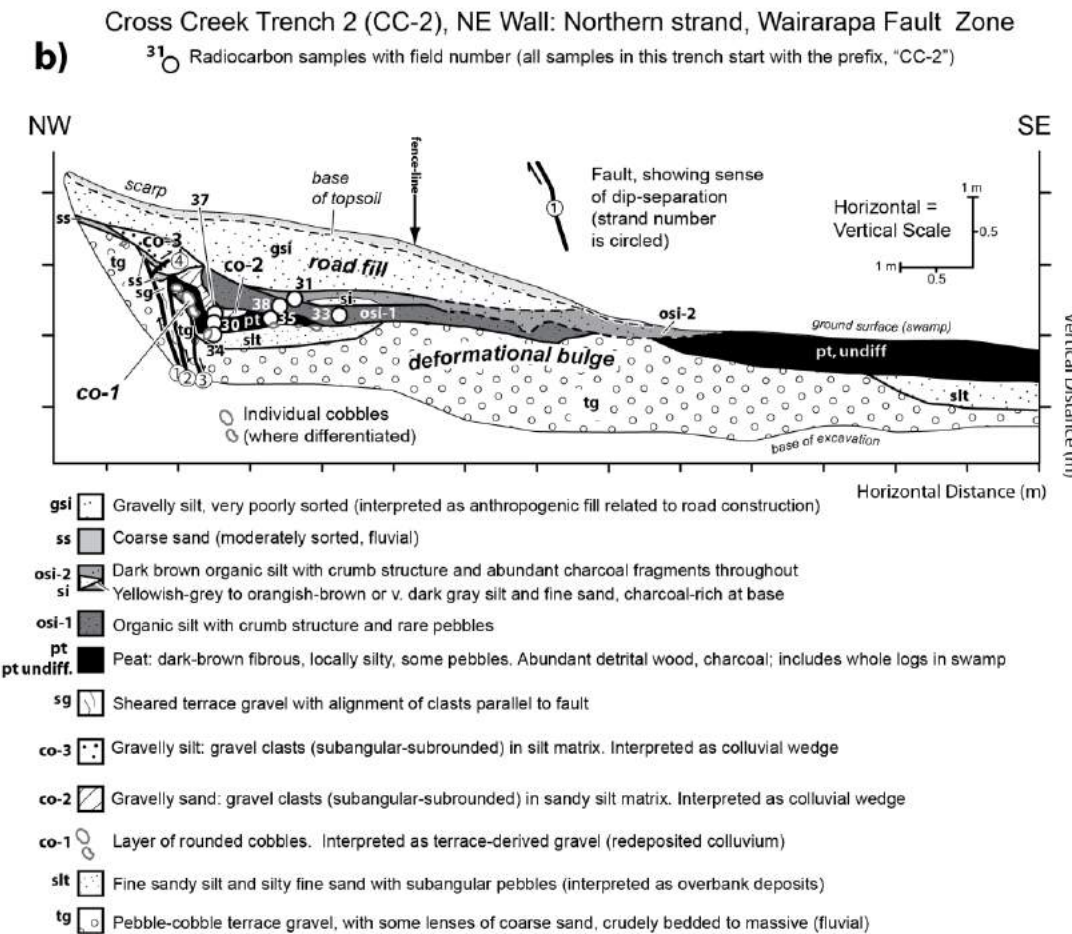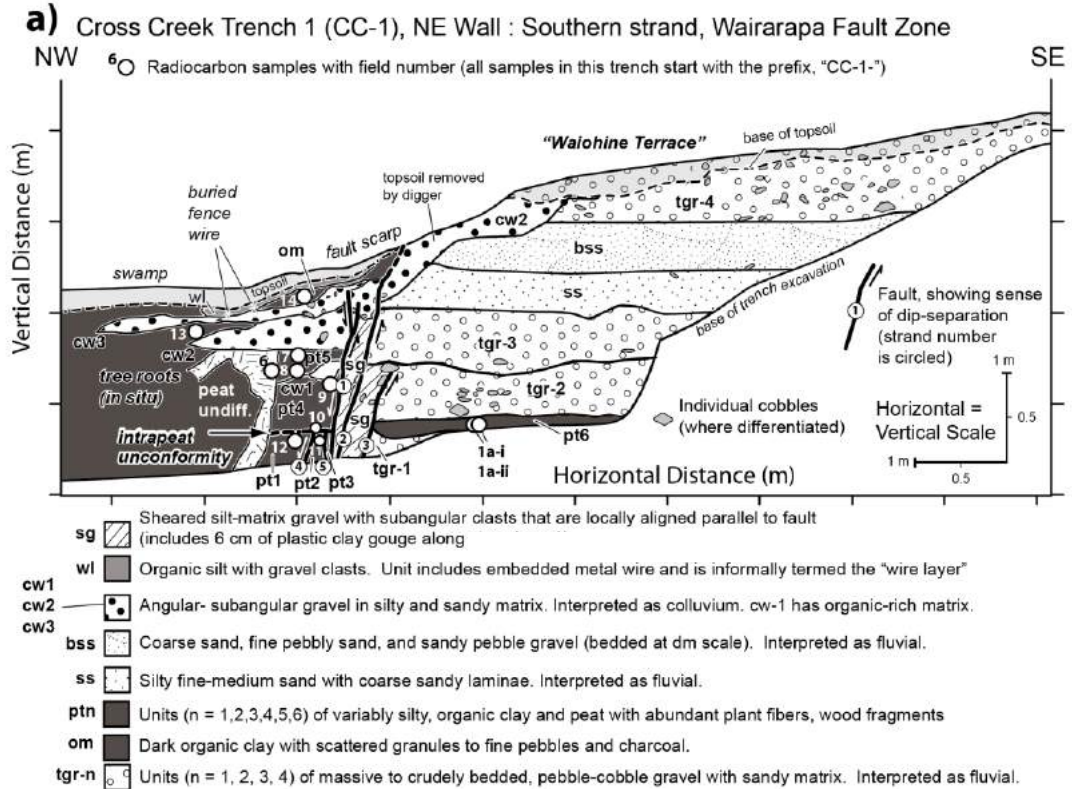
a) Cross Creek Trench 1 (CC-1), NE Wall : Southern strand, Wairarapa Fault Zone

Legend for (a):

sg	Sheared silt-matrix gravel with subangular clasts that are locally aligned parallel to fault (includes 6 cm of plastic clay gouge along
wl	Organic silt with gravel clasts. Unit includes embedded metal wire and is informally termed the "wire layer".
cw1 cw2 cw3	Angular- subangular gravel in silty and sandy matrix. Interpreted as colluvium. cw-1 has organic-rich matrix.
bss	Coarse sand, fine pebbly sand, and sandy pebble gravel (bedded at dm scale). Interpreted as fluvial.
ss	Silty fine-medium sand with coarse sandy laminae. Interpreted as fluvial.
ptn	Units (n = 1,2,3,4,5,6) of variably silty, organic clay and peat with abundant plant fibers, wood fragments
om	Dark organic clay with scattered granules to fine pebbles and charcoal.
tgr-n	Units (n = 1, 2, 3, 4) of massive to crudely bedded, pebble-cobble gravel with sandy matrix. Interpreted as fluvial.

b) Cross Creek Trench 2 (CC-2), NE Wall: Northern strand, Wairarapa Fault Zone

Legend for (b):

gsi	Gravelly silt, very poorly sorted (interpreted as anthropogenic fill related to road construction)
ss	Coarse sand (moderately sorted, fluvial)
osi-2 si	Dark brown organic silt with crumb structure and abundant charcoal fragments throughout / Yellowish-grey to orangish-brown or v. dark gray silt and fine sand, charcoal-rich at base
osi-1	Organic silt with crumb structure and rare pebbles
pt pt undiff.	Peat: dark-brown fibrous, locally silty, some pebbles. Abundant detrital wood, charcoal; includes whole logs in swamp
sg	Sheared terrace gravel with alignment of clasts parallel to fault
co-3	Gravelly silt: gravel clasts (subangular-subrounded) in silt matrix. Interpreted as colluvial wedge
co-2	Gravelly sand: gravel clasts (subangular-subrounded) in sandy silt matrix. Interpreted as colluvial wedge
co-1	Layer of rounded cobbles. Interpreted as terrace-derived gravel (redeposited colluvium)
slt	Fine sandy silt and silty fine sand with subangular pebbles (interpreted as overbank deposits)
tg	Pebble-cobble terrace gravel, with some lenses of coarse sand, crudely bedded to massive (fluvial)

Figure 11. Two trench logs across the southern (a) and northern (b) boundary faults of the Cross-Creek pull-part graben on the Wairarapa Fault. From Little et al., 2009.

Trenches CC-2 and CC-3 were excavated across the northwestern bounding fault of the pull-apart graben. Fig. 11b shows one of the logs from CC-2. None of the fault strands on the northern side of the graben cut to the surface, and the topographic scarp is offset ~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 road construction. Seven samples from trench CC-2 and five from CC-3 were ^{14}C 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, including the presence of variably tilted and deformed colluvial wedges, we recognize at least four earthquakes to have ruptured the northern bounding fault of the graben since ~5.2 ka. These events are labeled CC_{N4} (oldest) to CC_{N1} (youngest) on Fig. 12.

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 (south of Pigeon Bush, not visited on this fieldtrip), and by dating and correlating these using the 40 new ^{14}C samples, Little et al. (2009) 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.

