

RESEARCH ARTICLE



A quantitative assessment of GeoNet earthquake location quality in Aotearoa New Zealand

Emily Warren-Smith^a, Katrina Jacobs^a, Chris Rollins^a, Calum J. Chamberlain^b, Donna Eberhart-Phillips^a and Charles Williams^a

^aGNS Science/Te Pū Ao, Lower Hutt, New Zealand; ^bSGEES, Victoria University of Wellington, Wellington, New Zealand

ABSTRACT

Tens of thousands of earthquakes are located by GeoNet across Aotearoa every year. However, spatial variability – both in station coverage and earthquake distributions – produce heterogeneity in earthquake location quality throughout the GeoNet catalogue. Here we consider simple, established criteria (including station azimuthal coverage, minimum station distance, phase arrival coverage and fixed location criteria) to score earthquakes on a network location Quality Score (QS) scale of QS0 (unconstrained) to QS6 (best constrained). Significant variation in QS exists nationwide; 48% and 20% of earthquakes score QS6 for the North and South Islands respectively. The Hawkes Bay region scores highest (68% QS6) closely followed by other Hikurangi regions. However, several regions score extremely poorly, with Fiordland, West Coast, Nelson, Otago-Southland and Auckland-Northland regions having $\leq 5\%$ QS6 events and $>75\%$ of events scoring QS3 or lower. Low QS mostly arises from the failure of minimum distance criteria, whereby the closest station is too far from the earthquake to provide sufficient depth control. Our analysis quantitatively assesses the impact of network heterogeneity on GeoNet earthquake catalogue location quality to inform end users. This work also provides motivation for the expansion of the weak-motion network in critically under-instrumented regions, especially those with high seismic hazard.

ARTICLE HISTORY

Received 18 June 2024
Accepted 16 October 2024

HANDLING EDITOR

Tianhaoze Sun

KEYWORDS

Earthquake catalogue;
GeoNet; New Zealand;
seismicity; earthquake
location; seismic network

Introduction

Tens of thousands of earthquakes are catalogued by the New Zealand geohazards monitoring agency, GeoNet (Petersen et al. 2011), across the country every year (<https://quakesearch.geonet.org.nz/>). An earthquake's nucleation location – either specified in two dimensions by latitude and longitude (epicentre) or additionally including depth information in the third dimension (hypocentre) – is a fundamental parameter in the catalogue. This location is determined by several inverse methods which use earthquake phase-arrival information from a network of seismic stations and an approximation of earth structure (e.g. Milne 1886; Lee and Lahr 1975; Lomax et al. 2009).

An earthquake's location uncertainty is heavily dependent on several uncertain factors including: (1) the quality of the phase-arrival picks, (2) the accuracy of the seismic velocity model used to estimate wave travel times, (3) the inversion method used, (4) whether the depth is co-estimated with the location or fixed to a set value, as well as (5) the geometry of the recording seismic network (Lee and Stewart 1981; Husen and Hardebeck 2010). Spatial (and temporal) variability in these factors is not straightforward to quantify across a network such as GeoNet, where

nationwide disparities in station spacing (Figure 1), varying spatial distributions of earthquakes – especially with depth (Figure S1) – in contrasting tectonic regimes, alongside other data processing factors mean that reported hypocentral uncertainties are not representative of true uncertainties. Furthermore, a significant number of earthquakes in the GeoNet catalogue (up to 75% in some regions) are reported with analyst-fixed depths. GeoNet procedure dictates that earthquake depths are fixed when the closest recording station is farther than two focal depth's distance from the event's epicentre (H. Godfrey, pers. comm.), resulting in no depth uncertainties, only epicentral uncertainties which are likely underestimated. Therefore, assessment of location quality considering uncertainties alone is not possible, as this information is not properly propagated through the location process and is largely unavailable in some regions.

However, spatial heterogeneity in the recording network and its effect on location uncertainty is easier to quantify. Generally speaking, good epicentral precision requires sufficient azimuthal coverage by recording stations, while hypocentral uncertainties and depth precision are more strongly dependent on the horizontal proximity to recording seismic stations,

CONTACT Emily Warren-Smith  e.warren-smith@gns.cri.nz

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

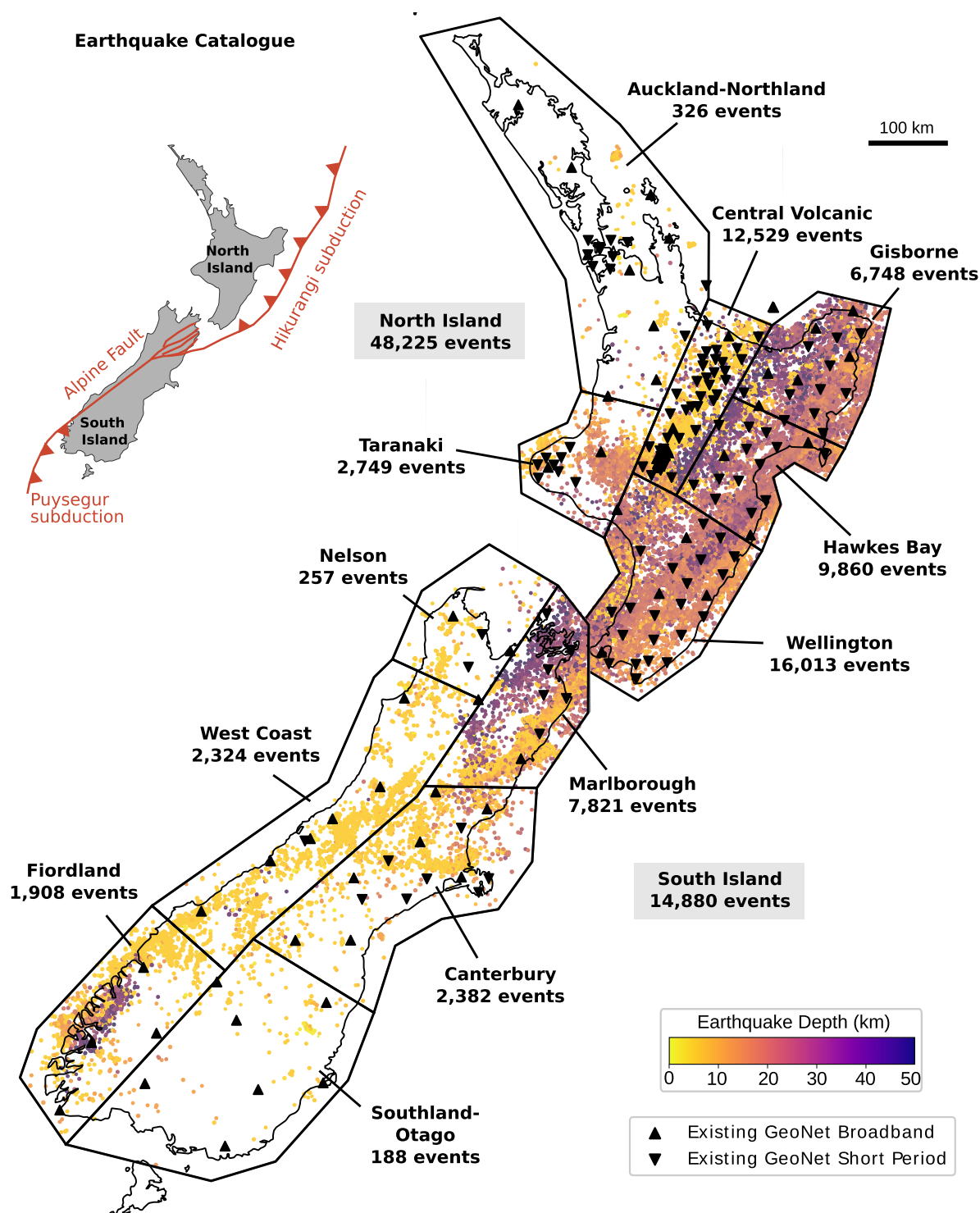


Figure 1. 63,105 earthquakes for which Quality Scores are calculated, selected from the GeoNet Catalogue (1/1/2018 to 1/1/2023, depths < 50 km) within polygons around the South and North Islands. Twelve sub-regions analysed in this study are also outlined (black lines). Labels show number of events analysed within each region. Earthquakes coloured by preferred origin depth. GeoNet broadband and short period weak-motion instruments are shown by upright triangles and inverted triangles, respectively.

in order to maximise the rate of change in travel times as the depth of the hypocentre is changed (Thurber 1985). Figure 2 demonstrates this effect, whereby a nearby station (R_2) experiences a larger effect on the travel times (which approximates path length) for different depth sources (S_1 , S_2) than a more distant station does (R_1).

