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Hatem, A.E., Dolan, J.F., Zinke, R.W. et al. (3 more authors) (2019) A 2000 yr paleoearthquake record along the Conway segment of the Hope fault : implications for patterns of earthquake occurrence in northern South Island and southern North Island, New Zealand. Bulletin of the Seismological Society of America. ISSN 0037-1106

https://doi.org/10.1785/0120180313

Author accepted manuscript
Bulletin of the Seismological Society of America, 2019, doi: 10.1785/0120180313

A 2000-year paleoearthquake record along the Conway segment of the Hope fault: Implications for patterns of earthquake occurrence in northern South Island and southern North Island, New Zealand

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Abstract

Paleoseismic trenches excavated at two sites reveal ages of late Holocene earthquakes along the Conway segment of the Hope fault, the fastest-slipping fault within the Marlborough fault system in northern South Island, New Zealand. At the Green Burn East site (GBE), a fault-perpendicular trench exposed gravel colluvial wedges, fissure fills, and upward fault terminations associated with five paleo-surface ruptures. Radiocarbon age constraints indicate that these five earthquakes occurred after 36 BCE, with the four most recent surface ruptures occurring during a relatively brief period (550 years) between c. 1290 CE and the beginning of the historical earthquake record c.1840 CE. Additional trenches at the Green Burn West site (GBW) site 1.4 km west of GBE reveal four likely co-seismically generated landslides that occurred at approximately the same times as the four most recent GBE paleoearthquakes, independently overlapping with age ranges of events GB1, GB2, and GB3 from GBE. Combining age constraints from both trench sites indicates that the most recent event (GB1) occurred between 1731–1840 CE, the penultimate event GB2 occurred between 1657-1797 CE, GB3 occurred between 1495-1611 CE, GB4 occurred between 1290-1420 CE, GB5 between 36 BCE and 1275 CE. These new data facilitate comparisons with similar paleoearthquake records from other faults within the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa (Al-Hp-JKN-Wr) fault system of through-going, fast slip rate (≥10 mm/yr) reverse-dextral faults that accommodate a significant portion of Pacific-Australia relative plate boundary motion. These comparisons indicate that combinations of the faults of the Al-Hp-JKN-Wr system may commonly rupture within relatively brief, ≤~100-year-long sequences, but that full "wall-to-wall" rupture sequences involving all faults in the system are rare over the span of our

paleoearthquake data. Rather, the data suggest that the Al-Hp-JKN-Wr system may commonly rupture in sub-sequences that do not involve the entire system, and potentially, at least sometimes, in isolated events.

Introduction

Documenting patterns of large-magnitude earthquake occurrence in space and time is of critical importance for both seismic hazard assessment and a deeper understanding of the mechanics of plate boundaries. Earthquake recurrence on individual faults has been shown to exhibit a wide variety of behaviors, from periodic [e.g., *Berryman et al.*, 2012], to quasi-periodic [e.g., *Weldon et al.*, 2004; *Scharer et al.*, 2007] to clustered [e.g., *Marco et al.*, 1996; *Dawson*, 2003; *Hartleb et al.*, 2003, 2006; *Kozacı et al.*, 2010; *Ferry et al.*, 2011; *Wechsler et al.*, 2014]. Most plate boundaries, however, exhibit multiple major faults that collectively operate as mechanically integrated fault systems. Thus, to understand the mechanics of earthquake occurrence along a plate boundary, it is necessary to document the spatial and temporal earthquake behavior of the primary, fast-slipping faults that make up the plate boundary.

To complete plate boundary system earthquake behavior analysis, we study the fastest-slipping strike-slip faults of the Australian-Pacific plate boundary of the northern South Island and southern North Island of New Zealand, where previous studies have documented patterns of earthquake recurrence on many of these major faults [e.g., *Cooper and Norris*, 1990; *Wells et al.*, 1999; *Langridge et al.*, 2003, 2013; *Mason et al.*, 2006; *Sutherland et al.*, 2007; *Little et al.*, 2009; *Van Dissen and Nicol*, 2009; *Berryman et al.*, 2012a, 2012b; *De Pascale and Langridge*, 2012; *Howarth et al.*, 2012, 2014, 2016; *Clark et al.*, 2013, 2015; *Nicol et al.*, 2016; *Khajavi et al.*, 2016; *Cochran et al.*, 2017; *Nicol and Dissen*, 2018]. The Hope fault, the subject of this manuscript, is the central link between high slip-rate faults to the southwest (Alpine fault) and northeast (Jordan-Kekerengu-Needles fault and the Wairarapa fault in southern North Island). This >850-km-long system (Alpine fault through to Wairarapa fault) of dextral strike-slip and oblique reverse-dextral faults accommodates the majority of the ~39 mm/yr of relative Pacific-Australia plate boundary motion in central and northern South Island [*DeMets et al.*, 2010; *Wallace et al.*, 2012], with the exception of the Wairarapa fault, which, together with the BooBoo and Needles faults, serves to connect the Marlborough Fault System from South Island to North Island (Figure 1). Although the Wairarapa fault slips at about half the rate of the South Island faults, the Wairarapa fault carries the predominant portion of onshore slip of the plate boundary in southern North Island.

In central South Island, much of the relative plate motion is accommodated on the oblique reverse-dextral Alpine fault, with a right-lateral strike-slip rate of 23-27 mm/yr [*Berryman*, 1992; *Norris and Cooper*, 2001; *Sutherland et al.*, 2006]. At ~42.8°S, 171.5°E the Alpine fault splays northeastward into multiple parallel, predominantly dextral strike-slip faults, referred to collectively as the Marlborough Fault System (MFS) (Figure 1). The four major faults of the MFS are, from north to south, the Wairau, Awatere, Clarence and Hope faults. Within the MFS, the southernmost Hope fault, with a slip rate of ~20-25 mm/yr, accommodates more than half of the total relative plate motion [*Van Dissen*, 1989; *McMorran*, 1991; *Van Dissen and Yeats*, 1991; *Langridge et al.*, 2003; *Stirling et al.*, 2012; *Hatem et al.*, 2016], with most of the remaining ~15-20 mm/yr occurring on the other main MFS faults [*Van Dissen*, 1989; *Van Dissen and Yeats*, 1991; *Holt and Haines*, 1995; *Walcott*, 1998; *Wallace et al.*, 2007, 2012; *Litchfield et al.*, 2014; *Reyners*, 2018]. Along the east-central part of the Hope fault, the 65-km-long Conway segment, the focus of this study, is structurally bounded between the transtensional Hanmer

Basin to the west [*Wood et al.*, 1994] and the transpressional Jordan fold and thrust belt to the east [*Van Dissen*, 1989; *Van Dissen and Yeats*, 1991]. At the northeastern end of the Conway segment, the Hope fault transfers slip northeastward onto the Jordan thrust system and its northeastward extension, the Kekerengu fault, which has a dextral slip rate of ~ 25 mm/yr [*Van Dissen et al.*, 2016]. Farther to the northeast, the Kekerengu fault extends offshore into Cook Strait as the Needles fault [*Barnes and Audru*, 1999; *Kearse et al.*, 2017], transferring dextral slip northward onto the BooBoo and Wairarapa faults, the latter of which has a slip rate of ~11 mm/yr, in southern North Island [*Little et al.*, 2009; *Pondard and Barnes*, 2010]. Thus, the Alpine, Hope, Jordan, Kekerengu, Needles, and Wairarapa faults (Al-Hp-JKN-Wr) constitute a >850-km-long, through-going system of fast-slip rate (≥ 10 mm/yr) dextral and oblique reverse-dextral faults that collectively serve to accommodate the majority of Australia-Pacific relative plate motions at their respective locations. Of the major faults comprising the Al-Hp-JKN-Wr system, only the Alpine fault and the Conway segment of the Hope fault have not generated a surface-rupturing earthquake during the historical period, which began with European settlement c.1840 CE.

Whereas a >2,000-year-long paleoearthquake record has been documented for the Alpine fault [*Berryman et al.*, 2012b; *Howarth et al.*, 2012, 2014, 2016; *Clark et al.*, 2013; *Cochran et al.*, 2017; see *Howarth et al.,* 2018 for review], the paleoearthquake record of the Conway segment of the Hope fault is not well documented beyond an approximate age of the most recent event [*Langridge et al.*, 2003]. In this study, we document and provide age constraints for at least the five most recent events along the Conway segment. These new data facilitate comparisons of earthquake occurrence in time and space on other faults within the Al-Hp-JKN-Wr fault system, providing insight into the system-level behavior of these major plate-boundary faults. Such comparisons have important implications for understanding seismic hazard in New Zealand, and more generally, for understanding the spatial and temporal earthquake behavior of similar fault systems around the world.

The Green Burn East and Green Burn West study sites

The Green Burn study area is located on the eastern part of the Conway segment of the Hope fault (Figure 1). Along the Green Burn reach, the Hope fault is generally expressed as a linear, single fault trace that, along much of this stretch, extends along the northern base of a sequence of ~4-8-m-high shutter ridges that are located ~50 m to the south of and sub-parallel to the main, south-facing mountain front (Figure 2). The presence of these shutter ridges, particularly at our study sites, causes sediment to pond to the north, resulting in fault-parallel marshes between the fault and the mountain front to the north. The shutter ridges at our trench sites appear to be long-lived features, as reconstruction of ~200 m of right-lateral Hope fault slip restores a prominent, NNW-trending reach of a stream that has deeply incised through the shutter ridge at Green Burn East (see figure S1 available in the electronic supplement to this article for reconstructions of this offset).

Langridge et al. [2003] conducted paleoseismic investigations on this stretch of the Hope fault at the Green Burn Stream (GBS) site (-42.395914°, 173.392075°) (Figure 2A). They used greywacke cobble weathering-rind thickness age estimates (a semi-quantitative geochronometer specific to New Zealand [*Knuepfer*, 1988]) to suggest that the most recent event (MRE) at their site occurred c. 1780 ± 60 CE. Additionally, radiocarbon ages show that the penultimate surface rupture occurred after 1295 CE and before the beginning of the historic era in this part of New Zealand (c. 1840).

In the current study, we excavated trenches at two localities, one to the east (Green Burn East [GBE]) (Figure 2B), and another to the west (Green Burn West [GBW]) (Figure 2C, figure S2 available in the electronic supplement) of the original Langridge et al. [2003] GBS excavations. We selected the GBE and GBW sites using air photo analyses and reconnaissance field mapping. These new excavations allow us to extend the paleoearthquake record further back in time and to place tighter constraints on the timing of late-Holocene Conway segment Hope fault surface ruptures.

At the GBE site (-42.393212°, 173.405528°), we excavated a 14-m-long, 1.5-m-deep, fault-perpendicular trench across the Hope fault that extended from the northern slope of the local shutter ridge/scarp northward into the ponded marshy area to the north (Figure 2B). We selected GBE as a paleoseismic trench site with the hypothesis that during surface ruptures, colluvial wedges would be shed northward off the scarp and deposited downslope across the surface rupture trace and into the marsh deposits to the north, possibly with interfingering relationships between colluvial and organic-rich marsh deposits, dateable by radiocarbon, that would help refine event ages (Figure 3). The GBE trench was field logged on grid paper at a scale of 1:20. We also created high-resolution photomosaics of the trench walls using Agisoft Photoscan photogrammetry software [*Bemis et al.*, 2014], which not only provides an archive of the trench exposures (see Supplementary Information Figure S3), but also facilitated detailed mapping of the finer-scale features once out of the field; this additional mapping focused on documenting clast size and distribution within the colluvial wedges observed at the GBE site.

