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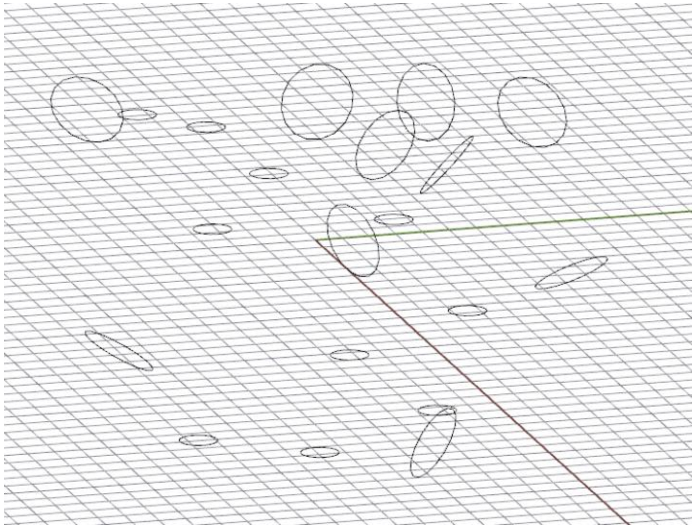
Next Generation Geomechanics Simulation



Dr. Adriana Paluszny
Dept. of Earth Science and Engineering
Imperial College London

May 23rd, 2019

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Fractures underpin a range of Technologies and Fields

I have created a rigorous 3D computational geomechanics framework that can be applied to numerous fields

Unconventional gas extraction
Create fractures to increase permeability.

Geothermal energy
Create fractures to increase permeability.

CO_2 sequestration: caprock integrity
Prevent fractures in caprocks to prevent leakage.

Oil/Gas
Fractures are in reservoirs and caprocks.

Geology
How do patterns form?

Bioengineering
What makes bones strong?

Advanced materials
Control fractures in designed materials.

Civil/Mechanical engineering
Prevent fractures in objects and structures.

Drilling
Drill deeper, reduce cost.

Mining fragmentation
Reduce cost of crushing rocks. Enhance permeability.

Geological storage of radioactive waste
Quantify permeability of potential storage sites.

How can we study fractures?

Why develop a computational model?

- Subsurface geomechanical systems are difficult to observe
- High pressure and high temperature *in situ* conditions
- Variety of length and time scales
- Effects of multiple natural or engineered events

Is there a computational method available?

- Civil/Mechanical Engineering: most accurate but focused on the growth of <u>single fractures</u>, do not generally model the post-failure regime
- Reservoir Engineering: does <u>not rigorously model growth</u>
- Hydrogeology: coupled thermo-poro-mechanical tools consider fractures, but <u>not fracture/fault growth, simplified apertures</u>
- Mining: fragmentation modelled using mostly <u>empirical models</u>, not coupled with flow and temperature

<u>There is no "off-the-shelf" solution</u>

Challenges:

- The problem involves a lot of physics: mechanics, fluid flow, thermal effects
- Solving coupled equations of fluid flow and mechanics is computationally expensive
- It is difficult to resolve geometric changes during growth and resolve intersections
- Requires adjusting the discretisation of the model; this is expensive
- A true coupled simulation requires computing fracture apertures
- The 3D problem is considerably more challenging than in 2D

My approach:

- ✓ treat each challenge using the most robust technique possible,
- ✓ model fractures in the greatest detail possible,
- ✓ and solve challenges one at a time.

In 2010, I created a new simulator: the Imperial College Geomechanics Toolkit

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Overview of my core research

Subsurface flow and permeability

Coupled thermo-poro-mechanics

SIMULATOR: Imperial College Geomechanics Toolkit (ICGT)

created by Adriana Paluszny

Fracture pattern growth

Multiple scale heterogeneities

current funding

Royal Society Fellowship

+ Research Grant

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1

Mining

funding

Rio Tinto

National Oilwell Varco

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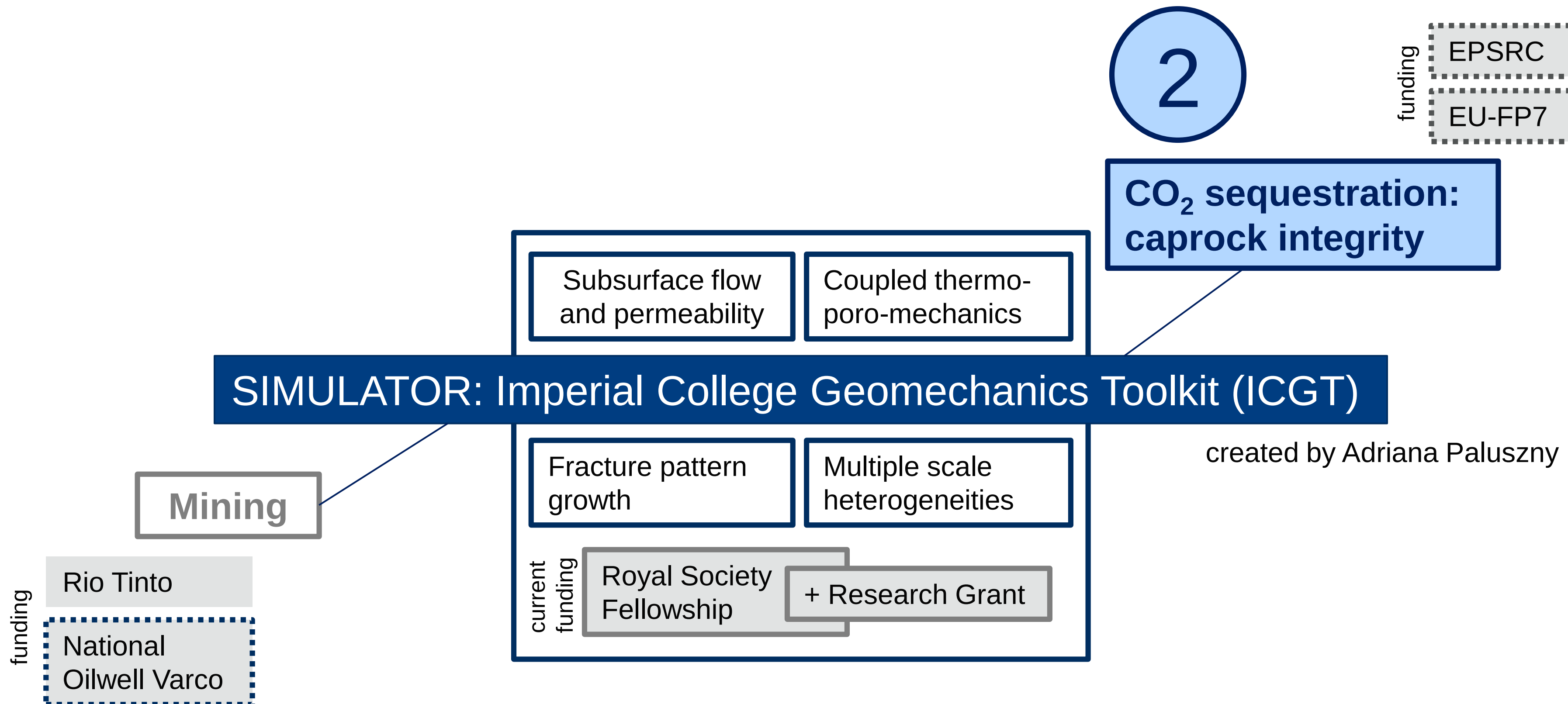
Overview of my research



Overview of my research

current funding: NERC-UH

3

Unconventionals

funding: EPSRC, EU-FP7

CO_2 sequestration: caprock integrity

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Fracture pattern growth

Multiple scale heterogeneities

current funding: Royal Society Fellowship + Research Grant

Mining

funding: Rio Tinto, National Oilwell Varco

Overview of my research

NERC

current funding

Swedish Waste Management Co

4

Radioactive waste disposal

current funding

NERC-UH

Unconventionals

funding

EPSRC

EU-FP7

CO_2 sequestration: caprock integrity

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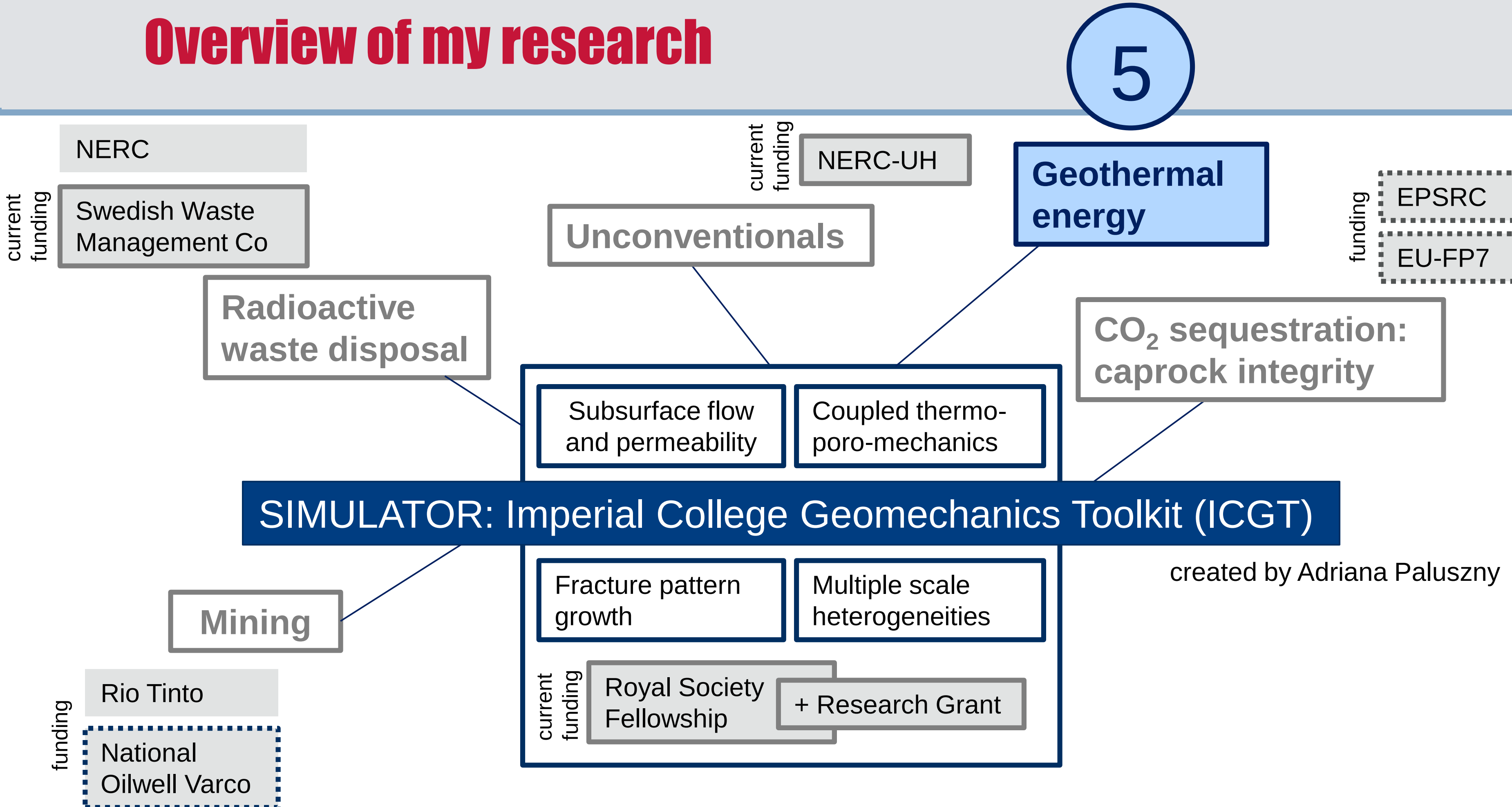

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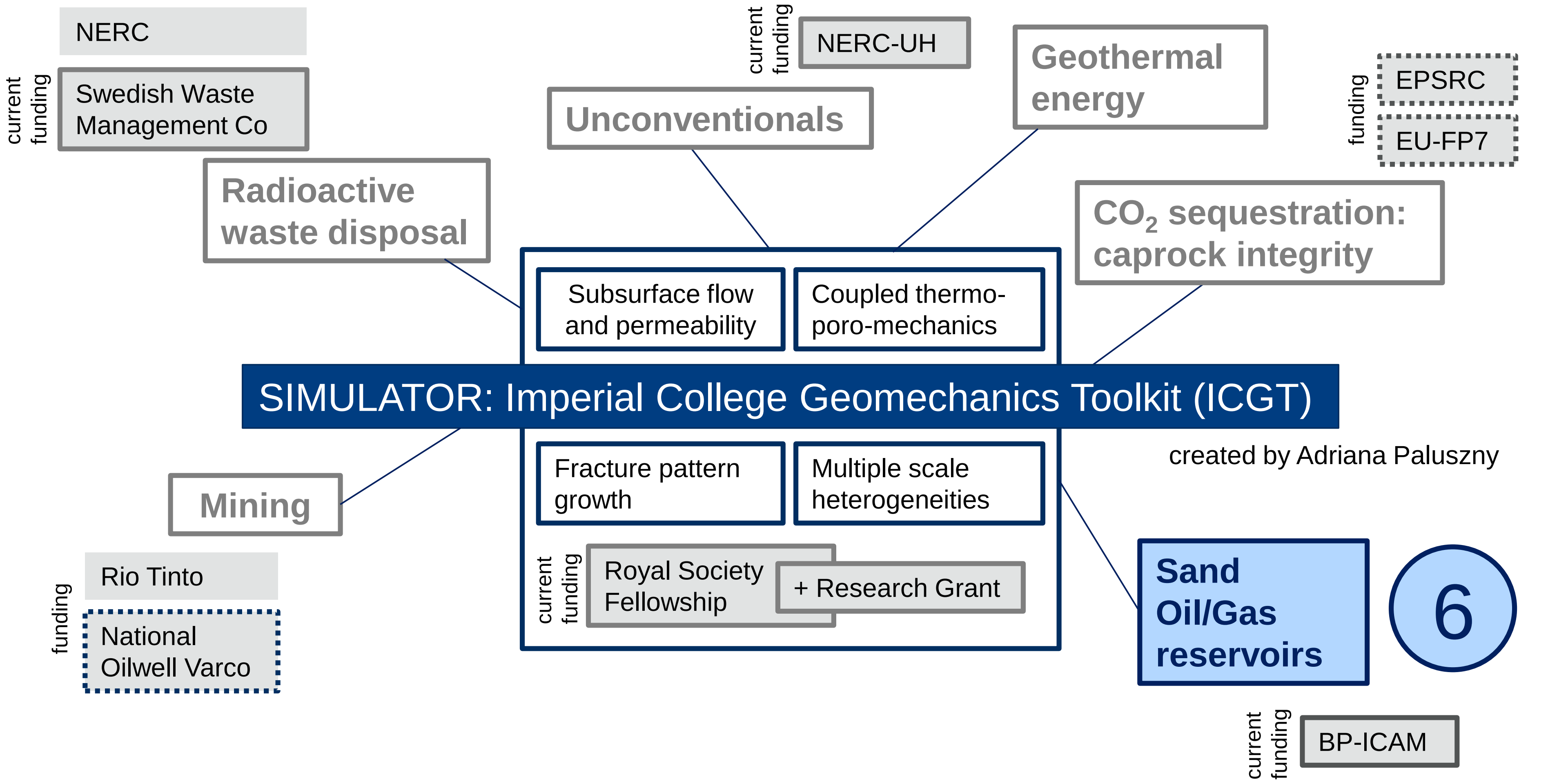

