Concept of an Integrated Workflow for Geothermal Exploration in Hot Sedimentary Aquifers

J. Florian Wellmann, Franklin G. Horowitz, Klaus Regenauer-Lieb
Western Australian Geothermal Centre of Excellence, UWA-CSIRO-CURTIN
ARRC 29, Dick Perry Avenue 6165 Kensington
wellmann@cyllene.uwa.edu.au

Geothermal exploration is currently performed in different steps and on different scales, from the initial, large-scale resource estimation going down to local reservoir sustainability analysis for a specific application. With this approach, it is not possible to explore directly for requirements dictated by a geothermal application.

If we, for example, consider the exploration for a direct heat-use application we could require a pumping rate of 100 l/s at a minimum temperature of 70°C. Economic constraints could be a maximum drilling depth and the minimum years lifetime of the system. The direct map-based exploration for the best locations considering these constraints is not possible with the standard workflow.

We present here an approach to overcome this limitation. We combine geological modelling, geothermal simulation and reservoir estimation into one consistent location-based method. Outcomes of this integrated workflow are map-based reservoir and resource analyses that can directly be used as guidance in the exploration for the best possible location of a geothermal application. Our workflow is specifically developed for applications in hot sedimentary aquifers but can be extended to other geothermal settings.

Keywords: Geological Modelling, Geothermal Simulation, Direct Heat Use, Integrated Workflow, Hot Sedimentary Aquifers

Geothermal Exploration

Geothermal exploration for hot sedimentary aquifers usually consists of the following steps (not necessarily in this order):

- Geological Modelling for a resource area
- Resource Base Estimation in a large-scale target area (accessible and useful resources)
- Market analysis and other local considerations (e.g. power lines, infrastructure)
- Above-ground installation and technical application (direct heat use, power generation)
- Detailed resource analysis in a smaller scale (economic resources for a specific application)
- Local reservoir exploration and sustainability analysis
- Financial modelling

Depending on the reservoir type, further analyses are necessary (e.g. stress-field, permeability optimisation, etc.). The single parts of this workflow are usually performed separately and in a sequential order. Our method combines the steps from geological modelling to sustainability analysis which are briefly described below.

Geological Modelling

A structural geological 3-D model is an important basis for geothermal exploration. It allows the visualisation of geological structures in the subsurface and can directly be used to identify relevant areas (e.g. from fault structures, etc.). Also, a 3-D geological model is the basis for other types of analyses, like the geothermal simulation.

A large variety of tools exist to construct geological models, ranging from map-based interpolation of structures (2.5-D methods, e.g. depth to basement maps interpolated from drillhole data) to full 3-D geological modelling that can consider complicated structures like reverse faulting or doming structures (Turner, 2006).

Geothermal Simulation

Numerical geothermal simulation is the next important step in the exploration. Based on physical constraints and subsurface data, a model of the temperature distribution below ground is simulated. This is the basis for the geothermal resource estimation and allows first estimates of drilling depth to a desired temperature.

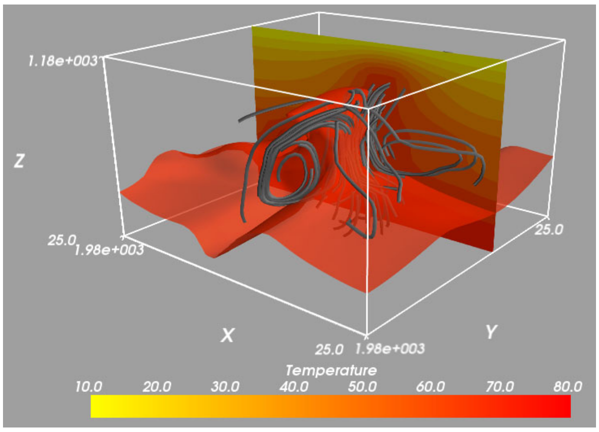

Figure 1: Example of a simulated fluid and heat flow field. The section shows a contour map of temperatures, the plane is a temperature isosurface, and streamlines (gray) indicate fluid flow paths.

Similar to geological modelling, a variety of different methods and codes are available for geothermal simulation. Main differences are the complexity of the simulation, i.e. from simple heat conduction simulation to coupled simulation of fluid and heat to complex multi-phase flow and reactive transport. (Kohl et al., 2007). The application of a code strongly depends on the geothermal reservoir type. In the case of hot sedimentary aquifers, fluid flow has to be considered as a heat transport mechanism and a suitable code should be used.

