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An Integrated Approach to 3-D Modelling to Better Understand Geothermal Reservoirs

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ABSTRACT

This study presents some tools and techniques to construct an integrated 3-D model of a geothermal field. A synthetic dataset is used to build a model using Leapfrog Geothermal software. The geological setting of the field is defined from surface geological data and borehole information. Hydrothermal alteration mineralogical and chemical zoning is represented in detail, in combination with temperature measurements to characterise particular reservoir conditions. The combination of multiple datasets in one single interface is providing the tools necessary to solve a multidisciplinary challenge and better correlate available information. Fast 3-D interpolation techniques are used to generate geological models and interpolant models. Powerful and flexible visualisation tools facilitate our interpretation of the data and models and identification of possible correlation to improve our understanding of the dynamics and evolution of a geothermal field.

This example demonstrates the strength of an integrated approach to help better understand the geological framework and evolution of geothermal reservoir, improves the operator confidence and supports drilling strategies and day-to-day management of the resource.

1. INTRODUCTION

Sustainable management of a geothermal reservoir guarantees the longevity and upkeep of the resource for power generation or direct use. It requires a sound understanding of the geological framework of the area, including stratigraphic correlations and structure, alteration signature, as well as the hydrology and evolution of the systems. It presents an interdisciplinary challenge and for a long time, geological, geophysical and reservoir models were created independently, hindering correlations and detrimental to an integrated approach. In recent years, the geothermal industry has been taking advantages of major technical improvements in geoscientific modelling, focussing on moving from traditional 2-D interpretation and visualisation towards the 3-D and even 4-D space, and looking into better data integration to build comprehensive models in an attempt to represent spatially complex and temporally varying geothermal systems.

Specifically due to the geothermal reservoir complexity and high costs of collecting data, 3-D modelling software used in the geothermal industry must be capable of handling complex geological geometries and reservoir data from irregularly spaced sparse data sets (Teng and Koike, 2007). Software packages that are intuitive to use, allow 3-D models to be quickly and efficiently built, and routinely updated are most desirable (Cowan et al., 2002). This is generally the case when selecting a software tool, but it is particularly true in the geothermal industry where additional drill holes and surveys will yield additional information which must be used to update the existing models.

To address these challenges, a 3-D software package known as Leapfrog Geothermal was developed by New Zealand based software developer ARANZ Geo Limited in collaboration with key players of the New-Zealand geothermal community. Leapfrog Geothermal is specifically designed for our industry and provides a unique interface that allows the integration of geothermal datasets such as geology, structure, temperature, hydrothermal alteration, feed zones, geophysical data and Tough2 numerical models. This field-wide multidisciplinary data is directly visualised, compared and modelled in one single environment (Alcaraz et al., 2010, 2011; Milicich et al., 2010; Massiot et al., 2011; Pearson et al., 2012).

This paper presents a case study using synthetic datasets illustrating the tools and techniques available to build an integrated 3-D model of a geothermal field. First we present the methodology followed to build models using Leapfrog Geothermal, and then use commonly available datasets to create a simple geological model which is used as the platform for further data integration. We include temperature data and focus on hydrothermal alteration signature and chemical variations to better understand the properties of the reservoir and its evolution. This model is used as a case study to demonstrate what is achievable using a standard dataset in a geothermal field exploration to production setting.

2. METHODOLOGY

Leapfrog Geothermal implements implicit modelling techniques to provide a dynamic solution to solve geological modelling problems. It uses fast 3-D interpolation to derive a continuous function from the data which is evaluated at any point in the model. This is advantageous over a discrete model as the primary data is retained and the model can be re-evaluated at any new resolution from the underlying mathematical function (Cowan et al., 2003). Modelling is automated where possible to decrease processing time and remove hidden biases using an iterative and transparent model building process.

2.1 Data input

The sparsity of geothermal datasets means there are multiple interpretations that although consistent with the data have very different scientific implications. Multi-disciplinary data integration is key for modellers to create informed models and test possible solutions. The Leapfrog Geothermal interface facilitates this process by providing tools to highlight the geological relationships between datasets, which may then be visualised or used to model the region. It supports various industry standard data formats and models (e.g. Magnetotelluric.OUT file, Gocad models, Tough2 grids) and the most common and widely used datasets to represent surface information (e.g. geology maps, surface faults), sub-surface data (e.g. resitivity, microseismicity) and borehole data (e.g. localised measurements or interval data). It can also be used to create outputs including cross sections and viewer files to confirm interpretations in both 2-D and 3-D.

