Next Generation Resource Discovery linking Geophysical Sensing, Modelling and Interpretation

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SUMMARY

We present a status report on the next generation data assimilation techniques for Resource Discovery using a new multidisciplinary fundamental science approach. We combine a recent multiphysics, multiscale geodynamic theory with laboratory and modern computational assisted petrophysics and material science concepts with the aim of linking it "on the fly" to geological and geophysical field data acquisition. This solid science base is designed to build the platform for enabling a data intensive paradigm for the resource industry. Such a physics-based big data interpretation opportunity has not yet been exploited in current geoscience applications. In other disciplines the approach is, however, fully realized. Owing to its major impact it has been hailed by the US National Research Council [*ICME*, 2008] as a transformational discipline for improved competitiveness and national security. The approach has been pioneered in polymer sciences, the automotive and aerospace engineering as well as in computational biomechanics, via a so-called "Integrated Computational Materials Engineering" (ICME) cyber-infrastructure. An ICME system unifies materials information into a multi-scale system that is linked by means of software integration tools to a designer knowledge base containing tools and models from different scales and different disciplines.

Key words: Physics-based modelling, multiscale, multiphysics, data assimilation

INTRODUCTION

Australia has pioneered innovative WEB- based data compilations through the AUSCOPE NCRIS funding and its Portal as an entry web application for the Earth Science community and other interested users to discover and acquire data from various services of interest (http://portal.auscope.org/portal/gmap.html). There have also been pioneering attempts at merging the data using the machine learning algorithms (https://www.nicta.com.au/category/research/machine-learning/projects/geothermal-data-fusion/). To this date this has been achieved without full physics-based ways to connect the data at the different scales and relate the information to the specific processes that operated to produce mineralisation.

We emphasize that a simplified machine learning approach is insufficient as the dominant physics is not well-established, the (macroscopic) conservation laws are inapplicable and the classical continuum mechanics are inadequate. In order to boost mineral resource discovery rates, we need to go beyond such first simple modelling attempts and use robust multiscale data assimilation workflows for the determination of a common model of physical parameters, geological structure and deformation history. We report here on extending and integrating a petroleum industry standard micro-CT based material characterisation method into a fully integrated data assimilation (data compression- acquisition) workflow for next generation resource discovery.

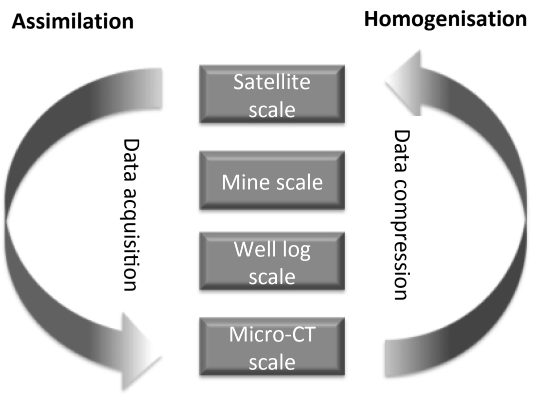

Figure 1 The classical multi-scale data assimilation approach in ICME applied to resource engineering applications.

METHOD AND RESULTS

DATA COMPRESSION (Homogenisation):

Data compression or homogenisation (Figure 1) 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 [Regenauer-Lieb et al., 2014; Wellmann and Regenauer-Lieb, 2012] quantifying the inherent structural complexity, the stochastic nature of geological structures and the time-dependent material variability. 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. is flexibility as to the naming of the section (or sections) that provide information on your method and results. In the following sections we describe the current developments for uncertainty quantification and data fusion from core scale to satellite scale.

Micro-CT scale (Core scale)

Recently an innovative technique has been developed that has the potential to provide a common basis for rock properties such as seismic velocities, thermal and electrical conductivity, magnetic properties, permeabilities, elastic and plastic mechanical properties and flow rules [*Arns et al.*, 2005; *J. Liu et al.*, 2015; *Jie Liu et al.*, 2014; *Regenauer-Lieb et al.*, 2014]. The advantage of this approach is that all properties are related thus narrowing the search space and defining uncertainties in the most fundamental form. This innovative technology has reached industry standard maturity and is currently used in petroleum resource engineering. One of their major achievements in this area is the creation of Digital Rock Technology. Launched in 2009 as Digitalcore, this unique technology was produced as a result of joint Australian National University and UNSW research, and enables digital rock analysis for the efficient recovery of hydrocarbon resources. Its recent merge with the Norwegian spin-off Numerical Rocks gave rise to Lithicon AS, which has been sold for $68 million to a US-based company. Importantly, digital rocks constructed from tomographic images have fed into the development of structural description including the solution of relevant physical equations and upscaling and, finally, post-processing including a local analysis of results with an increased understanding of rock properties through integration with experiments. For geophysical interpretation we appeal in particular to being able to explicitly obtain linked material properties from one and the same data set thus reducing the uncertainty significantly through a “common material model”.

