New Zealand Paleoseismic Site Database: Design and Overview of Version 1.0

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ABSTRACT

The *New Zealand Paleoseismic Site Database* (new term, new database) contains paleoseismic data (grouped into Slip Rate, Earthquake [EQ] Timings and Recurrence Interval [RI], and Single-Event Displacement [SED]) collected at specific sites along active faults throughout New Zealand. The database was developed as part of the New Zealand National Seismic Hazard Model 2022 Revision Project (NSHM 2022). The primary purpose is to compile paleoseismic data at specific sites to be used either as inputs into, or to constrain/validate outputs from, the Seismicity Rate Model. This report describes the purpose and design of the database, as well as the compilation process and contents of the first edition (Version 1.0).

The New Zealand Paleoseismic Site Database has two components: a Microsoft Excel spreadsheet, which is a stand-alone database and the focus of this report, and a Geographic Information System (GIS) feature class dataset that is a subset of, and is intended to be entered back into, the *AF.Points* (Active Fault Point features) layer in the Active Faults Database of New Zealand. The Excel Slip Rate worksheet was initially adapted from the UCERF3 Geologic-Slip-Rate Data spreadsheet, and the EQ Timings RI and SED worksheets were adapted from the Slip Rate worksheet. Each worksheet has a high-level division into two sets of attributes – Fault Data and Site Data. The Fault Data attributes pertain to faults in the New Zealand Community Fault Model (CFM) and are the data most likely to be used for the Seismicity Rate Model. The Site Data component includes the site-specific data, and a site is defined as a location where paleoseismic data, generally field data, has been obtained. A site must therefore have a grid reference, but some published combined records are also included where data from two or more sites have been aggregated (e.g. a composite earthquake record derived from two or more trench sites). Most rows in the spreadsheet are therefore Site Data, but, in the EQ Timings RI worksheet, each row is an inferred earthquake. The definitions, formats and guidelines for compiling each attribute in both the Excel spreadsheet and GIS feature class are described in a companion Data Dictionary (Litchfield 2022).

Version 1.0 of the New Zealand Paleoseismic Site Database was compiled by NL, JH, RM, RL and GC in 2020 and 2021, with input from RVD and other members of the New Zealand paleoseismology community. Version 1.0 contains both published and unpublished data, mostly onshore, and many sites were relocated using high-resolution Light Detecting and Ranging (LiDAR) Digital Elevation Models and orthophotos. The total number of sites is 2136, with 68 combined records, which have a reasonable geographic spread, particularly across onshore faults with slip rates of ≥1 mm/yr. The Slip Rate worksheet contains 862 sites situated on 189 CFM faults. The EQ Timings RI worksheet contains 304 sites and 953 records (earthquakes and combined records), situated on 99 CFM faults. The EQ Timings RI worksheet also includes Last Event (314) and previously documented (Reported) RI (100) records. Ninety-nine EQ Timings sites have three or more earthquakes that are currently being used for RI calculations in the NSHM 2022. The SED worksheet contains 970 sites and 17 combined records, situated on 90 CFM faults. The majority of SED sites are field-based displacement measurements for historical earthquakes, dominated by the 2010 Darfield and 2016 Kaikōura earthquakes.

Version 1.0 is considered as complete as possible in the time available for data compilation, but there are known data that could be compiled in future versions, including student theses and data currently being obtained and published. New versions are contingent upon funding but could be partial (e.g. regional) or full (~5 yearly?) updates. Two known issues that could be addressed in future versions are calibration of radiocarbon ages with consistent calibration curves and inclusion of more SED data from cumulative displacements.

KEYWORDS

Paleoseismic, active fault, database, slip rate, paleoearthquake, recurrence interval, single-event displacement

1.0 INTRODUCTION

The *New Zealand Paleoseismic Site Database* is a new database that contains paleoseismic data (grouped into Slip Rate, Earthquake [EQ] Timings and Recurrence Interval [RI], and Single-Event Displacement [SED]) collected at specific sites along active faults throughout New Zealand. These are primarily on-land faults, but some information on offshore faults is also included.

The New Zealand Paleoseismic Site Database was developed as part of the New Zealand National Seismic Hazard Model 2022 Revision Project (NSHM 2022, which started in earnest in late 2020) but should be useful for a range of other purposes. The primary purpose was to compile paleoseismic data at specific sites along faults in the New Zealand Community Fault Model (CFM) (Van Dissen et al. 2021; Seebeck et al. 2022) to be used either as constraints on inputs into the Geologic Deformation Model of the NSHM 2022 (e.g. slip rates) or to constrain and/or validate outputs from the Seismicity Rate Model (e.g. earthquake timings, reported recurrence intervals, single-event displacements).

Paleoseismic site data had not previously been compiled on this scale for New Zealand. The Active Faults Database of New Zealand (NZAFD; Jongens and Dellow 2003; Langridge et al. 2016) includes a points layer (*AF.Points*; Active Fault Point features) that includes some paleoseismic site data, primarily in the Wellington region and Marlborough Fault System, as well as New-Zealand-wide paleoseismic trench sites (Figure 1.1). However, the NZAFD *AF.Points* layer does not include many of the attributes required for the NSHM 2022, is out of date, contains a lot of low-quality data, and the database structure is challenging to revise. As a result, a new Microsoft Excel database (spreadsheet) was developed, accompanied by a Geographic Information System (GIS) feature class for entering into the *AF.Points* layer in the NZAFD.

The New Zealand Paleoseismic Site Database can therefore be considered to have two components, a Microsoft Excel spreadsheet, which is a stand-alone database, and a GIS feature class that is a subset of, and is intended to be entered back into, the *AF.Points* layer in the NZAFD. The definitions, formats and guidelines for compiling each attribute in both components are described in a companion Data Dictionary (Litchfield 2022). This report focuses on the stand-alone Excel database and provides an overview of the purpose (this section), the database design (Section 2) and the contents of Version 1.0 (Section 3). Version 1.0 is available at https://doi.org/10.21420/QFNX-0M28 and as Appendix 1.

