TARGETING LOCALISED UPWELLINGS WITH A NEW MULTIPHYSICS SIMULATOR

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Keywords: *multiphysics simulation, numerical stability analysis, convection, advection, shear heating*

ABSTRACT

A paradigm shift in geothermal engineering is to target specifically fault zones of high permeability and potential convection. By embracing the concept of convection as an efficient mode of heat transfer, the drilling costs may be reduced significantly as localised upwellings can be targeted. The problem remains to identify the location and depths of these potential upwellings from geophysical and geological data.

We present a new multiphysics simulator where the occurrence of convection can be made using a fundamental stability analysis known as the pseudo-arclength continuation method. We find that localised convection can be triggered by a local additional heat source in active faults (known as frictional or shear heating). Another finding is that deep advective topography-driven sweeps can be pinned on suitably located fault zones. With these additions, we can better numerically simulate convection in fault zones with more realistic parameters such as lower permeabilities and narrower fault damage zones. These findings can be significant in case studies in major geothermal sites. We present a preliminary analysis from two extension zones: 1) the Perth Basin half-graben setting in Western Australia, and 2) the Rhine Graben setting (Soultz-sous-Forêts, Landau).

1. INTRODUCTION

1.1 Regional and Geological setting of the Perth Metropolitan Area and Rhine Graben

This section briefly presents the regional and geological setting of two example extension rift basins; the Perth Metropolitan Area in Western Australia and the Rhine Graben in Europe.

1.1.1 Perth Basin, Western Australia, Australia

The Perth Metropolitan Area (PMA) lies in the Perth Basin, located on the southwest margin of Australia. It is bounded on the east by a craton and extends to the edge of the continental shelf on the west. Figure 1 presents a simlified cross-section of the PMA, listing various aquifers and confining layers present.

The evidence of convection in this region was investigated by Sheldon et al., (2012), Schilling et al., (2013), and Irvine et al., (2015), which conclude that fluid flow is primarily driven by the effects of conduction, advection, and convection. Advection is present from flow driven from topographic head; the background groundwater flow from the craton to the ocean, and convection arises from flow driven by temperature and salinity density gradients.

