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Innovative Geochemical Approaches to Mapping Fluid Pathways in Geothermal Reservoirs

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ABSTRACT

Understanding fluid movement in geothermal systems is crucial for optimizing resource extraction, managing reservoirs sustainably, predicting geohazards, and reducing the risk of drilling non-productive wells. In epithermal ore deposits - formed in settings analogous to modern geothermal systems - multi-element geochemical techniques are often employed to map hydrothermal alteration zonation as a proxy for fluid conditions. However, these techniques are rarely applied in geothermal studies. This study aims to bridge this gap by adapting multi-element geochemical techniques, commonly used in mining, to a geothermal field in New Zealand. 43 new samples were collected to complement existing data, resulting in over 200 samples from various studies. The results were visualised and modelled in 3D alongside existing data, integrating insights from the geothermal field's 3D geological model. This allowed a more robust, geochemically informed delineation of trace element assemblages produced in high temperature, high fluid-flux conditions, leading to an enhanced understanding of fluid movement within the reservoir. This study demonstrates the potential to repurpose geochemical techniques from the mining sector for geothermal applications. This approach may contribute to improved exploration strategies, well targeting and reservoir management by enhancing our understanding of fluid movement within the geothermal reservoir.

1 INTRODUCTION

There is an established connection between epithermal mineral deposits and modern high-temperature geothermal systems, the former being recognised as 'fossil' equivalents of the latter (Henley & Ellis, 1983; Henley, 1985; Henley et al. 1986). Active geothermal systems such as those in New Zealand's Taupo Volcanic Zone (TVZ) are frequently studied as analogues for active depositional environments of epithermal Au-Ag (Simmons and Browne, 2000; Cooke and Simmons 2000; Rowland and Simmons, 2012). Although naturally occurring deposits of precious metals in economic concentrations have not been identified in TVZ geothermal fields, the connection is evidenced through the presence of gold, silver and copper deposits in scale accumulated on pressure plates in geothermal production wells at Ohaaki and Kawerau geothermal fields in the TVZ (Brown, 1986).

Geochemical exploration methods are often used across the mineral exploration and resource development process, notably the use of pathfinder elements which occur in anomalously high concentrations in proximity to mineral deposits, and similarly to many hydrothermal minerals, under well-defined conditions (Simmons et al., 2005; Christie, 2019). In recent decades there has been a marked increase in the use of multi-element geochemical analyses in the mineral exploration process, which provide a means of identifying pathfinder elements, lithological compositions and aspects of hydrothermal mineralogy through a single analytical process (Halley, 2020). Analytical results can be efficiently visualised and modelled in 3D along with other downhole data such as logged/modelled geology, temperatures and fluid flow using Leapfrog, an industry-standard geological modelling software.

This approach is rarely used in exploration and development of active geothermal systems, but offers significant advantages. This paper describes a simple first-pass method of interpreting sub-surface conditions using multi-element geochemical data, by modelling patterns of pathfinder element distribution and correlating them with known subsurface conditions.

2 OHAAKI GEOTHERMAL SYSTEM: GEOLOGICAL SETTING AND BACKGROUND

The Taupō Volcanic Zone (TVZ) is an active, NE-trending volcano-tectonic intra-arc rift in the North Island of New Zealand (Figure 1). It hosts at least 6 inactive and 2 active rhyolitic caldera complexes and 23 major active geothermal systems which accommodate much of the crustal heat transfer in the TVZ (Figure 1)(Hochstein,1995; Wilson and Rowland, 2016). Stratigraphy in the TVZ comprises voluminous volcanic and

sedimentary packages, underlain and bounded by a package of partially metamorphosed Mesozoic sandstones and argillites, collectively (and herein) referred to as greywacke (Mortimer et al., 2023).