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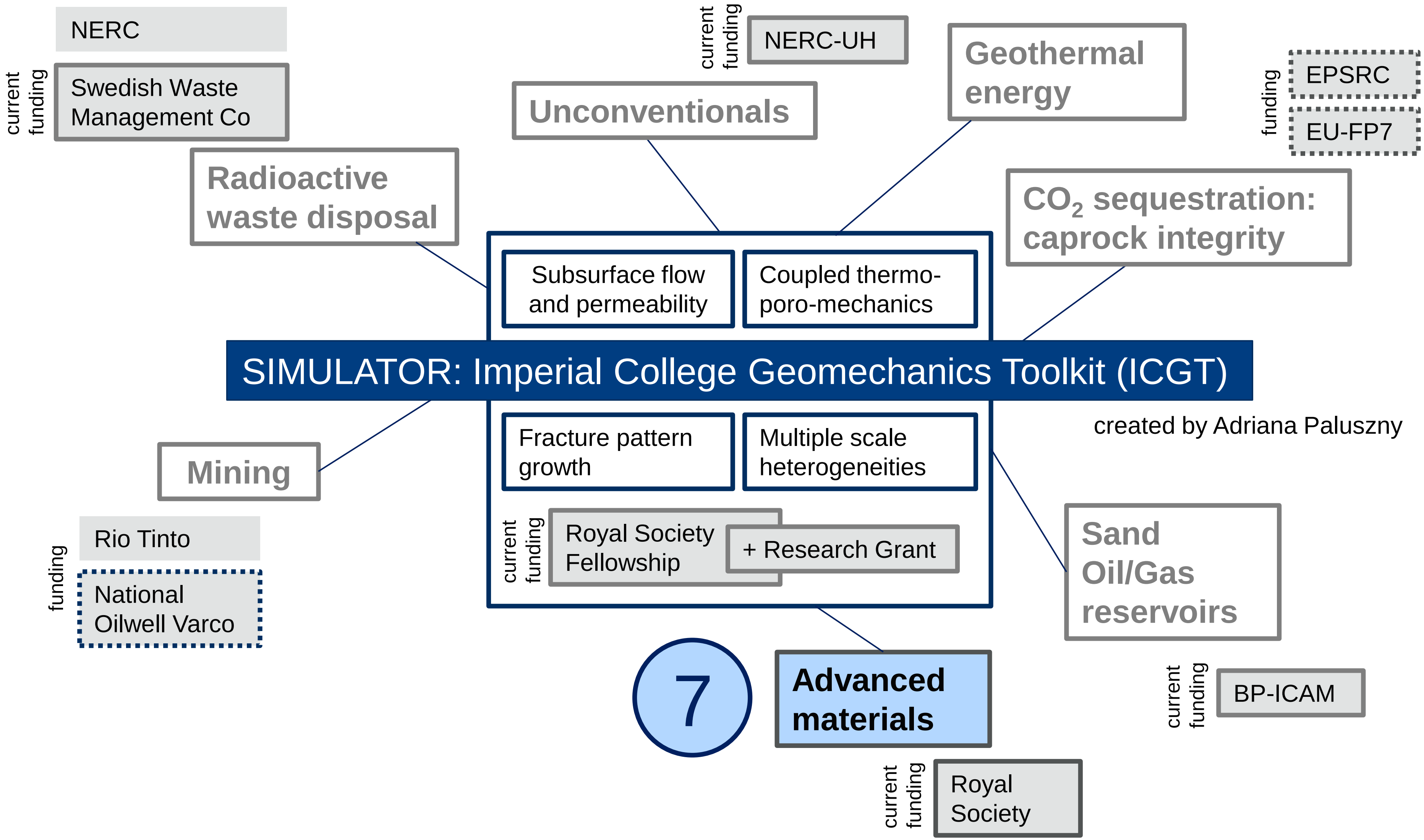
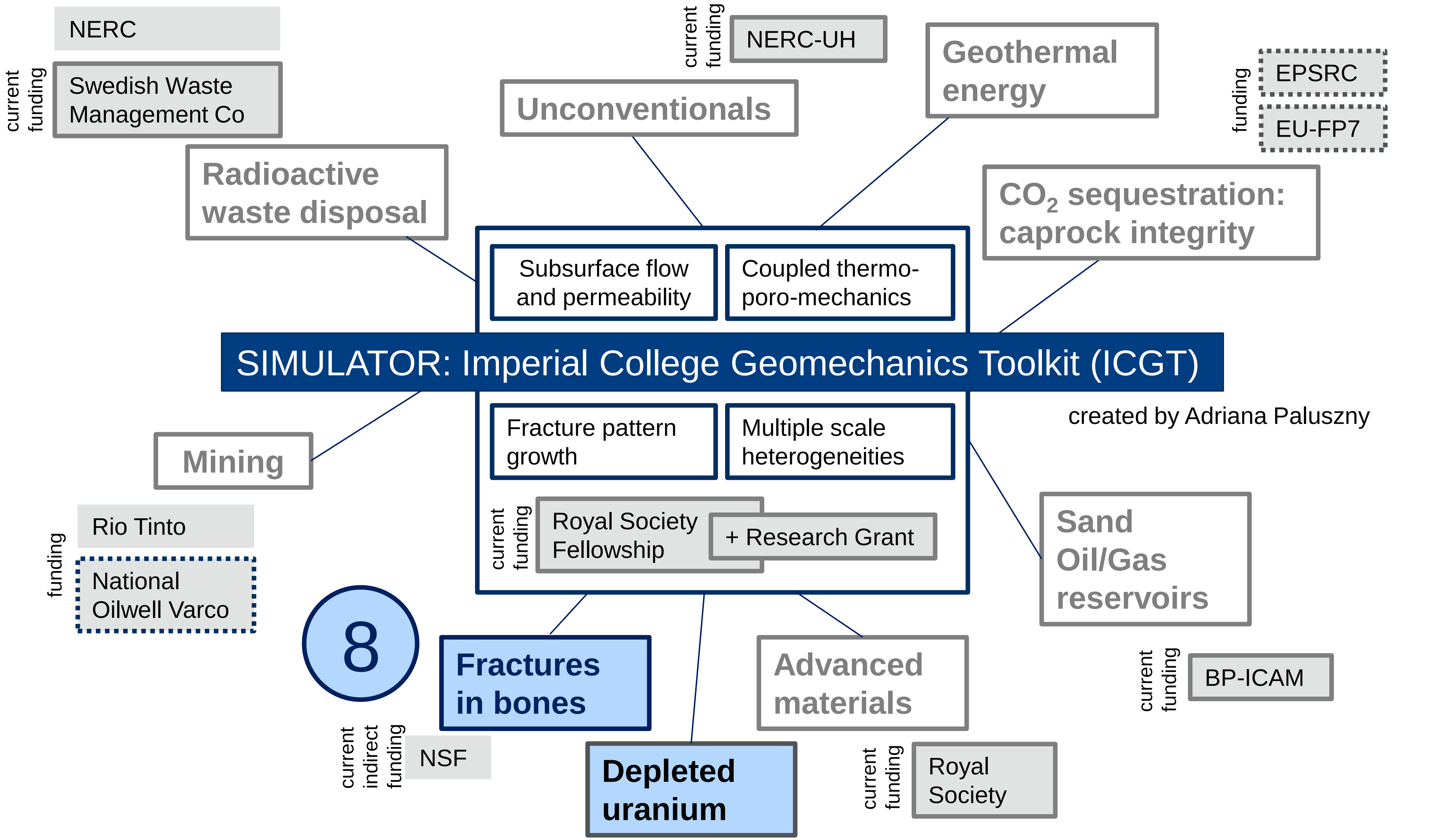
Overview of my research



Overview of my research



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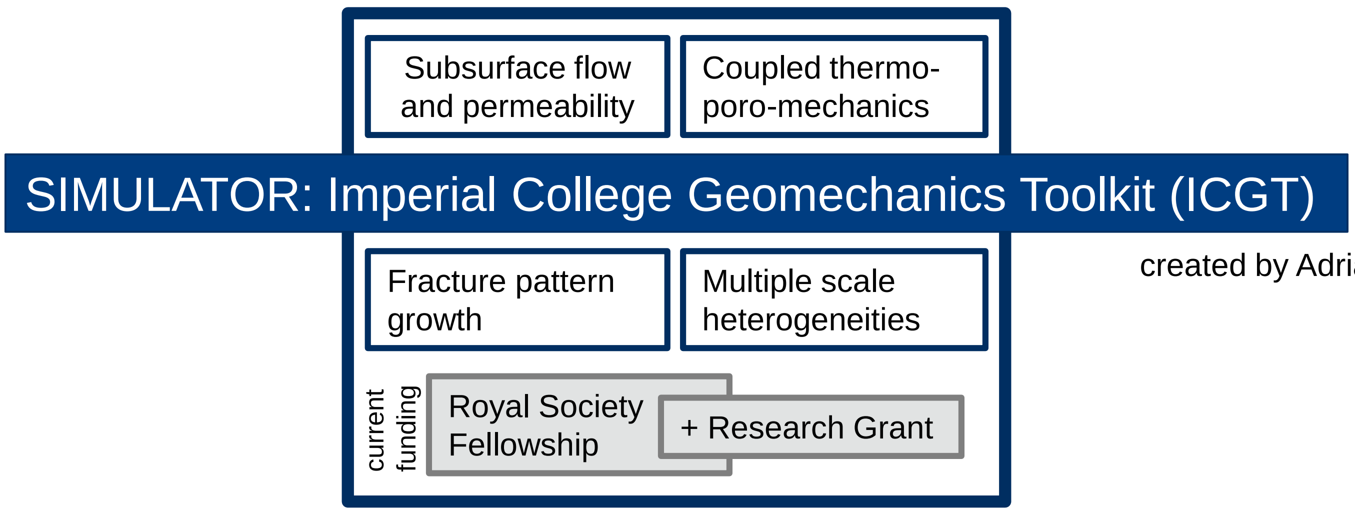
Overview of my core research



created by Adriana Paluszny

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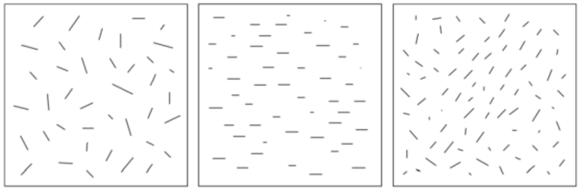
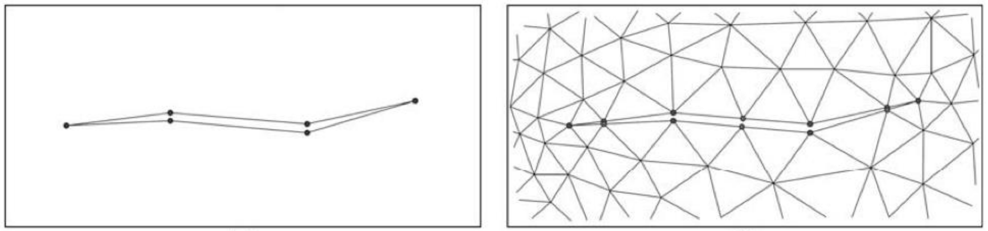
Simulation Methodology

- Non-planar 3D multiple fracture growth
- Based on the solution of first principle continuum mechanics equations
- Solves monolithically coupled thermo-poro-mechanical deformation
- Computes energy concentrations at the tips

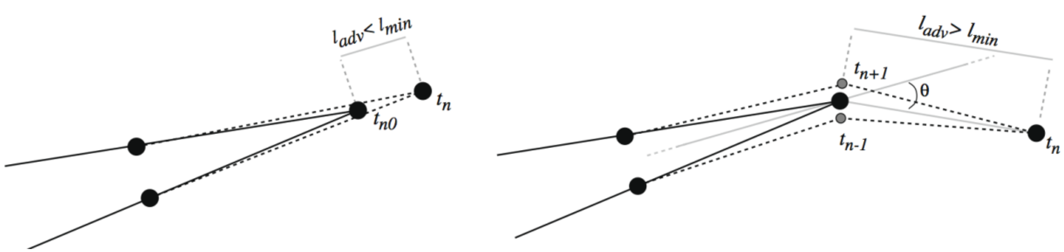
Initial flaws/fractures



Growth independent from mesh: adaptive remeshing



Energy-based growth laws: propagation extension and angle



Paluszny & Matthäi, IJSS, 2009; Paluszny & Zimmerman, CMAME 2011, EFM 2013; Salimzadeh et al., 2017, 2018; various Paluszny ARMA publications

Governing equations

Measurable input properties (Young's modulus, Poisson's ratio, toughness, friction, matrix permeability, Biot coefficient, thermal coefficients)

The displacement governing equation, the linear momentum balance equation for a fully-saturated fractured rock matrix, is given by:

$$\int_{\Omega} [\mathrm{div}(\mathbf{D}\boldsymbol{\varepsilon} - \alpha p_m \mathbf{I} - \beta_s K(T_m - T_0)\mathbf{I}) + \mathbf{F}] d\Omega + \int_{\Gamma_c} [(\boldsymbol{\sigma}_c - p_f \mathbf{n}_c) + \mathbf{F}_{\Gamma_c}] \partial\Gamma = 0$$

Includes tractions and stick/slip conditions for friction solved using a contact-based, augmented-Lagrangian approach (Nejati, Paluszny, Zimmerman, CMAME, 2016)

The matrix flow governing equation is given by:

$$\int_{\Omega} \mathrm{div}\left(\frac{\mathbf{k}_m}{\mu_w}(\nabla p_m - \rho_w \mathbf{g})\right) d\Omega$$

$$= \int_{\Omega} \left[\alpha \frac{\partial(\mathrm{div}\,\mathbf{u})}{\partial t} + \left(\phi c_w + \frac{\alpha - \phi}{K_s}\right)\frac{\partial p_m}{\partial t} - ((\alpha - \phi)\beta_s + \phi\beta_w)\frac{dT_m}{dt} - Q_{p_m}\right] d\Omega + \int_{\Gamma_c} \frac{k_n}{\mu_w}\frac{\partial p}{\partial \mathbf{n}_c} d\Gamma$$

And, the governing equation for fluid flow through the fracture, incorporating thermal effects, is:

$$\int_{\Gamma} \mathrm{div}\left(\frac{a_f{}^3}{12\mu_w}\nabla p_f\right) d\Gamma = \int_{\Gamma} \left[\frac{\partial a_f}{\partial t} + a_f c_w \frac{\partial p_f}{\partial t} - a_f \beta_w \frac{\partial T_f}{\partial t} - Q_{p_f} - \frac{k_n}{\mu_w}\frac{\partial p}{\partial \mathbf{n}_c}\right] d\Gamma$$

where apertures are defined as (Paluszny & Matthäi, 2009):

$$a_f = (\mathbf{u}^+ - \mathbf{u}^-).\mathbf{n}_c + a_f{}^c$$

Laminar flow in fractures, Darcy flow in matrix
Two additional equations govern thermal conduction and advection

Discretisation of the equations

The finite element method is used to numerically solve governing equations.

Spatial discretisation is performed through the Galerkin method, while finite difference techniques are used to solve time evolution.

The set of discretised equations can be expressed in matrix form of

$$\mathbb{S}\mathbb{X} = \mathbb{F}$$

where

$$\mathbb{S} = \begin{bmatrix} \mathbb{S}_{uu} & \mathbb{S}_{up} & \mathbb{S}_{uT} \\ \mathbb{S}_{pu} & \mathbb{S}_{pp} & \mathbb{S}_{pT} \\ \mathbb{S}_{Tu} & \mathbb{S}_{Tp} & \mathbb{S}_{TT} \end{bmatrix}$$

the system is monolithically coupled

and

$$\mathbb{F} = \begin{Bmatrix} \mathrm{F_u} \\ \mathrm{F_{p_m}} \\ \mathrm{F_{p_f}} \\ \mathrm{F_{T_m}} \\ \mathrm{F_{T_f}} \end{Bmatrix} = \begin{Bmatrix} \mathbf{F} + \mathbf{C}_{\mathrm{uT_m}} \widehat{\mathbf{T}}_0 \\ \mathbf{C}_{\mathrm{p_m}}^{\mathrm{T}} \widehat{\mathbf{u}}^{\mathrm{t}} + \mathbf{M}_{\mathrm{p_m,p_m}} \widehat{\mathbf{p}}_{\mathrm{m}}{}^{\mathrm{t}} - \mathbf{C}_{\mathrm{p_m,T_m}} \widehat{\mathbf{T}}_{\mathrm{m}}{}^{\mathrm{t}} + \mathbf{Q}_{\mathrm{p_m}} \mathrm{dt} + \mathbf{n}_{\mathrm{G}} \mathrm{dt} \\ \mathbf{C}_{\mathrm{p_f}}^{\mathrm{T}} \widehat{\mathbf{u}}^{\mathrm{t}} + \mathbf{M}_{\mathrm{p_f,p_f}} \widehat{\mathbf{p}}_{\mathrm{f}}{}^{\mathrm{t}} - \mathbf{C}_{\mathrm{p_f,T_f}} \widehat{\mathbf{T}}_{\mathrm{f}}{}^{\mathrm{t}} + \mathbf{Q}_{\mathrm{p_f}} \mathrm{dt} \\ C_{T_m u} \widehat{\mathbf{u}}^{\mathrm{t}} + \mathbf{M}_{\mathrm{T_m,T_m}} \widehat{\mathbf{T}}_{\mathrm{m}}{}^{\mathrm{t}} - \mathbf{C}_{\mathbf{T_m p_m}} \widehat{\mathbf{p}}_{\mathrm{m}}{}^{\mathrm{t}} + \mathbf{Q}_{\mathrm{T_m}} \mathrm{dt} \\ \mathbf{M}_{\mathrm{T_f,T_f}} \widehat{\mathbf{T}}_{\mathrm{f}}{}^{\mathrm{t}} - \boldsymbol{C}_{\boldsymbol{T_f p_f}} \widehat{\mathbf{p}}_{\mathrm{f}}{}^{\mathrm{t}} + \mathbf{Q}_{\mathrm{T_f}} \mathrm{dt} \end{Bmatrix}$$

Salimzadeh, Paluszny, Zimmerman, Geothermics, 2018

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Stress intensity factors

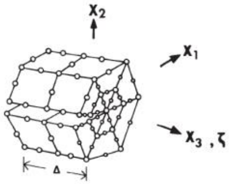
The onset and path of fracture growth is governed by something called the “stress intensity factor”

Once the displacement field is computed we can derive strains and stresses, assuming that the matrix is linear elastic and isotropic

We can define the path independent J-integral (rate of change of net potential energy with respect to crack advance per unit thickness of crack front), as follows

$$J_V = \frac{1}{A_c}\int_V \left(\sigma_{ij}\frac{\partial u_j}{\partial x_k} - W\delta_{ik}\right)\frac{\partial q_k}{\partial x_i}\,dV$$

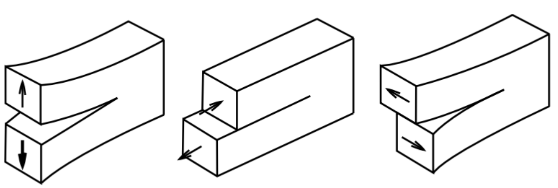
J is essentially the energy flow into the crack tip



and for a linear elastic material $J = \frac{K^2}{E_{eff}}$ where E_{eff} is the effective elastic modulus

and the stress intensity factor can be decomposed into the three modalities of deformation (tension, in-plane and out-of-plane shear), as

$$K = \frac{K_{\mathrm{I}}}{2} + \frac{1}{2}\sqrt{K_{\mathrm{I}} + 4(\alpha_1 K_{\mathrm{II}})^2 + 4(\alpha_2 K_{\mathrm{III}})^2}$$



Mode I, K_I Mode II, K_{II} Mode III, K_{III}

This can be further extended to compute each modality independently using the Nakamura and Parks Interaction Integral. I developed a new method to compute this integral over a virtual domain.