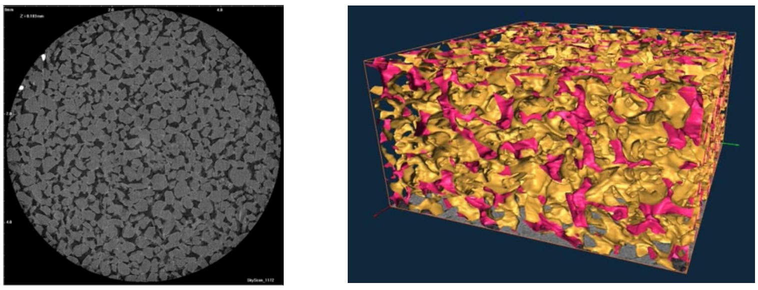

Figure 2: Gray scale image of a slice of the synthetic sandstone (left) and 3D image of the connected pore network supporting Darcy flow of fluids in red (right). We have used this ideal rock as a benchmark for testing our digital-rock simulator [*J Liu and Regenauer-Lieb*, 2011].

Well-log scale

Materials are heterogeneous at all scales. Of particular concern is connecting the “common material model” derived from core scale to the length scale of the wavelength of the geophysical analysis. If boreholes through the region of interest are available we can extend the technique from the digital rock analysis of the micro-CT scale to the borehole logs thus supplying an upscaled material property at the appropriate wavelength for the mine scale geophysical inversion (see next chapter). In most cases boreholes are not available and we have to resort to a physics based upscaling technique. This is a relatively new field of research and possibly the most interesting for the resource discovery as it allows to predict the relevant geophysical properties of the target resource material allowing a much improved fine-tuned geophysical exploration for resource discovery.

In this context the identification and characterization of fractures and their mineralized damage zones is of interest. We have recently developed a physics-based model for damage zones which has been tested successfully on a fault zone in New Zealand (unpublished work). The method has originally been developed to model the equivalent ductile localization features such as the periodically banded dolomites that are frequently associated with mineralization of the Mississippi Valley-Type deposits (Fig. 2).

We transfer a technology successfully used to upscale the properties of a nuclear fuel rod to the full scale reactor modelling [*D R Gaston et al.*, 2015]. The approach has been tested and pioneered by “Fuels Modelling and Simulation Department, Idaho National Laboratory (INL)” in the United States. The computational method is a finite element-based multiphysics, multiscale solver with solid mechanics and heat transfer using the multiphysics object oriented simulation environment MOOSE [*D Gaston et al.*, 2009]. We have a long-standing collaboration with INL and have developed our own open source REDBACK (https : //github.com/pou036/redback) module for MOOSE.

Mine scale

For mine scale forward modelling and data assimilation we use the above described enriched continuum formulation based on MOOSE. The formulation averages the log-scale features in terms of a thermodynamically consistent damage mechanics formalism capturing the discrete instabilities of log-scale as “smeared continuum damage”. This formulation has successfully been used to model the damage zones supporting fluid flow in the 5km deep geothermal project in the Innamincka granite (project for Geodynamics Ltd in the Cooper Basin). The deep granitic fluids have been found to be of igneous origin confirming the K-Feldspar dissolution-precipitation mechanism that was found to support damage zones observed for > 230°C [*Schrank et al.*, 2012].

