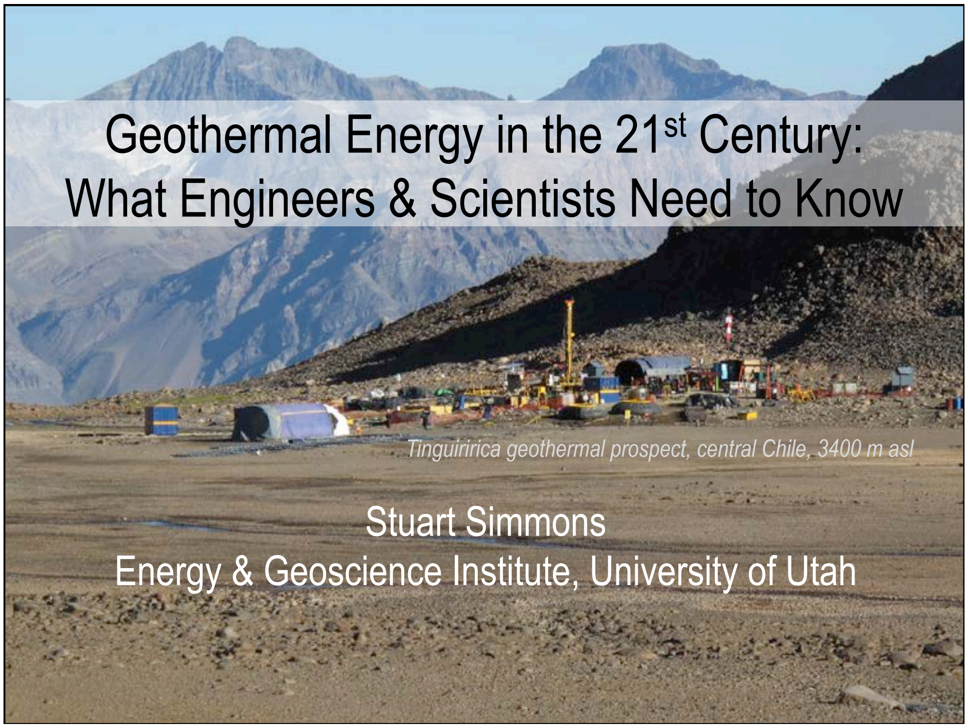


Summary

- Geothermal energy (heat from the Earth's interior) is utilized for thermal energy and electrical energy production.
- The resource is huge but low grade; the best/hottest resources are localized, dependent on geology.
- Conventional hydrothermal resources have been in production for ~100 yrs; but long payback period + financial risks due to uncertainty in fluid flow systems & resource assessment.
- Unconventional resources EGS-type resources are difficult to develop; i.e., how do you produce energy from a large volume (100-500 km^3), hot "dry" rock at 3-5 km depth?
- DOE FORGE represents new, big R&D support for an EGS field laboratory; new opportunity for advancing novel technologies. Utah test site is being proposed.

Why use geothermal energy?

Strengths	Weaknesses
Clean, renewable energy	Long lead time: concept to production
Base load generation	Large entry barriers
Low cost to maintain	High upfront costs/risks
Climate/weather independent	Cannot be stored/exported
Reliable	Location controlled by geology

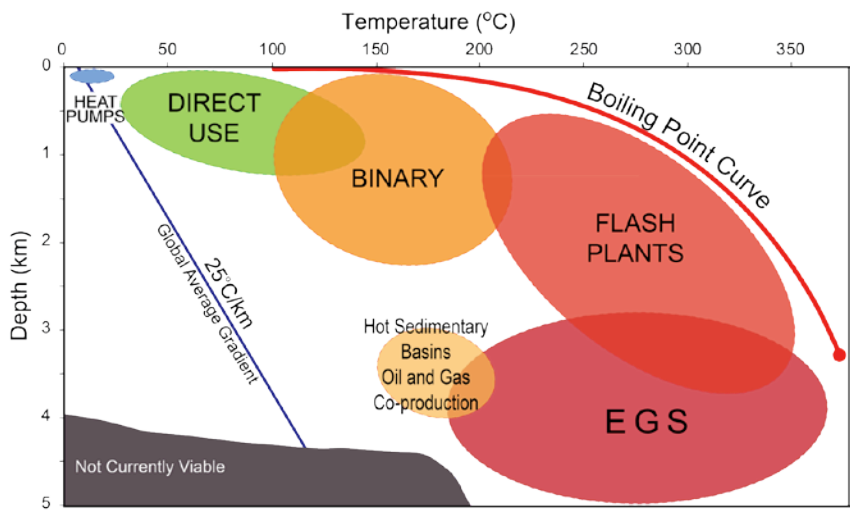
Commercial considerations

Resource information
Managing risks & costs
Electicity generation

Location with respect to grid & market
Availability of skilled personnel
Direct use

Efficient use of geothermal energy involves direct heating applications

Diverse Nature of Geothermal Resources



Moore & Simmons, Science, 2013

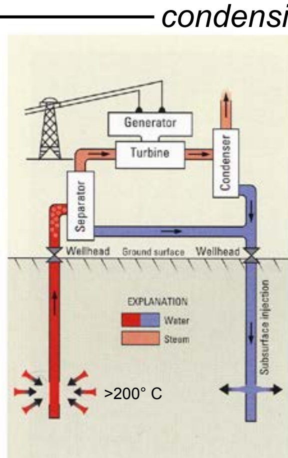
Total Installed Electricity Generation ~11-12 GWe

Mokai: parallel development of high & low enthalpy resource use

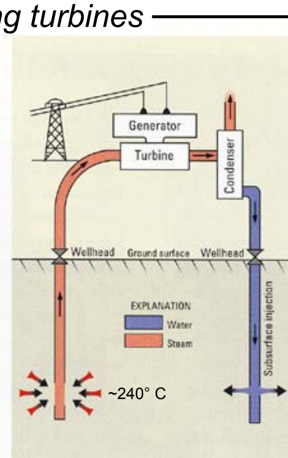
Taupo Volcanic Zone, North Island, New Zealand

