

Ten years after the 2011 Christchurch Earthquake

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The Christchurch earthquake of 22 February 2011 had a modest magnitude (Mw 6.2) but caused an extraordinarily large amount of damage because it was located directly beneath the city of Christchurch. The ground motions were amplified by rupture directivity and basin resonance effects that helped to cause them to exceed building code levels, especially for midrise structures. Liquefaction of the ground due to strong shaking caused unprecedented levels of damage to foundations that resulted in the demolition of many houses and the exclusion of large housing tracts from future habitation. Ground failure beneath foundations combined with strong ground shaking resulted in the demolition of the vast majority of the commercial buildings in the CBD. This outcome came as a profound shock to the inhabitants of Christchurch and to the earthquake engineering community worldwide because Professors Park and Pauley at the University of Canterbury in Christchurch had written the definitive book on the structural design of reinforced concrete buildings (Park and Pauley, 1975), leading to the expectation that New Zealand was a world leader in building design and construction. The extraordinary complexity of the insurance issues that had to be addressed, including the damage due to ground deformation, the extended earthquake sequence, and the increase in building code ground motion levels, have been described by King et al. (2014).

The earthquake highlighted the mismatch between societal expectations and the reality of the seismic performance of modern buildings (Pampanin, 2012). With a few tragic exceptions, modern multi-storey buildings performed as expected by the building code, especially in view of the code-exceeding intensity of shaking that they experienced. Consistent with capacity design principles, plastic hinges formed in discrete regions, allowing the buildings to sway and stand and people to evacuate. However, in many cases, these buildings were deemed too expensive to repair and were consequently demolished.

Although current building codes are nominally designed to provide life safety, this goal is no longer sufficient for modern society, at least for new buildings. This has caused a distinct paradigm shift towards damage control design, stimulating the exploration of the objectives and cost-effectiveness of engineering approaches to the design of buildings capable of sustaining a low level of damage, and thus limited business interruption after a design level earthquake. Extensive research and development has occurred in jointed ductile connections based upon controlled rocking and dissipating mechanisms for reinforced concrete and laminated timber structures.

Even before the Christchurch earthquakes, New Zealand law permitted the use of new structural systems. Several novel structural systems and new inexpensive construction techniques had been developed, and the price of structural steel had dropped considerably from its 2008 high. In the course of reconstruction of the 74 multistory buildings constructed in central Christchurch since 2011 and considered by Filiatreau and Macrae (2017; 2019), the numbers of buildings with steel, concrete, and



The Christ Church Cathedral is still under repair 10 years after the deadly earthquake rocked the city.

Source: Getty Images

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timber lateral force-resisting systems have been in the ratio of approximately 10:10:1, while the respective floor area ratio was 79:20:1, and most concrete buildings had structural steel gravity frames. Concrete structures in the reconstruction were nearly all structural wall systems, but steel buildings have been constructed using a variety of lateral load-resisting systems, some of them novel, many using buckling restrained braces (BRB's) that provide diagonal bracing of the steel frame.

During Christchurch's reconstruction, occupant expectations were shown to have a strong influence on the choice of structural systems for individual buildings, either directly or indirectly (Bruneau and Macrae (2017; 2019). Tenant expectations led developers to construct buildings to meet their post-earthquake expectations, with input from architects and engineers. The stakeholder industry practices which had evolved over many years prior to the earthquakes, and which tended to ensure predictable return on investment and profitability for all involved by maintaining similar practices over time, were significantly disrupted by the earthquake. In response to the increased uncertainty and risk, new practices emerged, and these opportunities were used to construct building systems that were not common in the past. Decisions about structural form were influenced by many factors, including public perceptions, economy, ease of design, and architectural issues, and the most important ones are as follows.

There are widespread perceptions among the Christchurch public, which includes many of the future building occupants and tenants, that reinforced concrete buildings suffer damage that is difficult to repair, in contrast to steel structures that can behave well and be repairable if necessary. The stakeholders have responded accordingly, embracing steel design and construction.

