Geophysical imaging of the Paeroa Fault for improved earthquake modelling

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Executive Summary

The Paeroa Fault is one of the most significant active faults in the Taupō Rift and poses a substantial seismic hazard to central New Zealand. Current national hazard assessments simplify the fault's subsurface geometry due to limited data, particularly regarding its dip angle and the connectivity of multiple surface fault strands. This uncertainty directly affects estimates of the fault's maximum earthquake size and therefore influences building standards, infrastructure planning, and emergency management.

This project aimed to reduce this uncertainty by testing whether a Dense Nodal Seismic Array (DNSA), combined with ambient noise tomography, could image the shallow subsurface structure of the Paeroa Fault. A network of 147 nodal seismometers was deployed across an 8 by 10 km area at the northern end of the fault for approximately one month, recording continuous seismic data. Ambient noise generated by natural and anthropogenic sources was analysed to derive shear-wave velocity models of the upper ~1 km of the crust.

The seismic data quality was high, with clear and symmetric wave propagation indicating favourable conditions for ambient noise analysis. Velocity models derived from the data show a broadly layered structure with increasing velocity at depth, along with several localised velocity anomalies. However, these anomalies do not clearly align with the mapped surface trace or expected orientation of the Paeroa Fault. As a result, the preliminary velocity model does not yet provide strong constraints on fault dip or subsurface fault geometry.

Despite this, the project successfully demonstrates that DNSA deployments and ambient noise tomography can be applied effectively in the Taupō Rift, a geologically complex volcanic and geothermal environment. The study provided valuable experience in deploying nodal seismic networks, and established data processing workflows that can be applied in future projects to speed up data analysis and interpretation.

Overall, while the immediate goal of constraining the Paeroa Fault's geometry has not yet been achieved, the project provides valuable proof of concept and lays the groundwork for future studies. These methods show strong potential for improving subsurface imaging of faults, and volcanic and geothermal systems in New Zealand, with important long-term implications for seismic hazard assessment and risk reduction.

Abstract

The Paeroa Fault is a major active structure within the Taupō Rift, capable of generating large (Mw ≥ 6.8) earthquakes, yet its subsurface geometry—particularly fault dip and the connectivity of multiple surface strands—remains poorly constrained. This uncertainty propagates into New Zealand's National Seismic Hazard Model, where the fault is currently represented as a single planar structure with a fixed 60° dip. To investigate whether higher-resolution constraints on shallow fault structure could be obtained, we deployed a Dense Nodal Seismic Array (DNSA) comprising 147 broadband and short-period nodal seismometers across an 8 x 10 km area at the northern end of the Paeroa Fault. Continuous seismic data were recorded over approximately one month and analysed using ambient noise tomography methods.

Cross correlations of ambient seismic noise exhibited clear symmetric moveout at ~2.1 km/s, indicating favourable noise source distribution and enabling reliable dispersion analysis. Group and phase velocity dispersion curves were manually picked from high-signal-to-noise cross correlations and inverted for 1D shear-wave velocity profiles using an evolutionary inversion algorithm. These profiles were integrated to produce 2D shear-wave velocity depth slices to ~1 km depth.

The resulting velocity model shows a general increase in velocity with depth and several lateral velocity anomalies; however, these features do not clearly align with the mapped surface trace or expected geometry of the Paeroa Fault. Consequently, the preliminary results do not yet provide robust constraints on fault dip or subsurface fault connectivity. Despite this, the study demonstrates that DNSA deployments combined with ambient noise tomography can successfully image shallow crustal structure in the Taupō Rift. Incorporation of short-period instruments and more sophisticated joint inversion approaches may improve resolution in future analyses. Overall, the results highlight both the potential and current limitations of ambient noise methods for fault imaging in volcanic and geothermal settings.

