The Vernon Fault: Onshore paleoseismicity, constraints on slip rate, and contribution to Holocene tectonic subsidence of Big Lagoon, South Island, New Zealand

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TECHNICAL ABSTRACT

The Vernon fault lies within the northern part of Marlborough fault system; it splays from the Awatere fault ~12 km from the east coast and continues into Cook Strait for a further ~25 km northeast-wards. Although a relatively minor component of the plate boundary zone, the Vernon fault is significant because it lies adjacent to Big Lagoon, a coastal wetland that potentially holds a geologic record of tectonic subsidence related to subduction earthquakes. The southern Hikurangi subduction interface dips westward beneath the Cook Strait region, and has the potential to rupture in large to great earthquakes. A subduction earthquake on the southern Hikurangi margin is potentially one of the biggest hazards in central New Zealand. Quantifying the contribution of Vernon fault displacement to the tectonic subsidence of Big Lagoon is the main objective of this study.

The 7 km section of the Vernon fault lying adjacent to Big Lagoon was studied in detail, two trenches were excavated across, or near the fault and several offset geomorphic features were topographically surveyed and dated. The geomorphology indicates the onshore Vernon fault is dominantly strike-slip. It has a varying and minor component of vertical slip (up to 0.14 ±0.05 mm/yr) and a changing sense of throw. The variation in throw sense is consistent with the character of a strike-slip fault as it changes in orientation. The strike-slip nature of the fault means most deformation is horizontal rather than vertical. Therefore, the Vernon fault has probably had negligible, to no, effect on the Holocene subsidence of Big Lagoon. Tectonic subsidence of Big Lagoon is probably driven by subduction interface earthquakes or a combination of minor contributions from other faults in the region and the subduction interface.

Three paleoearthquakes have been identified from the Balfour 1 trench, 4.7 km from the coast; this is the first paleoseismic data obtained from the onshore Vernon fault. The oldest event exposed in the trench, event 1, occurred between 11,000 – 9,000 years BP, event 2 at ~9,000 years BP, and event 3 at < 9,000 years BP. Events 1 and 2 correlate to paleoearthquakes identified offshore from seismic data across the fault. However, the offshore data shows two events <9,000 years while the trench data shows only one. It is possible that one of the mid-Holocene earthquakes on the offshore Vernon fault did not rupture as far as the onshore section of the fault. A dextral slip rate of ≤3.9 mm/yr has been obtained for the Vernon fault; this is not inconsistent with a large portion of slip from the eastern Awatere fault being transferred to the Vernon fault but further work is required to better refine the slip rate.

LAYPERSON'S ABSTRACT

The Vernon fault is part of the Marlborough fault system, a wide zone of faulting in the northern South Island. Underlying the northern part of the fault system is the boundary between the Australian and Pacific plates. While earthquakes on faults within the Marlborough fault system are hazardous in their own right, a major earthquake on the plate boundary (called a subduction earthquake) is considered to be one of the biggest hazards in central New Zealand. A geologic record of sea-level changes caused by subduction earthquakes is potentially found within Big Lagoon, near Blenheim. However, Big Lagoon is bordered by the Vernon fault. This project aims to understand whether the Vernon fault could have caused subsidence (down-dropping) of Big Lagoon, or whether subsidence may be caused by subduction earthquakes.

By looking at displaced landforms along the Vernon fault, and digging trenches across the fault, we can estimate when past earthquakes on the fault occurred and understand the sense of movement on the fault. Evidence of three ground surface-rupturing earthquakes in the past 11,000 years has been documented from a trench exposure across the Vernon fault. This is largely consistent with an offshore record of paleoearthquakes on the Vernon fault, although one extra earthquake is recorded offshore. The Vernon fault is dominantly strike-slip; this means most movement on the Vernon fault is horizontal. Small amounts of vertical motion do occur but these are not significant enough to have caused subsidence within Big Lagoon. Therefore most subsidence in Big Lagoon has probably been caused by subduction earthquakes.

KEYWORDS

Vernon Fault, Big Lagoon, Marlborough fault system, paleoearthquakes, trenching, subduction earthquakes.

1.0 INTRODUCTION

The Vernon fault is in the northern part of Marlborough fault system; it splays northeast-wards from the Awatere fault ~12 km from the South Island's east coast and continues into Cook Strait for a further ~25 km (Fig. 1). The Vernon fault is a small component of the central New Zealand plate boundary zone, and as such, little study has been directed towards this fault. Consequently little is known about it regarding the slip rate, sense of movement and the timing and size of past earthquakes. Recently, two studies have revealed reasons why the onshore segment of the Vernon fault deserves more attention. Firstly, the Vernon fault is adjacent to Big Lagoon which is a site that potentially records subsidence during subduction earthquakes (Clark et al., 2011). Secondly, studies of the offshore Vernon fault show evidence of three Holocene (the last ~10,000 years) paleoearthquakes (Pondard and Barnes, 2010), suggesting the fault poses a reasonable seismic hazard in itself.

Discovering how the Vernon fault may contribute to Big Lagoon deformation, and its potential impact on a subduction earthquake record, is the primary objective of this study. A great subduction earthquake (M_W >8) along the Hikurangi margin is potentially the most significant natural hazard to affect the east coast of the North Island, the greater Wellington region and the northeastern South Island. A subduction earthquake could cause significant and widespread shaking, uplift and subsidence of the coast, and probably generate a large tsunami. There have been no great subduction earthquakes along the Hikurangi margin in historic times (post- AD 1840) and the only probable prehistoric evidence is from the central Hikurangi margin (Cochran et al., 2006). The southern segment of the Hikurangi margin (Cape Turnagain to Marlborough) is strongly interseismically coupled and the current accumulation of elastic plate motion is likely to be released by sudden rupture of the plate interface (Wallace et al., 2009; Wallace et al., 2004). However, due to the present lack of geologic data, we have no knowledge of how often, how large and how widespread plate interface rupture events typically are for this segment of the Hikurangi margin.

At Big Lagoon, evidence of Holocene subsidence has been found in cores of intertidal estuarine sediments. These show that sediments that accumulated near mean sea level are presently located several metres below that elevation (Fig. 2, Clark et al., 2011). Models of upper plate deformation produced by rupture of the southern Hikurangi plate interface suggest the Big Lagoon area would subside in a subduction earthquake, so a possible mechanism for the Holocene subsidence at Big Lagoon is subduction earthquakes (Clark et al., 2011). The Clark et al. (2011) study did not identify any coseismic events within the 7,000 year record of estuarine sediments of Big Lagoon, but ongoing work by Clark et al. has identified evidence for a probable paleo-earthquake and paleo–tsunami at approximately 800 years BP. Thus far, Big Lagoon is the most prospective location for obtaining a subduction earthquake history of the southern Hikurangi margin. However, the extent to which the Vernon fault contributes to Big Lagoon subsidence was, prior to this study, unknown.

This study focuses on the 7 km section of the Vernon fault that lies adjacent to Big Lagoon, informally referred to hereafter as the Big Lagoon section (Figs. 1 and 2). Two trenches were excavated across the fault and several offset geomorphic features were surveyed and dated. The objectives of this study are to estimate the dextral and vertical slip rates of the fault and to identify and date paleoearthquakes on the onshore Vernon fault. In doing so, we hope to place constraints on how much, if any, of the previously documented subsidence in Big

Lagoon, could be caused by the Vernon fault and, conversely, by inference, how much may be driven by large or great subduction earthquakes.

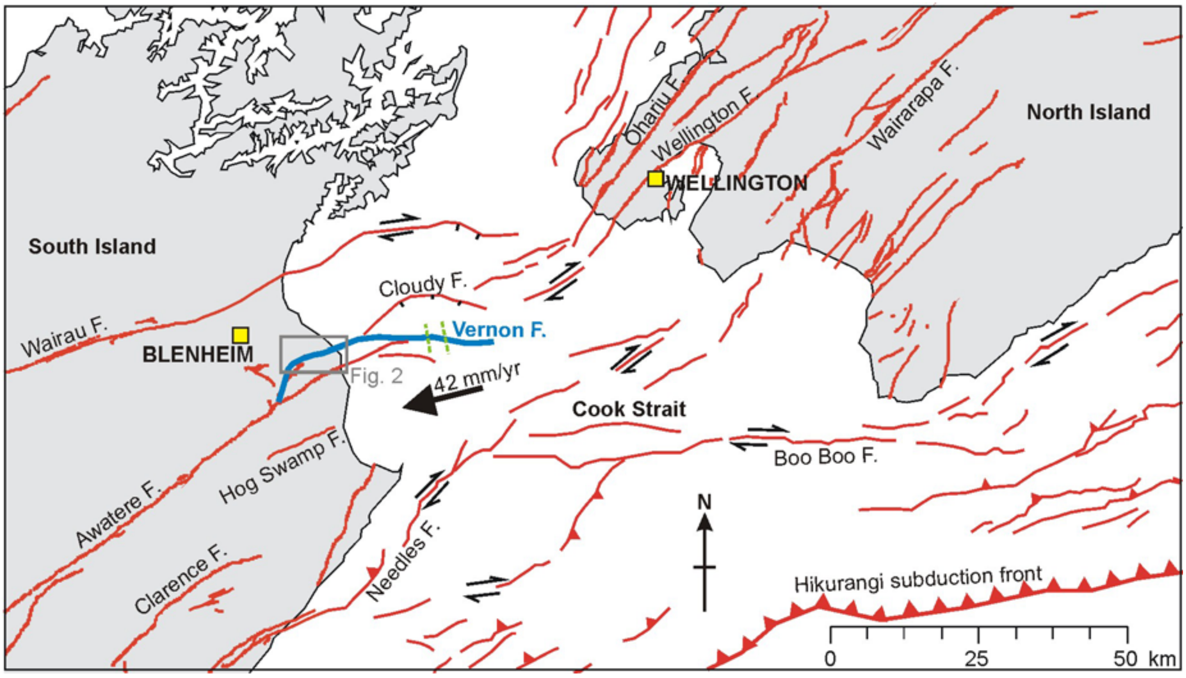


Figure 1 Active faults of central New Zealand encompassing the southern Hikurangi margin and the northern Marlborough fault system. The Marlborough fault system comprises the Wairau fault, the Awatere fault, the Clarence fault and the Hope fault (not pictured), and related subsidiary faults. The Vernon fault is highlighted in blue. Onshore faults are from the NZ Active Faults Database (http://data.gns.cri.nz/af/), offshore faults from Pondard and Barnes (2010). The two dashed green lines show the seismic lines studied for the offshore paleoearthquake record by Pondard and Barnes (2010).

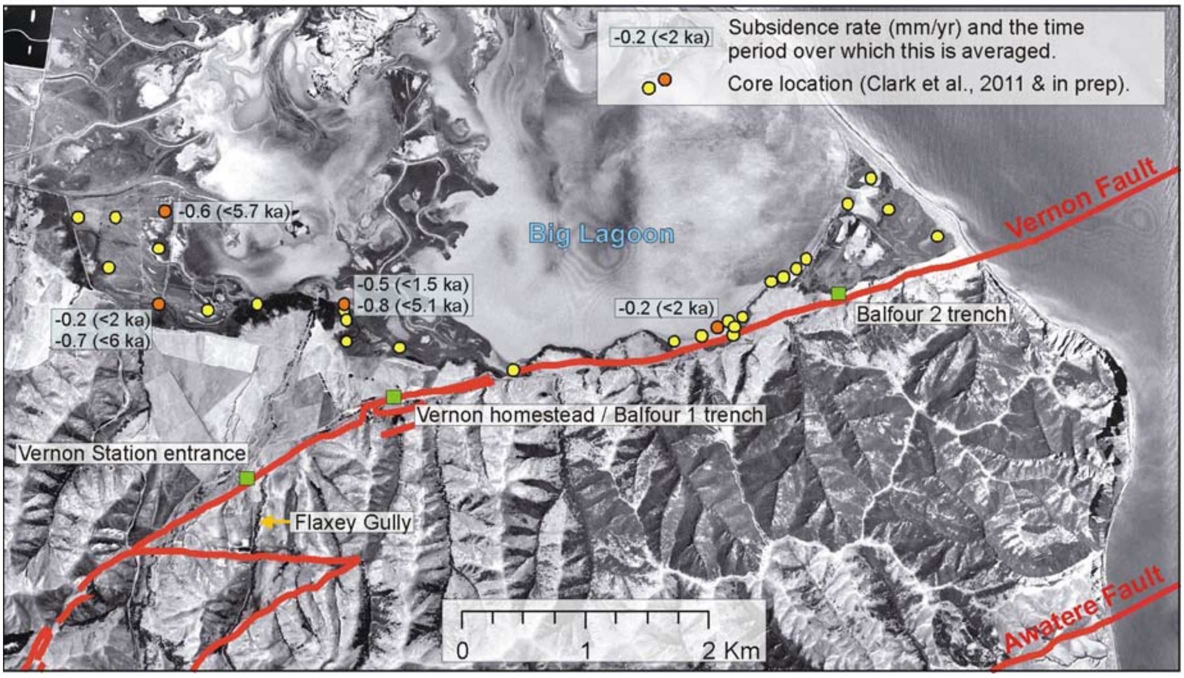


Figure 2 Airphoto of the section of the Vernon fault adjacent to Big Lagoon. The Vernon fault location is from the NZ Active Faults Database. The locations of detailed investigation in this study are shown by the green boxes. The location of cores obtained for paleo-sea level studies by Hayward et al. (2010) and Clark et al. (2011 and in prep) are shown, along with the rates of Holocene subsidence.