In response to post-earthquake sentiment that the performance objective of simply designing and constructing structures to prevent loss of life is no longer sufficient for a good modern structure, the design and construction industry, without governmental intervention, has moved away from traditional code-compliant systems with high expected ductility demand and high displacement and drift, which can significantly damage the frames, floor systems, and nonstructural elements. This change has occurred because many of these structures were difficult to inspect, repair, and reinstate, leading many to be demolished.

This has caused a major nationwide move in New Zealand towards structural systems for which lower damage and higher seismic performance is anticipated than for those used in the past, and New Zealand is a world leader in these developments (Pampanin, 2012). Some of this has been achieved at a cost premium using novel low damage systems, while other ways to control building damage has simply involved using some of the traditional systems while limiting drift and ductility demands. However, with the passage of time, fewer owners and developers are asking for, or prepared to pay for, the novel low-damage systems. Also, even when considering resilient low-damage construction, return on investment is found to be a most important consideration for structural system selection by owners.

The need for practicing structural engineers in Australia to gain a deeper understanding of earthquake resistant design than that provided in prescriptive building codes such as 1170.4, and to achieve seismic performance beyond life safety in them, has been recognized by the Australian Earthquake

Engineering Society (AEES). AEES held a series of seminars on the implications of the 2011 Christchurch earthquake for engineering design in November 2014, followed by a series of seminars on seismic design and detailing for reinforced concrete buildings in May 2016. Both of these seminars placed a focus on robustness, which is accomplished by the careful detailing of connections between columns and beams such that, if their strength is exceeded by the earthquake demand, they fail in a ductile manner by holding together, and not in a brittle manner that leads to collapse.

After the 2011 Christchurch event, earthquake engineering is facing the extraordinary challenge of providing low-cost, and thus more widely affordable, high seismic performance structures capable of sustaining a design level earthquake with limited or negligible damage, minimum disruption of business, and controllable socio-economical losses. This challenge was abruptly heightened by the failure of pre-cast concrete floors in numerous structures in Wellington after the 14 November 2016 Mw 7.8 Kaikoura earthquake. Although the closest approach of the earthquake rupture to Wellington was 40 km, its ground motions exceeded the building code for midrise buildings having natural periods of vibration of about 1.5 seconds ([Risk Frontiers Briefing Note 333](#)). The much closer proximity to Wellington of other major faults, including the Wellington Fault that runs through the Wellington CBD and the Hikurangi subduction zone that lies beneath Wellington ([Risk Frontiers Briefing Note 332](#)), presents a daunting challenge to earthquake engineering in New Zealand.

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Implications of the 5 March 2021 New Zealand and Kermadec earthquakes

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Tectonic setting and the earthquake sequence

The occurrence of a sequence of earthquakes off the East Cape of New Zealand and midway between there and Tonga have important implications for the future occurrence of large earthquakes on the Hikurangi subduction zone of the east coast of the North Island. The Hikurangi subduction zone is the southern part of the Kermadec subduction zone, which extends from the Cook Strait in the south to the Tonga Islands to the north, as shown in Figure 1.

The earthquake sequence began with a Mw 7.3 earthquake within the subducting Pacific plate at a depth of 20 km off the coast of East Cape, between events that occurred in 1995 and 2016. About 4 hours later and 1,000 km to the north, a Mw 7.4 earthquake occurred at a depth of 45 km on the interface between the Australian and Pacific plates, which in turn was followed in 2 hours by a Mw 8.1 earthquake on the shallow plate interface. The earthquake sequence is shown on the right side of Figure 1.

It seems evident that the Mw 7.4 event triggered the nearby Mw 8.1 earthquake in the Kermadec subduction zone. The Mw 7.3 East Cape event occurred within the subducting Pacific plate, not on the interface between the Pacific plate and the Australian plate as was the case for the two Kermadec events. Further, the large separation of about 1,000 km between the East Cape and Kermadec events makes it unlikely that there was sufficient stress transfer for triggering to have occurred. Nevertheless, the East Cape and Kermadec events are both associated with the Kermadec subduction zone, and both may have been responding to some other unknown effect.