Geothermal Resource Base Estimation

Standard methods for the quality estimation of a geothermal resource are based on Muffler and Cataldi (1978). They describe several different approaches, most widely known is the volume method, often referred to as "heat-in-place". The total thermal energy contained in a volume V of rock is estimated based on specific heat of rock c_r and fluid c_w, porosity ϕ, density ρ and a temperature difference ΔT:

$$H_{ip} = \left[(1-\phi)c_r\rho_r + \phi c_w\rho_w\right]\cdot V\Delta T$$

The calculation of heat-in-place is usually performed for an estimated total volume, mean temperature and porosity of a resource rock.

Other estimations are possible and depend on the geological situation and geothermal resource type.

The evaluated resource base has to be further subdivided (Fig. 2) into accessible heat, usually defined by the maximum depth of drilling (this is what is usually considered in a standard "heat-in-place" analysis). But not all heat from the accessible heat is actually useful, based on physical limitations, reservoir lifetime and legal and environmental considerations. Finally, only a fraction of the useful heat can be considered as economic, which Muffler and Cataldi (1978) define as the geothermal energy that can be extracted in the lifetime of a reservoir at costs comparable to other energy sources.

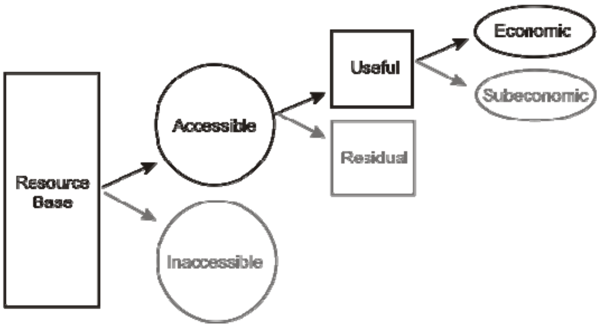

Figure 2: From the broad geothermal resource base to estimation of the economically useable resource (redrawn from Muffler and Cataldi, 1978).

Estimation of Extractable Energy

The amount of extractable heat depends on many geological, physical and technical factors. These are usually combined into a general "recovery factor" as a broad estimation.

For a hot sedimentary aquifer, Gringarten (1978) defines a heat recovery factor, R_g, as a the ratio of extracted heat, $Q_{\max}\Delta t\rho_w c_w\Delta T$, to the total theoretically recoverable heat-in-place as given above. Here Δt is the producing time, the quantity $Q_{\max}$ is the maximum production flow rate that can be maintained either indefinitely (for a truly sustainable system) or over the assumed economic lifetime of the geothermal system and $\rho_w c_w$ is the volumetric heat capacity of water. Writing

$$R_g = \frac{1}{\phi + (1-\phi)(\rho_r c_r / \rho_w c_w)} \frac{Q_{\max}\Delta t}{V}$$

we find the heat recovery factor is dominated by $Q_{\max}\Delta t$ for a porosity of ϕ: the recovery factor is a function of time. The maximum sustainable pumping rate $Q_{\max}$ for a doublet well (pumping and re-injection) over a production time Δt can be analytically estimated from heat and flow equations. Gringarten (1978) presents an analytical approximation and derives the following relationships for the pumping rate Q:

$$Q = \frac{\pi\rho_a c_a}{3\rho_w c_w}\frac{h}{\Delta t}D^2$$

and

$$Q = 2\pi\frac{1}{\ln(D/r_w)}Ts$$

The first equation describes the pumping rate as a function of production time, thickness *h* of the aquifer and distance *D* between pumping and re-injection well. The second equation includes the maximum drawdown *s*, the well diameter r_w and transmissivity *T*. Temperature is implicit in these equations as density of water and transmissivity are a function of temperature.

The combined solution of these equations provides an estimate of the maximum pumping rate $Q_{\max}$ and the minimal distance *D* required between the pumping and re-injection well in the aquifer to avoid a thermal breakthrough during the production lifetime of the doublet.

The result can be considered a very conservative estimate as an application may still be possible after thermal breakthrough for some time. Also, as soon as a natural hydraulic gradient is present, a layout of the re-injection well downstream from the pumping well will increase the lifetime even more (Banks, 2009).