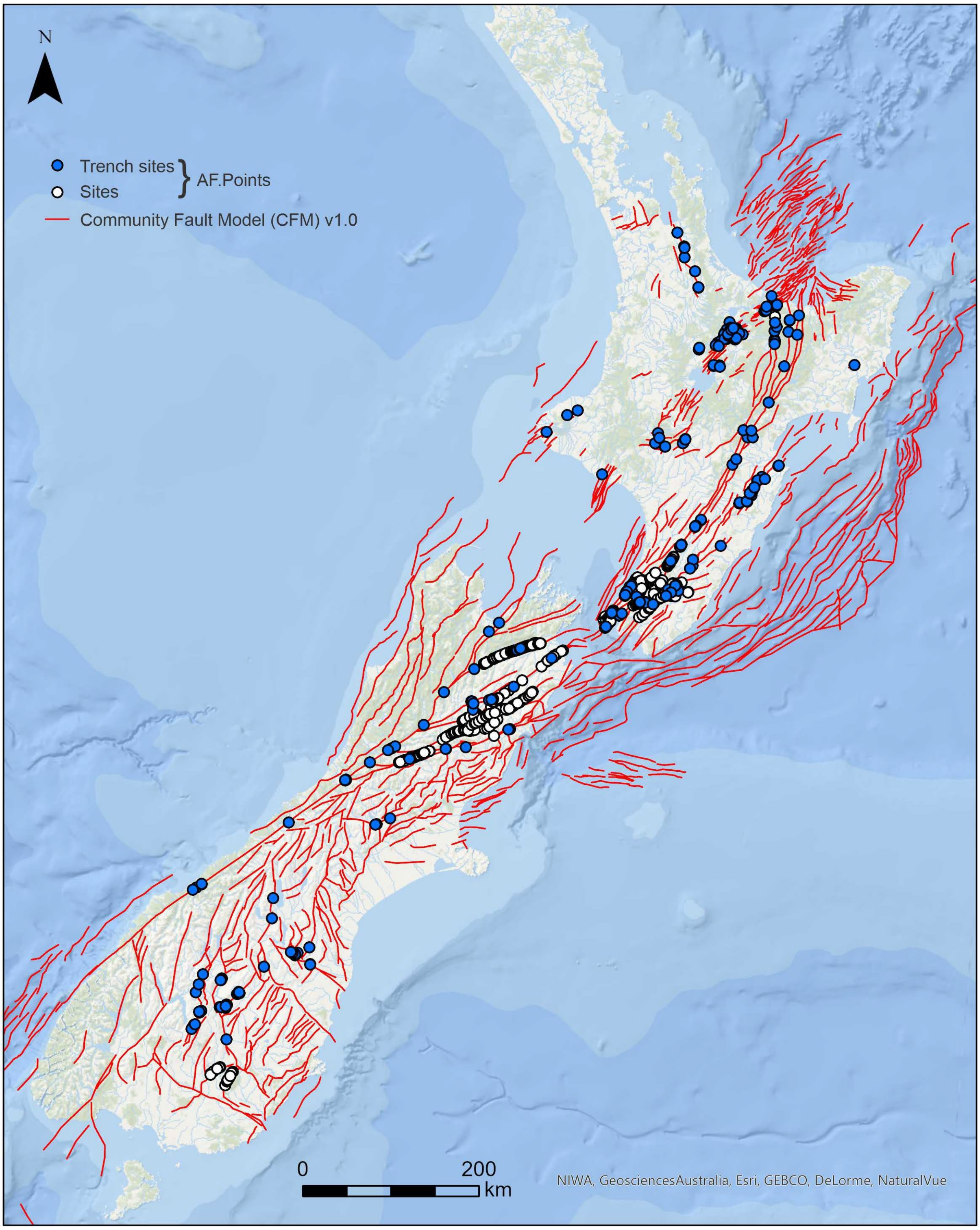

Figure 1.1 *AF.Points* layer of the New Zealand Active Faults Database. These are all of the data as at 12 October 2021 (n = 1984 points), but most were compiled prior to 2010. For comparison, see Figure 3.1, which shows the site locations in New Zealand Paleoseismic Site Database Version 1.0.

1.1 Definitions of Active Faults, Sites and Combined Records

The New Zealand Paleoseismic Site Database uses the same definition for an active fault as the NZAFD (Langridge et al. 2016) – for most parts of New Zealand, an active fault is defined as a fault that shows evidence of surface rupture or ground deformation in the last 125,000 years. The exception is in the Taupō Rift, where an active fault is defined as a fault that shows evidence of fault rupture during the last 25,000 years.

A site is defined in the New Zealand Paleoseismic Site Database as a location where paleoseismic data, generally field data, has been obtained. A site must have a grid reference (easting and northing in New Zealand Transverse Mercator projection and as accurate as possible; Litchfield 2022). The grid reference does not need to be unique, as, for example, multiple types of data (e.g. slip rate, earthquake timings and recurrence interval) are sometimes obtained from a single trench. There are two further nuances to the definitions of a site in Version 1.0 of the New Zealand Paleoseismic Site Database, as outlined in the next two paragraphs.

Some of the well-known New Zealand paleoseismic sites have been separated into different sites if paleoseismic data have been obtained from different markers at that location. For example, the 'Saxton River site' is a classic slip-rate location on the Awatere Fault (e.g. Zinke et al. 2017) (Figure 1.2). However, the slip rate, calculated from a series of offset river terrace risers, has been shown to vary through time. To capture this variability in the New Zealand Paleoseismic Site Database, two sets of sites have been included – one for each riser, and one for each incremental slip rate calculated between pairs of risers (Figure 1.2). The incremental Slip Rate sites are situated mid-way between the relevant pair of risers.

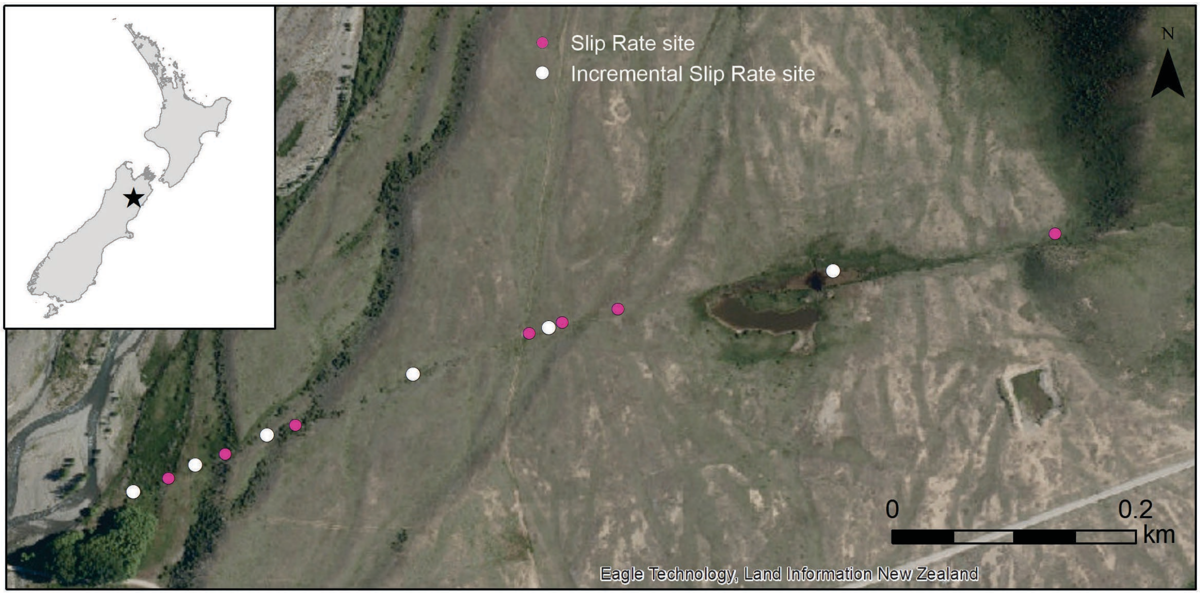

Figure 1.2 The classic 'Saxton River site' on the Awatere Fault in the northern South Island (see inset) where variable slip rates have been calculated (e.g. Zinke et al. 2017). These have been included as multiple sites in the New Zealand Paleoseismic Site Database.

For some multi-trace faults, such as those in the Taupō Rift, slip rates have been calculated by summing offsets on multiple traces along a transect (e.g. the Waihi and Poutu faults; Gómez-Vasconcelos et al. 2017; Figure 1.3). In Version 1.0 of the New Zealand Paleoseismic Site Database, these transects are represented by a single site, situated on the scarp with the largest offset.

Finally, there are some records included in Version 1.0 of the New Zealand Paleoseismic Site Database that are aggregated from two or more sites (e.g. an earthquake record from two or more nearby trench sites on the same fault). These are included because they provide information that is useful for aggregating site data to CFM faults (e.g. utilisation of a combined earthquake timing record to derive a recurrence interval for a specific fault so as to constrain the activity rate of that fault in the NSHM 2022 Seismicity Rate Model). These are referred to as 'combined records' but do not have a grid reference and are not included in the GIS feature class for uploading into the *AF.Points* layer of the NZAFD.