The tsunamis that arrived presented no risk, but the earthquake sequence was an extraordinary challenge for tsunami warning ([Risk Frontiers Briefing Note 438](#)). The first earthquake, the magnitude 7.3 event off East Cape, was felt throughout New Zealand at 2.27am. Many people did the right thing, evacuating without waiting for an official warning (Cochrane, 2021). However, Hawke's Bay's Civil Defence Emergency Management Group initially noted in a Facebook post that the 2.27am quake was unlikely to pose a tsunami

threat, which is inconsistent with Government messaging that 'if a quake is long or strong, get gone' (Hawke's Bay Today, 2021). The post was edited half an hour later to match the national Civil Defence advice to take refuge on higher ground. In Gisborne, residents received a cancellation notice for a warning that they had not received (Angeloni, 2021). Northland coped well with the evacuation warning after the Mw 8.1 Kermadec earthquake except for gridlock in Whangarei, whose CBD is in a tsunami evacuation zone (Northern Advocate, 2021).

Increased seismic activity off the northeast coast of the South Island

A map of significant earthquakes in New Zealand is shown in Figure 2. It is notable that all the events off the east coast of the South Island have occurred since the 2010 Mw 7.0 Darfield earthquake. This event was the beginning of a sequence of earthquakes in the Canterbury Plain that included the much smaller Mw 6.2 Christchurch earthquake of 2011, which was very damaging because of its occurrence beneath the city.

A few years later, the Cook Strait and Grassmere earthquakes occurred in 2013 at the northeast corner of the South Island. Taken together, these two sets of events suggested the accumulation of stress in this region, and indeed this was manifested in the 2016 Mw 7.8 Kaikoura earthquake (left side of Figure 3). The Kaikoura earthquake occurred mostly onshore on a complex set of faults within the overriding Australian plate, but had the effect of accommodating east-west convergence between the Australian plate and the Pacific plate on the southern end of the Hikurangi-Kermadec subduction zone.

The occurrence of the Kaikoura earthquake in 2016 gave rise to concern that this event may have transferred stress onto the Hikurangi subduction zone and onto faults including the Wellington and Wairarapa faults at the southeast end of the North Island, increase the likelihood of earthquakes on these faults (Risk Frontiers, 2016; Gerstenberger et al., 2017).

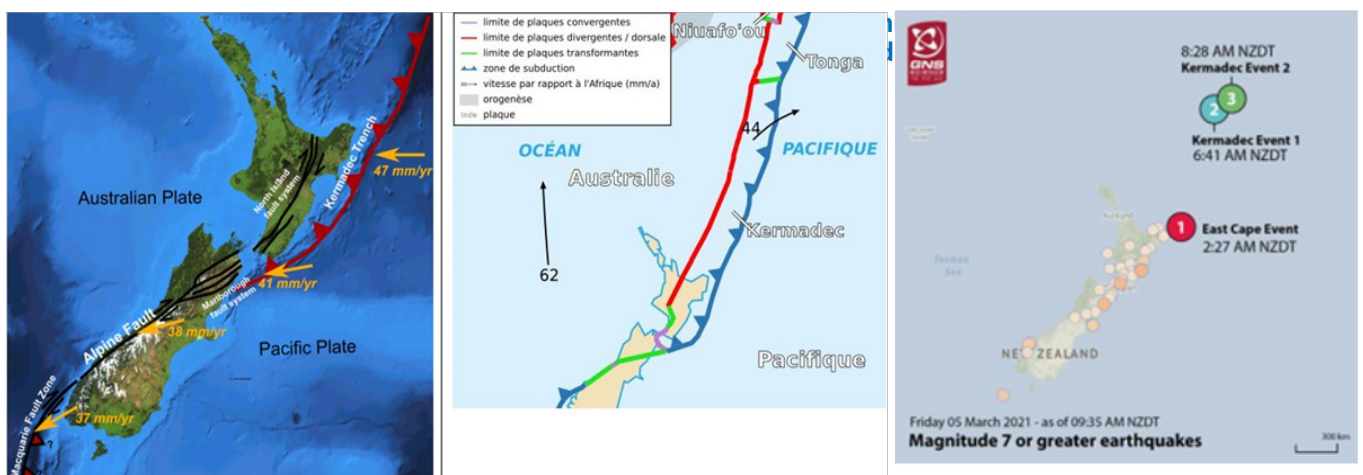


Figure 1. Left: Plate motions and boundaries in New Zealand; the Kermadec Trench marks the location of the Hikurangi subduction zone. Source: GNS Science. Centre: The Hikurangi-Kermadec subduction zone. Right: The 5 March 2021 earthquake sequence, showing the East Cape event at the northeast end of the north Island of New Zealand. Source: USGS.

