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The utility of earth science information in post-earthquake land-use decision-making: the 2010–2011 Canterbury earthquake sequence in Aotearoa New Zealand

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All references cited in this document are provided in the accompanying manuscript.

All GNS reports cited in Table S2 are available from
https://shop.gns.cri.nz/publications/science-reports/

Section S1: ***Science response: fault rupture***

This section summarizes extra details that supplement the discussion of fault rupture hazards in Quigley et al. (2020). It further acts as a companion explainer for Table 2 in that paper.

Within 20 to 30 seconds of the Darfield earthquake (4:35 am local time), residents of Christchurch, New Zealand experienced MMI 7-8 shaking. Local earthquake scientists commenced telephone conversations within 5 minutes of the earthquake. A small team of earthquake geologists from the University of Canterbury (UC) was assembled and deployed to the field within 3 hours. As part of the Geonet event response, scientists from the Dunedin GNS Science office assembled and drove north towards Christchurch within an hour of the earthquake and undertook reconnaissance observations of the epicentral area by helicopter within 3 hours. GNS Science field teams from Wellington travelled by vehicle and ferry and arrived at the epicentral area by 5 pm; they were unable to travel by air because the Christchurch airport was closed. A collaborative surface rupture field team, comprising university academics, postgraduate students, and GNS Science researchers, was organized by phone that evening and first assembled in the field on the morning of 5 September, at which time field mapping commenced. Field mapping teams were typically comprised of at least one GNS scientist and one UC postgraduate student.

Preliminary estimates of the earthquake location (Canterbury Plains or eastern Southern Alps), magnitude (Richter magnitude 7.2 to 7.4, Mw 7.0), depth (10 km, 12 km), and mechanism (reverse faulting, strike-slip faulting) from GNS Science and USGS respectively, suggested to earthquake scientists that a ground surface rupture was likely to have been generated. The GNS active fault database (https://data.gns.cri.nz/af/; the most updated fault map source available at the time) did not show a mapped fault within 12 km of the epicentre; no previously mapped faults were specifically targeted for initial field reconnaissance. Initial observations proximal to the earthquake epicentre did not identify evidence for ground surface rupture. At approximately 9 am the UC field team was alerted to a 'broken road' by a Selwyn District Council infrastructure repair team. This site (~4.5 m horizontal, ~0.9 m vertical displacement; Fig. 4) was first observed by the UC team at ~ 9.30 am on 4 September and become one of the most identifiable locations in the immediate aftermath of the earthquake, hosting thousands of visitors including then-Prime Minister John Key and featuring in numerous media articles, television programs, and documentaries. Within a day or two, the surface rupture had been named the Greendale Fault after the small nearby settlement of Greendale.

Mapping of the Greendale Fault ground surface rupture commenced on 5 September. An independent inspection of historical aerial photographs to identify whether any surface evidence for pre-2010 (predecessor) ground surface ruptures on the Greendale Fault was evident was immediately undertaken by GNS Science. A GNS Science press release published on 6 September (GNS Media Release, 2010) stated that the "*Canterbury fault had not ruptured for at least 16,000 years*" based on an absence of evidence for pre-2010 surface faulting and assumptions that the land surface was post-last glacial in age (Forsyth et al., 2008). These comments featured in national and international newspapers on 7 September 2010.

A proposal to the Environment Canterbury Regional Council (hereafter referred to as Environment Canterbury) by the NHRP to fund the acquisition of airborne LiDAR data over the Greendale Fault for the purposes of fault mapping was submitted within days of the

earthquake. LiDAR data was collected on 11 September, as part of a larger scale LiDAR acquisition program over urban Christchurch, with a primary focus on observing land surface elevation changes in liquefaction-affected areas. Additional areas of ground surface rupture on the western Greendale Fault were only discovered after the LiDAR data was collected, and thus were not covered by this data. The UC-GNS rupture mapping team was under significant time-pressure to map the fault rupture traces because many landowners had commenced land repairs that removed surface evidence for faulting. By the time the LiDAR data was available to the UC-GNS team (20 September) the field mapping program had been completed and much of the evidence of surface rupture had been removed or modified. The LiDAR data was useful for validating field measurements (Litchfield et al., 2014), obtaining better constraints on distributed deformation, and producing final fault surface rupture maps (Villamor et al., 2011, 2012). Fortuitously, pre-earthquake LiDAR data (obtained for the purposes of regional flood mapping) was also available for small isolated sections of Greendale Fault, thereby enabling LiDAR differencing to be used to characterise high-resolution ground rupture displacements for one of the first times globally (Duffy et al., 2014).