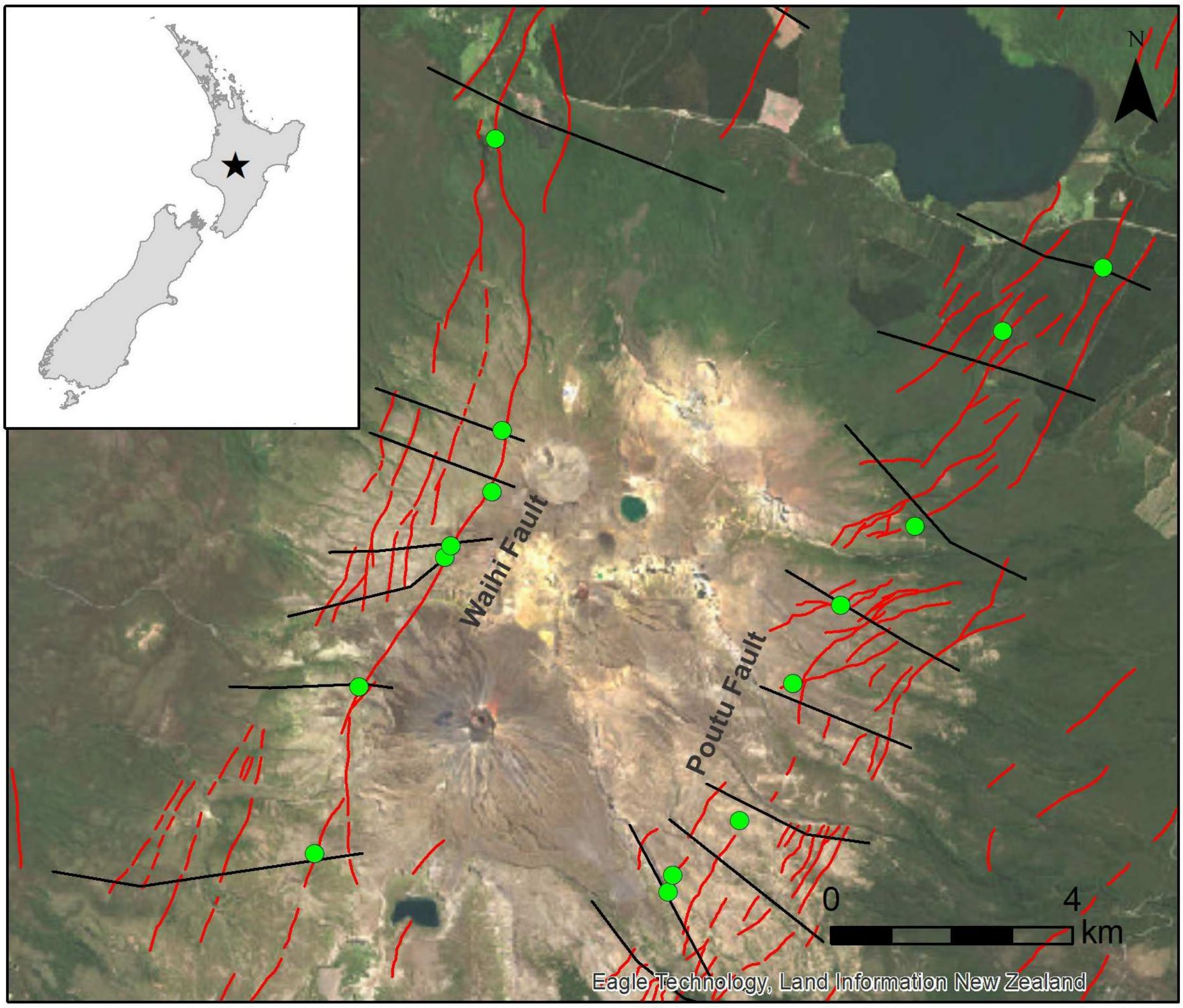

Figure 1.3 The Waihi and Poutu faults in the Taupō Rift (see inset), for which slip rates have calculated from measurements on several traces projected to transects (black lines, Gómez-Vasconcelos et al. 2017). These have been included in the New Zealand Paleoseismic Site Database as single sites situated on the traces with the largest offsets (green dots).

2.0 DATABASE DESIGN

The overall process for developing the New Zealand Paleoseismic Site Database Microsoft Excel spreadsheet structure and attributes was iterative – NL developed an initial version, which was modelled on the Uniform California Earthquake Rupture Forecast 3 (UCERF3) paleoseismic databases (Field et al. 2013). This was then trialled through populating some data, and adjustments were made. Next, it was distributed to the other compilers (JH, RM, RL and GC) and further changes were made. It is likely that additional changes will be required in the future as new types of datasets are added or the database is used for other purposes.

The spreadsheet contains four worksheets. Three contain the paleoseismic site data:

1. Slip Rate
2. Earthquake (EQ) Timings and Recurrence Interval (RI)
3. Single-Event Displacement.

The fourth worksheet,

4. Reference List,

accompanies the first three worksheets and contains the references and, where possible, their GNS Science Bibliographic Database (Bib) ID for all of the data in worksheets 1–3. Below, we describe the design of worksheets 1–3.

2.1 Slip Rate Worksheet Design

The Slip Rate worksheet was the first worksheet to be developed (and compiled; completed May 2021), adapted from the UCERF3 Geologic-Slip-Rate Data spreadsheet by Timothy Dawson and Ray Weldon (Appendix B of Field et al. [2013]). Table 2.1 shows mapping of attributes between the two databases.

Table 2.1 Attributes in the UCERF3 Geologic-Slip-Rate spreadsheet and the New Zealand Paleoseismic Site Database Slip Rate worksheet. Attribute definitions for the latter are contained in Litchfield (2022).

UCERF3 Geologic-Slip-Rate Data	New Zealand Paleoseismic Site Slip Rate Worksheet[1]
Fault Section	**Fault Data**
-	Fault
UCERF3 Fault Section	CFM Name
ID #	CFM No.
Style	CFM Sense Dominant
-	CFM Sense Secondary
Dip	CFM Dip (°)
Rake	CFM Rake (°)
Recency of Activity	-
USGS Slip Rate Category (mm/yr)	-
UCERF2 Section Slip Rate (mm/yr)	-
UCERF3 Slip Rate Bounds	-
UCERF3 Best Estimate Rate (mm/yr)	CFM Net SR (mm/yr)

UCERF3 Geologic-Slip-Rate Data	New Zealand Paleoseismic Site Slip Rate Worksheet[1]
UCERF3 assigned rate comments	CFM Net SR comments
Site-Specific Data	**Site Data**
-	Site DB ID
Site Name	Site Name
Longitude	Easting (NZTM)
Latitude	Northing (NZTM)
Local strike	Local Strike
UCERF3 Geologic Site Slip Rate (fault parallel, mm/yr)	CFM SR (mm/yr)
Reported Geologic Rate (mm/yr)	Reported SR (mm/yr)
Reported Component (slip rate)	Reported Component (SR)
Maximum Slip Rate (mm/yr)	Reported SR (mm/yr) Min.
Minimum Slip Rate (mm/yr)	Reported SR (mm/yr) Max.
-	SR (mm/yr) Calculated Uncertainties
Quality Rating	
QR1	QR1 Offset Feature (A–D)
QR2	QR2 Dating (A–D)
QR3	QR3 Overall (A–D)
Reported component (offset)	Reported Component (Offset)
Preferred Offset (m)	Reported Offset (m)
Maximum Offset (m)	-
Minimum Offset (m)	-
Offset Feature	Offset Feature(s)
-	No. of Measurements
-	Reported Age (ka)
Preferred Start Age (ka)	Start Age (ka) Pref.
Maximum Start Age (ka)	Start Age (ka) Max.
Minimum Start Age (ka)	Start Age (ka) Min.
Preferred End Age	End Age (ka) Pref.
Maximum End Age	End Age (ka) Max.
Minimum End Age	End Age (ka) Min.
Dating Method	Dating Method
Slip rate time frame category (ka)	SR Timeframe Category (ka)
Preferred Number Events	No. of Events Pref.
Number Events (max)	No. of Events Max.
Number Events (min)	No. of Events Min.
Comments regarding geologic slip rate	Comments Regarding SR
-	Comments Regarding Dating

UCERF3 Geologic-Slip-Rate Data	New Zealand Paleoseismic Site Slip Rate Worksheet[1]
Citation	Data Source
-	Initially Compiled By
-	Last Updated
-	Updated By
-	Last QA'd
-	QA'd By

[1] The order of some of these attributes differs from the worksheet in order to do the mapping.

As can be seen from Table 2.1, the overall layout of the UCERF3 database was adopted, with a high-level division of the attributes into two sets: (1) Fault Data (worksheet columns A–I) and (2) Site Data (worksheet columns J–AU).

For the New Zealand Slip Rate worksheet, the Fault Data attributes pertain mainly to the CFM faults[1], but the Fault attribute in the first column (A) is the name of the fault that is commonly used in the NZAFD and/or in the publication from which the data were obtained. Other differences between the UCERF3 and New Zealand Paleoseismic Site Database Fault Data attributes include:

- the addition of CFM Sense Secondary to avoid any potential confusion between the dominant and secondary components;
- not including Recency of Activity, which is captured in the CFM database (Seebeck et al. 2022); and
- not including UCERF2- and UCERF3-specific attributes.

For the Site Data, the differences are:

- the addition of SR (mm/yr) Calculated Uncertainties to record uncertainties that were not included in the original data and have been calculated by the compiler;
- not including specific attributes for Maximum and Minimum Offset, which are included in the Reported Offset (m) attribute;
- the addition of the No. of Measurements, as sometimes several measurements are combined to calculate slip rate;
- the addition of Reported Age (ka), to preserve the original age in the original format and to enable quick double-checking of the Start and End ages;
- the addition of attributes recording who compiled and reviewed (QA'd) the data and the dates, to keep a track record of updates.

The Quality Rankings are almost identical to the UCERF3 Geologic-Slip-Rate Data, with some minor changes such as adding New Zealand examples (e.g. Last Glacial Maximum [LGM] aggradational terrace and replacing the Bishop ash Dating datum) and QR2 Dating B, including 'Low-quality radiometric dates'.

1 CFM attributes of Sense, Dip and Rake are included in the Paleoseismic Site Database because they are the attributes required to calculate CFM slip rate and also allow tracking of these back to the original site data.