Little et al. (2009) suggest several processes, both tectonic and non-tectonic, 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).
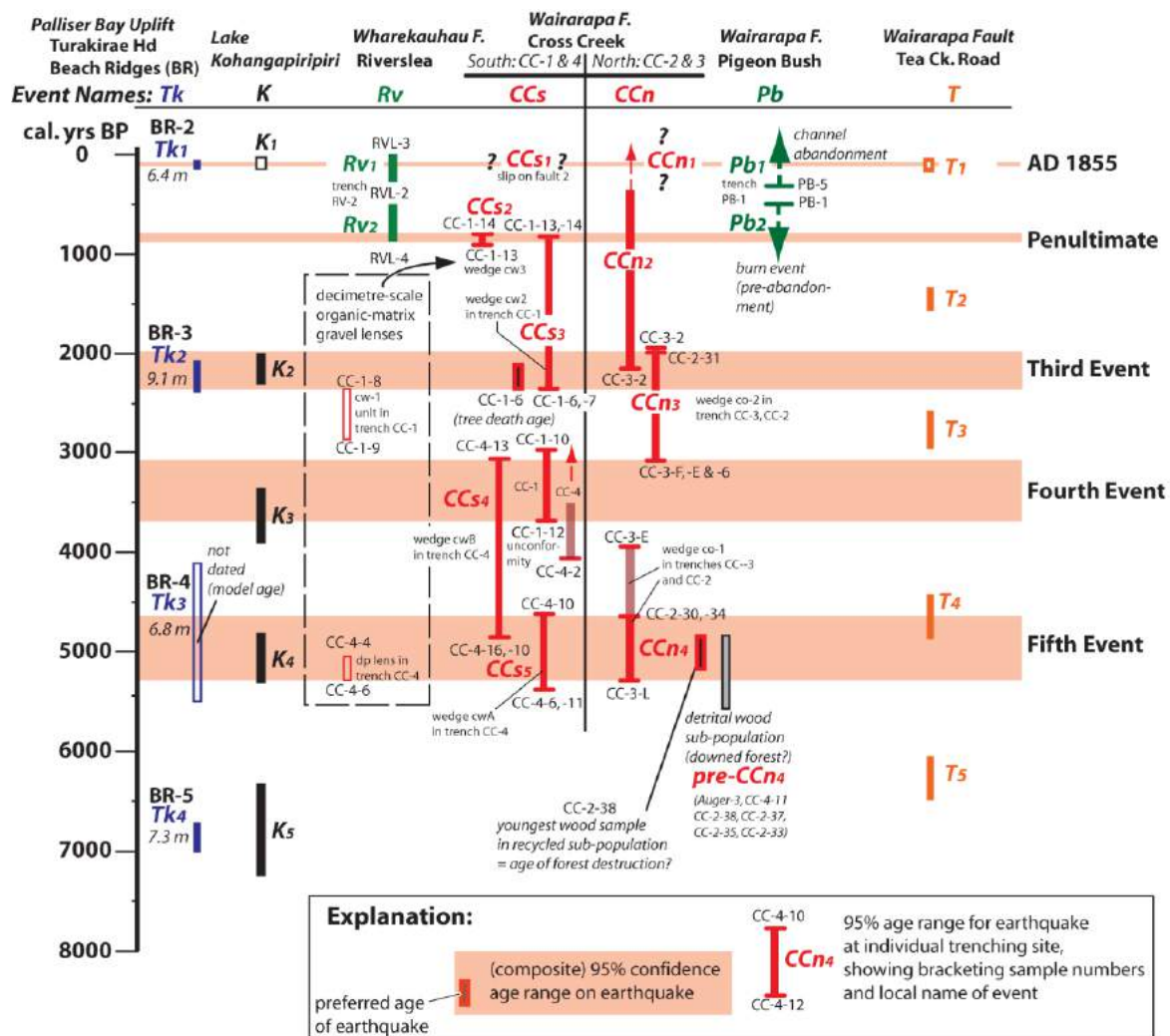
Figure 12. Time-space plot of surface-rupturing Wairarapa fault earthquake events inferred from all available types of paleoseismological data (from Little et al., 2009). Data for Tea Creek trench (events labelled, *T*) are from Van Dissen and Berryman (1996, and unpub. [14]C data). Diatom-based paleoenvironmental 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 ^{14}C 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 ^{14}C results.

STOP 3. 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 3a**). Proceed upstream (about 20 minutes) to an exposure of unit 3 (**Stop 3b**) and further upstream to a large exposure of the Wharekauhau thrust (**Stop 3c**). Return downstream and take the farm track up to the ridgetop (large flat paddock) between Te Mahonge and Wharekauhau Streams (**Stop 3d**). Walk down the track to Te Mahonge stream to see the Wharekauhau thrust exposed on the track (**Stop 3e**) and the west bank of the stream (**Stop 3f**). Return along the coast to vehicles. Total time away from vehicles approximately 3 hours.*

Arriving at the Ocean Beach, we drop below a Last Interglacial and younger, marine-fluvial terrace surface to reach Wharepapa River (Fig. 13). Along the banks of Wharepapa River and on the sea cliffs at 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. Figure 14 shows the elevation of the top of the marine unit to the east (~20 m) and to the west (~15 m) of Wharepapa River. Several relationships, including the late Last Glacial gravels lapping up against an older (Last Interglacial) marine bench to the east (Schermer et al., 2009), the elevation difference of the Last Interglacial marine deposits across Wharepapa River, and the presence of a significant negative gravity anomaly there, points to the presence of a buried fault along Wharepapa River (e.g., Kingma, 1967; Rollo 1992; Begg and Mazengarb 1996; McClymont 2000). The unusually deep incision of the Waiohine surface in the area to the west of Wharepapa River (e.g, in Wharekauhau Stream) also supports this interpretation of a west-dipping blind thrust (Schermer et al., 2009).

STOP 3a: 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
deformation near the Wairarapa fault since ~125 ka. To the west of the Wharekauhau thrust, the late Quaternary sequence was deposited unconformably above Mesozoic greywacke, 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, 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 (see Fig. 15) 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 elevated to the 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 footwall of the thrust at the mouth of Wharekauhau Stream, unit 1 overlies fluvial gravels possibly belonging to the Te Muna Formation. OSL samples of marine sands collected from unit 1 by Schermer et al. (2009) yielded ages of 106 ±24 ka (NI48) and 71±8 ka (NI42) (2σ errors). A third beach sand

collected from the elevated marine bench to the east of Wharepapa Stream yielded an age of 127±20 ka, cannot be not geomorphically correlated with the beach deposits exposed at the mouth of Wharekauhau Stream, and may be older. The three samples of marine sands yield ages that are indicative of the last interglacial sea-level highstand (oxygen isotope stage [OIS] 5).
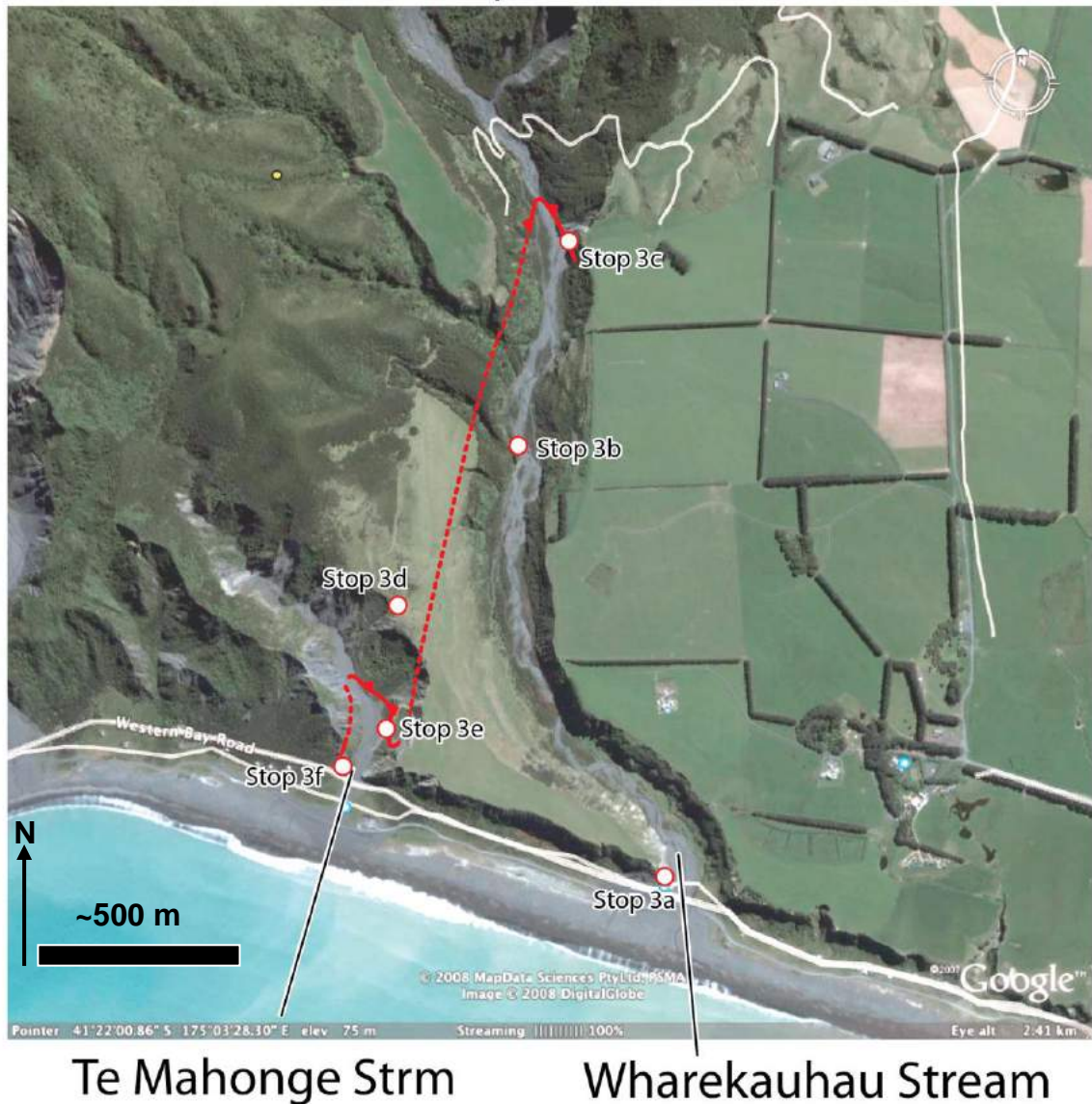

