An integrated Python-based workflow for geological and geothermal fluid flow modelling to investigate lateral fluid movement in the Taupō Volcanic Zone

Sophie Pearson-Grant[1], John O'Sullivan[2], Lucy Carson[3], Hannu Seebeck[1], Adrian Croucher[2], Jenny Barretto[1], Jeremy Riffault[2], Michael Gravatt[2], Mike O'Sullivan[2], and Edward Bertrand[1]

[1] Earth Sciences New Zealand, Lower Hutt, New Zealand

[2] University of Auckland, Auckland, New Zealand

[3] Earth Sciences New Zealand, Wairakei Research Centre, Taupo, New Zealand

s.pearson-grant@gns.cri.nz

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ABSTRACT

Lateral fluid flow within geothermal systems significantly affects reservoir sustainability, resource targeting, and surface expressions, but remains challenging to predict in structurally complex volcanic settings like the Taupō Volcanic Zone (TVZ). This study introduces a python-based workflow that couples 3D geological models with supercritical heat and fluid flow simulations to investigate geological conditions that promote lateral geothermal fluid movement.

We are developing a methodology to couple structural and stratigraphic modelling with multiphase fluid and heat flow simulations using open-source tools where possible. Geological models are constructed in GemPy, with custom Python scripts employed to extract rock types and fault geometries. Geological units are then parameterised for fluid flow modelling, building on the University of Auckland's modelling framework. Finally, we use the supercritical AUTOUGH simulator to model the high-temperature, high-pressure environments characteristic of the deep roots of geothermal systems. This approach enables dynamic, repeatable population of reservoir models, supporting flexible natural state simulations and quantification of geological uncertainty.

Modelling the deep roots of the Ohaaki geothermal system provides a case study for this work. Unusually, magnetotelluric imaging suggests that fluids beneath Ohaaki move ~5 km laterally between 8 and 3 km depth. Geological structures inferred from gravity and magnetics provide possible fluid pathways or permeability contrasts that redirect fluid flow. Our preliminary models are exploring variations in lithological properties, fault permeability, intrusive heat sources, and anisotropy, allowing systematic analysis of how different geologies influence lateral flow.

1. INTRODUCTION

Many New Zealand geothermal systems appear to be fed by the buoyancy-driven flow of hot fluids, with flow pathways influenced by the location of deep heat sources as well as topography nearer the surface (Pearson-Grant et al., 2024). Fluid flow at several geothermal fields, however - Ohaaki, Haroharo, and Te Kopia – follow less predictable, lateral pathways. Horizontal and vertical migration of hot fluids can be influenced by field-scale geological features, such as volcanic intrusions, major fault zones, and the permeability contrast between basement and volcanic cover. In areas that lack drillholes to constrain geology, understanding how these factors affect flow pathways is challenging but important because of its implications for reservoir sustainability, resource targeting, and protection of surface geothermal features.

Geothermal reservoir modelling allows us to explore controls on geothermal fluid flow, as well as supporting geothermal exploration and field management. Generally, one static geological model is used as the basis for a reservoir model. Parameters such as permeability or deep fluid/heat input are then varied until model results replicate observed data. Ensemble methods provide a powerful tool to compare a range of models to observations (Omagbon et al., 2021), however these can be challenging to implement with traditional geological modelling techniques.

We are developing an integrated, Python-based workflow which facilitates multiple geological realisations leading to many geothermal reservoir models. This will allow geological as well as reservoir modelling uncertainties to be quantified. Ultimately, this workflow could also incorporate geophysical data directly allowing an integrated, streamlined process from field data to calibrated reservoir model (Figure 1). This paper introduces the different elements of the workflow, and presents a case-study of models exploring deep lateral fluid flow to the northwest of Ohaaki as imaged by magnetotellurics (Bertrand et al., 2013).