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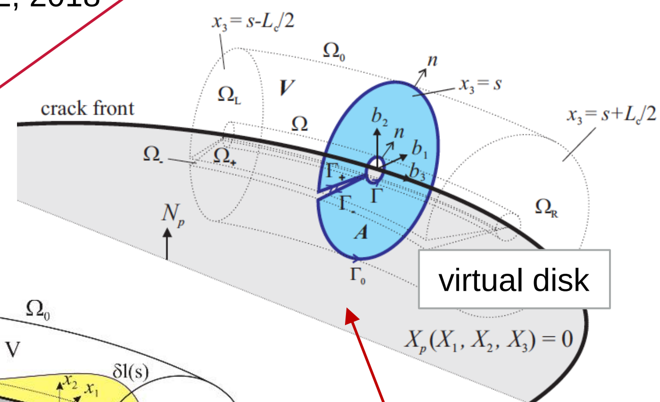
New method to integrate stress intensity factors

Increasing accuracy of energy estimates while relaxing discretisation constraints

My method to compute this integral over a virtual domain allows modelling 3D fracture growth using unstructured meshes

Thomas, Paluszny & Zimmerman, JGR:SE, 2018

2018

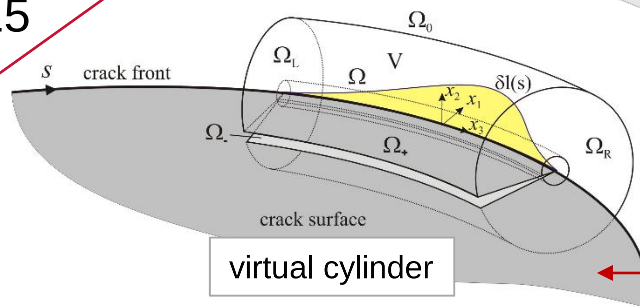


virtual disk

Nejati, Paluszny & Zimmerman, IJSS, 2015

Nejati, Paluszny & Zimmerman, EFM, 2015

2015



virtual cylinder

Paluszny & Zimmerman, CMAME, 2011

2010

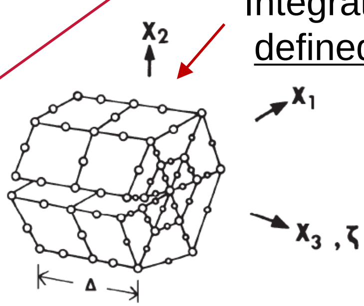
Integration domain is virtually defined

This is much better!

Rajaram *et al.* 2000

Cervenka & Saouma 1997

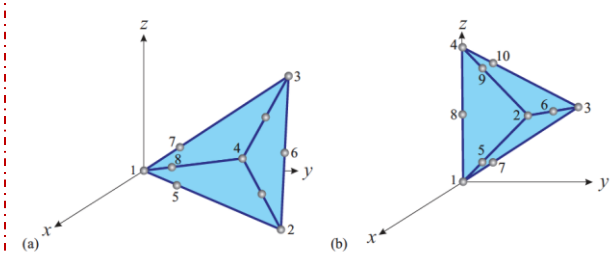
1960



Integration domain is defined by the mesh

We don't want this!

Efficient numerical elements for 3D fracture tips: quarter point quadratic tetrahedra



How stress intensity factors translate into growth

Propagation Law. The relative growth of any node *n* along a three-dimensional fracture tip is defined as follows:

$$\Delta a_n = \Delta a_{max}\left(\frac{K_n}{K_{max}}\right)^{\beta}$$

A variation of this method has been validated against outcrop data by Renshaw & Pollard

Angle Law. The angle of fracture growth is a function of all three SIFs. Richard et al. (2014) define the propagation angle as

$$\varphi = \mp\left[A\frac{|K_{II}|}{K_I+|K_{II}|+|K_{III}|} + B\left(\frac{|K_{III}|}{K_I+|K_{II}|+|K_{III}|}\right)^2\right]$$

where φ is the propagation angle (with 0^o being along the fracture plane), A = 140^o and B = -70^o.

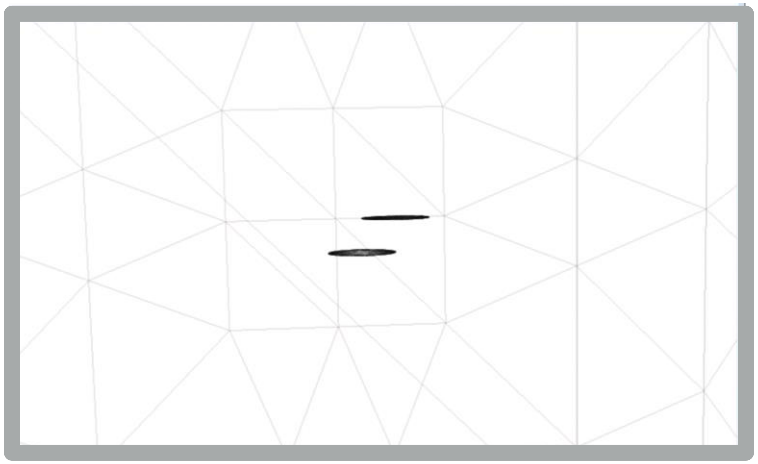
There are many extensively-validated variations for “propagation and angle laws”, and they rely on stress intensity factor computations.

Discretisation and Geometric representation

Fractures are represented by smooth surfaces and triangles

The matrix is discretised by tetrahedra and the fracture by triangles

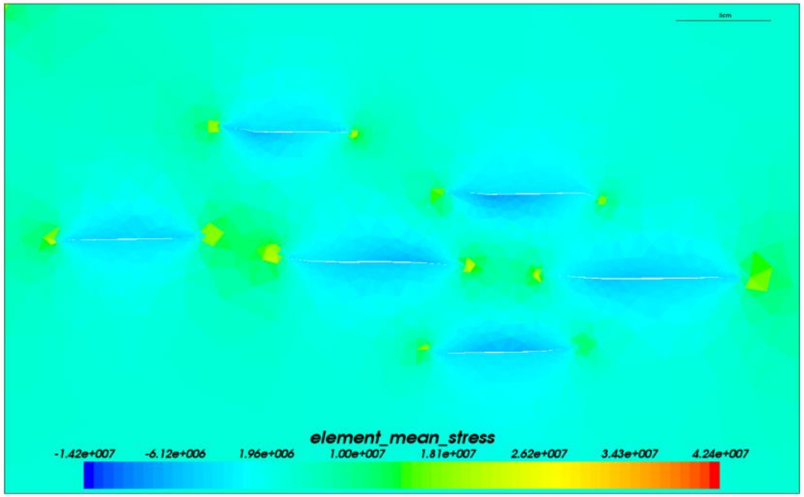
Developed in C++, parallelised for shared memory workstations



Two fractures growing and interacting under tension

Fractures growing and interacting

Stress concentrations around the tips and stress shadows around the body of the fracture emerge during the simulation

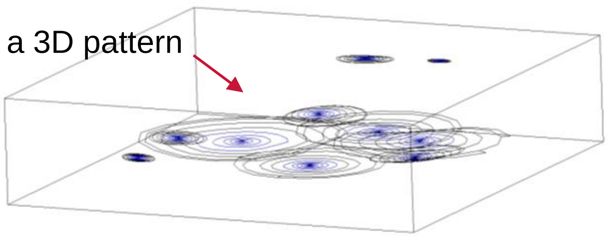


Paluszny & Matthäi, IJSS, 2009
Paluszny & Matthäi, JGR:SE, 2010

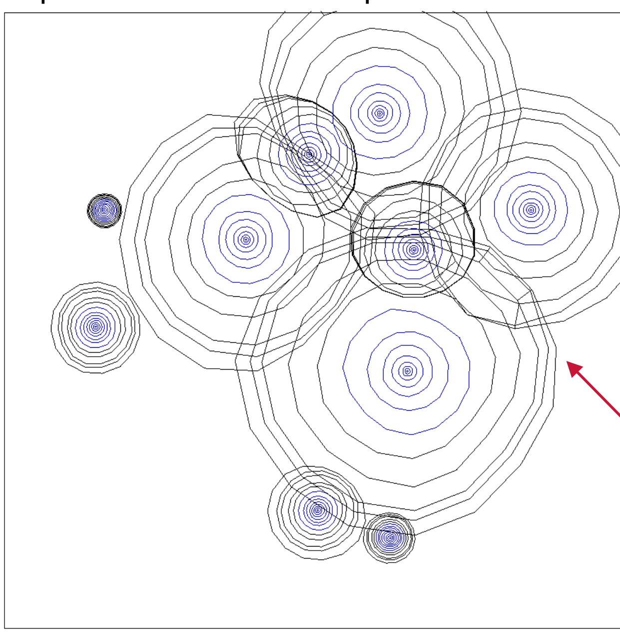
Fracture set growth

Fractures behave as single larger entities prior to intersection:

a 3D pattern



top view of the same 3D pattern

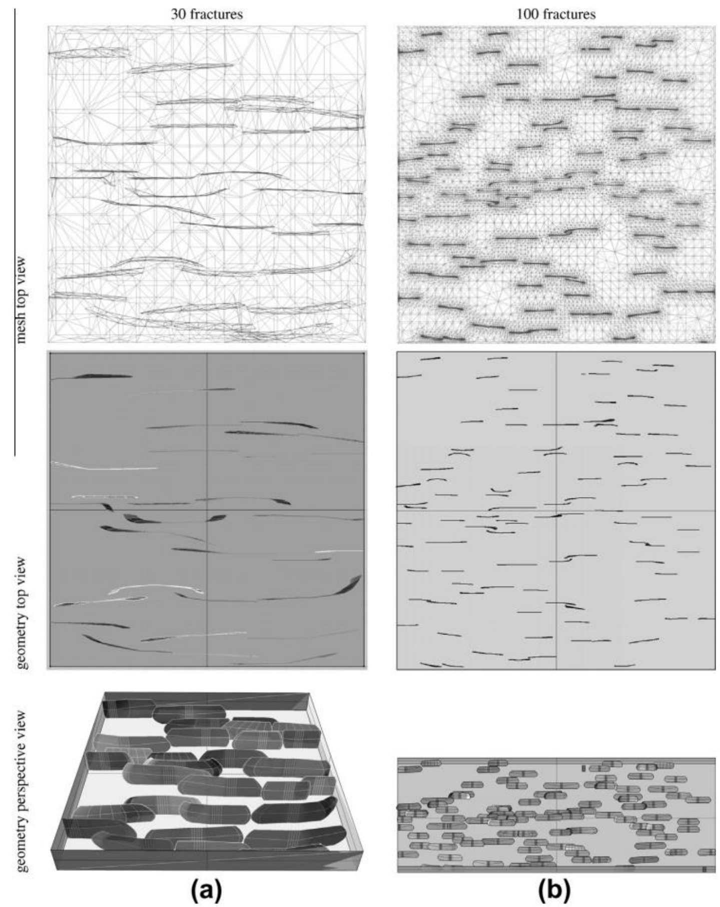


This cluster of fractures is in the process of becoming a single, larger fracture

Fractures growing within single layers of rock:

Predicting how patterns are linked to the processes that form them is a key challenge

How do pre-existing patterns affect new patterns; can we predict what will happen?



Paluszny & Zimmerman, EFM, 2013

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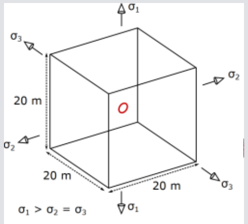
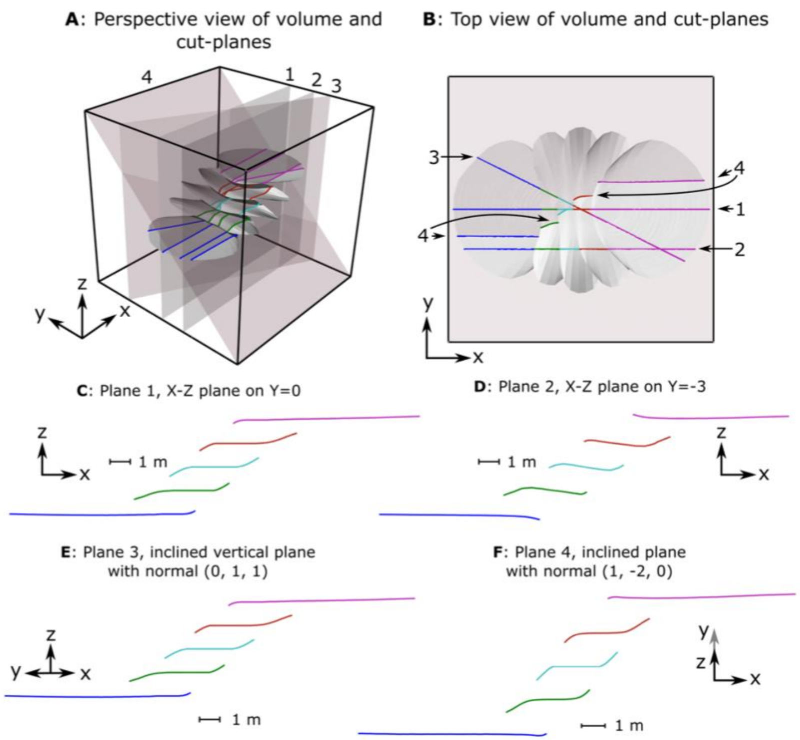
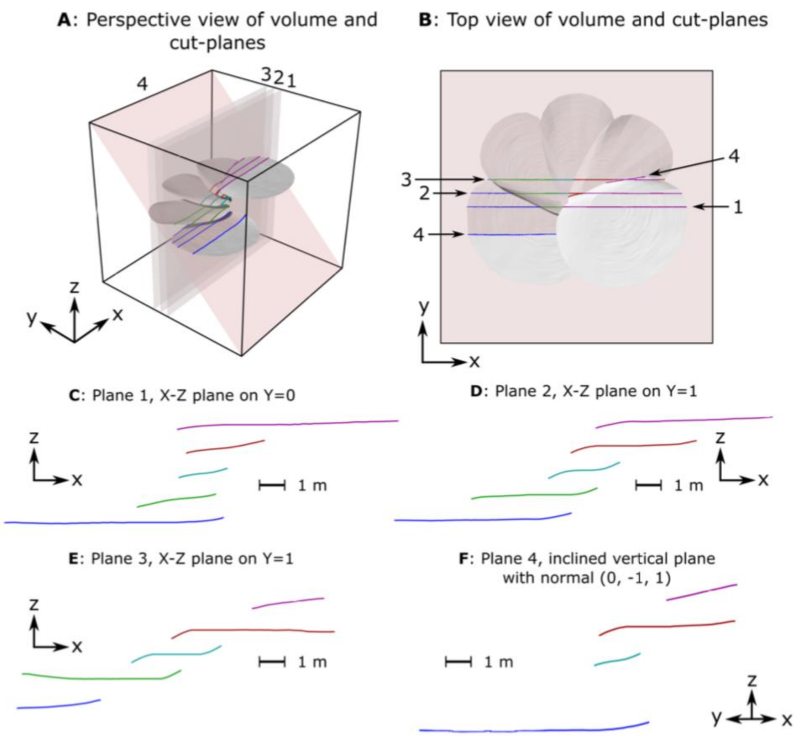
The growth of a fracture array



<u>aligned</u> array of fractures



<u>spiral</u> array of fractures



Can we distinguish these in an outcrop?