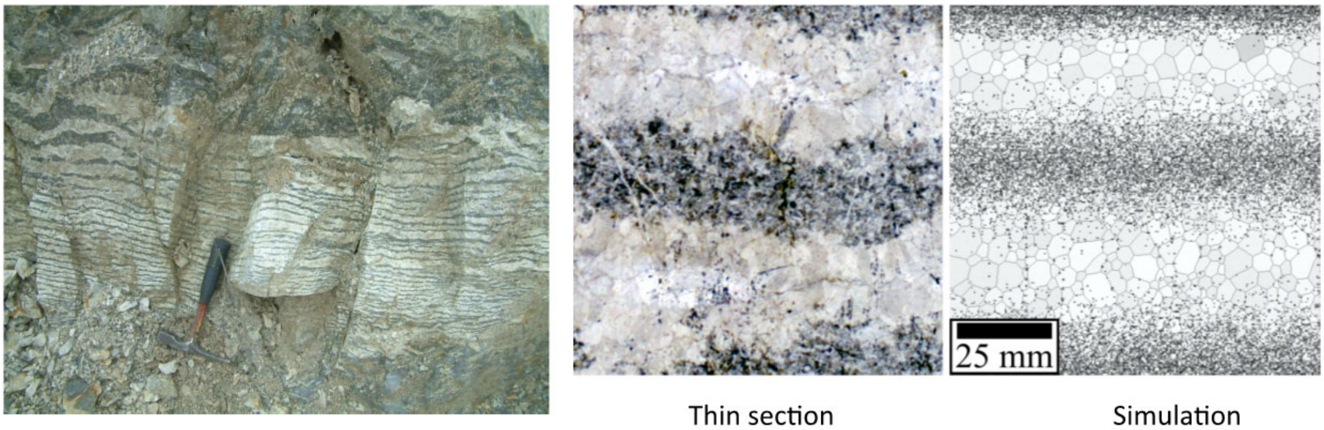

Figure 2: The first mineralisation model of the new log-scale data compression approach reveals the multiphysics mechanism that underpins the "Zebra Band" pattern formation in Mississippi Valley-Type deposits. In addition to the physics based upscaling methods this knowledge allows us to infer from the distance measure of the "Zebra Bands" basic material properties, fluid (mass) flow associated with the deposits, critical condition for formation of bands and from a forward model for filling data acquisition gaps [*Kelka et al.*, 2016].

Satellite scale

This is the largest scale of the geophysical forward calculations using the same (micro-log-scale derived) damage mechanics approach as for the mine scale calculations but investigating deformation processes over longer time and length scales (tens to hundred million years, thousands of kilometres). We have already tested a first multiscale application that allows linking our existing advanced material characterization methods from nanoscale through laboratory-, field and geodynamic scales into a new rock simulation framework [*Regenauer-Lieb et al.*, 2015]. The outcome of our simulation is that the diachronous Australian intraplate orogenic events (Musgrave and Arunta) are found to be caused by a non-linear progression of a fundamental buckling instability of the Australian intraplate lithosphere subject to long-term compressive forces.

DATA ACQUISTION (Data Assimilation)

The above described physics-based multiscale upscaling methods provide the basis for a fully quantitative uncertainty framework for exploration decisions in an uncertain world with more complex deposits as the area for the mining of the future. Future mining will be characterized by the necessity to mine deeper ores of lower grade; exploration efficiency will be paramount in supporting a sustainable mining industry. In order to boost mineral 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. We have not yet implemented data assimilation beyond the micro-CT scale but describe here the framework that is currently developed. In order to illustrate the multiscale data assimilation method, we come back to the analogy discussed in the introduction of the data compression section.

Data acquisition is the opposite physical process to data compression. It imposes the necessary restrictions to the simulations and allows prediction of past and future states of the system based on comparing the proposed physics with the data. In the data assimilation step the physical model used in the forward model, used for homogenisation, is interrogated by the data available at both scales through an inversion process. This allows considerations of uncertainty in the data and optimisation of model prediction. For example in a sunset image, the process of the sunset will tell the observer what gradients we can be expected from one colour to their nearest neighbour. The modeller can make a good guess for the neighbouring colour and verify the prediction in the data assimilation step. The observation on this scale therefore helps to filter out the information and reduces the uncertainty.

A fully integrated data acquisition template for log-satellite scale requires a probabilistic inversion scheme as shown in Figure 3 [*Hauser et al.*, 2015] 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.

MULTI APP SOFTWARE FRAMEWORK ENABLING MULTISCALE DATA ASSIMILATION

The core numerical engine supporting the above-described workflow 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 resource applications.

Of particular interest to the suggested data assimilation framework is the MultiApp capabilitiy 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 (Figs. 1).

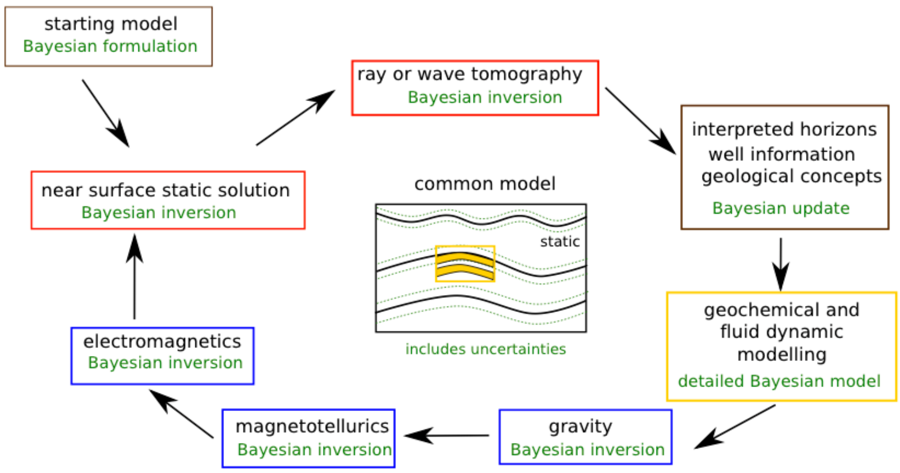

Figure 3: **Common Earth model with uncertainties [*Hauser et al.*, 2015].**

CONCLUSIONS

This paper describes the first steps for implementing an ICME framework for resource discovery. ICME for earth resources 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 will 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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