Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

GOCAD® Mining Suite Software as a Tool for Improved Geothermal Exploration

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Keywords: GOCAD, geothermal exploration, 3D GIS, 3D geological modelling, 3D geophysical modelling, quantitative targeting, integrated interpretation

ABSTRACT

The GOCAD Mining Suite is an advanced, geoscience software platform, originally developed for the oil & gas industry, which is used to build and analyze quantitative, multi-disciplinary 3D Earth models. High quality 3D Earth models, such as those made with GOCAD, form the basis for sound decision making to reduce drilling risk in geothermal exploration. Core capabilities of the GOCAD Mining Suite software include: precise structural modelling, surface (wireframe) construction, stratigraphic and regular block modelling, as well as geostatistical analysis. Various add-on software modules are available which provide several 3D geological modelling environments, natural connections to geologically-constrained geophysical forward modelling and inversion, multi-disciplinary 3D exploration targeting, exploratory and geochemical data analysis, and geotechnical hazard estimation and monitoring. A key tool in the GOCAD Mining Suite is 3D-GIS, an interpretive environment in which 3D spatial data can be queried, manipulated, and represented in a meaningful manner so as to provide insight into exploration problems. This paper will present an Integrated Interpretation Workflow which utilizes the GOCAD Mining Suite software. The Integrated Interpretation Workflow is a geologically-based approach to geophysical data interpretation which incorporates geophysical data, geological data, borehole and well data, seismic data, interpreted cross-sections, and other information as available. The approach utilizes forward and inverse geophysical modelling techniques to help build a geologically-constrained 3D Earth model. The output is a robust 3D model of the subsurface consistent with all geoscience datasets. Such a 3D model of the Earth augments understanding of the subsurface, increases confidence in the selection of drilling targets and, therefore, can add significant value to a geothermal exploration program.

1. INTRODUCTION

Exploration for geothermal resources in the 21st century is challenging. Most of the easy-to-find geothermal reservoirs have already been found. In addition, subsurface geology in geothermal environments is complex and inherently 3D in nature. Furthermore, most geothermal reservoirs are found at depths greater than 2 km which requires effective tools for deep exploration. In order to minimize early-stage exploration risk and maximize the likelihood of success, the geothermal sector requires the best possible tools to help locate these deep geothermal reservoirs in geologically complex environments. One very important tool to reduce risk in geothermal exploration is a software platform that can: 1) house all pertinent geoscience data in one place in an accessible and visual 3D environment, 2) allow for dynamic 3D visualization, interrogation, quantitative modelling, and interpretation of the 3D geoscience data volume, and 3) enable more confident targeting of geothermal well locations based-upon rigorous 3D interpretation of multiple streams of quantitative geoscience evidence. The GOCAD Mining Suite is a software platform with these characteristics. It has been used extensively in the mineral exploration industry for 15 years and has clear applicability to help the geothermal sector overcome some of the most pressing exploration challenges. This paper describes the main features of GOCAD Mining Suite software platform as well as several add-on software modules which provide additional functionality. This paper concludes with a discussion of an Integrated Interpretation Workflow, a method which quantitatively integrates geoscience datasets in 3D using GOCAD. The output of the Integrated Interpretation Workflow is a 3D geological model of the subsurface, consistent with all datasets, which may be used to more confidently identify drilling targets.

2. ABOUT GOCAD MINING SUITE

The GOCAD Mining Suite is an advanced, geoscience software platform which is used to build and analyze quantitative, multi-disciplinary 3D Earth models. The GOCAD Mining Suite is a customized extension of GOCAD software, which has been developed for the petroleum industry by Paradigm™. GOCAD Mining Suite software leverages very significant oil and gas R&D investment to address 3D earth modelling challenges in the mining industry. Since geothermal exploration has many facets similar to mineral exploration (and others analogous to oil and gas exploration) the GOCAD Mining Suite software has capabilities which meet the broad, multi-sector needs of geothermal exploration. From data import to exploration drillhole design, geothermal geoscientists can manage their project from one central software application which houses all of their geoscience data. Both static (non-time varying) and dynamic (time-varying) data can be accommodated in GOCAD through the appropriate assignment of time-stamps on imported data. The GOCAD Mining Suite enables precise geological modelling (wireframe), block modelling, and property modelling. Also, the GOCAD Mining Suite is a modularized software which consists of a main software platform and add-on software modules which extend functionality and allow seamless communication with external geochemical and geophysical software applications. For example, the add-on modules provide capabilities which include: geologically-constrained geophysical modelling and inversion, multi-disciplinary 3D exploration targeting using both knowledge and data-driven approaches, exploratory and geochemical data analysis, and geotechnical hazard estimation. In addition, the GOCAD Mining Suite has a fully integrated 3D-GIS query environment to allow quantitative interrogation and analysis of complex 3D datasets. The software also provides a best-in-class 3D visualization environment. Overall, when utilized for geothermal exploration, the advanced capabilities of the GOCAD Mining Suite become the basis of sound and rapid decision-making that reduces exploration risk. What follows here is an overview of some of the characteristics of the GOCAD Mining Suite software platform and the various add-on modules.