2.2 Earthquake Timings and Recurrence Interval Worksheet Design

The Earthquake Timings and Recurrence Interval (EQ Timings RI) worksheet was the second to be developed (and compiled; completed August 2021) and was initially adapted from the Slip Rate worksheet, as there is no equivalent UCERF3 database. However, it does contain some features of the UCERF3 Recurrence Database by Ray Weldon et al. (Appendix G of Field et al. [2013]). The features adopted from the UCERF3 database include listing each inferred Earthquake (Event) on a separate row and referring to the maximum and minimum ages as ‘Old’ and ‘Young’, respectively.

As in the Slip Rate worksheet, there is a high-level division of the attributes into two sets: (1) Fault Data (worksheet columns A–J) and (2) Site Data (worksheet columns K–AJ) (Table 2.2). The Fault Data attributes pertain mainly to the CFM faults, except for the Fault attribute in the first column (A), which is the name of the fault that is commonly used. CFM Name, Number and Dominant and Secondary Sense are included, but the remainder of Fault Data pertain to the Reported (previously documented) RI for each CFM Fault. It should be noted that the New Zealand CFM does not explicitly contain earthquake timings or recurrence intervals, but they are compiled for use in other projects. EQ Timings records from off-fault sites (e.g. lake cores, marine terraces) are assigned to CFM faults where possible, but, where there is uncertainty as to the relevant CFM fault, the Fault attribute is listed as ‘Off-fault’.

Overall, there are fewer Site Data attributes in the EQ Timings RI worksheet (26) than the Slip Rate worksheet (38), and these attributes are further subdivided into two subsets: (1) Reported RI data for each site (worksheet columns K–R) and (2) EQ data for each site (worksheet columns S–AD) (Table 2.2).

Table 2.2 Attributes in the New Zealand Paleoseismic Site Database EQ Timings RI worksheet. Attribute definitions are contained in Litchfield (2022).

Fault Data	Site Data – Reported RI	Site Data – Earthquakes
Fault	Site DB ID	Earthquakes
CFM Name	Site Name	Reported EQ Age
CFM No.	Easting (NZTM)	Old (cal. yr BP) Pref.
CFM Sense Dominant	Northing (NZTM)	Old (cal. yr BP) Min.
CFM Sense Secondary	Reported RI (years)	Old (cal. yr BP) Max.
RI (years)	No. of EQs	Young (cal. yr BP) Pref.
No. of Earthquakes	Reported RI Method	Young (cal. yr BP) Min.
QR RI (A–C)	QR RI (A–C)	Young (cal. yr BP) Max.
RI Comments	-	QR1 Earthquake Dating (A–C)
RI Data Source	-	QR2 Earthquake Evidence (A–C)
-	-	QR3 Overall (1–3)
-	-	Comments
-	-	Data Source
-	-	Initially Compiled By
-	-	Last Updated
-	-	Updated By
-	-	Last QA’d
-	-	QA’d By

EQ Timings are reported in two formats: (1) in the original format as documented (Reported EQ Age – calibrated or uncalibrated) and (2) in calibrated years before present (Old and Young ages). Radiocarbon ages have not been recalibrated to a consistent calibration curve (e.g. SHCAL20 or MARINE20), but, when documented, the calibration curve used by the authors is noted in the Comments attribute. Uncalibrated (conventional) radiocarbon ages have also not been compiled.

The timing of the Last or Most Recent Event is not included as a separate attribute but is instead included as EQ1 (LE) for each site or combined record. Likewise, the penultimate and antepenultimate earthquakes are included as EQ2 (PE) and EQ3 (APE). It should be noted that the 'LE' is the Last Event reported at a site but may not necessarily be the LE for the entire fault.

The EQ Timings Quality Rankings (QRs) were developed specifically for this database and are modelled on those developed for (off-fault) Hikurangi subduction earthquake records by Clark et al. (2019). Three quality rankings are given – for the certainty of the earthquake dating (QR1), for the certainty that the event in question is an earthquake (QR2) and an overall ranking (QR3) from a matrix based on QR1 and QR2 (Table 2.3). For example, an event horizon in a trench or a core may be able to be precisely dated using Bayesian statistical modelling of multiple radiocarbon ages and thus have a high QR1 (A). However, there may be other possible explanations for the event horizon, such as a large storm, resulting in a moderate QR2 (B). Using the matrix, this would result in an overall QR3 of 2.

Table 2.3 EQ Timings overall quality ranking matrix. The number of records in Version 1.0 are given in brackets and are discussed in Section 3.4.

Matrix – Overall Earthquake Certainty Ranking (QR3) 1 = High, 2 = Moderate, 3 = Low		**Quality of Earthquake Dating (QR1)**		
		A – Good	**B – Average**	**C – Poor**
Evidence Event is an Earthquake (QR2)	A – Strong	1 (n = 60)	2 (n = 184)	3 (n = 83)
	B – Moderate	2 (n = 118)	2 (n = 216)	3 (n = 168)
	C – Weak	3 (n = 1)	3 (n = 47)	3 (n = 50)

2.3 Single-Event Displacement Worksheet Design

The Single-Event Displacement (SED) worksheet was the final component to be developed (and compiled; completed October 2021) and was initially adapted from the Slip Rate worksheet, as there is no equivalent UCERF3 database. The UCERF3 Slip-in-the-Last-Event Data by Chris Madden et al. (Appendix R of Field et al. [2013]) was consulted, but it contains aggregated data for Fault Sections rather than site-specific data. The SED worksheet includes SED estimates from both the last ground-surface-rupturing earthquake (slip-in-the-last-event) and cumulative offsets from multiple earthquakes.

As per the Slip Rate and EQ Timings RI worksheets, there is a high-level division of the attributes into two sets: (1) Fault Data (worksheet columns A–I) and (2) Site Data (worksheet columns J–AA) (Table 2.4). The Fault Data attributes pertain primarily to CFM faults and are the same as the Slip Rate worksheet, except for columns H and I, which are SED Net (m) and Net SED Comments rather than CFM Net SR (mm/yr) and CFM Net SR Comments, respectively. It should be noted that the New Zealand CFM does not explicitly contain SED, but they are compiled for use in other projects.

Table 2.4 Attributes in the New Zealand Paleoseismic Site Database Single-Event Displacement worksheet. Attribute definitions are contained in Litchfield (2022).

Fault Data	Site Data
Fault	Site DB ID
CFM Name	Site Name
CFM No.	Easting (NZTM)
CFM Sense Dominant	Northing (NZTM)
CFM Sense Secondary	Reported SED (m)
CFM Dip (°)	Reported Component (SED)
CFM Rake (°)	No. of Measurements
SED Net (m)	SED Net (m)
Net SED Comments	Net SED Comments
-	QR SED (A–C)
-	Offset Feature
-	Comments Regarding SED
-	Data Source
-	Initially Compiled By
-	Last Updated
-	Updated By
-	Last QA’d
-	QA’d By

The SED Site Data worksheet has the fewest number of attributes (18) of the three datasets, as information such as ages are not included as explicit attributes. However, if these are known (e.g. the year of a historical earthquake), they are included in the Comments Regarding SED attribute. Like the Slip Rate worksheet, both the reported SED and a Net SED are included, as often the latter has been calculated for this compilation using the CFM dip.

A single Quality Ranking was developed specifically for this database and is relatively simple, based upon the number and resolution of the measurements.

3.0 NEW ZEALAND PALEOSEISMIC SITE DATABASE VERSION 1.0

3.1 Compilation Process and Philosophy

Version 1.0 of the New Zealand Paleoseismic Site Database was compiled by NL, JH, RM, RL and GC in 2020 and 2021. RVD and other members of the New Zealand paleoseismology community were consulted on the overall process, attributes and to obtain data as required. To avoid duplication, each compiler started their site database ID numbers at an interval of 1000 (e.g. NL started at 1, JH started at 1000, RM started at 2000, etc). As a result, there are gaps in the site database ID numbers.

In order to include as much paleoseismic site data as possible, Version 1.0 includes both published and unpublished data. Preference was given to data published in peer-reviewed journals, followed by data documented in 'grey literature' reports such as consulting/client reports and fieldtrip guides, followed by student theses. Some undocumented slip rate sites developed for Version 1.0 of the CFM (Seebeck et al. 2022) are also included.

Paleoseismic site data were identified through consulting previous compilations (e.g. the *AF.Points* layer in the NZAFD; Litchfield et al. 2014; Nicol et al. 2016), personal knowledge, checking with colleagues in the New Zealand paleoseismology community and literature searches. There are some known paleoseismic sites (e.g. trenches) that have not been included because there is not enough documentation to do so (*AF.Points* sites are discussed in Section 3.2), such as if the site cannot be located or key information missing (e.g. offset for slip rate).