At the GBW site (-42.396560°, 173.388838°), we excavated a 16-m-long, 1.5-m-deep trench (T-1) that extended northward from the local shutter ridge into a flat, marshy area at the base of a steep, landslide-prone slope (Figure 2C). We also excavated a short (1.7-m-long) 1.5-

m-deep trench (T-2) located ~25 m north of the fault at the base of the steep, landslide-prone slope, ~7 m NNW of the northern end of the T-1 trench (Figure 2C). The GBW T-1 trench was designed to capture colluvial wedge deposition along with primary surface rupture indicators within the fault zone, as well as any possible long-runout landslides exposed in the northern end of the trench. GBW T-2 pit was excavated closer to the base of the landslide-prone slope to intercept more proximal paleo-landslide events that might have been shed off the mountain front during Hope fault surface rupturing earthquakes. Supplementary Figure S2 shows the shutter ridge to the south (left in the image) and landslide-prone slope of the main south-facing mountain front (right in the image). Previous reconnaissance mapping and trenches [e.g., *Langridge et al.,* 2003] demonstrated that much of the Green Burn reach of the Conway segment is affected by moderate- to shallow-seated landsliding, where the mountain front can collapse toward the fault zone. Such co-seismic, fault-controlled, landsliding was a common feature in northeastern South Island during to the 2016 M_w=7.8 Kaikōura earthquake [*Langridge et al.*, 2018; *Massey et al.*, 2018]. As with the GBE trench, we mapped the GBW trench exposures in detail, creating a 1:20 scale log of T-1 and a graphic strat column of T-2 in the field, and also created high-resolution photomosaics of the trench walls (Supplementary Information Figures 4 and 5).

Trench Results

Green Burn East (GBE) trench observations

The northern part of the GBE trench revealed a sequence of organic-rich silts, clays, and layers of compressed grasses/plants that we interpret as having been deposited in a marsh environment (M units) (Figure 3). In the southern part of the trench, clastic sediments comprising the scarp (CW units) overly basal silts and clays (B units) (Figure 3). The upper part of the scarp sequence consists of a series of pebble to large cobble gravel-rich units interpreted to be colluvial wedges, referred to as CW1 (youngest) to CW5 (oldest), as well as an older, potential colluvial wedge (CW6) that could not be confidently attributed to a specific paleoearthquake at GBE. These wedges were shed northward down the slope of the scarp from the main exposures of the Hope fault zone near the southern end of the trench. The colluvial gravel clasts, which are generally set within a silt to medium-grained sand matrix, consist almost exclusively of Torlesse greywacke, typical of bedrock exposures in this part of New Zealand [*Rattenbury et al.*, 2006]. The gravel clasts are typically sub-angular to sub-rounded and range in size from an average of ~5-11 cm to a maximum diameter of 20 cm. The colluvial gravels were derived from older alluvial gravels that locally mantle the shutter ridge scarp a few meters above and south of the southern end of the GBE trench. The colluvial wedges were differentiated from each other on the basis of variations in predominant clast size, weathering, abundance and type of matrix, and, in several instances, the presence of a prominent basal cobble layers that we interpret as mantling the ground surface at the time of deposition of each wedge. In general, the overall clast size and packing-density in the colluvial wedges increase downslope, reaching a maximum at their distal ends adjacent to the marsh deposits. The distal, northernmost toes of some of the colluvial wedges locally interfinger with marsh deposits (M units – described below) beneath the southern toe of the scarp. Table S1 (available in the electronic supplement to this article) provides all stratigraphic descriptions made in the field.

Beneath the colluvial wedges, the scarp is composed of highly sheared, locally highly indurated clay to clayey-silt units (B units). These basal clays are virtually clast free and typically massive, with limited discernible internal bedding. We differentiated three distinct units

(B1 [youngest] to B3 [oldest]) on the basis of clay to silt ratio, color, and degree of induration. B3, the most sheared and indurated of these units, may be deformed Torlesse bedrock. All of the scarp-derived colluvial wedges were deposited atop the basal clays; the base of the marsh (M) units in the northern part of the trench was not reached, and B units were not exposed north of ~ m 4 (Figure 3).

The generally massive marsh (M) units in the northern part of the trench consist of organic-rich silts, peats, and compressed marsh plant layers. In general, the marsh deposits dip gently to the south (i.e., towards the scarp), consistent with a long-term, minor, down-to-the-north (i.e., mountain side down) component of vertical motion along the predominantly dextral Hope fault exposed in the southern end of the trench. The marsh deposits contained individual seeds, grass blades in growth formation, and plant leaves/fronds and other macroflora indicative of *in situ* deposition within the marsh, as well as detrital charcoal and wood fragments. The marsh deposits were generally clast free, and showed no obvious sedimentary structures. Stratigraphic delineations were made on the basis of color, wetting characteristics, firmness, silt content, and the presence or absence of plant material.

Although some of the scarp-derived colluvial wedges do locally interfinger with the southern ends of the marsh strata, especially near the top and base of the trench (e.g., CW2 and M1; CW5 and M5-6), in general the northern marsh deposits and the southern scarp-derived deposits are separated into distinct stratigraphic and depositional sequences by a ~1.5- to 2-m-wide zone (~m 5–m 7 on the trench logs) of complex stratigraphy associated with a wood mass that may be a paleo-tree or trees that were either growing at the base of the scarp or fell along the base of the scarp (Figure 3). We could not correlate stratigraphic units across this wood-rich zone, and as we discuss below, upon dating the northern marsh section using apparently *in situ* seeds, leaves, and other plant material, we observed a large mismatch in age between the ages of the marsh units north of the wood-rich zone and the younger colluvial and marshy deposits to the south at similar depths (see Age Control section). Because we cannot correlate units either stratigraphically or chronologically across this mass of wood, we do not utilize the northern marsh stratigraphy in the age determinations of scarp-preserved events (GB1-GB5), as all of the sedimentological and structural evidence for the five most-recent paleo-surface rupture at GBE comes from the southern part of the trench, south of the wood-rich zone. We present the detailed logs for the southern eight meters of the trench in Figure 3 to highlight these relationships. North of the section of the trench exposure shown in Figure 3, the marsh units became massive and increasingly difficult to log with any certainty. Photomosaics of the full trench exposures of GBE are presented in Supplemental Figure 3, available in the electronic supplement to this article.

The Hope fault through the GBE trench is expressed as a 5-m-wide zone comprising five main fault strands, denoted as F1 (farthest south) to F5 (farthest north) between m 0 and m 5. The faults extend upward through the basal units and locally extend through (or are overlain by) the colluvial wedge gravels. Fault F1 dips steeply to the north, F2 is near vertical, F3 generally dips steeply to the south, F4 dips variably northward, and F5 dips more shallowly to the north. Most of these main faults exposed at the base of the trench splay upwards into subsidiary strands. The steeply north-dipping, southernmost, scarp-bounding fault (F1), separates the pervasively sheared, highly indurated local clay bedrock (B3) from the somewhat less-indurated basal clayey-silt layers B1 & B2, along with the colluvial wedges that overlie B1-3. Several of the Hope fault strands, particularly F1-F3, exhibit large, upward-opening fissure fills and local graben-like down-dropped blocks. In addition, basal unit B2 is locally tightly folded between strands F1 and F2, best observed on the east wall. The fault zone between meters 1.5 and 3.5, encompassing strands F2-F5, represents a wide, somewhat distributed shear zone, in which stratigraphy is less well expressed in the basal units which exhibit a locally pervasive, steeply dipping shear fabric, interpreted here as being indicative of relatively distributed shearing.

Evidence for Paleo-surface ruptures

In the following section, we describe structural and stratigraphic evidence for the five most-recent surface ruptures (events GB1-GB5, from youngest to oldest).

Event 1 (GB1)

Event GB1, the most recent event (MRE) observed in the GBE trench, is marked by both the deposition of colluvial wedge CW1 and the upward terminations of faults F1b and F1c at the base of CW1 on the eastern wall. Most of the strike-slip in event GB1 likely occurred along fault F1a, but this fault does not directly interact with CW1; instead, fault F1a terminates at the base of the A horizon on the East Wall near m 0. Faults F1b and F1c form a small graben into which CW1 was deposited either cosesimically or soon after slip in GB1. Another small graben was formed between a potential additional splay fault near m 0 and fault F1b. Both of these grabens were filled with by CW1 gravels. Colluvial wedge CW1 is a pebbly gravel, with a black to dark brownish-gray silt to medium-grained sand matrix, which is overlain by the generally clast-free, thin, active surface soil A horizon. The unit extends downslope from between m 0 and 1 to the base of the scarp at m 5, where it interfingers marsh unit M1 (Figure 3).

Event 2 (GB2)

Event GB2, the penultimate event observed in GBE trench, is recorded by deposition of colluvial wedge unit CW2 and upward termination of fault F4 at m 2.8 on west wall at the base of CW2 (Figure 3). Unit CW2 is a clast-supported, pebble (clast size 0.5-2 cm) gravel consisting of sub-rounded graywacke clasts in a gray to black silt to fine-grained sand matrix. CW2 is markedly different from overlying CW1, and is distinguished from CW1 by its greater clast content. Additionally, CW2 is marked by a predominance of distinctive orange, highly weathered, friable clasts that were not observed in any other unit in the GBE trench. These distinctive clasts also had a higher sand content than the generally finer-grained Torlesse greywacke clasts found in all of the other colluvial wedges we observed. The presence of these distinctive clasts in CW2, and their absence in all other scarp-derived colluvial gravels in the GBE trench, suggests that a small exposure of this source rock was first exposed in the fault scarp during event GB2, and was moved right laterally away from the trench locality by strike slip during GB1, leaving only typical older gray-colored Torlesse pebble and cobble alluvium exposed along the top of the shutter ridge above the trench during the MRE. In contrast to colluvial wedge CW1, colluvial wedge CW2 is only exposed on the lower, distal (northern) part of the slope. In addition to the presence of the distinctive colluvial wedge, event GB2 is marked by the presence of a small fault block with CW2 colluvium associated with the upward termination of fault F4 (splays 4a and 4b), best expressed at ~ m 2.8 on the eastern wall (Figure 3).

Event 3 (GB3)

Event GB3 is marked by not only the deposition of colluvial wedge CW3, but also the opening of a large fissure between faults F1a and F1b that was filled with CW3 colluvium at the south end of the trench between ~ m 0 and 1 (east wall), and folding and faulting of older units (B2, CW4, CW4a) onto which colluvial wedge CW3 was deposited. Unit CW3 is a clast-supported gravel characterized by numerous large (8-10 cm), sub-angular cobbles within a gray to pale brown, medium-grained sand to clay matrix. Unit CW3 does not contain any of the sandy orange clasts that characterize CW2. In the northern, downslope extent of CW3, we differentiate a subunit (CW3a), which is similar to CW3 in matrix composition but is relatively clast poor. Unit CW3 is the largest colluvial wedge observed in this trench, and was sourced from a scarp created during slip on the well-defined, southernmost fault F1. A cobble layer extends along and defines the base of CW3. Unit CW3 is not continuous along the length of the trench exposure, pinching out between m 2 and m 4, where colluvial wedge CW2 was deposited directly on underlying unit CW4 (Figure 3). This preserved geometry of CW3 may be due to discontinuous lateral deposition of CW3, and then subsequent strike-slip of CW3 along fault F4 in event GB2, which could juxtapose different portions of the CW3 deposit, therefore yielding the observed pinch-out of CW3. At the base of the scarp, the distal part of unit CW3 locally interfingers with marsh deposits M1-M3 near m 5. CW3 gravel also fills a small fissure formed by faults 2c and 2d terminating at the top of unit CW4/4a near m 1.8 on the east wall. Additionally, folding of units CW4 and CW4a between ~ m 0.5 and 1.5 likely also occurred during surface rupture GB3. Collectively, these observations underscore the extensive structural disruption and the large volume of the CW3 colluvial wedge relative to the other colluvial wedges observed at GBE.

Event 4 (GB4)

Event GB4 is marked by the deposition of colluvial wedge CW4, by infilling of fissures that opened in the GB4 surface rupture with CW4 cobble colluvium, and by upward termination of fault F2a at the base of the CW4 colluvial wedge, best observed on the east wall. Unit CW4 is a clast-supported colluvial gravel, with a dark brown to gray, medium-grained sand to silt matrix among sub-angular to angular pebble to cobble clasts (max 12 cm). In the southern, upslope part of CW4, we differentiate a subunit (CW4a) that is generally similar to CW4, with a similar matrix, but which has far fewer cobbles and is slightly paler in color.

The distal, downslope end of unit CW4 terminates against marsh units M4 and M5, as best observed on the east wall. Although in the eastern wall exposure this contact suggests minor interfingering between the CW4 wedge and M3/5, on the western wall the contact is marked by a near-vertical stone line where the colluvial wedge is juxtaposed with the marsh deposits. This relationship is markedly different than the distal end of underlying unit CW5 (described below), which extends farther out into the marsh.