2.1 Import/Export, 3D Visualization, and Exploratory Data Analysis

The GOCAD Mining Suite has been customized to support the import and export of virtually any data file format used in modern exploration. Whether it is a specific geophysical data format, geological data format, or a data file from another software package, import/export capabilities have been incorporated into GOCAD to enable easy data transfer from one software platform to another. Data is normally imported into GOCAD as one of the following types: points, curves (or polylines), surfaces, meshes, wireframes, grids, or drillholes. Once loaded into the software, these items are called GOCAD objects.

The 3D visualization capabilities of GOCAD are best-in-class. GOCAD objects can be made transparent, contours can be generated on surfaces with a single click, and you can quickly and easily slice through 3D block models in any direction. Of greater importance, however, is the ability to assign property values to individual data points. For example, an individual point can be assigned as many types of property values as you like such as density, rock type, alteration, temperature, etc. To better visualize and interpret complex, multi-disciplinary geoscience datasets, the data can be painted different colors according to the value of the property and/or made a different size according to the value of the assigned property. For example, data points collected on the land surface could be painted or sized according to rock type, density, and alteration so that relationships can be visually recognized. Downhole data (e.g. temperature, downhole resistivity, rock type, alteration, etc.) can similarly be colored, sized, or plotted in a wide variety of ways.

Making sense of complex geoscience datasets in 3D can be challenging. GOCAD Mining Suite has advanced tools for exploratory data analysis (EDA) to aid with this. For any dataset, a few clicks enable the generation of: basic statistics, cross-plots, and histograms. For structural data, stereonets are also easily generated. These EDA tools help explorers tear apart data, find out the distribution of the data, and answer important questions. Are the data bimodal? Are there basic statistical relationships in the data and, if so, what are they?

2.2 3D Surface Modelling, Block Modelling, and Property Modelling

One of the powerful features of GOCAD is the ability to create surfaces quickly and accurately. These surfaces could represent rock unit contacts, faults, or temperature iso-surfaces, among others. 3D surfaces can be created from points (e.g. a DEM), from markers on drillholes (e.g. lithologic horizons), or from curves (e.g. faults digitized from a geologic map). Surfaces can easily be cut against one another to create a “water-tight” 3D surface model. Surfaces can also be extracted from 3D block models. For example, if you have a 3D block model of resistivity derived from inversion of magnetotelluric survey data, GOCAD can easily extract surfaces within the block model that represent specific resistivity values.

Once the 3D model of surfaces is created, it is simple to convert that model into a 3D block model. A 3D geologic model that consists of only surfaces that represent rock unit contacts and faults is “empty” between the surfaces. This is great for visualization but not as valuable when it comes to data analysis and advanced interpretation. By converting the 3D surface model into a 3D block model, the space between the surfaces is filled up with a mesh of very small blocks, the size of which are user-defined (e.g. 10 m x 10 m x 10 m). The value here is that information (property values) can be attached to each of these small blocks. Examples of properties are: density, rock type, alteration, temperature, etc.

Lastly, once your 3D GOCAD model has been populated with properties, these properties can be modelled as well using a variety of interpolation, estimation and simulation methods. These include: inverse distance weighting, the discrete smooth interpolator, kriging and sequential simulations. Also, properties from one GOCAD object can be easily transferred to another GOCAD object. Property modelling is important because it enables powerful flexibility for integrating, interpreting, and visualizing complex, multi-disciplinary, 3D geoscience datasets.

2.3 3D GIS Querying

Another powerful tool in GOCAD is 3D GIS querying. 3D GIS is an interpretive environment in which 3D spatial data can be queried, manipulated, and represented in a meaningful manner so as to provide insight into geologic problems. As its name suggests, 3D GIS querying enables the explorer to interrogate a 3D volume of data to answer important questions. Many different types of 3D GIS query are available. Some are based on properties (e.g. find where temperature values in the 3D block model are greater than 150 °C). Others are geological, such as find specific rock units or contacts in drillholes. Still other 3D GIS queries are spatially oriented – find the distance to an object (e.g. a fault) or find where two objects intersect. Since the amount of information in a data-rich 3D environment can be complex and difficult to interpret, 3D GIS queries are valuable tools to interrogate 3D volumes of data to extract specific information that has interpretational value.

