An iTOUGH2 equation-of-state module for modeling supercritical conditions

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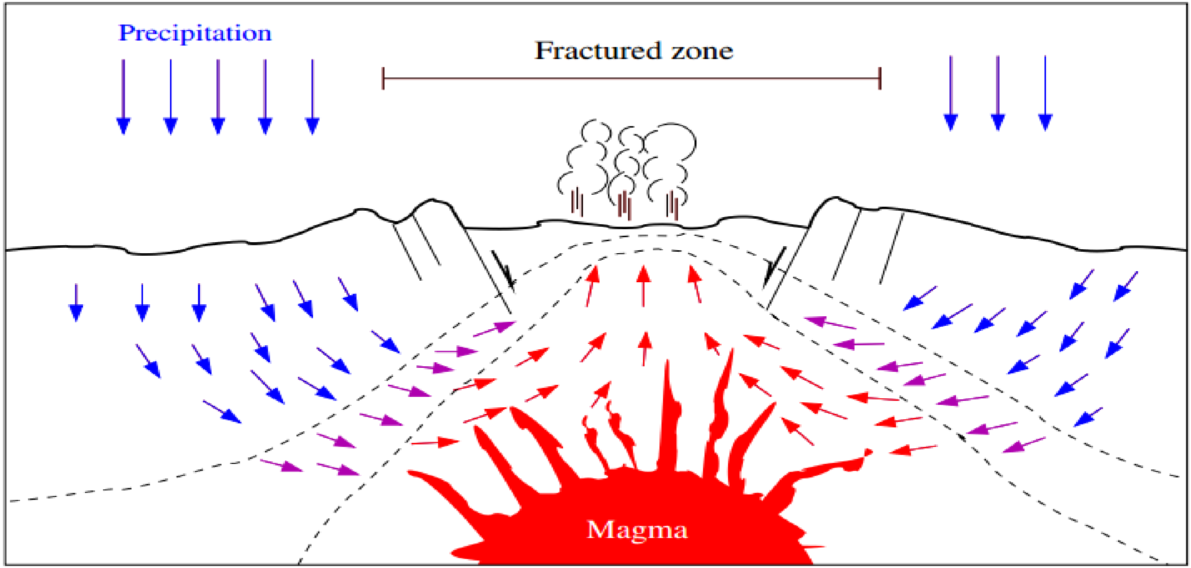
The Deep Roots of Geothermal Systems
Final Meeting

Objective

Find ways to incorporate the heat source and the entire water circulation into geothermal reservoir models



Outline

Extending iTOUGH2 to Supercritical Conditions

- Thermodynamic Formulations
- Implementation in iTOUGH2

Validation

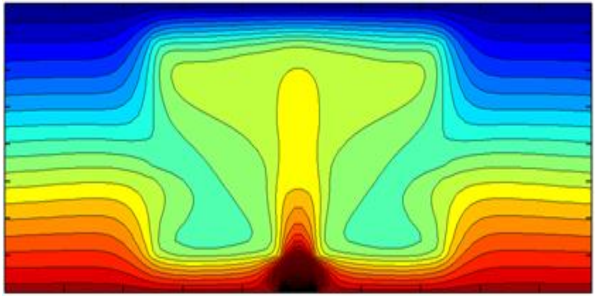
- 5-Spot Geothermal Problem
- Comparison to Hydrotherm