Power Cycles & Electricity Generation

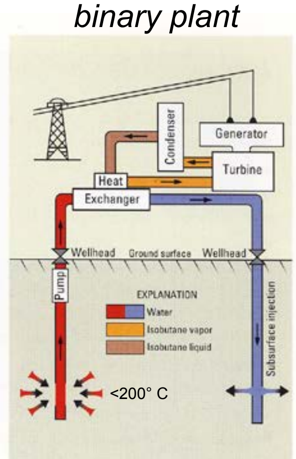
condensing turbines *binary plant*



liquid-dominated reservoir



vapor-dominated reservoir



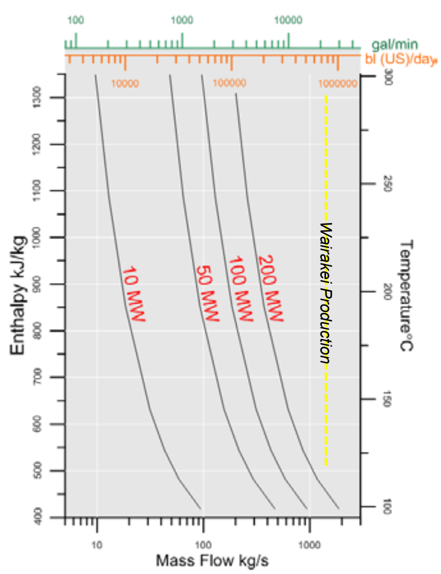
liquid-dominated reservoir

Graphics: Duffield & Sass, 2003

Wairakei 2010

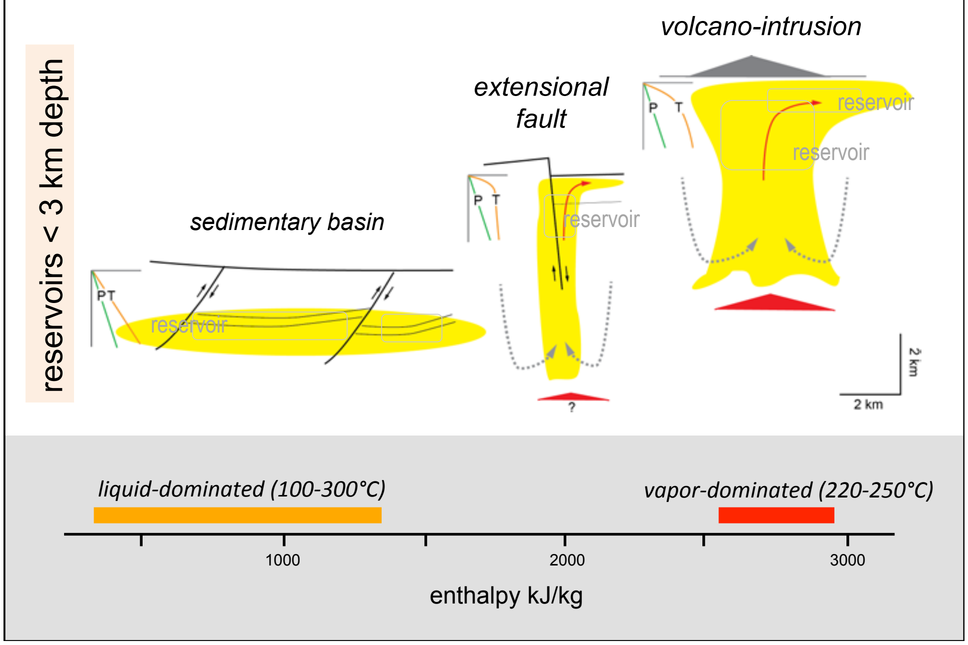
~235 MW capacity
1729 GWh of net generation
54.6 million tonnes geothermal fluid
60.8 petajoules thermal
>90% load factor
>50 years of production

