Electricity production from high-enthalpy geothermal systems

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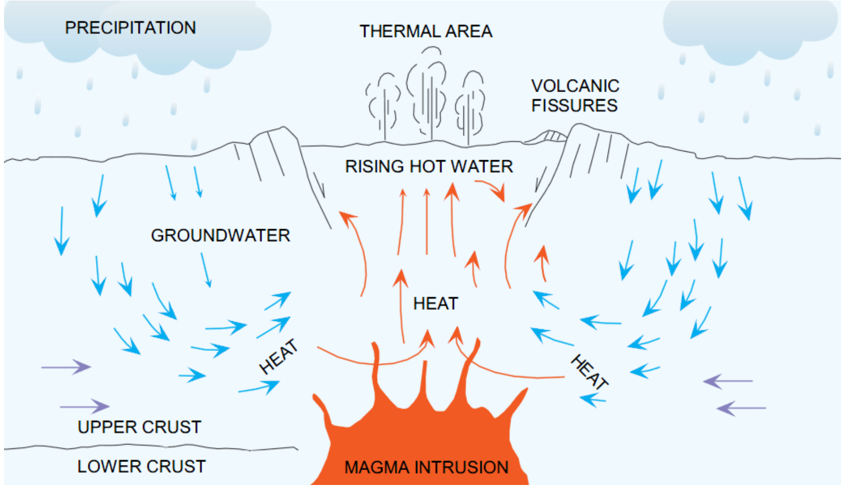
Overview

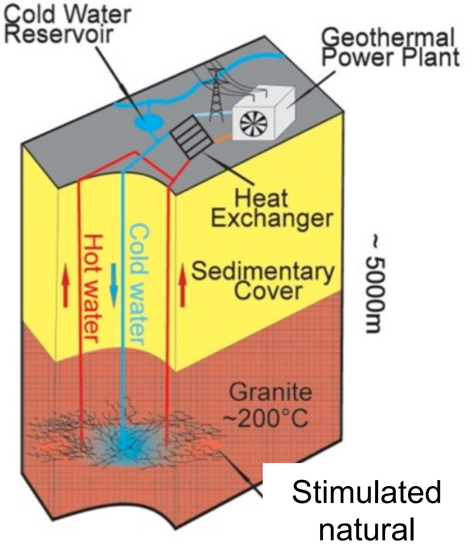
- Introduction
  - History/societal context
  - Types of geothermal resources
  - Geothermal power cycles
  - Fluid reservoirs
- Numerical modeling of fluid flow/heat transfer
  - Large-scale structure
  - ‘Supercritical’ fluid resources
- Conclusions

Geothermal Resources for Electricity Production

- Natural, high-enthalpy systems
  - T = 250+°C, 10-100s MW_e
  - Magma-driven, heat replenished



- EGS-type (not discussed here)
  - T ≤ 200°C, 1-10 MW_e
  - Low-enthalpy; mining stored heat



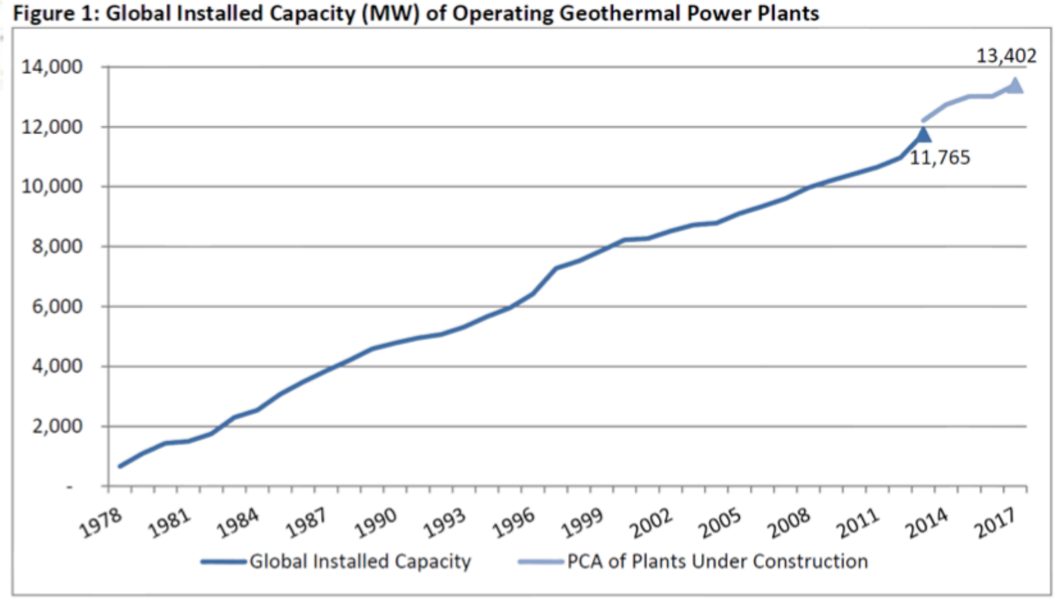
History of geothermal electricity production

- Lardarello, Italy (1904)

  <- Prince Piero Ginori Conti with his 15 kW geothermal steam engine

- Later development spurred on by oil crises
- Present installed capacity: 12,013 MW_e

Figure 1: Global Installed Capacity (MW) of Operating Geothermal Power Plants



Note: PCA (Planned Capacity Additions), Pilot plants and geothermal plants built in the first half of the 20th century and then decommissioned are not included. Source: Author

Geothermal Energy Association, 2014

Global distribution of geothermal resources

- High-enthalpy geothermal resources found in volcanic regions

	Number of active volcanoes	Identified resources (MW_e)	Installed capacity 2010 (MW_e)
Iceland	33	5,800	575
USA	133	23,000	3,098
Indonesia	126	16,000	1,197
Phillippines	53	6,000	1,904
Japan	100	20,000	535
Mexico	35	6,000	958
New Zealand	19	3,650	762
Italy (Tuscany)	3	2,000	843

Bertani, *Geothermics*, 2012

Advantages and disadvantages

Advantages:

- Renewable
- Low CO_2 emissions
- Simple technology
- Baseload power
- Zero fuel cost
- Low LCE (~$0.05/kWh)
- Local control of resource

Disadvantages:

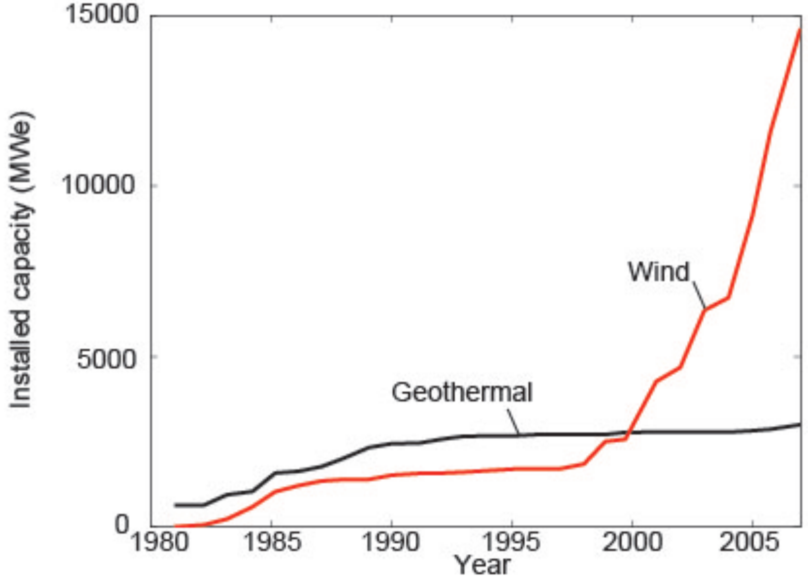
- Geographically restricted
- High upfront investment
- Long development times
- Pipe scaling/corrosion
- Resource risk
- Relatively low profit margins

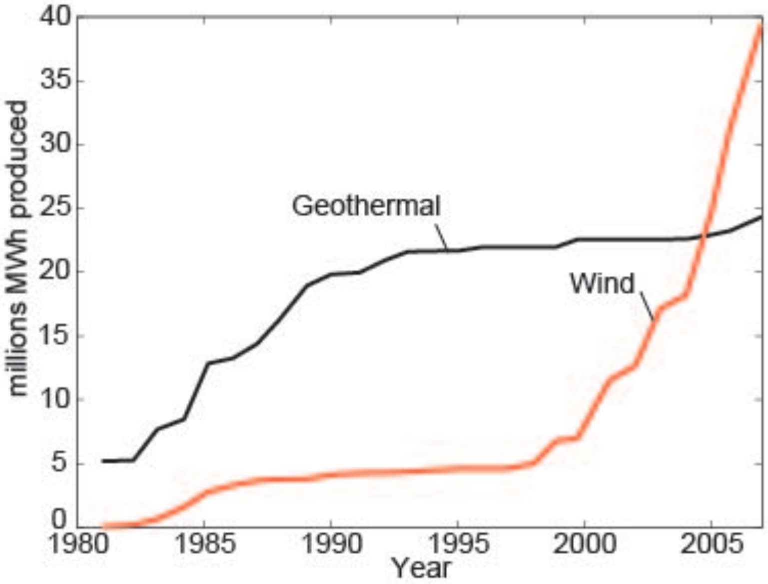
The importance of the capacity factor (*L*)

$$L = \frac{\text{actual electricity produced during given time}}{\text{theoretical maximum at full power operation}}$$

0.15-0.3 for wind
0.9-0.95 for geothermal

Energy Production (MWh_e/year) = Installed Capacity (MW_e) * 365 days/year * 24 hours/day * *L*