2.0 METHODS

A reconnaissance trip was undertaken to study the Big Lagoon section of the Vernon Fault, and on this trip the location of the fault scarp and possible offsets were identified. Suitable locations for excavating trenches were also selected. One trench site was selected (Balfour 1) because the fault formed an uphill facing scarp near a swamp, and therefore had the potential to trap organic material which is useful for dating. The other site (Balfour 2) was selected because it was not clear from surface topography whether the scarp related to faulting or other surface processes, therefore trenching was undertaken to resolve this. The topographic scarp at the Balfour 2 site was also close to the lagoon edge and downthrown on the Lagoon side, therefore potentially more directly related to lagoon subsidence than the Balfour 1 site.

The Balfour 1 trench was located near the Vernon Station farmhouse, and the Balfour 2 trench was located on a broad scarp 1 km from the coastline (Fig. 2). A soil pit was also excavated near the Vernon Station entrance for the purposes of exposing and sampling terrace stratigraphy. Topographic surveying was undertaken around both trenches using a real-time kinematic GPS. The surveying has an internal accuracy of ±0.05m. The RTK base station was set up upon, and calibrated to, geodetic mark ANL3. At the Vernon Station entrance an automatic level, staff and tape measure were used to survey the topography of the fault scarp at this locality.

Four charcoal samples were dated from the Balfour 1 trench; these were all dated at the Rafter Radiocarbon Laboratory, Lower Hutt. The conventional radiocarbon ages were calibrated using OxCal v.4.1 (Bronk Ramsey, 2001). All ages are reported in calibrated years before present (cal. yrs BP). Four silt samples were dated using optically-stimulated luminescence (OSL) at the Victoria University of Wellington Luminescence Dating Laboratory.

3.0 RESULTS

3.1 Vernon Station Entrance – Fault Scarp and Soil Pit

Near the entrance to Vernon Station is a well-expressed scarp of the Vernon fault cutting across a gently sloping fan surface coming down Flaxey Gully (Figs. 2 and 3). The scarp at this location has the largest vertical offset seen along the 7 km Big Lagoon section of the Vernon fault. The fault is downthrown to the northwest (to the Big Lagoon side). A topographic profile across the scrap shows that it is 1.8 ± 0.5 m high (Fig. 4).

Figure 3 The Vernon fault scarp at the entrance to Vernon Station. On the right is Redwood Pass Road. The red line shows the approximate location of the topographic profile (see Fig. 4). Also shown is the location of soil pit VF3 from which an OSL sample was collected and dated at 13,000 ± 1,200 years BP.

A soil pit was excavated on the downthrown surface of the offset fan (Fig. 3) and exposed gravels overlain by silt and silt-gravel coverbeds. The lowermost gravel unit is clast-supported gravel, with cobbles up to 15 cm diameter. This unit probably represents the main aggradational fan surface. The fan coverbed units above this are silt and matrix-supported gravel packages (see stratigraphic profile and photo in Appendix 1). The silt package immediately overlying the clast-supported gravel may be loess, although it does have fine gravels and coarse sand lenses, suggesting an alluvial origin is more likely. In either case this silt unit probably just post-dates the main aggradation phase of the fan. The silt was dated using the OSL technique and it yielded an age of 13,000 ± 1,200 years BP. Because the silt post-dates the main phase of fan aggradation the OSL age places a minimum constraint on the fan age, i.e. the fan is >13,000 ± 1,200 years BP. Accordingly, a **maximum vertical rate for the Vernon fault at the Vernon Station entrance** can be calculated based on the vertical scarp height of 1.8 ± 0.5 m and a minimum age for the displaced fan surface of 13 ± 1.2 ka = **0.14 ± 0.05 mm/yr**.

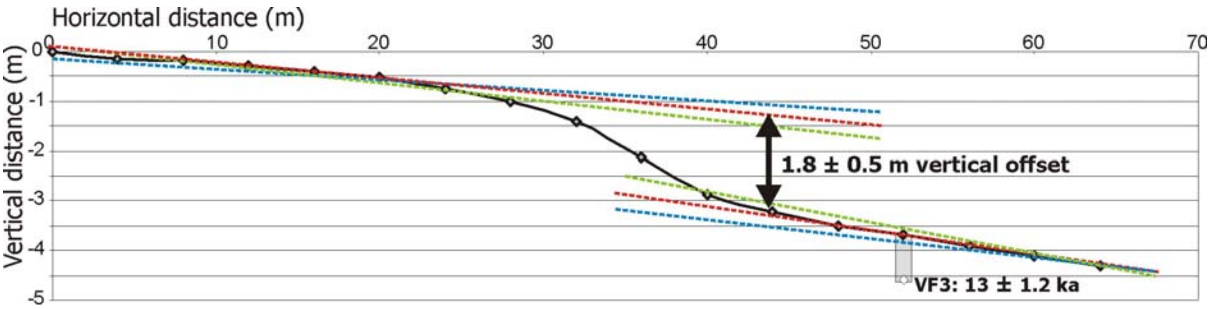


Figure 4 Topographic profile across the Vernon fault scarp at the entrance to Vernon Station. The scarp is approximately 20 m wide. The red line shows the preferred measurement of the vertical offset (1.8 m), the blue and green lines shows the minimum and maximum amounts of vertical offset that could be interpreted from the projections of the offset fan surface across the scarp. The different possible interpretations result in an uncertainty of ±0.5 m.

Approximately 150 m east of topographic profile shown in Fig. 4, the Vernon fault crosses Flaxey Gully (Fig. 2). Flaxey Gully is an ephemeral stream channel incised into the fan surface. It is significant because it is the only location at which a dextral slip rate for the Vernon fault has previously been calculated. Benson et al. (2001a) reported a 30 m dextral offset on Flaxey Gully, and using a fan age of 17,000 ± 2,000 years (based on correlation to dated fans in the Awatere Valley) they obtained a slip rate of <2 mm/yr. However, our own observations of Flaxey Gully were that a reliable dextral offset could not be ascertained and the offset measurement of 30 m was not repeatable. We observed that Flaxey Gully contains a meandering stream, so while there are sharp changes in stream direction they are typical of meander bends and not necessarily related to fault displacements. A clear fault scarp could not be observed across or on the sidewalls of Flaxey Gully. Therefore, at the Benson et al. (2001a) site we do not consider the 30 m reported right lateral offset in the course of Flaxey Gully as a robust and unambiguous dextral displacement for the Vernon fault. Furthermore, the OSL age of 13,000 ± 1,200 years BP obtained in this study is younger than the fan age assumed by Benson et al. (2001a). Therefore the previously calculated dextral slip rate of < 2 mm/yr is not considered reliable.

3.2 Balfour 1 Trench

3.2.1 Location and geomorphology

Balfour 1 trench was located across an uphill facing scarp near the Vernon Station homestead (Figs. 2, 5 and 6). The scarp presently impounds a farm pond but this has probably been artificially enlarged. We suspect that prior to artificial land disturbance a wetland or ephemeral swamp existed where drainage was impeded by the uphill-facing fault scarp. An unnamed ephemeral stream (here named Homestead Stream) approaches the fault scarp from the south. Before the stream reaches the fault it crosses a road and on the other side of the road all definition of the stream is lost. It is difficult to judge whether Homestead Stream has been artificially altered on the northern side of the road, or if it naturally turns into an alluvial fan, perhaps due to the rapid decrease in stream gradient as the scarp is approached. The stream is very well defined on the northern (upthrown) side of the fault where it is incised into the fan surface (yellow arrows, Fig. 5, and treeline in Fig. 6). On the northern side of the fault is a beheaded stream (blue arrows, Fig. 5); this probably matches with the small valley on the southern side of the fault by the homestead.

The area in which the Balfour 1 trench is located may be a small pull-apart basin at a fault step-over. In the NZ Active Faults Database (http://data.gns.cri.nz/af/) this section of the Vernon fault is mapped as having two fault strands either side of the pond, converging near the homestead and on the eastern side of the pond. However, it is not clear in aerial photographs or in the field that there are two fault traces here, and there has probably been significant disturbance by the road along the estimated position of the southern fault strand. Therefore, it is possible, but not proven, that there are two fault strands that bound the Balfour 1 trench site. We did not trench the possible southern fault strand as its location was too uncertain and it would have entailed blockage of the farm's main access road.

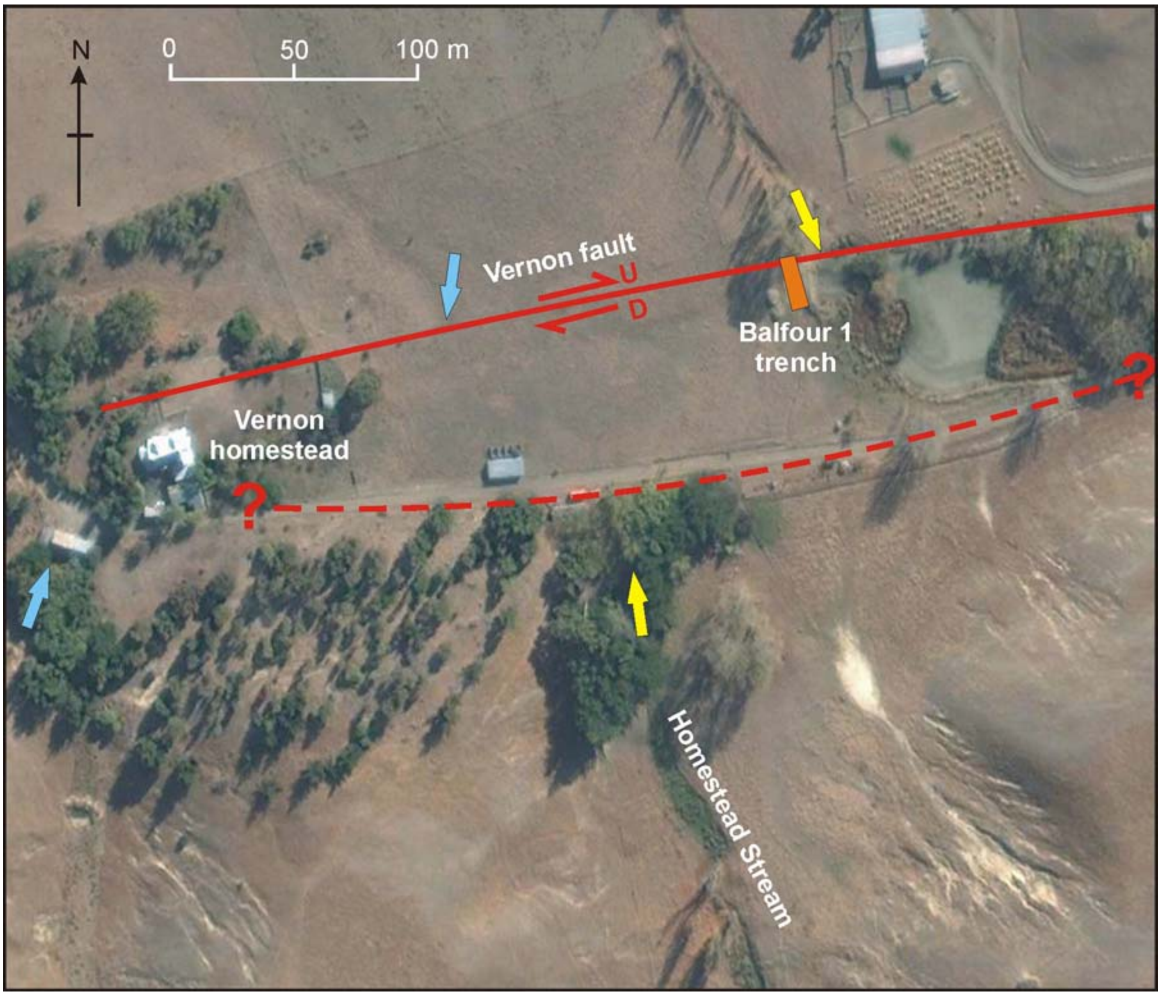


Figure 5 Satellite image of the Balfour 1 trench site. Solid red line shows the well-defined fault scarp, dashed red line shows where an inferred fault is shown in the NZ Active Faults Database. Yellow and blue arrows mark possible offset channels, both of these channels flow from south to north. Image from Google Earth (August, 2011).