Geothermal Power

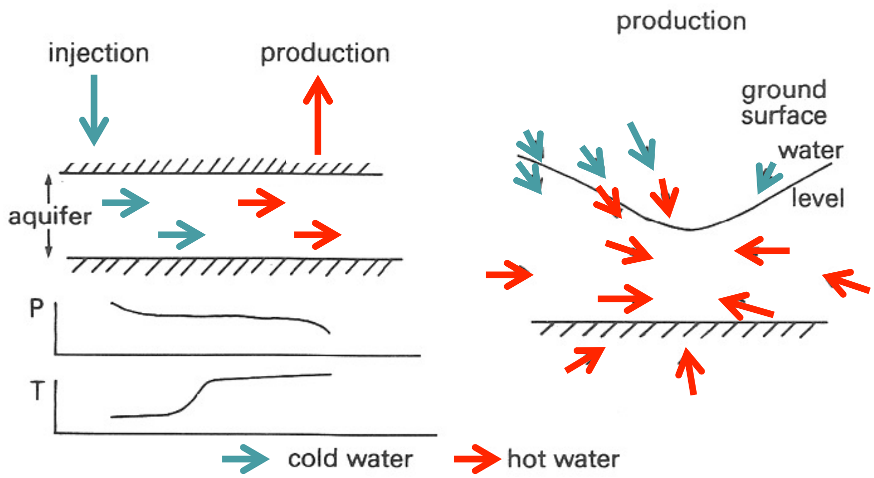


$MW_{th} = m \times (H_{reservoir} - H_{75°C})$

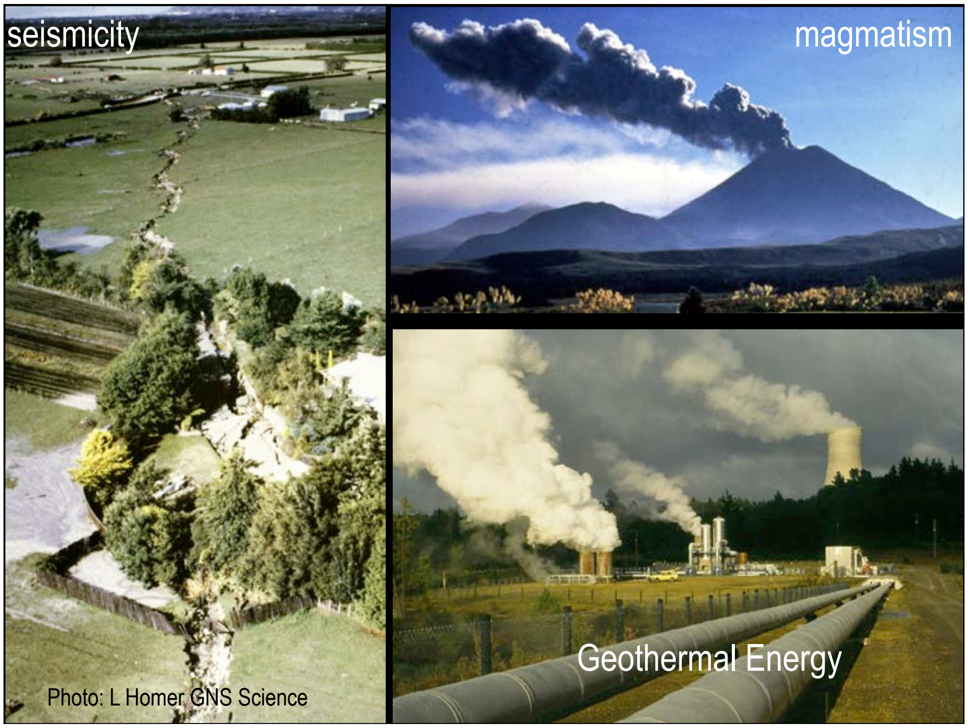
Geothermal Systems: Stored vs Flowing

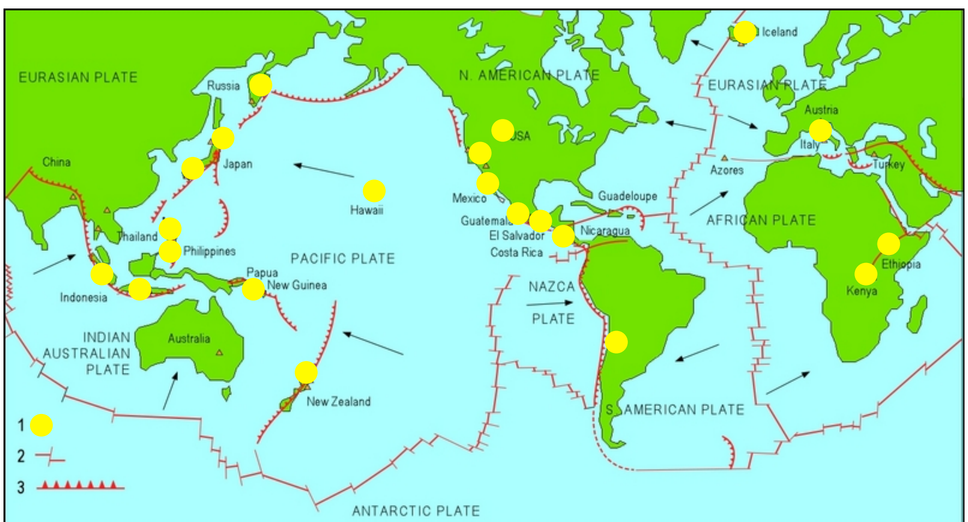


Reservoir Heat Transfer-Idealized



Grant et al. 1982

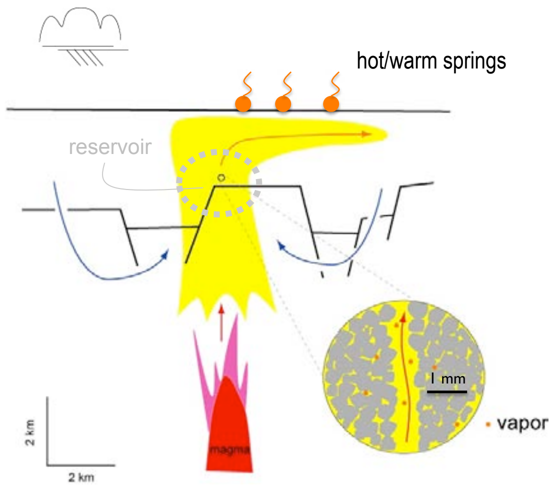


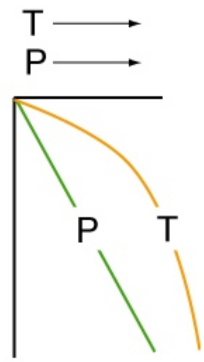


High Temperature Geothermal Resources: ~11,000 MWe installed; ~500-1500 active volcanoes

High temperature systems occur along plate boundaries, including: 1) mid-ocean ridges and continental rifts (Olkaria, Kenya; Aluto, Ethiopia) ; 2) ocean island (Hawaii, Iceland) and continental hot spots (Yellowstone, USA); 3) volcanic-magmatic arcs (Taupo Volc Zone, New Zealand, Sumatra & Java, Indonesia; Philippines; S. Kyushu, Japan; Central Mexico; El Salvador, Nicaragua, Costa Rica, Lardarello, Italy).

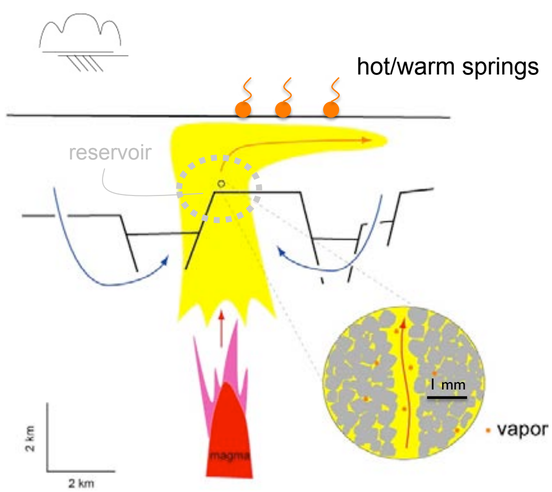
Conventional Geothermal Resource





Hydrostatic P gradient & boiling point for depth T gradient in upflow zone at <2 km depth

