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IDENTIFICATION AND GEOTHERMAL INFLUENCE OF FAULTS IN THE PERTH METROPOLITAN AREA, AUSTRALIA

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ABSTRACT

Faults are important for understanding geothermal systems due to their influence on the stratigraphic structure, and how that structure influences fluid flow. A new workflow has been developed by the Western Australian Geothermal Centre of Excellence (WAGCoE) to identify a fault network in urban areas and generate a 3D model of subsurface geology. The approach involves testing inferred fault models against progressively more complex data types.

We apply this methodology to create a series of new geological models of the Perth Metropolitan Area (PMA). One model involves significant flexure of the stratigraphic layers adjacent to the faults, and the other model involves stiffer stratigraphic layers and consequently larger fault displacements. Each model is consistent with the constraints from well data and gravity data, geologically plausible, and yet produces slightly different aquifer geometries.

The new faulted model is applied to calculate temperature and fluid flux in a three-dimensional hydrothermal model of the Perth Metropolitan Area. Fault locations, offsets, and properties greatly influence hydrogeologic recharge areas and the pattern of hydrothermal convection cells.

INTRODUCTION

Faults are important for understanding geothermal systems due to their influence on the stratigraphic structure, and how that structure influences fluid flow. Fault networks influence not only conventional geothermal plays, but also hot sedimentary aquifers. The Western Australian Geothermal Centre of Excellence (WAGCoE) focuses on hot sedimentary aquifer prospectivity in the state of Western Australia, and particularly in the Perth Basin.

Knowledge of the subsurface structure, and knowing the likelihood and location of faults, is crucial for understanding the source and movement of heat. In the Perth Metropolitan Area, Perth Basin, Western Australia, faults affecting deep aquifers have been barely studied. To assess the geothermal opportunities for the city, identifying the faults is a priority. Different techniques for identifying faults have been developed since the beginning of petroleum exploration; however their application for geothermal purposes can sometime be difficult.

The easiest way to identify a fault is using field observations. In the Perth Basin, the major deep aquifers are part of the Permian–Early Cretaceous sedimentary succession, which is highly faulted throughout the basin. However, those sediments in the Perth Metropolitan Area are covered by younger sediments, which are comparatively undeformed. Therefore, most of the faults affecting the deep aquifers are not exposed and impossible to map from the surface.

Standard geophysical techniques are also popular for investigating faults. However, those techniques are not easy to implement in metropolitan areas where many direct use geothermal applications are based. Seismic reflection and refraction are difficult to shoot in residential areas. Electromagnetic and magnetic methods can be useful for fault identification, but noise sources in urban areas limit their application. Gravity surveys can detect faults on regional scales, but for small areas like the Perth Metropolitan Area, datasets are usually too coarse.

Another commonly used way to identify faults, or test existing fault interpretations, is via boreholes and associated geophysical logs. Once again, working in metropolitan environments creates limitations. As petroleum exploration is nearly nonexistent, so are deep wells. In the Perth Metropolitan Area, only one petroleum well was drilled within 25 km of the city center, whereas shallow monitoring wells for water supply are distributed all over the area. Some of those wells intersect the top of the deep Yarragadee aquifer, but for no more than a few hundred meters. Gamma ray and resistivity logs are sometimes available, but usually in older analog format.

These factors necessitate innovative, multi-disciplinary approaches to characterize subsurface geology in the Perth metropolitan area.

MULTI-DISCIPLINARY METHODOLOGY FOR FAULT DETECTION

Although metropolitan areas rarely allow for conventional fault assessment techniques, some data are always available. Those data have different scales, different extents and different purposes but this diversity makes them complementary. It is essential that any inferred faults are consistent with all of the available datasets and compatible with existing geological knowledge.

The multi-disciplinary methodology for fault detection used in this paper is described in the flowchart of Figure 1. An initial 3D structural model is created using field data - such as maps, water bores, and petroleum wells – and geological knowledge. The 3D model is then used as a means to test fault interpretations, and iteratively improved based on the introduction of additional datasets. The fault network is dependent on the consistency of the 3D model, which is itself assessed through thickness maps of faulted formations.