Unit CW4 is folded and faulted in multiple places, and several fissures opened in this event. Specifically, faulting from event GB4 opened fissures near m 1.3 and m 2.6 that were filled with CW4 colluvium. The large fissure that opened along fault F2 at m 1.3 has an accumulation of large cobbles (max 20 cm) exposed near the base of the fissure fill on the eastern wall, consistent with filling of an open cavity. Similarly, the smaller fissure that opened between faults 3c and 3d at ~m 2.6 also has larger clasts near the base of the fissure, although these clasts were smaller (large pebbles) than the clasts at the base of the m 1.3 fissure fill. In both fissure fills, the clasts exhibited sub-vertical alignments sub-parallel to the fault-formed free-faces that once bounded the fissures.

<u>Event 5 (GB5):</u>

Event GB5 is marked by the deposition of the colluvial wedge CW5, which is a clast-supported pebble to cobble gravel with a medium brown, fine-grained sand to silt matrix, as well as pervasive shearing of CW5 not affecting younger units (e.g., CW4). This distributed shear zone is preserved at ~m 2.5 - 3.5 on the eastern wall, where the stratigraphy becomes difficult to differentiate between CW5 and undifferentiated sheared silty gravels. The shape of unit CW5 is similar to the overlying colluvial wedges, consistent with these gravels having been shed northward down the scarp and out into the marsh. Unit CW5 appears to have been shed off the northernmost fault zone (F4 on the eastern wall), and cannot be traced further southward towards the top of the scarp. At its distal end, the CW5 colluvial wedge is deposited on top of thinly bedded, organic-rich rich silt unit M6. This is particularly clear on the east wall of the trench, where the CW5 gravel extends northward beneath the peat-like, compressed grasses that make up unit M5, and overlies the older marsh unit M6. These relationships indicate that deposition of CW5 pre-dates deposition of unit M5 and post-dates deposition of M6.

Green Burn West (GBW) trench observations: Evidence for inferred landslides

At the Green Burn West (GBW) site 1.4 km west of the GBE trench, fault-perpendicular trench GBW T-1 extended 16 m from the lower part of the north-facing fault scarp northward across a marshy flat to near the base of the steep, south-facing mountain front (Figure 4, Figure S4, available in the electronic supplement to this article). The trench exposed a gently north-dipping fault with an ~10 cm-thick gouge zone (fault F1 on Figure 4) that juxtaposes basal sheared pale-gray siltstone bedrock (unit B1) against overlying moderately indurated, massive silt to gravelly silt (unit S1), which becomes progressively more clast-rich to the south. We did not observe any structural evidence of individual surface ruptures in this trench, although the southern end of the trench is marked by two gravel colluvial wedges (units CWa and CWb) composed of sub-angular to sub-rounded pebbles in a sandy silt, dark gray matrix that overlie ~1 meter of massive gravelly silt. Neither of these colluvial gravels was observed in direct contact with the fault, so we cannot attribute surface rupturing events to these colluvial wedges. As in the GBE trench, we interpret these colluvial wedges to have been sourced from the scarp at the south end of the trench, although this relationship was not exposed in GBW T-1. We did not recover any datable material from these colluvial gravels.

Trench GBW T-1 also exposed a tan- to orange-mottled, matrix-supported gravelly silt with local minor sub-rounded to sub-angular pebbles and rare cobbles (unit L*). This gravel overlies the buried, organic-rich A horizon of a paleosol (unit P*). The P* paleosol is a dark brown to black, organic-rich, sandy silt, and is similar to other marshy soils we observed at GBE. The L* gravelly unit thins southward towards the fault, and pinches out between m 10 and m 13 of T-1. This southward thinning indicates that the source of the L* unit must have been to the north, consistent with the possibility that L* was deposited in a paleolandslide derived from the steep, landslide-prone slope immediately north of the trench. Additionally, the basal depositional contact of the L* gravelly silt atop the P* organic-rich paleosol A horizon is extremely sharp, with evidence of local rip-up of the underlying paleosol, indicating likely high energy deposition, potentially during a landslide event. Moreover, the underlying paleosol is flat, indicating that the gravel did not fill a depression (i.e., channel). This observation, in addition to the fact that there is currently no active stream-flow across the location of T-1 and that the L* deposit does not fill a channel or exhibit a geometry that could have formed by channel flow, suggests that the L* deposit is not a fluvial channel deposit. Thus, although the gravelly sandy silt of the L* deposit itself could have had other possible origins, we consider the southward thinning of the deposit, coupled with the location of the L* deposit near the base of the steep, landslide-prone slopes ~10 meters to the north of the trench, and the absence of any evidence for stream-flow through the site or a channelized origin for L*, to provide strong evidence for a landslide origin for the L* deposit.

Overlying the L* inferred paleolandslide landslide deposit is a matrix-supported gravelly silt (unit G1) that has considerably fewer clasts than the inferred landslide deposit. The contact between the interpreted L* landslide deposit and the overlying sediment is diffuse in some places (e.g., m 13 & m 14, where the contact is denoted with the number 5 on the contact, indicating that the contact is diffuse over a width of 5 cm).

The shorter GBW T-2 trench was excavated closer to the base of the steep, south-facing bedrock slope, ~ 8 m northwest of the northern end of GBW T-1 (Figure 2C). Trench GBW T-2 revealed four gravel layers that we interpret as paleo-landslide deposits (units L1, L2, L3 and L4, from youngest to oldest) (Figure 5, Figure S5 available in the electronic supplement to this article). These matrix-supported gravels consist of sub-angular pebbles (1-8 cm diameter clasts), that are separated from one another by organic-rich, clast-free, silty buried paleosols (P1, P2 and P3, from youngest to oldest). L1 is the thinnest gravelly silt deposit (5-10 cm thick), with small sub-angular clasts (~1 cm) within an orange sandy silt matrix. The upper contact is gradational whereas the basal contact is a spatially varies between sharp and gradational, likely due to bioturbation. The L2 deposit is ~ 15 cm thick with a similar makeup to L1, but containing rare larger clasts and with areas of local reduced iron-bearing staining in the matrix, as evinced by blue coloration of the deposit. The basal contact of L2 against the underlying P2 paleosol is sharp along the whole contact, whereas the upper contact between L2 and overlying P1 is gradational. This observation supports our interpretation that L2 was deposited rapidly on top of P3, and that P2 gradually accumulated atop L2 over a longer period of time. Although L3 is a gravelly silt, this deposit is relatively clast poor compared to L1, L2 and L4. The upper and lower contacts of L3 are both diffuse, potentially due to bioturbation when this deposit was near the surface and the P3 paleo-A horizon was actively forming above L3. The L4 deposit is the most clast-rich of the four gravelly silts described in GBW T-2. We could not expose the base of L4 due to the shallow groundwater table at this site. The top contact of the L4 deposit with the overlying P3 paleosol is diffuse. This alternation in GBW T-2 between coarse-grained gravelly silt deposition and fine-grained deposition punctuated by periods of soil development is consistent with episodic deposition of the gravelly silts, potentially during landslides, with intervening periods of organic-rich silt accumulation and pedogenesis. We observe three full cycles of this behavior, ending at the development of the modern marshy organic-rich soil exposed at the surface.

Because the exposure of T-2 is considerably smaller than T-1, we could not observe changes in lateral thickness of the unit. However, several observations support our inference that these gravel deposits are paleolandslides derived from the hill to the north of T-2. Topographically, T-2 was excavated into a local high with no evidence stream flow, as can be seen in detailed, lidar-derived topographic maps of the site (Supplemental Figure 2). Geographically, T-2 is at the base of a steep, landslide-prone slope, directly in the fall path of any landslides off this slope, which is why we excavated trench T-2 where we did. Sedimentologically, the slope north of T-2 provides a source of the T-2 gravelly sandy silt deposits. Taken together, these lines of evidence are consistent with a landslide origin from gravelly silt deposits L1-L4.

In the following section, we discuss the rationale behind our suggestion that each of the four landslides in this trench records co-seismic landslide deposition during the four most recent large, surface-rupturing Hope fault earthquakes on the Conway segment along the Green Burn reach, and that the intervening paleosols represent the periods of soil development between major Conway segment surface ruptures. As we describe below, this interpretation is supported by the similar, but completely independent ages we determined for the past three events at GBW and GBE.

Coseismic origin of colluvial wedges and landslides observed at GBW/GBE: Observations of the Green Burn Reach following the 2016 M_w=7.8 Kaikōura earthquake

In addition to the evidence described above, our inference that the GBW landslides and the GBE colluvial wedges were only deposited during prior Hope fault surface ruptures is supported by our field observations of the Green Burn reach of the Hope fault following the 2016 M_w=7.8 Kaikōura earthquake, which occurred nine months after our trench studies were conducted. We visited our by-then backfilled trenches at both the GBE and GBW sites during our reconnaissance mapping following the earthquake to investigate whether any colluvium had accumulated at either the base of the steep slope we trenched at the GBW site or the fault scarp we trenched at the GBE site. Both of our trench sites experienced very strong ground motions during the 2016 earthquake. Specifically, the Green Burn trench sites likely experienced a shaking intensity of VII-VIII on the Modified Mercali Intensity scale, with peak ground accelerations of ~ 25% g and peak ground velocities of ~45 cm/s (KIKS station; see Data and Resources section). Despite the strong shaking that affected our GBE and GBW sites, we observed no mass wasting at either location, or anywhere else along the Green Burn reach of the fault. At the GBE site, our filled-in trench was found intact beneath a newly sprouted cover of grass. Similarly, we observed no landsliding at the GBW site, with the filled-in GBW T-1 and T-

2 trenches undisturbed and already re-vegetated by grasses and thistle. The only colluviation observed along the Green Burn reach were small slope failures along a dirt roadcut, and several small slides on steep stream banks.

During our reconnaissance mapping of the Hope fault following the Kaikōura event, we noted no definitive surface rupture along the Green Burn reach, in keeping with more extensive field and helicopter mapping of the entire Conway segment [*Litchfield et al.*, 2018]. In subsequent weeks of mapping, one area of potentially disturbed ground on a slope 4 km east of the GBE site suggested local ground cracking of 0.9-1.4 m of net (reverse-dextral) slip [*Litchfield et al.*, 2018], but most of the Conway segment did not experience any surface rupture.

As such, we did not observe any newly exposed, un-vegetated slopes along the Green Burn reach. The south-facing slopes north of GBE and GBW are both vegetated. In fact, the slope north of T-1 and T-2 at GBW has trees growing on it, and has not been disturbed for at least 50 years or more given the size of the trees, indicating that slope failures at this site are rare and not events typically triggered by rainfall. The creation of a scarp free-face during surface rupture, including extreme peak ground accelerations, on the Conway segment of the Hope fault thus appears to be necessary for colluviation or landsliding along the Green Burn reach. In addition to the supporting sedimentologic and geomorphic arguments indicating that these colluvial wedge and paleolandslide deposits likely originated during Conway segment surface rupturing earthquakes, we now present compelling age data showing that these deposition events are essentially coeval. Such age results indicate that GBW paleolandslide age ranges can be used to help constrain the timing of paleo-surface ruptures observed at the GBE trench.

Chronology of paleoseismic events observed at GBE and GBW

Age models and event boundary conditions

To provide age control on event horizons observed in the GBE and GBW trenches, we radiocarbon dated 53 samples, which consisted of detrital charcoal, wood, seeds, and plant material (Table 1). The samples were inspected under a microscope to ensure that no young roots were included, and individual organic fragments including leaves and seeds were used to date marsh samples. All samples were prepared with a standard acid-base-acid pre-treatment protocol, and analyzed at the W.M. Keck accelerator mass spectrometer (AMS) lab at the University of California, Irvine. The resulting radiocarbon ages were calibrated using OxCal 4.3.2 [*Bronk Ramsey*, 2017] and the most up-to-date southern hemisphere calibration curve, SHCal 13 [*Hogg et al.*, 2013].

