Development of the New Zealand Community Fault Model – version 1.0

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ABSTRACT

There has been a long-identified need in New Zealand for a community-developed, three-dimensional (3D) model of active faults that is publicly accessible and available to all practitioners. Over the past year, work has progressed on building and parameterising such a model – the New Zealand Community Fault Model (NZ CFM). The NZ CFM will serve as a unified and foundational resource for many societally important applications such as the National Seismic Hazard Model, Resilience to Natures Challenges Earthquake and Tsunami Programme, physics-based fault systems modelling, earthquake ground-motion simulations, and tsunami hazard evaluation.

Version 1.0 of the NZ CFM is nearing completion and release. NZ CFM v1.0 provides a simplified 3D representation of New Zealand's crustal-scale active faults (including a selection of potentially seismogenic faults) compiled at a nominal scale of 1:500,000 to 1:1,000,000. NZ CFM faults are defined based on surface geology, seismicity, seismic reflection profiles, wells, and geologic cross-

sections. The model presently incorporates more than 800 triangulated mesh surfaces as representations of active and/or potentially seismogenic faults linked to parameters such as dip and dip direction, seismogenic rupture depth, sense of movement, slip direction, and net slip rate.

1 INTRODUCTION

Community fault models (CFMs) aim to provide consistent and broadly agreed representations of fault structures in a specific region. CFMs are built to provide the basis for further applications that require, for example, understanding of the geometric and kinematic characteristics of seismogenic faults in a region. The most mature CFM, now into its second decade, is the Southern California Earthquake Center Community Fault Model (https://www.scec.org/research/cfm) that comprises a three-dimensional (3D) representation of active faults in southern California and adjacent offshore basins (Plesch et al. 2007, 2016, Nicholson et al. 2017).

GNS Science has long maintained products such as the National Seismic Hazard Model's active fault earthquake source model (Fig 1a) (e.g., Stirling et al. 2012; https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/National-Seismic-Hazard-Model-Programme/Previous-seismic-hazard-models/2010-National-Seismic-Hazard-Model), New Zealand Active Faults Database (Langridge et al. 2016; https://data.gns.cri.nz/af/), Active Fault Model of New Zealand (Fig 1b) (Litchfield et al. 2014; https://catalogue.data.govt.nz/dataset/new-zealand-active-fault-model), and national 1:1,000,000 and 1:250,000 scale digital geological maps (e.g., Rattenbury & Isaac 2012; https://www.gns.cri.nz/Home/Our-Science/Land-and-Marine-Geoscience/Regional-Geology/Geological-Maps), which provide a significant amount of basic fault information across onshore and offshore New Zealand. To date, however, a 3D model of active faults that represents New Zealand's collective scientific knowledge that can be easily used or adapted for multiple scientific and practical uses has not been available.

The New Zealand Community Fault Model (NZ CFM) is a recently-initiated, multi-organisational project led by GNS Science. The NZ CFM builds on the Active Fault Model of New Zealand (Litchfield et al. 2014), up-dates that model through community engagement and input, and extends the updated faults from the surface to seismogenic depths. This first 3D version is termed NZ CFM v1.0 (Fig 1c). The NZ CFM project has developed a 3D representation of important faults (primarily, but not exclusively, active faults[1]) across New Zealand to support downstream applications such as seismic hazard and synthetic seismicity modelling. These representations consist of fault features defined geometrically based on surface expression (traces and folds), seismicity, seismic reflection profiles, wells, and geological maps and cross-sections, and described in terms of kinematically relevant properties such as dip, rake, and slip rate. Further information about the NZ CFM project can be found at: https://www.gns.cri.nz/nzcfm.

