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3D GEOLOGICAL MODELLING USING NEW LEAPFROG GEOTHERMAL SOFTWARE

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ABSTRACT

Leapfrog Geothermal is an innovative 3-D modelling visualisation software and resource management tool, developed by ARANZ Geo (Applied Research Associates Ltd), with geoscientific input from GNS Science, to meet the 3-D computing needs of the geothermal industry. *Leapfrog Geothermal* is based on implicit modelling methods that represent geology, structure, geophysical and reservoir data with fitted mathematical functions. Complex geological models are built by combining measured field data, specialist interpretation and user editing. The advantage over conventional grid based systems is one of flexibility and speed, with a model that can be used to populate grids with a range of parameters, depending on user purpose.

Hydrothermal alteration, geophysical data, temperature and other reservoir data are modelled as transition surfaces and/or numerical models, and can be combined with rock property and well feed zone data to refine the hydrological structure of a geothermal system. Downhole logging data (e.g. BHTV images) can be integrated to help define fault geometries, lithological discontinuities, and fracture network patterns. The resultant geological model consists of closed unit boundaries that help establish structural and rheological controls on fluid flow (i.e. permeability structure) in the geothermal system.

A tool for drillhole design and well targeting has recently been added to Leapfrog Geothermal. Current development focuses on integration of output data from numerical reservoir simulation (e.g. Tough2, Feflow) software at the resolution and scale required to visualise the past and predicted response of the system to development, and aid resources management. Leapfrog Geothermal is already used by developers at geothermal fields in the Taupo Volcanic Zone (New Zealand), as it can rapidly build user-friendly models, assist drilling engineers and geoscientists in their day to day activities, and provide insights that support long-term, strategic field management decisions.

BACKGROUND

In the last few years, exploration, production and injection drilling have provided new information on the geology and structure of several geothermal fields in the Taupo Volcanic Zone, New Zealand (Figure. 1). Consequently, geological insights from deep drilling at Wairakei-Tauhara (Rosenberg et al., 2009, Bignall et al., 2010), Ohaaki (Milicich et al., 2008), Kawerau (Milicich et al., 2010a) have been used in combination with 3-D *Leapfrog Geothermal* modelling software to develop visualisation models of the geothermal fields. This paper describes *Leapfrog Geothermal* software, its development, and how it is being used to assist well targeting, and enhance our geological understanding of the fields.

From November 2005 to July 2007, ten production and two injection wells were drilled by Contact Energy Ltd. in the Ohaaki Geothermal Field (~20 km NE of Taupo), in areas where few wells had previously penetrated below -1000 m.a.s.l.. Whilst new information was obtained on the stratigraphy and basement structure, relationships between some geological units were difficult to resolve. This prompted GNS Science (GNS), in partnership with Applied Research Associates Ltd. (ARANZ) to develop a new 3D modelling tool, *Earth Research*, which extended the functionality of the mining industry software *Leapfrog*™ (Cowan et al., 2004) to aid geological interpretation, by adding specific geothermal tools and applications.