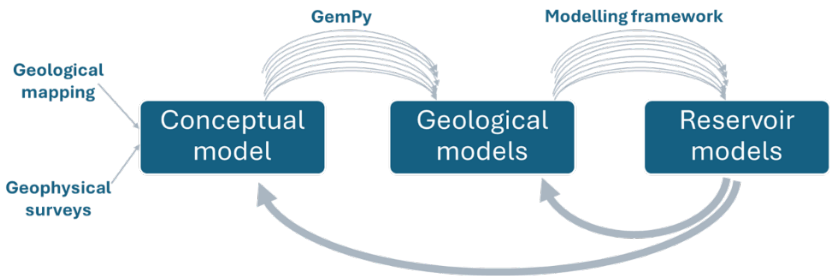

Figure 1 Inputs and models needed to create geothermal reservoir models, as well as the methods to move between them.

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2. MODELLING PROCESS

The modelling process starts with generating a static geological model from observed data and inferred subsurface structure. This static geological model provides the foundation for the subsequent geothermal reservoir model. While powerful commercial software tools have been designed to do this, we are exploring an open-source Python-based workflow that aims to facilitate customisation, collaboration, and user uptake. Currently, we are investigating GemPy for the generation of static geological models and using AUTOUGH for geothermal reservoir modelling, with a view to moving to supercritical Waiwera when it is available.

2.1 Geological modelling

GemPy is an open-source, Python-based software designed for 3D structural geological modelling (De La Varga et al., 2019). It employs an implicit modelling approach that allows simulation of complex geological structures such as faults, folds, and stratigraphic layers using interface and orientation data. GemPy's integration with probabilistic frameworks enables uncertainty quantification through Bayesian inference. It uses GPU-accelerated computation for efficiency and works with open-source visualisation tools such as PyVista.

To create models with GemPy, we create a spreadsheet of depths to geological contacts and fault surfaces, as well as their orientations. A Python script is used to delineate model extents and resolution, and to import geological information such as lithology, porosity, and permeability. Some clean-up of data is often necessary to ensure imported points are not contradictory and surfaces are not over- or under-constrained. We then export lithologies and faults from the resulting geological model using Python scripts, which can be used to create multiple realisations of the static geological model within uncertainty bounds for geothermal fluid flow modelling.

2.2 Fluid flow modelling

Supercritical AUTOUGH is an advanced extension of the AUTOUGH family of geothermal reservoir simulators, specifically adapted for modelling supercritical geothermal systems—where water exists above its critical temperature (374 °C) and pressure (22 MPa)(Croucher & O'Sullivan, 2008). In these extreme conditions, water exhibits unique thermophysical properties such as high enthalpy, low viscosity, and gas-like behaviour, which significantly enhance heat potential. Supercritical AUTOUGH incorporates thermodynamic formulations like IAPWS-IF97 to accurately simulate fluid properties across a wide pressure-temperature range, including transitions between subcritical and supercritical states (Croucher & O'Sullivan, 2008).

Fluid flow models are created using University of Auckland's geothermal modelling framework (O'Sullivan et al., 2023). Geological models are exported to create AUTOUGH models using a suite of Python scripts. These models are then run with different parameters such as permeability, basal heat input, and presence of fractures. Resulting temperature distributions are compared with magnetotelluric (MT) anomalies to try to find models that capture the main inferred fluid flow pathways.

