

Integrated 3D Geophysical Inversion and Geological Modelling for Improved Geothermal Exploration and Drillhole Targeting

Jeffrey B. Witter¹ and Nigel Phillips²

¹S. J. V. Consultants Ltd., Delta, BC, Canada

²Mira Geoscience, Advanced Geophysical Interpretation Centre, Vancouver, BC, Canada

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ABSTRACT

Choosing where to drill a geothermal well is perhaps the most important decision made in a geothermal exploration program. In this paper, we describe an improved exploration methodology that makes more effective use of existing exploration datasets, integrates all data in three dimensions, constrains data against one another, and employs a quantitative and comprehensive approach to selecting drill targets. The methodology has been adapted from the mining industry where it has found great success. An important component of the proposed approach involves 3D inversion of multiple geophysical datasets, in both unconstrained and constrained forms, as a way of delineating rock domains in the subsurface. The method culminates in the construction of a 3D Common Earth Model which is consistent with all datasets. Such a model provides the platform for further analysis, interpretation, hypothesis-testing, and ultimately, informed selection of drill targets. A quantitative drill targeting approach that utilizes specific exploration criteria is also presented. We argue that implementation of this approach in the geothermal sector will improve exploration programs and result in increased drilling success.

Introduction

Two recurring themes in the geothermal industry in recent years are “technology transfer” and “reduction of drilling risk.” Thanks to long-term research and development programs, the oil & gas and minerals industries have developed remarkable technologies that take advantage of advances in computing power to help achieve success in their exploration for subsurface resources. Many of these technologies are applicable to geothermal exploration and, therefore, adoption could provide near-term benefit to geothermal exploration programs. In this paper, we seek to facilitate such a technology transfer by describing a geoscience

exploration methodology which has found great success in the minerals industry. Our aim is to show how this new approach can improve our understanding of the subsurface prior to drilling and help reduce geothermal drilling risk.

For more than a decade, the Canadian mineral exploration industry has put significant effort into optimizing geophysical exploration methods to perform subsurface imaging in three dimensions. One example is the 3D geophysical inversion algorithms developed by a consortium of major mining companies under the auspices of the University of British Columbia Geophysical Inversion Facility. Various groups have generated multi-parameter 3D geophysical inversion models using these algorithms, integrated the results with surface information (e.g. topography, geology, roads, lease boundaries, etc.) and, in some cases, integrated borehole data as well to construct complex and well-constrained 3D geological models. The result is a Common Earth Model (our best representation of the earth, sometimes also called a 3D Geologic Map) from which a mineral potential index can be extracted to guide drill targeting. These 3D-focussed methods have been successfully applied to the mining sector worldwide for several years now contributing to the evaluation and discovery of mineral deposits.

In this paper, we present a current approach to geothermal exploration and then propose improvements that involve the application of 3D geophysical inversion and modelling methods used in the mining industry. We strongly believe that incorporation of these 3D methods into existing geothermal exploration programs will lead to greater drilling success at geothermal prospects as it has at mineral prospects over the last several years. A case study to be presented at the 2012 GRC conference will further demonstrate the application.

The Challenge of Geothermal Exploration

One of the primary purposes of a geothermal exploration program is to identify subsurface drill targets that maximize the chance of encountering high temperature and permeability and minimize the risk of a failed well. Various geoscience tools are often brought to bear to improve our understanding of the subsur-

face prior to drilling a geothermal prospect. However, one of the great challenges of geothermal exploration is that there is currently no geophysical imaging tool which can unequivocally map the subsurface distribution of temperature and permeability at depth. As a result, subsurface temperature and permeability need to be inferred or extrapolated from other data sources.

Common Uses of Geophysical Data for Geothermal Exploration

Three geophysical tools that are often used in geothermal exploration are gravity, magnetic, and magnetotelluric (MT) surveys. These survey types record the variations in physical properties of rocks in the subsurface, specifically density (for gravity surveys), magnetic susceptibility (for magnetic surveys), and resistivity (for MT surveys). These geophysical datasets can be analyzed and interpreted in different ways to obtain different types of information.