3. ADD-ON SOFTWARE MODULES

3.1 3D Geological Modelling

Two add-on software modules for advanced 3D geological modelling are SKUA and Sparse.

SKUA is an implicit modelling engine built by Paradigm™ which allows the user to quickly build 3D models defined by fault networks and stratigraphic horizons. SKUA uses a volumetric modelling algorithm that builds the entire 3D model in a single pass. Models are constrained by well/drillhole markers, interpretation points and curves, structural measurements and a stratigraphic column that defines stratigraphic rules between horizons. 3D models can quickly be updated (recomputed) to honor new drilling and other types of subsurface data.

Sparse is a module which enables construction of 3D structural geology models given sparse structural and geological data. It is a powerful tool to quickly build smooth 3D curves and surfaces that honour structural data. Sparse was developed by Mira Geoscience in collaboration with the Geological Survey of Canada.

3.2 Geologically-Constrained Geophysical Forward and Inverse Modelling

Two geophysics-related add-on software modules for the GOCAD Mining Suite are the Potential Fields module and the Seismic module.

The Potential Fields module is specifically used for 3D forward and inverse modelling of gravity and magnetic data. Importantly, it incorporates geological, structural, and petrophysical constraints to derive a geologically meaningful 3D model of the subsurface. The Potential Fields module includes traditional geophysical filtering and interpretation tools in addition to the advanced tools for 3D geophysical modelling. The Potential Fields module provides a seamless connection with VPmg software from Fullagar Geophysics as well as MAG3D and GRAV3D from UBC-GIF (Fullagar et al., 2008; Fullagar and Pears, 2007; Li and Oldenburg, 1998; Li and Oldenburg, 1996). The VPmg and UBC software packages are the actual geophysical inversion modelling engines and are sold separately to GOCAD.

The Seismic module enables 3D seismic forward modelling for hard rock environments. It can model seismic reflection data using 3D geological and petrophysical models as constraints. In addition, a 2D forward modelling and inversion code uses straight and curved ray travel time data within discretized 2D planes for cross-hole studies. Inversion of these data solve for seismic velocity fields between boreholes.

3.3 Quantitative Exploration Targeting

The Targeting Workflow is an add-on software module that helps explorers quantitatively combine geoscience datasets to select geothermal targets for follow-up or drilling. The Targeting Workflow is based upon established 2D resource potential mapping technology developed for the mining industry in the 1990's (Bonham-Carter, 1994). Targeting can be performed either in 2D (for map-based datasets on the land surface) or in 3D (for 3D volumes of data extending into the subsurface) to help meaningfully guide target selection in an objective and unbiased manner. The Targeting Workflow approach is a hands-on process combining the project team knowledge with technology. This approach is not a black box technique because, it provides, at all times, access to the input data and interpretation in order to build confidence through visual, as well as statistical, validation of target areas. A key component of the Targeting Workflow is that it quantitatively combines various "exploration criteria" which enables explorers to extract the most value out of their multi-disciplinary 3D geoscience datasets. Exploration criteria are specific features which are indicative of high geothermal resource potential. Examples of exploration criteria might include: faults of a certain orientation, intersecting faults, a hot well, hot springs, or porous/permeable rock units. The Targeting Workflow uses knowledge-driven and/or data-driven mathematical methods to highlight prospective ground. The knowledge-driven approach utilizes expert knowledge to identify the exploration criteria and weight the relative importance of each one. By contrast, data-driven methods identify points known to have high geothermal potential as "training cells". This information is then used to probabilistically evaluate the 3D volume for similar areas of geothermal potential. Quantitative analysis and advanced visualization tools are employed in the Targeting Workflow to identify and then rank specific targets from most prospective to least prospective. A unique workflow interface also dynamically guides the user through the Targeting Workflow process.

3.4 Geochemical Data Analysis

Another add-on software module called the ioGAS Link connects GOCAD to the ioGAS Geochemical Analysis software. The ioGAS software has been specially developed by REFLEX® for exploratory and geochemical data analysis and enables the user to easily and efficiently detect patterns, anomalies, and relationships across your data (geochemical or other data). The ioGAS Link creates a real-time connection between ioGAS software and GOCAD Mining Suite so that you can simultaneously analyse data both in data space (e.g. downhole temperature, geothermometry, or a Piper diagram) and 3D space (e.g. X, Y, Z locations). The ioGAS Link combines the power of exploratory and geochemical data analysis with advanced visualization and 3D-GIS query.