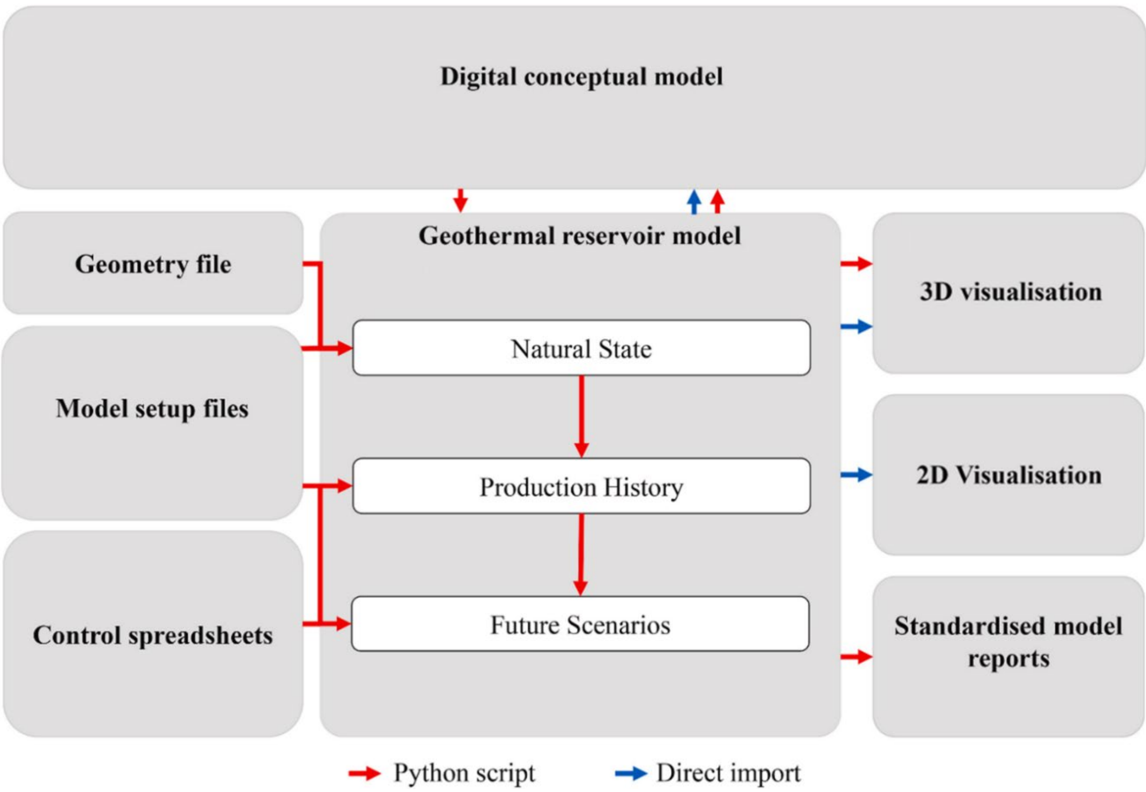

Figure 2 Diagram of University of Auckland's geothermal modelling framework used to carry out geothermal reservoir modelling studies (modified from O'Sullivan et al., 2023).

3. CASE STUDY

We are using deep fluid flow to the northwest of Ohaaki as a case-study to develop this workflow. In this area, MT imaging has suggested that fluids rising from ~8 to 3 km depth can move up to 5 km laterally (Figure 3)(Bertrand et al., 2013). These unusual lateral fluid flow paths suggest that large-scale geological features are likely very important in this region. However, it is not clear which geological features could cause this flow (Kissling et al., 2016). Therefore, exploring local geological uncertainty could have important implications for understanding geothermal fluid flow.

3.1 Fluid flow pathways

Magnetotelluric (MT) imaging has shown that basement greywacke directly beneath the Ohaaki geothermal field is highly resistive, indicating limited permeability in that zone (Figure 3). However, a dipping low-resistivity zone has been imaged that connects a shallow anomaly—associated with the geothermal reservoir—to a deeper, offset region to the northwest. This low-resistivity feature is interpreted as a fractured zone within the basement metasediments, likely serving as a conduit for upwelling high-temperature fluids from a deeper magmatic source (Bertrand et al., 2013).

These resistivity patterns have important implications for fluid flow within the Ohaaki system. The alignment and geometry of the low-resistivity zone suggest that fluid ascent is structurally controlled, with the dipping conductor acting as a preferential pathway for deep geothermal fluids. However, the structures that may provide pathways are deeply buried and how they interact with fluid flow cannot be imaged, therefore numerical modelling provides a powerful mechanism to explore how known and inferred geology could be facilitating this lateral flow of fluids.