By considering simple, established criteria (Husen and Hardebeck 2010) it is possible to assess the quality

of earthquake location precision arising from network geometry on a national and regional basis. Here, we consider these criteria, namely station azimuthal coverage, minimum station distance, P- and S-phase arrival coverage and fixed location criteria, to rank each catalogued earthquake (Figure 1) on a network location Quality Score (QS) scale of QS0 (unconstrained) to QS6 (best constrained) to quantitatively assess location quality.

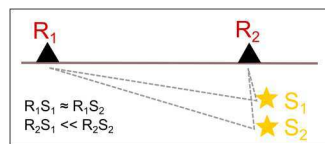


Figure 2. Simplified schematic of earthquake depth resolution using both a distant receiver (R_1) and a nearby receiver (R_2). Differences in depth between a shallow (S_1) and deeper source (S_2) are easier to resolve using R_2 , as the difference in path length (travel time) is more significant than for the difference in path length between R_1 and each source.

Our analysis provides a quantitative means of assessing the impact that network heterogeneity has on earthquake catalogue location quality – using Aotearoa New Zealand as an example – and is easily applicable to other catalogues and seismic networks globally. Furthermore, it enables the identification of where network improvements should be focussed to have the most impact on improving quality, and to understand and highlight the impacts that variable location quality has on downstream scientific analyses (e.g. statistical seismology (Christophersen et al. 2017), seismic hazard modelling (McGinty 2001; Gerstenberger et al. 2024) and tomographic inversions (Eberhart-Phillips et al. 2010) among others).

Our work was motivated and informed by recent consultation within the New Zealand earthquake science community around the need for geophysical network expansion (Warren-Smith et al. 2023), which emphasised sparse station spacing as a long-standing limitation on seismological research and event response. Overall, this work has three main benefits: (1) Alerting catalogue users to the highly variable level of location quality nationwide and providing a methodology for assessing location quality in the catalogue, (2) driving discussion around weak-motion network expansion in critically under-instrumented regions, especially those with high seismic hazard such as the late-interseismic Alpine Fault and (3) forming a baseline reference, against which proposed future network expansion can be tested to gauge any improvements and optimise impact.

Data and methods

GeoNet earthquake catalogue

The GeoNet earthquake catalogue contains technical information from earthquakes recorded by the permanent network of weak and strong motion seismic instruments across New Zealand since the 1930s, as well as oral and written records of earthquakes prior to instrumentation (GNS Science 1970; https://www.geonet.org.nz/data/types/eq_catalogue, <https://www.geonet.org.nz/data/network/sensor/search>). Each

earthquake's information is populated with a series of available attributes, including a unique ID, preferred and alternative solutions for origin time, epicentral location, depth, and magnitude, alongside phase-pick information used to calculate those solutions. These pick data, that GeoNet host in standardised formats (e.g. QuakeML), are a valuable resource for assessing the quality of the input data used for the final earthquake solution.

For our analysis, we focus on five years of GeoNet catalogued earthquakes between 1/1/2018 and 1/1/2023. This period was chosen to avoid the highest aftershock rate portion of the November 2016 M_w 7.8 Kaikōura earthquake, to reflect the current state of the operational GeoNet network, and to mostly include events catalogued by the 24/7 National Geo-Hazard Monitoring Centre (NGMC) (Godfrey et al. 2021) which started operating in December 2018, and to cover a period of minimal network change. We analyse events shallower than 50 km, as these are generally within the upper plate and represent the majority of earthquakes of both seismic and public interest. Due to our focus on improving the existing onshore instrumentation, we only consider earthquakes with geographic distributions that should enable reasonable location estimates with onshore sensors alone, defined as those events occurring onshore or within ~20 km of the coast (Figure 1).

We split the catalogue into twelve regions (Figure 1) based on regional variations in earthquake depth distributions, tectonic regimes (i.e. subduction vs. transpression) and permanent weak-motion station distributions, maintaining as much uniformity within regions as possible. The East coast of the North Island, dominated by Hikurangi subduction zone seismicity, is split into three regions (Gisborne, Hawkes Bay and Wellington) with similar characteristics to maintain a reasonable number of events in each region. We undertake analysis for each region, as well as comparing total combined analysis for both the North and South Islands.

Network location quality criteria and quality scoring

Five essential location quality network criteria have been established as requisite for a good hypocentral location by previous studies (Table 1) (Chatelain et al. 1980 Kissling 1988; Gomberg et al. 1990; Husen and Hardebeck 2010;). These include: a maximum azimuthal gap of stations recording the earthquake of less than 180° ($Max_az_gap < 180^\circ$), at least eight travel time arrivals ($Min_picks \geq 8$), of which at least one is an S-arrival ($Min_Spicks \geq 1$), at least one arrival on a station within a focal depth's distance of the epicentre ($Min_dist \leq depth$) and at least one S-arrival on a station within 1.4 focal depth's distance of

Table 1. The six quality criteria used for assessing earthquake location quality, informed by Husen and Hardebeck (2010).

Criteria	Requirement	Score	Description	Reference
<i>Max_az_gap</i>	< 180°	1	A maximum azimuthal gap in station coverage around the epicentre < 180°.	Kissling 1988
<i>Min_picks</i>	≥ 8	1	At least eight travel time arrivals.	Chatelain et al. 1980
<i>Min_Spicks</i>	≥ 1	1	At least one of those travel times is an S-pick.	Chatelain et al. 1980
<i>Min_dist</i>	≤ depth	1	At least one phase arrival recorded on a station within a focal depth's distance from the epicentre.	Chatelain et al. 1980
<i>Min_Sdist</i>	≤ 1.4*depth	1	At least one S-phase arrival recorded on a station within 1.4 focal depth's distance from the epicentre, to provide a unique constraint on focal depth.	Gomberg et al. 1990
<i>Fixed_depth</i>	FALSE	1	Focal depth must be free and not fixed by the analyst.	
Maximum possible Quality Score (QS):		6		

Earthquakes are assigned a maximum quality score (QS) of six if all criteria are met.

the epicentre ($Min_Sdist \leq 1.4 \times \text{depth}$). While strong motion stations are not generally useful for detecting and locating earthquakes of small magnitude, we do include picks made on these stations where they exist. We identify a sixth criterion whereby we require an earthquake's depth to not be fixed by an analyst ($Fixed_depth = \text{False}$), such that the reported depth accurately reflects the focal depth and uncertainty in the location can also be assessed. While this sixth criterion has some overlap with the two other distance criteria and hence could double penalise for epicentral distance in some cases, an earthquake may still be fixed (and location information lost) even if the two other distance criteria are met. We therefore consider it a useful criterion, especially in shallow seismicity regions.

Using these six criteria, we assign each earthquake a network location Quality Score (QS) from QS0 (no criteria met) to QS6 (all criteria met) and report on percentages of each score within each region (Table 2). Importantly, by applying these only to earthquakes that are present in the catalogue, we are not able to report on areas where detection may be so poor that earthquakes do not even trigger the system. Hence, the percentage of highest quality scores in each region is likely a maximum value, whereas the lowest quality scores are likely a minimum percentage, compared to the true numbers of earthquakes occurring.

Our network location Quality Scores can be considered as an indicator of the potential for good location precision, provided other sources of uncertainty are well constrained. For simplicity, our approach does not consider the effect of other uncertainty sources, such as using a simplified 1D velocity model (GeoNet use IASP91) – which does not represent the true heterogeneity in crustal structure at multiple scales – on event location quality. Similarly, Gomberg et al. (1990) discuss the significant impact incorrectly timed S-phase arrivals can have on location precision. We acknowledge that this effect and others relating to pick quality exist within any catalogue, but assume these inconsistencies are distributed homogeneously nationwide and

can effectively be ignored in this regional comparison focussed case, where we only consider the impact of the network. Most importantly, errors introduced through incorrect velocity model and pick timing can be addressed secondarily by researchers using improved picking and relocation routines, whereas network limitations remain fixed and therefore represent a critical primary source of uncertainty in catalogue locations, which is highly important and easier to quantify.

A Python code for calculating Quality Scores is provided to allow researchers to replicate the analysis for their own networks and catalogues, or for a different temporal or spatial selection of the GeoNet catalogue (see data accessibility statement).

Results

Azimuthal coverage (*Max_az_gap*)

Generally, a high percentage of analysed earthquakes fulfil the criterion to have a maximum azimuthal gap in station coverage around the epicentre of less than 180° (86% and 89% of events for the North and South Island, respectively) (Figure 3). As expected, inland regions perform well (blue colours, Figure 3), while coastal regions perform less well in spite of limiting our analysis to events within 20 km from the coast (red colours, Figure 3). Along the North Island's East coast, dense coastal instrumentation means generally all onshore events meet this criterion and only offshore events fail. However, in particularly sparsely instrumented coastal regions such as Fiordland and Northland, a large portion of onshore events also fail this criterion (only 37% and 48% of Fiordland and Northland events pass, respectively). Notably, the Central Volcanic region, despite being inland and densely instrumented, also exhibits many events with large azimuthal gaps. These events tend to be smaller magnitude earthquakes (Figure S2), which occur at the edge of, but are detected by, the densest volcanic network, and are too small to be detected on the sparser stations in Taranaki and Manawatū (Figure 3), resulting in poor azimuthal coverage. Additionally,

Table 2. Summary of quality performance for the North and South Islands, and twelve subregions.