The Mw 7.8 Hawkes Bay earthquake of 2 Feb 1931 is thought to have involved faulting within the overriding Australian plate, but it had the effect of accommodating east-west convergence between the Australian plate and the Pacific plate, as shown in the right-hand panel of Figure 3. In this respect it is comparable to the 2016 Kaikoura earthquake. All of the major earthquakes to the north of the Hawkes Bay event have occurred in the 25 years since the Mw East Cape earthquake of 1995, including the 20 December 2007 Mw 6.8 event and the 2 September 2016 Mw 7.1 event.

The 5 March 2021 East Cape earthquake occurred offshore between the 1996 and 2016 events. This sequence of events, like that off the east coast of the South Island, suggests the possible accumulation of stress in the region off East Cape, raising concern that these events may have transferred stress onto the Hikurangi subduction zone to the south or the Kermadec subduction zone to the north.

Potential for future occurrence of large earthquakes on the Hikurangi Subduction Zone

Although there is abundant geological evidence for the occurrence of large earthquakes on the Hikurangi subduction zone, there has been no such event in historical time. Clark et al. (2019) identified ten past possible subduction earthquakes over the past 7000 years along the Hikurangi margin. The last subduction earthquake occurred 520–470 years ago in the southern Hikurangi margin and the strongest evidence for a full margin rupture is at 870–815 years ago.

As described above, the two historical events that are most closely associated with the Hikurangi subduction zone are the 1931 Hawkes Bay and 2016 Kaikoura earthquakes, which both involved faulting within the overriding Australian plate in the vicinity of the plate interface. It is important to assess whether the recent sequences of earthquakes at either end of the Hikurangi subduction zone may signify the imminent occurrence of a large earthquake on this subduction zone.

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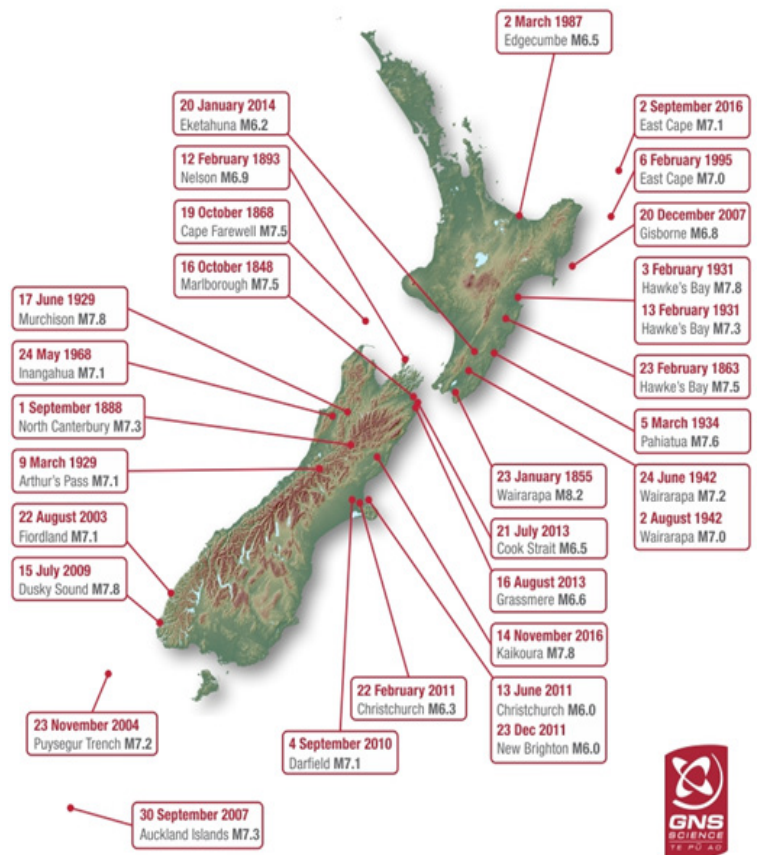


