Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Updates To The Volsung Geothermal Simulator

Jonathon Clearwater* and Peter Franz
Seequent, 20 Moorhouse Avenue, Addington, Christchurch 8011, NEW ZEALAND
jonathon.clearwater@seequent.com

Keywords: Volsung, Simulation, Modelling

ABSTRACT

This paper describes updates to the geothermal reservoir modelling software package Volsung that were completed between 2021 and 2026. At the 2021 World Geothermal Congress, Volsung was presented as a new, commercially-available simulation package that consisted of a reservoir simulator, a wellbore model, surface network model and a graphical user interface. Between 2021 and 2026 the user-base of Volsung grew steadily and features and updates were made to the software to address user demand. This included: inverse modelling and Monte Carlo forecasting; improved pipeline and power plants models; calculation of subsidence and microgravity changes; improved numerical methods; integration with Leapfrog geological model; support for corner point grids and distributed properties modelling; new equations of state for modelling carbon storage and groundwater; capability for modelling pumped wells and closed loop geothermal systems and a particle tracking module for tracer modelling. These updates are described with commentary on implementation challenges, validation methods and user applications.

1 INTRODUCTION

Volsung is an integrated simulation platform designed for the geothermal industry (Franz et al., 2019). At the time of the 2021 World Geothermal Congress the core functionality of the package had been developed. This included a reservoir model that simulates multi-phase, multi-component flow of heat and mass through porous and fractured media, a wellbore model to account for the flow of fluid from reservoir feed zones to wellhead, and a basic surface network simulator (Franz and Clearwater, 2021a). In 2021 Volsung had been utilized on a few real-world geothermal modelling cases, such as a transfer of the Tiwi TOUGH2 reservoir model into Volsung and several consulting projects in the Asia-Pacific region (Clearwater and Franz (2019), Cinco et al. (2020)). Between 2021 and 2026 the user-base of Volsung grew steadily and it now has widespread use amongst operating companies, consultancies and research organizations (E.g. Bravo et al. (2025), Clearwater et al. (2024), Dhakal et al. (2025), Kutun et al. (2024), Murphy et al. (2025)). With the growing user base came a growing list of feature requests, and in this paper we describe updates made to the software to address user demand.

2 UPDATES

2.1 New Physics: Equations of State for CO2 Storage and Isothermal Groundwater

New equations of state (EOS) were implemented to meet specific requirements for CO2 capture and storage (CCS), and for groundwater modelling. Both EOS fit well into the Volsung framework, i.e. thermodynamic properties are available using different thermodynamic setter types, they can be used in wellbore and surface network models, and multiple mass component tracers are available (for both H2O and CO2 components in case of the CCS EOS). As of March 2026, both the CCS and groundwater EOS are available as beta versions of Volsung.

The groundwater EOS is isothermal. Reference properties, such as liquid density, compressibility and viscosity, are specified at a fixed reference pressure and temperature. The EOS also models a gas phase for pressures below the reference pressure. However, the gas phase is simply needed to balance the internal mass equations when unsaturated conditions are encountered. Because the system is isothermal the linear solver can work on a smaller matrix, and there's no coupling between mass and heat equations. This results in significantly reduced model run times for groundwater applications.

The EOS for CCS is based on the CO2/H2O/NaCl mixing model published by Spycher & Pruess (2010) and uses pure substance properties of CO2 from Span & Wagner (1996) and Laesecke & Muzny (2017). It is applicable to temperature ranges 10-300C, pressures up to 600bar, and zero NaCl concentration up to solid halite precipitation. It models aqueous (brine, i.e. H2O + CO2 + NaCl), gaseous (H2O + CO2) and solid (NaCl) phases over its entire range, and a liquid (CO2 + H2O) phase below the critical point of CO2. Thermodynamic table tools

were created so that thermodynamic states can be set using either temperature or enthalpy as primary variables; these additional tools allow Volsung to use this EOS in its wellbore simulator and surface network, enabling more complex injection scenarios to be modelled.

When using the CCS EOS the reservoir simulator resembles an amalgamation of TOUGH's ECO2M (Pruess, 2011) and ECO2N-V2 (Pan et al, 2015) modules. Comparison of test cases with these two TOUGH EOS proved somewhat challenging. Models above the critical point of CO2 showed excellent agreement between Volsung and TOUGH when using ECO2N-V2. Below the critical point only the older ECO2M module could be used for comparison since ECO2N-V2 does not model both liquid and gaseous phases at the same time. However, ECO2M was built on earlier versions of the Spycher & Pruess mixing model, resulting in noticeable differences between Volsung and TOUGH, though the general behavior of the models is comparable. Since Volsung reproduces the published data of the Spycher & Pruess (2010) mixing model very well the differences between ECO2M and Volsung is attributed to the different mixing model versions used in these codes.