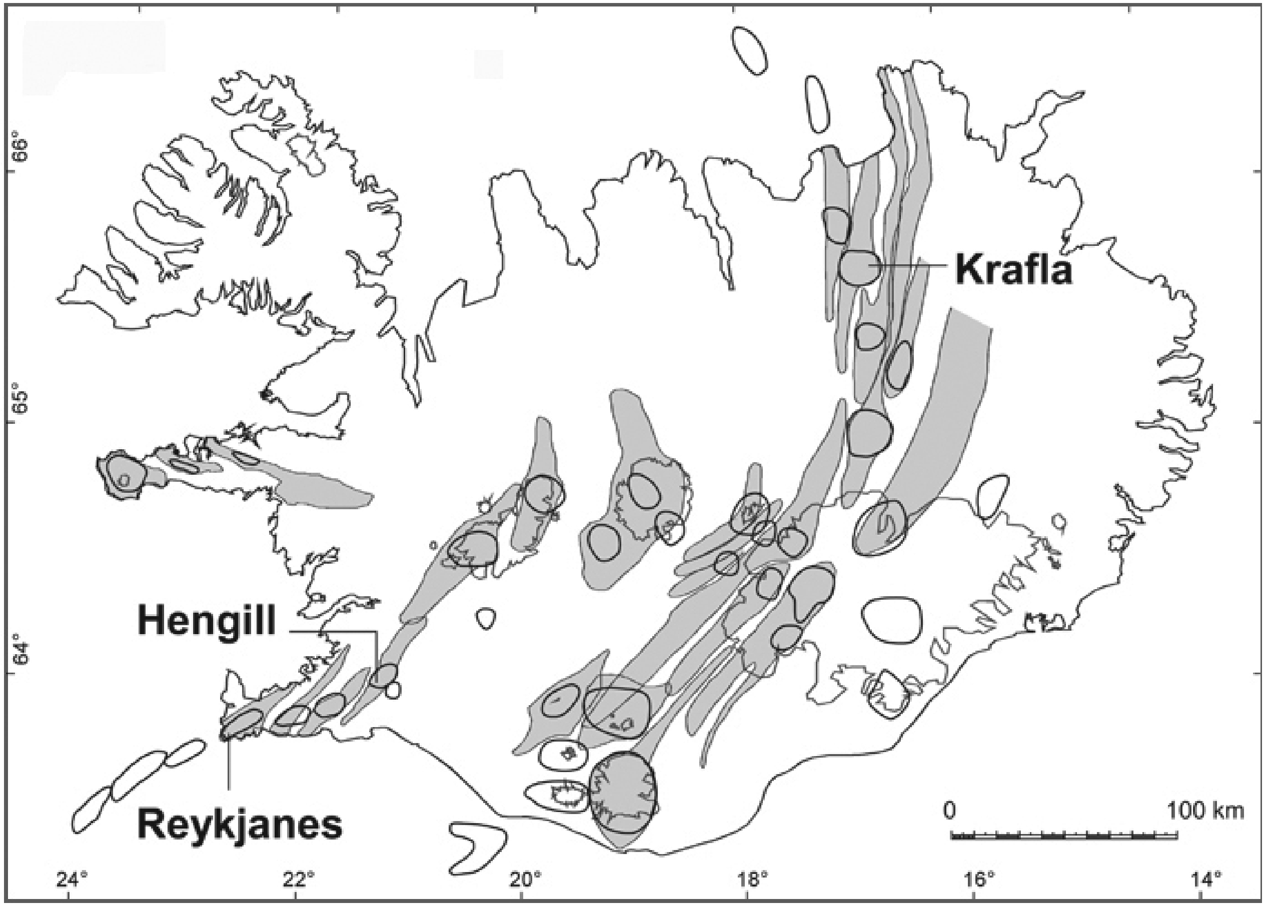


Total electricity production between 1981-2007 (U.S.A.)

Geothermal: ~480 million MWh_e, Wind: ~220 million MWh_e

Source: Geothermal Energy Association, 2014; American Wind Energy Association, 2010

Icelandic geothermal systems

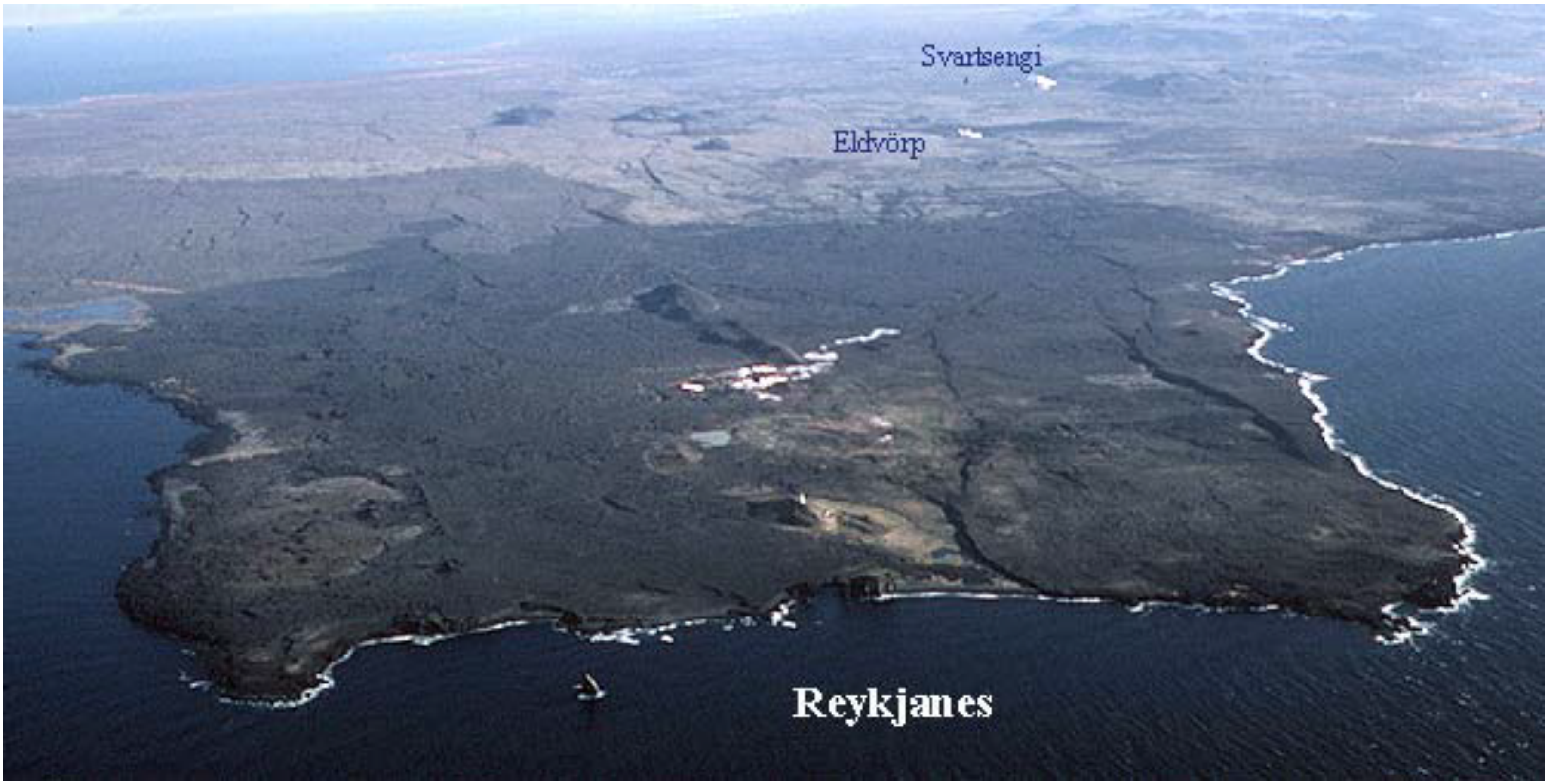


Elders et al., *Geothermics*, 2011

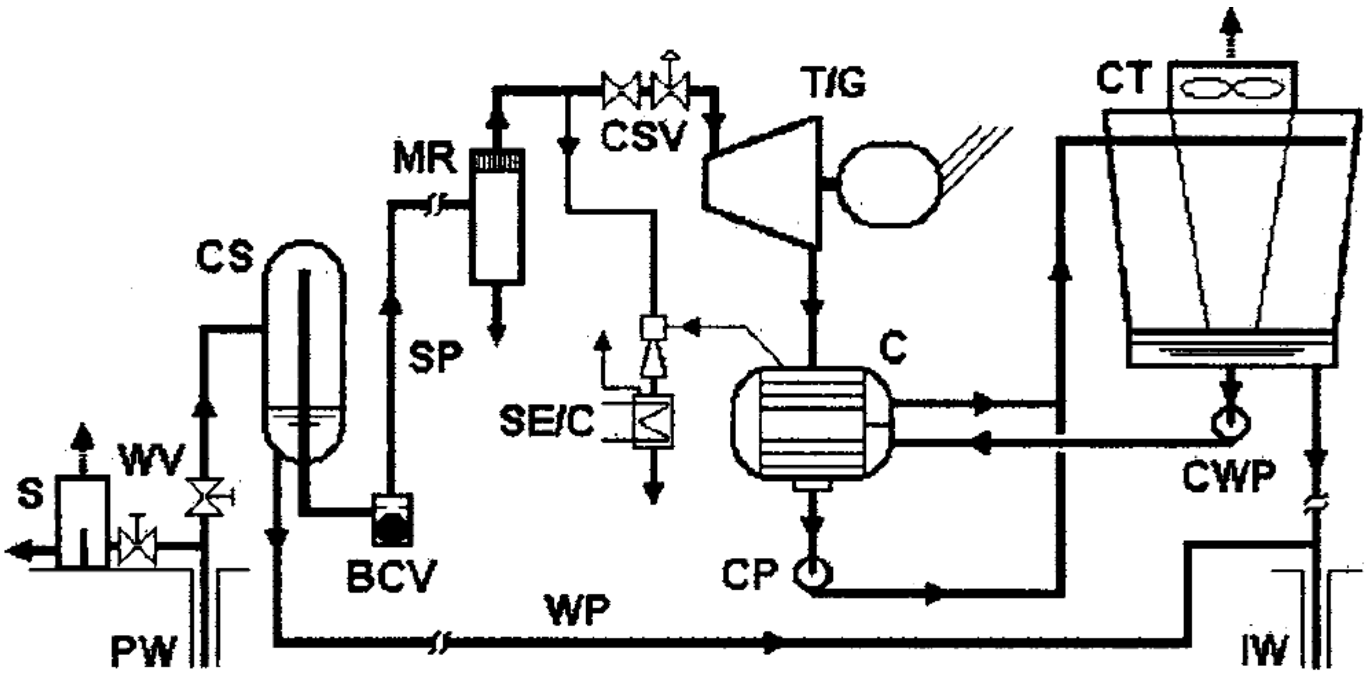
- 25-30 systems within active volcanic belts


Hengill (Nesjavellir)