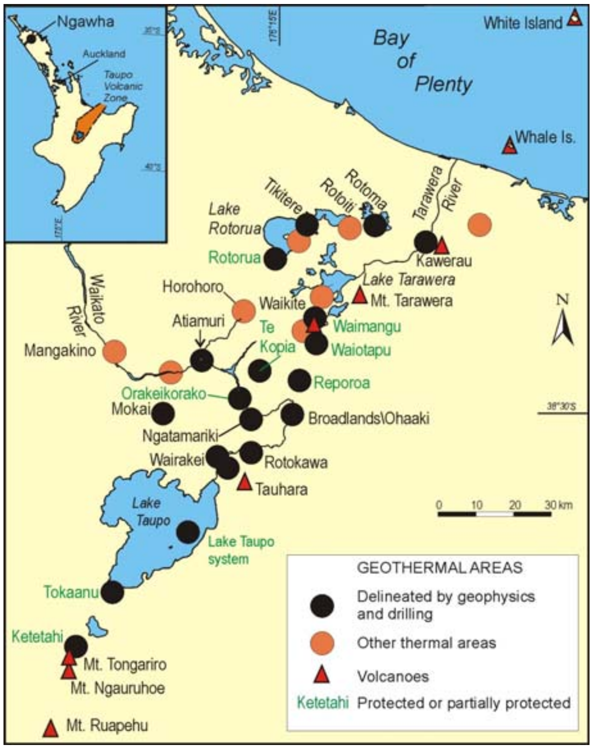

Figure 1: *Map of the Taupo Volcanic Zone, showing the location of geothermal fields delineated by geophysics and drilling.*

Whilst most 3D software work with predefined grids, *Earth Research* used an approach where stratigraphic surfaces and geological volumes are modelled using a class of implicit functions called radial basis functions (Carr et al., 2001). The implicit functions are based on stratigraphic data from drillhole logs, with interpolated surfaces used to create volumes that represent the geological units. Faults are visualised as surfaces that subdivide space.

The *Earth Research* 3D model of Ohaaki was presented at the World Geothermal Congress in 2010 (Milicich et al., 2010b).

Contact Energy Ltd. (Contact) commissioned GNS and ARANZ to build a 3-D geological model of the Wairakei Geothermal Field, as lateral and vertical lithological variations, and a complex fault structure, had made previous 3-D representations somewhat ambiguous. Indeed, several wells have been completed at Wairakei in recent years, to >1,500 m drilled depth, which provide new insight into the deep geology of the geothermal field (Rosenberg et al., 2009; Bignall et al., 2010), and the spatial distribution of geological units had proven difficult to interpret using traditional 2-D techniques.

To address this problem, ARANZ and GNS, in collaboration with Contact moved to improve *Earth Research* and enhance user capability of the software, whilst producing a new 3-D visualisation model of the Wairakei Geothermal Field. The result is enhanced 3D modeling software, now called *Leapfrog Geothermal*, that has proven to be an effective tool for well targeting and 3-D system visualisation, founded on geological reviews by Rosenberg et al. (2009) and Bignall et al. (2010). The Wairakei 3D model has recently been described by Alcaraz et al. (2010a).

The Wairakei 3D model provides a more accurate representation of the field geology than previous 2D cross-sections. Data is able to be interpolated in all directions, and errors resulting from projecting well data onto the 2D section are avoided. With the interpolation of the contacts, we can now better represent the morphology of the stratigraphic units and visualize target formations.

The 3-D geological visualisation model of the Wairakei Geothermal Field was built using geological information from 204 wells, and covers an area of ~90 km^2. Well data for the nearby Tauhara Geothermal Field was used to constrain the geology in the south-eastern part of the Wairakei 3-D model.

Most recently, a 3D geological model has been developed of the Kawerau Geothermal Field for Mighty River Power Ltd., using Leapfrog Geothermal (Alcaraz et al., 2010b).

The 3D geological model of the Kawerau geothermal system incorporated stratigraphic and structural (logging) data from 48 wells, and represented the best interpretation based on available well data, published logs, and findings from a stratigraphic review of the field (Milicich *et al*., 2010a). The review discussed uncertainties in correlating some lithologies across the Kawerau Geothermal Field. The 3D visualisation model provided a new perspective of the geology and structure of the Kawerau Geothermal Field, and highlighted issues of uncertainty where inferred geological relationships required further attention.

LEAPFROG GEOTHERMAL -SOFTWARE

The geothermal industry has long had need of a tool to effectively visualise geothermal systems in 3D, in order to help understand reservoir dynamics. By developing *Leapfrog Geothermal*, ARANZ and GNS Science had in mind that 3-D geological modelling software should be capable of handling complex geological information, from irregularly spaced data sets (e.g. from wells, and/or surface exposures). The visualisation/modelling software should also be easy-to-use, and allow 3-D models to be built up quickly and efficiently, and able to be routinely updateable.