Preliminary field maps of the surface rupture trace were made publicly available on GNS Science and individual websites (Quigley and Forte, 2017), and presented to affected parties (i.e., property owners in the fault zone and surrounding area) within six days of the Darfield earthquake. The first peer-reviewed articles to present fault rupture maps were published in December 2010 (Quigley et al., 2010a,b) but these were not of enough detail to develop fault avoidance zone maps consistent with available guidelines (Kerr et al., 2003). Public talks, reports to government agencies, media appearances, and research publications provided a diverse and effective communication platform that reached stakeholders and decision makers.

Six residential dwellings were damaged by the Greendale Fault ground surface rupture (Van Dissen et al., 2011). A power substation was impacted by the ground surface fault rupture but was repaired and is still in use. Four agricultural structures (implement or dairy sheds) were impacted by surface fault rupture but none were subsequently demolished. By November 2010, the Selwyn District Council recognized the need to obtain expert advice on the location and approximate recurrence intervals of surface rupture on the Greendale Fault, to assist them and owners of earthquake-damaged properties to better understand the spatial and temporal context of this hazard when considering rebuilding strategies. In New Zealand, it is a territorial authority's (city or district council's) responsibility under the Resource Management Act to set policies and rules in their district plan for managing development on or near active faults (Kerr et al, 2003). The Selwyn District Council initially commissioned an independent consultant to provide this advice; general advice on fault zone width and preliminary estimates of recurrence interval were given on 2 December 2010 but fault avoidance maps were not provided. Environment Canterbury commonly contributes technical information, planning and management advice, and funding to district councils for issues pertaining to geological hazards. Stimulated by increasing desire from property owners to gain certainty over rebuilding criteria, Environment Canterbury began to discuss the production of fault avoidance maps and likely recurrence interval class of the Greendale Fault with GNS Science (17 November 2010). GNS Science provided Environment Canterbury with a preliminary letter of recurrence interval class on 21 January 2011. Environment Canterbury commissioned GNS Science on 10 February 2011 to produce a detailed map of the fault avoidance zone, in accordance with best-practise guidelines outlined by the New Zealand Ministry for the Environment for developing on or near active faults, hereafter referred to as the MfE Active Fault Guidelines (Kerr et al., 2003). Fault avoidance zone maps were provided to the Selwyn District Council and

Environment Canterbury from GNS Science by 19 May 2011. Building consent for the first domestic building proximal to the fault zone was approved on 16 Feb 2011. A series of consents for demolition, relocation, new construction, repairs, and amendments to dwellings were issued by the Selwyn District Council beginning in March 2011.

Table S1: Mass movement timeline: list of scientist and decision-maker actions.

Item	**Date**	**Key publication (excluding academic publications)**	**Summary of report/actions/process**	**How used**	**Where used in policy decisions**
1	22/02/2011	Earthquake (EQ) happens, state of emergency declared			
2	22/02/2011	GeoNet landslide response to Port Hills	Initially GeoNet landslide team working for Urban Search and Rescue (USAR) to triage potentially life-threatening slope-related issues.	Identify the problem areas	
3	Feb 2011	Port Hills Geotechnical Group (PHGG) established a few days after the EQ	Geotech consultants, University of Canterbury staff and GeoNet landslide team combine efforts for Christchurch City Council (CCC) to identify and triage potentially life-threatening slope related issues.	Identify the problem areas	
4	Feb 2011	PHGG and CCC apply S124 notices to dwellings in the Port Hills for boulder rolls and cliff collapse and other mass movement hazards	The Port Hills is carved up into Sectors and lead consultants are given Sectors. GNS Science (GNS) provides an advisory role to all with respect to (wrt) mapping rockfalls and landslides, modelling their runouts, installing monitoring equipment and providing other Geotech and seismic advice.	To help affected people and to identify homes, and people in them that are exposed to high levels of risk from rockfalls and cliff collapses.	S124 placement by CCC
5	29/04/2011	State of emergency lifted			
6	Feb 2011 to Aug 2014	Community meetings	Many community meetings were attended by the team over the years. These started after the EQ's as street corner meetings, then later meetings were held in community centres and at the CCC buildings.	Dissemination of information	Public information