Krafla
Emil Thor


Svartsengi
Eldvörp
Reykjanes

Single-flash power cycle

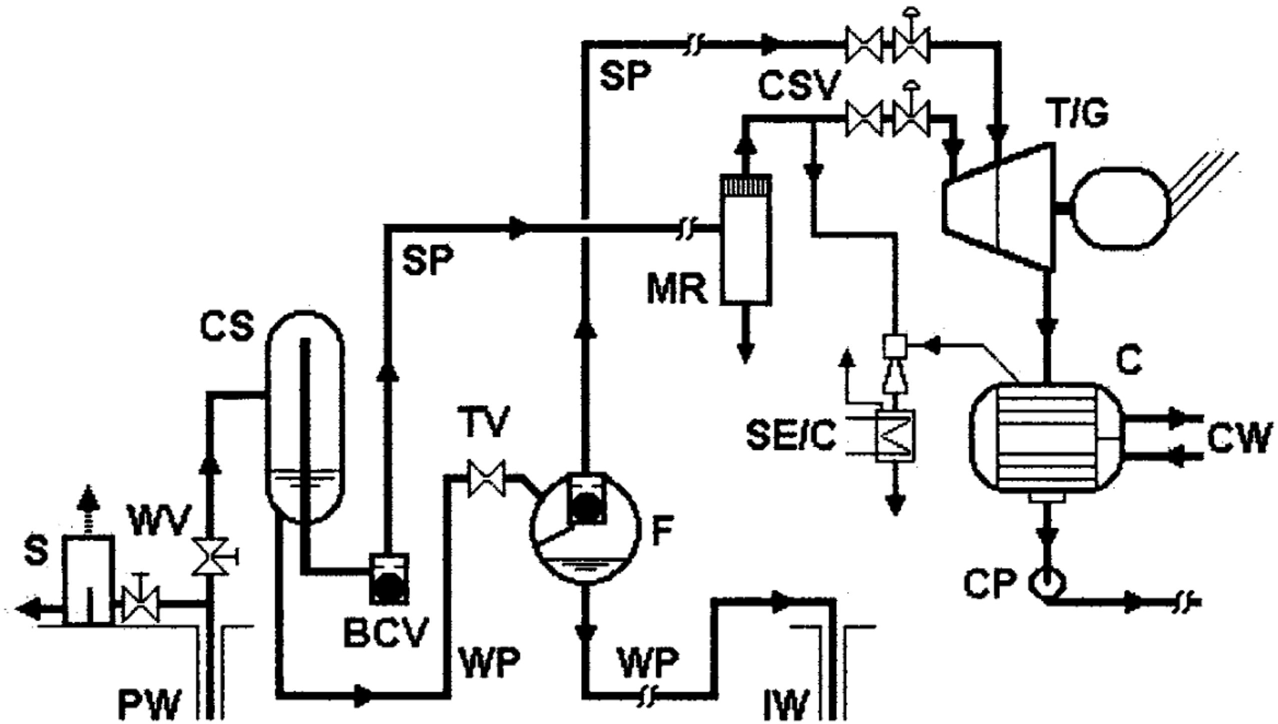


PW = Production Well
CS = Cyclone Separator
SP = Steam pipe
MR = Moisture Remover
T/G = Turbine/Generator
C = Condensor
SE/C = Steam Ejector/condensor
CT = Cooling Tower
WP = Water Pipe
IW = Injection Well

DiPippo, *Geothermal Power Plants*, 2006

- Turbines typically rated at 25-55 MW_e

Double-flash power cycle

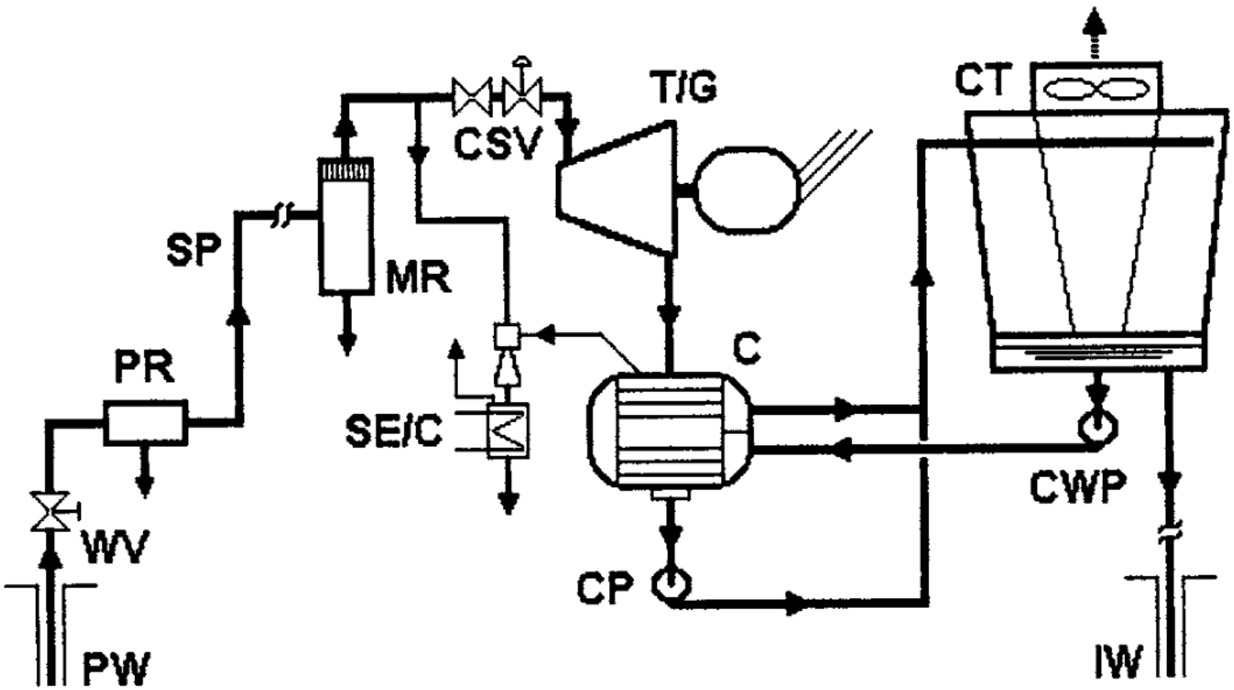


PW = Production Well
CS = Cyclone Separator
F = Flasher
SP = Steam pipe
MR = Moisture Remover
T/G = Turbine/Generator
C = Condensor
SE/C = Steam Ejector/condensor
CT = Cooling Tower
WP = Water Pipe
IW = Injection Well

DiPippo, *Geothermal Power Plants*, 2006

- Can produce 15-25% more power output for same geothermal fluid conditions

Dry-steam power cycle

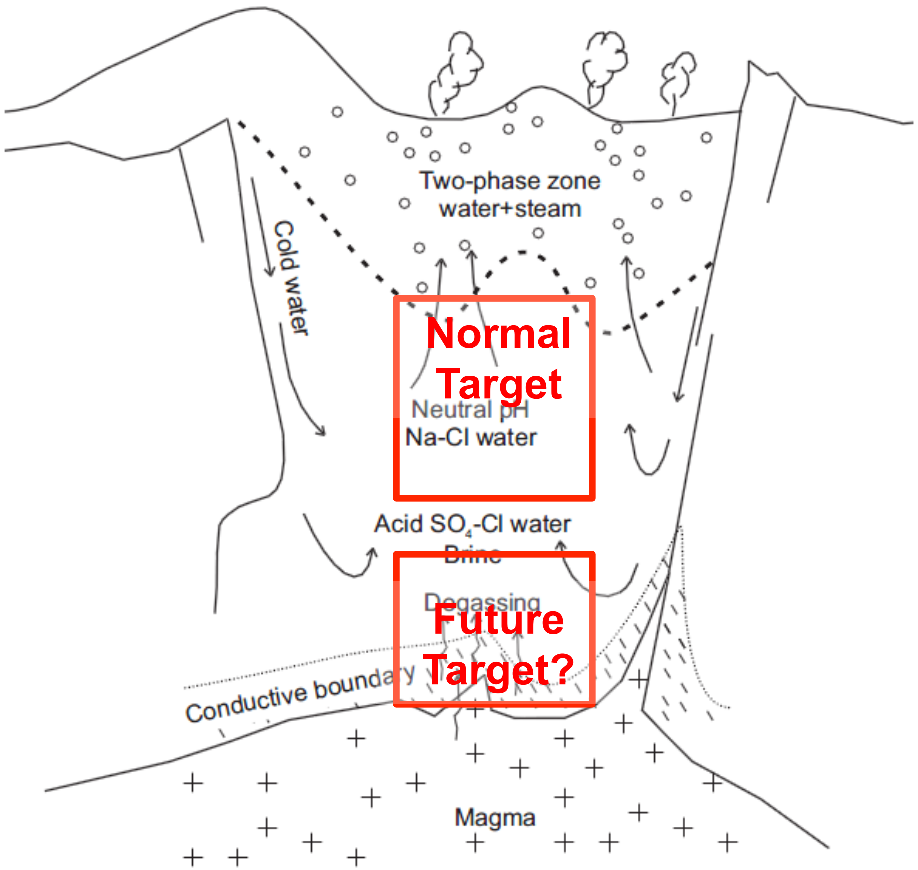


PW = Production Well
PR = Particle Remover
SP = Steam pipe
MR = Moisture Remover
T/G = Turbine/Generator
C = Condensor
SE/C = Steam Ejector/condensor
CT = Cooling Tower
WP = Water Pipe
IW = Injection Well

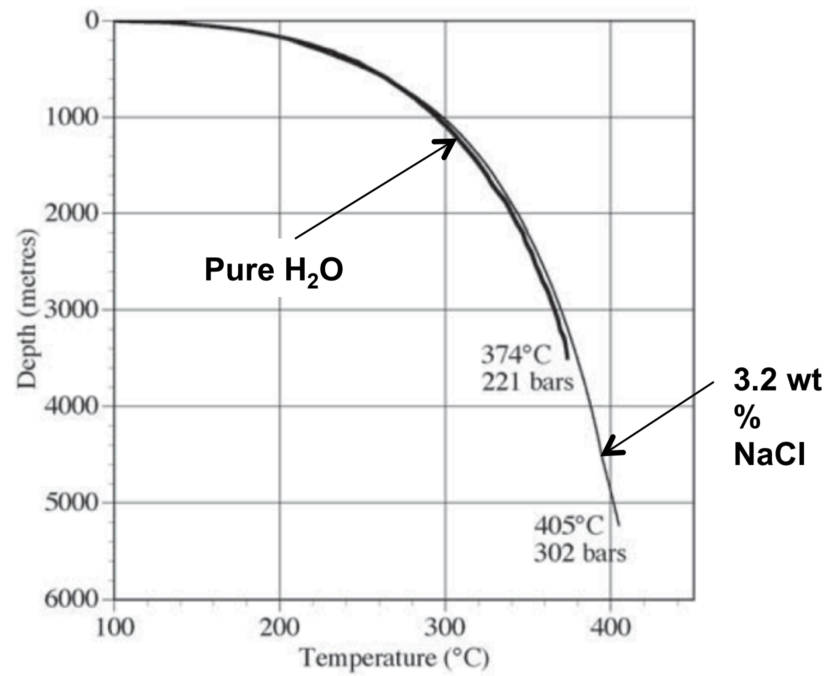
DiPippo, *Geothermal Power Plants*, 2006

- Simpler and less expensive... But reservoir pressures tend to decline more rapidly