For locations that have been studied more than once, and that use the same geomorphic markers, then only the most recent data were compiled. However, if the most recent studies only updated paleoseismic information for certain fault or landscape features (e.g. dated only one terrace riser), previous data were also included at the compilers discretion.

For the Slip Rate sites, the compilation started with the highest slip rate faults in the CFM and then continued in order of decreasing slip rate as time permitted. For the EQ Timings RI sites, the compilation started with well documented, published, trench sites and tried to incorporate as many trench sites as possible in the time available. The SED site compilation prioritised published, well-constrained SED sites, as well as historical earthquake displacements. For all datasets, a geographic spread as wide as possible was also attempted.

Sites were situated in a GIS as accurately as possible. Many older sites were relocated using higher-resolution maps such as Light Detecting and Ranging (LiDAR) Digital Elevation Models (DEMs) and orthophotos. For some sites, the relocation was undertaken by first plotting the site from a grid reference and then refining it based on figures and descriptions of the fault feature or offset marker. For some sites with no grid reference or detailed maps, there is considerable uncertainty in the relocation. The relocation method and uncertainty have been documented in the *Other_Info* and *Method_Acc* fields of the GIS feature class.

The data were compiled in separate spreadsheets and GIS feature class files by each compiler and were incorporated into master datasets by NL. The data were also reviewed by NL, which should ensure some consistency in the data compilation. To date, NL's data has not been reviewed.

3.2 Version 1.0 Overview

Version 1.0 of the New Zealand Paleoseismic Site Database is available at https://doi.org/10.21420/QFNX-0M28 and also as Appendix 1. It contains data for 2136 sites and 68 combined records. Site locations are shown in Figure 3.1, and a summary of the breakdown for each worksheet is contained in Table 3.1.

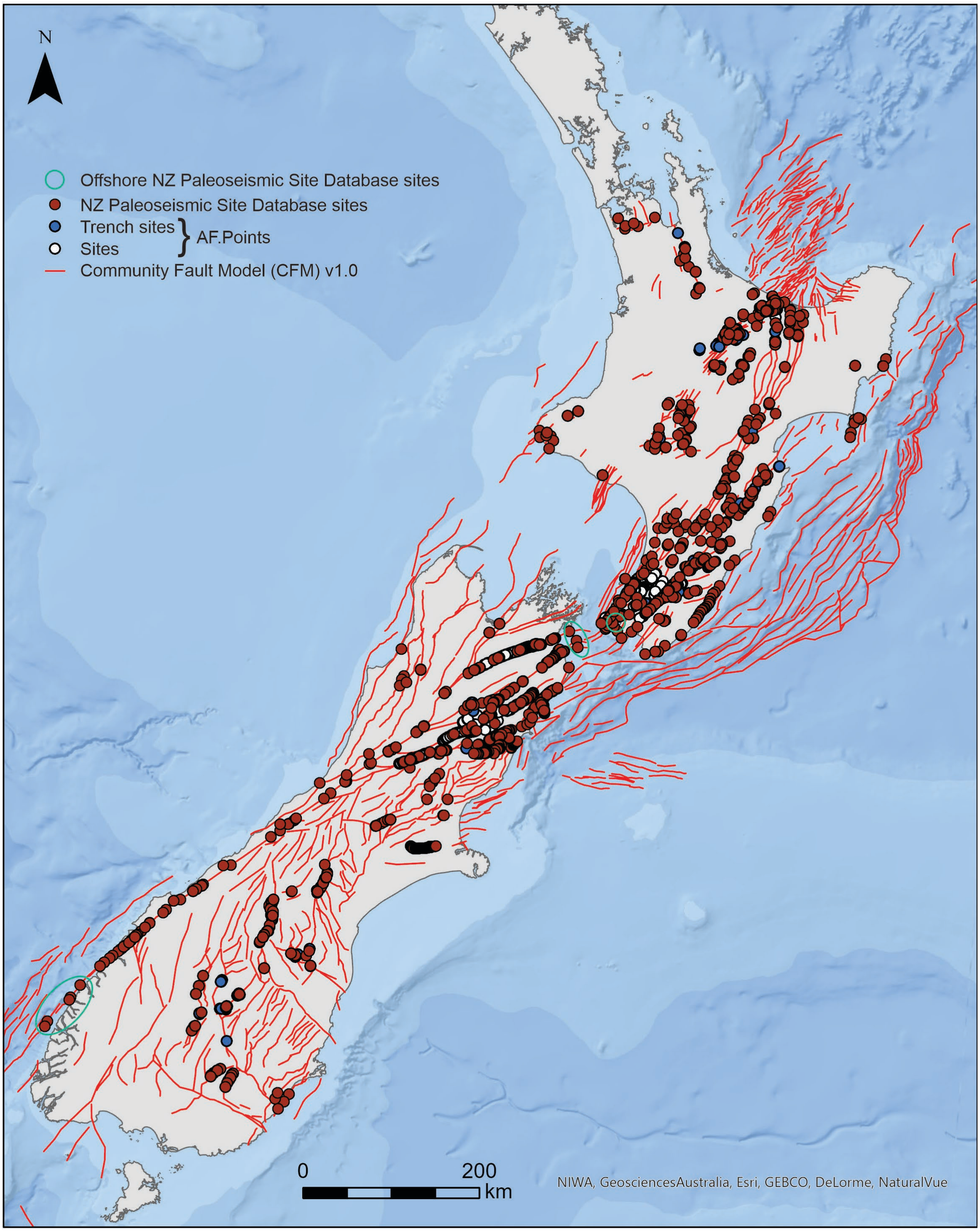

Figure 3.1 New Zealand Paleoseismic Site Database Version 1.0 overlain on the *AF.Points* layer of the New Zealand Active Faults Database (Figure 1.1). Sites on offshore faults are circled (green) and include the Alpine Fault off the southwest coast and the Wairau, Cloudy, Vernon and Aotea faults in central New Zealand.

Table 3.1 Number of records for each worksheet in Version 1.0 of the New Zealand Paleoseismic Site Database.

Worksheet	Total Records	Sites	Combined Records	Offshore Sites	Overall QRs	CFM Faults
Slip Rate	871	862	9	10	A – 189 (22%) B – 516 (60%) C – 151 (18%) D – 4 (0.5%)	189 (21%)
EQ Timings RI	953	304	42	4	1 – 60 (7%) 2 – 509 (55%) 3 – 350 (38%)	99 (11%)
Single-Event Displacement	987	970	17	4	A – 438 (45%) B – 464 (48%) C – 85 (9%)	90 (10%)
Totals	**2811**	**2136**	**68**	**18**	**-**	**214 (24%)**

Figure 3.1 shows that the 2136 sites compiled in the New Zealand Paleoseismic Site Database Version 1.0 include most, but not all, of the sites in the *AF.Points* layer of the NZAFD (also shown in Figure 1.1). The *AF.Points* sites not included in the New Zealand Paleoseismic Site Database include trenches that did not contain active faults or sites that have not been documented, either at all or to include key data such as offset measurements or ages.

The majority of sites in Version 1.0 are situated onshore (Figure 3.1, Table 3.1). Eighteen offshore sites have been included – ten Slip Rate sites on the southern, submarine part of the Alpine Fault and four EQ Timing RI and four SED sites on the northern, submarine parts of the Wairau, Cloudy, Vernon and Aotea faults. The Alpine Fault Slip Rate sites are included because key data, including grid references, have been published (Barnes 2009). The Wairau, Cloudy, Vernon and Aotea fault sites are included because they are the only published paleoearthquake records for submarine faults (Barnes and Pondard 2010; Pondard and Barnes 2010; Barnes et al. 2019). The locations of the Wairau, Cloudy, Vernon and Aotea fault sites are approximated as the centre of several seismic reflection profiles from maps in the publications. To include offshore sites for other submarine faults would require considerable effort to consult the original data (i.e. seismic line locations) and calculations and was considered beyond the scope of Version 1.0.

Version 1.0 sites are situated on 214 CFM faults, which is 24% of the total number of CFM faults (882) (Seebeck et al. 2022). The onshore sites are situated on 209 CFM faults, which are 42% of the CFM faults that are wholly, or partly, onshore (503). The breakdowns of these for each worksheet, as well as other aspects specific to each worksheet, are discussed in the following sections.

