Fast-tracking numerical modelling projects using Volsung and Leapfrog Energy

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ABSTRACT

The key input to a geothermal reservoir numerical model is a robust conceptual model, which is a concise representation of the primary structures and processes that determine a reservoir's characteristics and behaviours. These key elements are often modelled, updated and stored in Leapfrog Energy 3D models and presented graphically on cross sections or 3D scenes.

In this paper we present a workflow for quickly transferring model outputs from Leapfrog Energy to the Volsung flow simulation software to fast-track the development of the numerical reservoir model and ensure that it is based closely on sound geoscience. This workflow is based on using volumes and faults from the Leapfrog Energy model to define numerical model regions and adding qualitative conceptual model elements using geo-referenced cross section image files. Well track information can also be exported from Leapfrog Energy to Volsung. All data are represented and transferred independent of a particular explicit grid structure. Outputs from the numerical model simulation, such as the time-dependent spatial distribution of pressure and temperature, can be exported from Volsung and imported back into Leapfrog Energy to be visualized in conjunction with other multi-disciplinary geoscience data.

Any revision to the geological or conceptual model can easily be transferred to Volsung to update the associated reservoir numerical model, leading to a robust system for updating and maintaining models over the duration of a geothermal resource development.

This workflow is a practical and efficient methodology for fast-tracking the development of a numerical model. It reduces numerical model development time and enables teams of geoscientists to collaborate to produce better numerical models, leading to higher confidence in numerical model predictions and improved geothermal reservoir management.

1. INTRODUCTION

1.1 Background

This paper explains a practical and concise workflow for transferring data back and forward between conceptual and numerical models using two software platforms currently in use in the geothermal industry. Leapfrog Energy, an implicit 3D conceptual modelling software and Volsung, a software package for running geothermal reservoir, wellbore and surface network simulations (Franz et. al., 2019). Traditionally, conceptual models are developed by a team of geoscientists, whereas numerical models are developed by a reservoir modeller, with much of this work occurring independently. A growing awareness of the importance of basing a numerical model on a robust conceptual model, along with recent advancements in technology, has led to improvements in the data transfer, workflow and process for ensuring consistency between conceptual and numerical models. This paper continues this work in finding greater efficiencies for dynamically linking the conceptual and numerical models. In this section we describe conceptual and numerical models, introduce the two software packages, Volsung and Leapfrog Energy, and summarise recent work on this topic.

1.2 Conceptual Model

A conceptual model is a concise representation of the key structures and processes that determine a reservoir's characteristics and behaviors. Common features in a conceptual model include:

- Reservoir heat source and upflow locations;
- Reservoir boundaries, clay cap, indicative permeability and flow paths;
- Reservoir temperature distribution;
- Geology model including the spatial distribution and properties of different rock units and the locations of faults;
- Locations of liquid, two- phase and vapor-dominated regions of the resource;
- Locations and properties of any source of fluid recharge in the reservoir;
- Relevant fluid chemistry;
- Surface thermal manifestations;
- Uncertainties.

These key elements are often stored in 3D models and presented graphically on conceptual model cross sections or 3D scenes, with an example given in Figure 1.

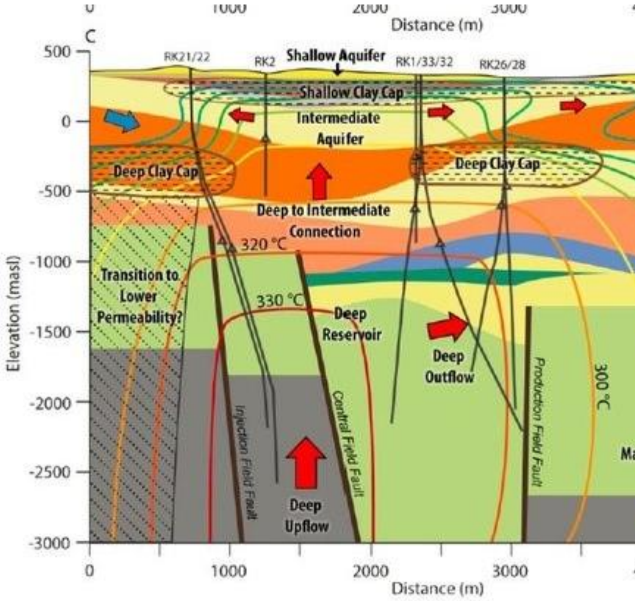

Figure 1: Conceptual model example from Addison et al. (2017)

