BEFORE THE CANTERBURY REGIONAL COUNCIL
AND THE ASHBURTON DISTRICT COUNCIL

IN THE MATTER	of the Resource Management Act 1991
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IN THE MATTER	of resource consent applications by Rangitata Diversion Race Management Ltd to the Canterbury Regional Council and Ashburton District Council for resource consents for the construction, operation and maintenance of the Klondyke Water Storage Facility, its associated water takes from and discharges to the Rangitata River, and all associated activities

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STATEMENT OF EVIDENCE OF DAVID JOHN ARNOLD BARRELL

Qualifications and experience

1. My name is David John Arnold Barrell and I am a senior scientist with the Institute of Geological and Nuclear Science Limited, trading as GNS Science. I have been employed by the company since 1994 in the general field of geology. My work focuses on geological mapping, mapping and interpretation of landforms, also known as geomorphology, and in the mapping and interpretation of geological hazard features such as landslides and active faults. I hold the degree of Bachelor of Science in Geology from the University of Canterbury, awarded in 1984, and the degree of Master of Science in Engineering Geology, also from the University of Canterbury, awarded 1989. I am a member of the New Zealand Geotechnical Society, and also the Geoscience Society of New Zealand. In 2012, I received the McKay Hammer award of the Geoscience Society of New Zealand, for the most meritorious publication relating to New Zealand geology in the preceding three years. The award was made for my work on glacier-related landforms of the Southern Alps (Barrell and others, 2011a).

1.1 I have been involved in geological and geomorphological mapping in the Southern Alps and Canterbury Plains since 1995, including in the area of the proposed Klondyke Water Storage Facility (Klondyke Pond). Publications arising from that work, and all of which include the area of the proposed Klondyke Pond, are listed as follows.[1]

1.1.1 Barrell DJA, Forsyth PJ, and McSaveney MJ. 1996. Quaternary geology of the Rangitata fan, Canterbury Plains, New Zealand. Institute of Geological and Nuclear Sciences Science Report 96/23.

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[1] Full citations are given in References list.

1.1.2 Cox SC, and Barrell DJA. 2007. Geology of the Aoraki area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map, number 15. It comprises a printed 1:250,000-scale map and a 71-page book.

1.1.3 Barrell DJA, Andersen BG, and Denton GH. 2011a. Glacial geomorphology of the central South Island, New Zealand. GNS Science Monograph, number 27. It comprises a printed 1:100,000-scale map in five overlapping sheets, and an 81-page book.

1.2 The Barrell and others (1996) report was a product of government-funded research work aimed at interpreting the recent geological history of the Rangitata sector of the Canterbury Plains area. The report is based on the examination, by me and colleagues Forsyth and McSaveney, of landforms and geology in the general area of the proposed Klondyke Pond during several field trips in 1995/1996. I undertook further field work in the general area in 2002, including high-precision GPS surveying along the Ealing-Montalto Road to determine the extent of fault-related prehistoric deformation of the ground, as described in the 2017 GNS Report.[2]

1.3 I led a Geological (now Geoscience) Society of New Zealand post-conference field trip in 2003 that examined some of the fault-related features in the general vicinity of the proposed Klondyke Pond. Its details are

1.3.1 Barrell, DJA, and Cox SC, 2003. Southern Alps tectonics and Quaternary geology. Post-conference field trip FT6, Geological Society of New Zealand Annual Conference, Dunedin, New Zealand.[3]

1.4 Since 2009, I have led commissioned work for the Canterbury Regional Council (ECan) delivering datasets on active faults in the Canterbury region, derived from the GNS Science regional geological mapping programme. Relevant to the proposed Klondyke Pond are reports on the active faults of the Timaru District and Ashburton District as set out below[4].

1.4.1 Barrell DJA. 2016. General distribution and characteristics of active faults and folds in the Timaru District, South Canterbury. GNS Science Consultancy Report 2014/308.

1.4.2 Barrell DJA, and Strong DT, 2009. General distribution and characteristics of active faults and folds in the Ashburton District, mid-Canterbury. GNS Science Consultancy Report 2009/227.

1.5 In 2013, I was lead author of a conference paper summarising the work commissioned by ECan:

1.5.1 Barrell DJA and 7 others, 2013. Characterisation of active faults in the Canterbury region: a tool for risk-based minimisation of fault surface-rupture hazards to communities and infrastructure. Published in the Proceedings of the 19th New Zealand Geotechnical Society Geotechnical Symposium, Queenstown, New Zealand.

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[2] See References list: McVerry GH and others, 2017.
[3] Full citation is given in References list.
[4] Full citations are given in References list.

1.6 I am a co-author of national-scale compilations of active fault information, as follows.[5]

1.6.1 I am 15th author on a report by Litchfield NJ and 19 others, 2013. A model of active faulting in New Zealand: fault zone parameter descriptions. GNS Science Report 2012/19. 120 pages.

1.6.2 I am 15th author on a paper by Litchfield NJ and 19 others, 2014. A model of active faulting in New Zealand. Published in the New Zealand Journal of Geology and Geophysics, volume 57, pages 32 to 56.

1.6.3 I am 6th author on a paper by Langridge RM, and 14 others, 2016. The New Zealand Active Faults Database. Published in the New Zealand Journal of Geology and Geophysics, volume 59, pages 86 to 96.

1.7 I was involved in early response to both the 2010 Darfield and 2016 Kaikōura earthquakes, as part of geological teams mapping the fault ruptures that occurred in each earthquake. As a result, I have direct experience in the nature and characteristics of fault ruptures of the ground. I was a contributing author to the publications of findings from those events with selected examples listed as follows:[6]

1.7.1 Barrell DJA and 23 others, 2011b. Strike-slip ground-surface rupture (Greendale Fault) associated with the 4 September 2010 Darfield earthquake, Canterbury, New Zealand. Published in the Quarterly Journal of Engineering Geology and Hydrogeology, volume 44, pages 283 to 291.

1.7.2 I am 2nd author on a paper by Van Dissen R and 28 others, 2011. Surface rupture displacement on the Greendale Fault during the M_W 7.1 Darfield (Canterbury) earthquake, New Zealand, and its impact on man-made structures. Published in the Proceedings of the 9th Pacific Conference on Earthquake Engineering, Auckland, New Zealand.

