Quaternary deformation along the Wharekauhau fault system, North Island, New Zealand: Implications for an unstable linkage between active strike-slip and thrust faults

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[1] The southern Wairarapa region of the North Island of New Zealand preserves a variably deformed late Quaternary stratigraphic sequence that provides insight into the temporal variability in the partitioning of contraction onto faults in the upper plate of an obliquely convergent margin. Detailed mapping, stratigraphic data, and new radiocarbon and optically stimulated luminescence ages from Quaternary units reveal the interaction between tectonics and sedimentation from ~125 ka to <9 ka along the Wharekauhau thrust and related faults (i.e., Wharekauhau fault system) at the southern end of the Wairarapa fault zone, a major oblique-slip fault in the upper plate of the Hikurangi Margin. The Wharekauhau thrust accommodated a minimum of 280 ± 60 m of horizontal shortening from ~70 to 20 ka. The inferred shortening rate, 3.5–8.4 mm/yr, may have accounted for 11–30% of margin-normal plate motion. By ~20 ka, the thrust was abandoned. Subsequent deformation at shallow levels occurred on a segmented fault system that accommodated <1 mm/yr shortening. Active deformation in the region is partitioned between slip on (1) the more western Wairarapa-Mukamuka fault system (dominantly dextral slip but also causing local uplift of the coast); (2) a series of discontinuously expressed strike-slip faults and linking blind oblique-reverse thrusts near the trace of the inactive Wharekauhau thrust; and (3) a blind thrust fault farther to the east. The spatial and temporal complexity of the Wharekauhau fault system and the importance it has had in accommodating upper plate deformation argue for an unsteady linkage between upper plate faults and between these faults and the plate interface.

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1. Introduction

[2] Oblique convergence along the Pacific-Australia plate boundary in New Zealand has been studied as a natural laboratory for understanding transpression and slip partitioning on fault systems [e.g., *Little et al.*, 2007; *Norris and Cooper*, 1995; *Teyssier et al.*, 1995; *Walcott*, 1984]. 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. This is the case in Japan (1995 Kobe M7.2), the Cascadia margin of the western U.S. (900AD Seattle fault M ~ 7), Nicaragua (1972 Managua M6.2), and New Zealand (1855 Wairarapa M ~ 8.2). Although progress has been made understanding how faults in the upper plates of subduction zones accommodate plate motion, 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 years, seismic cycle) versus on long (10^4–10^6 years) time scales? What factors determine the stability of fault segments and how is this recorded in the landscape? How is strain partitioned among oblique, reverse, and strike-slip faults and between the hanging wall and subduction zone faults on different timescales?

[3] 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 (Figure 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 (Figures 1 and 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; *Wallace et al.*, 2004]. The 1855 Wairarapa earthquake, which produced surface rupture along the Wairapapa fault zone (Figure 1) [*Grapes and Wellman*, 1988; *Grapes and Downes*, 1997; *Lyell*, 1856; *Ongley*, 1943], resulted in up to 6.4 m of coastal uplift, and up to ~18.5 m of dextral slip, the largest coseismic rupture documented for an historical earthquake worldwide [*McSaveney et al.*, 2006; *Rodgers and Little*, 2006]. Despite the proximity of the southern part of the Wairarapa fault zone to New Zealand's capital city of Wellington and