Keywords

Paeroa Fault, Dense Nodal Seismic Array, Ambient Noise, Shear-wave velocity, Earthquake, Quantifying Hazards and Impacts

Introduction

The Paeroa Fault is one of the largest and most active faults in the Taupō Rift, capable of generating magnitude Mw 6.8+ earthquakes on a millennial timescale (Berryman et al., 2008). It splays ENE into the Ngapouri Fault at its northern end, and numerous strands have been mapped at the surface, suggesting a complex subsurface structure of with interconnected fault planes (Figure 1). Despite its significance, the fault's geometry at depth—particularly its dip angle and the connectivity of multiple surface strands—remain poorly constrained. This results in significant uncertainty in estimates of the faults hazard potential. The Community Fault Model (CFM, Seebeck et al., 2023) simplifies the Paeroa Fault's geometry to a single plane with a standard dip angle of 60°, based on shallow ~5 m deep trench data. However, if the dip angle was instead 30°, the faults maximum rupture area and maximum magnitude would increase by 70%. This uncertainty is transmitted into the National Seismic Hazard Model (NSHM, Gerstenberger et al., 2023), which underpins building codes, infrastructure planning, and emergency management.

This project aimed to resolve this uncertainty by deploying a Dense Nodal Seismic Array (DNSA) across an 8 x 10 km area at the northern end of the Paeroa Fault to test the potential of ambient noise tomography imaging fault structures in the Taupō Rift. The expectation being that a high-resolution velocity model derived from ambient noise tomography would provide an image of the shallow (~ 1 km depth) earth structure across the deployment area, and provide some insight into the structure of the Paeroa Fault.