We observed that many of these samples were older than other samples from the same or underlying deposits, indicating that they had significant pre-depositional ages (i.e., were "reworked"). We created our age model using the philosophy that detrital charcoal included in a colluvial wedge must be the same age as or older than the depositional age of the unit from which they were sampled. This is always the case with detrital charcoal, except in the event that a younger charcoal sample was added to the deposit after deposition, as, for example, during bioturbation downward in a burrow from an overlying unit. In the specific case of our Green Burn excavations, introduction of younger detrital charcoal via bioturbation is unlikely because: (a) there is a lack of burrowing organisms in New Zealand, especially those that could bioturbate materials downward into the coarse-grained, pebble to cobble gravels of the GBE colluvial wedges; and (b) we observed no evidence of burrowing in the gravel colluvial wedge deposits. Furthermore, we observed no significant soils developed into the colluvial wedges at GBE. This is consistent with the relatively brief recurrence intervals that we document in the following section for the Conway segment of the Hope fault, which would have allowed only very limited time in between earthquakes for soil development. Thus, introduction of detrital charcoal samples downward into older colluvial wedges is unlikely to have occurred during pedogenesis at the GBE site.

Therefore, given the low likelihood that any of our detrital charcoal samples were introduced into underlying deposits during either bioturbation or pedogenesis, to get as close as possible to the true depositional age of the GBE colluvial wedges, we selected the youngest detrital charcoal age from a given colluvial wedge and discarded the older, reworked ages for each deposit. After determining which samples were reworked, the remaining ages were then used as inputs to stratigraphic ordering models in OxCal to create a Bayseian age model for each exposure [*Lienkaemper and Bronk Ramsey*, 2009]. All ages reported herein are calibrated, calendric ages in terms of BCE/CE.

We constructed six age models to provide timing constraints on the paleo-earthquakes at our Green Burn study sites (Figure 6; Table 1): one using ages only from the GBE trench scarp-derived colluvium (Figure 6A); one using ages only from the GBE scarp-derived colluvium and the GBE marsh deposits south of the wood mass (Figure 6B); one using ages only from the GBE marsh deposits north of the wood mass (Figure 6C); one using ages from only GBW T-2 (Figure 6D); one using ages from GBW T-1 and T-2 (Figure 6E); and a final, preferred model combining age constraints from the GBE scarp-derived colluvium and southern marsh section, as well as GBW T-1 and T-2 (Figure 6F). We excluded from consideration in our age models all samples that exhibited anomalously old ages indicative of inheritance (i.e., those samples with ages that are much older than underlying samples). In addition to the exclusion of a number of samples from the faulted, southern part of the GBE trench, we did not use the vertical profile of radiocarbon ages we collected from the marsh deposits in the northern part of the GBE trench north of the wood mass near m 5-6 (Figure 6C), as these ages were all significantly older at all stratigraphic levels than correlative scarp-derived colluvial deposits (Figure S6, available in the electronic supplement to this article). Moreover, as noted above, none of these deposits can be correlated confidently with the scarp-derived colluvial section that contains all of our stratigraphic and structural evidence for the five most recent earthquakes recorded at GBE (Figure 3; Figure 6A-C; Figure S6, available in the electronic supplement to this article). Complete documentation of all radiocarbon age data and associated metadata from the GBE and GBW trenches, including those ages that were not included in our age models, is presented in Table 1.

We present the results of our GBE-only age models first (Figure 6A-C), with detailed reference to all radiocarbon ages that were used to directly constrain the five well-constrained surface ruptures observed in the GBE trench. Following this discussion, we present our GBW age models (Figure 6D) and then the combined GBW and GBE model (Figure 6E), which uses the additional age constraints from the GBW landslide deposits to independently test and corroborate the ages of the GBE surface ruptures, and to more tightly constrain the age of the penultimate surface rupture (GB2) observed in the GBE trench. All 2σ event age ranges for each model are listed in Table 2.

Green Burn East Paleo-Surface Rupture Ages

All of the paleoearthquake event stratigraphy recorded in the GBE trench (i.e., fault terminations, folding, fissure fills) is contained within the scarp-derived colluvial units in the southernmost portion of the trench. In the following section, we present event ages based on samples collected only from the units that record the events (Figure 6A). Where possible (e.g., sample SF-5), we further constrain these event age ranges using samples from the marsh south of the wood mass at ~ m 5 (Figure 6B). We report individual sample ages as calibrated yet unmodeled ages, which are included (for all dated samples) Table 1.

In contrast to evidence for historical surface rupture of the Hope fault farther west during the 1888 M_w~7-7.3 Amuri earthquake [*McKay*, 1890; *Cowan*, 1991; *Khajavi et al.*, 2016], there is no record of historical rupture of the Conway segment of the Hope fault through the Green Burn sites. Thus, the most recent surface rupture we observe (GB1) must have occurred prior to European settlement, which began c. 1840 CE. Surface rupture GB1 is younger than detrital charcoal samples SF-33 (1680—1723 CE, or post-1802 CE) and SF-34 (1691—1728 CE, or post-1805 CE) included in colluvial wedge CW1, which we interpret as having been shed northward off the scarp during and soon after event GB1. Combining the historical constraint with the age constraints from the GBE scarp-derived, colluvial wedge ages-only OxCal model indicates that event GB1 occurred between 1722—1840 CE. This age range is similar to the 1780 ± 60 yBP age of the most recent event suggested by *Langridge et al.*, [2003] on the basis of weathering rind age estimates from their GBS trench.

Surface rupture GB2 is younger than the ages of the detrital charcoal samples collected from CW2 itself, as the material contained in the colluvial wedge must have existed higher on the scarp prior to deposition of the colluvial wedge. Thus, event GB2 is younger than samples SF-15 (1462—1627 CE) and SF-16 (1505—1643 CE), which were collected from within unit CW2. GB2 is stratigraphically older than CW1, and we make the assumption that this surface rupture occurred before the material included in CW1 was generated and then included in CW1. Thus, the ages of samples SF-33 and SF-34, collected from unit CW1, provide a minimum age for GB2. Taken together, our GBE scarp-derived colluvial samples-only age model indicates that the penultimate GBE surface rupture occurred between 1558 and 1724 CE. These data significantly narrow the previous post-1295 CE constraint for the occurrence of GB2 from *Langridge et al.,* [2003].

We constrain the age of GB3 using a similar rationale as used for dating the previous events. Specifically, charcoal samples SF-1 (1394—1425 CE), SF-2 (1496—1636 CE), SF-3 (1320—1410 CE) and SF-28 (1396—1436 CE) were collected from the CW3 colluvial wedge and therefore pre-date event GB3. However, sample SF-2 is significantly younger than SF-1, SF-3 & SF-28, indicating that the three older charcoal samples were likely incorporated into the soil and gravel mantle atop the shutter ridge/fault scarp about 100-150 years prior to incorporation of the SF-2 charcoal sample, and/or that these three samples were significantly older than SF-2 when they were all incorporated into the CW3 colluvial wedge. We infer that the three older charcoal samples were generated during an earlier brush fire (or fires) that occurred c. 1400 CE, whereas the sample SF-2 charcoal fragment was produced during a separate, younger brush fire during the late 1400s or 1500's CE. Given the apparent inheritance of samples SF-1, SF-3 & SF-28, we use the age of sample SF-2 as a maximum age for GB3. Charcoal samples SF-15 and SF-16, which were collected from the overlying colluvial wedge CW2, post-date GB3, as CW2 is deposited atop CW3. Using these constraints, the GBE scarp-derived colluvial sample-only age model (Figure 6A) produces an age range of GB3 as 1495—1610 CE.

As with the previous events, assuming material from within a colluvial wedge is older than the coseismic deposition of that wedge itself indicates that event GB4 is younger than charcoal sample SF-41 (1273-1380 CE), which was collected from CW4. Using sample SF-41 as a maximum age of GB4 with sample SF-2 from CW3 as minimum age, we model the age of GB4 as 1288—1532 CE.

To determine the maximum age for event GB5, we assume as in the case of the younger colluvial wedges that charcoal samples collected from the colluvial wedge are older than the coseismic deposition of that wedge. We therefore use sample SF-21 (195—52 BCE), collected from CW5, as a maximum age for event GB5. Knowing that CW4 was deposited atop CW5, and is therefore younger than CW5, we use sample SF-41 collected from CW4 as a minimum age constraint on event GB5. Using these two scarp-derived charcoal samples as constraints results in a modeled event range for event GB5 of 61 BCE—1277 CE.

We can further constrain the age of event GB5 by using charcoal ages collected from the coseismic colluvial wedge in combination with ages on plant material collected from the southern part of the marsh section, south of the wood mass, atop which the wedge was deposited. Specifically, the distal, downslope toe of colluvial wedge CW5 was deposited onto a thinly bedded organic silt/peat succession (units M6-M7), best observed at ~m 5 on the east wall (Figure 3). We collected wood sample SF-5 (99 BCE-115 CE) from peat layer M7, underlying CW5. We sub-sampled SF-5 as three separate pieces, and these yielded similar radiocarbon ages on all splits (SF-5a: 42 BCE—115 CE; SF-5b: 96 BCE—25 CE; SF-5c: 99 BCE—23 CE). Because sample SF-5 was a piece of wood, with an unknown amount of age inheritance, we can only use these ages as maximum ages because the wood deposited within the layer could potentially be much older than the deposit itself. Combining the ages of samples both from the scarp-derived colluvial deposits and from the marsh units south of the wood-rich section yields a modeled age range for event GB5 of 36 BCE—1275 CE.

Age control for GBE northern marsh strata

The ages determined from the vertical sampling profile we collected north of the wood mass at ~m 7 (Figure 3 east wall), are presented in Figure 6C. These 11 ages are primarily based on short-lived plant material, mainly leaves and seeds. The resulting ages and OxCal age model (Figure 6C) indicate that all samples are in correct stratigraphic order, recording semi-continuous deposition in the northern marsh from c.100-300 BCE at 1.5 m depth (sample SF-14 [350—104 BCE]) to c. 700-800 CE at 30 cm depth (sample SF-6 [681—862 CE]). Interestingly, these ages are significantly older at all depths relative to the scarp-derived colluvial section south of the wood-rich zone. Moreover, the fact that c. 1200- to 1300-year-old strata are exposed at only ~30 cm depth in the marsh north of the wood mass suggests that either there has been little deposition in the northern marsh over the past 1,000-plus years, and/or that the northern marsh section has experienced significant erosion during the same time period when the colluvial wedges marking that five most recent Hope fault surface ruptures were being deposited south of the wood mass.

This mismatch in ages suggests that the mass of wood acted as a barrier to sediment accumulation, effectively separating the southern, scarp-derived colluvial section from the northern marsh section for much of the time recorded in the GBE trench (Figure S5). Consequently, we cannot use the radiocarbon dates from the northern marsh section to constrain the ages of paleo-earthquakes, evidence for which is derived exclusively from the scarp-related section south of the wood-rich zone. Rather, we use only those radiocarbon ages collected from the scarp-derived, southern section to constrain the ages of the five most recent Green Burn surface ruptures.

Ages of GBW site landslides

The radiocarbon ages from GBW T-2 provide constraints on the ages of the four influxes of clastic sediment that we interpret as paleo-landslides observed at that site (Figure 6D). We collected two radiocarbon samples from the shallowest paleosol (P1) beneath the shallowest gravelly silt L1, a plant leaf sample from ~20 cm depth [LS2-6 (Modern)], and another plant leaf from ~35 cm depth [LS2-4 (1672—1743 CE, or post 1772 CE)]. Given the shallowness of sample LS2-6, and matrix-supported nature of the L1 deposit above sample LS2-6, we suspect that this sample may have been bioturbated into position from which it was collected. We therefore use sample LS2-4 to provide a maximum age for the overlying L1 interpreted landslide deposit. Alternatively, if this Modern plant sample LS2-6 from beneath the L1 gravelly silt was not bioturbated in to the sampling location, then the L1 deposit must be historical, likely mid-to-late 20th century following the production of bomb-generated radiocarbon testing in 1945 CE. This alternative explanation for the timing of L1 deposition makes no difference in the interpretation of the sample LS2-4, as that sample still post-dates inferred-landslide L2, which must pre-date any subsequent landslide following L2. To bracket the timing of deposition of inferred-landslide L2, we use the age of sample LS2-4 from paleosol 1 above the penultimate landslide L2 to post-date the L2 deposit, as well as the age of sample LS2-5 (1665—1895 CE) from paleosol 2 beneath L2. These ages indicate that L2 deposition occurred between 1668 and 1806 CE.