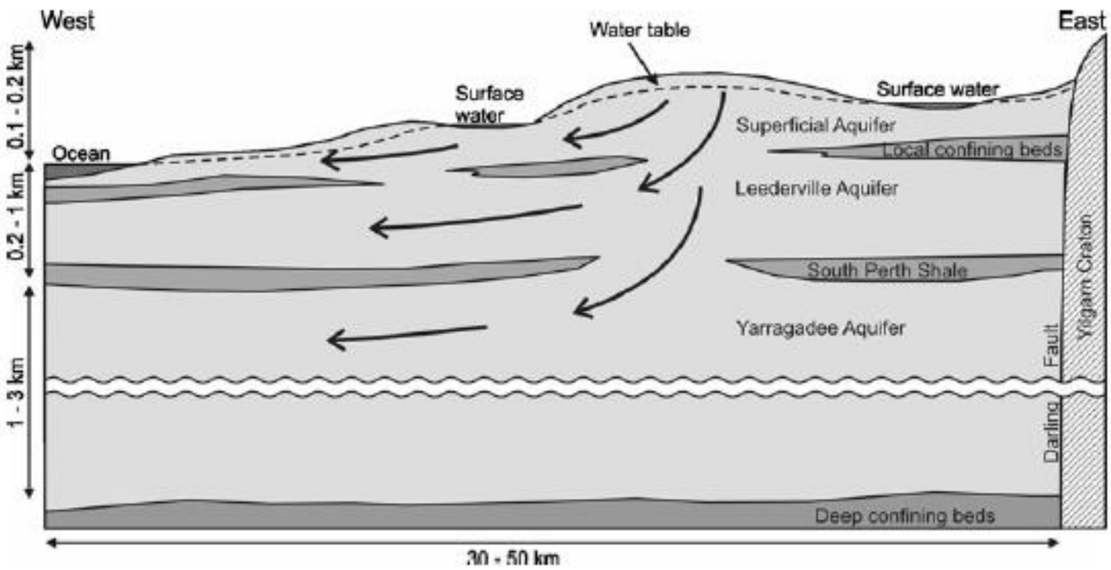

Figure 1: Schematic diagram of a cross-section through aquifers in the PMA, taken from Sheldon et al. (2012). Arrows denote direction of background fluid flow due to topography and meteotic recharge. Well data constrain shallow geology but the deeper geometry (below wavy lines) is largely unknown.

The combined effects of conduction, advection, and convection result in complex groundwater flow patterns which are then pinned by geometrical features such as faults. Figure 2 (right) displays the major faults in the PMA region, which are implemented in the numerical model (left).

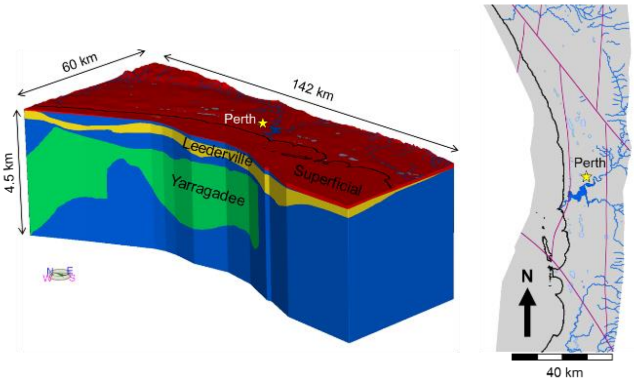

Figure 2: Numerical model displaying various aquifers (left) and top view of the PMA (right), where major faults in the region are outlined in purple Regenauer-Lieb, 2012).

1.1.2 Rhine Graben, Europe

The Rhine Graben in Europe is an extensional rift which spans France and Germany (see Figure 3). In particular, geothermal anomalies in the Upper Rhine Graben were investigated using several analytical and numerical models, proposing kilometre-scale hydrothermal convection as a driver for heat and fluid flow (Hoffers, 1981; Le Carlier et al., 1994; Dornstädter et al., 1999; Bachler et al., 2003; Guillou-Frottier et al., 2013).

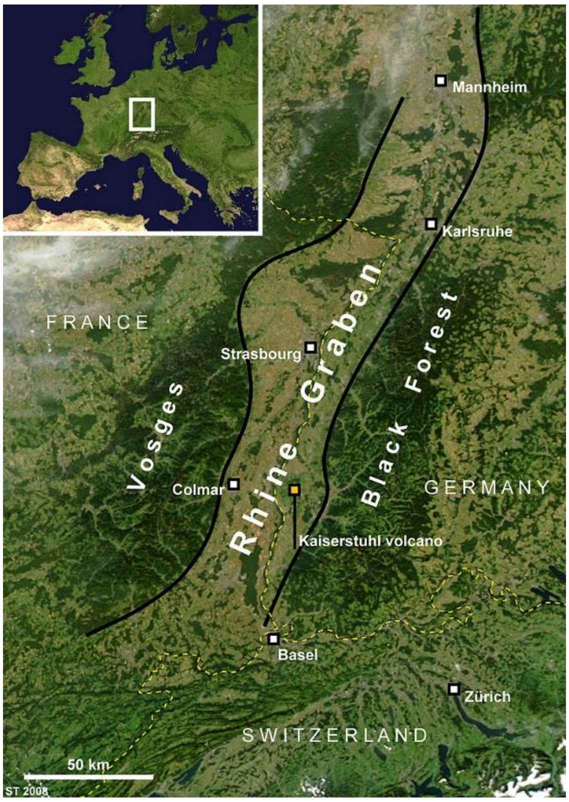

Figure 3: Location of the Rhine Graben in Europe. (Turner, 2008). The depth to basement in the Black Forest on the eastern flank has a higher elevation than the Vosges on the western flank.