Basic structure of volcanic geothermal systems



Arnórsson and Stefánsson, 2007



- Commonly boiling in upper 1.5 - 3 km
- Temperature corresponds to boiling point with depth

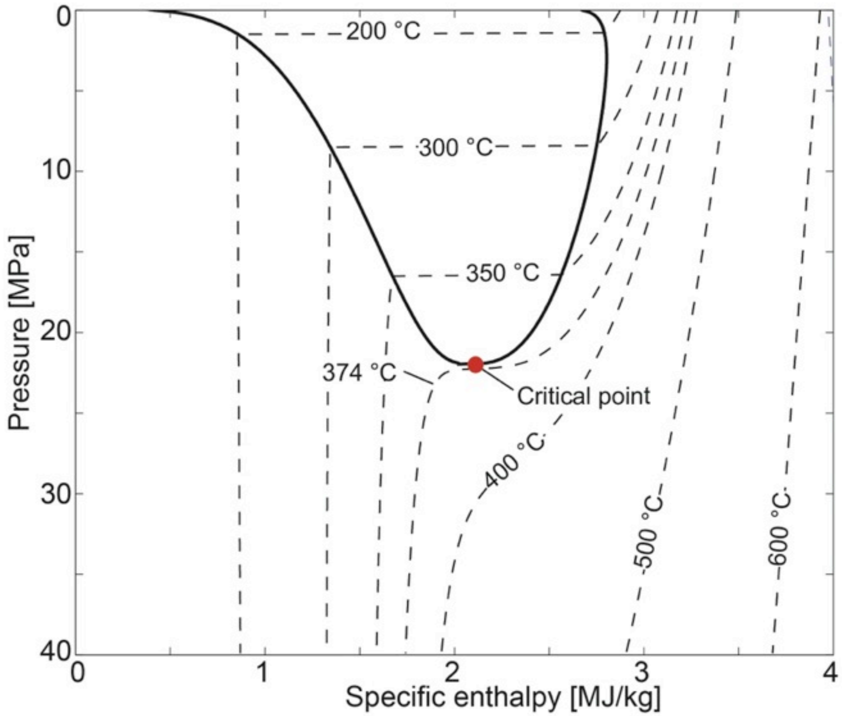
Geothermal aquifer fluid compositions

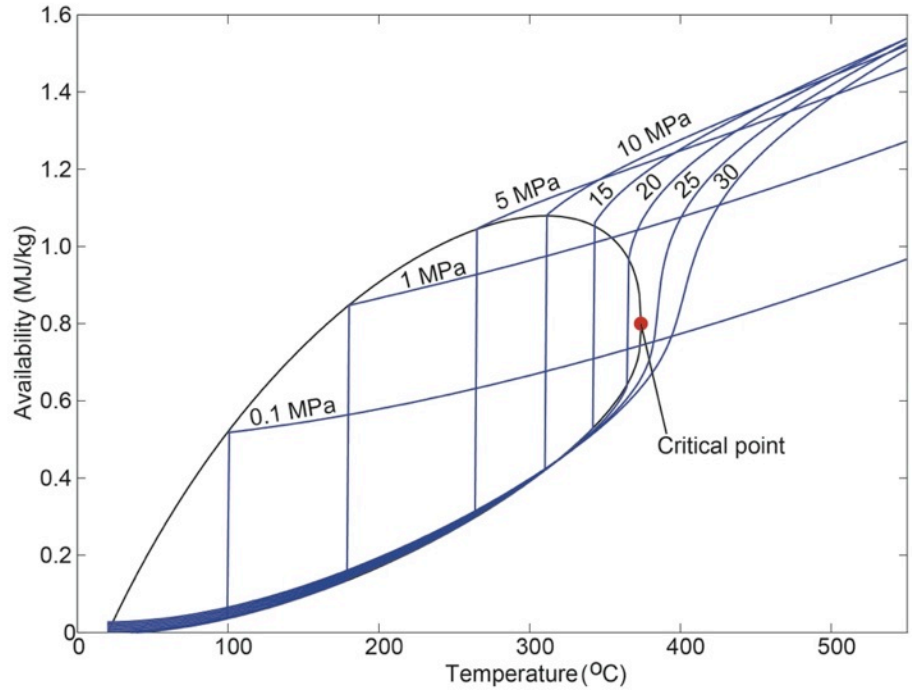
Component concentrations given in mg/kg

	Hellisheidi, Iceland[1]	**Olkaria, Kenya[2]**	**Mahanadong, Philippines[3]**	**Reykjanes, Iceland[4]**	**Salton Sea, USA[5]**
Aquifer Temp. (°C)	305	250	267	287	330
pH	7.28	6.7	5.88	5.313	5.1
SiO_2	622.6	452	508	613	>588
Na	92.9	391	1774	9172	54800
K	19.4	64.5	281	1294	17700
Ca	0.41	0.51	19.3	1516	28500
Cl	73.9	536	2924	17402	157500
SO_4	2	19.7	49	14.3	53
F	1.1	48.4	1.33	0.18	15
CO_2	362.4	752	717.2	781	1653
H_2S	212	37.0	36.72	26.1	10

1: Scott et al., 2014, **2**: Karingithi et al., 2010, **3**: Angcoy, 2010, **4**: Giroud et al., 2008, **5**: Williams and McKibben, 1989

Higher reservoir temperatures allow higher energy yield

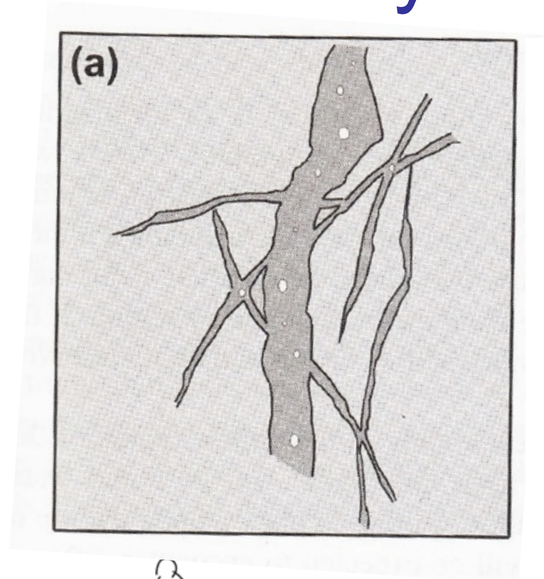


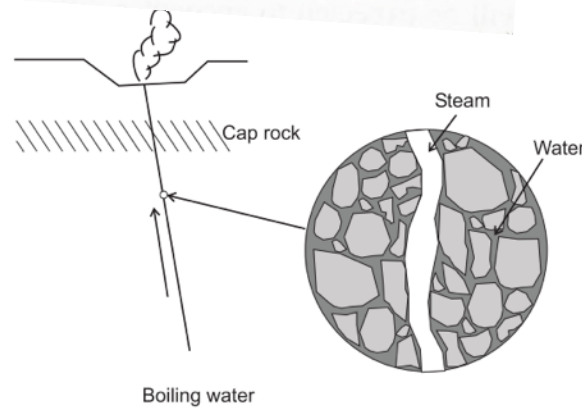


Availability (exergy) = $h - T_0 S$ (dead state: T_0 = 293 K, 0.1 MPa)

Types of high-enthalpy geothermal systems

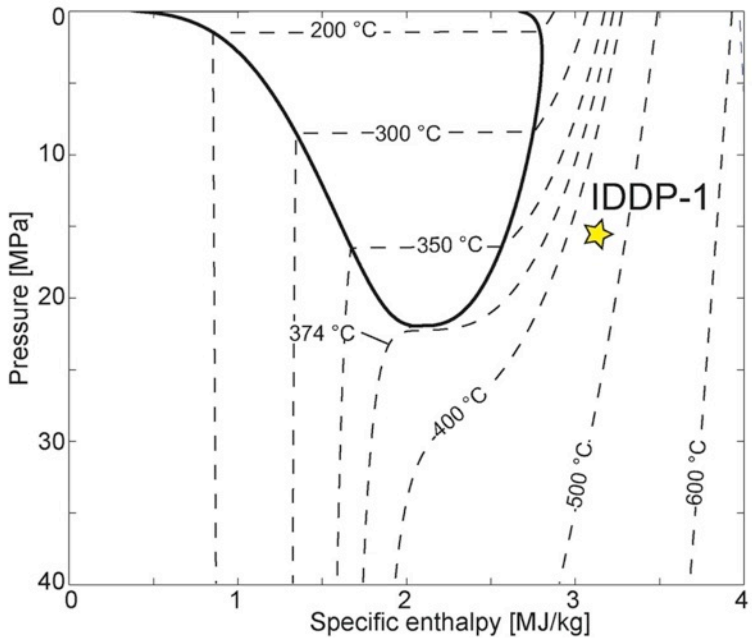
- Liquid-dominated
  - Liquid is mobile
  - Ex. New Zealand, Iceland
- Vapor-dominated
  - Vapor is mobile phase;
    liquid adheres to pore walls
  - Ex. Geysers, USA; Lardarello, Italy
- Supercritical





Grant and Bixley, 2007;
Arnorsson et al., *Rev. in Geochem. Min.*, 2007

Iceland Deep Drilling Project (IDDP)



- Initial aim to drill to sufficient temperatures (>370 °C) and depths (>4.5 km) to tap into a reservoir of supercritical fluid
- Drilled into a ~900°C magma body at 2.2 km depth in June 2009 at Krafla

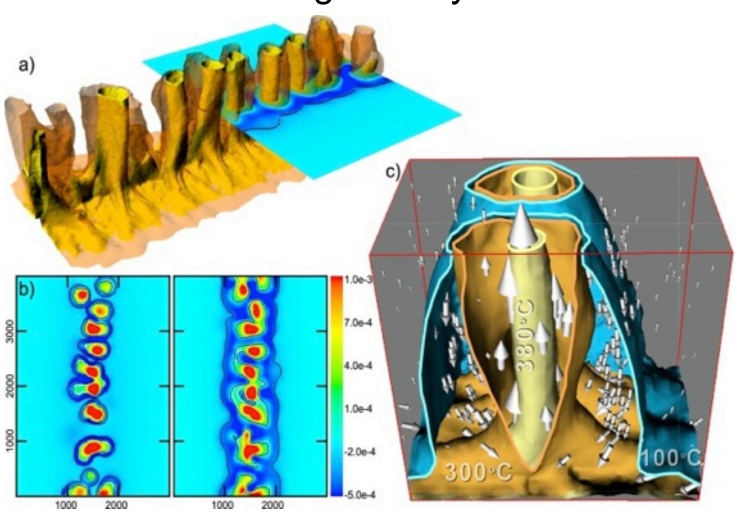
Motivation for numerical modeling:

