Chapter 19: New Zealand 3D Geological Mapping and Modelling

Mark Rattenbury1, Paul White2, Conny Tschretter2, Katie Jones1, Matthew Hill1, Samantha Alcaraz3, and Paul Viskovic4

1 Regional Geology, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
2 Hydrogeology, GNS Science, Private Bag 2000, Taupo 3352, New Zealand
3 Geothermal Science, GNS Science, Private Bag 2000, Taupo 3352, New Zealand
4 Petroleum Geoscience, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand

Introduction

The islands of New Zealand straddle the Australia-Pacific plate boundary in the south Pacific and are geologically complex, both spatially and temporally, abounding in geological resources and prone to geological hazards. The North and South islands have abundant petroleum, coal, gold, iron sand, groundwater and geothermal energy resources. Electrical power generation is greater than 85% renewable from hydroelectric, wind and, importantly, high-enthalpy geothermal sources. The Taranaki area has been a consistent producer of natural gas and oil since the 1970s and had smaller production over a century prior to that. Much of the country is generally well-endowed with clean surface water although groundwater adds significantly to meet agricultural, industrial and domestic needs.

New Zealand is subject to episodic, damaging geological hazards such as volcanic eruptions, earthquakes, landslides and tsunami. In only the last decade, the devastating 2010 Mw 7.1 Darfield, 2011 Mw 6.2 Christchurch and 2016 Mw 7.8 Kaikoura earthquakes have had wide and long-lasting repercussions. Those involved in the reconstruction process are acutely aware of siting and designing buildings and other infrastructure appropriately for local ground conditions, reinforced by mandatory Building Code requirements requiring knowledge of subsurface materials.

The geological resources and hazards of New Zealand have been the focus of surface geological mapping and other investigations for over a century. The increasing sophistication of 3D modelling software has resulted in growing construction and use of 3D geological and applied models over the last two decades.

Organizational Structure and Business Model

GNS Science is a government-owned research institute that provides leading geoscience and isotope research and consultancy services for the benefit of New Zealand. Since the formation of its oldest predecessor organisation, the New Zealand Geological Survey in 1865, the production of geological maps and applied geoscience research have been mainstream activities. Funding has changed from entirely government allocation to a mix of strategic base funding, secured contestable funding and commercial revenue. In 2017-2018, around two-thirds of the total revenue to GNS Science of $88M NZD (2018) was derived from research contracts to the New Zealand Government and the remainder from commercial contracts including the GeoNet geohazards monitoring service. The 400 staff include geologists, geophysicists, material and isotope scientists, technicians and administrative support, 80% of whom are based in two campuses in Lower Hutt, Wellington region, 17% in Wairakei near Taupo, 2% in Dunedin and 1% in Auckland. The organisation is structured around discipline-based groups and cross-cutting research themes focussing on underpinning earth science, geological hazards and risks, environment and climate, and energy, minerals and materials. GNS Science has recently undergone significant strategy development and has structurally reorganised to align to these themes in 2019. One of the likely outcomes of the restructure will be improved coordination of expertise such as 3D geological modelling across geoscience domains.

Overview of 3D Modelling Activities

Three-dimensional modelling activities at GNS Science are principally spread across the geoscience domains of groundwater, urban geology, geothermal and petroleum. These activities are project-led through research and commercial contracts, and there has been limited organisational coordination across these domains until now.
Computer-based 3D modelling techniques were first applied in New Zealand for representing geology and groundwater hydraulic properties (White 2001) and are now commonplace in groundwater research. Groundwater-focussed models have been built for many parts of the country (White and Close 2016), particularly where groundwater provides a critical contribution to water supply, for example, Christchurch, Wairau Plains, Wellington and the Taupo Volcanic Zone (Figure 1). These models typically represent Quaternary sedimentary basins classified in terms of hydrogeological units, that is, geological layers that are grouped by hydraulic properties. They inform on groundwater system characterization, groundwater-surface water interaction, protection and restoration of lake environments, groundwater allocation, and drilling programmes. Depending on the application, stratigraphic layer models and/or property voxel models are developed typically at sub-regional-to-catchment scales.