1.3 Numerical Model

A geothermal reservoir numerical model is a mathematical model of the geothermal resource where the reservoir is divided into a series of discrete regions in space known as model blocks. Each block is assigned a particular value for each of the parameters needed to describe the physical properties of the region, such as permeability and porosity and assigned initial thermodynamic conditions such as pressure and enthalpy. During a simulation a numerical code steps the system forward through time by solving the appropriate heat and mass flow equations for the given thermodynamic conditions. The outputs from the numerical model can be compared to measured field data and the model can be updated to obtain a better match to this data in a process known as model calibration. Numerical modelling enables the prediction of future reservoir responses to particular development scenarios, and, as such, plays a key role in the planning and management of geothermal developments.

A key input to the numerical model is a robust conceptual model. This helps the numerical modeler assign the distribution rock properties and boundary conditions in the model in a way that is consistent with geoscience. Numerical models that are based on a robust conceptual model are developed in less time and lead to a greater confidence in model predictions. Improvements in the workflow of transferring conceptual model information into the numerical modelling framework are therefore significant in leading to the better use of models in the geothermal industry and better management of geothermal resources.

1.4 Previous Approaches

Typically, a conceptual model is created and updated in a 3D conceptual modelling software such as Leapfrog Energy. The task is to transfer this 3D spatial information into a numerical model platform. Specifically, the reservoir simulator needs to assign certain rock properties, like permeability and porosity, to the blocks of the grid and the connections between them, in a manner that reflects the conceptual model. There are at least three general approaches to this:

1. Manually;
2. Automatically by generating the grid within the conceptual modelling software and using this as a basis for the numerical model;
3. Automatically by exporting the spatial data from the conceptual model in a format suitable for importing into the numerical model platform.

The first approach is essentially transferring the model “by eye”, making a visual comparison of the conceptual model and using that to build the numerical model. Historically this is how many geothermal models have been developed.

The second approach requires that the conceptual modeling software can generate grids and export the relevant spatial data in the suitable data format. Popineau et al. (2018) and O’Sullivan et al. (2023, 2023a) discuss this workflow in detail. In this approach the conceptual model is often upscaled from the original lithology classification based on their hydraulic parameters, or multiple models of different classifications are combined together, such as the lithology and clay cap boundary to allow appropriate parametisation in the numerical model.

The third approach is the focus for this paper, whereby the spatial data defining the conceptual model needs to be transferred between the conceptual and numerical modelling platforms in a suitable format. The numerical modeling platform needs to be able to read the outputs of the conceptual model and, likewise, the conceptual modelling platform needs to be able to load numerical model results to enable the visualisation of model output in context with broader geoscience data. This allows geoscientists to work in a gridless 3D space while still enabling integration of the conceptual model with the numerical model.

In Volsung there are several methodologies for assigning rock properties to grid blocks:

- In a cell-based approach, where each grid block gets a lithological unit type assigned individually, for example by generating the grid within the Leapfrog Energy and exporting a prepopulated numerical model grid, or by selecting regions of the model with the mouse.
- In a file-based approach, where the grid blocks read their lithology unit associations from a text-based file. This has been part of Volsung for several years and can be used with files generated by Leapfrog Energy. In this approach the block/rock association needs to be edited externally.
- In a spatially interpolated approach where permeability/porosity are described independently from discrete rock types. In this method the rock properties can be supplied as (x,y,z) point lists, and are evaluated at the block centres via interpolation methods.
- In a layer/fault based method whereby editable geometric shapes are used to describe the top of

lithological unit domains (layers) or assign units to grid blocks which are touched by the shape (faults). Further barriers can be used to modify individual connections on a sub-grid level.

For the work presented here we extended the layer/fault method by adding the capability to work with volumes, which enables a more concise, practical and flexible approach when working with conceptual models that have been developed in Leapfrog Energy.