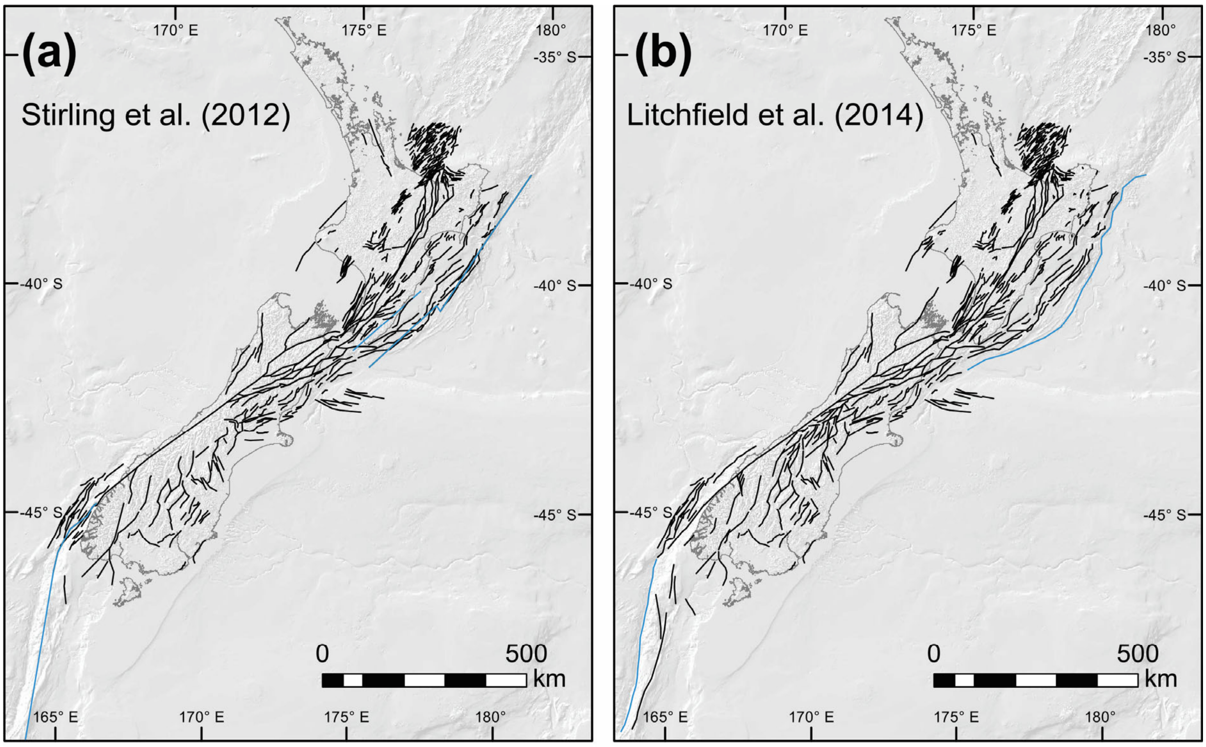
This paper briefly describes the compilation process of NZ CFM v1.0, the geometric and kinematic parameters encompassed by the model, the fault intersection and linkage rules employed to smoothly "mesh" the 3D faults at depth and along strike, and the software used to build the model in 3D. The paper also presents several figures that illustrate aspects of NZ CFM v1.0 (Figs 1-5).

2 PROCESS AND SCALE OF COMPILATION

Two recently-contracted national-scale seismic hazard programmes, the National Seismic Hazard Model Programme (https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/National-Seismic-Hazard-Model-Programme), and Resilience to Nature's Challenges Earthquake and Tsunami

[1] As defined here, and throughout most of New Zealand (excluding the Taupo volcanic region), a fault is classified as active if there is evidence of ground surface displacement/deformation in the past 125,000 years.

Programme (https://resiliencechallenge.nz/scienceprogrammes/earthquake-and-tsunami/) provided the impetus to embark on the NZ CFM project. Both these programmes need an up-to-date, widely agreed, national-scale 3D active fault model to underpin their research. The research delivery timelines established within those two programmes have influenced the rapid compilation timeframe for NZ CFM v1.0.