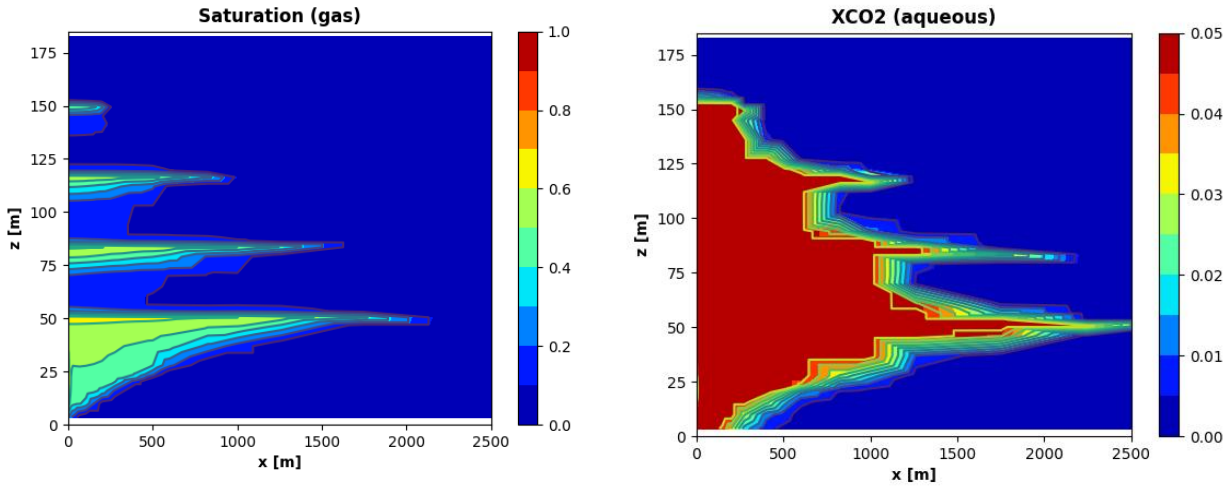


Figure 1: Comparison of the two-dimensional RTP7 example model from Pan et. al. (2015), between TOUGH (contour lines) and Volsung (filled areas). This example was based on conditions at the Sleipner CO2 storage project and was designed to investigate CO2 migration in a heterogeneous sand-shale sequence. The gas saturations in the model are nearly identical; small differences in XCO2 can be seen and are likely associated with small differences from the implementation of CO2 properties between the two simulators.

2.2 Updated to the Wellbore Model: Coaxial and Closed Loop Wells, Pumps

Changes to Volsung's wellbore simulator were made to change the internal coordinate system of wells from an elevation to a measured depth (MD) based system. This opened up the possibility to use the wellbore simulator outside of high-enthalpy geothermal systems by using different well geometries, like wells with horizontal sections, and coaxial flow paths.

The wellbore simulator can now also simulate closed loop (U-tube) style wells, where fluid injection from surface occurs at a different location from fluid production. Similarly, coaxial wells can now be modelled. Both U-tube and coaxial wells conserve the mass of the working fluid, which can be water or – when using the CCS EOS – carbon dioxide. Apart from this they work very similar to the classic geothermal wellbore models, where mass, energy and momentum are conserved through a set of ordinary differential equations.

