GNS Shaking Layers Tool: guidelines for end users

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BIBLIOGRAPHIC REFERENCE

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ABSTRACT

This report contains the user guidelines for GNS Shaking Layers, a tool that produces near-real-time shaking intensity maps following magnitude 3.5 or above earthquakes in New Zealand. Shaking Layers is a GNS Science product supported by GeoNet and the Rapid Characterisation of Earthquakes and Tsunami (R-CET) programme.

The Shaking Layers tool uses the ShakeMap software developed by the United States Geological Survey (USGS) to generate shaking maps. The guidelines focus on four topics: (1) overview of the Shaking Layers system and description of outputs; (2) the New-Zealand-specific data, models and configurations used in ShakeMapNZ; (3) guidelines for interpreting Shaking Layers data and maps; and (4) how to generate bespoke maps, as needed by the user, using the outputs provided by Shaking Layers.

KEYWORDS

Near-real-time data; ground motion; felt reports; shaking maps; shaking layers; ShakeMap; strong-motion data; emergency response; New Zealand; earthquakes

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1.0 INTRODUCTION

Following a significant earthquake, there is a need for rapid information on the level of ground shaking, its geographical distribution and the potential for damage. Emergency managers seek to know whether there was any damage and, if so, where it is concentrated so that they can prioritise the deployment of rapid-response teams. Engineers require estimates of ground motion that may have affected structures of interest in order to trigger inspections. Infrastructure providers are interested in knowing whether certain ground-motion thresholds were exceeded so that they can mobilise technicians and engineers to assess the damage and repair, where necessary, or stop services to prevent damage. The insurance sector wishes to know the scale of damage in order to calculate loss and the number of potential claims. The general public and media are also increasing their demand for information about the intensity of an earthquake and where the strongest shaking was experienced. They often want to validate their own personal experiences or to see what friends and families in different locations may have experienced.

GeoNet is New Zealand's geohazard monitoring programme, run by GNS Science. At present, rapid earthquake shaking-intensity and ground-motion data are available from disparate sources within GeoNet and are only available at certain locations where strong-motion stations are located or 'felt' reports reported. The GeoNet strong-motion network has an average station spacing of a few kilometres in urban areas, such as Wellington and Christchurch, but a spacing of tens to hundreds of kilometres in other areas. Ground motions can vary significantly over these inter-station distances, resulting in uncertainty for end users making decisions based on the currently available earthquake shaking information.

Since 2014, GNS Science seismologists have been producing maps of shaking across New Zealand following significant earthquakes using the ShakeMap software developed by the United States Geological Survey (USGS; Horspool et al. 2015). However, recent consultations with GeoNet and GNS Science stakeholders have revealed the need for shaking maps to be produced faster and automatically, with less reliance on individual response scientists. Furthermore, the ability to update these automatic maps as science evolves in a large earthquake response is considered a useful feature.

For this reason, GNS Science has developed Shaking Layers, a tool that provides near-real-time shaking-intensity maps following a magnitude 3.5 or above event in New Zealand. The Shaking Layers product is collaboratively being supported by GeoNet and the Rapid Characterisation of Earthquakes and Tsunami (R-CET) programme.

This document provides guidelines for using the Shaking Layers tool. Section 2 provides an overview of the Shaking Layers system and data products. Section 3 provides technical information on the specific New Zealand configuration of the ShakeMap software that is used to generate the maps. Section 4 provides some information on how to interpret shaking-intensity maps. Section 5 provides instructions on how to create custom map visualisations of Shaking Layers data. Section 6 includes some conclusions and future work.

Please note: some sections may be updated in the future. For any updates, please always check https://shakinglayers.geonet.org.nz/html/guidelines#updates

2.0 SHAKING LAYERS SYSTEM OVERVIEW

This section provides an overview of the Shaking Layers system. It outlines the system design, processing workflow and versioning.

Shaking Layers is the name of the system that generates shaking information (data and maps) following earthquakes and delivers it through the GeoNet website. *ShakeMap* is the scientific software used to combine shaking information from the GeoNet sensor network, as well as scientific models and understanding from across GNS Science, to produce estimates of shaking across the region.

2.1 System Overview

The Shaking Layers system runs on the GeoNet cloud-based architecture. The overview of the Shaking Layers system is shown in Figure 2.1.

The GeoNet sensor network is continuously streaming seismic waveform data to the automatic earthquake location system at GeoNet. The GeoNet SeisComp3 earthquake-location system automatically detects earthquakes and determines the initial solution (i.e. epicentre, depth, magnitude). This solution is given an ‘automatic’ quality tag. After a few minutes, the automatic solution(s) will be reviewed by a Geohazard Analyst within the National Geohazards Monitoring Centre (NGMC) and the earthquake quality tag will change to ‘preliminary’, at which point the Shaking Layers system will initiate. If the earthquake meets the event criteria set by Shaking Layers (Section 2.2 below), it will automatically trigger a ShakeMap processing job.

Subsequent runs will also take place as outlined below in Section 2.3. These may either be automatic updates to Shaking Layers with new GeoNet data and/or earthquake solutions or updates from GNS Science seismologists that incorporate new data, earthquake parameters and/or advanced models of the earthquake.

With each run, the Shaking Layers data is then automatically published to a database that is used by four data delivery streams (Section 2.4).

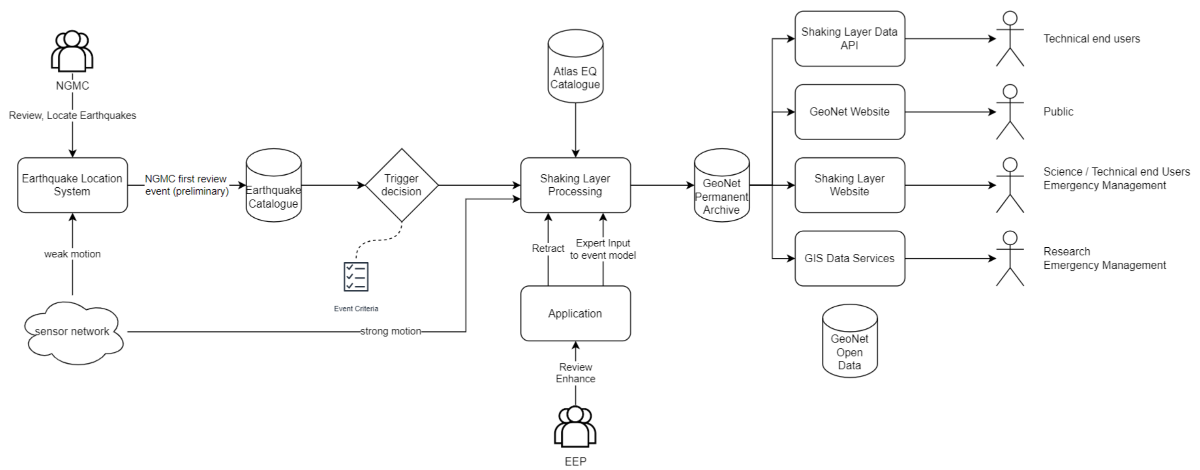

Figure 2.1 Shaking Layers system overview diagram. Shaking Layers processing is undertaken using the ShakeMap software. ‘NGMC’ is the National Geohazards Monitoring Centre based at GNS Science, and the ‘EEP’ is the GNS Science Earthquake Experts Panel, which can be activated for rapid response to significant earthquakes.

2.2 Criteria for the Generation of Shaking Layers Maps

At present, Shaking Layers maps will be generated using the following criteria:

- Earthquakes with a GeoNet magnitude of M3.5 or above with an epicentre location within 100 km of the New Zealand coast. This region is defined as 'onshore New Zealand' and is shown in Figure 2.2.
- Earthquakes with a GeoNet magnitude of M5.0 or above with an epicentre location further than 100 km from the New Zealand coast. This region is defined as 'offshore New Zealand' and is shown in Figure 2.2.

This criteria was developed in consultation with the 'Shaking Layers' project Science and End-User Advisory Panels and was approved by both panels.

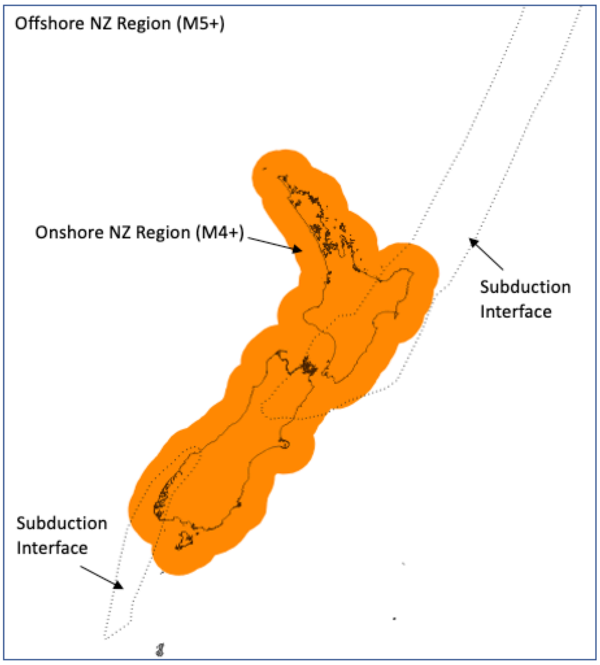

Figure 2.2 Map showing location of regions and magnitude threshold for triggering Shaking Layers. The blue box frame shows the extent of the offshore New Zealand region where M5.0 and above earthquakes will trigger a Shaking Layers run. The orange zone is the onshore New Zealand region where M3.5 and above earthquakes will trigger the Shaking Layers tool.

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

2.3 Shaking Layers Versions

Shaking Layers is a dynamic product that can be updated over time with increasing data, earthquake models and scientific knowledge (Figure 2.3). There are three different Shaking Layers versions: automatic, reviewed and revised.

The first version is *automatic* and is usually available 10–20 minutes following an event. An *automatic* version has not been reviewed or updated by seismologists. The system will then trigger subsequent *automatic* versions based on two criteria: if the GeoNet earthquake solution changes (i.e. epicentre, depth, magnitude) and at fixed times following an event (10 minutes, 20 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, 6 hours, 24 hours), which allows additional strong-motion data to be included if communications to relay this data back to GeoNet are delayed.

If the earthquake is significant, Shaking Layers may be updated manually by seismologists to capture evolving scientific knowledge. These maps contain the most up-to-date scientific models at the time of creation and will be available as *reviewed* versions through the Shaking Layers tool. *Reviewed* versions are generated and published by the GNS Science Earthquake Experts Panel (EEP) and its delegated seismologists. This panel provides rapid science advice and support following significant earthquakes. Expert GNS Science seismologists may modify earthquake parameters (e.g. the earthquake tectonic type, magnitude, mechanism, etc.) or add additional input models and data (e.g. the geometry of the fault rupture, felt reports, etc.) to improve the latest Shaking Layers version. These dynamic updates are discussed in more detail in Section 4 with examples. A seismologist will also undertake a quality assessment of any new reviewed run before it is approved for publication.

A *reviewed* run may also be automatically updated with further GeoNet earthquake solutions or strong-motion data that become available. If a *reviewed* version is updated automatically, it is called a *revised* version and has not been reviewed by a seismologist. These concepts are shown illustratively in Figure 2.3.

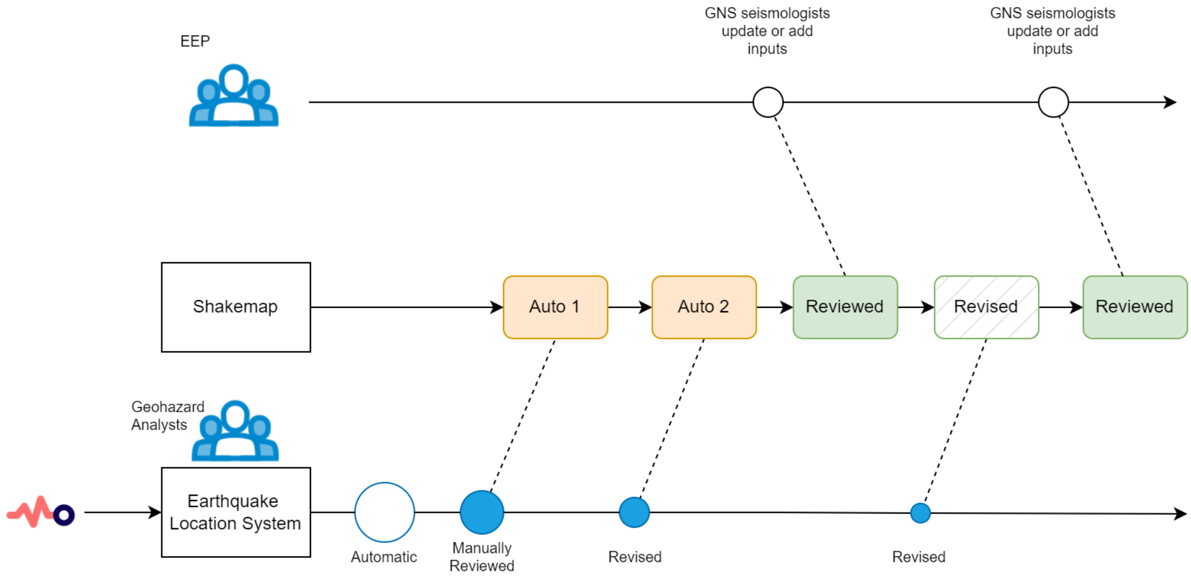

Figure 2.3 Schematic diagram showing the concept of different Shaking Layers versions over time.

Each version is named with the date-time stamp (UTC time) of when the run started (e.g. 2022-07-27T10:32:52), which in this example is 10:32:52 am UTC on 27 July 2022. The name also includes version type, which could be automatic, reviewed or revised, as described above.

2.3.1 Manual Retraction of Maps

Some earthquakes or versions of Shaking Layers may be retracted from the system for various reasons, including when:

- An event initially had an epicentre within the New Zealand boundary (see Section 2.2) but was relocated outside that boundary.
- An event has been identified as not being an earthquake (and thus removed from the GeoNet earthquake catalogue).
- Erroneous data has infiltrated the system and a Shaking Layers version used this data.

For all retracted events or versions, the created folder will be kept, but it will be indicated that the map has been retracted by a *retracted* tag.

2.4 Shaking Layers Data Streams

Shaking Layers are delivered through GeoNet. There are three data streams where an end user can get Shaking Layers information (data and maps). These are the:

- GeoNet Earthquake Event website.[1]
- GeoNet Shaking Layers Data website.[2]
- GeoNet Shaking Layers Data Automatic Programming Interface (API).[3]

A Shaking Layers Geographic Information System (GIS) web-service is also planned for the future to allow end users of GIS systems to access Shaking Layers data through their GIS software.

2.4.1 GeoNet Event Website

Shaking Layers maps are available on the main GeoNet website[4] on an earthquake event[1] page. Users can visualise the Shaking Layers maps on an interactive map and select layers to show, for example, shaking-intensity contours, shaking-intensity maps or GeoNet station data. The map can be panned and zoomed, and users can extract the shaking-intensity estimates at a given point by clicking on the location. Users can also access the Shaking Layers Data Website via the technical tab on the GeoNet website, as well as screen shot the maps to create a static map.

2.4.2 GeoNet Shaking Layers Data Website

The Shaking Layers Data[2] website is the location to manually download data, model and map files. Users can download individual files or all files for a Shaking Layers event and version. Users can search earthquakes by their GeoNet event ID or year and sort recent events by their magnitude, depth, region or time.

2.4.3 GeoNet Shaking Layers Data Automatic Programming Interface

The Shaking Layers Data API[3] provides a way for external applications to access Shaking Layers data through URL-based queries. The API allows users to query events that have Shaking Layers data, versions available for events and files available for versions, as well as to download specific files or all files.

2.5 Shaking Layers Data Products

This section describes the different data products produced by the Shaking Layers system and which data stream they are available from.

2.5.1 Shaking-Intensity Metric Types

There are a number of ways to describe the shaking at a location based on different intensity metric types. There are three main types produced by Shaking Layers: intensity, acceleration and velocity.

1 https://www.geonet.org.nz/earthquake
2 https://shakinglayers.geonet.org.nz/
3 https://shakinglayers.geonet.org.nz/api
4 https://geonet.org.nz

2.5.1.1 *Intensity*

Shaking intensity is a description of shaking as perceived by people and the effect on their environment. Shaking intensity is measured through the Modified Mercalli Intensity (MMI; Dowrick et al. 2008) scale as shown in Table 2.1. The MMI scale ranges from 1 to 12 and is often represented in roman numerals (e.g. I–XII). Each level also has an intensity level related to the perceived shaking level (e.g. light, moderate, strong). Both of these are used by GeoNet to describe shaking intensity. Shaking intensity information is collected through Felt Reports ('Felt Rapid' [GNS Science 2015a] or 'Felt Detailed' [GNS Science 2016]) on the GeoNet website.

Shaking Layers produces intensity data in the MMI scale units (i.e. 1 to 12).

Table 2.1 Modified Mercalli Intensity (MMI) scale, intensity level and description of each level. GeoNet uses both MMI and intensity levels to describe shaking.

MMI	Intensity	Description
1	Unnoticeable	Barely sensed only by a very few people.
2	Unnoticeable	Felt only by a few people at rest in houses or on upper floors.
3	Weak	Felt indoors as a light vibration. Hanging objects may swing slightly.
4	Light	Generally noticed indoors, but not outside, as a moderate vibration or jolt. Light sleepers may be awakened. Walls may creak and glassware, crockery, doors or windows rattle.
5	Moderate	Generally felt outside and by almost everyone indoors. Most sleepers are awakened and a few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.
6	Strong	Felt by all. People and animals are alarmed, and many run outside. Walking steadily is difficult. Furniture and appliances may move on smooth surfaces, and objects fall from walls and shelves. Glassware and crockery break. Slight non-structural damage to buildings may occur.
7	Severe	General alarm. People experience difficulty standing. Furniture and appliances are shifted. Substantial damage to fragile or unsecured objects. A few weak buildings are damaged.
8	Extreme	Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.
9	Extreme	Some buildings are damaged and many weak buildings are destroyed.
10	Extreme	Many buildings are damaged and most weak buildings are destroyed.
11	Extreme	Most buildings are damaged and many buildings are destroyed.
12	Extreme	All buildings are damaged and most buildings are destroyed.

2.5.1.2 Peak Acceleration

The peak (or strongest) accelerations are another intensity metric type used to describe shaking. There are a number of ways to express acceleration. Peak ground acceleration (PGA) is the largest acceleration from an event, whereas pseudo-spectral acceleration (PSA or SA) is related to the acceleration for a defined frequency (inverse of period) of shaking. Technically, it is the maximum response of a simple harmonic oscillator of a given natural frequency to the ground motion (assuming the commonly used 5% damping value). Spectral acceleration is related to how buildings of different heights respond to shaking. The taller a building, the longer the period of spectral accelerations it is sensitive too.

Shaking Layers produces data on PGA and also SA at 0.3 s, 1.0 s and 3.0 s periods. Units are in fractions of acceleration due to gravity (g), where 1.0 g is 100% the force of gravity. By default, Shaking Layers gives the value corresponding to the maximum of the two horizontal recording components.

2.5.1.3 Peak Velocity

Peak ground velocity (PGV) is a metric that describes the peak (or strongest) velocity observed. Units are in cm/s.

2.5.2 Data Formats

2.5.2.1 Data Files

There are two sets of data files produced by the Shaking Layers system: raw and standard files.

- **Raw Files:** The raw file set consists of default files that are generated by the ShakeMap software used to create Shaking Layers information (Worden et al. 2020). The raw files are not supported by GeoNet and may change at any time without warning. Units and file types may vary between files, and users should be aware of this. For information on the raw files, please refer to the USGS ShakeMap website[5].
- **Standard Files:** The standard file set is a set of files produced from the raw files that are stable and supported by GeoNet. The standard files are available through the Shaking Layers API. The standard file formats are very unlikely to change; GeoNet users will be notified of any changes. The standard files have units and file types that are consistent with other GeoNet products and are described in Table 2.2.

5 https://usgs.github.io/shakemap/manual4_0/ug_products.html#output-files-and-products

Table 2.2 Table describing the Standard File set. PGA = peak ground acceleration; PGV = peak ground velocity; PSA = pseudo-spectral acceleration.

Filename	File Format	Intensity Measure Type	Intensity Measure Type Unit	Description
intensity_mmi.tif	.geotiff	Intensity [1]	MMI [2]	Raster grid of intensity
intensity_mmi_stddev.tif	.geotiff	Intensity	MMI	Raster grid of intensity standard deviation (uncertainty)
intensity_mmi_contour_ lines.json	.geojson	Intensity	MMI	Generalised contour lines of intensity
intensity_mmi_contour_ polygons.zip	Shapefile (in a zipped file)	Intensity	MMI	Detailed contoured polygons of intensity
intensity_mmi_map.pdf	.pdf	Intensity	MMI	Static map of intensity with strong-motion stations
pga_g.tif	.geotiff	PGA	G	Raster grid of PGA
pga_g_stddev.tif	.geotiff	PGA	log(g)	Raster grid of PGA standard deviation (uncertainty)
pga_g_contour_ lines.json	.geojson	PGA	G	Generalised contour lines of PGA
pga_g_contour_ polygons.zip	Shapefile (in a zipped file)	PGA	G	Detailed contoured polygons of PGA
pgv_cms.tif	.geotiff	PGV	G	Raster grid of PGV
pgv_cms_stddev.tif	.geotiff	PGV	log(g)	Raster grid of PGV standard deviation (uncertainty)
pgv_cms_contour_ lines.json	.geojson	PGV	G	Generalised contour lines of PGV
pgv_cms_contour_ polygons.zip	Shapefile (in a zipped file)	PGV	G	Detailed contoured polygons of PGV
psa_0p3_g.tif	.geotiff	PSA for 0.3 s period	G	Raster grid of PSA for 0.3 s period
psa_0p3_g_stddev.tif	.geotiff	PSA for 0.3 s period	log(g)	Raster grid of PSA for 0.3 s period standard deviation (uncertainty)
psa_0p3_g_contour_ lines.json	.geojson	PSA for 0.3 s period	G	Generalised contour lines of PSA for 0.3 s period
psa_0p3_g_contour_ polygons.zip	Shapefile (in a zipped file)	PSA for 0.3 s period	G	Detailed contoured polygons of PSA for 0.3 s period
psa_1p0_g.tif	.geotiff	PSA for 1.0 s period	G	Raster grid of PSA for 1.0 s period
psa_1p0_g_stddev.tif	.geotiff	PSA for 1.0 s period	log(g)	Raster grid of PSA for 1.0 s period standard deviation (uncertainty)
psa_1p0_g_contour_ lines.json	.geojson	PSA for 1.0 s period	G	Generalised contour lines of PSA for 1.0 s period
psa_1p0_g_contour_ polygons.zip	Shapefile (in a zipped file)	PSA for 1.0 s period	G	Detailed contoured polygons of PSA for 1.0 s period

Filename	File Format	Intensity Measure Type	Intensity Measure Type Unit	Description
psa_3p0_g.tif	.geotiff	PSA for 3.0 s period	G	Raster grid of PSA for 3.0 s period
psa_3p0_g_stddev.tif	.geotiff	PSA for 3.0 s period	log(g)	Raster grid of PSA for 3.0 s period standard deviation (uncertainty)
psa_3p0_g_contour_ lines.json	.geojson	PSA for 3.0 s period	G	Generalised contour lines of PSA for 3.0 s period
psa_3p0_g_contour_ polygons.zip	Shapefile (in a zipped file)	PSA for 3.0 s period	G	Detailed contoured polygons of PSA for 3.0 s period
param.json	.json	-	-	Dictionary of earthquake and model parameters and references

[1] https://www.geonet.org.nz/earthquake/intensity

[2] https://www.geonet.org.nz/earthquake/mmi

2.5.2.2 Data Coordinate System

All standard and raw files are projected in WGS84[6] (CRS 4326), which has units of decimal degrees.

2.5.2.3 Software for Viewing or Analysing Data File Formats

The following describes how the data file formats provided in the Standard File set can be viewed or analysed using different software. The software list is not exhaustive and is just an example for how these files can be viewed.

- **Geotiff:** Geotiff is a raster file that can be opened in GIS software such as QGIS (free and open source) or ArcGIS (license required).
- **Shapefile:** Shapefiles are a set of vector files that can be opened in a GIS software such as QGIS (free and open source) or ArcGIS (license required).
- **GeoJson:** Geojson is an open data format for representing vector geographic features. Geojson files can be opened in GIS software or in the geojson website[7].
- **Json:** Json is a human and computer readable format. Json files can be viewed in a text editor or web browser.
- **PDF:** PDF files should open in a web browser when clicked. PDF files that are downloaded can be viewed in a PDF viewer such as Adobe Acrobat Reader.

6 https://epsg.io/4326
7 https://geojson.io/#map=2/0/20

3.0 SHAKEMAP TECHNICAL CONFIGURATIONS

In this section, a summary of the technical specifications of the Shaking Layers system and ShakeMap software is presented.

3.1 US Geological Survey ShakeMap

Shaking Layers is the system developed for New Zealand at GNS Science, while the shaking layer maps are generated by the ShakeMap software, developed and released as free and opensource software by USGS (Wald et al. 1999). The Shaking Layers system and ShakeMap software have been implemented with New-Zealand-specific data, configuration files, models and equations. We refer to the New Zealand implementation of ShakeMap as 'ShakeMapNZ' to distinguish it from the more widely used software and USGS implementation. For information on the USGS ShakeMap system, please refer to the manual (Worden et al. 2020).