3.3 Slip Rate Worksheet Version 1.0

The Slip Rate worksheet of Version 1.0 of the New Zealand Paleoseismic Site Database contains 862 Slip Rate sites and nine combined records (Appendix 1, Table 3.1, Figure 3.2). The sites are situated on 189 CFM faults, which is 21% of the total number of faults.

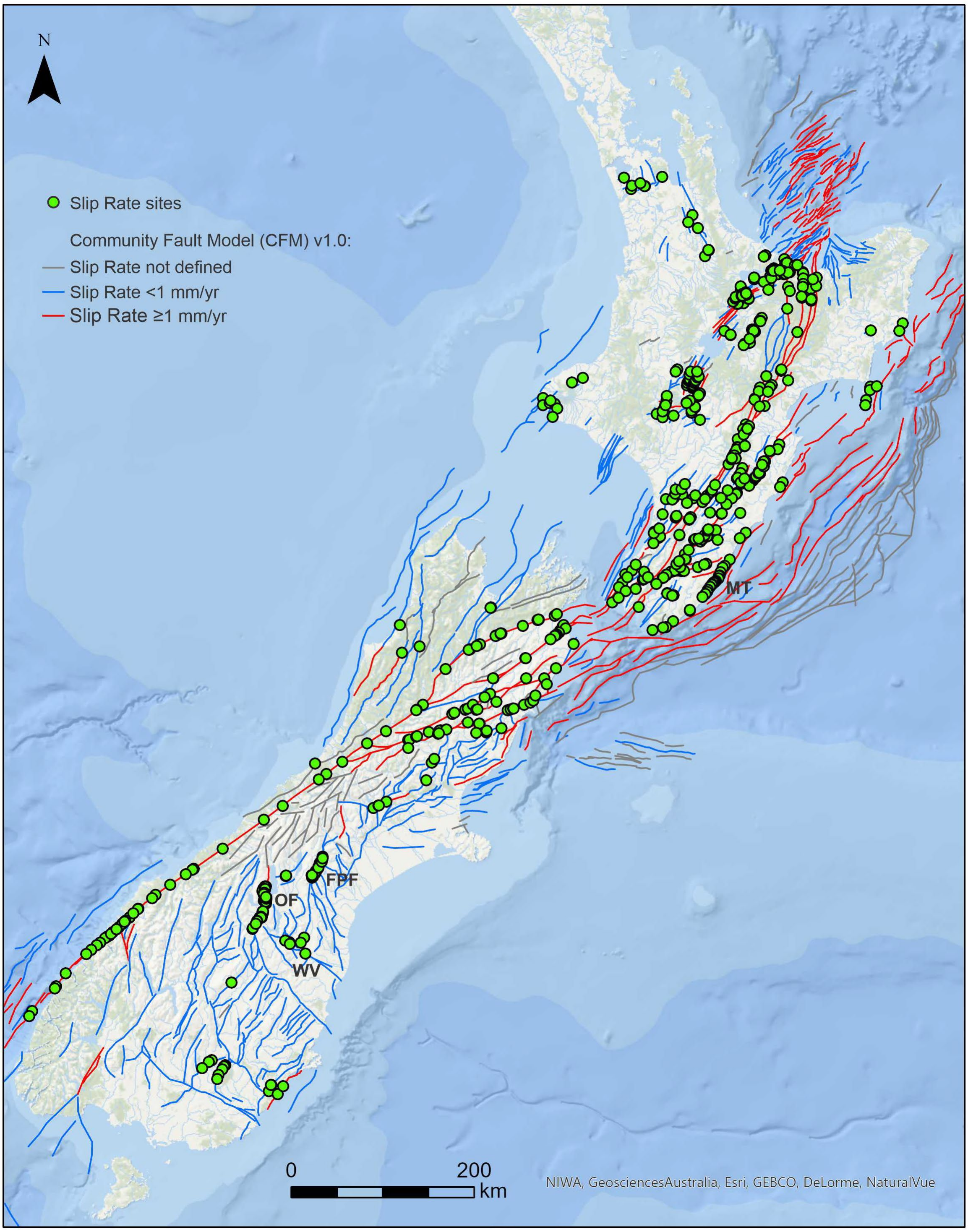

Figure 3.2 New Zealand Paleoseismic Site Database Version 1.0 Slip Rate sites. FPF is the Fox Peak Fault, MT is marine terrace, OF is the Ostler Fault, WV is the Waitaki Valley.

Figure 3.2 shows that there is a reasonable geographic spread of Slip Rate sites, and there are sites on the majority of onshore CFM faults with slip rates of ≥1 mm/yr. There are some concentrations of Slip Rate sites along a few faults reflecting the locations of detailed studies. For example, there are 151 sites along the Ostler Fault (OF) and 48 sites along the Fox Peak Fault (FPF), which are from two PhD studies (Amos et al. 2007, 2010; Stahl et al. 2016). There are other concentrations of Slip Rate sites, such as along the southeast coast of the North Island, which are marine terraces inferred to record uplift on nearshore faults (labelled 'MT' on Figure 3.2) and areas where site-specific hazard investigations have been undertaken (e.g. the Waitaki Valley, WV).

Almost all Slip Rate sites in Version 1.0 are from field data. Approximately two-thirds of offset measurements are from alluvial (fans or rivers) landform features; the remainder are dominated by tephra or volcanic landforms. Approximately 40% have some age constraints, mainly from Optically Stimulated Luminescence (OSL), radiocarbon, tephrochronology and weathering-rind dating techniques.

Quality Rankings have been assigned to almost all Slip Rate sites, except for a few that are currently being documented (North Leader and The Humps faults) and some combined records. Of these, the majority (82%) have an A or B ranking (Table 3.1). Only four sites with a D ranking are included, as D is defined as unreliable, and it was decided that compiling D sites was not a priority for Version 1.0.

3.4 Earthquake Timings and Recurrence Interval Worksheet Version 1.0

The EQ Timings RI worksheet of Version 1.0 of the New Zealand Paleoseismic Site Database contains a total of 953 records (earthquakes and combined records) on 304 sites (Appendix 1, Table 3.1, Figure 3.3). The sites are situated on 99 CFM faults, which is 11% of the total number of faults.

Figure 3.3 shows that there is a reasonable geographic distribution of EQ Timings RI sites, particularly on faults with slip rates of ≥1 mm/yr. Notable gaps are in the north (Auckland), NW Nelson and Southland, and there is work currently underway in each area, but particularly Southland (M Stirling, pers. comm. 2020).

The majority of EQ Timings RI sites are trenches, but there are also a few natural exposures, lake core and marine terrace records. The longest earthquake record is the 24 earthquake Alpine Fault Hokuri Creek record (e.g. Berryman et al. 2012), and there are a total of 99 sites with three or more earthquakes (Table 3.2).

Table 3.2 Numbers of sites with three or more earthquakes in the EQ Timings RI worksheet in Version 1.0 of the New Zealand Paleoseismic Site Database.

Number of Earthquakes	Number of Sites
24	1
15	1
13	1
12	1
9	3
8	2
7	2
6	11
5	12
4	29
3	36
Total	**99**