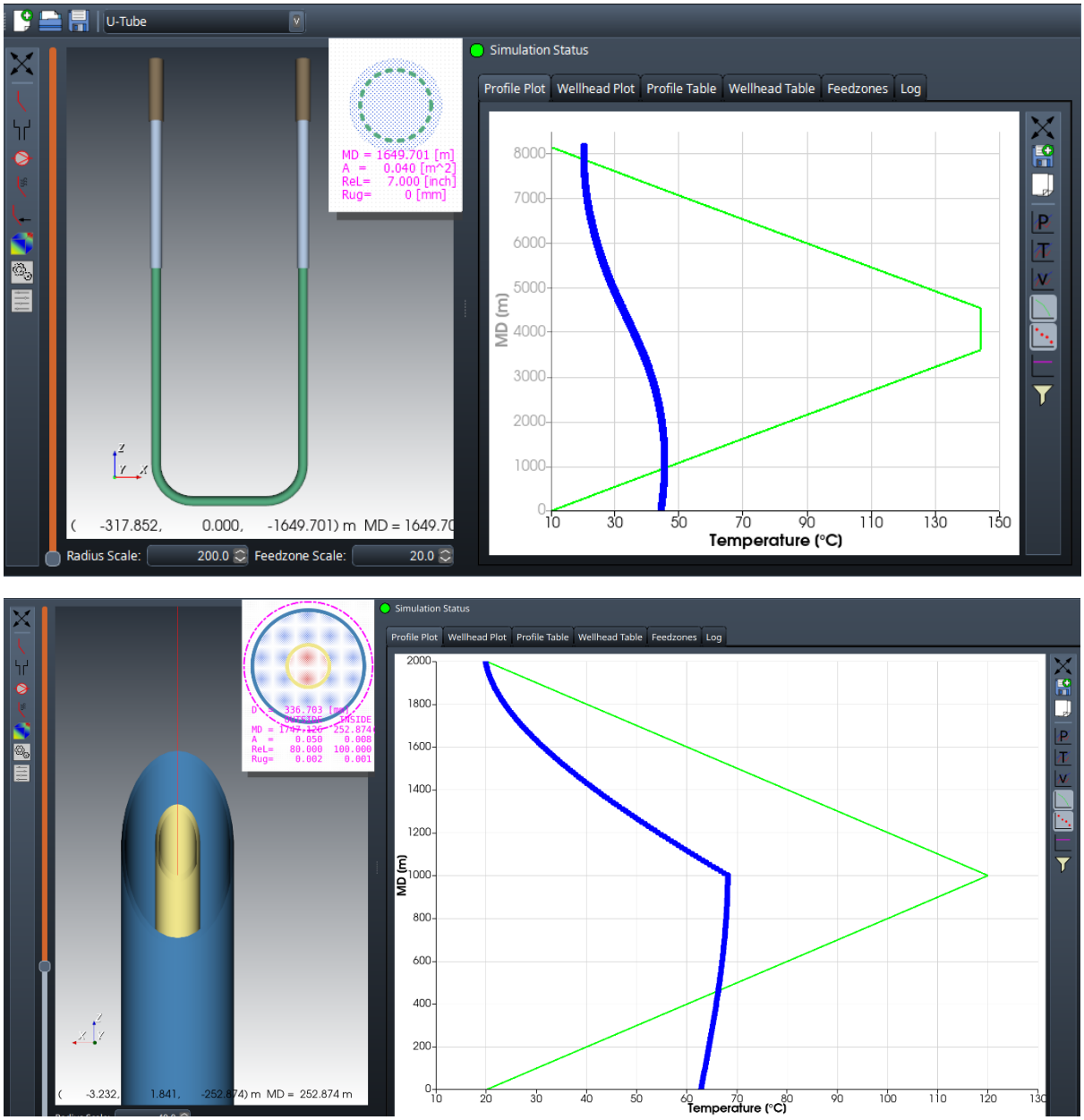


Figure 2. The top image shows a U-tube wellbore model simulation in Volsung using water as a working fluid. The left panel shows a 3D depiction of the well and the right hand panel shows the wellbore fluid temperature in blue and reservoir temperature in green. The bottom image shows a coaxial well in Volsung. The left hand panel shows a cross sectional cut through the well, with the blue outer and yellow inner casings shown. The right hand panel shows wellbore fluid temperature in blue and reservoir temperature in green. Note production from the well is at 0m MD for both the U-tube and coaxial well examples.

One distinction from the classic geothermal wells is the exchange of heat, both internally and externally. Internal heat transfer is a phenomenon in coaxial wells, where heat is exchanged between the downflow (in the outer annulus) and the upflow (in the inner pipe) by conduction. Volsung solves this problem iteratively, i.e. in the first downflow iteration no internal heat transfer takes place. Subsequent iterations can establish the temperature difference between inner and outer fluid and calculate the heat transfer accordingly.

Conductive external heat transfer between the wellbore and the formation, which usually plays a minor role in high-enthalpy geothermal wells, becomes a more critical process in U-tube and coaxial style wells for which the heat transfer is the primary process for generating energy. In pure conductive processes heat transfer between the well and formation decreases over time, as the formation outside the wellbore slowly transitions towards the internal temperature of the wellbore, hence decreasing the temperature gradient. Hasan & Kabir (1994, 2002) solved this problem using methods presented by Carslaw & Jaeger (1959) and gave approximations for the solution of the ‘dimensionless’ time and temperature problems which overcome the need to numerically solve complex integrals over Bessel functions.

However, the Hasan & Kabir (2002) approach assumes that the formation extends to infinity. In wellbore-reservoir coupled simulations the wells are embedded in grid blocks of finite size. Conceptually, heat should hence not be transported by the semi-analytical conductive method beyond its grid block dimension, since the reservoir simulator will take care of this process. In Volsung this is achieved by limiting the flowing time of the well to a maximum time. This maximum time corresponds to the time when the heat transfer using the infinite reservoir approximation equals the conductive heat transfer through a cylindrical conductor with a radius approximating the half-width of the grid block dimension. An approximation for this radius is found by considering a disc of the same area as the cross-sectional area of the grid block surrounding the well segment.