Conventional Geothermal Resource



<u>Reservoirs</u>

220 to >300°C

surrounded by cold rock

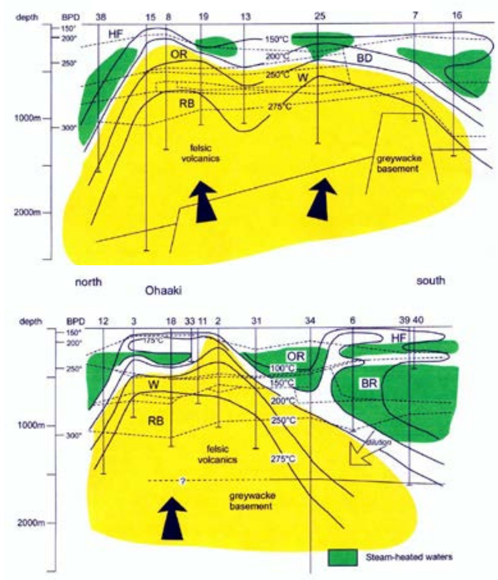
hydraulically connected

$>10^{17}$ J/km^3 in rock

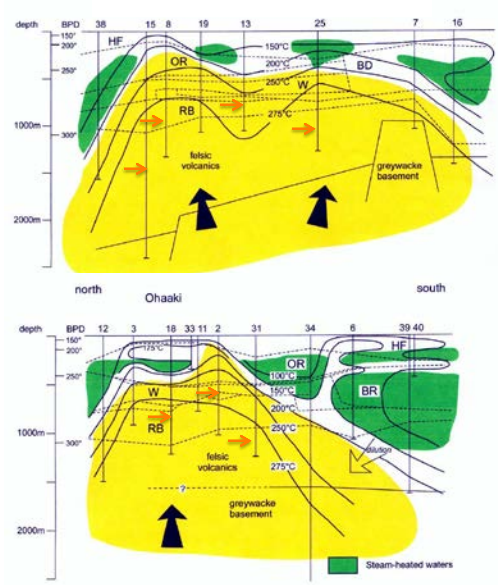
50-300 kg/s deep natural inflow

Hydrothermal System Lifespan 10,000 to >100,000 years

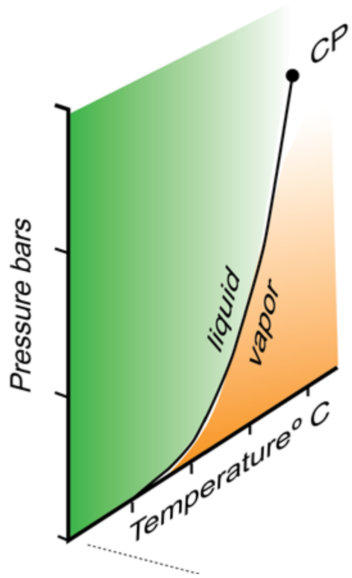
Broadlands-Ohaaki

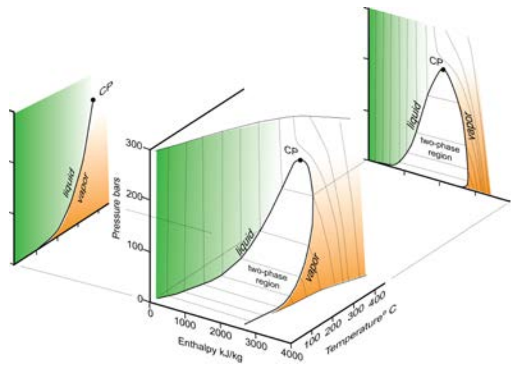


Broadlands-Ohaaki



Energy in Fluid: Vapor versus liquid H_2O

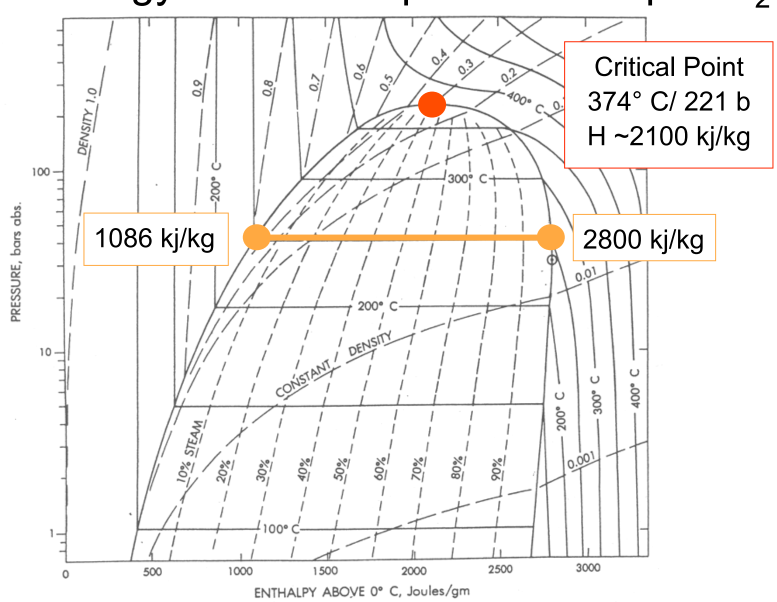




Critical Point: 374° C, 221 b
Enthalpy (H): 2100 kilojoules/kg

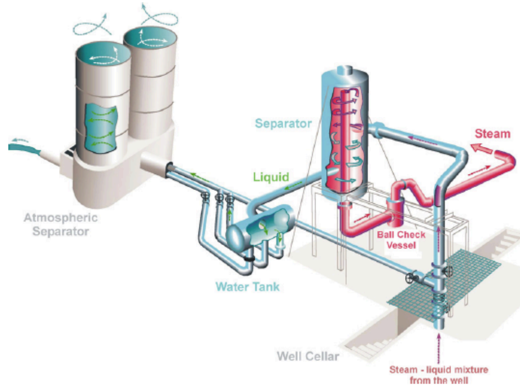
At 250° C H_{water}=1086 kj/kg
H_{vapor}=2800 kj/kg

Energy in Fluid: Vapor versus liquid H_2O



Cyclone Separator-Early Engineering Milestone

Wells produce two-phase fluid: 25% steam & 75% water. Steam/water separation plants were a key innovation that allowed development of liquid-dominated reservoirs. This technology was proven with the development of the Wairakei resource.



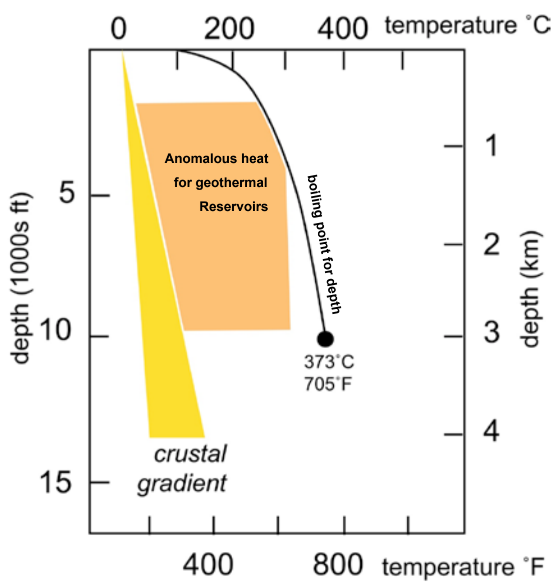
Thain & Carey 2009 (Geothermics)

Resource Assessment: Stored Thermal Energy

T gradients in crust

Boiling point for depth (hydrostatic pressure) is the max T gradient in high T systems

