Article:

1 **A 2000-year paleoearthquake record along the Conway segment of the Hope**

2 **fault: Implications for patterns of earthquake occurrence in northern South**

3 **Island and southern North Island, New Zealand**

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16   **<u>Abstract</u>**

17   Paleoseismic trenches excavated at two sites reveal ages of late Holocene earthquakes along the

18   Conway segment of the Hope fault, the fastest-slipping fault within the Marlborough fault

19   system in northern South Island, New Zealand. At the Green Burn East site (GBE), a fault-

20   perpendicular trench exposed gravel colluvial wedges, fissure fills, and upward fault

21   terminations associated with five paleo-surface ruptures. Radiocarbon age constraints indicate

22   that these five earthquakes occurred after 36 BCE, with the four most recent surface ruptures

23   occurring during a relatively brief period (550 years) between c. 1290 CE and the beginning of

24   the historical earthquake record c.1840 CE. Additional trenches at the Green Burn West site

25   (GBW) site 1.4 km west of GBE reveal four likely co-seismically generated landslides that

26   occurred at approximately the same times as the four most recent GBE paleoearthquakes,

27   independently overlapping with age ranges of events GB1, GB2, and GB3 from GBE.

28   Combining age constraints from both trench sites indicates that the most recent event (GB1)

29   occurred between 1731–1840 CE, the penultimate event GB2 occurred between 1657-1797 CE,

30   GB3 occurred between 1495-1611 CE, GB4 occurred between 1290-1420 CE, GB5 between 36

31   BCE and 1275 CE. These new data facilitate comparisons with similar paleoearthquake records

32   from other faults within the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa (Al-Hp-JKN-

33   Wr) fault system of through-going, fast slip rate (≥10 mm/yr) reverse-dextral faults that

34   accommodate a significant portion of Pacific-Australia relative plate boundary motion. These

35   comparisons indicate that combinations of the faults of the Al-Hp-JKN-Wr system may

36   commonly rupture within relatively brief, ≤~100-year-long sequences, but that full "wall-to-

37   wall" rupture sequences involving all faults in the system are rare over the span of our

38 paleoearthquake data. Rather, the data suggest that the Al-Hp-JKN-Wr system may commonly

39 rupture in sub-sequences that do not involve the entire system, and potentially, at least

40 sometimes, in isolated events.

41

42 **<u>Introduction</u>**

43   Documenting patterns of large-magnitude earthquake occurrence in space and time is of

44 critical importance for both seismic hazard assessment and a deeper understanding of the

45 mechanics of plate boundaries. Earthquake recurrence on individual faults has been shown to

46 exhibit a wide variety of behaviors, from periodic [e.g., *Berryman et al.*, 2012], to quasi-periodic

47 [e.g., *Weldon et al.*, 2004; *Scharer et al.*, 2007] to clustered [e.g., *Marco et al.*, 1996; *Dawson*,

48 2003; *Hartleb et al.*, 2003, 2006; *Kozacı et al.*, 2010; *Ferry et al.*, 2011; *Wechsler et al.*, 2014].

49 Most plate boundaries, however, exhibit multiple major faults that collectively operate as

50 mechanically integrated fault systems. Thus, to understand the mechanics of earthquake

51 occurrence along a plate boundary, it is necessary to document the spatial and temporal

52 earthquake behavior of the primary, fast-slipping faults that make up the plate boundary.

53   To complete plate boundary system earthquake behavior analysis, we study the fastest-

54 slipping strike-slip faults of the Australian-Pacific plate boundary of the northern South Island

55 and southern North Island of New Zealand, where previous studies have documented patterns of

56 earthquake recurrence on many of these major faults [e.g., *Cooper and Norris*, 1990; *Wells et*

57 *al.*, 1999; *Langridge et al.*, 2003, 2013; *Mason et al.*, 2006; *Sutherland et al.*, 2007; *Little et al.*,

58 2009; *Van Dissen and Nicol*, 2009; *Berryman et al.*, 2012a, 2012b; *De Pascale and Langridge*,

59 2012; *Howarth et al.*, 2012, 2014, 2016; *Clark et al.*, 2013, 2015; *Nicol et al.*, 2016; *Khajavi et*

60 *al.*, 2016; *Cochran et al.*, 2017; *Nicol and Dissen*, 2018]. The Hope fault, the subject of this

61 manuscript, is the central link between high slip-rate faults to the southwest (Alpine fault) and

62 northeast (Jordan-Kekerengu-Needles fault and the Wairarapa fault in southern North Island).

63 This >850-km-long system (Alpine fault through to Wairarapa fault) of dextral strike-slip and

64 oblique reverse-dextral faults accommodates the majority of the ~39 mm/yr of relative Pacific-

65 Australia plate boundary motion in central and northern South Island [*DeMets et al.*, 2010;

66 *Wallace et al.*, 2012], with the exception of the Wairarapa fault, which, together with the

67 BooBoo and Needles faults, serves to connect the Marlborough Fault System from South Island

68 to North Island (Figure 1). Although the Wairarapa fault slips at about half the rate of the South

69 Island faults, the Wairarapa fault carries the predominant portion of onshore slip of the plate

70 boundary in southern North Island.

71   In central South Island, much of the relative plate motion is accommodated on the

72 oblique reverse-dextral Alpine fault, with a right-lateral strike-slip rate of 23-27 mm/yr

73 [*Berryman*, 1992; *Norris and Cooper*, 2001; *Sutherland et al.*, 2006]. At ~42.8°S, 171.5°E the

74 Alpine fault splays northeastward into multiple parallel, predominantly dextral strike-slip faults,

75 referred to collectively as the Marlborough Fault System (MFS) (Figure 1). The four major faults

76 of the MFS are, from north to south, the Wairau, Awatere, Clarence and Hope faults. Within the

77 MFS, the southernmost Hope fault, with a slip rate of ~20-25 mm/yr, accommodates more than

78 half of the total relative plate motion [*Van Dissen*, 1989; *McMorran*, 1991; *Van Dissen and*

79 *Yeats*, 1991; *Langridge et al.*, 2003; *Stirling et al.*, 2012; *Hatem et al.*, 2016], with most of the

80 remaining ~15-20 mm/yr occurring on the other main MFS faults [*Van Dissen*, 1989; *Van Dissen*

81 *and Yeats*, 1991; *Holt and Haines*, 1995; *Walcott*, 1998; *Wallace et al.*, 2007, 2012; *Litchfield et*

82 *al.*, 2014; *Reyners*, 2018]. Along the east-central part of the Hope fault, the 65-km-long Conway

83 segment, the focus of this study, is structurally bounded between the transtensional Hanmer

84   Basin to the west [*Wood et al.*, 1994] and the transpressional Jordan fold and thrust belt to the

85   east [*Van Dissen*, 1989; *Van Dissen and Yeats*, 1991]. At the northeastern end of the Conway

86   segment, the Hope fault transfers slip northeastward onto the Jordan thrust system and its

87   northeastward extension, the Kekerengu fault, which has a dextral slip rate of ~ 25 mm/yr [*Van*

88   *Dissen et al.*, 2016]. Farther to the northeast, the Kekerengu fault extends offshore into Cook

89   Strait as the Needles fault [*Barnes and Audru*, 1999; *Kearse et al.*, 2017], transferring dextral

90   slip northward onto the BooBoo and Wairarapa faults, the latter of which has a slip rate of ~11

91   mm/yr, in southern North Island [*Little et al.*, 2009; *Pondard and Barnes*, 2010]. Thus, the

92   Alpine, Hope, Jordan, Kekerengu, Needles, and Wairarapa faults (Al-Hp-JKN-Wr) constitute a

93   >850-km-long, through-going system of fast-slip rate (≥ 10 mm/yr) dextral and oblique reverse-

94   dextral faults that collectively serve to accommodate the majority of Australia-Pacific relative

95   plate motions at their respective locations. Of the major faults comprising the Al-Hp-JKN-Wr

96   system, only the Alpine fault and the Conway segment of the Hope fault have not generated a

97   surface-rupturing earthquake during the historical period, which began with European settlement

98   c.1840 CE.

99   Whereas a >2,000-year-long paleoearthquake record has been documented for the Alpine

100 fault [*Berryman et al.*, 2012b; *Howarth et al.*, 2012, 2014, 2016; *Clark et al.*, 2013; *Cochran et*

101 *al.*, 2017; see *Howarth et al.,* 2018 for review], the paleoearthquake record of the Conway

102 segment of the Hope fault is not well documented beyond an approximate age of the most recent

103 event [*Langridge et al.*, 2003]. In this study, we document and provide age constraints for at least

104 the five most recent events along the Conway segment. These new data facilitate comparisons of

105 earthquake occurrence in time and space on other faults within the Al-Hp-JKN-Wr fault system,

106 providing insight into the system-level behavior of these major plate-boundary faults. Such

107 comparisons have important implications for understanding seismic hazard in New Zealand, and

108 more generally, for understanding the spatial and temporal earthquake behavior of similar fault

109 systems around the world.

110

111 **The Green Burn East and Green Burn West study sites**

112   The Green Burn study area is located on the eastern part of the Conway segment of the

113 Hope fault (Figure 1). Along the Green Burn reach, the Hope fault is generally expressed as a

114 linear, single fault trace that, along much of this stretch, extends along the northern base of a

115 sequence of ~4-8-m-high shutter ridges that are located ~50 m to the south of and sub-parallel to

116 the main, south-facing mountain front (Figure 2). The presence of these shutter ridges,

117 particularly at our study sites, causes sediment to pond to the north, resulting in fault-parallel

118 marshes between the fault and the mountain front to the north. The shutter ridges at our trench

119 sites appear to be long-lived features, as reconstruction of ~200 m of right-lateral Hope fault slip

120 restores a prominent, NNW-trending reach of a stream that has deeply incised through the shutter

121 ridge at Green Burn East (see figure S1 available in the electronic supplement to this article for

122 reconstructions of this offset).

123   Langridge et al. [2003] conducted paleoseismic investigations on this stretch of the Hope

124 fault at the Green Burn Stream (GBS) site (-42.395914°, 173.392075°) (Figure 2A). They used

125 greywacke cobble weathering-rind thickness age estimates (a semi-quantitative geochronometer

126 specific to New Zealand [*Knuepfer*, 1988]) to suggest that the most recent event (MRE) at their

127 site occurred c. 1780 ± 60 CE. Additionally, radiocarbon ages show that the penultimate surface

128 rupture occurred after 1295 CE and before the beginning of the historic era in this part of New

129 Zealand (c. 1840).

130   In the current study, we excavated trenches at two localities, one to the east (Green Burn

131   East [GBE]) (Figure 2B), and another to the west (Green Burn West [GBW]) (Figure 2C, figure

132   S2 available in the electronic supplement) of the original Langridge et al. [2003] GBS

133   excavations. We selected the GBE and GBW sites using air photo analyses and reconnaissance

134   field mapping. These new excavations allow us to extend the paleoearthquake record further

135   back in time and to place tighter constraints on the timing of late-Holocene Conway segment

136   Hope fault surface ruptures.

137   At the GBE site (-42.393212°, 173.405528°), we excavated a 14-m-long, 1.5-m-deep,

138   fault-perpendicular trench across the Hope fault that extended from the northern slope of the

139   local shutter ridge/scarp northward into the ponded marshy area to the north (Figure 2B). We

140   selected GBE as a paleoseismic trench site with the hypothesis that during surface ruptures,

141   colluvial wedges would be shed northward off the scarp and deposited downslope across the

142   surface rupture trace and into the marsh deposits to the north, possibly with interfingering

143   relationships between colluvial and organic-rich marsh deposits, dateable by radiocarbon, that

144   would help refine event ages (Figure 3). The GBE trench was field logged on grid paper at a

145   scale of 1:20. We also created high-resolution photomosaics of the trench walls using Agisoft

146   Photoscan photogrammetry software [*Bemis et al.*, 2014], which not only provides an archive of

147   the trench exposures (see Supplementary Information Figure S3), but also facilitated detailed

148   mapping of the finer-scale features once out of the field; this additional mapping focused on

149   documenting clast size and distribution within the colluvial wedges observed at the GBE site.