2.2 Surface and volume generation

Continuous downhole well measurements (e.g. temperature data, resistivity) are implicitly modelled to form what is termed an interpolant model. Leapfrog Geothermal derives a continuous function from the numeric data which it evaluates at any point to define the model value. A Radial Basis Functions (RBFs) based approach is used to implement the interpolant functions as it can be generated and evaluated rapidly (Carr et al., 2001), and best fitted when the data points do not lie on a regular grid and when the sampling density varies. This is displayed using isosurfaces, which are smooth surfaces that share a single value.

Categorised data (e.g. lithology, alteration) are used to construct geological models. These are built by creating boundary surfaces equivalent to the zero value isosurface derived from contacts between each category interval. The resulting surfaces are then combined to form volumes using constructive solid geometry (CSG) union, difference and intersection operations based on common geological processes (e.g. deposit, intrusion, erosion). These processes are both automated ensuring fast and consistent surface and volume generation where each volume represents a different category (e.g. a geological formation). It is possible to create multiple models using the same data to make sure the most appropriate interpretation is selected.

2.3 Building a geological model

Representing the geological environment of an exploration or producing field is often the first step in building an integrated geothermal model. At its most basic, a geological model is a volume that covers the region of interest constrained at surface by the topography. This forms the foundation from which the model is then successively refined adding structures and stratigraphy. The structure of the model is represented by purposely built fault surfaces which are combined to form faulted blocks, based on the interaction and chronology of the faults. The stratigraphic surfaces are built to represent a geological process, such as a deposit, erosion, a vein or an intrusion. Based on the chronological sequence and the formation type, the geological volumes are automatically generated within the faulted block boundaries.

During exploration or early development of a geothermal field, data may be scarce. A combination of inputs can be used to generate stratigraphic surfaces to allow the creation of a geological model. This can be started prior to drilling, with the use of surface data to define preliminary structures which can be used to help aid the placement of boreholes. Possible data inputs include GIS vectors (e.g. mapped geological boundaries), structural measurements, polylines which are manually drawn by the modeller, control points or any pre-existing surface, in addition to any borehole contact points. The complexity of the model and the amount of data available dictates the amount of manual input from the modeller, which can choose to use polyline edits and the use of both global and localised trends to account for variable anisotropy input into the model.

3. DEMONSTRATION MODEL

This demonstration model is presenting a collection of data typical of a geothermal field from an advanced exploration to producing setting. Surface mapping and chemical sampling identified the geothermal resource during the first phase of exploration, which was then confirmed during a successful drilling campaign. Downhole data include geological logs, alteration description and quantification, geochemical analyses and temperature data. Geophysical datasets are not presented in this example, but could likewise be integrated.

3.1 Surface data

Geological and geochemical investigations identified the potential for a high enthalpy geothermal resource on the eastern flank of a dacitic stratovolcano (Figure 1a). Surface mapping shows a series of dacitic lavas belonging to the main volcanic centre in the western part of the area, overlying an older dome complex to the north-east. Superficial deposits include recent alluvium in the main drainage valley eroding clay-rich lake sediments and a series of undifferentiated volcaniclastic sediments. An array of NW-SE trending fault structures are inferred from lineament analysis, displaced by a major NNE-SSW fault (Figure 1a).

Surface geothermal features include thermal springs southeast of the volcano and acid sulfate pools to the northeast. Sinter deposits have been identified a few kilometres downstream of the area (Figure 1a).

3.2 Sub-surface lithology

Nine deep wells (>1500 m) have been drilled in the area, providing geological insights at depth. Cuttings were collected at regular intervals and two cores cut at depth in GNS8 and GNS4. Petrographic descriptions provide detailed geological logs giving information on rock types, interpreted stratigraphic formations, and identified permeability indicators. Mineral markers are described in section 3.4.