7	Jun 2011	CCC - Port Hills Earthquake Remediation and Recovery Project initiated and a Project Control Group appointed (comprising senior managers from both Council and CERA)	It became apparent from the earlier work that rockfalls and cliff collapses, plus areas of incipient landsliding (cracks) were going to be a problem going forward, especially wrt identifying potentially too risky areas to continue to live in. The non-life risk hazards such as the toe slumps and associated cracking were not a priority at this stage. This work ran in parallel to the continued PHGG responses to individual home owners wrt their particular Geotech issues. PHGG had also been commissioned to install mitigation works where they through were needed, e.g. above homes etc. CCC realised early on that a systematic approach to assessing risk from slope hazards in the Port Hills (at a regional scale) was needed to underpin the policy decisions that would needed to be made in the coming months and years. CCC commissioned GNS to carry out this study, with the PHGG of consultants plus a peer review panel of experts. This was pre the 13 June EQ. The 13 June EQ showed how important the evacuation of people from dangerous homes was. Many of the homes evacuated were hit again by landslides. Also, the EQ showed the futility of the engineering mitigation approach of trying to stop landslides from occurring in situ. These works were substantially reduced in scope.	The first reports were pilot studies for the main areas affected by bolder rolls (rockfall) and cliff collapses - the life threatening hazards. These were used to get the method sorted. The approaches were then rolled out over the wider Port Hills.	Christchurch Earthquake Recovery Authority (CERA) white and green zoning and continued placement of S124 notices on dangerous properties. The issue with the S124 notice was that it relates to dangerous homes, but in these cases many were placed to do dangerous ground being above a home that could be impacted in the future if the ground were to fail
	Jun 2011 to May 2012	GNS works on: 1) Life risk criteria; 2) Rockfall and cliff collapse pilot studies; and 3) All of Port Hills rockfall and cliff collapse studies			
	1/03/2012	CR 2011_319 Risk_Criteria_FINAL_For_Release			
	1/03/2012	CR 2011-311 Rockfall_Pilot_FINAL ISSUE2			
	1/03/2012	CR 2012-57 Cliff_Pilot_FINAL_For_release			
	1/05/2012	CR 2012-123 Rockfall_ALL_PortHills_FINAL_ISSUE2 01AUG2013			
	1/05/2012	CR 2012-124 Cliff_ALL_PortHills_FINAL_ISSUE2			

8	Jun 2012	CERA - Crown red zone purchase offer announcements start	Mainly flat ground related, but Port Hills areas outside the identified rockfall and cliff collapse HAZARD (not risk) zones were classed as Green. Areas inside were classed as White. The hazard zones were defined based on the regional-scale studies including ALL potential source areas and debris runout zones - so they were considerably larger in area than the later risk-based zones.	Identify areas that are outside the slope hazard zones	White and green zoning
9	Jun 2012	GNS commissioned by CCC to investigate other mass movement areas	The earlier area-wide (regional-scale) rockfall and cliff collapse studies identified a few highly populated areas where more detailed work would be needed to investigate the landslide hazards and quantify the risk.	To get more clarity on the hazards and risk in several well-populated areas	White and green zoning plus later in Red zoning
10	Jun 2012 to Aug 2014	GNS works on Mass movement areas for CCC	This work was designed in a series of steps to provide information sequentially, both for the detailed studies but also for the regional-scale assessments of risk and the design of potential engineering mitigation measures.	Identify people and building /infrastructure at risk from mass movements at the site-specific scale	Red zoning and CCC compensation offers
	1/09/2012	CR 2012-015_Geomorph_mapping_FINAL	This was done to aid the site-specific and regional-scale assessments. It was also used in the rockfall runout modelling to define the substrate materials along the potential rockfall runout paths.	Rockfall runout modelling	
	1/08/2012	1st peer review workshop held at the GNS house in Sumner	Workshop held with peer review panel to go through the regional wide assessments and to help scope the site-specific assessments. Additional discussions were held with the CERA review panel at this time.	Review of work done to date by an international peer review team	