Geothermally-focussed 3D geoscience models guide exploration and sustainable extraction of hot water for power generation and industrial/domestic use. Three-dimensional modelling of geothermal fields began in New Zealand in the 1960s with a physical model (including temperature contours and geology) of the Wairakei geothermal field (Figure 2; White and Dawson 2018). Today, geothermal 3D models are built at all stages of geothermal development, from exploration to production stages, and range in extent from regional (the Taupo Volcanic Zone in the central North Island) to specific geothermal field areas. Modern digital 3D geothermal models integrate multidisciplinary data relevant to a region or a particular geothermal field, to understand the constraints on the location and characteristics of the heat source, the fluid preferential pathways related to formation and/or structural permeability, and the reservoir extent, thickness and overall characteristics. To achieve this, a geological framework model is built with surface and subsurface geological and structural data/interpretation, as well as rock property models, alteration zoning, natural state temperature models and information from geophysical datasets. The resulting model(s) enable visualisation of dynamic reservoir properties, such as changes in reservoir parameters under production. Aside from geophysical datasets and surface mapping, the primary source of data is from geothermal wells. These vertical or deviated wells are usually deep, ranging from 500 m to 3000 m depth.

**Figure 1.** The New Zealand region characterised in terms of a 3D seismic velocity model (Vp data extracted from the New Zealand Wide model 2.1 of Eberhart-Phillips et al. 2017). The ocean floor subduction front (dashed line) is where much of the displacement occurs across the Australia-Pacific plate boundary. Slower seismic velocities persist to greater depth in the continent-continent collision part of the plate boundary below the northern South Island. Place names refer to specific 3D geological, geothermal and groundwater models mentioned in the text.
response of near-surface materials and basin edge effects. The research follows the damaging Kaikoura 2016 earthquake and is driven by a need to better mitigate the effects of seismic amplification around Wellington harbour.

Petroleum 3D geological modelling has been undertaken to support the exploration of oil- and natural gas-prospective areas, notably capitalising on the substantial research and exploration undertaken in the Taranaki Basin of western North Island (see Figure 1). This effort has concentrated on developing high resolution 3D models to help understand the sedimentary and structural architecture of the Taranaki region. Three-dimensional seismic reflection data have been analysed to reconstruct sedimentary strata and lithology distributions. The results are integrated with high resolution mapping of faults. Well data were analysed to reconstruct stress fields and to map fault properties. Temporal components have been introduced into the model such as information on geological age to reconstruct the evolution of the sedimentary basin. Subsurface geometries have been restored through time to assess the architecture of carrier beds for fluid migration and their effectiveness in charging oil and gas accumulations at different times in basin history. These results are being integrated with geochemical information on source rocks and fluids to create advanced models of the movement of oil and gas in the subsurface.

Abundant seismic arrival data across a dense network of seismographs over many decades or recording have enabled the building of a detailed national seismic velocity model (see Figure 1, Eberhart-Phillips et al. 2010). A national 3D geological model is under development. The first iteration will model two layers; the Quaternary superficial sediments and volcanic deposits, collectively, and the Late-Cretaceous-Pliocene cover sedimentary rock dominated succession.

Resources Allocated to 3D Modelling Activities

There are few dedicated 3D modelling staff within GNS Science. Those with the requisite skills, 10-15 in number, are also typically engaged in other functions, either as scientists or in technical support. Modelling is commonly part of a defined project in a geoscience domain; a 3D geological or other model may be a product resulting from the project, and a process such as fluid flow may be modelled from that 3D geological model framework. A total annual budget for 3D modelling is difficult to calculate and investment levels vary each year depending on the number, size, duration and stage of the projects.