1.7.3 I am 6th author on a paper by Quigley M and 9 others, 2012. Surface rupture during the 2010 Mw 7.1 Darfield (Canterbury) earthquake: Implications for fault rupture dynamics and seismic-hazard analysis. Published in Geology, volume 44, pages 55 to 58.

1.7.4 I am 3rd author on a paper by Villamor P and 15 others, 2012. Map of the 2010 Greendale Fault surface rupture, Canterbury, New Zealand: application to land use planning. Published in the New Zealand Journal of Geology and Geophysics, volume 55, pages, 223 to 230.

1.7.5 I am 22nd author on a paper by Hamling I and 28 others, 2017. Complex multifault rupture during the 2016 MW 7.8 Kaikōura earthquake, New Zealand. Published in Science, volume 356, article eaam1794, 10 pages.

[5] Full citations are given in References list.
[6] Full citations are given in References list.

1.7.6 I am 10th author on a paper by Stirling MW and 56 others, 2017. The M_W7.8 2016 Kaikōura Earthquake: surface fault rupture and seismic hazard context. Published in the Bulletin of the New Zealand Society for Earthquake Engineering, volume 50, pages 73 to 84.

1.8 I have presented expert witness evidence on three occasions. In September 1996, following engagement by Southland Dairy Co-operative Limited, I gave evidence on the geological character of a groundwater aquifer at Edendale, Southland, at a Southland Regional Council hearing of a resource consent application to discharge dairy factory wastewater to land. In April 2012, following engagement by Otago Regional Council, I gave evidence on the nature of river landforms near Middlemarch, Otago, at a Dunedin District Court prosecution of a landowner for unauthorised disturbance of a river bed. In June 2013, I was engaged by Hurunui Water Project Limited to present evidence at a Canterbury Regional Council resource consent hearing of an application for water rights in relation to the proposed Waitohi Irrigation and Hydro Scheme, North Canterbury. The evidence concerned my peer review of an independent geotechnical report on the Hurricane Gully dam and reservoir component of the proposed scheme.

2. In preparing my evidence I have read and complied with the code of conduct for expert witnesses contained in part 7 of the Environment Court of New Zealand Practice Note 2014. I confirm that the issues addressed in this statement of evidence are within my area of expertise. Descriptions of the review and revision of active fault earthquake sources and parameters have been provided by me in GNS Science Consultancy Report 2017/160 (the 2017 GNS Report)[7]. As part of that work, I also reviewed the previous seismic hazard assessment for the Klondyke Pond, documented in GNS Science Consultancy Report 2014/82 (the 2014 GNS Report)[8]. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed.

Scope of evidence

3. My evidence covers review and revision of earthquake source parameters in relation to the proposed Klondyke Water Storage Facility (Klondyke Pond). This relates specifically the 2017 GNS Report. Those sections address geologically-based evidence and interpretation in regard to fault lines in the vicinity of the proposed Klondyke Pond. My evidence does not extend to details of scaling relations or fault source parameter methodologies, as outlined in section 2.1 of the 2017 GNS Report, because the information there is based upon previously published work and the detailed methodology is not within my area of expertise. The evidence of my GNS Science colleague, Dr Graeme McVerry, encompasses those aspects of the 2017 GNS Report that are not within my expertise.

4. In preparing this evidence, I have read the sections of the Klondyke Storage Proposal Engineering Report by MWH, dated August 2016 relevant to geological faults. In addition, I have read the Klondyke Storage Proposal Dam Break Assessment report by MWH, dated August 2016. I have also examined drafts of evidence by my GNS Science colleague Dr Graeme McVerry, and by MWH (now part of Stantec) engineers Mr

[7] See References list: McVerry GH and others, 2017.
[8] See References list: Stirling 2014.

Steven Woods (Engineering assessment) and Mr Nathan Fletcher (Dam break assessment) and the draft consent conditions attached to the evidence of Mr David Greaves.I have also read the Section 42A Officer's Report from the ECan and the Section 42A Planning Report from Ashburton District Council (ADC).

5. I have identified and read the following five submissions referring to aspects of seismic hazard assessment for the Klondyke Pond. I will address these submissions in my evidence.

6. Those submissions comprise: Submission 31195 on behalf of Save the Rivers by Mr Keith Gunn, concerning a large earthquake causing dam breach; Submission 31252 by Mr John Stack, who is concerned that not all fault lines have been evaluated; Submission 31253 by John McGregor Simpson, who expresses concern about the accuracy of the fault mapping; Submission 31256 on behalf of Early Family Trust by Ms Prudence Steven QC, regarding the question of hidden fault lines and magnitude of earthquakes; and Submission 31262 on behalf of Te Runanga o Arowhenua and Te Runanga o Ngai Tahu by Ms Kara Edwards, regarding the proximity of active tectonic faults to the proposed Klondyke Pond.

7. On 7 February 2018, I undertook a 2.5 hour walk-over inspection of the proposed Klondyke Pond site, examining the landform features in transects along the length and width of the proposed pond and embankment footprint. Observations made during the site visit have contributed to the information presented in my evidence.

Executive summary

8. My evidence relates to the re-evaluation and revision of active fault earthquake sources (as defined in paragraph 9) in the vicinity of the proposed Klondyke Pond (Figure 1) for the 2017 GNS Report. Some revisions have been made to modelling of potential active fault earthquake sources in the wider area. Those sources have some influence on the estimation of probabilities of the levels of earthquake shaking at the proposed Klondyke Pond. However, those amendments largely involved fine tuning of previous information and do not introduce notable changes to the hazard assessment. Consequently, those aspects are mentioned only briefly. The most important active fault earthquake source in regard to the proposed scheme is a feature identified as the Hutt Peel 2017 active fault earthquake source. The ground surface projection of that feature has been amended to more accurately reflect the geological and geomorphological evidence. In addition, two other potential active fault earthquake sources have been added to the previously defined active fault earthquake source model, the Klondyke-Moorhouse source and the Coal Creek source (Table 1). Both of those features have alignments that potentially bring them close to the proposed Klondyke Pond, but in my opinion, geological reasoning suggests that they are unlikely to extend as far as the footprint of the proposed Klondyke Pond. Thus, the Hutt Peel 2017 active fault earthquake source is likely to be the most significant source of seismic hazard to the proposed Klondyke Pond. Geological and geomorphological mapping indicates that its surface expression of previous rupture events lies at least 1 km south-east of the proposed reservoir embankment footprint and therefore a fault rupture hazard is not currently recognised as a potential hazard to the proposed Klondyke Pond.