3.2 Configuration of ShakeMapNZ

This section describes the New-Zealand-specific models, equations and configuration files used in Shaking Layers to make it a tool specifically designed to be used for New Zealand earthquakes, using the latest geological, seismological and geotechnical information.

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.1 Ground-Motion Models

Ground-motion models (GMM) are equations that estimate ground motions given a number of variables such as earthquake magnitude, distance from site to fault rupture, soil conditions or the tectonic type of earthquake (see Section 3.2.6), amongst others. The GMMs used in ShakeMapNZ are the same as those adopted in the 2022 New Zealand National Seismic Hazard Model (NSHM). The NSHM has recently undergone a significant update, which included evaluating, selecting and developing new GMMs for New Zealand (Bradley et al. 2022; Gerstenberger et al. 2022).

The list of GMMs and their weights for the three different tectonic-type earthquakes (crustal, subduction interface, subduction slab), as defined in the NSHM (Gerstenberger et al. 2022), are shown in Tables 3.1–3.3.

Table 3.1 List of ground-motion models (GMMs) used in ShakeMapNZ for crustal earthquakes and their weightings, which sum to 1.0 for each tectonic type, based on the weights developed by the recent update of the NSHM (Gerstenberger et al. 2022). The Sub Model captures the representation of the 'within-model' epistemic uncertainty for each GMM (either as specified within the given model or adopted as described in Gerstenberger et al. [2022]).

GMM Name	Sub Model	Weighting	Reference
S22	Upper	0.117	Stafford (2022)
S22	Central	0.156	Stafford (2022)
S22	Lower	0.117	Stafford (2022)
A22	Upper	0.084	Atkinson (2022)
A22	Central	0.117	Atkinson (2022)
A22	Lower	0.084	Atkinson (2022)
ASK14	sigma-mu-epsilon=1.28155	0.0198	Abrahamson et al. (2014)

GMM Name	Sub Model	Weighting	Reference
ASK14	sigma-mu-epsilon=0.00	0.0264	Abrahamson et al. (2014)
ASK14	sigma-mu-epsilon=-1.28155	0.0198	Abrahamson et al. (2014)
BBSA14	sigma-mu-epsilon=1.28155	0.0198	Boore et al. (2014)
BBSA14	sigma-mu-epsilon=0.00	0.0264	Boore et al. (2014)
BBSA14	sigma-mu-epsilon=-1.28155	0.0198	Boore et al. (2014)
CB14	sigma-mu-epsilon=1.28155	0.0198	Campbell and Bozorgnia (2014)
CB14	sigma-mu-epsilon=0.00	0.0264	Campbell and Bozorgnia (2014)
CB14	sigma-mu-epsilon=-1.28155	0.0198	Campbell and Bozorgnia (2014)
CY14	sigma-mu-epsilon=1.28155	0.0198	Chiou and Youngs (2014)
CY14	sigma-mu-epsilon=0.00	0.0264	Chiou and Youngs (2014)
CY14	sigma-mu-epsilon=-1.28155	0.0198	Chiou and Youngs (2014)
B13	sigma-mu-epsilon=1.28155	0.0198	Bradley (2013)
B13	sigma-mu-epsilon=0.00	0.0264	Bradley (2013)
B13	sigma-mu-epsilon=-1.28155	0.0198	Bradley (2013)

Table 3.2 List of ground-motion models (GMMs) used in ShakeMapNZ for subduction interface earthquakes and their weightings, which sum to 1.0 for each tectonic type, based on the weights developed by the recent update of the NSHM (Gerstenberger et al. 2022). The Sub Model captures the representation of the 'within-model' epistemic uncertainty for each GMM (either as specified within the given model or adopted as described in Gerstenberger et al. [2022]).

GMM Name	Sub Model	Weighting	Reference
A22	Upper	0.081	Atkinson (2022)
A22	Central	0.108	Atkinson (2022)
A22	Lower	0.081	Atkinson (2022)
AG20	sigma-mu-epsilon=1.28155	0.075	Abrahamson and Gülerce (2020)
AG20	sigma-mu-epsilon=0.00	0.1	Abrahamson and Gülerce (2020)
AG20	sigma-mu-epsilon=-1.28155	0.075	Abrahamson and Gülerce (2020)
PSBAH21	sigma-mu-epsilon=1.28155	0.072	Parker et al. (2020)
PSBAH21	sigma-mu-epsilon=0.00	0.096	Parker et al. (2020)
PSBAH21	sigma-mu-epsilon=-1.28155	0.072	Parker et al. (2020)
KBCG20	sigma-mu-epsilon=1.28155	0.072	Kuehn et al. (2020)
KBCG20	sigma-mu-epsilon=0.00	0.096	Kuehn et al. (2020)
KBCG20	sigma-mu-epsilon=-1.28155	0.072	Kuehn et al. (2020)

Table 3.3 List of ground motion models (GMMs) used in ShakeMapNZ for subduction slab earthquakes and their weightings, which sum to 1.0 for each tectonic type, based on the weights developed by the recent update of the NSHM (Gerstenberger et al. 2022). The Sub Model captures the representation of the 'within-model' epistemic uncertainty for each GMM (either as specified within the given model or adopted as described in Gerstenberger et al. 2022).

GMM Name	Sub Model	Weighting	Reference
A22	Upper	0.084	Atkinson (2022)
A22	Central	0.112	Atkinson (2022)
A22	Lower	0.084	Atkinson (2022)
AG20	sigma-mu-epsilon=1.28155	0.075	Abrahamson and Gülerce (2020)
AG20	sigma-mu-epsilon=0.00	0.1	Abrahamson and Gülerce (2020)
AG20	sigma-mu-epsilon=-1.28155	0.075	Abrahamson and Gülerce (2020)
PSBAH21	sigma-mu-epsilon=1.28155	0.069	Parker et al. (2020)
PSBAH21	sigma-mu-epsilon=0.00	0.092	Parker et al. (2020)
PSBAH21	sigma-mu-epsilon=-1.28155	0.069	Parker et al. (2020)
KBCG20	sigma-mu-epsilon=1.28155	0.072	Kuehn et al. (2020)
KBCG20	sigma-mu-epsilon=0.00	0.096	Kuehn et al. (2020)
KBCG20	sigma-mu-epsilon=-1.28155	0.072	Kuehn et al. (2020)

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.2 Intensity Prediction Equation

Intensity prediction equations (IPEs) are a type of GMM that estimate macroseismic intensity instead of the ground-motion metrics typically used in engineering (e.g. PGA, PGV, PSA, etc.). IPE are not used in the NSHM, so there is no recommended model to use for New Zealand. ShakeMapNZ uses the global Allen et al. (2012) IPE, which estimates shaking intensity aligned with New Zealand's MMI scale (Dowrick et al. 2008). This is a global model that includes macroseismic intensity data from earthquakes around the world, as well as over 100 events from New Zealand that were in the Dowrick and Rhoades (2005) MMI database. Testing of this model against GeoNet Felt Report data shows that this model performs well at near to intermediate distances (<150 km) but does attenuate (estimates lower intensities) faster than what is observed from the Felt Report data, which appears to 'flatten out' at larger distances. Work on developing an updated New-Zealand-specific IPE is in progress, and inclusion of this new model in ShakeMapNZ will be considered in the near future.

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.3 Ground Motion to Intensity Conversion Equation

Ground motion to intensity conversion equations (GMICEs) convert between different intensity metrics, such as macroseismic intensity (e.g. MMI) and engineering-based parameters, including PGA, PGV and SA, and vice versa. They are used in ShakeMap to convert between different intensity metrics so that all types of shaking data (e.g. strong-motion recordings and felt reports) are able to be used to generate maps.

The GMICE of Moratalla et al. (2021a) is used in ShakeMapNZ, as this is based on a dataset of 67,000 felt reports from 917 New Zealand earthquakes since 2004.

The GMICE to convert from peak ground motions (PGM) of PGA and PGV to MMI is:

$$MMI = b_1 logPGM + a_1 \ if \ logPGM < t \ logPGM$$

$$MMI = b_2 logPGM + a_2 \ if \ logPGM \geq t \ logPGM \quad \text{Equation 3.1}$$

The GMICE to convert from MMI to PGM of PGA and PGV to MMI is:

$$logPGM = \frac{(MMI - a_1)}{b_1} \ if \ MMI < t \ MMI$$

$$logPGM = \frac{(MMI - a_1)}{b_1} \ if \ MMI \geq t \ MMI\sigma \quad \text{Equation 3.2}$$

The parameters for the GMICE coefficients are shown in Table 3.4.

Table 3.4 Coefficients for New-Zealand-specific ground motion to intensity conversion equations used in ShakeMapNZ.

PGM	a_1	b_1	a_2	b_2	t logPGM	t MMMI	σ_{logPGM}	σ_{MMI}
PGV	4.107	1.6323	1.897	3.837	1.0024	5.7433	0.3455	0.6469
PGA	1.7601	1.992	-1.9095	3.9322	1.89137	5.5277	0.2769	0.6091

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.4 Vs30 Model

ShakeMapNZ requires a national model of Vs30 (time-averaged shear-wave velocity in the uppermost 30 m of the subsurface). This is required to apply site-amplification factors in ShakeMap and as a required input for GMMs.

ShakeMapNZ currently uses the Vs30 model of Perrin et al. (2015), sampled to a 1 km x 1 km grid. It should be noted that the mean Vs30 estimates given by the two published New Zealand Vs30 models of Foster et al. (2019) and Perrin et al. (2015) can differ from one another significantly, highlighting uncertainty arising from the different modelling assumptions. Both models are based on a limited set of underpinning Vs30 data. Newer versions of the Foster et al. (2019) model are being developed, which provide mean Vs30 estimates that are similar to or in between the two published estimates and appear to be more robust. We intend to include these models in ShakeMapNZ and Shaking Layers in future.

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.5 Earthquake Magnitude

The initial magnitude from GeoNet is used as automated input into ShakeMap. GeoNet provides a summary magnitude (M) that is influenced by local magnitude (M_L), whereas ShakeMap requires a moment magnitude (M_W). To convert between local and moment magnitude for the automatic map generation, the following equation is applied, based on the average correction value between these two metrics derived by Christophersen et al. (2022, pers. comm.):

$$M_W = M_L - 0.2$$ Equation 3.3

The Shaking Layers magnitude may be updated by GNS Science seismologists in *reviewed* versions of shaking layers. For very large earthquakes, a M_{WW} derived from w-phase inversion (Duputel et al. 2012) is considered the global international standard because it provides robust magnitudes that do not saturate (i.e. are not under-estimated in the largest earthquakes). W-phase inversions for New Zealand are now generated by the R-CET programme within 18–30 minutes of large earthquakes in New Zealand and the southwest Pacific (subject to quality criteria being met) (Fry et al. 2022). W-phase solutions are also available on variable timeframes from international agencies USGS or Geoscience Australia. For small to moderate earthquakes, M_W may also be directly estimated from Regional Moment Tensor inversion (e.g. Ristau 2013).

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.6 Earthquake Tectonic-Type Assignment

In order to select a set of appropriate GMMs for ShakeMapNZ calculations, a tectonic type must be assigned to the earthquake. There are three tectonic types applicable to New Zealand earthquakes: crustal, subduction interface and subduction slab. The NSHM has a GMM logic tree for each of these tectonic types. ShakeMap also allows use of a blend of tectonic types (if the type cannot be clearly identified) through the use of weights of each GMM set. For ShakeMapNZ, this means three weights adding to 1.0 are specified for crustal, interface and slab, respectively.

An algorithm was developed based on knowledge that there is large uncertainty in the initial depth of an earthquake and so tectonic assignment based on depth should reflect this uncertainty by assigning a blend of GMMs. The goal of this algorithm is to reduce variation between versions due to difference in tectonic-type assignment. It is anticipated that the tectonic type of the earthquake will likely be updated for significant earthquakes by seismology experts, producing a reviewed run (see Section 2.3).

To allow the Shaking Layers tool to automatically assign a tectonic type, a weighting scheme that depends on the hypocentre location and depth is implemented and outlined below (Table 3.5; Figure 3.1). The weighting scheme also seeks to account for the uncertainty in earthquake depth (and, by extension, tectonic type). Figure 3.1 shows the algorithm for assigning the tectonic weights:

1. Using the location of the earthquake, the tectonic zone is determined. This includes a non-subduction zone, the Hikurangi subduction zone or the Puysegur subduction zone.
2. If the earthquake is in the non-subduction zone area, and
   a. the depth is less than 40 km, it is assigned as a crustal earthquake and the crustal GMM set is given a weight of 1.00 and others a weight of 0.00.
   b. the depth is greater than or equal to 40 km, it is assigned as a subduction slab event and the subduction slab GMM set is given a weight of 1.00 and others a weight of 0.00.
3. If the earthquake is in one of the subduction zones, the distance to the subduction interface is calculated. The subduction interface is represented by a mesh of points. The nearest subduction interface point to the earthquake epicentre is selected and the

depth to interface extracted. The distance to interface ($DIST_{INT}$) is calculated by using the depth of the interface ($DEPTH_{INT}$) and depth of earthquake ($DEPTH_{EQ}$):

$$DIST_{INT} = DEPTH_{INT} - DEPTH_{EQ} \quad \text{Equation 3.4}$$

4. Using Table 3.5 below (and illustrated in Figure 3.2) the weighting for each GMM set is selected.
5. If the magnitude is M8.0 or above, any distance to interface rule is overridden. The earthquake is assumed to be a subduction interface event and a weighting of 1.00 is assigned to the subduction interface GMM set.

Table 3.5 Distance to interface ($DIST_{INT}$) and magnitude criteria for assigning ground-motion model sets based on tectonic type. The magnitude criteria overrides any distance to interface criteria.

Distance to Interface	Ground-Motion Model Set Weighting
$DIST_{INT} > 20$	Crustal: 1.00 / Subduction Interface: 0.00 / Subduction Slab: 0.00
$10 \leq DIST_{INT} < 20$	Crustal: 0.66 / Subduction Interface: 0.34 / Subduction Slab: 0.00
$0 \leq DIST_{NT} < 10$	Crustal: 0.34 / Subduction Interface: 0.64 / Subduction Slab: 0.00
$-10 \leq DIST_{INT} < 0$	Crustal: 0.00 / Subduction Interface: 0.64 / Subduction Slab: 0.34
$-20 \leq DIST_{INT} < -10$	Crustal: 0.00 / Subduction Interface: 0.34 / Subduction Slab: 0.66
$DIST_{INT} < -20$	Crustal: 0.00 / Subduction Interface: 0.00 / Subduction Slab: 1.00
Mag > 8.0	Crustal: 0.00 / Subduction Interface: 1.00 / Subduction Slab: 0.00

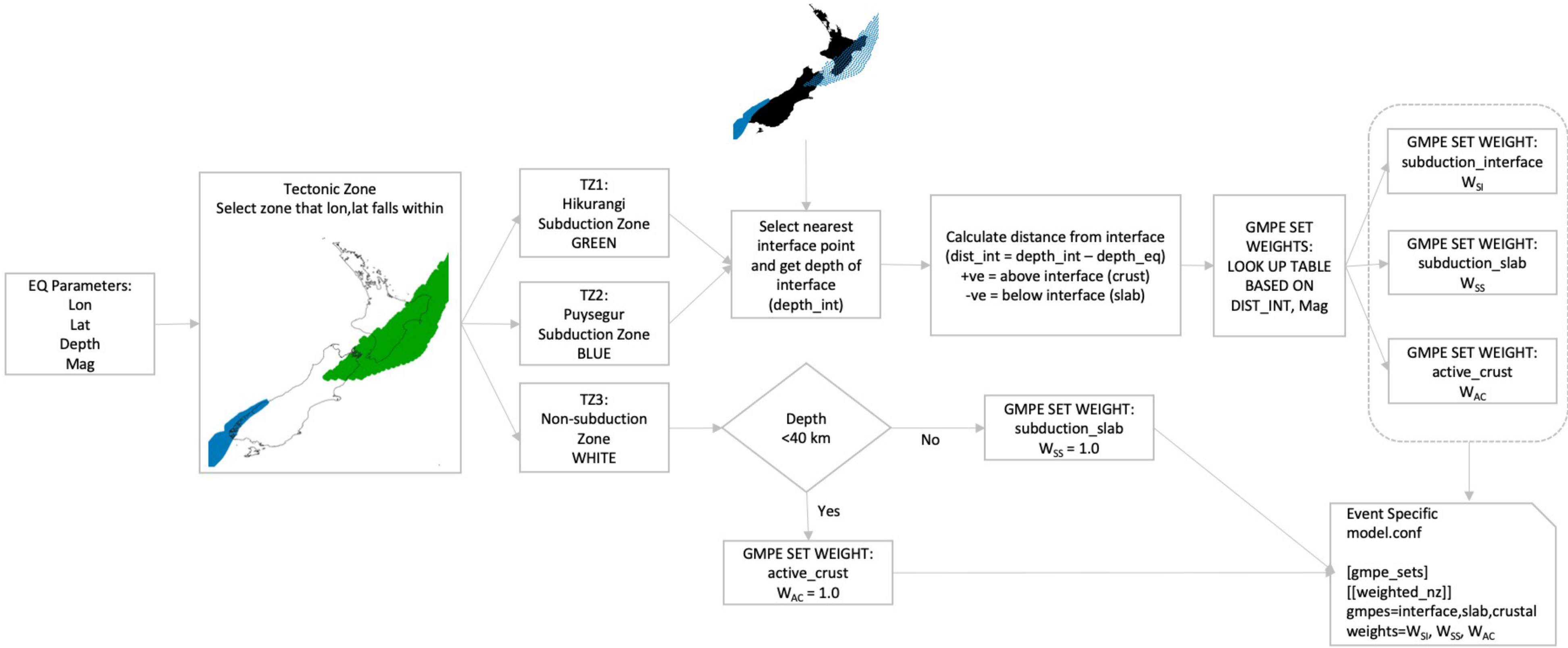

Figure 3.1 Logic for assigning tectonic-type weightings according to Table 3.5.

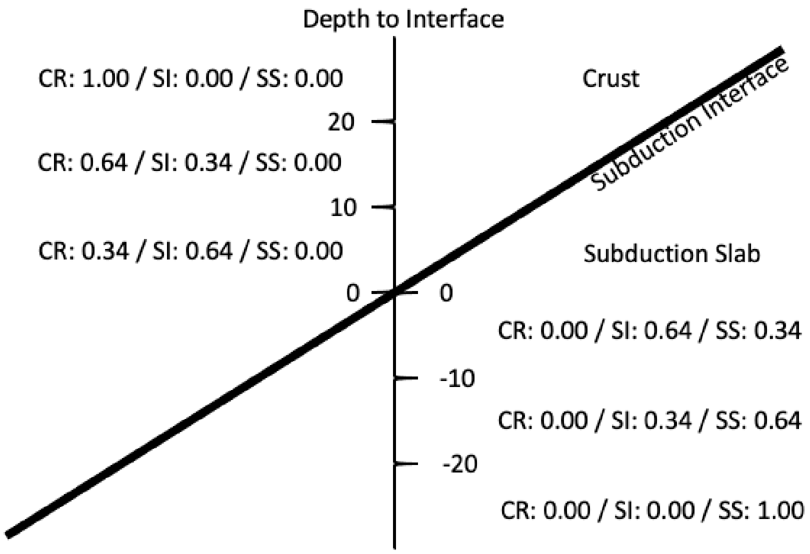

Figure 3.2 Schematic showing depth to interface and ground-motion model set weighting for crustal (CR), subduction interface (SI) and subduction slab (SS) tectonic types used by the automatic Shaking Layers system. These weights may be over-ridden by reviewed versions once seismologists have analysed the earthquake.

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

3.2.7 Additional Data in Reviewed Versions

This section provides an overview of additional data, earthquake parameters or models that may be included through revised runs by seismology experts. These include rupture models, which define the 3D subsurface geometry of the fault rupture during the earthquake, and Felt Reports, which are observations of shaking from the public.

A summary of key earthquake parameters, input models and their appropriate references is included in the *param.json* file available in the set of output files for each run (see Section 2.5.2). This file can be accessed through the Shaking Layers website (see Section 2.5.2).

3.2.7.1 Fault Rupture Models

When an earthquake has been detected and reviewed by the GeoNet 24/7 NGMC, the hypocentre and magnitude will be used to generate initial maps based on an earthquake 'point source' at the hypocentre.

The initial earthquake point-source model used in ShakeMapNZ is likely to be a reasonable representation for small- to moderate-sized earthquakes (less than magnitude 6) but may not adequately represent large earthquakes that could, for example, produce ruptures that are tens to hundreds of kilometres long.

Larger earthquake ruptures are better represented by a 3D fault plane, or multiple fault planes in the case of complex ruptures (see examples in Section 5 below). When 3D models of earthquake rupture are available, they will be reviewed by members of the GNS Science Earthquake Experts Panel and included as appropriate.

Earthquake fault-rupture models may be derived from a variety of sources, based on analyses including:

- Rapid W-phase inversion (Duputel et al. 2012; Fry et al. 2022), giving initial centroid moment tensor (CMT) and updated regional magnitude (M_{WW}) information; a near-real-time New Zealand tool is currently running under the R-CET programme.
- Rapid FinDer models (Andrews et al. 2022, submitted; Böse et al. 2017), giving representation of fault dimensions and orientation; a near-real-time New Zealand tool is currently running and under continuing development by the R-CET programme (Andrews et al., submitted).
- Seismic and geodetic source models derived from expert data analyses (some examples can be found at https://www.geonet.org.nz/data/supplementary/rupture).
- Surface rupture observations and ground deformation mapping (e.g. INSAR, field studies).

If used in a run, the fault model and its reference will be recorded in the summary *param.json* output file, and rupture model details are included in the *rupture.json* file available for download on the Shaking Layers technical website. When using or referring to the source rupture models, users are requested to cite the relevant rupture references.

3.2.7.2 Felt Report Data

Macroseismic intensity data in the New Zealand MMI scale can also be included from the use of felt reports collected by GeoNet. Two sets of felt reports are available to be tested in ShakeMapNZ: 'Felt Detailed' (FD; GNS Science 2016) and 'Felt RAPID' (FR; GNS Science 2015a). FD is a survey of around 40 questions that has been collected since 2004 (called 'Felt Classic' between 2004 and 2016 [GNS Science 2004]). FD provides detailed information on the respondent's experience after an earthquake, and the data provided consists of a weighted mean MMI value for a given New Zealand grid, with each grid cell being 0.02 degrees wide. Intensity values are only provided if the respondent has answered a minimum of questions, and a minimum of five reports per grid is required to provide an MMI value. Details on the method to assign intensity data from FD are provided in Goded et al. (2018) and Moratalla et al. (2021a). FR is a questionnaire available on the internet and mobile devices, where the person contributing their response chooses from a set of six cartoons (each corresponding to a different intensity level; between 3 and 8) depicting their experience of the earthquake (GNS Science 2015a). The purpose of FR is to obtain quick and numerous responses from the public using a simplified questionnaire. Data from FR reports is mainly used by the media and GeoNet as a public communication tool. Recently, weighted mean intensity data per community and grid has been obtained from FR. Research on FR data shows that, if enough data is available per grid, realistic intensity values are obtained, consistent with the ones derived from FD (Moratalla et al., submitted; Goded et al. 2021). Caution should be taken with low intensity values, as these are over-estimated due to the fact that the first cartoon corresponds to an MMI of 3, rather than 1 or 2 (Moratalla et al., submitted).

Shaking maps that use intensity data are manually reviewed by an expert. If maps look realistic and yield improvements, then a new reviewed version of ShakeMapNZ will be released that includes felt report data, and users will be able to download felt report input files (see Section 2.5.2).

These configurations may change in the future. Please check for any updates at https://shakinglayers.geonet.org.nz/html/guidelines#updates

4.0 SHAKING LAYERS MAP INTERPRETATION

In this section, we provide guidance on how to interpret certain features that may be observed in Shaking Layers products. This includes the evolution over time of Shaking Layers maps as new information is included. It also includes how to identify when there are mis-fits between the observed and modelled data in the map, e.g. ‘halo effects’.

4.1 Evolution of Shaking Layers Maps over Time

As described earlier, the first maps that are generated are automatic. The first map may only include the earthquake epicentre, depth and magnitude and no observed sensor data. In this case, the data and maps are ‘fully predictive’ in the sense that there is no observed data to calibrate the GMMs.

The subsequent maps will usually have observed strong-motion data included, and the GMMs are adjusted to fit the observed data. It should be noted that ShakeMapNZ is expected to produce maps with strong-motion data from the first map, as sensor data is streamlined real-time in GeoNet. Thus, no ‘fully predictive’ maps are intended to be included in ShakeMapNZ. However, there may be some rare cases when strong-motion data has not been received before the first ShakeMapNZ is triggered.

If the earthquake is significant, for example, it has a magnitude above ~6.0 or has interest to the public or other end users, information may be added or updated in *reviewed* runs (see Section 2.3). Updated information could include a new earthquake magnitude (i.e. M_W), location of rupture (centre rather than epicentre), earthquake mechanism or tectonic type. Additional information could include fault rupture geometry (i.e. 3D area that ruptured in the earthquake for large-magnitude earthquakes) or additional strong-motion observations from other networks or the inclusion of felt reports. Key information added in a run will be recorded in the *param.json* summary file available for download.

