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HOT SEDIMENTARY AQUIFER CHARACTERIZATION USING STRATIGRAPHIC FORWARD MODELLING, PERTH BASIN, AUSTRALIA

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ABSTRACT

Several geothermal projects in the Perth Metropolitan Area, Western Australia, have already demonstrated the geothermal potential of the area for aquifers down to 1 km depth. The Western Australian Geothermal Centre of Excellence (WAGCoE) was tasked with assessing the potential of deeper aquifers. Members of WAGCoE, in collaboration with CSIRO, investigated the use of stratigraphic forward modelling (SFM) techniques combined with geothermal reservoir definition to identify potential geothermal reservoirs in locations where data are sparse.

The major aquifer and low-temperature geothermal target in the Perth Basin, the Yarragadee Aquifer, provides a major portion of Perth's drinking water. Although the shallow part of the Yarragadee Aquifer has been well studied by hydrogeologists, the deeper part is still poorly characterized. Using the stratigraphic forward modelling package Sedsim, the sedimentation of the Yarragadee Formation was simulated over a period of 15.8 Ma. The simulation was calibrated against sparse seismic surveys, petroleum wells and core data. The final simulation volume was uplifted and eroded to the current state of the Yarragadee Formation, providing estimates of facies, grain size and porosity distributions for the entire formation.

Once the characterization of the Yarragadee Formation was achieved, the identification of geothermal reservoirs required investigating the suitability of the subsurface to deliver the energy required for a given geothermal application. Based on simple assumptions such as constant thermal conductivity, uniform geothermal gradient, and using pre-defined geothermal production design settings such as flow rate and maximum pressure drop, parameters such as the reservoir temperature and the reservoir producible power are evaluated. As different geothermal applications have different subsurface requirements, reservoirs are individually investigated for a specific geothermal applications. This methodology has been developed to allow rapid investigation of the local geothermal potential while changing the surface geothermal application requirements.

INTRODUCTION

Most sedimentary basins in Australia have been explored for petroleum prospectivity at some stage. Although geothermal and petroleum exploration differ in the resource they are looking for – high-temperature water versus hydrocarbons, most data collected for petroleum exploration can and have been used for geothermal exploration (Deming 1989). However, as opposed to petroleum fields, viable geothermal fields need to be close to consumers, especially for direct use applications. Using petroleum data becomes then more challenging, as the closer to cities, the sparser the data.

The most common approaches used to spatially characterize sedimentary architectures are currently geostatistics and object-based stochastic modelling (De Marsily et al. 2005). These structure-imitating approaches do directly invoke the physical processes by which sediment bodies and stratal architecture formed. In this paper, we describe the use of a Stratigraphic Forward Modelling program (Sedsim) to characterize potential geothermal fields using geological process understanding. The dataset generated by Sedsim, can then be used for simple static geothermal assessments, as discussed in this paper, or for more complex coupled heat and fluid flow simulations.

SEDSIM STRATIGRAPHIC FORWARD MODELLING

Stratigraphic Forward Modelling (SFM) is a sedimentary process simulation that replays the way that stratigraphic successions develop and are preserved. It reproduces numerically the physical processes that eroded, transported, deposited and modified the sediments over varying time periods. In a forward modelling approach, data are not used as the anchor points for facies interpolation or extrapolation, but to test and validate the results of the simulation. Stratigraphic forward modelling is an iterative approach, where input parameters have to be modified until the results are validated by actual data. The workflow is described in Figure 1. One of the major benefits of using SFM to characterize sedimentary successions is the fact that the results will always make sense from a geological point of view. It is also possible to test different geological scenarios, environments or conceptual models, to assess their impact on the stratal geometry and better understand the depositional processes. Ultimately, it enables the prediction of facies and porosity distributions in areas where data are sparse, unevenly distributed, or at inappropriate resolution.

For this study we used the Sedsim three-dimensional stratigraphic forward modelling package that was developed originally at Stanford University by D. Tetzlaff and J. Wendebourg under the supervision of Prof. J. Harbaugh. It has since been modified and extended at the University of Adelaide and CSIRO by C. Dyt, F. Li and T. Salles (Griffiths et al, 2001). Sedsim enables the simulation of major depositional processes including marine, lacustrine, aeolian, fluvial, density flow, carbonate, vegetation and others.

