NEXT GENERATION RESERVOIR ENGINEERING FOR A GEOTHERMAL FUTURE

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ABSTRACT

We postulate that the timing is ripe for Geothermal Energy to trigger a technological change within the coming 10 -15 years. This time frame is considered to be normal to push innovation for e.g. the medical sector from prototype to field test to 50% commercial penetration. Because of the massive scale of operation, the pace of technological change in the energy sector has, however, traditionally lagged behind by a factor of 2-3. The much-needed energy transition away from fossil fuels can only be accelerated by a global initiative where research-industry-and government join forces.

The proposed innovation, developed in our Unconventional Geomechanics/Geodynamics Team (*UGG-Team*), is a prototype reservoir simulation approach that uses knowledge about THMC processes to replace the current empirically based theories by a fundamental physics-based approach. The multi-scale simulator allows an **I**ntegrated **C**omputational **M**aterials **E**ngineering [*ICME*, 2008] approach for geosciences (dubbed "*Next Generation Reservoir Engineering"*).

1. INTRODUCTION

1.1 The Deep Geothermal Energy Dream

Deep energy extracted from hot basement rocks would allow proliferation of geothermal energy extraction beyond traditional volcanic sources. It is an international research challenge pushing the frontiers of geosciences and engineering sciences. Deep geothermal energy (in excess of 5 km depth) may present unexpected opportunities for deep reservoir engineering and beyond. While most projects have so-far been government funded Australia has made a first attempt at harvesting deep geothermal energy through private moneys and industry investment with only minimal government support. The results and the collected learnings of the project are that economical extraction of deep geothermal energy cannot be solved by classical concepts.

A new strategy for harvesting deep energy must be based on the unconventional nature of the material behaviour at high temperature and great depth. The deep geothermal power plant in Australia (1 MW) has shown that deep geothermal energy is a future energy source, however, it also revealed that classical reservoir engineering is not suitable to make it a full commercial success. We emphasize here that deep geothermal energy needs a careful quantification of uncertainties from exploration to production. This paper lays out a multiphysics based uncertainty protocol that respects the unconventional nature of the deep geothermal energy resource.

1.2 Working Hypothesis

Deep geothermal energy breaks into new frontiers in energy technologies and earth sciences. A careful design is required that acknowledge the unconventional nature of this new energy resource. On the other hand, it also offers new opportunities of co-production of valuable minerals that should be considered at an early stage in the process. The discovery of naturally occurring deep geothermal brines in otherwise low porosity/permeability environments was perhaps the most spectacular outcome of the continental deep drilling project (KTB) in Germany and the deep Australian geothermal prospect. Problems stemming from the lack of strategies for well control to deal with the unexpected extreme chemistry and the enormous overpressures of these deep fluids were lastly the reason for the failure of both projects. It is, however, argued here that this is not an intractable problem but rather an opportunity.

Because of their vast abundance these deep fluids may be regarded as game-changers for securing our future economy. As a side effect, they also allow the harvesting of minerals as or mineral by-products from deep geothermal fluid sources. This opportunity has been identified as one of the top-10 technologies that could transform our future by the World Economic Forum in Davos [*Summit*, 2014]. Such a disruptive technology would open the way for a new energy and resources industry assisting an imminent energy transformation through unlocking new geothermal resources with optimal environmental protection and assurance.

We propose to use the Unconventional Geomechanics/Geo-dynamics multiscale approach of coupling chemical, mechanical, thermal and hydrological processes and their interactions that operate over long-time scales to form and characterise the porosity/fracture networks in conventional and unconventional geothermal reservoirs. We apply that understanding to engineer that structure for the purpose of energy extraction and resource discovery. The interdisciplinary approach links geoscience, engineering and computational science disciplines with the potential to provide a step change in exploration and exploitation technologies.

2. MULTISCALE DATA ASSIMILATION METHOD

Data assimilation is based on a workflow of data acquisition and data compression (Figure 1). We present here a physics and chemistry based micro-structure material characterisation method augmented into a fully integrated data assimilation (data compression- acquisition) workflow from micro-scale to geodynamic scale (Fig. 1).

2.1 Why are current Big Data Workflows Insufficient?

Modern multi-sensor systems allow acquisition of what is commonly labelled "big data". Traditional data analysis cannot handle such volumes of data and new data processing methods have been designed to use the incoming information. These new methods are called data fusion, data wrangling, data mining and data integration followed by reduction or replacement. Such data compression is assisted by artificial intelligence or machine learning methods that try to identify and decode patterns in the data without knowledge of the underlying processes forming them.

