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Invited Review

The 2010–2011 Canterbury Earthquake Sequence: Environmental effects, seismic triggering thresholds and geologic legacy

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ABSTRACT

Seismic shaking and tectonic deformation during strong earthquakes can trigger widespread environmental effects. The severity and extent of a given effect relates to the characteristics of the causative earthquake and the intrinsic properties of the affected media. Documentation of earthquake environmental effects in well-instrumented, historical earthquakes can enable seismologic triggering thresholds to be estimated across a spectrum of geologic, topographic and hydrologic site conditions, and implemented into seismic hazard assessments, geotechnical engineering designs, palaeoseismic interpretations, and forecasts of the impacts of future earthquakes. The 2010–2011 Canterbury Earthquake Sequence (CES), including the moment magnitude (M_w) 7.1 Darfield earthquake and M_w 6.2, 6.0, 5.9, and 5.8 aftershocks, occurred on a suite of previously unidentified, primarily blind, active faults in the eastern South Island of New Zealand. The CES is one of Earth's best recorded historical earthquake sequences. The location of the CES proximal to and beneath a major urban centre enabled rapid and detailed collection of vast amounts of field, geospatial, geotechnical, hydrologic, biologic, and seismologic data, and allowed incremental and cumulative environmental responses to seismic forcing to be documented throughout a protracted earthquake sequence. The CES caused multiple instances of tectonic surface deformation (≥3 events), surface manifestations of liquefaction (≥11 events), lateral spreading (≥6 events), rockfall (≥6 events), cliff collapse (≥3 events), subsidence (≥4 events), and hydrological (10s of events) and biological shifts (≥3 events). The terrestrial area affected by strong shaking (e.g. peak ground acceleration (PGA) ≥0.1–0.3 g), and the maximum distances between earthquake rupture and environmental response (R_{rup}), both generally increased with increased earthquake M_w, but were also influenced by earthquake location and source characteristics. However, the severity of a given environmental response at any given site related predominantly to ground shaking characteristics (PGA, peak ground velocities) and site conditions (water table depth, soil type, geomorphic and topographic setting) rather than earthquake M_w. In most cases, the most severe liquefaction, rockfall, cliff collapse, subsidence, flooding, tree damage, and biologic habitat changes were triggered by proximal, moderate magnitude ($M_w \leq 6.2$) earthquakes on blind faults. CES environmental effects will be incompletely preserved in the geologic record and variably diagnostic of spatial and temporal earthquake clustering. Liquefaction feeder dikes in areas of severe and recurrent liquefaction will provide the best preserved and potentially most diagnostic CES features. Rockfall talus deposits and boulders will be well preserved and potentially diagnostic of the strong intensity of CES shaking, but challenging to decipher in terms of single versus multiple events. Most other phenomena will be transient (e.g., distal groundwater responses), not uniquely diagnostic of earthquakes (e.g., flooding), or more ambiguous (e.g. biologic changes). Preliminary palaeoseismic investigations in the CES region indicate recurrence of liquefaction in susceptible sediments of ~100 to 300 yr, recurrence of severe rockfall event(s) of ca. 6000 to 8000 yr, and recurrence of surface rupturing on the largest CES source fault of ca. 20,000 to 30,000 yr. These data highlight the importance of utilising multiple proxy datasets in palaeoearthquake studies. The severity of environmental effects triggered during the strongest CES earthquakes was as great as or equivalent to any historic or prehistoric effects recorded in the geologic record. We suggest that the shaking caused by rupture of local blind faults in the CES comprised a 'worst case' seismic shaking scenario for parts of the Christchurch urban area. Moderate M_w blind fault earthquakes may contribute the highest proportion of seismic hazard, be the most important drivers of landscape evolution, and dominate the palaeoseismic record in some locations on Earth, including locations distal

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from any identified active faults. A high scientific priority should be placed on improving the spatial extent and quality of 'off-fault' shaking records of strong earthquakes, particularly near major urban centres.

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1. Introduction

Many damaging and fatal earthquakes of moderate moment magnitude (~ M_w 5.5 to 6.9) are sourced from faults that do not cause discrete surface rupture (i.e. blind faults) and thus leave no direct surface evidence for seismogenic faulting. Recent historical examples include the 2014 M_w 6.2 Mae Lao, Thailand (2 fatalities), 2012 M_w 5.9 and 5.8 Emilia–Romagna, Italy (27 fatalities, ~$17 B USD damage), 2011 M_w 5.8 Mineral, Virginia, U.S.A. (>$ 200 M USD damage), 2011 M_w 6.2 Christchurch, New Zealand (NZ) (185 fatalities, ~$ 15 B USD damage, part of an earthquake sequence with damage exceeding $30 B USD), 2003 M_w 6.5 Bam, Iran (>26000 fatalities), 1994 M_w 6.7 Northridge, U.S.A. (57 fatalities, ~$15 B USD damage), 1994 M_w 6.9 Loma Prieta, U.S.A. (63 fatalities, ~$10 B USD damage), 1987 M_w 6.0 Whittier Narrows, U.S.A. (10 fatalities), and 1983 M_w 6.5 Coalinga, U.S.A. (~$10 M USD damage) events. Fault populations and earthquake frequency–magnitude distributions typically adhere to Gutenberg–Richter (G–R) scaling (Main, 1996). This implies that unmapped smaller active blind faults with lower M_w potentials may greatly exceed the number of mapped larger faults with larger M_w potentials that have been identified based on surface evidence for faulting (e.g. Nicol et al., 2011). To address this issue, probabilistic seismic hazard analysis (PSHA) typically