Using 3D geological models to assess the faults' reliability ensures consistency between all data sets and allows the testing of different scenarios. For example, offsets in sparse well data could indicate either the presence of a fault, folded strata, or both. Checking the potential fault location and orientation against gravity surveys or poor quality seismic lines supports the existence of the fault or not. The inference of faults via independent criteria from several different data sources increases confidence in interpretation. The use of "worms", also known as multiscale edge analysis of potential fields (Hornby

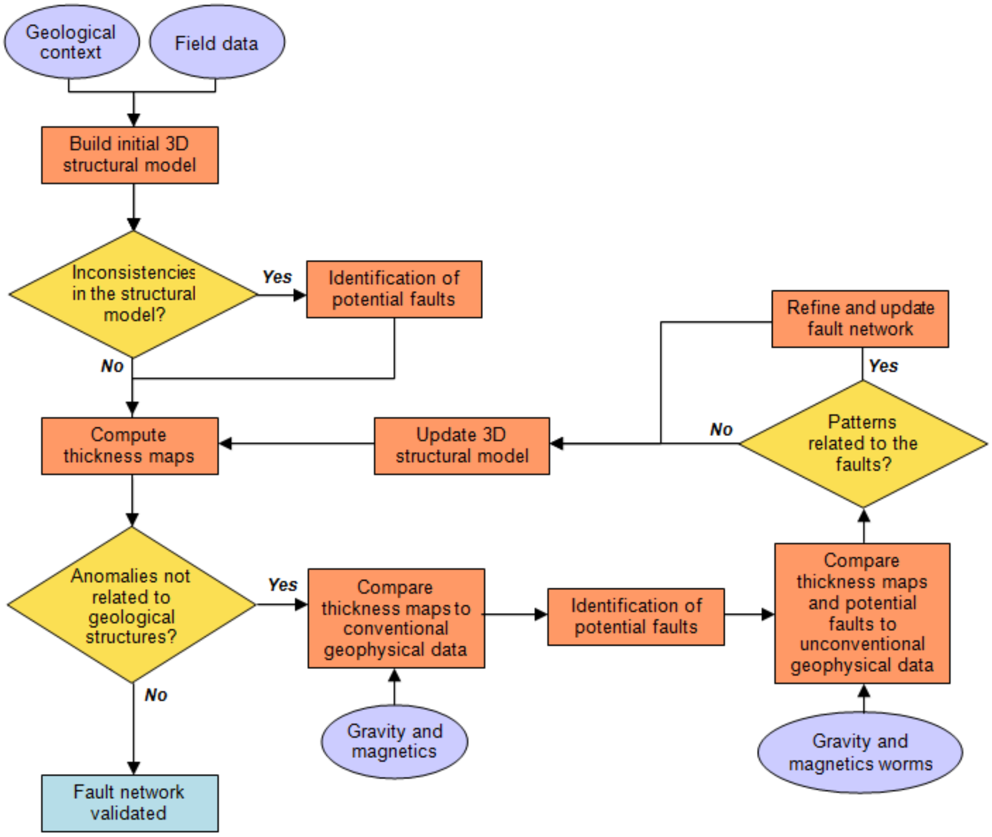


Figure 1: Iterative workflow to assess fault networks in metropolitan areas, depending on data available.

et al. 1999) is also an important step in the workflow. Worms enable the characterization of faults in term of location, depth and dip. Interpreting worms in the absence of other data is however a complex task. Therefore, worms are the last dataset we incorporate into our 3D model. At that step, some faults will have already been identified and they can be used as a training set to interpret the worms.

This methodology was developed specifically for the Perth Metropolitan Area. However it is flexible enough to be implemented in any metropolitan area or poorly explored region. Depending on the data available, the complexity of the geology and the quality of geophysical surveys, the workflow can be easily adapted. Nowadays, most areas have geophysical surveys of acceptable quality. The most problematic dataset would likely be generating the worms, as it requires reasonable resolution and operator skill to provide meaningful results.