Thomas, Paluszny, Zimmerman, 2019, under review

Overview of my research

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created by Adriana Paluszny

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Mining

funding

Rio Tinto

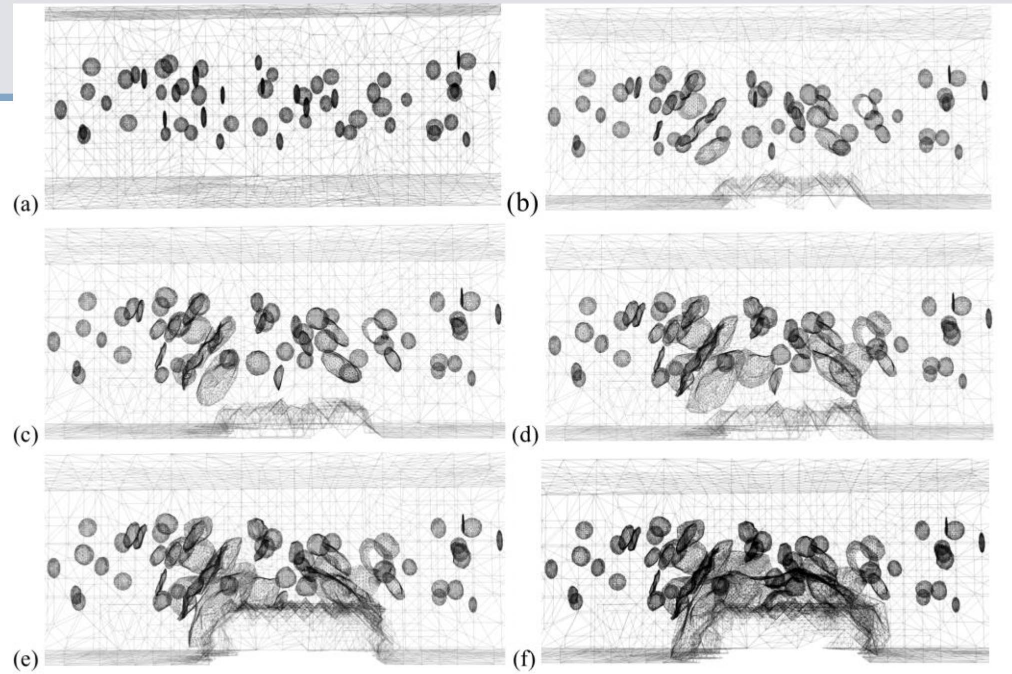
National Oilwell Varco

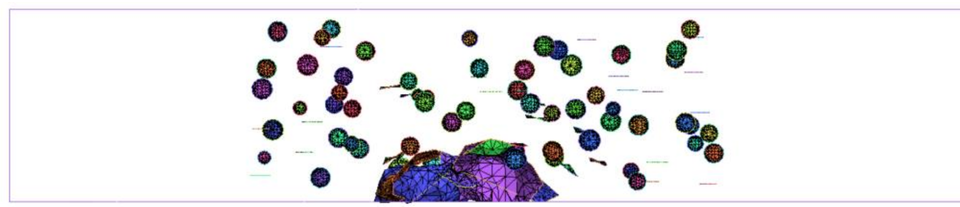
Imperial College London

Post-doc funded by: RioTinto

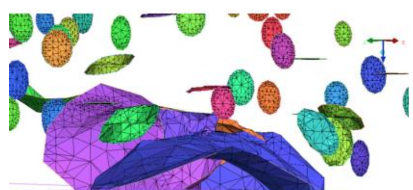
Fractures and Caving

A fracture set responds to an undercut. Cave shapes depend on the initial fracture pattern.

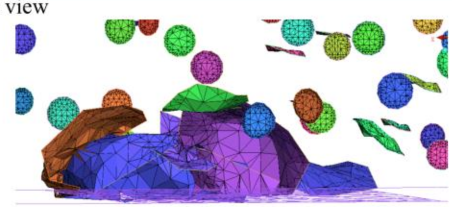




(a) front view



(b) side view of rendered fracture surfaces



(c) rotated side view

Paluszny & Zimmerman, Geomech. Geophys. Geo-Energy Geo-Resour., 2017

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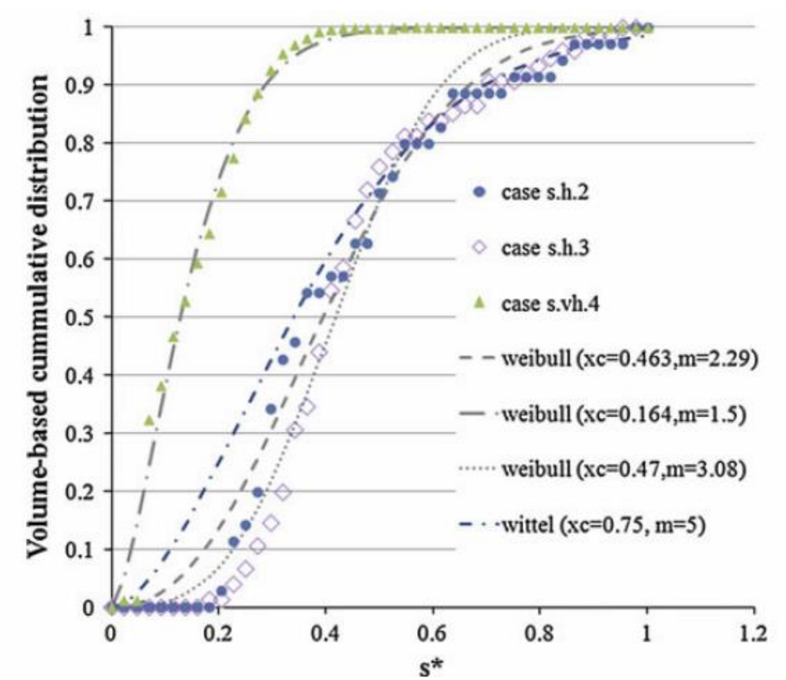
Post-doc funded by: RioTinto

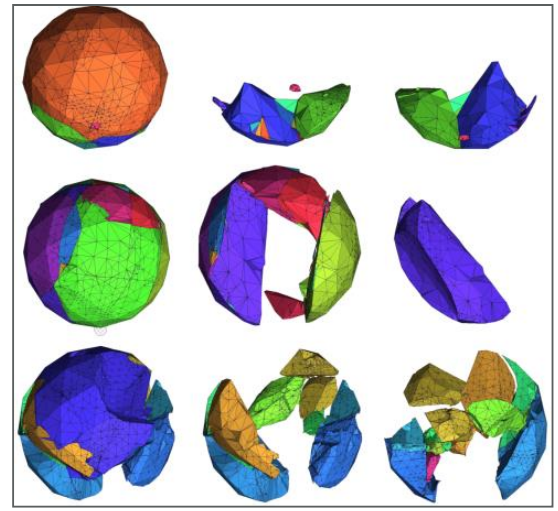
“Secondary fragmentation” in block caving

- Modelled fracture leading to fragmentation

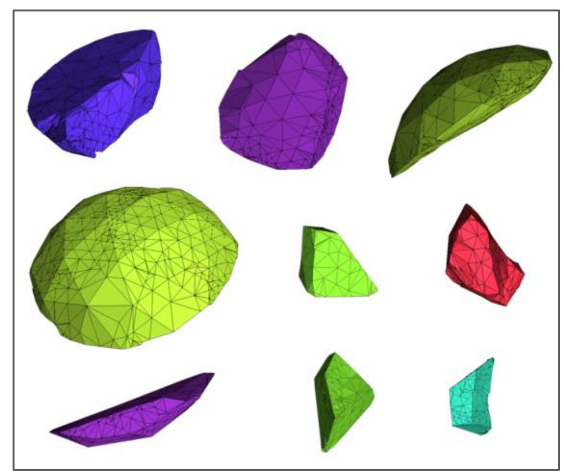
- Fragment volumes followed a Weibull distribution that matched experimental results



velocity-dependent fragmentation pattern



fragment shapes



Paluszny & Zimmerman, Computational Mechanics, 2013

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Overview of my research

2

funding
EPSRC
EU-FP7

CO_2 sequestration: caprock integrity

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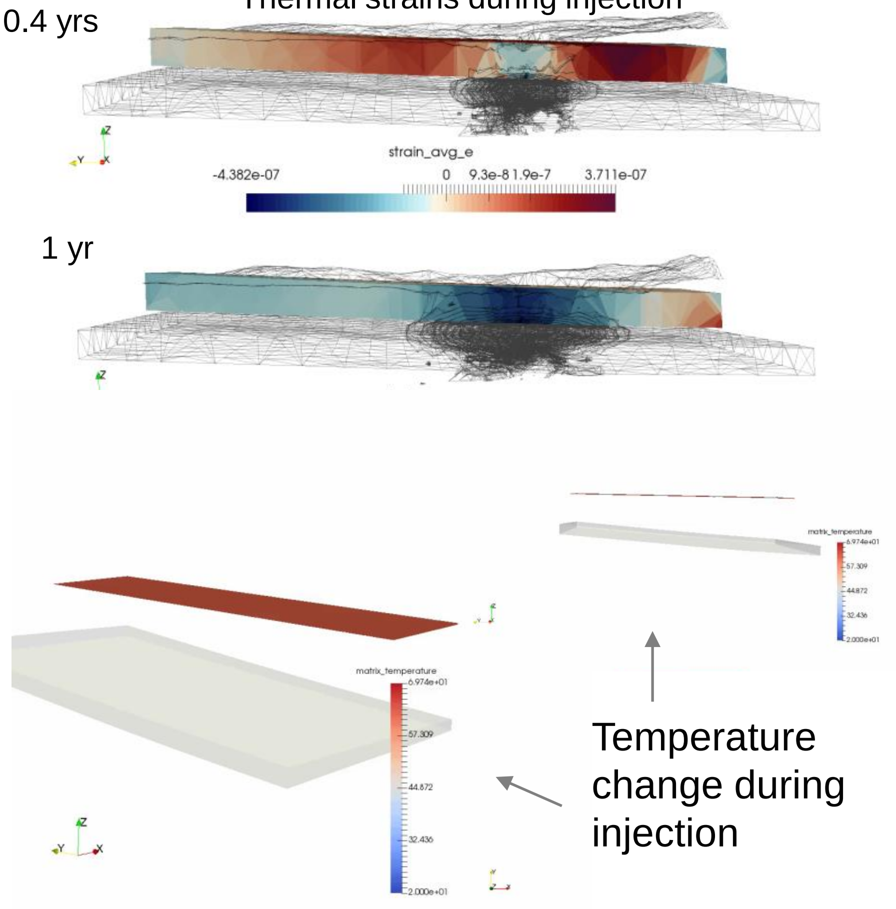
Rio Tinto
National Oilwell Varco

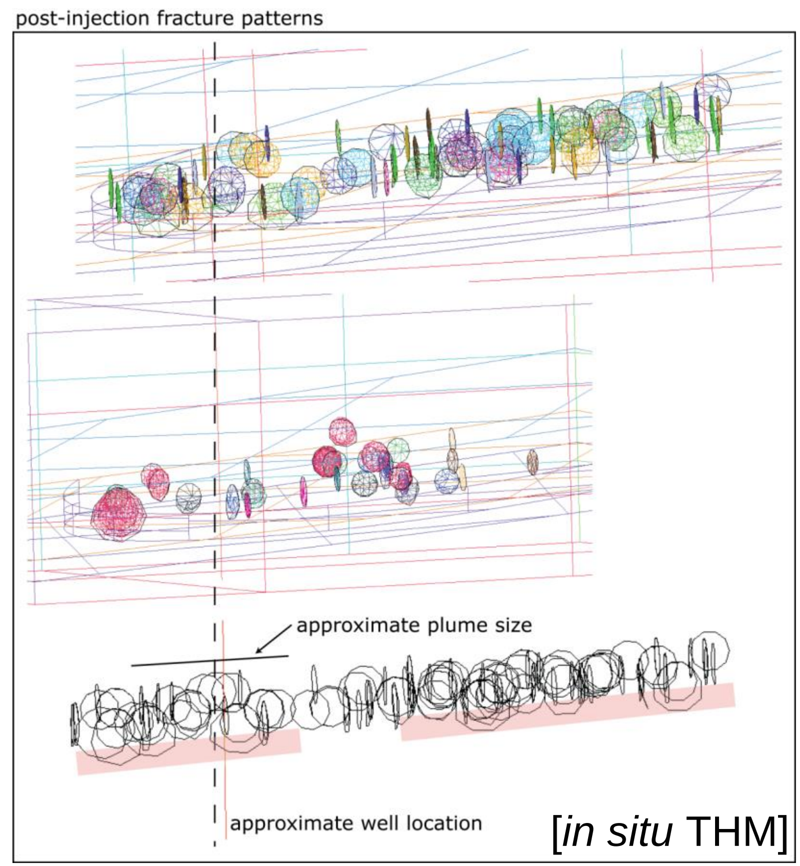
Fractures in shale caprocks during cold CO_2 injection

Thermal strains during injection



Temperature change during injection

Fracture growth is evaluated regionally as a function of local fluid injection



co-I
TRUST project
large consortium

Paluszny, Salimzadeh, Tempone, Zimmerman, ARMA, 2017

Fault apertures as a function of temperature contrast

The Captain sandstone is located at a depth of 2600 m; hence, the vertical stress is set to 55 MPa, and the horizontal stresses are set to 45 MPa. *In situ* temperature is assumed to be 83 C.

Inj: 20 C

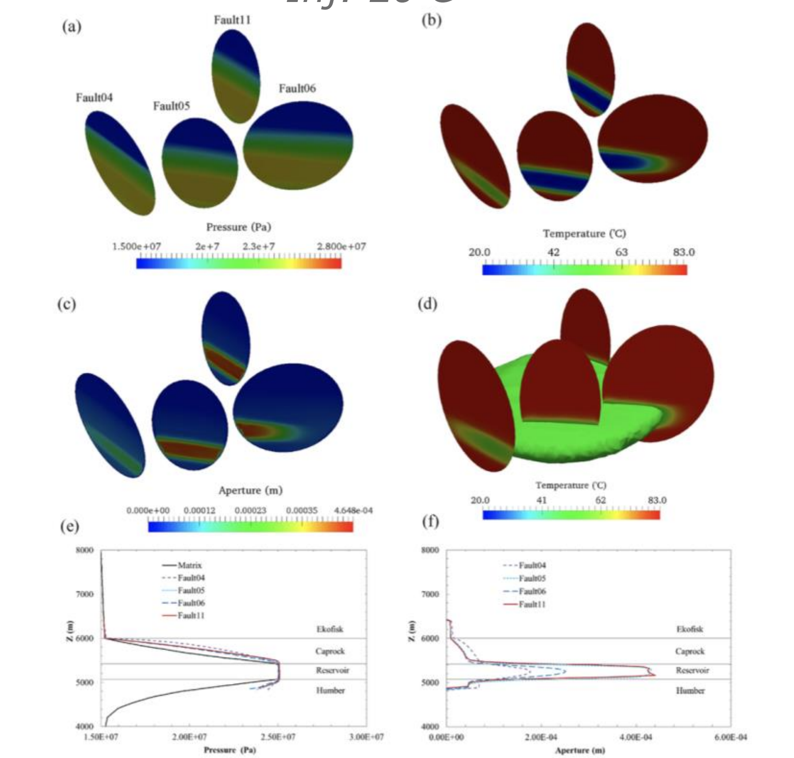


Fig. 2. The fluid pressure (a), temperature (b), and aperture distribution (c), on the faults, the 50 °C temperature plume within the reservoir layer (d), pressure profile along a vertical line passing through faults (e), and the aperture profile along a vertical line passing through the centre of the faults (f), after 160 years for the case: $E = 20$ GPa, $T_{inj} = 20$ °C.

Inj: 40 C

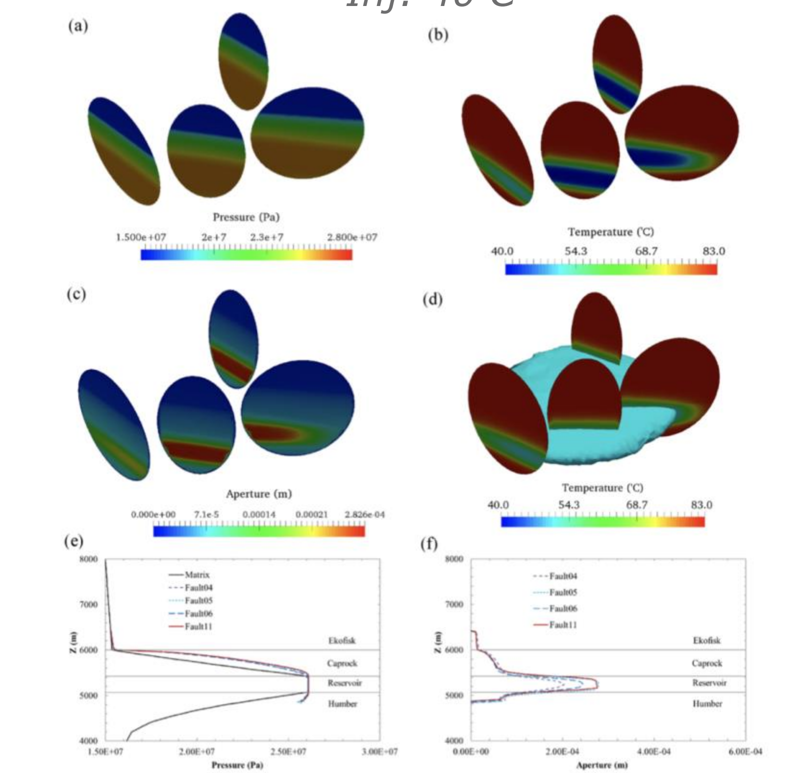


Fig. 3. The fluid pressure (a), temperature (b), and aperture distribution (c) on the faults, the 50 °C temperature plume within the reservoir layer (d), pressure profile along a vertical line passing through faults (e), and the aperture profile along a vertical line passing through the centre of the faults (f), after 160 years for the case: $E = 20$ GPa, $T_{inj} = 40$ °C.