Figure 2 outlines this workflow. Here the conceptual model is built using Leapfrog Energy and the numerical modelling component uses Volsung.

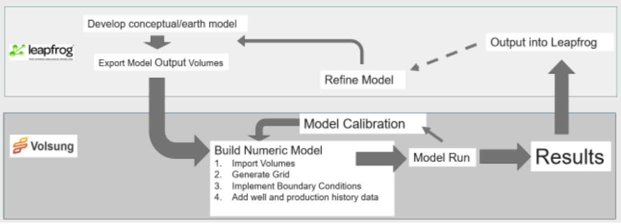

Figure 2: Diagram of workflow to integrate data from conceptual model in Leapfrog with the Numerical model in Volsung.

2. NEW WORKFLOW

In this section we describe the new workflow and the updates to the software platforms to enable this workflow.

2.1 Technology Update

The primary software update was to extend the layer/fault method in Volsung by adding the capability to work with volumes. Volumes are described by a two-dimensional mesh which encloses a three-dimensional volume. Grid blocks which have their cell centre located within the volume are assigned the lithological unit associated with that volume.

To determine if a cell centre is within the 2D mesh describing the surface of the volume, a ray is cast from the cell centre. The block is considered to be inside the volume if the ray intersects the surface mesh an odd number of times. This method can also deal with very complex volumes containing concave folds.

However, it was noted that in some cases this method fails if the ray intersects the surface mesh exactly on an edge between two surface mesh cells, i.e. it produces false negatives. It was found that this situation is resolved very effectively by repeating the test using different directions for the rays, and using random numbers for the angles between different ray directions.

This method is of order O(m*n), i.e. approximately m*n ray/cell intersection tests need to be performed, where m is the number of blocks in the model and n the number of cells in the surface mesh of the volume. The operation hence would be very slow to the point that it would quickly become unworkable. However, it can be accelerated using an intelligent locator algorithm, where only approximately O(log(n)) surface mesh cells need to be used in the ray/cell intersection tests and therefore the overall method changes to order O(m*log(n)). In the new implementation the whole operation is done within fractions of a second even for highly discretized meshes.

The surface meshes describing the volume can currently be supplied to the simulator in three different ways:

- As a 3D Delaunay triangulation from a point cloud. This triangulation always results in a convex volume, but can be easily created and edited in the GUI using mouse interaction.
- A VTK compatible file describing the volume; this method is very general and the corresponding VTK files can be generated in multiple ways.
- Using a Leapfrog Energy mesh file (LFM).

The Leapfrog Energy LFM files are a proprietary format; in essence they contain zipped binary data describing the surface triangles of the enclosed volumes, as well as some meta data like the names of the associated volumes and colour information. Volsung can pick up these files and allows the modeller to associate a lithological unit with one or more volumes from the LFM file. It can also associate the correct colour with the lithological unit, making it visually appealing since colours are the same in both the Leapfrog Energy and Brynhild user interfaces.

In addition to the new volume approach described above there is also added support for meshes in the GOCAD file format. Surfaces, in particular faults, can be exported by Leapfrog Energy into a number of file formats, in particular the commonly used DXF format. This format has previously been implemented in Volsung, but resulted in comparatively slow meshing operations, often taking tens of seconds per exported fault. The new implementation of the GOCAD format in Volsung has resulted in much faster meshing operations. This allows the export faults from Leapfrog Energy without the tedious requirement to downsample them.

2.2 Step 1: Develop a Conceptual Model

Developing a conceptual model in Leapfrog Energy is described in (Alcaraz et. al., 2011, Newson et. al., 2012, Poux et. al., 2021). To illustrate the process in this workflow, a practical worked example is presented, based on a synthetic dataset originally developed by GNS Science. This dataset is loosely derived from a typical New Zealand geothermal field and the lithological units were built from downhole well data and a surface geology map. These units are defined in Figure 3 and consist of a Basement, Andesitic Breccia, Rhyolite, Andesite, Ignimbrite, Sediments, dacite and Alluvium lithologies. The fault surfaces were built in the fault system section of the geological model using GIS data defined from the geology map.