Anomalous heat measured against normal gradient



ΔQ_R heat stored in rock (J/m^3)
ΔQ_F heat stored in pore fluid (J/m^3)

$$\Delta Q_R = (1-\Phi)\,\rho_P\, c_R\,[T_z - T_{z0}]$$

Φ porosity, ρ_P density, c_R specific heat, T_z & T_{z0} temperatures in & out

$$\Delta Q_F = (\Phi)\,\rho_L\,[h_z - h_{z0}]$$

Φ porosity, ρ_L density, h_z & h_{z0} enthalpies in & out

$\Sigma Q = \Delta Q_R + \Delta Q_F$ Total Stored Heat

Note sources of uncertainty:

- reservoir volume (diffuse vs sharp boundary)
- reservoir temperature
- recoverable energy not considered

Geothermal Energy

GEOLOGY

Physical: Heat & mass transfer
Temperature-pressure gradients
Permeability-porosity
Hydrology & fluid flow

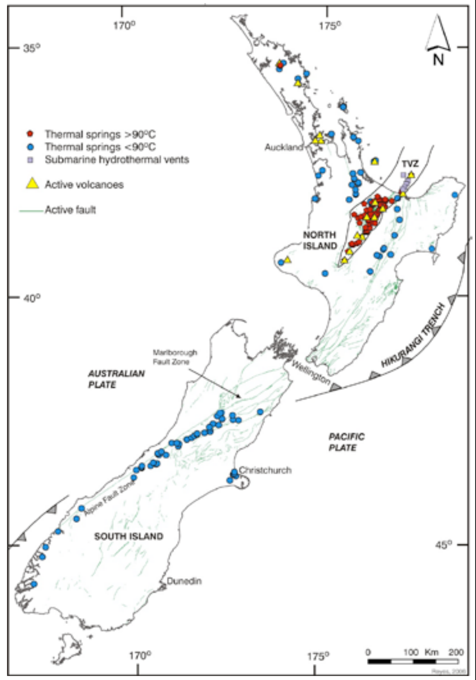
Chemical: Fluid compositions
Fluid-mineral equilibria
Mineral corrosion/deposition
Hydrothermal alteration

New Zealand Geothermal Energy

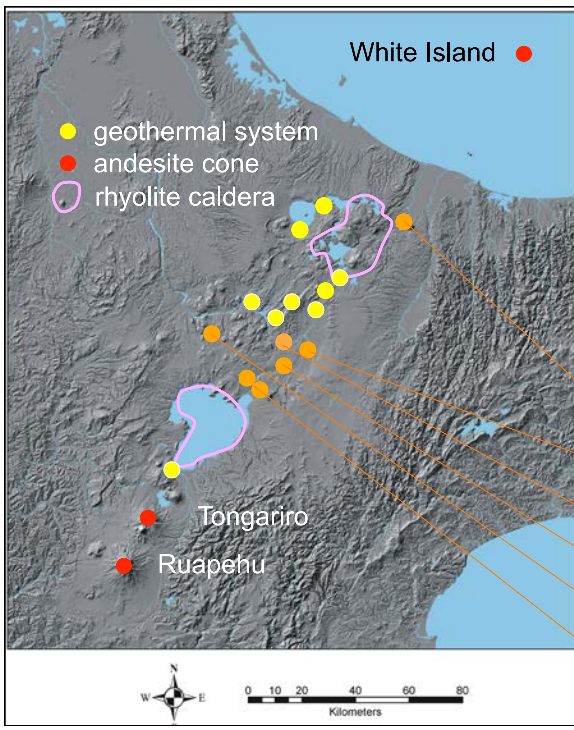
Unique tectonic setting straddling a plate boundary.

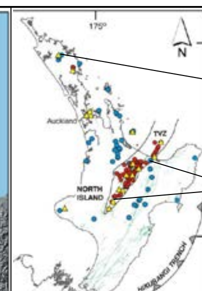
Extensional volcanic arc (10 mm/y) due to oblique subduction (North Island)

Transpressional transform fault-Alpine Fault (South Island)



map: Reyes and Jongens, 2003





Ngawha 25 MW

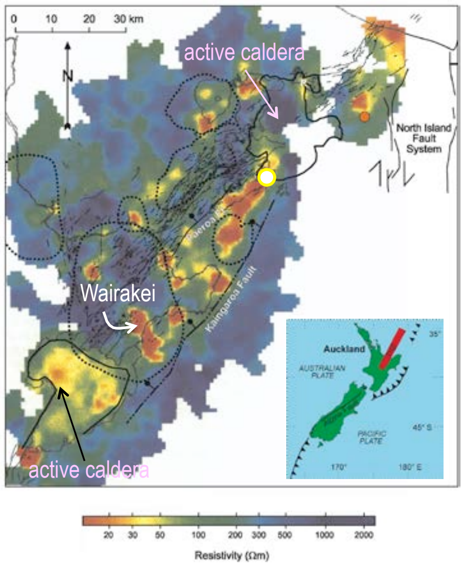
TVZ 890 MW

~15% NZ elec.

TVZ generation	MW
Kawerau	147
Ohaaki	45 (114)
Ngatamariki	82
Rotokawa	175
Mokai	111
Wairakei-Tauhara	330 (250+)

Taupo Volcanic Zone Geothermal Fields

Rowland & Simmons 2012; Geophysics image: dipole-dipole resistivity (Stagpoole & Bibby, 1998)



Extensional basin-volcanic arc high heat flow volcanism, seismicity & hydrothermal activity

Structures segmented rift NE-SW normal faults caldera volcanoes

Hydrothermal systems (red=low resistivity)

Compare the locations of volcanic centers, faults, & hydrothermal systems

Wairakei (>50 yrs)

25 km^2 (reservoir 10 km^2)

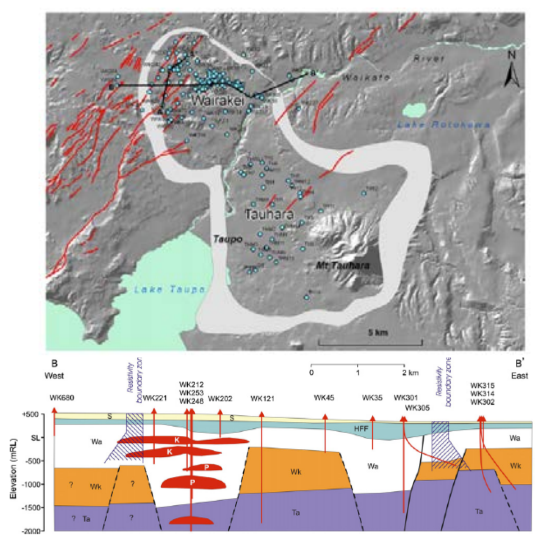
Hot springs & geysers in valley on northern edge

Fumaroles & steaming ground in the south

Borefield in between surface features.