APPLICATION TO THE YARRAGADEE FORMATION, PERTH BASIN

The Yarragadee Aquifer in the Perth Basin has been used for geothermal purposes for a few decades now. It is currently involved in six direct use geothermal projects (Pujol 2011), mainly swimming pool heating. Although the upper part of the aquifer is well characterized in the Perth Metropolitan area thanks to water supply exploration and development, the deeper part has been poorly explored.

Using the Yarragadee Formation as a case study, we will demonstrate the use of Stratigraphic Forward Modelling to characterize poorly explored aquifers for geothermal purposes.

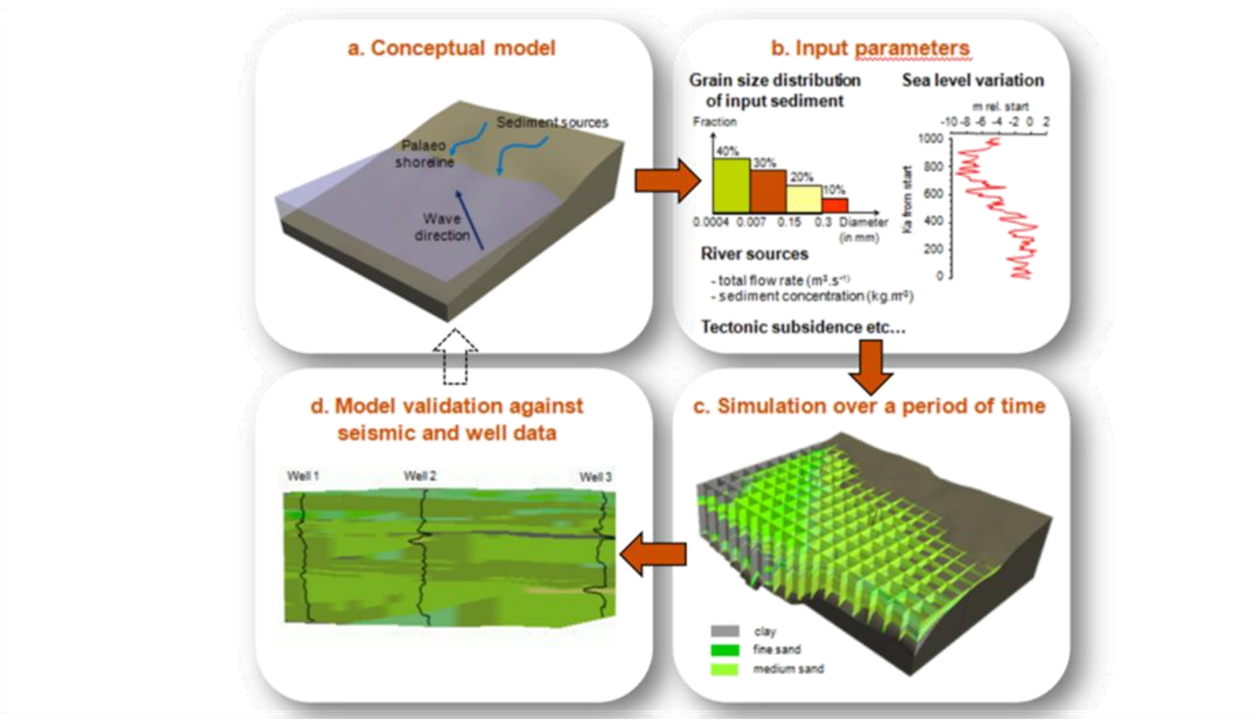

Figure 1: Stratigraphic Forward Modelling has a four step iterative workflow. The simulation workflow is repeated while modifying the conceptual model and input parameters until appropriate convergence with available data is achieved.