In *Leapfrog Geothermal*, stratigraphic (formation contact) surfaces are modelled using Radials Basis Functions (RBFs).

RBFs are a class of implicit functions, which were first used by Hardy (1971) to interpolate scattered topographic data. The implementation developed by ARANZ allows a geologist to use millions of data points to create a smooth interpolation surface, which is ideal for aspects of geological modelling (Carr et al., 2001; Cowan et al., 2002; Frank et al., 2007).

The technology was initially used in Leapfrog™ for grade modelling drillhole data (Cowan et al., 2002). The application of RBFs was extended by ARANZ to create lithological contact surfaces from drillhole data, to complement other point data and lines drawn by a geologist. Anisotropy is applied to make the surfaces geologically consistent, with formation contacts used to carve up space and create 3-D stratigraphic units. Many types of data can be loaded into the software (Table 1), to support the modelling and enhance visualisation of key geothermal features.

Table 1: *Data types that can be loaded in Leapfrog Geothermal.*

EARTH RESEARCH INPUT DATA	
Images	**GIS data (points, polylines, polygons)**
Topographic maps	topographic data
Aerial photography	geological maps
Satellite images	samples location
Maps	structural measurements
Topographic data	**Cross Section**
DTMs raster	traditional 2D cross section
ASCII grids	geophysical / seismic
Borehole data	**Numerical data**
Collar	assays / chemistry
Survey	temperature
Intervals:	seismic data
Geology / alteration etc	
Numerical Simulation	**Borehole logging data**
Tough2 grids	Fractures & Faults measurements
simulation outputs	Beddings measurements
	Fracture density

Implicit functions are generally less demanding of hard disk space and computer memory, and operate on original data rather than evolved iterations. The high processing speed and data capacity of implicit modelling means 3D geology models can be readily updated with new data, or can be used to test ideas in near-real time (Cowan et al. 2002).

Leapfrog Geothermal modelling software honours measured or known data values, such as lithological contacts, and can incorporate 'a priori' knowledge, such as geological interpretation. As a consequence, subjective data can be saved separately from known data, although both sets of data are merged in the building process to produce a consistent model.

The 3-D objects are saved as continuous functions, and are used to generate surfaces at user-defined resolutions. The end user influences the modelling by modifying high level parameters, such as the anisotropy. When data is added or modified, the surfaces are quickly and automatically rebuilt.

A representative view of the 3D geological model of the Wairakei Geothermal Field is shown in Figure 2. Volcaniclastic units, such as Waiora Formation, are built using contact points from drillhole data (after Bignall et al., 2010). Continuous surfaces represent the interface between formations; e.g. between