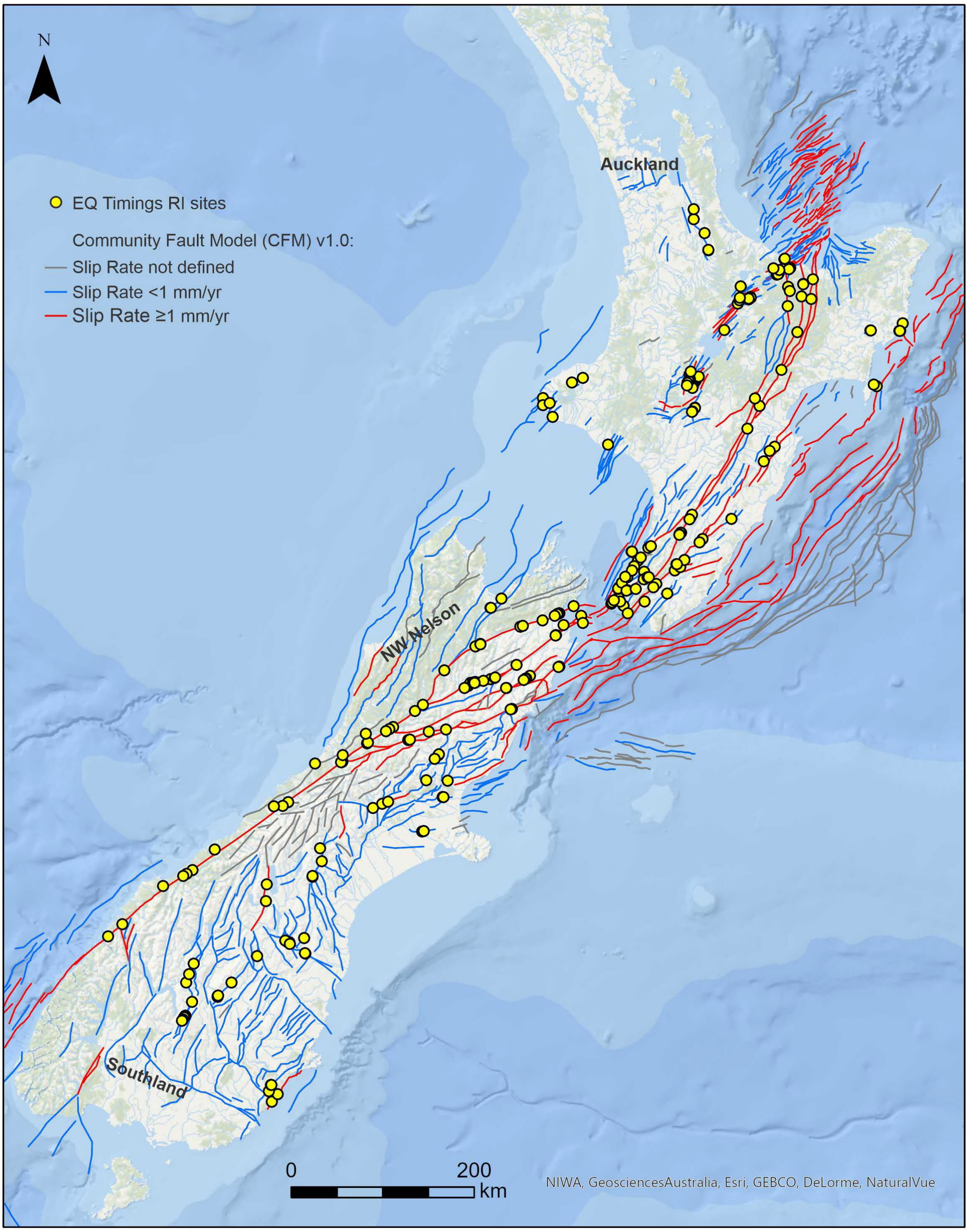

Figure 3.3 New Zealand Paleoseismic Site Database Version 1.0 EQ Timings RI sites.

Quality Rankings have been assigned to almost all of the earthquakes. Of these, 60 have an overall QR of 1 (7%), 509 have an overall QR of 2 (55%) and 350 an overall QR of 3 (38%). The breakdown to the Dating QR1 and Earthquake Evidence QR2 is contained in Table 2.3. This shows that the majority (400) of records with an overall QR of 2 (509) are because the Dating QR1 is considered to be average (B). These include some records dated by radiocarbon dating, but not using Bayesian statistical modelling, from tephrochronology, which are either from inferred correlations or only loosely constrained earthquake ages or from records with only a few radiocarbon dates and earthquake ages are inferred from sedimentation rates. Thus, if there is a desire for further granulation of the overall QRs, QR1 and QR2 could be used.

The Last Event has been compiled for 314 records and 98 CFM faults. Of the 314 records, 32 have an overall QR of 1 (10%), 135 have an overall QR of 2 (43%) and 141 have an overall QR of 3 (45%). The remainder have not been assigned a QR because they do not have ages.

The RI data in Version 1.0 of the New Zealand Paleoseismic Site Database are previously documented values. That is, they are RIs documented or published for sites or faults, and no attempt has been made to calculate RI from the EQ Timings data. This is being undertaken elsewhere for the NSHM 2022 using the EQ Timings data in the site database, so the calculated RIs could be entered in future versions. Of the 100 Reported RI (worksheet column O) Site Data records compiled, three have a QR of A, 39 have a QR of B and 53 a QR of C. Fault Data RI (worksheet column F) has only been compiled for a handful of CFM faults where there is a good correlation between a fault with a well-constrained reported RI and the CFM fault or where there is high confidence in the applicability of the reported RI. For example, the Dunstan Fault RI is assigned to the CFM Dunstan Fault, and the RI from the Hokuri Creek record is assigned to the Alpine: George to Jacksons CFM fault.

3.5 Single-Event Displacement Worksheet Version 1.0

The Single-Event Displacement (SED) worksheet of Version 1.0 of the New Zealand Paleoseismic Site Database contains 970 SED sites and 17 combined records (Appendix 1, Table 3.1, Figure 3.4). The sites are situated on 90 CFM faults, which is 10% of the total number of faults.

The SED sites are the least geographically spread of the three datasets, but many are on onshore faults with slip rates of ≥1 mm/yr (Figure 3.4). They are strongly clustered on faults that have ruptured in the written historical period (post ~1840 AD), and few SEDs have been compiled from cumulative displacements from multiple earthquakes because of uncertainty in the calculation of the number of earthquakes or in relocating the sites. The breakdown per historical earthquake and CFM fault is contained in Table 3.3 and shows, not surprisingly, that the majority of historical earthquake SED sites are from the most recent 2010 Darfield and 2016 Kaikōura earthquakes. However, it should be noted that the data for these earthquakes are primarily from field data, not from multiple LiDAR and orthophoto data (Litchfield et al. 2014), LiDAR differencing (Duffy et al. 2013) or optical image correlation (Zinke et al. 2019; Howell et al. 2020). Sites from older historical earthquakes are generally very incomplete, as the location information for many of the reported displacements is not accurate enough to allow plotting as a point in GIS.

Quality Rankings have been assigned to all SED records, and the majority are QR A or B (91%). Those assigned QR A are dominated by the highest-quality displacements measured for the 2010 Darfield and 2016 Kaikōura earthquakes and also include prehistoric SEDs calculated from back-slip of fault-offset landscape features using detailed topographic maps constructed from Real-Time Kinematic Global Navigational Satellite System (RTK-GNSS) or LiDAR data (e.g. Little et al. 2010; Manighetti et al. 2015; Zinke et al. 2021).