	Region	Max Depth (km)	Median Depth (km)	Number of EQs	Mean Min_dist (km)	Max_az < 180 (%)	Min_picks ≥ 8 (%)	MinS_picks ≥ 1 (%)	Min_dist ≤ depth (%)	Min_Sdist ≤ 1.4*depth (%)	Depth not Fixed (%)	QS≥4 (%)	QS=6 (%)
South Island	South_Island	50	7	14880	20	89	99.9	83	31	28	60	50	20
	Fiordland (F)	50	5	1908	32	37	99.9	94	12	16	30	19	5.2
	West_Coast (WC)	50	5	2324	23	94	100	86	5.7	8	24	15	2.5
	Nelson (N)	50	5	257	26	90	100	84	7	6	35	23	2.7
	Marlborough (M)	50	12	7821	17	97	99.9	79	48	40	80	71	31
	Southland_Otago (SO)	50	5	188	30	88	100	80	4.8	5.3	22	12	4.3
	Canterbury (C)	50	5	2382	15	98	100	86	24	20	59	48	15
North Island	North_Island	50	19	48225	14	86	99.9	85	68	61	90	82	48
	Taranaki (T)	50	17	2749	20	82	100	91	37	50	86	76	27
	Auckland_Northland (AN)	50	5	326	40	48	99.4	86	3.7	4	28	12	0.9
	Gisborne (G)	50	24	6748	15	76	100	77	83	66	97	83	54
	Hawkes_Bay (HB)	50	25	9860	14	90	100	84	88	77	98	93	68
	Wellington (W)	50	21	16013	15	90	100	83	78	70	94	89	59
	Central_Volcanic (CV)	50	5.2	12529	9.8	84	99.7	91	40	37	75	70	20
South Island	South_Island	15	5	11648	21	89	100	88	21	20	49	42	13
	Fiordland (F)	15	5	1568	33	36	100	94	1	2.6	16	5	0.3
	West_Coast (WC)	15	5	2288	22	94	100	86	4.8	7	23	14	1.6
	Nelson (N)	15	5	235	25	90	100	89	3	4.3	30	20	1.3
	Marlborough (M)	15	8.6	5162	15	98	100	89	35	33	70	66	24
	Southland_Otago (SO)	15	5	184	30	88	100	80	2.7	3.8	21	10	2.7
	Canterbury (C)	15	5	2211	15	99	100	86	20	17	56	45	12
North Island	North_Island	15	6.1	17456	12	82	99.8	89	32	32	71	63	16
	Taranaki (T)	15	9.8	1022	19	69	100	94	19	25	64	50	11
	Auckland_Northland (AN)	15	5	296	37	50	99.3	90	2	3	21	11	0.7
	Gisborne (G)	15	10	943	13	75	100	78	33	36	80	61	18
	Hawkes_Bay (HB)	15	11	964	14	73	99.8	70	35	30	84	57	14
	Wellington (W)	15	12	3351	18	75	100	86	35	39	73	60	17
	Central_Volcanic (CV)	15	5	10880	8.8	87	99.7	92	33	32	71	67	16

Max depth defines the maximum earthquake depth considered in analysis. Median earthquake depth refers to the median depth of earthquakes above that maximum depth used for analysis. Mean Min_dist is the average distance to the closest picked station for all events in that region, indicative of relative station spacing. Columns in yellow present percentages of events fulfilling each of the six quality criteria outlined in Table 1 for each region. Blue columns present percentages of events scoring full quality scores. Cells are coloured to graphically present relative percentages more clearly. Cells with red text and pink shading are those which perform particularly poorly, having less than 30% of events fulfilling that criterion or quality score.

high attenuation in the volcanic region results in limited raypath coverage along some azimuths (P. Herath, pers. comm).

It is possible that the use of a simplified global 1D velocity mode (IASP91) by the NGMC for their routine location analysis, which doesn't represent the lateral variation in velocity, also contributes to the apparent lack of azimuthal coverage in some areas. Hypocentral locations will have higher residuals (and therefore may become unresolvable) when stations in highly contrasting velocity regions are used jointly, rather than only using stations within a single region with more similar material properties and therefore similar misfit to the 1D model. An example of this is the northern offshore end of the Central Volcanic Region (Bay of Plenty) whereby the inclusion of Gisborne stations could provide improved azimuthal coverage for coastal events but have contrasting misfit to the simplified velocity model and therefore degrade any location, so are typically excluded during manual review.

Minimum picks (Min_picks, Min_Spicks)

GeoNet operational practice requires that an earthquake triggers on at least ten stations for it to be detected. The NGMC also creates events manually if

significant shaking is observed across the network. In theory, all events should therefore fulfil the criterion requiring at least eight travel time arrivals. In general, all regions score very well on this criterion, but a very small percentage of earthquakes (<0.5% in some regions) do not include eight or more travel time arrivals. This discrepancy likely results from triggering phases not being of high enough quality (too emergent, or low signal to noise) to be clearly identified and their picks saved. More surprisingly, as many as 20% of earthquakes in some regions (Marlborough, Gisborne and Southland and Otago) don't include even a single S-phase pick and fail this criterion. This may be due to S-phases needing manual addition, while P-phases are automatically picked.

Minimum distance constraints and fixed events (Min_dist, Min_Sdist, Fixed_depth)

The poorest performance is observed against the three minimum distance and depth constraint criteria. The first, *Min_dist*, requires one phase arrival recorded on a station within a focal depth's distance from the epicentre, and the second, *Min_Sdist*, requiring at least one S-phase arrival recorded on a station within 1.4 focal depth's distance from the epicentre. These criteria (alongside the related *Fixed_depth* = False