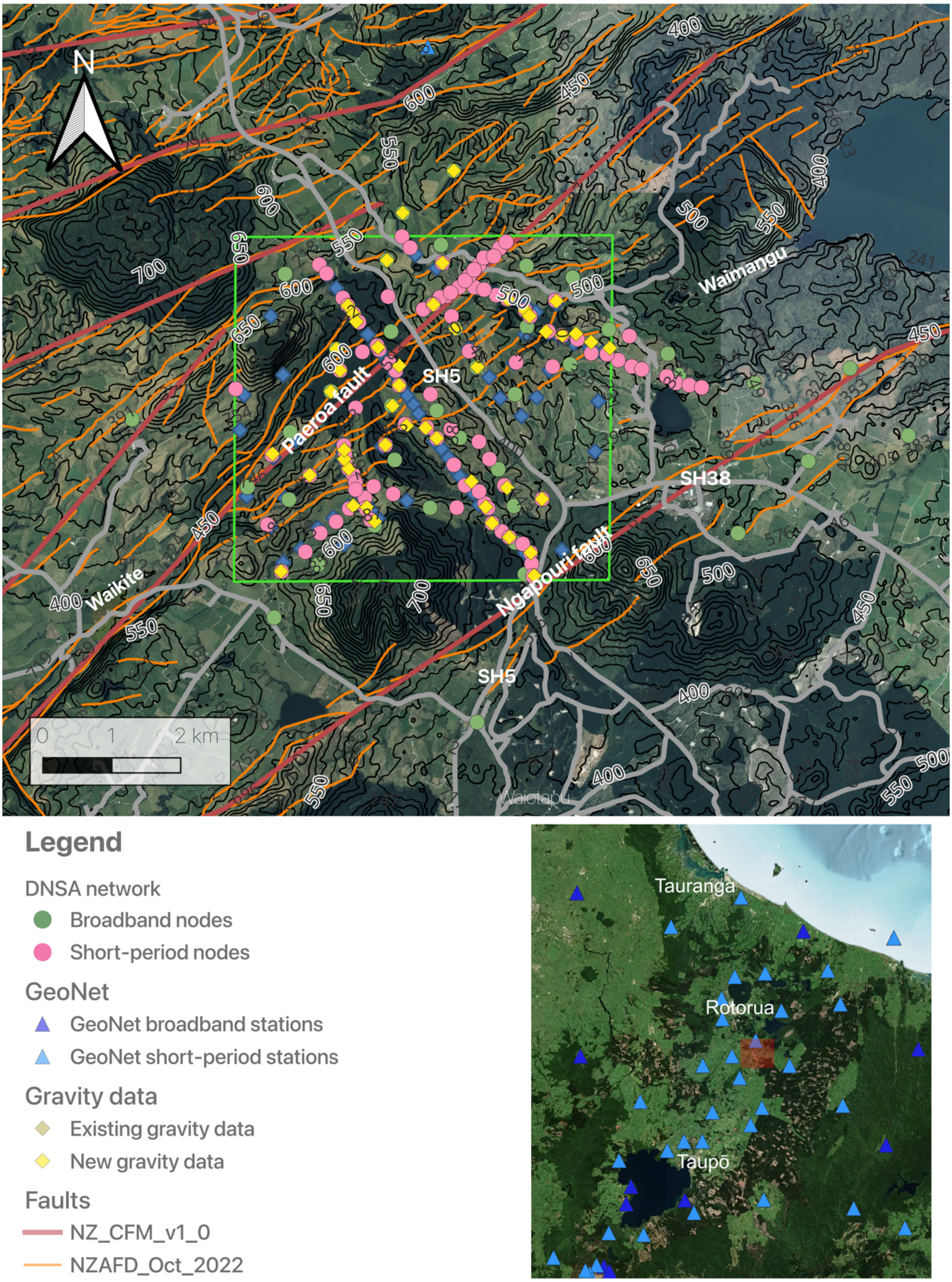

Figure 1: Map of study area, showing existing and newly acquired data. The green box shows the initial area of interest, and the red box on the regional map shows the location of the broader study area. Community Fault Model fault traces are marked in dark red, and NZ Active Fault Database fault traces are marked in orange, with Paeroa and Ngapouri Faults labelled. The Waikite and Waimangu geothermal areas are also labelled, along with State Highways 5 and 38. Elevation data is contoured every 25 m, and labelled every 50 m.

Methodology

Our array consisted of 147 broadband (IGU-BD3C-5) and short-period (IGU-16HR 3C) SmartSolo nodal seismometers, deployed for approximate 1 month from December 2023 to January 2024 (Figure 1). These instruments recorded continuously at 250 Hz to build up a dataset for analysis with ambient noise tomography methods. This approach utilises persistent background seismic noise (typical sources include ocean swell, heavy traffic, or the wind through a nearby forest) as a “signal” that can be extracted by computing cross correlations between pairs of seismic stations (e.g. Benson et al., 2007).

Dispersion curves (phase or group velocity as a function of period) are extracted from these cross correlations. These dispersion curves can then be inverted for a model of shear-wave velocity beneath your seismic array. These velocity models can be interpreted for earth structure, and can potentially resolve the structure of faults as a function of depth (Wang et al., 2019, Fu et al., 2022).

Our analytical approached followed Benson et al., 2007. So far, we have focused our analysis on the broadband instruments, due to their better response at low frequencies where ambient seismic noise energy is typically concentrated (0.2-0.5 Hz), and a more manageable dataset size (882 possible station pairs, compared to 10,731 with the full dataset).

Data from our DNSA was downloaded and converted to miniSEED format. It was then downsampled to 25 Hz, cut to 12-hour time chunks, and saved to HDF5 format. Bandpass filtering, spectral whitening, and one-bit normalisation were applied, and cross correlations computed using the python package *noisepy* (Jiang and Denolle, 2020).

The *EGFAnalysisTimeFreq* Matlab codes (Yao, H., 2015) were used to quality control the resulting cross correlations, and manually pick group and phase dispersion curves. A SNR ratio of at least 10 was required for a dispersion curve to be considered for picking, and picks were considered valid out to a station separation distance of 1.5 times wavelength.

1D velocity profiles were computed from these dispersion curves using the python package *evodcinv* (Luu, K. 2023). This is an evolutionary search algorithm, where random permutations on an initial velocity model are generated and their resulting dispersion curves computed. The best fitting subsets are then selected to be the source of permutations for the next iteration. This algorithm tries to simultaneously fit the group and phase dispersion curves if they are both available.