	22/01/2013	CR 2013-10LR 3D Geovert modelling FINAL	The 3D rockfall modelling was commissioned by CERA to aid both the rockfall risk assessments and the design of potential mitigation works comprising rockfall catch fences. It was later decided by CERA to not opt for mitigation solutions given their uncertainty wrt All of Life costs, and risk reduction impact, but also people did not want to live downslope of fences. The prelim designs showed that some suburbs would have been "fenced in", like a prison.	Rockfall runout modelling	
	1/08/2013	CR 2012-317 Stage 1 Mass_Movement_FINAL 2013-08-01	This report identified and classified mass movement areas within the larger regional-scale assessments - mass movement is a term used to incorporate all slope hazards as some were not just related to landsliding. This was done to triage those areas where the slope hazards pose a lifer risk versus those areas where buildings/infrastructure were at risk.		
	17/10/2013	2nd peer review workshop held at Akaroa CR 2013-225LR	Preliminary Peer-review findings from a Workshop in Akaroa (16-20 September 2013)	By GNS to tweak and change the assessments based on the review panel feedback	
	1/10/2013	Mass Movements web FINAL	Summary brochures for the public produced that describe the results from the CR 2012-317 Stage 1 Mass_Movement report	Dissemination of information to the public	
	1/03/2014	SR 2014-013 Broadband_Modelling_ChchQuake	Provided synthetic earthquake (time-acceleration histories), for the 5 main EQs in the Canterbury Earthquake Sequence (CES), at each of the sites being investigated.	Used in the numerical simulations of slope stability	

	1/04/2014	CR 2013-171_Triggering_FINAL	Provided guidance to CCC on EQ- and rain-induced landslide trigger thresholds for the Port Hills as well as advice wrt responding to such events. This was done because CCC, based on the advice from GNS, established a Geotech Rapid Response team for the Port Hills. These responses were carried out by the PHGG.	To set response triggered levels for landslides	
	1/06/2014	CR 2014-121 EQC_PortHills FINAL			
	1/07/2014	CR 2014-053 Port_Hills_LabTest_FINAL	Results from lab testing carried out on Port Hills materials	Used in the numerical simulations of slope stability	
	1/08/2014	CR 2014-034 Richmond_Hill_FINAL	These reports contained the results of the site-specific risk assessments.	Used by CCC to purchase properties were risk was assessed as being too high	
	1/08/2014	CR 2014-67 Defender Lane FINAL			
	1/08/2014	CR 2014-73 Cliff St_FINAL			
	1/08/2014	CR 2014-75 Quarry Road FINAL			
	1/08/2014	CR 2014-76_Clifton_Terrace_FINAL			
	1/08/2014	CR 2014-77_Deans Head_FINAL			
	1/08/2014	CR 2014-78 Redcliffs_FINAL			
	1/08/2014	CR 2014-78 Redcliffs_FINAL_ISSUE2_FEB2016			
	1/08/2014	CR 2014-79 Maffeys Rd FINAL			
11	Aug 2012	Crown red zone purchase offer 2nd announcement	These mainly concerned the flat ground areas. Some of the Port Hills areas outside		

12	Sep 2012	Crown red zone purchase offer 3rd announcement	the identified rockfall and cliff collapse HAZARD (not risk) zones were further classed as Green; thus reducing the White zone area.		
13	Sep 2012	GNS produce summary brochures for the public			
	1/09/2012	CliffCollapse web FINAL	Summary brochures for the public produced that describe the results from the CR 2012-317 Stage 1 Mass_Movement report	Dissemination of information to the public	Public information
	1/09/2012	Rockfalls web FINAL			
	1/09/2012	UnderstandingLifeRisk web FINAL			
14	Sep-Dec 2012	CERA zoning review			
	1/09/2012	CR 2012-214 Rockfall_sensitivity_FINAL_For_Release	This work link back (above in the column) work on the area-wide (regional scale assessments) CERA asked GNS to review these based on changing some of the input parameters used in the risk model. This was done to assess the sensitivity of the models and to explore zoning options	Red zone decision making	Red zoning
	26/10/2012	CR 2012-268LR_FINAL	Preliminary hazard assessment for Lucas Lane - CERA used this to designing mitigation works as only a few homes were at risk from the potential slope failure. Some people in S124 homes, used this to question why mitigation works were not done elsewhere, in similar settings.	Red zone decision making	Red zoning
	20/11/2012	Letter to CCC RE: changes to the rockfall risk maps and CERA zoning	The CERA review meant that a few changes to the risk maps were needed based on field inspections	Red zone decision making	Red zoning
	11/12/2012	Letter to CCC RE: changes to the rockfall risk maps post the CERA independent review			