Figure 2. Map of significant earthquakes in New Zealand. Source: GNS Science

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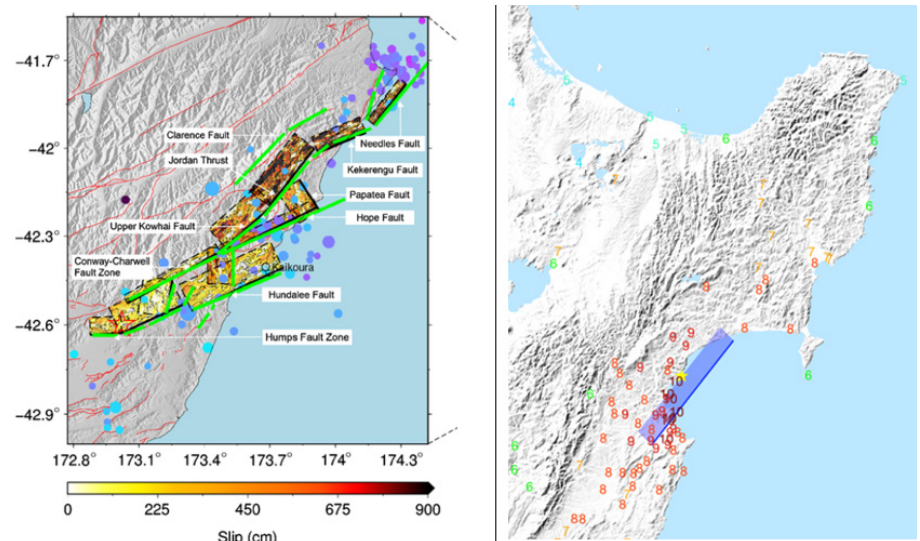


Figure 3. Left: Fault model of the 2016 Mw 7.8 Kaikoura earthquake. Source: Bradley et al., 2017. Right: Fault model and observed intensities of the 1931 Mw 7.8 Hawkes Bay Earthquake. Source: Bayless et al., 2017. In both figures, the top edges of the dipping faults are marked by lines on their east edges.

Charges filed against scientists and tour operators stemming from the 9 December 2019 White Island Volcanic Eruption, New Zealand

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The 9 December 2019 White Island eruption was a steam-driven eruption, caused by the sudden expansion of magma-heated water into steam, which can occur at supersonic speed as the water expands into 1,700 times its original volume. Unlike magmatic eruptions, steam-driven eruptions usually happen suddenly and with little to no warning. The expansion energy can shatter solid rock, excavate craters and eject rock fragments and ash out to hundreds of metres away from the vent. Violent ejections of hot blocks and ash, and the formation of hurricane-like currents of wet ash and coarse particles radiating from the explosion vent, can cause impact trauma, burns and respiratory injuries.



Figure 1. White Island Volcano three days after the 9 December 2019 eruption.
Source: NASA.

The event

Cronin (2020a,b) has reviewed the circumstances surrounding this volcanic eruption. Forty-seven people were on Whakaari (White Island), located 52 kilometres offshore from Whakātane when the crater erupted on December 9 2019, showering tourists and guides with rocks, clouds of ash and toxic gases, killing 22 people and injuring 25. The victims were tourists and their guides on an adventure tourism visit to the island and the volcanic vent.

Many survivors suffered horrific burns and Ngāti Awa-owned tour operator White Island Tours came under scrutiny for continuing to run guided trips, even though GNS Science had raised its volcanic warning to alert level 2 two weeks earlier and banned its staff from going near vents a week before the eruption. It appears that even though the volcanic alert level had been raised to “unrest” several days before the eruption, the visitors and their guides were unaware of the likelihood and consequences of an eruption. WorkSafe chief executive Phil Parkes said that those who went to the island did so with the reasonable expectation that there were appropriate systems in place to ensure they made it home healthy and safe.