Bottom-hole temperature (BHT) from pre-existing boreholes provided information regarding the subsurface temperature in the Rhine Graben (see Figure 4). The largest thermal anomaly lies at Soultz-sous-Forêts, which is currently the site of an EGS project. Similar to the PMA's geological setting, the eastern flanks are bounded by the Black Forest which are approximately 200m higher than the Vosges on the west, which creates a contrast in topograhic head for fluid flow. In addition to this, an east-west regional groundwater flow with internal advection and convection in permeable geological units is postulated. The depth to crystalline basement also increases west to east, thus enhancing the western heat flow by radiogenic heat production (Bachler et al., 2003). The combination of these circumstances contributes to the build up of thermal anomalies on the western border of the Graben faults.

1.3 Effect of Faults

In both geological settings of the PMA and Rhine Graben, faults play an important role; either as pinning convective cells (Reid et al., 2012), or acting as pathways to transport heat and fluid to the surface. Therefore, the understanding of conductive, convective and advective processes in and around faulted regions can greatly contribute to optimising geothermal production.

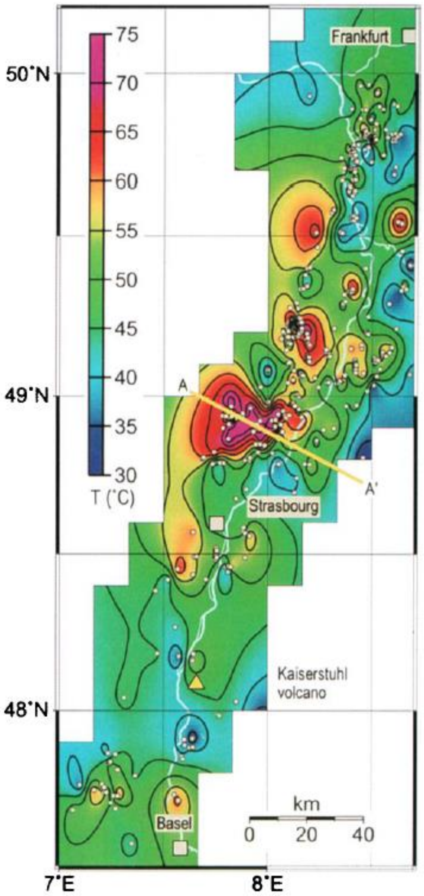

Figure 4: Temperature profiles at a depth of 800m. The most prominent thermal anomaly is located at Soultz-sous-Forêts, which intersects the cross section A-A'. For more details, see Pribnow and Schellschmidt (2000).

Faults play an important role as they can exhibit the behaviour of being both an impermeable seal and a fluid pathway. Faults are often regarded as being static in human timescales, whilst demonstrating more dynamic behaviour in geological timescales; which can be exhibited in both large magnitude movements (e.g. large magnitude earthquake) and a steady creep. In geological timescales, the steady of creep of faults generates an internal frictional heat, known as shear heating. This heat is expected to impact temperature-sensitive processes such as the onset of convection. Understanding preliminary results of shear heating on the onset and pattern of convection (Tung et al., 2017) can be used as a basis to target localised upwellings for better geothermal energy production.

2. METHODOLOGY

In the classical case of hydrothermal convection in porous media, the system of equations solved traditionally assume the Boussinesq approximation and incompressible solid and fluid (Horton&Rogers, 1945). A comprehensive review of convection in porous media can be found in Nield and Bejan (2013), in which also provides the system of equations:

$$0 = \nabla \cdot v$$

$$0 = -\, c_a \rho_0 \partial_t v - \nabla \mathrm{P} - \frac{\mu}{K} v + \rho_f g$$

$$0 = (\rho c)_m \partial_t T + (\rho c_P)_f v \cdot \partial_k \mathrm{T} - k_m \partial_{ii}^2 T$$

$$\rho_f = \rho_0 [1 - \beta(T - T_0)]$$

where ρ_f the pore pressure of the fluid, v is the seepage velocity, P is the pressure, c_a the acceleration coefficient tensor of the medium, ρ the density, μ the dynamic viscosity, β the thermal volume expansion coefficient, k_m the overall thermal conductivity, c the specific heat, and K the permeability.