Figure 13. Google Earth map of Stop 3 showing round-trip walking route between Wharehauhau and Te Mahonge Streams and sites visited along the trace of the Wharekauhau thrust near the Palliser Bay coast.
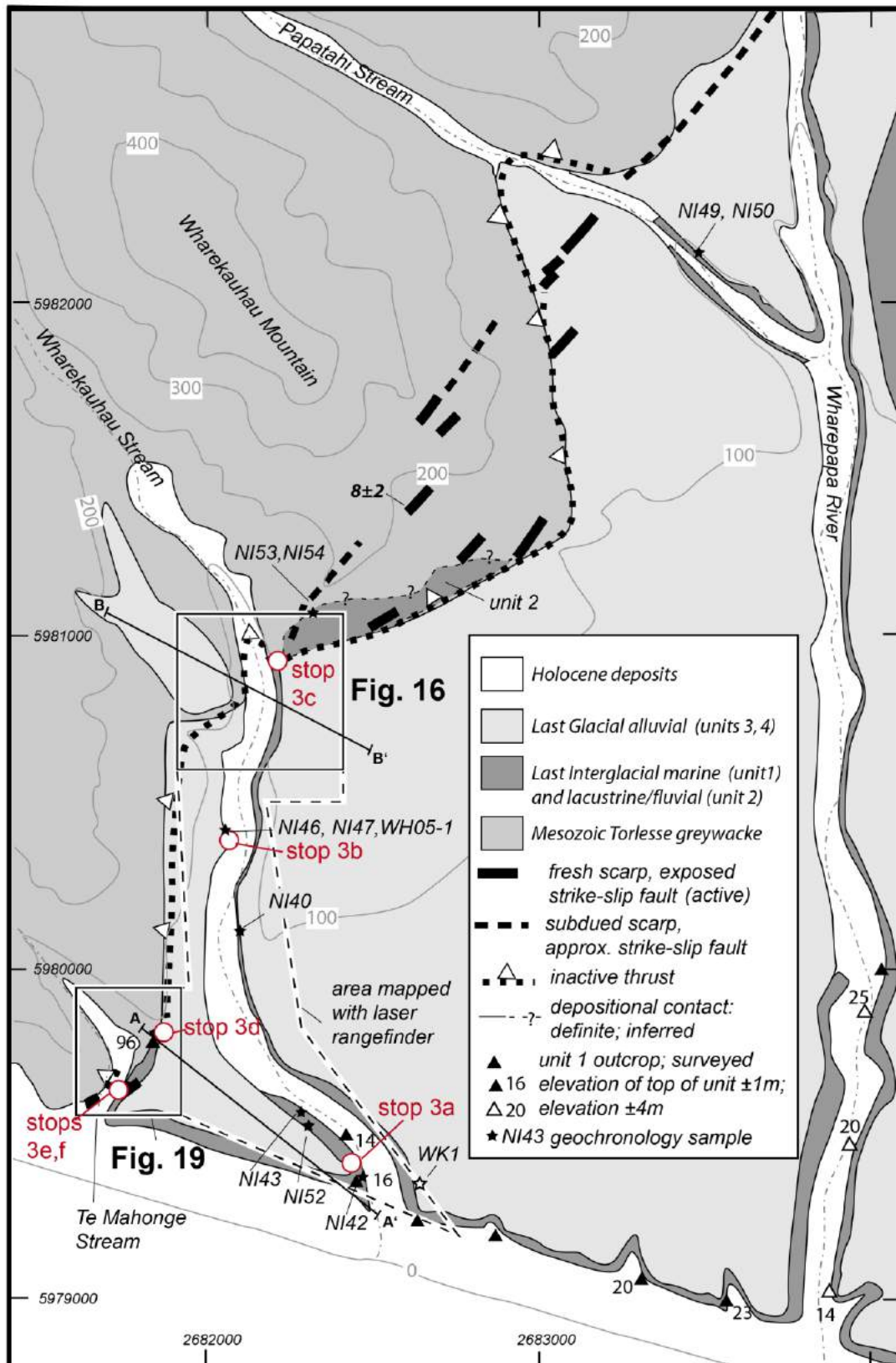
Figure 14. Geology of Wharekauhau segment, showing Quaternary unit designations as described in text and Figure 15, fault and fold traces, sample locations, and field trip stops. Open star shows sample location from Wang (2001). Surveyed elevation of the top of unit 1 shallow marine deposits is indicated 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 16, 19. 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. From Schermer et al, 2009.
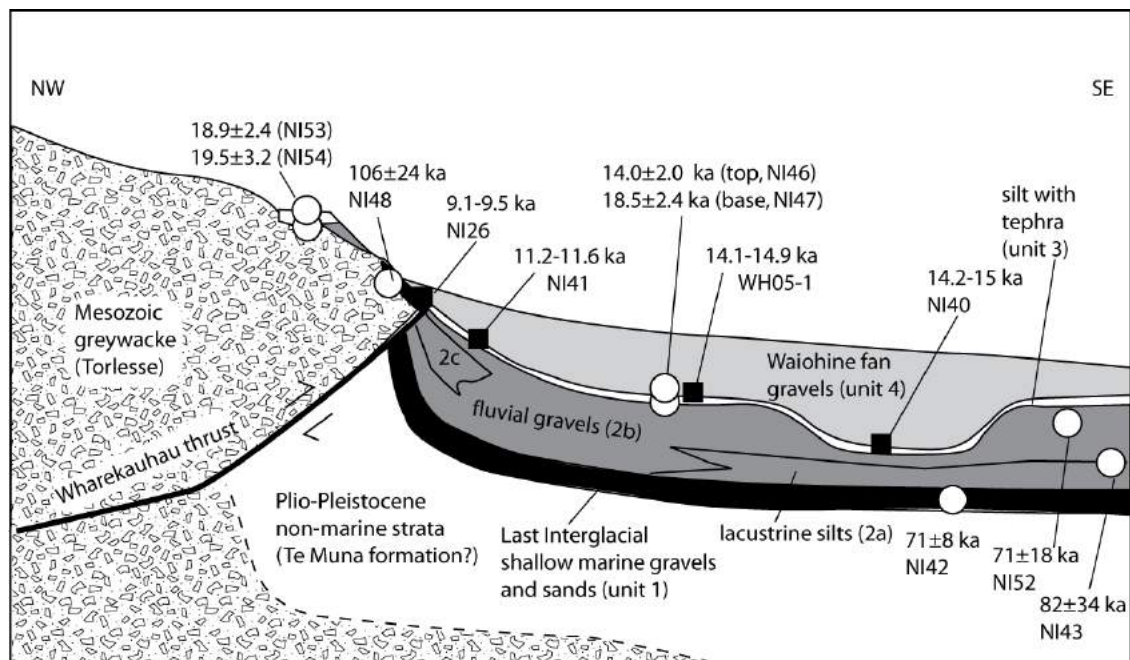
Figure 15. Schematic cross section of stratigraphy in the detailed study area of Figure 14 (Wharekauhau Stream). Squares=location of radiocarbon samples (wood from in-situ roots, stumps); circles=location of OSL samples (silts, fine sands). Age ranges for radiocarbon samples are calibrated age range at 95% confidence. Errors on OSL ages are 2σ. See Figures 14 and 16 for detailed sample locations. From Schermer et al, 2009.

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 3c.

Samples from unit 2 yielded OSL ages that are consistent with deposition near the end of the last interglacial at ~80-70 ka (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 ~16 m above a sample of unit 2a dated at 117 ±60 ka (Marra, 2003)(2σ 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 3b: 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 ~2 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. 15). [14]C samples from the top of unit 3 range from 15 ka to ~9 ka, with age decreasing northward and with elevation (Fig. 15). 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 (i.e., 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 3a (sample WK-1; Fig. 14).