Figure 6 Photo of the Balfour 1 trench site, the fault scarp is shown by the fenceline and Big Lagoon can be seen in the background. View looks to the north.

3.2.2 Trench description and evidence of paleoearthquakes

Sediments exposed within the Balfour 1 trench consist of gravels, silt (and loess), peat and sand (Fig. 7, Table 1). The gravels are typically poorly-sorted, subrounded-subangular greywacke pebbles to cobbles. There is a range in the degree of matrix- to clast-supported gravels, and the clast-supported gravels range from loose to densely packed. Some gravel units have very distinctive brown manganese-weathering rinds on the clasts. The silt units are orange-grey to brown, very stiff and usually have scattered gravel clasts. Unit 11 (Fig. 7) is probably a loess package; it is a massive silt with vertical veins of weathering throughout, and only occasional clasts < 1 cm in diameter. On the southern ends of both trench walls are peat units, these are typically dark brown to black, richly-organic silts and clays with scattered charcoal fragments and gravel clasts. The peat units have a nested channel form (Fig. 7). Also on the southern ends of both walls are small lenses of sandy silt and fine sand. Both trench walls expose a substantial thickness of artificial fill on the southern end of the trench. The artificial fill was probably spread across the trench site when the pond was enlarged to create water storage.

Three OSL ages and four radiocarbon ages were obtained from the Balfour 1 trench. The silt samples range from 31,000 to 9,000 years while the charcoal samples are all <730 cal. yrs BP (Table 2).

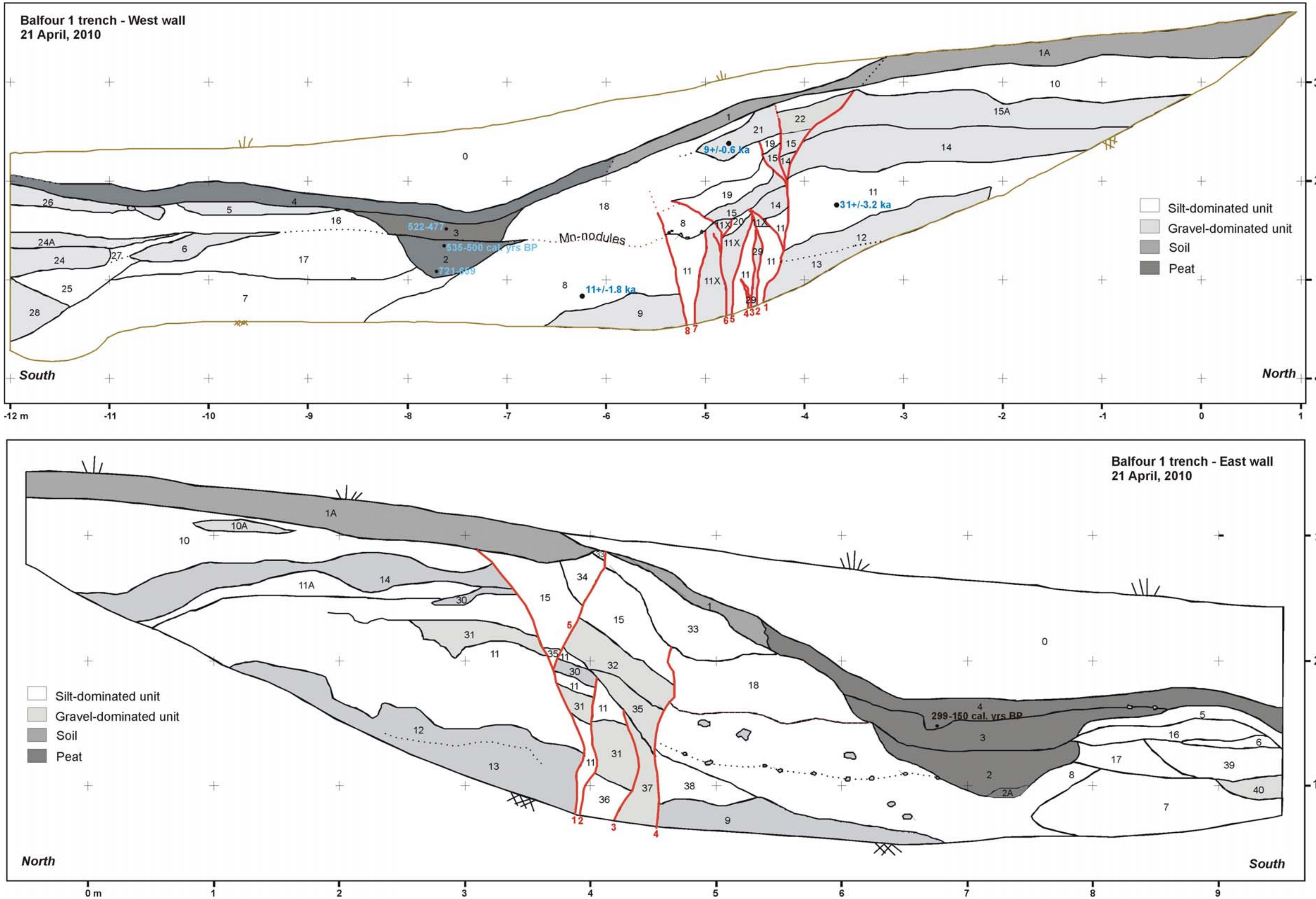


Figure 7 Trench logs of the Balfour 1 trench. All unit descriptions are in Table 2, Unit numbering does not follow stratigraphic order. Faults are numbered in bold red numerals, the fault numbering does not signify correlation between the two walls. Trench location: NZMG 5960096N/2600076E.

Table 1 Balfour 1 trench unit descriptions.

Unit #	Short description	Full description
0	Fill	Crudely stratified, basal 10-30 cm is mixed peat, silt, greywacke cobbles, dark brown-black organic-rich silt. Above it is 10-20 cm thick chaotic silt and cobbles, silt-matrix-supported, becomes richer in silt toward ground surface.
1A	Topsoil	Light grey-brown loose silt, scattered rounded pebble < 2 cm diameter.
1	Paleosol	Silty brown-grey paleosol
2	Peat	Dark grey-brown organic clay, mottled, scattered with rounded clasts to 3 cm diameter, and charcoal fragments. Radiocarbon ages of 721-659 cal. yrs BP (lower part) and 536-600 cal. yrs BP (upper part) obtained from this unit.
3	Peat	Massive medium brown organic clay, moderately stiff, very rare scattered pebbles, subrounded up to 2 cm diameter. Radiocarbon age of 522-477 cal. yrs BP obtained from this unit.
4	Peat	Dark brown-black, clayey organic silt with soil structure (nutty, crumbly). Very rare clasts, angular to 6 cm diameter. Radiocarbon age of 299-272, 216-150 cal. yrs BP obtained from this unit.
5	Gravel	Equivalent to 6 but with more weathered clasts
6	Gravel	Grey poorly sorted gravel, rounded to subrounded, closely packed, clasts 2 - 5 cm diameter, gritty silty matrix
7	Clayey silt	Medium grey-orange mottled silty clay, massive and stiff
8	Silt	Stiff, medium-grey silt, slightly clayey, some orange Fe-staining, sparse subangular pebbles within silt. Upper 30-40 cm is rich in Mn nodules (weathering zone). OSL date of 11,000 ±1,800 years BP obtained from this unit.
9	Clayey gravel	Medium-grey silty clay with frequent pebbles. Subrounded to rounded up to 8 cm diameter.
10	Silt	Light yellow-grey compact silt, frequent rounded to subangular clasts up to 8 cm diameter, average size 2 cm.
11	Silt / loess	Loess (?). Massive light orange-grey silt, vertically veined throughout, veins becoming more densely spaced toward fault zone, occasional subangular pebbles (< 1 cm diameter). OSL date of 31,000 ± 3,200 years BP obtained from this unit.
11X	Gravel	Very sheared compact, poorly sorted gravel. Mostly medium-grey with Mn and Fe staining. Clayey-silty matrix, average clast size 3 cm (mx 8 cm), subangular to angular, possibly equivalent to unit 14.
12 & 13	Gravel	Medium orange-grey, very compact, dominantly subangular gravel. Stiff silty matrix, abundant iron-staining and manganese. Strongly weathered. Poorly sorted, clasts 1 - 12 cm. Contained a fine sandy marker layer 4 cm thick.
14	Gravel	Very poorly sorted silty gravel, rounded to subangular clasts, 1 to 6 cm diameter. Contains occasional silty sand lenses, some crude horizontal bedding. Locally iron-stained.
15 & 15A	Gravel	(Source of unit 15) Moderately loose grey-brown gravel with fine sandy matrix, abundant tightly packed medium-fine pebbles, contains some subangular clasts up to 12 cm diameter (especially near base).
16	Silt	Medium brownish grey silt, iron-stained, pebbles to 3 cm diameter.
17	silt	Medium grey silt, orange mottled, occasional subrounded pebbles up to 1 cm diameter.
18	Massive silt	Massive light yellow-grey to light orange-grey silt, very stiff.
19	Silt	Very stiff light yellow-grey silt with many subangular to subrounded clasts 2-5 cm diameter. Some Mn staining.
20	Silt	Medium orange-grey silt, some fine sand and scattered subangular clasts up to 2 cm diameter.

Unit #	Short description	Full description
21	Silty gravel	Very compact, light yellow-grey silt with frequent pebbles. Subangular to subrounded 2-5 cm diameter, pebbles decrease towards south. OSL date of 9,000 ± 600 years BP obtained from this unit.
22	Silty gravel	Medium brown-grey silty gravel, Mn weathering, very compact angular to rounded clasts 1- 3 cm diameter.
23	Silt	Pale yellow stiff silt with scattered pebbles < 2 cm diameter.
24	Fine gravel with cobbles	Medium grey silty fine gravel, rounded to subrounded to angular clasts, mean size < 4 cm, max 10 cm. Well-sorted pebble layer at base (1cm size).
25	Sandy silt	Dark grey massive medium sandy silt, occasional rounded pebbles up to 3 cm diameter.
26	Gravel	Dark brown gravelly silty, clasts up to 6 cm diameter, rounded, matrix-supported, fresh to well-weathered clasts
27	Sand	Medium grey silty fine sand and medium sand, soft
28	Coarse gravel	Dark grey cobble gravel, silty grey-brown matrix, slightly organic, cobbles of mean size 10 cm.
29	Sheared silt	Sheared version of unit 11 silt. More weathered and contained scattered angular pebbles ~ 1 cm diameter.
Units only on the East wall		
10A	Fine gravel	Fine gravel, like unit 10 but more gravel
11A	Silt	Similar to 11 of west wall but absence of veining and Fe-staining.
2A	Organic silt	Same as unit 2 but more organic material
30	Fine gravel	Very compact silty pebbly gravel, pale yellow grey, mean clast size 1 cm diameter.
31	Fine gravel	Very stiff, tightly packed silty pebbly gravel, Fe-stained, moderate Mn development, subrounded to angular clasts, mean diameter 2 cm
32	Gravelly silt	Pale brown very gritty silt, scattered rounded to angular clasts, moderate Mn development.
33	Blocky silt	Pale grey-brown very stiff gritty silt, minor Mn nodules, scattered subrounded clasts to 3 cm diameter.
34	Pebbly gravel gravel	Pale brown pebbly gravel with loose silty crumbly matrix. Clasts subrounded to subangular, 1-5 cm diameter, similar texture to unit 15 but no Mn development.
34	Gravelly silt	Same as 11 but more clasts, subangular to subrounded, average 1 cm, mean 4 cm diameter, very sheared.
35	Silty gravel	Light brown grey very compact silty gravel, moderate Mn development, clasts rounded to subangular, clast size and cobbles increase near base up to 8 cm diameter, 4 cm at top.
36	Silt	Massive silt, very sheared, contains many angular pebbles.
37	Gravel	(fault slice) Medium grey very stiff clayey gravel, strong Mn development, angular to subrounded, 1 cm average clast size, 3 cm max.
38	Silt with gravel	Medium grey silt, slightly Fe-stained, scattered subangular clasts, many pebbles <1 cm, up to 6 cm diameter near base.
39	Fine grey sand	Medium grey silty fine sand, massive, coarsens upward, rare subangular clasts up to 3 cm diameter.
40	Gravel	Medium grey clayey silty cobbley gravel.