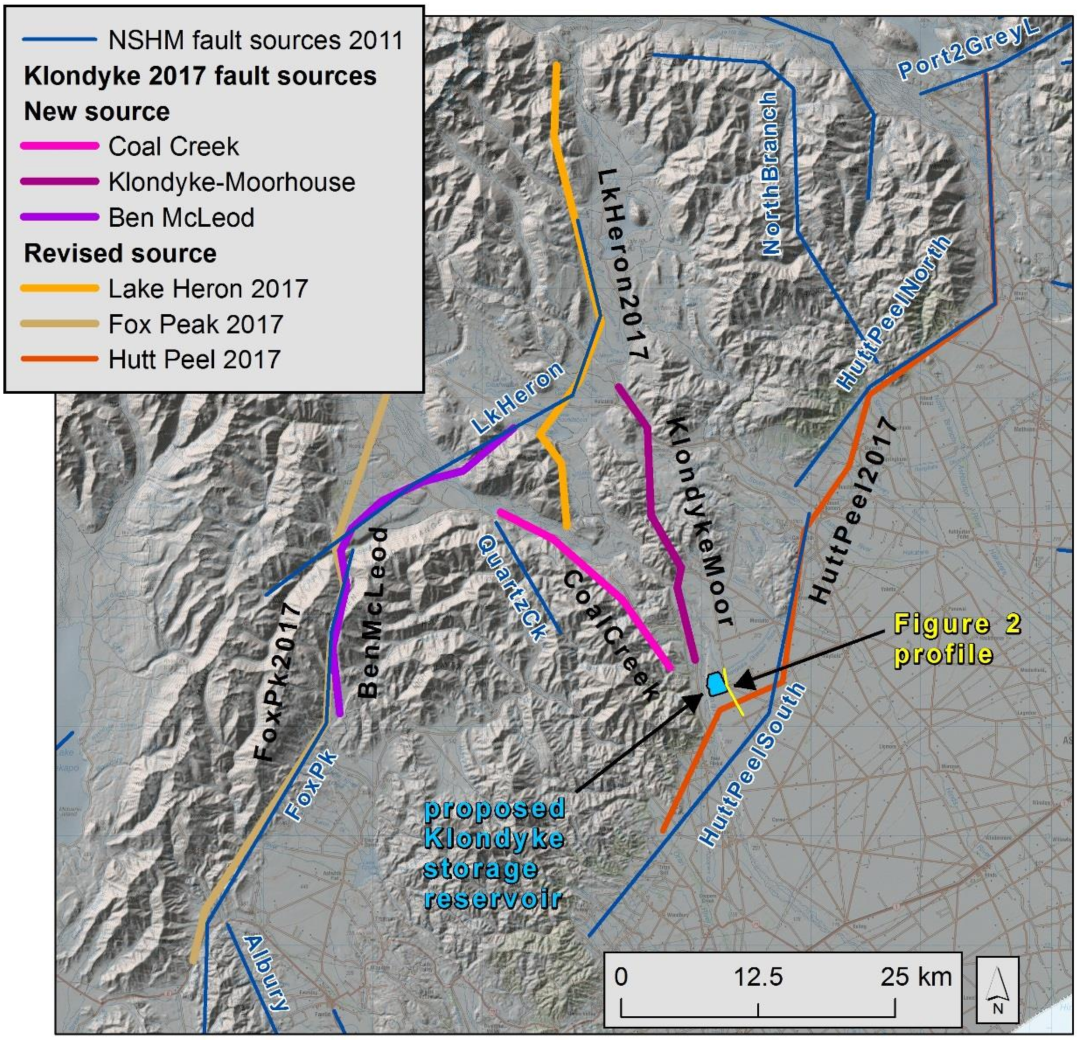

Figure 1. Active fault earthquake sources in relation to the proposed Klondyke Pond. Thin blue lines with blue labels denote pre-existing National Seismic Hazard Model (NSHM) sources. Thicker, colour-coded, lines with black labels are the new or revised fault sources that replace the pre-existing HuttPeelSouth, HuttPeelNorth, FoxPk, QuartzCk and LkHeron sources. Reproduction of Figures ES1 and 2.1 from the 2017 GNS Report, with minor presentational improvements.

National Seismic Hazard Model and active faults

9. The National Seismic Hazard Model for New Zealand (referred to hereafter as NSHM) is described and documented in a paper published in the Bulletin of the Seismological Society of America (the 2012 NSHM paper)[9]. The model comprises two components for the simulation of earthquake shaking. The active fault earthquake sources component consists of a large number of earthquake-generating entities at prescribed 3-dimensional geographic locations, based on surface geological evidence. The second component is referred to as the distributed seismicity component. Its purpose is to account for the occurrence of moderate-to-large earthquakes on unmapped or unknown faults. The Mw 7.1, 4 September 2010, Darfield earthquake is an example of an event associated with a distributed seismicity source. This is because the existence of an active fault at that location was not known prior to the earthquake.

[9] See References list: Stirling and others, 2012.

10. The distributed seismicity earthquake source component is described in the 2012 NSHM paper. That aspect of the NSHM has not been modified in relation to the Klondyke Pond project, and is not discussed further in this brief.