Reservoir boundaries unknown when first drilled

Faulted volcanic stratigraphy



Rosenberg et al. 2009 (Geothermics)

Wairakei (>50 yrs)

50/150 wells (<2.5 km)

3 km^3 fluid produced

2750 Petajoules

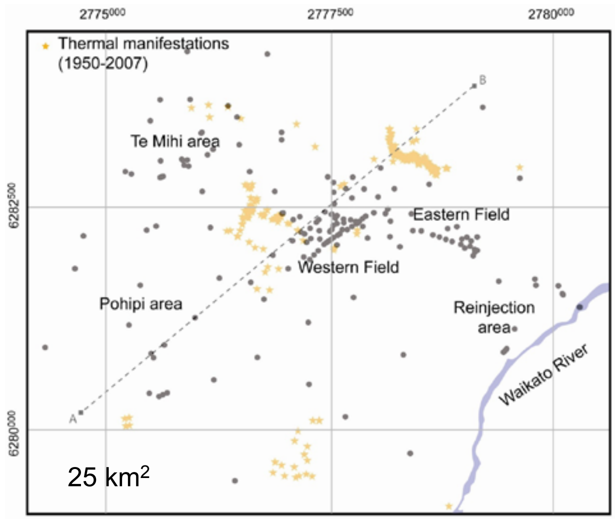
1450 kg/s

1130 kilojoules/kg

20 bar pressure drop

No injection

Bixley et al. 2009 (Geothermics)



Wairakei: Next 50 Years

- Total fluid production matches estimates of total pore fluid in reservoir, but exceeds natural flow rate. Production increases 1.7x this year.
- No signs of reservoir degradation/cooling. Implies deep inflow has substantially increased as a result of production stimulation-unpredicted.
- Additional 166 MWe was just commissioned. Numerical models forecast sustainable production for next 50 years.

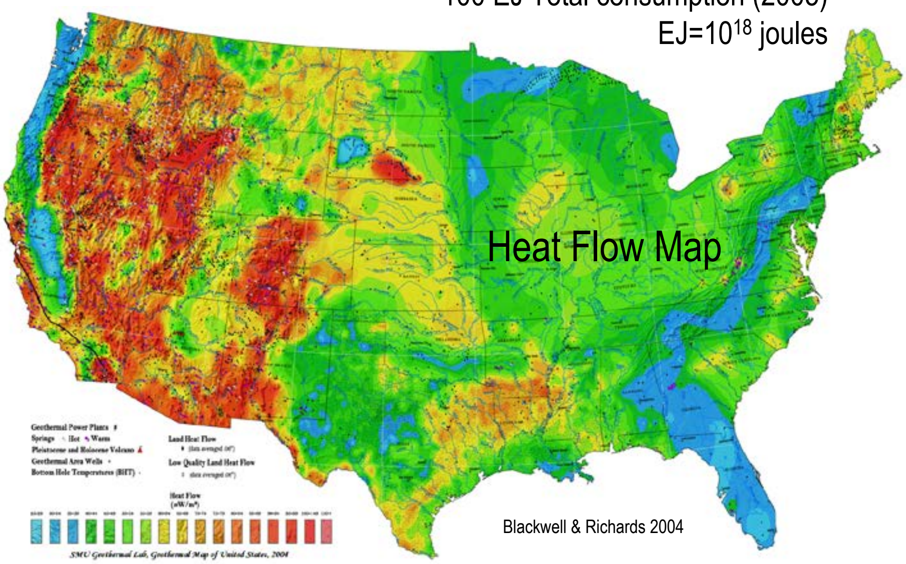
USA Resource Potential

14.0×10^6 EJ Stored thermal energy 3-10 km depth

0.28×10^6 EJ requires 2% Recovery

100 EJ Total consumption (2005)

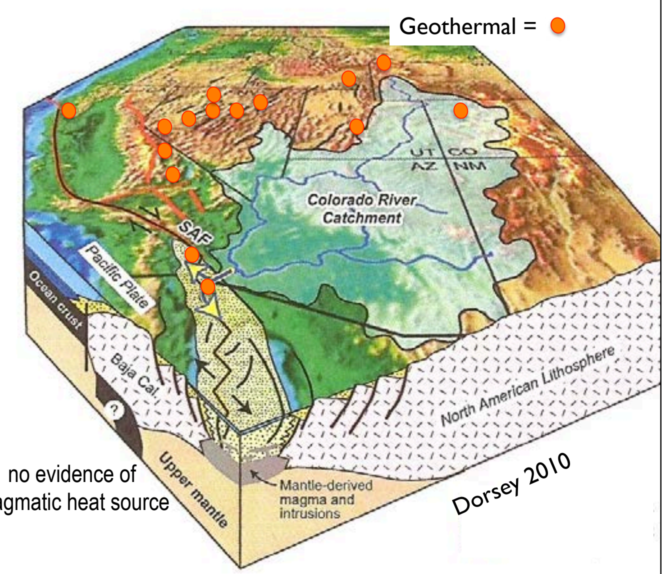
EJ=10^{18} joules



*the Future of Geothermal Energy: Impact of Enhanced Geothermal Systems on the United States in the 21st Century, Tester et al. 2006

San Andreas Fault System & Great Basin

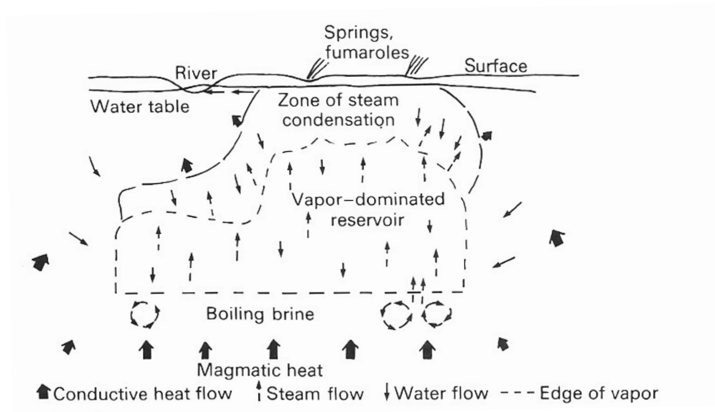
Project	MWe
Geysers	850
Cerro Prieto	750
Salton Sea	410
Coso	302
Roosevelt	26
Steamboat Spgs	48
Mammoth	40
Beowawe	18
Dixie Valley	66
Raft River	13