An additional new feature is the possibility to add pumps into the wellbore simulation. Pumps are defined as simple objects at a given location, with an interpolation table provided by the user to specify pump head and power consumption versus flow rate. When the simulator encounters a pump in the flow path it uses the current flow rate to determine the pressure gain and power consumed. This enables feasibility studies to determine the parasitic load of a pumped well versus its expected power/heat generation over its lifetime in coupled reservoir/wellbore models.

2.3 New Surface Network Objects: Smart Power Plants and Surface Network Optimization

The original surface network model presented at the 2021 World Geothermal Congress had the capability to model production wells, injection wells, separators, heat exchangers and simple power plants. The original power plant model was designed for modeling steam plants and was parameterized in terms of turbine efficiency. Users requested greater flexibility in modeling power generation, including modeling binary plants, direct use and plants based on steam usage rates. To address this request a universal generator surface network object was developed.

The universal generator has a flexible number of input and output ports. The flow properties on the output ports are calculated as functions of the conditions on the input ports using a function parser. As such, relatively complicated transfer functions can be defined to encapsulate the real-world performance of a variety of power generation technologies. Each input port contains an input stream that is defined by the primary thermodynamic variables pressure and enthalpy along with its mass rate and component mass fractions. Any thermodynamic property can be calculated by the use of steam tables in the equation builder. For example, the liquid phase density of the fluid on input port 0 would be accessed by the variable "rho_liquid_0". The performance of the power plant can model changes over time by using the time variable, which returns the current simulation time, and efficiency can be changed dependent on ambient temperature conditions by using the "T_amb" keyword. The Universal Generator is a convenient object to calculate power generation based on the thermodynamic properties of the incoming fluid and specify the properties of the fluid on the downstream side of the power plant. For example, the downstream mass rate could be set as a percentage of the incoming mass rate, and the downstream enthalpy and component mass fractions could be set to mimic the properties of real world reinjection fluid. Experience has proven the Universal Generator to be a useful object to model a variety of real world power plants.

The surface network is capable of modelling the flow of heat and mass through surface networks consisting of production wells, pipelines, separators, unions, power plants, splitters and injection wells. Production wells in the surface network can be operated at fixed mass rates, fixed wellhead pressures, or allowed to throttle with some constraints. Throttling production wells are controlled by smart objects in the surface network such as the Universal Generator, and their flow rates will be determined by the surface network optimizer. In general, the goal of the surface network optimizer is to enable the smart object to achieve its target, in the case of a Universal Generator this is usually a generation target in electrical power, and also ensuring that pressures are matched throughout the network and the mass and energy balance requirements are fulfilled.

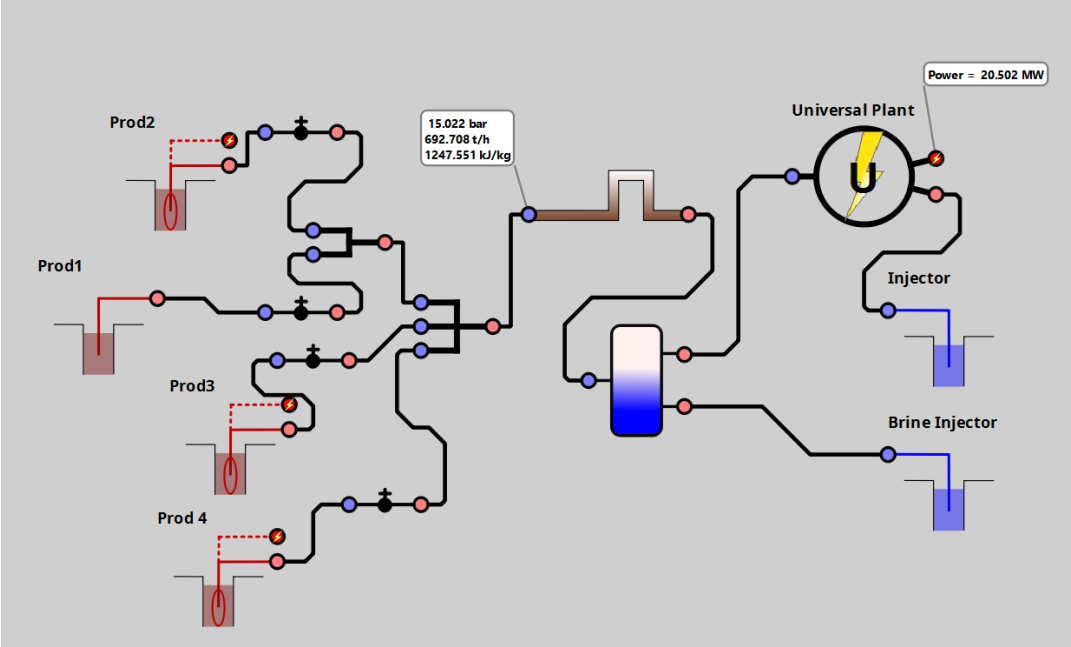


Figure 3. A simple surface network consisting of four production wells, a pipeline, separator, steam plant and two injection wells in Volsung.