11. A conceptual distinction exists between the geologically-identifiable, surface expression of a particular fault, and its characterisation as a subsurface entity on which earthquakes are initiated due to fault rupture. The representation of each active fault earthquake source for seismic hazard analysis requires considerable interpretation of available evidence. The landscape expression of past ruptures of a fault typically diminishes over time, due to the effects of weathering, sedimentation or erosion. This results in discontinuous preservation of fault surface rupture expression in the landscape. A range of geological or topographic considerations are commonly used to define the full length of an active fault. It is generally considered that in this part of the eastern South Island, a fault must extend for a geographic length of more than about 20 km in order for its rupture to reach to the ground surface.[10] Specific considerations used to define the length of a fault include: the existence of relationships within the geological bedrock that requires the presence of a fault; the length of a fault-uplifted mountain range; or the need to account for field observations associated with the sizes or rates of past prehistoric movements of a fault. In the case of the Klondyke-Moorhouse active fault source (Figure. 1), the ground surface expression of its most recent rupture can be traced for only 2 km across the Rangitata River terraces close to the Rangitata Diversion Race intake near Klondyke, However, the fault source is extended 18 km north along the eastern side of the Moorhouse Range, to account for geological bedrock relationships and topographic considerations, and 7 km south of Klondyke, in order to attain sufficient length. The Klondyke-Moorhouse active fault source is discussed further in paragraphs 42-46. Another example of how NSHM fault sources have been constructed is the ‘Port2GreyL’ fault source (Figure 1). This represents an interpreted entity comprising an array of individually-named surface faults, that are considered capable of rupturing sequentially in a single earthquake event, extending from the Lake Coleridge area northeast for between 80 and 100 km to Mt Grey in North Canterbury. This illustrates the distinction between geologically-mapped faults, and how they may be represented in an active fault earthquake source model. This is expanded upon below in paragraphs 12-18.

Table 1 Summary of adopted parameters of the three closest faults to the proposed Klondyke Pond that are identified as active fault earthquake sources. Paragraphs 19 to 27 explain the nature of these parameters.

Name	Length (km)	Dip (°)	SR (mm/yr)	Moment magnitude (Mw)	SED (m)	RI (years)
Hutt Peel 2017	78	45	0.9	7.5	5.4	6000
Klondyke-Moorhouse	27	75	0.12	6.8	1.9	16,000
Coal Creek	22	45	0.08	6.8	1.5	19,000

SR = slip rate, SED = single-event displacement, RI = recurrence interval, yr = year.
These faults are taken as having oblique reverse mechanisms and maximum depths of 12 km.

[10] See References list: Stirling and others, 2012; Litchfield and others 2014.

12. For reasons of economy, I refer henceforth to the active fault earthquake source component of the NSHM as the ‘fault source model’, and an individual entity within that model as a ‘fault source’ or, in plural, ‘fault sources’.

13. The fault sources are related to geologically-identified faults at the ground surface, which are assessed as being ‘active’. In New Zealand, an active fault is commonly defined as being a fault that has undergone a ground-surface rupturing earthquake movement within the past 125,000 years. For most faults in New Zealand, there is no direct dating of their past movements. In practice, physical landform features are used as a means by which a fault is identified as active, or not. The presence of fault-offset landform features, such as river terraces, are taken to indicate a fault movement in the recent geological past, thus qualifying it for being regarded as active. In some instances, other lines of geological reasoning may be used as a basis for classifying a fault as active, on a case-by-case basis.

14. Being classified as ‘active’ does not mean that the fault is actively moving all the time. Rather, the fault is judged to have experienced at least one large, ground-deforming earthquake in the recent geological past. Thus, the fault is tagged as having the potential to experience a similar such earthquake in the future.

15. There are at least four different nationwide datasets in New Zealand that provide information on the locations and extents of active faults[11]. One is the regional geological map database at 1:250,000 scale, for example as represented at the proposed Klondyke Pond by the Cox and Barrell (2007) map. Another is the New Zealand Active Faults Database (AFDB) (Langridge and others, 2016), which represents the locations of active faults at a nominal scale of 1:250,000. A third dataset is the New Zealand Active Fault Model (AFM), documented by Litchfield and others, 2013 and 2014. A fourth dataset is the fault source component of the NSHM, which provides yet another representation of faults that are classified as active. The locations of active faults represented geographically in the AFM and NSHM are much less detailed than in the 1:250,000-scale datasets.

16. A fifth type of active fault dataset comprises information held by territorial or regional governmental authorities. A good example is the 1:250,000-scale datasets provided to ECan by GNS Science, documented in the vicinity of the proposed Klondyke Pond in reports by Barrell and Strong (2009) and Barrell (2016)[12].

17. All of those datasets have slightly differing purposes, and some are more accurate at different scales. Most of them are at least slightly different from one another in regard to fault locations and extents. The NSHM is the appropriate one to use in conjunction with the estimation of seismic shaking hazards for the proposed Klondyke Pond, as described in paragraph 11.

18. The appropriate dataset to use for examining the potential for fault-related ground deformation at the proposed Klondyke Pond are the ECan datasets (Barrell and Strong, 2009 and Barrell, 2016). This is because those datasets include more information about the nature of the surface fault and fold features than does the regional geological map dataset (Cox and Barrell, 2007). Furthermore, the ECan

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[11] Full citations to these documents are provided in the References list.
[12] Full citations for these reports are in the References list.

datasets include active fold deformation, which is not represented in the AFDB. Finally, the 1:250,000-scale datasets are considerably more detailed in the locations of active faults than the much more generalised (less accurate) representations in the AFM and NSHM.

Fault source component of the National Seismic Hazard Model

19. The methodology used for calculating earthquake magnitudes and single-event fault displacements is set out in the 2012 NSHM paper[13]. The methodology is summarised in the 2017 GNS Report. I do not repeat any of that information in this evidence brief, but instead give an outline of the input data that form the basis for the calculations of fault source parameters in the NSHM.

20. Expert-defined inputs to the parameterisation for each fault source comprise a unique name, the length of the fault source in kilometres, the inclination below horizontal (dip) of the fault plane in degrees, a representative direction of the dip of the fault plane in degrees of azimuth, an estimate of the depth to the base of the fault plane in kilometres, and an estimate of the activity of the fault expressed as a mean slip rate in units of millimetres per year. From those inputs, equations are used to calculate earthquake magnitudes, single-event displacements in metres, and a mean recurrence interval for earthquakes in years, for each fault source.

21. The input estimates of fault length, dip, and dip direction are usually based on surface geological observations, such as may be recorded on geological maps, or other published or unpublished observations. It is rare to have any definitive exact constraints on fault length or dip. Accordingly, for each fault source, the length and dip parameters are expressed as a range defined by three values; a maximum estimate, a minimum estimate, and an 'adopted' value.

22. The adopted value is commonly midway between the maximum and minimum, but this is not necessarily always the case. There may be geological information indicating that a particular fault is best characterised by a value close to, or at, either the minimum or maximum estimate. Commonly used synonyms for the adopted value include 'best', 'preferred' or 'median'. I use the term 'adopted' because I consider it to be a more accurate descriptor.