Table 2 Dated samples from the Balfour 1 trench.

Sample	***Method***	***Age , 2σ uncertainty (years BP)***
Balfour 1	OSL	31000 ± 3200
Balfour 4	OSL	9000 ± 600
Balfour 5	OSL	11000 ± 1800
Balfour B	C14	535-500
Balfour C	C14	721-696, 692-659
Balfour D	C14	522-486, 480-477
Balfour J	C14	299-272, 216-150

In the middle of the scarp there is a fault zone approximately 1.5 – 2 m wide consisting of ~ 8 bifurcating-upward faults. No units can be traced across the whole fault zone (except the overlying paleosol which is not cut by any faults), but some units can be traced across several fault blocks. The offset of units and the upward terminations of the faults yield information about the number and sequence of paleoearthquakes exposed in the trench. In this section we explain the evidence for each paleoearthquake:

- Event 1 (oldest):
  - West wall: Evidence for this event is from the upward terminations of faults 1 (left splay), 2, 3, 5, 6 (right splay), and 7. All of these fault strands terminate at an unconformity at the top of units 9, 20, 11X and 11, the fault terminations are overlain by units 15 and 8. This event probably also ruptured fault 8 and juxtaposed unit 11 against unit 8. Unit 8 must have existed at this time because it has acted as a buttress against which units 11 and 11X were faulted. The line of manganese-nodules at the top of unit 8 may correlate with a period of weathering that occurred at the same time the unconformity above units 9, 20, 11X and 11 developed. Unit 18 was probably deposited after Event 1. The timing of this event is constrained by OSL ages from units 8 and 21. Unit 8 pre-dates Event 1, and unit 21 was deposited sometime after Event 1. Therefore Event 1 occurred between 11,000 ± 1800 years BP (unit 8) and 9,000 ± 600 years (unit 21).
  - East wall: Evidence for this event is from the upward terminations of Faults 2, and 3 rupture. Fault 1 (left splay) also ruptured in this event. Units 11, 30, 31, 34 and 37 are downthrown across Faults 1 (left splay), 2 and 3. Unit 35 overlies the terminations of Faults 2 and 3 and therefore must post-date the fault rupture. There are no age constraints on this wall of the trench, but unit 11 is the same unit that was dated at 31,000 ± 3200 years BP on the west wall. Therefore this event is only constrained at < 31,000 ± 3200 years BP on this wall. This event may have triggered deposition of the stone-line within unit 8.

During the inter-event time an unconformity developed across both traces of faults 1 (1st left splay), 2, 3, 5, 6 (right splay), and 7on the West wall, and faults 2 and 3 on the East wall. Above the unconformity units 15 and 19 were deposited on the West wall. Unit 15 has similar characteristics to 15A gravel on the upthrown side of the fault, implying 15A was probably the source of unit 15. In this time period the manganese-nodules at the top of unit 8 probably developed on the West wall. Above the unconformity on the East wall units 32, 35 and 15 were deposited.

- Event 2:

  - West wall: Evidence for this event is from the upward terminations of Faults 1 (2^{nd} left splay), 6 and 8. Each of these faults terminates at an unconformity (Faults 1 and 6) or mid-way within a unit (Fault 8). The fault ruptures offset Units 8, 14, 15, and 19. Fault 8 ruptured to its full extent and offset the weathering horizon of manganese-nodules. Fault 1(2^{nd} left splay) ruptured up to the base of unit 21. Unit 21 is a wedge-shaped unit, thickest near the fault zone, and thinning out towards the south (away from the fault zone), it is comprised of silty gravel with the subangular-subrounded gravel clasts decreasing toward the south. Due to the geometry of Unit 21 we conclude it is a colluvial wedge that was shed from the fault scarp immediately following event 2. Event 2 must have occurred during deposition of unit 18 because the colluvial wedge interfingers with unit 18. The colluvial wedge (unit 21) has been dated at 9,000 ± 600 years BP. Assuming this dates the time of exposure of the wedge material and that it was covered up by continued deposition of unit 18 relatively quickly after the event, then the age of 9,000 ± 600 years BP is the best estimate for the timing of event 2.

  - East wall: The best evidence for this event is the upward termination of Fault 4 at the base of unit 33. The left and right splays of Fault 1 also ruptured in this event as evidenced by the offset of unit 15. Units 32, 35, 15 and 18 are offset by Faults 1 and 4, but unit 33 is unfaulted. Unit 33 has a wedge-shaped geometry and we propose it is a colluvial wedge, equivalent to unit 21 on the west wall. Unit 34 appears to be faulted by the right splay of Fault 1 but we propose it is a post-event unit that infilled the triangular-shaped depression created by rupture of the right splay of Fault 1. On the right splay of fault 1 the sense of movement is appears to be upthrown to the south, a contrast to the typical sense of downward-to-the-south. This anomaly could also be due to strike-slip faulting which juxtaposes different units from along fault strike against one another. The changes in the elevations and shapes of sedimentary units along the strike of the fault can create apparent changes in fault throw when they are bought together by fault rupture. There are no age constraints on the age of event 2 from the east wall.

- Event 3 (youngest):

  - West wall: The evidence for this event (the youngest in the trench) comes from Fault 1 (middle splay) which must have ruptured in order to cut unit 21 (the colluvial wedge deposited after the previous event). The only age constraint on event 3 is that it must be <9,000 ± 600 years BP because it cuts colluvial wedge 21. The right splay of fault 1 may have also ruptured in this event. It was not possible to distinguish if the right splay of fault 1 ruptured all the way to the base of the topsoil, if it did then this splay probably did rupture in event 3. If not then this splay may have ruptured in event 1 and unit 10 was deposited in the interseismic period between events 2 and 3.

  - East wall: In this event the right splay of Fault 1 must have ruptured in order to offset the lower contact of unit 33. Unit 33 is the colluvial wedge deposited immediately after event 2, so the rupture of its lower contact must have occurred in a subsequent event. The sense of dip-slip movement on this fault in Event 3 is downthrown to the south, in contrast to the previous event, this apparent throw reversal is likely due to the strike-slip nature of the fault offset. No age constraints on this event are available from the east wall. It is possible that the left splay of fault 1 also ruptured in this event, the fault goes right up to the base of the topsoil so it is likely that it did rupture in the most recent event.

In addition to the three events described above there is evidence of at least one older event. At the base of the fault zone on the West wall the silt and gravel units (units 11 and 11X) have been pervasively sheared, the degree of deformation is much greater than that of overlying silt and gravel units. The highly-sheared basal units have probably been through more than three earthquakes. Abutted against the base of the fault zone on both trench walls are clay and silt-rich gravel units (units 38 and 9) which may have a wedge-like geometry judging from the exposed upper contacts. The lower wedges may relate to earthquakes older than event 1.

Units to the south of the fault zone are dominated by peats, gravels, silts and fine sand. The relationship of these units to the fault zone is not well understood because there are no units that correlate directly across to the fault zone (Fig. 7). Radiocarbon dates on charcoal fragments from the peat units show the peats are all <730 cal. yrs BP. Initially it was thought that peat unit 2 on the West wall interfingered with units 8 and 18. However, the age of 721-659 cal. yrs BP from the peat layer conflicts with the OSL ages of 11,000 – 9,000 years from units 8 and 18, so they cannot have been deposited in similar time periods. The appearance of peat unit 2 interfingering between units 8 and 18 on the West wall is probably due to weathering that occurred while unit 2 was forming in a wetland environment.

The channelized and lens-like shape of the sand and gravel units at the southern end of the Balfour 1 trench indicate they were probably deposited in a fluvial environment (Fig. 7). We suggest they were deposited by Homestead Stream, their overlapping and interfingering geometry are consistent with deposition on an alluvial fan. The peat units were probably the last units to have formed. The peats occupy the lowest point in the trench (if the anthropogenic fill is backstripped) and they represent a wetland environment ponded up against the uphill-facing scarp. The peat units do not appear to have erosional basal contacts, they may have developed in-situ as the organic material in the wetland gradually weathered the silt units below.

3.2.3 Vernon fault recurrence interval and slip rate at the Vernon homestead site

An OSL sample from unit 11 on the upthrown (northern) side of the fault zone yielded an age of 31,000 ± 3,200 years BP. The characteristics of unit 11 (massive silt, vertical veins, mantling paleotopography) suggest it is a loess package. The loess was probably deposited after the period of aggradation that formed the fan surface; therefore, the minimum age of the surface is 31,000 ± 3,200 years BP. The dating results suggest the Balfour 1 trench surface is older than the dated fan surface at the entrance to Vernon Station.

The Balfour 1 trench surface has certainly been through 3 events but more likely 4+ events. If we conservatively estimate 4 events this yields a maximum recurrence interval of ≤8,000 years. Just taking the last three events which all occurred within the past 11,000 ± 1800 years yields a recurrence interval of ~3700 ± 600 years. The difference in recurrence interval estimates may be due to variation in fault behaviour over time (e.g. perhaps the last 11,000 years captured a cluster of earthquakes), but it is more likely that 4 events over 31,000 years is an underestimate.

The age of the surface at the Vernon homestead site can be used to estimate the vertical slip rate of the fault. A topographic survey of the trench area shows that the fault scarp at the trench site is ~1.2 m high (Fig. 8). The scarp height decreases to the west as it approaches the apex of an alluvial fan which abuts the scarp. Clearly the alluvial fan has been infilling the depression created by the fault scarp, and the trench shows that there is a varying thickness of artificial fill above the natural ground surface. Therefore the scarp height of 1.2 m is a minimum. If the age of the surface is estimated at 31,000 years, and it has a minimum vertical offset of 1.2m, this yields a vertical throw rate of ≥0.04 mm/yr.

A dextral slip rate for the Vernon fault can be estimated but it has large uncertainties due to poor definition of the Homestead Stream on the southern side of the fault (Fig. 8). The dextral offset between a straight-line projection of the stream on the southern side to the fault, to the piercing point of the stream on the northern side of the fault is ~ 122 m (Fig. 8). Assuming a surface age of 31,000 years and an offset of 122 m yields a dextral slip rate of 3.9 mm/yr. However, Homestead Stream may not have followed a straight line course to the fault; it could have occupied any position on the alluvial fan (shown by the white shaded area on Fig. 8, the fan probably also sweeps to the left but this area was not surveyed). Comparison to modern alluvial fans along the edge of Big Lagoon shows that the streams can occupy any position from the middle to the side of the fan. The estimated offset of ~122 m presented here is based on the stream occupying the apex of the fan and running straight to the fault scarp. Therefore, the estimated slip rate of 3.9 mm/yr has a high, and difficult to quantify, degree of uncertainty.