Given the dynamic nature of the maps, it is useful to understand how Shaking Layers data and maps may evolve with new science input for particular response scenarios. Below in Figures 4.1–4.4 are examples of how Shaking Layers could evolve based on four historical earthquakes. In general, significant changes through time could be expected for the largest earthquakes (e.g. 2016 Kaikōura earthquake in Figure 4.1), where the initial point source approximation may not capture the full extent of earthquake shaking.

A list of additional examples is provided in Appendix 1, with examples of observed events or scenarios where different parameters have been either changed (e.g. magnitude, epicentre) or added (e.g. fault rupture or MMI derived from felt report data).

4.1.1 2016 Kaikōura Earthquake

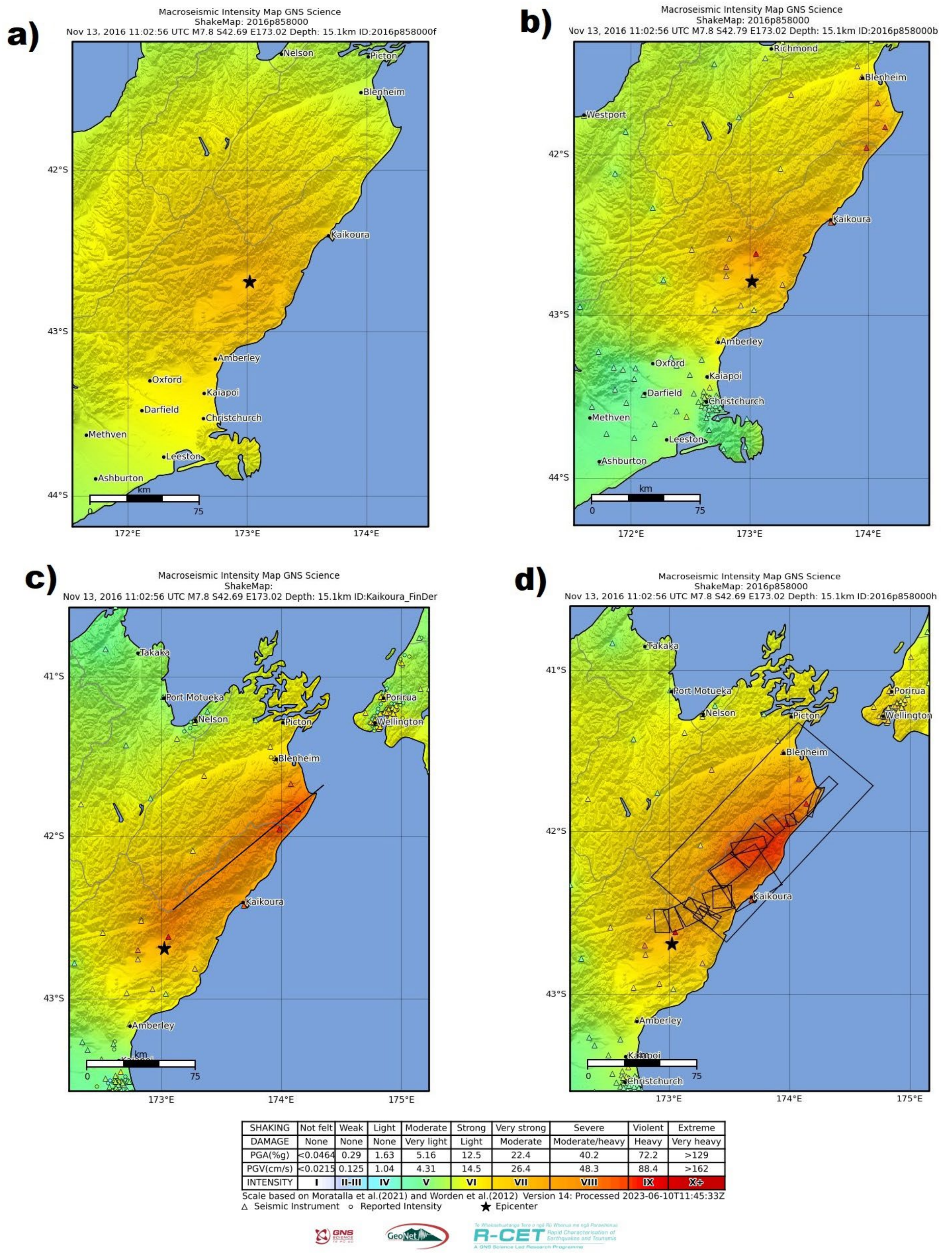

Figure 4.1 Modified Mercalli Intensity shaking layer corresponding to the M7.8 14/11/2016 Kaikōura earthquake with (a) point source only; (b) point-source and strong-motion data; (c) source, strong-motion data and initial fault rupture from a FinDer solution (Andrews et al. 2022, submitted); and (d) source, strong-motion data and detailed fault rupture of Hamling et al. (2017).

4.1.2 2010 Darfield Earthquake

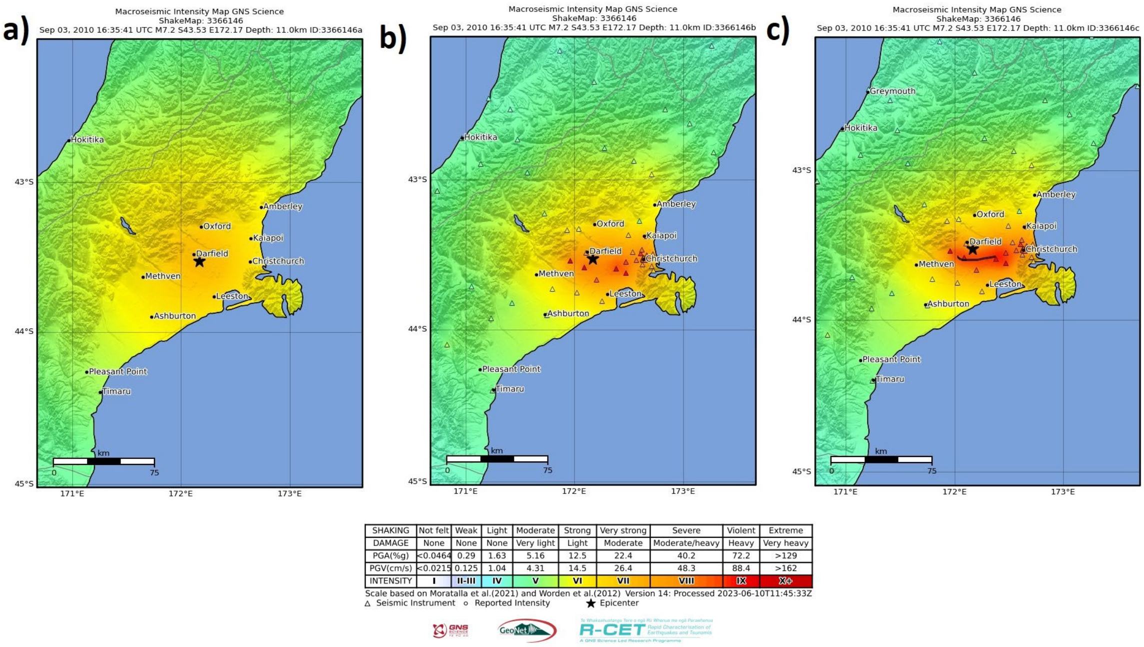

Figure 4.2 Modified Mercalli Intensity shaking layer corresponding to the M7.1 4/9/2010 Darfield earthquake with (a) point source only; (b) point-source and strong-motion data; and (c) source, strong-motion data and fault rupture, sourced from the New Zealand Active Faults Database (GNS Science 2015b).

4.1.3 2011 Christchurch Earthquake

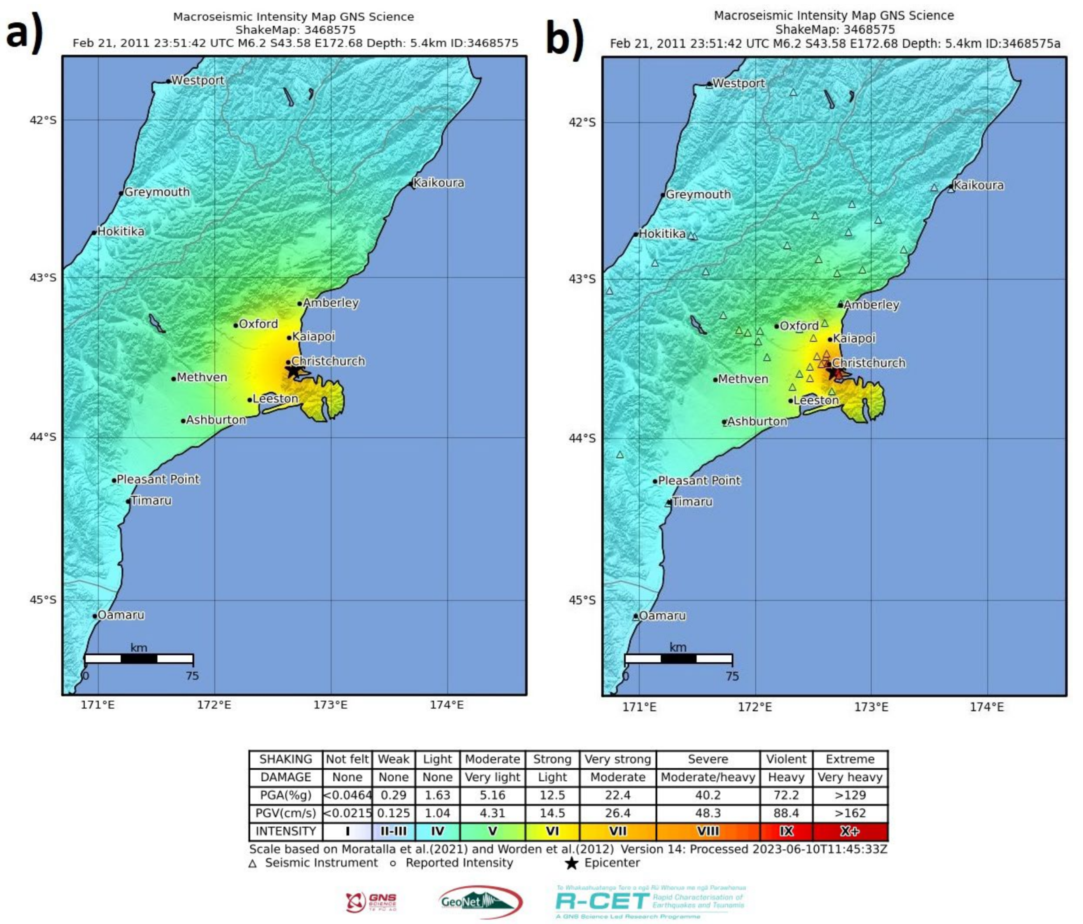

Figure 4.3 Modified Mercalli Intensity shaking layer corresponding to the M6.2 22/2/2011 Christchurch earthquake with (a) point source only and (b) point-source and strong-motion data.

4.1.4 2013 Cook Strait Earthquake

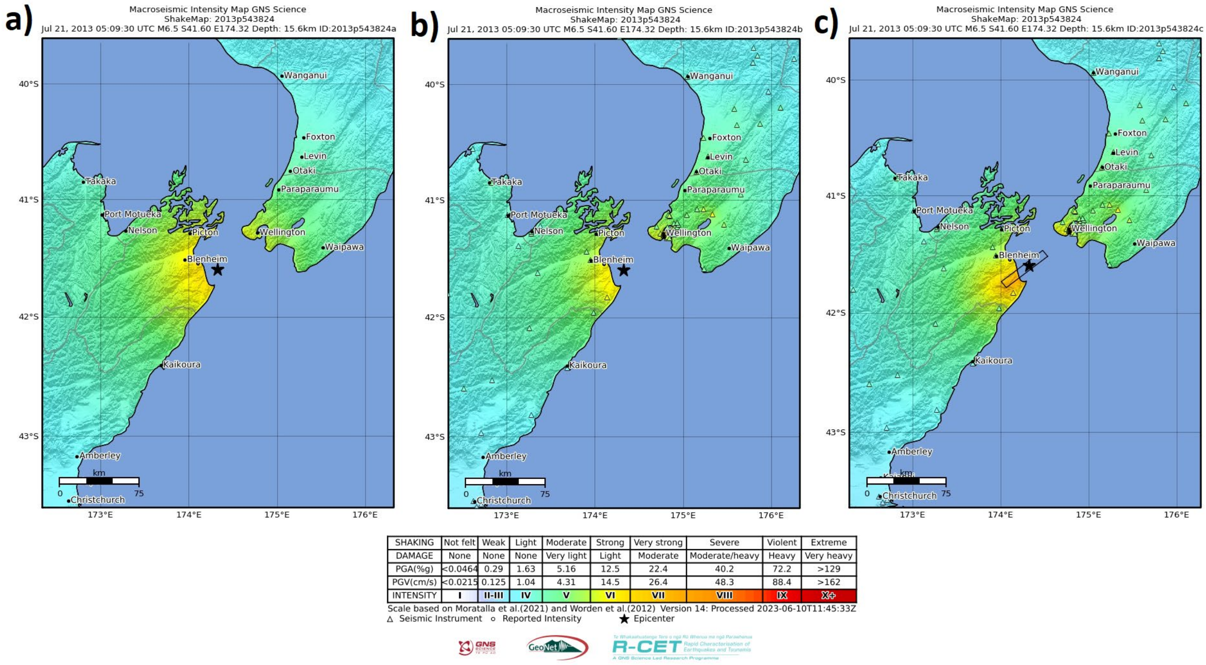

Figure 4.4 Modified Mercalli Intensity shaking layer corresponding to the M6.6 21/7/2013 Cook Strait earthquake with (a) point source only; (b) point-source and strong-motion data; and (c) source, strong-motion data and fault rupture (Hamling et al. 2014).

4.2 Mismatch between Station Recordings and Model Predictions (Halo Effects)

Strong-motion data may sometimes have an observation that is far larger or smaller than expected from the Shaking Layers model predictions. In this case, the map will show a 'halo' effect, where the area immediately around the station is also higher or lower than the 'background' model (e.g. Figure 4.5). These effects are visible in the intensity maps but can also influence contoured maps of other ground-motion metrics. This is because ShakeMap uses an approach that weights observations and GMMs to determine the shaking at a given location. Near strong-motion stations, the observation at that station is given a higher weight, and, as the location moves further from the strong-motion station, the GMM is given more weight and the station observation less weight.

Care must be taken when using maps where strong halo effects are observed. A station 'halo' may indicate a genuine under-prediction or over-prediction of the model; for example, when the station observation is correct and the background ground-motion predictions do not fully capture the local shaking. This could be due to simplification of the earthquake representation, or strong local 'site effects' that influence a given station location but are not fully captured in the model predictions.

Alternatively, a halo effect may indicate an erroneous or biased observation, which is not a good representation of the true ground shaking in the area. This may happen if, for example, the station recording is affected or contaminated by local noise, or the instrument itself has been disrupted during an earthquake, or other factors. Observations that are considered to be erroneous may be removed after review by a seismologist.

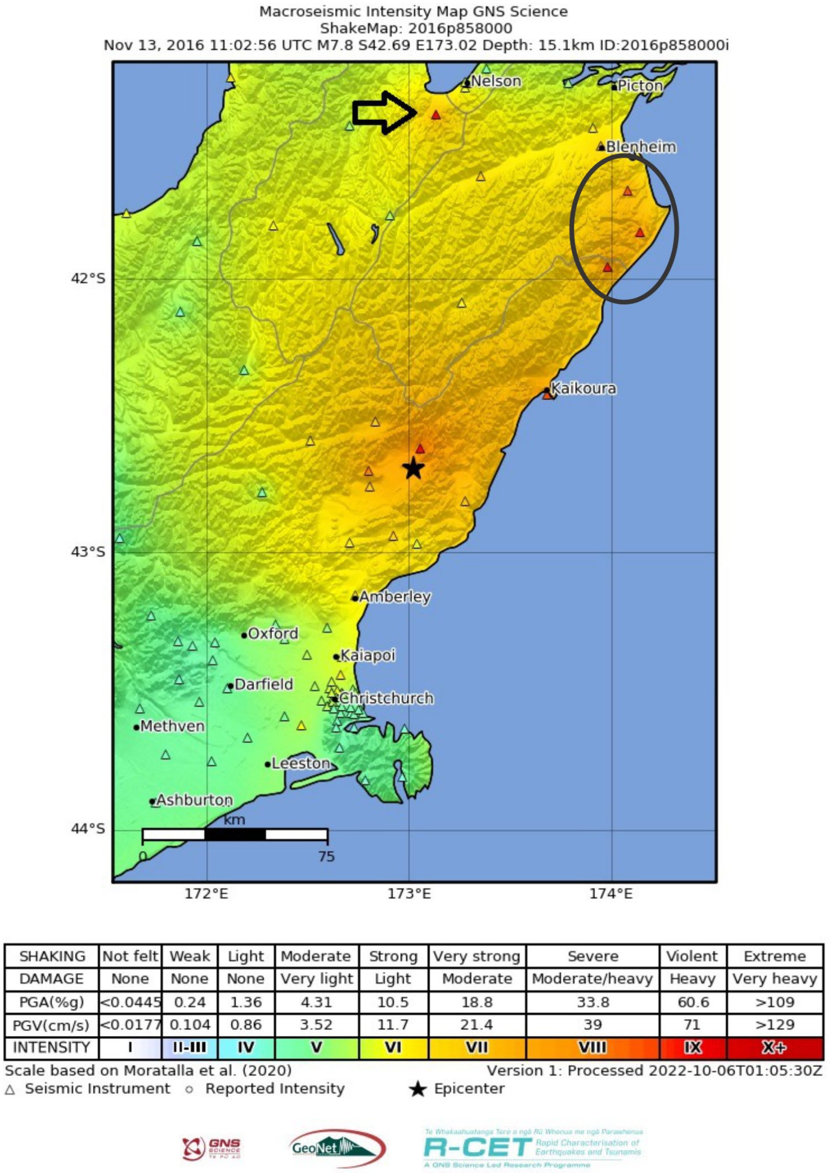

Figure 4.5 A ShakeMap created for a Kaikōura earthquake scenario, where an ‘outlier’ station has been creating a false station reading (shown by the black arrow). This shows up as a ‘halo effect’ at this station. Note: other halo effects are also present at the circled stations in the northeast, but these are due to real observations that are not well predicted by the background model. In this example, it is difficult to tell the cause of halo effects from the map; care should be taken when using maps that show such ‘halo effects’.

4.3 Examples of Map Updates for Large or Significant Earthquakes

The GMMs used in ShakeMap require only the earthquake magnitude and hypocentre location to estimate shaking across the region. However, these first shaking models may be too simplistic for very large earthquake ruptures. These first models can be improved if additional information about the earthquake source or additional shaking estimates, such as felt reports, are included (see Section 4.1 and Figures 4.1–4.4).

4.3.1 Earthquake Magnitude

First estimates of earthquake magnitude from GeoNet may be updated during an earthquake response once robust moment magnitudes (M_W) are available. This may somewhat reduce mismatch between model predictions and observations and reduce ‘halo effects’ (e.g. the example for the 2016 Kaikōura earthquake in Figure 4.6).

For very large earthquakes, first-magnitude estimates can often ‘saturate’ and initially under-estimate the true size of an earthquake until robust measures, for example, M_{WW} from W-phase solutions (Duputel et al. 2012; Fry et al. 2022), are available.

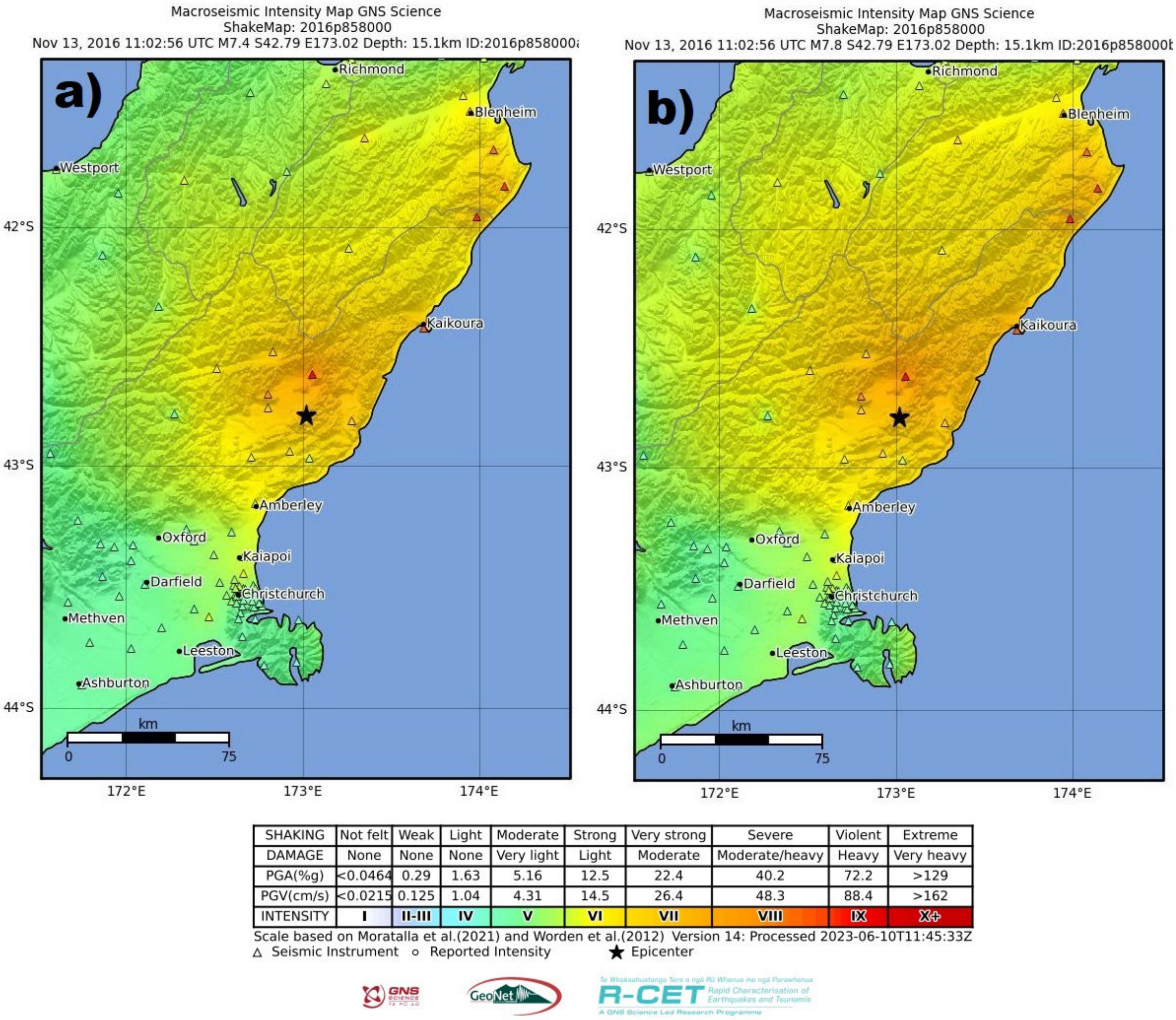

Figure 4.6 Modified Mercalli Intensity shaking layer corresponding to the M7.8 14/11/2016 Kaikōura earthquake with (a) initial M_L 7.4 magnitude and (b) final M_{WW} 7.8 magnitude.

4.3.2 3D Earthquake Rupture Models

For large earthquakes where the fault geometry is many tens to hundreds of kilometres long, the initial representation of the earthquake as a ‘point source’ in ShakeMap will not accurately reflect the true fault-rupture geometry. This will cause inaccuracies between the estimated and actual earthquake rupture to site distance calculations. This may also cause a ‘halo effect’ at stations that are far from the earthquake epicentre but in fact close to the true rupture (although this is not known). Adding 3D fault-rupture models (Section 3.2.7.1) can significantly improve estimates of shaking immediately surrounding the earthquake rupture.

An example for the 2016 Kaikōura earthquake is shown in Figure 4.1. In this case, stations in the northern South Island were within a few kilometres of the actual fault rupture, but, because the epicentre was at the southern end of the rupture, the initial versions of ShakeMap strongly under-estimated shaking in these regions.

Including 3D rapid fault models from FinDer (Andrews et al. 2022, submitted; e.g. Figure 4.1c), or detailed scientific models available later in the response (e.g. Hamling et al. 2017; Figure 4.1d) can significantly improve the shaking maps. This allows the earthquake source-to-site distances to be correctly estimated and GMM predictions to be more accurate.

4.3.3 Felt Reports

Felt reports (see Section 3.2.7.2) can also be added to ShakeMaps, providing additional observations of shaking to refine shaking models.

These data can also help better capture ground shaking intensity close to the earthquake source, particularly when station observations are sparse or unavailable – an example for the 1968 M7.2 Inangahua earthquake is shown in Figure 4.7 below.

Figure 4.8 shows an example from the M_W 6.1 15/02/2023 Paraparaumu earthquake, where felt reports provide additional observations of intensity in areas of sparse station recordings.