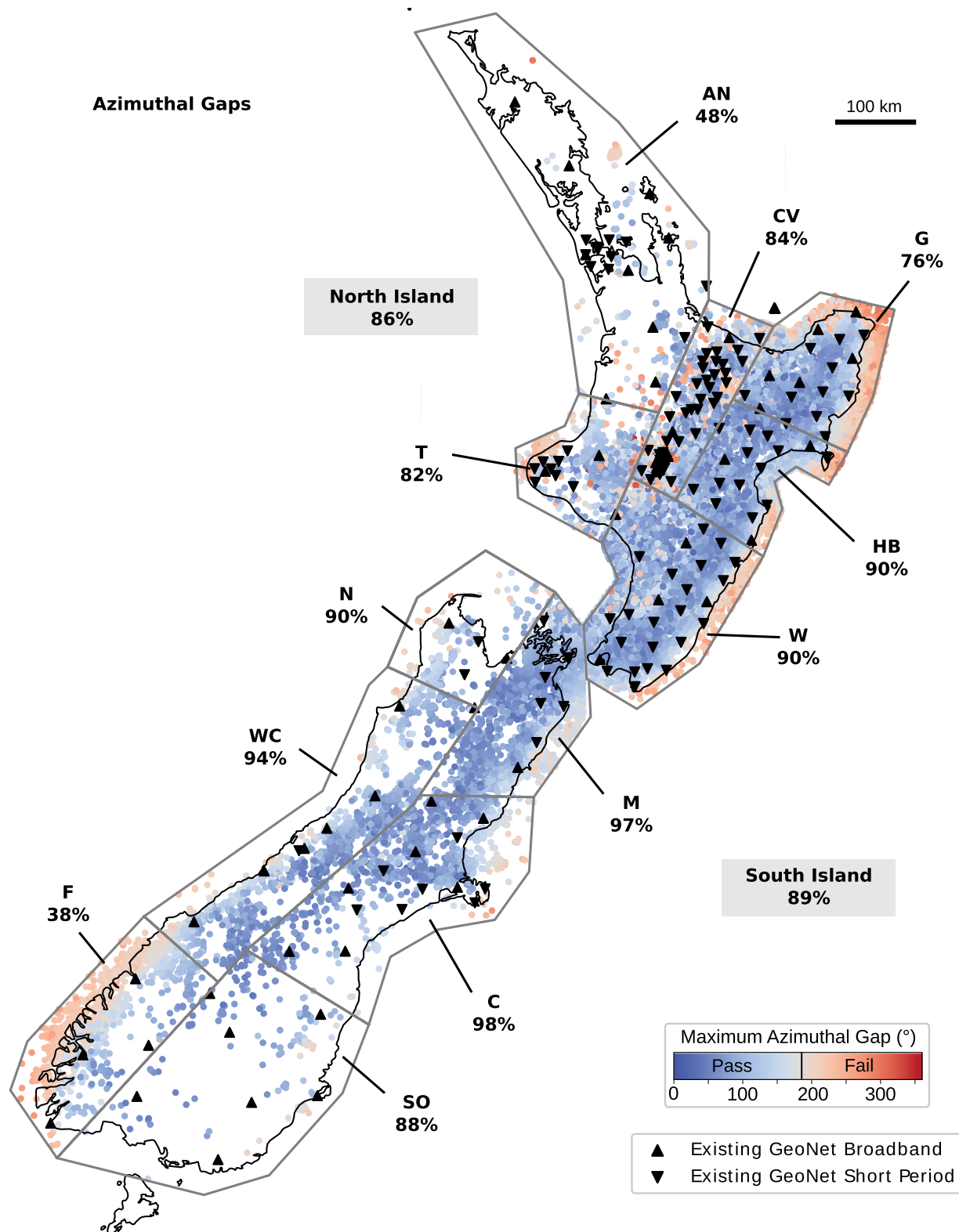


Figure 3. Maximum azimuthal gaps for all earthquakes analysed. Earthquakes are coloured such that blue shades denote an azimuthal gap less than 180° (fulfilling criterion) and red shades denote an azimuthal gap greater than 180° (failing criterion). Percentages for each region show percentages of events passing with an azimuthal gap less than 180° . Regional labels abbreviated as follows: F is Fiordland, WC is West Coast, N is Nelson, SO is Southland Otago, C is Canterbury, M is Marlborough, W is Wellington, HB is Hawkes Bay, G is Gisborne, CV is Central Volcanic, T is Taranaki and AN is Auckland Northland.

criterion) are fundamentally dependent on both the network spacing and earthquake depth distributions within each region; a region with sparser station

spacing but typically deeper seismicity will score better than the same stations used to locate a shallower seismicity distribution.

This is evident in the criteria scores, whereby regions with deeper, subduction-related seismicity and relatively dense stations (Gisborne, Hawkes Bay, Wellington, Marlborough) score much higher (up to 88% fulfilment) than sparsely instrumented regions with shallower, upper-crustal seismicity (e.g. West Coast, Southland-Otago and Auckland-Northland) which score very poorly, with fulfilment percentages as low as 4%. Horizontal streaks in-depth plots

(Figures 4a, c, e) highlight where analysis has fixed the earthquake depths, most commonly 5 and 12 km, and less commonly 33 km. Within regions, percentages of events with fixed depths, and therefore only qualitative depth information, vary considerably from less than 2% (Hawkes Bay) to over 75% (West Coast, Southland Otago) (Table 2).

Given the 10-station trigger requirement for GeoNet event detection, the three distance criteria are not

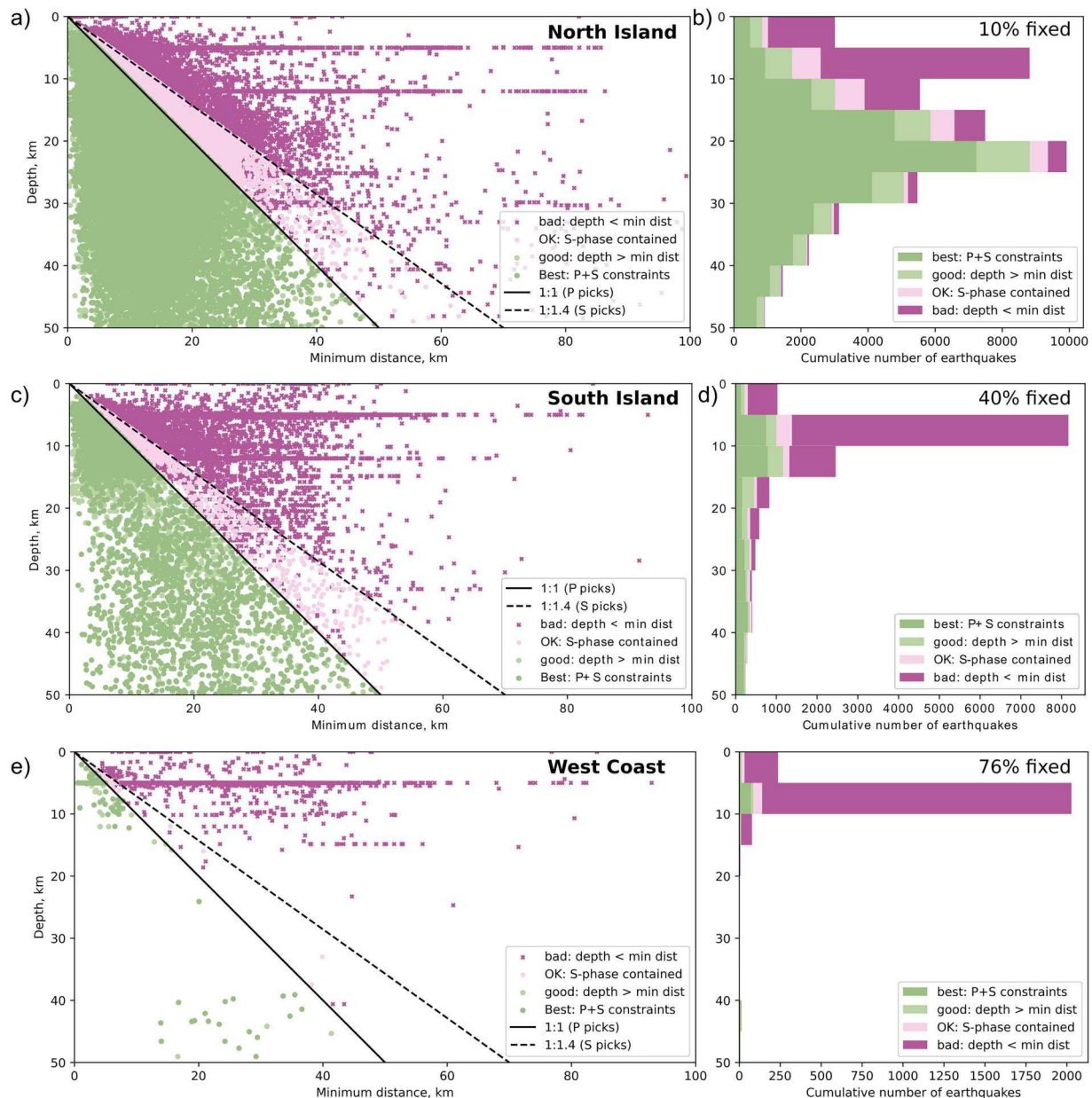


Figure 4. Assessment of minimum distance criteria for a-b) the North Island, c-d) the South Island and e-f) the West Coast region. Panels on the left (a, c, e) show a scatter plot of the minimum (horizontal) distance to a recording station against depth for each earthquake. The solid black line indicates a 1:1 slope such that events plotting to the left are classified as 'good' and fulfil the first distance criteria to have one pick on a station within a focal depth of the epicentre (green symbols, i.e. minimum distance is less than depth). The dashed black line indicates a 1:1.4 slope pertaining to the criterion to have one S-pick within 1.4 focal depth's distance and represents the limit at which locations can still be considered 'OK'. Earthquakes satisfying that criteria to the left of the line are shown in light purple (do not also fulfil first criterion) or dark green (also fulfil first criterion). Events in dark purple do not fulfil either criterion. Dark purple events to the left of the dashed black line have a recording station within 1.4 focal depths distance, but this station has no recorded S-phase. Light green events fulfil the first criterion but have no S-pick. Panels on the right (b, d, f) show the distributions of earthquakes in 5km depth bins, coloured to match symbols in the left hand panels, with no overlap in categories. The percentage of earthquakes with fixed depths is given for each panel.

expected to be magnitude dependent, unlike the azimuthal criterion (e.g. in the Central Volcanic Region, Figure S2). Because the closest station should usually have the largest signal, it will frequently be included for all earthquakes large enough to trigger across a 10 station sub-network. Exceptions may occur if, for example, the S-P time is very short (overlapping phases) or arrivals are clipped at high amplitudes.

Network location quality scores

Results of using the six-point quality scoring system (Table 1) to score all earthquakes from QS0 (unconstrained) to QS6 (very well constrained) are presented in Table 2 and Figure 5.

Significant variation in network location Quality Scores exists nationwide, especially in the highest QS scores (QS4–6) as shown in Table 2. The North–South divide is particularly stark at QS6 level, with nearly half (48%) of North Island earthquakes scoring QS6, versus only 20% for the South Island. The highest scoring region is Hawkes Bay, with 68% QS6, followed by other Hikurangi Margin regions including Gisborne and Wellington (54% and 59% respectively). However, several regions score extremely poorly, with Fiordland, West Coast, Nelson, Otago–Southland and Auckland–Northland regions having $\leq 5\%$ QS6 events and more than three-quarters of events scoring QS3 or lower.