150   At the GBW site (-42.396560°, 173.388838°), we excavated a 16-m-long, 1.5-m-deep

151   trench (T-1) that extended northward from the local shutter ridge into a flat, marshy area at the

152   base of a steep, landslide-prone slope (Figure 2C). We also excavated a short (1.7-m-long) 1.5-

153   m-deep trench (T-2) located ~25 m north of the fault at the base of the steep, landslide-prone

154   slope, ~7 m NNW of the northern end of the T-1 trench (Figure 2C). The GBW T-1 trench was

155   designed to capture colluvial wedge deposition along with primary surface rupture indicators

156   within the fault zone, as well as any possible long-runout landslides exposed in the northern end

157   of the trench. GBW T-2 pit was excavated closer to the base of the landslide-prone slope to

158   intercept more proximal paleo-landslide events that might have been shed off the mountain front

159   during Hope fault surface rupturing earthquakes. Supplementary Figure S2 shows the shutter

160   ridge to the south (left in the image) and landslide-prone slope of the main south-facing

161   mountain front (right in the image). Previous reconnaissance mapping and trenches [e.g.,

162   *Langridge et al.,* 2003] demonstrated that much of the Green Burn reach of the Conway segment

163   is affected by moderate- to shallow-seated landsliding, where the mountain front can collapse

164   toward the fault zone. Such co-seismic, fault-controlled, landsliding was a common feature in

165   northeastern South Island during to the 2016 M_w=7.8 Kaikōura earthquake [*Langridge et al.*,

166   2018; *Massey et al.*, 2018]. As with the GBE trench, we mapped the GBW trench exposures in

167   detail, creating a 1:20 scale log of T-1 and a graphic strat column of T-2 in the field, and also

168   created high-resolution photomosaics of the trench walls (Supplementary Information Figures 4

169   and 5).

170

171   **Trench Results**

172   **Green Burn East (GBE) trench observations**

173   The northern part of the GBE trench revealed a sequence of organic-rich silts, clays, and

174   layers of compressed grasses/plants that we interpret as having been deposited in a marsh

175   environment (M units) (Figure 3). In the southern part of the trench, clastic sediments comprising

176   the scarp (CW units) overly basal silts and clays (B units) (Figure 3). The upper part of the scarp

177   sequence consists of a series of pebble to large cobble gravel-rich units interpreted to be colluvial

178   wedges, referred to as CW1 (youngest) to CW5 (oldest), as well as an older, potential colluvial

179   wedge (CW6) that could not be confidently attributed to a specific paleoearthquake at GBE.

180   These wedges were shed northward down the slope of the scarp from the main exposures of the

181   Hope fault zone near the southern end of the trench. The colluvial gravel clasts, which are

182   generally set within a silt to medium-grained sand matrix, consist almost exclusively of Torlesse

183   greywacke, typical of bedrock exposures in this part of New Zealand [*Rattenbury et al.*, 2006].

184   The gravel clasts are typically sub-angular to sub-rounded and range in size from an average of

185   ~5-11 cm to a maximum diameter of 20 cm. The colluvial gravels were derived from older

186   alluvial gravels that locally mantle the shutter ridge scarp a few meters above and south of the

187   southern end of the GBE trench. The colluvial wedges were differentiated from each other on the

188   basis of variations in predominant clast size, weathering, abundance and type of matrix, and, in

189   several instances, the presence of a prominent basal cobble layers that we interpret as mantling

190   the ground surface at the time of deposition of each wedge. In general, the overall clast size and

191   packing-density in the colluvial wedges increase downslope, reaching a maximum at their distal

192   ends adjacent to the marsh deposits. The distal, northernmost toes of some of the colluvial

193   wedges locally interfinger with marsh deposits (M units – described below) beneath the southern

194   toe of the scarp. Table S1 (available in the electronic supplement to this article) provides all

195   stratigraphic descriptions made in the field.

196   Beneath the colluvial wedges, the scarp is composed of highly sheared, locally highly

197   indurated clay to clayey-silt units (B units). These basal clays are virtually clast free and

198   typically massive, with limited discernible internal bedding. We differentiated three distinct units

199   (B1 [youngest] to B3 [oldest]) on the basis of clay to silt ratio, color, and degree of induration.

200   B3, the most sheared and indurated of these units, may be deformed Torlesse bedrock. All of the

201   scarp-derived colluvial wedges were deposited atop the basal clays; the base of the marsh (M)

202   units in the northern part of the trench was not reached, and B units were not exposed north of ~

203   m 4 (Figure 3).

204   The generally massive marsh (M) units in the northern part of the trench consist of

205   organic-rich silts, peats, and compressed marsh plant layers. In general, the marsh deposits dip

206   gently to the south (i.e., towards the scarp), consistent with a long-term, minor, down-to-the-

207   north (i.e., mountain side down) component of vertical motion along the predominantly dextral

208   Hope fault exposed in the southern end of the trench. The marsh deposits contained individual

209   seeds, grass blades in growth formation, and plant leaves/fronds and other macroflora indicative

210   of *in situ* deposition within the marsh, as well as detrital charcoal and wood fragments. The

211   marsh deposits were generally clast free, and showed no obvious sedimentary structures.

212   Stratigraphic delineations were made on the basis of color, wetting characteristics, firmness, silt

213   content, and the presence or absence of plant material.

214   Although some of the scarp-derived colluvial wedges do locally interfinger with the

215   southern ends of the marsh strata, especially near the top and base of the trench (e.g., CW2 and

216   M1; CW5 and M5-6), in general the northern marsh deposits and the southern scarp-derived

217   deposits are separated into distinct stratigraphic and depositional sequences by a ~1.5- to 2-m-

218   wide zone (~m 5–m 7 on the trench logs) of complex stratigraphy associated with a wood mass

219   that may be a paleo-tree or trees that were either growing at the base of the scarp or fell along the

220   base of the scarp (Figure 3). We could not correlate stratigraphic units across this wood-rich

221   zone, and as we discuss below, upon dating the northern marsh section using apparently *in situ*

222   seeds, leaves, and other plant material, we observed a large mismatch in age between the ages of

223   the marsh units north of the wood-rich zone and the younger colluvial and marshy deposits to the

224   south at similar depths (see Age Control section). Because we cannot correlate units either

225   stratigraphically or chronologically across this mass of wood, we do not utilize the northern

226   marsh stratigraphy in the age determinations of scarp-preserved events (GB1-GB5), as all of the

227   sedimentological and structural evidence for the five most-recent paleo-surface rupture at GBE

228   comes from the southern part of the trench, south of the wood-rich zone. We present the detailed

229   logs for the southern eight meters of the trench in Figure 3 to highlight these relationships. North

230   of the section of the trench exposure shown in Figure 3, the marsh units became massive and

231   increasingly difficult to log with any certainty. Photomosaics of the full trench exposures of GBE

232   are presented in Supplemental Figure 3, available in the electronic supplement to this article.

233   The Hope fault through the GBE trench is expressed as a 5-m-wide zone comprising five

234   main fault strands, denoted as F1 (farthest south) to F5 (farthest north) between m 0 and m 5.

235   The faults extend upward through the basal units and locally extend through (or are overlain by)

236   the colluvial wedge gravels. Fault F1 dips steeply to the north, F2 is near vertical, F3 generally

237   dips steeply to the south, F4 dips variably northward, and F5 dips more shallowly to the north.

238   Most of these main faults exposed at the base of the trench splay upwards into subsidiary strands.

239   The steeply north-dipping, southernmost, scarp-bounding fault (F1), separates the pervasively

240   sheared, highly indurated local clay bedrock (B3) from the somewhat less-indurated basal

241   clayey-silt layers B1 & B2, along with the colluvial wedges that overlie B1-3. Several of the

242   Hope fault strands, particularly F1-F3, exhibit large, upward-opening fissure fills and local

243   graben-like down-dropped blocks. In addition, basal unit B2 is locally tightly folded between

244   strands F1 and F2, best observed on the east wall. The fault zone between meters 1.5 and 3.5,

245 encompassing strands F2-F5, represents a wide, somewhat distributed shear zone, in which

246 stratigraphy is less well expressed in the basal units which exhibit a locally pervasive, steeply

247 dipping shear fabric, interpreted here as being indicative of relatively distributed shearing.

248

249   **Evidence for Paleo-surface ruptures**

250   In the following section, we describe structural and stratigraphic evidence for the five

251 most-recent surface ruptures (events GB1-GB5, from youngest to oldest).

252   Event 1 (GB1)

253   Event GB1, the most recent event (MRE) observed in the GBE trench, is marked by both

254 the deposition of colluvial wedge CW1 and the upward terminations of faults F1b and F1c at the

255 base of CW1 on the eastern wall. Most of the strike-slip in event GB1 likely occurred along

256 fault F1a, but this fault does not directly interact with CW1; instead, fault F1a terminates at the

257 base of the A horizon on the East Wall near m 0. Faults F1b and F1c form a small graben into

258 which CW1 was deposited either cosesimically or soon after slip in GB1. Another small graben

259 was formed between a potential additional splay fault near m 0 and fault F1b. Both of these

260 grabens were filled with by CW1 gravels. Colluvial wedge CW1 is a pebbly gravel, with a black

261 to dark brownish-gray silt to medium-grained sand matrix, which is overlain by the generally

262 clast-free, thin, active surface soil A horizon. The unit extends downslope from between m 0 and

263 1 to the base of the scarp at m 5, where it interfingers marsh unit M1 (Figure 3).

264

265   Event 2 (GB2)

266   Event GB2, the penultimate event observed in GBE trench, is recorded by deposition of

267 colluvial wedge unit CW2 and upward termination of fault F4 at m 2.8 on west wall at the base

268   of CW2 (Figure 3). Unit CW2 is a clast-supported, pebble (clast size 0.5-2 cm) gravel consisting

269   of sub-rounded graywacke clasts in a gray to black silt to fine-grained sand matrix. CW2 is

270   markedly different from overlying CW1, and is distinguished from CW1 by its greater clast

271   content. Additionally, CW2 is marked by a predominance of distinctive orange, highly

272   weathered, friable clasts that were not observed in any other unit in the GBE trench. These

273   distinctive clasts also had a higher sand content than the generally finer-grained Torlesse

274   greywacke clasts found in all of the other colluvial wedges we observed. The presence of these

275   distinctive clasts in CW2, and their absence in all other scarp-derived colluvial gravels in the

276   GBE trench, suggests that a small exposure of this source rock was first exposed in the fault

277   scarp during event GB2, and was moved right laterally away from the trench locality by strike

278   slip during GB1, leaving only typical older gray-colored Torlesse pebble and cobble alluvium

279   exposed along the top of the shutter ridge above the trench during the MRE. In contrast to

280   colluvial wedge CW1, colluvial wedge CW2 is only exposed on the lower, distal (northern) part

281   of the slope. In addition to the presence of the distinctive colluvial wedge, event GB2 is marked

282   by the presence of a small fault block with CW2 colluvium associated with the upward

283   termination of fault F4 (splays 4a and 4b), best expressed at ~ m 2.8 on the eastern wall (Figure

284   3).