APPLICATION TO PERTH METROPOLITAN AREA

The Perth Basin is an elongate, north-south trending basin on the western coast of Australia. The basin was formed through rifting of Greater India and Australia and contains a Permian to Cretaceous succession overlying Precambrian basement. The basin is divided into sub-basins of similar structural style bounded by transfer faults. The Perth Metropolitan Area (PMA) is located in the Onshore Central Perth Basin, on the Mandurah Terrace.

The offshore Central Perth Basin has been well explored for petroleum prospects and lately CO_2 sequestration. The most comprehensive study of the onshore part was completed by hydrogeologists (Davidson and Yu, 2006) for the Perth regional aquifer modeling system (PRAMS) and is presented in Figure 2.

Data available in the Perth Metropolitan Area and its surroundings are summarized in Figure 3A and consist of:

- Around 180 shallow water bores
- 6 petroleum wells
- Coarse regional gravity survey
- Finer gravity survey focused on PMA

Using petroleum wells and water bores, a 3D structural model of the PMA was created, down to the top of the known faulted Permian–Early Cretaceous sediment succession. Following work done in the offshore part of that sub-basin (Bale, 2004), we postulated that the sediments post-dating that succession had also been faulted to a smaller extent. Therefore, we focused our work on creating a consistent geological model for those formations.

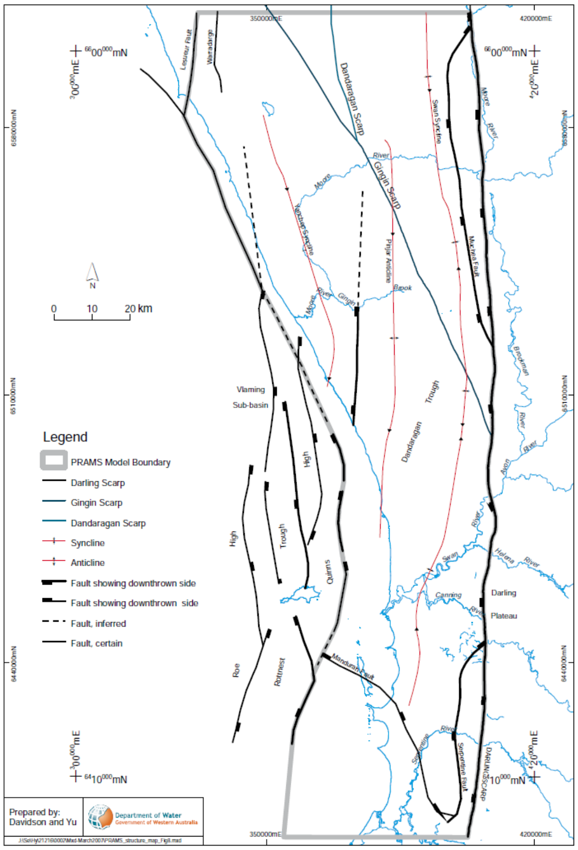


Figure 2: Structure map of the Perth Metropolitan Area and its surroundings (Davidson and Yu, 2006)

It took several iterations before a fault network was obtained that is consistent with all the data. Some stages of the iterative process are presented in Figure 3.

In the local Perth Metropolitan Area, the gravity worms provided more details at the city location, where direct use applications are more likely to be located (Figure 3C). However, because only one set of data was available to identify those faults, their reliability is not as good as the other faults. To incorporate this reliability into the fault network, we decided to rank the probability of fault existence depending on the number of sources showing evidence of their existence. A visualization of the final fault network is presented in Figure 4.