Overview of Regional Geological Setting

The New Zealand land mass is underlain, in simplistic terms, by thinned continental crust basement of Paleozoic-Early Cretaceous metasedimentary and plutonic-dominated igneous rocks, exposed over much of the South Island and in ranges of the North Island (Edbrooke 2017). These basement rocks are overlain by variable thick and semi-continuous succession of Late Cretaceous-Cenozoic sedimentary rocks, with significant volcanic outpouring at various periods, notably in the Miocene-Quaternary in northern and central North Island. The rocks are complexly faulted, in part a consequence of the present Australia-Pacific plate boundary that divides the South Island and lies east of the North Island coast. Discrete plate boundary processes were active in the Cambrian, Devonian-Carboniferous and Permain-Mesozoic, and these have resulted in major basement structures that have preconditioned the structural complexity of the modern plate boundary. The plate boundary is wide and is actively extending across the central North Is-
land whereas shortening is occurring across the South Island and eastern North Island. Deformation is expressed in contractional, extensional and lateral faults through the country, locally elevating or subsiding ground. This in turn has resulted in major downslope movement of eroded material through alluvial processes and the formation of extensive alluvial plains. Many of these alluvial sand and gravel layers are important aquifers.

The steep topography in many parts of the country has focused people, buildings, roads and other infrastructure into valleys and coastal plain areas and these are flooded in poorly consolidated sediment, commonly bounded by or masking active faults. Changing sea levels through the Quaternary have resulted in marine incursions into low-lying coastal areas. The sediments associated with these incursions have been susceptible to liquefaction in historic earthquakes, most notably during the 2010 M=7.1 Darfield and nearby 2011 M=6.2 Christchurch events.

**Data Sources**

New Zealand has abundant high-quality surface geoscience data onshore. The modern digital topographic base is accurate for district and smaller-scale applications and abundant and growing LiDAR coverage is particularly useful for larger scales. High-quality surface geological map data are available nationally at regional and smaller scales in richly attributed GIS formats. Some areas of greater geological detail exist in many cities and other areas. The stratigraphic framework is well established and there are specific digital databases for active faults and landslides.

Drillhole and well data are dense in many places, depending on their purpose. Petroleum-related exploration and production wells are numerous in onshore and offshore Taranaki and are sporadic elsewhere. These have detailed logs of geological and geophysical parameters. Major urban centres have abundant geotechnical and engineering drillhole and probe data, particularly in their inner-city areas. The quality of drillhole logging is highly variable although recent trends are towards digital capture to industry data standards (AGS4 http://www.agsdataformat.com). Geothermal areas are typically abundantly-drilled through their exploration to production transition and their drillhole logs are typically very detailed. The logs are commonly confidential to the companies that are developing geothermal fields and therefore may be unavailable for building public domain 3D models. Some areas have significant extraction of groundwater through a network of wells, for example, Canterbury has more than 40,000 wells, many with useful geological logs. In general, however, most groundwater wells only have lithological logs of variable quality and no geological interpretation. Additional analysis of the well data is required to use these logs for geological modelling.

Different types of geophysical data are available in many areas and these include gravity, magnetics, magnetotellurics, active source seismic surveys, passive seismic and ambient noise methods and ground-penetrating radar. These surveys include crust-mantle tomography (Eberhart-Phillips et al. 2017), upper crustal 3D seismic (Bull et al. 2010) and surficial cone penetration test data (Begg et al. 2015). Approximately one third of New Zealand’s land surface is covered by high resolution airborne geophysics (aeromagnetics ± radiometrics ± aerogravity ± electromagnetics at 200-300 m line spacing). Some of these data have been forward modelled or have inversion techniques applied to derive shapes and constrain depths of subsurface boundaries. Urban areas are challenging places to acquire many of these types of data without significant noise. Active source seismic surveys, particularly when tied to well data, can provide useful constraints and extend geometries.