285

286   Event 3 (GB3)

287   Event GB3 is marked by not only the deposition of colluvial wedge CW3, but also the

288   opening of a large fissure between faults F1a and F1b that was filled with CW3 colluvium at the

289   south end of the trench between ~ m 0 and 1 (east wall), and folding and faulting of older units

290   (B2, CW4, CW4a) onto which colluvial wedge CW3 was deposited. Unit CW3 is a clast-

291 supported gravel characterized by numerous large (8-10 cm), sub-angular cobbles within a gray

292 to pale brown, medium-grained sand to clay matrix. Unit CW3 does not contain any of the sandy

293 orange clasts that characterize CW2. In the northern, downslope extent of CW3, we differentiate

294 a subunit (CW3a), which is similar to CW3 in matrix composition but is relatively clast poor.

295 Unit CW3 is the largest colluvial wedge observed in this trench, and was sourced from a scarp

296 created during slip on the well-defined, southernmost fault F1. A cobble layer extends along and

297 defines the base of CW3. Unit CW3 is not continuous along the length of the trench exposure,

298 pinching out between m 2 and m 4, where colluvial wedge CW2 was deposited directly on

299 underlying unit CW4 (Figure 3). This preserved geometry of CW3 may be due to discontinuous

300 lateral deposition of CW3, and then subsequent strike-slip of CW3 along fault F4 in event GB2,

301 which could juxtapose different portions of the CW3 deposit, therefore yielding the observed

302 pinch-out of CW3. At the base of the scarp, the distal part of unit CW3 locally interfingers with

303 marsh deposits M1-M3 near m 5. CW3 gravel also fills a small fissure formed by faults 2c and

304 2d terminating at the top of unit CW4/4a near m 1.8 on the east wall. Additionally, folding of

305 units CW4 and CW4a between ~ m 0.5 and 1.5 likely also occurred during surface rupture GB3.

306 Collectively, these observations underscore the extensive structural disruption and the large

307 volume of the CW3 colluvial wedge relative to the other colluvial wedges observed at GBE.

308

309   <u>Event 4 (GB4)</u>

310   Event GB4 is marked by the deposition of colluvial wedge CW4, by infilling of fissures

311 that opened in the GB4 surface rupture with CW4 cobble colluvium, and by upward termination

312 of fault F2a at the base of the CW4 colluvial wedge, best observed on the east wall. Unit CW4 is

313 a clast-supported colluvial gravel, with a dark brown to gray, medium-grained sand to silt matrix

314 among sub-angular to angular pebble to cobble clasts (max 12 cm). In the southern, upslope part

315 of CW4, we differentiate a subunit (CW4a) that is generally similar to CW4, with a similar

316 matrix, but which has far fewer cobbles and is slightly paler in color.

317   The distal, downslope end of unit CW4 terminates against marsh units M4 and M5, as

318 best observed on the east wall. Although in the eastern wall exposure this contact suggests minor

319 interfingering between the CW4 wedge and M3/5, on the western wall the contact is marked by a

320 near-vertical stone line where the colluvial wedge is juxtaposed with the marsh deposits. This

321 relationship is markedly different than the distal end of underlying unit CW5 (described below),

322 which extends farther out into the marsh.

323   Unit CW4 is folded and faulted in multiple places, and several fissures opened in this

324 event. Specifically, faulting from event GB4 opened fissures near m 1.3 and m 2.6 that were

325 filled with CW4 colluvium. The large fissure that opened along fault F2 at m 1.3 has an

326 accumulation of large cobbles (max 20 cm) exposed near the base of the fissure fill on the

327 eastern wall, consistent with filling of an open cavity. Similarly, the smaller fissure that opened

328 between faults 3c and 3d at ~m 2.6 also has larger clasts near the base of the fissure, although

329 these clasts were smaller (large pebbles) than the clasts at the base of the m 1.3 fissure fill. In

330 both fissure fills, the clasts exhibited sub-vertical alignments sub-parallel to the fault-formed

331 free-faces that once bounded the fissures.

332

333   Event 5 (GB5):

334   Event GB5 is marked by the deposition of the colluvial wedge CW5, which is a clast-

335 supported pebble to cobble gravel with a medium brown, fine-grained sand to silt matrix, as well

336 as pervasive shearing of CW5 not affecting younger units (e.g., CW4). This distributed shear

337   zone is preserved at ~m 2.5 - 3.5 on the eastern wall, where the stratigraphy becomes difficult to

338   differentiate between CW5 and undifferentiated sheared silty gravels. The shape of unit CW5 is

339   similar to the overlying colluvial wedges, consistent with these gravels having been shed

340   northward down the scarp and out into the marsh. Unit CW5 appears to have been shed off the

341   northernmost fault zone (F4 on the eastern wall), and cannot be traced further southward towards

342   the top of the scarp. At its distal end, the CW5 colluvial wedge is deposited on top of thinly

343   bedded, organic-rich rich silt unit M6. This is particularly clear on the east wall of the trench,

344   where the CW5 gravel extends northward beneath the peat-like, compressed grasses that make

345   up unit M5, and overlies the older marsh unit M6. These relationships indicate that deposition of

346   CW5 pre-dates deposition of unit M5 and post-dates deposition of M6.

347

348

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

350

351   At the Green Burn West (GBW) site 1.4 km west of the GBE trench, fault-perpendicular

352   trench GBW T-1 extended 16 m from the lower part of the north-facing fault scarp northward

353   across a marshy flat to near the base of the steep, south-facing mountain front (Figure 4, Figure

354   S4, available in the electronic supplement to this article). The trench exposed a gently north-

355   dipping fault with an ~10 cm-thick gouge zone (fault F1 on Figure 4) that juxtaposes basal

356   sheared pale-gray siltstone bedrock (unit B1) against overlying moderately indurated, massive

357   silt to gravelly silt (unit S1), which becomes progressively more clast-rich to the south. We did

358   not observe any structural evidence of individual surface ruptures in this trench, although the

359   southern end of the trench is marked by two gravel colluvial wedges (units CWa and CWb)

360   composed of sub-angular to sub-rounded pebbles in a sandy silt, dark gray matrix that overlie ~1

361   meter of massive gravelly silt. Neither of these colluvial gravels was observed in direct contact

362   with the fault, so we cannot attribute surface rupturing events to these colluvial wedges. As in the

363   GBE trench, we interpret these colluvial wedges to have been sourced from the scarp at the south

364   end of the trench, although this relationship was not exposed in GBW T-1. We did not recover

365   any datable material from these colluvial gravels.

366   Trench GBW T-1 also exposed a tan- to orange-mottled, matrix-supported gravelly silt

367   with local minor sub-rounded to sub-angular pebbles and rare cobbles (unit L*). This gravel

368   overlies the buried, organic-rich A horizon of a paleosol (unit P*). The P* paleosol is a dark

369   brown to black, organic-rich, sandy silt, and is similar to other marshy soils we observed at GBE.

370   The L* gravelly unit thins southward towards the fault, and pinches out between m 10 and m 13

371   of T-1. This southward thinning indicates that the source of the L* unit must have been to the

372   north, consistent with the possibility that L* was deposited in a paleolandslide derived from the

373   steep, landslide-prone slope immediately north of the trench. Additionally, the basal depositional

374   contact of the L* gravelly silt atop the P* organic-rich paleosol A horizon is extremely sharp,

375   with evidence of local rip-up of the underlying paleosol, indicating likely high energy deposition,

376   potentially during a landslide event. Moreover, the underlying paleosol is flat, indicating that the

377   gravel did not fill a depression (i.e., channel). This observation, in addition to the fact that there

378   is currently no active stream-flow across the location of T-1 and that the L* deposit does not fill

379   a channel or exhibit a geometry that could have formed by channel flow, suggests that the L*

380   deposit is not a fluvial channel deposit. Thus, although the gravelly sandy silt of the L* deposit

381   itself could have had other possible origins, we consider the southward thinning of the deposit,

382   coupled with the location of the L* deposit near the base of the steep, landslide-prone slopes ~10

383   meters to the north of the trench, and the absence of any evidence for stream-flow through the

384   site or a channelized origin for L*, to provide strong evidence for a landslide origin for the L*

385   deposit.

386   Overlying the L* inferred paleolandslide landslide deposit is a matrix-supported gravelly

387   silt (unit G1) that has considerably fewer clasts than the inferred landslide deposit. The contact

388   between the interpreted L* landslide deposit and the overlying sediment is diffuse in some places

389   (e.g., m 13 & m 14, where the contact is denoted with the number 5 on the contact, indicating

390   that the contact is diffuse over a width of 5 cm).

391   The shorter GBW T-2 trench was excavated closer to the base of the steep, south-facing

392   bedrock slope, ~ 8 m northwest of the northern end of GBW T-1 (Figure 2C). Trench GBW T-2

393   revealed four gravel layers that we interpret as paleo-landslide deposits (units L1, L2, L3 and L4,

394   from youngest to oldest) (Figure 5, Figure S5 available in the electronic supplement to this

395   article). These matrix-supported gravels consist of sub-angular pebbles (1-8 cm diameter clasts),

396   that are separated from one another by organic-rich, clast-free, silty buried paleosols (P1, P2 and

397   P3, from youngest to oldest). L1 is the thinnest gravelly silt deposit (5-10 cm thick), with small

398   sub-angular clasts (~1 cm) within an orange sandy silt matrix. The upper contact is gradational

399   whereas the basal contact is a spatially varies between sharp and gradational, likely due to

400   bioturbation. The L2 deposit is ~ 15 cm thick with a similar makeup to L1, but containing rare

401   larger clasts and with areas of local reduced iron-bearing staining in the matrix, as evinced by

402   blue coloration of the deposit. The basal contact of L2 against the underlying P2 paleosol is

403   sharp along the whole contact, whereas the upper contact between L2 and overlying P1 is

404   gradational. This observation supports our interpretation that L2 was deposited rapidly on top of

405   P3, and that P2 gradually accumulated atop L2 over a longer period of time. Although L3 is a

406   gravelly silt, this deposit is relatively clast poor compared to L1, L2 and L4. The upper and lower

407   contacts of L3 are both diffuse, potentially due to bioturbation when this deposit was near the

408   surface and the P3 paleo-A horizon was actively forming above L3. The L4 deposit is the most

409   clast-rich of the four gravelly silts described in GBW T-2. We could not expose the base of L4

410   due to the shallow groundwater table at this site. The top contact of the L4 deposit with the

411   overlying P3 paleosol is diffuse. This alternation in GBW T-2 between coarse-grained gravelly

412   silt deposition and fine-grained deposition punctuated by periods of soil development is

413   consistent with episodic deposition of the gravelly silts, potentially during landslides, with

414   intervening periods of organic-rich silt accumulation and pedogenesis. We observe three full

415   cycles of this behavior, ending at the development of the modern marshy organic-rich soil

416   exposed at the surface.

417   Because the exposure of T-2 is considerably smaller than T-1, we could not observe

418   changes in lateral thickness of the unit. However, several observations support our inference that

419   these gravel deposits are paleolandslides derived from the hill to the north of T-2.

420   Topographically, T-2 was excavated into a local high with no evidence stream flow, as can be

421   seen in detailed, lidar-derived topographic maps of the site (Supplemental Figure 2).

422   Geographically, T-2 is at the base of a steep, landslide-prone slope, directly in the fall path of

423   any landslides off this slope, which is why we excavated trench T-2 where we did.

424   Sedimentologically, the slope north of T-2 provides a source of the T-2 gravelly sandy silt

425   deposits. Taken together, these lines of evidence are consistent with a landslide origin from

426   gravelly silt deposits L1-L4.

