Paleoseismology of the Hyde and Northwest Cardrona faults, Otago.

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Technical Abstract

This report is a precis of work carried out over the period 2018-2020 on characterising active fault sources for seismic hazard assessment in the Otago region. Specifically, the earthquake recurrence behaviour of the Hyde and Northwest (NW) Cardrona faults are characterised from paleoseismic investigations and preparation of trench logs. The Hyde Fault study reveals that two ground rupturing earthquakes occurred on the fault at 22.8±1.8 and 10.2±1.3 kyrs, respectively, which loosely constrains a recurrence interval of c. 9.5-16 kyrs. The study represents the first paleoseismic investigations ever carried out on the Hyde Fault. The NW Cardrona study reveals three events to have ruptured the fault, at: 37.8 ± 4 -39.3 ± 4.4; 27.2 ± 2.8 - 28.2 ± 2.6; and 3.3 ± 0.6–14.3 ± 1.4 kyrs. These data constrain a recurrence interval of 11-13 kyrs. The NW Cardrona trench is a re-excavation of a trench originally excavated for hydro-electric power development in the 1980s, when dating techniques were largely unavailable. The results of these studies will be used to update earthquake recurrence estimates for the 2022 update of the national seismic hazard model.

Non-technical Abstract

The Otago region has seen very few earthquakes over the last two centuries, and this is due to the region being well to the east of the main boundary of the Australian and Pacific tectonic plates. A formidable task is therefore to decide where major earthquakes will occur in the future. The experience of Christchurch showed that a major earthquake can occur out of the blue, and have devastating consequences. With this concern in mind our work over the period 2018-2020 has focused on using geological data and methods to find out how often large earthquakes have occurred over geologic time on two major Otago faults. These are the Hyde and Northwest (NW) Cardrona faults, which would cause damaging shaking in Dunedin, Wanaka and Queenstown if they produced major earthquakes. We excavated two trenches across the Hyde Fault and one across the NW Cardrona Fault, and worked out when major earthquakes occurred on them. We found that two major earthquakes occurred on the Hyde Fault about 23 and 10 kyrs ago. The study is the first of its kind to be

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carried out on the Hyde Fault. Our study of the NW Cardrona study showed that three major earthquakes occurred on the fault, about 38, 28, and 3-14 kyrs ago. The NW Cardrona trench was a re-excavation of a trench originally excavated for hydro-electric dam site development in the 1980s, when sediment age dating techniques were largely unavailable. The results of these studies will be used in the 2022 update of the New Zealand national seismic hazard model.

Introduction

This report briefly documents paleoseismic studies of the Hyde and NW Cardrona faults of the central Otago Range and Basin province (Fig. 1). Central Otago is an area of contractional tectonics to the east of the boundary of the Pacific and Australian plates, and accommodates less than 3 mm/yr of the oblique plate convergence (Beavan et al., 2016). The topography shows smooth topped mountain ranges which are the uplifted, unglaciated remnants of the Tertiary Waipounamu Erosion Surface (WES; Landis et al., 2008). The surface is a ubiquitous element of the central Otago landscape, and a useful datum for estimating total late-Cenozoic throw on the faults.

Central Otago's first paleoseismic investigations took place in the 1980s, and were motivated by proposed hydroelectric dam developments on the Clutha River. Paleoseismic investigations were limited to the Dunstan, NW Cardrona, and Nevis faults, whereas other faults (e.g. Pisa and Grandview faults) received lesser attention. Since then, only the Dunstan Fault has been reinvestigated using modern dating techniques (Van Dissen et al., 2007). Our studies of the Hyde and NW Cardrona faults therefore represent the first paleoseismic investigations to have been carried out in the region in over a decade, and the first-ever paleoseismic investigations of the Hyde Fault. While the NW Cardrona Fault was already studied in the 1980s, the earthquake recurrence behaviour of the fault was largely unconstrained due to the lack of dating techniques available at the time (other than conventional radiocarbon). Our studies use Optically Stimulated Luminescence (OSL) dating techniques to constrain the earthquake recurrence behaviour of the two faults.

While this report is only a brief overview of our studies of the two faults, we hasten to add that the two studies have been substantially documented in the PhD and MSc theses of Jonathan Griffin and Ella van den Berg, respectively (Griffin, in preparation; van den Berg, 2020). Journal papers have also been published or are in preparation as a result of this work (Griffin et al., 2020; van den Berg et al., in preparation), and results presented at the 2019 and 2020 Geoscience Society of New Zealand conferences. We also note that the scope of our study differs somewhat from the original contract brief, in that we do not develop actual earthquake sources to directly inform the national seismic hazard model (NSHM), other than providing estimates of recurrence interval for the two faults. This is because of large delays in the initiation of the present update of the NSHM.