Mapped geological units have been encountered at shallow level in the drillholes, including superficial alluvium, dacitic lava flows and lake sediments. Binocular examination confirmed the high clay content of the lake deposits and their apparent low-permeability. Below the volcaniclastic sediments, a localised highly brecciated andesite has been found overlaying two series of ignimbrites. Cavities, fractures and veins in the andesite are lined by prismatic crystals indicating open spaces. Wells to the north-east intersected a deep rhyolitic formation (about 2000 m deep) that overlies the basement. Fracture and veins filled with epidote are common in the rhyolite. One well (GNS8) intersected a dioritic intrusion southeast of the volcano. Insights on fault displacement at depth can be assessed from key stratigraphic offsets, in particular within the basement, the rhyolite and the deepest ignimbrite.

Surface geology is imported into Leapfrog Geothermal as GIS layers (Geographical Information System), including fault traces, and formation outlines. Structural measurements, when available, are imported in a tabulated form, including location, dip and dip azimuth. Borehole data is tabulated and separated in three key mandatory components; a location file that includes well location and depth, a survey file including deviation surveys for each well and an interval table (e.g. lithology). Well points measurements (e.g. mineral first occurrences, temperature measurements) are also loaded as a borehole dataset but are not essential. Tables are imported into Leapfrog Geothermal from a database or simple text file.

The geological model boundary is defined to cover the inferred geographic extent of the reservoir. It is bounded at surface by the topography, to a depth of -4500 m. No lateral extents were used in this example. The model's internal structure is refined including faults and contact surfaces that will be used to generate the geological volume outputs.

1. Fault surfaces were built using the GIS vectors of the fault surface traces and using structural measurements as a guide and/or direct input to define fault's dip and dip orientation. The NNE-SSW fault (Fault 1 in Figure 1a) is the youngest as it cross-cuts and displaces the NW-SE structures, thus allowing the fault chronology and fault relationships to be defined in the fault interface.
2. The stratigraphic sequence was built using borehole contact points as primary input. Most formations were modelled as 'deposit-type' surfaces to illustrate the geological process of conformable deposition on the underlying formations. The exceptions are the recent alluvium, modelled as being erosive, and the diorite modelled as an 'intrusion-type' surface which is intruding through any pre-existing formation. The dacite and old dome lavas are extrusive rocks and can be modelled using either of these techniques.
3. The geological map was used as input to constrain the formations outcropping at surface (alluvium, dacite, lake sediments and volcaniclastic sediments). The outline of each formation at surface was imported as a GIS vector line and added as an additional input to constrain the relevant contact surfaces.
4. The stratigraphic sequence is defined and geological volumes processed. Faulted formations will use the data present in their respective faulted blocks, some of which contain little or no data. Local polyline edits were manually added to constrain the geometry of some formations (e.g. rhyolite and diorite) where the primary input data is insufficient to constrain surfaces.