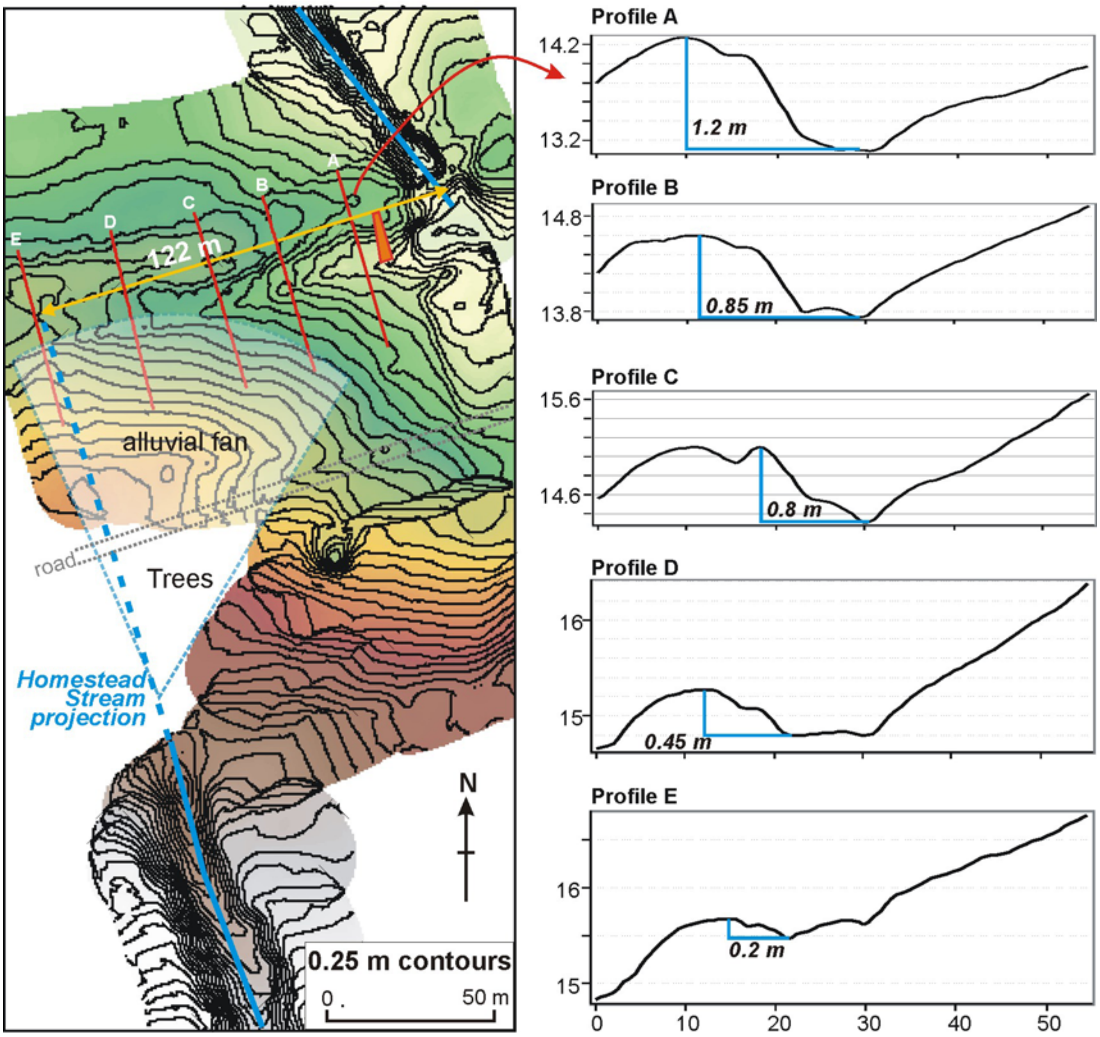


Figure 8 Topographic map of the Balfour 1 trench area (trench = orange rectangle). Survey undertaken using an RTK GPS. The estimated offset of the Homestead Stream is shown (yellow arrow) along with the shape of the alluvial fan (white shading). The stream could have occupied any position on the fan therefore the estimated offset has a high degree of uncertainty. Profiles on the right show the scarp topography, the scarp decreases in height as it gets closer to the apex of the infilling younger alluvial fan.

3.3 Balfour 2 Trench

3.3.1 Location and geomorphology

Nearer the coast the Vernon fault traverses a series of active alluvial fans and there is some uncertainty as to the precise location of the fault. The fault is mapped in the NZ Active Faults Database as running along the mid-point between the steep hills and the lagoon edge, but there are no distinct fault scarps along this mapped location (red line, Fig. 9A, B). This could be because the fault is continually being covered up by alluvial fan aggradation. Alternatively, the sharp break in slope between the hillsides and the alluvial fans could mark the fault trace, although there are also no distinct dextral stream offsets at this point (blue arrows, Fig. 9A, B). Another possibility is that the fault runs along the edge of the lagoon (yellow arrows, Fig. 9A, B). The lagoon edge is remarkably straight for approximately 1 km and there is a small step between sloping grassed fans and the saltmarsh. This was considered the most prospective feature to be an active fault scarp.

The Balfour 2 trench was located on the suspected fault scarp adjacent to Big Lagoon, 1.2 km from the coastline (Fig. 9). We found a location where the scarp crossed a paddock in between two alluvial fans. It was not feasible to trench where the suspected scarp was directly next to the salt marsh because the salt marsh has conservation reserve status. The north-facing topographic scarp at the trench location is 2 m high (Fig. 9C). The length of the trench was 23 m, although only the middle 16 m was logged.

3.3.2 Trench description and evidence of paleoearthquakes

The Balfour 2 trench is dominated by gravel packages that slope gently northwards toward the lagoon edge (Fig. 10). The gravels are generally well-rounded, moderately well-sorted, and of a pebble to cobble size. The well-rounded nature of the gravel clasts is because they have been recycled from the Miocene-late Pliocene conglomerate which forms the bedrock of the hills south of Big Lagoon. Some crude bedding is seen within some of the gravel units, but most of the gravel units display no internal sedimentary structure. In the middle of the trench is an unconformity that traverses between all the gravel units.

There is no evidence of faulting in the Balfour 2 trench. The topographic scarp is probably due to erosion associated with stream channel migration on the alluvial fans. An illustration of the probably paleogeography and stratigraphic development is shown in Fig. 11. The fan gravels on the south side of the trench initially sloped all the way to the lagoon edge. At some point the stream originating at a valley 500 m west of the trench switched position and scoured out the gravel packages at the northern end of the Balfour 2 trench. Erosion created the major unconformity seen in the middle of the trench. Subsequent alluvial fan aggradation infilled the depression (Fig. 11). It was initially suspected that coastal erosion during a time period when Big Lagoon had a greater tidal influence (Hayward et al., 2010) could have created the scarp. However, the gravels on the northern side of the trench have no shells or other indicators of a marine origin. Therefore fluvial erosion, rather than coastal erosion, most likely created the scarp at the location of the trench. Due to the absence of faulting, no samples were dated from the Balfour 2 trench (nor was there any suitable material for dating).

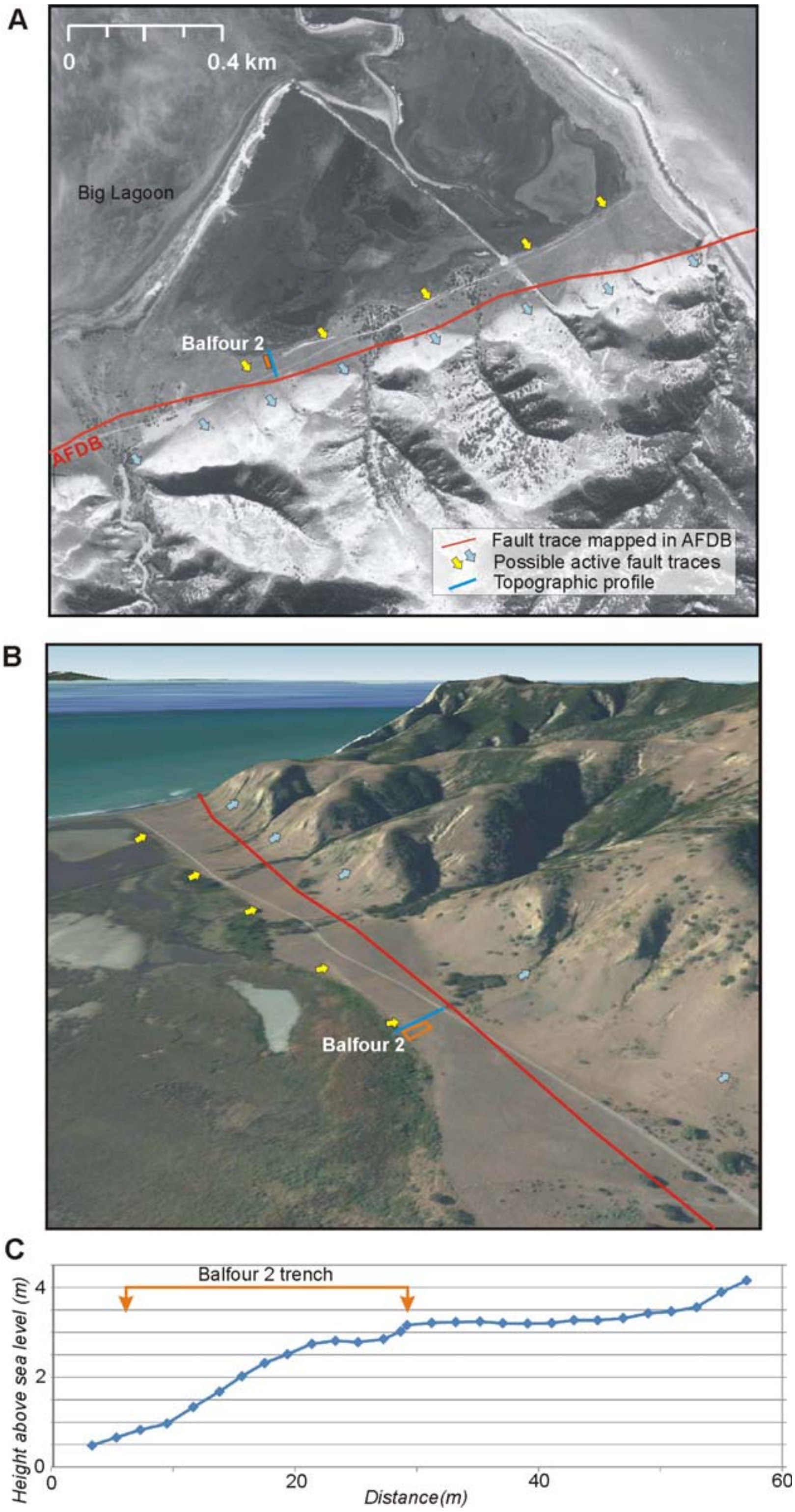
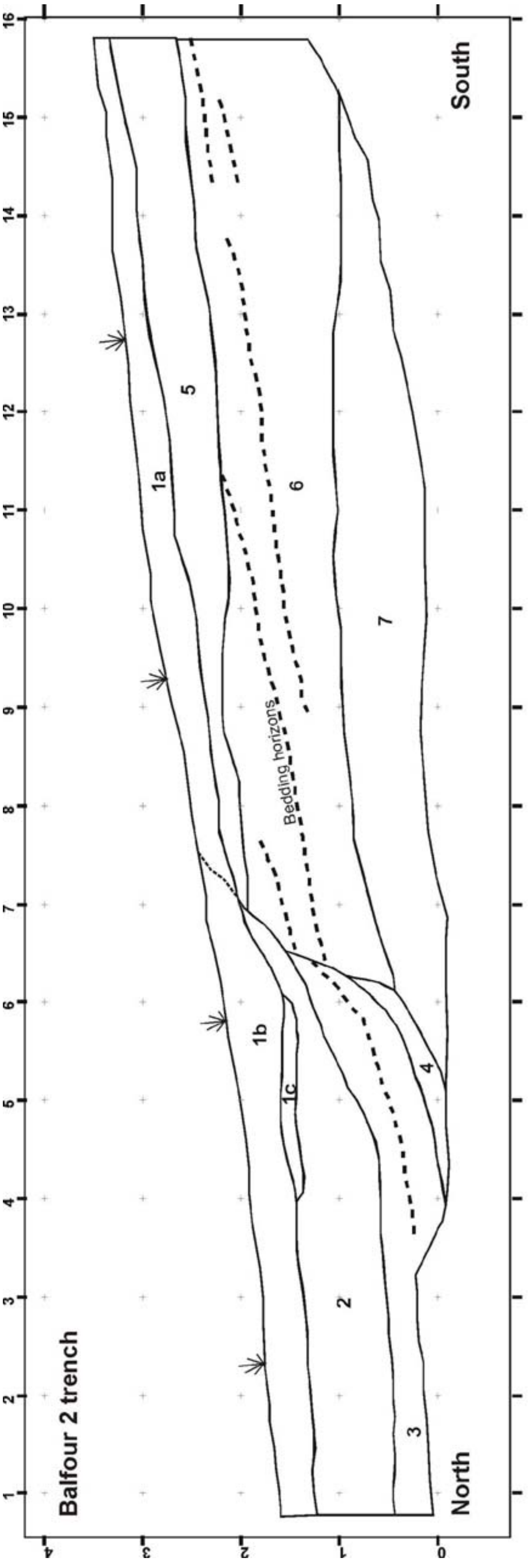


Figure 9 A: Aerial photo showing the location of the Balfour 2 trench and the possible locations of the Vernon fault. AFBB: NZ Active Faults Database (http://data.gns.cri.nz/af/). B: Oblique 3D satellite image of the Balfour 2 location showing the possible locations of the Vernon fault, this image better illustrates the sharp break in slope between the hillslopes and the alluvial fans. Image source: Google Earth, August 2011. C. A topographic profile across the scarp at the Balfour 2 trench site.