Most of the data obtained for government or councils on public land are publicly available and are subject only to light attribution licence constraints. Some data, however, when supplied by a commercial client and used in 3D models can result in confidentiality restrictions placed upon them. Data obtained from private land and used in published models that could disadvantage the owner would contravene the Privacy Act 1993. The growing trend to supply input data with the 3D models to better ensure product longevity requires diligence from GNS Science to ensure data confidentiality and privacy requirements are met.

**3D Modelling Approach**

The modelling approach varies between, and to some extent within the geoscience domains, and is in part dictated by the choice of modelling software. The petroleum models are built with a combination of explicit Gocad and implicit Skua software approaches. The geothermal, urban and many of the groundwater models use implicit modelling tools from Leapfrog Geo/Geothermal and EarthVision software but commonly utilise explicit control points to guide surface generation. In general, only single models are built although probabilistic models are important in groundwater research, where aquifers and aquicludes occur side-by-side in similar geological materials (Figure 3).

Model confidence has been empirically assessed for some 3D models, typically based on distance from input data, subjective estimate of the quality of the input data and depth below surface. Probabilistic models of gravel distribution were found to produce reasonable predictions of aquifer location (White and Reeves 1999).
Clients

The primary end users and stakeholders for the 3D models vary between and within the various geoscience domains and include central and regional government, industry, consultants and the general public. The level of interaction with the end user varies accordingly. In some cases, the 3D model can be interrogated through a web application, for example, the groundwater-based Earth Beneath Our Feet [https://data.gns.cri.nz/ebof/] or virtual cross-sections in the Taranaki Basin [https://data.gns.cri.nz/pbe/index.html?map=South_Taranaki], and the model itself is not transferred. In some cases, the 3D model is part of a published product, for example, the Christchurch geological map [Begg et al. 2015]. The client will use the presented model typically through a 3D viewer application. Derivative layers and volumes provided as part of the data product may be used by the client in GIS or other specialist software. Free 3D viewer software is an important visualisation tool for all clients. The limited functionality of the 3D models provided for these software is balanced by them being free-to-use and comparatively easy to manipulate. The 3D viewer models are commonly used for technical educational training. Movies derived from 3D models are another important way of conveying understanding of modelled earth systems to many end users [White et al. 2018a].

Many geothermal and groundwater models have been built and retained within GNS Science with industry or regional council collaboration. This may include their ongoing support for development of the model in return for specific information from it, particularly where there are ongoing temporal changes to model inputs. Groundwater levels and flows are recorded by sensors in many aquifers and these result in changes to water allocation models. For geothermal fields, new drilling results are incorporated into the 3D model for the client as part of a standard contractual service.

Recent Case Studies Showcasing Application of 3D Models

Wairau Plains 3D Groundwater Model

Groundwater is a very important resource in the Wairau Plains (see Figure 1) located in the Marlborough region in northern South Island. Water management challenges in the Wairau Plains include an increase in water use over time and degradation of groundwater quality that has been linked to land use. These challenges require better characterisation of the system’s hydrogeology, including the coastal Holocene gravel aquifer, and surface hydrology. To achieve this, 3D lithological models can be used that represent the 3D distribution of lithological descriptors, for example, gravel identified in well logs.

One of these lithological models, a probabilistic model of gravel distribution in the coastal Wairau Plains (Figure 4) was used to develop a groundwater budget of the Wairau Plains that showed that co-management of land and water is required to address current pressures on water resources in the study area because of the hydraulic links between land, the Wairau River, the Holocene aquifer and spring-fed streams [White et al. 2016].

Current 3D-related research in the Wairau Plains include time-series facies models and the 3D printing of physical models [White et al. 2018a].

Rotorua 3D Geothermal Model

A 3D geoscience model of the Rotorua Geothermal Field (see Figure 1) and surrounding areas of the central North Island have been built with Leapfrog Geothermal software to better understand and visualise its geological setting. The Rotorua geological model was built for the Bay of...
Plenty Regional Council (Figure 5; Alcaraz and Barber 2015) to support the council policies and decision making for managing the sustainable use of the resource. The model facilitates conceptual understanding of the field and constrains numerical simulations of the geothermal reservoir behaviour and response to utilisation (for example, Ratouis et al. 2017).