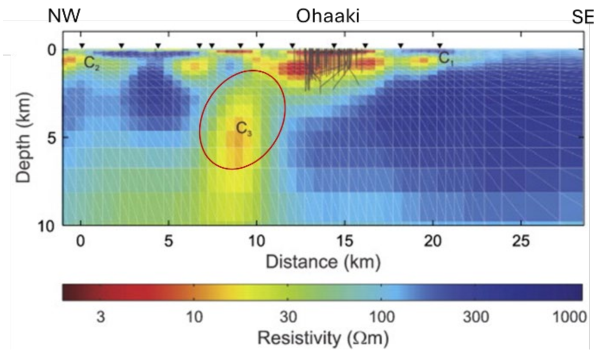

Figure 3. MT profile beneath Ohaaki, showing a resistive anomaly dipping to the northwest (red oval) thought to be a structurally-controlled fluid pathway (Bertrand et al., 2013).

3.2 Potential geological influences

Local geology in the area is complex, and to the northwest of Ohaaki is mainly inferred from geophysical data. We have therefore started from a relatively simple geological model incorporating major geological features that could have implications for fluid flow.

Lithology in the area includes greywacke basement overlain by volcanic cover rocks (O'Sullivan et al., 2025). Gravity surveys show residual Bouguer anomalies in the area range from -39 to +1 mgals (Stagpoole et al., 2020), generally increasing from NW to SE, which are linked to geological structures (Figure 4). The anomaly low to the northeast of Ohaaki is the gravity signature of Reporoa Caldera, and to the west is the Mihi gravity low (MGL), which may represent a buried caldera (Stagpoole et al., 2020). These features appear to be nested within a larger gravity low which may be a larger caldera complex (Stagpoole et al., 2020). The anomaly high to the southeast of Ohaaki corresponds to the Kaingaroa Plateau which is underlain by ignimbrites on top of greywacke basement (Milicich et al., 2018). Depth to the basement is between ~1 and 3 km, increasing to the northwest. The Waikora formation, a greywacke pebble conglomerate, is thought to be present in discrete lenses within the volcanic cover rocks (Mroczek et al., 2016).

There are several major faults in the region, which result in offset geological layers and could provide pathways for hot fluid upflow or cold fluid recharge (O'Sullivan et al., 2025). We have identified five main faults in our study area - Aratiatia, Broadlands, Kaingaroa, Ohaaki, and Ohaaki_West.

Reduced-to-pole total magnetic intensity grid of the upper North Island (Barretto & Caratori Tontini, 2022) shows magnetic anomalies from -722 nT to +1544 nT in the study area (Figure 5) related to geological features. Magnetic lows coincide with the southern and eastern boundaries of the Mihi gravity low and Reporoa Caldera. The magnetic lows may indicate demagnetization due to hydrothermal alteration along caldera margins. Inside the Mihi gravity low and Reporoa Caldera are short-wavelength magnetic highs superimposed on long-wavelength magnetic highs. Mapped outcrops of rhyolite lavas coincide with a number of these short-wavelength highs indicating that similar adjacent highs may be due to other shallow buried rhyolite lavas (Soengkono 2013). The long-wavelength magnetic highs suggest deeper magnetic sources. 3D magnetic modelling of lower resolution magnetic data shows that Kairuru rhyolites (at the SE margin of Reporoa Caldera, Figure 5) are connected to a larger rhyolite body (Hochstein & Soengkono, 1997). This large deep intrusive body can potentially deviate flow of hydrothermal fluids towards more permeable zones and may help explain the orientation of MT conductive anomalies west of Ohaaki (Rae et al., in prep).