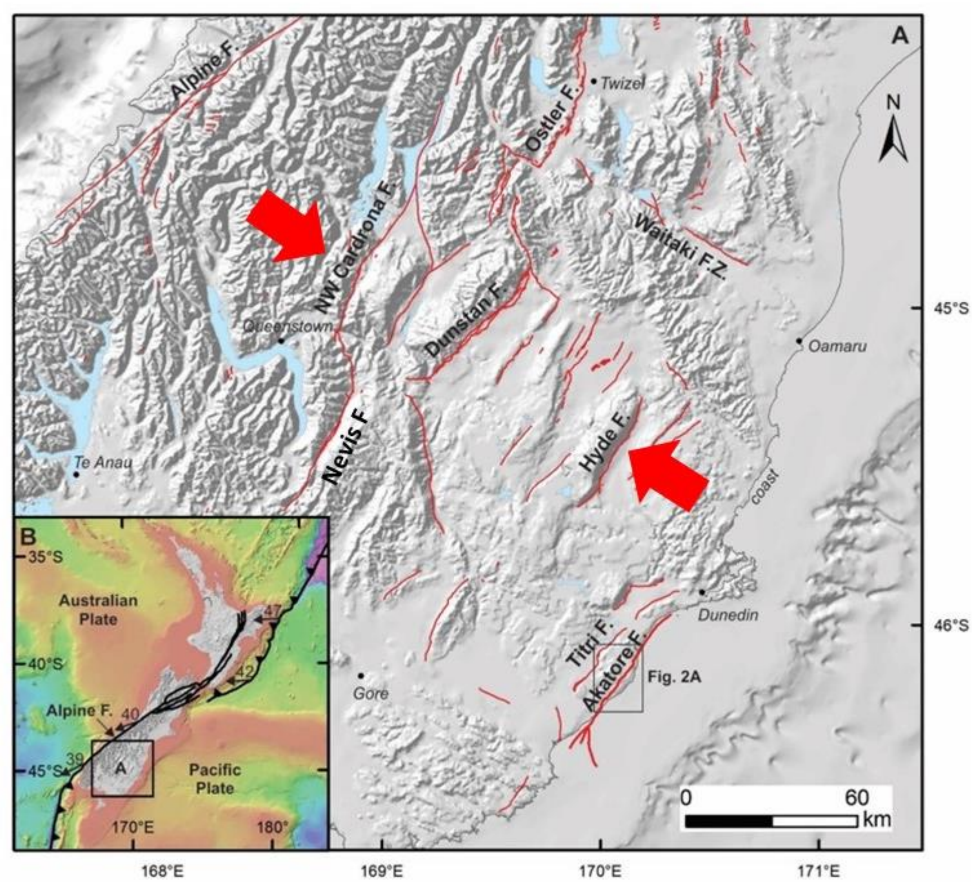


Figure 1: The central Otago region (A), showing the Hyde and NW Cardrona faults (red arrows), and the location of the region in relation to the plate boundary.

Hyde Fault

The Hyde Fault strikes northeast along the southeastern base of the Rock and Pillar Range (Fig. 2). The fault has vertically offset the WES by c.1000 m. A southward extension of the Hyde Fault known as the Twins Fault offsets the WES by a maximum of 400 m, with total offset decreasing to the south. The Twins Fault could potentially rupture with the main Hyde Fault in a single earthquake of M_w 7.6, while a M_w 7.4 earthquake could be expected from full rupture of only the main Hyde Fault (Villamor et al., 2018).

The Hyde Fault is visible as a discontinuous fault scarp extending for at least 55 km in length along the Rock and Pillar range front. Scarp height vary from < 1 m across young alluvial surfaces, to up to ~30 m where resistant bedrock schist has overthrust alluvial fan sediments.

The south-eastern flank of the range is marked by numerous landslides. Several upland basins feed into alluvial fans in the Strath-Taieri Basin. Active fan development in east Otago is thought to have primarily occurred during glacial periods (Litchfield & Lian, 2004).