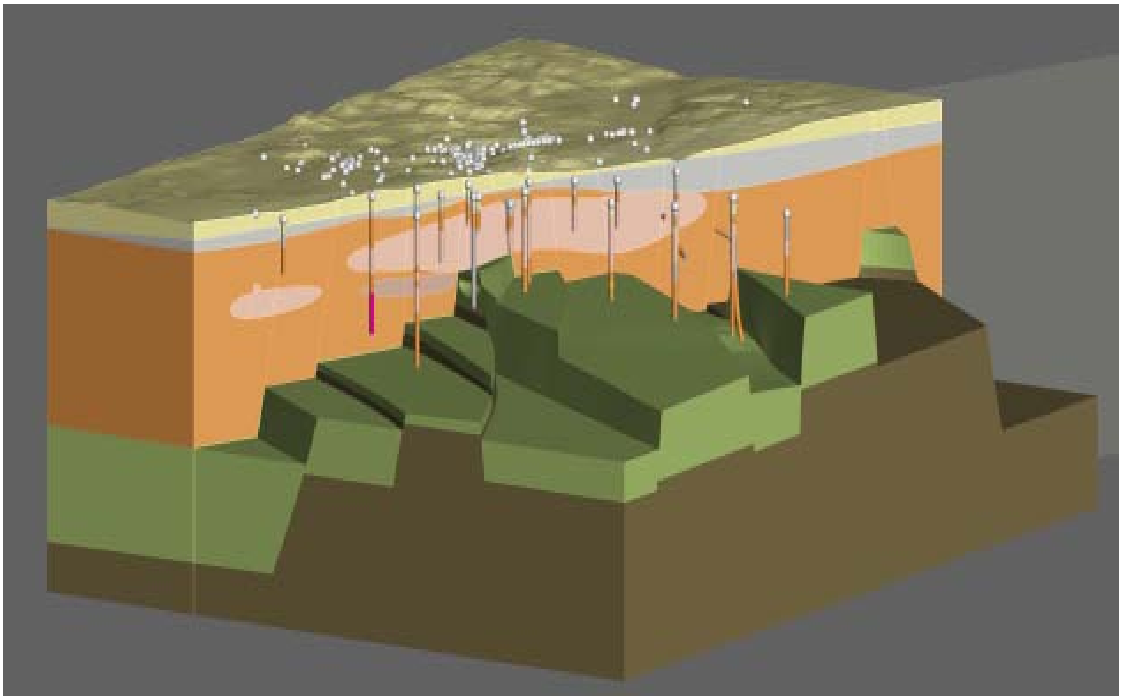

Figure 2: 3D geological model of the Wairakei Geothermal Field, highlighting the complex fault structure, and unconformity of Tahorakuri Formation (brown) with overlying Wairakei Ignimbrite (green).

Waiora Formation (orange unit in Figure 2) and Huka Falls Formation (shown in pale grey). Once the stratigraphic order is defined, the software generates each formation as a volume. Lava bodies such as rhyolitic domes (e.g. Karapiti Rhyolites) are built as closed surfaces, cross-cutting the stratigraphic layers.

Structural features are incorporated during the surface generation by specifying planes that subdivide interpolation space into individual domains. Structural inferences across the Wairakei Geothermal Field were guided by inferred stratigraphic offsets in the Tahorakuri Formation and Wairakei Ignimbrite (Figure 2).

Additional Attributes of Leapfrog Geothermal

***Well targeting*:** Wairakei and Ohaaki 3-D geological models have been used by geologists at GNS Science and Contact Energy Ltd. to design wells that intersect inferred structural and lithological targets.

Prior to drilling, the *Leapfrog Geothermal* model is used to predict the geology likely to be encountered by a new well (Figures 3, 4), taking into account a range of drill hole scenarios, including (bottom hole) depth, kick-off depth, well azimuth etc. Subsequently, new data can be added to the model as drilling proceeds, which is of immediate value to the developer, and supports a flexible drilling strategy.

***Hydrothermal alteration and reservoir parameters*:** Hydrothermal alteration (e.g., intensity, rank), and modelled (inferred) temperature profiles (c.f. GNS's 3-D geological model of the Ohaaki Geothermal Field; Milicich et al., 2010b) can also be incorporated into the 3-D model. Milicich et al. (2010b) highlighted how reservoir parameters (such as temperature and chemistry) can be visualised spatially and temporally using *Leapfrog Geothermal*, to help resolve the evolution of a geothermal system.

***Numerical reservoir simulation*:** A complementary objective of 3D geological visualisation is the use of *Leapfrog Geothermal* to improve reservoir numerical simulation. Consequently, *Leapfrog Geothermal* is being upgraded, to complement TOUGH2 models developed using grids manually populated with geology from the 3D models. In fact, *Leapfrog Geothermal* can directly populate the cell properties of TOUGH2 grids (Figure 5) and load the simulation output, thus integrating geological modelling and reservoir simulation. Heat flows can also be represented, which provides invaluable insights concerning the role of fractures and faults in focussing fluid flow.