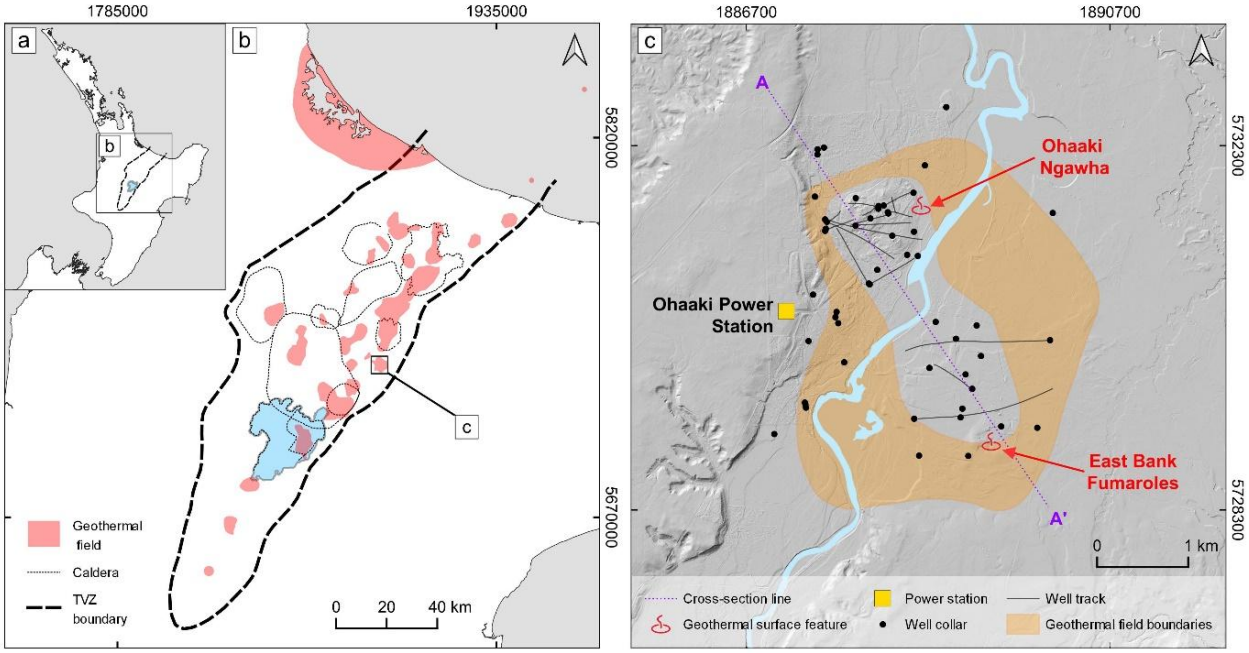


Figure 1: a) North Island of New Zealand, with location of the TVZ (boundaries after Stagpoole et al., 2021); b) TVZ outline, caldera boundaries (after Stagpoole et al., 2021) and geothermal fields; c) Location map of Ohaaki Geothermal Field (after O'Sullivan et al. 2025).

The Ohaaki geothermal field is located in the central TVZ near its eastern margin (Figure 1). Over 70 geothermal wells drilled over the last 60 years have defined the stratigraphic sequence and informed an existing 3D geological model which has been constructed and updated over recent decades (Mroczek et al., 2016; O'Sullivan et al., 2025). The stratigraphy comprises a 'layer cake' sequence of volcanic and volcano-sedimentary deposits, including ignimbrites, tuffs, lavas, siltstones and breccias, overlying the greywacke basement which is steeply downfaulted to the west and forms a horst structure to the east (Figure 2; O'Sullivan et al., 2025).

The Ohaaki geothermal system is characterised by high reservoir temperatures (exceeding 300°C), with dilute NaCl fluids containing high CO_2 content (Hedenquist 1990, Giggenbach, 1995; Simmons and Browne, 2000; Mroczek et al., 2016). Variability in fluid chemistry between the northeastern ('East Bank') and southwestern ('West Bank') parts of the field has been investigated through numerical modelling incorporating downhole pressure data, fluid geochemistry data, magnetotelluric modelling (Bertrand et al. 2015), geological models and fracture permeability (Mroczek et al. 2016). This reservoir model suggests that the deep liquid reservoir across the field is fed by two upflows: a major liquid upflow in the West Bank and a secondary liquid and vapour upflow in the East Bank (Mroczek et al. 2016).