For geothermal exploration, gravity and magnetic data are commonly interpreted only in map view and they are often used to help identify specific faults or obtain an overview of structural trends for an area. Interpreted gravity and magnetic maps are often compared with geologic maps to ascertain whether faults mapped in the field by a geologist coincide with faults inferred from the geophysical data. If agreement is found, that increases confidence that the identified fault might be significant, possibly permeable, and therefore, a potential drill target. One of the flaws in this approach is that it is a map view analysis in only two dimensions – the third dimension remains obscure. Faults dip at a variety of angles and a fault identified at the surface may be at an entirely different location deep in the subsurface. A more advanced analysis of gravity and magnetic data that would enable three dimensional interpretations of density and magnetic susceptibility distributions in the subsurface would be a significant improvement for geothermal exploration.

Unlike gravity and magnetic data, the industry-standard for MT surveys provides a result which is interpretable in three dimensions. Delivered models from an MT survey reveal the distribution of resistivity in the subsurface and are commonly presented as a series of vertical cross-sections, horizontal slices at various depths, or a three dimensional block (i.e. a voxel model). Resistivity variations are often used to help identify “clay caps” that may overlie a geothermal reservoir.

Depictions of geothermal conceptual models often include 2D MT resistivity cross-sections with borehole data superimposed on them as well as downhole temperature iso-contours overlain (e.g. Figure 1). Geological data such as rock type and faulting may also be overlain in an attempt to better define the subsurface. One of the flaws to this approach, however, is that it limits the explorationist to visualising in only two dimensions. In addition, the gravity and magnetic data, having been interpreted only in map view, are generally not integrated into the MT cross-section in a way that is quantitative and meaningful. Additionally, boreholes that have been drilled directionally cannot be properly plotted on a 2D cross-section unless they lie on the plane of the section. Furthermore, it would be advantageous to explicitly include any

existing borehole information in the generation of the 3D MT resistivity model.

It is clear that our understanding of the subsurface would be improved if we could: 1) have a three dimensional, interpretable result for all geophysical datasets (e.g. 3D geophysical inversions of gravity, magnetic, and MT data) and 2) integrate and visualize all data together in three dimensions (e.g. geophysics, borehole information, rock type, structural geology, temperature, etc.) We would also hope to be able to do much more than simply integrate the various datasets in 3D space for visual comparison. Of greater value to geothermal exploration would be to let the data “talk to each other.” That is to say, develop a means to use the independently derived geoscience datasets to test the accuracy of one another and answer the question “Which one is right?” in areas where data might not agree. In this manner, explorationists would be able to test the veracity of exploration hypotheses in areas of low confidence. We think that such an approach would go a long way towards improving understanding of the subsurface and ultimately increase drilling success.

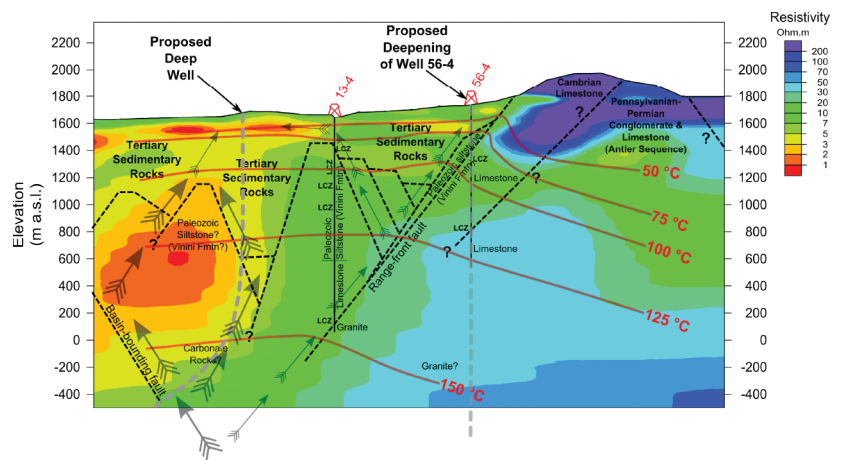


Figure 1. Example of a 2D cross-section generated for geothermal exploration at the Reese River prospect, Nevada (USA) that attempts to integrate various geoscience datasets. Reproduced from Witter et al. (2009).