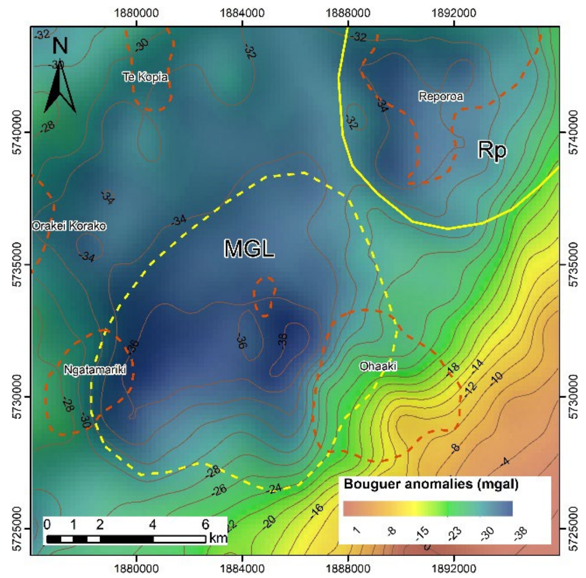

Figure 4. Map showing Bouguer gravity anomalies within the area of interest and outlines of Mihi gravity low (MGL; yellow dashed line) and Reporoa Caldera margin (Rp; solid yellow line) that correlate with gravity low (Stagpoole et al., 2020). Resistivity boundaries (30 ohm-m) of geothermal fields (red dashed lines) are also shown.

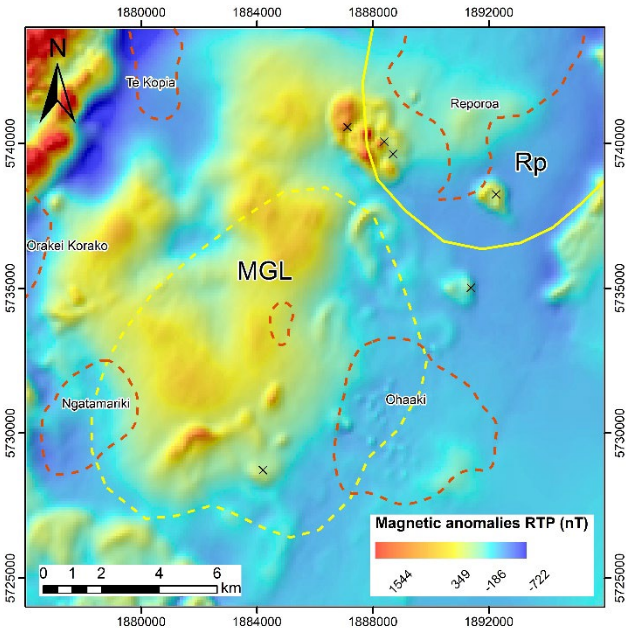

Figure 5. Map showing reduced-to-pole magnetic anomalies and plots of Mihi gravity low (MGL; yellow dashed line) and Reporoa Caldera margin (Rp; solid yellow line) (Stagpoole et al., 2020). Resistivity boundaries (30 ohm-m) of geothermal fields (red dashed lines) are also shown. Exposed rhyolite lavas are marked with Xs.

3.3 Modelling geological influences on fluid flow pathways

We have created a simplified, preliminary geological model in GemPy which covers an area of 20 km by 20 km down to 5 km depth. It has a refinement level of eight for the octree grid to balance resolution and efficiency. It includes two lithological units (basement and volcanic cover) as well as major faults (Figure 6). Work is on-going to make this model more detailed and realistic.

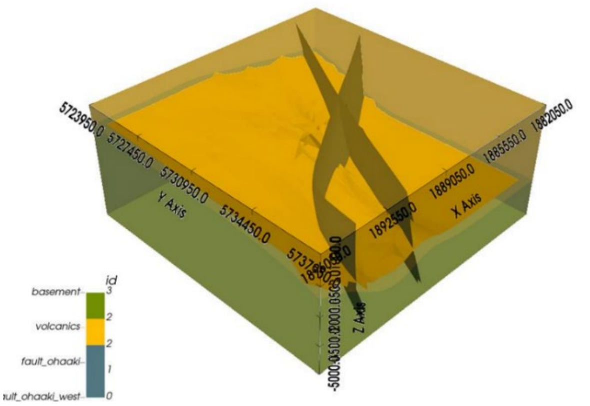

Figure 6. Preliminary geological model of our study area created using GemPy software.