STOP 3c: 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. 16, 17). 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 hangingwall 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 and 2b 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 (buttress) unconformity. In the hangingwall of the thrust above the north end of the outcrop, unit 3 occurs as a 5-6 m-thick massive silt that is not 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 ~30° here (Fig. 16), but disappears to the south (e.g., stop 3b).
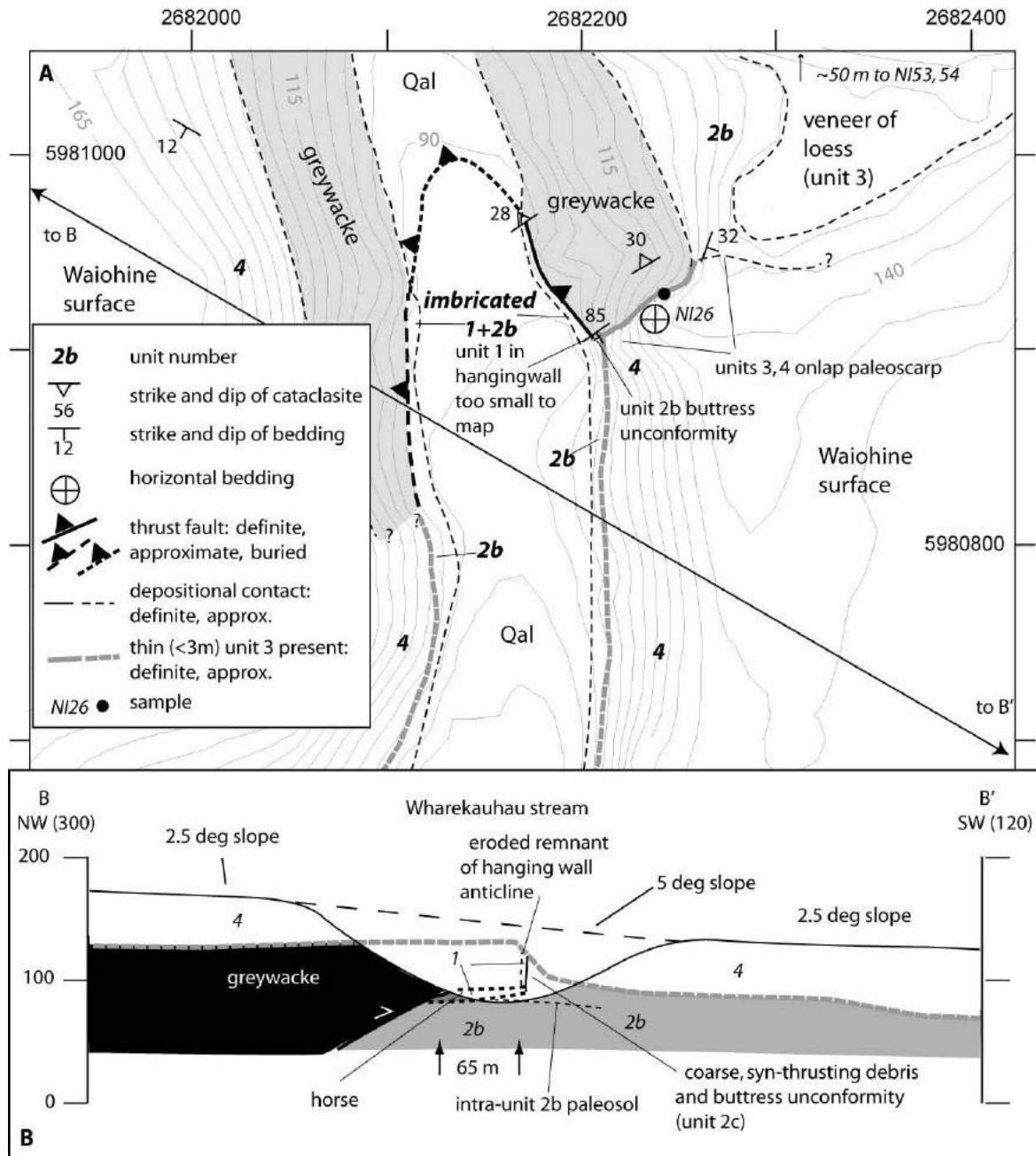
Figure 16. a) Detailed map of Wharekauhau Stream area (Stop 3c) derived from surveying topography and geologic contacts with a laser rangefinder. Locations of geochronological samples shown with black dots. b) Cross section B-B', no vertical exaggeration constructed perpendicular to a thrust strike of 210 (N30E) consistent with the structure contours drawn across Wharekauhau stream and the regional trend of the fault. Location shown on Figure 14. Fine dashed lines show bedding traces. From Schermer et al., 2009.
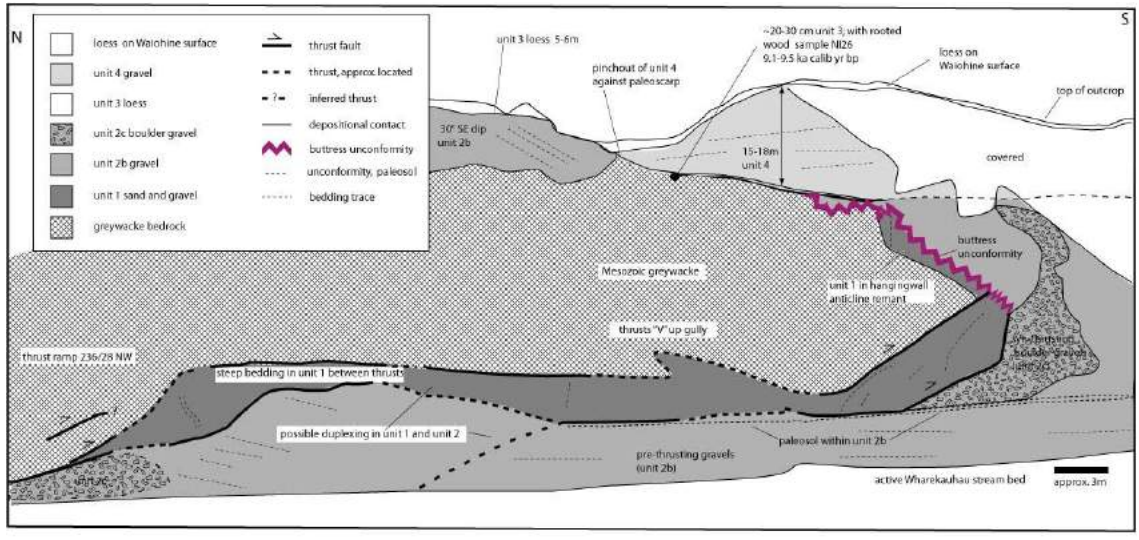
Figure 17. Tracing of a photograph of an outcrop of the thrust at Stop 3c. Duplexing in unit 2b is inferred from discontinuities in bedding; duplexing in unit 1 is inferred from extreme thickening of unit in horse relative to undeformed exposures. The annotated photographs, below and next page, also show the interpreted geology, as looking east at this exposure. From Schermer et al., 2009.

UNITS

| 4 | Unit 4- "Waiohine" fan gravels |
3	Unit 3- sandy silt marker layer with *in situ* wood
2	Unit 2- fluvial gravels: 2a, organic-rich lacustrine unit 2b, bench-forming lower gravel unit , capped by thin paleosoil layer 2c, massive yellowish-weathering upper bouldery facies at fault
1	Unit 1- last interglacial beach gravels
0	Unit 0 (coast only). Prelast glacial alluvial gravels (thickness unknown).
gw	Crushed Torlesse Terrane
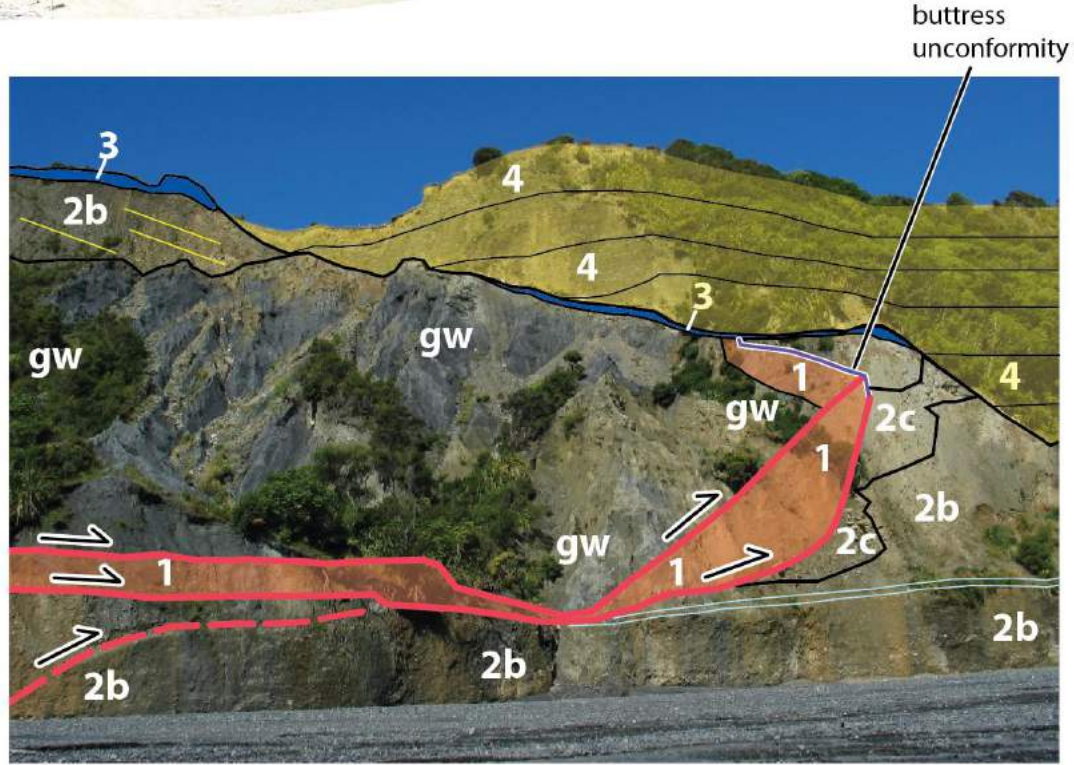
Fig. 17 (Continued)
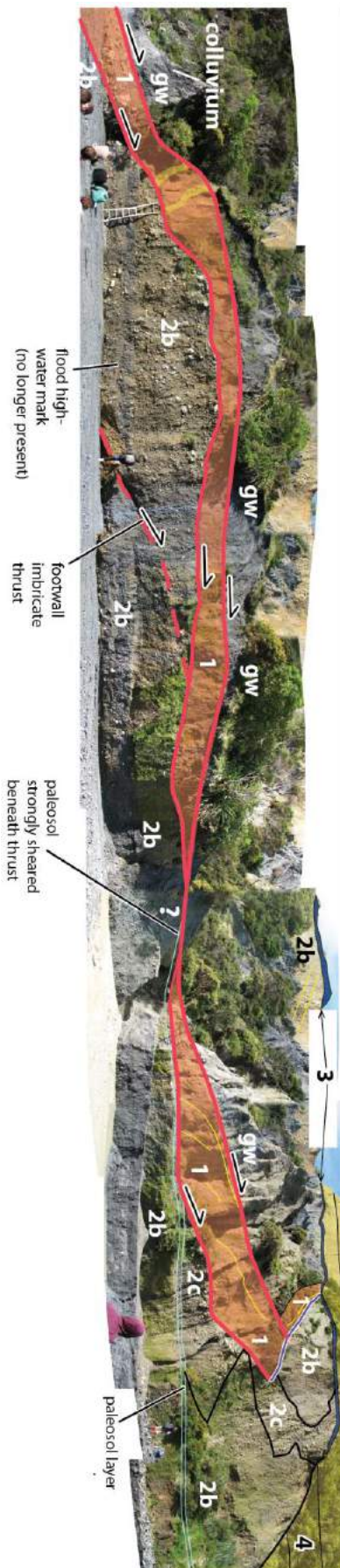
The Wharekauhau thrust here consists of two subparallel thrust planes that are spaced ~1-1.5 m apart, and that flatten from ~30° NW true dip to horizontal (apparent dip) towards the south (Fig. 17). The higher thrust juxtaposes highly fractured Cretaceous Torlesse greywacke (foliated cataclasite) in its hangingwall to the northwest above a steeply dipping beds of well-rounded, unit 1 beach gravels to the southeast. The lower thrust juxtaposes the beach gravels above gently dipping fluvial 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 occur within unit 2 beneath the lower thrust (one is shown as a dashed red line in the annotated photographs of Fig. 17).