The evolution of convection is typically represented by a dimensionless group called the Rayleigh number. This value is dependent on the solid and fluid properties, boundary conditions and geometrical configurations of the problem at hand (Rayleigh, 1916). Various definitions of the Rayleigh number exist, and an example for the problem of a homogeneous horizontal fluid-saturated porous medium is:

$$Ra = \frac{\kappa \alpha \rho_0^2 c_f g H \Delta T}{\mu \lambda}$$

where κ is the permeability, α the thermal expansion coefficient, ρ_0 the reference fluid density, c_f the fluid specific heat capacity, H the thickness of the porous medium, ΔT the temperature difference across the layer, μ the dynamic viscosity, and λ the thermal conductivity. Convection is predicted to occur at a certain critical Rayleigh number (Ra_c). Among all the parameters present in the Rayleigh number, permeability is considered the driving parameter as it can vary over several orders of magnitude within a reservoir.

With the assumptions of simple geometry and incompressible homogeneous media, the analytical calculation of the critical Rayleigh number of an ideal system can be easily determined. In non-ideal natural systems however, the material properties and geometry of the media are often complex and data regarding the system have to be inferred. The use of numerical methods and simulators provide the ability to model more realistic geometries and material properties, identify key driving parameters, and perform uncertainty quantifications; with the objective to better approximate the critical Rayleigh number. However, the use of numerical methods to determine the critical Rayleigh number is limited for systems close to criticality. Elder (1967) shows that the closer a system is to criticality, the more time it takes for convection to establish in a transient simulation. Hence, a linear stability analysis can be used to track the onset and evolution of convection by varying the Rayleigh number (Elder 1967, Bories 1987). This study uses a pseudo-arclength continuation method (Keller, 1977) to evaluate the onset of convection by varying the Rayleigh number and tracking the steady state curve using the Nusselt number. The Nusselt number is the ratio of convective heat transfer to pure diffusion and in this study is expressed as:

$$Nu = 1 + \frac{max\|\nabla \mathrm{T}_{conv}\|_\Omega}{max\|\nabla \mathrm{T}_{diff}\|_\Omega}$$

where $max\|\nabla \mathrm{T}_{conv}\|_\Omega$ is the maximum of the norm of convection over the entire model, and $max\|\nabla \mathrm{T}_{diff}\|_\Omega$ the maxium of the norm of diffusion over the entire domain. The advantage of this definition

2.1 Numerical Implementation

The numerical tool used for this study is REDBACK, a new open source multiphysics simulator (Poulet et al., 2017). REDBACK is based on MOOSE, a finite-element multiphysics framework (Gaston et al., 2009). Details of the numerical implementation can be found in Tung et al., (2017); this section briefly summarises the main points.

In the context of hydrothermal convection in an active tectonic setting, the assumptions of an incompressible fluid and media degenerate and the momentum, mass, and energy balance equations then become:

$$0 = \partial_j \sigma'_{ij} - \partial_i p_f + \bar{\rho} g \delta_{i3}$$

$$\begin{aligned} 0 = \bar{\beta}\partial_t p_f - \bar{\lambda}\partial_t T + \left[(1-\phi)\beta_s v_k^{(s)} + \phi\beta_f v_k^{(f)}\right]\partial_k p_f \\ - \left[(1-\phi)\lambda_s v_k^{(s)} + \phi\lambda_f v_k^{(f)}\right]\partial_k T \\ + \partial_k\left(\phi\left(v_k^{(f)} - v_k^{(s)}\right)\right) + \partial_k v_k^{(s)} \end{aligned}$$

$$0 = \overline{\rho C_p}(\partial_t T + \overline{v_\iota}\partial_i T) - \kappa \partial_{ii}^2 T + \chi \sigma'_{ij} \cdot \dot{\epsilon}_{ij}^{vp}$$