Limitations of the standard approaches

The presented standard methods to evaluate a geothermal resource and its sustainable application are performed on two different scales. Whereas the heat-in-place estimation is performed for a whole resource, the estimates for a sustainable pumping rate are performed on the local scale. It is not possible to derive a location-based analysis of heat in the subsurface (i.e. how is the total heat-in-place distributed in space) or to analyse a whole area for a required pumping rate (i.e. where can a certain pumping rate be obtained for a minimum time). Thus, the combined analysis of both factors is not possible for a whole resource region.

To overcome this limitation, we present an approach to down-scale the heat-in-place estimation for a regional analysis and to extend the Gringarten estimations to a whole area, all within the context of geological modelling and geothermal simulation.

Integrated Geothermal Exploration

Concept of workflow

In our workflow (Fig. 3), we combine the steps from geological modelling to resource and sustainability estimations.

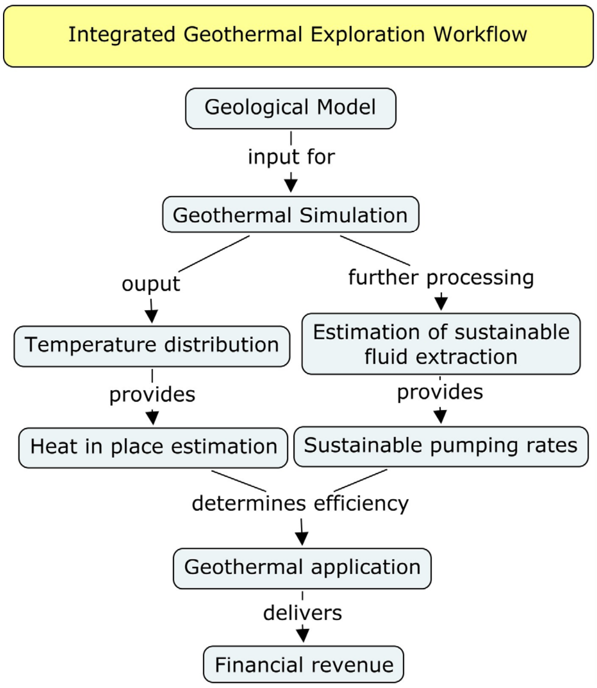

Figure 3: workflow of our approach from geological model to efficiency estimation of geothermal application

The starting point for our workflow is a full 3-D geological model. We use GeoModeller (www.geomodeller.com) for the modelling as it is capable of dealing with complicated 3-D geological settings and provides a very fast and efficient way to create realistic geological models directly based on input data (e.g. Calcagno, 2008). It is thus possible to quickly test several geological scenarios as the starting point for the geothermal simulation.

We link the geological model directly to a geothermal simulation code. The simulation is performed with a fully coupled fluid, heat and reactive transport simulation code (SHEMAT). All relevant physical properties are calculated as a function of temperature in each time step. It is also possible to include anisotropies in thermal conductivity and permeability (see Clauser, 2003 for a detailed description). The simulation code is thus capable of dealing with complex settings (from hot dry rock to hydrothermal) and has been applied to many geothermal simulations (e.g. Soultz-sous-Foret (France), Waiwera (New Zealand)).

Now, we process the results of the geothermal simulation further for two analyses: (1) the distribution of heat in the subsurface and (2) estimation of the sustainable pumping rates. The main difference to the standard approaches is that we create a map view of the distribution of both properties in the whole resource area.

The simulated temperature and fluid flow field and the distribution of physical properties in 3-D are then processed further with a set of programs to derive several characteristic parameters (e.g. transmissivity, mean water density, mean temperature of one formation at depth). Essentially, we analyse the physical properties in the subsurface at every location in space. This is then used as an input for the extended volumetric heat-in-place calculation (following Muffler and Cataldi, 1978) and the well doublet spacing and maximum pumping rate analysis from Gringarten (1978) and Banks (2009), as described above.

The distribution of temperatures, local heat-in-place and the evaluation of sustainable pumping rates in the resource area now directly allows the exploration for a suitable area given the characteristics of a geothermal application. For example, we can now identify areas in the map where we can achieve the required pumping rate for a given minimum temperature and available heat which, in the end, determines the economics of a geothermal application.

Example Model

We apply our workflow for geothermal resource estimation to a full 3-D geological model to local heat-in-place and sustainable pumping rate evaluation. The model is situated in a half-graben setting (Fig. 4). A large normal fault in the east off-sets the basement creating a basin. This basin is filled with several sedimentary formations that are furthermore displaced by normal faults, leading to an internal graben structure. The scale of the model is 8 km x 8 km x 5 km.