Conceptual model presentation

The Perth Basin, at the time the Yarragadee Formation formed, is believed to have been a vegetated floodplain traversed by meandering rivers. At that time Antarctica, Australia and Greater India still formed one continent and a large fluvial system drained northwards from Antarctica into the rift system between Greater India and the current Yilgarn Block, Australia (Figure 2). Some small alluvial fans and tributary rivers are also believed to have formed at the time along the flanks of the rift (Tait 2007). Although no evidence has been found until now, it is quite likely that other minor sediment sources were also coming from Greater India.

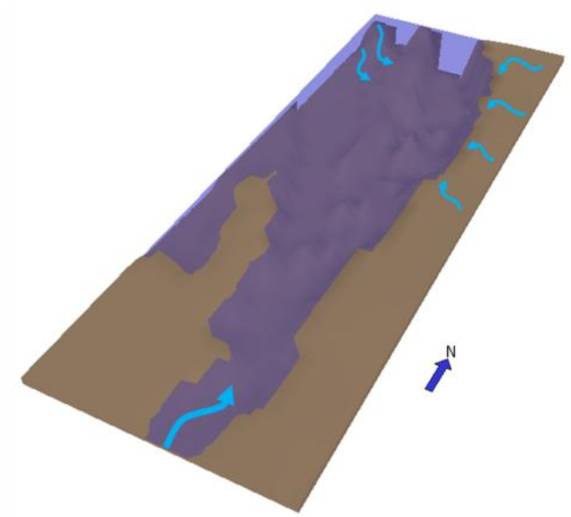

Figure 2: Conceptual model for the Yarragadee Formation deposition. The surface topography is represented in brown, the sea level in purple, and the different sediment sources as blue arrows.

The simulation was run for 15.8 Ma, from Middle Jurassic at 160 Ma to Late Jurassic at 144.2 Ma. The model was run over the entire Perth Basin to capture the complexity of the sedimentary processes, although the main focus was the Perth Metropolitan Area. The grid spacing was set at 3710 m, yielding 179 x 61 cells to cover the entire area of 660 km x 225 km.

Review of input parameters

Like any other computer modelling process, Stratigraphic Forward Modelling is only as good as the validity of the input data. Therefore a thorough analysis of available data is necessary before determining the main input parameters.

Sediments **-** Four siliciclastic grain sizes were used, based on sample data from petroleum wells (Table 1).

Table 1: Grain size parameters

	Coarse sand	Medium sand	Fine sand	Clay
Diameter (mm)	0.45	0.15	0.03	0.0003
Density (kg.m^{-3})	2650	2600	2600	2550

Sediment sources – The location of the main source was decided from the literature. The minor sources from the Yilgarn Block (Beard 1999) were derived partly from the location of palaeo-river valleys related to the present-day rivers. The sources from Greater India were added after several simulation runs showed a sediment deficiency to the western side of the basin. These proposed sources have yet to be verified by field observations.

Topography – The initial topography was based on current basement shape from OZ SEEBASE™ (FrogTech, 2005).

Subsidence – Initial subsidence rates were computed from seismic and well data and subsequently modified after several simulation runs.

Sea level - The sea level was extracted from Haq and Schutter (2008), modulated with Milankovich frequencies and resampled at 40 ka.

Porosity table – The rate of porosity reduction due to overburden stress was calculated from a porosity–depth curve derived from Cockburn-1 and Gingin-1 wells (Figure 3).

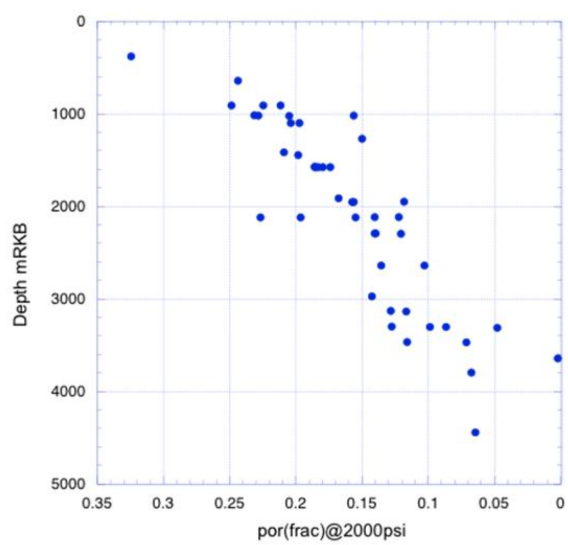

Figure 3: Core plug porosity values for Yarragadee Fm. samples in Cockburn-1 and Gingin-1 wells, for samples with an estimated mean grain size above 0.15 mm

Compaction – Sedsim models both syn- and post-depositional compaction by calculating the reduction of porosity due to overburden stress for different grain-size ratios. Post-depositional compaction was calculated on the basis of preserved Yarragadee tops.

