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Introduction to the Canterbury earthquake sequence special issue

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This special issue of the *New Zealand Journal of Geology and Geophysics* addresses different facets of the Canterbury earthquake sequence that commenced with the M_W 7.1 Darfield (Canterbury) earthquake on 4 September 2010 and continued during a prolonged aftershock sequence that included the fatal M_W 6.2 Christchurch earthquake of 22 February 2011. The timespan of the sequence referred to in the special issue title has been adopted because the studies presented here mostly address events of 2010 and 2011. However, as of mid-2012, this aftershock sequence continues to produce potentially damaging ($M_L > 4$) earthquakes in the vicinity of Christchurch city and in the surrounding region.

In compiling this special issue, our goal has been to facilitate broad-ranging documentation and analysis of the characteristics and impacts of the Canterbury earthquake sequence, with a principal focus on the Darfield and Christchurch earthquakes. The first six papers discuss the geological, structural and tectonic contexts for the seismicity based on field mapping, geophysical studies and an analysis of historical seismicity. The next two papers document the location and amount of slip on the major faults that ruptured during the sequence. The following four papers characterise the hydrological, geological and geomorphic impacts of the largest earthquakes. These papers are followed by four papers addressing seismological aspects of the sequence as a whole. The final paper in the volume addresses the role of geoscientific research – and geoscientists themselves – in the governmental and societal response to and recovery from these earthquakes. We hope that this special issue will provide a long-lasting and influential repository of important scientific results that will be of use to not only the scientific community, but also to educators, policy-makers and the media throughout New Zealand and overseas.

The opening paper by Campbell et al. synthesises several decades of field-based research into active deformation beneath the Canterbury Plains and the eastern foothills of the Southern Alps. The authors present structural and geomorphic evidence for the eastward propagation of kinematically linked east-striking transpressional dextral strike-slip faults and NE-striking thrust faults in northern Canterbury, which provide more evolved analogues for the fault system that ruptured in the Darfield earthquake. Campbell et al. argue that east-striking faults such as the Greendale Fault, a previously unrecognised fault that ruptured during the Darfield earthquake, seem to be either entirely activated or selectively accelerated to the surface, in association with the major fault propagation folds of the thrust system. The authors suggest that strike-slip faults will tend to emerge while related thrust faults remain blind, that slip distributions on the strike-slip faults will be strongly controlled by the geometry and displacement rates on the hidden adjacent thrusts and that pre-historic surface rupture lengths will thus under-represent the rupture areas of the associated earthquakes. All of these conclusions have implications for deducing the magnitude potential of earthquake sources from the geological record of faulting.

The tectonic history of the region and its detailed subsurface structure are also discussed by Jongens et al. and Ghisetti & Sibson based on data from regional maps, gravity, and oil exploration seismic lines and wells. Jongens et al. describe the subsurface structure of the whole Canterbury plains and link it with the geomorphic expressions of active faults (or lack thereof). The authors demonstrate that Late Cretaceous east-striking normal faults have been reactivated as strike-slip/reverse faults during the late Cenozoic and propose that the Greendale fault is one of these reactivated structures. The paper also suggests that NE-striking reverse faults close to the ranges are likely to be newly formed and to have played a role in the deformation associated with the recent and ongoing seismicity.

Ghisetti & Sibson describe a similar reactivation history for the Ashley fault, which they infer to be a close mechanical analogue to the Greendale Fault. The authors document similarities between the orientation and predominant sense of movement of different fault segments delineated by the current seismicity (including the Greendale Fault) and the general structures of the area (including the Ashley Fault). The orientations and senses of motion of these structures are consistent with those expected given the prevailing stress regime. Ghisetti & Sibson further describe

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the growth of new, immature fault splays that link with older inherited segments.

Davy et al. present the results of new gravity and aeromagnetic geophysical surveys conducted across the Christchurch region following the Christchurch earthquake. The data reveal distinct NNE- and east-trending sets of basement-penetrating lineaments, which the authors interpret as Cretaceous faults that have been reactivated in the late Cenozoic. The spatial correlation between some of the seismicity in the Canterbury earthquake sequence and these lineaments suggests that some of the earthquakes in the sequence were concentrated on pre-existing structures. This inference is supported by the geological interpretations of the authors above, and the seismological results presented in later papers.

Browne et al. provide a succinct analysis of the development of basement faults and the sedimentary sequence in the Canterbury region in response to changes in the configuration of the plate boundary. This paper reinforces the importance of understanding the geological history of a region in order to assess ground shaking levels and other seismic hazards influenced by, among other factors, the locations of inherited structures, volcanic edifices, the depths of sedimentary basins and the distribution and thicknesses of young, poorly consolidated sediments.