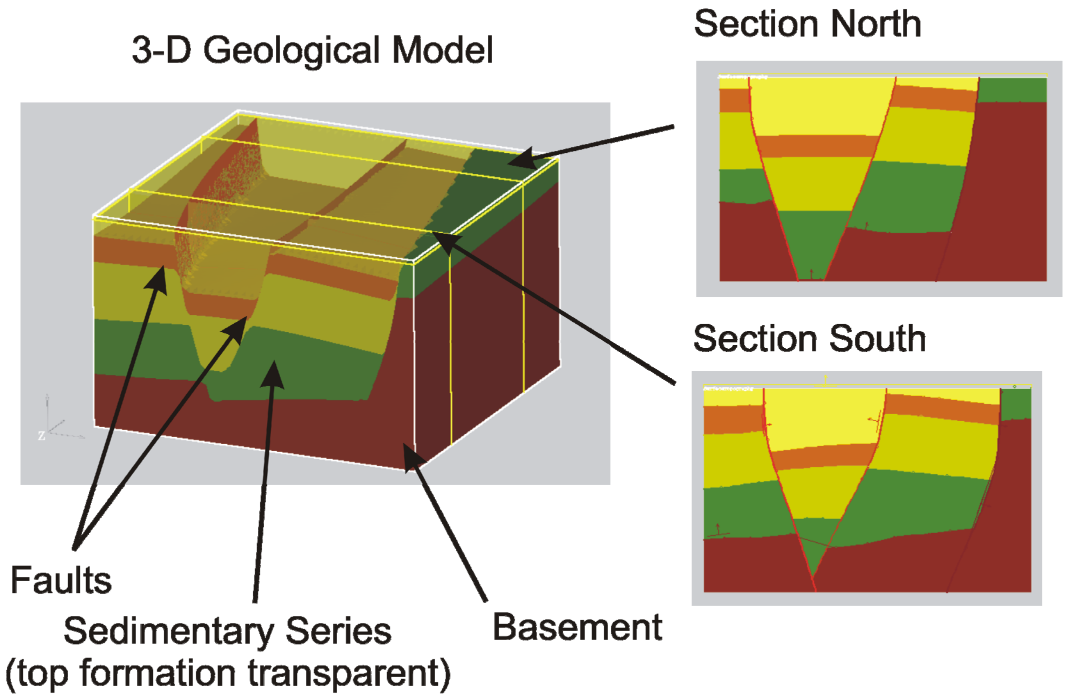

Figure 4: Simple geological model used for the application of the workflow. The structural setting is a half-graben structure; the basin is filled with sedimentary formations that are further cut by faults.