In 2021 we described the basic operation of the surface network including the Temperature Parallel Simulated Annealing surface network optimizer (Franz er al. 2021). In this optimizer a simulated annealing algorithm is used to vary free parameters and optimize the objective function until its global optimum has been found. This optimizer performs well, especially when solving complex surface networks. However, in some cases, especially when the solution is not unique, we found that this optimizer could lead to non-smooth well behavior. Although mathematically correct, this behavior is not wanted for some scenarios. Accordingly we implemented an approach recommended to us by Dr Mauro Parini (pers. Coms) referred to as the Producers Common Scale Factor. This optimization algorithm is simpler than the previously described optimizers. It is tailored towards a widely used scenario in geothermal reservoir simulations where producing wells are set to a certain wellhead pressure. If the flow of these wells exceeds the demand of the plant then all wells are throttled back using a common scaling factor. On the other hand, if the flow at the given wellhead pressure can't meet the plant target then makeup wells are brought online. In this approach the pressures are not automatically matched throughout the network and it is up the user to specify sensible wellhead pressure constraints on individual production wells.

2.4 Dealing with Uncertainty: Inverse Modelling and Monte Carlo Forecasting

Uncertainty is at the core of geothermal reservoir simulation. It plays a key role in both model calibration and model forecasting. At the start of a modelling process the parameters that define the model, such as the distribution of rock permeability, are highly uncertain. The parameters are typically somewhat constrained by measurement and geologic plausibility and then further refined through model calibration. Unfortunately, the calibration process can be time consuming. The modeler needs to select a reasonable parameter set, prepare the model, run a simulation and then plot the appropriate outputs comparing model and measured calibration data. The parameters are then adjusted, the model rerun and updated outputs compared to see if the new parameter values improve the match to measured data. Normally this process is done manually, and can take a long time, depending on field complexity and the experience of the modeler. Inverse modelling provides a complimentary approach to calibrate models, whereby the modeler defines reasonable constraints on parameter sets and the process of model calibration is automated. To support this approach in Volsung we developed a coupling between Volsung and PEST (Doherty, 2010) as described in Franz et. al., 2021b. The use of PEST to automatically calibrate models is also employed in Swanhild, Volsung's numerical pressure transient analysis tool (McLean et. al., 2020).

During the model calibration process it is common for some parameters to be constrained by measured calibration data, while others will remain highly uncertain. For example, obtaining a model match to natural state temperature data may involve modifying the location, mass rate and enthalpy of hot upflows into the geothermal system and assigning appropriate permeabilities to model regions so that flow paths are developed that reproduce the measured temperature profiles. This constrains the range of possible upflow and permeability

parameter values. However, some parameters may not be constrained at all by the calibration process. A typical example is fracture spacing when only natural state calibration is performed. Fracture spacing has a strong influence on the interaction between low permeability matrix rock and high permeability fractures. As such, fracture spacing can have a large influence on predictions of thermal drawdown. However, fractures and matrix are usually in thermal equilibrium in natural state conditions, so calibration to natural state temperature provides no constraint at all on possible reservoir fracture spacing values. It's also possible to identify the parameters that are unconstrained by the calibration using parameter sensitivity analysis during the inverse modelling calibration process. In either case, it is helpful to obtain an understanding of how much these unconstrained parameters can influence model results. A useful approach to doing this is by applying Monte Carlo methods. Essentially, the modeler specifies a probability distribution for uncertain parameters, and then the model is run numerous times, with particular parameter values for each deterministic run sampled from the assigned probability distribution. Specified outputs from each model run are collated and analyzed to determine the spread in possible outputs. A simple, but useful, analysis is simply reporting the P10, P50 and P90 values to indicate the uncertainty in model predictions.

To support Monte Carlo analysis in Volsung we developed the Modor application. Modor allows users to specify normal, uniform, triangular and sine distributions to specify the distribution of uncertain input parameters in a base model. These uncertain parameters are sampled in Modor using the Latin-Hypercube algorithm. The run control is handled by Modor with the option to run simulations in serial or parallel. Simulations can be run on a local computer or remote servers. The outputs of interest are specified in Modor and these are stored locally once the simulations runs have been completed. Currently Modor can plot time series outputs with min, max and P10, P50, P90 outputs, and future work is planned to extend this with tornado plots to analyze parameter sensitivity.