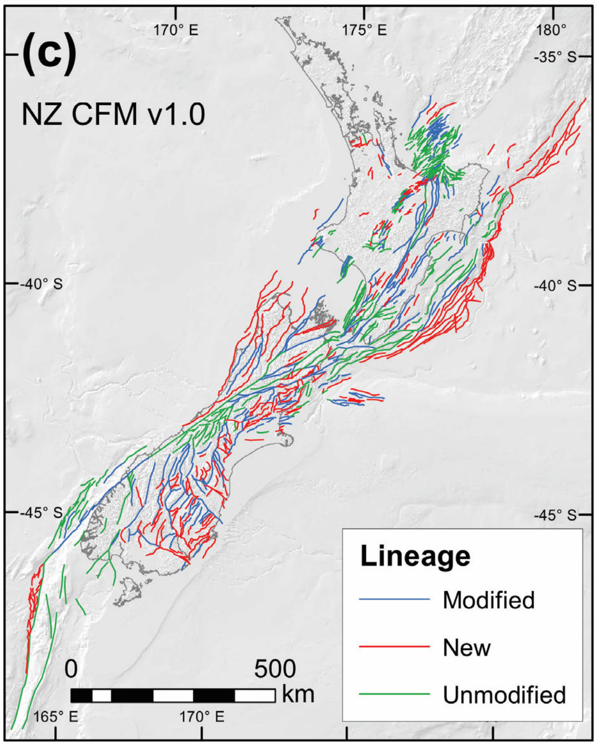


*Figure 1: Comparison of the active fault representations in the: (a) 2010 version of the National Seismic Hazard Model (n = ~540 fault sections) (Stirling et al. 2012), (b) Active Fault Model of New Zealand (n = ~640 fault sections) (Litchfield et al. 2014), and (c) NZ CFM v1.0 (n = ~860 fault sections). Fault sections in (a) and (b) are shown as black lines with the upper edges of the subduction interfaces depicted as blue lines. In (c), "*Lineage*" attribute of new, modified and unmodified faults in NZ CFM v1.0 (preliminary version - March 2021) are shown relative to Litchfield et al. (2014).*

The NZ CFM project got underway in earnest with an inaugural all-day workshop hosted at GNS Science, Lower Hutt, on 27 September 2019. About 50 earthquake scientists, engineers and policy makers attended. Details of the workshop, including copies of the presentations given at the workshop, can be found at: https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Community-Fault-

Model/CFM-workshops. Shortly after the inaugural workshop, a policies and procedures document was commissioned (Rattenbury 2020) to guide compilation and documentation of the NZ CFM and to ensure that the NZ CFM meets FAIR Data Principles, that is, be **F**indable through ISO19115-compliant metadata stored in a harvestable metadata catalogue, **A**ccessible via a shared server identified by the metadata, **I**nteroperable through common file formats used and wanted by the community, and **R**eusable where the terms of use are fully understood and the build history and assumptions of the model are well-described.