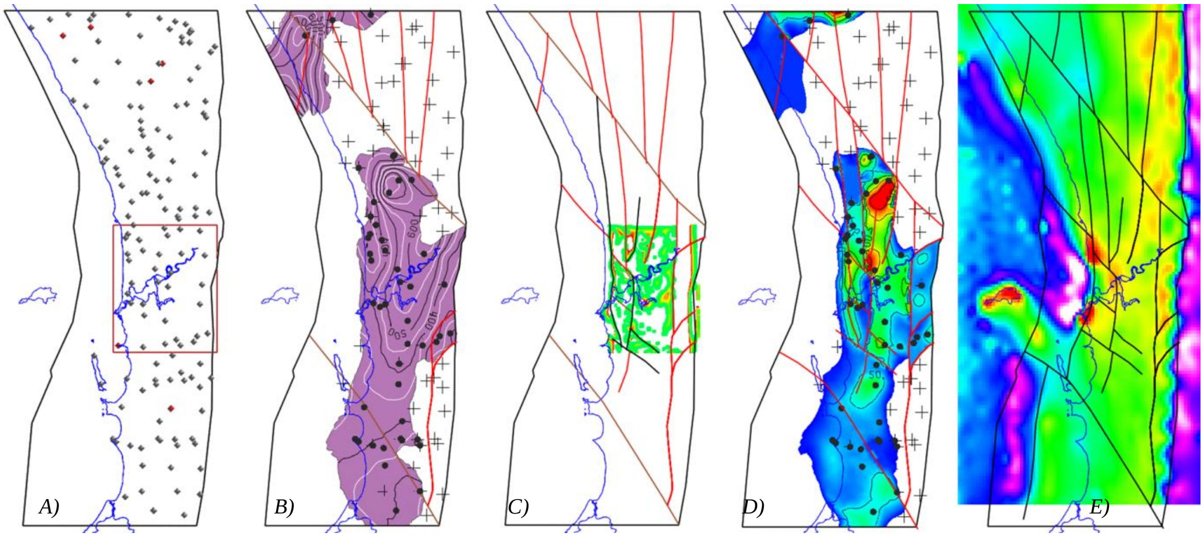


Figure 3: A) Data distribution over our area of interest in black. Water bores are represented in gray dots, petroleum wells in red dots and the extent of the fine gravity survey is outlined in brown,
B) Fault network after the first run and unfaulted geometry of the Gage Formation. The cross represents well that do not intersect the formation, while the dots are wells intersecting the formation, therefore constraining the formation depth.
C) Fault network after several iterations and gravity worms. The black faults were inferred using mainly the worms, whereas the red faults had already been detected thanks to other datasets.
D) Thickness map of the Gage Formation close to the last iterations.
E) Vertical gradient of the regional isostatic residual gravity and final fault network

To illustrate the fault ranking, let’s take the example of the north-south fault at the west boundary of the Perth Area. This fault is ranked as reliable because it was detected first from the well data, then the gravity worms and finally confirmed by the vertical gradient of the regional isostatic residual gravity.

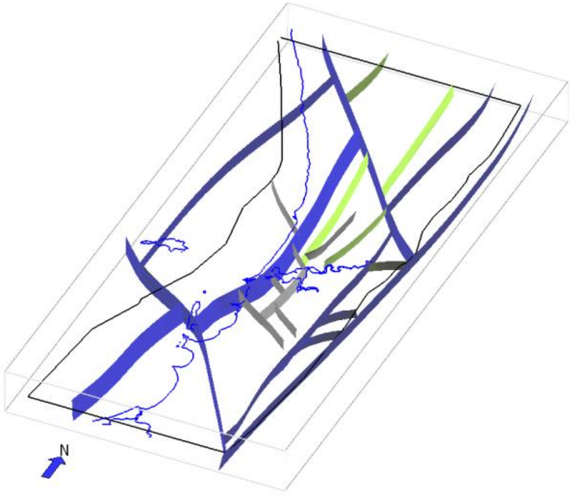


Figure 4: Final fault network of the Perth Metropolitan Area. The faults in blue are faults which were inferred from more than two datasets, the green one were inferred from two concordant datasets and the grey ones from only one dataset.