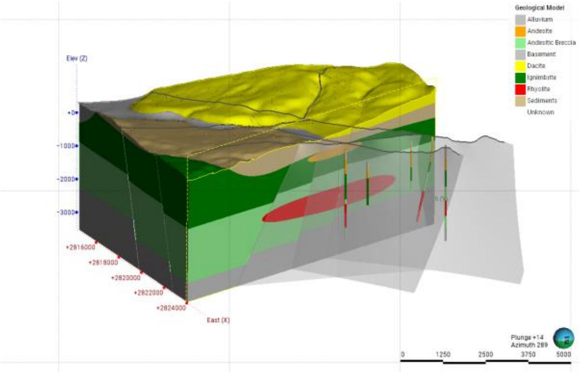

Figure 3: Synthetic conceptual geological model used in this case study.

2.3 Step 2: Exporting Conceptual Model Outputs

A conceptual model in Leapfrog Energy can be built using a combination of different model types. These are defined in Leapfrog Energy as a geological model (GM) which is used to model any categorical data such as lithology and alteration, a numeric model (NM), created using Leapfrog's radial basis function implicit modelling, being a 3D contour representation of numerical data, with common variables modelled being temperature, pressure and chemistry. A combined model (CM), which generates a dynamic boolean of intersecting volumes from either GM or NM.

Both GM and NM comprise open meshes (a triangulated mesh approximating the interpolant) which define the layers and closed output volume meshes, defining different zones located inside the model boundaries. The CM only derives closed volume meshes in its output. It is the closed output volumes in this workflow which are exported as one LFM file.

Faults in Leapfrog Energy are represented as an open mesh. This is typically found either in the fault system component of a GM or as a standalone mesh surface. The surfaces are exported as GOCAD files.

Given a conceptual model often comprises of multiple models such as geology, alteration and temperature. These file exports allow for diversity in conceptual model development workflows in Leapfrog Energy such as creating a CM of two GM representing the lithology and alteration. It also enhances the flexibility to generate fault zones from surfaces outside of the fault system, allowing quick rocktype classification of finite faults in the numerical model inputs.

While the volumes and fault surfaces are used directly to define the grid parameters, other data, such as downhole well data and cross sections also supports understanding of the conceptual model. Downhole well data needs to be exported as an X,Y,Z pointset from Leapfrog Energy and cross sections should be in JPEG file format with note of the location co-ordinates for each end to easily incorporate into Volsung.

2.4 Step 3: Import Conceptual Model into Volsung

Once the LFM file, GOCAD files, image files and well track files have been exported from Leapfrog Energy these can be imported in using Volsung. First a set of lithological units need to be created, that corresponds to the units in the LFM file. Then the LFM file can be imported, and individual or sets of volumes are allocated the properties of the lithological units. This is done manually via the Volsung graphical user interface, but normally only takes a few minutes to complete for a typical geothermal model. Since the LFM file also contains colour information, functionality was also added to Volsung to enable the lithological units to have the same colour scheme as displayed in Leapfrog Energy. An example of this is shown in Figure 4 where the conceptual model, rendered in Leapfrog Energy, can be compared to the numerical model in Volsung. After the initial import of volumes and faults the model can be inspected visually to assess whether the numerical grid refinement is sufficient to capture the relevant conceptual model elements. If elements are not represented adequately in the numerical grid, the grid can be refined, or conceptual model elements can be entered manually by the numerical modeler by creating volumes, layers and faults directly within Volsung to supplement the spatial datasets imported from Leapfrog Energy.