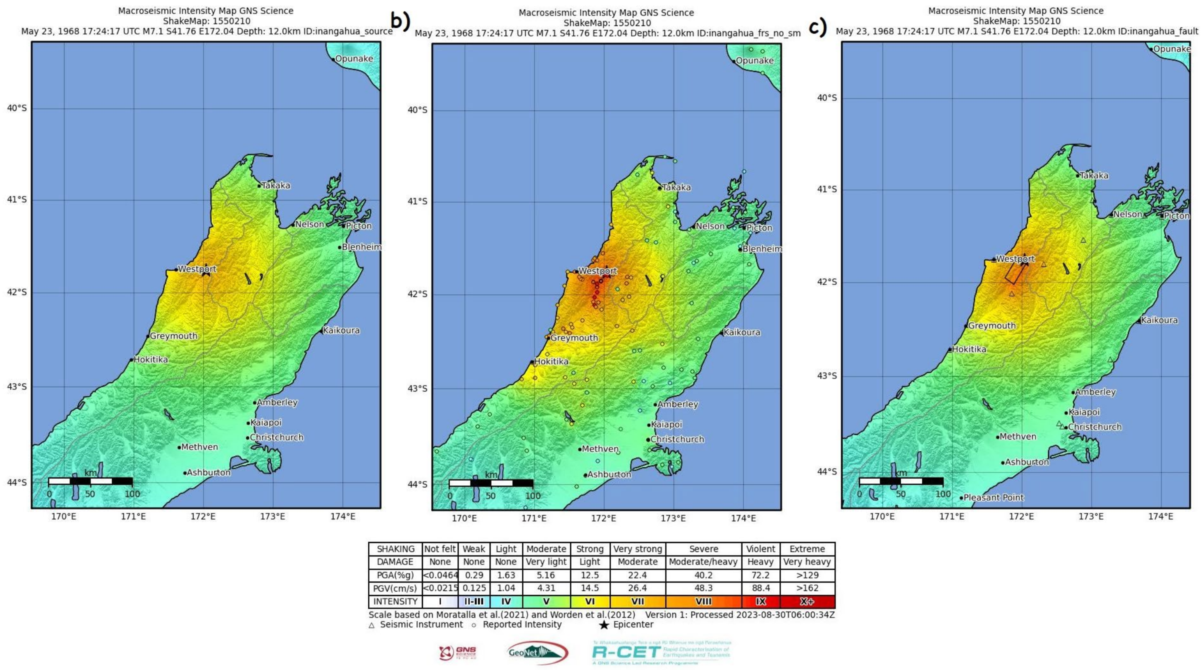

Figure 4.7 Modified Mercalli Intensity shaking layer corresponding to the M7.2 23/5/1968 Inangahua earthquake with the (a) point source only; (b) felt reports (circles) and (c) estimated 3D fault-rupture model and a limited set of strong-motion recordings. In this example, adding felt reports has a similar effect to adding a 3D fault-rupture model through more accurately capturing high ground motions close to the earthquake source.

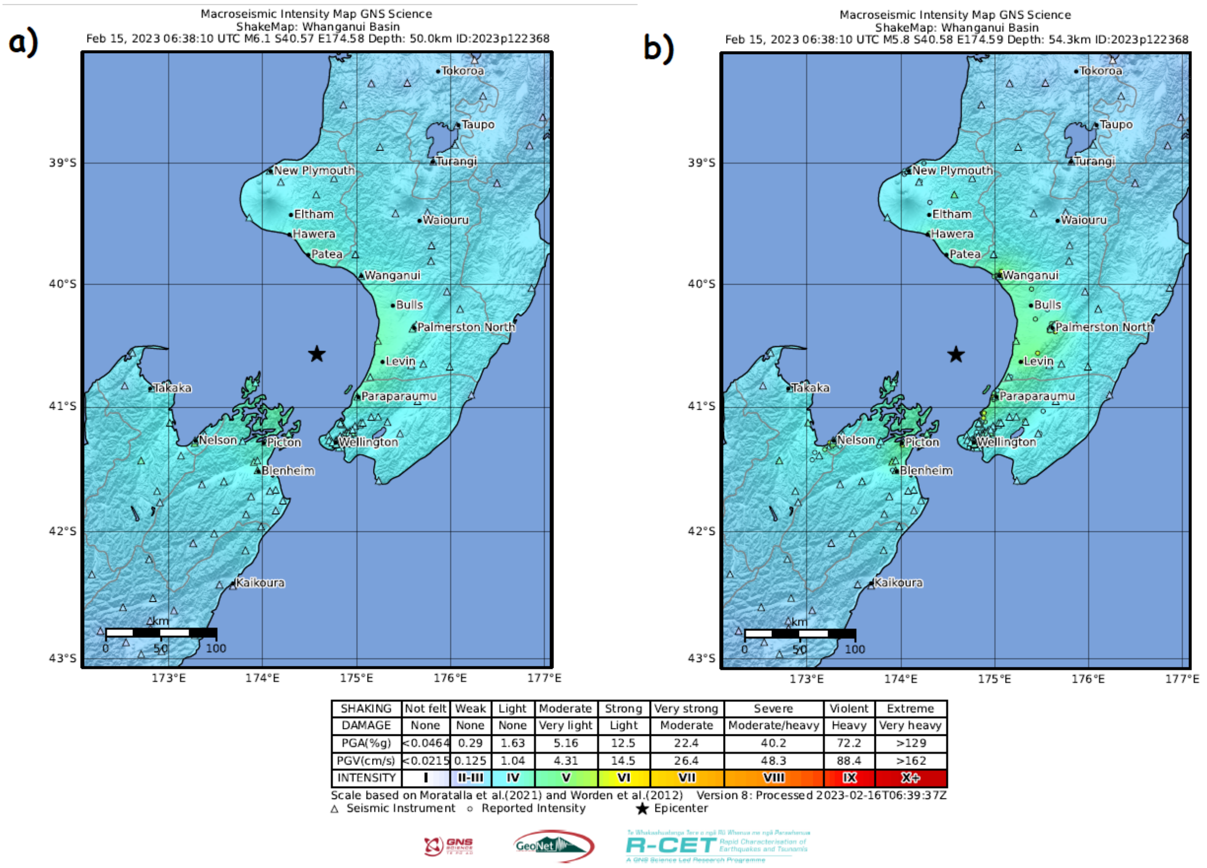

Figure 4.8 ShakeMap for the M6.2 15/02/2023 Paraparaumu earthquake with (a) basic point source information and (b) felt reports included (indicated by circles).

5.0 CREATING SHAKING LAYER MAPS WITH UNCERTAINTY

In some circumstances, end users may wish to create customised shaking maps using a different percentile GMM prediction than the mean. One example of this is a conservative map at a higher percentile. Note that this method captures the uncertainty in GMM predictions (assuming the earthquake or rupture model used to generate them is robust).

The Shaking Layers tool produces the mean estimate of shaking (e.g. *pga_g.tiff*), as well as the uncertainty (*pga_g_std.tiff*), represented by the standard deviation of the ground-motion uncertainty. Some end users may be interested in producing a custom shaking map that combines these two layers to produce estimate of shaking at a high percentile level. This can be undertaken in a raster calculator in a GIS system such as QGIS or ArcGIS or through a programming language such as Python or GDAL. Below, we show the equation to combine the mean and standard deviation layers to produce a custom map at a different uncertainty level.

In this example, we want to calculate a conservative shaking map that shows the mean plus 2 standard deviation (i.e. the 95th percentile shaking). To do this, the following equation would be used in a raster calculator or code:

$$mean\_plus\_2stddev.tiff\ =\ exp(\ log(pga\_g.tiff)\ +\ (2\ x\ pga\_g\_std.tiff)) \qquad \text{Equation 5.1}$$

First, we convert the mean PGA layer (*pga_g.tiff*) from units in g into units in log space, log(g), as this are the units of the standard deviation file. We then multiply the standard deviation PGA layer (*pga_g_std.tiff*) by the number of standard deviations above the mean that we are interested in. If we were interested in +1 standard deviation, this number would be 1 instead of 2. These values are added together. If we were interested in the mean minus 2 standard deviations, then we would subtract instead of adding. We then take the exponential of this value to convert out of log space back into units of g. This operation assumes that the uncertainty of the ground motion is lognormally distributed, which, for most GMMs, is the case. Note that, for MMI, the units are non-log so the equation is simply:

$$mean\_plus\_2stddev.tiff = intensity\_mmi.tiff + (2\ x\ mmi\_intensity\_std.tiff) \qquad \text{Equation 5.2}$$

Examples of the three files as described above are shown in Figure 5.1.

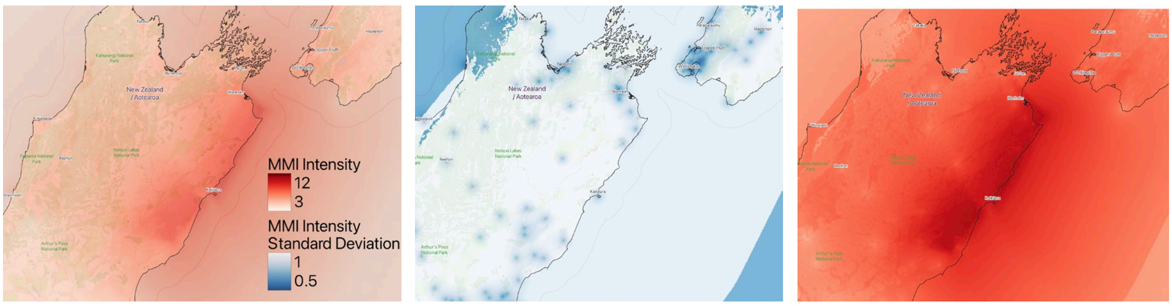

Figure 5.1 Example of mean ground motion, uncertainty and upper-percentile shaking maps for the Kaikōura earthquake. Left: MMI map (mean) where dark red is stronger shaking. Centre: Uncertainty map where dark blue indicates less uncertainty. Right: MMI map (mean plus two standard deviations), calculated as described in Equation 5.2.

6.0 FUTURE WORK

There are a number of areas that are being explored to continue to improve the Shaking Layers tool. These include but are not limited to:

- Continuing to improve the speed and accuracy of Shaking Layers for large earthquakes through testing the use of near-real-time fault-rupture models generated by a suite of other R-CET tools.
- Including additional SA periods beyond 0.3 s, 1.0 s and 3.0 s to allow Shaking Layers spectra to be used for engineering responses.
- Developing New-Zealand-specific soil amplification factors for ShakeMapNZ.
- Implementing automatic generation of community MMI from Felt Rapid felt reports.
- Implementing data streaming to ingest strong motion from non-GeoNet sensors that are publicly available.

7.0 DATA AND RESOURCES

The availability of the data used in this project is as follows:

- Felt Rapid data is publicly available through the GeoNet website if the earthquake ID is known; for example, for the Kaikōura earthquake (ID 2016p858000), results can be obtained from: https://api.geonet.org.nz/intensity?type=reported&publicID=2016p858000
- Felt Classic and Felt Detailed data are not publicly available. To protect the privacy of individuals, these can only be used for research purposes if the research team has obtained ethical approval. The use of Felt Classic data for research purposes in this project has been approved as a Low Risk project by the Massey University Human Ethics Committee, on a letter dated 5 November 2018.
- Strong-motion data used in Shaking Layers is also available for download through the GeoNet Strong Motion Tool (https://strongmotion.geonet.org.nz/).
- The USGS ShakeMap Documentation website has further information on the ShakeMap software or Raw File outputs (Worden et al. 2020).
- Earthquake models used in published Shaking Layers versions are included in the output files *param.json* and *rupture.json*, together with the appropriate references for citation.
- More information about the MBIE Endeavour R-CET programme can be found here: https://www.gns.cri.nz/research-projects/rcet/

8.0 SHAKEMAPNZ DISCLAIMER

The following are the disclaimers associated with the GeoNet Shaking Layers products.

8.1 GeoNet Disclaimer

Please read these terms of use. Use of this website and the information on it will be deemed to be acceptance of these terms.

The GeoNet project is core funded by the Ministry of Business, Innovation & Employment (MBIE), Toka Tū Ake EQC and Land Information New Zealand (LINZ) to facilitate improved detection and understanding of geological hazards. This website is designed, installed and operated by GNS Science under the GeoNet project.

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8.2 Shaking Layers Data Website API and Event Website Disclaimer

Please read these terms of use / disclaimers. Use of ShakeMapNZ Maps and any associated data or information will be deemed to be acceptance of these terms of use / disclaimers.

(A1) All Shaking Layers are a model of the ground motion field for a specific intensity measure, based on a model of an earthquake. This has the following implications:

- *Different source information, strong-motion or felt report data or equations will result in different shaking layers, including significant differences between models.*
- *There is no unique solution, nor unique shaking layers.*

(A2) Errors: ShakeMapNZ's Maps are, by default, automatic, computer-generated maps and have not necessarily been checked by human oversight, so they may contain errors. Further, the input data are raw and unchecked and may contain errors. It should be noted that the first ShakeMapNZ released for each event will be automatic. Following that first map, further versions for that same event might be either automatic, reviewed or revised. The status of the map will be indicated in all outputs. Shaking layers may be updated manually by seismologists to capture evolving scientific knowledge. These maps contain the most

up-to-date scientific models available for Shaking Layers at the time of creation; though we note all models contain uncertainties and underlying assumptions. These versions will be available as reviewed versions through the Shaking Layers tool. If a reviewed version is updated automatically it is called a revised version, and has not been reviewed by a seismologist. See more details in section 2.3.

(A3) Shaking Layers versions: for a single earthquake, there could be several versions of ShakeMapNZ Maps produced through time. All maps produced for the same event will be archived. It is the responsibility of the end-user to use the latest published ShakeMapNZ available for a particular event.

(A4) Contours can be misleading since data gaps may exist. Caution should be used in deciding which features in the contour patterns are represented by the data. Ground motions and intensities can vary greatly over small distances, so these maps are only approximate. In addition, the contours provided in the geoJSON files have been smoothed and are thus not suitable for anything but plotting and approximate analysis.

(A5) Locations mapped within the same intensity area will not necessarily experience the same level of damage since damage depends heavily on the type of structure, the nature of the construction, and the details of the ground motion at that site. For these reasons, more or less damage than described in the intensity scale may occur. The ground motion levels and descriptions associated with each intensity value are based on recent damaging earthquakes. These parameters may be revised as more data become available or due to further improvements in methodologies.

(A6) ShakeMapNZ does not provide site-specific intensity estimates. ShakeMapNZ is based on a coarse-scale regional Vs30 map for New Zealand (e.g. Perrin et al. 2015). Thus, there is no guarantee that this is a reasonable representation of site conditions at a given location or that a Vs30-based ground motion estimate is appropriate for a particular site. This should be especially taken into account when looking at intensity information at specific locations.

(A7) Large earthquakes can generate very long period ground motions that can cause damage at great distances from the epicentre; although the intensity estimated from the ground motions may be small, significant effects to large structures (e.g. bridges, tall buildings, storage tanks) may be notable. In addition, additional induced seismic and post-seismic hazards such as landslides, liquefaction, and tsunami are not modelled by ShakeMapNZ.

(A8) Felt report data is used on some ShakeMapNZ Maps and not on others. Felt report data will be taken from one of the two felt report datasets from GeoNet, either 'Felt RAPID' or 'Felt Detailed'. The inclusion of felt report data will be a decision made by experienced experts, and the potential ShakeMapNZ improvements when adding felt report data will be assessed by an expert before a map with felt report data is published. The number of stations (shown as triangles) and felt report intensity points (depicted by circles) are given in the metadata. Several filtering and quality control

strategies are in place (e.g. Goded et al. 2018), but erroneous or suspect data cannot always be identified. While we make efforts to provide consistent quality control of the data, the felt report data depends upon open, citizen-science based input from the public. Several studies have shown these data to be generally reliable, but the data reliability may vary from event to event.

(A9) Fault rupture information is used in some events and not others. This will depend on the availability of fault rupture information at the time when the map was produced. Fault rupture information might significantly change through time, especially for large and/or complex events. This will likely cause a significant change in the ShakeMapNZ parameters on the maps.

(A10) There is no formal 'final' version of any ShakeMapNZ Map. Maps are subject to change due to change in source parameters, new fault ruptures or felt report data available, updates in ShakeMap software, etc. This could happen even years after the event. Thus, a ShakeMapNZ Map can never be considered final. However, the latest version will always be the most updated version of a ShakeMap and should be the one used by end-users. All versions of all products are permanently archived in the GeoNet database. ShakeMapNZ version numbers and timestamps are provided on the each ShakeMapNZ Map, grid file, and in the metadata.

(A11) Reasonable endeavours. All reasonable endeavours are made to ensure the accuracy of ShakeMapNZ Maps. However, ShakeMapNZ Maps are provided without warranties of any kind including accuracy, completeness, timeliness or fitness for any particular purpose.

(A12) Exclusion of liability. The Institute of Geological Sciences Limited excludes to the full extent permitted by law liability for any loss, damage or expense, direct or indirect, and however caused, whether through negligence or otherwise, resulting from any person or organisation's use of, or reliance on, the information and data provided in ShakeMapNZ Maps.

9.0 ACKNOWLEDGMENTS

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APPENDICES

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APPENDIX 1 USE CASES

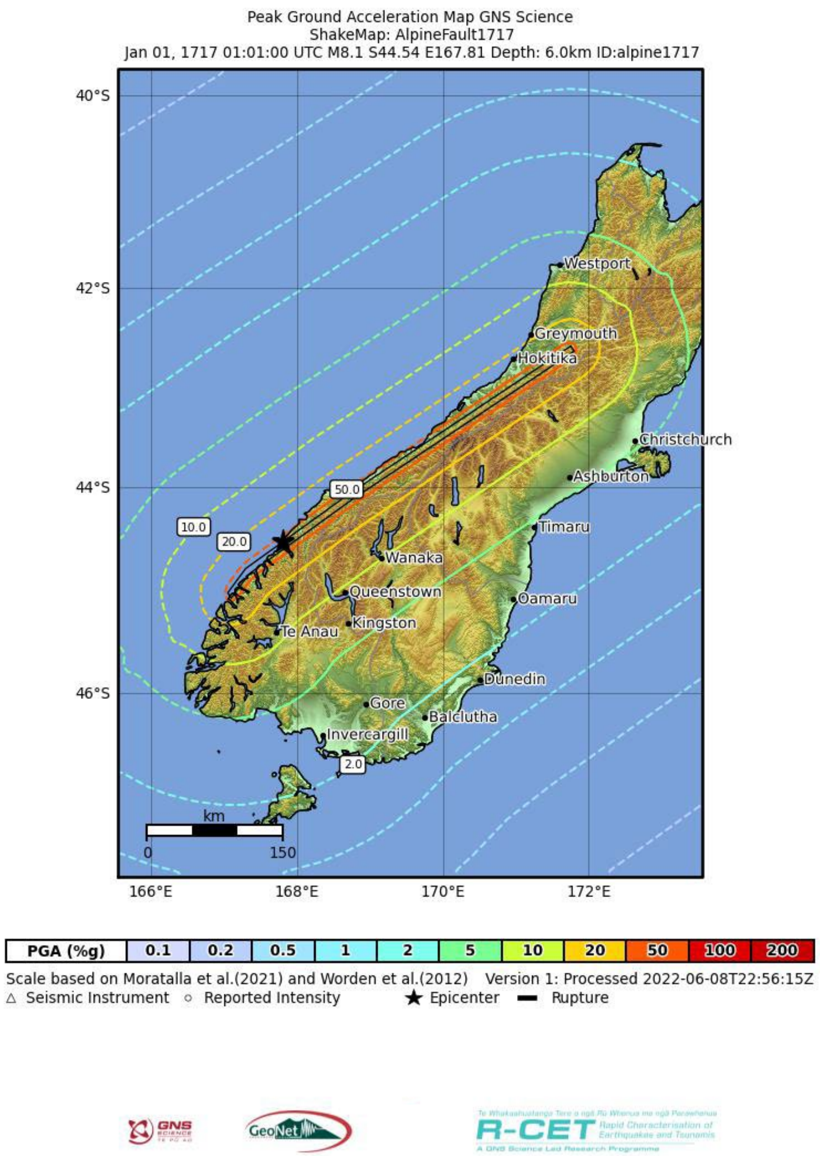
This appendix shows the Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) Shaking Layers of the 23 use cases used in this document.

Table A1.1 Shaking Layers use cases for guidelines. TRT = tectonic regime: CR = crustal, SI = interface, SS = slab; SM = strong-motion data; RF = rupture file; FR = felt report file; Type of event: H = historical, P = paleoevent, S: synthetic/scenario event, I = instrumental event.

Ref.	ID	Name	Date and Time	Magnitude	Depth (km)	Latitude	Longitude	TRT	SM	RF	FR	Type of Event	Description
1	-	Alpine Fault 1717	-	8.1	6	-44.54	167.82	CR	NO	YES	NO	H/P	-
2	-	Alpine F2K	-	8.1	6	-44.06	168.72	CR	NO	YES	NO	S	-
3	-	AlpineK2T	-	7.7	6	-42.26	172.34	CR	NO	YES	NO	S	-
4	-	Southern Hik Subduction A	-	8.4	25	-41.29	174.78	SI	NO	NO	NO	S	What could a Hikurangi subduction ShakeMap look like when automatically generated? Epicentre at southern end.
5	-	Southern Hik Subduction B	-	8.4	17.5	-40.97	175.73	SI	NO	NO	NO	S	What could a Hikurangi subduction ShakeMap look like when automatically generated? Epicentre in middle.
6	-	Southern Hik Subduction C	-	8.4	17.5	-40.97	175.73	SI	NO	YES	NO	S	What could a Hikurangi subduction ShakeMap look like with a rough fault plane?
7	-	Hik ALL Subduction A	-	9	14.5	-38.19	178.59	SI	NO	NO	NO	S	What could a Hikurangi subduction ShakeMap look like when automatically generated? Epicentre at southern end.

Ref.	ID	Name	Date and Time	Magnitude	Depth (km)	Latitude	Longitude	TRT	SM	RF	FR	Type of Event	Description
8	-	Hik ALL Subduction B	-	9	14.5	-39.71	177.39	SI	NO	NO	NO	S	What could a Hikurangi subduction ShakeMap look like when automatically generated? Epicentre in middle.
9	-	Hik ALL Subduction C	-	9	14.5	-41.13	175.79	SI	NO	NO	NO	S	What could a Hikurangi subduction ShakeMap look like with a rough fault plane?
10	-	Hik ALL Subduction D	-	9	14.5	-39.71	177.39	SI	NO	YES	NO	S	What could a Hikurangi subduction ShakeMap look like with a rough fault plane?
11	-	Tohoku	-	9.1	26	-39.44	176.69	SI	YES (fake)	YES	NO	S	Megaquake 'worst case', using the 2011 M9.1 Tohoku scenario with projected strong-motion data in New Zealand.
12	3468575	Christchurch Feb 2011 A	2011-02-21 T23:51:42Z	6.2	5	-43.58	172.68	CR	YES	NO	NO	I	Example of a reasonably good urban automatic ShakeMap, only strong-motion data.
13	3468575	Christchurch Feb 2011 B	2011-02-21 T23:51:42Z	6.2	5	-43.58	172.68	CR	YES	NO	YES	I	Ref. 12 with felt report data.
14	3468575	Christchurch Feb 2011 C	2011-02-21 T23:51:42Z	6.2				CR	YES	YES	NO	I	Ref .12 with fault rupture.
15	3468575	Christchurch Feb 2011 D	2011-02-21 T23:51:42Z	6.2				CR	YES	YES	YES	I	Ref. 12 with fault rupture and felt report data.
16	2014p051675	Eketahuna 2014	2014-01-20 T02:52:45Z	6.2	34	-40.62	175.87	SS	YES	NO	YES	I	Depth/location significantly changed through time; Example of a slab event.

Ref.	ID	Name	Date and Time	Magnitude	Depth (km)	Latitude	Longitude	TRT	SM	RF	FR	Type of Event	Description
17	2015p012816	Wilberforce 2015	2015-01-05 T17:48:41Z	6	5	-43.06	171.25	CR	YES	NO	YES	I	Depth/location significantly changed through time; Example of an event in a more-sparse instrument area.
18	2016p118944	Valentine's Day 2016	2016-02-14 T00:13:43Z	5.7	8	-43.50	172.76	CR	YES	NO	YES	I	Example of a good urban automatic ShakeMap.
19	2016p858000	Kaikoura 2016 A	2016-11-13 T11:02:56Z	7.4 (MLv),	15	-42.69	173.02	CR	YES	NO	NO	I	Large earthquake – influence of updates in strong-motion data and source information and how it relates to ShakeMap accuracy. Only strong-motion data, under-estimates magnitude.
20	2016p858000	Kaikoura 2016 B	2016-11-13 T11:02:56Z	7.8 (Mw)	15	-42.69	173.02	CR	YES	NO	NO	I	Ref. 19 with final magnitude.
21	2016p858000	Kaikoura 2016 C	2016-11-13 T11:02:56Z	7.8	15	-42.69	173.02	CR	YES	NO	YES	I	Ref. 20 with felt report data.
22	2016p858000	Kaikoura 2016 D	2016-11-13 T11:02:56Z	7.8	15	-42.69	173.02	CR	YES	YES	YES	I	Ref. 20 with fault and felt report data.
23	2018p816466	Taumarunui 2018	2018-10-30 T02:13:41Z	6.2	207.15	-39.00	175.01	SS	YES	YES	YES	I	Example of a slab event.