In the future, it is planned that *Leapfrog Geothermal* 3D geological and structural models will incorporate more chemical and reservoir parameter data. It is also intended that flow simulators will be integrated into a single interface that will allow better understanding of the complexities of the geothermal system, for better resource management and sustainability.

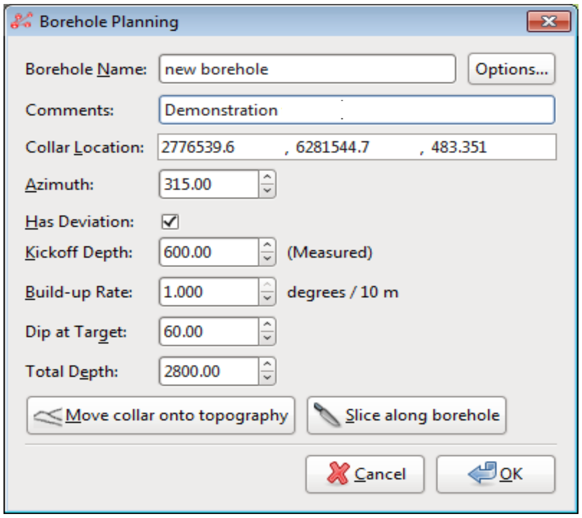

Figure 3: Indicative borehole planning spreadsheet

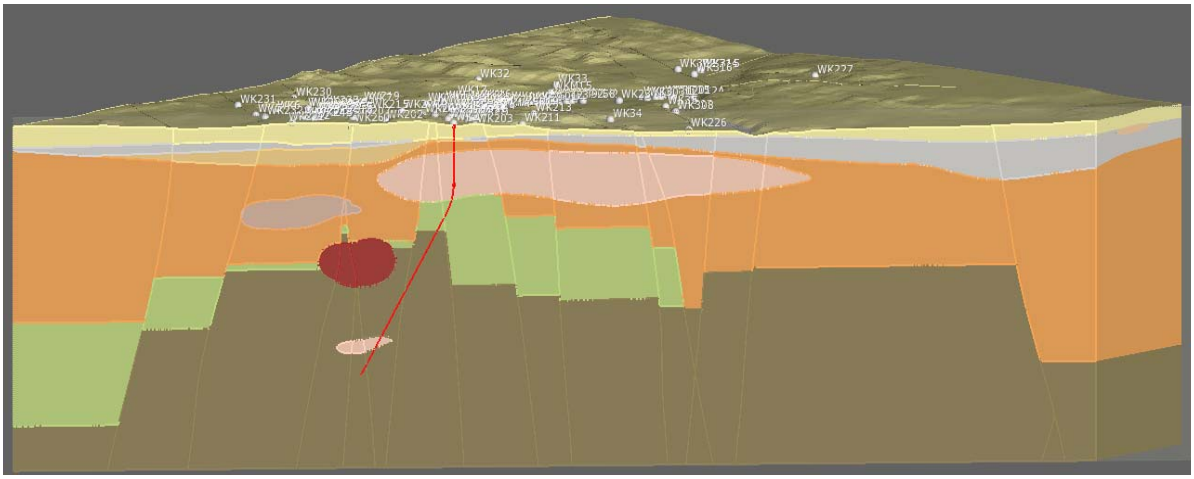

Figure 4: Indicative trajectory of proposed new drillhole, Wairakei Geothermal Field

Fracture representation: *Leapfrog Geothermal* can incorporate structural measurements, e.g. open hole logging by acoustic formation imaging technology (AFIT), to understand the nature of fracturing in geothermal systems. *Leapfrog Geothermal* allows inferred structural and geological data to be incorporated into the 3-D model, with added value for constraining fault location, modelling fault plane geometry, resolving geological contacts, and correlating fracture density variations between wells.

Modelling these parameters help constrain the role of fault and fracture permeability. Modelling and visualising structural features, geological formations, and associated permeability and feed zones, is essential for designing drilling strategies.