Studies on the hydrothermal alteration mineralogy show that the distribution of hydrothermal minerals reflects the temperature, fluid compositions and intensity of fluid flow encountered in geothermal wells (e.g. Hedenquist, 1990; Lonker et al., 1990; Simmons and Browne, 2000; MacIntosh, 2000; Yang et al., 2001; Chambefort and Dilles, 2023). Zonation of temperature-sensitive minerals, including smectite, illite-smectite and illite clays, broadly reflects the thermal structure of the system (Simmons and Browne, 2000; Yang et al. 2001), while the abundance of adularia and quartz increases with proximity to upflow zones (Simmons and Browne, 2000, MacIntosh, 2000).

The transport and deposition of metals and other trace elements, both within the Ohaaki geothermal system and in the wider TVZ, has been investigated through studies of both fluid and rock geochemistry (e.g. Ewers and Keays, 1977; Simmons and Browne, 2000; Simmons and Brown, 2007; Simmons et al., 2016a; 2016b; Chambefort and Dilles, 2023). These studies have shown that significant concentrations of hydrothermal precious metals such as Au and Ag are present in fluids at Ohaaki, although mechanisms for deposition at economic concentrations appear to be lacking (Simmons and Brown, 2007; Simmons et al., 2016a). However, enrichments in pathfinder elements such as As, Sb and Cs in whole rock samples are comparable to those used

in mineral exploration, indicating these and other pathfinders may still be valid as proxies for subsurface conditions (e.g. Chambefort and Dilles, 2023).

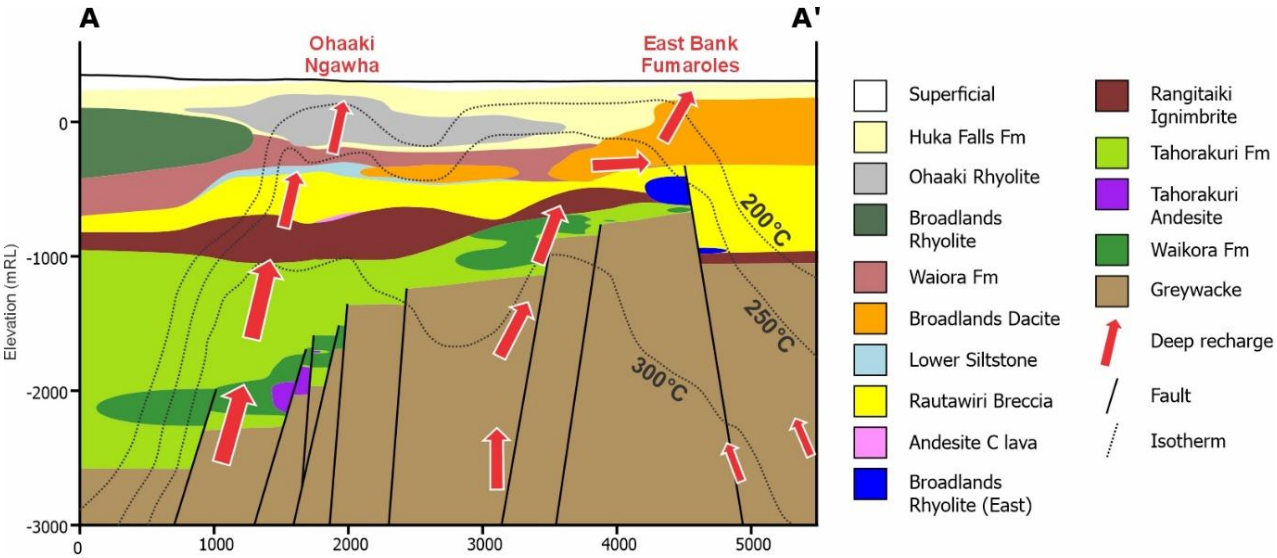


Figure 2: NW-SE cross section AA' – modelled geology of the Ohaaki Geothermal Field with natural state isotherms and deep recharge zones, modified from O'Sullivan et al., 2025.