23. The characterisation of depth to the base of the fault plane similarly comprises maximum minimum and adopted values. These have been determined on a regional scale from geophysical and seismological considerations. For this part of the South Island, assigned values of 10, 12, and 14 km represent the minimum, adopted, and the maximum depths.

24. Slip rate estimates are obtained from the surface geological record, preserved as fault-offset geological deposits or landforms. Most faults in New Zealand have not been investigated in specific detail with regard to their degree of activity. Commonly, slip rate estimates are assigned on the basis of broad-scale observations of the size of landform offsets, in conjunction with an approximate, expert, inference of the age of the landform. Another tool used for estimating slip rates on poorly studied faults is via comparison with other similar faults whose degree of activity is better known.

[13] See References list: Stirling and others, 2012.

25. For slip rate, each fault source is characterised by way of three values, maximum, minimum and adopted.

26. Following the assignment of these expert-defined values, equations are used to calculate values for earthquake magnitude, single-event displacement in metres, and a mean recurrence interval for earthquakes in years, for each fault source.

27. Although maximum, minimum and adopted values are assigned or calculated for each of these parameters, only the adopted values are used in the NSHM computations to simulate seismic shaking levels. The maximum and minimum values indicate a range of expert-estimated uncertainties in relation to the adopted values. The adopted values, and a range of values spanning the maximum and minimum values, are presented in Tables 2.1 and 2.2 respectively of the 2017 GNS Report. The maximum and minimum values were employed in sensitivity testing of the probabilistic seismic hazard spectra, as presented in Section 4.1.3 of the 2017 GNS Report, and covered in the evidence of my GNS Science colleague Dr Graeme McVerry.

Revisions to fault sources for the proposed Klondyke Pond

28. No specific review or revision of the fault source model was done as part of the previous seismic hazard assessment for the proposed Klondyke Pond (2014 GNS Report). The bulk of the fault source characterisation and parameterisation for the NSHM 2010 update (the 2012 NSHM paper) was undertaken between 2005 and 2008 by an 8-member panel of GNS Science earthquake geologists, according to Litchfield and others (2013). I was not a member of that panel, though did subsequently contribute as a co-author to the publications by Litchfield and others (2013 and 2014).[14]

29. Some revisions of the NSHM fault sources in the mid-Canterbury area, specifically the northern part of the Ashburton District, and for the Hutt Peel fault source, were undertaken for the preparation of a 2010 report in relation to a proposed water scheme near Lake Coleridge, of which I was a co-author[15]. That work took account of the regional geological mapping results of Cox and Barrell (2007). The changes to fault sources arising from the 2010 report were incorporated into the 2012 NSHM paper[16].

30. Over the passage of time since the 2007 publication of the regional geological map by Cox and Barrell (2007), additional thinking and interpretation of active faults has been undertaken, contributing to the interpretations in the Barrell and Strong (2009) report, and especially to the interpretations in the Barrell (2016) report[17]. Those interpretations form the main basis for amendments to NSHM fault sources for the present project, as explained below. Also, relevant to the revisions are the direct observations of fault rupture phenomena documented in publications arising from the 2010 Darfield Earthquake and the 2016 Kaikōura Earthquake, and of which I am co-author.

31. For the purposes of the proposed Klondyke Pond, I reviewed information on the fault sources in the NSHM within an approximately 50 km radius of the proposed Klondyke Pond. The primary information source for this was the tabular documentation

[14] Citations for these information sources are provided in the References list.
[15] See References list: Buxton and others, 2010.
[16] See References list: Stirling and others, 2012.
[17] Citations are provided in the References list.

provided in the 2012 NSHM paper[18]. I also had access to a Geographic Information System (GIS) digital map of the fault source locations and a master spreadsheet used for the entry of expert-defined values and calculation of derivative parameters for each fault source.

32. Except for the revised Fox Peak 2017 fault source, slip rates for new or revised fault sources presented in the 2017 GNS Report were obtained by inference from landform offsets. More specific information exists for the Fox Peak Fault, as a result of a research project recently completed at University of Canterbury by T. Stahl[19].

33. The review and revision of fault sources for the purposes of this project enabled the rationalisation of several problematic previous interpretations, as set out in the 2017 GNS Report. All relevant information is set out in that report or, where cross-referenced in the 2017 GNS Report, in the report by Barrell (2016). Changes to the rendering in the NSHM of the Fox Peak 2017 and Lake Heron 2017 fault sources, and the addition of the Ben McLeod fault source resolve several interpretive difficulties, such as opposing senses of throw along the length of the fault, and difficulties around having sufficient length of fault to account for the observed surface expressions.

34. As discussed in the Barrell (2016) report and the 2017 GNS Report, there are interpretive problems in regard to the pre-existing Quartz Creek fault source in the NSHM. It is argued in the latter report that the nearby, much larger, Coal Creek Fault likely truncates the Quartz Creek fault (which incidentally is more correctly referred to as the Hewson Fault), at relatively shallow depth. Instead, it is suggested that the landform offsets associated with the Hewson Fault are more likely to be a secondary expression of rupture on the Coal Creek Fault. Accordingly, the so-called Quartz Creek (a.k.a. Hewson) fault source has been removed from the NSHM, and replaced with a new source representing the Coal Creek Fault. Like the Klondyke-Moorhouse fault source, the Coal Creek fault source also has a very low slip rate. As explained in paragraph 44, the Coal Creek fault source is inferred to terminate 5 km northwest of the surface projection of the Hutt Peel 2017 fault source

35. Changes to the Hutt Peel 2017 fault source, relative to what was previously in the NSHM, include an adjustment of the location of projected surface expression to more closely accord with geological mapping and the amalgamation of what were previously regarded as two adjacent, independent, northern and southern, sources (Hutt Peel North and Hutt Peel South) into one single source.