In this study, we assume a tectonically active fault in geological timescales. This can be represented by a steadily creeping fault (which is past its yield criterion) in a relatively shallow reservoir. We implement the conservation equations in REDBACK using the normalisation parameters:

$$p^* = \frac{p_f}{\rho_o g H}, x^* = \frac{x}{H}, T^* = \frac{T - T_b}{T_b}, t^* = \frac{c_{th}}{H^2} t$$

We obtain the final set of equations solved for convection in reservoirs with creeping faults, where dimensionless terms are defined in Table 1:

$$0 = \partial_t p_f - \Lambda \partial_t T + v_i^p \partial_i p_f - v_i^T \partial_i T - \partial_i \left[\frac{1}{Le}\left(\partial_i p_f + p_f g_i \delta_{i3}\right)\right]$$

$$0 = \partial_t T + \overline{v}_i \partial_i T - \partial_{ii}^2 T - Gr\, \sigma_{ij} \dot{\epsilon}_{ij}^{vp}$$

Group	***Name***	***Definition***	***Interpretation***
Λ	Thermal pressurisation coefficient	$\frac{\bar{\lambda}}{\bar{\beta}} \frac{\delta T_{ref}}{\sigma_{ref}}$	Ratio of thermal expansion over compressibility of the mixture
Le	Lewis number	$\frac{\mu_f c_{th} \beta_m^*}{\kappa_\pi \sigma_{ref}}$	Ratio of thermal over mass diffusivities
Gr	Gruntfest number	$\frac{\chi \sigma_{ref} \dot{\epsilon}_{ref} x_{ref}^2}{\alpha \delta T_{ref}}$	Ratio of heat generated from mechanical deformation over the rate of diffusive processes

Table 1: Definition of dimensionless groups found in equations detailed in Section 2. In some groups, δ represents a free parameter used for numerical rescaling purposes.

In our system of equations solved, we use the Lewis number to detect the onset and evolution of convection. The drivving parameter for convection is permeability, which is present in both the Rayleigh and Lewis numbers. With respect to permeability, it can be noted that the Rayleigh and Lewis numbers are inversely proportional to each other hence, a system predicted to convect above a critical Rayleigh number will convect below a critical Lewis number. In this study, the effects of mechanical deformation from fault movement is expressed as shear heating. This mechanical dissipation is expressed by the Gruntfest number, Gr. In the case of a classical hydrothermal convection where no mechanical deformation is present, $Gr = 0$. Conversely, settings where shear heating is present will result in $Gr > 0$.

3. RESULTS

This section presents the results of the onset of convection using the pseudo-arclength continuation method in both cases of a rigid and tectonically active porous medium.

3.1 Convection in a Rigid Porous Media

In this section we show the results of a numerical bifurcation analysis for convection in a rigid porous medium. The equations solved for this problem correspond to the classical Horton-Rogers-Lapwood equations detailed in the previous section. Figure 5 (top) presents the transient simulation results of two scenarios with different critical Rayleigh numbers due to variations in boundary conditions. The corresponding critical Lewis numbers which predict the onset of convection are clearly marked in the stability curves presented below each transient result. Both models are homogeneous and have identical fluid and solid material properties.