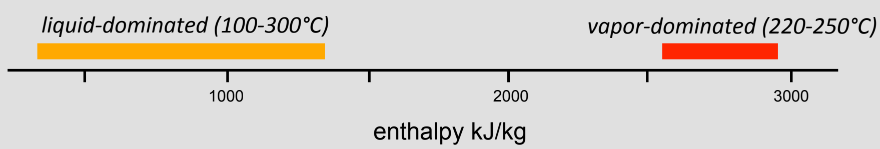


no evidence of magmatic heat source

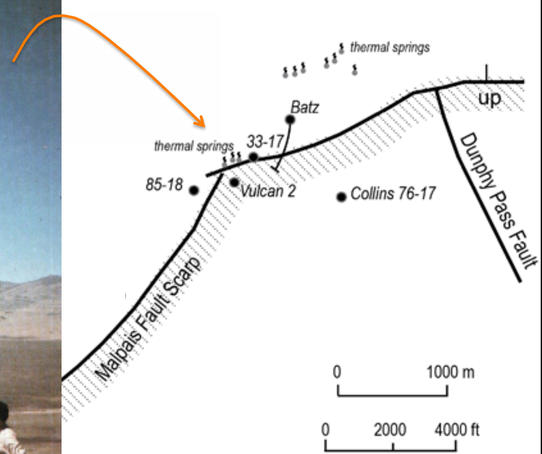
Geysers: Vapor-Dominated Reservoir

reservoirs < 3 km depth



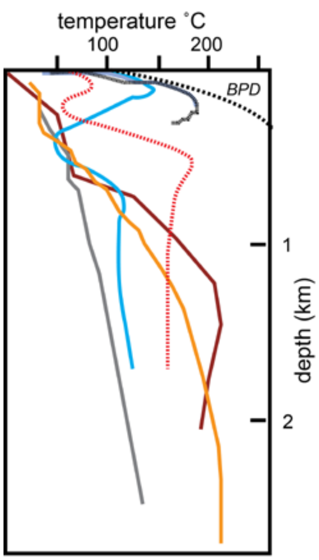


Beowawe

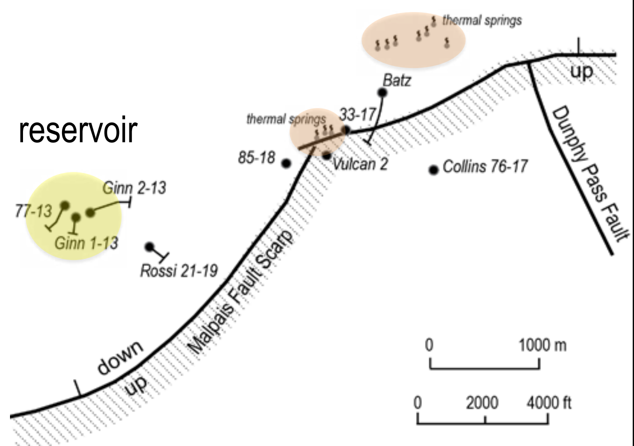


First wells drilled 1959
Boiling point for depth to ~200 m
Temperature reversals at depth

Beowawe



Faulder et al 1997

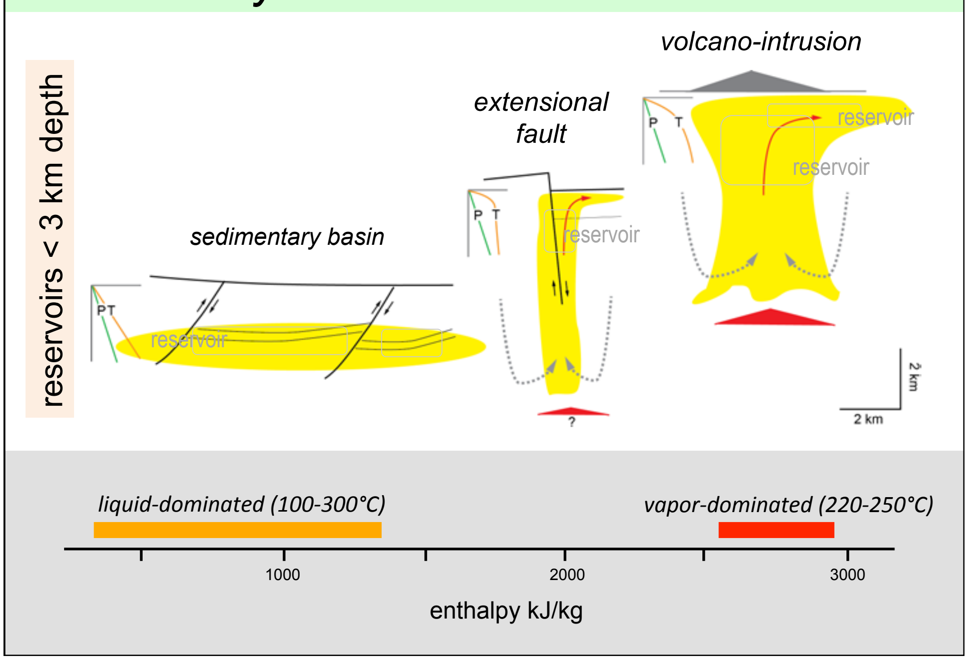


Resource discovery drilled 1974
215°C @ 1200 to >2000 m depth
Reservoir: Valmy Fm & Malpais fault damage zone

Natural heat flow 17 MWth~230° C at 20 kg/s
Resource permeability in fracture mesh in the hanging wall
Deep thermal water-Pleistocene, dilute, bicarbonate-rich, alkaline pH
Plume rises at an angle along basin bounding fault zone

Power plant commissioned 1985; Reservoir volume <1 km^3
Cool water inflow reduced production (later recovered)
Modern production history 250-260 kg/s at ~215° C sustains ~17 MWe
Total fluid production is 40% greater than reservoir resource
Deep inflow stimulation likely

Diversity of Conventional Resources



Unconventional Resources

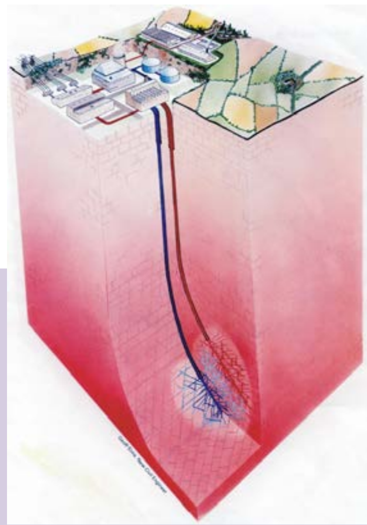
Engineered Geothermal Systems (EGS)