The geometric and stratigraphic relationships suggest initital formation of a fault-propagation fold and/or ramp anticline in the beach gravels (unit 1), followed by the fault tip propagating across this fold upward to the surface, and cutting off the steep forelimb. The eastward shallowing of the thrust planes, and the coincidence of the flat thrust surface with the paleosol within unit 2b (Fig. 16) suggests that the thrust ramped upward to the contemporary free surface represented by that paleosol 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 ±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. 16b). 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 <15 m difference in the calculated heave.

STOP 3d: 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 cross-section of the "fault and fissure" in "Te Mangonge" Stream (Fig. 18a). 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. 19a) 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 3e, 3f) 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 ~1 mile (1.6 km) north of the coast (i.e., 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. (2009) and shown here in Fig. 14. 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 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).
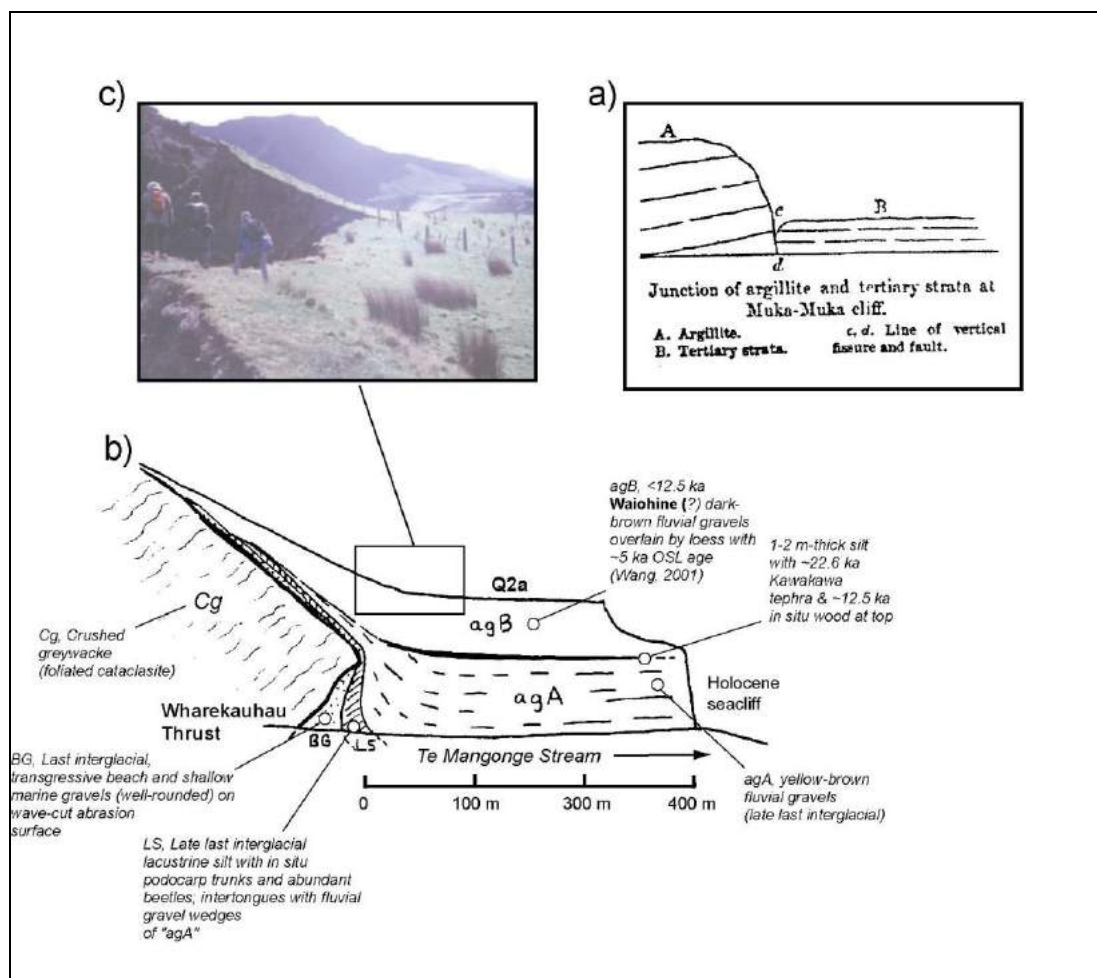
Figure 18. Previous interpretations of the Wharekauhau thrust as exposed in Te Mahonge and Wharekauhau Streams near the Palliser Bay coast. a) diagram of Te Mahonge Stream exposure of the fault (illustration in Lyell, 1868; note the steep dip of the fault); b) diagram after Grapes and Wellman (1993) 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. (2009), as used in this guide).

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 <1 km 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. 18c), 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 little-deformed tread of the Waiohine gravels (unit 4) is mantled (downlapped) by a younger layer of colluvium that is derived from the hilly topography northwest of the inactive thrust trace. The strata in unit 4 are everywhere subhorizontal and onlap depositionally against the more steeply dipping strata in the thrust hangingwall (Fig. 19). 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 3c, 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. 16b). 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. 16b). We interpret the dips as primary features of an alluvial fan surface. If the change in slope is indeed due to thrusting, the active fault must lie below the surface, and cannot have the same near-surface expression as the (inactive) Wharekauhau thrust.

STOP 3e: 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°, and units 3 and 4, which dip <10° (Figs. 19d, 20). 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. 19a, b).

The two thrusts flatten in an eastward direction from NW dipping to subhorizontal (Fig. 19b). On the west bank of Te Mahonge Stream (stop 3f), both thrusts are steeply dipping (Fg. 19a). To the east, both thrust planes are subhorizontal (Figs. 19b, 19c). The cataclasite fabric in the hangingwall greywacke also flattens upward and eastward (Fig. 19c). Within the horse, unit 1 is folded by "drag" on the upper thrust (photograph on cover page of this field guide).

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. 20).

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. 19d). 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°) 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).

Despite the above, structural evidence exists for minor, steeply dipping faults that post-date motion on the Wharekauhau thrust. Although we have not found a continuous, 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 (Figs. 19a, 19b). In outcrop, exposures in Te Mahonge Stream suggest that following erosion of the thrust and deposition of unit 3, several steeply dipping faults cut through the Quaternary units (Figs. 19, 20). Just south of the thrust exposure on the east side of the stream, a fault oriented ~075/80SE causes ~3m 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. 19b). 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 hangingwall strata in the slip face exposure to the north of this stop, but most are too small to show on the map (Fig. 19a). These faults are NE-striking, steeply dipping faults with at most a few meters of vertical and horizontal separation (Fig. 19e). 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.

STOP 3f: Wharekauhau thrust exposed at mouth of Te Mahonge Stream
Walk across the stream to the true right bank. Total time at this stop about 20 minutes.