36. By way of background, the Hutt Peel fault source was originally delineated as a single entity by Pettinga and others (2001) and Stirling and others (2008). However, landform evidence indicates a considerable (~5 km) step-over (i.e. a gap between two strands of the fault) in the ground-surface location of the fault (Cox and Barrell 2007) in the Mt Somers area. This was the basis for dividing the fault into two separate sources in the NSHM revision undertaken in relation to the Buxton and others (2010) report.[20]

37. The impetus for my re-establishing the Hutt Peel fault source as a single entity stems largely from the faulting phenomena documented from the 2010 Darfield and 2016

[18] See References list: Stirling and others, 2012.
[19] See References list: Stahl 2014 and Stahl and others, 2016.
[20] See the References list: Cox & Barrell 2007; Pettinga and others, 2001; Stirling and others 2012; Buxton and others 2010.

Kaikōura earthquakes. Of particular significance were unexpected complexities of those fault ruptures and, in the case of the latter earthquake, very large step-overs in surface fault rupture locations. Fault rupture step-overs during the Kaikōura Earthquake of up to 10 km or more were much larger than the ~5 km step-over associated with the Hutt Peel fault source near Mt Somers. Further, the form and size of the ground surface offsets of the Hutt Peel fault source are not notably different in either the northern or southern sectors. Therefore, I consider there is no convincing evidence for interpreting a difference in recent rupture history in the north versus the south sectors.

38. From all these considerations, in my opinion there is no sound justification for preferring a two-fault model over a one fault model. I consider that reverting to a single entity Hutt Peel 2017 fault source is more defensible scientifically as it is a simpler interpretation.

39. A longer Hutt Peel 2017 fault source will produce a larger earthquake than it would if separated into two shorter, independent, sources. Because the proposed Klondyke Pond is very close to the Hutt Peel 2017 fault source, identifying its potential to experience a larger rather than smaller earthquake means that its seismic design will accommodate a plausible, more worse-case scenario than would previously have been implied by the scenario of two separate, shorter, independent fault sources.

40. Close to the proposed Klondyke Pond site, the surface expression of the Hutt Peel 2017 fault source is a broad flexure of the ground, identified by the name 'Ruapuna flexure' in the report by Barrell and others (1996), rather than a sharp offset (Figure 2). In this area, the main pre-existing landform is the main surface of the Canterbury Plains (RG5, Fig. 2), and an adjacent inset terrace (RG4, Fig. 2), on which the Klondyke Pond is proposed to be sited. I interpret the plains and this terrace to be about 18,000 years old, on account of their likely association with glacial moraines in the Rangitata Gorge. Although there is no direct dating of the glacial landforms in that area, or of the landforms on that sector of the Canterbury Plains, wider research has shown that major retreat of glaciers at the end of the last ice age in the Southern Alps commenced about 18,000 years ago, as documented for example in research papers by Putnam and others, 2013a and 2013b. A particular consequence on the Canterbury Plains of major glacier retreat in the headwaters would have been the incision of the rivers into the gravels of the plains, due to hydrological and sedimentological factors.[21]
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41. The landform of the terrace and the plains indicate that there has been no discernible disruption of these river-formed features any closer than about 1 km southeast of the proposed Klondyke Pond site (Fig. 2), since the surfaces of the terrace and plains were formed, interpreted to be about 18,000 years ago. On my walk-over inspection of the proposed Klondyke Pond site, I saw natural landforms that relate only to past river action, such as channels, bars, and inset terraces. I estimate that the river landforms are sufficiently well expressed and distributed that any subsequent differential offset of the ground by fault movement of a metre or more would be visible. I saw nothing to indicate any metre-scale differential fault offset of the ground in the area of the proposed Klondyke Pond and embankment footprint. I conclude that there has been no recognisable fault-related differential deformation of the ground surface at the proposed Klondyke Pond in at least the past 18,000 years.

[21] See the References list: Barrell and others, 1996; Putnam and others, 2013a and 2013b.

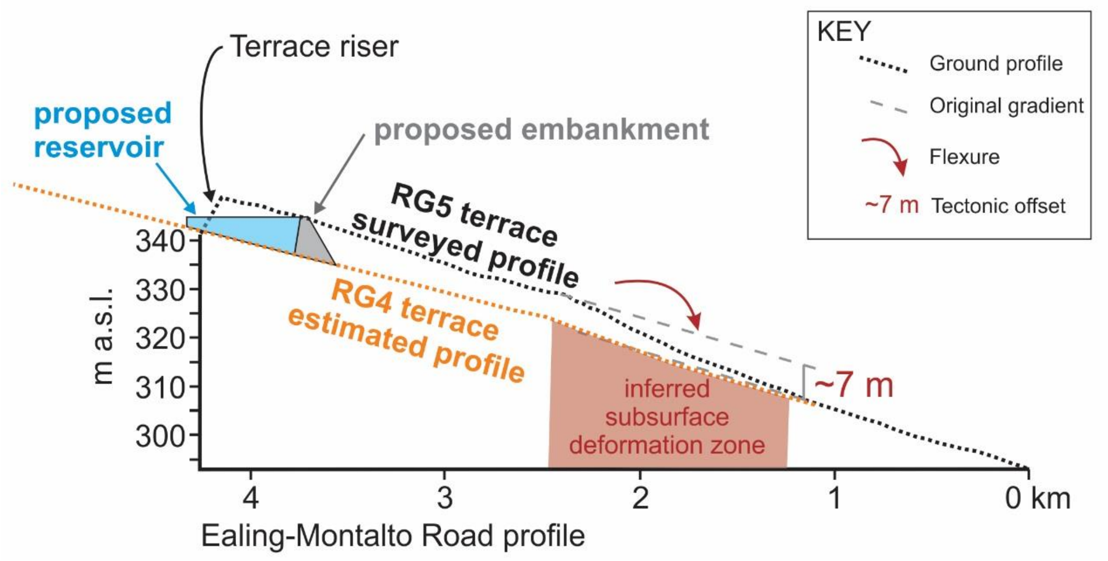

Figure 2. Topographic profile surveyed using high-resolution GPS along Ealing-Montalto Road in 2002 (Barrell, unpublished data), on the main surface of the Canterbury Plains, designated 'RG5', in this area. An elevation profile has been inferred for the 'RG4' terrace (on which the proposed Klondyke Pond (reservoir) will sit), based on the Satellite Radar Tracking Mission (SRTM) digital elevation model (DEM) that accompanies Google Earth, as described in Section 2.3 of the 2017 GNS Report. Based on the ground surface profiles, the inferred zone of subsurface deformation is illustrated by the red band. The left and right margins of the deformation zone are drawn with a 45° dip towards the northwest, but rendered here more steeply to accord with the large vertical exaggeration in this diagram, in which the vertical scale is ~25 times larger than the horizontal scale. Content of the diagram is the same as presented in Fig. 2.6 of the 2017 GNS Report, but is re-drawn here with larger text and linework, and with the addition of the inferred subsurface deformation zone.