- Geothermal is often seen as risky
  - Drilling is very expensive yet essential for ‘proving’ a resource
- Geological/geophysical/geochemical characterization of the sub-surface is difficult
- Numerical modeling builds quantitative understanding of the physics governing these systems
- Only recently have numerical models had sufficient “physical realism” to apply to natural examples
- Many fundamental questions remain to be answered…

Complex Systems Modeling Platform (CSMP++)

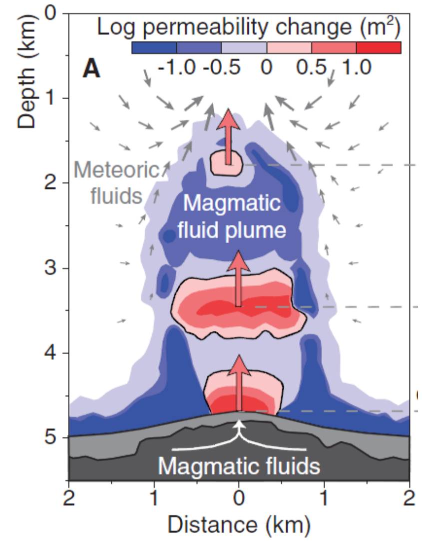
- Control volume-finite element
  - FE: diffusion-type equations
  - CV: advection-type equations
- Goal: accurately describe the physics/thermodynamics
- Additional constraint provided by geology (model set-up)

Mid-ocean ridge HT Systems



Coumou et al., *Science*, 2008

Porphyry Copper Deposits



Weis et al., *Science*, 2012

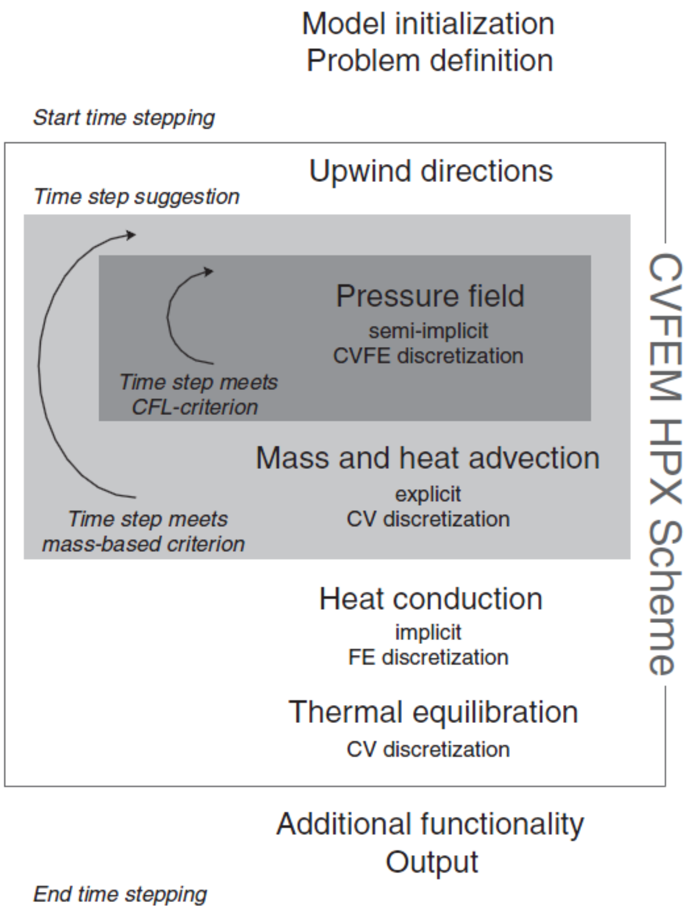
Governing equations

- Two-phase Darcy's law $$v_i = -k \frac{k_{ri}}{\mu_i} (\nabla p - \rho_\mathrm{i} g) \qquad i = \{v, l\}$$
- Mass conservation $$\frac{\delta(\varphi(S_l \rho_l + S_v \rho_v))}{\delta t} = -\nabla \cdot (v_l \rho_l) - \nabla \cdot (v_v \rho_v) + \mathrm{Q}_{\mathrm{H2O}}$$
- Energy conservation $$\frac{\delta((1-\varphi)\rho_r h_r + \varphi(S_l \rho_l h_l + S_v \rho_v h_v))}{\delta t} =$$ $$-\nabla \cdot (K \nabla T) - \nabla \cdot (v_l \rho_l h_l) - \nabla \cdot (v_v \rho_v h_v) + \mathrm{Q}_\mathrm{e}$$
- Pressure diffusion $$\rho_f [\phi \beta_f + (1-\phi)\beta_r] \frac{\delta p}{\delta t} =$$ $$\nabla \cdot [k(\frac{k_{rl}\rho_l}{\mu_l} + \frac{k_{rv}\rho_v}{\mu_v}) \nabla p] - k(\frac{k_{rl}\rho_l^2}{\mu_l} + \frac{k_{rv}\rho_v^2}{\mu_v}) g + \mathrm{Q}_{\mathrm{H2O}} + \mathrm{Q}_\mathrm{p}$$

Weis et al., *Geofluids*, 2014

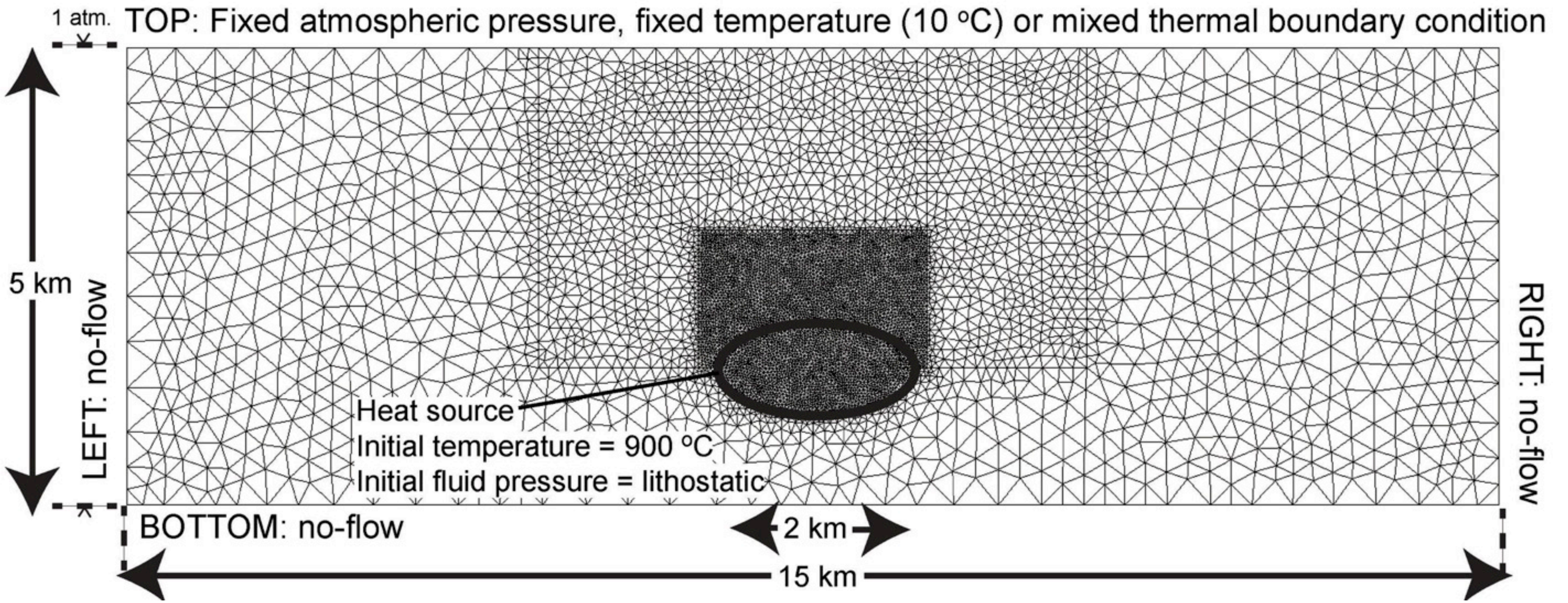
Computational method

- Strongly coupled equations split up using sequential approach
- Upwinding of fluid properties
- Mixture of implicit, semi-implicit, and explicit discretizations



Weis et al., *Geofluids*, 2014

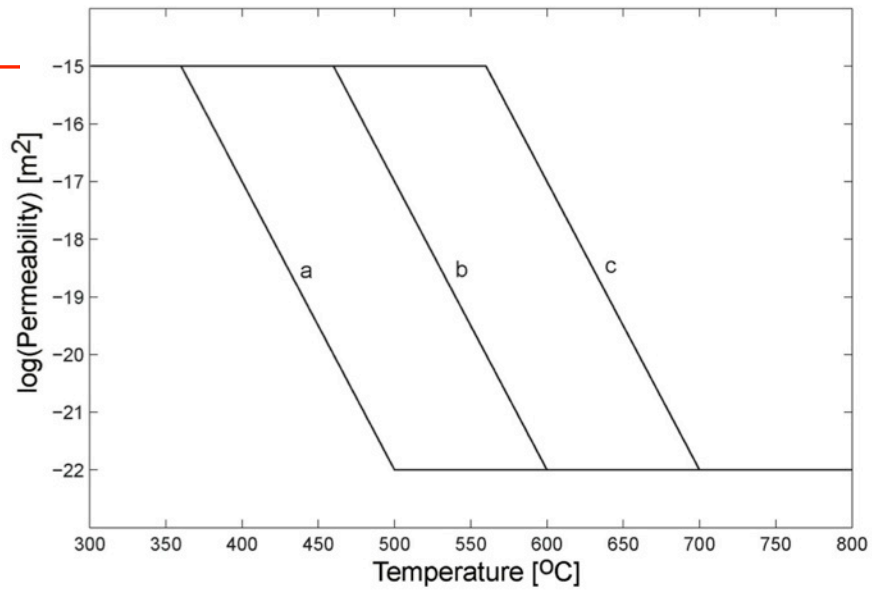
Typical model set-up



Temperature-dependent permeability

- Mimics the brittle-ductile transition in rocks
- Change from advection to conduction-dominated heat transport