EPSRC
Pioneering research and skills

co-I
CONTAIN project
with BGS and Cardiff University

Salimzadeh, Paluszny, Zimmerman, 2018, IJGGC

Imperial College London

Overview of my research

current funding

NERC-UH

3

Unconventionals

funding

EPSRC

EU-FP7

CO_2 sequestration: caprock integrity

Subsurface flow and permeability

Coupled thermo-poro-mechanics

SIMULATOR: Imperial College Geomechanics Toolkit (ICGT)

created by Adriana Paluszny

Fracture pattern growth

Multiple scale heterogeneities

Mining

current funding

Royal Society Fellowship

+ Research Grant

funding

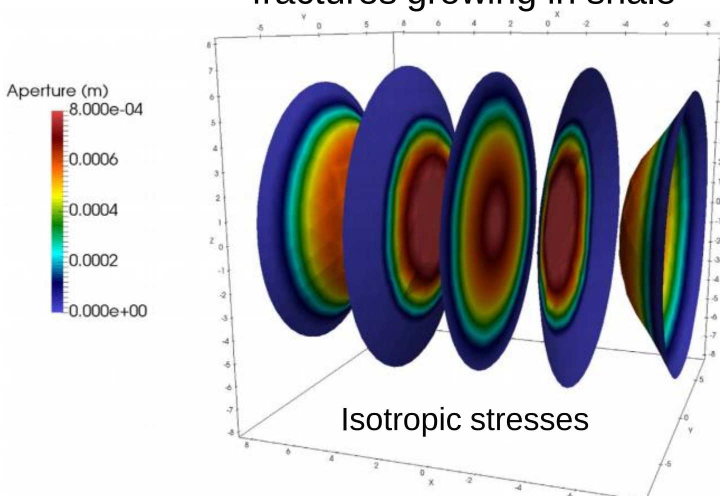
Rio Tinto

National Oilwell Varco

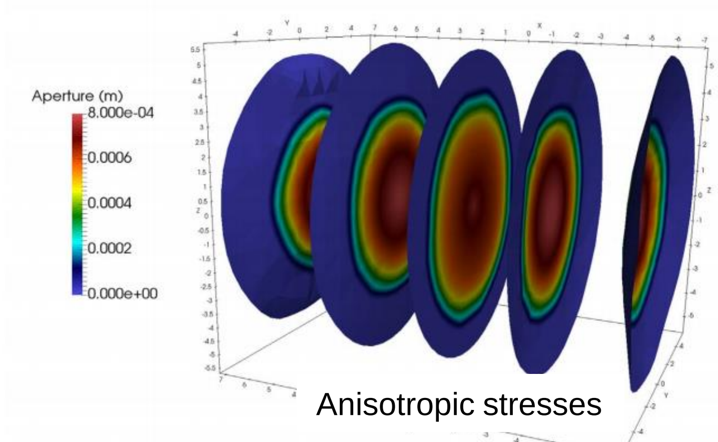
Imperial College London

Simultaneous growth of multiple hydraulic fractures

fractures growing in shale



(a)



(b)

- Fractures growing in a poroelastic medium
- Under isotropic and anisotropic *in situ* stresses
- Apertures do not follow the geometry of the fractures
- Apertures are also affected by interaction

Grant Awarded:
Effect of heterogeneities on growth, as part of NERC-UH

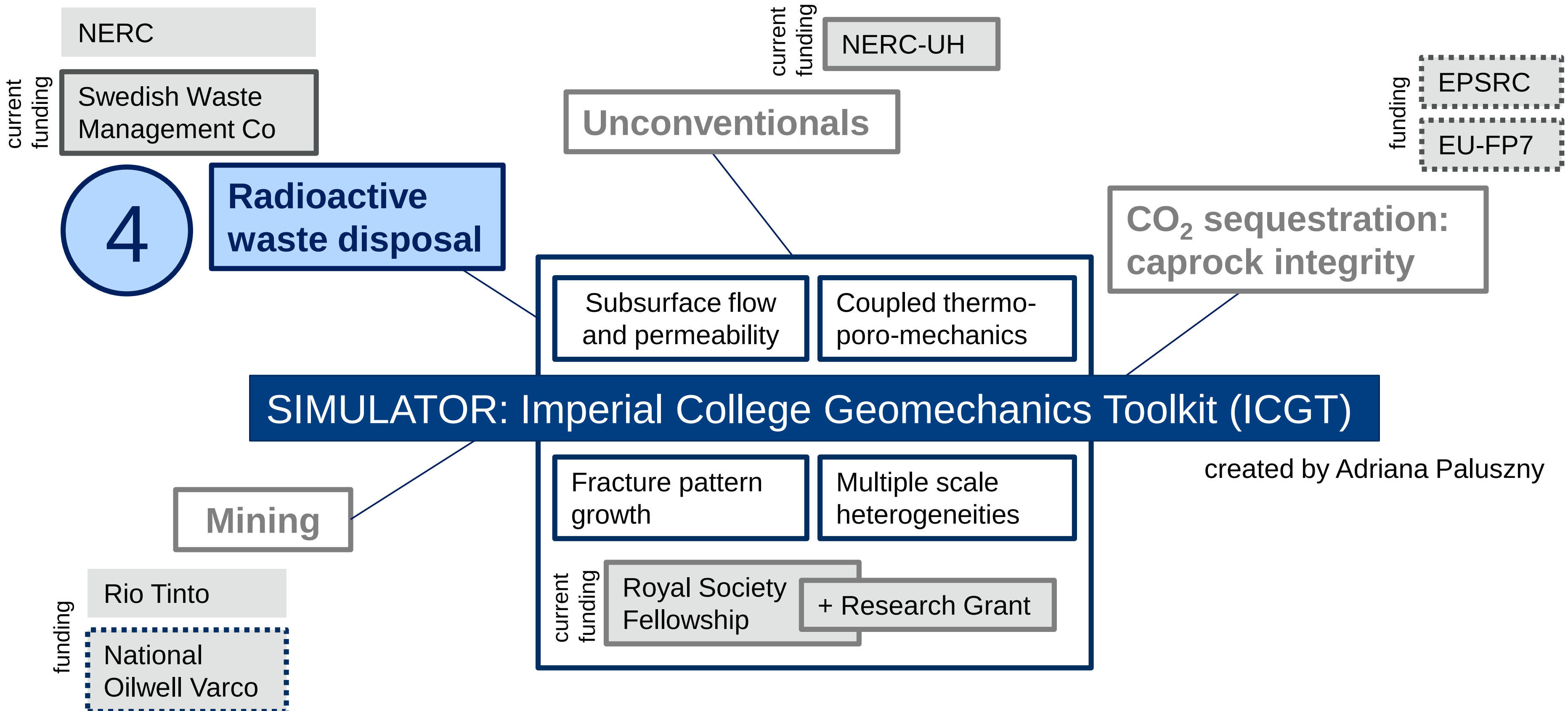
NERC SCIENCE OF THE ENVIRONMENT

Co-I, Funding:
PDRA
Robin Thomas
2018-2020

Salimzadeh, Paluszny, Zimmerman, IJSS, 2017
Salimzadeh, Usui, Paluszny, Zimmerman, IJRMMS, 2017
Paluszny, Salimzadeh, Zimmerman, HFM, 2018

Imperial College London

Overview of my research



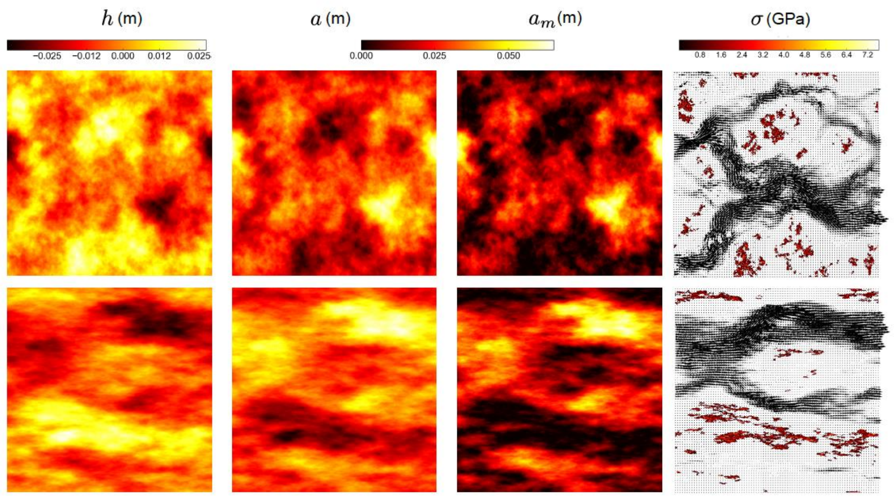
created by Adriana Paluszny

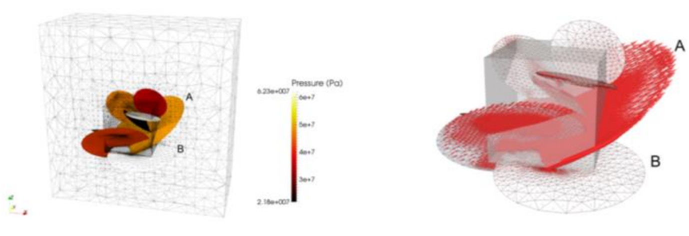
Imperial College London

Funded by:

Radioactive Waste Management

Multi-scale modelling of surface roughness effects





(a) (b)

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

AN AGU JOURNAL

Research Article | Open Access

Relationship Between the Orientation of Maximum Permeability and Intermediate Principal Stress in Fractured Rocks

Philipp S. Lang, Adriana Paluszny, Morteza Nejati, Robert W. Zimmerman

First published: 19 October 2018 | https://doi.org/10.1029/2018WR023189

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Abstract

Flow and transport properties of fractured rock masses are a function of geometrical structures across many scales. These structures result from physical processes and states and are highly anisotropic in nature. Fracture surfaces often tend to be shifted with respect to each other, which is generally a result of stress-induced displacements. This shift controls the fracture's transmissivity through the pore space that forms from the created mismatch between the surfaces. This transmissivity is anisotropic and greater in the

Grant awarded:
Micro-scale effect on growth and intersections in hydro-mechanically coupled systems!

THE ROYAL SOCIETY

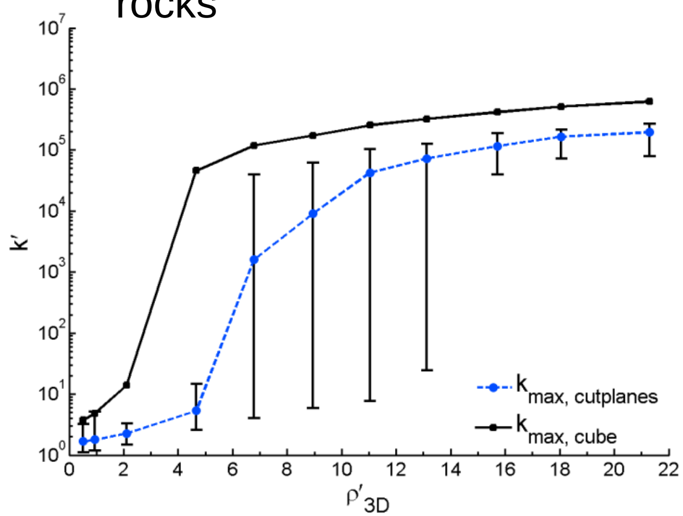
PI
PhD studentship
Advertising now
2019-2022

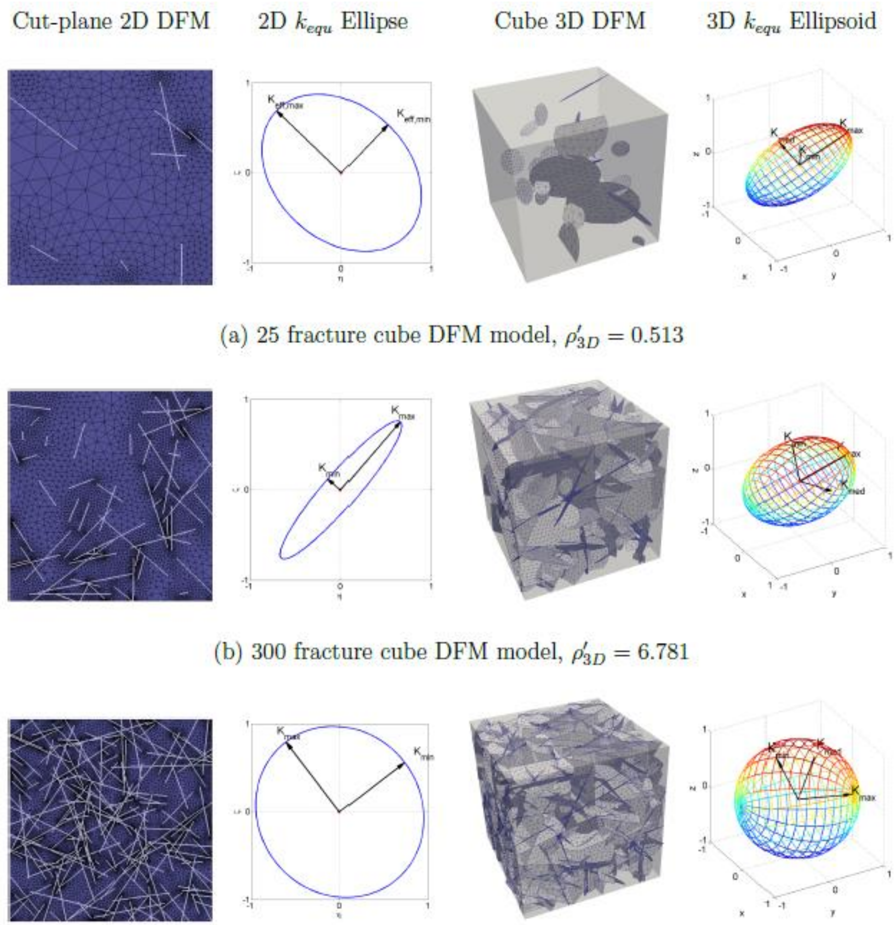
Lang, Paluszny, Nejati, Zimmerman, Water Resources Research, 2018

Tensorial permeability of a fractured rock

- Permeability of a 3D network is very difficult to approximate based on 2D, both in magnitude and orientation

- Novel method to numerically compute the tensorial permeability of 3D fractured rocks





(a) 25 fracture cube DFM model, $\rho'_{3D} = 0.513$

(b) 300 fracture cube DFM model, $\rho'_{3D} = 6.781$

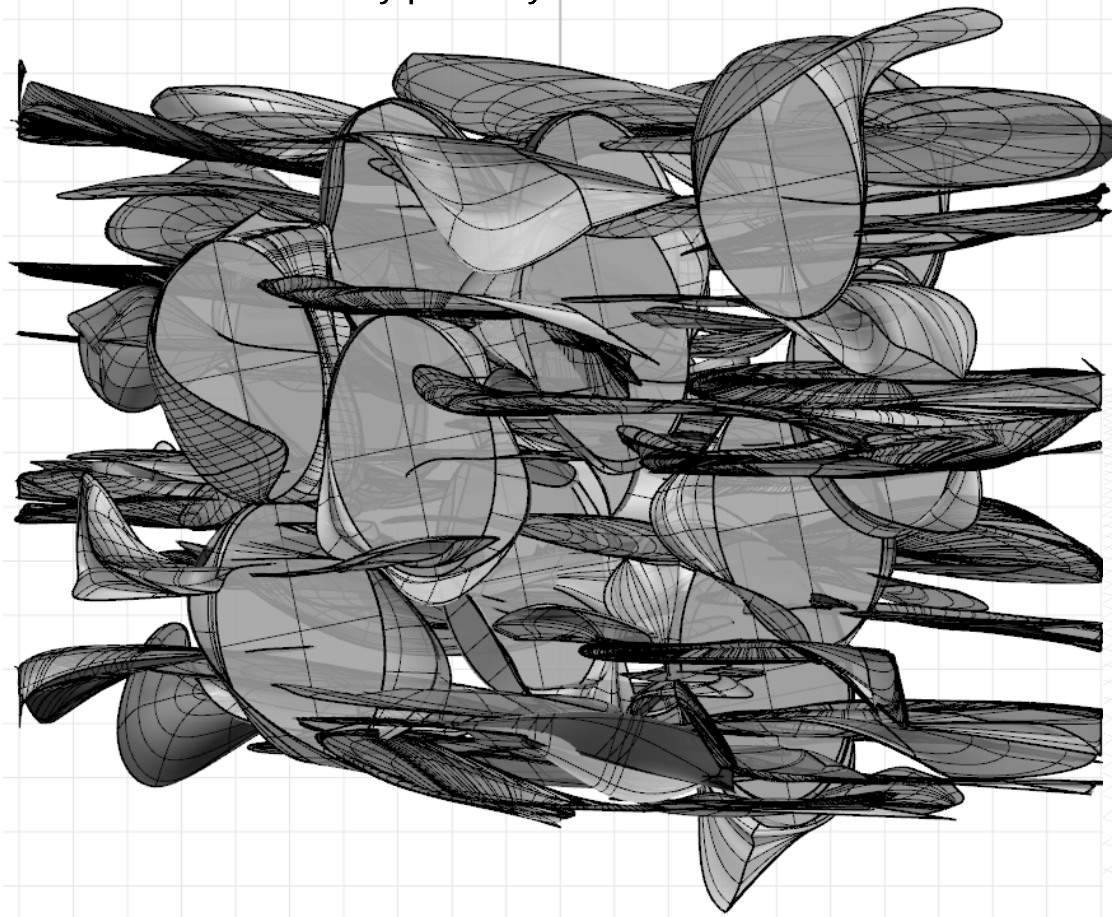
(c) 900 fracture cube DFM model, $\rho'_{3D} = 21.256$

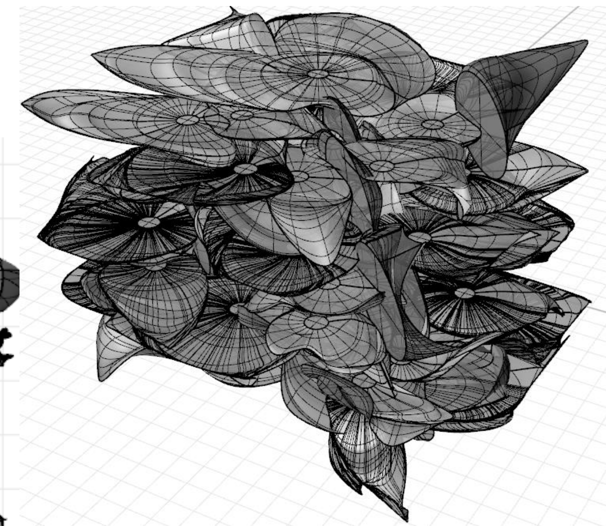
Lang, Paluszny, Zimmerman, JGR:SE, 2014

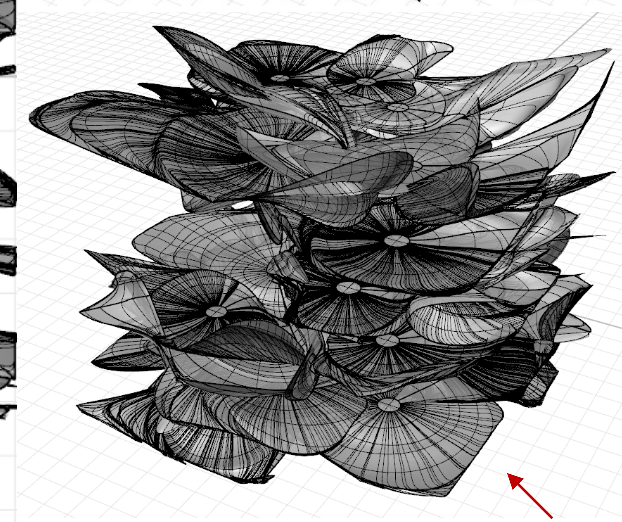
Network geometry

How do we know if this is “realistic”?