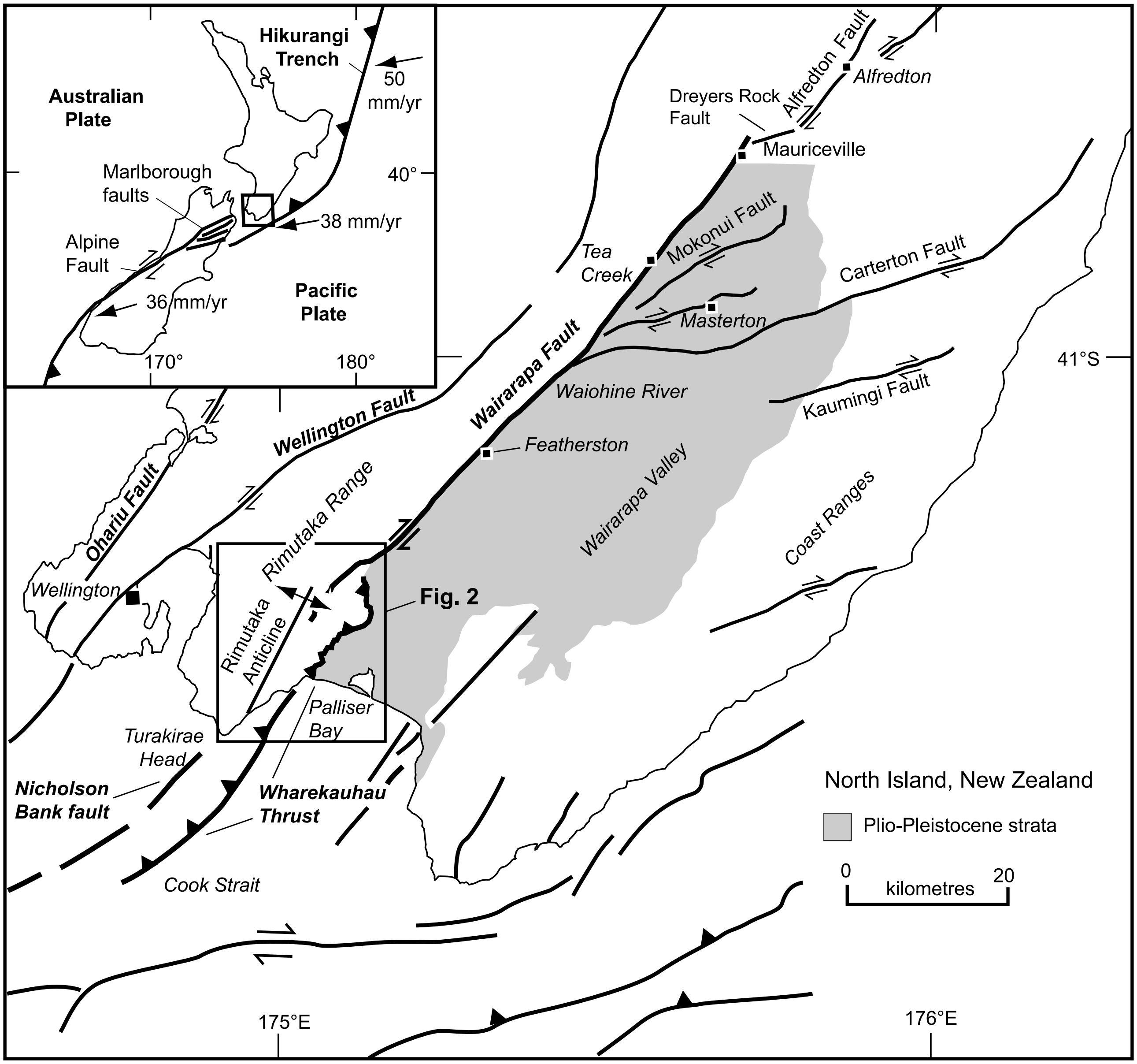

Figure 1. Generalized map showing major active faults and other structures of the southern North Island, New Zealand [after *Barnes*, 2005; *Begg and Johnston*, 2000; *Lee and Begg*, 2002], localities mentioned in text and box outlining Figure 2. Inset shows plate tectonic setting of New Zealand (plate motions taken from *DeMets et al.* [1990, 1994]).

the seismic hazard that it poses, there are surprisingly few constraints on the structural geology of the fault, the geometry and location of its earthquake ruptures, or on the relationship of Wairarapa fault earthquakes to uplifting of the Rimutaka Range and the coastal platform. Preserving a rich and variably deformed late Quaternary stratigraphic sequence, and benefiting from several superb coastal exposures, the region is also of special interest for the insight it can provide on the temporal variability (since ~125 ka) in the partitioning of contractional fault slip onto (and off) a major fault on the upper plate of an obliquely convergent subduction zone.