EFFECT OF FAULTS ON HEAT TRANSPORT AND FLUID FLOW

Given the new structural representation developed here, we investigated how this new information would affect geothermal prospecting. Previous case studies have indicated faults have a significant influence on thermal anomalies (Lopez & Smith, 1994, Garibaldi et al. 2010).

3D hydrothermal model of the PMA

Faults in sedimentary basins may have higher or lower permeability than their host rocks, and thus may act either as fluid pathways or barriers to fluid flow (e.g. Barnicoat et al., 2009; Fisher and Knipe, 2001; Knipe, 1992). Research conducted by WAGCOE indicates that faults in the Perth Basin are likely to act as barriers to fluid flow (Olierook, 2011). Faults also create offsets in geological layers, juxtaposing units with different hydraulic and thermal properties. Thus, faults can have a large impact on patterns of fluid flow and heat transport in sedimentary basins, which in turn has implications for geothermal and other resources.

To assess the impact of faults on temperature distribution and fluid flow in the PMA, hydrothermal simulations were performed using the new faulted model to constrain the geometry of the aquifers and aquitards. The model extended from the water table to 4.5 km depth, encompassing the entire thickness of the Yarragadee Aquifer and the top of the Cattamarra

Coal Measures. The geological units of the PMA model were grouped into aquifers and aquitards. Faults were represented either as offsets in the geological layer boundaries, or as vertical low-permeability layers linking the offsets. Simulations were performed using Feflow, a finite element modelling package which solves the equations of groundwater flow, heat and mass transport in two or three dimensions (Diersch and Kolditz, 1998).

The model domain comprises porous rocks saturated with saline pore fluid. Heat and salt are transported by advection (i.e. with the moving pore fluid) and diffusion. Fluid flow is driven by gradients in hydraulic head, which arise from variations in height of the water table, and from density gradients due to variations in temperature and salinity. Convection can occur if the buoyancy forces arising from density gradients are sufficient to overcome diffusion and viscous resistance to flow; such conditions may arise in thick, highly permeable aquifers such as the Yarragadee Aquifer.

Properties and boundary conditions

Tables 1 and 2 list the property values used in the hydrothermal models. Fluid density was modelled using an equation of state for pure water (Magri, 2009) adjusted for salinity using the saline expansion coefficient (Table 1). Fluid viscosity was varied with temperature and salinity according to Feflow's built-in viscosity function. Permeability is the least well-constrained of all the rock properties, with measurements typically spanning several orders of magnitude even within a geological unit. The permeabilities shown in Table 2 are representative values for each unit based on the PRAMS calibration report (Department of Water, 2008) and permeability measurements in the PressurePlot database (www.pressureplot.com). Permeability was assumed to be anisotropic (Bear, 1972), with vertical permeability 10 times smaller than horizontal permeability.

The highest vertical extent of the model was the topography (onshore) and sea level (offshore). The water table or ocean elevation was set as a fixed hydraulic head boundary condition. Temperature was fixed at the mean annual surface temperature (MAST) of 20 °C on the top boundary. Salinity was fixed on the top boundary at 35000 kg/m^3 offshore and 0 kg/m^3 onshore. Temperature was fixed at 110 °C on the bottom boundary, representing a geothermal gradient of ~20 °C/km (exact value depends on elevation of the top of the model), which is a conservative value for the PMA (Crostella and Backhouse, 2000). Salinity was set to 15000 kg/m^3 on the bottom boundary. The sides of the model were impermeable and non-conductive to heat or salt. Simulations were run in transient mode for a period of 10^9 days (~2.7 million years).

Table 1: Fluid and rock properties treated as constants in the hydrothermal models.