3.5 Geotechnical Hazard Estimation

The Geotech add-on module is an integrated, 4D-GIS based geotechnical hazard assessment tool, originally developed for open pit and underground mines. It can also be used in geothermal applications in areas of steep slopes and hydrothermal alteration where slope stability issues can be problematic. The Geotech module allows for multiple geoscience criteria to be combined using knowledge-driven and data-driven methods to highlight specific areas of hazardous ground. The workflow interface guides the user through the construction of a hazard model and then applies it in either a standard or real-time monitoring mode. Hazard definitions, normalizations and weightings under the main categories of geology, rock quality, seismicity, structure, stress and geometry are completely user-defined. Slope stability issues can be significant for geothermal development because: a) many geothermal areas are located on the flanks of volcanoes which have steep slopes, b) geothermal areas are commonly coincident with zones of extensive hydrothermal alteration which may be prone to failure, c) injection of geothermal fluids underground in injection wells can lubricate faults and other sliding surfaces which can lead to slope failure.

4. INTEGRATED INTERPRETATION WORKFLOW

We have developed an Integrated Interpretation Workflow which specifically takes advantage of the 3D geologic modelling capabilities of the GOCAD software platform and the Potential Fields software module. Our approach also maximizes value out of 3D geophysical modelling with VPmg software from Fullagar Geophysics. This workflow was originally developed for exploration in the mining industry (Chalke et al., 2012), yet it has clear application to geothermal exploration. In our view, traditional geophysical data interpretation is insufficient for today's geothermal exploration challenges. For example, traditional map-based geophysical interpretation (e.g. drawing interpretation lines on 2D maps) does not provide enough information about the subsurface. In addition, 3D geophysical inversion modelling that does not incorporate geological or other constraints commonly result in "blobby" 3D geophysical models that lack geological realism. As 21st century geothermal exploration gets more and more challenging, we must do our job better as explorers to be successful. The approach proposed here is to model and interpret geophysical data in 3D and make it geologically meaningful using the Integrated Interpretation Workflow.

4.1 What is it?

The Integrated Interpretation Workflow is a geologically-based approach to geophysical data interpretation. It primarily utilizes gravity and magnetic geophysical data to help build and test a 3D geological model. If available, geological data, drillholes, seismic data, interpreted cross-sections, and other data are incorporated into the process. The output of the modelling effort is a geologically-plausible 3D model of the subsurface. The Integrated Interpretation Workflow approach utilizes forward and inverse geophysical modelling techniques to characterize discrete 3D geological domains that generate the same geophysical response seen in geophysical surveys. In the end, a 3D geological model is generated which is quantitatively consistent with the geophysical data.

4.2 What are the Benefits?

The Integrated Interpretation Workflow is vital in areas with abundant alluvial cover and/or little geologic outcrop. Gravity and magnetic data is usually collected to cover an entire prospect. Therefore, the approach proposed here can help "fill in the gaps" to generate an informed geological framework over the entire area of interest. The Integrated Interpretation Workflow helps to maximize value out of all exploration data by incorporating it into a single 3D model of the earth. Importantly, because this approach combines different, independently-derived datasets collected over the same area, it can be used to rigorously test the viability of the 3D geologic model prior to drilling. In other words, the constructed 3D geologic model of the subsurface must be consistent with both the gravity and the magnetic datasets collected at the surface. If not, something is incorrect about the 3D geologic representation of the subsurface (or, alternatively, the geophysical data are erroneous). Investigating these issues is the best way to develop the best and most accurate 3D model of the subsurface. A better 3D geological model leads to greater confidence in selecting drill targets and ultimately reduces exploration risk. Overall, the Integrated Interpretation Workflow is a relatively low-cost strategy to increase geological understanding before embarking upon expensive drilling campaigns or more costly types of geophysical surveys (e.g. magnetotellurics).

4.3 How does it Work?

Here, we present a brief overview of the four main steps in the Integrated Interpretation Workflow.

The first step in the Integrated Interpretation Workflow is to interpret the geological and geophysical data at hand. For example, identify how the geophysical signatures relate to the geology, assess rock properties (e.g. density and magnetic susceptibility) associated with the geology, and interpret structural features and geological domains on 2D maps. Data processing or enhancements of the geophysical data (e.g. depth to source, vertical or horizontal derivative filters, etc.) may be helpful in this initial interpretation step. It is important to develop a geological (exploration-driven) hypothesis to test which guides the rest of the workflow.