The Rotorua Geothermal Field is located in the southern part of the Rotorua caldera. Active faults are mapped south and north-east of the caldera rim, while the structures within the caldera have been buried under young sedimentary and volcaniclastic layers.

The drilling of geothermal bores started in 1920 and there are now more than 1,300 boreholes in the area. Most bores are shallow (< 150 m drilled depth) and reliable subsurface geological data are scarce.

Results from geophysical surveys (seismic, gravity, magnetotellurics) have been used to define geological structures at greater depth.

Lithological models have since been built from rock type descriptions to represent permeability variation in the rhyolite and sediments forming the shallow part of the Rotorua reservoir. These models help identify fluid flow pathways within the heterogeneous sediments.

Temperature logs from monitoring bores and surveyed features at the ground surface enables modelling of the temperature distribution within the reservoir. Combining the temperature model with a 3D magnetotelluric model allows us to better understand the hydrology of the system and better constrain the conceptual model that underpins the reservoir simulation grids (Figure 6).

Christchurch 3D Urban Geotechnical Model

The aftermath of the 2010 Mw 7.1 Darfield and 2011 Mw 6.2 Christchurch earthquakes resulted in a massive rebuilding of the mid Canterbury area involving reinstatement of buildings, roads, pipe and cable networks and other infrastructure. The susceptibility of some earth materials to seismic shaking was exposed during these earthquakes and precipitated more than 10,000 cone penetration test (CPT) soundings to better understand near-surface ground conditions.

These CPT sounding data are measures of sleeve friction, cone penetration resistance and pore water pressure. Earth material proxies such as soil behaviour type can be derived from them. The 3D geotechnical numerical model (Figure 7; Begg et al. 2015; Rattenbury et al. in press) was built with Leapfrog Geo software utilising 0.2 m aggregated measurements.
Figure 5. 3D geological model of Rotorua: A) Geological units mapped at ground surface. The Rotorua caldera boundary is indicated by the purple line. B) 3D view of the Model. C) WNW-ESE slice through the model. D) and E) Cross-sections through the model.
from around 1,500 selected soundings at an average horizontal spacing of 127 m. Spatial interpolation between CPT soundings was conditioned by an oriented spheroid that reflected trends defined by a conceptual model of depositional geometry, that is, interfingering terrestrial and marine sediments dipping very gently south-east.

**Taranaki Basin 3D Geological Modelling**

The Taranaki Basin petroleum province (see Figure 1) is being progressively modelled in 3D (Figure 8) as part of the “4D Taranaki Project”. The overall objective of the project is to improve our knowledge of the structurally complex Taranaki Basin and better define its remaining petroleum potential through seismic interpretation and 3D static structural modelling.

Interpreted seismic horizons and faults are modelled in two-way-time (TWT) using Paradigm® SKUA-GOCAD™ software. The aim of the implicit static modelling was to best represent the basin fill on a sub-regional scale.

Lateral modelling resolution is variable (ranging from 500–2000 m) and was adjusted for different volumetric regions according to computation limitations, seismic line spacing, and in some cases to better fit prominent anticlinal structures and well markers. Computation limitations meant that the mapping area could not be modelled as one volume, but as a small number of constituent volumes. The modelled results from each constituent area were then merged together to produce output grids that are continuous across the mapping area (Bull et al. 2015).

**Current Challenges**

The main challenge GNS Science faces with 3D modelling is organisational; our applications necessarily vary between geoscience domains and are further constrained by an organisationally-imposed project-driven structure. Different software, needed for specific domain modelling, requires software-specific specialisation and this restricts interchangeability of staff and methodologies. There is limited overview and coordination across domains. Finding, using and understanding 3D models across geoscience domains is not commonly needed, and is made harder by project-focussed network folder storage and insufficient metadata availability.