427   In the following section, we discuss the rationale behind our suggestion that each of the

428   four landslides in this trench records co-seismic landslide deposition during the four most recent

429 large, surface-rupturing Hope fault earthquakes on the Conway segment along the Green Burn

430 reach, and that the intervening paleosols represent the periods of soil development between

431 major Conway segment surface ruptures. As we describe below, this interpretation is supported

432 by the similar, but completely independent ages we determined for the past three events at GBW

433 and GBE.

434

435 **Coseismic origin of colluvial wedges and landslides observed at GBW/GBE: Observations**

436 **of the Green Burn Reach following the 2016 M$_w$=7.8 Kaikōura earthquake**

437   In addition to the evidence described above, our inference that the GBW landslides and

438 the GBE colluvial wedges were only deposited during prior Hope fault surface ruptures is

439 supported by our field observations of the Green Burn reach of the Hope fault following the 2016

440 M$_w$=7.8 Kaikōura earthquake, which occurred nine months after our trench studies were

441 conducted. We visited our by-then backfilled trenches at both the GBE and GBW sites during

442 our reconnaissance mapping following the earthquake to investigate whether any colluvium had

443 accumulated at either the base of the steep slope we trenched at the GBW site or the fault scarp

444 we trenched at the GBE site. Both of our trench sites experienced very strong ground motions

445 during the 2016 earthquake. Specifically, the Green Burn trench sites likely experienced a

446 shaking intensity of VII-VIII on the Modified Mercali Intensity scale, with peak ground

447 accelerations of ~ 25% g and peak ground velocities of ~45 cm/s (KIKS station; see Data and

448 Resources section). Despite the strong shaking that affected our GBE and GBW sites, we

449 observed no mass wasting at either location, or anywhere else along the Green Burn reach of the

450 fault. At the GBE site, our filled-in trench was found intact beneath a newly sprouted cover of

451 grass. Similarly, we observed no landsliding at the GBW site, with the filled-in GBW T-1 and T-

452   2 trenches undisturbed and already re-vegetated by grasses and thistle. The only colluviation

453   observed along the Green Burn reach were small slope failures along a dirt roadcut, and several

454   small slides on steep stream banks.

455   During our reconnaissance mapping of the Hope fault following the Kaikōura event, we

456   noted no definitive surface rupture along the Green Burn reach, in keeping with more extensive

457   field and helicopter mapping of the entire Conway segment [*Litchfield et al.*, 2018]. In

458   subsequent weeks of mapping, one area of potentially disturbed ground on a slope 4 km east of

459   the GBE site suggested local ground cracking of 0.9-1.4 m of net (reverse-dextral) slip

460   [*Litchfield et al.*, 2018], but most of the Conway segment did not experience any surface rupture.

461   As such, we did not observe any newly exposed, un-vegetated slopes along the Green

462   Burn reach. The south-facing slopes north of GBE and GBW are both vegetated. In fact, the

463   slope north of T-1 and T-2 at GBW has trees growing on it, and has not been disturbed for at

464   least 50 years or more given the size of the trees, indicating that slope failures at this site are rare

465   and not events typically triggered by rainfall. The creation of a scarp free-face during surface

466   rupture, including extreme peak ground accelerations, on the Conway segment of the Hope fault

467   thus appears to be necessary for colluviation or landsliding along the Green Burn reach. In

468   addition to the supporting sedimentologic and geomorphic arguments indicating that these

469   colluvial wedge and paleolandslide deposits likely originated during Conway segment surface

470   rupturing earthquakes, we now present compelling age data showing that these deposition events

471   are essentially coeval. Such age results indicate that GBW paleolandslide age ranges can be used

472   to help constrain the timing of paleo-surface ruptures observed at the GBE trench.

473

474   **Chronology of paleoseismic events observed at GBE and GBW**

475   **Age models and event boundary conditions**

476   To provide age control on event horizons observed in the GBE and GBW trenches, we

477 radiocarbon dated 53 samples, which consisted of detrital charcoal, wood, seeds, and plant

478 material (Table 1). The samples were inspected under a microscope to ensure that no young roots

479 were included, and individual organic fragments including leaves and seeds were used to date

480 marsh samples. All samples were prepared with a standard acid-base-acid pre-treatment protocol,

481 and analyzed at the W.M. Keck accelerator mass spectrometer (AMS) lab at the University of

482 California, Irvine. The resulting radiocarbon ages were calibrated using OxCal 4.3.2 [*Bronk*

483 *Ramsey*, 2017] and the most up-to-date southern hemisphere calibration curve, SHCal 13 [*Hogg*

484 *et al.*, 2013].

485   We observed that many of these samples were older than other samples from the same or

486 underlying deposits, indicating that they had significant pre-depositional ages (i.e., were

487 "reworked"). We created our age model using the philosophy that detrital charcoal included in a

488 colluvial wedge must be the same age as or older than the depositional age of the unit from

489 which they were sampled. This is always the case with detrital charcoal, except in the event that

490 a younger charcoal sample was added to the deposit after deposition, as, for example, during

491 bioturbation downward in a burrow from an overlying unit. In the specific case of our Green

492 Burn excavations, introduction of younger detrital charcoal via bioturbation is unlikely because:

493 (a) there is a lack of burrowing organisms in New Zealand, especially those that could bioturbate

494 materials downward into the coarse-grained, pebble to cobble gravels of the GBE colluvial

495 wedges; and (b) we observed no evidence of burrowing in the gravel colluvial wedge deposits.

496 Furthermore, we observed no significant soils developed into the colluvial wedges at GBE. This

497 is consistent with the relatively brief recurrence intervals that we document in the following

498 section for the Conway segment of the Hope fault, which would have allowed only very limited

499 time in between earthquakes for soil development. Thus, introduction of detrital charcoal

500 samples downward into older colluvial wedges is unlikely to have occurred during pedogenesis

501 at the GBE site.

502   Therefore, given the low likelihood that any of our detrital charcoal samples were

503 introduced into underlying deposits during either bioturbation or pedogenesis, to get as close as

504 possible to the true depositional age of the GBE colluvial wedges, we selected the youngest

505 detrital charcoal age from a given colluvial wedge and discarded the older, reworked ages for

506 each deposit. After determining which samples were reworked, the remaining ages were then

507 used as inputs to stratigraphic ordering models in OxCal to create a Bayseian age model for each

508 exposure [*Lienkaemper and Bronk Ramsey*, 2009]. All ages reported herein are calibrated,

509 calendric ages in terms of BCE/CE.

510   We constructed six age models to provide timing constraints on the paleo-earthquakes at

511 our Green Burn study sites (Figure 6; Table 1): one using ages only from the GBE trench scarp-

512 derived colluvium (Figure 6A); one using ages only from the GBE scarp-derived colluvium and

513 the GBE marsh deposits south of the wood mass (Figure 6B); one using ages only from the GBE

514 marsh deposits north of the wood mass (Figure 6C); one using ages from only GBW T-2 (Figure

515 6D); one using ages from GBW T-1 and T-2 (Figure 6E); and a final, preferred model combining

516 age constraints from the GBE scarp-derived colluvium and southern marsh section, as well as

517 GBW T-1 and T-2 (Figure 6F). We excluded from consideration in our age models all samples

518 that exhibited anomalously old ages indicative of inheritance (i.e., those samples with ages that

519 are much older than underlying samples). In addition to the exclusion of a number of samples

520 from the faulted, southern part of the GBE trench, we did not use the vertical profile of

521   radiocarbon ages we collected from the marsh deposits in the northern part of the GBE trench

522   north of the wood mass near m 5-6 (Figure 6C), as these ages were all significantly older at all

523   stratigraphic levels than correlative scarp-derived colluvial deposits (Figure S6, available in the

524   electronic supplement to this article). Moreover, as noted above, none of these deposits can be

525   correlated confidently with the scarp-derived colluvial section that contains all of our

526   stratigraphic and structural evidence for the five most recent earthquakes recorded at GBE

527   (Figure 3; Figure 6A-C; Figure S6, available in the electronic supplement to this article).

528   Complete documentation of all radiocarbon age data and associated metadata from the GBE and

529   GBW trenches, including those ages that were not included in our age models, is presented in

530   Table 1.

531   We present the results of our GBE-only age models first (Figure 6A-C), with detailed

532   reference to all radiocarbon ages that were used to directly constrain the five well-constrained

533   surface ruptures observed in the GBE trench. Following this discussion, we present our GBW

534   age models (Figure 6D) and then the combined GBW and GBE model (Figure 6E), which uses

535   the additional age constraints from the GBW landslide deposits to independently test and

536   corroborate the ages of the GBE surface ruptures, and to more tightly constrain the age of the

537   penultimate surface rupture (GB2) observed in the GBE trench. All 2σ event age ranges for each

538   model are listed in Table 2.

539   **Green Burn East Paleo-Surface Rupture Ages**

540   All of the paleoearthquake event stratigraphy recorded in the GBE trench (i.e., fault

541   terminations, folding, fissure fills) is contained within the scarp-derived colluvial units in the

542   southernmost portion of the trench. In the following section, we present event ages based on

543   samples collected only from the units that record the events (Figure 6A). Where possible (e.g.,

544   sample SF-5), we further constrain these event age ranges using samples from the marsh south of

545   the wood mass at ~ m 5 (Figure 6B). We report individual sample ages as calibrated yet

546   unmodeled ages, which are included (for all dated samples) Table 1.

547   In contrast to evidence for historical surface rupture of the Hope fault farther west during

548   the 1888 M$_w$~7-7.3 Amuri earthquake [*McKay*, 1890; *Cowan*, 1991; *Khajavi et al.*, 2016], there

549   is no record of historical rupture of the Conway segment of the Hope fault through the Green

550   Burn sites. Thus, the most recent surface rupture we observe (GB1) must have occurred prior to

551   European settlement, which began c. 1840 CE. Surface rupture GB1 is younger than detrital

552   charcoal samples SF-33 (1680—1723 CE, or post-1802 CE) and SF-34 (1691—1728 CE, or

553   post-1805 CE) included in colluvial wedge CW1, which we interpret as having been shed

554   northward off the scarp during and soon after event GB1. Combining the historical constraint

555   with the age constraints from the GBE scarp-derived, colluvial wedge ages-only OxCal model

556   indicates that event GB1 occurred between 1722—1840 CE. This age range is similar to the

557   1780 ± 60 yBP age of the most recent event suggested by *Langridge et al.*, [2003] on the basis of

558   weathering rind age estimates from their GBS trench.

559   Surface rupture GB2 is younger than the ages of the detrital charcoal samples collected

560   from CW2 itself, as the material contained in the colluvial wedge must have existed higher on

561   the scarp prior to deposition of the colluvial wedge. Thus, event GB2 is younger than samples

562   SF-15 (1462—1627 CE) and SF-16 (1505—1643 CE), which were collected from within unit

563   CW2. GB2 is stratigraphically older than CW1, and we make the assumption that this surface

564   rupture occurred before the material included in CW1 was generated and then included in CW1.

565   Thus, the ages of samples SF-33 and SF-34, collected from unit CW1, provide a minimum age

566   for GB2. Taken together, our GBE scarp-derived colluvial samples-only age model indicates that

567   the penultimate GBE surface rupture occurred between 1558 and 1724 CE. These data

568   significantly narrow the previous post-1295 CE constraint for the occurrence of GB2 from

569   *Langridge et al.,* [2003].