Stratigraphic Forward Modelling simulation

SFM simulations can provide several outputs. Grain size distribution, porosity distribution and sediment sorting are the major outputs. However, outputs such as distance to source, distance to shore or silt fraction can also be generated. Post-depositionally, Sedsim is also able to uplift, erode and compact the sediments to their present-day state. The resulting grid and its properties can be imported into any 3D geological package for further analysis of the results.

For the Yarragadee Formation simulations, the main outputs were the grain size distribution (Figure 4) and the porosity distribution.

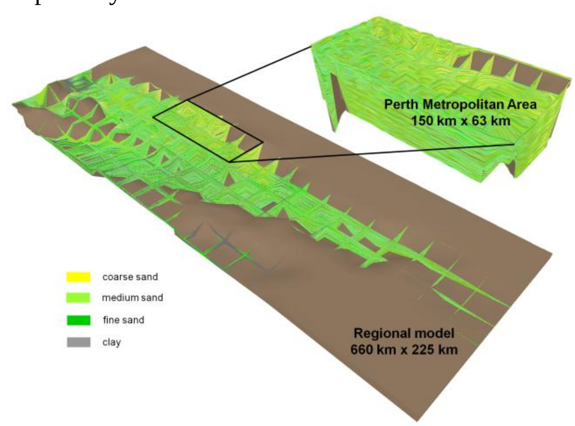

Figure 4: Porosity distribution of the Yarragadee Formation for the entire Perth Basin and Perth Metropolitan Area

A permeability distribution was also computed, using a porosity-permeability relationship based on core data from a few petroleum wells (Israni and Delle Piane 2010).

Testing and calibration of simulations

Sedsim output enables simulations to be verified in many ways. It is possible to generate synthetic seismic profiles from the simulation, to compare the stratal architecture to actual seismic lines. It is also possible to generate synthetic geophysical logs, such as gamma-ray and porosity, to compare with petrophysical logs from petroleum wells. However, the synthetic logs are recorded at preserved geological time steps (every 50000 years in this case) which at any one location may result in a single bed 10 m thick or a layer 2 mm thick at one time step. This makes direct comparison with wireline logs challenging, apart from the fact that the wireline tool has sampled a cross-sectional area of around 10 m^2 while in the present simulation the Sedsim grid node represents a sediment cross-sectional area of over 15 km^2. However, in the case of a grid node being close to a well location, and the rate of lateral change of facies thickness being low then a net to gross comparison may be used based on the upscaled values from the wireline logs that would be used in a reservoir simulator block.

The simulation results of the Yarragadee Formation were validated against a 2D seismic profile available just south of the Perth Metropolitan Area and against petrophysical logs available from petroleum wells unevenly spaced in the Perth Basin. One example of data validation is given in Figure 5.

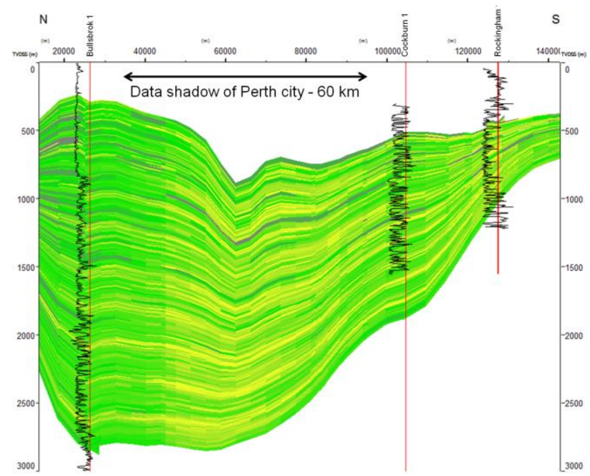

Figure 5: North-south cross-section of the grain size distribution of the Sedsim model, through Perth Metropolitan Area

Over 50 calibration runs were necessary to obtain results in accord with the available data. During the test and calibration stages, the parameters which required most adjustments were the sediment sources, the deposition parameters of the main source, and the subsidence rate.