At the outcrop, greywacke-derived cataclasite is well exposed. Looking east across Te Mahonge Stream from this location, one 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. 19). Relations at Te Mahonge Stream constrain the geometry of the thrust-related deformation, and allow estimates of the minimum shortening and slip rates accommodated along the thrust (Fig. 20). These are summarized in the next section.
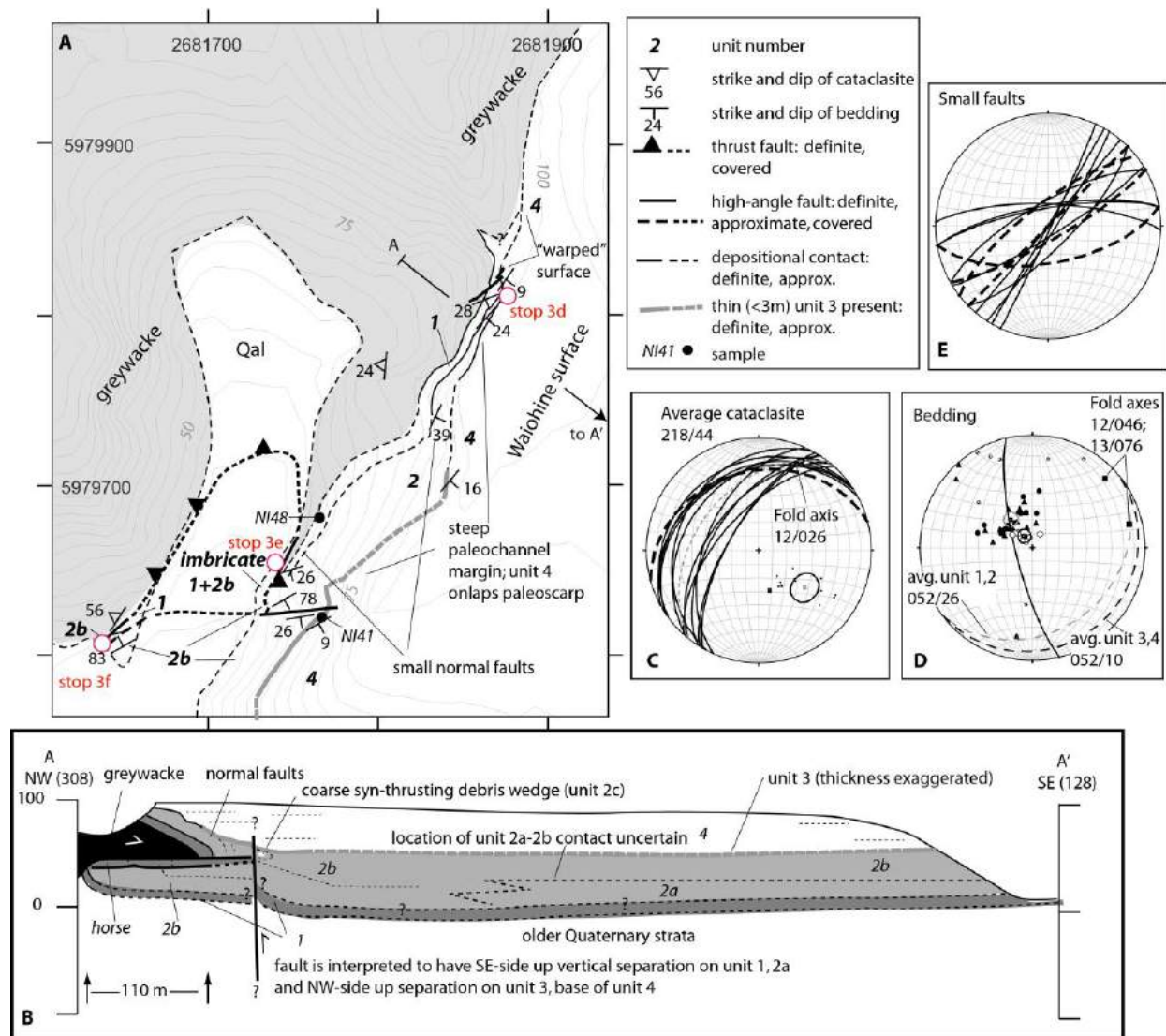
Figure 19. a) Detailed map of Te Mahonge Stream area (stops 3d, 3e, 3f) derived from surveying topography and geologic contacts with a laser rangefinder. Contour interval is 5m. b) Cross section A-A' (location on Fig. 14), no vertical exaggeration, constructed perpendicular to the average cataclasite 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 hangingwall 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. From Schermer et al., 2009.
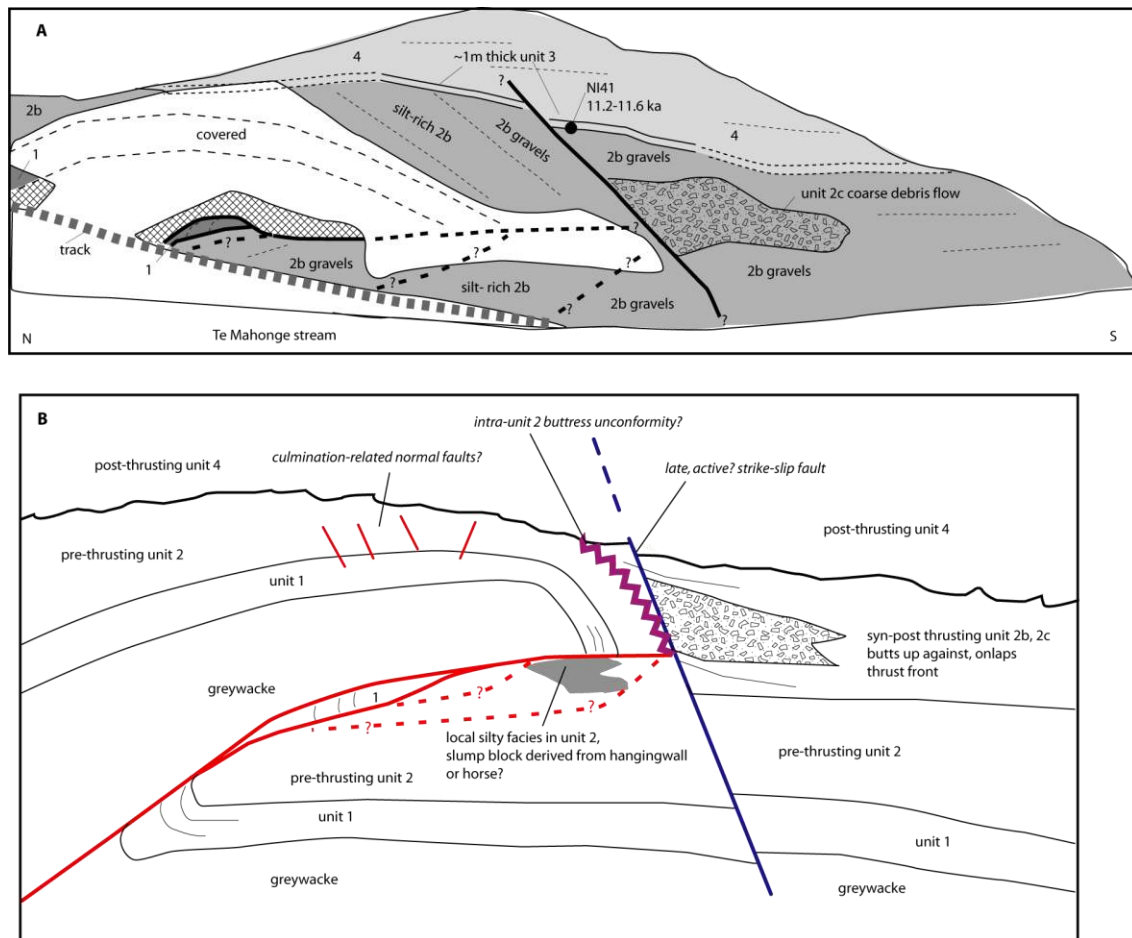
Figure 20. a) Tracing of a photograph of an outcrop of the thrust at Stop 3e. b) Interpretation of fold and thrust geometry in Te Mahonge Stream, including data from area to north of Stop 3e. From Schermer et al., 2009.

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 than in Wharekauhau Stream because the hangingwall cutoffs of the contacts between greywacke, unit 1, and unit 2 are exposed on the east side of the stream 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. 19a), so both could be accurately mapped. Reconstruction of cross sections from Te Mahonge stream (e.g., A-A', Fig. 19b) 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. 19d). 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. 15). Two locations at the base of unit 3 are dated by OSL at ~18-20 ka (samples NI54, NI47, Fig. 15), 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 ^{14}C 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.

Slip rate and relationship of Wharekauhau Thrust to the subduction interface

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 92-102 m. 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 the time of 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 total margin-normal component of plate motion. This high shortening rate suggests that the Wharekauhau thrust was kinematically linked to, and merged with, the subduction interface; however, the stratigraphic relationships and dating indicate that this situation that was short-lived. After abandonment of the thrust at ~20 ka, deformation at shallow levels in this region has occurred primarily on a segmented system of minor faults that accommodate 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.

Stop 4. Overview of uplifted Pleistocene marine terraces along the southern Wairarapa coast
Looking at the terraces at Wharekauhau and those to the east, along the coast towards Cape Palliser. Total time at this stop about ~30 mins.

Across southern North Island, shore platforms created during the Pleistocene (>12 ka) have been uplifted above the level of marine processes to remain preserved in the landscape as marine terraces. The terraces formed as a result of sustained erosion and weathering of coastal bedrock which can occur during sea level highstands that accompany warm periods (interglacials or interstadials). Now found discontinuously along ~100 km of coastline between Cape Terawhiti (west of Wellington) and Cape Palliser (see Fig. 1a), these remnant marine terraces are positioned along the south coast in an orientation that is near-parallel to the Pacific-Australian plate motion, providing a valuable set of markers with which to undertake a direct study of tectonic deformation across the southern Hikurangi margin.

In the past, measurements of terrace elevation were typically made relative to the top of their variably sediment-mantled tread, and age estimates were often not based on radiometric dating but rather on correlations with other terraces sequences, including ones from other sites around the world (e.g. Ghani, 1974; 1978). As a result, previous margin-wide terrace correlations and corresponding uplift estimates along the south coast of New Zealand are subject to large uncertainties.

Based on new field and LiDar mapping, Global Navigational Satellite System Real Time Kinematic (GNSS RTK) surveying, and Optically Stimulated Luminescence (OSL) dating of the overlying beach deposits (21 new ages) - we have mapped the distribution of Pleistocene shore platforms and obtained the first radiometrically-determined ages for the majority of the terraces along the south coast. We have identified six shore platforms, the oldest found at heights of up to ~400 m above current day sea level, although the preservation of this sequence varies between localities.