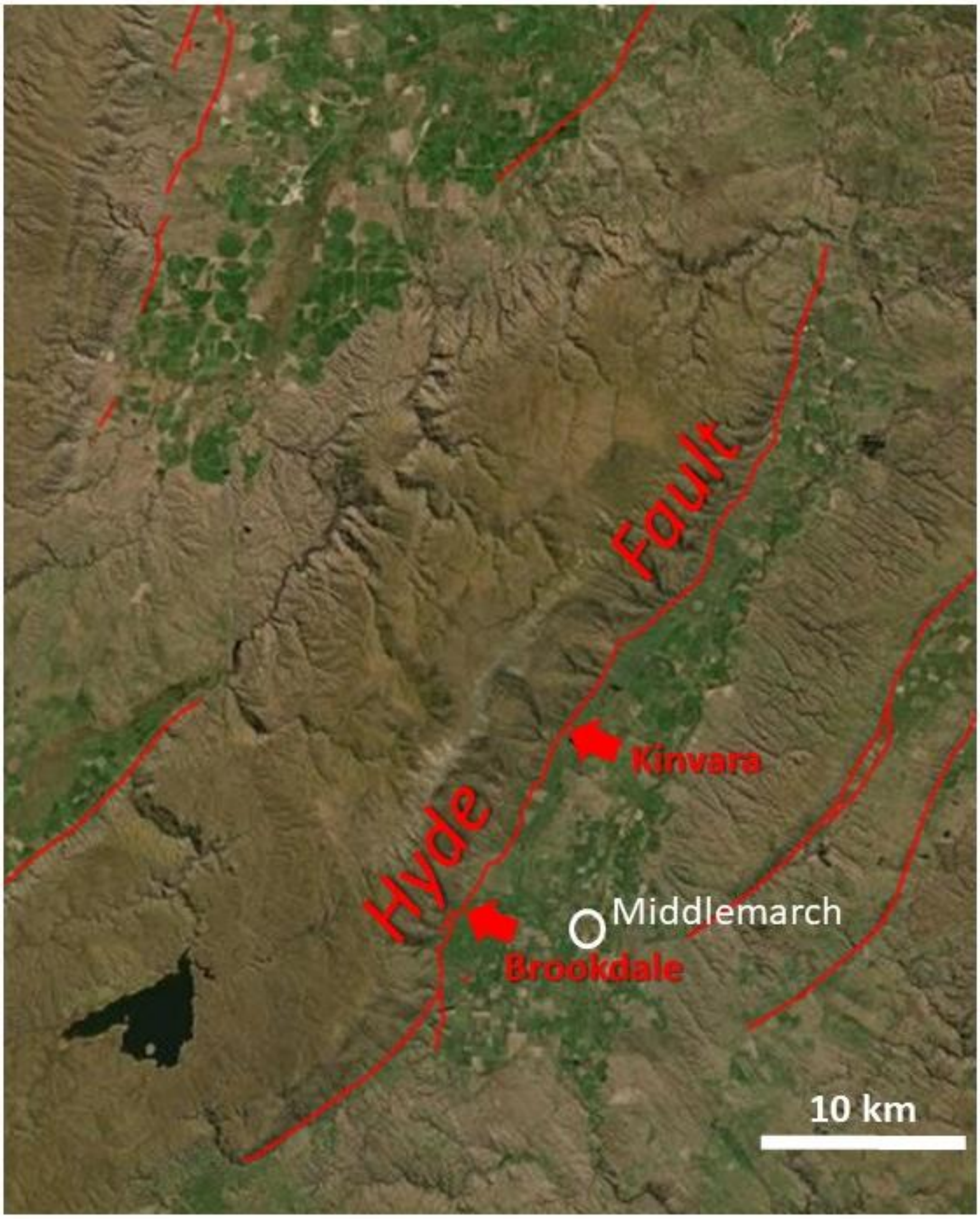


Figure 2: Hyde Fault, showing the overall geomorphology of the fault, and the two trench sites. Source of the fault trace information is the GNS Science Active Fault Database.

Kinvara and Brookdale trench sites

Two sites (Kinvara and Brookdale) were chosen for trenching following Lidar interpretation, field inspection and negotiation with landholders (Fig. 2).

The **Kinvara** trench was located on the north-eastern flank of the extensive Six-Mile Creek fan. Here the fault scarp is c.5 m high, and is clearly visible on satellite imagery from a change in vegetation greenness across the fault. Relatively greener vegetation grows on the footwall compared with the well-drained alluvium on the hanging wall. Springs are also observed on the fault about 300 m to the north of the trench site, showing that the fault provides controls on local groundwater flows.

Trench logs and orthophotos of the Kinvara trench are shown in Figure (north wall) and Figure (south wall). The fault consists of a main lower fault plane along which most of the slip appears to have occurred. In the lower part of the trench a mixed zone of sheared alluvium overlies the main fault plane, with a secondary fault plane separating the mixed zone from overlying strata. This upper fault plane terminates in a tight fold axis. Other minor folds are also evident in the hanging wall. The upper fault plane is interpreted as a shear axis, with only a minor component of slip likely to have occurred along this plane.

Two events are interpreted in the Kinvara trench. In the north wall of the trench the penultimate event is indicated by a low-angle termination of the fault above footwall silts and gravels. The most recent event (MRE) has then faulted the colluvial wedge unit that formed after the penultimate event, and has caused tight folding and overturning of hanging wall sediments. Determining the uppermost extent of deformation caused by the MRE is difficult as the upper deformation zone and overlying sediments are dominated by massive silts, with only occasional gravels and sand stringers providing constraints on bedding orientation and deformation (Fig. 3). Erosion of surficial pre-faulting silt units on the up-thrown hanging wall added further challenges to our interpretations.

The **Brookdale** trench was located on a c.5 m scarp crossing a narrow interfluve. The site is surrounded by scarps of varying heights along the strike of the fault, including large (c.30 m high) scarps where schist has overthrust fan sediments. No major fans are present at the site. Instead, the site is close to the range, and several smaller fans have deposited very coarse alluvium, including many large boulders. Some of the boulders are coincident with the actual fault, providing some difficulties in interpreting near-fault stratigraphy. Trench logs and orthophotos are shown in Figure 5 (north wall) and 6 (south wall). One clear fault plane is evident within the Brookdale trench.

The penultimate event in the Brookdale trench is indicated by a coarse colluvial wedge in the north wall, and the MRE has then faulted the colluvial wedge. As with the Kinvara trench, overlying footwall sediments are predominantly massive silts with limited constraints on bedding orientation, which makes the interpretation of the youngest faulting a difficult task. Two OSL samples taken from the north wall of the trench were dated, and these are used with the Kinvara OSL dates to constrain the MRE.