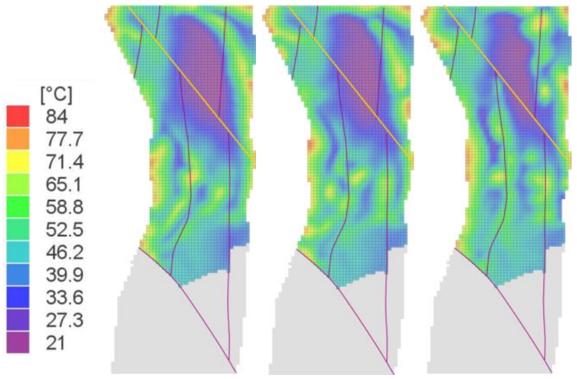
Property	Value (units)	References
Longitudinal dispersivity	5 m	(Arya et al., 1988)
Transverse dispersivity	0.5 m	(Arya et al., 1988)
Specific storage	10^{-6} m^{-1}	(Turcotte and Schubert, 1982) (Strategen, 2004)
Specific heat capacity (rock)	850 J/kg/K	(Vosteen and Schellschmidt, 2003; Waples and Waples, 2004)
Specific heat capacity (fluid)	4150 J/kg/K	(Wagner et al., 2000)
Thermal conductivity (fluid)	0.65 W/m/K	(Wagner et al., 2000)
Saline expansion coefficient	-7.5 x 10^{-4} m^3/kg	(IOC et al., 2010)
Diffusion coefficient of salt	4.5 x 10^{-9} m^2/s	(Li and Gregory, 1974; Poisson and Papaud, 1983)

Table 2: Properties varying by geological unit in the hydrothermal models. References: (1) CSIRO PressurePlot database (www.pressureplot.com); (2) PRAMS calibration report (Department of Water, 2008); (3) Hot Dry Rocks Pty Ltd (2008); (4) Reid et al. (2011); (5) Geological Survey of Western Australia (2011).

	Porosity	**Horizontal hydraulic conductivity (m/d)**	**Thermal Conductivity (W/m/K)**	**Radiogenic heat production (μW/m3)**
Superficial Aquifer	0.3	10	1.6	0.2
Kings Park Formation	0.1	0.1	1.4	0.3
Kardinya Shale	0.1	10^{-4}	0.4	0.6
Leederville Aquifer	0.3	1	3.4	0.6
South Perth Shale	0.1	10^{-4}	1.8	0.8
Parmelia Formation	0.2	10^{-4}	3.1	0.5
Yarragadee Aquifer	0.2	0.1	4.3	0.5
Cattamarra Coal Measures	0.1	10^{-4}	4.1	0.5
References:	*1*	*1, 2*	*3*	*4, 5*

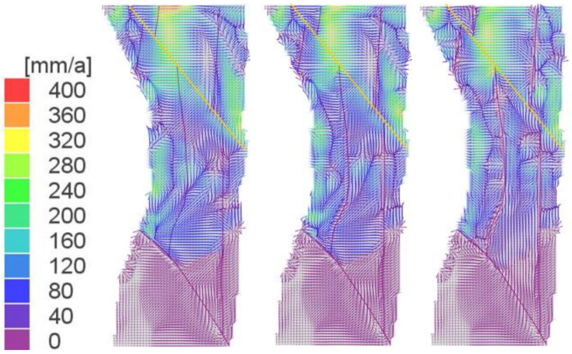
Results

The results show clearly the influence of faults on fluid flow and heat transport in the PMA. Figure 5 to 7 show temperature and fluid flux after 10^9 days in three fault scenarios: (A) Faults as offsets, (B) faults with permeability 10 times smaller than the surrounding rocks, and (C) faults with very low permeability (effectively impermeable).