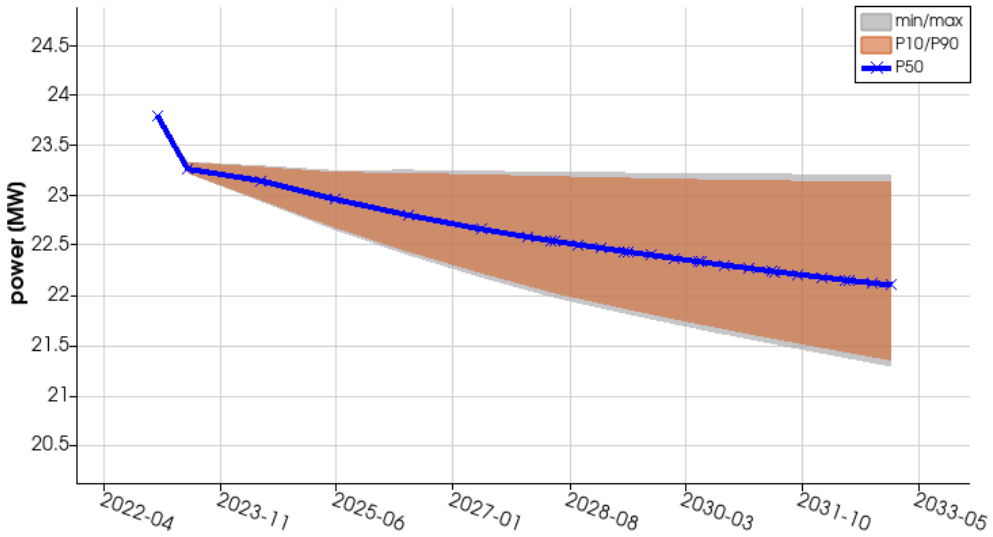


Figure 4. An example output from Volsung using Monte Carlo forecasting showing the uncertainty in forecasted future power generation based on the uncertainty in input variables.

2.5 Microgravity, Subsidence, and Fluid Level

Apart from performing the key calculations necessary to simulate the flow of fluid and heat in the reservoir Volsung can execute further computation intensive routines to generate additional data. These extra modules collate data during the simulation and perform their calculations. However, the general concept is that the simulator does not utilize output from these modules in its further calculations.

Some of the more interesting extra modules are those to calculate changes in microgravity, subsidence and fluid level. Output from their simulation data can be directly compared to field surveys and hence give additional calibration options for reservoir models.

The aforementioned modules have in common that they use data from the 3D reservoir to calculate 2D maps. To boost performance, Volsung first computes geometrical factors or auxiliary functions so that later changes in the observations can be easily tied to changes in density, temperature, pressure, gas saturation etc. Then,

whenever output of data is required, these geometrical factors can be utilized to quickly compute the results without having to analyze the system again.

Microgravity calculates geometric factors between each survey station and each grid block, i.e. an MxN problem. Each grid block is treated as a polyhedral cell of arbitrary shape, and the exact method by Singh & Guptasarma (2001) is used for the calculation of the auxiliary factors. The gravity at a station is then simply the sum over the products between the geometric factor of a grid block and the block's average density. The results can be expressed as delta-values using a particular simulation time as offset, plotted as a color map in 2D, and compared to field data in various forms. Simple models, like the gravity inside/outside a solid sphere and a cube, were used for validating the method.

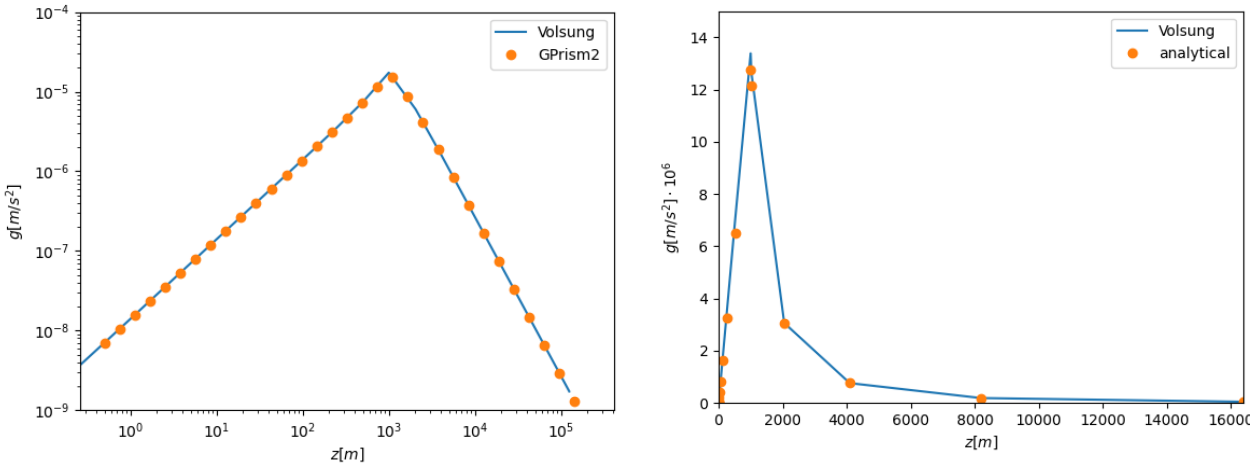


Figure 5: Validation of microgravity. (LEFT) Comparison of gravity both inside and outside of a 1000m cube against the GPrism2 (external code previously used in Tiwi model) function. (RIGHT) Similarly, gravity calculated and compared to analytical solution for a 1000m sphere.