[4] In this paper we present stratigraphic, geomorphic, and structural data to document Quaternary deformation along the Wharekauhau thrust and related faults (Wharekauhau fault system) at the southern end of the greater Wairarapa fault zone (Figure 2). Our aim is to understand the structural development of the Wharekauhau fault system and the style of its rupture (if any) during the 1855 and earlier earthquakes, and to constrain the short- and long-term slip rates on this part of the Wairarapa fault zone. We document major spatial and temporal changes in strain partitioning at the southern end of the greater Wairarapa fault zone, including a brief (~50 ka) period of rapid slip on the Wharekauhau

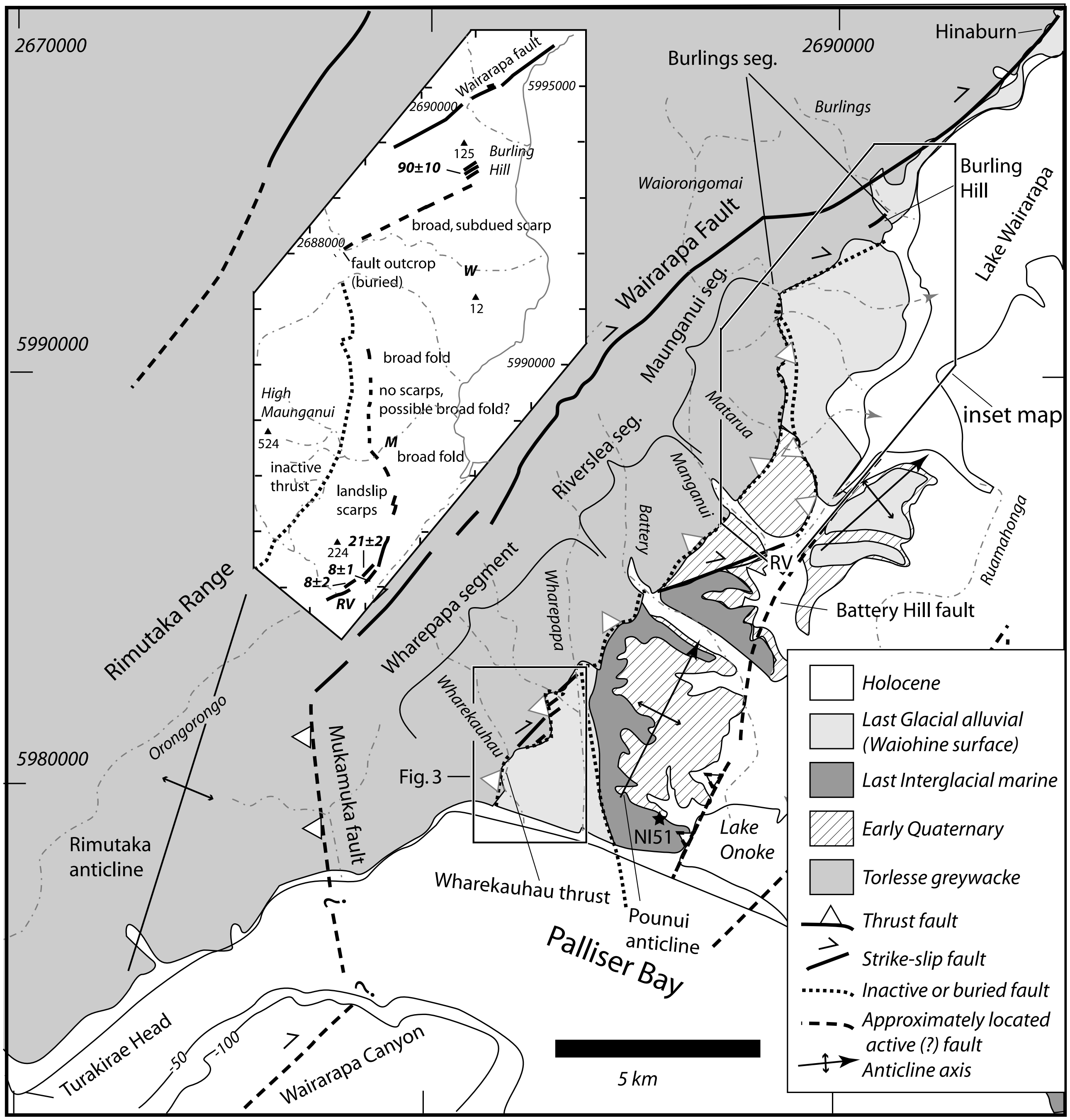

Figure 2. Quaternary to Recent fault traces and folds along the Wharekauhau fault system in the southern part of the Wairarapa fault zone. Geologic map base simplified from *Begg and Johnston* [2000], revisions by *Little et al.* [2008]. Segments of Wharekauhau thrust are discussed in text; stream names are shown in italics. Boxes outline inset to left and location of Figure 3. Star indicates location of OSL sample NI51. Inset shows enlarged map of Maunganui segment and part of Riverslea segment. Bold numbers indicate locations where dextral separation of surface features was measured in this study. W, Waiorongomai River; M, Matarua Stream; RV, Riverslea. Grid marks (in meters) refer to the New Zealand Map Grid Coordinate System.