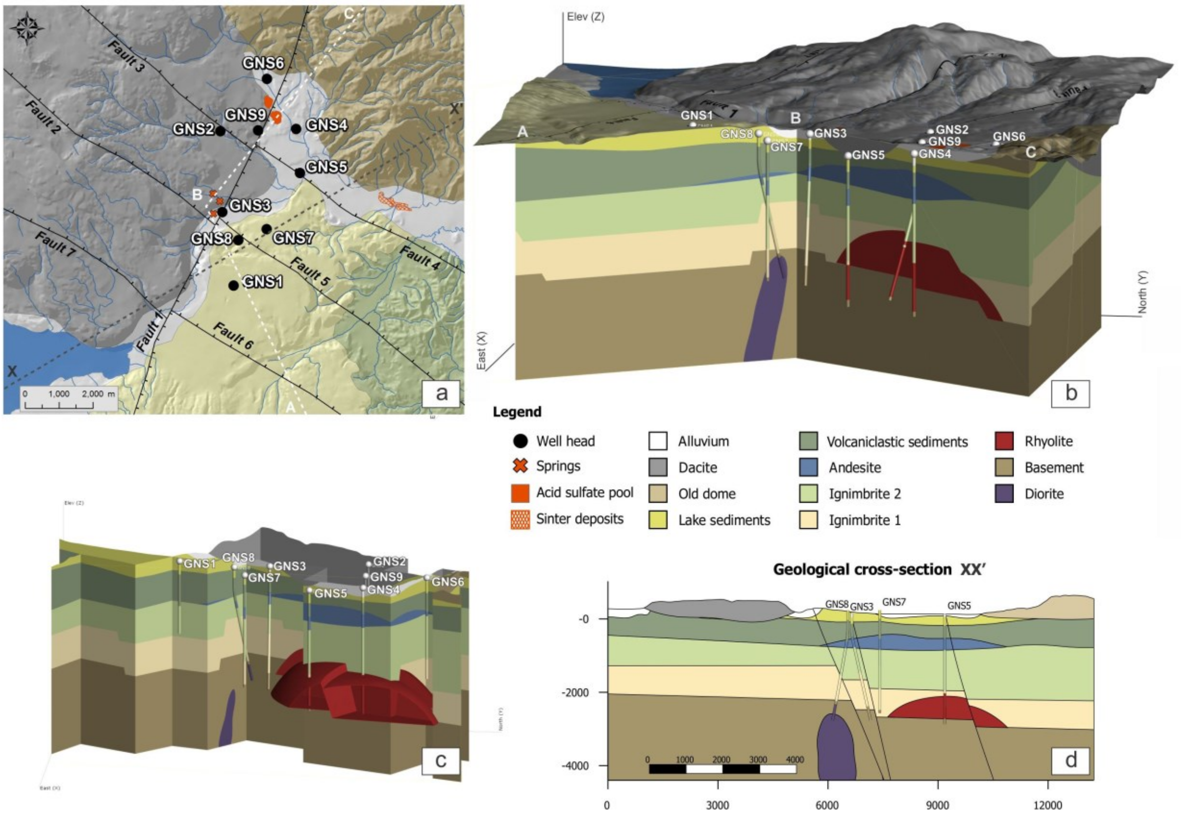

Figure 1: Geological model of the area. A. Geological map used as input in the model. B. 3-D geological model computed from surface map, borehole geological logs, and local edits from the modeller. C. Fence sections through the 3D model are useful outputs. They are derived automatically from the model therefore present a perfect fit (e.g. the rhyolite in red). D. Traditional 2-D cross section as a possible output from the 3-D model.

Figure 1b illustrates the resulting 3-D geological model and Figure 1c-d common outputs from Leapfrog Geothermal. The modeller has full control on the display options, with the ability to modify the symbology and transparency, turn the visibility on or off and select the slicing option for each layer through the model.

The borehole intervals are colour-coded as per formation/rock type which is reflected in the model output volumes. Cross sections (3-D fence sections or 2-D planes, Figure 1c, 1d) are direct outputs from the model and are generated automatically and interactively by the software at the desired locations. They are automatically adjusted as the 3-D model itself is modified with any changes reflected in the display options.

3.2 Temperature model

Downhole temperature profiles representing inferred stable reservoir conditions are common datasets integrated in a geothermal model. Temperature data are numeric values at different depths for each well. They are easily tabulated, and can be imported into the model as a borehole point file. An interpolant model is then created and isosurfaces representing selected temperature values (isotherms) are processed and displayed (Figure 2a). Temperature volume intervals are also outputs of the interpolant model (Figure 2b).

Leapfrog Geothermal supports linear and spheroidal interpolant models. In this example, a linear interpolant is used as a good general purpose model which works particularly well for data with localised high resolution data. No anisotropy was introduced, but contoured temperature measurements at surface were added as additional input to the model.

The highest temperatures at depth are recorded in wells GNS9 and GNS4 with the strongest thermal anomaly recorded in GNS9, where it reaches >200° C at 600 m depth (Figure 2). Nearby wells GNS6 and GNS2 have temperatures of 200°C at 1400 m depth and 2200 m depth respectively. Similarly, GNS3, GNS7 and GNS8 (wells to the south) are between 180° and 200°C at 2000 m depth.