Comparison of quality scores with other metrics

We compare our QS scores with the network metric score (ΔU) of Bondár and McLaughlin (2009), which does not consider pick counts and station distances as our QS scores do, but aims to identify potential bias in locations arising from azimuthal clustering of stations (Figure S3). ΔU ranges from 0 (indicating an evenly distributed network with no azimuthal clustering) to 1 (indicating highly clustered stations and therefore potential bias). Generally, our highest QS scores correspond to low $\Delta U < 0.4$. We find that spatial patterns in ΔU closely follow those we already identified in the maximum azimuthal gap (Figure 3), especially in the South Island where stations are generally evenly spaced; only events with high azimuthal gaps around the coast also show higher values of ΔU . However, ΔU is higher through central parts of the North Island, suggesting the clustered line of Central Volcanic Region stations may bias locations using paths aligned with the trend of that zone. We recommend that analysis of location quality in this region should therefore also consider the effect of azimuthal bias.

We also compare our QS scores with reported depth and horizontal uncertainties from the GeoNet catalogue, where available for non-fixed events (Figure S4). This shows that our higher Quality Scores (QS5 and QS6) correspond to events with low depth and low

horizontal uncertainty values. We emphasise that this is not because these two metrics are interchangeable, rather than the network-related uncertainties (i.e. our QS scores) are one important component in the overall uncertainty values, given that other uncertainty sources are treated broadly homogeneously in the reported catalogue uncertainties.

Discussion

Causes and implications of network location quality scores

The quantitative application of network location quality criteria described above demonstrates that there is significant variation in earthquake location quality within the GeoNet catalogue across Aotearoa New Zealand. Regions along the East Coast of the North Island (Wellington, Hawkes Bay, Gisborne) score particularly well for events shallower than 50 km. By considering only shallow earthquakes (depth < 15 km, Figure S5), it is clear that high location Quality Scores (QS4+) along the eastern North Island are not just related to the deeper seismicity distribution here, but also to the denser station spacing. While Wellington, Hawkes Bay and Gisborne regions exhibit a drop in QS4+ percentages when deep events (> 15 km depth) are excluded, they still consistently score higher than other more sparsely instrumented regions (Table 2, Figures 5, Figure S5).

However, our analysis highlights a drastically reduced quality of locations throughout the South Island compared to the North Island. Low Quality Scores are prevalent in many regions where the minimum distance quality criteria are not met (i.e. the closest station is too far from the earthquake to provide sufficient depth control). Our results show that the quality of earthquake locations differs significantly across the country and that the current distribution of weak-motion instrumentation is insufficient to produce high-quality earthquake catalogue locations across significant parts of the plate boundary zone.

On a nationwide scale, this is fundamentally due to the sparsest station spacing coinciding with regions of shallow, upper-crustal seismicity (South Island plate boundary zone), whereas deeper, subduction-related seismicity beneath the North Island is coincident with much denser station spacing (Figure 6). While dense stations allow for lower magnitude earthquakes to be detected in regions of interest (e.g. Hikurangi), from a location perspective the network should ideally be the densest where the seismicity is the shallowest, to allow as many earthquakes as possible to be located using a station within one focal depth's distance.

Our network location Quality Scoring is dependent not just on station distribution but may also

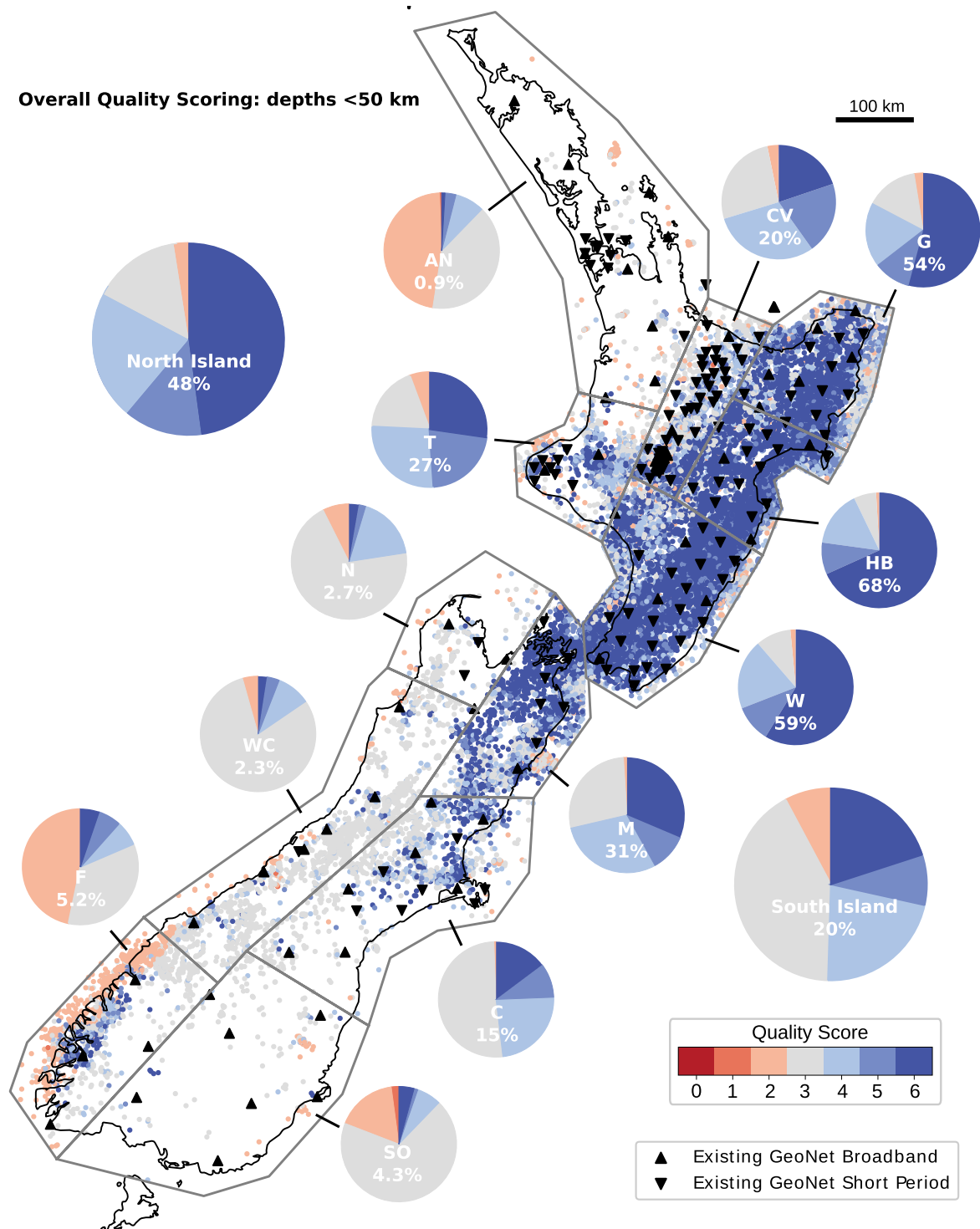


Figure 5. Earthquakes coloured by network location Quality Score (QS) for all earthquakes analysed above 50 km depth. The same figure for events shallower than 15 km is available in the supplementary material. Pie charts show proportions of QS0-QS6 for each region, labelled percentage is for events scoring QS6. Regional labels abbreviated as in Figure 3.

be influenced by non-accurate locations. Some earthquakes with low QS may have their scores improved if they were relocated using realistic velocity models that account for lateral heterogeneities alongside double-difference or cross-correlation methods. However, this will only improve ‘marginal’ events – those only needing small location adjustments to fulfil distance criteria for example – and we do not expect these to influence the overall patterns we observe. Most events with low QS scores are

fundamentally limited by network coverage not designed to resolve their hypocentral location; secondary re-picking and relocation analysis cannot offer improvements in these cases. Additional analyses incorporating depth phases, for example, would possibly improve location uncertainties, but this is not possible for most events.