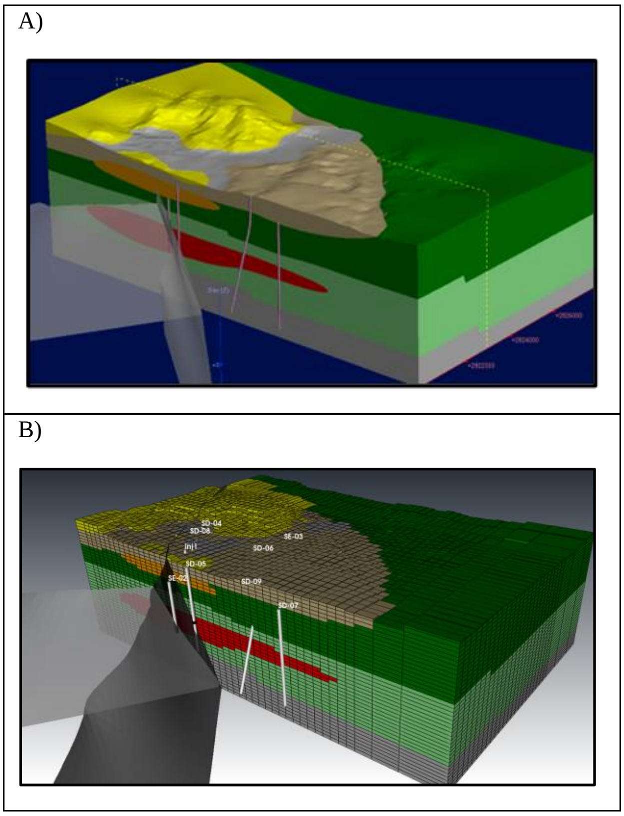

Figure 4. A) shows the conceptual model in Leapfrog Energy, and B) shows the numerical model after the relevant data has been imported in Volsung

It's common for additional conceptual model details to be presented on cross sections. These can be imported into Volsung and georeferenced using coordinate points at the corner of the image. An example of this is shown in Figure 5 using a well-known cross section from Cumming (2007). Having the numerical model rock properties, thermodynamic conditions and flow vectors displayed in the same 3D space as the conceptual model slice is both helpful for rapid model development and serves as a qualitative constraint on the model.

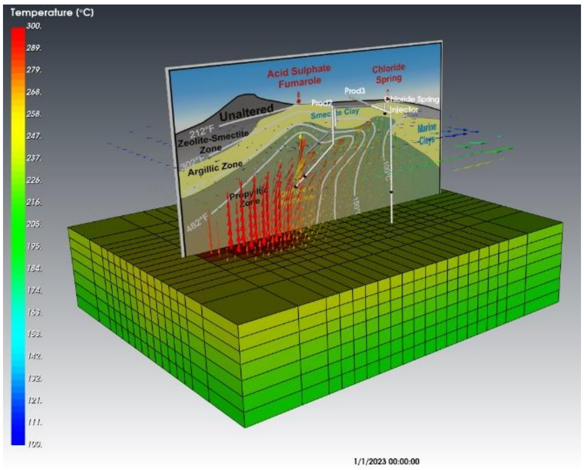

Figure 5. Showing a conceptual model cross section displayed in Volsung. Model grid blocks are coloured by temperature and the flow vectors indicate flow in the numerical model.

2.5 Step 4: Numerical Model Calibration and Boundary Conditions

Importing the conceptual model is only the starting point for developing a calibrating numerical model suitable for use in forecasting future reservoir behaviour and well performance. It is typical for a reservoir modeller to spend many weeks updating and refining the numerical model in order to match measured field data. This process usually involves adding and updating boundary conditions and changing the distribution of rock properties in the model. In Volsung, a key design philosophy is that these elements are implemented independently of the grid. This massively simplifies the task of regridding a model or developing sector or process models of a particular sub-region of an existing model. The data imported from Leapfrog Energy into Volsung, the geology volumes, fault meshes, well tracks and conceptual model cross sections, are all grid independent. The refinements to the model that occur during calibration are also implemented independently of the grid by using points, lines, surfaces and volumes located in space to define new regions of different rock types, source terms or boundary conditions. This includes model upflows and outflows, constant pressure boundaries, regions of heat flux and all the typical features of a full field reservoir model. With this approach the reservoir modeller is able to fast-track the development of the numerical model by quickly and easily importing conceptual model features from Leapfrog Energy, and then continue working independently to update and calibrate the model without having to go back to make changes within Leapfrog Energy. Furthermore, all conceptual model features, whether imported from Leapfrog Energy or developed within Volsung, are independent of the model grid, which makes it easier to update and maintain the model in the future. Once the model has been calibrated within Volsung it can be used for forecasting and results can also be loaded back into Leapfrog Energy to enable additional data visualisations and ongoing collaboration with geoscientists.