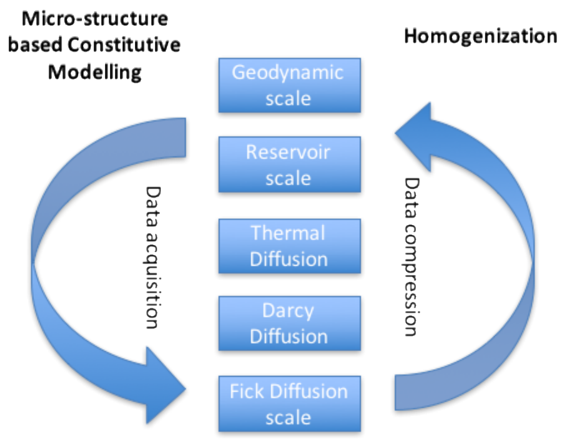

Figure 1: Multiscale-Multiphysics coupling with data assimilation.

Nonlinear system identification, inductive or descriptive statistics or Bayesian algorithms are conventionally used for pattern deduction and system identification (here called data compression (homogenization). Empirical or instinctual knowledge can also be used in the data compression step. In such an approach know-how of best practices of individuals is augmented and shared as "tribal knowledge".

This method is currently trialled by the Petroleum industry (https://www.ibm.com/watson/stories/woodside.html) on a remote oil platform in the North-Western Shelf of Australia.

We argue, however, that neither classical data fusion techniques nor cognitive learning (tribal knowledge) approaches will enable extraction of deep geothermal energy. This is because rocks at high temperatures and pressures behave different from their surface siblings. Their behaviour is simply outside of the realm of direct human observation and they can rarely be tested in the laboratory on time-scales that are relevant for the reservoir processes. An empirical approach, based on laboratory constrained classical continuum mechanics and fluid dynamics, is therefore not appropriate.

The main reason for the failure of classical models is that the dominant physics of processes in deep geothermal reservoirs is not well-established, the (macroscopic) conservation laws are inapplicable and consequently the classical continuum mechanics constitutive laws are inadequate. In order to facilitate deep geothermal extraction, we need to go beyond such first attempts and use robust multiscale data assimilation workflows for the determination of a common model of physical parameters, geological structure and deformation history. We develop in the following a physics-based data fusion approach based on the multi-physics processes that control the multi-scale porous media or fractured media permeability relationships.

2.1.1 Chemical Diffusion Length Scale

The surprising geochemical results of the nature of deep fluids encountered in the Habanero Wells in the Cooper Basin is here taken as a starting hypothesis for the porosity generation mechanism in deep granites. Geodynamics Ltd provided to the authors an unpublished but unclassified internal report entitled "Fluid Chemistry of the Innamincka Granite understandings of June 2010". The report indicates that the nature of the formation fluids is probably an igneous brine. All water derived from the granite is distinctively high in four elements: These are boron 220ppm, lithium 200 ppm, caesium 50 ppm, and rubidium 18 ppm. Samples with lower salinity are slightly lower in these elements. The unexpected presence of hydrogen in the formation waters (leading to the catastrophic hydrogen embrittlement problem and the blowout through 7 meters of concrete) suggests to us that the basic chemical reaction forming the fluids may be the dissolution precipitation reaction of K-Feldspar illustrated in Figure 2 where K-feldspar plus H^+ dissolves into Muscovite plus K^+ and Quartz in aqueous solution.

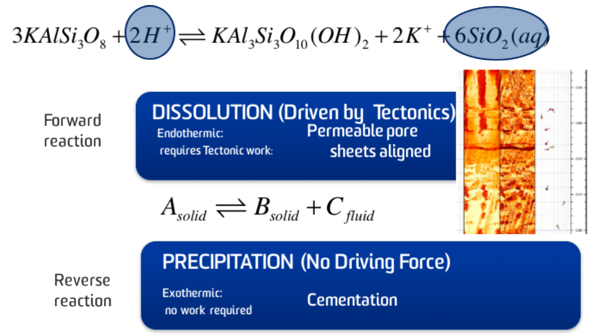

Figure 2: Chemical dissolution-precipitation reaction and creep fractures.