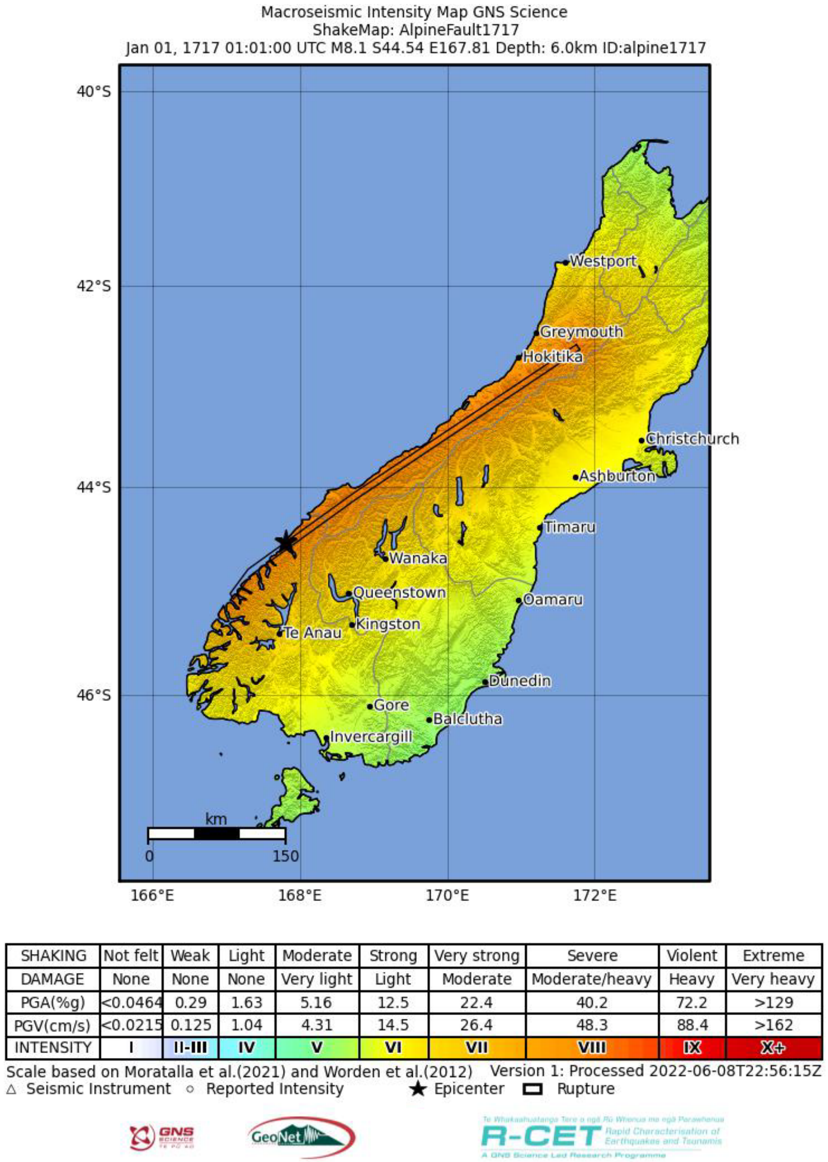
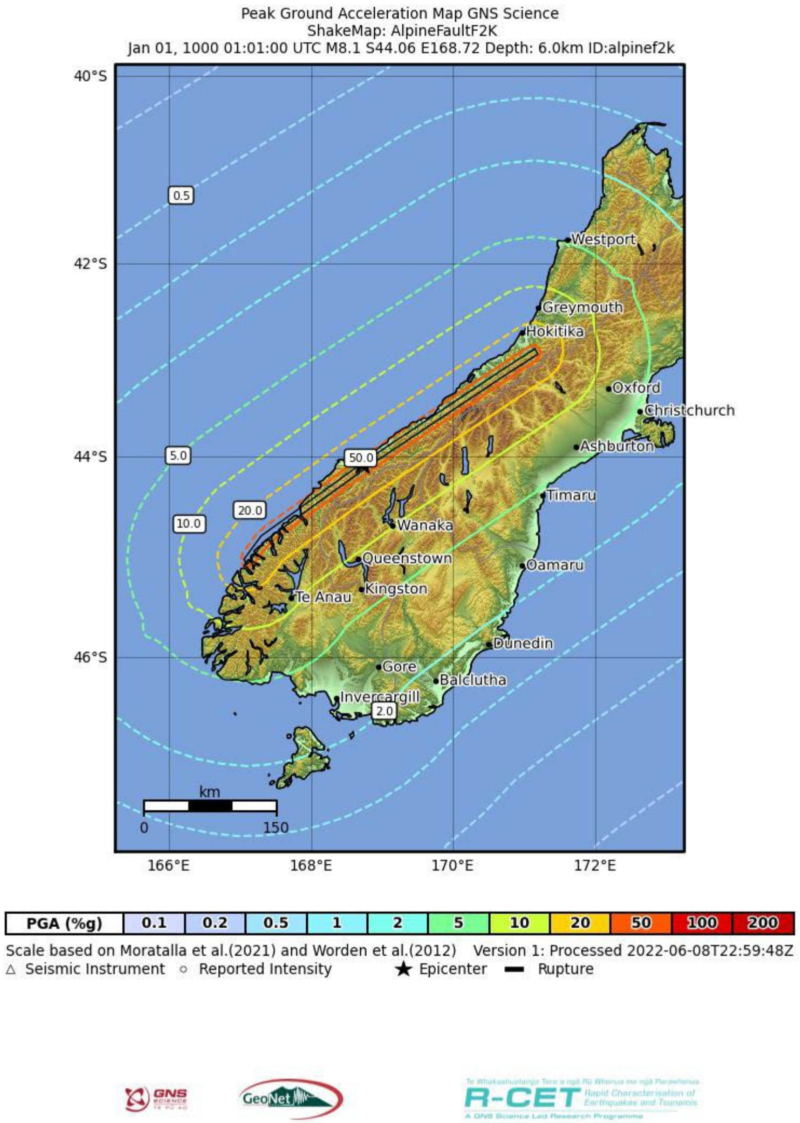
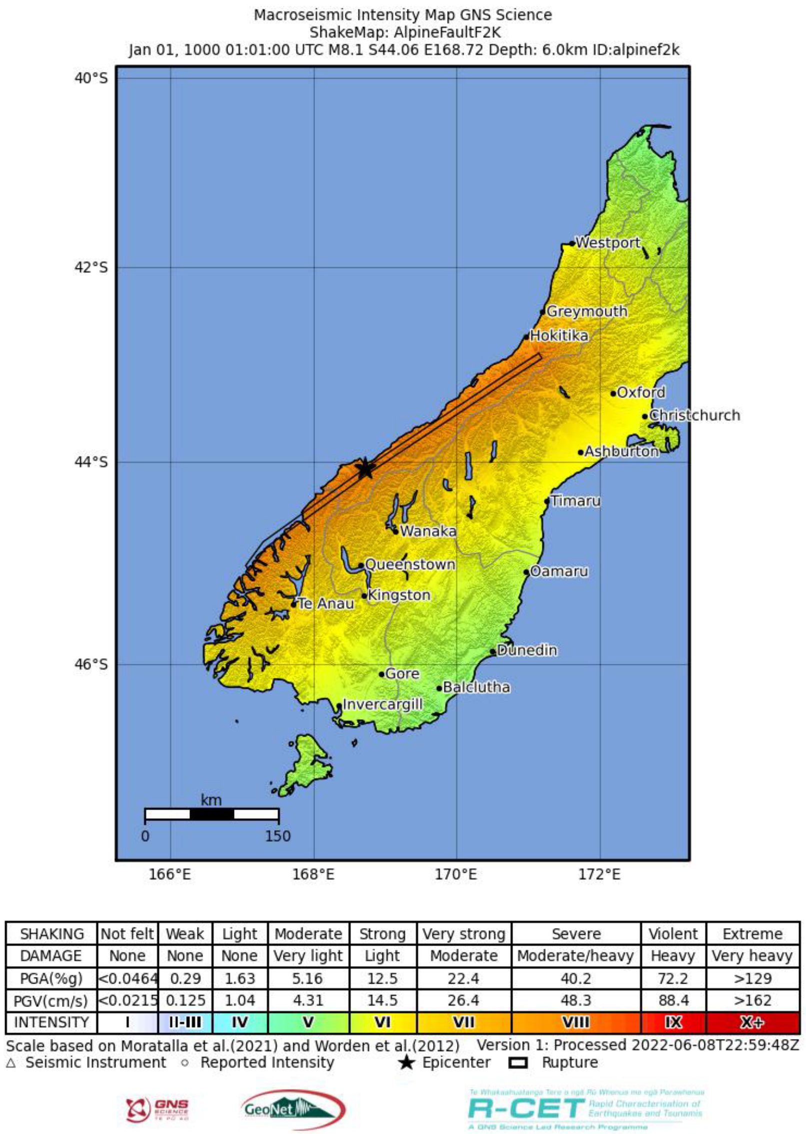


Figure A1.1 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M8.1 Alpine Fault 1717 paleoearthquake (Ref. 1, Table A1.1).





SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure A1.2 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M8.1 Alpine Fault F2K segment paleoearthquake (Ref. 2, Table A1.1).

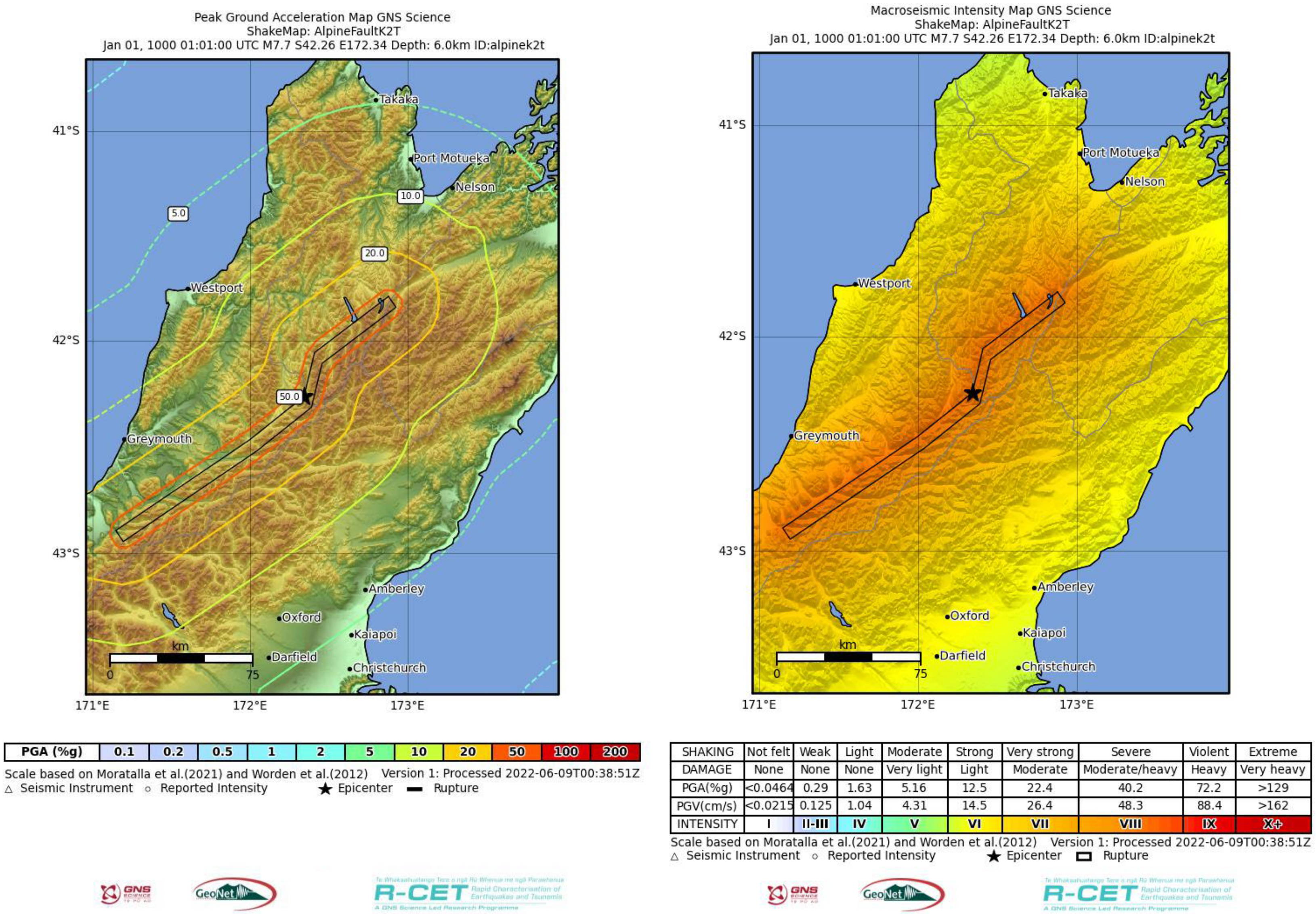
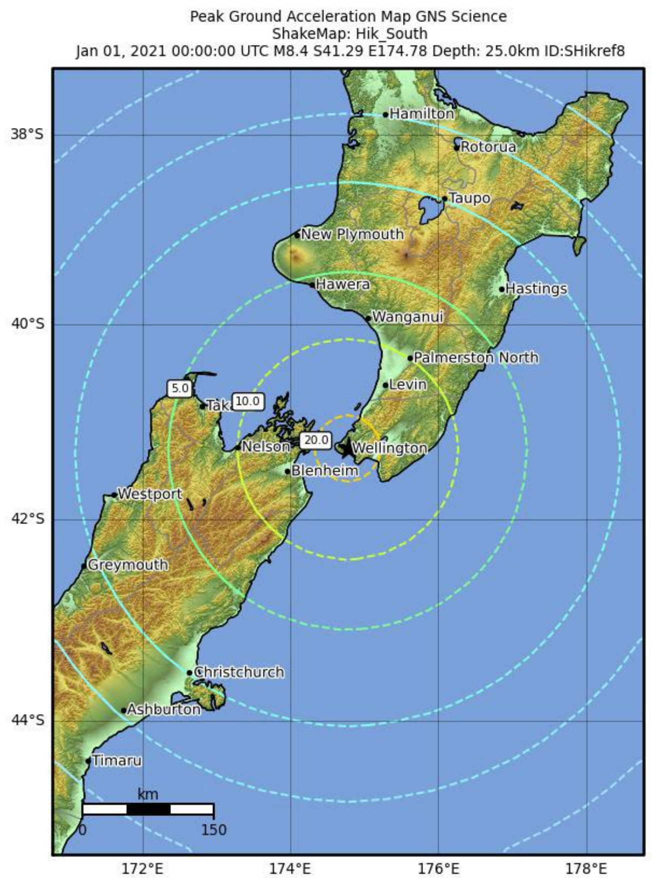
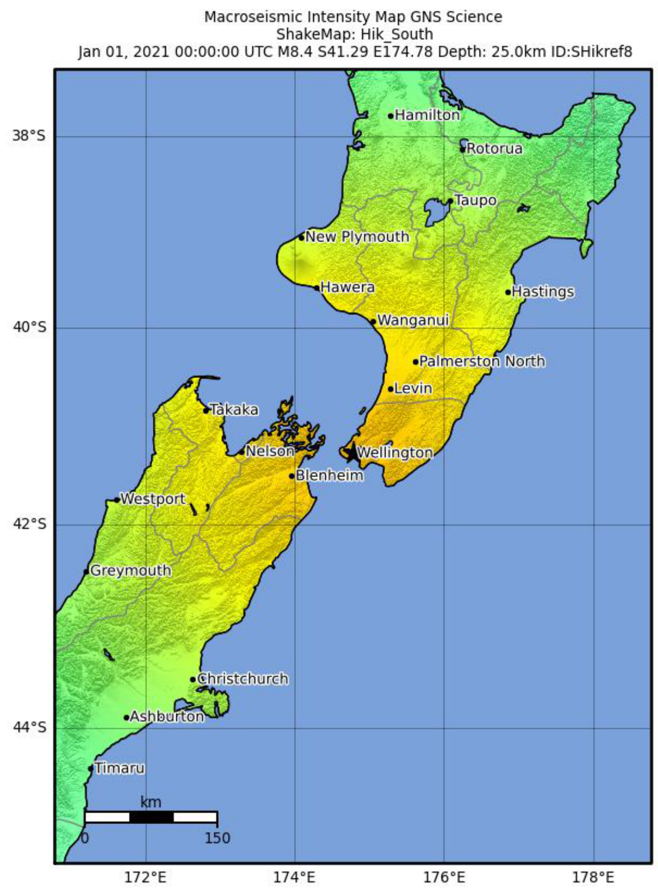


Figure A1.3 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M7.7 Kellys-Tophouse segment of the Alpine Fault (Alpine K2T) earthquake scenario (Ref. 3, Table A1.1).





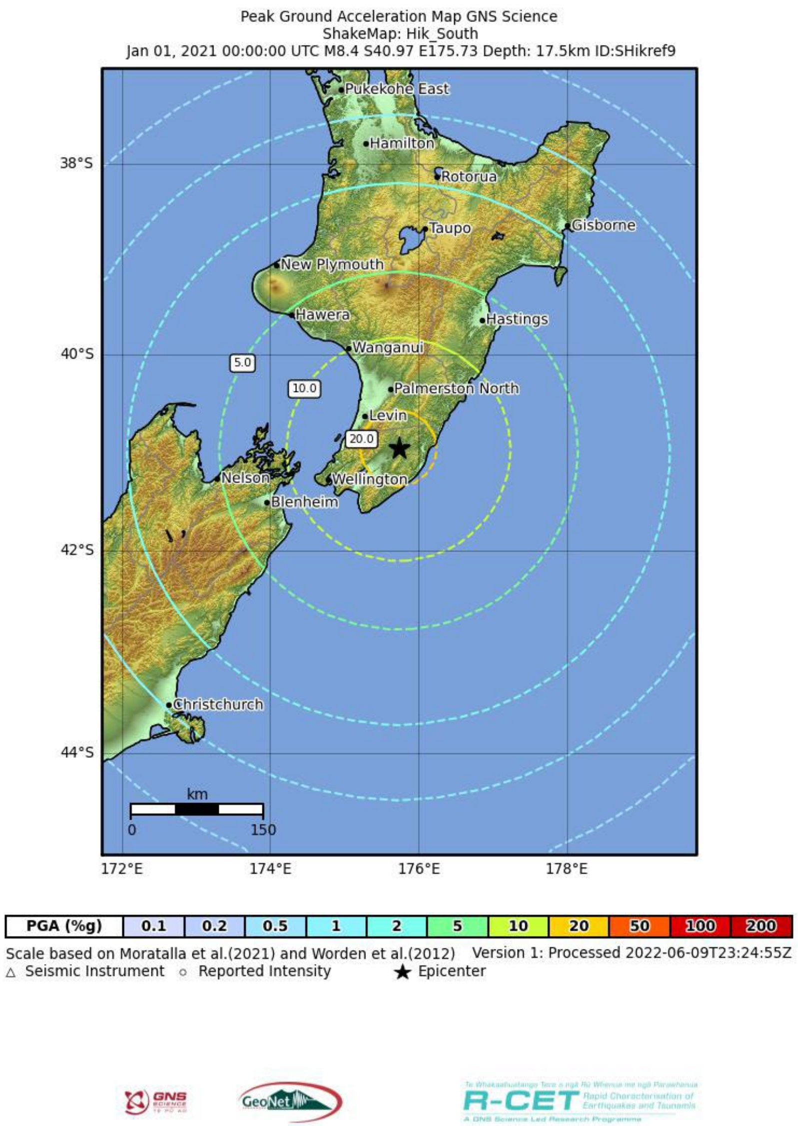
PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:20:34Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:20:34Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure A1.4 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M8.4 Southern Hikurangi subduction scenario A (Ref. 4, Table A1.1).



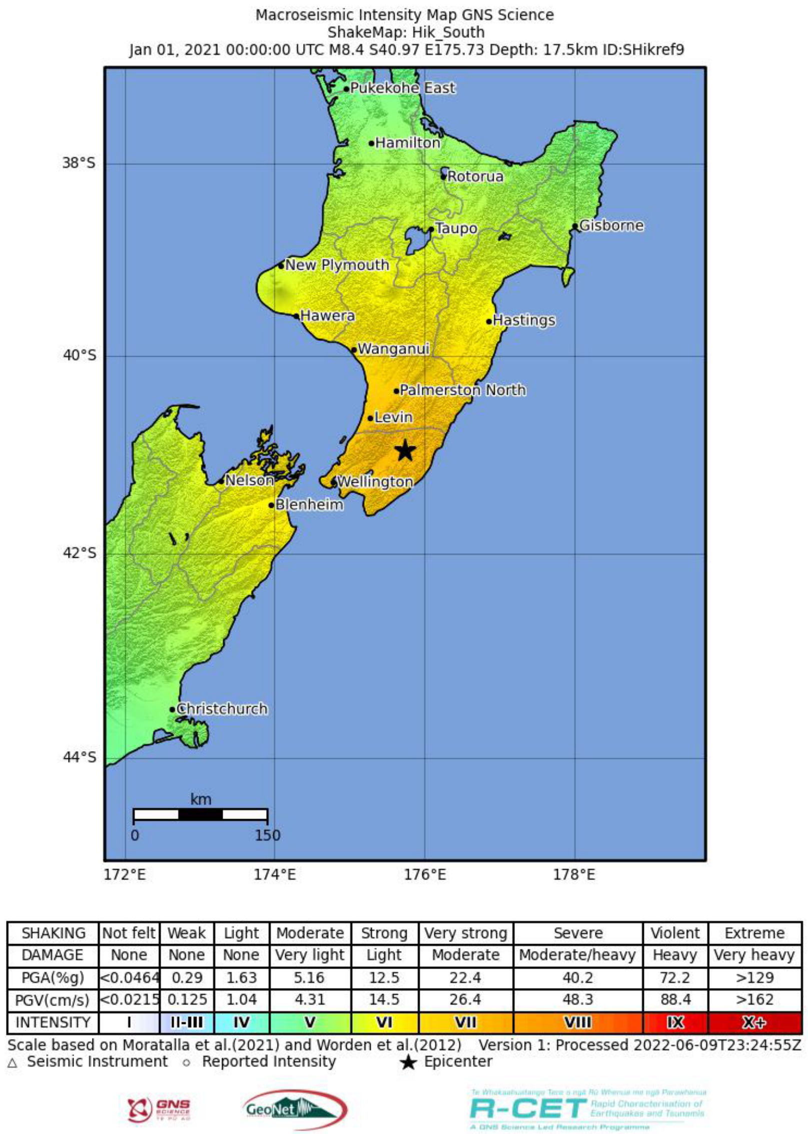


Figure A1.5 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M8.4 Southern Hikurangi subduction scenario B (Ref. 5, Table A1.1).

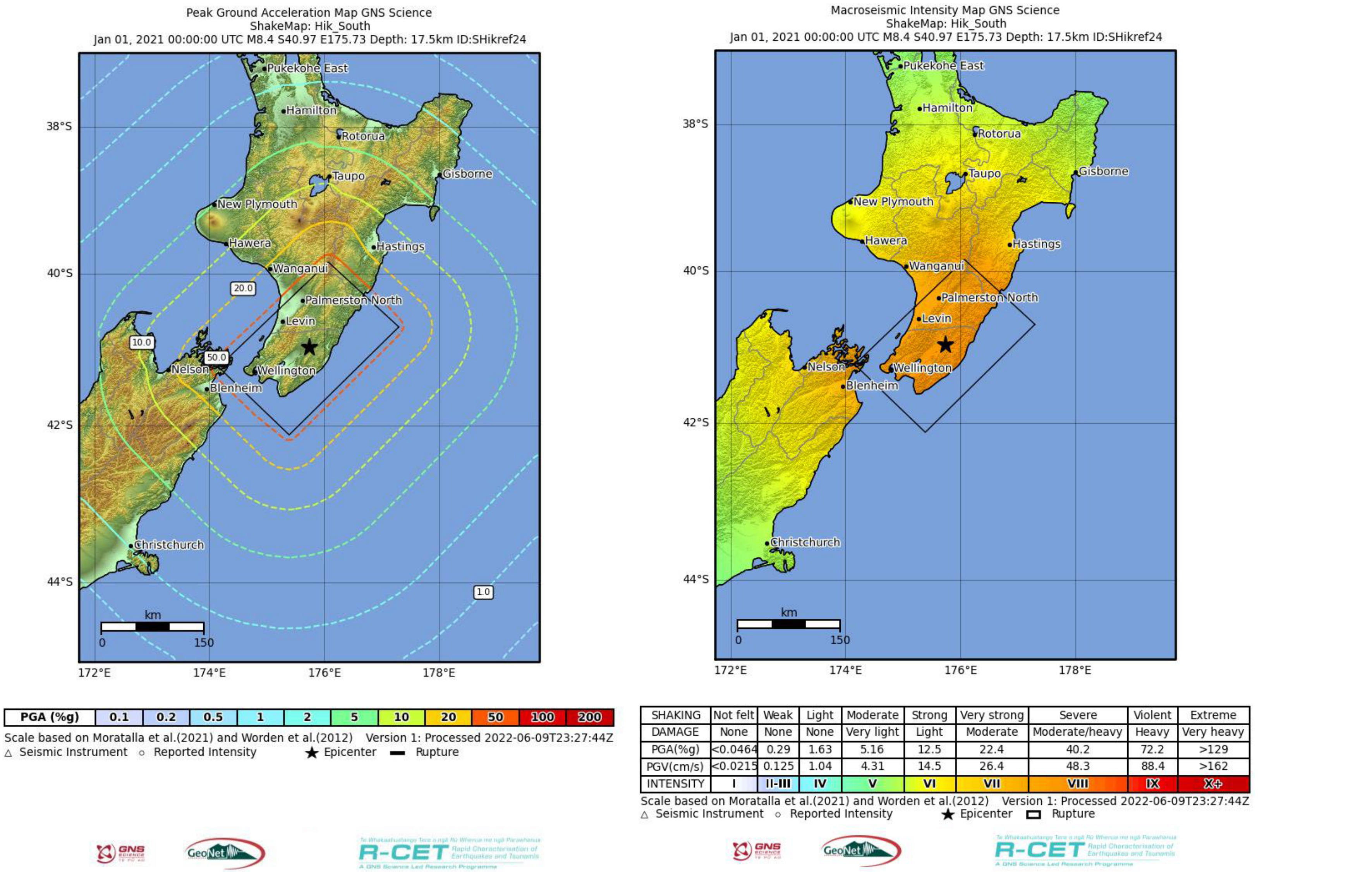


Figure A1.6 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M8.4 Southern Hikurangi subduction scenario C (Ref. 6, Table A1.1).