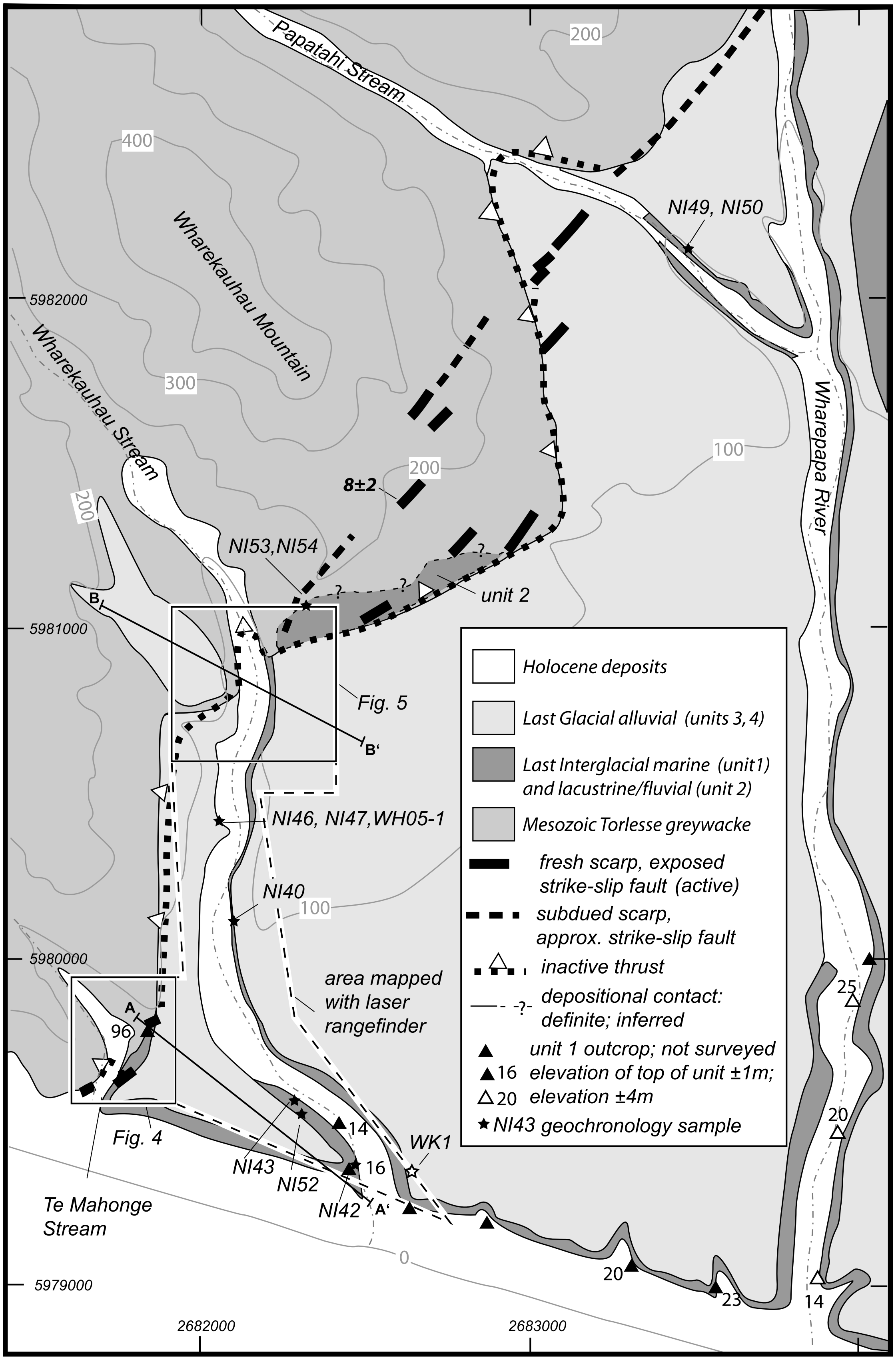
Papatahi Stream
200
400
Wharekauhau Mountain
NI49, NI50
5982000
Wharekauhau Stream
300
200
100
Wharepapa River
8±2
200
NI53,NI54
unit 2
B
5981000
Fig. 5
B'
Holocene deposits
Last Glacial alluvial (units 3, 4)
Last Interglacial marine (unit1) and lacustrine/fluvial (unit 2)
Mesozoic Torlesse greywacke
fresh scarp, exposed strike-slip fault (active)
subdued scarp, approx. strike-slip fault
inactive thrust
depositional contact: definite; inferred
unit 1 outcrop; not surveyed
16 elevation of top of unit ±1m;
20 elevation ±4m
NI43 geochronology sample
NI46, NI47,WH05-1
NI40
100
5980000
area mapped with laser rangefinder
A
96
25
Fig. 4
14
WK1
20
NI43
16
NI52
NI42
A'
Te Mahonge Stream
0
20
23
14
5979000
2682000
2683000

Figure 3

thrust. We analyze the implications of these data for the kinematic linkage between the Wairarapa, Wharekauhau, and adjacent faults at different times.

2. Tectonic Setting

[5] 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 (Figure 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]. The convergent component is accommodated by thrust faults and related folds in the offshore region and adjacent to the southeast coast, 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; *Nicol et al.