The two wood samples that we radiocarbon dated from within the L3 landslide (LS2-2 [693-891 CE] and LS2-11 [1032-1151 CE] are older than underlying samples, and are not considered further. The age of L3 is, however, constrained by charcoal samples LS2-5, collected from paleosol P2 above the L3 deposit, and LS2-9 (1184—1267 CE), collected from paleosol P3 beneath L3. These ages bracket the timing of L3 deposition to 1225-1685 CE. We can further refine this age range by incorporating charcoal sample HL16-04 (1400-1440 CE) from GBW trench T-1, which was collected from the paleosol (P*) that was over-ridden by perhaps the only landslide observed in that trench (L*), which we correlate with L3 based on the age correlation of L3 with GB3 (discussed in the subsequent section) (Figure 6D). This additional constraint narrows the age range for L3 to 1414-1694 CE. Using sample HL16-04 to pre-date L3 deposition and LS2-5 to post-date L3 deposition, we arrive at a revised age range for L3 deposition as 1415—1711 CE.

We were unable to collect any samples from beneath the fourth landslide back (L4), but the age of charcoal sample HL16-04 from paleosol directly below the inferred landslide deposit in T-1, as well as the age of sample LS2-9 collected from P3 in T-2 indicates that L4 was deposited before 1400—1440 CE, providing the youngest possible age for event GB4.

Combined Age Model for GBW and GBE sites

The ages of the five event horizons we identified at GBE based on fault terminations, fissure fills, folding, and colluvial wedge deposition overlap in time with the deposition of the four inferred-landslide silty gravel units in GBW T-2 (Supplemental Figure S7). As discussed earlier, we observed no evidence of colluviation or landsliding along the Green Burn Reach following the M_w=7.8 Kaikōura earthquake, providing support for our inference that landslide deposition at GBW occur only during surface rupturing events along the Green Burn Reach of the Hope fault. We therefore combine age models from GBE and GBW using independent age constraints to more precisely determine the ages of the five surface rupturing events observed at GBE. One could arrive at these combined event ages by averaging together the probability density functions from GBE and GBW, an approach similar to that of *Biasi and Weldon* [2009]. We present those results, along with comparisons of the GBE and GBW probability density functions and the OxCal combined age results, in the electronic supplement to this article in Figure S7.

Using the preferred OxCal age combination approach, inclusion of sample LS2-4 from the youngest paleosol P1 at GBW as an additional constraint on the maximum age of the most recent surface rupture observed in the GBE trench overlaps with the age of event GB1, and slightly tightens the possible age range from 1722—1840 CE in the GBE-only age model to 1731-1840 CE. Similarly, addition of sample LS2-5 from paleosol P2 in the combined GBE-GBW age model narrows the possible age of event GB2 to between 1657 and 1797 CE (1558—1724 CE for GBE-only model). Additionally, inclusion of the ages of GBW samples LS216-5, collected from the paleos~~e~~ol P2 above the third-most-recent inferred-landslide (L3) at GBW, and samples HL16-04 & LS2-9, collected from below L3, in the combined GBE–GBW age model yields a nearly identical age range for event GB3 of 1496-1611 CE (1495—1610 CE for GBE only model). The two age models produce similar age ranges from GB3 because the additional sample from GBW T-1 of HL16-04 is slightly older than the sample SF-2 from GBE (Figure 6B vs 6F). Finally, the age range of event GB4 is shortened markedly by incorporating the 1400-1440 CE age of sample HL16-04, which was collected from GBW T-1 paleosol P*, on which L* was deposited; we interpret L* deposition to be contemporaneous with deposition of colluvial wedge CW3 in the GBE trench during event GB3, which post-dates deposition of CW4 in GB4. Although sample LS2-9 (1184—1267 CE) was also collected from paleosol 3 in GBW T-2, we do not use the LS2-9 date in further age modeling of event GB4 because this sample is slightly older than sample SF-41, which was collected from CW4 at GBE, and which therefore must pre-date event GB4. Thus, the older age of sample LS2-9 suggests that this sample had some inherited, pre-event GB4 age before it was incorporated into the paleosol overlying inferred-landslide L4. Including the age of sample HL16-04 into the combined GBE-GBW age model yields a revised age range for event GB4 of 1290-1420 CE, somewhat older than the 1288—1532 CE age range from the GBE-only age model.

Discussion

The Green Burn trenches reveal the occurrence of five surface rupturing earthquakes on the Conway segment of the Hope fault during the past c. 2000 years. The more tightly constrained ages for the past four GBE events suggest potentially irregular earthquake occurrence. Specifically, whereas the two most recent events (GB1—GB2) occurred within a relatively brief, <183-year period between 1657 and 1840 CE (mean RI between GB1 and GB2 = 58 years), they were preceded by events GB3 and GB4, which occurred over a maximum of 321 years from 1290-1611 CE (mean RI between GB3 and GB4 = 198 years). The oldest event, GB5, has a long possible age range, therefore making the resulting recurrence interval less informative than for the younger events; although we did not observe evidence of events between GB4 and GB5, or events older than GB5 in the GBE trench, we may have an incomplete event record prior to GB4. Event GB5 aside, the younger two events may thus represent a temporal cluster during which earthquake recurrence was more frequent than average. Interestingly, event GB3, the third earthquake back, which precedes these two events, exhibited much more significant structural disruption in the GBE trench and resulted in deposition of a much more extensive colluvial wedge than previous or more recent Conway segment surface ruptures, suggesting that it may have been a larger-displacement surface rupture at the GBE site. The large displacements suggested by these observations are consistent with possible time-predictable behavior [*Shimazaki and Nakata*, 1980] of the Hope fault, with the large inferred displacement at the Green Burn sites in GB3 being followed by a period of time with shorter than average recurrence intervals. Analysis of small offsets in lidar and ground-penetrating radar data on the Conway segment, however, suggests that the past three earthquakes have each produced, on average, ~3-4 m of displacement [*Beauprêtre et al.*, 2012], and thus that the inferred larger displacements in the Green Burn trenches may have been a local feature of that event and are not necessarily indicative of GB3 being a larger-magnitude earthquake.

Plate Boundary System-Level Rupture Behavior

The new Green Burn data add to a growing body of paleo-earthquake age constraints from multiple sites along the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa (Al-Hp-JKN-Wr) system of major dextral strike-slip and oblique reverse-dextral faults that collectively accommodate significant portions of Pacific-Australia relative plate motion in South Island and southern North Island [*Pondard and Barnes*, 2010; *Robinson et al.*, 2011; *Litchfield et al.*, 2014]. Specifically, paleoseismologic records are now available from the Hope fault along the Hurunui and Hope River segment from the Matagouri Flats (MF) [*Langridge et al.*, 2013] and Hope Shelter (HS) [*Khajavi et al.*, 2016] sites ~100 km west of the GBE site, from the Kekerengu (EK) fault at a site ~ 100 km northeast of the Green Burn sites [*Little et al.*, 2018], from the Cross Creek (CC) site on the Wairarapa fault, an extension of this fault system northward into southern North Island [*Little et al.*, 2009], and from multiple sites along the central Alpine fault (A) with dendrochronologically dated records of tree disturbance [*Wells et al.*, 1999] and records of strong ground shaking from paleo-seismite records in lakes in the footwall of the Alpine fault on the coastal plain of the Southern Alps [*Howarth et al.*, 2012, 2014, 2016]. It is worth pointing out, in contrast to paleoseismic results from trenches of the active fault traces, the dendrochronology and paleo-seismite data record strong ground shaking at the site off of the active fault traces, and thus could record earthquakes generated by other faults. We summarize these on- and off-fault paleoseismic records in Table 3. We included all preferred events described in these paleoseismic studies and the preferred paleo-event age ranges of the original authors. In addition to these records, we discuss the 2016 Kaikōura earthquake, and its potential implications, in a separate section below. We can use all of these data to address important questions about earthquake occurrence in the Al-Hp-JKN-Wr fault system.

The most basic question we address in our analysis is whether the faults of the Al-Hp-JKN-Wr typically rupture together or in brief sequences of along-strike ruptures, or whether different sections of the fault system rupture independently in isolated events. Although hampered by the long possible allowable age ranges of some events at some sites (e.g., GB5, HS2, EK4), the available data allow us to examine the system-level behavior of the Al-Hp-JKN-Wr fault over the past 1,000-plus years. In Figure 7, we show available paleoseismic constraints on the faults at the specific paleoseismic sites discussed above.

In an attempt to assess the possibility that large parts of the Al-Hp-JKN-Wr system rupture together in brief sequences, we interrogate 100-year-long intervals where there is overlap between the 2σ age ranges of more than two ruptures along the different faults. Specifically, if there is overlap between events, we show a pink bar, labeled S_x, across all sites that could potentially have ruptured within a ≤100-year-long sequence (Figure 7). Although the 100-year time window is arbitrary, it was chosen because it is shorter than the average recurrence intervals at all sites, and helps to bring into focus possible brief sequences involving rupture of large sections of this fault system. We attempt to minimize the number of sequences within the Al-Hp-JKN-Wr system. That is to say, we select the temporal placement of the 100-year-long possible-sequence "bar" shown in Figure 7 across as many faults as is allowable within the given 100-

year time window. This analysis is designed to highlight possible multi-fault sequences, and does not necessarily indicate that all paleoearthquake ruptures occurred in the given 100-year time windows. Conversely, this analysis can point out the occurrence of an isolated event in the case of a lack of paleoeathquakes on neighboring faults.

For example, one issue we explore is whether the record indicates that the 65-km-long Conway segment, which is bounded on both the east and west ends by major structural complexities [*Van Dissen*, 1989; *McMorran*, 1991; *Wood et al.*, 1994], may commonly rupture by itself in isolated M_w~7 earthquakes, or whether it typically ruptures within a short period of time with other parts of the Al-Hp-JKN-Wr plate-boundary fault system. We define isolated events as rupture of a fault segment without rupture defined on adjacent fault segments. We denote any potentially isolated earthquakes with blue horizontal bars labeled Is_x on Figure 7 (e.g., GB4, A3 & A5).

We investigate the most recent possible multi-fault rupture sequence (S1) by comparing the age of the most recent event at Green Burn (GB1), which occurred sometime between 1730 and before the period of European settlement began c. 1840 CE, with ages from other sites along the fault system to the northeast and southwest. The 1730-1840 CE age range of the GB1 is similar to the 1700-1840 CE time range of the most-recent surface rupture documented on the Kekerengu fault by *Little et al.* [2018], indicating that the Conway segment and the Kekerengu fault likely both ruptured within a <~100-year-long time window just prior to the beginning of European settlement. Subsequently, the historical 1855 M_w~8.1 Wairarapa earthquake ruptured a ~160-km-long section of the Wairarapa fault extending into Cook Strait [*Grapes and Downes*, 1997; *Rodgers and Little*, 2006], and the 1888 M_w~7-7.3 Amuri earthquake ruptured the Hurunui and Hope River sections of the central Hope fault [*McKay*, 1890; *Cowan*, 1990, 1991; *Cowan* *and McGlone*, 1991; *Khajavi et al.*, 2016]. Thus, if the most recent events on the Conway segment (GB1) and the Kekerengu fault (EK1) occurred relatively late during their allowable time ranges, the events observed at all four sites could record a temporally brief sequence of large-magnitude earthquakes that ruptured the entire fault system northeast of the Alpine fault during the late 18^{th} and 19^{th} centuries [*Little et al.*, 2018]. Alternatively, if the prehistoric GB1 and EK1 most recent events occurred early in their allowable time ranges (i.e., as early as 1730 CE and 1700 CE, respectively), they might have occurred within a short period of time of the most-recent, c. 1717 CE earthquake on the Alpine fault, which ruptured a ≥375-km-long section of that fault as far north as the Alpine-Hope fault intersection [*Wells et al.*, 1999; *De Pascale and Langridge*, 2012; *Howarth et al.*, 2018]. If so, then the Alpine fault, the Hope fault Conway segment, and the Kekerengu fault ruptures may have occurred long before the historical 1855 and 1888 earthquakes, and thus these events may not have been part of a brief sequence including these historical ruptures. Earthquake occurrence on this system over the past c. 300 years has may therefore have been more random in time and space, with ruptures occurring piecemeal over the entire length of the Al-Hp-JKN-Wr system. However, it seems less likely that GB1 ruptured early in the allowable 1730—1840 CE age range, given that the 2σ age range of the penultimate surface rupture GB2 (1657—1797 CE) significantly overlaps with the GB1 range (Figure 6, Supplementary Figure S7). For this reason, we suggest that GB1 likely occurred late in its allowable time range, just prior to the beginning of the historic era, suggesting the possibility that the entire Hp-JKN-Wr part of the system may have ruptured in a brief sequence beginning just prior to the historic era and ending with the 1888 earthquake.