570   We constrain the age of GB3 using a similar rationale as used for dating the previous

571   events. Specifically, charcoal samples SF-1 (1394—1425 CE), SF-2 (1496—1636 CE), SF-3

572   (1320—1410 CE) and SF-28 (1396—1436 CE) were collected from the CW3 colluvial wedge

573   and therefore pre-date event GB3. However, sample SF-2 is significantly younger than SF-1, SF-

574   3 & SF-28, indicating that the three older charcoal samples were likely incorporated into the soil

575   and gravel mantle atop the shutter ridge/fault scarp about 100-150 years prior to incorporation of

576   the SF-2 charcoal sample, and/or that these three samples were significantly older than SF-2

577   when they were all incorporated into the CW3 colluvial wedge. We infer that the three older

578   charcoal samples were generated during an earlier brush fire (or fires) that occurred c. 1400 CE,

579   whereas the sample SF-2 charcoal fragment was produced during a separate, younger brush fire

580   during the late 1400s or 1500's CE. Given the apparent inheritance of samples SF-1, SF-3 & SF-

581   28, we use the age of sample SF-2 as a maximum age for GB3. Charcoal samples SF-15 and SF-

582   16, which were collected from the overlying colluvial wedge CW2, post-date GB3, as CW2 is

583   deposited atop CW3. Using these constraints, the GBE scarp-derived colluvial sample-only age

584   model (Figure 6A) produces an age range of GB3 as 1495—1610 CE.

585   As with the previous events, assuming material from within a colluvial wedge is older

586   than the coseismic deposition of that wedge itself indicates that event GB4 is younger than

587   charcoal sample SF-41 (1273-1380 CE), which was collected from CW4. Using sample SF-41 as

588   a maximum age of GB4 with sample SF-2 from CW3 as minimum age, we model the age of

589   GB4 as 1288—1532 CE.

590   To determine the maximum age for event GB5, we assume as in the case of the younger

591   colluvial wedges that charcoal samples collected from the colluvial wedge are older than the

592   coseismic deposition of that wedge. We therefore use sample SF-21 (195—52 BCE), collected

593   from CW5, as a maximum age for event GB5. Knowing that CW4 was deposited atop CW5, and

594   is therefore younger than CW5, we use sample SF-41 collected from CW4 as a minimum age

595   constraint on event GB5. Using these two scarp-derived charcoal samples as constraints results

596   in a modeled event range for event GB5 of 61 BCE—1277 CE.

597   We can further constrain the age of event GB5 by using charcoal ages collected from the

598   coseismic colluvial wedge in combination with ages on plant material collected from the

599   southern part of the marsh section, south of the wood mass, atop which the wedge was deposited.

600   Specifically, the distal, downslope toe of colluvial wedge CW5 was deposited onto a thinly

601   bedded organic silt/peat succession (units M6-M7), best observed at ~m 5 on the east wall

602   (Figure 3). We collected wood sample SF-5 (99 BCE-115 CE) from peat layer M7, underlying

603   CW5. We sub-sampled SF-5 as three separate pieces, and these yielded similar radiocarbon ages

604   on all splits (SF-5a: 42 BCE—115 CE; SF-5b: 96 BCE—25 CE; SF-5c: 99 BCE—23 CE).

605   Because sample SF-5 was a piece of wood, with an unknown amount of age inheritance, we can

606   only use these ages as maximum ages because the wood deposited within the layer could

607   potentially be much older than the deposit itself. Combining the ages of samples both from the

608   scarp-derived colluvial deposits and from the marsh units south of the wood-rich section yields a

609   modeled age range for event GB5 of 36 BCE—1275 CE.

610

611   **Age control for GBE northern marsh strata**

612   The ages determined from the vertical sampling profile we collected north of the wood

613 mass at ~m 7 (Figure 3 east wall), are presented in Figure 6C. These 11 ages are primarily based

614 on short-lived plant material, mainly leaves and seeds. The resulting ages and OxCal age model

615 (Figure 6C) indicate that all samples are in correct stratigraphic order, recording semi-continuous

616 deposition in the northern marsh from c.100-300 BCE at 1.5 m depth (sample SF-14 [350—104

617 BCE]) to c. 700-800 CE at 30 cm depth (sample SF-6 [681—862 CE]). Interestingly, these ages

618 are significantly older at all depths relative to the scarp-derived colluvial section south of the

619 wood-rich zone. Moreover, the fact that c. 1200- to 1300-year-old strata are exposed at only ~30

620 cm depth in the marsh north of the wood mass suggests that either there has been little deposition

621 in the northern marsh over the past 1,000-plus years, and/or that the northern marsh section has

622 experienced significant erosion during the same time period when the colluvial wedges marking

623 that five most recent Hope fault surface ruptures were being deposited south of the wood mass.

624   This mismatch in ages suggests that the mass of wood acted as a barrier to sediment

625 accumulation, effectively separating the southern, scarp-derived colluvial section from the

626 northern marsh section for much of the time recorded in the GBE trench (Figure S5).

627 Consequently, we cannot use the radiocarbon dates from the northern marsh section to constrain

628 the ages of paleo-earthquakes, evidence for which is derived exclusively from the scarp-related

629 section south of the wood-rich zone. Rather, we use only those radiocarbon ages collected from

630 the scarp-derived, southern section to constrain the ages of the five most recent Green Burn

631 surface ruptures.

632   **Ages of GBW site landslides**

633   The radiocarbon ages from GBW T-2 provide constraints on the ages of the four influxes

634 of clastic sediment that we interpret as paleo-landslides observed at that site (Figure 6D). We

635   collected two radiocarbon samples from the shallowest paleosol (P1) beneath the shallowest

636   gravelly silt L1, a plant leaf sample from ~20 cm depth [LS2-6 (Modern)], and another plant leaf

637   from ~35 cm depth [LS2-4 (1672—1743 CE, or post 1772 CE)]. Given the shallowness of

638   sample LS2-6, and matrix-supported nature of the L1 deposit above sample LS2-6, we suspect

639   that this sample may have been bioturbated into position from which it was collected. We

640   therefore use sample LS2-4 to provide a maximum age for the overlying L1 interpreted landslide

641   deposit. Alternatively, if this Modern plant sample LS2-6 from beneath the L1 gravelly silt was

642   not bioturbated in to the sampling location, then the L1 deposit must be historical, likely mid-to-

643   late 20th century following the production of bomb-generated radiocarbon testing in 1945 CE.

644   This alternative explanation for the timing of L1 deposition makes no difference in the

645   interpretation of the sample LS2-4, as that sample still post-dates inferred-landslide L2, which

646   must pre-date any subsequent landslide following L2. To bracket the timing of deposition of

647   inferred-landslide L2, we use the age of sample LS2-4 from paleosol 1 above the penultimate

648   landslide L2 to post-date the L2 deposit, as well as the age of sample LS2-5 (1665—1895 CE)

649   from paleosol 2 beneath L2. These ages indicate that L2 deposition occurred between 1668 and

650   1806 CE.

651   The two wood samples that we radiocarbon dated from within the L3 landslide (LS2-2

652   [693-891 CE] and LS2-11 [1032-1151 CE] are older than underlying samples, and are not

653   considered further. The age of L3 is, however, constrained by charcoal samples LS2-5, collected

654   from paleosol P2 above the L3 deposit, and LS2-9 (1184—1267 CE), collected from paleosol P3

655   beneath L3. These ages bracket the timing of L3 deposition to 1225-1685 CE. We can further

656   refine this age range by incorporating charcoal sample HL16-04 (1400-1440 CE) from GBW

657   trench T-1, which was collected from the paleosol (P*) that was over-ridden by perhaps the only

658   landslide observed in that trench (L*), which we correlate with L3 based on the age correlation

659   of L3 with GB3 (discussed in the subsequent section) (Figure 6D). This additional constraint

660   narrows the age range for L3 to 1414-1694 CE. Using sample HL16-04 to pre-date L3 deposition

661   and LS2-5 to post-date L3 deposition, we arrive at a revised age range for L3 deposition as

662   1415—1711 CE.

663   We were unable to collect any samples from beneath the fourth landslide back (L4), but

664   the age of charcoal sample HL16-04 from paleosol directly below the inferred landslide deposit

665   in T-1, as well as the age of sample LS2-9 collected from P3 in T-2 indicates that L4 was

666   deposited before 1400—1440 CE, providing the youngest possible age for event GB4.

667

668   **Combined Age Model for GBW and GBE sites**

669   The ages of the five event horizons we identified at GBE based on fault terminations,

670   fissure fills, folding, and colluvial wedge deposition overlap in time with the deposition of the

671   four inferred-landslide silty gravel units in GBW T-2 (Supplemental Figure S7). As discussed

672   earlier, we observed no evidence of colluviation or landsliding along the Green Burn Reach

673   following the M_w=7.8 Kaikōura earthquake, providing support for our inference that landslide

674   deposition at GBW occur only during surface rupturing events along the Green Burn Reach of

675   the Hope fault. We therefore combine age models from GBE and GBW using independent age

676   constraints to more precisely determine the ages of the five surface rupturing events observed at

677   GBE. One could arrive at these combined event ages by averaging together the probability

678   density functions from GBE and GBW, an approach similar to that of *Biasi and Weldon* [2009].

679   We present those results, along with comparisons of the GBE and GBW probability density

680   functions and the OxCal combined age results, in the electronic supplement to this article in

681   Figure S7.

682   Using the preferred OxCal age combination approach, inclusion of sample LS2-4 from

683   the youngest paleosol P1 at GBW as an additional constraint on the maximum age of the most

684   recent surface rupture observed in the GBE trench overlaps with the age of event GB1, and

685   slightly tightens the possible age range from 1722—1840 CE in the GBE-only age model to

686   1731-1840 CE. Similarly, addition of sample LS2-5 from paleosol P2 in the combined GBE-

687   GBW age model narrows the possible age of event GB2 to between 1657 and 1797 CE (1558—

688   1724 CE for GBE-only model). Additionally, inclusion of the ages of GBW samples LS216-5,

689   collected from the paleoseol P2 above the third-most-recent inferred-landslide (L3) at GBW, and

690   samples HL16-04 & LS2-9, collected from below L3, in the combined GBE–GBW age model

691   yields a nearly identical age range for event GB3 of 1496-1611 CE (1495—1610 CE for GBE

692   only model). The two age models produce similar age ranges from GB3 because the additional

693   sample from GBW T-1 of HL16-04 is slightly older than the sample SF-2 from GBE (Figure 6B

694   vs 6F). Finally, the age range of event GB4 is shortened markedly by incorporating the 1400-

695   1440 CE age of sample HL16-04, which was collected from GBW T-1 paleosol P*, on which L*

696   was deposited; we interpret L* deposition to be contemporaneous with deposition of colluvial

697   wedge CW3 in the GBE trench during event GB3, which post-dates deposition of CW4 in GB4.

698   Although sample LS2-9 (1184—1267 CE) was also collected from paleosol 3 in GBW T-2, we

699   do not use the LS2-9 date in further age modeling of event GB4 because this sample is slightly

700   older than sample SF-41, which was collected from CW4 at GBE, and which therefore must pre-

701   date event GB4. Thus, the older age of sample LS2-9 suggests that this sample had some

702   inherited, pre-event GB4 age before it was incorporated into the paleosol overlying inferred-

703   landslide L4. Including the age of sample HL16-04 into the combined GBE-GBW age model

704   yields a revised age range for event GB4 of 1290-1420 CE, somewhat older than the 1288—

705   1532 CE age range from the GBE-only age model.