Results

The cross correlations were plotted as a function of distance (Figure 2), and this showed a clear symmetric moveout at a velocity of ~2.1 km/s, indicating a good azimuthal distributions of noise sources. This means the causal (positive lag) and acausal (negative lag) can be stacked, improving the signal to noise ratio for dispersion analysis and velocity inversion.

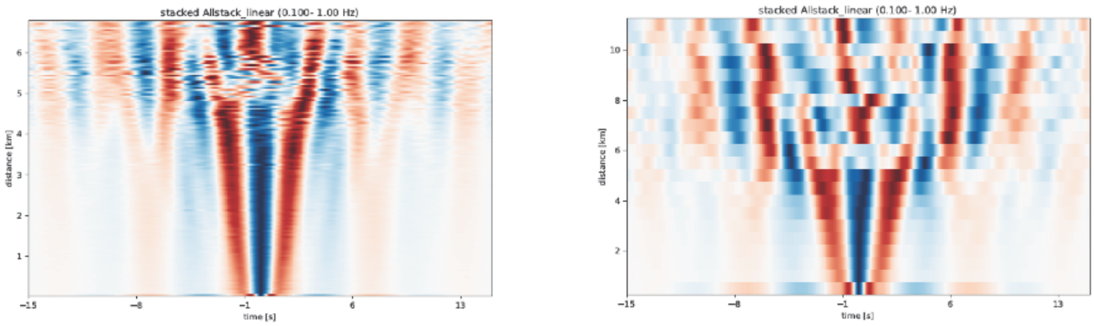

Figure 2: Moveout stacks for the short period (left) and broadband (right) cross correlation data.

Dispersion curves generally showed a coherent band of energy between 1-5 s period, with slight decrease at longer periods being common (Figure 3). This was not expected, as velocity generally increases with period, but was a persistent feature of our dataset so we believe it is a real signal. 812/861 cross correlations met our SNR criteria, and from these 282 group velocity and 215 phase velocity curves were picked.

1D velocity models were generated from the dispersion curves at each station pair using *evodcinv* (Luu, K. 2023). We set a 9-layer initial model and created 100 permutations, and iterated 150 times to yield a final set of velocity models. The algorithm generally converged on a stable solution after about 50 iterations. Various starting models were also tested to confirm the robustness of the solution. An example best fitting model for station pair BB032-BB051 is shown in Figure 4.

The resulting 1D velocity profiles at each station pair were then combined and translated to 2D depth slices using anisotropic gaussian kernels to distribute the velocity profile from each station pair across the study area. Depth slices at 200, 500, 750 and 100 m from our best fitting model are shown in Figure 5.