Utilization

- Hengill
- IDDP-2 at Reykjanes

Improvements

Summary

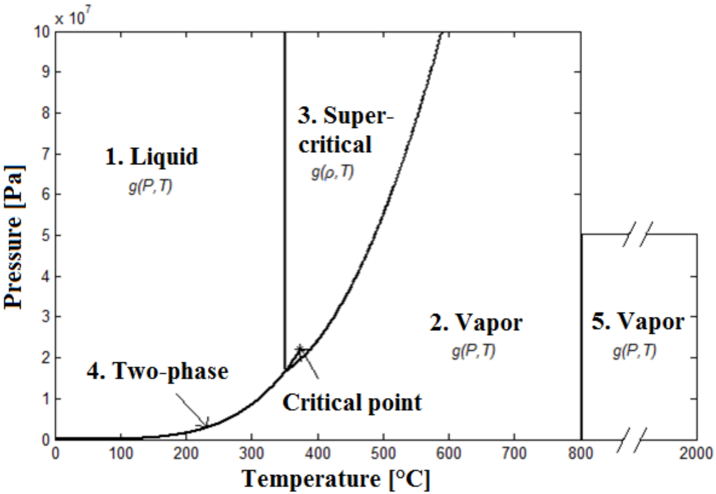


IAPWS-IF97

Accurate for supercritical conditions

Approximation of IAPWS-95

Faster than IAPWS-95



International standard	Simulator	Temperature range [ºC]	Pressure range [MPa]
IFC-67	TOUGH2, iTOUGH2	0-800	0-100
IAPWS-95	iTOUGH2-EOS1sc	0-1,000	0-1,000
IAPWS-IF97	AUTOUGH2, iTOUGH2-EOS1sc	0-800	0-100
Revised region 5 of IAPWS-IF97	iTOUGH2-EOS1sc	800-2,000	0-50

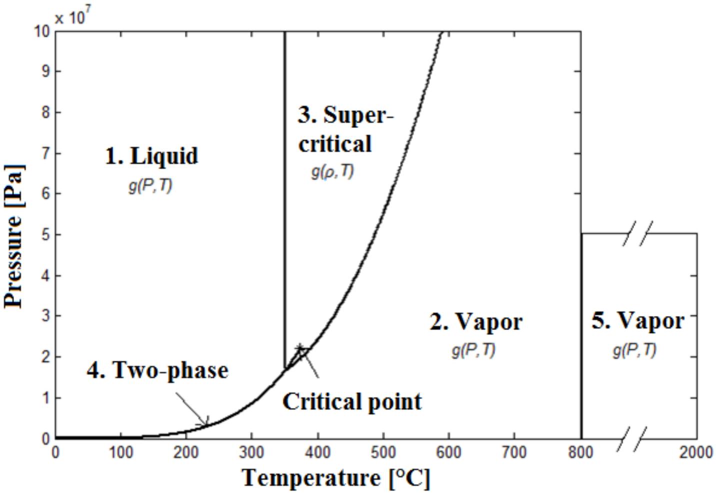
Primary variables

IFC-67 (iTOUGH2):

- Single phase: *P*, *T*
- Two phase: Pg, Sg

IAPWS-IF97:

- **Single phase: *P*, *T***
- **Two phase: P_g, S_g**
- **Supercritical: *ρ*, *T***



Primary variables chosen for EOS1sc

IAPWS-95:

- Single phase, two phase and supercritical: *ρ*, *T*

➔ iterative function inversion required in iTOUGH2

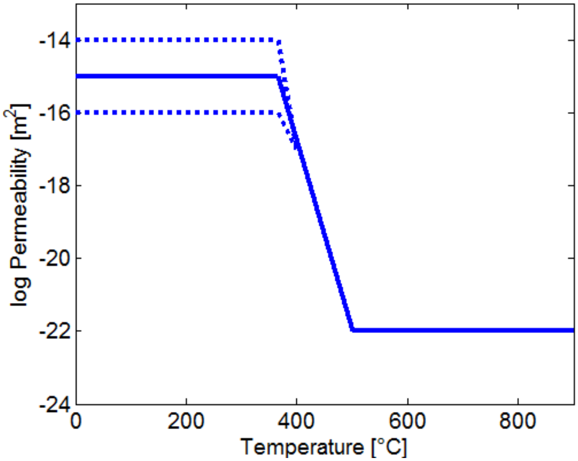
Temperature and depth dependent rock properties