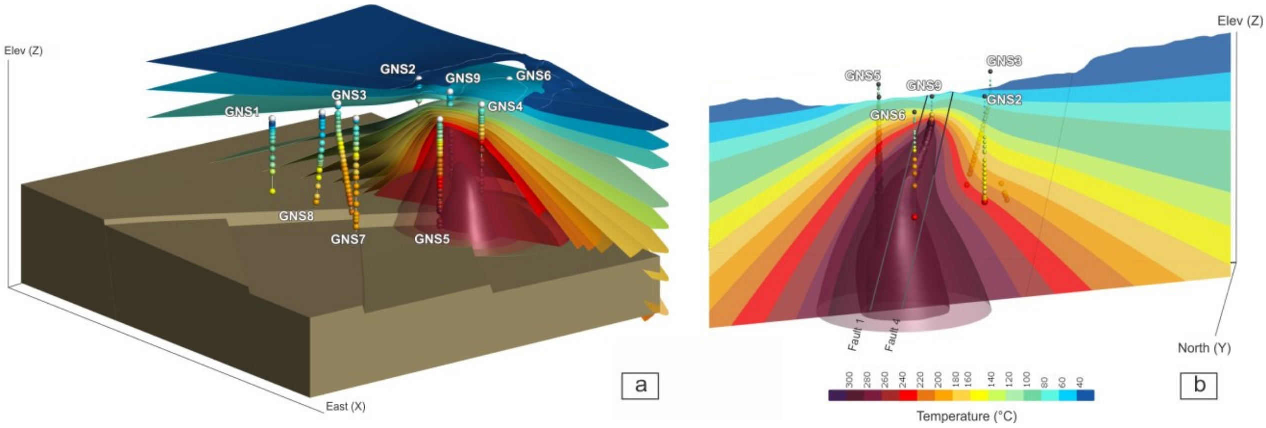

Figure 2: Downhole temperature model. Outputs of the model are isosurfaces and temperature interval volumes. A: 3-D Isotherm surfaces at 20°C intervals showing the highest temperature recorded in GNS4 and GNS9. B. Cross section through the temperature model, representing 20°C temperature intervals, showing the thermal anomaly in GNS9 between Fault 1 and Fault 4.

3.3 Mineral markers

Mineralogical information from logged drill core and cuttings are reported for each well. Macroscopic description of the rocks, thin section petrography, XRD clay separate analysis and short wave near infrared spectroscopy (SWIR) analysis are used to identify key mineral markers and clay distribution at depth. The data is tabulated and imported as either borehole point data (e.g. first occurrence of epidote at 765 m depth in GNS9) or borehole intervals (e.g. Alunite + Dickite mineral assemblage in GNS8 from 500-630m). A surface representing the first occurrence of the key mineral of interest is interpolated from the points, while volumes are generated from interval data following the same method used to create geological models.

Geologists report the occurrence of temperature dependent and/or pH dependent minerals such as: epidote and illite (which formed at T > 240°C, and T>220°C; Browne and Ellis, 1970, Browne, 1978), and/or kaolinite (pH<4), or alunite (pH<1), characteristic of acid, and acid sulfate environments. Minerals such as e.g. actinolite, diaspore, biotite are also temperature and/or pH mineralogical markers. However, it is important to understand that marker minerals are symptomatic of the physical parameters (P-T-pH-fO_2-fS) at the time of crystallization and until proven otherwise are not necessarily in equilibrium with the reservoir.

In this demonstration model, geologists logged evidence of abundant epidote and illite alteration at depth. Both minerals are temperature dependent and represent past or present day temperature estimates. Epidote is found in the northern wells only (GNS2, GNS6, GNS9, GNS4 and GNS5) while illite is identified in all wells (Figure 3). Rare to common shreddy biotite is described at depth in well GNS8. Two acid sulfate zones were also identified at shallow depth (<500m), wells GNS3 and GNS8 intercept a ~150 m thick zone where coarse-grained alunite and dickite are occurring, while clay analyses of GNS9 and GNS4 cuttings at shallow depth reported the presence of finely and poorly crystallized kaolinite (Figure 3).

3.4 Lithogeochemistry

Complete lithogeochemistry characterisation can be plotted and zones of specific element enrichment are reported directly into the 3-D visualisation. Here we report variation in As, Li and Cu (Figure 4) to show how geochemistry can be integrated into the conceptual geothermal model. Geochemical data is tabulated, imported as a borehole dataset and an interpolant model is created for each modelled element. Isosurfaces of the geochemical trace elements, in part per million (ppm), are reported along with the well trajectory projections and the geology (Figure 4), but some data can be represented with temperatures and/or feed zones.