The shore platforms are formed on basement rock whose age and composition varies along the coast (Fig. 21a). The eroded bedrock shore platforms are unconformably overlain by both marine and non-marine Pleistocene deposits. Marine deposits consist of well-sorted and well-rounded sands, pebbles and gravels, directly overlying the shore platform, not dissimilar to the modern-day beach deposits seen on this coastline. Younger, non-marine deposits are commonly alluvial in origin, and/or massive, homogeneous deposit of silt-size grains, suggesting an aerial deposition such as loess. Originating from the cliffs behind the terraces, angular and irregular-sized clasts commonly form colluvial fan deposits that overlie and bury the older marine and fluvial coverbeds (Fig. 22).
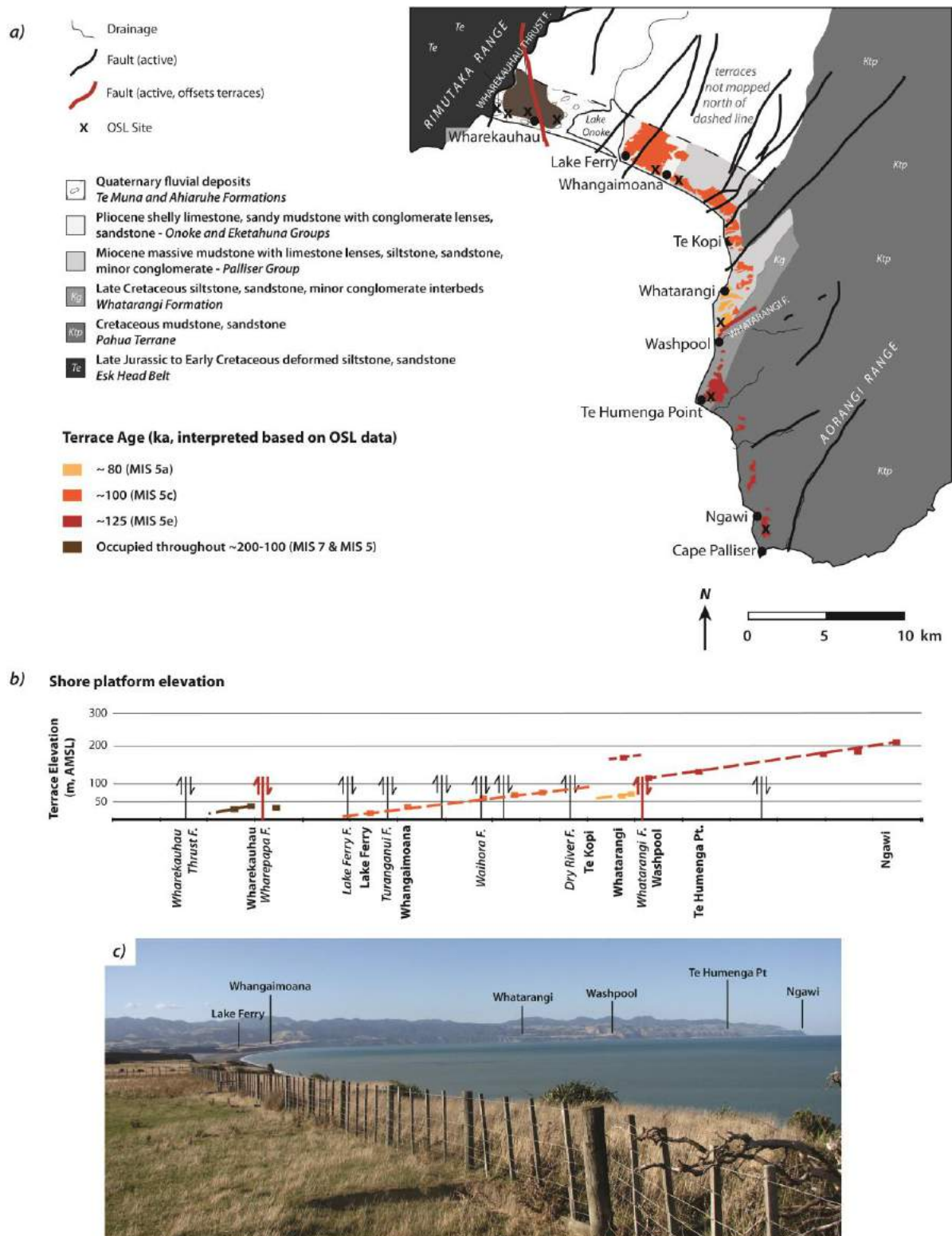
Figure 21. a) Map showing terrace outlines and place names referred to in the text, interpreted terrace ages and geology of the shore platforms. Known active faults are shown in black, faults that offset the terrace shore platforms are shown in red.
b) Elevations (in metres AMSL) of the different aged terraces, projected onto a NW/SE orientated profile. c) Photo of Palliser Bay coastline taken atop of the terrace at Wharekauhau, looking towards the southeast, showing sites of interest (photo taken by N. Litchfield).

Figure 22. Stratigraphic logs of marine terrace exposures from OSL sample collection sites, showing OSL ages (to 1σ). See Fig. 21 for locations.
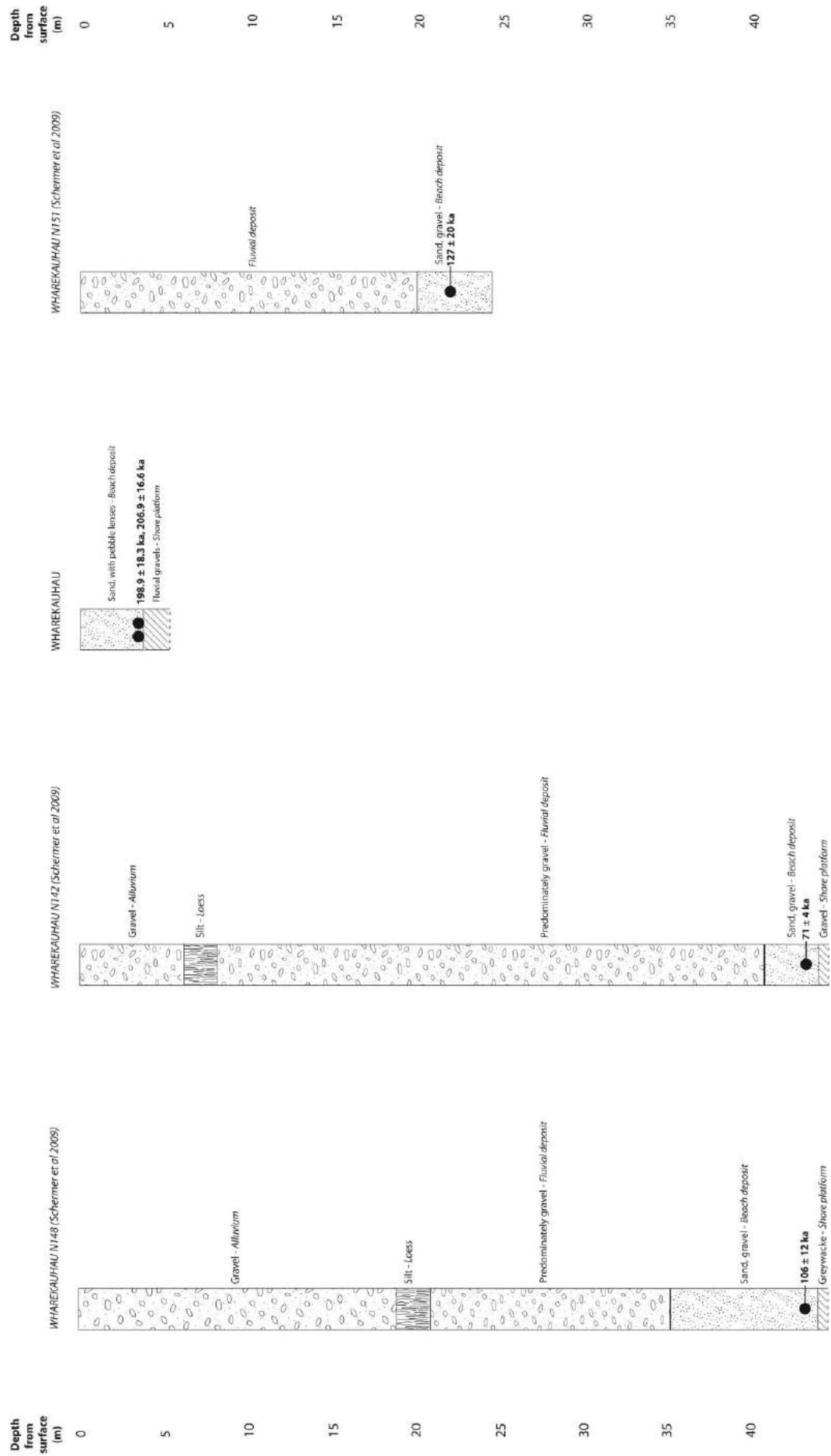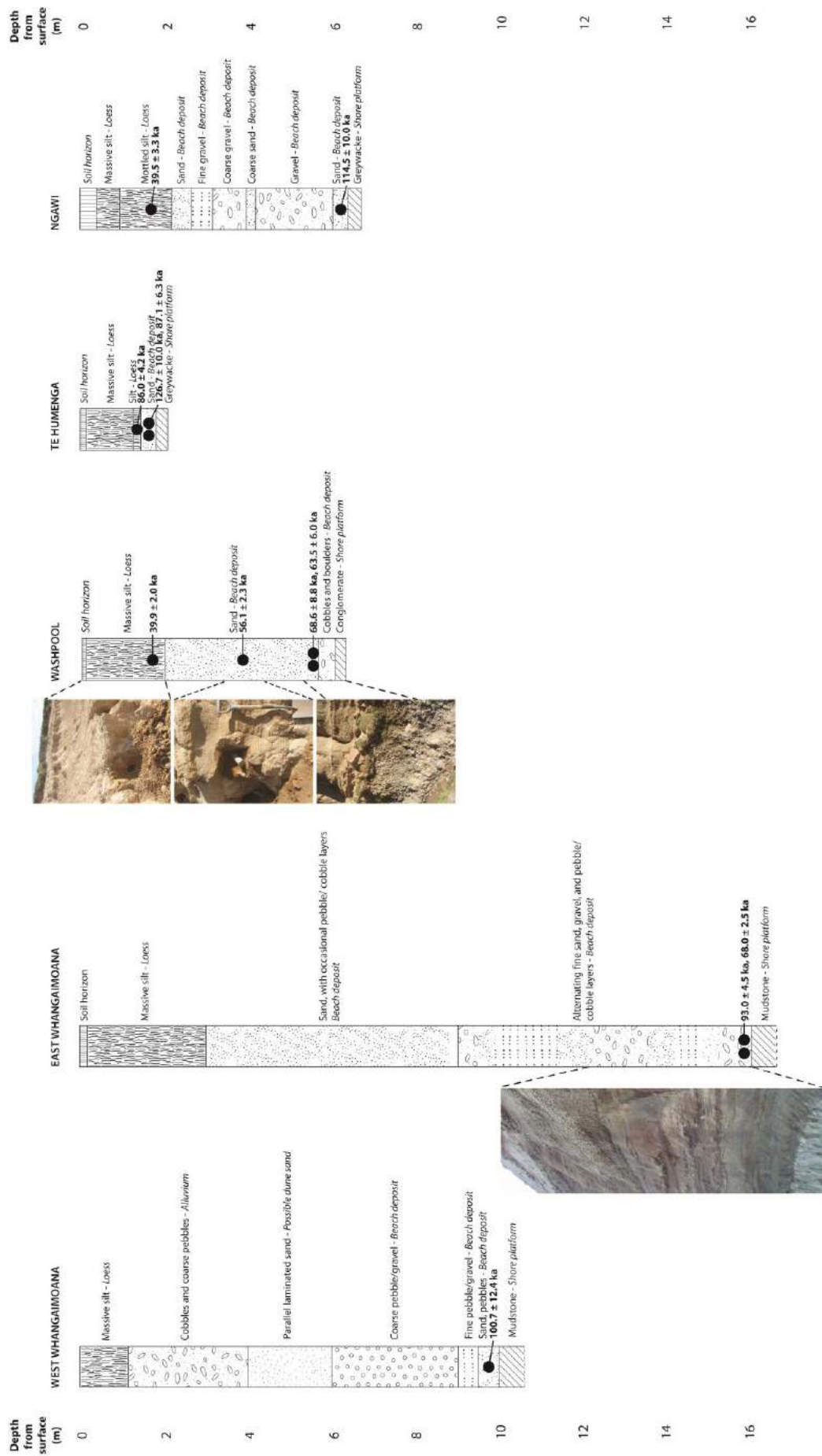
Figure 22. Continued.