As illustrated by Downes & Yetton, moderate-magnitude damaging seismicity had occurred in historical times prior to 2010 near Christchurch. Downes & Yetton describe the M_W 4.7–4.9 Christchurch earthquake of 1869 and the M_W 5.6–5.8 Lake Ellesmere earthquake of 1870, both of which occurred less than 15 years after Christchurch became a city in 1856. While the lack of instrumental records for either earthquake makes detailed comparisons with recent seismicity difficult, the distribution of shaking intensities reported after the 1869 earthquake is consistent with that following the similar-sized Boxing Day earthquake of 26 December 2010. In view of the extensive ground damage and liquefaction observed during the earthquakes of 2010 and 2011, Julius von Haast's observations quoted by Downes & Yetton regarding the influence of the Avon River on the intensity of shaking are starkly prescient.

Beavan et al. present a detailed analysis of geodetic observations made with GPS and satellite radar. The resulting fault slip models emphasise the geometric complexity of rupture during the four largest earthquakes in 2010 and 2011, which Beavan et al. suggest may be characteristic of intraplate-like faults with long repose times. This complexity may also be a factor controlling the long duration of the earthquake sequence as a whole and the heterogeneous distribution of aftershocks. The geodetic results (and aftershock relocations, such as those of Syracuse et al. and Bannister & Gledhill, referred to below) also highlight an area west of Christchurch that has not produced substantial moment release in the current earthquake sequence. What this signifies is not yet clear, emphasising the crucial importance of ongoing seismological and geodetic monitoring and analysis.

A map of the surface rupture of the Greendale Fault compiled from data collected during field surveys undertaken immediately following the 4 September 2010 Darfield earthquake and from LiDAR observations is presented by Villamor et al. Several houses were damaged along the fault line during the Darfield earthquake. In the aftermath of the earthquake, there was a pressing need to map the fault and assess the future potential of rupture during the recovery phase and for the purposes of longer-term land-use planning. As Villamor et al. demonstrate, the Greendale Fault's surface rupture pattern is one of the most spectacular recorded examples of strike-slip faulting in quasi-homogeneous materials (Quaternary gravels).

The Darfield earthquake induced hydrological changes of greatly varying spatial and temporal characteristics recorded within the epicentral region and as far afield as the northern North Island. Cox et al. review these effects, many of which reoccurred later in 2010 and 2011 but which were less well-documented then because of damage to the hydrological monitoring infrastructure. The extensive liquefaction induced in and around Christchurch during the earthquake sequence is hypothesised by Cox et al. to represent fluid release from confined aquifers in response to dynamic stressing. The degree to which this mechanism has controlled the extent and severity of liquefaction, as opposed to other mechanisms such as sediment consolidation, is an important and unresolved question that relates directly to the issue of how liquefaction hazards might be mitigated in Christchurch and elsewhere.

Two papers address the impacts of earthquake-induced liquefaction in the Christchurch area. Reid et al. document the surface and subsurface morphologies of sand volcanoes produced by liquefaction in the Avon–Heathcote Estuary following the 22 September 2010 Darfield earthquake and the 22 February 2011 and 13 June 2011 aftershocks. The authors conclude that while the surface expressions of these features will be rapidly removed due to marine erosion, the subsurface feeder pipes of these volcanoes have higher preservation potential that could be enhanced by coseismic subsidence. Their observations are obviously relevant to the search for palaeo-liquefaction both in this location and elsewhere in the geological record.

Cubrinovski et al. describe the characteristics of lateral spreading and discuss its impacts in Kaiapoi and along the Avon River in Christchurch. Ground surveying has been used to document permanent lateral ground displacements of 2.0–3.5 m extending away from waterways to distances of 100–250 m. The differing styles and spatial distributions of lateral spreading are attributed by Cubrinovski et al. to varying soil conditions, topography, river geometry and local depositional environments. The effects of lateral spreading on built structures (houses, buildings, bridges and pipes) are also summarised. Documentation of these effects provides a useful reminder of the importance of making good land-use decisions in the rebuilding of Christchurch.