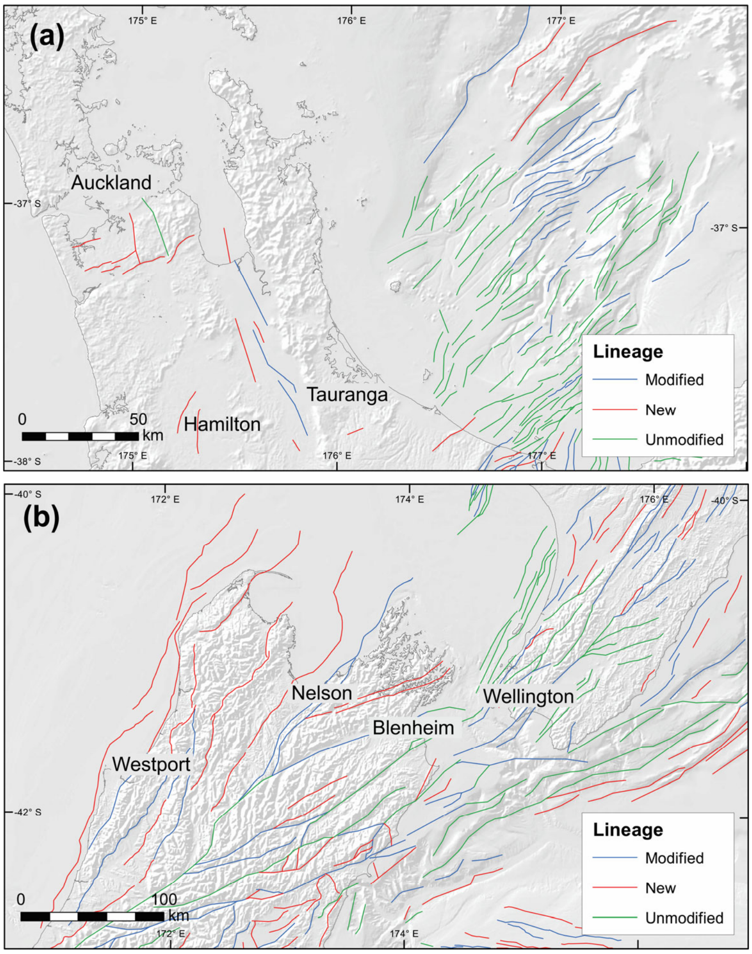


Figure 2: Examples of Lineage *attribute for new, modified and unmodified faults relative to Litchfield et al. (2014) for: (a) Auckland and Bay of Plenty region, and (b) central New Zealand in NZ CFM v1.0 (preliminary version - March 2021).*

An important decision early in the project was selecting an appropriate compilation scale; detailed enough for known downstream applications, but not so detailed as to jeopardise timely compilation or usability. A nominal compilation scale of 1:500,000 – 1:1,000,000 was chosen. Fault trace representations in NZ CFM v1.0 are thus more detailed than those presented in Litchfield et al. (2014) through, for example, the addition of vertices so as to bring the line work into better accordance (and to share common locations) with the more detailed fault trace representations in 1:250,000 geological map-based fault layers and the closely-aligned Active Faults Database 1:250,000 (Rattenbury & Isaac 2012, Langridge et al. 2016). At a compilation scale of 1:500,000 – 1:1,000,000, the fault trace representations in NZ CFM v1.0 are simplified and are inappropriate for any purposes relating to local land-use or site-specific engineering development.

As compilation progressed, including specific input from select expert regional compilers, so too did the spread of COVID-19. This caused a delay in the project and necessitated alteration of delivery timeframes. In late November 2020, eight regionally-focused, half-day, on-line review workshops were convened to discuss, debate and evaluate compilation of NZ CFM, including individual fault parameters, intersection relationships and seismogenic potential. About 40 earth scientists and engineers participated in these workshops, typically 10-20 in any one half-day session.

Changes and updates garnered from the review workshops have been incorporated into the NZ CFM and the model will undergo a final review in February 2020. Consequently, the figures presented in this paper depict a preliminary version of NZ CFM v1.0 which is subject to modification through the review process. After model review and documentation is completed, NZ CFM v1.0 will be published and made freely available via a link on the NZ CFM webpage (https://www.gns.cri.nz/nzcfm).

3 PARAMETERS ENCOMPASSED BY NZ CFM v1.0

Fault-specific parameters defined in NZ CFM v1.0 are: (i) name status*; (ii) lineage* (Figs 1c & 2); (iii) net slip rate (Fig 3); (iv) slip rate timeframe*; (v) sense of movement (Fig 4a); (vi) dip; (vii) dip-direction; (viii) rake; (ix) up-dip depth*; (x) fault status* (Fig 4b); and (xi) quality code.

Those denoted by an * are new parameters relative to the Active Fault Model of Litchfield et al. (2014). Detailed definitions and descriptions of the above parameters are provided in the document titled "NZ Community Fault Model v1.0: Parameter Definitions" available for download at: https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Community-Fault-Model/References-and-related-projects.