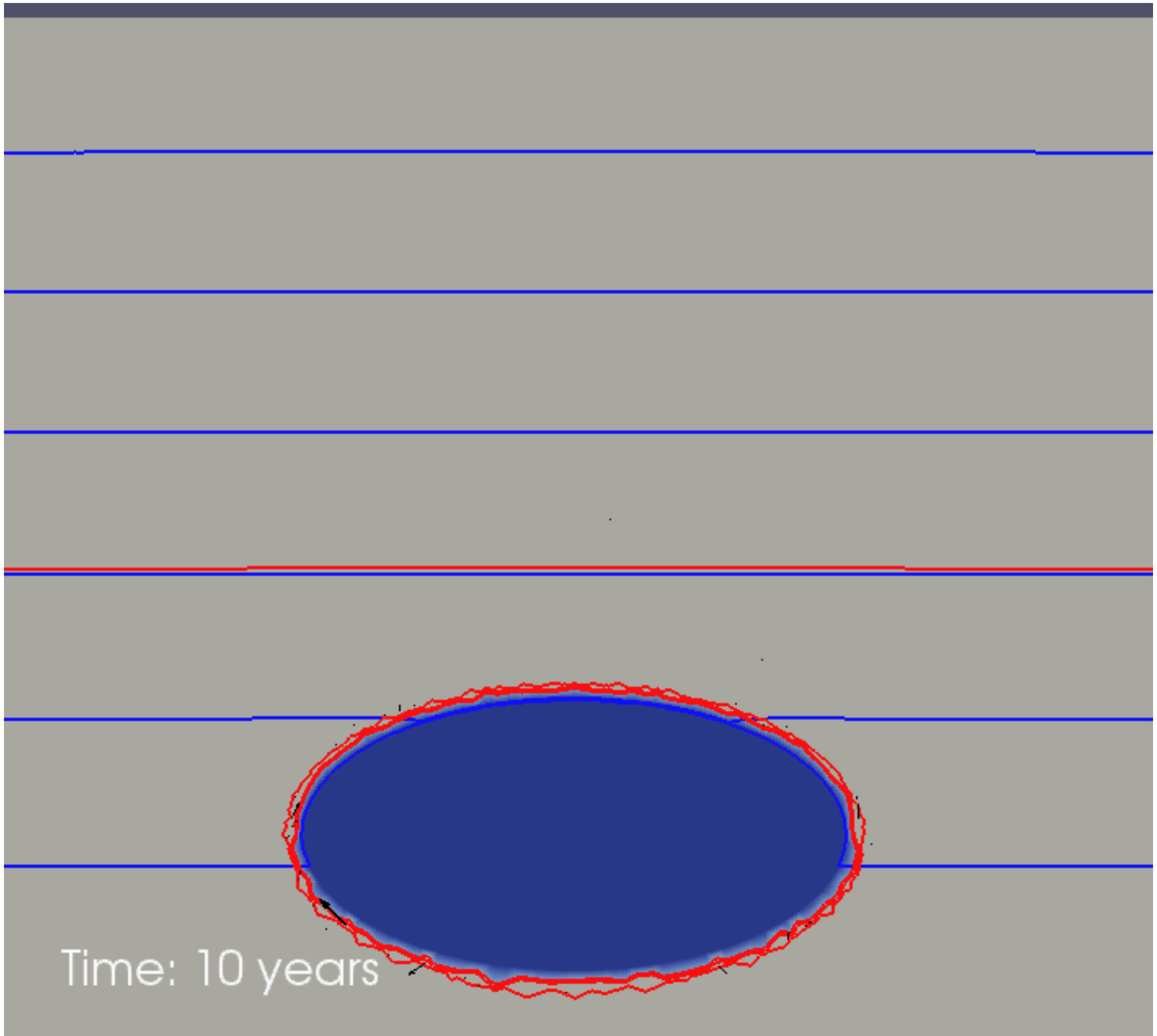
Background, 'system-scale' permeability (k_0)



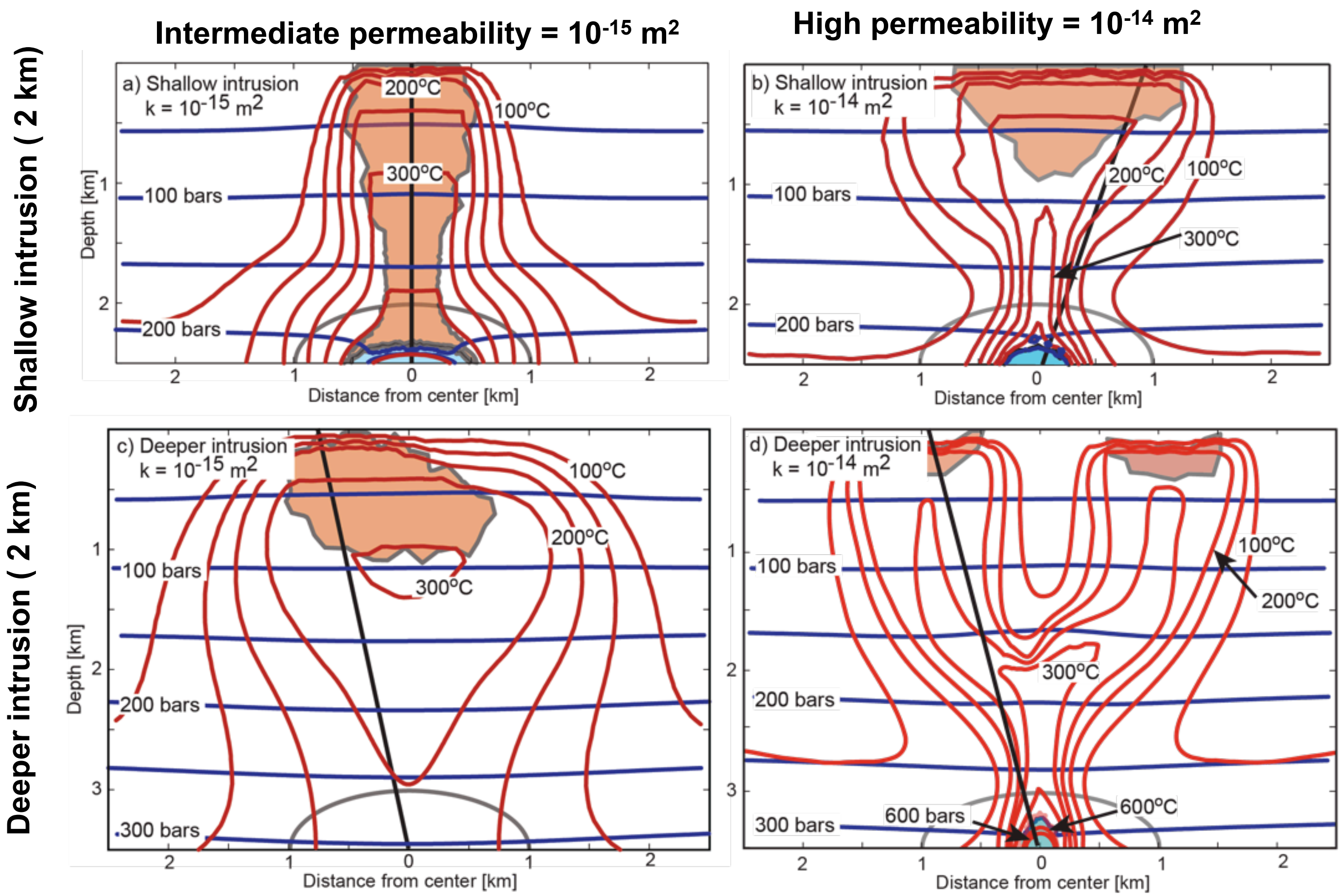
a **b** **c**

Brittle-ductile transition onset temperature (T_{BDT})

Example results – Transient evolution

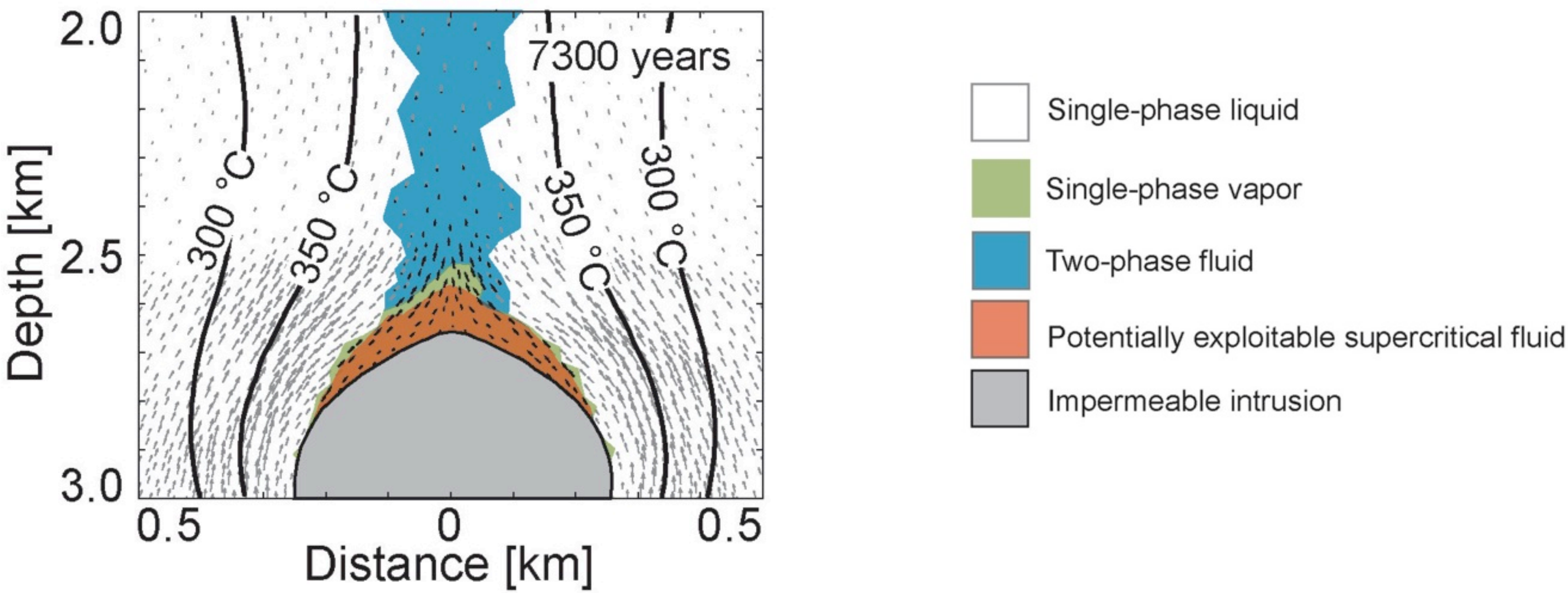


- Large-scale differences in thermal structure result from ‘small’ changes in permeability and intrusion depth