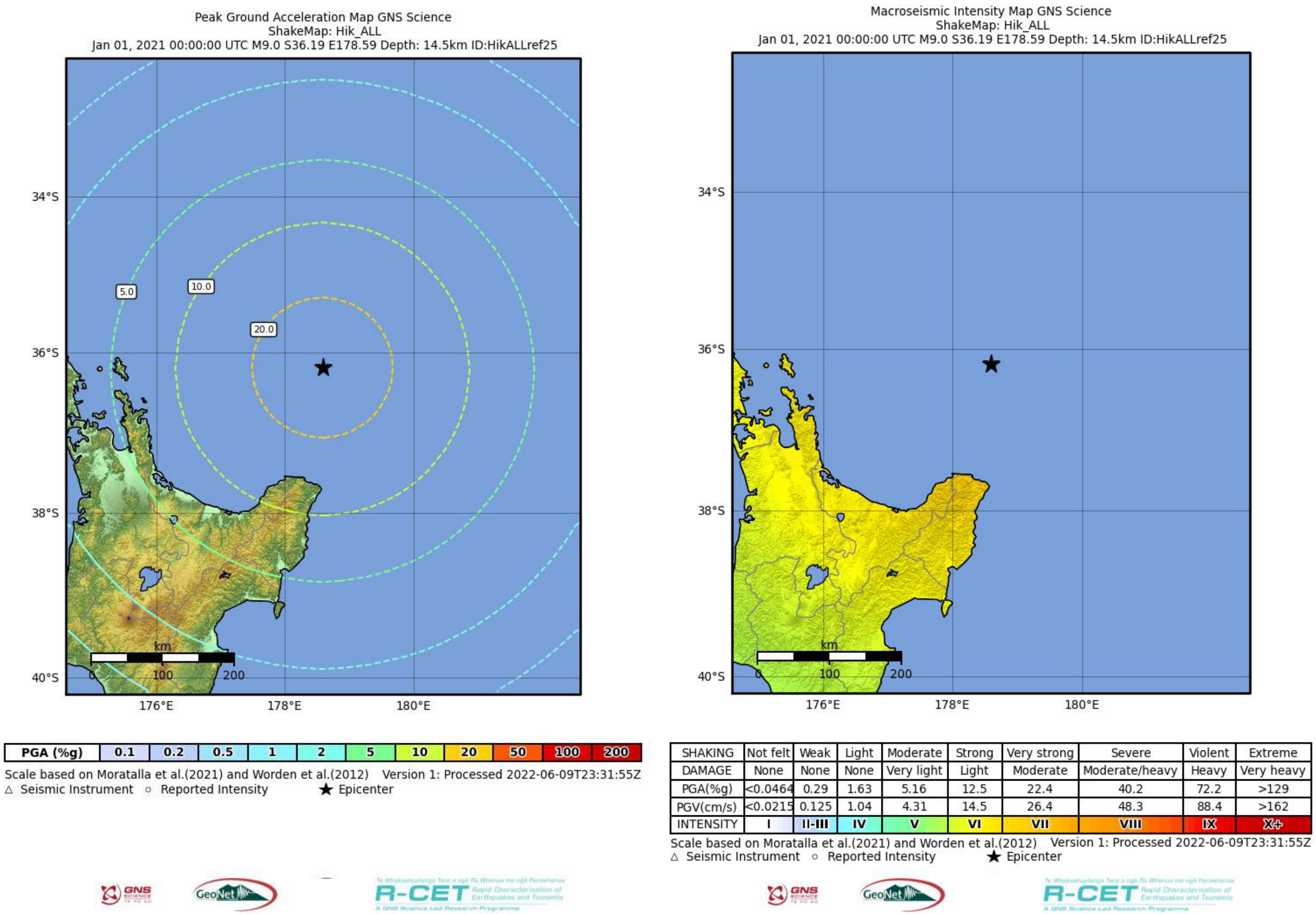
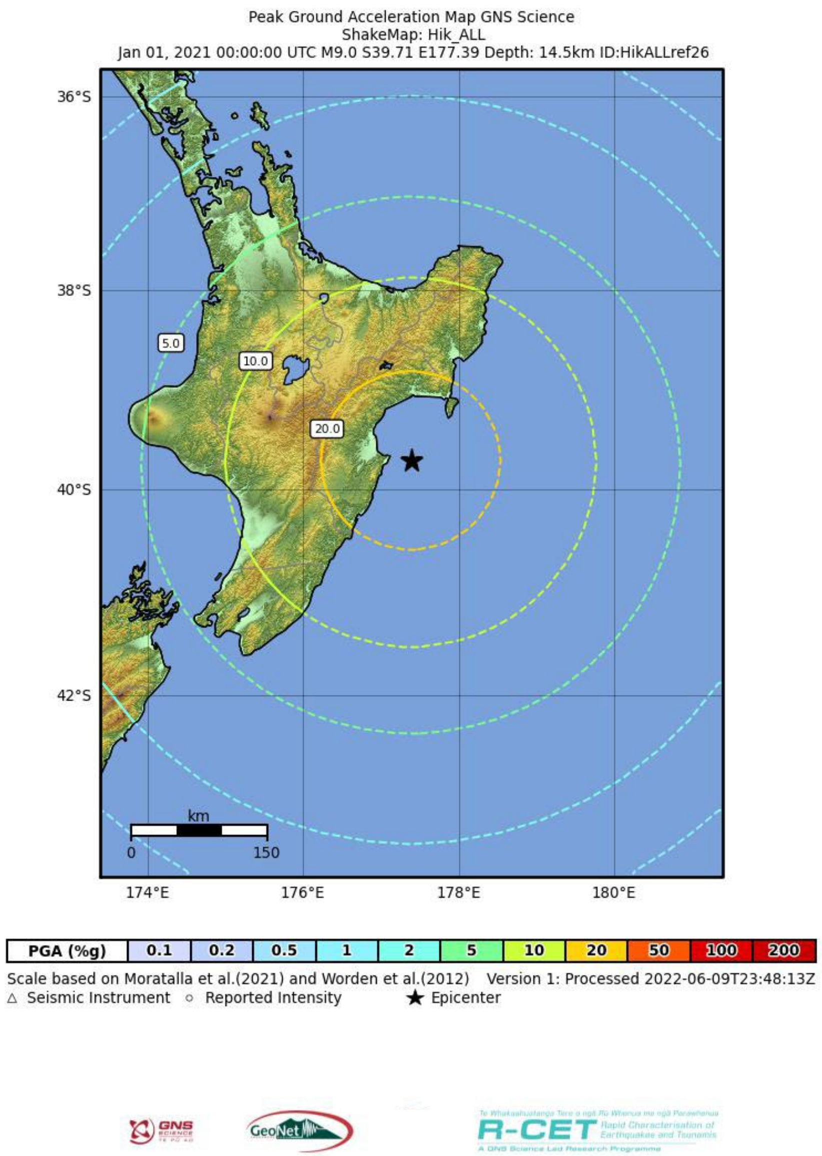
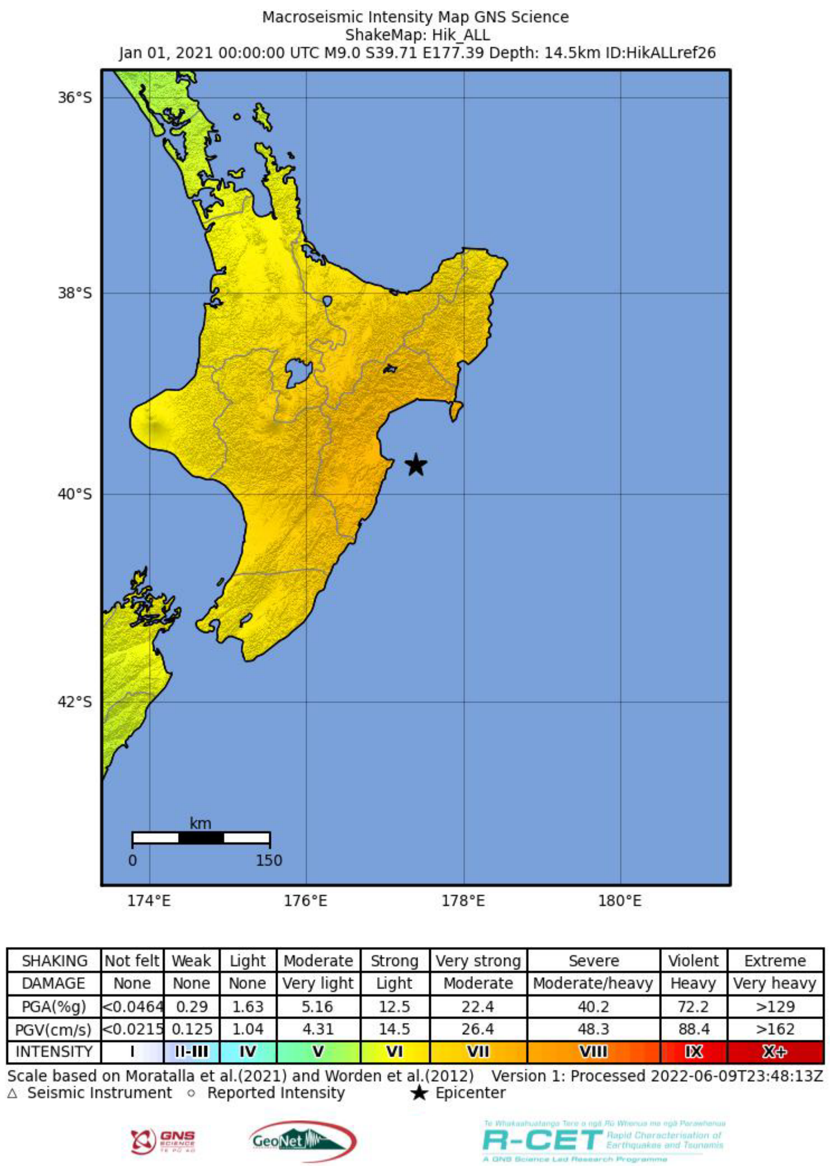


Figure A1.7 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M9.0 Hikurangi ALL subduction scenario A (Ref. 7, Table A1.1).





SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure A1.8 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M9.0 Hikurangi ALL subduction scenario B (Ref. 8, Table A1.1).

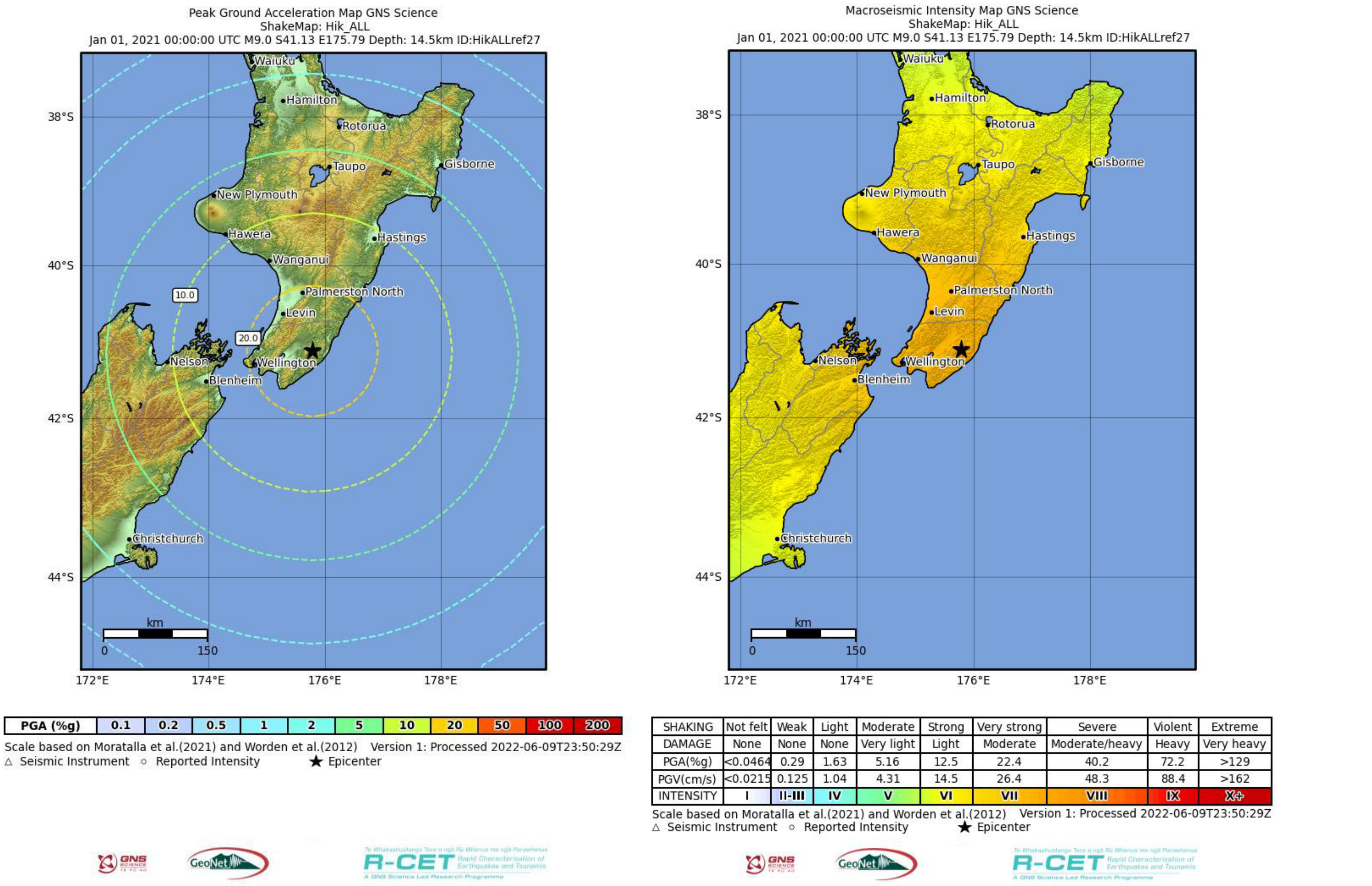
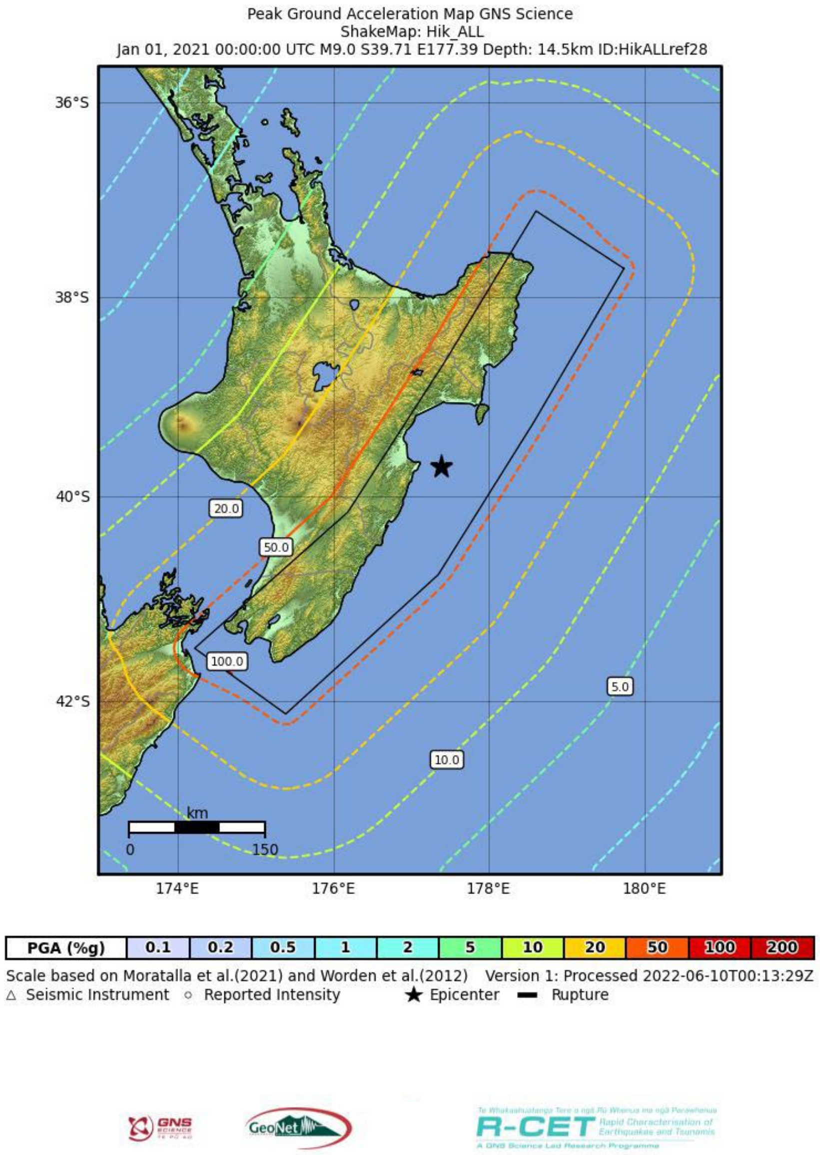


Figure A1.9 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M9.0 Hikurangi ALL subduction scenario C (Ref. 9, Table A1.1).



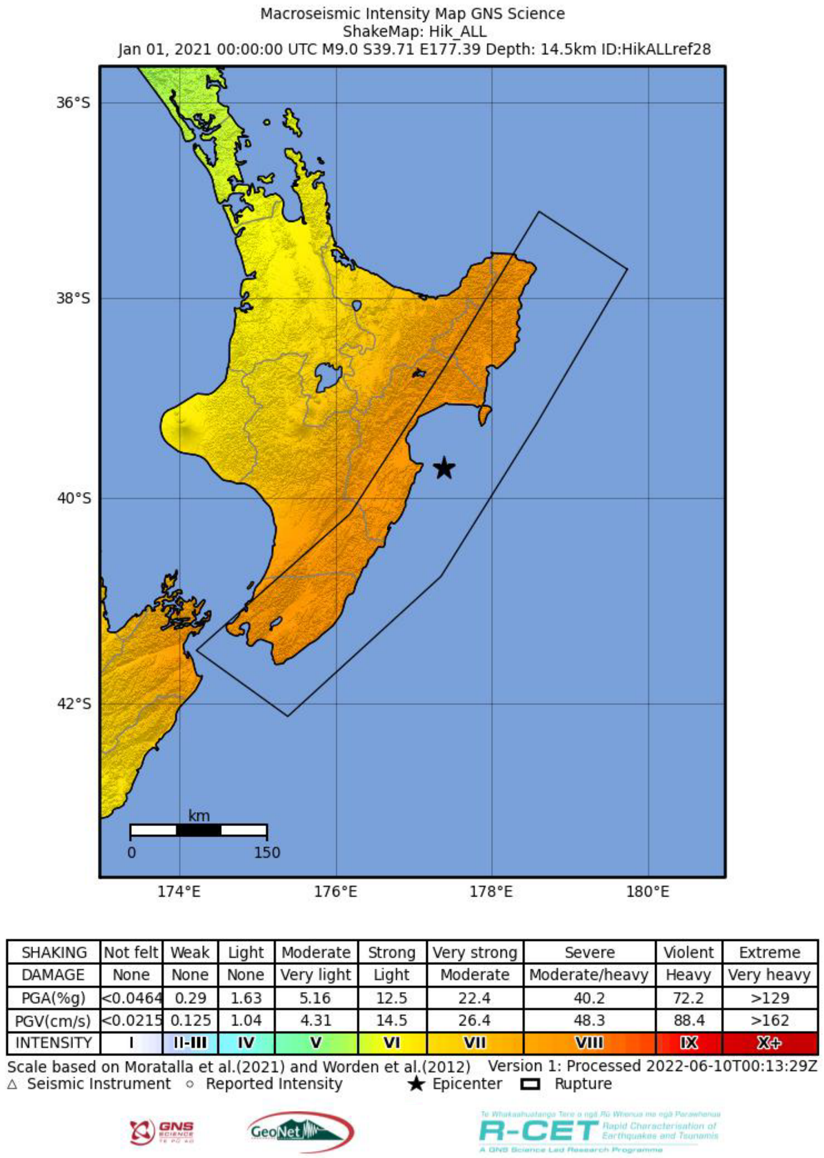


Figure A1.10 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M9.0 Hikurangi ALL subduction scenario D (Ref. 10, Table A1.1).

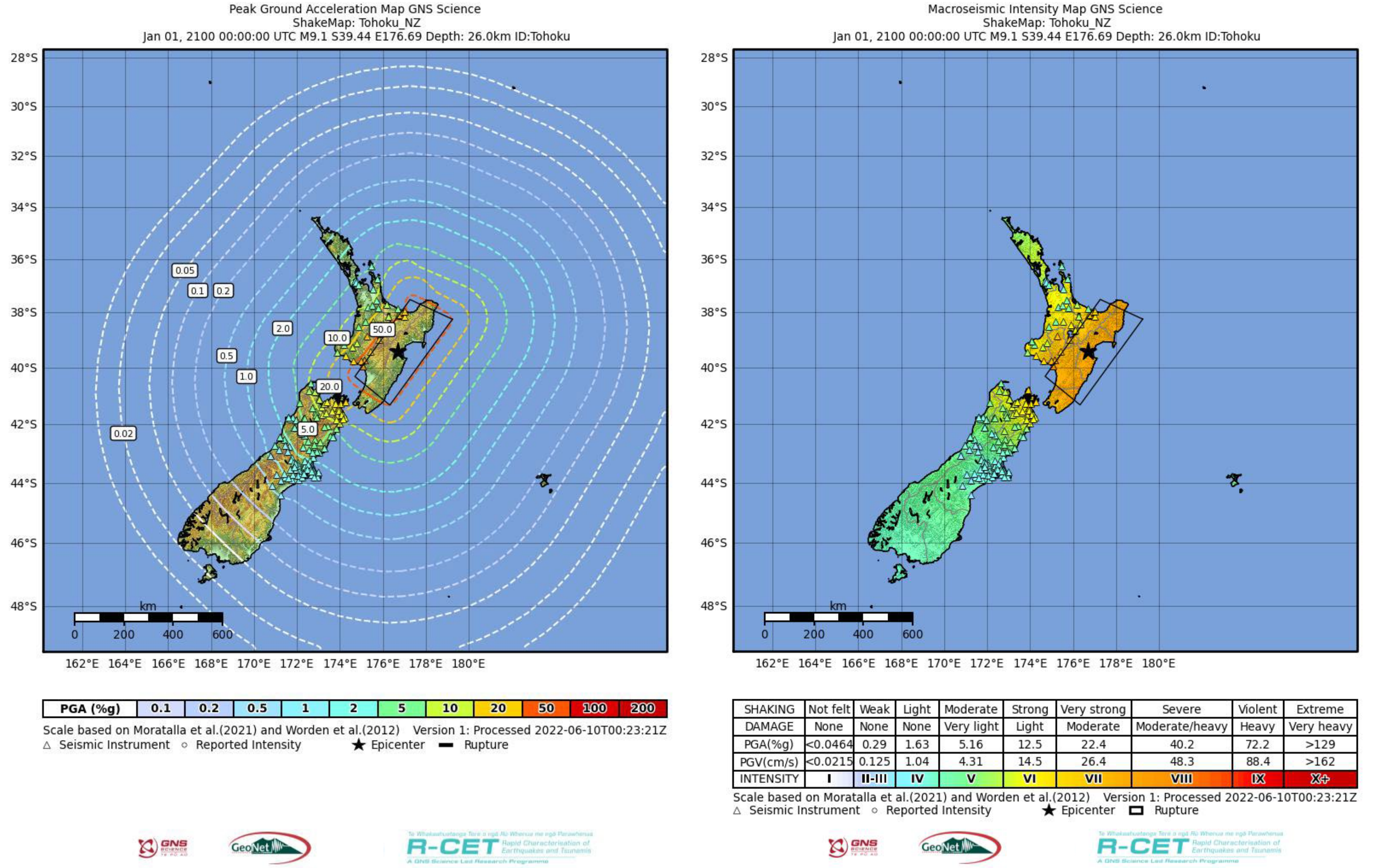


Figure A1.11 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M9.1 Tohoku scenario (Ref. 11, Table A1.1). Please note that strong-motion data have been developed using Tohoku strong-motion data projected to New Zealand using updated site effects. For more information, see Moratalla et al. (2021b).