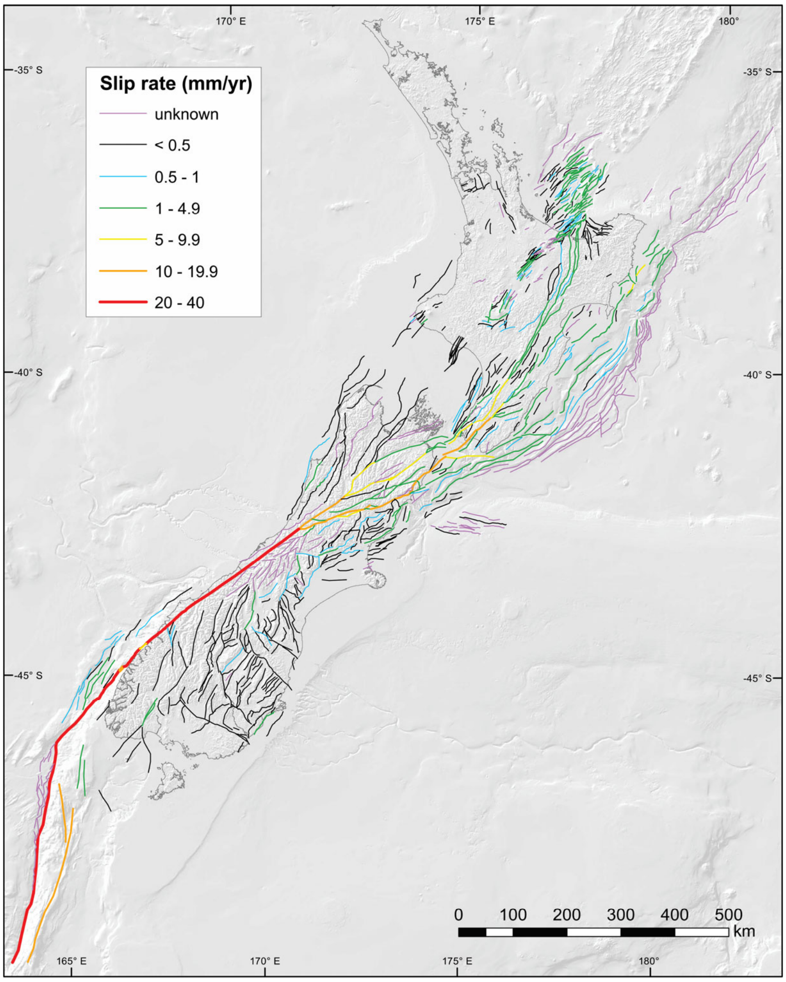


Figure 3: Surface fault trace representation of the NZ CFM v1.0 (preliminary version - March 2021). Fault zones coloured according to the best estimate of their net slip rate. The map highlights that the highest slip rates are along the main plate boundary faults with the notable non-slip-rate-characterisation of the Hikurangi subduction interface. The Hikurangi interface is no longer represented by a single fault at the surface (see Figs 1a & 1b for comparison) but by a three-dimensional surface at depth after Williams et al. (2013) (cf. Fig 5b).

Of the new parameters, *Fault Status* is the one that most warrants further explanation. About half of all shallow large earthquakes (<25 km; $M_w \geq 7.0$) in New Zealand since about 1850 ruptured faults that, based on today's state of knowledge of active-fault location, would not have been identified as active prior to the event (Nicol et al. 2016). Thus, just because a fault has not been proven to be active does not necessarily mean the fault is not capable of producing large earthquakes. As one of the primary goals of NZ CFM v1.0 is to facilitate seismic hazard applications, we consider it prudent to include select faults that are considered potentially capable of producing large earthquakes even if they have not been proven to be active. These are referred to as "capable faults" and are identified in NZ CFM v1.0 via the *Fault Status* term of N-PS (Fig 4b), where the three *Fault Status* terms are defined as follows:

A-LS = Active and likely to be seismogenic.
The vast majority of faults in NZ CFM v1.0 fall within this *Fault Status* category.

A-US = Active but unlikely to be seismogenic.
Examples of faults within this category are those along the eastern-most Hikurangi margin that almost certainly have moved within the last 125,000 years but propagate through relatively shallow and poorly-consolidated sediments and thus may not be able to generate large earthquakes. These individual faults may not pose a ground shaking hazard but may rupture, for example, coseismically with the subduction interface and thus be important for evaluating tsunami hazard.

N-PS = Not proven active but considered potentially capable of being seismogenic.
In NZ CFM v1.0, these are termed capable faults. Examples include some of the reverse faults in NW Nelson that are not proven active but are considered potentially capable of being seismogenic because they have orientations and characteristics nearly identical to nearby faults that are known to be active and that have also hosted moderate to large historic earthquakes. Other examples include many of the offshore faults in deeper water where markers of 125,000 years or younger have yet to be dated (or are not present) and therefore the faults cannot be conclusively proven as active.