It is important to note that Quality Scores of QS4 and below essentially render those earthquakes unsuitable for use (even with re-picking and relocation) in

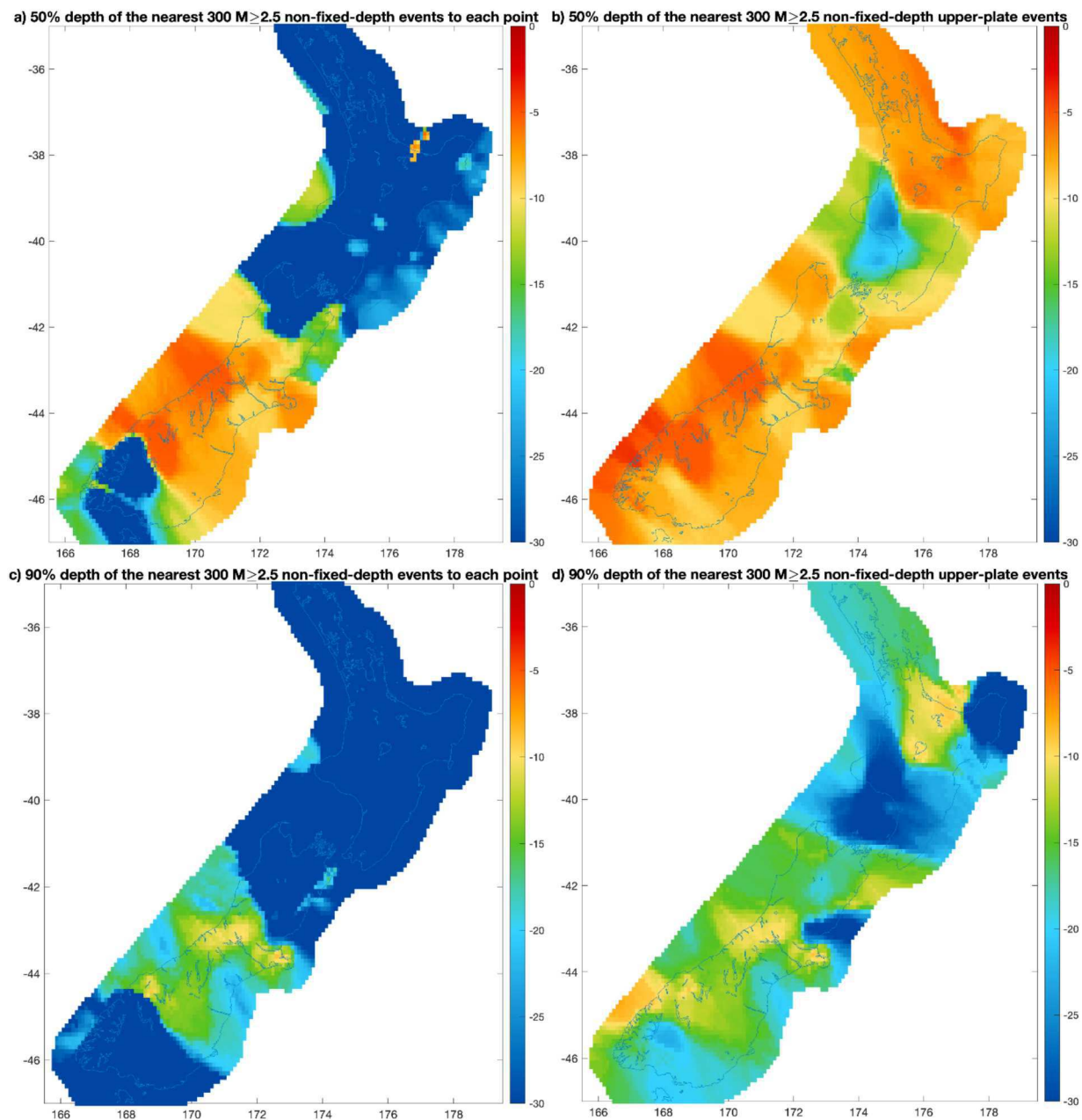


Figure 6. Spatial distribution of earthquake depths in New Zealand based on the catalogue of Rollins et al. (2022) (Figure S2). a) The coloured surface shows the 50th-percentile (median) depth of seismicity at each grid point, using the depths of the nearest 300 $M \geq 2.5$ events (to each point) that do not have analyst-fixed depths. The subducting plate beneath the North Island means that the majority of seismicity is rather deep (>30 km, dark blue), whereas seismicity is relatively shallow in the central South Island (orange) due to the absence of a subduction zone. b) Same as a) but excluding all events classified as subduction or intraslab, so that only upper-plate events are counted (details in Rollins et al. 2022). Even with this, the central South Island is still the seismologically thinnest part of New Zealand (red-orange). c) Same as a) but using the 90th-percentile depth of seismicity at each point. d) Same as b) but using the 90th-percentile depth of seismicity (similar to Ellis et al. (2024)). In the central South Island, very little seismicity is deeper than 15 km.

many scientific applications (e.g. tomographic inversions, 3D fault analysis, spatiotemporal monitoring) which rely on high-resolution location information. This makes such methods extremely challenging in regions with very low QS scores, which includes most of the South Island. Particularly concerning are the very low scores in regions of high seismic hazard (e.g. Alpine Fault and Fiordland Subduction Zone, Gerstenberger et al. 2024). Figure 7 outlines the disparate relationship between station spacing and seismic

shaking hazards within the North and South Islands. In the North (Figure 7b), network sites serving regions with high seismic hazard (>0.6 PGA, 10% probability of exceedance in 50 years) all have a network spacing less than ~ 30 km. Contrastingly, in the South Island (Figure 7a), all sites serving the highest hazard regions are spaced more than ~ 30 km apart, some as far as 85 km apart. While sparsely instrumented regions like Fiordland and the West Coast are also sparsely populated, they have a high potential to produce great

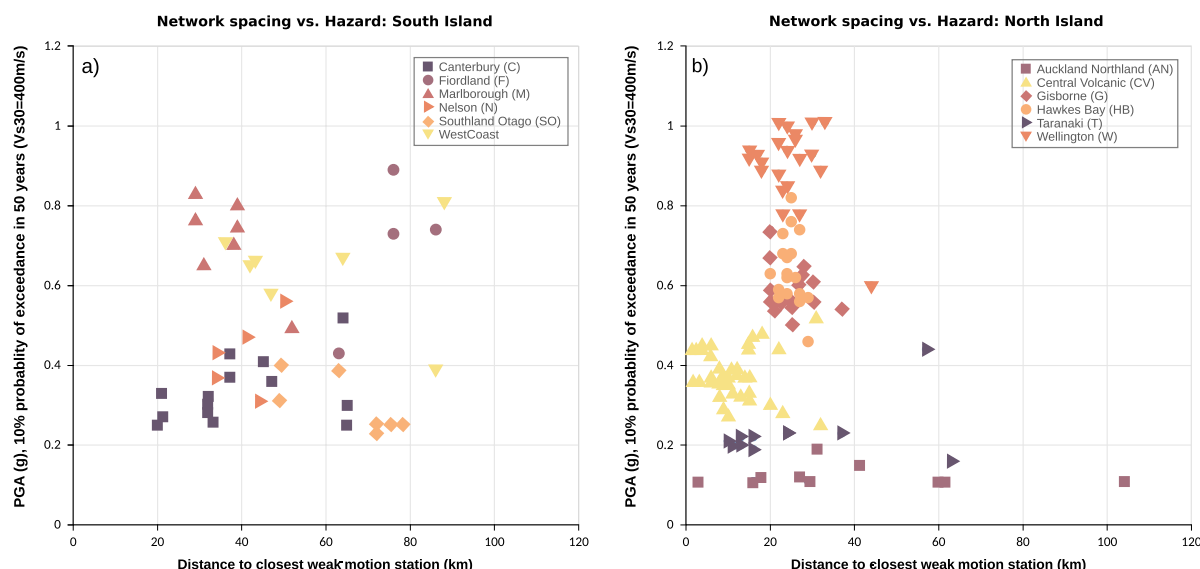


Figure 7. Comparison between weak motion station spacing and seismic shaking hazard from the 2022 National Seismic Hazard Model (Gerstenberger et al. 2024). Distance to closest station (km) versus Peak Ground Acceleration (PGA) (10% probability of exceedance in 50 years, $V_{s30} = 400\text{m/s}$) stations in each region in the a) South Island and b) North Island.

magnitude earthquakes with national-scale impact (Orchiston et al. 2016). Regions with very low overall QS scores are also likely to have completely undetected, or at least uncatalogued seismicity. Currently, accurate monitoring of spatial and temporal changes in seismicity patterns in these zones is unviable without additional instrumentation.

Quality scoring for improving earthquake catalogues and networks

We consider the analysis outlined herein useful in several ways to those working with earthquake catalogues in New Zealand and more broadly.

Firstly, while the GeoNet catalogue is used extensively by researchers in New Zealand and globally, a summary of its location quality does not exist in the literature, yet its heterogeneity needs to be considered in many disciplines. We hope that this work provides a simple reference for groups both familiar and unfamiliar with catalogue quality limitations, as well as helping to identify regions where additional stations are required for sufficient scientific resolution.