Our new OSL data suggest that the marine terraces along the Palliser Bay coastline formed during MIS5a (peak age 82 ka), MIS5c (96 ka), MIS5e (123 ka) and MIS7 (191-243 ka) (ages from Lisiecki & Raymo, 2005) (see Fig. 21a, b). Here at Wharekauhau, our OSL dating has yielded ages of 206.9 ± 16.6 ka and 198.9 ± 18.9 ka, from an exposure within the Wharepapa River valley (~500 m upstream from the river mouth) which suggests that this shore platform was formed during MIS 7. Interestingly, however, the Wharekauhau Fault investigation by Schermer *et. al.* (2009), which also produced OSL ages, yielded younger ages; 71 ± 4 ka from a site within the nearby Wharekauhau Stream (near the river mouth), 106 ± 12 ka from a site ~1 km west of Wharekauhau Stream, and 127 ± 10 ka near the intersection of Wharekauhau Road and Western Lake Road (~1 km from the coast), ages all within MIS 5 (see Figs. 21 & 22). Such variable ages suggest that shore platform along this section of the Palliser Bay coast has not been rapidly uplifted, but rather remained at approximately the same altitude throughout MIS 7 to MIS 5, and was re-occupied by the sea during successive highstands.

Eastward, between Lake Ferry and Te Kopi, OSL dating of the marine deposits overlying the shore platform at two sites near Whangaiomana beach has yielded ages of 100.7 ± 12.4 ka and 93.0 ± 4.5 ka, indicating that this shore platform was most likely cut during MIS 5c. At Washpool/Whatarangi, a locally-preserved terrace which is slightly lower in elevation than that those preserved either side, has yielded OSL ages of 63.5 ± 6.0 ka and 68.8 ± 8.8 ka. We believe this terrace formed during MIS 5a. To the east of Washpool/Whatarangi, and continuing towards Cape Palliser, the coastal-most terrace has yielded OSL ages of 114.5 ± 10.0 ka, 87.1 ± 6.3 ka and 126.7 ± 10.0 ka . Based on the older two ages and the fact that this terrace is higher in elevation than the others along the coast, we infer that this terrace formed during MIS 5e.

Analysis of shore platform elevation data reveal that the terraces are locally offset by a number of upper plate faults that cross the coast (See Fig, 21c). Marine terraces are not preserved in the landscape to the immediate west (the upthrown side) of the Wharekauhau Fault. A few kilometres to the east, the Wharepapa Fault locally offsets the shore platform by ~5 m, uplifted to the west. East of Whangaimoana Beach an un-named fault offsets the shore platform there by a similar amount, again uplifted to the west. Movement on the Whatarangi Fault has locally offset the MIS 5e shore platform there by about ~40 m uplifted to the west, and may be responsible for the preservation of MIS 5a terraces exclusively at Washpool/ Whatarangi.

In addition to these local offsets, all terraces are gently tilted (decreasing in elevation) towards the west, by about 1.5-2.5°. Recently published evidence for subduction earthquakes subsidence events in the northern South Island (Clark *et. al.* 2015) suggest that repeated rupture on the Hikurangi subduction interface is a possible cause of the observed long-wavelength uplift and westward tilting of the terraces across the south coast. Dislocation modelling of rupture of the currently locked part of the subduction interface suggests that the maximum uplift from slip on the subduction interface would occur along the eastern North Island and would taper out to no uplift a few kilometres west of Wharekauhau. This is generally consistent with what we see with the marine terraces along the Palliser Bay coast; the maximum uplift is observed at Ngawi, where the ~125 ka terrace is now ~215 m above sea level, providing an uplift rate here of ~1.7 mm/yr. The exception to the uplift pattern shown by Clark *et. al.* 2015 is near Lake Onoke, where the marine terraces are locally absent. Evidence for subsidence has previously been reported north of Lake Onoke, at Lake

Wairarapa (Clark *et. al.,* 2011), and it may be that this subsidence extends southward to Lake Onoke, locally submerging the shore platform there.
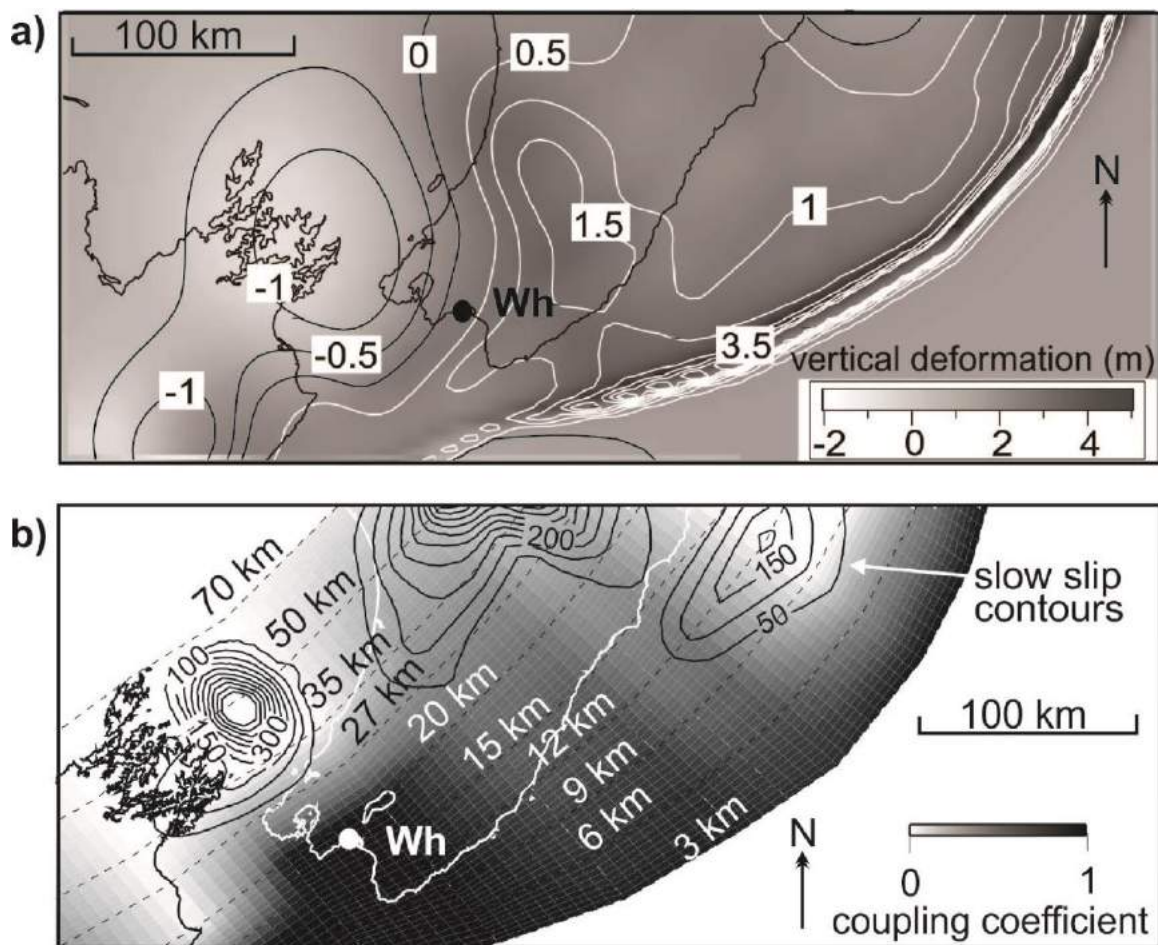

Figure 23. a) Upper plate deformation derived from elastic dislocation half-space modelling of a subduction earthquake scenario with 500 years of accumulated slip based on the present-day pattern of interseismic locking shown in (a). White contours show areas of uplift, black contours show areas of subsidence (contour intervals are 0.5 m, in metres). Wh is Wharekauhau Stream mouth. (b). coupling coefficient on the southern Hikurangi subduction interface determined from GPS measurements over the last 15 years; the velocities used average through slow slip events. Black contours show total slip (in mm) detected in slow-slip events on the Hikurangi subduction interface since 2002 using continuous GPS data. Dashed black lines are depth contours to the subduction interface. Wh is Wharekauhau Stream mouth. Both figures modified from Clark et al. (2015).

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