CONCLUSIONS

Visualisation and 3D modelling software, "*Leapfrog Geothermal*", has been used image the geology of the Wairakei, Ohaaki and Kawerau geothermal systems (New Zealand). *Leapfrog Geothermal* has been developed specifically for the geothermal industry, and provides a major advance on traditional 2-D representations of field stratigraphy, structure and hydrothermal alteration. Work is advanced to include a TOUGH2 reservoir simulation capability.

Leapfrog Geothermal provides a user-friendly, efficient 3-D-modelling environment to integrate geothermal data. Stratigraphic contacts and hydrothermal alteration are modelled using implicit functions based on drillhole data, with user-defined variograms, anisotropy and resolution. Structural features defined by planes that divide interpolation space into discrete domains.

Developed 3-D models have been used by GNS to resolve structural and formation targets, and successfully design well trajectories for production and injection wells at Wairakei and Ohaaki, with drilling results incorporated into refined geological framework models.

The processing speed and data capacity of implicit modelling means *Leapfrog Geothermal* 3-D geology models are able to be modified, and represent new information, in near-real time – with immediate value during well drilling operations, as well as for ongoing resource management.

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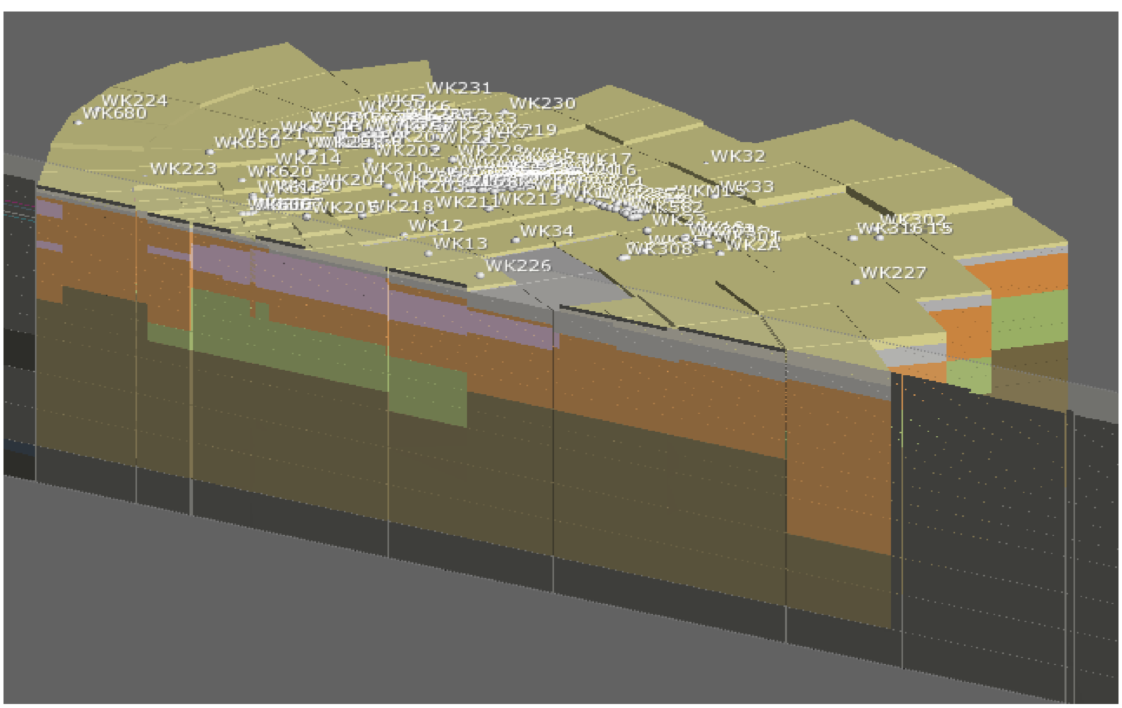

Figure 5: 3D block geological model of the Wairakei Geothermal Field.

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