706

707   **Discussion**

708   The Green Burn trenches reveal the occurrence of five surface rupturing earthquakes on

709   the Conway segment of the Hope fault during the past c. 2000 years. The more tightly

710   constrained ages for the past four GBE events suggest potentially irregular earthquake

711   occurrence. Specifically, whereas the two most recent events (GB1—GB2) occurred within a

712   relatively brief, <183-year period between 1657 and 1840 CE (mean RI between GB1 and GB2

713   = 58 years), they were preceded by events GB3 and GB4, which occurred over a maximum of

714   321 years from 1290-1611 CE (mean RI between GB3 and GB4 = 198 years). The oldest event,

715   GB5, has a long possible age range, therefore making the resulting recurrence interval less

716   informative than for the younger events; although we did not observe evidence of events between

717   GB4 and GB5, or events older than GB5 in the GBE trench, we may have an incomplete event

718   record prior to GB4. Event GB5 aside, the younger two events may thus represent a temporal

719   cluster during which earthquake recurrence was more frequent than average. Interestingly, event

720   GB3, the third earthquake back, which precedes these two events, exhibited much more

721   significant structural disruption in the GBE trench and resulted in deposition of a much more

722   extensive colluvial wedge than previous or more recent Conway segment surface ruptures,

723   suggesting that it may have been a larger-displacement surface rupture at the GBE site. The large

724   displacements suggested by these observations are consistent with possible time-predictable

725   behavior [*Shimazaki and Nakata*, 1980] of the Hope fault, with the large inferred displacement at

726   the Green Burn sites in GB3 being followed by a period of time with shorter than average

727   recurrence intervals. Analysis of small offsets in lidar and ground-penetrating radar data on the

728   Conway segment, however, suggests that the past three earthquakes have each produced, on

729   average, ~3-4 m of displacement [*Beauprêtre et al.*, 2012], and thus that the inferred larger

730   displacements in the Green Burn trenches may have been a local feature of that event and are not

731   necessarily indicative of GB3 being a larger-magnitude earthquake.

732   **Plate Boundary System-Level Rupture Behavior**

733   The new Green Burn data add to a growing body of paleo-earthquake age constraints

734   from multiple sites along the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa (Al-Hp-JKN-

735   Wr) system of major dextral strike-slip and oblique reverse-dextral faults that collectively

736   accommodate significant portions of Pacific-Australia relative plate motion in South Island and

737   southern North Island [*Pondard and Barnes*, 2010; *Robinson et al.*, 2011; *Litchfield et al.*, 2014].

738   Specifically, paleoseismologic records are now available from the Hope fault along the Hurunui

739   and Hope River segment from the Matagouri Flats (MF) [*Langridge et al.*, 2013] and Hope

740   Shelter (HS) [*Khajavi et al.*, 2016] sites ~100 km west of the GBE site, from the Kekerengu

741   (EK) fault at a site ~ 100 km northeast of the Green Burn sites [*Little et al.*, 2018], from the

742   Cross Creek (CC) site on the Wairarapa fault, an extension of this fault system northward into

743   southern North Island [*Little et al.*, 2009], and from multiple sites along the central Alpine fault

744   (A) with dendrochronologically dated records of tree disturbance [*Wells et al.*, 1999] and records

745   of strong ground shaking from paleo-seismite records in lakes in the footwall of the Alpine fault

746   on the coastal plain of the Southern Alps [*Howarth et al.*, 2012, 2014, 2016]. It is worth pointing

747   out, in contrast to paleoseismic results from trenches of the active fault traces, the

748   dendrochronology and paleo-seismite data record strong ground shaking at the site off of the

749   active fault traces, and thus could record earthquakes generated by other faults. We summarize

750   these on- and off-fault paleoseismic records in Table 3. We included all preferred events

751   described in these paleoseismic studies and the preferred paleo-event age ranges of the original

752   authors. In addition to these records, we discuss the 2016 Kaikōura earthquake, and its potential

753   implications, in a separate section below. We can use all of these data to address important

754   questions about earthquake occurrence in the Al-Hp-JKN-Wr fault system.

755   The most basic question we address in our analysis is whether the faults of the Al-Hp-

756   JKN-Wr typically rupture together or in brief sequences of along-strike ruptures, or whether

757   different sections of the fault system rupture independently in isolated events. Although

758   hampered by the long possible allowable age ranges of some events at some sites (e.g., GB5,

759   HS2, EK4), the available data allow us to examine the system-level behavior of the Al-Hp-JKN-

760   Wr fault over the past 1,000-plus years. In Figure 7, we show available paleoseismic constraints

761   on the faults at the specific paleoseismic sites discussed above.

762   In an attempt to assess the possibility that large parts of the Al-Hp-JKN-Wr system

763   rupture together in brief sequences, we interrogate 100-year-long intervals where there is overlap

764   between the 2σ age ranges of more than two ruptures along the different faults. Specifically, if

765   there is overlap between events, we show a pink bar, labeled S_x, across all sites that could

766   potentially have ruptured within a ≤100-year-long sequence (Figure 7). Although the 100-year

767   time window is arbitrary, it was chosen because it is shorter than the average recurrence intervals

768   at all sites, and helps to bring into focus possible brief sequences involving rupture of large

769   sections of this fault system. We attempt to minimize the number of sequences within the Al-Hp-

770   JKN-Wr system. That is to say, we select the temporal placement of the 100-year-long possible-

771   sequence "bar" shown in Figure 7 across as many faults as is allowable within the given 100-

795 *and McGlone*, 1991; *Khajavi et al.*, 2016]. Thus, if the most recent events on the Conway

796 segment (GB1) and the Kekerengu fault (EK1) occurred relatively late during their allowable

797 time ranges, the events observed at all four sites could record a temporally brief sequence of

798 large-magnitude earthquakes that ruptured the entire fault system northeast of the Alpine fault

799 during the late 18th and 19th centuries [*Little et al.*, 2018]. Alternatively, if the prehistoric GB1

800 and EK1 most recent events occurred early in their allowable time ranges (i.e., as early as 1730

801 CE and 1700 CE, respectively), they might have occurred within a short period of time of the

802 most-recent, c. 1717 CE earthquake on the Alpine fault, which ruptured a ≥375-km-long section

803 of that fault as far north as the Alpine-Hope fault intersection [*Wells et al.*, 1999; *De Pascale and*

804 *Langridge*, 2012; *Howarth et al.*, 2018]. If so, then the Alpine fault, the Hope fault Conway

805 segment, and the Kekerengu fault ruptures may have occurred long before the historical 1855

806 and 1888 earthquakes, and thus these events may not have been part of a brief sequence

807 including these historical ruptures. Earthquake occurrence on this system over the past c. 300

808 years has may therefore have been more random in time and space, with ruptures occurring

809 piecemeal over the entire length of the Al-Hp-JKN-Wr system. However, it seems less likely that

810 GB1 ruptured early in the allowable 1730—1840 CE age range, given that the 2σ age range of

811 the penultimate surface rupture GB2 (1657—1797 CE) significantly overlaps with the GB1

812 range (Figure 6, Supplementary Figure S7). For this reason, we suggest that GB1 likely occurred

813 late in its allowable time range, just prior to the beginning of the historic era, suggesting the

814 possibility that the entire Hp-JKN-Wr part of the system may have ruptured in a brief sequence

815 beginning just prior to the historic era and ending with the 1888 earthquake.

816   The next-older possible-sequence (sequence S2) includes the most recent event on the

817 Alpine fault (c. 1717 CE), MF2, HS2, and GB2. We note that the c. 1717 CE Alpine event

818   occurred within a brief period of time with ruptures along the Hurunui, Hope River and Conway

819   segments of the Hope fault, but without rupture of the Kekerengu fault. As noted above, based

820   on the occurrence of the 1855 M_w~8.1 Wairarapa rupture to the northeast of the Kekerengu fault,

821   and the occurrence of GB1 to the southwest of the Kekerengu fault, we assume that EK1 likely

822   occurred during the most-recent, possible-sequence 1. If so, then the data suggest that possible-

823   sequence 2 did not extend northeastward beyond the Hope fault. This would be consistent with

824   the idea that portions of the Al-Hp-JKN-Wr system rupture in sub-sequences that involve only

825   part of the system, rather than as system-wide, "wall-to-wall" sequences.

826   Possible-sequence S3 encompasses ruptures on all faults in the system except for the

827   Wairarapa, including events A2, MF3, HS2, GB3 and EK2. *Howarth et al.,* [2014, 2016, 2018]

828   have called into question the source fault causing paleo-seismite deposition in event A2, which is

829   marked in sediment cores by submarine slope failure in all three examined lakes, but did not

830   include a strong signature of post-seismic landsliding [*Howarth et al.*, 2014]. Event A2 is

831   therefore equivocal with respect to an Alpine fault source—either A2 occurred on another nearby

832   fault in the Southern Alps, or the event occurred on the Alpine fault and only weakly shook the

833   region (MMI ~VI as opposed to IX) [*Howarth et al.*, 2014, 2018]. Given the apparent weaker

834   shaking intensity during event A2, it is possible that this event A2 did not occur on an Alpine

835   fault source and instead occurred on a smaller fault neighboring the Alpine fault. Alternatively,

836   given the "bimodal" rupture model of *DePascale et al.* [2014], the Alpine fault may rupture most

837   of its length in M_w 8+ events, or may rupture in parts in M_w ~6-6.5 events. These latter, smaller

838   magnitude events would not be recorded in paleoseismic trenches, but may be recovered in off-

839   fault records of lake seismites [*DePascale et al.*, 2014; *Howarth et al.*, 2018]. Given the fact that

840   these records of lake seismites are off-fault records of Alpine fault seismicity, it remains possible

841 that these seismities represent earthquakes with sources on faults adjacent to the Alpine fault, of

842 which many have been documented [e.g., *Cox et al.*, 2012; *DePascale et al.*, 2016]. We denote

843 this uncertainty as a more transparent box for possible-sequence 3 on Figure 7. If event A2 did

844 occur on the Alpine fault, possible-sequence 3 could potentially represent a near-complete

845 sequence of events that ruptured the Al-Hp-JKN faults. However, notably, this rupture sequence

846 did not cross Cook Strait onto the Wairarapa fault. This observation likely reflects the fact that

847 the Wairarapa fault exhibits a slower slip rate fault of 11 ± 3 mm/yr [*Little et al.*, 2009], much

848 slower than the fast slip rates of the Kekerengu, Hope, and Alpine faults (~20-25+ mm/yr; [*Van*

849 *Dissen and Yeats*, 1991; *Berryman*, 1992; *Norris and Cooper*, 2001; *Hatem et al.*, 2016; *Van*

850 *Dissen et al.*, 2016] in South Island as slip is transferred northeastward onto the Wairarapa fault

851 as well as the offshore BooBoo fault [*Robinson et al.*, 2011], with a modeled slip rate of 11

852 mm/yr [*Pondard and Barnes*, 2010], and ultimately onto the underlying Hikurangi megathrust

853 fault beneath North Island [*Rodgers and Little*, 2006; *Wallace et al.*, 2012].