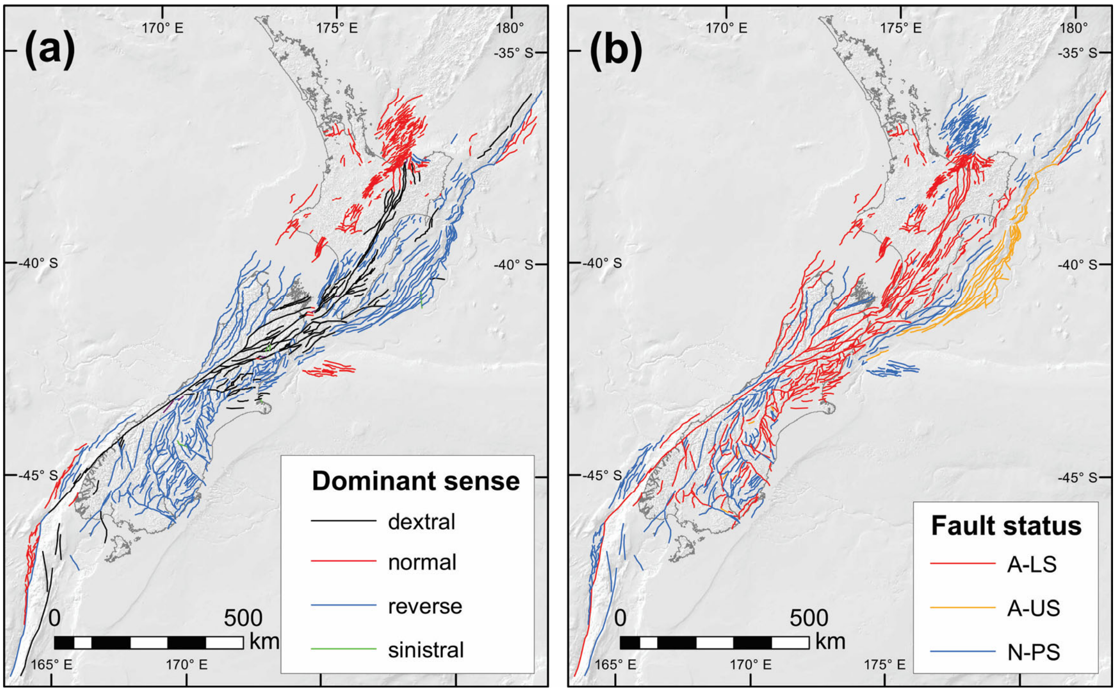


Figure 4: Selected attributes of the NZ CFM v1.0 (preliminary version - March 2021). Fault zones coloured according to their (a) dominant sense of movement and (b) their fault status. Fault status abbreviations: A-LS = Active and likely to be seismogenic; A-US = Active but unlikely to be seismogenic; N-PS = Not proven active but considered potentially capable of being seismogenic. Further explanation of these fault status terms is found in the main text.

4 3D MODEL BUILD

The 3D faults in NZ CFM v1.0 are being built using MOVE geological modelling software from Petroleum Experts Ltd (formerly Midland Valley) using the GIS-generated surface traces as a starting point. The software uses a mix of implicit mathematical fitting of surfaces between constraining points and user-defined settings to create an explicit, coordinate-based, triangulated mesh. Triangular meshes are better suited to describing the geometry of complex fault surfaces and their intersections than rectangular-based meshes. In NZ CFM v1.0 the mesh aperture is nominally 1–2 km, similar in scale to the minimum length of fault trace representations. NZ CFM v1.0 is a single, expert-led, explicit model representation of active and potentially seismogenic faults and does not incorporate alternative interpretations. It is hoped that future versions will.

A key modelling decision has been the down-dip treatment of faults. Given the limited time-frame over which NZ CFM v1.0 was to be produced, all crustal faults (excluding the Hikurangi and Fiordland-Puysegur subduction interfaces) have been modelled with constant dip with depth. The nominated dip is a "best guess" average for each fault section based on observations and interpretation. Subsequent versions of the NZ CFM may use, where data support, more accurate portrayals of fault shape with depth, such as listric geometries.