42. The fault entity referred to as Klondyke-Moorhouse was probably the first active fault to be recognised and reported in this sector of Canterbury. It was first noted in 1941, as recounted in section 2.2.7 of the 2017 GNS Report. The ground-surface expression of the fault is an approximately 2 m high offset of a flight of river terraces. This fault has not previously been incorporated into the NSHM. I surmise that this is probably a consequence of its context having been poorly understood. It was not until the report of Barrell and Strong in 2009 and the report by Barrell in 2016 that an explanation of the likely wider context of this fault was put forward. This was expanded upon in the 2017 GNS Report in relation to its incorporation as a fault source in the revised NSHM.[22]

43. The Klondyke-Moorhouse fault source is characterized as lying on the northwestern side of the Hutt Peel 2017 fault source, at depth. In my opinion, this relationship places geometric and kinematic limits on the south-eastern length of the Klondyke-Moorhouse fault source.

44. The reasoning is that the Hutt Peel 2017 fault source represents a major geological feature, with an adopted length of almost 80 km (Table 1). It has been responsible for elevating the rock of the Canterbury foothills by as much as 2 km relative to the Canterbury Plains. In my opinion, it seems unlikely that much shorter fault sources, such as the Klondyke-Moorhouse and Coal Creek, would rupture through and dislocate, the subsurface plane of the much longer, and well-defined, Hutt Peel 2017

[22] See References list for citations to the Barrell & Strong 2009 and Barrell 2016 reports.

fault source. On that basis, I consider that the Coal Creek and Klondyke-Moorhouse fault source ruptures are likely to peter out approaching the Hutt Peel 2017 fault source. The interpretive map in Figure 3 illustrates my thinking behind this interpretation.

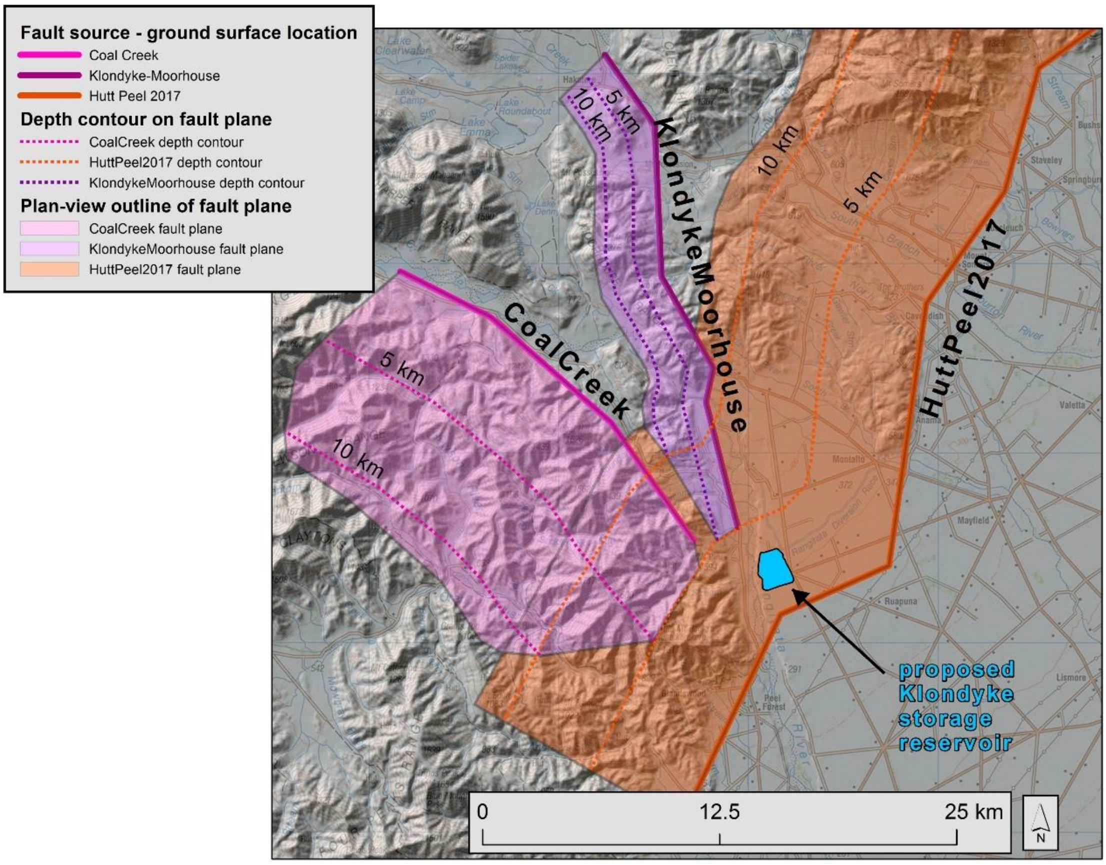

Figure 3. A map illustrating interpreted subsurface relationships between the Hutt Peel 2017, Coal Creek and Klondyke-Moorhouse fault sources. The interpretation is based on extrapolating the adopted dip and dip direction values for each fault into the subsurface from their depicted ground surface location (see Table 1). Coloured areas represent the extent of each fault plane, as viewed from above, extrapolated to 12 km depth, the adopted value for fault source depth. Dotted lines represent 5 km and 10 km depth contours on each fault plane.