An Improved Approach to Geothermal Exploration

The improved approach to geothermal exploration proposed here has as its foundation a three dimensional subsurface depiction of the geothermal prospect. This 3D model would be populated by the following:

1. 3D topography
2. Cultural information overlain on the land surface (e.g. roads, lease boundaries, etc.)
3. Geoscience information overlain on the land surface (e.g. geologic map, drill collars, gravity map, etc.)
4. Subsurface borehole traces in 3D
5. Downhole information plotted along the borehole traces (e.g. geology, loss of circulation, etc.)
6. Temperature isosurfaces interpolated between boreholes
7. 3D geology constructed from: surface mapping, the known stratigraphy of the area, and sound geological principles

Fortunately, there already exist several commercial and open source software packages which enable explorationists to integrate and visualize their data in 3D in this way. A few recent examples of this 3D approach to geothermal exploration can be found in the literature (e.g. Siler et al., this volume; McDowell & White, 2011; Van Gundy et al., 2010). The specific improvement that we propose here involves integrating into the 3D model all geophysical data in a three dimensional and quantitative manner. Geophysical data can be incorporated into 3D models as *unconstrained* physical property models for early stage geothermal projects where data is limited. Alternatively, more advanced *constrained* geophysical inversions use rock physical property values (measured from boreholes or the surface, or obtained from a suitable database) and structure to constrain inversion models and thereby build a self-consistent model that more accurately represents the subsurface. The role of physical properties should not be overlooked as they bring information necessary to both constrain inversions and quantitatively interpret the inversion results.

A further description of unconstrained and constrained geophysical inversions follows. The paper concludes with a short description of a statistical approach which integrates available data according to exploration criteria to create a geothermal potential index and identify specific drill targets.

Unconstrained 3D Geophysical Inversion

The purpose of geophysical inversion is to estimate the distribution of the physical properties of rocks in the subsurface based on the geophysical data collected at the surface. Geophysical measurements made at the surface are strongly influenced by the physical properties of rocks with the influence decreasing dramatically with distance. As such, mathematical algorithms can be used to convert these surface measurements into a 3D picture of the subsurface: a process called geophysical inversion. In areas that are relatively unexplored (i.e. no boreholes yet), inversions are commonly run without constraints and a physical property model which “best fits” only the surface geophysical data is the result. Unfortunately, the unconstrained inversion output is not a single, unique solution. Indeed, there are many different possible subsurface 3D physical property models that could fit the surface geophysical measurements. Despite this limitation, however, unconstrained inversion can be a powerful tool to help identify the major subsurface features which are required by the surface geophysical data. For example, possible faults can be inferred in 3D in areas which display marked contrasts in physical properties. In addition, the results of unconstrained geophysical inversions can be used to formulate hypotheses about the locations, sizes, and depths of various rock domains that have specific combinations of physical properties (Table 1). When this information is integrated with geological information from surface mapping and boreholes, a much clearer understanding of the subsurface begins to unfold.

3D Geological Modelling and Constrained 3D Geophysical Inversion

Constructing a three-dimensional geologic model can be advantageous in different ways. Importantly, it forces observers of the model to think in three-dimensions (as opposed to multiple 2D cross-sections). Furthermore, as geologists interpret the data, the

Table 1. Possible geological interpretations of subsurface regions characterized by specific combinations of the physical properties density, magnetic susceptibility, and resistivity.

Density	Magnetic Susceptibility	Resistivity	Possible Interpretation
Low	Low	Low	Heavily altered, clay-rich zone
Low	Low	High	Clean, quartz sandstone
Low	High	Low	Magnetite-bearing and salt-bearing sediments
High	Low	High	Quartzite
Low	High	High	Magnetite-bearing quartz sandstone
High	Low	Low	Muddy limestone
High	High	Low	Weakly altered intrusive rock
High	High	High	Unaltered intrusive rock

available geologic evidence must be reconciled with geological principles in 3D leading to a more advanced and coherent model. A geologic model will undoubtedly contain different geologic domains and it can be constructed in terms of rock-type, lithology, alteration, or all three. Construction of a geologic model normally begins with a topological model (i.e. surfaces representing domain boundaries or faults). A voxel (raster) model can also be generated at a desirable scale for hosting the continuous and discrete properties needed to describe various earth parameters which are incorporated into the model. The resulting model becomes the foundation for the 3D Common Earth Model.

Geochemical and rock physical property data (or other sparse 3D information) can be subsequently interpolated onto the geologic model using different geostatistics within each geologic domain. Importantly, the geologic model can also be the starting point for fluid flow modelling.