We argue that the nature of the fractures shown in the borehole image in Figure 2 is triggered by the far field stress field of the collision of Australia with Papua-New-Guinea. This led to the propagation of a thrust faulting system, enabled and lubricated by the porosity generation of the dissolution reaction. Alternatively, it may have reactivated an earlier fault system.

Porosity generation in creeping faults is well known to self-organize into void sheets ultimately causing so-called ductile- or creep fractures [*K. Regenauer-Lieb*, 1999; *Rybacki et al.*, 2008]. The necessary thermal activation of the process suggests that the fractures are only possible at elevated temperatures which could be an explanation for the observation that fractures are not recorded in the borehole images below a temperature of 230°C.

This is an extremely important observation and could be key to a fundamental process that would allow a predictive process-based multiscale framework. The process must be observed in any granite under similar conditions and should be universally encountered. It can hence be tested in other applications. Consequently, we have developed a multiscale approach based on these observations and applied it to explain the unsolved geodynamic problem of the Musgrave and Arunta orogeny in Australia, which may have led to the apparent buckling of the interior of the Australian continent [*K. Regenauer-Lieb et al.*, 2015].

The approach can be extended to any lithology through the generic porosity/fluid generation reaction A_{solid} forming a solid compound B_{solid} and a fluid compound C_{fluid} (Fig.2). The chemical reaction has a length scale that is controlled by Fick's law. However, it is capable to jump the scales from millimeters to meters by the production of the fluid phase which is transferred to the porous matrix by Darcy's diffusion law.

Chemical processes can be investigated in the synchrotron at high enough resolution by SAX images which allows identification or verification of the basic mechanism of porosity generation.

2.1.2 Darcy Diffusion Length Scale

If the porous network is sufficiently large we may homogenize it by Darcy's law and thus encounter a new length scale which as a general rule is given by the square root of the product of diffusivity times the time until the process reaches a steady state. This length scale is on the order of millimeters to centimeters and can be imaged by high resolution X-Ray CT images.

2.1.2 Fourier Diffusion Length Scale

The diffusion of heat is the main process of interest for a geothermal problem and also the largest scale of the multi-physics mechanical coupling. The thermal diffusion length scale (again the square root of the product of thermal diffusivity times the time to reach thermal equilibrium) is controlling all observations at reservoir and geodynamics scale and can be derived from the width of fault zones imaged by geophysical observations of the reservoir.

2.1.2 Reservoir and Geodynamics Length Scale

Deep faults can be detected by imaging methods using advanced geophysical imaging, geological and geochemical methods. Deep exploration forms the first step in the deep geothermal energy strategy. Promising geophysical techniques are seismics combined with magnetotelluric methods and inverse methods. The proposed techniques are therefore a combination of Magneto Telluric (MT) and seismic methods. The MT method allows characterization of the electrical conductivity at great depth but has resolution limits of around 100m at 5 km depth. The seismic method, conversely, is much more accurate in spatial resolution but does not indicate the fluid transmissivity. A combination of both methods allows a characterization of the deep structure. Using existing natural geological faults (to be enhanced) instead of the old (unsuccessful) concept of engineering a hydraulically fractured volume in between the injection and production wells highlights the need of this important geophysical/geological structure identification. This information needs to be combined with other geophysical/ geological/chemical and mechanical information in a quantitative uncertainty analysis to clearly identify the economic factors and the risk of the project.

Deep faults are also visible through their geochemical fingerprint as they degas volatiles, which ultimately get trapped in the groundwater. Integration of other geophysical (gravity, magnetic, electric, seismic) and geological (geochemical, structural) databases should allow the design of a first target reservoir model. As this first model is largely unconstrained an important aspect is the quantification of uncertainty.

2.2 Data Compression

Data compression or homogenization is using knowledge of the physics (and chemistry) of the processes to correctly average the next scale up using a forward simulation tool. The outcomes are a simpler (lower dimensional) model definition for the next scale up respecting the material heterogeneity at smaller scale, a determination of the critical parameters underpinning dynamic material behaviour such as instabilities and the development of innovative uncertainty measures quantifying the inherent structural complexity, the stochastic nature of geological structures [*Wellmann et al.*, 2010; *Wellmann and Regenauer-Lieb*, 2012] and the time-dependent material variability [*K Regenauer-Lieb et al.*, 2010]. Communication of uncertainty also applies to the above-described multi-scale coupling and homogenisation.