45. Expanding upon the features illustrated in Figure 3, because the Hutt Peel 2017 fault source is much longer and has experienced greater geological-scale displacement than either of the other two faults (also see Figure 1), I consider it to be the dominant fault. On that basis, I regard it as very unlikely that either of the smaller faults offsets the Hutt Peel 2017 fault, and therefore their extent must be confined to the rock mass above the Hutt Peel 2017 fault plane. Considering a scenario where rupture commences on either the Coal Creek or Klondyke-Moorhouse fault source, towards the southeast the rupture will encounter the Hutt Peel 2017 fault plane, and will be forced to rupture upwards along the intersection between the fault planes. In other words, it will be forced up a shallowing wedge of rock above the Hutt Peel 2017 fault plane. Intersection with the Hutt Peel 2017 fault plane will increase friction, and I consider that all these factors will tend to arrest the rupture of either of the smaller faults as the rupture is increasingly absorbed as it ascends along the intersection with the Hutt Peel 2017 fault plane. I interpret a depth of ~5 km on the Hutt Peel 2017 fault plane as a round-number, plausible limit for the arresting of rupture on either of the smaller faults. The adopted dip of the Hutt Peel 2017 fault source is 45° northwest and therefore the Hutt Peel 2017 fault source will be 5 km deep at a distance of 5 km

northwest from where it meets the ground surface. Based on this reasoning, an expected termination point for the two smaller fault sources is 5 km northwest of the surface projection of the Hutt Peel 2017 fault source (Figure 3). I am not aware of any existing professional practice for addressing the question of how faults may interact at depth, in regard to seismic hazard modelling. The approach used here has been devised by me as the best way, in my professional judgement, to address this issue in regard to this project.

46. The line of the Klondyke-Moorhouse fault source projects close to the location of the proposed Klondyke Pond (Figure 3). By the reasoning set out above, a rupture of the Klondyke-Moorhouse fault source would stop short of the location of the proposed Klondyke Pond. Even if this interpretation were not correct, there is no recognised indication, in the landforms of assumed ~18,000 year age, of surface fault displacement of the proposed Klondyke Pond and embankment footprint since ~18,000 years ago. A point of note is that the Klondyke-Moorhouse fault source has a much smaller slip rate, and thus activity, than the Hutt Peel 2017 fault source. The Klondyke-Moorhouse fault source is therefore a seismic source of lesser significance in respect of the proposed Klondyke Pond.

47. I consider that the presence of a major, known, fault underlying the proposed Klondyke Pond provides some reassurance against the presence of unknown, hidden, faults. As outlined above, I regard it as unlikely that some other fault will rupture through the Hutt Peel 2017 fault entity. The possibility exists that a rupture of the Hutt Peel 2017 fault source may break out, or cause buckling, at locations other than where those effects have happened previously.

Submissions

48. Five submissions relate to earthquake or fault matters.

49. Submission 31195 on behalf of Save the Rivers by Mr Keith Gunn raises the question of a large earthquake causing breach of the dam. The issue of appropriate earthquake design parameters is addressed in the evidence of my GNS Science colleague Dr Graeme McVerry.

50. Submission 31252 by Mr John Stack expresses concern that not all fault lines have been evaluated, but is not specific about which fault lines are not addressed. I suggest that 2017 GNS Report has presented a wider explanation of the fault hazard than was covered in the 2014 GNS Report, and may address some of the concerns in the submission. It is true that following standard practice, the hazard assessment only addresses those geological faults that are classified as active.

51. Submission 31253 by John McGregor Simpson expresses concern about the accuracy of the fault mapping. Mr Simpson’s submission refers to page 9 of the Klondyke Storage Proposal Engineering Report by MWH, dated August 2016, which reproduces a map from the 2014 GNS Report. The subsequent 2017 GNS Report provides a much more detailed discussion of fault mapping and classification than did the 2014 GNS Report. The submission refers to a Blandswood Fault, and a Coleridge Fault. I have not heard of those terms before, and cannot comment on these entities without knowing the source of that information, or where they are positioned. The submission also refers to an Ealing Fault. There is an entity called the Ealing Fault (Cox and Barrell 2007), which has been identified beneath the Canterbury Plains by historic oil exploration geophysical surveys. It runs southeast from Arundel towards the Lowcliffe

area, and its mapped position is at least 10 km south of the proposed Klondyke Pond site. In any case, it is not regarded as an active fault.

52. Submission 31256 on behalf of Early Family Trust by Ms Prudence Steven QC, regarding the question of a hidden fault line and magnitude of earthquakes. The question of a hidden fault line was raised in the 2014 GNS Report, but was in my opinion a poorly worded reference to the Hutt Peel 2017 fault source which underlies the proposed Klondyke Pond site. The question of hidden faults is addressed in my evidence above. The question of earthquake magnitudes and motions in regard to embankment design is addressed in the evidence of my GNS Science colleague Dr Graeme McVerry.

53. Submission 31262 on behalf of Te Runanga o Arowhenua and Te Runanga o Ngai Tahu by Ms Kara Edwards, regards the proximity of active tectonic faults to the proposed Klondyke Pond site. This issue is addressed in detail in the 2017 GNS Report, and covered above in my evidence. It is my hope that this information provides clarity on the matter raised in this submission.

Officer's reports

54. I have read the Section 42A Officer's Report by Natalia Ford for ECan, the Section 42A Planning Report prepared on behalf of ADC by Nicholas Boyes of Planz Consultants Limited, and the report by Tim Morris of Tonkin & Taylor Limited who was engaged by ECan to review aspects of hazards, design and construction in relation to the proposed storage pond, including the GNS 2017 report. The GNS 2017 Report is discussed in paragraphs 197 to 199 of Ms Ford's report and paragraphs 71 and 72 of Mr Boyes' report. Minor comments in relation to seismic aspects mentioned in those reports are addressed by my GNS Science colleague Dr McVerry. I have no disagreement with any of the content of the Officer's Reports in regard to matters covered in my evidence.

Conditions

55. I have reviewed the conditions recommended in the Officer's Reports and none of the conditions specifically address faults. In the event of an unanticipated fault rupture causing deformation (offset or buckling) of the ground at the pond site, I am aware that the conditions require an Emergency Action Plan, which would come into operation in the event of associated damage to the embankment. The Emergency Action Plan is addressed in the evidence of Mr Nathan Fletcher.

Conclusion

56. A review of active fault earthquake sources in the wider vicinity of the proposed Klondyke Pond has resulted in some improvements being made to the interpretation of fault sources.

57. There is no evidence that that differential tectonic deformation has affected the proposed Klondyke Pond site within at least the past 18,000 years. The issue of earthquake motions in regard to the nearby Hutt Peel 20167 fault source is covered in the evidence of my GNS Science colleague Dr Graeme McVerry.

David Barrell
28 March 2018

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