The spatial variability in strong ground motions during the Canterbury earthquake sequence is documented in different ways by Khajavi et al. and Bradley. Khajavi et al. present finite transport distances and azimuths, morphologies and site characteristics for boulders in the Port Hills that were displaced in the 2010 Darfield earthquake but not in the 2011 Christchurch earthquake. The prevailing boulder horizontal displacement azimuth they document is subparallel to the direction of instrumentally recorded transient peak ground horizontal displacements, but boulder displacement distances have no correlation to displacement azimuths, boulder masses or soil socket depths and only a partial correlation to adjacent slopes. By combining geological field observations with instrumental records and 2D numerical modelling, the authors argue that ground motions in the Darfield earthquake were topographically amplified on some ridges in the Port Hills relative to the surrounding areas and that small-scale ground motion was variable due to shallow phenomena such as variability in soil depth, bedrock fracture density and/or microtopography on the bedrock–soil interface. Their results have implications for inferring pre-historic earthquake characteristics from displaced boulders and/or rockfalls as well as characterising the effects of topography on earthquake-generated ground shaking.

Bradley focuses on the very different severity and character of ground motions recorded in Christchurch city during the 4 September 2010 Darfield earthquake (the epicentre of which was 35 km from the city centre) and the 22 February 2011 Christchurch earthquake (4 km). Of particular interest is the observation that pronounced differences exist in the response spectra of sites that have the same nominal ‘site class’ under the New Zealand building loading standards, and that these spectra differ from the design response spectra. Bradley challenges those responsible for refining New Zealand building loading standards to consider incorporating site-specific response characteristics as part of engineering design at sites with very soft soils.

Syracuse et al. and Bannister & Gledhill address different spatiotemporal characteristics of the earthquake sequence using relocated seismicity catalogues. Syracuse et al. use data recorded on temporary and permanent seismometers between mid-September 2010 and mid-January 2011 to examine the subsurface geometries of the fault segments that ruptured during the Darfield earthquake. Their analysis supports the interpretations made by Beavan et al. regarding the major fault segments, and further suggests the existence of a seventh segment not clearly resolved by the GPS data. Syracuse et al. also examine spatial variations in horizontal seismic anisotropy to address whether the Greendale Fault is an old, reactivated structure that happens to be well-oriented with respect to the present-day tectonic stress field or a relatively newly formed structure. On the basis of the fault-parallel seismic anisotropy, they conclude that the fault is old enough to have developed an ingrained fabric.

Bannister & Gledhill discuss the Canterbury earthquake sequence as a whole, focusing on the largest and most disruptive earthquakes up until early 2012. As they emphasise, the sequence has been particularly prolonged and the large earthquakes particularly damaging due to their complex rupture geometries, high stress drops and high ground accelerations. These features of the sequence, and the fact that it has been well recorded using dense networks of instruments, make the Canterbury earthquake sequence of global interest from both the scientific and engineering standpoints.

Shcherbakov et al. examine the statistical characteristics of the Canterbury earthquake sequence. They derive ‘a’ and ‘b’ values using the Gutenberg–Richter scaling relation and use these parameters and a modified version of Båth’s law to estimate the magnitude of the largest aftershock of the Darfield earthquake sequence, obtaining a value of M_L 6.3 in agreement with the magnitude of the 22 February 2011 Christchurch earthquake that eventuated. Based on this agreement, they argue that the statistical characteristics of the aftershock sequence enable reliable estimations of the largest aftershock magnitude. The authors also report that the rates of decay of aftershocks followed the modified Omori law for three different time windows between the larger earthquakes in the Canterbury earthquake sequence.

In the concluding paper, Berryman provides a synthesis of the geological and financial impacts of the Canterbury earthquake sequence, and highlights the importance of strong inter-institution partnerships, robust science, and clear and consistent scientific messaging in the earthquake response and recovery process. Berryman demonstrates that geoscience research and data are key inputs into rebuilding decisions being taken by the Canterbury Earthquake Recovery Authority (CERA) and other agencies, and emphasises the vital role of geoscientists in providing robust, objective information that will make this region, and New Zealand, more resilient to future natural disasters.

The Canterbury earthquake sequence has been exceptionally well documented with a diverse range of datasets collected using complementary techniques, and the papers in this special issue make clear that the sequence will serve as a target of scientific, engineering and social scientific research into earthquake phenomenology for years to come. In particular, lessons learned from Canterbury regarding long-lived complex aftershock sequences and the effects on built structures of moderate-magnitude earthquakes happening nearby will be of relevance in earthquake-prone areas around the world. To that end, the supplementary materials that accompany several of the papers in this special issue will, we hope, enable researchers in New Zealand and elsewhere to revisit and reinterpret key datasets as part of ongoing collaborative work.

We are grateful to the authors of all the papers published in this special volume for taking on the task of writing and revising manuscripts at the same time, in many cases, as working to analyse data and provide advice to central and local government agencies and the public. We also acknowledge the vital assistance of the many peer reviewers, some of whom were also involved in the scientific response and all of whom provided prompt and timely input to the manuscripts.