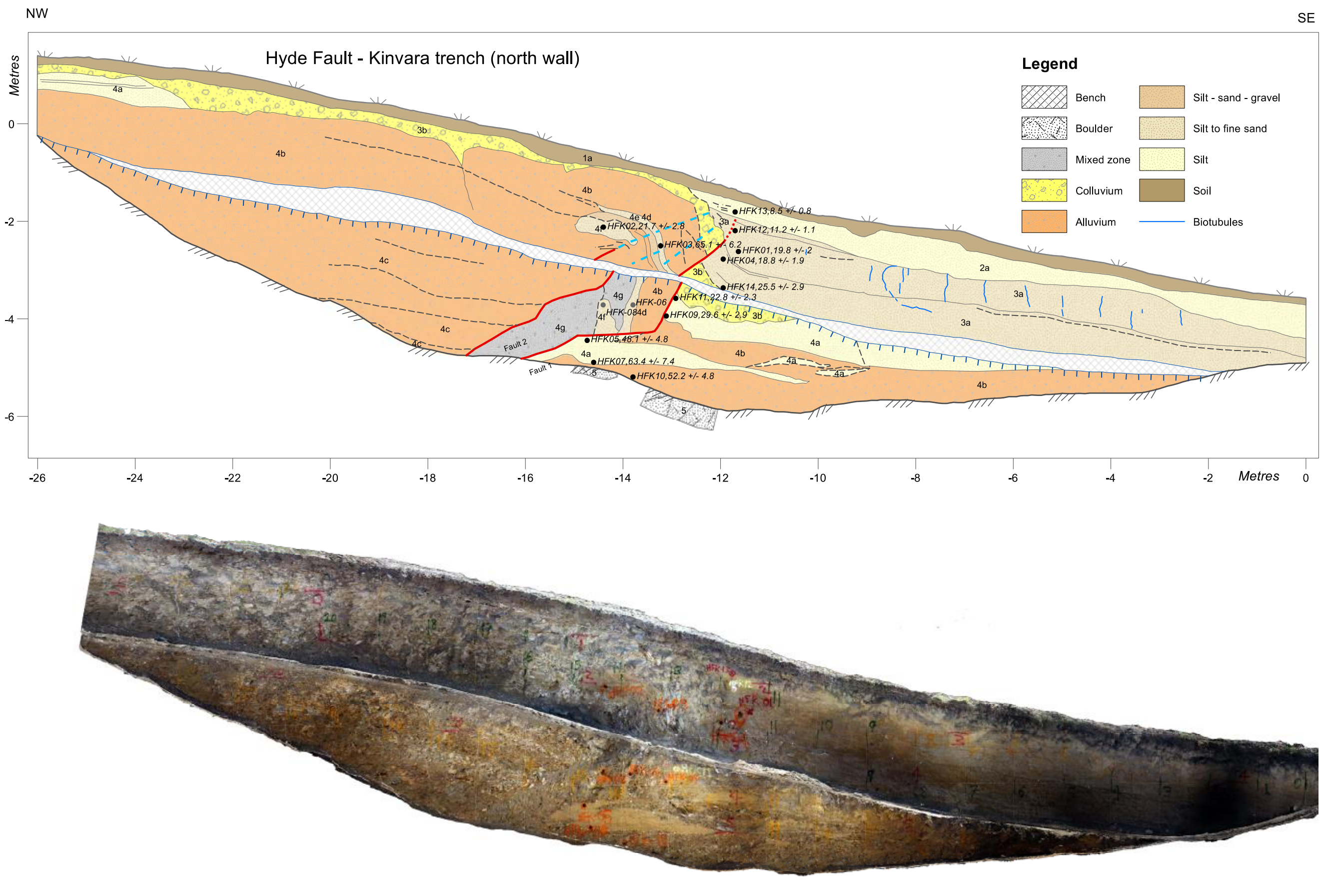


Figure 3: North wall of the Kinvara trench showing (a) interpreted log; and (b) orthophoto mosaic. The actual Hyde Fault is shown by the red lines. Source is Griffin (in preparation).

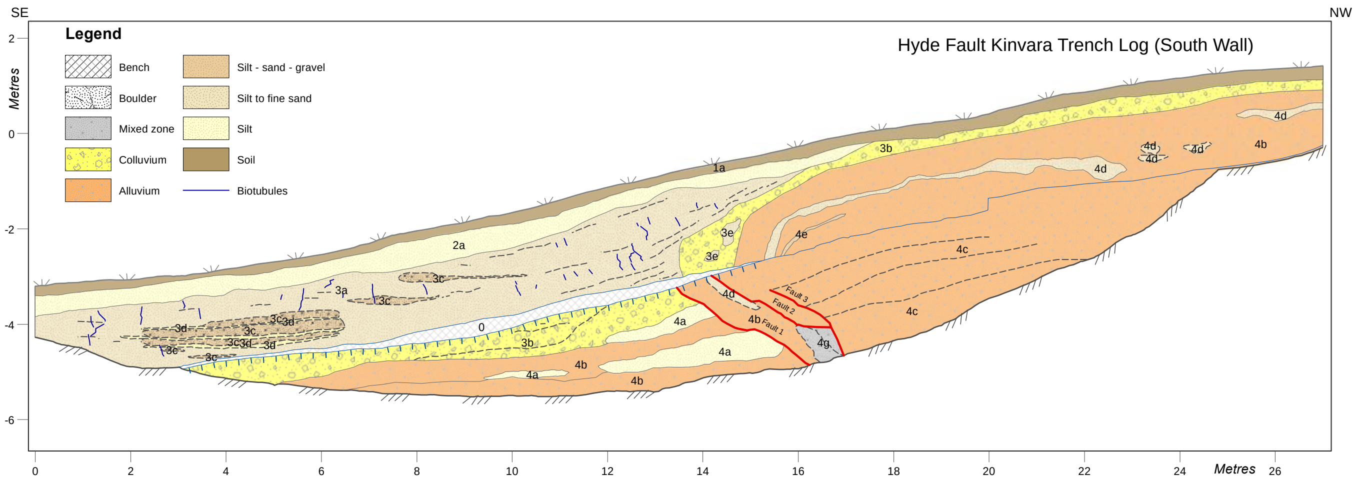


Figure 4: South wall of the Kinvara trench showing (a) interpreted log; and (b) orthophoto mosaic. The actual Hyde Fault is shown by the red lines. Source is Griffin (in preparation).