(A) (B) (C)

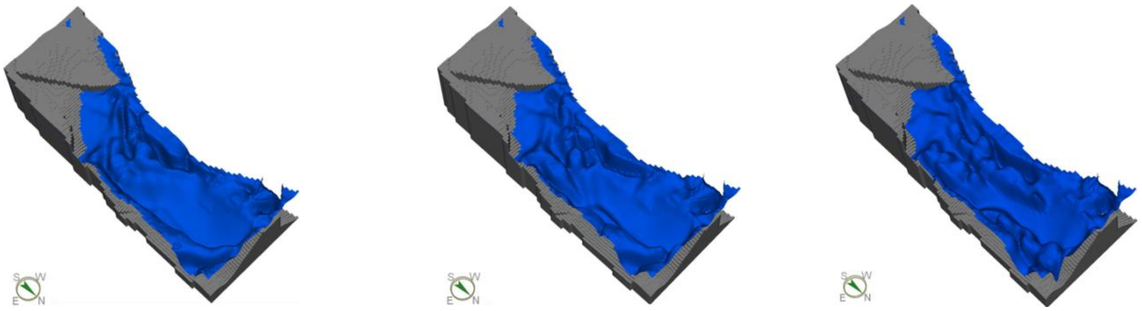
Figure 5: Temperature at 1171 m depth (a horizontal plane through the Yarragadee Aquifer) after 10^9 days. (A) Faults as offsets. (B) Low permeability faults. (C) Impermeable faults. In all cases, the orange colored fault was only treated as an offset, not as a low-permeability fault.



(A) (B) (C)

Figure 6: Darcy fluid flux at 1171 m depth after 10^9 days. (A) Faults as offsets. (B) Low permeability faults. (C) Impermeable faults. In all cases, the orange colored fault was only treated as an offset, not as a low-permeability fault.

In all three cases, the main area of recharge and discharge from the overlying Leederville Aquifer into the Yarragadee Aquifer is in the northern part of the model, creating a relatively cold region. All cases exhibit convection within the Yarragadee Aquifer in the central part of the model. Convection is indicated by the pattern of thermal highs and lows in the central area (Figs. 5 and 7), and by the alternating directions of fluid flow in this region (Fig. 6). The convection cells migrate from north to south (driven by recharge to the north) and are continuously regenerated at the northern end of the convecting area. However, the exact pattern of convection is strongly influenced by the faults. When the faults are represented purely as offsets (Part A in Figs. 5, 6 and 7), the convection cells follow roughly a NE-SW trend. This trend is disrupted when the faults have lower permeability than the surrounding rocks (Part B in Figs. 5 to 7). When the faults are effectively impermeable, the convection cells align along the faults (Part C in Figs. 5 to 12). There is also some convection in the NE corner of the model in the impermeable fault scenario.



A) B) C)

Figure 7: 45 °C temperature isosurface after 10^9 days. A) Faults as offsets. B) Low permeability faults. C) Impermeable faults.

DISCUSSION AND CONCLUSION

The multidisciplinary methodology presented here for identifying faults is a straightforward technique which can be utilized in many locations without an abundance of data. It is suitable for early exploration as it does not require large expenditures of money to perform geophysical surveys or drill wells to generate new data. Faults can be ranked based on how well they fit with the numerous types of data, which provides a measure of uncertainty on the analysis.

The methodology does have shortcomings. It does not identify some geometric constraints on the faults, such as throw or thickness. Nor does it identify any alteration in rock properties near or across faults. These limitations make hydrothermal numerical modeling based on the structural model uncertain, but this uncertainty would subsist whether faults exist or not. The iterative methodology provides increasingly complicated structural scenarios which can be tested with future data collection, and encourages well-informed exploration.

The shape and location of faults, and their permeability, clearly have a strong influence on fluid flow and heat transport in the PMA. Incorporating faults into the hydrothermal models affects the location of convective upwellings in the central part of the PMA, and influences the path of fluids recharging the Yarragadee from above. Thus, faults influence the likely location of geothermal resources in the PMA.

The fault detection workflow presented here is likely to benefit geothermal exploration in other regions, as evidenced by a large number of hydrothermal studies discussing the importance of faults on fluid and heat flow (see e.g. Lopez & Smith, 1995; Garibaldi et al. 2010). In general, fluid recharge areas which drive the hydrogeologic system will be fault-constrained.

The influence of faults on pinning the location of convection cells over geologic time is particularly useful for providing certainty in geothermal exploration.

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