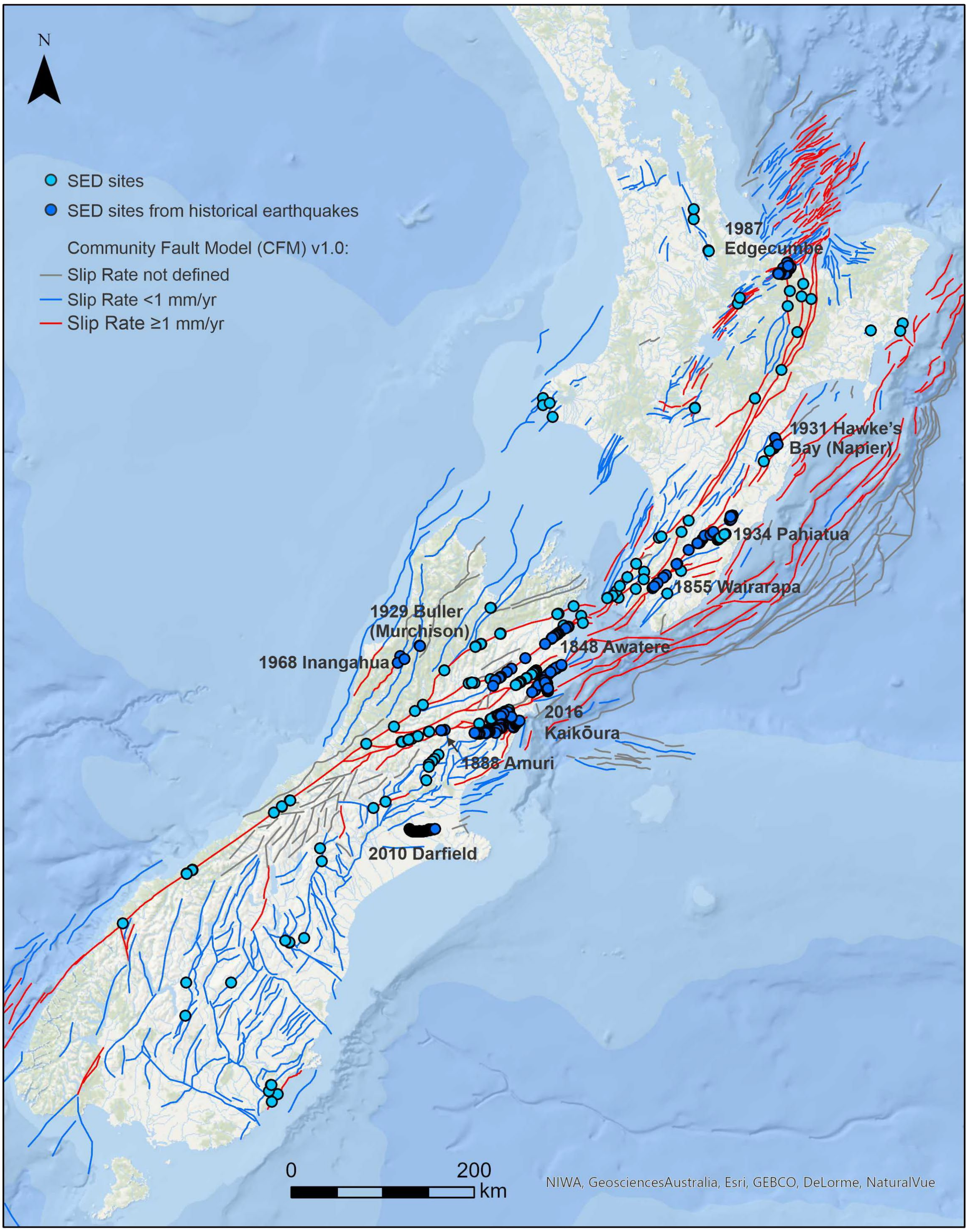

Figure 3.4 New Zealand Paleoseismic Site Database Version 1.0 Single-Event Displacement (SED) sites. Note the historical period is post ~1840 AD.

Table 3.3 Historical earthquake Single-Event Displacements (SED) in Version 1.0 of the New Zealand Paleoseismic Site Database.

Earthquake Year and Name	CFM Fault	Number of SED Sites
1848 Awatere	Awatere: Northeast 1	37
	Awatere Northeast 2	6
	Barefell	4
	Sub-total	47
1855 Wairarapa	Alfredton North	1
	Alfredton South	7
	Saunders Road?*	3
	Wairarapa: 2	19
	Wairarapa: 3	3
	Sub-total	30 or 33*
1888 Amuri	Hope: Hope River	3
1929 Buller (Murchison)	White Creek	4
1931 Hawke's Bay (Napier)	Awanui	3
	Waipukurau – Poukawa	4
	Sub-total	7
1934 Pahiatua	Saunders Road?*	3
	Waipukaka	11
	Sub-total	11 or 14*
1968 Inangahua	Inangahua	1
	Lyell	1
	Maimai North	1
	Sub-total	3
1987 Edgecumbe	Awaiti	4
	Edgecumbe 1987	23
	Otakiri	2
	Rotoitipakau	14
	Te Teko	2
	Sub-total	45
2010 Darfield	Greendale	203
2016 Kaikōura	Hundalee	27
	Jordan	14
	Kekerengu 1	97
	Leader: Central	5
	Leader: North	25
	Leader: South	29
	Papatea	106
	Stone Jug	5
	The Humps	117
	Upper Kowhai – Manakau	2
	Sub-total	433

* Schermer et al. (1998) could not distinguish if ruptures on the Saunders Road fault occurred in the 1855 Wairarapa or 1934 Pahiatua earthquakes, so they are listed under both, and the totals for each earthquake are shown including and not including these SEDs.

4.0 SUMMARY AND TOWARD VERSION 2.0

4.1 Summary

The New Zealand Paleoseismic Site Database was developed as part of the NSHM 2022 Revision Project. The purpose is to compile paleoseismic data at specific sites along faults in the New Zealand CFM to be used either as inputs into, or to constrain/validate outputs from, the Seismicity Rate Model, but it should also be useful for a range of other purposes.

The database contains two components, a Microsoft Excel spreadsheet, which is a stand-alone database, and a GIS feature class dataset that is a subset of, and intended to be entered back into, the *AF.Points* layer in the NZAFD. The Excel spreadsheet contains four worksheets:

1. Slip Rate
2. Earthquake (EQ) Timings and Recurrence Interval (RI)
3. Single-Event Displacement
4. Reference List.

The Slip Rate worksheet was initially adapted from the UCERF3 Geologic-Slip-Rate Data spreadsheet, and the EQ Timings RI and Single-Event Displacement worksheets were adapted from the Slip Rate worksheet.

Each worksheet is divided into two parts – Fault Data pertaining to the CFM faults and Site Data containing the site-specific data, including quality rankings, and compilation information. The attributes are described in a separate Data Dictionary (Litchfield 2022).

Version 1.0 of the New Zealand Paleoseismic Site Database was compiled by NL, JH, RM, RL and GC in 2020 and 2021, and NL reviewed the data compiled by others. The database includes both published and unpublished data, mostly onshore, and many sites were relocated using high-resolution LiDAR DEMs and orthophotos. Overall, Version 1.0 contains data for 2136 sites and 68 combined records, situated on 214 CFM faults.

The Slip Rate worksheet contains 862 sites situated on 189 CFM faults. Almost all Slip Rate sites are from field data and the majority (82%) have an A or B quality ranking.

The EQ Timings RI worksheet contains 304 sites and 953 records (earthquakes and combined records), situated on 99 CFM faults. The majority of EQ Timings RI sites are trenches, but there are also some natural exposures, lake core and marine terrace records. The Last Event has been compiled for 314 records and 98 CFM faults, and there are 99 records of three earthquakes or more. Overall quality rankings for the EQ Timings have been assigned based on a matrix of Dating and Earthquake Evidence: 60 have an overall QR of 1 (7%), 509 have an overall QR of 2 (55%) and 350 an overall QR of 3 (38%). The RI data are restricted to previously documented values and have not been calculated from the EQ Timings data. Reported RI has been compiled for 100 records, but only a handful of CFM faults. The majority have a quality ranking of B or C.

The Single-Event Displacement worksheet contains 970 sites and 17 combined records, situated on 90 CFM faults. The majority of SED sites are field-based displacements for historical earthquakes and are dominated by the 2010 Darfield and 2016 Kaikōura earthquakes. The majority have a quality ranking of A or B.

4.2 Toward Version 2.0

Version 1.0 of the New Zealand Paleoseismic Site Database is considered as complete as possible in the time that was available. The compilations were completed for the Slip Rate, EQ Timings RI and Single-Event Displacement worksheets in May, August and October 2021, respectively, and so should contain most of the published and many unpublished data available at those dates. However, there are known data that could be compiled in future versions, such as data in grey literature (e.g. consulting reports, student theses), as well as new data that are currently being obtained and will no doubt be published in due course.

New versions of the New Zealand Paleoseismic Site Database will be contingent upon appropriate funding, but it is anticipated that periodic review and update could be undertaken on a frequency similar to that proposed for updates of the NSHM (i.e. every ~5 years). A working version 1.1 is currently being maintained by GNS Science, and interim, partial, updates (i.e. versions 1.2, 1.3, etc.) could be undertaken if a large dataset becomes available in one or more regions. For example, update of the Single-Event Displacement worksheet following a surface-rupturing earthquake or the Slip Rate or EQ Timings RI worksheets following the publication of a large regional dataset. We anticipate that future updates would likely be led by the authors of this report with input from the New Zealand paleoseismology community. We are not currently soliciting data for future updates, but welcome feedback, suggestions for improvement and notification of missing and new datasets.

There are likely several improvements that could be made to the New Zealand Paleoseismic Site Database, but one key known issue is that the radiocarbon ages in Version 1.0 have not been recalibrated to a consistent calibration curve (e.g. SHCAL20 or MARINE20). This was not undertaken for Version 1.0 because it is a very large job and beyond the scope and time available. It would be ideal if this could be done in future versions to update calculations, such as slip rates, to allow better comparison of earthquake timings between sites and to update the timing of the most recent earthquakes for calculations of conditional probability. Another known issue with Version 1.0 is that the SED data are dominated by historical earthquake data, and more effort could be undertaken to compile SED data from cumulative displacements in multiple earthquakes.

5.0 ACKNOWLEDGMENTS

The New Zealand Paleoseismic Site Database development and compilation, and this report, were funded by the New Zealand Ministry of Business, Innovation & Employment to GNS Science via the National Seismic Hazard Model 2022 Revision Project (contract 2020-BD101). The report was reviewed by Nick Horspool and Delphine Fitzenz.

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APPENDICES

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APPENDIX 1 NEW ZEALAND PALEOSEISMIC SITE DATABASE VERSION 1.0

Appendix 1 is provided as a Microsoft Excel file attachment in the PDF.

www.gns.cri.nz

Principal Location

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