2.6 Step 5: Integrating Numerical Model Outputs

The 3D simulation outputs can be imported back into Leapfrog Energy for visualisation and understanding of its relation to all conceptual model data. This closes the loop of collaboration between the conceptual model and the outputs tested in the numerical model. While it is common to reimport the TOUGH output grid format (Popineau et. al., 2018; O'Sullivan et. al., 2023; O'Sullivan et. al., 2023), this is limited to simply visualising results. To enable further analysis of the results in Leapfrog Energy, the outputs are integrated using the time dependent point tool. This is a point file of each cell centroid where the timestep is represented in the standard date format required by Leapfrog Energy along with the attribute output data of the numeric model.

Each timestep can be contoured and changes compared. Figure 6 shows the contoured outputs of the 200ºC isotherm, highlighting changes between the initial and final timestep of a production run. Here a distance function is used to calculate the difference between contoured surfaces generated at the start and end of the simulation. This approach can help identify small changes, and in the particular simulation analysed we can see temperature change concentrated in the upflow near the production well.

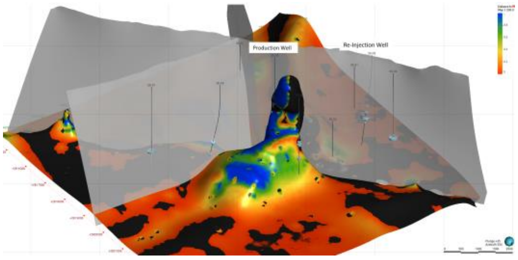

Figure 6: Difference between the 200ºC isosurfaces of the first and last timestep results from the numeric model. Red represents the least change, blue larger change and black the first timestep surface. Downhole traces with feedzones and faults in grey.

3. DISCUSSION

To ensure numerical models are developed to represent the subsurface as accurately as possible, the conceptual model must form the basis of input. Historically, the integration between technology was not developed to allow seamless and efficient workflows between the two. While progress has been made with the development of integration tools to the conceptual model in Leapfrog Energy, as discussed by O'Sullivan et. al. (2023, 2023a), we still see some technological limitations in this space. In applying the layer/fault method as volumes in Volsung, it enables greater flexibility in the generation of volumes from multiple data sources within Leapfrog Energy compared to the existing workflow of grid generation within it. It still allows collaboration between teams while allowing individuals to work in the 3D space appropriate to the model type they are working in. For the conceptual model, this is a grid-less environment and a gridded environment for the numerical model.

The categorisation of rock parameters for the numerical model are designed to represent volumes of different permeable zones. This is catered for in the workflow by allowing complex volumes to be built in Leapfrog Energy. It is restrictive in the conversion of surface data such as faults onto the grid. The current capabilities allow for one additional rock type per surface in the numerical model. Realistically, in a structure such as a fault a variety of permeable zones will be present based on the lithology units.

This can be accounted for by setting up the volumes in Leapfrog Energy prior to export, however understanding of the grid dimensions of the numerical model are required to implement successfully.

3.1 Future Work

The approach described in this paper is based on what might be called a rock-type approach, whereby a lithological unit or fault is initially assumed to have uniform properties, and this is updated to add heterogeneity as the numerical model is calibrated to match measured field data. An alternative approach is what might be called the spatially interpolated approach, whereby rock properties are prescribed at certain locations in space, and these are interpolated and extrapolated to assign properties across the model extent. This approach is currently supported in Leapfrog Energy using geostatistical methods and can result in rock properties populated onto a block model. In Volsung, this approach is supported by the functionality to set rock properties in a table specifying spatial coordinates and parameter values. Future work will refine this approach into a practical workflow.

The existing workflow requires the transfer of data and models by exporting and importing files. This work could be extended to take advantage of a cloud based ecosystem approach where desktop or cloud applications can publish to and consume from other applications in the workflow via a standardised object service. This will provide a number of benefits including audit trails, rich metadata including creation and update dates, coordinate reference system definitions for correct geo-location, versioning and notifications of updates to linked data and models.

4. CONCLUSION

This paper highlights a workflow for quickly transferring model outputs from Leapfrog Energy into Volsung to fast-track the development of the numerical reservoir model and ensure that it is based closely on sound geoscience. Improved interaction between industry standard tools reduces model development time and enables for more auditability around how models are built, managed, and run.

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