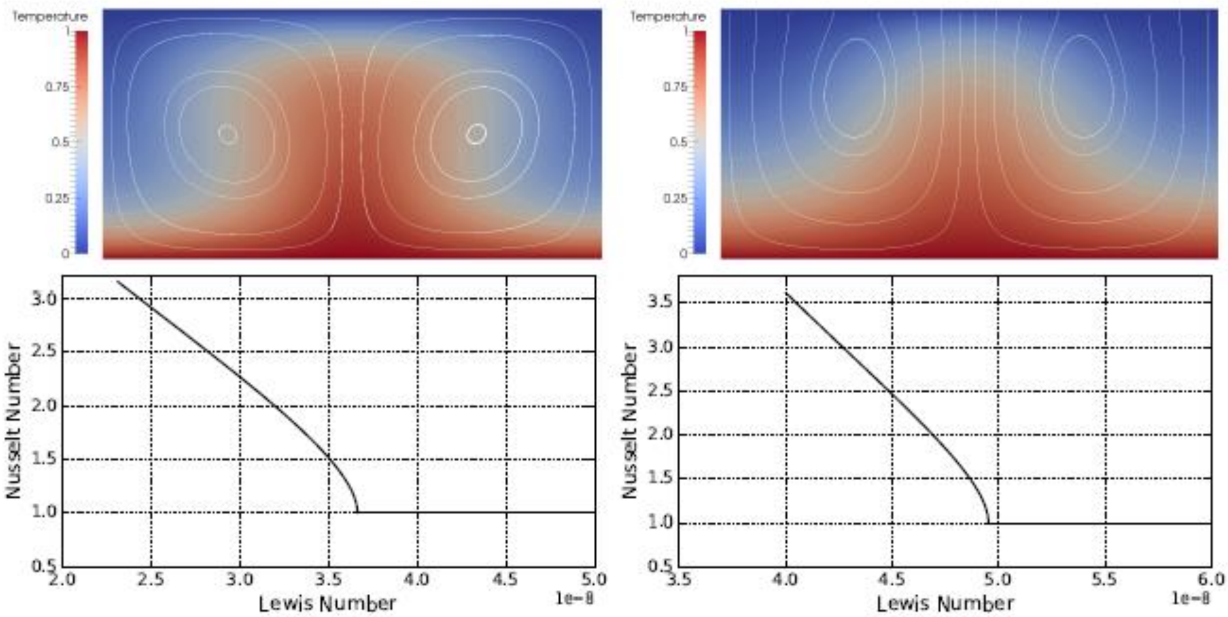

Figure 5: Results for the classical case of the onset of convection, taken from Tung et al., (2017). The two upper figures present the steady-state temperature profiles from a transient simluation. The bottom figures are the stability analyses for each case shown in the upper figures.

3.2 Convection in Porous Media with Creeping Faults

In the case of a steadily creeping fault, the effect of shear heating is expressed by the Gruntfest number; $Gr > 0$. The geometry consists of a 2D block with a fault cutting across a homogeneous geological unit. Initially, a simulation is run with the absence of mechanical deformation simulating classical hydrothermal convection (i.e. $Gr = 0$) to obtain the steady-state response of the system. Next, simulations with the addition of shear heating are run (i.e. increasing Gr). Figure 6 presents the steady-state responses of both the classical case of convection (top) and a case where $Gr = 10^{-2}$ (bottom) for this specific geometry.