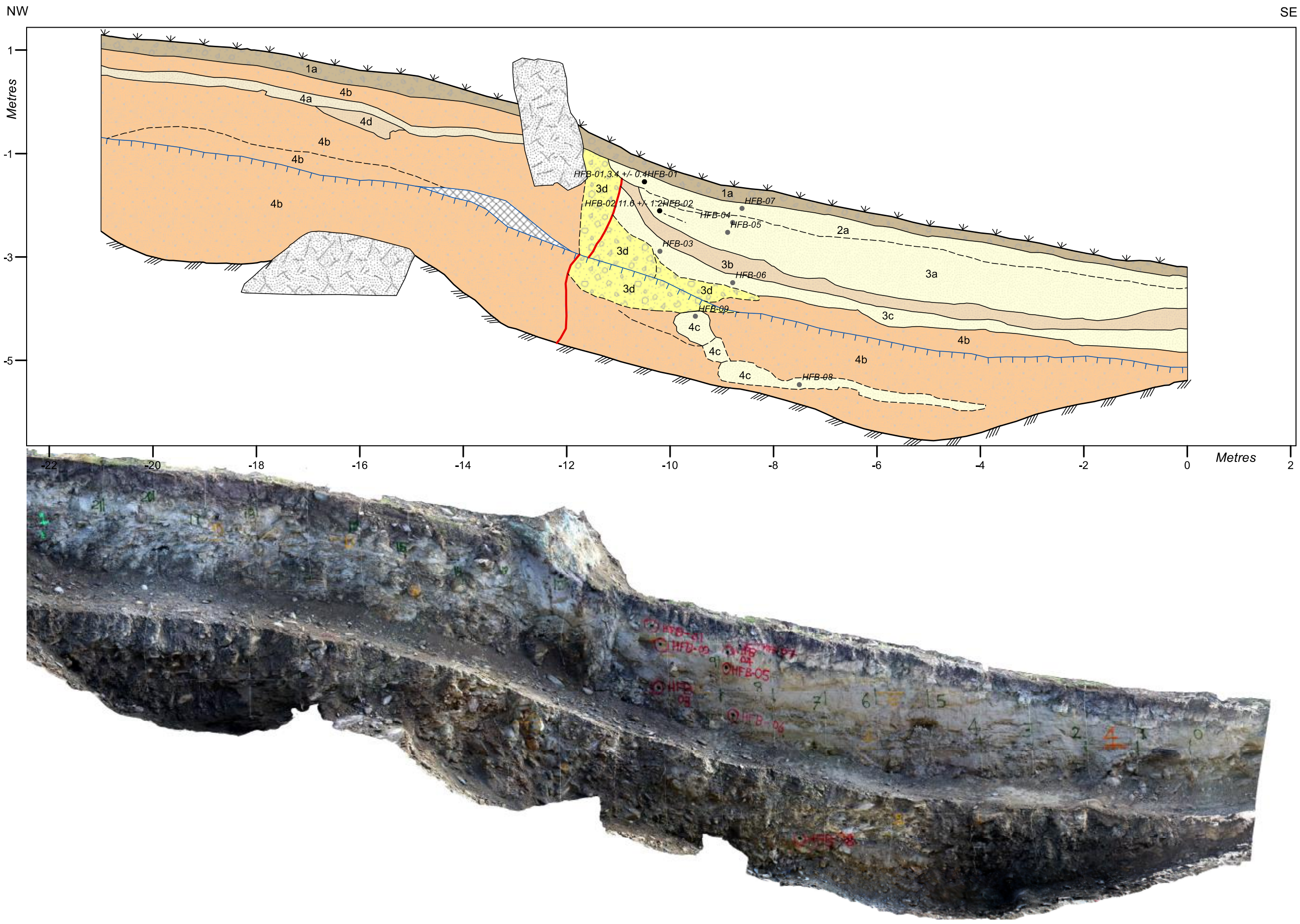


Figure 5: North wall of the Brookdale trench showing (a) interpreted log; and (b) orthophoto mosaic. The actual Hyde Fault is shown by the red lines. Source is Griffin (in preparation).