The Balfour 2 trench demonstrates that the remarkably straight lagoon edge within 1 km of the coastline is not fault controlled. This leaves four possible scenarios for the location of the Vernon fault:

- the fault is near the Balfour 2 trench site but the high rates of fan aggradation and fluvial erosion have obscured any evidence of the fault,
- the fault lies further back towards the hills but is covered by recent fan aggradation,
- the Vernon fault surface ruptures have widely distributed surface displacement and no distinct scarp is produced. For example, the Greendale fault rupture of Sept. 4, 2010, saw average fault displacement of 2.5 m distributed across a zone up to 30 to 300 m wide (Quigley et al., in press).
- the Vernon fault is purely strike-slip and no distinctive vertical offset is produced in surface rupturing earthquakes (in which case, you would still expect to see the fault in a trench). This scenario is unlikely because the undulating topography across fans means that at some locations one would expect to see a scarp where surfaces of different heights were juxtaposed.

With the data available at this time, it is not possible to conclude which of the first three scenarios is most likely.



Balfour 2 Unit descriptions	
East Wall	
1a	Strong brown silty gravel, well-rounded clasts, predominantly pebbles, some cobble > 10 cm, loose, moderately sorted.
1b	Green-black, loose, silty pebble-cobble gravel, < 10 cm, majority pebbles, moderately sorted.
1c	Black gravelly silt, pebble-sized, mostly well-rounded, some subangular.
2	Light brown to light grey, slightly compact, moderately well-sorted, pebble gravel with some pockets of cobbles, massive to crudely decimetre-bedding, well-rounded, sparse subangular clasts.
3	Light brown compact, sandy, moderately sorted pebble gravel, rare cobbles, well-rounded clasts, rare subangular clasts.
4	Grey, slightly compact, sandy pebble-cobble gravel, well-rounded with rare subangular clasts, moderately-poorly sorted.
5	Light brown, loose to slightly compact, pebble to cobble gravel with some sand, massive, moderately sorted, well-rounded to subrounded.
6	Grey to light reddish brown, sandy pebble to cobble gravel, moderately bedded, well-rounded with some subangular clasts, slightly compact to compact.
7	Grey, sandy, cobble gravel with some pebbles, well-rounded to subrounded, sightly compact, massive, clasts <20 cm, typically ~10 cm.

Figure 10 Stratigraphic log of the Balfour 2 trench. Trench located at NZMG 2603601E/5960925N. The table below describes the units.

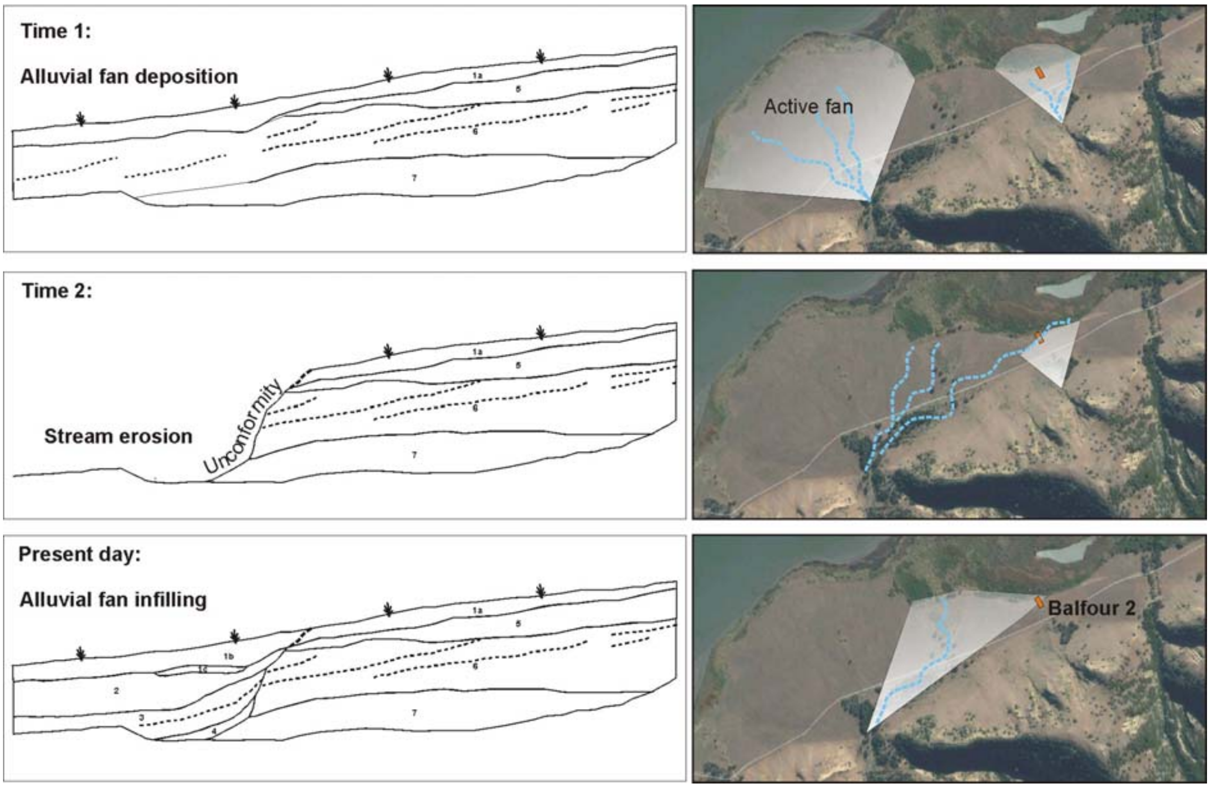


Figure 11 Illustration of the paleogeography and stratigraphic development of the Balfour 2 trench. No age constraints are available to inform on the timing of these events.

4.0 DISCUSSION

4.1 Contribution of the Vernon fault to subsidence of Big Lagoon

Cores of intertidal sediments from the margins of Big Lagoon show Holocene subsidence at rates varying from 0.2 to 0.8 mm/yr (Fig. 12). Eustatic sea level change and other non-tectonic causes have been ruled out, so the driver of subsidence must be permanent tectonic deformation (Clark et al., 2011). Possible causes of the tectonic subsidence are (1) subsidence of the northern block of the Vernon fault, (2) subduction earthquakes on the southern Hikurangi plate interface, or (3) a combination of the two sources along with other faults in the Marlborough/Cook Strait area.

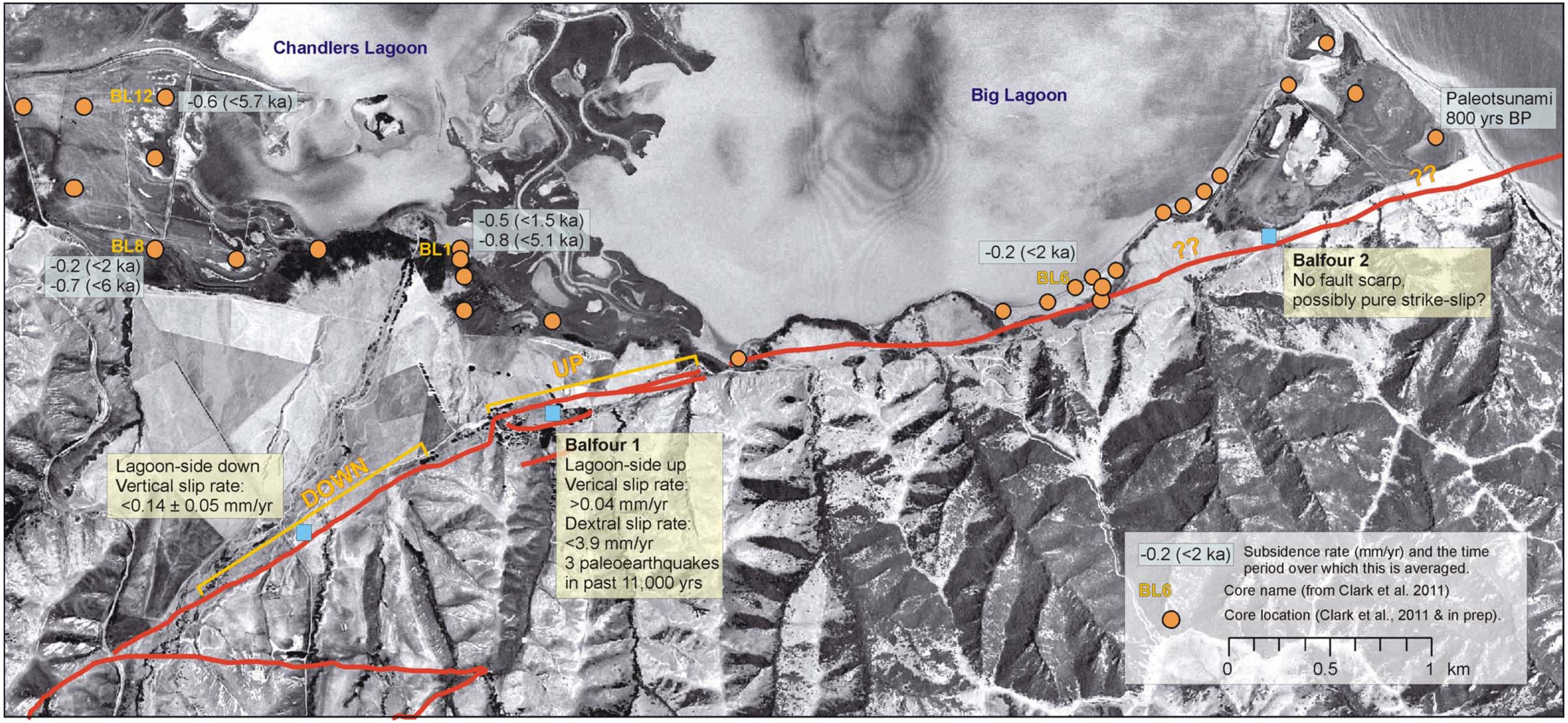


Figure 12 Summary of the slip rates and paleoseismology of the section of the Vernon fault adjacent to Big Lagoon. Also shown are the Big Lagoon Holocene subsidence rates (after Clark et al., 2011).

Determining the type of fault and sense of throw on the Vernon fault is crucial for assessing its impact on Big Lagoon. In order for the Vernon fault to be the main contributor to Big Lagoon subsidence it would have to be a predominantly normal fault dipping to the north-northwest (Fig. 13). Typically when normal faults rupture most of the absolute movement is downthrow of the hanging wall (Jackson et al., 1988; McAlpin, 2009). Therefore if the Vernon fault were a normal fault then rupture would see subsidence of Big Lagoon (Fig. 13). Reverse faults tend to produce absolute uplift of the hanging wall; therefore this is not a viable scenario for causing subsidence of Big Lagoon (although some subsidence can be caused by tectonic loading). Strike-slip faults produce mostly horizontal motions, but there can be subordinate uplift and subsidence at fault bends and stepovers, or some relative vertical motion if there are transpressional or transtensional stresses.

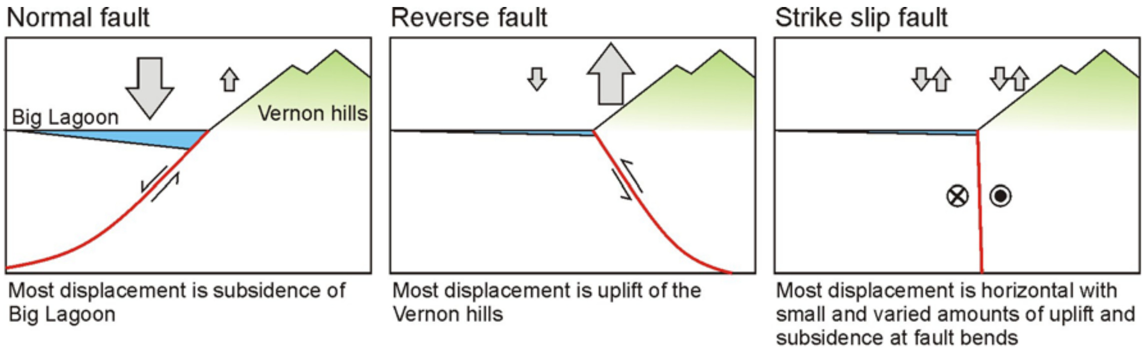


Figure 13 Simple faulting scenarios of the Vernon fault along the Big Lagoon segment. Each scenario illustrates the dominant absolute movements associated with each type of fault: normal fault, reverse fault, strike-slip fault.