3 METHODOLOGY

3.1 Sample collection and analytical techniques

Existing multi-element geochemical datasets collected using the similar analytical methods as this study were compiled, including 19 samples of Huka Falls Formation sediments (Turnbull et al. 2019) and 33 samples from the illite-bearing zone across multiple rock types (Chambefort and Dilles 2023).

XRF datasets, including 66 analyses for As and Sb (Simmons and Browne, 2000), 47 samples of from Rautawiri Breccia, Ohaaki Rhyolite and Tahorakuri Formation (MacIntosh, 2000), 14 samples from basement greywacke (Absar 1988), 3 samples from volcanic units (Bignall, 1994) were also compiled.

43 samples of drill core (n=38) and cuttings (n=5) were collected for this study to fill spatial gaps in the existing geochemical coverage, as well as to ensure representative samples from each major lithology with varying degrees of hydrothermal alteration. Sample coverage was limited by the availability of drill core, which was used preferentially over drill cuttings where possible to avoid mixing or contamination issues.

Analyses were conducted on the 43 at ALS Laboratories Brisbane using method CCP-PKG01. Major, trace and volatile elements, and base metals were detected using ICP-MS or ICP-AES following a combination of digestion methods, and carbon and sulfur by induction furnace.

3.2 Modelling pathfinder element distributions in Leapfrog

Modelling of 'pathfinder' element distributions in 3D was carried out in Leapfrog Energy software. Originally developed for the application of grade modelling drillhole data in the mining industry, Leapfrog's implicit method of modelling is now widely used in mining and geothermal industries (Alcaraz et al., 2011). In this workflow, Leapfrog Energy's numerical modelling functionality was used to construct 3D contours of the linked point data with numeric attributes. The numerical modelling workflow uses radial basis functions (RBFs) which are a group of global interpolation methods and dependent on all data points (Cowan et al., 2002).

Selected elements were modelled using available analytical data from this study and compiled from previous studies. Numerical interpolant parameters deemed reasonable for the spacing and abundance of data points, as well as the geological setting and underlying processes, were applied. Interpolant (isosurface/contour) values were selected for each element with to delineate zones of anomalous concentrations. Accurate average abundances for unaltered rocks within the field were difficult or impossible to ascertain, as the vast majority of rocks sampled were at least partially altered. Interpolant values for each element shown were therefore informed by existing estimates of average crustal abundance (Halley, 2015) and geochemical studies of

unaltered rocks from other parts of the Taupo Volcanic Zone (Briggs et al., 1993; Sutton et al., 1995; Beresford et al., 2000; Simmons and Brown, 2007; Johnson et al., 2013, Wilson et al., 2006).