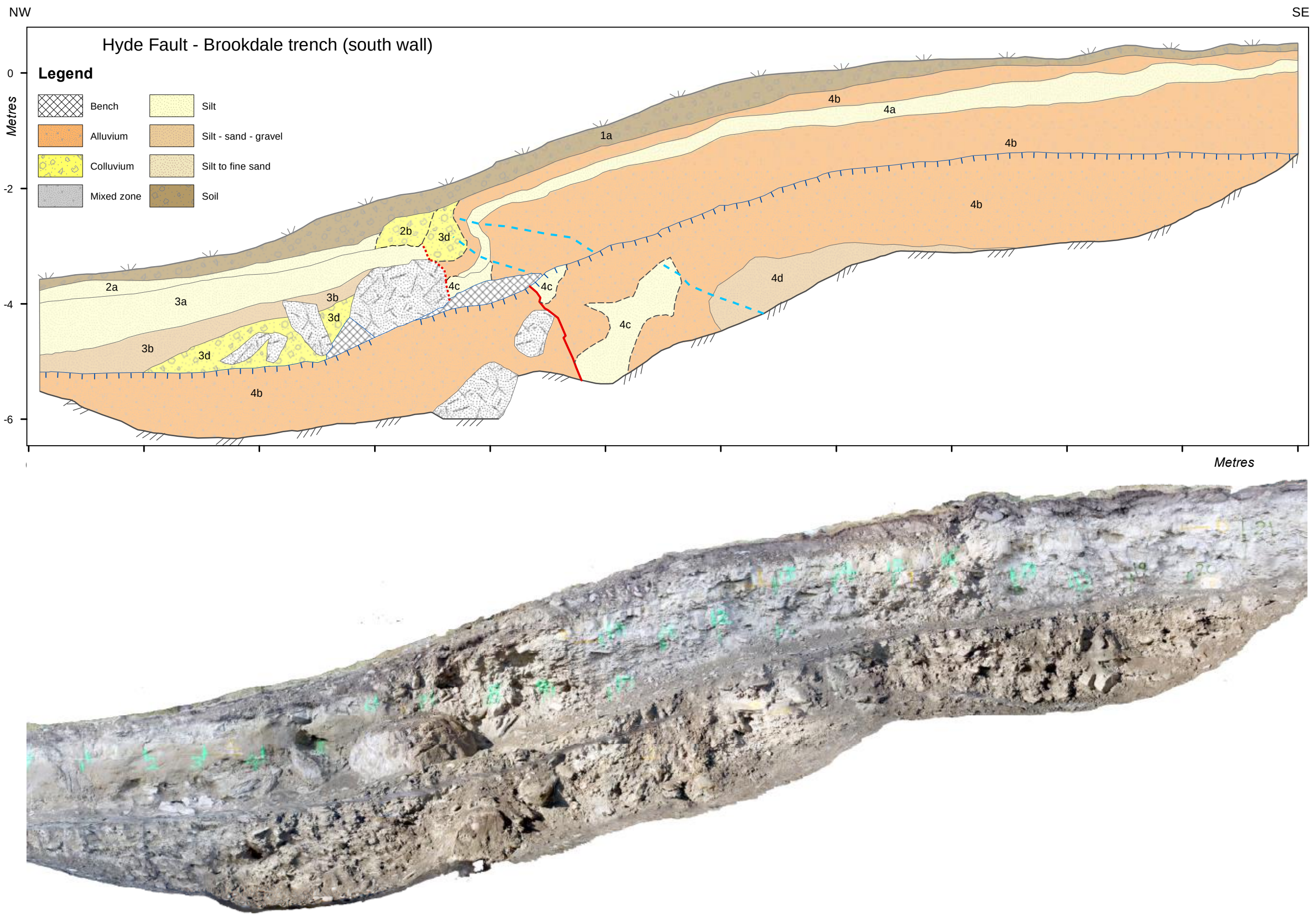


Figure 6: South wall of the Brookdale trench showing (a) interpreted log; and (b) orthophoto mosaic. The actual Hyde Fault is shown by the red lines. Source is Griffin (in preparation).

Earthquake chronology

Both trenches demonstrate evidence for two ground rupturing earthquakes on the Hyde Fault. The penultimate event is well-constrained by OSL dating above and below the colluvial wedge in the Kinvara trench to 22.8±1.8 ka. The MRE is less well constrained due to challenges in interpreting the upper limit of faulting within massive silt units and lack of clearly defined colluvial wedge. The MRE could have occurred any time between 21.1 ka and 7.7 ka. However, our preferred interpretation is that the MRE occurred around 10.2 ± 1.3 ka, based on several lines of evidence for tectonic deformation from the two trenches (Griffin, in preparation).

NW Cardrona Fault

We excavated one trench on the NW Cardrona Fault at the Branch Creek site in the Cardrona Valley (Fig. 7). While the NW Cardrona Fault is generally an east-facing scarp along most of the fault length, and is responsible for uplift of the Cardrona Range to the west, the scarp of the fault at the Branch Creek site is west-facing. In other words, the sense of throw on the fault is opposite to that of the cumulative throw on the fault. We interpret the Branch