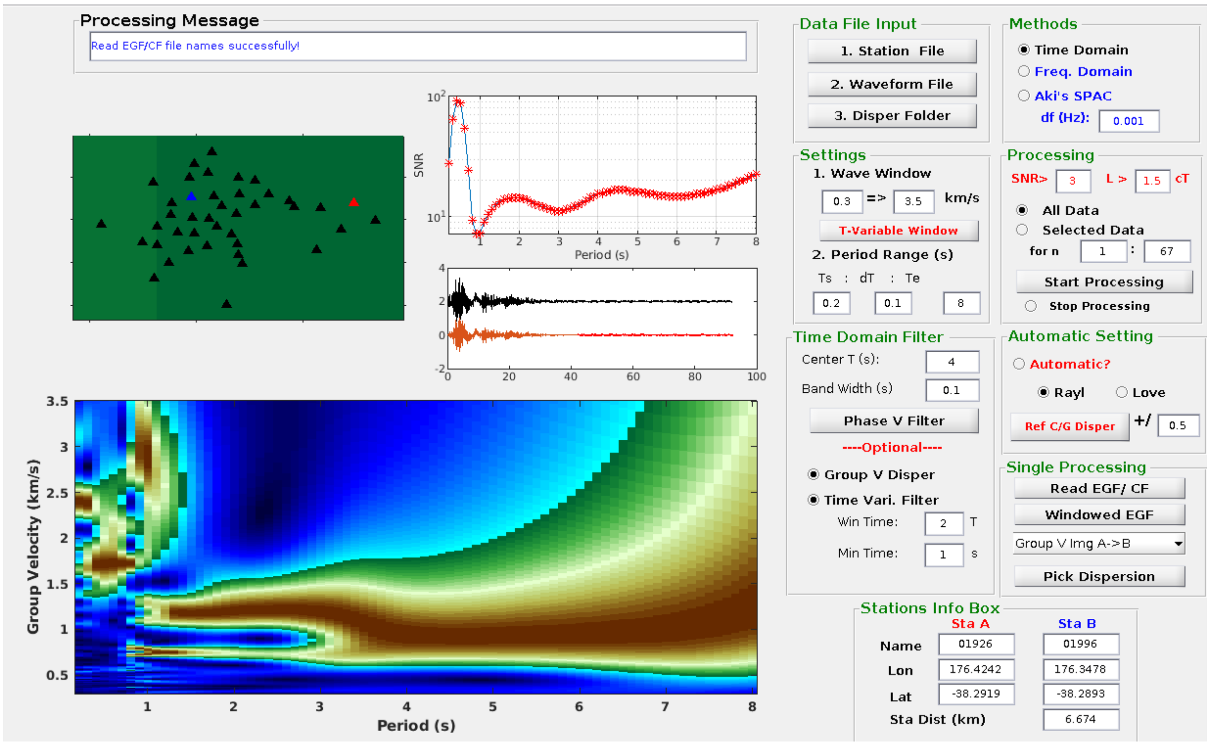

Figure 3: An example of dispersion curve and the picking software, *EGFAnalysisTimeFreq*. The dispersion curve is shown bottom left, the broadband network is top left, and the causal (black) and acausal (red) cross correlation functions and SNR ratio top middle.

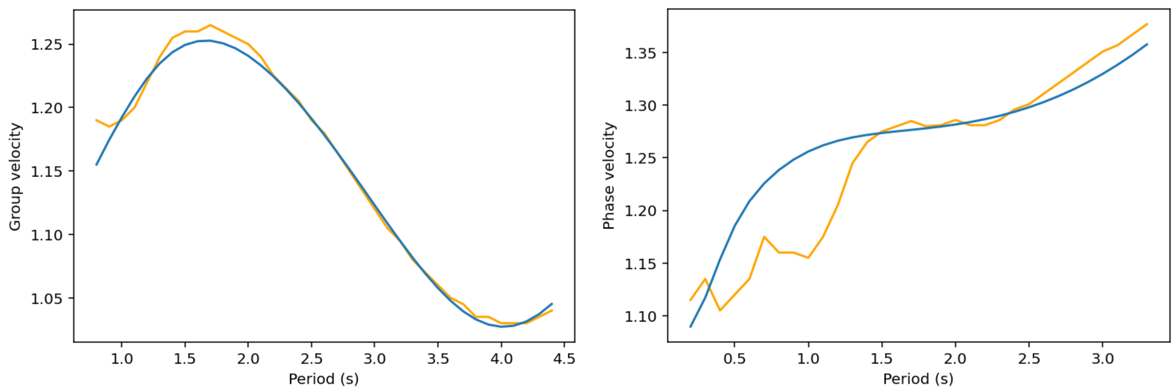

Figure 4: An example solution from station pair BB032-BB051 from *evodcinv*. The orange line is the picked dispersion curve, and the blue line is the best fitting result from an inversion run.