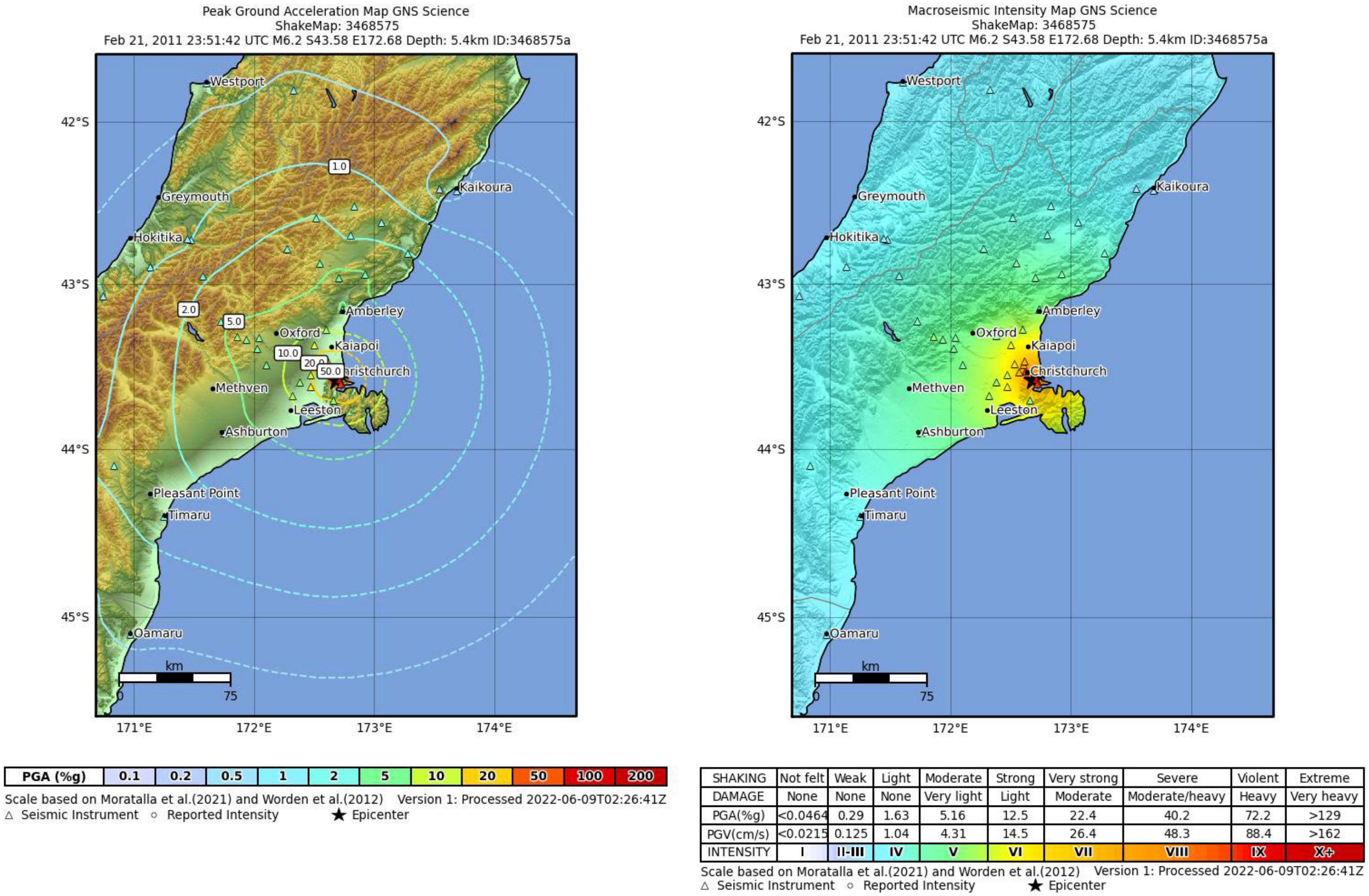


Figure A1.12 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 22/2/2011 Christchurch earthquake, case A (Ref. 12, Table A1.1).

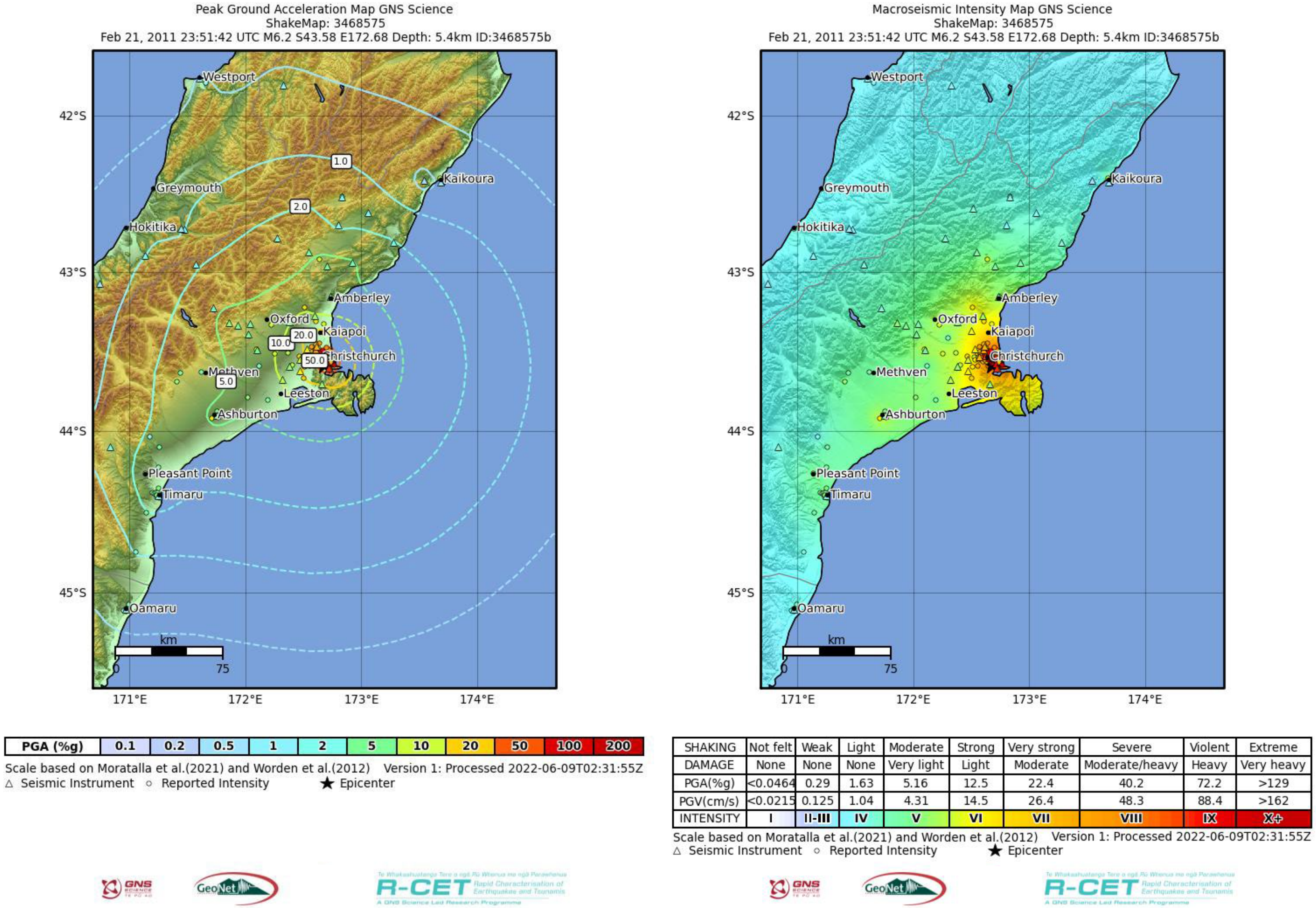
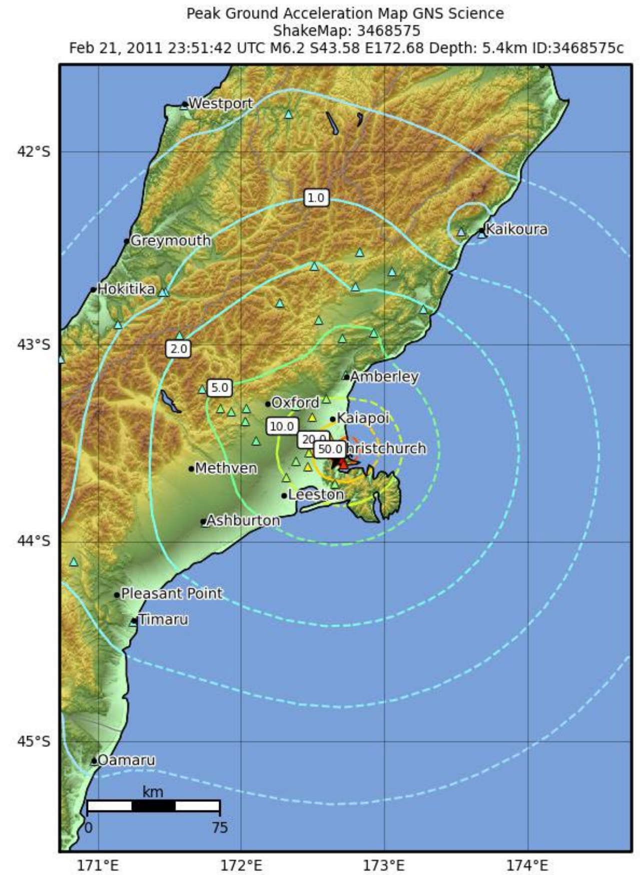
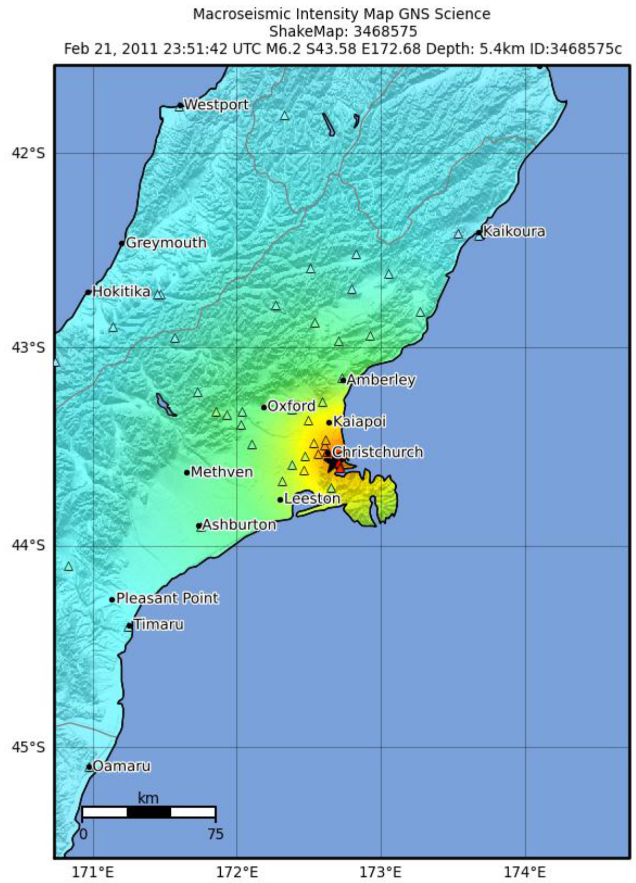


Figure A1.13 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 22/2/2011 Christchurch earthquake, case B (Ref. 13, Table A1.1).



PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:02:13Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▬ Rupture



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:02:13Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

Figure A1.14 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 22/2/2011 Christchurch earthquake, case C (Ref. 14, Table A1.1).

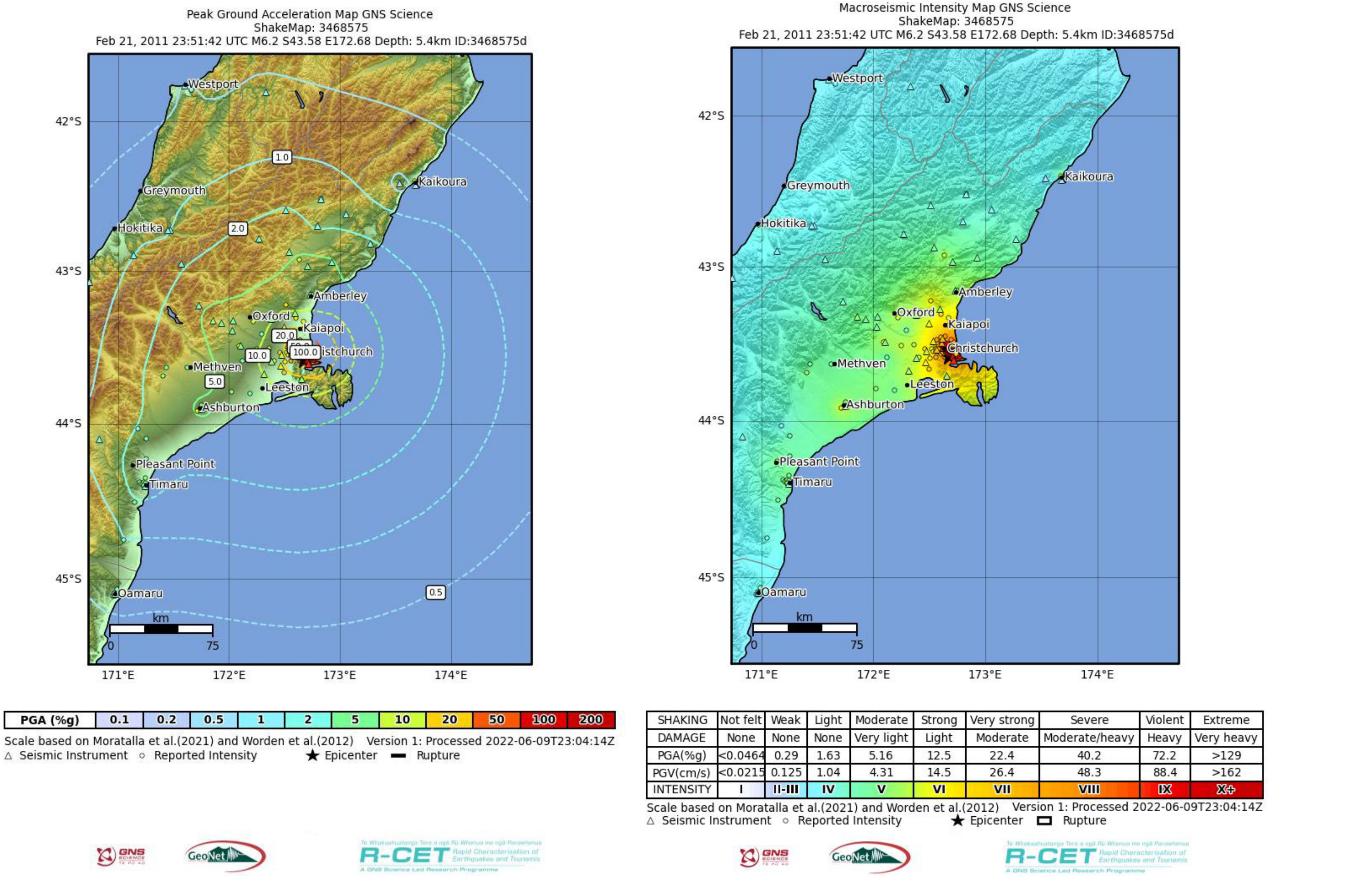
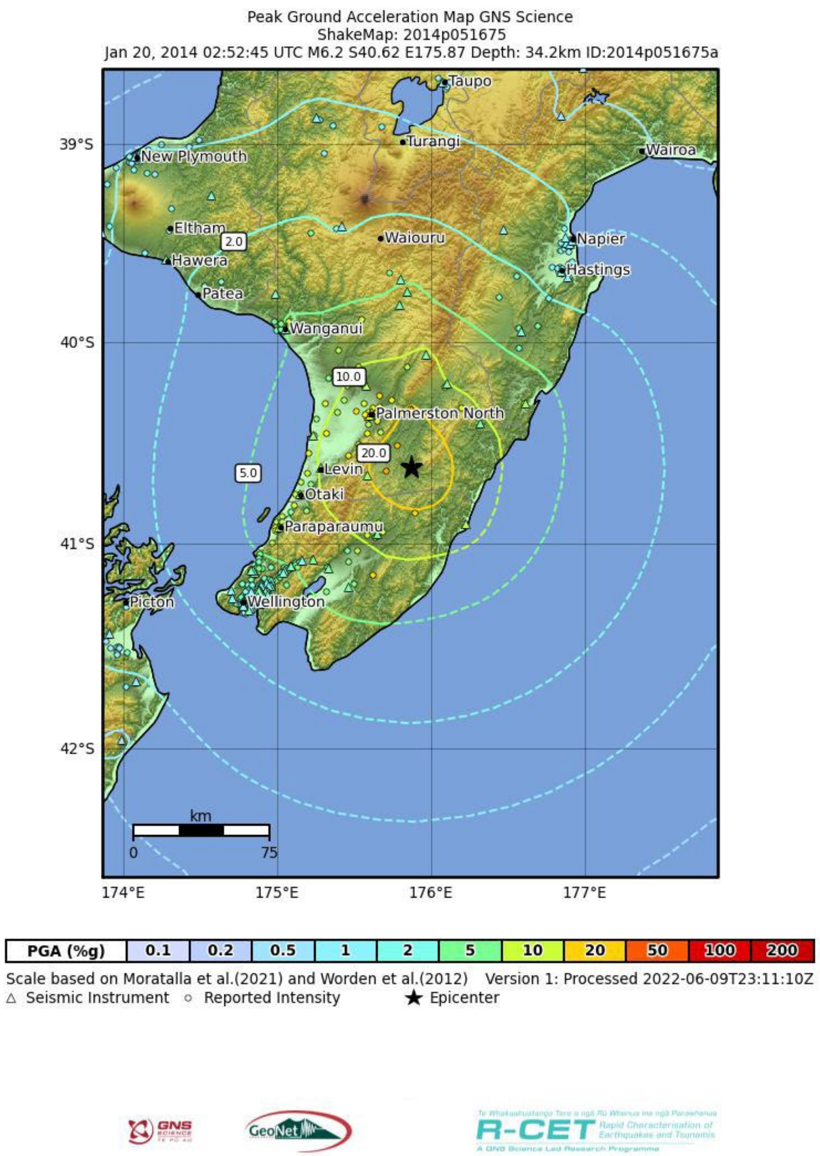


Figure A1.15 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 22/2/2011 Christchurch earthquake, case D (Ref. 15, Table A1.1).



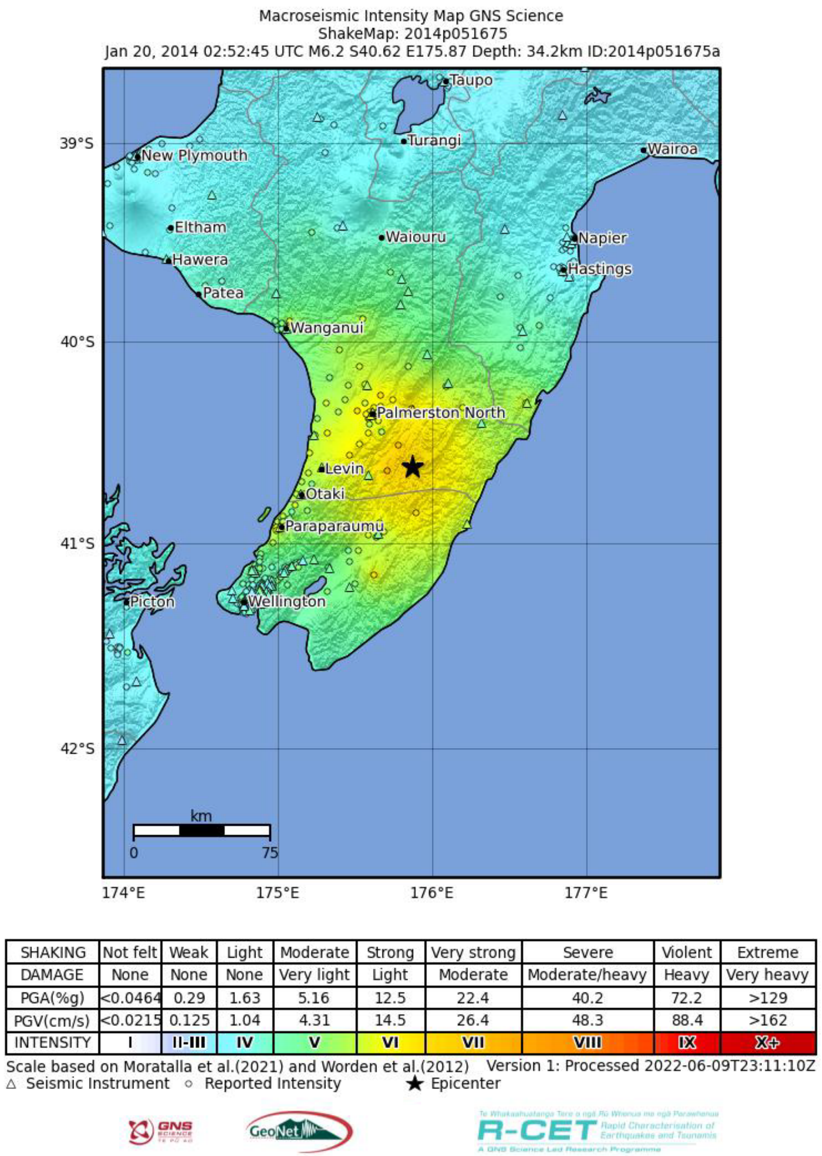
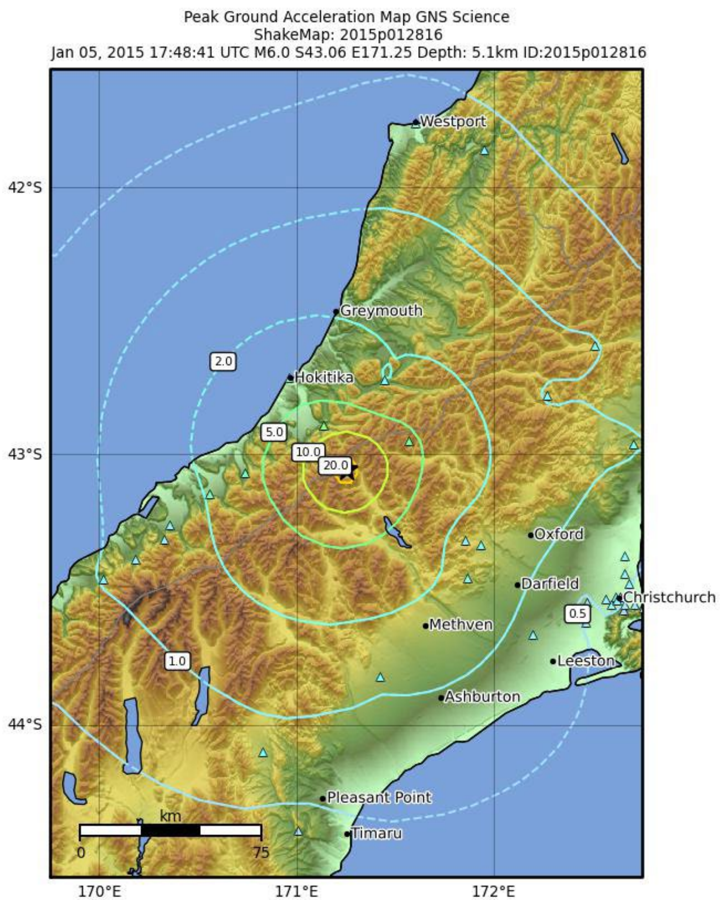
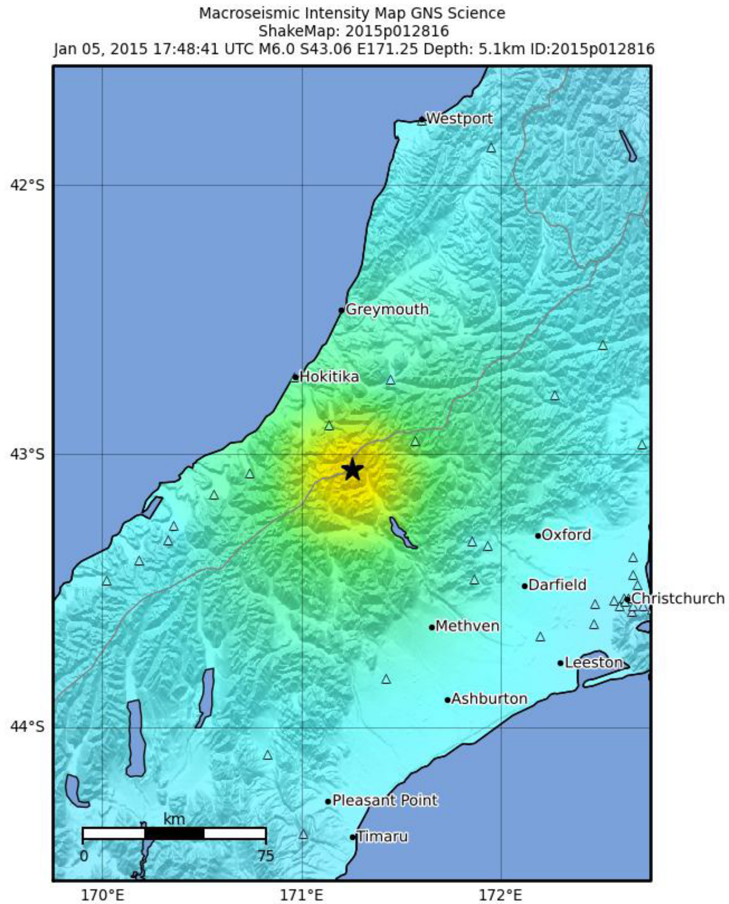


Figure A1.16 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 20/1/2014 Eketāhuna earthquake (Ref. 16, Table A1.1).



PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-08T22:52:39Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-08T22:52:39Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure A1.17 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.0 5/1/2015 Wilberforce earthquake (Ref. 17, Table A1.1).