854   We observe a long (c. 400 year) lull in potential sequence activity between possible-

855 sequences S3 and S4, with two temporally isolated earthquakes (Is1 & 2) occurring on the

856 Alpine and Hope faults, respectively. Specifically, events A3 (1388—1407 CE), which

857 potentially ruptured the central Alpine fault, and GB4 (1230—1420 CE), which ruptured the

858 Conway segment of the Hope fault, do not overlap with the 2σ age ranges of any other events

859 that have not already been plausibly assigned to a possible earthquake sequence. Although the

860 age range of A3 overlaps with the age range of GB4, we do not include these events as part of a

861 larger sequence because no faults with available paleoseismic data ruptured on either side of the

862 Alpine or Conway fault during this time period in surface-rupturing earthquakes that have not

863 already been included in sequence S3. For example, event GB4 does overlap in time with HS2,

864 but HS2 has been previously assigned to possible-sequence 3. Although events GB4 and HS2

865 could have ruptured within a brief time of one another as part of a sequence, our preferred

866 interpretation is that HS2 occurred in the same sequence as MF3, as these sites are only ~ 30 km

867 apart along strike of the Hurunui segment of the Hope fault, and thus likely record the same

868 earthquake. Events A3 and GB4 may represent a discontinuous sequence along the plate

869 boundary. Our preferred interpretation, however, is that events A3 and GB4 represent isolated

870 events because of the lack of spatial continuity and paucity of faults that ruptured during this

871 time period. Alternatively, it is possible that both A3 and GB4 were part of a brief, continuous

872 sequence of events that involved rupture along the southern Kakapo strand of the central Hope

873 fault system, and potentially bypassing the Matagouri Flats and Hurunui Shelter paleoseismic

874 sites of *Langridge et al.* [2013] and *Khajavi et al.* [2016], which are located on the northern

875 Hurunui and Hope River segments of the Hope fault. Currently, there are no paleoseismic data

876 available for the Kakapo strand with which to constrain this possibility.

877   This possible lull in potential sequence behavior was preceded by sequence S4, the only

878 inferred possible "wall-to-wall" rupture of the entire Al-Hp-JKN-Wr plate boundary system

879 during the past 2000 years. Specifically, between 1000 and 1100 CE ruptures along the Alpine

880 (A4), Hurunui (HS4), Conway (GB5), Kekerengu (EK3) and Wairarapa (CC2) are all

881 permissible, suggesting the possibility that the entire >850-km-long fault system may have

882 ruptured during a brief sequence of large-magnitude events. Such a wall-to-wall sequence

883 involving rupture faults of different recurrence intervals, with the Wairarapa hosting events

884 about every c. 1000 years [*Little et al.*, 2009] and other faults in the system hosting events about

885 every ~300 years or less [*Langridge et al.*, 2013; *Khajavi et al.*, 2016; *Howarth et al.*, 2018;

886 *Little et al.*, 2018, this study], highlights the importance of understanding fault connectivity and

887   potential rupture patterns, such as those that occurred in the M_w=7.8 Kaikōura earthquake

888   [*Litchfield et al.*, 2018].

889   Although the allowable age range of GB5 is quite long and could possibly belong to

890   another, older rupture sequence, we think it unlikely that a rupture sequence rupturing from the

891   Alpine to the Wairarapa would bypass the Conway segment, given its central role in transferring

892   relative plate motion through northeastern South Island. Moreover, Coulomb failure function

893   modeling shows that rupture on the Jordan fault system increases the likelihood of rupture on the

894   Conway segment by 30% [*Robinson*, 2004], highlighting the strong relationship between these

895   two faults. Given these kinematic arguments, we favor placing GB5 in sequence S4.

896   In the above interpretation of possible-sequence S4, we assume that events HS3, GB5,

897   and EK3 ruptured within a short time of Alpine fault rupture A4 and Wairarapa fault rupture

898   CC2, with preceding Alpine fault event A5 marked as an isolated event (Figure 7). However, it is

899   equally allowable that events HS4, GB5, and EK3, rather than rupturing as part of a brief

900   sequence involving A4, ruptured as part of a slightly older sequence involving A5, in which case

901   A4 was likely an isolated event. If this slightly older sequence did occur c. 900-950 CE, it cannot

902   have involved rupture of the Wairarapa fault in southern North Island, as event CC3 significantly

903   post-dates event A5. The Alpine fault paleoseismic constraints for event A4 and A5 allow only

904   one of these possibilities to be correct.

905   If sequence S4 did occur as is presented above and in Figure 7, it appears to have been

906   preceded by a several hundred-year-long lull in potential sequence-like behavior. Specifically,

907   although the Alpine fault ruptured in A5 (915—961 CE), potentially as an isolated, Alpine fault-

908   only rupture, the preceding Alpine fault rupture A6 occurred between 592—646 CE. The Hope

909   fault Hurunui segment record [*Khajavi et al.*, 2016] also suggests a long-duration lull during this

910   interval prior to event HS4. The record is less clear for the remaining parts of the system to the

911   northeast, as the age ranges of events on those faults permit multiple possible interpretations. For

912   example, the long possible age range of GB5 spans the occurrence of possible-sequence S4,

913   possible-sequence S5, and the intervening apparent lull. The only possible 100-year-long period

914   during which the Alpine fault could potentially have ruptured during a brief sequence together

915   with the Hope and Kekerengu faults occurred between 525 and 625 CE, encompassing A6, HS4,

916   and EK4. As noted above, however, the potential age ranges of EK4 is quite long, yielding

917   relatively low confidence in the occurrence of this possible-sequence S5. Given that the age

918   range of GB5 is so long, and the fact that the eastern Kekerengu and Hope Shelter sites record

919   multiple events over this time period, it remains a possibility that we are missing an additional

920   event over the GB5 time interval. However, because we have not documented a separate GB

921   event, we cannot assign an event at Green Burn to sequence S5 (note break in S5 pink box across

922   GB domain on Figure 7).

923   Possible-sequence S6 is marked by rupture A7 on the Alpine fault and rupture HS5 on

924   the Hurunui segment of the Hope fault. It is perhaps noteworthy that all of the possible later

925   sequences encompass ruptures of both the Conway and Hurunui/Hope River segments of the

926   Hope fault. Thus, while it is possible that there was an as-yet unrecorded surface-rupturing

927   earthquake at Green Burn during possible-sequence S6, the Green Burn paleoseismic record does

928   not preserve a separate event during this time, so this possibility must remain speculative.

929   Although the paleoseismic timing constraints are too imprecise in many instances to

930   prove sequence-like behavior, the data are consistent with the possibility that large parts of the

931   Al-Hp-JKN-Wr fault system commonly rupture in brief (i.e., ≤ 100 year) sequences of large-

932   magnitude events. The available historical and paleoseismic records for the Hope, Kekerengu,

933   and Wairarapa faults, however, indicate that such possible-sequences are not always simple,

934   along-strike progressions of large-magnitude events. For example, the observation that the most

935   recent surface ruptures along the Conway segment of the Hope fault and the Kekerengu fault

936   occurred prior to European settlement, whereas the historical 1855 M_w~8.1 Wairarapa and 1888

937   M_w~7-7.3 Amuri earthquakes occurred to the northeast and southwest, respectively, indicates

938   complex spatial patterns of earthquake occurrence. An obvious possible complicating factor in

939   the occurrence of individual events during any possible-sequence is the occurrence of major

940   earthquakes on other nearby faults, such as the close temporal relationship between the 1855

941   M_w~8.1 Wairarapa earthquake and the 1848 M_w~7.4-7.5 Awatere earthquake, which ruptured

942   ~105 km of the Awatere fault north of the Hope fault [*Grapes et al.*, 1998]. Coulomb stress

943   modeling of these two events, for example, indicates that stresses related to the 1848 earthquake

944   elevated failure stresses along the future rupture plane of the 1855 event [*Pondard and Barnes*,

945   2010].

946   The fact that the c. 1000-1100 CE possible-sequence S4 is the only possible "wall-to-

947   wall" sequence of its kind over the past >1,000 years suggests that while such system-wide

948   behavior is possible, it is uncommon. Two of the past possible-sequences (S3 and S5) appear to

949   have encompassed rupture of all faults from the Alpine fault in the southwest to the Kekerengu

950   fault on the northeast, but neither of these possible-sequences extended across the Cook Strait

951   onto the Wairarapa fault. This could simply reflect the slower rate of elastic strain accumulation

952   and accommodation on the Wairarapa fault, inferred from its long recurrence interval compared

953   to the South Island faults [e.g., *Little et al.*, 2009; *Litchfield et al.*, 2018]. In contrast to possible-

954   sequences S2, S3, S4, as noted above, sequence S1 encompassed ruptures of the Hope,

955   Kekerengu, and Wairarapa faults, but did not include rupture of the Alpine fault. Thus, the

956 individual sequences do not always conform to the same pattern of ruptures. Whereas the

957 occurrence of individual events on the Al-Hp-JKN-Wr system is likely modulated by the

958 occurrence of earthquakes on other faults, leading to different patterns of ruptures and rupture

959 locations, the basic observation is that most large-magnitude earthquakes in the Al-Hp-JKN-Wr

960 system over the past >1,000 years appear to have occurred as parts of relatively brief (≤~100-

961 year-long) sequences.

962   The most recent earthquake generated within this plate boundary system, the 2016

963 M$_w$=7.8 Kaikōura earthquake, ruptured most of the Jordan-Kekerengu-Needles fault [*Litchfield*

964 *et al.*, 2018; *Kearse et al.*, 2017], as well as other faults to the south of the Hope fault [*Nicol et*

965 *al.*, 2018; *Williams et al.*, 2018], and likely parts of the subduction megathrust beneath

966 northeastern South Island [*Duputel and Rivera*, 2017; *Hamling et al.*, 2017; *Hollingsworth et al.*,

967 2017; *Kaiser et al.*, 2017; *Litchfield et al.*, 2018; *Wen et al.*, 2018]. Interestingly, no other major

968 ruptures have occurred on the plate-boundary fault system since the 1888 Mw~7-7.3 Amuri

969 earthquake that ruptured the Hurunui and Hope River segments of the central Hope fault

970 [*McKay*, 1890; *Khajavi et al.*, 2016]. Thus, the 2016 event was preceded by a 128-year-long lull

971 in which the entire Alpine-Hope-Kekerengu-Wairarapa fault system remained dormant. It

972 remains to be seen whether the complex, multi-fault 2016 Kaikōura event is a harbinger of a

973 near-future sequence of large-magnitude earthquakes on the Al-Hp-JKN-Wr system, as occurred

974 during previous possible-sequences S3 (c. 1500—1600 CE) and S5 (c. 525—625 CE).

975 Alternatively, we have shown that some sequences may have included temporally and spatially

976 isolated large-magnitude earthquakes (Is 1&3 on the Alpine fault, Is 2 on the Conway segment),

977 and it is possible that the 2016 Kaikōura event is an isolated rupture. However, although

978 simultaneous rupture of the specific faults that occurred during the Kaikōura event was a rare

979   occurrence, due to involvement of the slow slip-rate faults in the North Canterbury District

980   [*Nicol et al.*, 2018], as well as the Papatea fault [*Langridge et al.*, 2018] and Hundalee fault

981   [*Williams et al.*, 2018], with large displacements on the Jordan-Kekerengu-Needles fault system

982   [*Kearse et al.*, 2017]. Furthermore, post-Kaikōura Coulomb stress changes along the major plate

983   boundary faults in northeastern South Island [*Hamling et al.*, 2017] suggest that the 2016

984   earthquake may presage another sequence along the Al-Hp-JKN-Wr to begin (S_o).