Similarly, our approach is easily adaptable for assessing the impact of any additional stations on improving catalogue quality. New Quality Scores can be computed for each earthquake in the original catalogue by assuming that (1) picks are made on all new stations within the median epicentral distance of the original recording network, (2) that an S pick is made on the closest station, and (3) that the earthquake depth would be fixed if the closest station was more than two focal depth's distance away. Figure 8 shows an example of this using a region in South Westland where several temporary stations operate.

In this case, it is estimated that the additional stations could have produced twenty times more QS6 events (0.9% to 18.1%), and nearly four times as many QS4 + events, were they used to locate the GeoNet catalogued seismicity. Note that this does not account for additional detectability improvements. We hope this analysis is of use as a benchmark and testing set for future network expansion opportunities, both for identifying regions in need of expansion, and for testing station placement. Since our analysis a dozen new broadband instruments have already been deployed in Northland, reducing the station spacing to c. 20 km in parts of the peninsula (<https://www.geonet.org.nz/data/network/sensor/search>), which will greatly improve detection and location quality in the region.

Finally, we provide a simple framework, with accessible, reproducible code, to apply this approach to any seismicity catalogue and seismic network (see data accessibility statement). This framework allows for quantitative filtering of high-location quality events for catalogue analysis, highlighting heterogeneity in location quality across networks of any scale and is easily applicable.

Suggested improvements in the New Zealand context

Some suggestions – both short-term and longer-term – are included here to aid improvements to location quality, based on observations made during this analysis.

1. **Seismic station density within a region should reflect both seismicity depth distributions and seismic hazard.** In Aotearoa, network

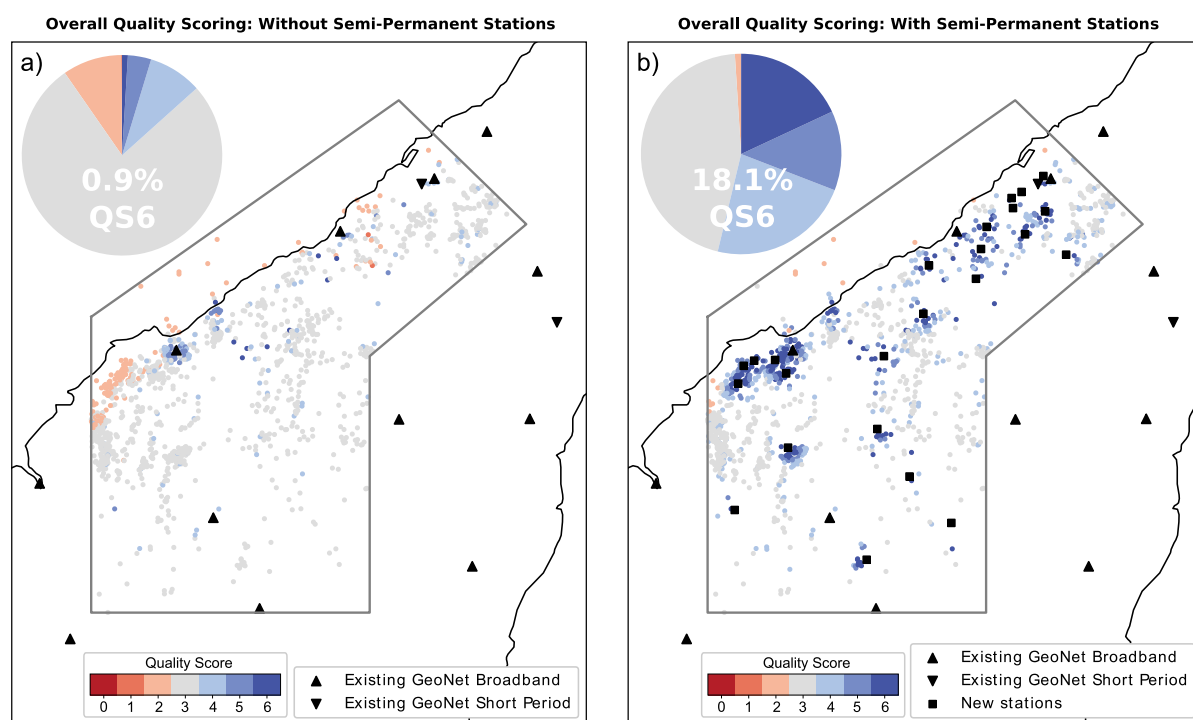


Figure 8. Improvement in network location Quality Scores for a region in South Westland and Central Otago covered by semi-permanent research networks SAMBA (Boese et al. 2012; Baratin et al. 2018), COSA (Warren-Smith et al. 2017) and DWARFS (Warren-Smith et al. 2022). a) Quality Scores using existing GeoNet weak-motion instrumentation. Less than 1% of earthquakes score QS6 and <14% of events score QS4+. b) Quality Scores for the same region but assuming semi-permanent research sites were available and used for location (black squares). This way, more than 18% of events score QS6 and >50% of events score QS4+, demonstrating the significant impact these third-party stations could have on location quality.

densification to a spacing appropriate for each region's earthquake depth distribution – especially those with shallow seismicity and high seismic hazard – is required to bring the catalogue location quality to an acceptable level. This recommended spacing is – as a bare minimum – no sparser than twice the depth to deeper seismicity (90% depth) (Figure 6c, d), and ideally twice the median depth of seismicity (50% depth) (Figure 6a, b, Table 2), or denser. The former, in theory, should produce good depth resolution for the base of the seismogenic zone, but this alone is insufficient to precisely locate seismicity actually occurring within the seismogenic zone on the upper crustal faults.

2. **Careful placement of coastal stations to improve azimuthal coverage.** Improvements should be considered in conjunction with other location factors (e.g. noise suppression) when installing stations in coastal regions. Regions with a high number of events along the coastline would benefit from stations placed to minimise the azimuthal gap, e.g. Fiordland and Northland, making use of offshore islands where suitable.
3. **A minimum trigger of eight stations in low-station density regions.** GeoNet currently uses an event trigger threshold of ten stations, but we recommend that only eight are used, as this is the number required to produce a good-quality

location. Reduction of the station trigger threshold to eight in sparsely instrumented regions would improve detectability without compromising location quality.

4. **S-phases should be picked on nearby stations.** Where possible, S-phases should be picked on stations as close to the epicentre (within 1.4 focal depth's distance) as possible to ensure good depth constraints as well as improved epicentral precision (Gomberg et al. 1990).
5. **Only fixing event depths when absolutely necessary.** Some regions have a high number of fixed events with minimum distance values less than the depth, meaning in theory a good solution could have been found during location. For example, 34% of fixed events in the Central Volcanic Region were found to have minimum distances good enough to not be fixed according to GeoNet procedure, when assuming the fixed depth was true depth (Figure S6). While seismicity in the volcanic regions may indeed be shallower than 5 km, fixing of events depth within a kilometre of a recording station is surprising, yet appears to be commonplace. This may be a consequence of using an inappropriate velocity model for this seismicity, or the inversion scheme (locsat) not considering local topography. Care should be taken to ensure any fixing is essential so as to not lose

important depth data in the catalogue. Otherwise, the argument for densification of stations is weakened if those stations are not actually being used to improve depth information during location.

6. **Inclusion of a network location Quality Score in the catalogue.** A simple indicator of location quality, such as our QS system, within the GeoNet catalogue would make the data quality more evident to users. Similar simple measures are routinely used elsewhere (e.g. SCSN, <https://scedc.caltech.edu/data/eq-catalogs.html>), and provide a quick way to consider which earthquakes are suitable for a range of scientific and operational applications. Users should take note that these scores are only an indicator of the potential for good location quality; locations may still be imprecise and inaccurate if other uncertainty metrics (e.g. pick timing, velocity model uncertainties) are not well constrained. We encourage users to undergo additional uncertainty improvement steps when working with the GeoNet catalogue and to consider the temporal consistency of the chosen timeframe also.

Conclusions

Earthquake location quality is strongly controlled by the location of the earthquake relative to the network of stations on which seismic waveforms are recorded and phase-arrivals picked. Hence, variability in earthquake location quality is present within the resulting earthquake catalogue, arising from heterogeneities in networks and earthquake location distributions. To quantify and explain this heterogeneity in the Aotearoa New Zealand setting, we develop and apply a simple scoring system to quantify an earthquake's location quality based on network constraints. This approach allows us to identify regions where the network is performing well for locating earthquakes, as well as regions where the network is insufficient to produce good quality locations. Following this analysis, we conclude that:

1. Significant heterogeneity in the quality of earthquake locations exists across Aotearoa New Zealand, arising from spatial heterogeneities in both earthquake depth distributions and network spacing.
2. Earthquake location quality is highest along the eastern North Island, where a denser weak-motion network is well designed for locating Hikurangi subduction zone seismicity.
3. Earthquake location quality is poor in regions with sparse station spacing and shallow seismicity, such as the West Coast of the South Island, Otago and Northland.
4. Low-quality locations mostly arise from the minimum distance quality criteria not being met (i.e. the closest station is too far from the earthquake

to provide sufficient depth control). This may be improved by installing denser seismic networks in regions with shallow seismogenic zones.