	13/12/2012	2012-12-13 DonMacfarlane Ground Truthing statistics FINAL			
	20/12/2012	CR 2012-327LR_FINAL	GNS methods and process standards followed in assessing life-risk from rock fall (boulder rolls). This report summarised the method and processes we followed to estimate risk from rockfalls and cliff collapses in the area-wide studies.	Dissemination of information to the public	Public information
15	Dec 2013	Crown red zone purchase offer announcement post Zoning Review (carried out Nov-Dec 2012)	This was when the results from the zoning review (held in Nov 2012) were released to the public. In the year between the review and the release, CERA met and worked with affected property owners. Another factor in this delay was the court case being hear against CERA wrt the flat land zoning.	N/A	N/A
	26/02/2014	8 Balmoral lane CR2014-37LR DRAFT_FINAL	Report written in response to a request from CERA to assess a property that had been overlooked in the zoning review.	Red zone decision making	Red zoning
16	Aug 2014	Council announced that a further 37 "green zone" properties were considered to be at an intolerable life risk from mass movement.	These properties were originally zoned green by CERA in 2012. But based on the results from the site-specific assessment (Item 10) they were red zoned and offered a buyout by CCC and CERA	Red zone decision making	Red zoning
18	Jan 2015 to Jan 2016	Christchurch replacement district plan Hearings process	The risk zones defined in Items 7 and 10 were used by CCC to underpin their replacement district plan. The plan was notified and a few property owners contested the proposed hazard zones. The plan went through the hearing and the zones were endorsed by the hearings panel. A notable item included in the plan at the request from GNS was the ability for people to contest the hazard zones. This meant that people in the rockfall hazard	CCC replacement District Plan	Defining hazard zones in the plan
	Mar 2015	Christchurch Replacement District Plan Hearings			
	17/07/2015	Christchurch Replacement District Plan Hearings Panel Decision			

			zones could re-assess the risk, but only adopting the same method as the original assessment.		
	Jan 2016	Hearings panel reconvened for appeal to hear submission on Cliff collapse Management Area strategy	An overseas-based property group appealed on a point of law and were granted a hearing in Jan 2016. The appeal was based on the fact that there was no provision in the plan to challenge the cliff collapse hazard zones.		
19	Apr 2019	CCC agree to revise a few of their district plan rockfall hazard zones.	New information identified that a few of the original rockfall hazard zones needed to be tweaked. In one case the risk was now assessed as being higher than previously assessed. In a few other cases the risk was thought to be lower as mitigation works had been carried out by home owners to reduce the risk by removing the hazard.		

Table S2: Summary of the parameters adopted by the Christchurch City Council and the Canterbury Earthquake Recovery Authority as inputs to the landslide life risk models used to define the Hazard Management Areas and the residential Red Zones in the Port Hills after the 22 February 2011 earthquake.

Christchurch City Council	**Risk Model Assumptions**		
Hazard Management Area	Occupancy (% of time present in a dwelling)	Seismicity (year of model estimates used)	Evacuation (of residents post major events)
Cliff Collapse 1 (AIFR 10^{-2} threshold)	100	2012	No
Cliff Collapse 2 (AIFR 10^{-4} threshold)	100	2012	No
Rockfall 1 (AIFR 10^{-4} threshold)	67	2016	Yes
Rockfall 2 (AIFR 10^{-4} threshold)	100	2016	No
Mass movement 1 (AIFR 10^{-4} threshold)	67	2016	Yes
Mass movements 2 and 3	No life risk model used as risk to buildings and infrastructure only		
Canterbury Earthquake Recovery Authority			
Rockfall: Residential Red Zone AIFR $\geq 10^{-4}$	67	2016	Yes
Cliff Collapse: Residential Red Zone AIFR $\geq 10^{-4}$	67	2016	Yes
Landslide (mass movement areas): Residential Red Zone AIFR $\geq 10^{-4}$	67	2016	Yes