985   Although this study focuses on the paleoearthquake behavior of the fast-slipping strike-

986   slip and oblique-slip faults of the Al-Hp-JKN-Wr system, the presence of the Hikurangi

987   megathrust fault beneath these upper plate faults in northeastern South Island and southern North

988   invites comparison with the paleoearthquake record inferred from off-fault studies of potentially

989   co-seismic subsidence events in the area [*Clark et al.*, 2015, 2019]. The most proximal

990   subsidence site to the upper-plate faults analyzed for this study is the Big Lagoon site ~35 km

991   northwest of the Kekerengu-Needles fault system [*Clark et al.*, 2015] ("BL" on Figure 1, "Big

992   Lagoon" on Figure 7). Clark et al. [2015] document two young subsidence events at Big Lagoon,

993   one at 1433—1480 CE (520—470 yBP), and a second one at 1070—1150 CE (880-800 yBP);

994   both events are marked by the abrupt deposition of marine mud above a paleosol, and the older

995   event horizon is overlain by a sand that the authors interpret as a paleo-tsunami deposit. These

996   authors infer that the subsidence events recorded at Big Lagoon are indicative of paleo-

997   earthquakes on the Hikurangi subduction megathrust beneath southern North Island and

998   northeastern South Island. If this is correct, the similarity in ages between their most-recent

999   subsidence event (BL1) and possible-sequence S3 identified by our study (c. 1400—1500 CE),

1000   and their penultimate subsidence event (BL2) and our possible-sequence S5, suggests that the

1001   megathrust may sometimes rupture together with, or within a short time of, major rupture

1002   sequences on the Al-Hp-JKN-Wr system (blue vertical bars on Figure 7). Specifically,

1003   subsidence BL1 overlaps with event GB3 on the Conway segment, as well as events A2 on the

1004   Alpine fault, events MF3 and HS2 on the Hurunui—Hope River segments of the Hope fault and

1005   event EK2 from the Kekerengu fault during possible-sequence S3. Similarly, the age range of the

1006   penultimate Big Lagoon subsidence event BL2 overlaps with events A4, HS4, GB5, EK3 on

1007   Alpine and Hope faults, as well as event CC2 on the Wairarapa fault during possible-sequence

1008   S5, which is the only sequence that could represent a wall-to-wall rupture of the entire Al-Hp-

1009   JKN-Wr system. *Clark et al.,* [2015; 2019] noted the temporal overlap between the penultimate

1010   event on the Wairarapa fault (CC2) and the subsidence event recorded at Big Lagoon, and

1011   suggest that either the BL2 subsidence event was due to rupture that involved both the

1012   megathrust and the Wairarapa fault (as is postulated to have happened in the 1855 event of the

1013   Wairarapa fault [*Little et al.*, 2009]), or a situation where the Wairarapa and megathrust faults

1014   ruptured separately but in temporally closely spaced events. These observations suggest that, at

1015   least sometimes, the megathrust fault may rupture together with, or within a short time of, brief

1016   sequences of events on the Al-Hp-JKN-Wr upper plate fault system. It is worth noting, however,

1017   that if the Big Lagoon record is complete, significant slip on the shallow parts of the megathrust

1018   does not occur in every upper-plate system sequence.

1019

1020   **Conclusions**

1021   We present new paleoearthquake ages using primary event evidence from the Green Burn

1022   reach of the Hope fault. We document the occurrence of five surface ruptures along the Conway

1023   segment of the Hope fault at two sites along the Green Burn (GB) reach of the fault. These

1024   earthquakes have occurred during the past c. 2000 years, with preferred 2σ event ages as follows:

1025 GB1: 1731—1840 CE, GB2: 1657—1797 CE, GB3: 1496—1611 CE, GB4: 1290-1420 CE,

1026 GB5: 36 BCE–1275 CE. The new Green Burn data, together with other previously documented

1027 on-fault and off-fault paleo-earthquake age constraints from the various faults of the >850-km-

1028 long Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa system of fast-slipping plate-boundary

1029 faults in South Island and southern North Island, are consistent with the possibility that several of

1030 the Green Burn surface ruptures could have occurred during relatively brief (≤100 years)

1031 sequences that involved rupture of large sections of the fault system. However, the available data

1032 indicate that "wall-to-wall" rupture of the entire Alpine-Hope-Jordan-Kekerengu-Needles-

1033 Wairarapa system during brief sequences that ruptured all faults in the system must be a rare

1034 event. Indeed, the only possible such sequence occurred c. 1,000-1100 CE, during which all

1035 faults in the system, from the Alpine fault in the southwest, to the Wairarapa fault in the

1036 northeast, allowably ruptured during the same brief (≤100-year) time interval. Partial rupture of

1037 the Alpine-Hope-Jordan-Kekerengu-Needles-Wairarapa fault system in the M_w=7.8 2016

1038 Kaikōura earthquake may be a harbinger for future events within a potential new rupture

1039 sequence along the plate boundary (S_o), potentially involving the Conway segment of the Hope

1040 fault adjacent to the Jordan-Kekerengu-Needles system, and even the underlying Hikurangi

1041 subduction megathrust.

1042

1043 **Acknowledgments**

1051

Data and Resources

1053   The background imagery used in Figure 1 is from GeoMapApp http://www.geomapapp.org

1054   [*Ryan et al.*, 2009]. Station metadata from KIKS sensor referenced in section "Coseismic origin

1055   of colluvial wedges and landslides observed at GBW/GBE: Observations of the Green Burn

1056   Reach following the 2016 M_w=7.8 Kaikōura earthquake" can be accessed at

1057   https://www.geonet.org.nz/data/network/sensor/KIKS (last accessed November 19, 2018) and

1058   associated shake maps from the 2016 M_w=7.8 Kaikōura earthquake can be accessed at

1059   https://earthquake.usgs.gov/earthquakes/eventpage/us1000778i/shakemap/pgv (last accessed

1060   November 19, 2018). Lidar data was acquired by LINZ immediately following the M_w=7.8

1061   Kaikōura earthquake; similar data is publically available for download from

1062   www.opentopography.org (DOI: 10.5069/G93J3B2J).

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1325   Figure Captions

1326   Figure 1: (a) Map of New Zealand with plate motion vectors [DeMets et al., 2010] WLG-

1327   Wellington, CHC-Christchurch. Red lines delineate major active faults of northern South Island

1328   and southern North Island. (b) Regional fault map showing Alpine fault, Marlborough fault

1329   system, and North Island faults. Conway segment of Hope fault is shown in yellow; yellow star

1330   denotes Green Burn study site (GB). Hope fault system includes Kelly fault, Hurunui segment,

1331   Hope River segment, Conway segment, and Seaward segment. KF-Kakapo fault, HB-Hanmer

1332   Basin, EF-Elliott Fault, JT-Jordan thrust, PF-Papatea fault, OhF- Ohariu fault, ClF-Cloudy fault,

1333   VnF-Vernon fault, WgF-Wellington fault, WrF-Wairarapa fault. Fault maps adapted from

1334   Langridge et al., [2016]. Circle with BL label marks Big Lagoon subsidence site [*Clark et al.,*

1335   2015]. To view this figure in color, the reader is directed to the online version of this manuscript.

1336

1337   Figure 2: Location maps generated using lidar digital elevation model (DEM) collected by GNS

1338   Science/LINZ following the Mw=7.8 2016 Kaikōura earthquake. See Data and Resources for

1339   access to lidar data. (a) Hillshaded DEM of Green Burn stretch of Conway segment of Hope

1340   fault. GBW-Green Burn West (this study) (-42.396560°, 173.388838°), GBS-Green Burn Stream

1341   (Langridge et al., [2003]) (-42.395914°, 173.392075°), GBE-Green Burn East (this study) (-

1342   42.393212°, 173.405528°). (b) Hillshaded DEM with 50 cm contours at the Green Burn East

1343   site, showing the fault-perpendicular trench. Small landslides are denoted with gray outlines (ls).

1344   (c) Hillshaded DEM with 50 cm contours at the Green Burn West site, showing T-1 and T-2.

1345   Small landslides are denoted with gray outlines (ls). To view this figure in color, the reader is

1346   directed to the online version of this manuscript.

1347

1348   Figure 3: Composite field and photomosaic logs of GBE (a) East wall (inverted) and (b) West

1349   wall. Unadulterated photomosaic is presented in Figure S3, available in the electronic

1350   supplement to this article. Colluvial wedge deposits are denote in shades of purple, clay units are

1351   shades of brown, shear zones are shades of red, and marsh units are shades of blue. Pebbles and

1352   cobbles and distinctive orange clasts from unit CW2 were logged on photomosaics after field

1353   work. Radiocarbon ages are colored yellow for samples included in age models; gray samples

1354   were not included in the age model, but results are listed in Table 1. To view this figure in color,

1355   the reader is directed to the online version of this manuscript.

1356

1357   Figure 4: Log of west wall of GBW T1 atop photomosaic. Unadulterated photomosaic is

1358   presented in Figure S4, available in the electronic supplement to this article. Note landslide tip

1359   (opaque purple) atop paleosol (green) at northern end of the trench near between m 11 and 16.

1360   Radiocarbon sample used in age models are shown in yellow. To view this figure in color, the

1361   reader is directed to the online version of this manuscript.

1362

1363   Figure 5: Log of GBW T2. Unadulterated photomosaic is presented in Figure S5, available in the

1364   electronic supplement to this article. Landslide deposits are shown in light gray with purple

1365   outlines, and paleosol is gradational from blue to purple. Radiocarbon samples used in GBW age

1366   models are showing in yellow. To view this figure in color, the reader is directed to the online

1367   version of this manuscript.

1368

1369   Figure 6: OxCal derived age models. (a) GBE colluvial samples only, (b) GBE colluvial and

1370   south marsh samples, (c) GBE north marsh samples only, (d) GBW T2 only, (e) GBW T1 & T2.

1371   (f) Preferred age model, which incorporates GBE, GBW T1 and T2.

1372

1373   Figure 7: Events through time along the north-central Alpine, Hurunui (Hope), Conway (Hope)

1374   Kekerengu-Needles and Wairarapa faults. Top map shows faults with study sites labeled; see

1375   Table 3 for citations and age information. Individual event names are indicated with a capital

1376   letter for each site with a number as shown in Table 3. Bottom panel shows temporal length of

1377   events (2σ age range) with vertical gray bars. Horizontal pink-shaded boxes represent 100-year-

1378   long potential "clustered event" sequences (see text for explanation), and are label SX near each

1379   box. Horizontal blue-shaded boxes represent isolated earthquakes, and are labeled IsX near each

1380   box. Thin, horizontal, red bars represent known surface rupture earthquakes on the Al-Hp-JKN-

1381   Wr system, either in the historical period [McKay, 1890; Little et al., 2009; Khajavi et al., 2016;

1382   Kearse et al., 2017] or using tree ring disturbance analysis [Wells et al., 1999]. Paleoseismites

1383   recovered at Lake Ellery after 370 CE have poorly constrained rupture limits and may not have

1384   occurred on the central-northern Alpine fault [Howarth et al., 2016]. To view this figure in color,

1385   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.

Event	GBE+GBW (preferred)		GBW T1 & T2		GBW T2 only		GBE colluvial and so. marsh		GBE colluvial only		GBE north marsh	
	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	
	A2	1549	1594	S3	
	A3	1388	1407	Is1	Wells et al., 1999; Howarth et al., 2012; 2014; 2016; 2018
	A4	1008	1213	S4	
	A5	915	961	Is3	
	A6	592	646	S5	
	A7	370	416	S6	
Hope (Hurunui)	MF1	1888	--	S1	
	MF2	1652	1840	S2	Langridge et al., 2013
	MF3	1630	1424	S3	
Hope (Hurunui)	HS1	1888	--	S1	
	HS2	1818	1840	S2	
	HS3	1233	1735	S3	Khajavi et al., 2016
	HS4	821	1100	S4	
	HS5	439	587	S5	
	HS6	375	428	S6	
Hope (Conway)	GB1	1730	1840	S1	
	GB2	1657	1797	S2	
	GB3	1495	1611	S3	This study
	GB4	1230	1277	Is2	
	GB5	476	1240	S4	
	GB6	476	1240	S5	
eastern Kekerengu	EK0	2016	--	N/A	
	EK1	1701	1840	S1	
	EK2	1422	1594	S3	Little et al., 2018
	EK3	701	1047	S4	
	EK4	224	857	S5	

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