*, 2002, 2007; *Nicol and Wallace*, 2007]. The margin-parallel component is accommodated by strike slip and dextral-reverse slip on the North Island Dextral fault belt (NIDFB), an array of NNE striking faults, including the Wellington and Wairarapa faults (Figure 1) [e.g., *Beanland*, 1995; *Mouslopoulou et al.*, 2007; *Van Dissen and Berryman*, 1996], by clockwise vertical axis rotation of an eastern part of the North Island [*Nicol et al.*, 2007; *Wallace et al.*, 2004], by strike slip on active ENE striking structures in Cook Strait, and by oblique slip on other, NE striking offshore faults, including the subduction megathrust [*Barnes and Mercier de Lépinay*, 1997; *Barnes et al.*, 1998; *Barnes and Audru*, 1999]. Seismicity data suggest that faults of the NIDFB intersect the subduction zone at depths of 20–30 km beneath the Wairarapa region [*Reyners*, 1998]. GPS geodetic data suggest that this segment of the subduction interface is currently "locked" and is accumulating elastic strain [*Wallace et al.*, 2004]. The interaction of the subducting plate interface and faults of the NIDFB is poorly understood, although GPS modeling suggests that the locked megathrust is loading at least some of the crustal faults at depth beneath the southern North Island [*Darby and Beaven*, 2001; *Wallace et al.*, 2004]. *Rodgers and Little* [2006] have suggested that the 1855 earthquake coruptured the Wairarapa fault and a part of the subduction interface.