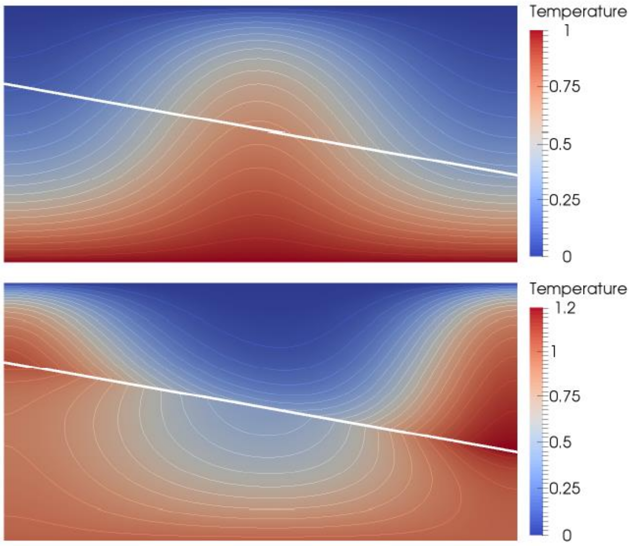

Figure 6: Steady-state results for the case of classical hydrothermal convection (top) and the addition of shear heating (bottom), taken from Tung et al., (2017). Temperature values are normalised between 0 and 1; however in the presence of creeping faults, additional heat is present in the system and is shown to localise along the fault.

In the case of no shear heating, the convective pattern across the model is predictably symmetrical and the presence of the fault has no effect on the pattern of convection. However with the presence of shear heating, the additional heat in the system increases the maximum temperature of the boundary conditions and localises along the fault (Figure 6, top).

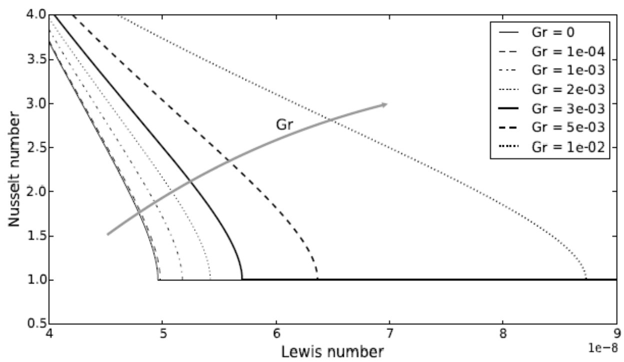

Figure 7: Stability analyses for varying Gruntfest numbers. As mechanical dissipation increases (i.e. higher Gruntfest), the critical Lewis value for the onset of convection is lowered.

Numerical bifurcation analyses were performed for the same material and geometrical properties, however only varying the Gruntfest number to evaluate the effect of shear heating on the onset of convection. Figure 7 presents the results for various values of Gruntfest.

With respect to the critical permeability at which convection is predicted to occur, it is observed in Figure 7 that, when more mechanical dissipation is present in the system (represented by increasing values of Gruntfest), the critical permeability required for the onset of convection is lowered. These results indicate that shear heating could potentially trigger convection in an initially non-convecting system.

4. CONCLUSIONS

The Perth Metropolitan Area (PMA) and Soultz-sous-Forêts (Rhine Graben) are exemplary major geothermal sites. In both locations, conductive, convective and advective processes play a vital role in transporting heat and fluid to the relatively shallow subsurface. Advective sweeps are driven by changes in hydraulic gradient and large permeability contrasts within the aquifers. Major faults play a fundamental role in both basins by pinning convection cells in the PMA, and acting as a fluid and heat conduit in the Soultz region. The understanding of heat-sensivite processes in and around faults are important as they can affect the onset and patterns of convection, which in turn has promising implications for the future of geothermal energy. The understanding of heat transfer in active shear zones can optimise geothermal production in significantly reducing drilling costs by targeting convective upwellings and localised regions.

These preliminary results, if evident in real cases, could also lead to new geophysical interpretations. By combining geophysical methods with numerical backward/forward modelling, the concept of this study can also be extended to greater scales and depths, such as investigating mantle topography and its relationship with crustal rheology.

ACKNOWLEDGEMENTS

This work was supported by the close collaboration between UNSW Australia and CSIRO under the auspices of an Unconventional Resources Research Initiative. K. Regenauer-Lieb, T. Poulet, S. Alevizos and M. Veveakis also acknowledge support by the Australian Research Council (ARC Discovery grants no. DP170104550, DP170104557). R. Tung was supported by the Australian Government Research Training Program Scholarship and acknowledges support from the Australian Technology Network's Industry Doctoral Training Centre (ATN-IDTC Scholarship).

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