Brittle/ductile transition

- Treat permeability as a function of temperature

Latent heat of crystallization

- Double the heat capacity of the pluton for high temperatures



ROCKS.4

IPFT = 1 Linear permeability changes
2 Log-linear permeability changes

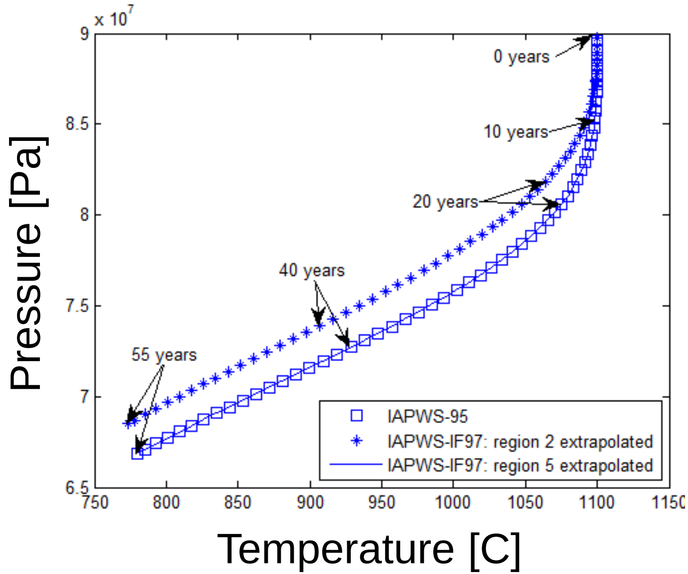
ROCKS.5

ICFT = 1 Linear heat capacity changes
2 Log-linear heat capacity changes

Five-spot geothermal problem

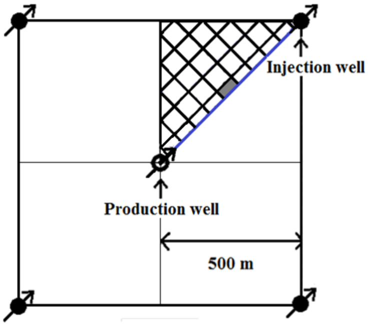
Supercritical conditions with extreme temperature and pressure

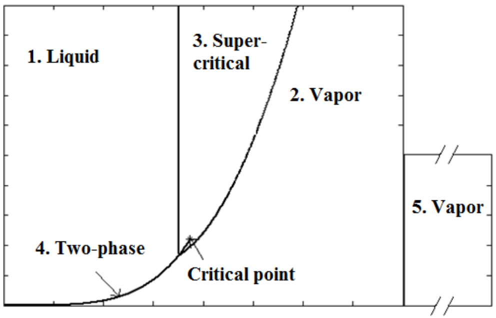
- Initial conditions:1100ºC, 90 MPa
- Enthalpy of injected fluid: 3000 kJ/kg
- Injection/production rate: 24 kg/s



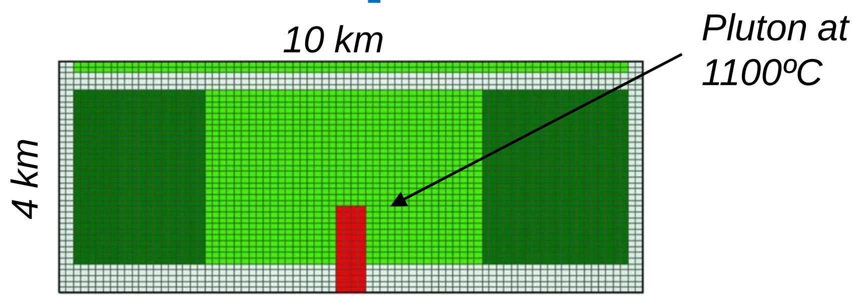
CPU time decreases by a factor of 10 when using IAPWS-IF97 instead of IAPWS-95

➔ use IAPWS-IF97

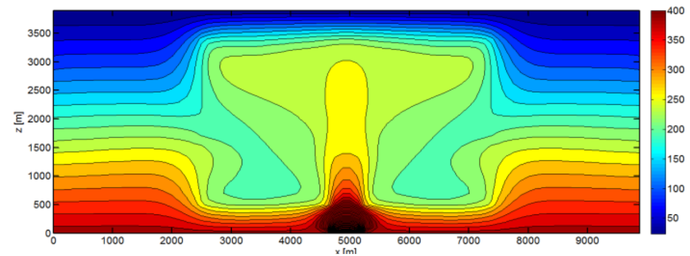




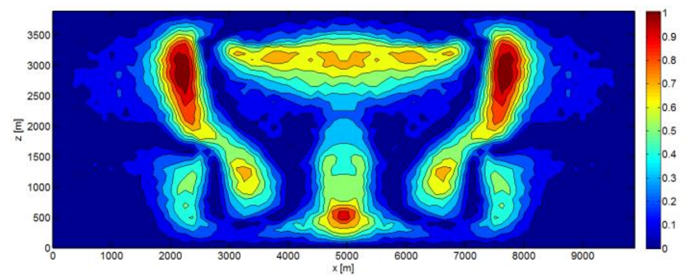
Cooling Pluton, comparison to Hydrotherm