Rules for fault intersections and linkages in the model have also been developed. This was necessary so as to thwart the proliferation of, for example, unrealistic cross-cutting relationships at depth at the hundreds of fault intersections in the model. These rules were universally applied throughout the model to avoid bespoke, and individually subjective intersections at each fault junction. Detailed descriptions, including examples, of these rules are provided in the document titled "Fault intersection and linkage rules" available at https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Community-Fault-Model/References-and-related-projects. An example of a fault intersection rule is as follows: the primary fault (or section of fault) will be the one that the secondary fault (or section of fault) joins onto (i.e., does not cross-cut), and the primary fault will be the one with the highest slip rate or, if that is not known, the longest length (Fig 5).

The depths to which faults extend is also an important consideration. In NZ CFM v1.0 the subduction interfaces are modelled down to an arbitrarily chosen depth of 75 km. For the Hikurangi interface, the geometry is based on Williams et al. (2013), and for the Fiordland-Puysegur interface the geometry is a compromise between the Hayes (2018) model north of the southern Fiordland coastline and the Hayes & Furlong (2010) model south of the southern Fiordland coastline. Excluding the subduction interfaces, the vast majority of faults in NZ CFM v1.0 extend to a regionally determined maximum seismogenic rupture depth. As part of the NZ CFM project an investigation is underway to evaluate this depth range throughout the country based on seismologic, rheologic and thermal considerations (Ellis et al. 2021). Once these results are available they will be incorporated into NZ CFM v1.0 prior to public release.

The NZ CFM v1.0 will be released in early 2021 in at least two formats; a 2D ESRI shapefile GIS format of surface fault traces with embedded fault parameter attributes, and as a T-surface 3D mesh ASCII format that can be imported into many 3D modelling software products. The T-surface format does not support attributes but can be linked to an accompanying table of parameters via the fault/fault segment name. The data will be accompanied by metadata and a report.

5 CONCLUSIONS

NZ CFM v1.0 provides a simplified 3D representation of New Zealand's crustal-scale active faults (including a selection of potentially seismogenic faults). It is compiled at a nominal scale of 1:500,000 – 1:1,000,000 with crustal faults having a constant dip with depth and the two subduction interfaces having variable dips with depth. The model presently incorporates over 800 objects (i.e., faults or sections of faults), which include fault trace line-work and 3D triangulated surface representations of those faults and associated parameters such as dip and dip direction, maximum seismogenic rupture depth, sense of movement, slip direction, and net slip rate.