Key benefits

In areas of sparse well coverage, and in the need for lateral facies distributions below seismic resolution, or in the absence of seismic data such as below urban areas, then the alternatives are either a geostatistical interpolation, or a linear interpolation of facies boundaries. The major advantage of Stratigraphic Forward Modelling is the fact that it directly uses and tests our understanding of the sedimentary processes that led to the preserved depositional succession. Petroleum wells intersecting the Yarragadee Formation in the Perth Basin are unevenly distributed, with only one of them within 20 km of Perth city centre. Because we understand now how the basin was filled, and the model has been validated against available data throughout the entire basin, we have increased confidence in the result in the Perth Metropolitan Area even with no data all available yet in that specific area.

The second main benefit is that using the grain size, porosity and permeability distributions generated by Sedsim it is possible not only to characterize the reservoir in term of rock properties but also in terms of heat and flow behaviour, so decisive for geothermal applications. For example, the Stratigraphic Forward Modelling of the Yarragadee Formation shows that under the Perth Metropolitan Area, the aquifer cannot be treated as a single reservoir. Three main silty bodies divide the formation in four sub-reservoirs. Other smaller impermeable bodies with smaller extents should also be taken into account for flow and transport simulations, although they do not compartmentalise the reservoirs.

USING STRATIGRAPHIC FORWARD MODELLING OUTPUTS FOR GEOTHERMAL EXPLORATION

A major challenge for geothermal companies is how to find the optimal location for given geothermal applications. A geothermal application is generally defined by the working temperature, a minimum energy supply which is related to the temperature difference and the sustainable flow rate. Additional requirements such as project economics are creating limitations on the maximum reservoir pressure drop, the maximum production interval thickness and the project lifetime. Using Sedsim results, we propose a method based on simple reservoir engineering considerations, that allows rapid assessment of the reservoir potential of an area for a given geothermal application.

Reservoir Assessment Methodology

The assessment methodology is divided into three steps. First, temperature, water density, heat capacity and flow rate are computed using the SFM outputs, for each grid cell of the model. Subsurface temperature in the Perth Basin was computed assuming a vertical conduction heat transfer, a constant geothermal gradient of 25 ˚C.km^{-1} (Reid, submitted) and a constant ground temperature of 20 ˚C. Water density and heat capacity are computed function of temperature only and the flow rate using a doublet flow rate equation (Gringarten 1978):

$$Q = \frac{(2\pi \Delta P K)}{\mu \ln\left(\frac{d_{well}}{r_{well}}\right)} H$$

where ΔP pressure difference between injection and production wells in Pa
K permeability in m^2
d_{well} distance between wells in m
r_{well} well radius in m
μ water viscosity in Pa.s
H reservoir cell thickness in m

Geothermal reservoirs are then defined by vertically summing grid cells, up to a given reservoir thickness. For each of the reservoirs, average temperature, cumulative flow rate and the energy that can be extracted from the geothermal fluid for a given geothermal application are also computed. The reservoir thickness depends on the geothermal application one wants to test. To assess the impact of the screening interval planned for an application, it is easy to simply modify the reservoir thickness and check the effect on the flow rate.

The energy extractable from the geothermal fluid, E_{th} (in MW_{th}), is computed using the following equation:

$$E_{th} = COP \cdot \rho C_p Q \Delta T$$

where COP Coefficient of Performance function of the geothermal application
ρ water density in kg m^{-3}
C_p water heat capacity in kJ kg^{-1} K^{-1}
ΔT temperature difference between extracted and reinjected water in ˚C

Finally, optimal locations for a given geothermal application can be identified using thresholds on the reservoir temperature, flow rates or extractable energy. The thresholds can be quickly modified depending on the main parameters of the geothermal application and the appropriate locations quickly updated.