The second step involves initial geological modelling in 3D. This initial geological modelling is performed in GOCAD. The following data sources are used to build your geological model: 1) interpretation lines (from Step #1), structural and stratigraphic information (e.g. strikes and dips), drillhole data, geologic maps, cross-sections, and seismic sections. The primary goal is to model in 3D the contacts and/or boundaries of key geological domains. Once the surfaces have been generated to divide up the model into different domains, you convert the geological model into a solid 3D "block model" discretized with an appropriate cell size. The final action is then to populate the block model with reasonable physical property values. Density and magnetic susceptibility values used here can be derived from field measurements at outcrops, measurements on drill core, or educated estimates based upon average values for specific rock types.

The third step in the Integrated Interpretation Workflow involves geophysical forward modelling in 3D. This step is performed using the Potential Fields module and VPmg software from Fullagar Geophysics. Geophysical forward modelling takes the 3D block model (populated with values of density and magnetic susceptibility) and compares the geophysical response calculated from this initial block model with the actual observed gravity and magnetic data measured from the field. Does your initial geological model match the main features of the geophysical survey? If not, an adjustment of the rock properties assigned to the different domains is required. Alternatively, an update to the 3D geological model is necessary. This process is repeated until a geologically-reasonable 3D model is created which is consistent with the main features of the gravity and magnetic data.

The fourth, and final, step involves geophysical inversion modelling in 3D. This step utilizes the full power of the Potential Fields module and VPmg software. The goal of this step is to refine and improve the initial 3D geological model using three different geophysical inversion modelling techniques: homogeneous-domain modelling, heterogeneous-domain modelling, and geometry modelling. Homogeneous-domain modelling determines the optimal physical property value for each individual geo-domain (using a uniform, or homogeneous, value for the whole domain). The aim is to provide the best match between the 3D geological model and the geophysical data. We all know that a body of rock does not normally have perfectly uniform physical properties (e.g. density) over a large area – there are variations. This is where the heterogeneous-domain modelling technique comes into play. Heterogeneous-domain modelling also determines the optimal physical property values for each geo-domain but, it lets these values vary over a specified range within each domain. For example, let's say you have a granite pluton exposed at the surface and measurements of density on 20 hand samples from this rock unit show that it has a range in density between 2.60 and 2.65 g/cm^3. This information is incorporated into VPmg and guides the geophysical inversion modelling step to populate the granite body in the 3D geological model with density values which are consistent with field measurements. Lastly, geometry modelling is a final inversion technique which allows the boundaries of the different geo-domains to move to better match the observed geophysical response. For example, let's say you have a 3D geologic model which includes granite (dense) in contact with a thick section of volcaniclastic rocks (less dense). You know the densities of these rock units because you drilled one hole through them and you've measured the densities of each from core samples. The drillhole gives you information about the depth to the contact between these two rock units in only one location. How can you learn about the granite/volcaniclastic contact away from the drillhole? Drilling more holes is expensive. Using the VPmg geometry inversion modelling technique, you can fix the location of the granite/volcaniclastic contact in one spot (the drillhole), fix the density (or range of densities) for the rock units, and then use VPmg to model the contact away from the drillhole. VPmg will move the granite/volcaniclastic contact up or down to find the optimal match to the observed gravity data. Overall, the goal of this geophysical inversion modelling step is to add details to the 3D geological model. This final step also highlights conflicts between the geophysical data and the geological model which helps advance the geological interpretation.

5. CONCLUSIONS

The GOCAD Mining Suite is a powerful, geoscience software platform used to build and analyze complex 3D Earth models. It brings geological, geophysical, and geochemical data together in a quantitative manner to output a robust 3D model of the subsurface consistent with all geoscience datasets. This type of approach adds significant value to the exploration effort and can help reduce early-stage exploration risk in geothermal exploration. The GOCAD Mining Suite consists of a main software platform with various add-on software modules which extend the functionality of the software.

The Integrated Interpretation Workflow proposed here utilizes the GOCAD Mining Suite software and VPmg software from Fullagar Geophysics. The Integrated Interpretation Workflow is a geologically-based approach which incorporates gravity and magnetic data primarily, but also other available geoscience datasets. The approach utilizes forward and inverse geophysical modelling techniques to help build a robust 3D geologic model of the subsurface consistent with all geoscience datasets. This type of 3D model of the Earth advances our understanding of the subsurface and improves our ability to confidently select drilling targets. This type of approach can lead to greater drilling success in a geothermal exploration program.

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