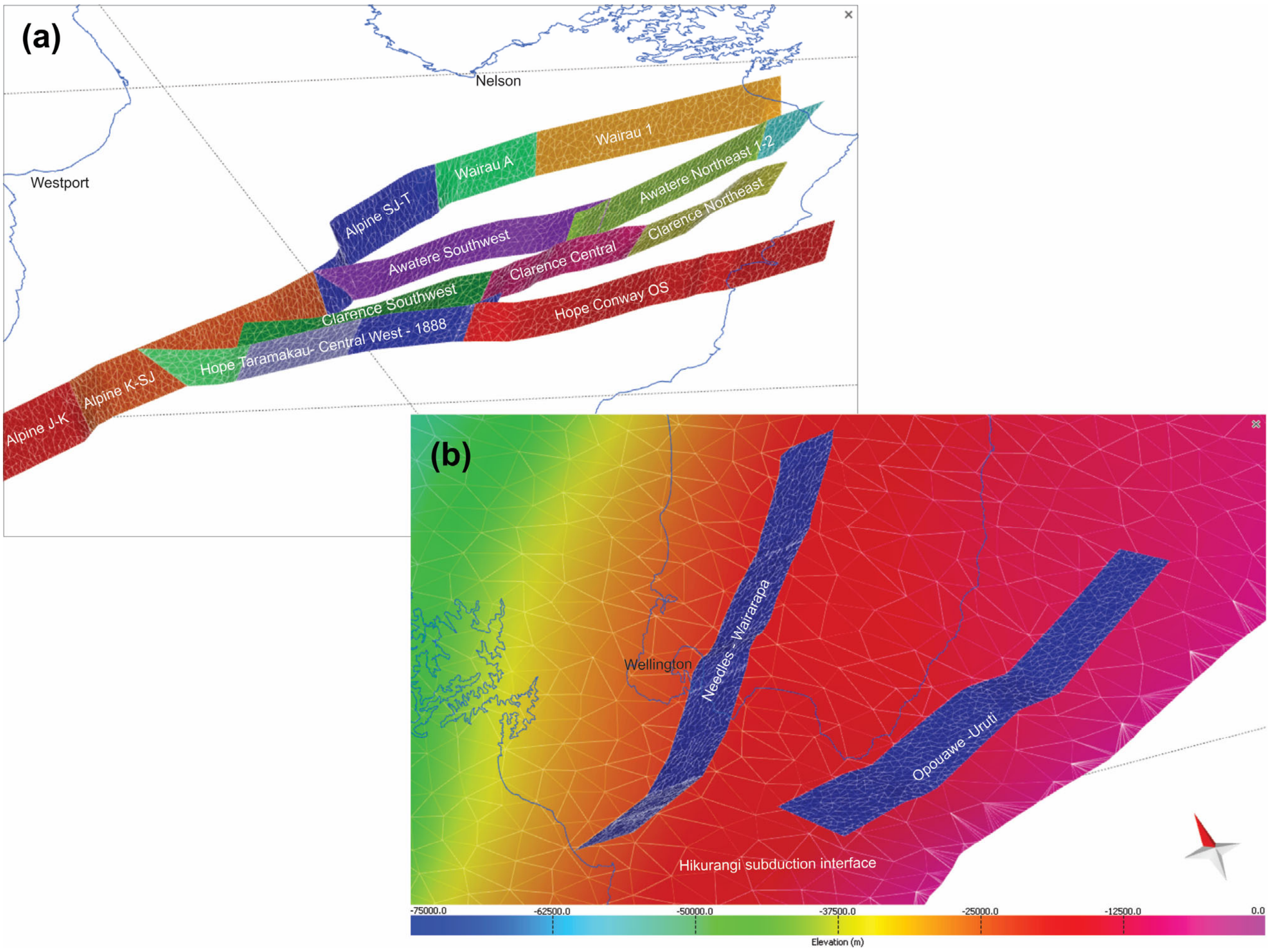


Figure 5: Examples of selected 3D triangulated-mesh fault representations. (a) Strike slip faults of the northern South Island. Fault sections are shown by differing colours and have smoothly joined intersection geometries as per fault intersection rules detailed in the text (e.g., intersections of the of the Awatere Southwest and Hope-Taramakau fault sections with the Alpine Fault). Abbreviations: Alpine J-K = Alpine Fault - Jackson to Kaniere; Alpine K-SJ = Alpine Fault - Kaniere to Springs Junction; Alpine SJ-T = Alpine Fault - Springs Junction to Tophouse. (b) Southern North Island strike slip (Needles - Wairarapa) and reverse (Opouawe-Uruti) faults smoothly merging with the Hikurangi subduction interface (rainbow coloured surface) at variable depths between 10-25 km. Note, naming conventions for fault sections in NZ CFM are currently under review with the aim of providing a greater degree of standardisation. Accordingly, the names eventually used in the final version of NZ CFM v1.0 may differ from those depicted here.

NZ CFM v1.0 is nearing completion. By the time of the 2021 NZSEE Annual Conference it is hoped that compilation will be finalised, and the model will be ready for public release. NZ CFM v1.0 would not have been possible without the input from over 40 earth scientists and engineers throughout New Zealand and abroad. It builds on, and represents a significant update of, the previous Active Fault Model of New Zealand (Litchfield et al. 2014). If the notable uptake and high citation rate of that model is anything to go by, we anticipate that NZ CFM v1.0 will also be a highly valued and utilised resource for many (and varied) earth science, and earthquake hazard and risk endeavours.

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