Reservoir Assessment Application

The above methodology has been applied for the prospectivity of direct use geothermal application within the Yarragadee Formation in the Perth Metropolitan Area with the following parameters:

- d_{well} = 1855 m, half a grid cell
- R_{well} = 0.15 m
- H (Perforation interval) = 300 m
- ΔP = 200000 Pa, a head difference of around 20 m

As mentioned before, swimming pool heating has already been proven successful in the Perth Metropolitan Area, therefore we decided to look at another direct application, air conditioning. We are taking the example of an absorption chiller (Wang et al., submitted) to see what cooling load could be met with the following characteristics:

- Coefficient of performance = 0.67
- ΔT = 20 ˚C
- Temperature range = 75 ˚C - 85 ˚C
- Minimum extractable energy = 1 MW_{th}

The results are presented in map view on Figure 6. Those results are first order estimations and must be taken with care. Although they give a preliminary idea of the feasibility of a given geothermal application, further work including economic studies linked to pumping costs must be done before taking any decision. We have also been conservative in the parameter values we used.

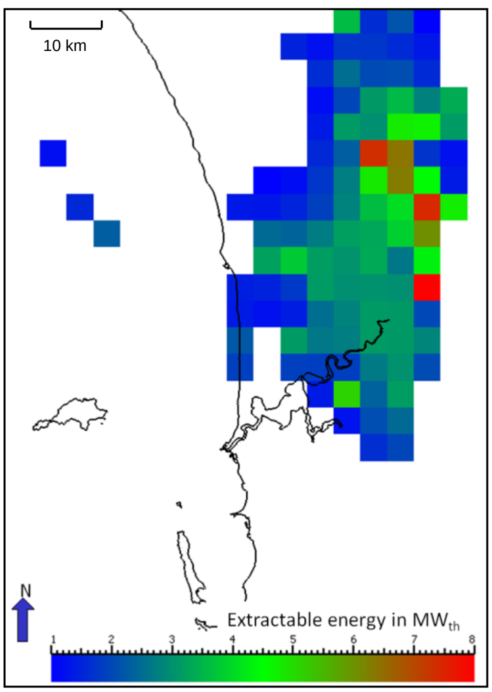

Figure 6: Map view of reservoirs potentially fulfilling the parameters we defined for successful chiller applications

Testing different application settings is quite easy with this methodology, as the flow rates and extractable energy can be computed on the fly. The different potential reservoirs can also be analyzed further using histograms, cross-plots and cross-sections in 3D. Although Figure 6 shows only the upper reservoirs fulfilling our application criteria, deeper reservoirs might be located in the same area with different extractable flow rates and energy.

DISCUSSION AND CONCLUSION

Stratigraphic Forward Modelling was successfully applied to characterize the unexposed and poorly quantified Yarragadee Formation in the Perth Basin. It proved its efficiency at predicting grain size and porosity distributions based on geological reasoning rather than interpolation between sparse data. It provided insight into, and numerical predictions of, the distribution of sediments and their properties below ground, based on an understanding of the depositional processes involved.

Although SFM ensures that simulation results make geological sense, the simulation quality is highly dependent on the input data and the expertise of the modeller. Permeability distribution is also not computed during the simulations, but can only be inferred using porosity-permeability relationships based on core data - the more data, the better the results.

Stratigraphic Forward Modelling generates high resolution datasets of porosity, grain size and depositional facies that can be used to produce 3D synthetic seismic volumes and synthetic petrophysical logs for validation. Such extensive datasets may potentially reduce risk for geothermal exploration which always suffers from a lack of subsurface data. We presented a quick way to easily assess the geothermal potential of an area for a given application, given an understanding of the processes involved and minimal well and seismic data. This method could also enable us to test the influence of different parameters of a geothermal application to better understand its feasibility.

Stratigraphic Forward Modelling output could also be used for more complex geothermal exploration purposes, either at reservoir or basin scale. Most geothermal simulations are run using laterally homogeneous layering, while SFM results can help identify lateral porosity and permeability variation, baffles, and highly permeable layers to provide more realistic models.

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