4 RESULTS/DISCUSSION

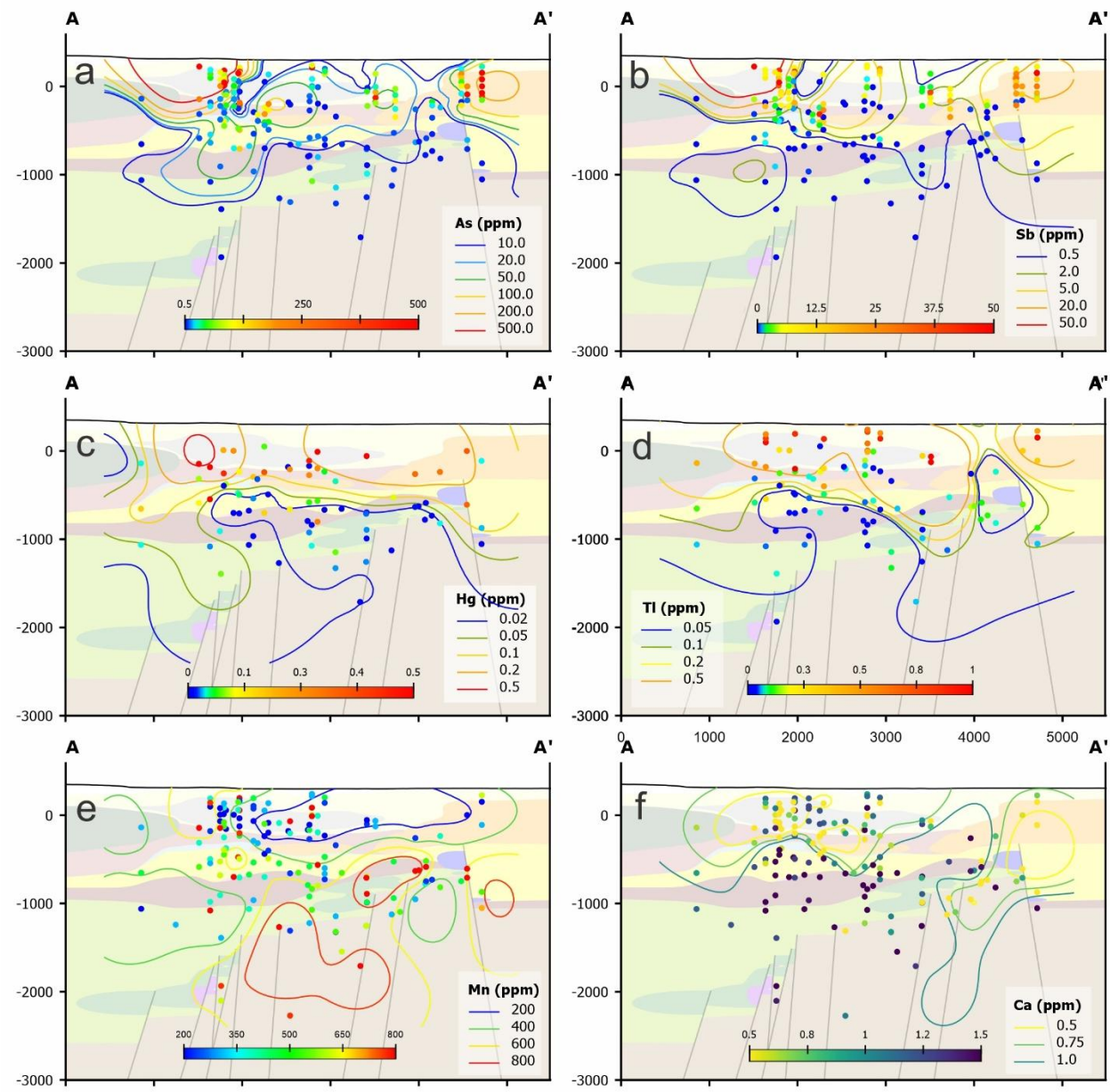


Figure 3: Slice through modelled contours of pathfinder element distributions for a) As, b) Sb, c) Hg, d) Tl, e) Mn and f) Ca. Locations of samples are projected on the section, coloured by abundance indicated by scale bars on each plot. *note ppm range on colour bars does not indicate full range of concentrations.

Selected modelled pathfinder element distributions are shown in Figure 3, projected onto cross-section AA'.