The geomorphology and the fault exposures in the Balfour 1 trench demonstrate that the Vernon fault is not a pure normal or reverse fault. The evidence consistently suggests the Vernon fault is dominantly strike-slip. This is demonstrated by the ~122 m dextral offset of the Homestead Stream, and the contrast between the dextral slip rate of ≤3.9 mm/yr and the dip-slip rate of ≥0.04 mm/yr. The Balfour 1 fault exposures also commonly show juxtaposition of dissimilar stratigraphic units indicating the fault mainly translates material laterally into the trench section, rather than dip-slip faulting which translates material within the plane of the trench exposure.

The changing character of relative vertical movement across the Vernon fault over short wavelengths (hundreds of metres) is also characteristic of strike-slip faulting (Fig. 12). At the Vernon Station entrance the northwest side of the fault is downthrown, <1 km along strike at the Vernon homestead the northern block is upthrown, then < 1 km further to the east no scarp can be detected (although this may be due to young fan material burying the scarp rather than a change in fault style). The variation in throw-direction along strike is probably related to bending of the Vernon fault as it undergoes a ~60° change in strike. From the coastline to Vernon homestead the fault is relatively straight with a strike of 075°, near Vernon homestead it starts to bend southward and a further 5 km along strike it has an orientation of 015° (Figs. 1 and 2). Strike-slip faults typically develop transtensional (pull-apart basins) or transpressional (push-up ridges) features to accommodate fault bends or stepovers (e.g. Cowgill et al., 2004; Cunningham and Mann, 2007). The variation in the sense of dip-slip movement on the Vernon fault as the fault starts to change orientation is consistent with strike-slip faulting.

The postulated dominantly strike-slip character of the Vernon fault is consistent with the regional tectonic environment. The relative plate motion between the Pacific and Australian plates in the Cook Strait area is parallel with the strike of the Vernon fault where it is adjacent to Big Lagoon (~075°). Nearby faults such as the Awatere Fault and the Wairau Fault, with similar northeast to east-northeast strikes, are also predominantly strike-slip (Benson et al., 2001b; Mason et al., 2006a; Zachariasen et al., 2006).

One anomalous aspect of the predominantly strike-slip character of the Vernon fault is that the range of hills to the south of the fault implies long-term uplift. These hills may have been uplifted in an earlier phase when the Vernon fault was oriented more obliquely to the plate convergence vector. Tectonic block rotations inferred from paleomagnetic data suggest most of the Marlborough fault system structures were thrusts in the early Miocene but gradual tectonic rotation saw them evolve to dominantly dextral strike-slip faults by the Plio-Pleistocene (Randall et al., 2011). Therefore the hills bounded to the north by the Vernon fault and to the south by the Awatere fault may be a remnant of an earlier phase of more oblique thrust faulting, rather than the current phase of dominantly strike-slip faulting.

In terms of Big Lagoon subsidence, the current strike-slip character of the Vernon fault, particularly in the segment adjacent to Big Lagoon, means it is unlikely to be the main driver of Big Lagoon subsidence. The comparison between the subsidence rates in Big Lagoon and the dip-slip rates of the Vernon fault show a large difference. At the southwestern corner of Big Lagoon subsidence rates are typically 0.55 mm/yr. The maximum dip-slip rate on the fault at the Vernon station entrance is 0.14 ± 0.05 mm/yr. If all the dip-slip motion on the Vernon fault was accommodated by absolute subsidence of the northern block of the fault it would still only account for ~26% of the observed subsidence in Big Lagoon. The value of 0.14 mm/yr may be a maximum subsidence rate because the fault is dextral-reverse at the Vernon Station entrance site and the dip-slip component is potentially accommodated by absolute uplift of the southern block, rather than downthrow of the north block. At the Vernon Homestead site the dip-slip component of >0.04 mm/yr is probably accommodated by downthrow of the southern block, so again, the Big Lagoon side of the fault may experience negligible, to no, absolute motion during Vernon fault rupture.

Given the conclusion that the Vernon fault contributes only a small portion (at the most 25%) of Big Lagoon subsidence this means other faults must be responsible for Big Lagoon subsidence. The options are the southern Hikurangi plate interface, or a combination of the interface plus regional fault sources. Regional faults include the Wairau, Awatere, Cloudy and Wairarapa faults (Fig. 1). The Wairau Fault is an unlikely cause of Big Lagoon subsidence because it is dominantly strike-slip and does not show a distinctive scarp across the lower Wairau Valley. The Awatere fault is also unlikely because it is dominantly strike slip and the AD 1848 earthquake did not cause subsidence of Big Lagoon. There were reports from the lower Wairau Valley of features consistent with liquefaction (i.e. sandblows and localised areas of subsidence) following the 1848 earthquake but not widespread subsidence (Grapes and Downes, 1997).

The effect of Cloudy fault rupture on Big Lagoon is not yet understood. The Cloudy fault is entirely offshore, it has a 23 km-long curved trace that possibly connects at its western end with the offshore Vernon fault. The southern block of the Cloudy fault is downthrown and it has a dip-slip rate of 1.5 mm/yr (Pondard and Barnes, 2010). Vertical displacements of 1–6.4 m per event have been estimated from boomer seismic profiles. The interaction between the Cloudy fault and the Vernon fault is the subject of a study currently in progress

(T. Bartholomew, MSc thesis) and this should inform on how the Cloudy fault might affect Big Lagoon subsidence.

The Wairarapa fault is considered a potential driver of Big Lagoon subsidence because the 1855 M_W>8.1 Wairarapa earthquake caused subsidence at Big Lagoon (Grapes and Downes, 1997). There are historical accounts of the subsidence (Grapes and Downes, 1997) and stratigraphic evidence of subsided soils have been found within Big Lagoon (Clark et al., 2011; Hayward et al., 2010). It is debateable whether the subsidence was tectonic in nature or simply due to liquefaction and sediment settlement (Grapes and Downes, 1997). Hayward et al. (2010) documented an area of ~50 m x 50 m where buried peat was found and they concluded this localisation was consistent with patchy liquefaction-driven subsidence. Clark et al. (2011) found evidence of <0.15 m and <0.1 m of subsidence possibly related to 1855, and also concluded this was more consistent with sediment settlement than tectonic subsidence. Beavan and Darby (2005) modelled upper plate deformation associated with the 1855 earthquake and found that subsidence in the lower Wairau Valley could only have been produced if the deep part of the subduction interface also slipped during the event. Therefore either Big Lagoon subsidence in 1855 was due to sediment compaction, hence non-tectonic, or it was driven by plate interface slip, rather than the Wairarapa fault.

Evaluation of nearby fault sources suggests that no upper plate fault on its own could be entirely responsible for Big Lagoon subsidence. Contributions from several faults along with a major contribution from the subduction interface, seems to be the most likely scenario to explain Big Lagoon subsidence.

4.2 Dextral slip rate of the Vernon fault

The dextral slip rate of the Vernon fault has not been well-established previously. In a study that focused on the Awatere fault, Benson et al. (2001a) included some preliminary observations of the Vernon fault. From an estimated 30 m offset of Flaxey Gully they calculated a slip rate of < 2 mm/yr. Our observations found that a measurement of 30 m was not repeatable, and the fan surface may be younger than that estimated by Benson et al. (2001a). More recently a slip rate of 4.5 mm/yr has been inferred by Barnes et al. (2008), Robinson et al. (2011) and Wallace et al. (in press). This slip rate for the Vernon is based largely upon a change in slip rate of the Awatere fault. The slip rate of the Awatere fault is ~6 mm/yr west of the Vernon fault splay, and east of the splay it is ~1.5 mm/yr, although this latter slip rate is relatively poorly constrained (Little et al., 1998). Therefore it was assumed that the deficit of 4.5 mm/yr is transferred onto the Vernon fault.

This study has not focussed on obtaining a slip rate, but at the Balfour 1 trench site an estimated slip rate of ≤3.9 mm/yr has been obtained. This dextral slip rate has a high degree of uncertainty because the piercing point of the offset stream is not well-defined on the southern side of the fault (Fig. 8). Nevertheless, the slip rate of ≤3.9 mm/yr is relatively consistent with the model-driven slip rate of 4.5 mm/yr (Pondard and Barnes, 2010; Robinson et al., 2011; Wallace et al., in press). The small difference between the two slip rate estimates may be because not all of the presumed 4.5 mm/yr from the Awatere fault is transferred directly onto the Vernon fault. Some slip is probably transferred to other splays of the Vernon fault (Fig. 2), or as Little et al. (1998) suggested, some slip may get transferred to the Hog Swamp fault, south of the Awatere fault (Fig. 1). Further study of the Vernon fault slip rate is being pursued by Bartholomew (MSc thesis, in prep).

4.3 Paleoseismology of the Vernon fault

From the Balfour 1 trench, at least three paleo-earthquakes on the Vernon fault over the past ~11,000 years have been identified. Event 1 occurred between 11,000 – 9,000 years BP, event 2 at ~9,000 years BP, and event 3 at < 9,000 years BP. This is the first onshore paleoseismic data from the Vernon fault and it has some similarities and some differences to the offshore record of Vernon fault paleoearthquakes obtained by Pondard and Barnes (2010, Fig. 14).

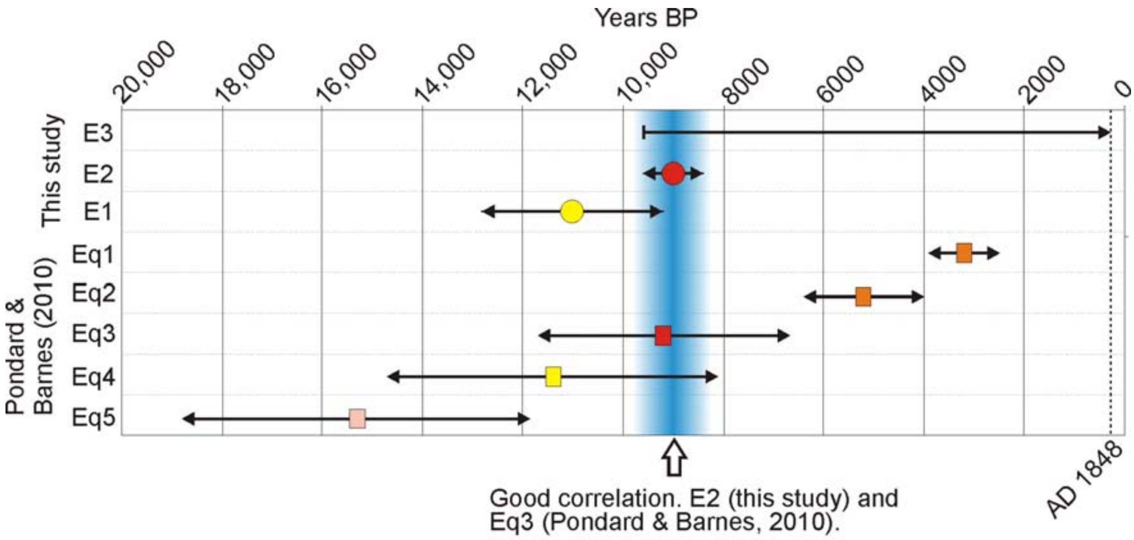


Figure 14 Comparison between the timing of onshore (this study) and offshore (Pondard and Barnes, 2010) paleoearthquakes on the Vernon fault.

The main point of similarity between the two records is in the timing of paleoearthquakes at ~9,000 years BP and ~11,000 years (Fig, 14). In this study the timing of event 2 was estimated at 9,000 ± 600 years BP by dating a coseismic colluvial wedge. Pondard and Barnes (2010) have an estimate for the timing of Eq3 of 9,200 ± 2,500 years BP. The Pondard and Barnes (2010) study uses high-resolution seismic profiles to measure displacements within fault growth sequences. The timing of the displacements is calculated by assuming a uniform sedimentation rate since the time of post-glacial transgression (see Barnes and Pondard, 2010, for further methodology details). Event 1 of this study at 11,000 ± 1,800 to 9,000 ± 600 potentially correlates to offshore Eq4 dated at 11,400 ± 2,500 years BP (although Eq4 also could correlate to onshore event 1, Fig. 14). The interpretation of Eq4 is tentative because it has a small vertical displacement of 0.4 m, which is at the maximum resolution of the seismic data (Barnes and Pondard, 2010), but onshore results support the existence of this event. Onshore event 1 is unlikely to correlate with the next oldest offshore earthquake, Eq5 at 15,300 ± 3,500 years BP, although the age ranges of the events do marginally overlap at 12,000 – 13,000 years. It is more likely that Eq4 correlates to event 1.