To model fluid flow, we have created an AUTOUGH model encompassing the same 20 km by 20 km region. Horizontal grid spacing is 500 m by 500 m. The base of the model is at 8 km below sea level, while the top surface follows topography to a maximum elevation of 700 m above sea level (LINZ, 2021). Vertical grid spacing is 500 m below 3 km depth, 100 m above (Figure 7). Heat is injected across the base of the model, with extra heat input in the area of the resistive MT anomaly (Figure 3). Basement rocks are overlain by volcanic cover at depths measured in boreholes and inferred from geophysics (Alcaraz et al., 2012). Permeability of basement, cover rocks, and faults are varied to explore their influence on fluid flow. Models were run from uniform atmospheric temperature and pressure until temperature variations were no longer sensitive to initial conditions.

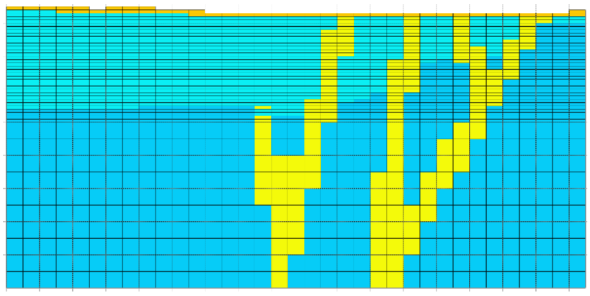

Figure 7. AUTOUGH model grid showing faults (yellow), basement rocks (blue), and cover rocks (green).

3.4 Preliminary results

More complex geological modelling is required to explain lateral flow paths to the northwest of Ohaaki. If faults are assigned similar permeability to host rock, most fluid flows vertically to the northwest of the study area (Figure 8). There is minimal lateral fluid flow. If faults are assigned higher permeability than host rock, they mainly act as pathways for cold downwelling recharge (Figure 8). These preliminary results are not unexpected, but form a first step towards building multiple geologically realistic fluid flow models that can explain lateral fluid flow as observed in the TVZ.

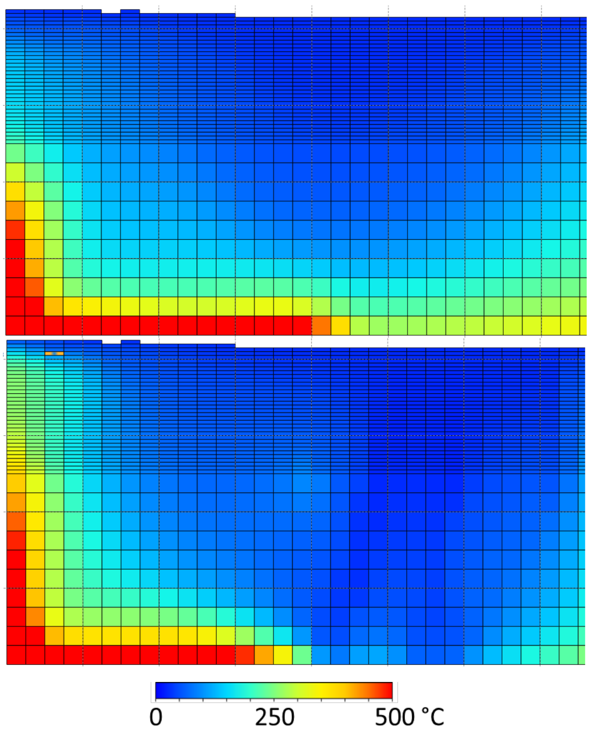

Figure 8. Preliminary modelled temperature results. Top unfaulted, with basement half the permeability of cover rocks. Bottom, with the addition of permeable faults as in Figure 7.

CONCLUSIONS

We are developing a Python-based, predominantly open-source workflow to create geothermal reservoir models from static geological models. This will create a more streamlined process that facilitates quantification of uncertainties in reservoir models due to geological uncertainties. To demonstrate the workflow, deep fluid flow to the northwest of Ohaaki geothermal system was simulated. Model results suggest that geological structures must be important for lateral fluid flow. However, known faults and permeability contrasts alone cannot explain the distribution of low-resistivity MT anomalies in the region. By creating many geothermal reservoir models from multiple geophysically-based geological realisations, we hope to determine the range of geological phenomena that could help to cause inferred ~5 km lateral migration of hot buoyant fluids as they rise from depth in the eastern part of the TVZ.

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