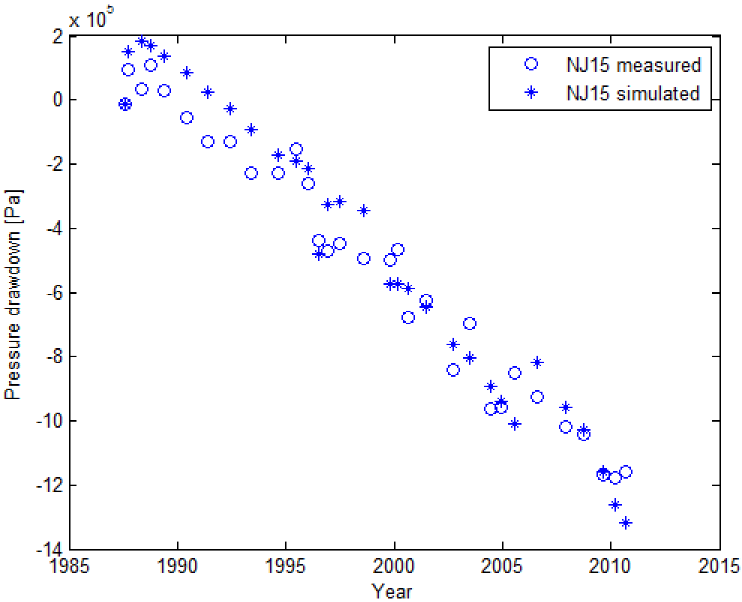
Temperature after 5000 years:

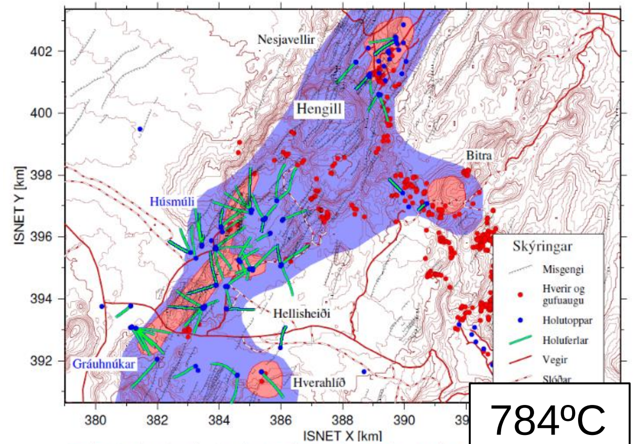


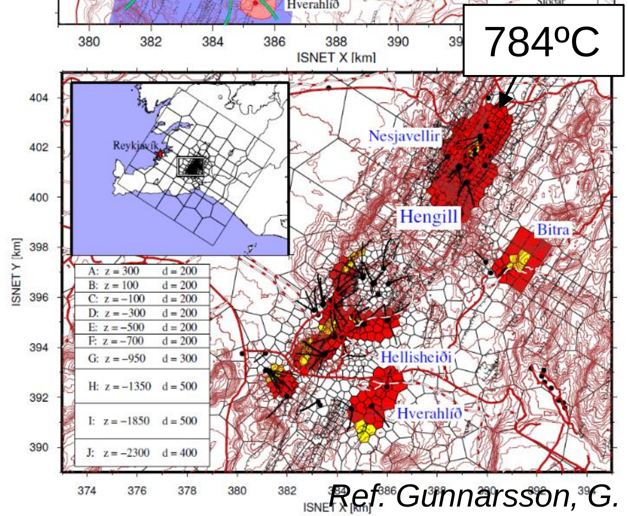
Absolute temperature difference:



EOS1sc used to model deep roots of Hengill







Ref: Gunnarsson, G.