The charges

WorkSafe has filed charges against 13 parties over the Whakaari eruption (Worksafe, 2020). WorkSafe chief executive Phil Parkes said that no details of the investigation would be released, to avoid compromising the court process, and he would not name any of the parties facing prosecutions over the tragedy. However, GNS Science, which is responsible for monitoring volcanic activity on the island; the National Emergency Management Agency (Civil Defence) and tour operators Volcanic Air and Ngāti Awa-owned White Island Tours have all confirmed they are facing charges. Parkes said the investigation did not consider the rescue and recovery of victims after the eruption, no enforcement action had been taken over those matters and they would be the subject of other proceedings, such as a coronial inquest.

Ten parties have been charged under the Health and Safety at Work Act: nine under section 36 for failing to ensure the health and safety of workers and others and one facing a charge as a person controlling a business. Each of these charges carries a maximum penalty of a fine of \$1.5 million. Three individuals are also charged under section 44 of the Act, which requires directors or individuals with the influence of a company to exercise due diligence that the company meets its health and safety obligations. Each charge carries a maximum fine of \$300,000. The first court date is December 15 in the Auckland District Court.

White Island Tours has not publicly commented in any detail on its response, but Paul Quinn of Ngāti Awa Holdings previously told media that at level 3 alerts and above they liaised more directly with GNS, and that level 2 (which was the level at the time of the 9 December 2019 eruption) was still within operational guidelines. In a statement on its website, GNS Science said it had not yet been advised of the nature of the charges it was facing, and it would co-operate fully with the authorities while continuing its monitoring role.

Monitoring volcanic eruptions

New Zealand’s GeoNet is a network of monitoring instruments that measure miniscule earth movements continuously, and it delivers high-rate data from volcanoes, including Whakaari. However, it is not currently used as a real-time warning system for volcanic eruptions. Although aligned with international best practice, GeoNet’s current Volcano Alert Level (VAL) system is updated too slowly, because it relies mainly on expert judgement and consensus. Rather than estimating the probability of a future eruption, it gives a view of the state of the volcano in hindsight. All past eruptions at Whakaari occurred at alert levels 1 or 2 (unrest), and the level was then raised only after the event. The last five eruptions at Whakaari were not predicted, despite constant seismic monitoring over this time.

Dempsey and Cronin (2020) have developed an early warning system that, in retrospect, would have raised an alert for four of the last five major eruptions at Whakaari, and would have provided a 16-hour warning for the 2019 eruption. They have been operating this system for five months now, on a 24/7 basis, and are working with GNS Science on how best to integrate this to strengthen their existing protocols and provide more timely warnings at New Zealand volcanoes.



Figure 2. Photograph of the eruption of White Island Volcano taken by a visitor

The way forward

In the current situation, fear of being held legally or socially culpable for well-intentioned but ultimately incorrect advice inhibits innovation and delays the implementation of new technologies. Priority should be given to developing a more proactive volcano warning system that operates in real time and is more physically based than the current volcanic alert level approach used widely around the world. We need implementation of new monitoring technologies like that of Dempsey and Cronin (2020), and the testing of physics-based methods of predicting eruptions. The prime minister's chief science advisor, Juliet Gerrard, has issued a statement highlighting the importance of science advice in emergencies.

Attempts to limit access to science through institutional or other barriers and preventing scientists from giving their free and frank advice in emergency situations [...] places a handicap on good decision-making by our officials and politicians. Only by being able to access all the available knowledge, including its level of uncertainty and whether it is disputed, can decision-makers effectively weigh up the possible consequences of the paths forward, guided by the best evidence.

We need to be much clearer on how volcanic hazard and risk are communicated to tourists, especially on volcanoes with a history of frequent eruptions.

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QuakeNZ

Risk Frontiers' QuakeNZ covers earthquake ground shaking and liquefaction damage throughout New Zealand. The model features a variable resolution grid that is as fine as 500 m in the populated regions. Each grid cell contains no more than 200 addresses. The liquefaction hazard is mapped at an even finer resolution of 16 m to capture the extremely localized risk related to soil type, distance to water, and slope.

QuakeAUS

Risk Frontiers' QuakeAUS is built on Risk Frontiers' extensive knowledge and expertise in Australian seismic hazards. We participated in the development of Geoscience Australia's 2018 National Seismic Hazard Model (NSHA18), which includes the Risk Frontiers earthquake source model. We use the ground motion predictions equations of Somerville et al. (2009) developed specifically for Australia.