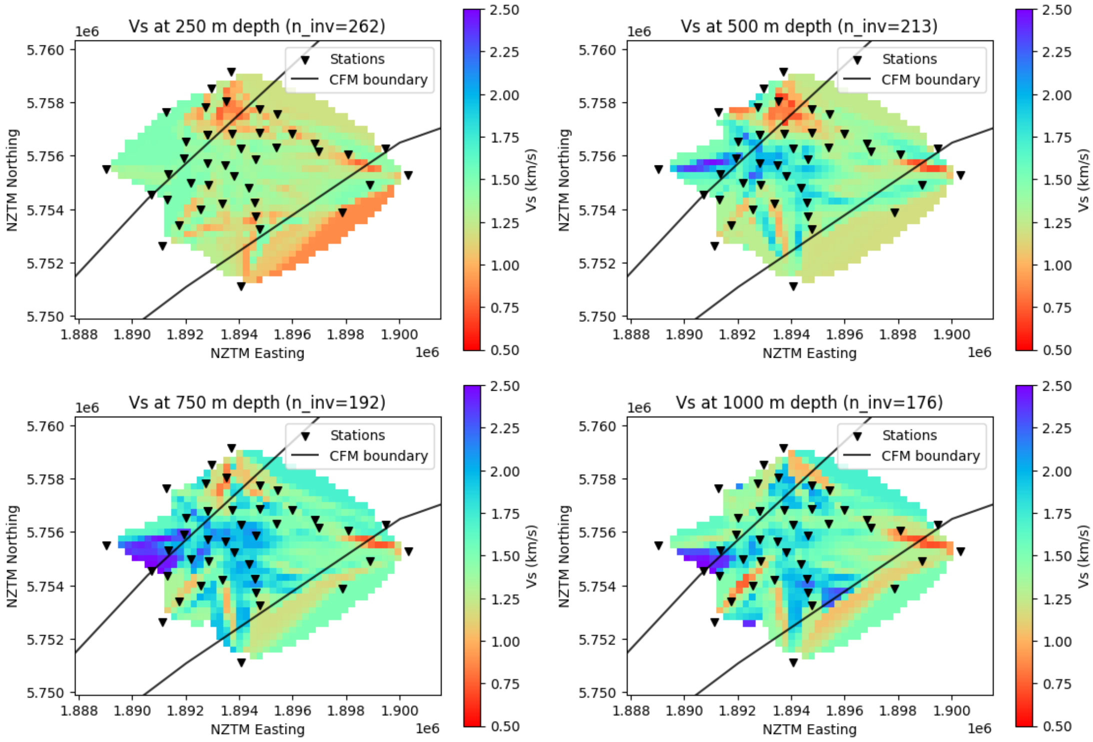

Figure 5: 2D depth slices at 250, 500, 750 and 1000 m depth through the integrated velocity model. Broadband seismic stations used in the inversion are marked by inverted triangles. The Paeroa and Ngapouri Fault traces from the Community Fault Model (CFM) are marked top and bottom, respectively.

Discussion

In this project we deployed a nodal seismic network across the northern end of the Paeroa Fault and collected ~1 month of continuous seismic data for analysis using ambient noise tomography methods. While our analysis has focused on a subset of the data to date, we have shown that ambient noise methods can be successfully applied to DNSA data in the Taupō Rift, with the clear symmetric moveout (Figure 2) showing that passive seismic signals were clearly present in the data, and successfully extracted.

Picking dispersion curves was challenging and time consuming, as we elected to process the broadband data manually. While this is ultimately slower than an automatic processing algorithm, exploring this data manually initially allows us to get a better “feel” for our dataset, and gives us a better understanding of what signals are real and how they might translate to geological structure. In future work (e.g. in analysing the short-period data) we will likely use an automated picking algorithm (e.g. *disperpicker*, Yang et al., 2022), and review the picks manually.

Inverting the dispersion data for a velocity model was also challenging, with some of the algorithms we were hoping to test running into compilation issues (e.g. *dsurftomo*, Fang et al., 2016, *disbatomo,* Pan et al., 2019). While the *evodcinv* codes we used performed well for 1D velocity inversions at individual station pairs, a more sophisticated approach that inverts all dispersion curves together and accounts for topography would provide a more robust approach for interpreting geological structures (e.g. *BayesBay*, Magrini et al., 2025). These will be trialled for the final inversions as part of future work.