Correlation 98%

Correlation for initial conditions: Pressure 97%, Temperature 84%

EOS1sc utilized at Reykjanes

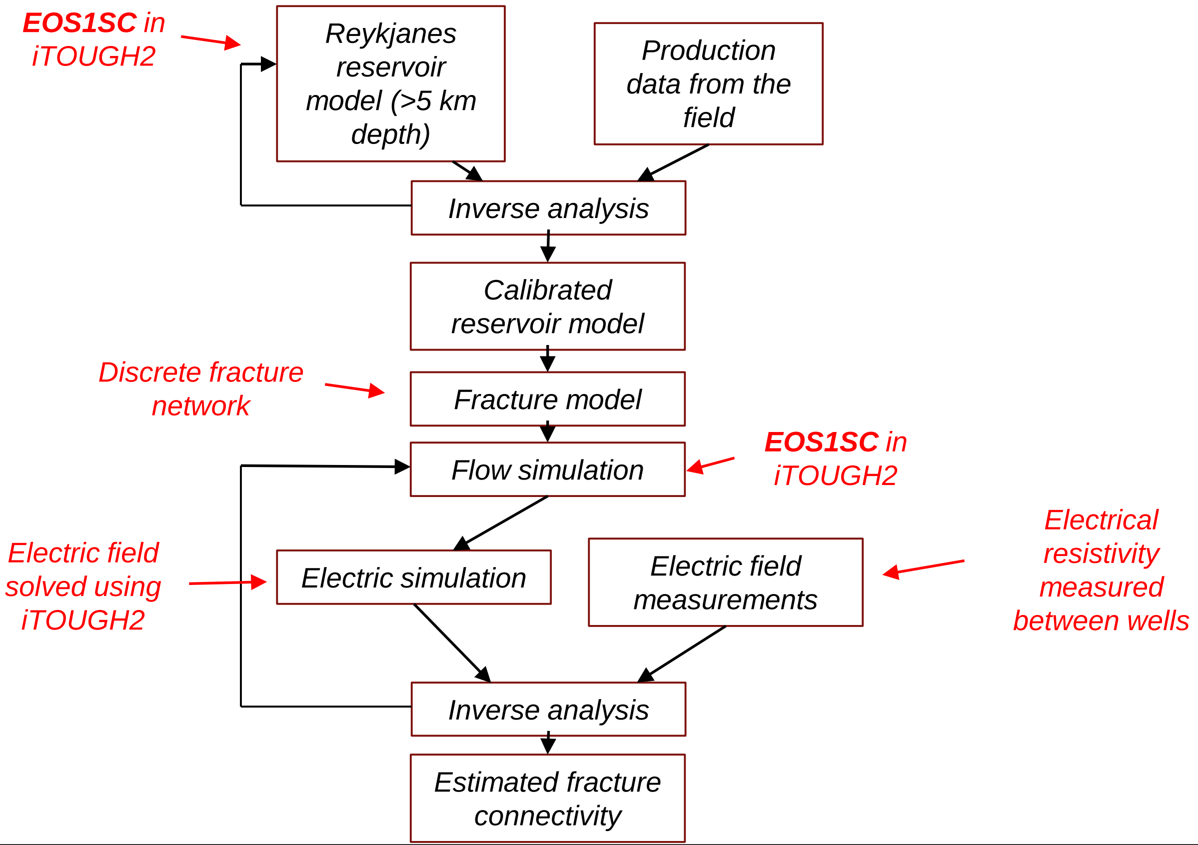
Estimate fracture connectivity at Reykjanes with an inverse analysis using direct current electric potential measurements during water injection

If water with less electrical conductivity than brine is injected into a geothermal reservoir, electrical potential in the field will increase as the injected water fills fracture paths

Time-lapse electric potential data is related to the connectivity of the fracture network

Materials	**Resistivity [ohm-m]**
Pure water	1,000,000
Natural waters	1-1,000
Sea water	0.2
Saline water (20%)	0.05
Clay	5-150
Gravel	480-900
Limestone	350-6,000
Sandstone (consolidated)	1,000-4000
Igneous rock	100-1,000,000