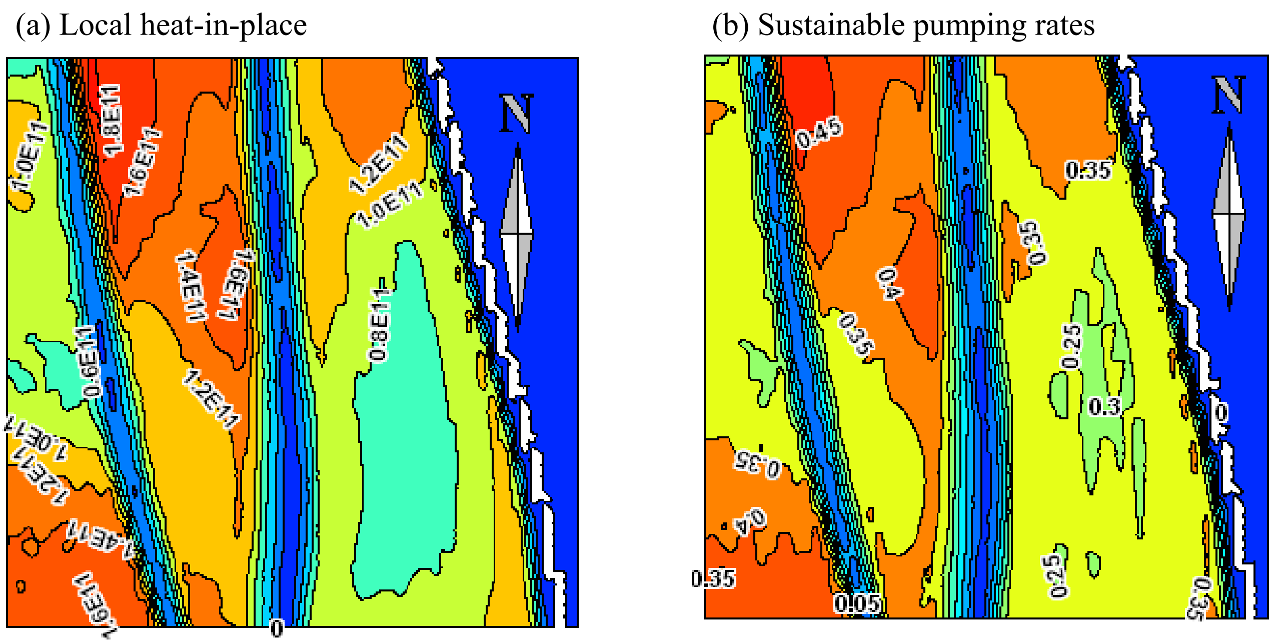

Figure 5: Selected results of our workflow. Analyses are performed for the second lowest sedimentary formation (light green in Fig. 4).

(a) local heat-in-place, normalised to m^2. (b) Sustainable pumping rates [m^3/s] for a production period of 30 years. We can clearly identify the most promising areas.

This structural set-up happens to be similar to areas in the Perth Basin and representative of geological settings in other sedimentary basins. Values for thermal conductivity and hydraulic properties are also similar to formations in the Perth Basin.

Results

The maps in Figure 5 show the most important results of our integrated workflow, i.e. the local heat-in-place and the maximum pumping rate for one formation. These maps are created in a GIS framework and can directly be used for a location-based analysis. We obtain the local heat-in-place in addition to the total heat-in-place which is usually estimated (it would be approximately 5.2E18 J in this example).

The map dimensions are the same as for the model (8 x 8 km). Displayed is the analysis for the second lowest sedimentary formation (light green in Fig. 4). We can see that most of the heat in place (Fig. 5a) is located within the Northern part of the graben. In the same area, we can obtain the highest sustainable pumping rates (here determined for a total lifetime of 30 years). The patterns coincide in this case as we are considering a simple structure with homogeneous permeabilities and thus pumping rates are strongly related to temperature (which is, in this simple case, also reflected by the local heat-in-place pattern). In other cases (e.g. in lower permeability settings like Enhanced Geothermal Systems), we might obtain a completely different picture for local heat-in-place and sustainable pumping rates.

Discussion

We presented an integrated geothermal resource evaluation workflow that combines and extends classical methods. Starting from a full 3-D geological model and relevant physical properties, we simulate the temperature and fluid flow fields and use these as a basis for a variety of estimations. Firstly, we calculate the overall heat-in-place, as defined in Muffler and Cataldi (1978). We extend this classical method to a location-based analysis to identify directly the position of a valuable resource. We also use the results of the simulation for an estimation of a well doublet scheme and sustainable pumping rates, after Gringarten (1978) and Banks (2009) and extend it to a resource-wide estimation. The main benefit of our workflow is that it directly combines these standard methods for a location-based geothermal resource and sustainability analysis.

As the results from our integrated workflow are location-/map-based, it is possible to combine them with other relevant location factors. We can, for example, combine our analyses with a map of the depth of a formation and a maximum drilling depth. Other map-based economic constraints can directly be implemented, e.g. the distance to the market or available infrastructure. Our workflow thus opens up the way to an integration of geological, geothermal, technical and financial considerations within one combined framework.

Furthermore, our workflow can be extended to scenario testing. All the single steps in the workflow are linked. It is thus possible to directly test the effect of a change in the geological model or the physical properties on the estimation of the sustainable pumping rate. This is not possible with common standard approaches.

The results of our simple example model (Fig. 5) are based on several assumptions and simplifications (see Gringarten, 1978, and Muffler and Cataldi, 1978, for a detailed description of their assumptions). The calculated estimations have to be considered in the light of these assumptions. Still, in a recent review of these methods, Banks (2009) points out that they are applicable in many cases and provide a rather conservative estimate. We interpret the numbers as a guideline but the distribution in space as very valuable information as this directly points out the location of a probable geothermal resource.

Our approach is flexible and can be applied in simple and complex settings. The geological modelling is capable of dealing with complicated geological settings, like reverse faulting or overturned folding and doming structures (e.g. Calcagno, 2008). The geothermal simulation can be extended to include reactive transport and species transport (Clauser, 2003). Furthermore, the applied simulation code can also model pumping and re-injection. This will be implemented in the future into our workflow. It will thus be possible to directly validate the effect of long-term pumping in the fluid and heat flow field in complex geological settings in an identified target area.

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