Complex networks develop relationships that go beyond density and connectivity. The interaction of fractures during growth enhances connectivity pathways.



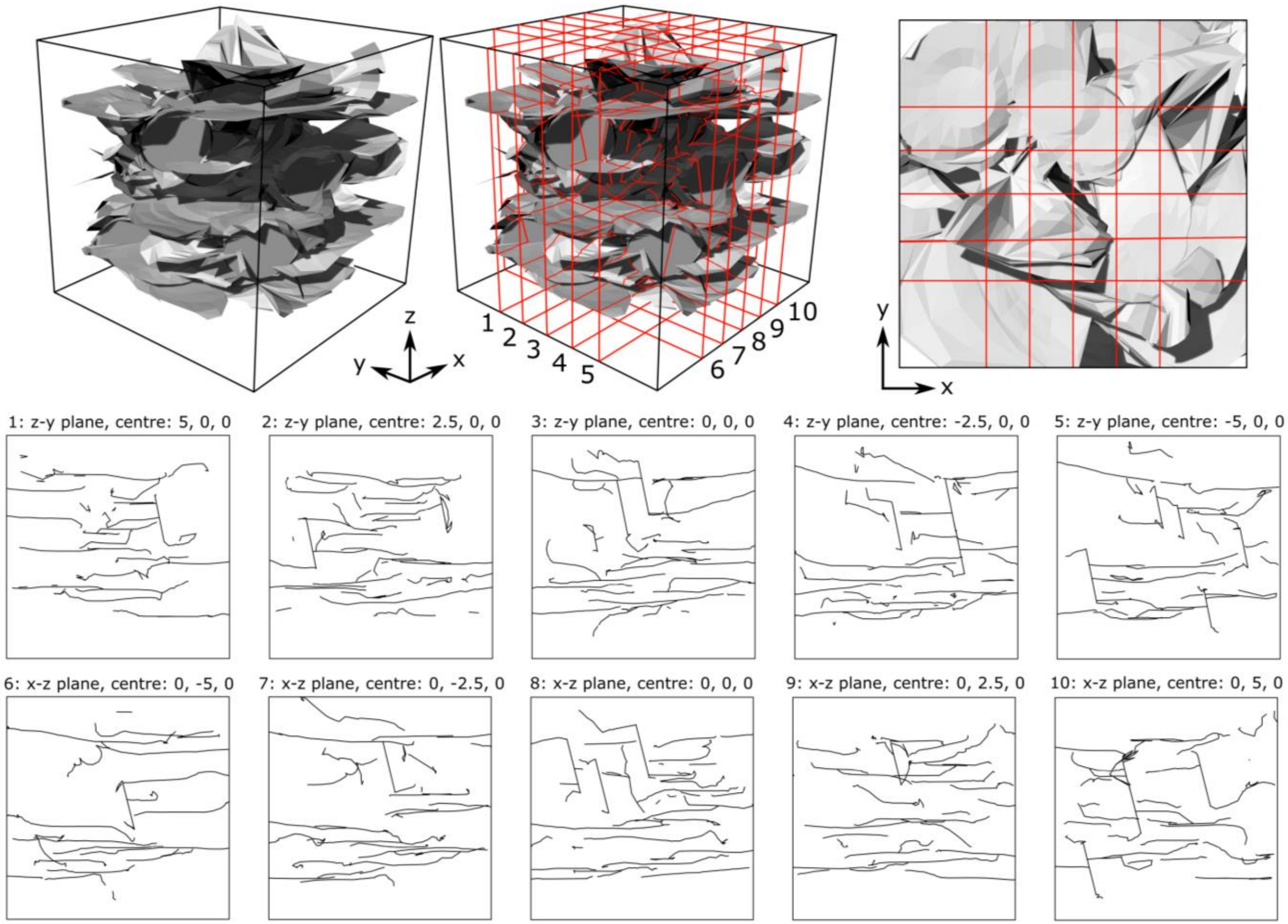




“NURBS” fractures

Imperial College London

New methods to quantify the evolving geometry



[Thomas, Paluszny, Zimmerman, submitted]

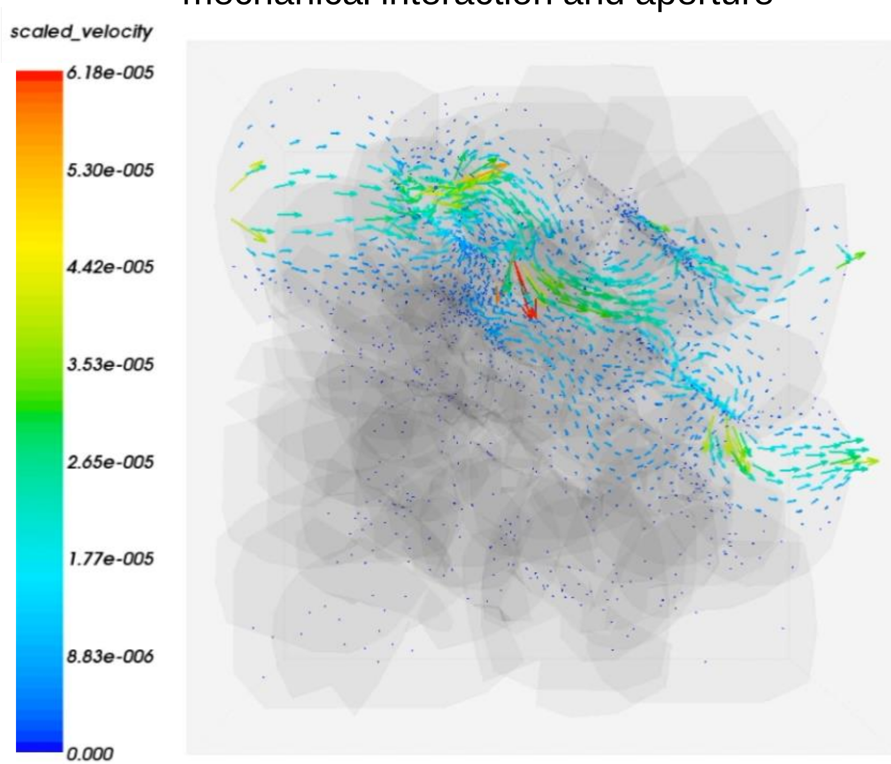
This ability to create complex 3D networks and accurately model coupled thermo-poro-mechanics led to an industrial grant sponsored by SKB (2018-2022)

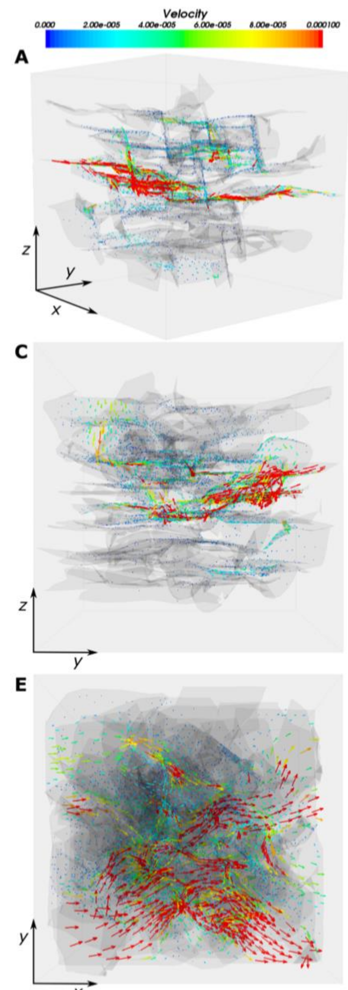
Co-PI
Industry-funded PhD studentship
Cristina Saceanu
2018-2020

Numerically generated “outcrops”

Flow channels

Fluid flow channeling as a result of fracture mechanical interaction and aperture





Volume under tension

($1x10^7$ Pa)

90 initial fractures

(75 horizontal, 15 vertical)

Channels emerge in the system, and they change as a function of growth and in situ stresses

Paluszny, Thomas, Zimmerman, CouFrac, 2018

Thomas, Paluszny, Zimmerman, to be submitted 2019 Q2

Overview of my research

5

NERC

current funding: Swedish Waste Management Co

Radioactive waste disposal

current funding: NERC-UH

Unconventionals

Geothermal energy

funding: EPSRC, EU-FP7

CO_2 sequestration: caprock integrity

Subsurface flow and permeability

Coupled thermo-poro-mechanics

SIMULATOR: Imperial College Geomechanics Toolkit (ICGT)

created by Adriana Paluszny

Fracture pattern growth

Multiple scale heterogeneities

current funding: Royal Society Fellowship + Research Grant

Mining

Rio Tinto

funding: National Oilwell Varco

Imperial College London

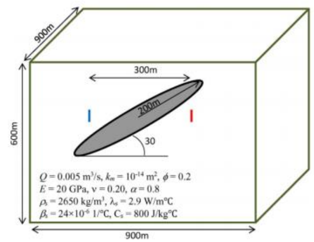
Paluszny was co-I in both projects

EPSRC Pioneering research and skills

SEVENTH FRAMEWORK PROGRAMME

Thermo-hydro-mechanical deformation of fractures

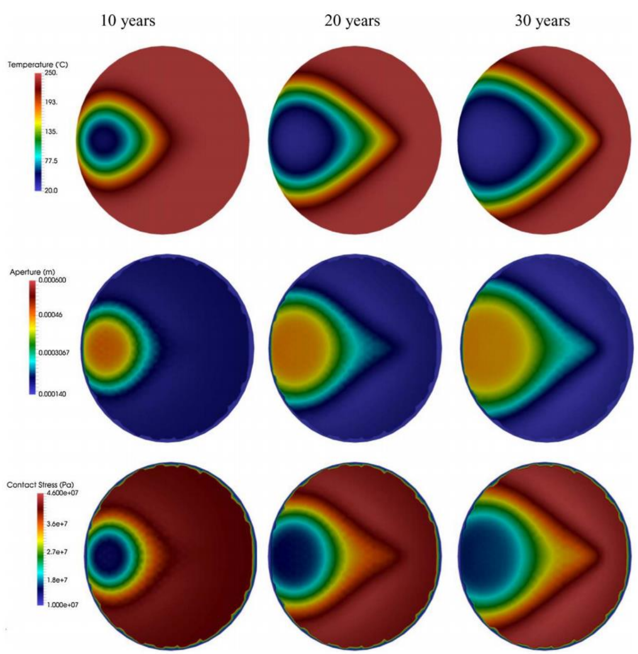
Geothermal stimulation of a 100 m radius fracture

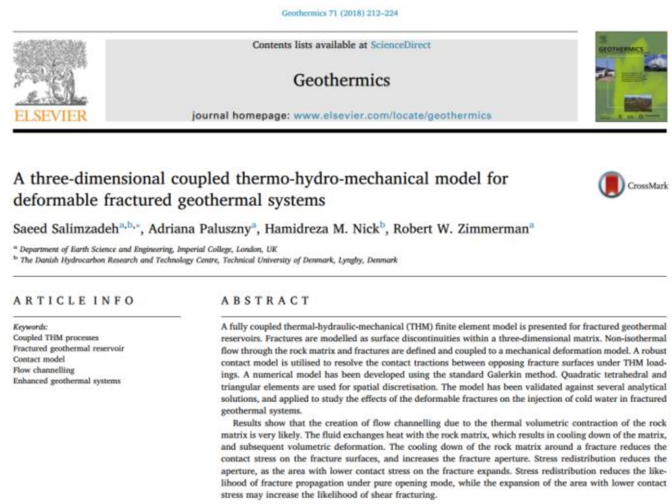


temperature

apertures

contact stresses





Geothermics 71 (2018) 212–224

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

A three-dimensional coupled thermo-hydro-mechanical model for deformable fractured geothermal systems

Saeed Salimzadeh[a,b,*], Adriana Paluszny[a], Hamidreza M. Nick[b], Robert W. Zimmerman[a]

[a] Department of Earth Science and Engineering, Imperial College, London, UK

[b] The Danish Hydrocarbon Research and Technology Centre, Technical University of Denmark, Lyngby, Denmark

ARTICLE INFO

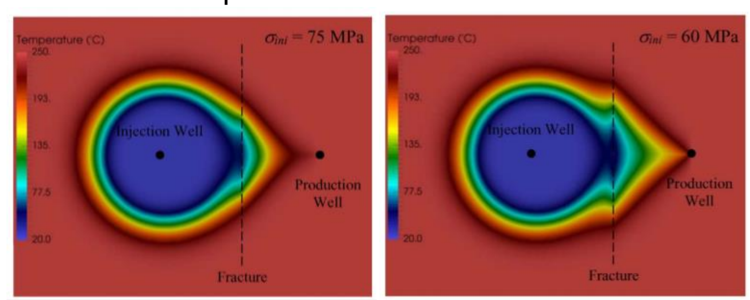
Keywords:
Coupled THM processes
Fractured geothermal reservoir
Contact model
Flow channelling
Enhanced geothermal systems

ABSTRACT

A fully coupled thermal-hydraulic-mechanical (THM) finite element model is presented for fractured geothermal reservoirs. Fractures are modelled as surface discontinuities within a three-dimensional matrix. Non-isothermal flow through the rock matrix and fractures are defined and coupled to a mechanical deformation model. A robust contact model is utilised to resolve the contact tractions between opposing fracture surfaces under THM loadings. A numerical model has been developed using the standard Galerkin method. Quadratic tetrahedral and triangular elements are used for spatial discretisation. The model has been validated against several analytical solutions, and applied to study the effects of the deformable fractures on the injection of cold water in fractured geothermal systems.

Results show that the creation of flow channelling due to the thermal volumetric contraction of the rock matrix is very likely. The fluid exchanges heat with the rock matrix, which results in cooling down of the matrix, and subsequent volumetric deformation. The cooling down of the rock matrix around a fracture reduces the contact stress on the fracture surfaces, and increases the fracture aperture. Stress redistribution reduces the aperture, as the area with lower contact stress on the fracture expands. Stress redistribution reduces the likelihood of fracture propagation under pure opening mode, while the expansion of the area with lower contact stress may increase the likelihood of shear fracturing.