The next-older possible-sequence (sequence S2) includes the most recent event on the Alpine fault (c. 1717 CE), MF2, HS2, and GB2. We note that the c. 1717 CE Alpine event occurred within a brief period of time with ruptures along the Hurunui, Hope River and Conway segments of the Hope fault, but without rupture of the Kekerengu fault. As noted above, based on the occurrence of the 1855 M_w~8.1 Wairarapa rupture to the northeast of the Kekerengu fault, and the occurrence of GB1 to the southwest of the Kekerengu fault, we assume that EK1 likely occurred during the most-recent, possible-sequence 1. If so, then the data suggest that possible-sequence 2 did not extend northeastward beyond the Hope fault. This would be consistent with the idea that portions of the Al-Hp-JKN-Wr system rupture in sub-sequences that involve only part of the system, rather than as system-wide, "wall-to-wall" sequences.

Possible-sequence S3 encompasses ruptures on all faults in the system except for the Wairarapa, including events A2, MF3, HS2, GB3 and EK2. *Howarth et al.,* [2014, 2016, 2018] have called into question the source fault causing paleo-seismite deposition in event A2, which is marked in sediment cores by submarine slope failure in all three examined lakes, but did not include a strong signature of post-seismic landsliding [*Howarth et al.*, 2014]. Event A2 is therefore equivocal with respect to an Alpine fault source—either A2 occurred on another nearby fault in the Southern Alps, or the event occurred on the Alpine fault and only weakly shook the region (MMI ~VI as opposed to IX) [*Howarth et al.*, 2014, 2018]. Given the apparent weaker shaking intensity during event A2, it is possible that this event A2 did not occur on an Alpine fault source and instead occurred on a smaller fault neighboring the Alpine fault. Alternatively, given the "bimodal" rupture model of *DePascale et al.* [2014], the Alpine fault may rupture most of its length in M_w 8+ events, or may rupture in parts in M_w ~6-6.5 events. These latter, smaller magnitude events would not be recorded in paleoseismic trenches, but may be recovered in off-fault records of lake seismites [*DePascale et al.*, 2014; *Howarth et al.*, 2018]. Given the fact that these records of lake seismites are off-fault records of Alpine fault seismicity, it remains possible that these seismities represent earthquakes with sources on faults adjacent to the Alpine fault, of which many have been documented [e.g., *Cox et al.*, 2012; *DePascale et al.*, 2016]. We denote this uncertainty as a more transparent box for possible-sequence 3 on Figure 7. If event A2 did occur on the Alpine fault, possible-sequence 3 could potentially represent a near-complete sequence of events that ruptured the Al-Hp-JKN faults. However, notably, this rupture sequence did not cross Cook Strait onto the Wairarapa fault. This observation likely reflects the fact that the Wairarapa fault exhibits a slower slip rate fault of 11 ± 3 mm/yr [*Little et al.*, 2009], much slower than the fast slip rates of the Kekerengu, Hope, and Alpine faults (~20-25+ mm/yr; [*Van Dissen and Yeats*, 1991; *Berryman*, 1992; *Norris and Cooper*, 2001; *Hatem et al.*, 2016; *Van Dissen et al.*, 2016] in South Island as slip is transferred northeastward onto the Wairarapa fault as well as the offshore BooBoo fault [*Robinson et al.*, 2011], with a modeled slip rate of 11 mm/yr [*Pondard and Barnes*, 2010], and ultimately onto the underlying Hikurangi megathrust fault beneath North Island [*Rodgers and Little*, 2006; *Wallace et al.*, 2012].

We observe a long (c. 400 year) lull in potential sequence activity between possible-sequences S3 and S4, with two temporally isolated earthquakes (Is1 & 2) occurring on the Alpine and Hope faults, respectively. Specifically, events A3 (1388—1407 CE), which potentially ruptured the central Alpine fault, and GB4 (1230—1420 CE), which ruptured the Conway segment of the Hope fault, do not overlap with the 2σ age ranges of any other events that have not already been plausibly assigned to a possible earthquake sequence. Although the age range of A3 overlaps with the age range of GB4, we do not include these events as part of a larger sequence because no faults with available paleoseismic data ruptured on either side of the Alpine or Conway fault during this time period in surface-rupturing earthquakes that have not already been included in sequence S3. For example, event GB4 does overlap in time with HS2, but HS2 has been previously assigned to possible-sequence 3. Although events GB4 and HS2 could have ruptured within a brief time of one another as part of a sequence, our preferred interpretation is that HS2 occurred in the same sequence as MF3, as these sites are only ~ 30 km apart along strike of the Hurunui segment of the Hope fault, and thus likely record the same earthquake. Events A3 and GB4 may represent a discontinuous sequence along the plate boundary. Our preferred interpretation, however, is that events A3 and GB4 represent isolated events because of the lack of spatial continuity and paucity of faults that ruptured during this time period. Alternatively, it is possible that both A3 and GB4 were part of a brief, continuous sequence of events that involved rupture along the southern Kakapo strand of the central Hope fault system, and potentially bypassing the Matagouri Flats and Hurunui Shelter paleoseismic sites of *Langridge et al*. [2013] and *Khajavi et al.* [2016], which are located on the northern Hurunui and Hope River segments of the Hope fault. Currently, there are no paleoseismic data available for the Kakapo strand with which to constrain this possibility.

This possible lull in potential sequence behavior was preceded by sequence S4, the only inferred possible "wall-to-wall" rupture of the entire Al-Hp-JKN-Wr plate boundary system during the past 2000 years. Specifically, between 1000 and 1100 CE ruptures along the Alpine (A4), Hurunui (HS4), Conway (GB5), Kekerengu (EK3) and Wairarapa (CC2) are all permissible, suggesting the possibility that the entire >850-km-long fault system may have ruptured during a brief sequence of large-magnitude events. Such a wall-to-wall sequence involving rupture faults of different recurrence intervals, with the Wairarapa hosting events about every c. 1000 years [*Little et al.*, 2009] and other faults in the system hosting events about every ~300 years or less [*Langridge et al.*, 2013; *Khajavi et al.*, 2016; *Howarth et al.*, 2018; *Little et al.*, 2018, this study], highlights the importance of understanding fault connectivity and potential rupture patterns, such as those that occurred in the M_w=7.8 Kaikōura earthquake [*Litchfield et al.*, 2018].

Although the allowable age range of GB5 is quite long and could possibly belong to another, older rupture sequence, we think it unlikely that a rupture sequence rupturing from the Alpine to the Wairarapa would bypass the Conway segment, given its central role in transferring relative plate motion through northeastern South Island. Moreover, Coulomb failure function modeling shows that rupture on the Jordan fault system increases the likelihood of rupture on the Conway segment by 30% [*Robinson*, 2004], highlighting the strong relationship between these two faults. Given these kinematic arguments, we favor placing GB5 in sequence S4.

In the above interpretation of possible-sequence S4, we assume that events HS3, GB5, and EK3 ruptured within a short time of Alpine fault rupture A4 and Wairarapa fault rupture CC2, with preceding Alpine fault event A5 marked as an isolated event (Figure 7). However, it is equally allowable that events HS4, GB5, and EK3, rather than rupturing as part of a brief sequence involving A4, ruptured as part of a slightly older sequence involving A5, in which case A4 was likely an isolated event. If this slightly older sequence did occur c. 900-950 CE, it cannot have involved rupture of the Wairarapa fault in southern North Island, as event CC3 significantly post-dates event A5. The Alpine fault paleoseismic constraints for event A4 and A5 allow only one of these possibilities to be correct.

If sequence S4 did occur as is presented above and in Figure 7, it appears to have been preceded by a several hundred-year-long lull in potential sequence-like behavior. Specifically, although the Alpine fault ruptured in A5 (915—961 CE), potentially as an isolated, Alpine fault-only rupture, the preceding Alpine fault rupture A6 occurred between 592—646 CE. The Hope fault Hurunui segment record [*Khajavi et al.*, 2016] also suggests a long-duration lull during this interval prior to event HS4. The record is less clear for the remaining parts of the system to the northeast, as the age ranges of events on those faults permit multiple possible interpretations. For example, the long possible age range of GB5 spans the occurrence of possible-sequence S4, possible-sequence S5, and the intervening apparent lull. The only possible 100-year-long period during which the Alpine fault could potentially have ruptured during a brief sequence together with the Hope and Kekerengu faults occurred between 525 and 625 CE, encompassing A6, HS4, and EK4. As noted above, however, the potential age ranges of EK4 is quite long, yielding relatively low confidence in the occurrence of this possible-sequence S5. Given that the age range of GB5 is so long, and the fact that the eastern Kekerengu and Hope Shelter sites record multiple events over this time period, it remains a possibility that we are missing an additional event over the GB5 time interval. However, because we have not documented a separate GB event, we cannot assign an event at Green Burn to sequence S5 (note break in S5 pink box across GB domain on Figure 7).

Possible-sequence S6 is marked by rupture A7 on the Alpine fault and rupture HS5 on the Hurunui segment of the Hope fault. It is perhaps noteworthy that all of the possible later sequences encompass ruptures of both the Conway and Hurunui/Hope River segments of the Hope fault. Thus, while it is possible that there was an as-yet unrecorded surface-rupturing earthquake at Green Burn during possible-sequence S6, the Green Burn paleoseismic record does not preserve a separate event during this time, so this possibility must remain speculative.

Although the paleoseismic timing constraints are too imprecise in many instances to prove sequence-like behavior, the data are consistent with the possibility that large parts of the Al-Hp-JKN-Wr fault system commonly rupture in brief (i.e., ≤ 100 year) sequences of large-magnitude events. The available historical and paleoseismic records for the Hope, Kekerengu, and Wairarapa faults, however, indicate that such possible-sequences are not always simple, along-strike progressions of large-magnitude events. For example, the observation that the most recent surface ruptures along the Conway segment of the Hope fault and the Kekerengu fault occurred prior to European settlement, whereas the historical 1855 M_w~8.1 Wairarapa and 1888 M_w~7-7.3 Amuri earthquakes occurred to the northeast and southwest, respectively, indicates complex spatial patterns of earthquake occurrence. An obvious possible complicating factor in the occurrence of individual events during any possible-sequence is the occurrence of major earthquakes on other nearby faults, such as the close temporal relationship between the 1855 M_w~8.1 Wairarapa earthquake and the 1848 M_w~7.4-7.5 Awatere earthquake, which ruptured ~105 km of the Awatere fault north of the Hope fault [*Grapes et al.*, 1998]. Coulomb stress modeling of these two events, for example, indicates that stresses related to the 1848 earthquake elevated failure stresses along the future rupture plane of the 1855 event [*Pondard and Barnes*, 2010].

The fact that the c. 1000-1100 CE possible-sequence S4 is the only possible "wall-to-wall" sequence of its kind over the past >1,000 years suggests that while such system-wide behavior is possible, it is uncommon. Two of the past possible-sequences (S3 and S5) appear to have encompassed rupture of all faults from the Alpine fault in the southwest to the Kekerengu fault on the northeast, but neither of these possible-sequences extended across the Cook Strait onto the Wairarapa fault. This could simply reflect the slower rate of elastic strain accumulation and accommodation on the Wairarapa fault, inferred from its long recurrence interval compared to the South Island faults [e.g., *Little et al.*, 2009; *Litchfield et al*., 2018]. In contrast to possible-sequences S2, S3, S4, as noted above, sequence S1 encompassed ruptures of the Hope, Kekerengu, and Wairarapa faults, but did not include rupture of the Alpine fault. Thus, the individual sequences do not always conform to the same pattern of ruptures. Whereas the occurrence of individual events on the Al-Hp-JKN-Wr system is likely modulated by the occurrence of earthquakes on other faults, leading to different patterns of ruptures and rupture locations, the basic observation is that most large-magnitude earthquakes in the Al-Hp-JKN-Wr system over the past >1,000 years appear to have occurred as parts of relatively brief (≤~100-year-long) sequences.