EOS1sc utilized at Reykjanes



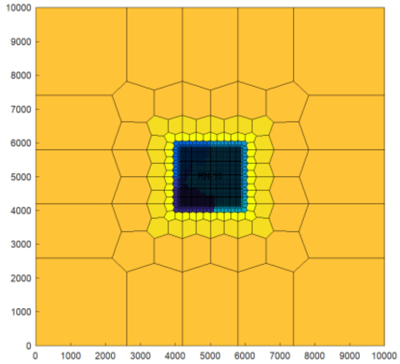
Numerical Model of Reykjanes

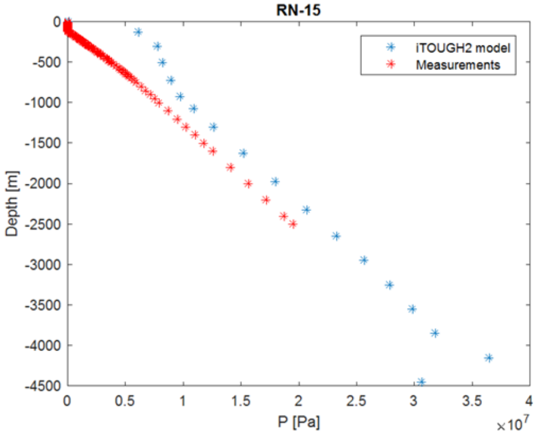
Include magmatic intrusions

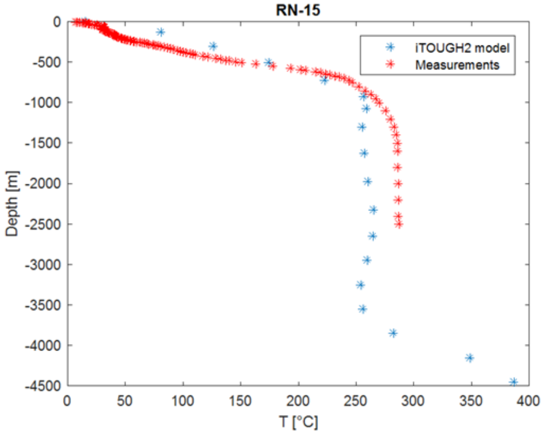
>5 km depth

Steady-state and production simulated

Pressure and temperature before and during production used to calibrate model



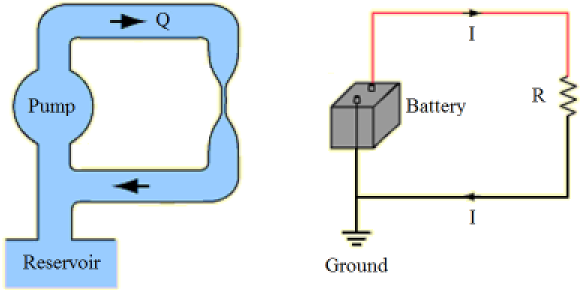




Electric Field Solved Using iTOUGH2

Ohm's law: $J = -\sigma \nabla V$

Darcy's law: $q = -\frac{k}{\mu} \nabla p$



Source: Hyperphysics, Georgia State University

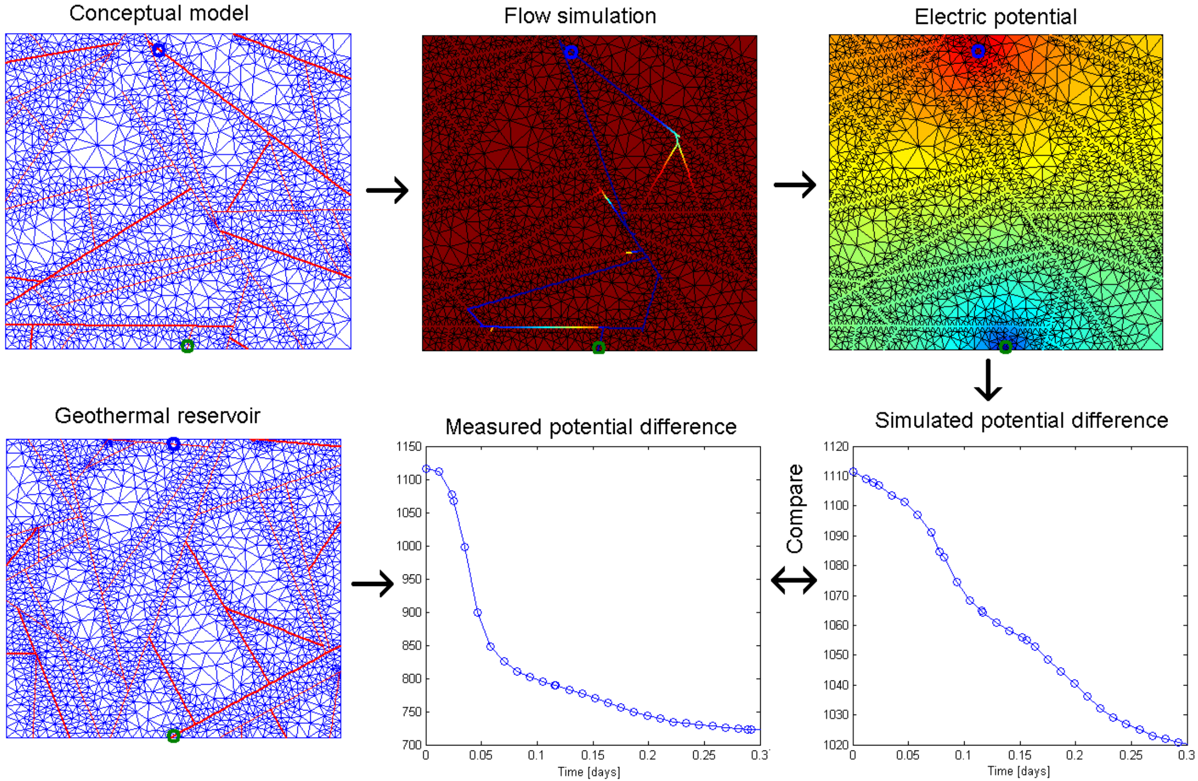
Analogy between Darcy's law and Ohm's law

	Darcy's law:	**Ohm's law:**
Flux of:	Water q	Charge J
Potential:	Pressure p	Voltage V
Medium property:	Hydraulic conductivity k/μ	Electrical conductivity σ