4.1 Spatial distributions of pathfinder elements

Concentrations of As and Sb, detected in shallow parts of the system (<~1000 m below surface) are anomalous (Figure 3), significantly exceeding estimated average crustal abundances and estimated abundances in unaltered TVZ volcanic rocks (Briggs et al., 1993; Beresford et al., 2000; Johnson et al., 2013; Halley, 2015). Zones of highly anomalous As (50 times estimated TVZ background abundance) and Sb (100 times estimated crustal abundance) are co-located in the shallow ~500 metres of the subsurface in the western upflow zone beneath Ohaaki Ngāwhā. This is consistent with previous studies that document zonation of these metals with depth and infer their deposition have occurred via boiling (Simmons and Browne, 2000; Simmons et al. 2016; Chambefort and Dilles, 2023). While anomalous concentrations of these elements is fairly ubiquitous in the shallow portion of the system, modelling and visualisation in 3D shows concentrations are zoned laterally as well as vertically,

increasing significantly proximal to known upflow zones. As these two datasets contain a relatively high number of data points (As n=172, Sb n=161) compared to other pathfinder elements, the modelled zonation is considered fairly robust, particularly where sample/well density is highest. Distribution of Hg is similar to that of As and Sb, with higher concentrations occurring in the shallow subsurface (<400 m below surface), and a localized zone of higher concentration below the Ohaaki Ngāwhā, however with fewer samples analysed for Hg (n=75), interpretation of the spatial distribution is less robust – particularly interpretation of the lateral distribution. Similarly, Tl shows clear vertical zonation, with the highest concentrations (up to 20 times average crustal abundance (Halley, 2015)) occurring in the shallow portion of the system. Again, a sparser, irregularly spaced dataset (n=94) means that lateral zonation cannot be interpreted reliably, however the clear localized enrichment apparently independent of lithology indicates that Tl distribution is likely influenced by reservoir processes and a larger, more closely spaced dataset could provide significant insight into these processes. Depletion in certain elements (e.g. Mn and Ca, Figure 3) can also provide valuable insights into reservoir processes. Both Mn and Ca show broad zones of depletion in the shallow subsurface, likely representing leaching of these elements through steam-heated alteration above the smectite clay zone, while a localized zone of depletion of Ca also appears to correlate with the shallow part of the vapour-dominated upflow in the East Bank.

4.2 Leapfrog modelling workflow

The Leapfrog numerical modelling workflow offers an effective tool for data-poor geothermal systems, enabling intuitive 3D representation of pathfinder element zonation. While current models assume a subvertical upflow, future iterations could incorporate lithological controls and localised structural trends—similar to grade modelling in mineral systems—provided a more comprehensive dataset is available. However, the workflow is constrained by low sample density, necessitating a high interpolant range that risks over-interpolation. This is evident in ambiguous zonation patterns (e.g. Hg and Tl), which may reflect artefacts rather than true geological features. Applying vertical trends could mitigate this but may obscure lithological permeability effects. Increasing sample density per borehole would enhance model reliability and allow for more nuanced trend application.

5 CONCLUSIONS

This study highlights the value of integrating legacy and newly acquired geochemical data to model pathfinder element distributions in a geothermal system using Leapfrog Energy software. The 3D modelling of elements such as As, Sb, Hg, Tl, Mn, and Ca reveals both vertical and lateral zonation patterns, with strong enrichment of As and Sb in the shallow subsurface beneath the Ohaaki Ngāwhā, consistent with boiling-related deposition processes. While these elements represent only a small subset of the available geochemical suite, their distributions clearly reflect reservoir processes - and similar zonation in other elements is likely to yield further insights.

Despite limitations due to sparse sampling and uneven data coverage, the modelling workflow effectively highlights zones of elemental enrichment and depletion, offering a glimpse into the potential of multi-element geochemical datasets. Beyond visualising correlations, such datasets could be applied to quantitative calculations of alteration mineral abundance, lithogeochemical classification, and numerical modelling of cation movement as proxies for permeability. Future work incorporating lithological and structural controls, supported by a more comprehensive and spatially dense dataset, would enhance model accuracy and deepen understanding of subsurface geochemical and hydrothermal processes.

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