The most recent earthquake generated within this plate boundary system, the 2016 M_w=7.8 Kaikōura earthquake, ruptured most of the Jordan-Kekerengu-Needles fault [*Litchfield et al.*, 2018; *Kearse et al.*, 2017], as well as other faults to the south of the Hope fault [*Nicol et al.*, 2018; *Williams et al.*, 2018], and likely parts of the subduction megathrust beneath northeastern South Island [*Duputel and Rivera*, 2017; *Hamling et al.*, 2017; *Hollingsworth et al.*, 2017; *Kaiser et al.*, 2017; *Litchfield et al.*, 2018; *Wen et al.*, 2018]. Interestingly, no other major ruptures have occurred on the plate-boundary fault system since the 1888 Mw~7-7.3 Amuri earthquake that ruptured the Hurunui and Hope River segments of the central Hope fault [*McKay*, 1890; *Khajavi et al.*, 2016]. Thus, the 2016 event was preceded by a 128-year-long lull in which the entire Alpine-Hope-Kekerengu-Wairarapa fault system remained dormant. It remains to be seen whether the complex, multi-fault 2016 Kaikōura event is a harbinger of a near-future sequence of large-magnitude earthquakes on the Al-Hp-JKN-Wr system, as occurred during previous possible-sequences S3 (c. 1500—1600 CE) and S5 (c. 525—625 CE). Alternatively, we have shown that some sequences may have included temporally and spatially isolated large-magnitude earthquakes (Is 1&3 on the Alpine fault, Is 2 on the Conway segment), and it is possible that the 2016 Kaikōura event is an isolated rupture. However, although simultaneous rupture of the specific faults that occurred during the Kaikōura event was a rare occurrence, due to involvement of the slow slip-rate faults in the North Canterbury District [*Nicol et al.*, 2018], as well as the Papatea fault [*Langridge et al.*, 2018] and Hundalee fault [*Williams et al.*, 2018], with large displacements on the Jordan-Kekerengu-Needles fault system [*Kearse et al.*, 2017]. Furthermore, post-Kaikōura Coulomb stress changes along the major plate boundary faults in northeastern South Island [*Hamling et al.*, 2017] suggest that the 2016 earthquake may presage another sequence along the Al-Hp-JKN-Wr to begin (S_o).

Although this study focuses on the paleoearthquake behavior of the fast-slipping strike-slip and oblique-slip faults of the Al-Hp-JKN-Wr system, the presence of the Hikurangi megathrust fault beneath these upper plate faults in northeastern South Island and southern North invites comparison with the paleoearthquake record inferred from off-fault studies of potentially co-seismic subsidence events in the area [*Clark et al.*, 2015, 2019]. The most proximal subsidence site to the upper-plate faults analyzed for this study is the Big Lagoon site ~35 km northwest of the Kekerengu-Needles fault system [*Clark et al.*, 2015] ("BL" on Figure 1, "Big Lagoon" on Figure 7). Clark et al. [2015] document two young subsidence events at Big Lagoon, one at 1433—1480 CE (520—470 yBP), and a second one at 1070—1150 CE (880-800 yBP); both events are marked by the abrupt deposition of marine mud above a paleosol, and the older event horizon is overlain by a sand that the authors interpret as a paleo-tsunami deposit. These authors infer that the subsidence events recorded at Big Lagoon are indicative of paleo-earthquakes on the Hikurangi subduction megathrust beneath southern North Island and northeastern South Island. If this is correct, the similarity in ages between their most-recent subsidence event (BL1) and possible-sequence S3 identified by our study (c. 1400—1500 CE), and their penultimate subsidence event (BL2) and our possible-sequence S5, suggests that the megathrust may sometimes rupture together with, or within a short time of, major rupture sequences on the Al-Hp-JKN-Wr system (blue vertical bars on Figure 7). Specifically, subsidence BL1 overlaps with event GB3 on the Conway segment, as well as events A2 on the Alpine fault, events MF3 and HS2 on the Hurunui—Hope River segments of the Hope fault and event EK2 from the Kekerengu fault during possible-sequence S3. Similarly, the age range of the penultimate Big Lagoon subsidence event BL2 overlaps with events A4, HS4, GB5, EK3 on Alpine and Hope faults, as well as event CC2 on the Wairarapa fault during possible-sequence S5, which is the only sequence that could represent a wall-to-wall rupture of the entire Al-Hp-JKN-Wr system. *Clark et al.,* [2015; 2019] noted the temporal overlap between the penultimate event on the Wairarapa fault (CC2) and the subsidence event recorded at Big Lagoon, and suggest that either the BL2 subsidence event was due to rupture that involved both the megathrust and the Wairarapa fault (as is postulated to have happened in the 1855 event of the Wairarapa fault [*Little et al.*, 2009]), or a situation where the Wairarapa and megathrust faults ruptured separately but in temporally closely spaced events. These observations suggest that, at least sometimes, the megathrust fault may rupture together with, or within a short time of, brief sequences of events on the Al-Hp-JKN-Wr upper plate fault system. It is worth noting, however, that if the Big Lagoon record is complete, significant slip on the shallow parts of the megathrust does not occur in every upper-plate system sequence.

Conclusions

We present new paleoearthquake ages using primary event evidence from the Green Burn reach of the Hope fault. We document the occurrence of five surface ruptures along the Conway segment of the Hope fault at two sites along the Green Burn (GB) reach of the fault. These earthquakes have occurred during the past c. 2000 years, with preferred 2σ event ages as follows:

GB1: 1731—1840 CE, GB2: 1657—1797 CE, GB3: 1496—1611 CE, GB4: 1290-1420 CE, GB5: 36 BCE–1275 CE. The new Green Burn data, together with other previously documented on-fault and off-fault paleo-earthquake age constraints from the various faults of the >850-km-long Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa system of fast-slipping plate-boundary faults in South Island and southern North Island, are consistent with the possibility that several of the Green Burn surface ruptures could have occurred during relatively brief (≤100 years) sequences that involved rupture of large sections of the fault system. However, the available data indicate that "wall-to-wall" rupture of the entire Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa system during brief sequences that ruptured all faults in the system must be a rare event. Indeed, the only possible such sequence occurred c. 1,000-1100 CE, during which all faults in the system, from the Alpine fault in the southwest, to the Wairarapa fault in the northeast, allowably ruptured during the same brief (≤100-year) time interval. Partial rupture of the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa fault system in the M_w=7.8 2016 Kaikōura earthquake may be a harbinger for future events within a potential new rupture sequence along the plate boundary (S_o), potentially involving the Conway segment of the Hope fault adjacent to the Jordan-Kekerengu-Needles system, and even the underlying Hikurangi subduction megathrust.

Acknowledgments

We thank Robert Langridge and Lise Alalouf for their assistance in the field, and Mark Koopman for permission to excavate our trenches at Hawk Hills Station. We are also grateful to Chanda Bertrand and John Southon at UC Irvine for their assistance with radiocarbon sample preparation and dating. The manuscript benefited from thoughtful reviews by Gregory

DePascale, Chris DuRoss, and Associate Editor Rich Briggs. This project was funded by the US National Science Foundation grants EAR-1321914 (Dolan) and EAR-1321912 (Rhodes), with additional funding provided by GNS Science.

Data and Resources

The background imagery used in Figure 1 is from GeoMapApp http://www.geomapapp.org [*Ryan et al.*, 2009]. Station metadata from KIKS sensor referenced in section "Coseismic origin of colluvial wedges and landslides observed at GBW/GBE: Observations of the Green Burn Reach following the 2016 M_w=7.8 Kaikōura earthquake" can be accessed at https://www.geonet.org.nz/data/network/sensor/KIKS (last accessed November 19, 2018) and associated shake maps from the 2016 M_w=7.8 Kaikōura earthquake can be accessed at https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i/shakemap/pgv (last accessed November 19, 2018). Lidar data was acquired by LINZ immediately following the M_w=7.8 Kaikōura earthquake; similar data is publically available for download from www.opentopography.org (DOI: 10.5069/G93J3B2J).

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Figure Captions

Figure 1: (a) Map of New Zealand with plate motion vectors [DeMets et al., 2010] WLG-Wellington, CHC-Christchurch. Red lines delineate major active faults of northern South Island and southern North Island. (b) Regional fault map showing Alpine fault, Marlborough fault system, and North Island faults. Conway segment of Hope fault is shown in yellow; yellow star denotes Green Burn study site (GB). Hope fault system includes Kelly fault, Hurunui segment, Hope River segment, Conway segment, and Seaward segment. KF-Kakapo fault, HB-Hanmer Basin, EF-Elliott Fault, JT-Jordan thrust, PF-Papatea fault, OhF- Ohariu fault, ClF-Cloudy fault, VnF-Vernon fault, WgF-Wellington fault, WrF-Wairarapa fault. Fault maps adapted from Langridge et al., [2016]. Circle with BL label marks Big Lagoon subsidence site [*Clark et al.,* 2015]. To view this figure in color, the reader is directed to the online version of this manuscript.

Figure 2: Location maps generated using lidar digital elevation model (DEM) collected by GNS Science/LINZ following the Mw=7.8 2016 Kaikōura earthquake. See Data and Resources for access to lidar data. (a) Hillshaded DEM of Green Burn stretch of Conway segment of Hope fault. GBW-Green Burn West (this study) (-42.396560°, 173.388838°), GBS-Green Burn Stream (Langridge et al., [2003]) (-42.395914°, 173.392075°), GBE-Green Burn East (this study) (-42.393212°, 173.405528°). (b) Hillshaded DEM with 50 cm contours at the Green Burn East site, showing the fault-perpendicular trench. Small landslides are denoted with gray outlines (ls). (c) Hillshaded DEM with 50 cm contours at the Green Burn West site, showing T-1 and T-2. Small landslides are denoted with gray outlines (ls). To view this figure in color, the reader is directed to the online version of this manuscript.

Figure 3: Composite field and photomosaic logs of GBE (a) East wall (inverted) and (b) West wall. Unadulterated photomosaic is presented in Figure S3, available in the electronic supplement to this article. Colluvial wedge deposits are denote in shades of purple, clay units are shades of brown, shear zones are shades of red, and marsh units are shades of blue. Pebbles and cobbles and distinctive orange clasts from unit CW2 were logged on photomosaics after field work. Radiocarbon ages are colored yellow for samples included in age models; gray samples were not included in the age model, but results are listed in Table 1. To view this figure in color, the reader is directed to the online version of this manuscript.

Figure 4: Log of west wall of GBW T1 atop photomosaic. Unadulterated photomosaic is presented in Figure S4, available in the electronic supplement to this article. Note landslide tip (opaque purple) atop paleosol (green) at northern end of the trench near between m 11 and 16. Radiocarbon sample used in age models are shown in yellow. To view this figure in color, the reader is directed to the online version of this manuscript.

Figure 5: Log of GBW T2. Unadulterated photomosaic is presented in Figure S5, available in the electronic supplement to this article. Landslide deposits are shown in light gray with purple outlines, and paleosol is gradational from blue to purple. Radiocarbon samples used in GBW age models are showing in yellow. To view this figure in color, the reader is directed to the online version of this manuscript.

Figure 6: OxCal derived age models. (a) GBE colluvial samples only, (b) GBE colluvial and south marsh samples, (c) GBE north marsh samples only, (d) GBW T2 only, (e) GBW T1 & T2. (f) Preferred age model, which incorporates GBE, GBW T1 and T2.