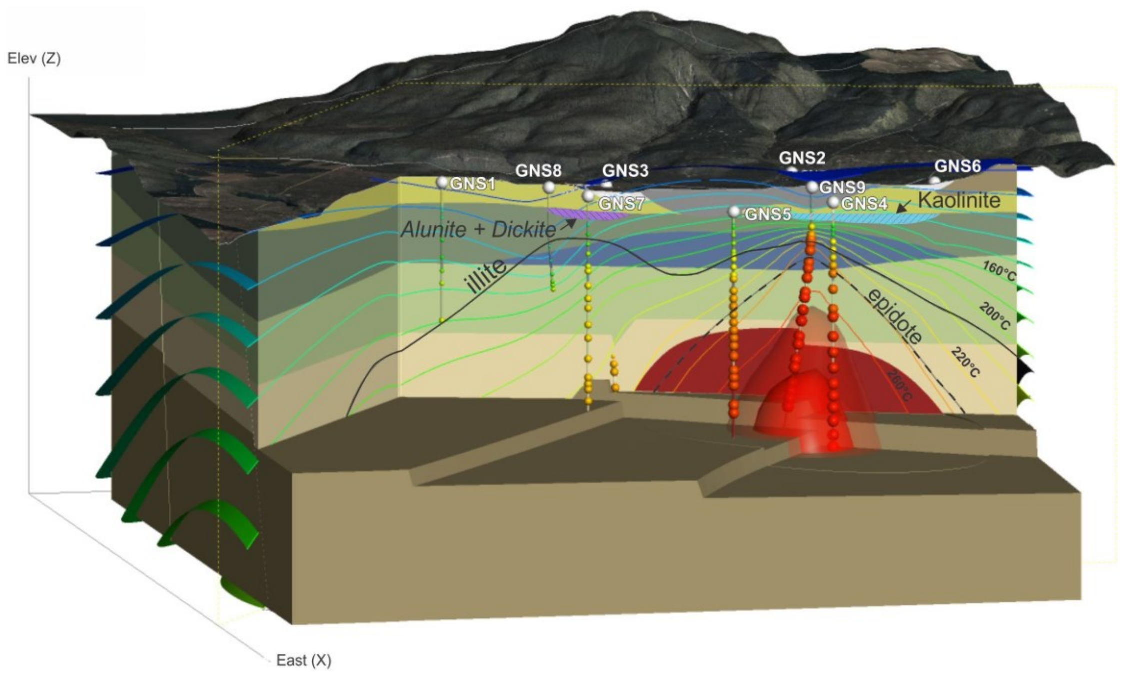

Figure 3: 3-D view of the geological model with downhole isotherms and interpolated surfaces of the first occurrence of epidote and illite in the system. Acid sulfate zones are also displayed and labelled.

Zones of Cu enrichment are presented at depths associated with the intrusion in GNS8. The same well presents an As anomaly at shallower depth. As is also enriched below the cap rock, right below the kaolinite zone, and where the temperature anomaly exists in the present day system. Lithium data appear to be independent of the geology or the temperature system, with an almost continuous enrichment toward the surface.