Subsidence is calculated using the 'buried disc' method described by Geertsma (1973), extended to account for thermal expansion and the Multiple INteracting Continua (MINC) method Volsung employs to model flow in fractured media. Here a disc deep within a reservoir changes its volume due to thermal expansion and/or compression due to change in pressure. To be clear, the actual geometric deformation of the grid block is not calculated and would require coupling to a geomechanics simulator. The change in volume of the disc is propagated through the reservoir, treating the non-affected formation outside the disc as incompressible. Analysis of this problem revealed that it follows the same general problem as encountered for gravity, i.e. it has a 1/r^2 dependency when considering a buried sphere instead. The mathematical framework for microgravity hence was re-used for this problem in an adapted form. Validation was performed using a model consisting of a very thin buried disc and comparing the results to the example values published by Geertsma (1973), which yielded excellent reproducibility of their data.

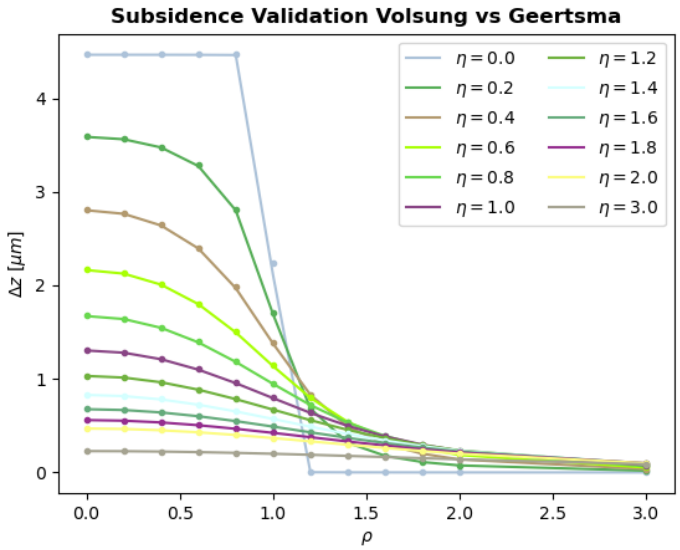


Figure 6: Validation of buried disc subsidence using values from table 1 in Geertsma (1973). Lines are results from Volsung, points are tabled values.

The fluid level module calculates the elevation of the gas phase interface in the model and it can be used as to track the modelled water table over time. For each grid block a set of auxiliary functions is calculated by geometric analysis. These auxiliary functions yield the relationship between fluid level and occupied gas volume in the block, assuming the gas phase resides in the top of the block. A 2D map can be created by casting vertical rays through the reservoir; the fluid level is established from the fluid level in the blocks hit by the rays. Note that this method may fail if the solution is not unique, for example when a bubble forms in the reservoir.

2.6 New Geology Models: Integration with Leapfrog, Distributed Properties Modelling, Corner Point Grid Geometry

A key aspect of developing a reservoir simulation model is the distribution of rock properties to regions of space. In 2021, the workflow implemented in Volsung enabled the user to define 3D surfaces using points. These points could be added in table format, or interactively in the 3D GUI, and then converted into a surface such as a polygon or using a Delaunay triangulation. Many geothermal fields have a conceptual model developed in Leapfrog Energy, and users requested a convenient workflow to develop a reservoir simulation model based on the conceptual information in Leapfrog. In 2023 we developed a workflow to support this using the Leapfrog LFM file, a file that contains the zipped binary data describing the surface triangles of enclosed volumes (Baxter et al., 2023). In developing this workflow we updated the layer/fault method in Volsung to work with volumes and enabled the direct import of volumes from Leapfrog LFM files. In 2024 this workflow was extended to allow the Leapfrog volumes to be down-sampled and edited in Volsung, making it possible for the user to take a geospatial volume developed in Leapfrog and import and edit it within Volsung.

Historically, most geothermal models have been developed with rock-type based philosophy. That is, a spatial area is defined as being a particular rock-type, and that rock-type is associated with a set of rock properties such as permeability, porosity and thermal conductivity. However, in the real world lithological units vary in their characteristics over space. In a rock-type based approach this heterogeneity is dealt with by subdividing a particular unit into sub-units based on well data, fault interactions or model calibration. In complex reservoirs this can lead to a very large number of rock-types, which can be unwieldy. An alternative approach is to move away from the rock-type based approach and just assign the rock characteristics to individual grid blocks. To support this approach in Volsung we implemented a spatially interpolated geology model, where users need to enter a table of x,y,z spot points along with the rock characteristics at that point. The system then interpolates the data from these points to assign rock properties to individual grid blocks.