Figure 7: Events through time along the north-central Alpine, Hurunui (Hope), Conway (Hope) Kekerengu-Needles and Wairarapa faults. Top map shows faults with study sites labeled; see Table 3 for citations and age information. Individual event names are indicated with a capital letter for each site with a number as shown in Table 3. Bottom panel shows temporal length of events (2σ age range) with vertical gray bars. Horizontal pink-shaded boxes represent 100-year-long potential "clustered event" sequences (see text for explanation), and are label SX near each box. Horizontal blue-shaded boxes represent isolated earthquakes, and are labeled IsX near each box. Thin, horizontal, red bars represent known surface rupture earthquakes on the Al-Hp-JKN-Wr system, either in the historical period [McKay, 1890; Little et al., 2009; Khajavi et al., 2016; Kearse et al., 2017] or using tree ring disturbance analysis [Wells et al., 1999]. Paleoseismites recovered at Lake Ellery after 370 CE have poorly constrained rupture limits and may not have occurred on the central-northern Alpine fault [Howarth et al., 2016]. To view this figure in color, the reader is directed to the online version of this manuscript.

Table 1: Radiocarbon Information

Table 1: Radicarbon sample data for all dated samples along Green Burn reach. **Bold** typeface indicate inclusion of a sample into an age model (Figure 6).

Count	Sample Name	Strat Unit	fraction modern	±	$D^{14}C$ (‰)	±	14C age (BP)	±	Unmodeled Maximum Age (BCE/CE)	Unmodeled Minimum Age (BCE/CE)	Unmodeled Maximum Age (yBP)	Unmodeled Minimum Age (yBP)	Dated material
1	SF-1	CW3	0.9299	0.0017	-70.1	1.7	585	15	1394	1425	557	525	charcoal
2	**SF-2**	**CW3**	**0.9560**	**0.0020**	**-44.0**	**2.0**	**360**	**20**	**1496**	**1636**	**454**	**315**	**charcoal**
3	SF-3	CW3	0.9257	0.0014	-74.3	1.4	620	15	1320	1410	631	541	charcoal
4	SF-4	B2	0.8178	0.0021	-182.2	2.1	1615	25	417	568	1534	1382	wood
5	**SF-5a**	**M7**	**0.7805**	**0.0017**	**-219.5**	**1.7**	**1990**	**20**	**-42**	**115**	**1991**	**1835**	**wood**
6	**SF-5b**	**M7**	**0.7727**	**0.0019**	**-227.3**	**1.9**	**2070**	**20**	**-96**	**25**	**2045**	**1925**	**wood**
7	**SF-5c**	**M7**	**0.7724**	**0.0016**	**-227.6**	**1.6**	**2075**	**20**	**-99**	**23**	**2048**	**1927**	**wood**
8	**SF-6**	**nM1**	**0.8516**	**0.0015**	**-148.4**	**1.5**	**1290**	**15**	**684**	**862**	**1267**	**1088**	**seed**
9	**SF-7**	**nM2**	**0.8506**	**0.0016**	**-149.4**	**1.6**	**1300**	**15**	**681**	**857**	**1270**	**1094**	**seed**
10	**SF-8**	**nM2**	**0.8218**	**0.0014**	**-178.2**	**1.4**	**1575**	**15**	**473**	**587**	**1478**	**1363**	**wood**
11	**SF-9**	**nM2**	**0.8318**	**0.0014**	**-168.2**	**1.4**	**1480**	**15**	**595**	**648**	**1356**	**1302**	**plant fragment**
12	**SF-10**	**nM2**	**0.8157**	**0.0013**	**-184.3**	**1.3**	**1635**	**15**	**417**	**524**	**1533**	**1426**	**plant frond**
13	**SF-11**	**nM3**	**0.7818**	**0.0028**	**-218.2**	**2.8**	**1975**	**30**	**-46**	**196**	**1995**	**1755**	**seed**
14	**SF-12**	**nM4**	**0.7743**	**0.0015**	**-225.7**	**1.5**	**2055**	**20**	**-63**	**30**	**2012**	**1920**	**seed**
15	**SF-13**	**nM4**	**0.7692**	**0.0013**	**-230.8**	**1.3**	**2105**	**15**	**-137**	**-51**	**2086**	**2000**	**plant frond**
16	**SF-14**	**nM5**	**0.7627**	**0.0013**	**-237.3**	**1.3**	**2175**	**15**	**-350**	**-104**	**2299**	**2053**	**seed**
17	**SF-15**	**CW2**	**0.9531**	**0.0021**	**-46.9**	**2.1**	**385**	**20**	**1462**	**1627**	**489**	**323**	**charcoal + org rich mud**
18	**SF-16**	**CW2**	**0.9583**	**0.0016**	**-41.7**	**1.6**	**340**	**15**	**1505**	**1643**	**445**	**307**	**charcoal + org rich mud**
19	SF-18	CW2	0.9259	0.0019	-74.1	1.9	620	20	1319	1411	632	539	charcoal + org rich m
20	SF-19	CW2	0.9233	0.0021	-76.7	2.1	640	20	1312	1405	638	546	charcoal
21	**SF-21**	**M7**	**0.7682**	**0.0017**	**-231.8**	**1.7**	**2120**	**20**	**-195**	**-52**	**2144**	**2001**	**charcoal**
22	**SF-22**	**B1**	**0.5998**	**0.0010**	**-400.2**	**1.0**	**4105**	**15**	**-2838**	**-2488**	**4787**	**4437**	**charcoal**
23	**SF-23**	**B1**	**0.6426**	**0.0013**	**-357.4**	**1.3**	**3555**	**20**	**-1920**	**-1749**	**3869**	**3698**	**charcoal**
24	**SF-24**	**nM4**	**0.7572**	**0.0016**	**-242.8**	**1.6**	**2235**	**20**	**-362**	**-201**	**2311**	**2150**	**wood**
25	SF-25	B2	0.1256	0.0089	-874.4	8.9	16660	570	-19649	-16866	21598	18815	charcoal
26	SF-28	CW3	0.9316	0.0019	-68.4	1.9	570	20	1396	1436	554	515	charcoal
27	SF-29	CW5	0.9248	0.0016	-75.2	1.6	630	15	1319	1404	632	546	charcoal
28	SF-30	CW2	0.9241	0.0019	-75.9	1.9	635	20	1315	1406	635	544	charcoal

29	SF-31	CW1	0.9173	0.0014	-82.7	1.4	695	15	1292	1388	659	562	plant fragment
30	SF-32	CW5	0.5959	0.0016	-404.1	1.6	4160	25	-2871	-2576	4820	4525	charcoal
31	**SF-33**	**CW1**	**0.9807**	**0.0020**	**-19.3**	**2.0**	**155**	**20**	**1680**	**…**	**270**	**...**	**wood**
32	**SF-34**	**CW1**	**0.9820**	**0.0020**	**-18.0**	**2.0**	**145**	**20**	**1691**	**…**	**259**	**...**	**charcoal**
33	SF-3536	CW2	0.9169	0.0018	-83.1	1.8	695	20	1288	1390	663	560	charcoal
34	SF-37	M1	0.9287	0.0025	-71.3	2.5	595	25	1322	1430	628	520	charcoal + org rich m
35	SF-38	M4	0.9065	0.0031	-93.5	3.1	790	30	1220	1296	730	655	plant fragment
36	SF-39	M3	0.9729	0.0034	-27.1	3.4	220	30	1647	...	304	...	wood fiber
37	SF-40	M3	0.9022	0.0019	-97.8	1.9	825	20	1220	1276	730	674	plant fragment
38	**SF-41**	**CW4**	**0.9113**	**0.0019**	**-88.7**	**1.9**	**745**	**20**	**1273**	**1380**	**678**	**571**	**charcoal**
39	SF-42	M3	0.9759	0.0026	-24.1	2.6	195	25	1664	...	286	...	plant fragment
40	SF-43	M5	0.8584	0.0019	-141.6	1.9	1225	20	772	956	1179	995	wood
41	SF-44	M5	0.8374	0.0025	-162.6	2.5	1425	25	604	681	1346	1270	wood
42	SF-45	M4	0.9428	0.0021	-57.2	2.1	475	20	1431	1480	520	470	plant fragment
43	SF-46	M4	0.9398	0.0019	-60.2	1.9	500	20	1423	1456	528	494	wood
44	**SF-48**	**nM1**	**0.8555**	**0.0015**	**-144.5**	**1.5**	**1255**	**15**	**772**	**880**	**1179**	**1070**	**wood**
45	LS2-2	P3 (top)	0.8556	0.0024	-144.4	2.4	1255	25	693	891	1257	1060	wood
46	**LS2-4**	**P1 (base)**	**0.9788**	**0.0019**	**-21.2**	**1.9**	**170**	**20**	**1672**	**...**	**278**	**...**	**plant**
47	**LS2-5**	**P2 (top)**	**0.9772**	**0.0043**	**-22.8**	**4.3**	**185**	**40**	**1665**	**...**	**286**	**...**	**wood**
48	LS2-6	P1 (top)	1.3882	0.0032	388.2	3.2	Modern	--	--	--	--	--	plant
49	**LS2-9**	**P3**	**0.8981**	**0.0018**	**-101.9**	**1.8**	**865**	**20**	**1184**	**1267**	**767**	**683**	**seed**
50	LS2-11	L3	0.8842	0.0017	-115.8	1.7	990	20	1032	1151	919	800	wood
51	HL16-3	paleosol atop ls tip	1.0522	0.0072	52.2	7.2	Modern	--					seed
52	**HL16-4**	**paleosol below ls tip**	**0.9324**	**0.0020**	**-67.6**	**2.0**	**560**	**20**	**1400**	**1439**	**551**	**512**	**charcoal**
53	HL16-7	silt below ls tip	0.3706	0.0010	-629.4	1.0	7975	25	-7030	-6686	8979	8635	charcoal

Table 2: Paleoearthquake age ranges for all age models presented for Green Burn record. Negative ages represent BCE.

	GBE+GBW (preferred)		**GBW T1 & T2**		**GBW T2 only**		**GBE colluvial and so. marsh**		**GBE colluvial only**		**GBE north marsh**	
Event	*Minimum age (CE)*	*Maximum age (CE)*	*Minimum age (CE)*	*Maximum age (CE)*	*Minimum age (CE)*	*Maximum age (CE)*	*Minimum age (CE)*	*Maximum age (CE)*	*Minimum age (CE)*	*Maximum age (CE)*	*Minimum age (CE)*	*Maximum age (CE)*
GB1	1731	1840	1722	1840	1728	1840	1722	1840	1722	1840	--	--
GB2	1657	1797	1669	1806	1668	1806	1558	1724	1558	1724	--	--
GB3	1495	1611	1415	1711	1225	1685	1495	1610	1495	1610	--	--
GB4	1290	1420	--	1440	--	--	1288	1532	1288	1532	--	--
GB5	-36	1275	--	--	--	--	-36	1277	-61	1277	--	--

Table 3: Two-sigma age ranges of plate boundary paleo-event plotted in Figure 7

Fault	Event	Minimum age (CE)	Maximum age (CE)	Preferred sequence	Reference
Alpine	A1	1717	--	S2	Wells et al., 1999; Howarth et al., 2012; 2014; 2016; 2018
	A2	1549	1594	S3	
	A3	1388	1407	Is1	
	A4	1008	1213	S4	
	A5	915	961	Is3	
	A6	592	646	S5	
	A7	370	416	S6	
Hope (Hurunui)	MF1	1888	--	S1	Langridge et al., 2013
	MF2	1652	1840	S2	
	MF3	1630	1424	S3	
Hope (Hurunui)	HS1	1888	--	S1	Khajavi et al., 2016
	HS2	1818	1840	S2	
	HS3	1233	1735	S3	
	HS4	821	1100	S4	
	HS5	439	587	S5	
	HS6	375	428	S6	
Hope (Conway)	GB1	1730	1840	S1	This study
	GB2	1657	1797	S2	
	GB3	1495	1611	S3	
	GB4	1230	1277	Is2	
	GB5	476	1240	S4	
	GB6	476	1240	S5	
eastern Kekerengu	EK0	2016	--	N/A	Little et al., 2018
	EK1	1701	1840	S1	
	EK2	1422	1594	S3	
	EK3	701	1047	S4	
	EK4	224	857	S5	

Wairarapa	CC1	1855	--	S1	Little et al., 2009
	CC2	1030	1150	S4	