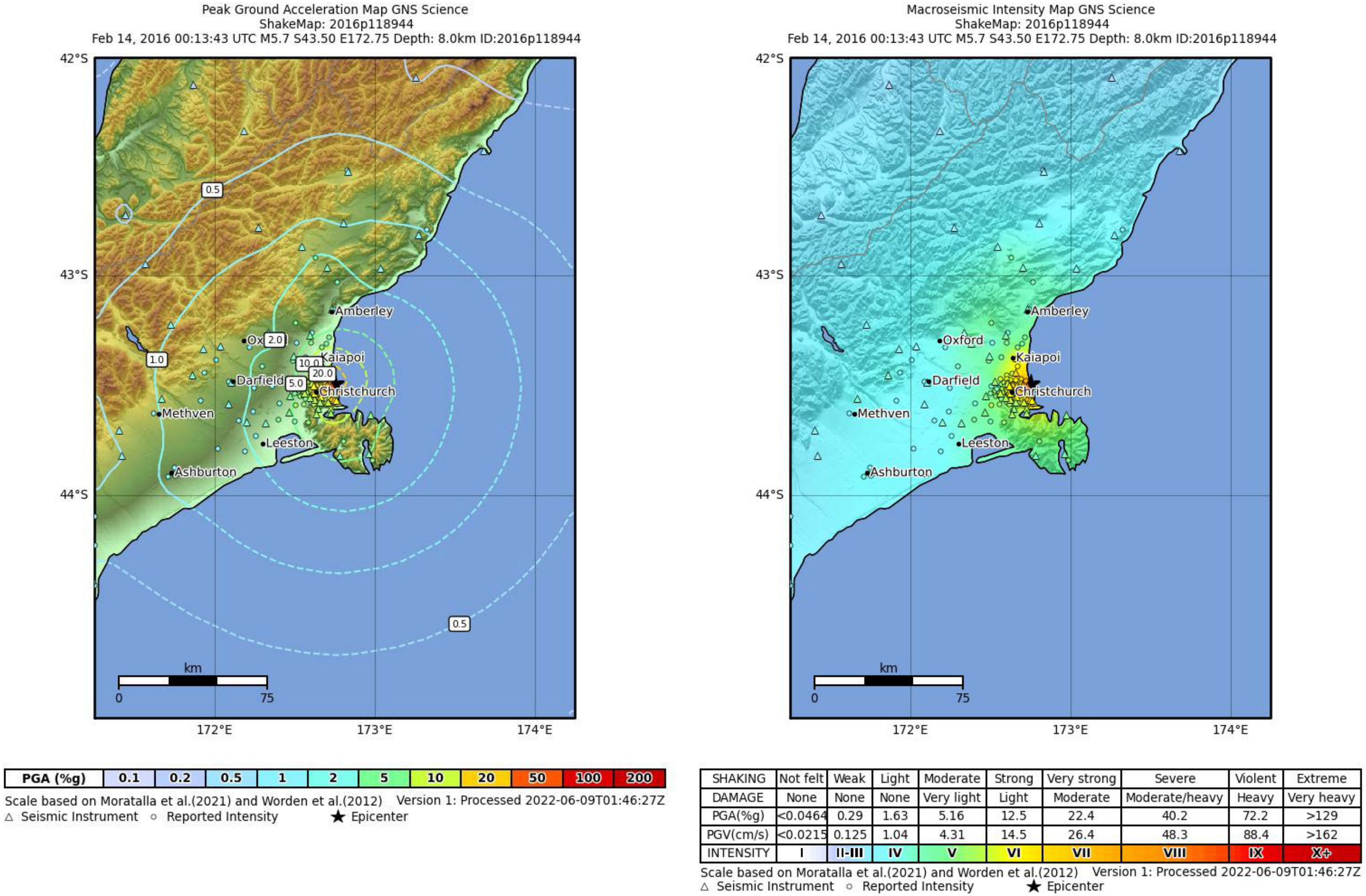


Figure A1.18 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M5.7 14/2/2016 Valentine's Day Christchurch earthquake (Ref. 18, Table A1.1).

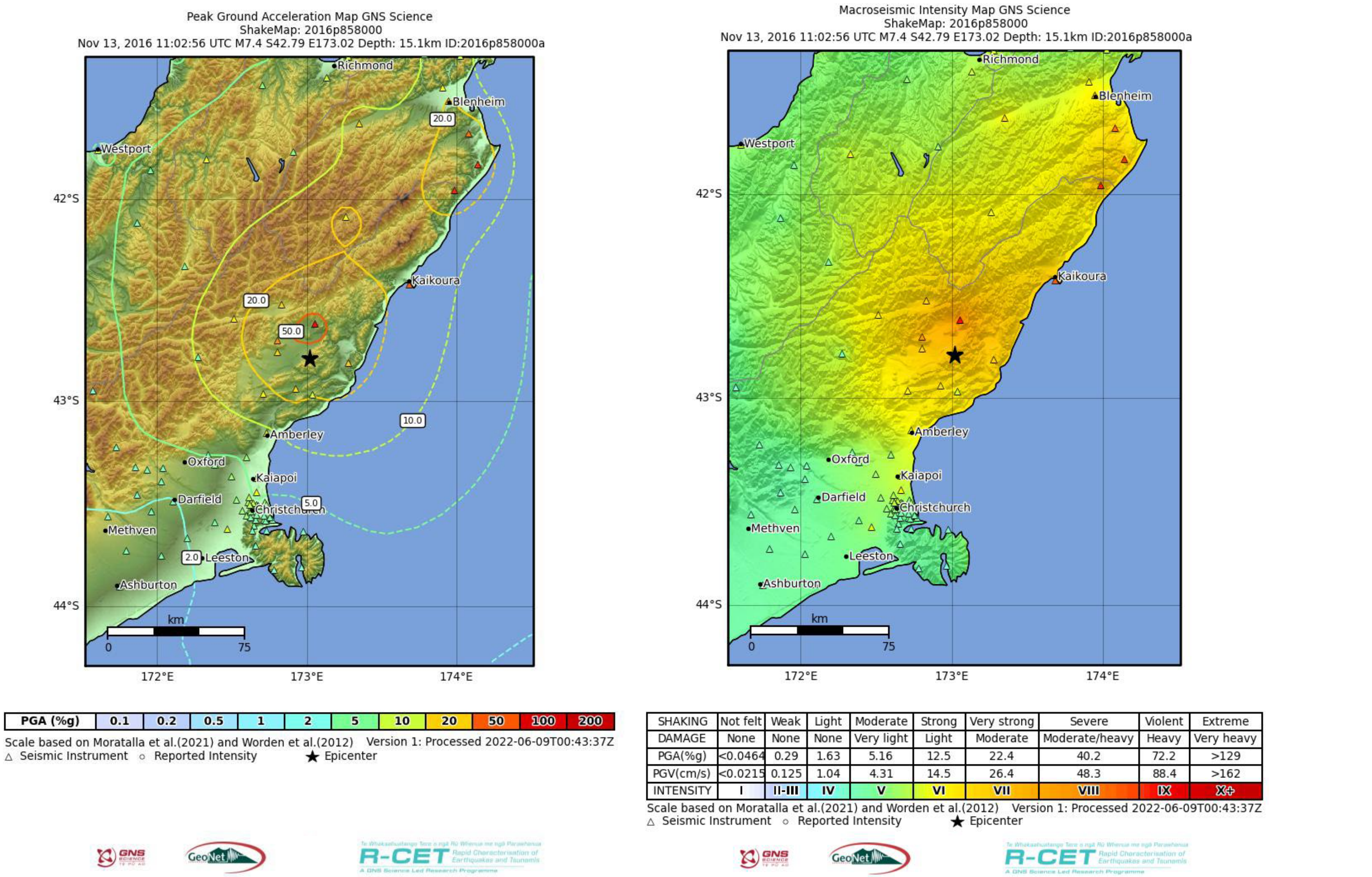
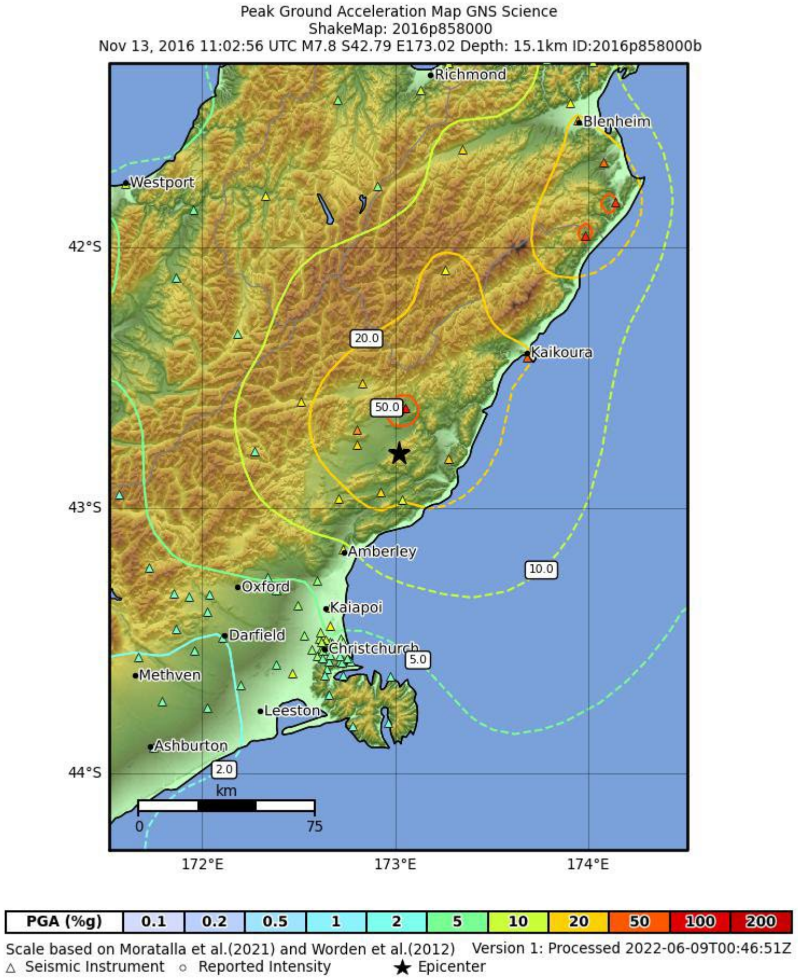


Figure A1.19 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M7.8 14/11/2016 Kaikōura earthquake, case A, with the preliminary magnitude of 7.4 (Ref. 19, Table A1.1).



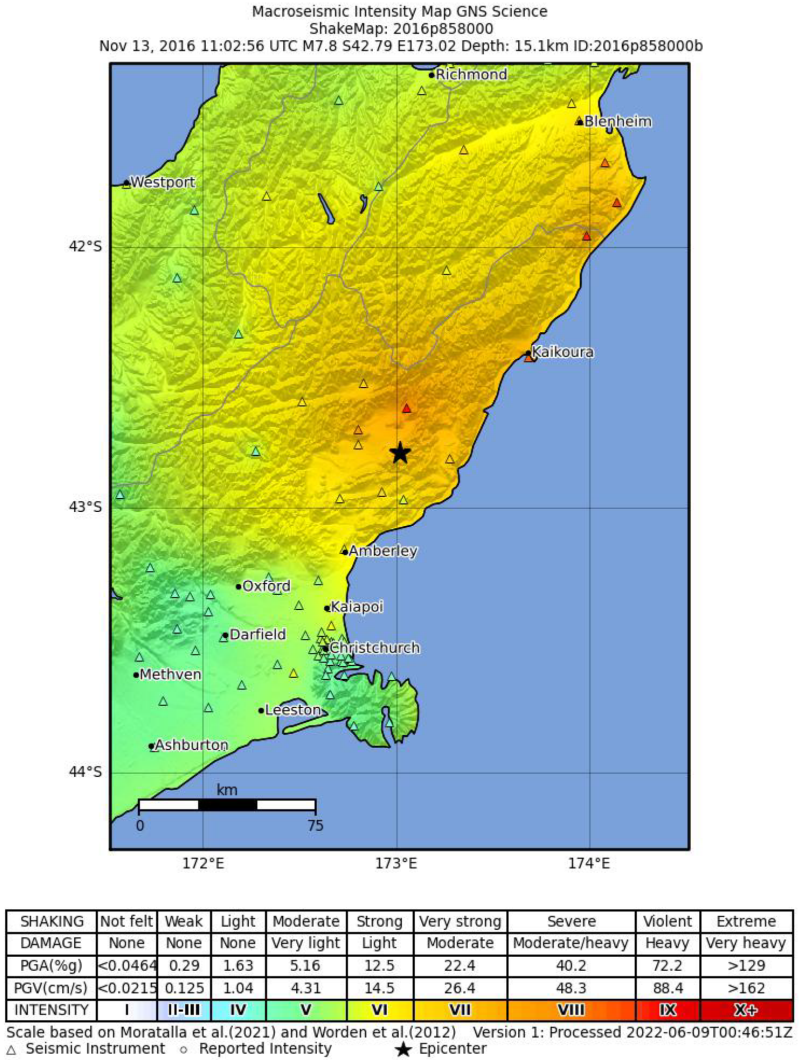


Figure A1.20 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M7.8 14/11/2016 Kaikōura earthquake, case B (Ref. 20, Table A1.1).

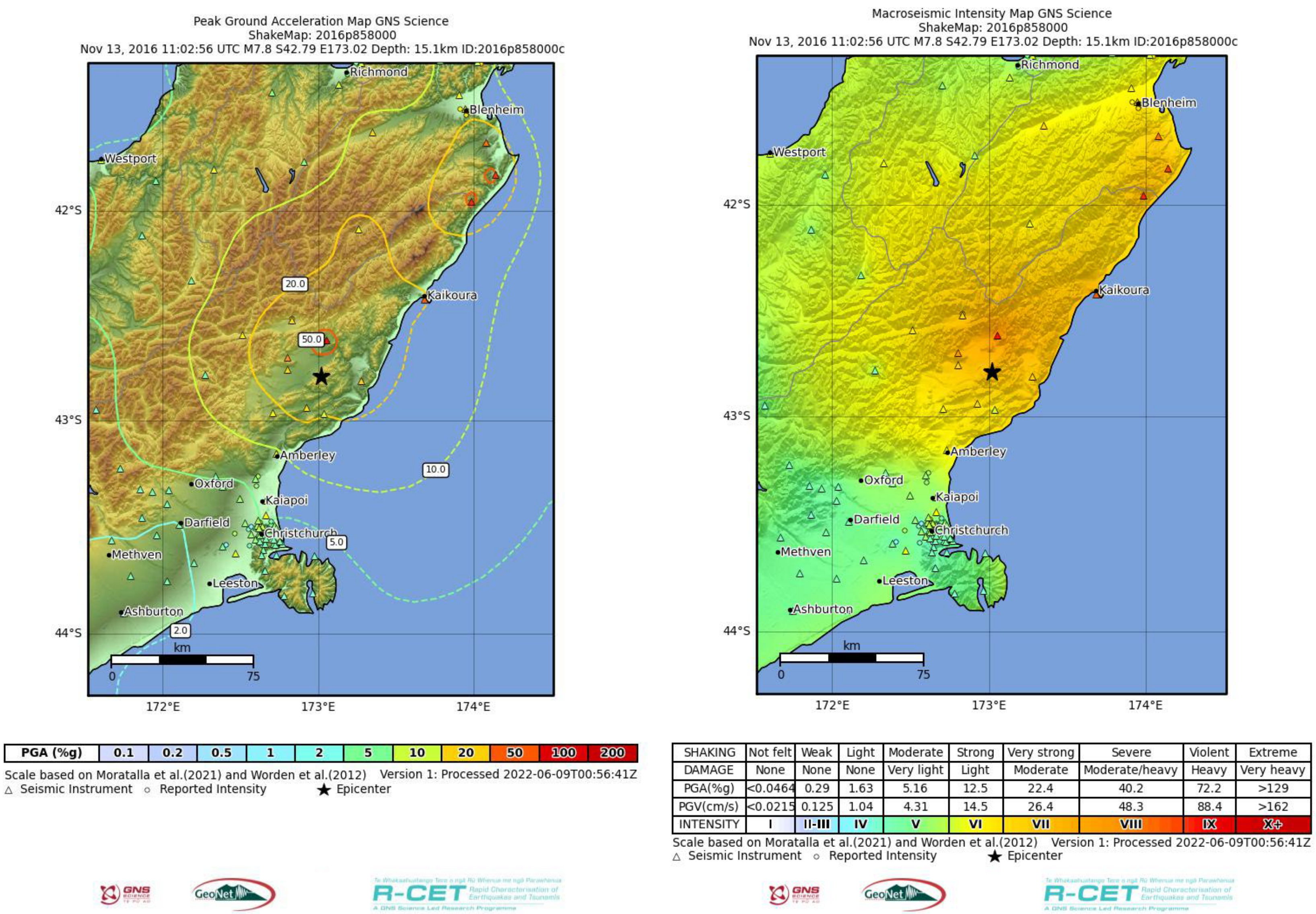


Figure A1.21 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M7.8 14/11/2016 Kaikōura earthquake, case C (Ref. 21, Table A1.1).

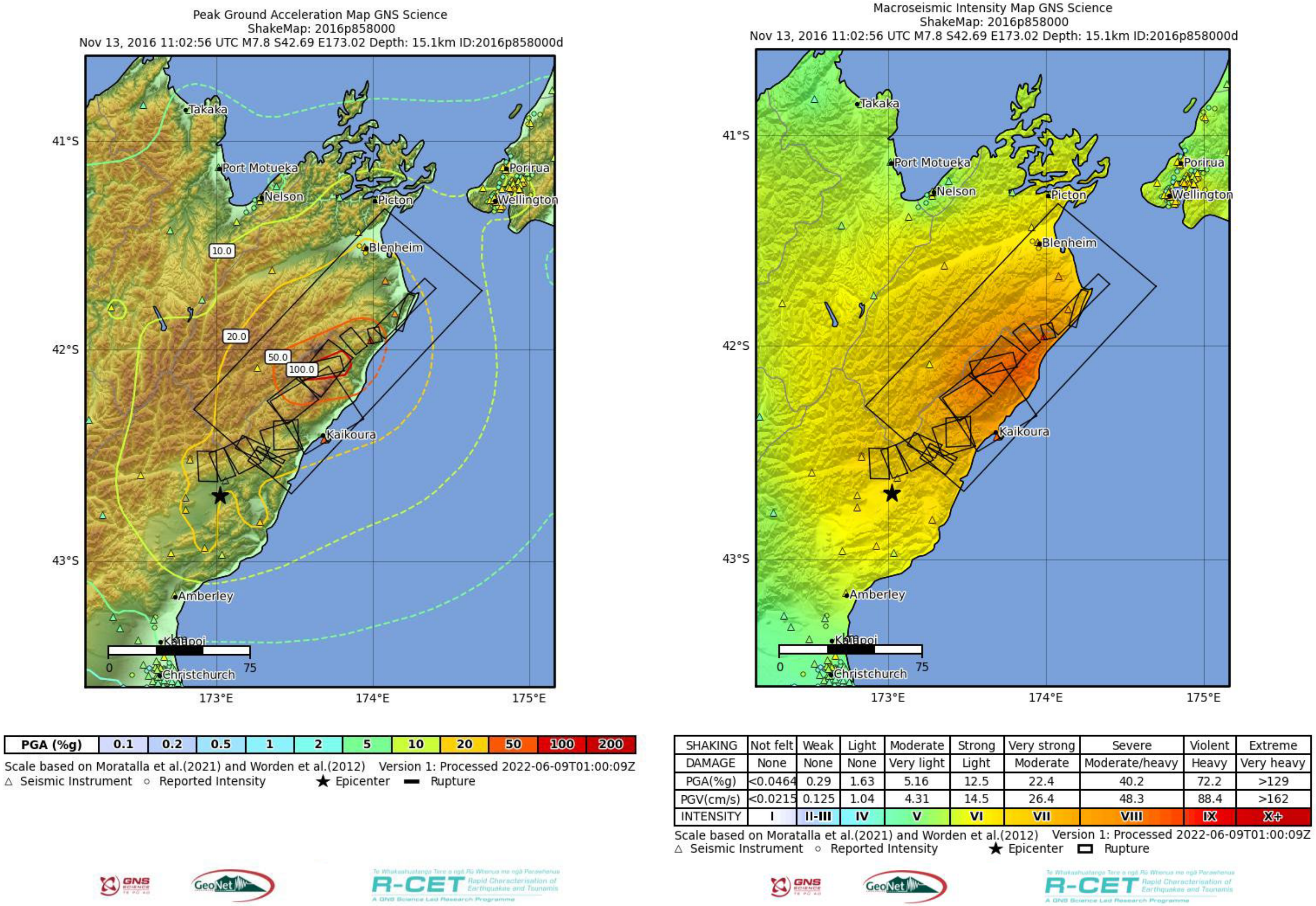
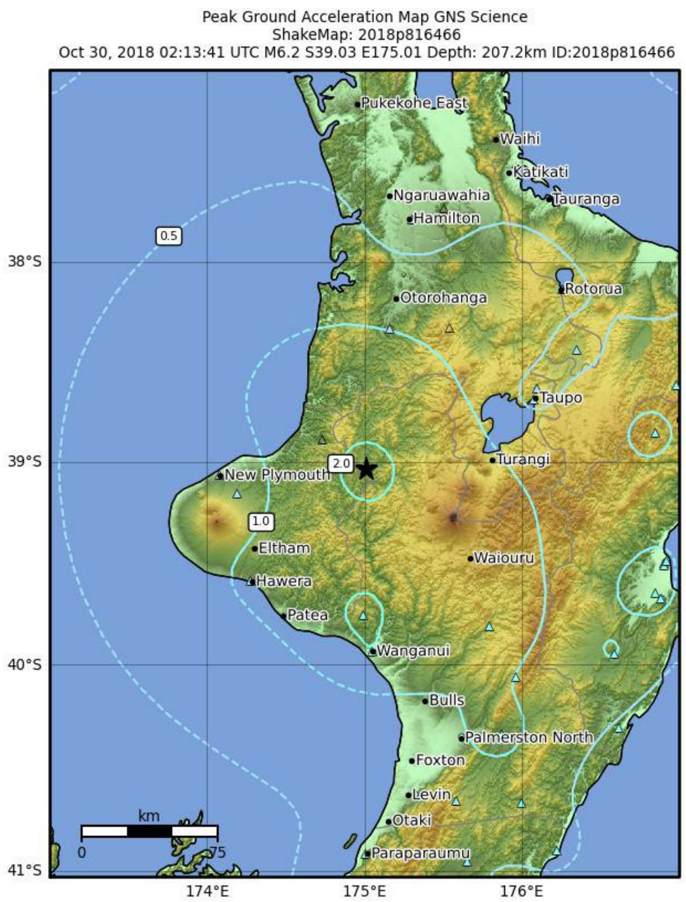
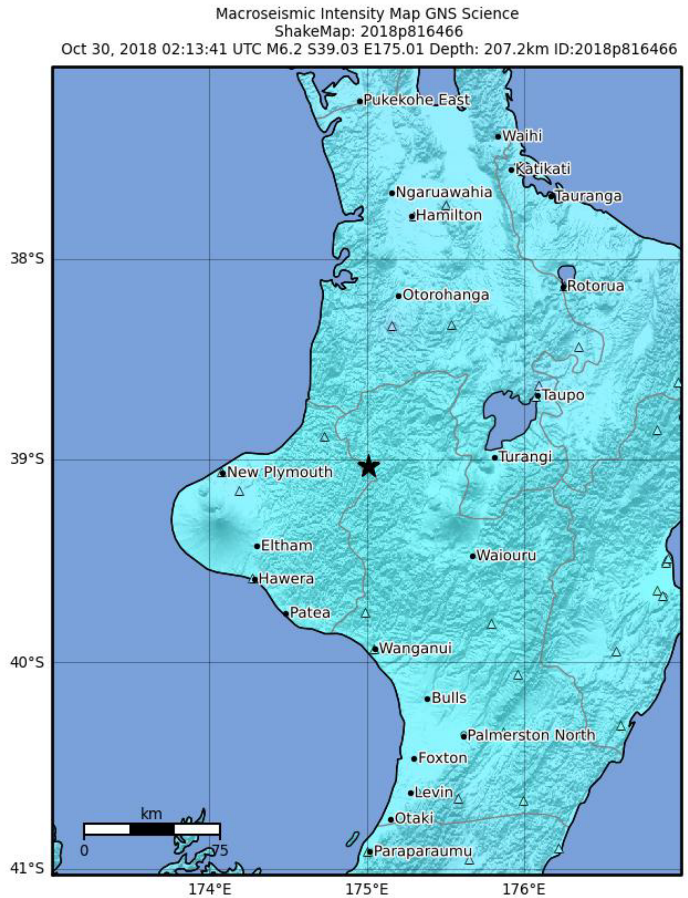


Figure A1.22 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M7.8 14/11/2016 Kaikōura earthquake, case D (Ref. 22, Table A1.1).



PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:14:19Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.29	1.63	5.16	12.5	22.4	40.2	72.2	>129
PGV(cm/s)	<0.0215	0.125	1.04	4.31	14.5	26.4	48.3	88.4	>162
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Moratalla et al.(2021) and Worden et al.(2012) Version 1: Processed 2022-06-09T23:14:19Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure A1.23 Peak Ground Acceleration (left) and Modified Mercalli Intensity (right) Shaking Layers corresponding to the M6.2 30/10/2018 Taumarunui earthquake (Ref. 23, Table A1.1).

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