Scott et al., 2014

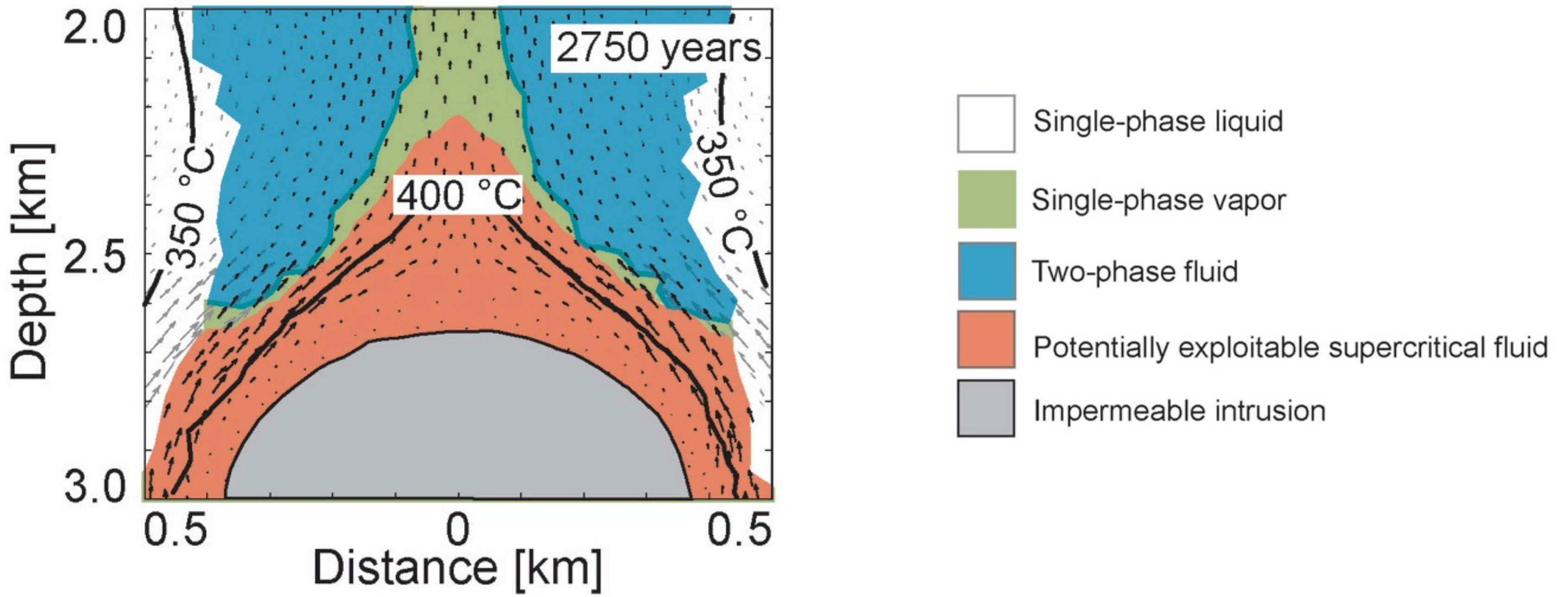
Example results – T_{BDT} = 360 ºC, permeability (k_0) = 10^{-15} m^2



- 'Potentially exploitable supercritical resources' defined as:
  - $T > 373.9$ ºC, $h > 2.086$ MJ/kg, $k > 10^{-16}$ m^2
- Low T_{BDT} inhibits formation of sizeable resources

Scott et al., in review

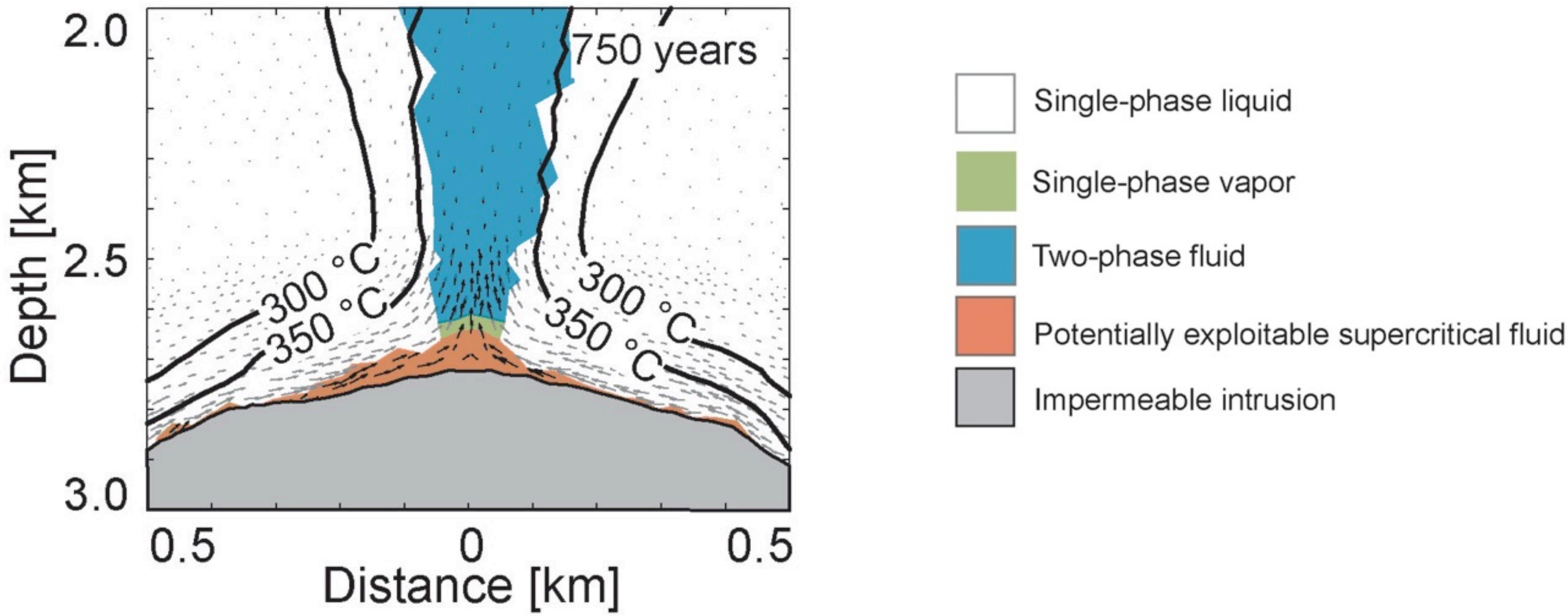
Example results – T_{BDT} = 450 ºC, $k_0 = 10^{-15}$ m²



- Basalt: higher brittle-ductile transition temperature
- Sizeable resources form near intrusion

Scott et al., in review

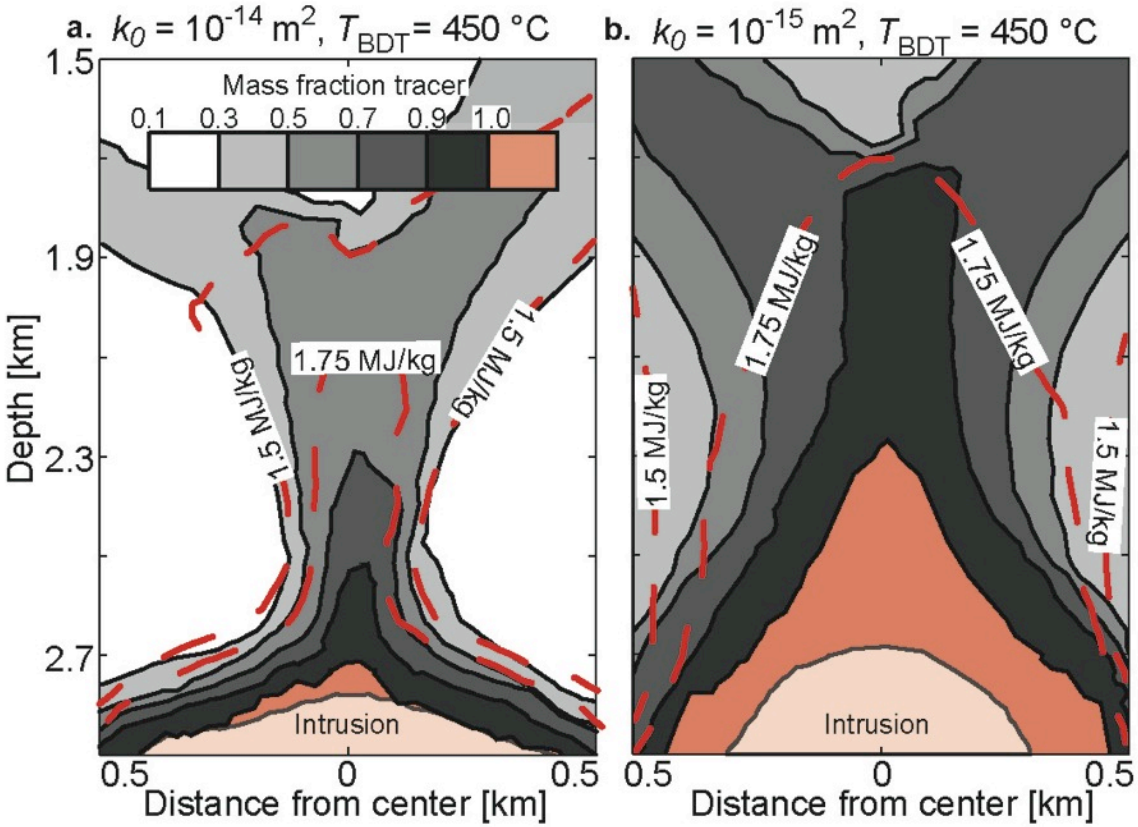
Example results – T_{BDT} = 450 ºC, $k_0 = 10^{-14}$ m²