5. Fiordland subduction zone seismicity – whilst deeper than the shallow crustal seismicity across most of the South Island – does not have well-constrained earthquake locations, owing to sparse station spacing and loss of azimuthal coverage around the coast.
6. High seismic hazard regions, such as Fiordland and the West Coast, have very sparse station spacing, meaning adequate monitoring of seismicity there is very challenging. These regions should be prioritised for future network expansion.

Acknowledgements

Funding was provided by an internal Sustainable Development Fund (SDF) project from GNS Science, awarded to C. Williams, E. Warren-Smith and K. Jacobs, supported by Strategic Science Investment Funding (SSIF) from the Ministry of Business Innovation and Employment. C. J. Chamberlain is grateful for support through a Royal Society Te Apārangi Rutherford Discovery Fellowship (21-VUW-024). The authors thank GeoNet for providing open access earthquake catalogue and pick data for analysis. The authors thank Chris Di Caprio for providing seismic hazard values for each GeoNet station for use in Figure 7. The authors thank Pasan Herath and Stephen Bannister for early reviews of the manuscript. The authors report there are no competing interests to declare.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Crown Research Institutes: [Grant Number Strategic Science Investment Fund (SSIF) Strategic]; Royal Society Te Apārangi: [Grant Number Rutherford Discovery Fellow (21-VUW-024)].

Data availability statement

The earthquake catalogue, including phase pick information, and seismic network inventory used in this analysis are available from <https://www.geonet.org.nz/data/access/FDSN>, last accessed June 2023. A Jupyter Notebook and accompanying Python code used to calculate Quality Scores and make plots shown in this paper is available in a Github repository here: https://github.com/calum-chamberlain/EQ_catalog_location_quality. Supplemental figures can be found here: [10.5281/zenodo.13943115](https://doi.org/10.5281/zenodo.13943115)

References

- Baratin LM, Chamberlain C, Townend J, Savage MK. 2018. Focal mechanisms and inter-event times of low-frequency earthquakes reveal quasi-continuous deformation

- and triggered slow slip on the deep Alpine Fault. *Earth and Planetary Science Letters*. 484:111–123.
- Boese CM, Townend J, Smith E, Stern T. 2012. Microseismicity and stress in the vicinity of the Alpine Fault, central Southern Alps, New Zealand. *Journal of Geophysical Research: Solid Earth*. 117(B2).
- Bondár I, McLaughlin KL. 2009. A new ground truth data set for seismic studies. *Seismological Research Letters*. 80(3):465–472. doi:10.1785/gssrl.80.3.465.
- Chatelain JL, Roecker SW, Hatzfeld D, Molnar P. 1980. Microearthquake seismicity and fault plane solutions in the Hindu Kush region and their tectonic implications. *Journal of Geophysical Research: Solid Earth*. 85 (B3):1365–1387. doi:10.1029/JB085iB03p01365.
- Christophersen A, Rhoades DA, Gerstenberger MC, Bannister S, Becker J, Potter SH, McBride S. 2017, Apr 26–29. Progress and challenges in operational earthquake forecasting in New Zealand. New Zealand Society for Earthquake Engineering Annual Technical Conference.
- Eberhart-Phillips D, Reyners M, Bannister S, Chadwick M, Ellis S. 2010. Establishing a versatile 3-D seismic velocity model for New Zealand. *Seismological Research Letters*. 81(6):992–1000. doi:10.1785/gssrl.81.6.992.
- Ellis S, Bannister S, Van Dissen R, Eberhart-Phillips D, Boulton C, Reyners M, Funnell R, Mortimer N, Upton P, Rollins C, Seebeck H. 2024. New Zealand fault-rupture depth model v.1.0: a provisional estimate of the maximum depth of seismic rupture on New Zealand's active faults. *Bulletin of the Seismological Society of America*. 114(1):78–94. doi:10.1785/0120230166.
- Gerstenberger MC, Bora S, Bradley BA, DiCaprio C, Kaiser A, Manea EF, Nicol A, Rollins C, Stirling MW, Thingbaijam KKS, et al. 2024. The 2022 Aotearoa New Zealand national seismic hazard model: process, overview, and results. *Bulletin of the Seismological Society of America*. 114 (1):7–36. doi:10.1785/0120230182.
- GNS Science. 1970. New Zealand Earthquake Catalogue [Data set]. GNS Science, GeoNet. doi:10.21420/0S8P-TZ38.
- Godfrey HJ, Crighton M, Wright KR, Banks MP, Fromont A, Gomez A, Helliwell M, James LM, Legenkyy A, McClintock JD, O'Hagan S. 2021, September. The National Geohazards Monitoring Centre Te Puna Morearea i te Ru, GNS Science, New Zealand. In: SEG International Exposition and Annual Meeting (p. D011S102R001). SEG.
- Gomberg JS, Shedlock KM, Roecker SW. 1990. The effect of S-wave arrival times on the accuracy of hypocenter estimation. *Bulletin of the Seismological Society of America*. 80(6A):1605–1628. doi:10.1785/BSSA08006A1605.
- Husen S, Hardebeck JL. 2010. Earthquake location accuracy. Community Online Resource for Statistical Seismicity Analysis. doi:10.5078/corssa-55815573. Available at <http://www.corssa.org>.
- Kissling E. 1988. Geotomography with local earthquake data. *Reviews of Geophysics*. 26(4):659–698. doi:10.1029/RG026i004p00659.
- Lee WH, Lahr JC. 1975. *HYP071* (revised; a computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes (No. 75-311). US Dept. of the Interior, Geological Survey, National Center for Earthquake Research.
- Lee WHK, Stewart SW. 1981. Principles and applications of microearthquake networks (Vol. 2). New York: Academic Press.
- Lomax A, Michelini A, Curtis A, Meyers RA. 2009. Earthquake location, direct, global-search methods. *Encyclopedia of Complexity and Systems Science*. 5:2449–2473. doi:10.1007/978-0-387-30440-3_150.
- McGinty P. 2001. Preparation of the New Zealand earthquake catalogue for a probabilistic seismic hazard analysis. *Bulletin of the New Zealand Society for Earthquake Engineering*. 34(1):60–67. doi:10.5459/bnzsee.34.1.60-67.
- Milne J. 1886. Earthquakes and other earth movements (Vol. 56). London: Kegan Paul, Trench, & Company.
- Orchiston C, Davies T, Langridge R, Wilson T, Mitchell J, Hughes M. 2016. Alpine Fault magnitude 8 hazard scenario. Report Commissioned by Project AF8, Environmental Southland, Invercargill, 45.
- Petersen T, Gledhill K, Chadwick M, Gale NH, Ristau J. 2011. The New Zealand national seismograph network. *Seismological Research Letters*. 82(1):9–20. doi:10.1785/gssrl.82.1.9.
- Rollins C, Thingbaijam KKS, Hutchinson J, Gerstenberger MC, Christophersen A, Eberhart-Phillips D, Rastin SJ, Van Dissen RJ. 2022. An augmented New Zealand earthquake catalogue, event classifications, and models of the depth distribution of shallow earthquakes in the greater New Zealand region. Lower Hutt (NZ): GNS Science. 83 p. (GNS Science report; 2021/58). doi:10.21420/XT4Y-WY45.
- Thurber C. 1985. Nonlinear earthquake location: theory and examples. *Bulletin of the Seismological Society of America*. 75(3):779–790. doi:10.1785/BSSA0750030779.
- Warren-Smith E, Jacobs KM, Williams CA, Wallace LM, Taylor-Offord S, Abbott ER, D'Anastasio E, Hamling IH, Spesivtsev A, Rollins C. 2023. Summary report for science-case for GeoNet expansion SDP workshop #1. Lower Hutt, NZ: GNS Science. GNS Science miscellaneous series 146. 22 p.; doi:10.21420/64AZ-8Z54.
- Warren-Smith E, Lamb S, Stern TA, Smith E. 2017. Microseismicity in southern South Island, New Zealand: implications for the mechanism of crustal deformation adjacent to a major continental transform. *Journal of Geophysical Research: Solid Earth*. 122(11):9208–9227. doi:10.1002/2017JB014732.
- Warren-Smith E, Townend J, Chamberlain CJ, Boulton C, Michailos K. 2022. Heterogeneity in microseismicity and stress near rupture-limiting section boundaries along the late-interseismic alpine fault. *Journal of Geophysical Research: Solid Earth*. 127(10):e2022JB025219.