2.1. Geology of the Wairarapa Fault Zone

[6] 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 fore arc relative to the Pacific Plate [*Beanland*, 1995; *Beanland and Haines*, 1998; *Kelsey et al.*, 1995]. The dextral-reverse fault, dipping steeply northwest, extends from Mauriceville in the north to Lake Wairarapa in the south (Figures 1 and 2). In the southern Wairarapa, the Wairarapa fault is the easternmost strike-slip fault in the NIDFB, while margin-perpendicular shortening is accommodated by folding and thrusting further to the east [*Formento-Trigilio et al.*, 2003; *Nicol et al.*, 2002]. The northern and central sections of the Wairarapa fault are typically expressed by a ~250–500 m wide zone of mostly left-stepping en echelon traces [*Grapes and Wellman*, 1988; *Rodgers and Little*, 2006]. Southwest of Lake Wairarapa, the fault trace is more complex: a western strand continues southwestward into the Rimutaka Range, whereas an eastern strand steps eastward ~5–6 km before deflecting back to a southwestward trend and bordering the range front as far as the southern coast [*Begg and Mazengarb*, 1996; *Begg and Johnston*, 2000; *Grapes and Wellman*, 1988] (Figure 2).

2.2. Wharekauhau Fault System

[7] We refer to the faults that comprise the eastern strand of the greater (southernmost) Wairarapa fault zone as the "Wharekauhau fault system." This strand has been previously been interpreted to consist 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 [*Begg and Mazengarb*, 1996; *Begg and Johnston*, 2000; *Grapes and Wellman*, 1988]. For this paper, we will restrict the term "Wharekauhau thrust" to a specific thrust that is well exposed near the Palliser Bay coast and emplaces Mesozoic greywacke in its hanging wall over Quaternary strata in its footwall. As we document below, we infer this major fault to be inactive and not to have ruptured (at least as a thrust) in 1855. Other smaller-displacement (and in part younger and steeper dipping) faults in Wharekauhau fault system are clearly active dextral-slip (or dextral-reverse) structures, some of which did rupture in 1855, but we do not refer to these as the "Wharekauhau thrust."

[8] 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 consist of last interglacial marine deposits and alluvial fan gravels derived from the Rimutaka Range. The most widespread and conspicuous of these are the latest Pleistocene to Holocene fan gravels referred to as the "Waiohine gravels" by many previous workers in the region (Figures 2 and 3). The top surface of this abandoned fan (the "Waiohine surface") has been widely mapped along the western side of the Wairarapa valley and dips gently eastward beneath Lake Wairarapa [*Begg and Johnston*, 2000;

Figure 3. Geology of Wharekauhau segment, showing Quaternary unit designations as described in text, fault and fold traces, and sample locations (not including samples shown in Figures 4 and 5). Open star shows sample location from *Wang* [2001]. Outcrops of unit 1 are indicated by filled triangles; where surveyed, the elevation of the top of unit 1 is indicated. No outcrops of unit 1 occur north of the northernmost symbols. Open triangles indicate locations with elevations estimated from topographic maps. Dashed outline shows area of detailed mapping and laser surveying, two portions of which are detailed in Figures 4 and 5. Location of cross sections A-A′ and B-B′ (Figures 4b and 5b) are indicated. Topographic contours are in meters; grid marks (in meters) refer to the New Zealand Map Grid Coordinate System.