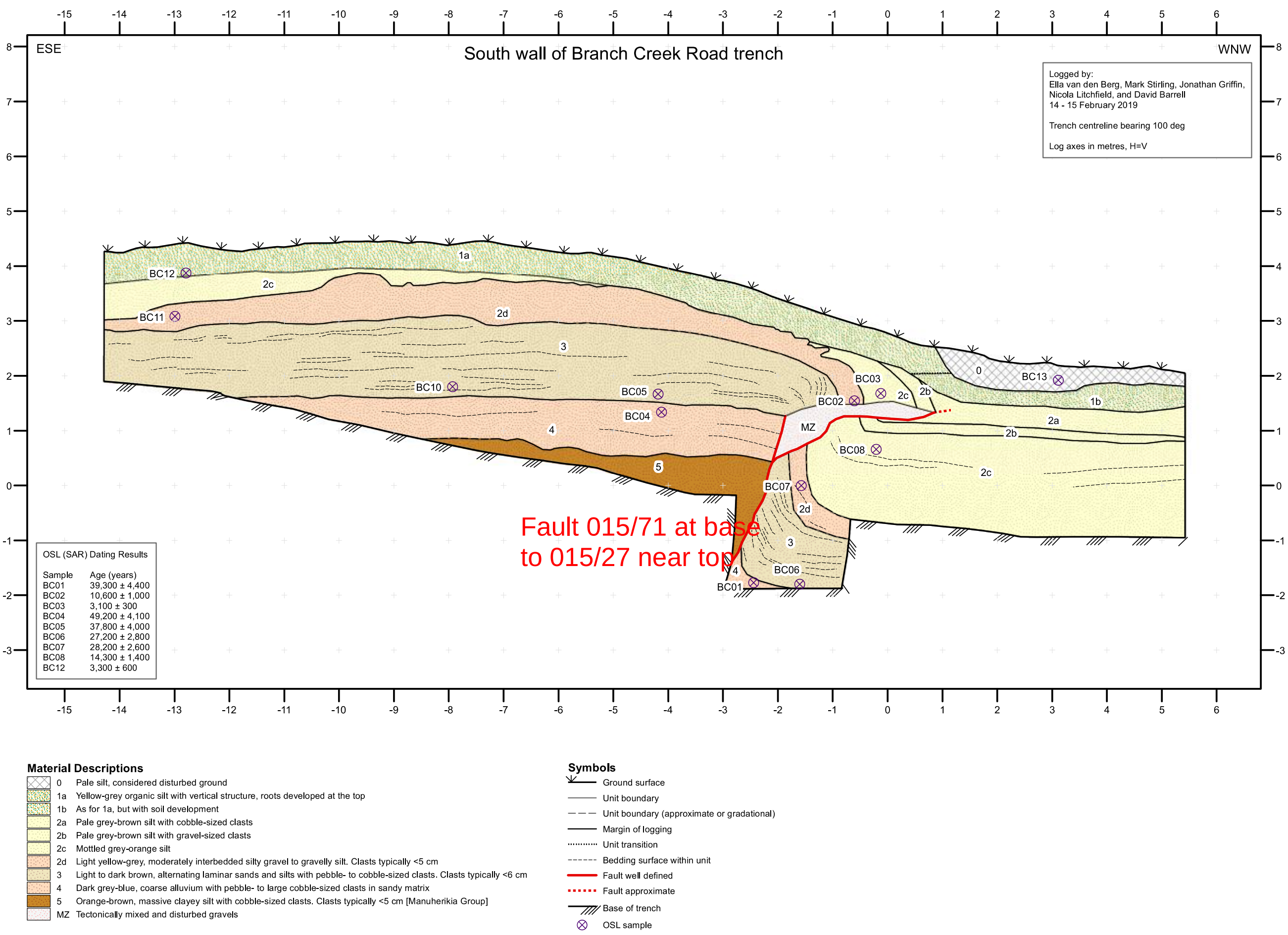
Creek section of the fault to be a short-lived structural complexity, and acknowledge the possibility that it may not have recorded all the earthquakes on the NW Cardrona Fault. A more optimistic interpretation is that this part of the fault is accommodating surface slip above a blind master NW Cardrona Fault. If this were the case ruptures on the Branch Creek trace would be directly linked to ruptures on the master NW Cardrona Fault.

We had originally planned to trench the fault at a site to the north where the scarp is east facing and much more prominent, but late-stage land management decisions unfortunately prevented us from doing so. We were subsequently granted permission to trench the Branch Creek site, and at the same site as that of Beanland and Barrow-Hurlbert (1988). While their early interpretations suggested the occurrence of three rupture events at the site, age control on the timing of these events could not be obtained due to the limited dating techniques of the time.

Figure 7: NW Cardrona Fault, showing the location of the Branch Creek trench site. Source of the fault trace information is the GNS Science Active Fault Database.

Branch Creek Trench

The trench was orientated NW-SE across a west-facing scarp of c. 3-4 m height. The scarp displaces an alluvial surface assumed to be Hawea age (c. 16 kyrs) across a c. 200 m wide terrace remnant. The trench revealed a sequence of blue-grey to yellow-brown gravels and silts displaced by an east-dipping reverse fault (Fig. 8). Tertiary sediments of the Manuherikia Group were also exposed in the hanging wall at the base of the trench. The fault has a steep dip in the lower part of the trench, and sub-horizontal in the upper part. Three earthquake events are interpreted from the trench, with uncertainty surrounding the youngest sediments displaced by the MRE. This is due to the near-surface silts not being conducive to revealing fault displacements. The three events interpreted from the trench are the same as the number interpreted by Beanland and Barrow-Hurlbert (1988). OSL samples taken from the trench are shown as circled crosses in Figure 8.