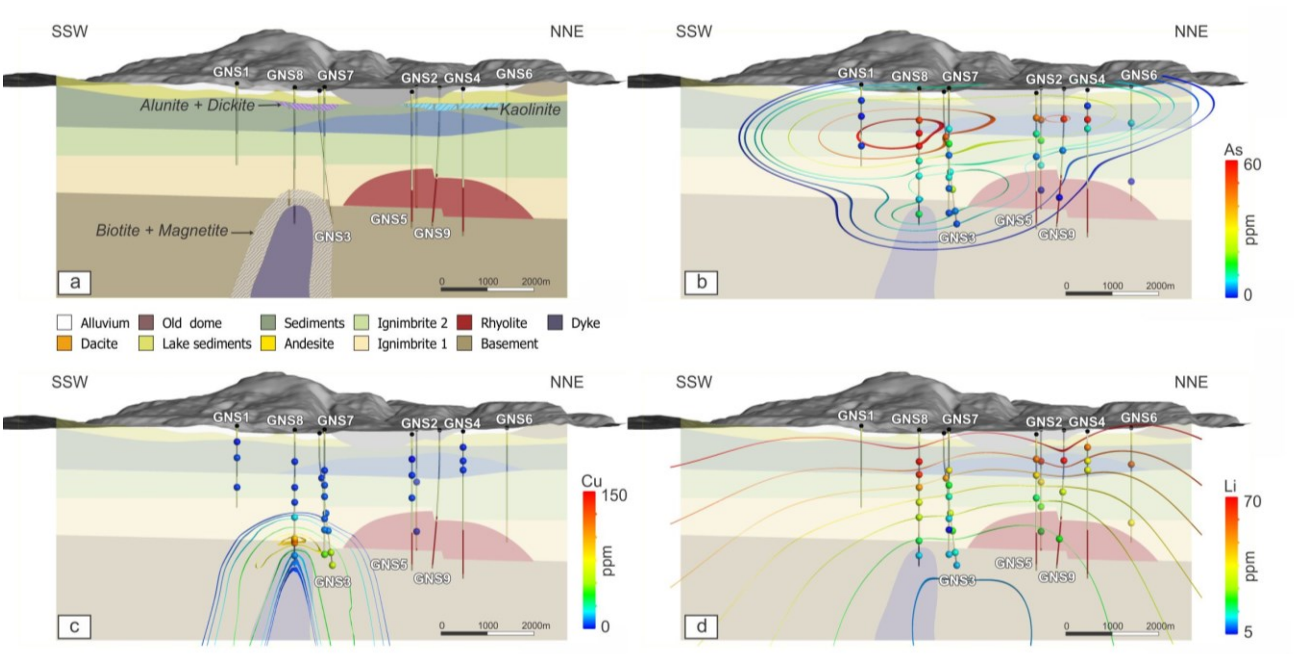

Figure 4: SSW-NNE cross-sections through the geological model with isosurfaces of the geochemical trace elements. A. Geological cross section with alteration halo of Biotite + Magnetite and acid sulfate zones of Kaolinite and Alunite + Dickite for reference. B. Arsenic distribution. C. Copper distribution. D. Lithium distribution.

4. DISCUSSION

Integrating multidisciplinary data in a 3-D interface is a rapid and visually powerful way of studying a geothermal reservoir. This demonstration model combines geology with temperature data and focuses on hydrothermal alteration signature and chemical variations. Data such as feed zones, short wave infrared, magnetic, gravity and magnetotelluric can likewise be included in a model.

4.1 Geological interpretation

Geological interpretation from surface mapping and logging of wells GNS1 to GNS9 allow us to represent with good confidence the geology of the field. The nine wells intercept with depth: alluvium, dacite, surface dome deposits, lake sediments, volcaniclastic sediments, andesite, ignimbrite 2 and 1, rhyolite, a dioritic intrusion and basement rocks. The structural network of the area is defined from surface lineaments and offsets at depth between lithological contacts of the basement, rhyolite and ignimbrite 1 (Figure 1). Fault 1 is the main structure in the area with a NNE-SSW trend that crosscuts an array of older NW-SE faults. Offsets in the shallow part of the field are not significant, though the faults may still be active. The diorite intrudes the basement underneath GNS8 in a "cold" part of the reservoir.

Cuttings/core description provides some indication on permeability. The clay-rich lake sediments have a low-permeability and act as the cap rock of the geothermal system in the area. The andesite at depth is highly brecciated and represents a highly permeable horizon with evidence of open space deposited minerals while sealed fractures and veins are common in the rhyolite.

Downhole temperature measurements show that the main upflow of the geothermal system is located below GNS4 and GNS9 and is likely structurally controlled by a zone of weakness at the intersection of Fault 1 and Fault 4 (Figure 2). Temperatures reach >280°C at depth. The occurrence of epidote and illite in the northern wells (GNS2, GNS4, GNS5, GNS6, GNS9), both mineral temperature indicators, is in agreement with measured temperature in these wells. Illite however is also abundant in the southern part of the field at shallow depth where temperatures are the coolest, around 120°C (Figure 3). The illite is not in equilibrium with the present-day P-T conditions. Epidote though is not present in this part of the field indicating that the conditions at the time were not favourable for its crystallisation. A high content of CO_2 in acidic hydrothermal water would have precluded the formation of epidote.

Acid minerals have been reported in two areas. The first one in the north is dominated by kaolinite. This zone is delineated by the lake sediment and is likely to be associated with cold water influx coming from the north, underneath this cap rock and mixing up with rising hot H_2S-bearing fluids, creating acidification and precipitation of kaolinite. Some permeable zones in the cap rock near the faults could explain the presence of acid sulfate waters at surface around GNS9 and GNS6 (pools, Figure 1a). The second acid zone is characterised by dickite associated with alunite below the thermal springs at shallow depth in GNS8 and GNS3.