- More rapid fluid circulation means fluid heated to lower *T*

Scott et al., in review

The role of permeability on fluid mixing dynamics

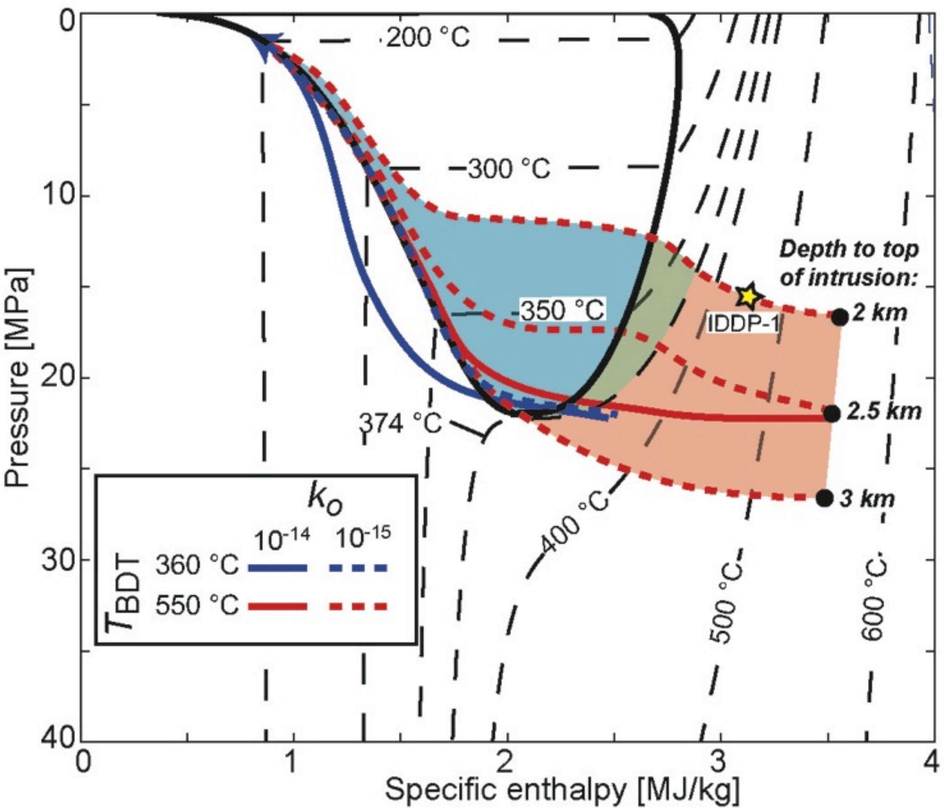


- Conventional geothermal resources result from mixing of ascending supercritical and cooler circulating waters

Scott et al., in review

Summary

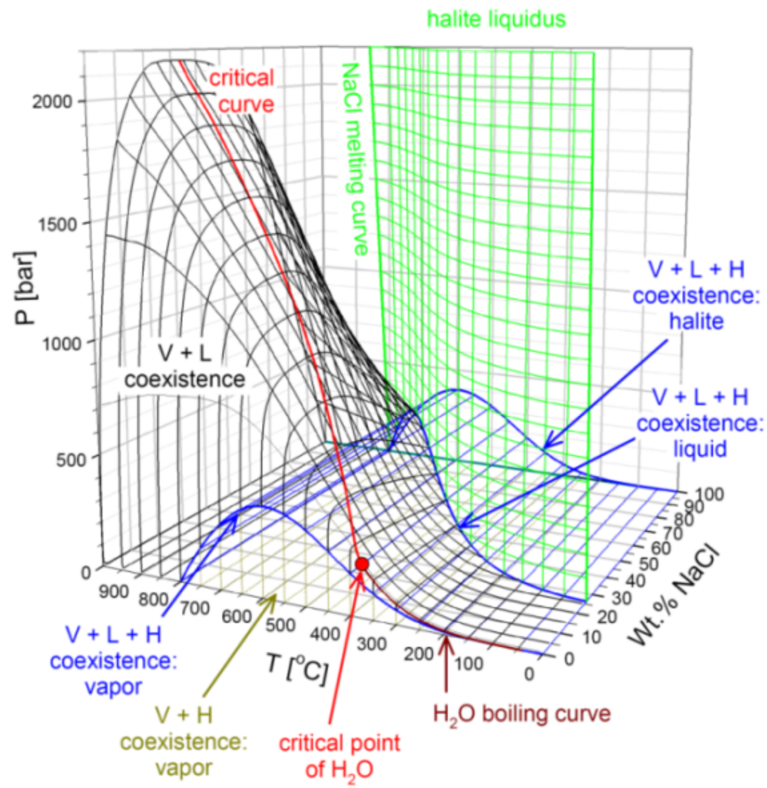
- Supercritical resources favored by:
  - Permeability near 10^{-15} m^2
  - Brittle-ductile transition temperature ≥ 450 °C
  - Shallower depth of intrusion



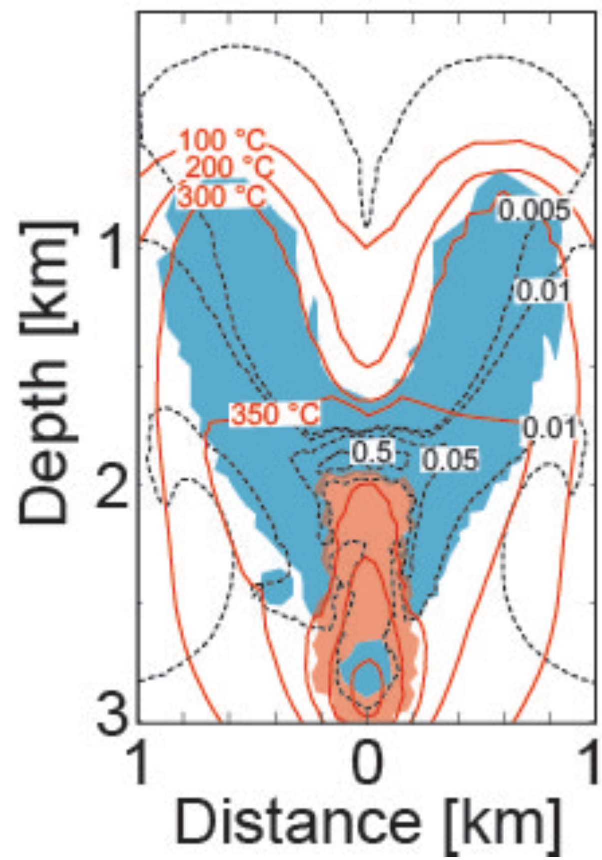
- IDDP: Measured reservoir conditions match predicted values assuming appropriate values for the geologic controls

Scott et al., in review

The role of fluid salinity (work in progress)



Driesner & Heinrich, *GCA*, 2007



- Increasing salt content shifts comparable resources to greater depths/higher temperatures

Conclusions

- High-enthalpy geothermal: the neglected cousin of the renewable energies who comes from an exotic country
  - Geology is of decisive importance
- Future directions:
  - Low-T binary cycles
  - Ultra-high T 'supercritical' geothermal (IDDP)
- Numerical modeling: improve conceptual understanding, enhance resource predictability, reduce risk
- Early results suggest supercritical fluids may be a common and important feature of high-enthalpy systems


Thanks for listening...
Questions? Comments?

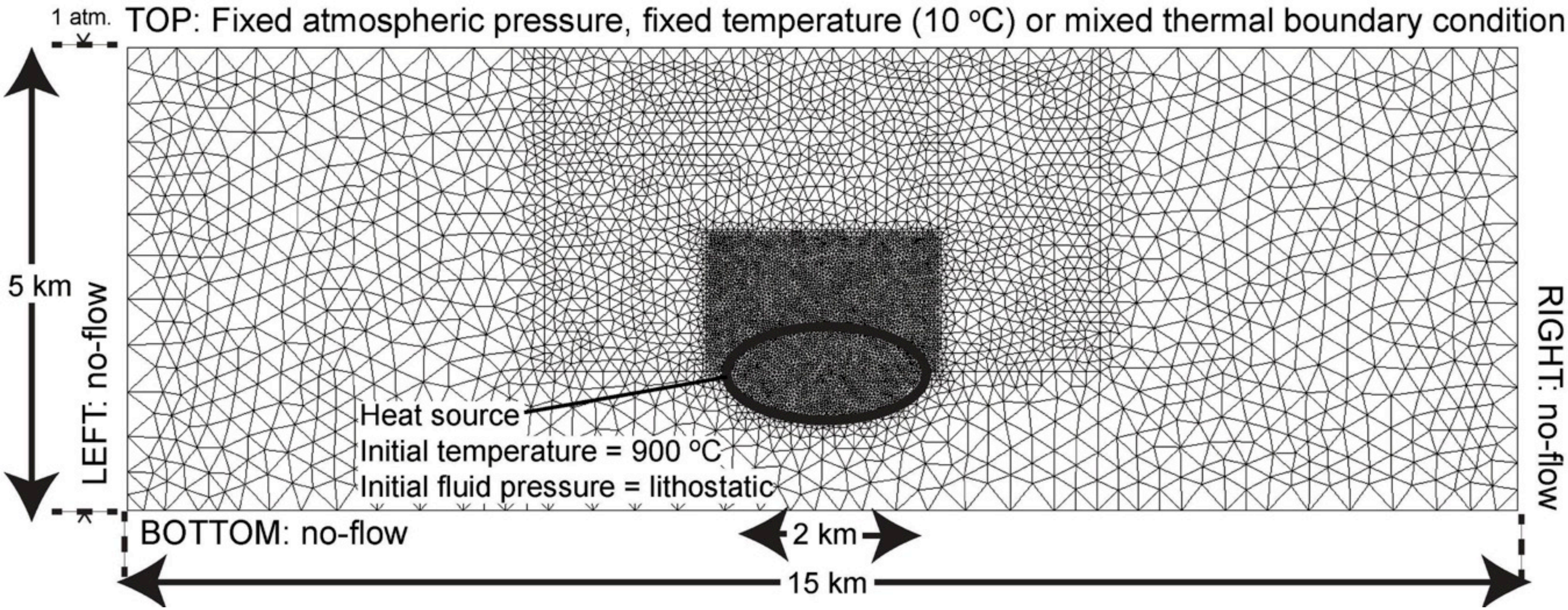
Fluid flow velocities depend on Darcy's law

$$v_i = -k \frac{k_{ri}}{\mu_i}(\nabla P - \rho_i g \nabla z)$$

i = liquid, vapor
v = Darcy flux (m/s)
k = rock permeability (m^2)
k_r = relative permeability (-)
μ = viscosity (Pa s)
P = fluid pressure (Pa)
ρ = fluid density (kg m^3)
g = gravitational acc. (9.8 m/s^2)
z = vertical coordinate (m)

- Numerous complicating factors:
  - Non-linear changes in fluid properties with pressure and temperature
  - 'Relative' permeabilities of phases depend on volumetric saturation
  - Porous medium approach usually implies static rock

Typical model set-up



Initial Rock Property	Host rock	Magma chamber	Unit
Temperature	+45°C/km depth	900	°C
Porosity	0.1	0.05	-
Permeability	$10^{-14} – 10^{-15}$	10^{-22} (where T>500°C)	m^2
Heat capacity (isobaric)	880	Temperature-dependent	J/kg°C
Compressibility	10^{-20}	10^{-20}	/bar
Density	2,750	2,750	kg/m^3
Thermal conductivity	2.25	2.25	W/m°C

Initial fluid property	Value	Unit
Temperature	+45°C/km depth	°C
Pressure	Hydrostatic (in magma chamber:lithostatic)	bar
Heat capacity (isobaric)	EOS[1]	J/kg°C
Compressibility	EOS[1]	/bar
Density	EOS[1]	kg/m^3
Dynamic viscosity	EOS[1]	bar s
Thermal expansivity	EOS[1]	/°C
Enthalpy	EOS[1]	J/kg

1. Haar et al., 1984