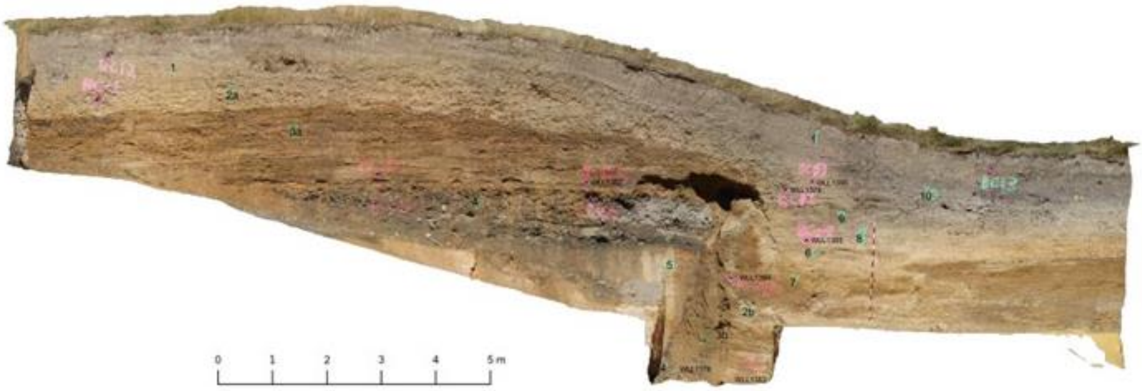


Figure 8: South (only) wall of the Branch Creek trench, showing interpreted log (top) and orthophoto mosaic (bottom). The actual NW Cardrona Fault is shown by the red lines. Source is van den Berg (2020).

Earthquake chronology

Three earthquake events are interpreted from the Branch Creek trench, which supports the earlier interpretations of Beanland and Barrow-Hurlbert (1988). With the aid of nine OSL samples, the timing of these events has been constrained to the following: an antepenultimate event at 37.8 ± 4 – 39.3 ± 4.4 kyrs; a penultimate event at 27.2 ± 2.8 – 28.2 ± 2.6 kyrs; and the MRE between 3.3 ± 0.6 and 14.3 ± 1.4 kyrs. The 3.5 m of cumulative dip-slip displacement measured across these three events equates to an average dip-slip single-event displacement of c. 1.2 m.

While these data on the timings of earthquakes cannot be directly compared to the earlier studies of the site (Beanland and Barrow-Hurlbert, 1988) due to the lack of age control, the trench dates can be compared to a trench at the south end of the NW Cardrona Fault (Kawarau trench, c. 20km to the south). Three events were interpreted in the Kawarau trench by Beanland and Barrow-Hurlbert (1988), and the age control from that trench allows for the penultimate and MRE of the Kawarau trace to overlap with our MRE from the Branch Creek trench. This means that at least one of the earthquakes appears to have ruptured both sites, and raises the possibility that the Nevis and NW Cardrona faults rupture together in some earthquakes (Fig. 1).

Earthquake recurrence estimates for the Hyde and NW Cardrona faults

Hyde Fault

Estimates of recurrence interval for the Hyde Fault are made from the inter-event time interpreted from the Kinvara and Brookdale trench data. The timing of the penultimate and MRE of 22.8±1.8 and 10.2±1.3 kyrs, respectively, gives an interevent time of c. 9.5-16 kyrs. This interevent time effectively represents a poorly constrained recurrence interval. However, it is likely that there have been no additional events within the past c. 65 kyrs, so the concept of a single recurrence interval may be of limited relevance to the fault. The suggestion that faults exhibit strongly aperiodic behaviour is a topic of ongoing research in central Otago and other areas that are away from major plate boundaries (Griffin et al., 2020).

While we have not estimated magnitude from our studies, we would expect the above events to be associated with large earthquakes on the Hyde Fault. The regional study of Villamor et al. (2019) provided an estimate of Mw7.4 for rupture of the full length of the Hyde Fault, and possibly as much as Mw7.6 if a rupture involved both the Hyde Fault and the Twins Fault to the south.

NW Cardrona Fault

Estimates of slip rate, recurrence interval and magnitude are made for the NW Cardrona Fault from displacement information (amount and timing) in the Branch Creek trench, and from measurements of fault length (van den Berg, 2020). A slip rate of c. 0.1 mm/yr is estimated from the cumulative displacement in the trench divided by the age of oldest sediments exposed in the trench. A recurrence interval of 11-13 kyrs is then estimated by dividing the range of single event displacements by the slip rate. This is longer than the 4-9 kyrs estimated for the NW Cardrona Fault by Beanland and Barrow-Hurlbert (1988), the latter based on sparse age control, and no age control at the actual Branch Creek site. Estimates of magnitude from a scaling relation used by Stirling et al. (2012) range from Mw7.3 for rupture of the full length of the NW Cardrona Fault (c. 50km), and Mw7.5 for rupture of the combined length of the Nevis and Cardrona faults (c. 100 km).

Conclusions

This report has provided a precis of paleoseismic work carried out over the period 2018-2020 to constrain the earthquake recurrence behaviour of the Hyde and Northwest (NW) Cardrona faults. The Hyde Fault study has constrained a recurrence interval of c. 9.5-16 kyrs, and the NW Cardrona study has constrained a recurrence interval of 11-13 kyrs. The results of these studies will be used to update earthquake recurrence estimates for the 2022 update of the national seismic hazard model.

Acknowledgements

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