The method of data compression is best explained by the following analogy: Consider an image on a computer screen, which when viewed close up can be seen to be made up of individual red, green and blue dots of varying intensity. At a greater distance these dots are not seen by the human observer but blurred, whereby all the different colour dots are merged into an apparent new homogenous colour. Thus, the complexity (dimensionality) of the problem breaks down because the reds, greens and blues and intensities are compressed into a single colour and intensity value. Observed at a larger scale the homogenised colours create a picture (e.g. a sunset), which conveys information that would be very difficult to discern observing the individual dots.

3. PUTTING IT ALL TOGETHER

The complete physics-based data assimilation framework requires forward and inverse modelling efforts of the underpinning multi-scale processes. This is a plan for the future as it would require collaboration of a large group and cannot be done in a single team. A pilot study has already been put forward as part of a collaboration between UNSW and CSIRO for the similar problem of mineral exploration and is shortly described below.

3.1 Geophysical Inverse Modelling

The above described framework allows us to provide robust estimate of risk and uncertainties. This is needed to make exploration decisions in an uncertain world with more complex deposits being the area for the mining or geothermal prospects of the future. Next generation reservoir models will be characterized by the necessity to go deeper in order to achieve higher temperatures; exploration efficiency will be paramount in supporting a sustainable geothermal and industry. In order to boost deep geothermal resource discovery rates, we need to go beyond drilling and mapping and use robust inversion workflows for the determination of a common model of physical parameters, geological structure and deformation history.

A fully integrated data acquisition template for log-satellite scale requires a machine learning algorithm (Figure 3) to be linked at appropriate scale to the various scales of the physics based forward common material model, derived from the forward model (at the respective scale) from micro-CT to satellite scale.

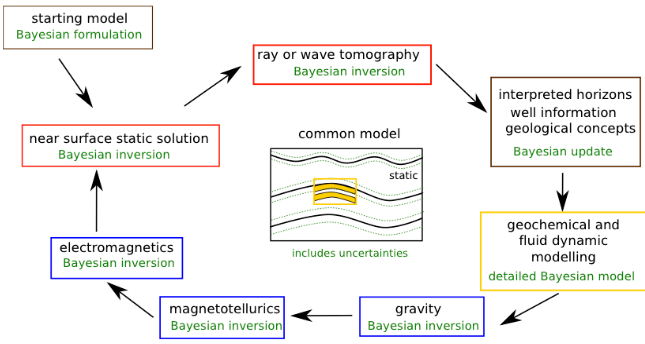

Figure 3: Inverse Modelling framework with uncertainties (Juerg Hauser, CSIRO).

3.2 Multiphysics Forward Model

The core numerical engine supporting the forward model is the MOOSE (Multiphysics Object Oriented Simulation Environment) framework developed for fully coupled, nonlinear, multiphysics applications. Here, ‘‘fully coupled’’ refers to solving all of the coupled partial differential equations (PDEs) simultaneously. Each MOOSE based application is made up of physics ‘‘modules’’ that describe the PDEs to be solved, material properties, boundary and initial conditions, postprocessed quantities, etc. We have recently released the open source MOOSE module REDBACK [*Poulet and Veveakis*, 2016] specifically designed to transfer the technology from physics-based nuclear reactor modelling to the geothermal/mineral next generation reservoir engineering applications.

Of particular interest to the suggested data assimilation framework is the MultiApp capability of MOOSE. MultiApp applications to run simultaneously in parallel. A single MultiApp might represent thousands of individual solves (for example, thousands of individual microstructure calculations in a multiscale simulation). Each subsidiary application (or ‘‘sub-app’’) within a MultiApp is considered to be an independent solve. There is always a ‘‘master’’ application at the top level and a hierarchy of MultiApps beneath it.

4. CONCLUSION

ICME for solving the deep geothermal energy challenge is expected to be particularly rewarding as it allows us for the first time to link and test via multi-scale computational experiments processes that may require engineering intervention in seconds to those that span the entire reservoir lifetime of the resource. These processes can in turn be carefully calibrated through existing laboratory data or an intermediate step of laboratory based experiments and field observations at multiple scales. ICME is the missing glue between the seemingly disparate chemical-microphysical-reservoir engineering-geophysical and geological-disciplines and observations.

More succinctly this computational architecture will allow an explosion of accurate simulations in solving previously intractable earth sciences and engineering problems. It may allow us for the first time to link reservoir scale chemistry, physics and its multiscale geological and geophysical processes. As such, the outcomes may by far exceed our present view of the capacity of quantitative modelling in earth sciences and engineering.

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