The 2D slices through our integrated velocity model (Figure 5) show a generally increasing trend with depth, and a few anomalous velocity zones (e.g. a low velocity zone in the north of our model, and a higher velocity region below ~500 m running NW-SE through the central part of the model). These anomalous zones don't line up with the NNE trend of the Paeroa Fault however, and may therefore be unrelated to fault structures. It is possible a more sophisticated inversion algorithm, and/or the higher resolution provided by the addition of the short-period instruments to the analysis will reveal a different picture, However based on these initial results our analysis may not provide any clues on the dip or structure of the Paeroa Fault, as was initially hoped.

We still believe DNSA surveys and ambient noise methods have a lot of potential in imaging the subsurface in volcanic and geothermal regions, as study's overseas have shown very promising results (e.g. Stumpp et al., 2025, Muñoz-Burbano et al., 2024, Wu et al., 2024, Cabrera-Pérez et al., 2021). Now that we have gained some experience in DNSA deployments and ambient noise analysis, and established a processing workflow, we expect the data processing and analysis phase in future projects to be much faster, and we hope to apply our experience to new DNSA and ambient noise projects in the near future.

Conclusions

Nodal seismometers and DNSA surveys can be used with ambient noise tomography methods to retrieve S-wave velocity structure of the shallow (~1 km depth) subsurface in the Taupō Rift.

In our preliminary results our velocity model has not provided much insight into the dip angle of the Paeroa Fault, as initially hoped. However, it is possible some structure across the fault plane may still be revealed when the short-period instruments are included in the analysis and more sophisticated velocity inversion algorithms are employed.

Despite this, we still believe DNSA surveys and ambient noise methods have plenty of potential in imaging the shallow (~1 km depth) earth structure across fault planes and in volcanic and geothermal systems, and we will our work in refining the method and adapting to New Zealand's geological conditions.

Outputs and dissemination

- Presented a progress report at the 46th New Zealand Geothermal Workshop in Auckland in November 2024.
- Attended Workshop on Computational Earth, in Elba, Italy from 12-17th of October to share our results on the project and learn from other scientists doing similar studies.
- Presented results at the Geosciences conference in Auckland in November 2025.
- Internal briefing of preliminary results to Matt Gerstenberger from the NSHM team (16th December, 2025).

Publications, communications and engagement

Journal papers:

- [Draft] Keats, B., Bannister, S., Massiot, C., Miller, C., Henrys, S., Jiang, C., (to be submitted 2026). Geophysical imaging of the Paeroa Fault: Insights from a dense nodal seismic array. *Journal TBD*.

Conferences proceedings:

- Keats, B., Bannister, S., Massiot, C., Miller, C., Henrys, S., Brakenrig, T., Coup, L., Macdonald, N., Kurimura, O., Werahiko, L., Werahiko-Mita, U., Phillips, M., Jiang, C., Tahu, N., & Whaoa, N. (2024, November). Geophysical imaging of the Paeroa Fault: Insights from a dense nodal seismic array. Proceedings 46th New Zealand Geothermal Workshop. https://worldgeothermal.org/geothermal-data/conference-paper-database.

Media stories:

- Media story on NHC website, that was subsequently picked up and re-published by *scoop* and *sunlive* (https://www.naturalhazards.govt.nz/news/humming-planet-reveals-secrets-of-paeroa-fault/, https://community.scoop.co.nz/2024/07/humming-planet-reveals-secrets-of-paeroa-fault/, https://www.sunlive.co.nz/news/346806-humming-planet-reveals-secrets-of-paeroa-fault.html)
- Media story on GNS Science website (https://www.gns.cri.nz/news/taking-a-passive-approach-to-seismic-vibration-reading/)
- Radio interview on 9th of July (unsure if this one went to air)
- Radio interview with Dale Husband on Waatea News (https://waateanews.com/2024/07/17/dr-brooke-keats-geophysicist-and-project-lead/)

Social media posts:

- [Upcoming] NHC social media post on the educational outreach day we participated in at Mataarae marae.

Outreach and engagement activities:

- Visit to Mataarae marae to take part and present at an educational outreach day organised by Ngati Tahu-Ngati Whaoa Runanga staff (1st of October, 2025).

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