Corner point, or pillar, grids are widely used in oil and gas modelling workflows. These grids consist of hexahedron cells with corner points located on a set of straight line pillars. As the use of Volsung grew outside of traditional geothermal models we received requests to add support for corner point grids. Volsung can now import corner point grid geometry in GRDECL format. To further support migration of models, the porosity and permeability data can also be imported into Volsung.

2.7 Particle Tracking Module for Tracer Modelling

The traditional approach to modelling tracers in geothermal reservoir simulation is to treat the tracer as an additional mass component in the finite volume method. This approach has shortcomings due to the discretized nature of reservoir models and the additional time required to run multi-component models. Reservoir models often use grid blocks with greater than 100 m scale grid blocks and, when modelling tracers as additional mass components, numerical dispersion can strongly influence tracer simulation results. Numerical dispersion tends to smear out the tracer return, but this dispersion will be dependent on grid block size. This is a numerical effect and not the same as actual hydrodynamic dispersion. Furthermore, modelling tracers as an additional mass component requires careful management of initial conditions and can significantly increase simulation run times. Accordingly, we implemented an alternative approach referred to as particle tracking. In this method the tracer is modelled as an ensemble of virtual tracer particles which move through the reservoir along the velocity field established by the reservoir simulator. This allows the tracer to move as a sharply defined front, with the return curve shape reflecting different pathways through the reservoir and their relative importance. Development and testing of the particle tracking method is described in detail in Franz et al. (2025). Particle tracking is a relatively novel approach for modelling tracers in the geothermal industry, and it has not yet achieved widespread use. The method has been applied on several operational geothermal fields, often in conjunction with the additional component method so the results of the different methods can be compared. Feedback received so far on this method has been positive in terms of ease of use, implementation time and ability to visualize flowpaths. Questions have arisen about the different first arrival times predicted by the particle tracking method and finite volume method, indicating a requirement for more education around the role of numerical dispersion and the requirement to add explicit modelling of hydrodynamic dispersion to the particle tracking method.

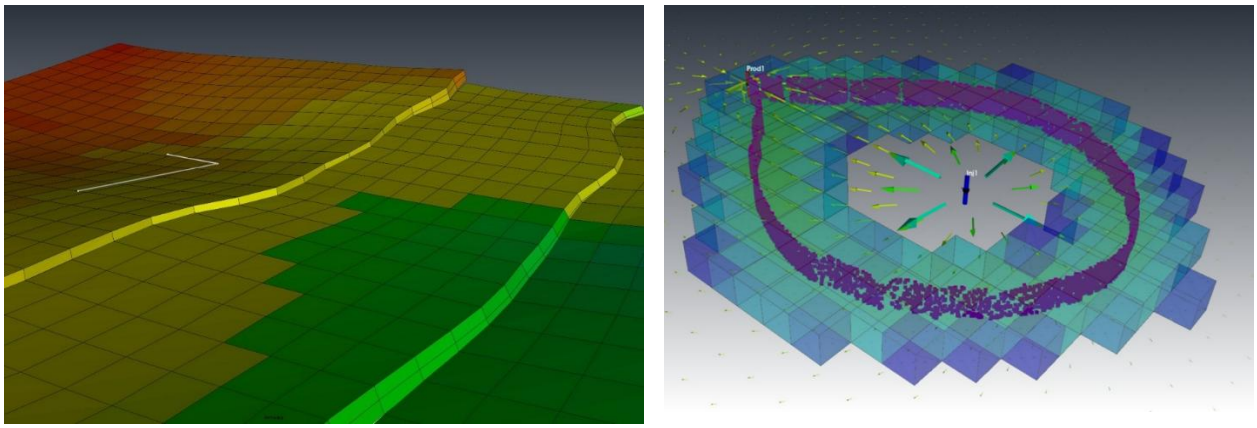


Figure 7. The left hand image shows a corner point grid imported in Volsung. The right hand image shows outputs from a Volsung model in which tracer injection into Inj1 was simulated using both tracer particles and as an additional component in the finite volume method. Grid blocks are colored by tracer concentration, and grid blocks with negligible levels of tracer are not shown. Note the spread of the component tracer versus the sharp front defined by the particle tracer method.

3 CONCLUSION

In this paper we have summarized the key updates to Volsung that were completed between 2021 and 2026. These updates were made in response to user requests and reflect the broadening out of the software package to enable advanced simulation techniques and support a wider range of fluid types and geothermal technologies.

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