$$k = \sigma\mu$$

$$\dot{m} = \rho Q = \rho I$$

Inverse Analysis



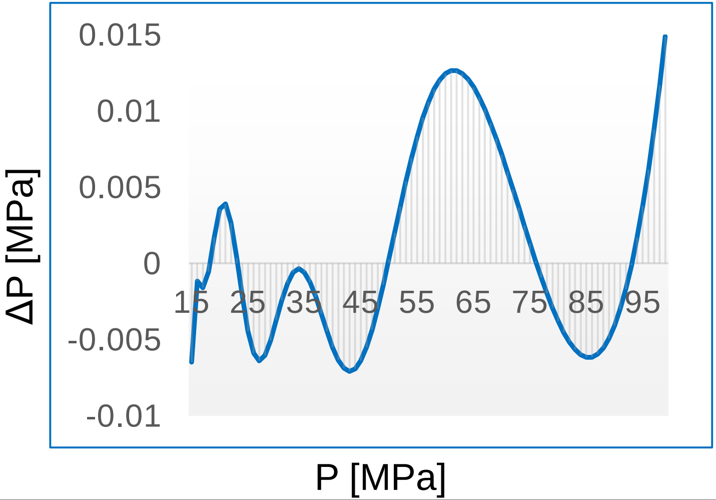
Improvements to EOS1sc

Bézier curve implemented to eliminate discontinuities across boundaries of the thermodynamic regions

Backward equation for specific volume as a function of pressure and temperature for Region 3 of IAPWS-IF97 implemented

- Newton-Raphson iteration eliminated
- 7 times faster than before

Discrepancies in P between Region 1 and Region 3



Summary

EOS1sc in iTOUGH2 developed for supercritical conditions

Temperature and depth dependent rock properties

Validation of EOS1sc

Examples showing the use of EOS1sc

Improvements to EOS1sc

Acknowledgments

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Thank you!