Complex 3D models stretch computing resources to breaking point. File sizes and memory requirements are constantly pushing hardware limits and some software have internal limitations. There is an ongoing tension between resolution and model extent dictated by computing capabilities. Modelling at the limits of computing constraints can significantly slow progress and can result in frequent software crashes and potentially model corruption.

New Zealand has a comparatively low investment in subsurface infrastructure, attributable to our relatively low population density, and this has restricted the amount of information relevant for 3D geological modelling. Some urban geology and groundwater
study areas are not well constrained by available drill hole data, to the extent that 3D models have not been considered because of the large uncertainties. Conversely data overload can also be challenging for the modeler as well as the end user, particularly for applications such as geothermal systems where there are multiple variables interacting in 3D space (and further complicated by a temporal dimension).

As a geological survey, an important function for GNS Science is to preserve geoscience information for the long term. The rapid evolution of 3D modelling software has already resulted in some early-version models being unreadable in later-version software. Unless completed models can be regularly upgraded with new software, an impost on already stretched resources, then significant work could become digitally unreachable. Solutions for the moment include generic databases to store raw data (such as spreadsheets to store well log data) and to deconstruct completed models into component parts such as individual surfaces and volumes in generic ASCII or widely interchanged file formats such as T-surfaces, shapefiles and common raster types (Rattenbury and Jones 2015). Most GNS Science 3D models are accompanied by a report that describes construction of the model and the input data, but some historic models are not well described.

**Lessons Learned**

Our experience is that expectations associated with 3D modelling can be unrealistically high. The models can be visually compelling and appear authoritative but conveying often high levels of uncertainty and non-uniqueness of the interpretation where data are lacking is challenging. Many
Figure 8. Cross section slice through South Taranaki static model, part of the 4D Taranaki Project (after Bull et al. 2015). The coloured surfaces are key stratigraphic horizons, locally offset by faults (grey), including the basin-defining Taranaki Fault on the left edge. Kupe and Maui are the major oil and gas producing fields in this view.
model features have limited attributes attached and end users can struggle to understand what is being depicted. Their usability in real-world applications can be more limited than expected as end users typically do not have 3D modelling software to work with production models. Free viewer software is available, but functionality is typically limited and the end user can struggle to interleave their own data, commonly from GIS platforms, to contextualise the 3D geological data supplied.

For some applications, 3D geological models have proved to be a useful adjunct to, but not a replacement for, surface-based geological mapping and other data. Interpreted drillhole data can be effective enough for conveying subsurface lithological or stratigraphic variation where data are sparse, and they also convey where constraining data are.

Three-dimensional geological models can be re-engineered in terms of other properties and this has proved to be useful for validating surface measurements, for example, seismic site period, and interpolating or extrapolating them. For the geothermal industry, the models have been really successful for well planning, effective for integrating all available information, and promoting multi-disciplinary studies.

Next Steps

Three-dimensional modelling, for geological and applied purposes, is an important part of GNS Science’s research programme and information management and delivery. For some geoscience domains such as urban and petroleum geology, 3D models and interpreted drillhole datasets are provided to complement other more conventional data products such as 2D maps and cross-sections. Providing a variety of map and model data products caters for end users who have varying levels of technical capability and different applications; 3D geological models are unlikely to supplement surface geological maps for urban applications, for example. Other domains use 3D geological models as starting points to model processes, notably fluid flow relating to groundwater and geothermal applications as well as petroleum. The development of some of these models already involves collaboration with specific clients who require results generated by these models rather than the acquiring the models themselves.

Coordinated 3D geological modelling across geoscience domains will be facilitated by the implementation of GNS Science’s new organisational structure that is currently being rolled out. There is also accelerated implementation of good dataset management practice in general across GNS Science. There is a clear need to improve data management of our 3D models and their associated data, starting with metadata to enable their discovery and understand their lineage.

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