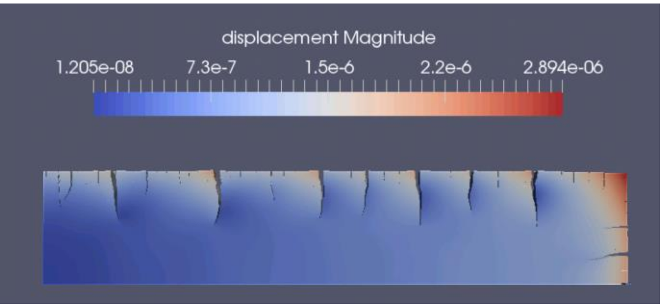
Interaction of a fracture with another intersecting fracture, effect on the thermo-poro-mechanical apertures

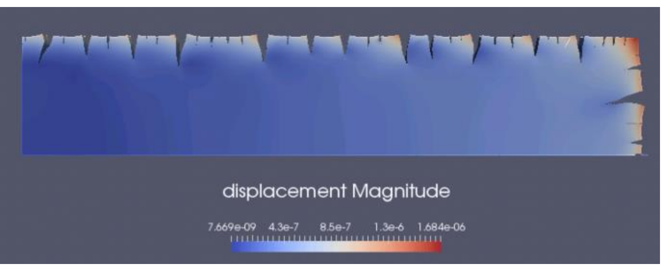


Salimzadeh, Paluszny, Nick, Zimmerman, Geothermics, 2018

Imperial College London

Modelling of thermal shock-induced fracture growth

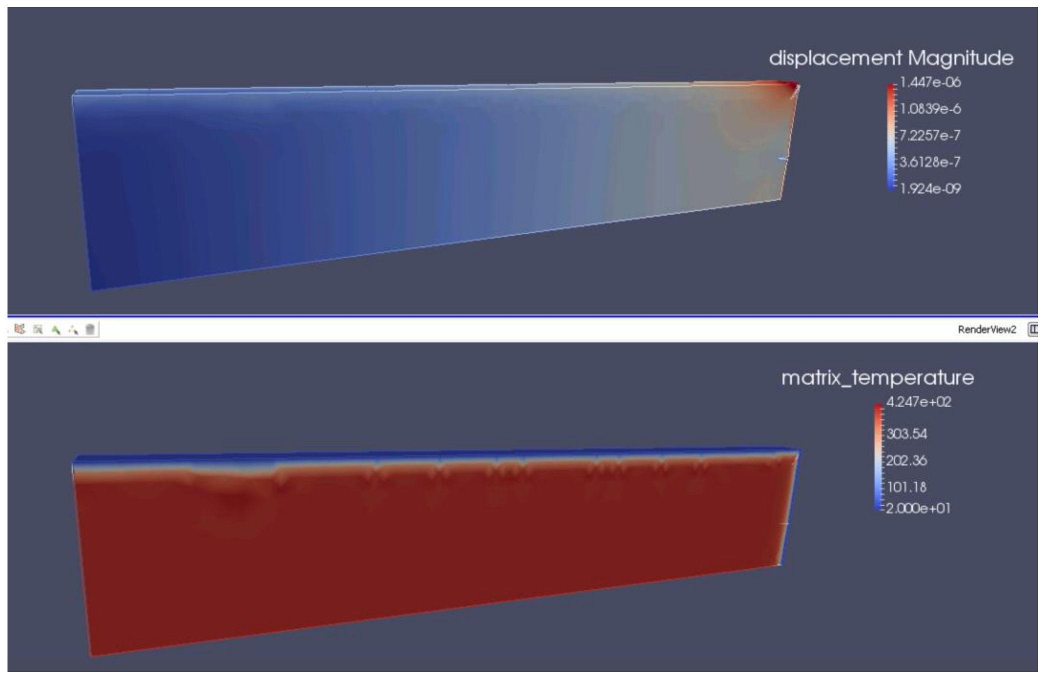




Quenching of an aluminium oxide plate 5cm
400-500 C contrast over seconds

Validation: Towards accurate geothermal thermal fracture predictions

I am currently building this into the simulator’s core



displacement

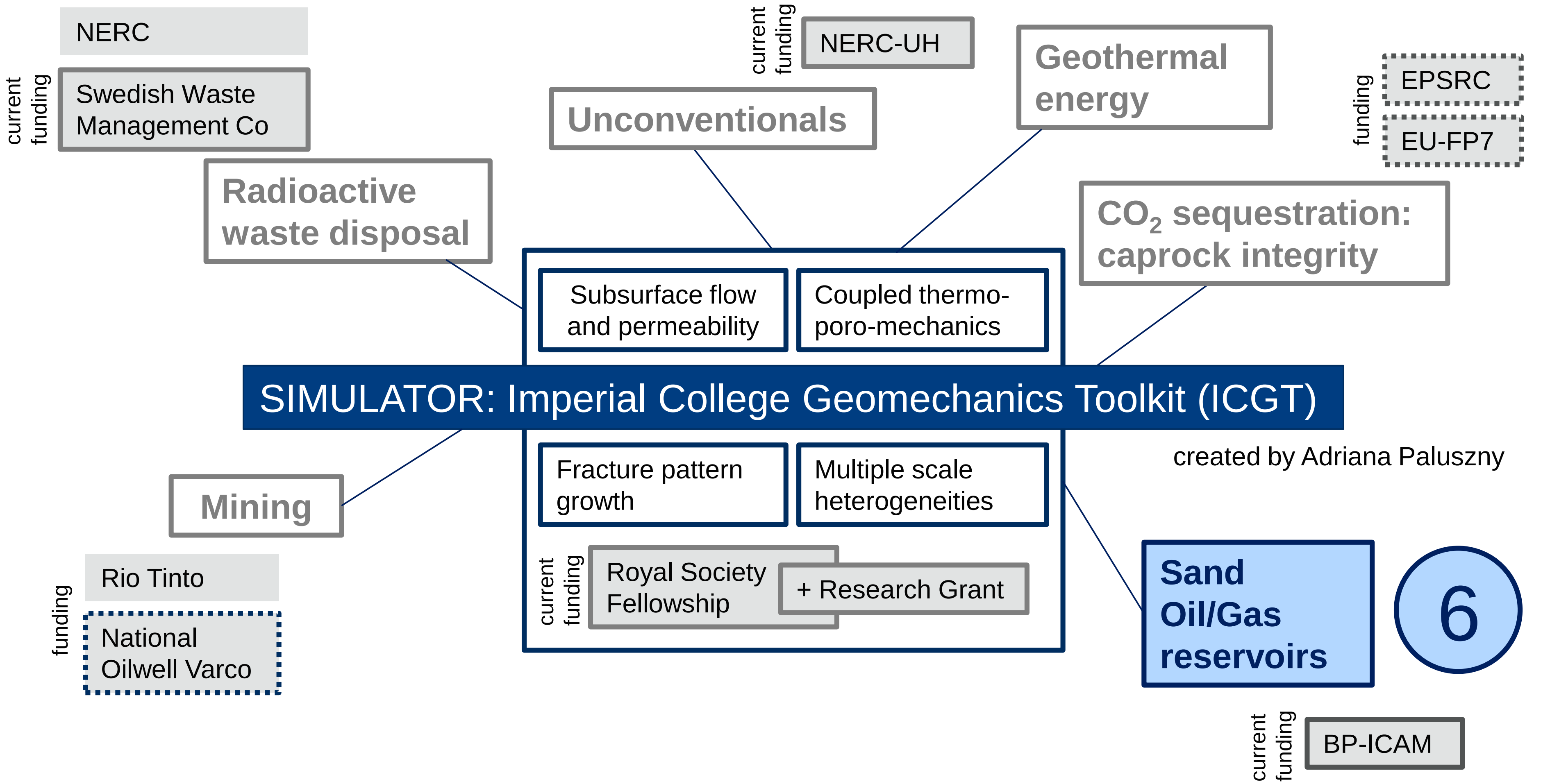
temperature

This is part of my strategy:
Find true validation cases beyond the rock mechanics literature

Stefansson, Berre, Keilegavlen, Paluszny, European Geothermal Workshop, 2018

Imperial College London

Overview of my research



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funded by:

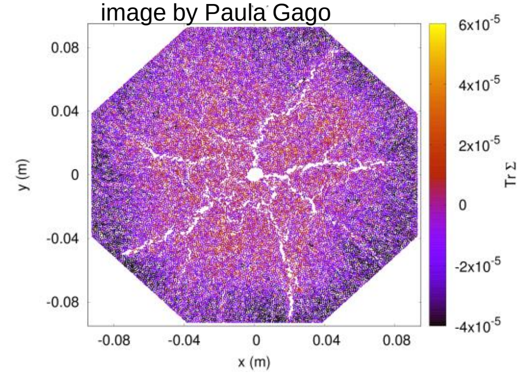
in collaboration with:

Fracture growth in soft sand

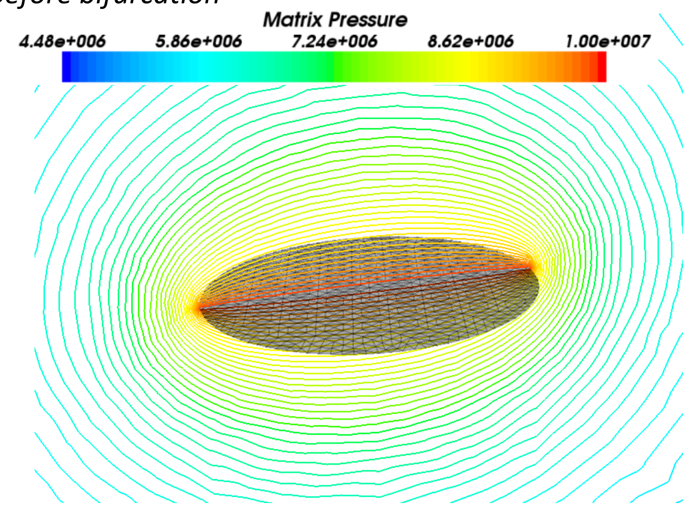
- Extending the simulator to model fracturing in soft sands

- Using a multi-scale approach involving grain scale modelling (using OpenFoam and CFDEM Ligghts)

image by Paula Gago



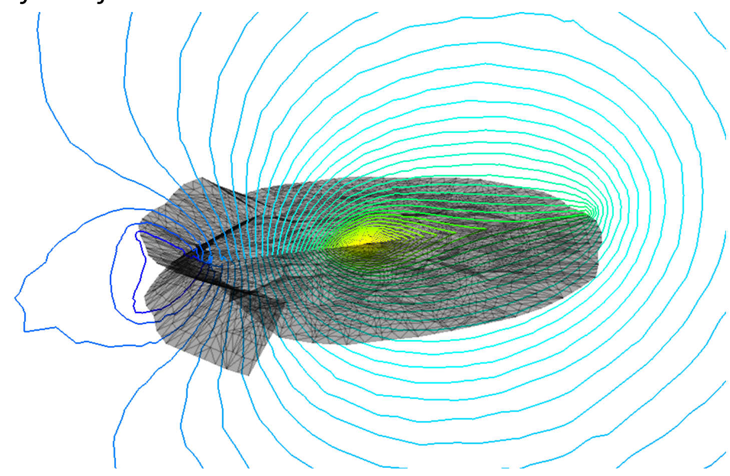
Before bifurcation

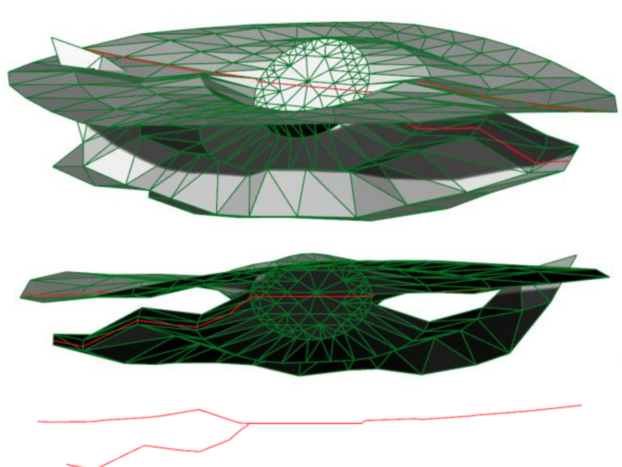


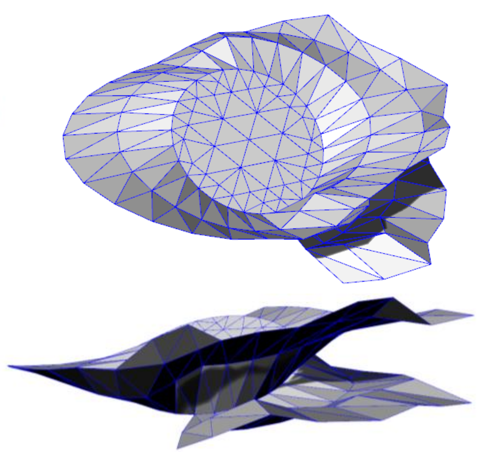
Hydraulic fracture

Tensile fracture

After bifurcation

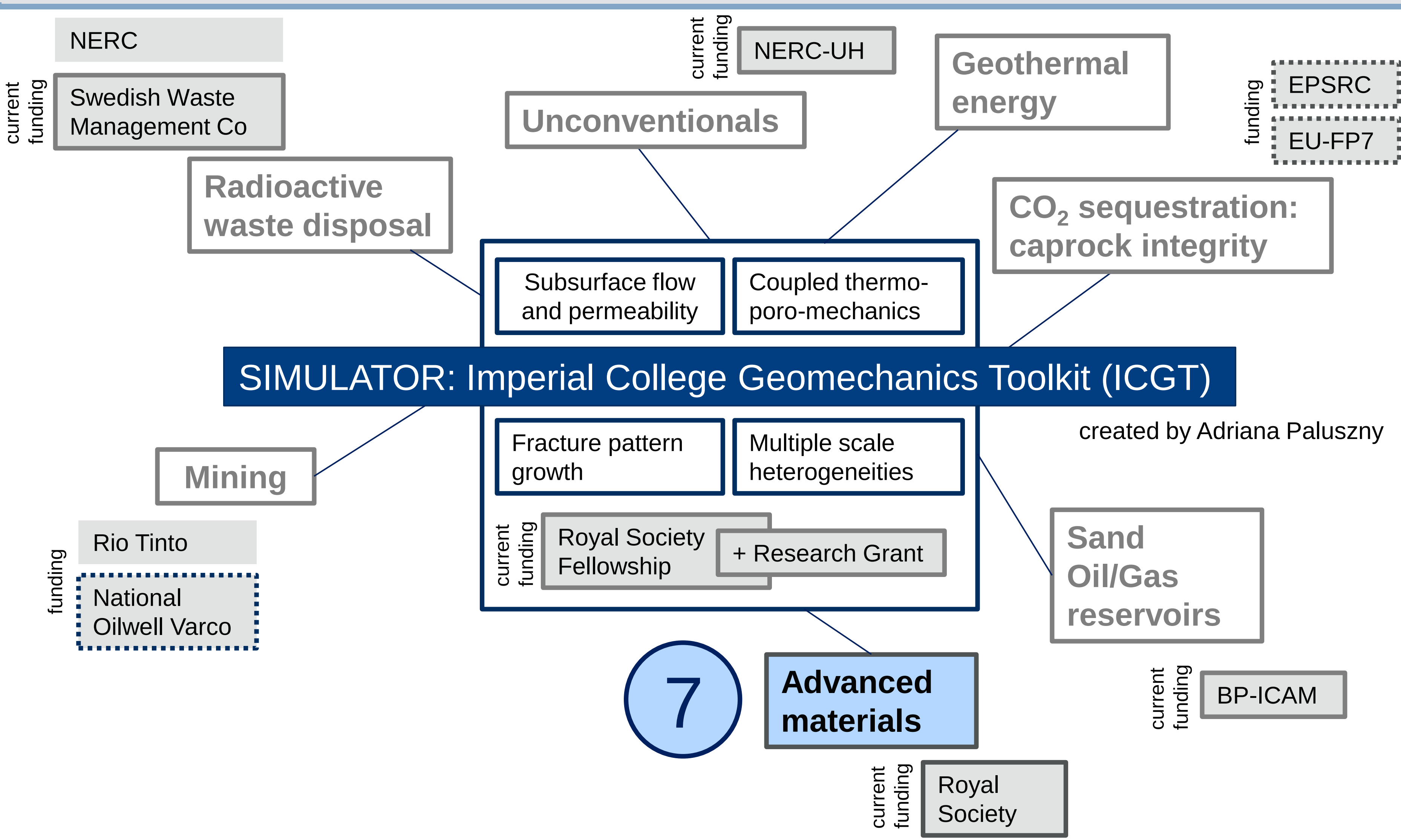






Imperial College London

Overview of my research



Imperial College London

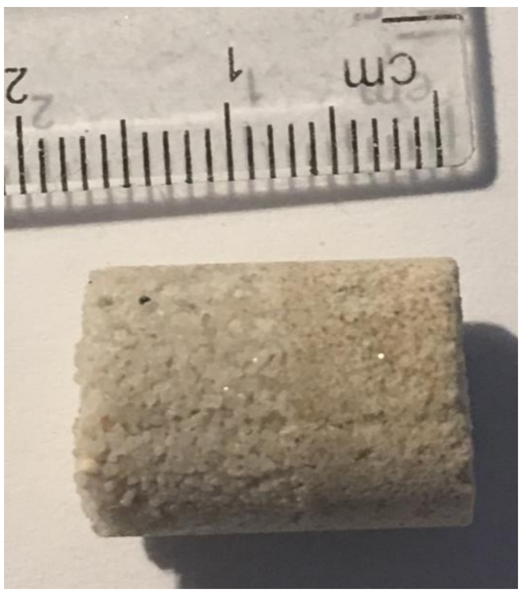
Visiting scholar at:

UNIVERSITY OF OXFORD

OxfordMaterials

Effect of heterogeneities on growth

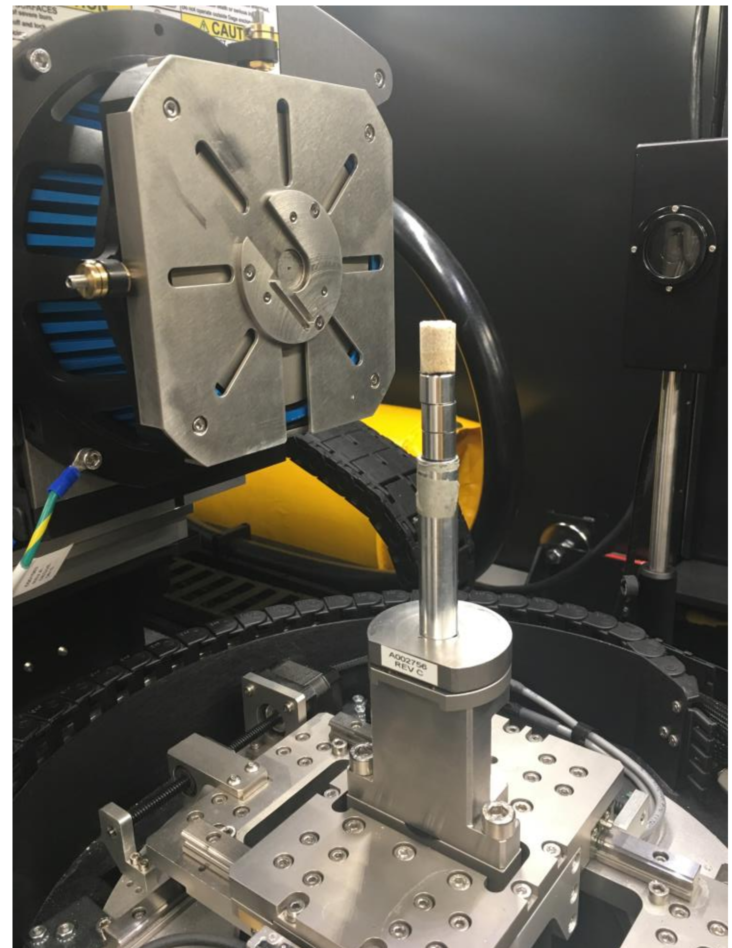
Bio-cemented heterogeneous synthetic sandstones created at Cambridge University



Deformed *in situ*

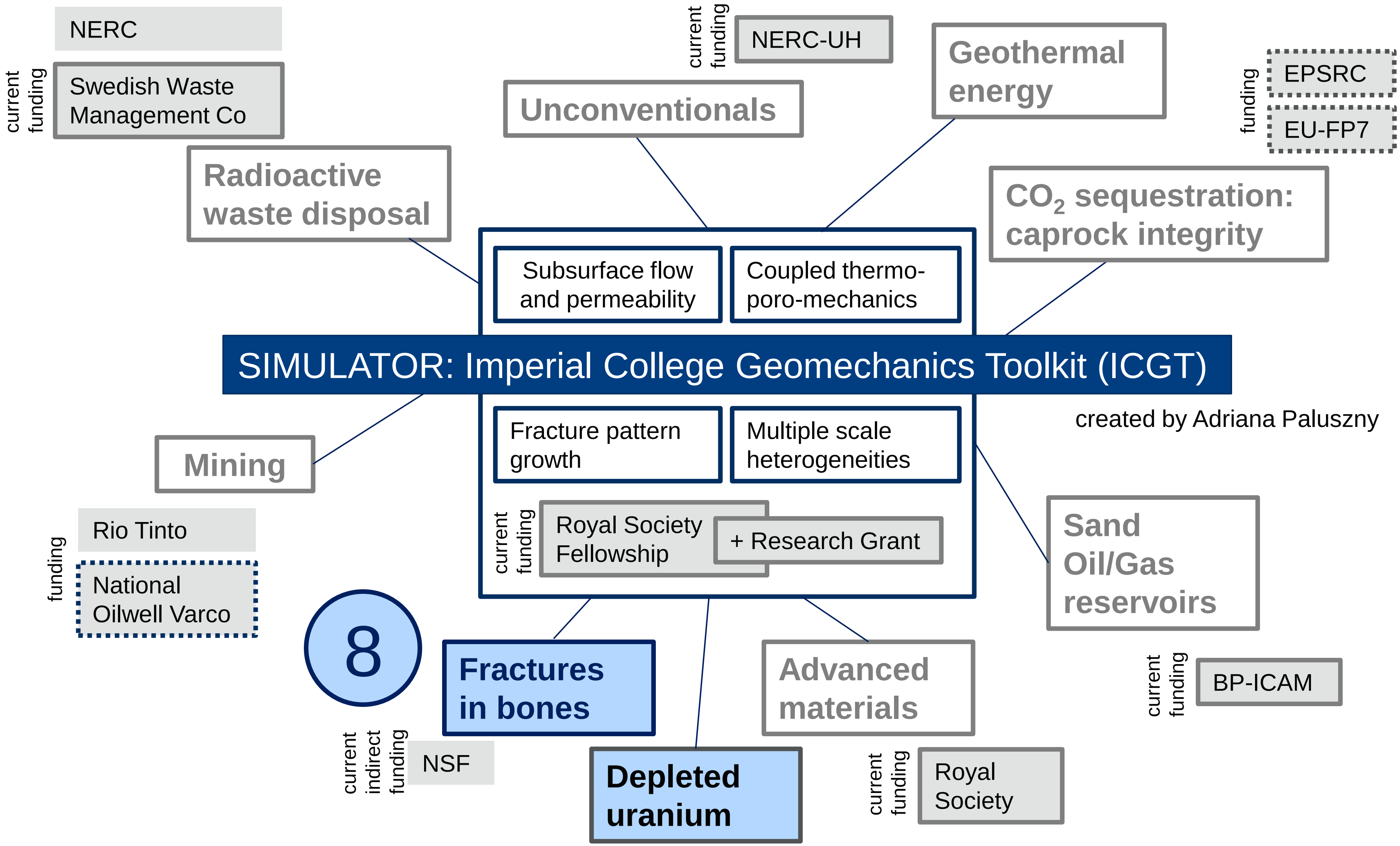
Fractured *in situ*

microCT acquisition for Digital Volume Correlation:
New <u>validation</u> for stress intensity factors



Imperial College London

Overview of my research



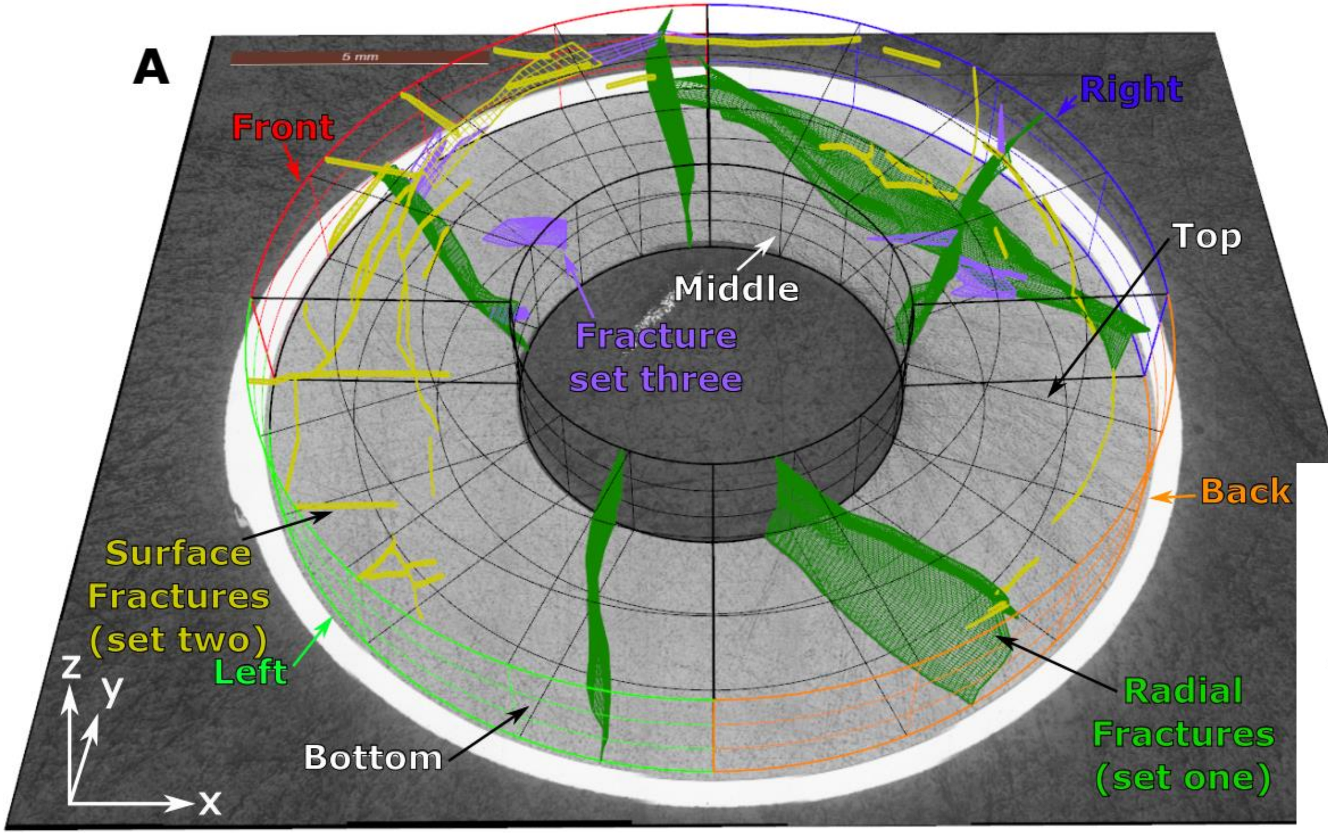
Imperial College London

in collaboration with:

NATIONAL NUCLEAR LABORATORY

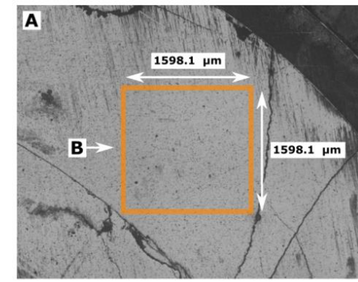
Permeability of depleted Uranium fuel pins

Reconstructed fracture network from microscopic images of sequentially grinded material

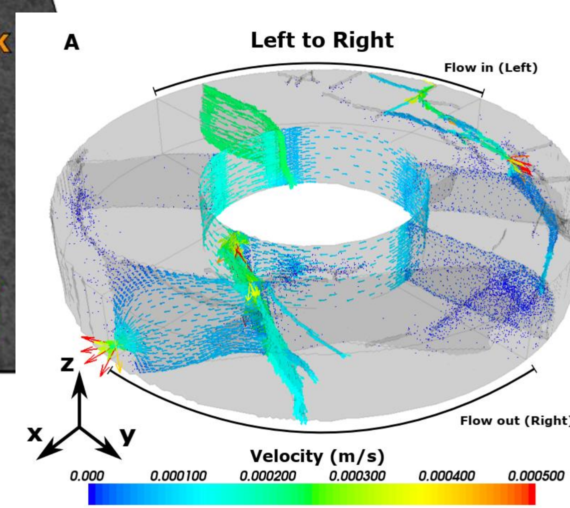


Good match obtained with gas permeability measurements published after submission of this article

Approximated matrix permeability



Quantified effective permeability

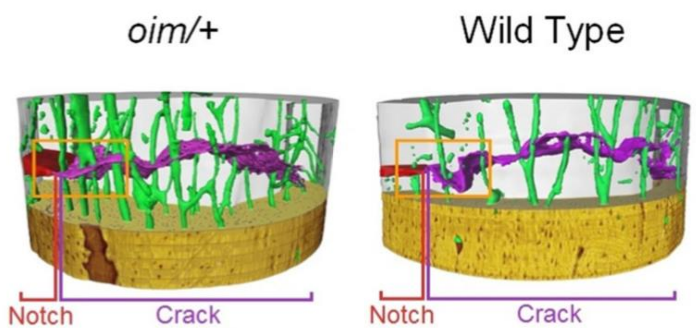


Thomas, Paluszny, Hambley, Hawthorne, Zimmerman, Journal of Nuclear Materials, 2018

Imperial College London

How tough is brittle bone?

Evaluated the effect of different vascular heterogeneities on crack growth in mouse bones



Work on bone will continue as NSF funding has been secured by collaborator for two PhD studentships which will model growth using ICGT

Journal of Bone and Mineral Research
JBMR
ASBMR
The American Society for Bone and Mineral Research

Original Article | Free Access

How Tough Is Brittle Bone? Investigating Osteogenesis Imperfecta in Mouse Bone

Alessandra Carriero, Elizabeth A Zimmermann, Adriana Paluszny ... See all authors

First published: 13 January 2014 | https://doi.org/10.1002/jbmr.2172 | Cited by: 49

ROR and SJS contributed equally to this work.

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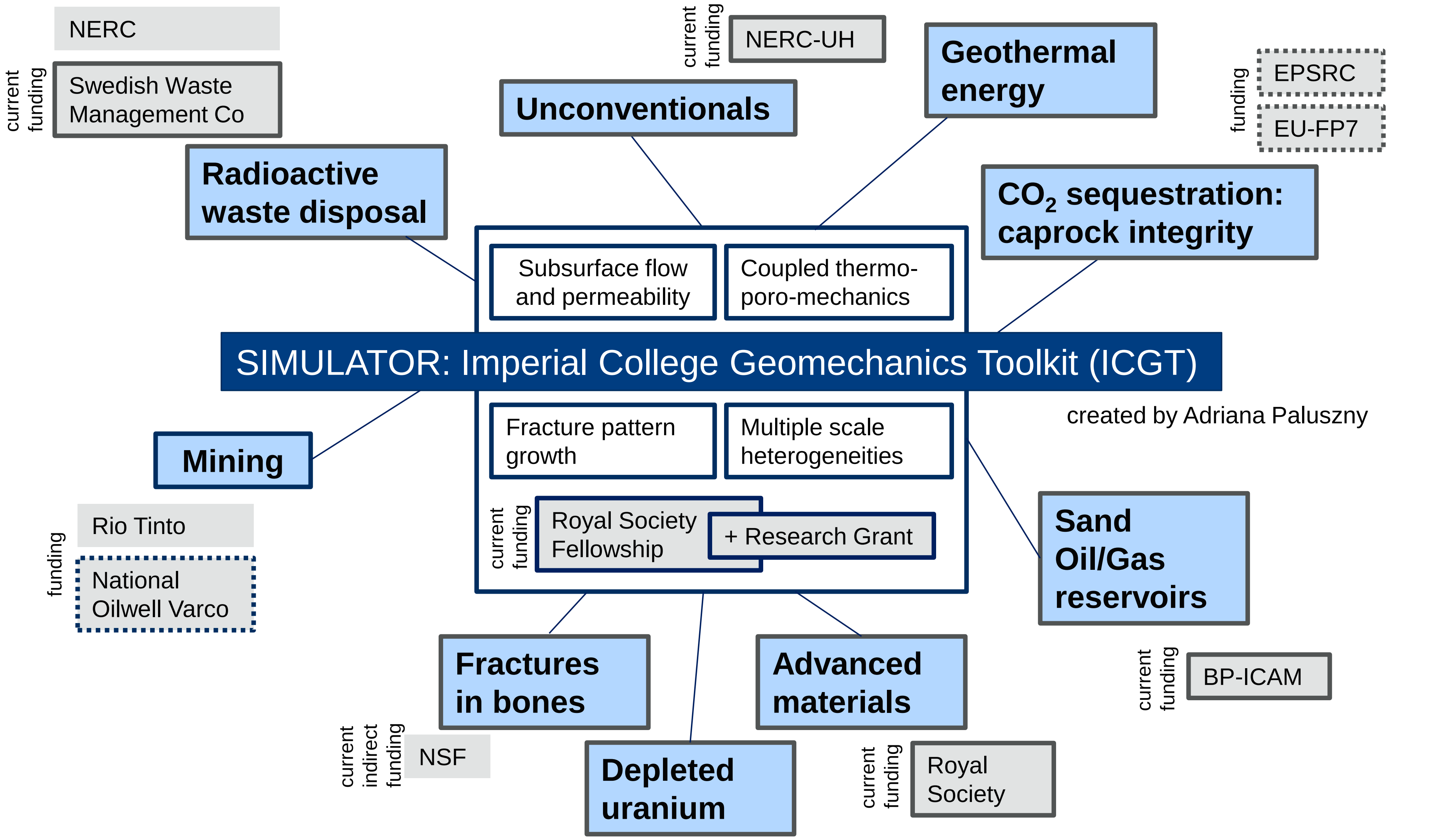
ABSTRACT

The multiscale hierarchical structure of bone is naturally optimized to resist fractures. In osteogenesis imperfecta, or brittle bone disease, genetic mutations affect the quality and/or quantity of collagen, dramatically increasing bone fracture risk. Here we reveal how the collagen defect results in bone fragility in a mouse model of osteogenesis imperfecta (*oim*), which has

Carriero, Zimmermann, Paluszny, Tang, Bale, Busse, Alliston, Kazakia, Ritchie, Shefelbine, Journal of Bone and Mineral Research, 2014

Imperial College London

Overview of my research



Funding

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NERC SCIENCE OF THE ENVIRONMENT

EPSRC Pioneering research and skills

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SEVENTH FRAMEWORK PROGRAMME

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Radioactivity And The Environment

NOV NATIONAL OILWELL VARCO

Radioactive Waste Management

RioTinto