The main dissimilarity between the onshore and offshore records is in the number of paleoearthquakes since ~9,000 years BP. Onshore trenching data suggests just one event, which is only constrained at <9,000 ± 600 years, while the offshore data shows two earthquakes at 3,200 ± 700 years BP and 5,200 ±1,200 years BP. There are several possible scenarios to explain this difference: (1) an event <9,000 years is missing from the onshore trench record, (2) there is an over-estimation of the number of events recorded offshore, or (3) the offshore part of the Vernon fault ruptured, but the onshore section did not.

The onshore trench data does not support more than one event after the deposition of the colluvial wedge. The only possible location for an extra event is if the middle or right splays of fault 1 (west wall) re-ruptured. Rupturing the existing fault planes cannot be eliminated. There is a possibility that a fault rupture occurred onshore but was not recorded at the Balfour 1 trench because another strand of the Vernon fault ruptured. For example, rupture could have occurred on the possible fault that lies to the south of the Balfour 1 trench, along the road, forming a pull-apart graben (see Section 3.2.1, Fig. 5). An analog situation is seen along the Wairarapa fault, where Little et al. (2009) trenched a pull-apart graben on a strike-slip fault. Two trenches were excavated on both strands that define the graben (four trenches in total). In four out of five cases both sides of the graben ruptured in each specific event, but there was one event that appeared to have ruptured only one side of the graben. Therefore, if another fault strand exists south of the Balfour 1 trench site this might have ruptured in an events which didn't rupture at the trench site, hence our calculation of one post-9,000 yr earthquake may be an underestimate.

In the offshore seismic data the evidence for two events post-9,000 years is convincing: both events are recorded in two seismic lines and have several metres of displacement (1.1 – 3.5 m). Therefore it is unlikely that the offshore data overestimates the number of post-9,000 year earthquakes.

The remaining explanation for the difference in event chronology post-9,000 years BP is that the offshore section of the Vernon fault had a surface-rupturing earthquake, which did not cause surface rupture onshore at the Balfour 1 trench site. The Balfour 1 trench site and the nearest seismic line studied by Pondard and Barnes (2010) are 22 km apart (Fig. 1), a sufficient distance that it is not surprising a surface rupture should be present at one site but not another. Further work by Bartholomew (MSc thesis, in prep) will trace the paleoearthquake displacements landward along the Vernon fault from the seismic lines of Pondard and Barnes (2010). This work may resolve whether one of the offshore paleoearthquakes diminishes in expression landwards. A further possibility is that one of the paleoearthquakes recorded on the offshore Vernon fault ruptured the Awatere fault along strike, rather than the Vernon fault. The location of the seismic lines studied by Pondard and Barnes (2010) are east of the area where the Awatere fault comes close to the Vernon fault, in fact the two faults may merge at depth. The rupture recorded east of this junction could have propagated westward onto the Awatere fault, rather than the Vernon fault. Paleoearthquakes on the eastern Awatere fault have been identified at 3000-3300, 4000-4600 and 5910-6180 years BP (Benson et al., 2001b; Mason et al., 2006b), any one of these could correlate to the offshore events, Eq1 or Eq2, on the Vernon fault.

4.3.1 Paleoseismology and slip rate relationships of the Vernon fault

A recurrence interval of 3700 ± 600 years for earthquakes over the past 11,000 years has been calculated from the Balfour 1 trench and a maximum slip rate of 3.9 mm/yr was calculated from the offset of the Homstead Stream (Section 3.2.5). If the recurrence interval is correct, and if the maximum slip rate is actually the true rate, then it implies that each earthquake would produce a very high amount of slip at ~14 m (3.7 ka x 3.9 m/ka = 14.4 m). This amount of slip-per-event appears to be anomalously high, particularly given the relatively short mapped length of the fault (~40 km).

Comparisons with the fault scaling relationships of Wells and Coppersmith (1994) suggest a 40 km surface rupture length would produce an average fault displacement of 2 m, conversely a 14 m maximum fault displacement should relate to a 300 km surface rupture length. Although the Wells and Coppersmith (1994) dataset is global, and regional variations mean it does not necessarily perfectly fit to application for New Zealand (e.g. Dowrick and Rhoades, 2004), the great discrepancies between the inferred fault displacement given the fault length, indicates that there is something anomalous about the parameters of the Vernon Fault.

To decrease the average amount of displacement per event, the recurrence interval either could be lower (i.e. more paleoearthquakes) or the slip rate could be lower. Pondard and Barnes (2010) calculated a mean recurrence interval of 3,100 ± 1000 for the offshore Vernon Fault. While we acknowledge the onshore paleoearthquake data may be missing one post-9,000 year event, the close correspondence between the onshore and offshore paleoearthquake records suggests that the recurrence interval of ~3000-4000 years is reasonably robust. The more likely explanation for the anomalous Vernon Fault parameters is that the maximum slip rate estimate 3.9 mm/yr is just that, a maximum. At the Homestead Stream site both the age of the surface is poorly constrained and the exact amount of displacement is poorly defined because the stream piercing point on the southern side of the fault is not clear. Further research on refining the Vernon Fault slip rate and perhaps obtaining geological evidence of the amount of displacement per event should resolve this issue.

5.0 CONCLUSIONS

- The Vernon fault is predominantly strike-slip. It has a varying and minor component of dip-slip (up to 0.14 ±0.05 mm/yr) and a changing sense of throw. The variation in dip-slip direction and throw is consistent with the character of a strike slip fault as it changes in orientation.

- A maximum dextral slip rate of ≤3.9 mm/yr has been obtained for the Vernon fault but it has a high degree of uncertainty. This slip rate is higher than the previous estimate of < 2 mm/yr (Benson et al., 2001a), but slightly lower than other model-driven estimates of 4.5 mm/yr (Barnes et al., 2008; Wallace et al., in press).

- Movement on the section of the Vernon fault adjacent to Big Lagoon has probably had negligible to no effect on the Holocene subsidence of Big Lagoon. Subsidence rates of ~0.5 mm/yr in Big Lagoon are far larger than the dip-slip rates recorded on the Vernon fault. The strike-slip nature of the fault means most deformation is likely to be horizontal rather than vertical. Furthermore, a portion of the dip-slip motion that does occur on parts of the Vernon fault may result in absolute uplift of the hills to the south of the fault, rather than absolute subsidence of the lagoon.

- Tectonic subsidence of Big Lagoon is probably driven by subduction interface earthquakes or a combination of minor contributions from other faults in the region (such as the Cloudy fault) and the subduction interface.

- Three paleoearthquakes have been identified from the Balfour 1 trench; this is the first paleoseismic data from the onshore Vernon fault. Event 1 occurred between 11,000 – 9,000 years BP, event 2 at ~9,000 years BP, and event 3 at < 9,000 years BP.

- Event 2 has a good correlation to a paleoearthquake identified on the offshore Vernon fault by Pondard and Barnes (2010). Event 1 also potentially correlates to an offshore paleoearthquake, although the uncertainties are larger. The offshore Vernon fault has two paleoearthquakes <9,000 years BP while the onshore section has only one event; there are several possible reasons for this. There is a possibility of another strand of the onshore Vernon fault ruptured, rather than the strand we trenched. Alternatively, one mid-Holocene earthquake on the offshore Vernon fault may not have ruptured as far as the onshore section of the fault, or that offshore rupture propagated onto the Awatere fault.

- The current estimates of a fault slip rate of ≤3.9 mm/yr and recurrence interval of 3,000-4,000 years yields an anomalously high slip per event value of ~14 m. This suggests the slip rate estimate may be too high. Further work refining the slip rate or obtaining geological evidence of single-event displacements may resolve this.

6.0 FUTURE WORK

Further studies on the Vernon fault and the eastern Awatere fault are being undertaken by Tim Bartholomew as part of his MSc thesis in geology at Victoria University of Wellington. Tim is studying the geomorphology and slip rates of the Awatere and Vernon faults onshore and also studying nearshore seismic profiles across the Vernon fault. Tim's thesis will present an overview of the kinematics of the Vernon-Awatere fault systems. The thesis is being supervised by Tim Little (VUW), Phil Barnes (NIWA) and Kate Clark (GNS).

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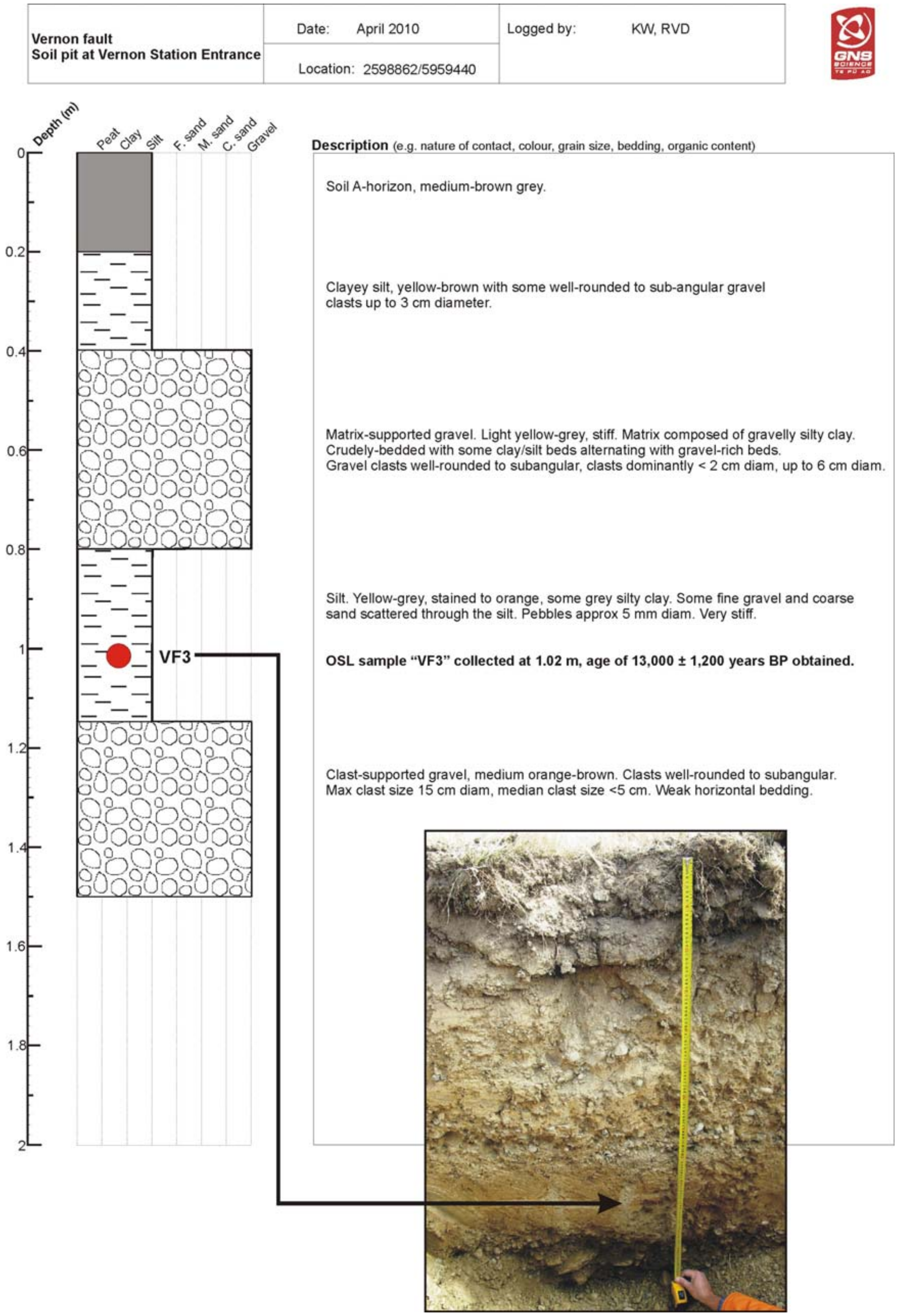
APPENDIX 1 STRATIGRAPHIC DESCRIPTION OF THE VERNON STATION ENTRANCE SOIL PIT



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