The combination of low temperature conditions not in equilibrium with illite, the presence of an intrusion at depth and the close proximity of a dacitic volcano suggest that a fossil hydrothermal system was probably associated with the intrusion. The presence of biotite, copper enrichment at depth and arsenic anomaly in the alunite zone is in agreement with a magmatic-hydrothermal fossil system present in the southern part of the field. This system is now cooled as shown by the current isotherms.

4.2 Geothermal potential and implication for drilling

The highest temperature of the current geothermal system is located at the junction between Fault 1 and Fault 4 suggesting that permeability at depth must be fracture-controlled. The deep reservoir should thus be targeted along the major faults and fractures of the basement and rhyolites. An intermediate reservoir is present in the andesite which has been described as a permeable horizon with measured temperature >180°C in its southern extent (>1km^3). Importing feed zones in the model would help better target the resource.

The southern wells have shown signatures of a relic hydrothermal system likely related to the diorite intrusion. No primary permeability was identified in this area and evidence of structural permeability is limited to surface hot springs. Present conditions testify that the system has cooled and the southern part of the field is less prospective for high temperature resources. Any further drilling should focus on the northern and eastern part of the field where the current upflow zone is located and the rock properties are adequate to host a high temperature reservoir.

Shallow acid zones have been identified in the relic as well as in the current system. Acid corrosion is likely to be an issue in the geothermal field and the appropriate casing steel should be used.

4.2 Advantages of a 3-D integrated approach

In this example we integrated geology with mineral markers, temperature measurements, alteration distribution and geochemical trace elements. The combination of multiple datasets in one single interface is giving us the tools necessary to solve a multidisciplinary challenge and better correlate available information. Fast 3-D interpolation methods are used to create a geological model (categorised data) and interpolant models (numeric data). The factual data available and the complexity of the area dictate the amount of manual input required from the modeller. Powerful and flexible visualisation tools facilitate our interpretation of the data/model and identification of possible correlation to improve our understanding of the dynamics and evolution of a geothermal field. When studied individually, each model may bring some information, however once correlated we gain insights on the reservoir location, extent and evolution, and preferred fluid flow path from primary and/or secondary permeability are better identified. This demonstration model does not include any feed zone locations or geophysical dataset such as magnetic, gravity, magnetotelluric or microseismicity data, but they could easily be added to provide even more information on the field's current and past conditions.

The figures presented here are common outputs that illustrate the amount of information that can be communicated in one image using 3-D data integration. It facilitates discussion and dissemination of the models between parties involved in the development of the resources (e.g scientific, engineers, sponsors and stakeholders).

5. CONCLUSIONS

This paper presents a case study using a synthetic dataset to demonstrate the strength of an integrated 3-D model approach to study and better understand a geothermal field. We used Leapfrog Geothermal, which offers a complete solution for creating and visualising geothermal models. This example uses datasets commonly gathered during the exploration to production phases of a geothermal field. We created a simple geological model using surface mapping and well geological logs. We imported reservoir temperature data and created a temperature model, before looking into more details at mineral markers and lithogeochemistry results. The integration of these datasets and use of powerful visualisation tools allowed us to better understand the system.

A high temperature geothermal resource is present and overprinting an older hydrothermal system related to a shallow intrusion that has cooled down. The present day up-flow zone is structurally controlled with a heat source located further to the east. The reservoir at depth is fault/fracture controlled, while some primary permeability can be targeted in rocks at intermediate depth. A shallow unit acts as the cap rock in the area and contains the geothermal fluids to the exception of some minor leaks along some fault structures where surfaces features occur. Inflow of colder fluid from the north interacts with hot geothermal fluids creating some acidification. Care should be taken while casing in this area.

This demonstration model focusses on geological descriptions and rock analyses versus temperature data. Geophysics, reservoir and fluids properties are other datasets commonly used to better constrain a conceptual model. The amount of details and confidence in the model depends on the amount and quality of the data. A comprehensive model will improve the operator confidence and support drilling strategies. 3-D integrated models are now routinely used in New Zealand and are proven invaluable tools for day-to-day management of the resource.

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