Constrained geophysical inversions use all relevant and available geoscience data to recover a new model that honors both the geophysical data and the prior constraining data. The 3D geological model is the natural input to this process, along with borehole information (including rock type, physical properties, and location/orientation of faults/contacts). Some constrained geophysical inversions will adjust the geometry of the geologic model during inversion, while other inversions will focus on updating the physical properties of the model. Overall, a well-constrained 3D Common Earth Model dramatically improves our understanding of the subsurface for more confident and informed selection of drill targets.

Targeting

Choosing where to drill expensive geothermal wells is, arguably, the most important decision in a geothermal exploration program. Drill targets are often selected by the explorationist based upon subjective interpretation of all the available geoscience data. An alternative approach described here, that we term “targeting,” depends strongly on the data itself to provide a more objective approach to selecting drill targets. The output of a “targeting” exercise is a geothermal potential index (Figure 2) for the subsurface that delineates areas that are more promising as opposed to areas that are less-promising. Any spatially located 3D information that is integrated into the Common Earth Model can be used as part of a targeting exercise. The information is then quantitatively combined based on exploration criteria. Examples of exploration

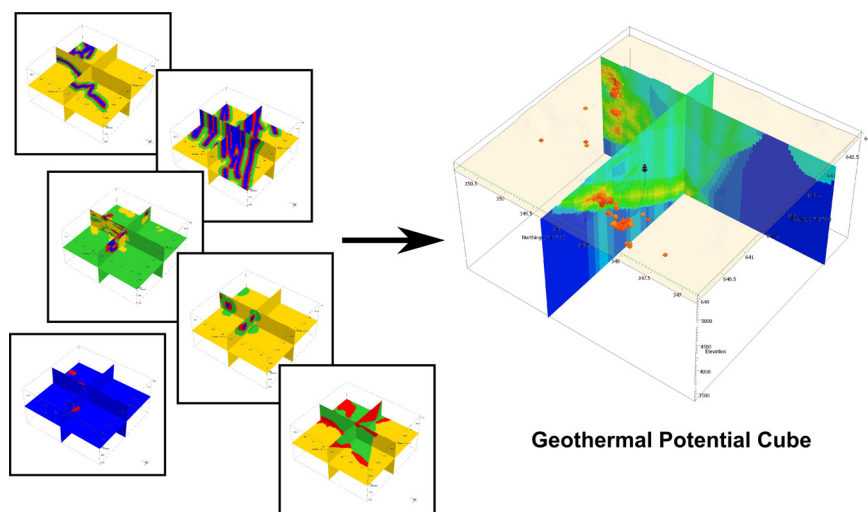


Figure 2. Conceptual diagram showing how a geothermal potential index (right) can be created for a 3D volume of the subsurface by quantitatively integrating various exploration datasets (left). The geothermal potential index identifies potential drill targets based upon specific exploration criteria.

criteria might include: temperature, abundant fractures, distance to major fault intersections, specified alteration type, high magnetic susceptibility, etc. Exploration criteria can be prioritized in two ways. The first is a knowledge-driven approach where experts define the quantitative exploration criteria. The second is based on weights of evidence where known resources are used as training data for the criteria to be applied.

The exploration criteria are applied using a Multi-Class Index Overlay (MCIO) method (Bonham-Carter, 1994). The MCIO method involves a combination of discrete (multi-class) input properties. Each property is assigned a weight and each individual evidential property class is assigned a score. Weights and scores are defined by the expert or evidence, and are based on the significance of the property/class to the exploration model. In the combination algorithm, class scores are multiplied by property weights and summed then normalized by the sum of the property weights. The result is a 3D model showing geothermal potential. Targets can be extracted and ranked based on size and strength, and boreholes planned. The targeting approach is a dynamic one in which new information can

easily be used to update either the Common Earth Model or the exploration criteria.

Conclusions

There are a variety of additional datasets that could be incorporated into a 3D model of a geothermal prospect that we do not discuss here. Examples include: 3D seismic velocity blocks, microseismic hypocenters to identify zones of possible fault movement, and 3D stress models indicating areas of likely fault dilation. Addition of these types of data would only enhance the 3D Common Earth Model approach we describe here.

Overall, we propose that exploration for geothermal resources can benefit from the application of advanced earth modelling methods. Both unconstrained and constrained geophysical inversions used to generate quantitative 3D physical property models can significantly improve the quality of information available for interpretation. Furthermore, quantitative targeting methods based on the development of a Common Earth Model can best use all 3D information.

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