Deep hot rock

Induce fracture permeability

Inject fluid to advect thermal energy to surface

35 years of R&D (USA, Japan, Europe, Australia)



1.5 MWe plant Soults-sous-Forêts (France)

4 wells: 2 to 5 km depth, ~200°C

Temperature gradient: 40°C/km

Extensional tectonics: fracture connectivity restricted in granite basement (>1400 m depth)

Induced seismicity causes delays

Enhanced/Engineered Geothermal Systems (EGS)

Fenton Hill (USA)

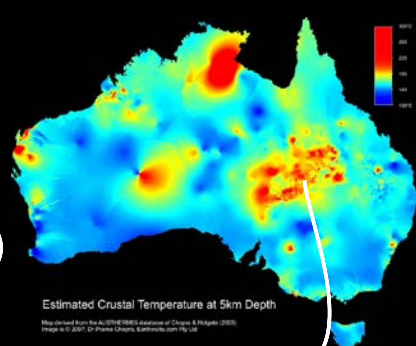
Rosemanowes (UK)

Hijiori-Ogachi (Japan)

Soults-sous-Forêts (France)

Basel (Switzerland)

Cooper Basin (Australia)



EGS Cooper Basin, Australia

Prospect area 2000 km^2

Hot granite (radiogenic heat) beneath 4 km sedimentary rk

4 wells: >4 km depth, whp 350 bar, >240°C

Temperature gradient: ~60°C/km

Horizontal compression: Flat fracture system-connectivity between wells

1 MW power plant commissioned 2012

Development suspended because of insufficient funds & excess supply

Steam flow Habanero 3 (March, 2008; Geodynamics Annual Report 2008)

Magmatic geothermal resources (unconventional)

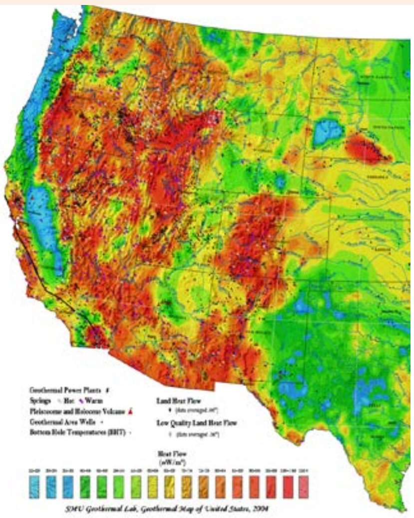
Krafla, Iceland (50 MWe)

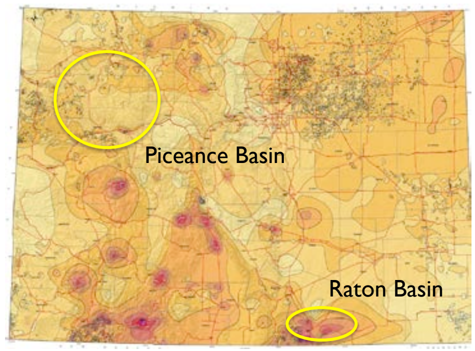
volcanic eruption 1975-1984

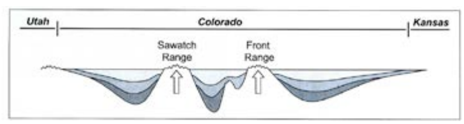
intruded volume:	1 m wide 9 km long 7 km deep
erupted volume:	100×10^6 m^3
temperature:	>1100° C

Geothermal Energy: Sedimentary Basins

Heat Transfer: Hybrid Applications







Geothermal Heat Transfer: Hybrid Applications

Piceance Basin

T gradient >40°C/km

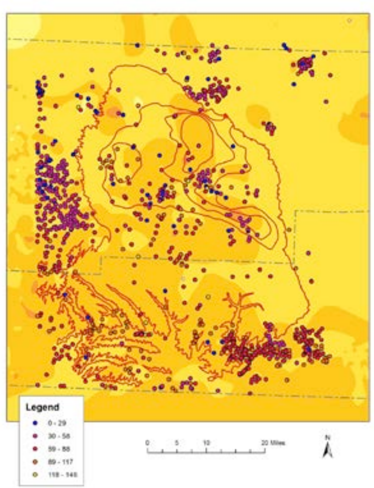
>250°C at 7 km

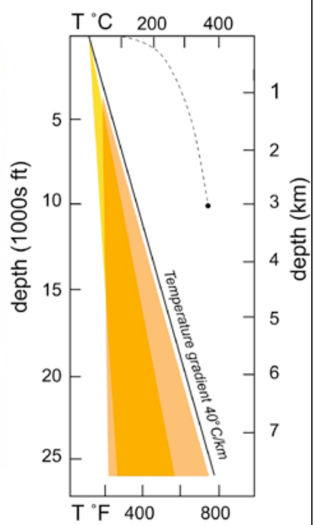
2×10^{17} J/km^3

Hot rock volume >6000 km^3

70 $MW_{thermal}$/km^3 for ~100 yrs

Incentive for research





Geothermal-Hydrocarbons

Heat Transfer: Hybrid Applications

Piceance Basin

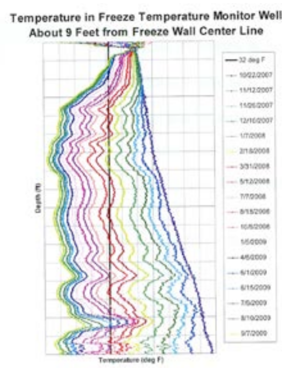
High demand for cooling & heating

>300°C required

Water demand

Geothermal for preheating over long term

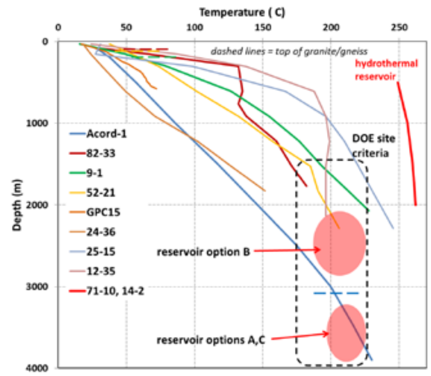
Time span ~100 yrs

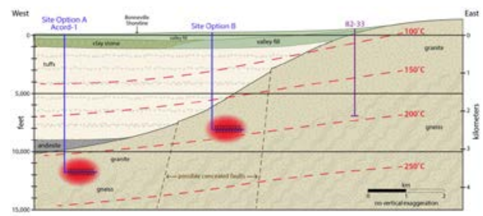


DoE-FORGE

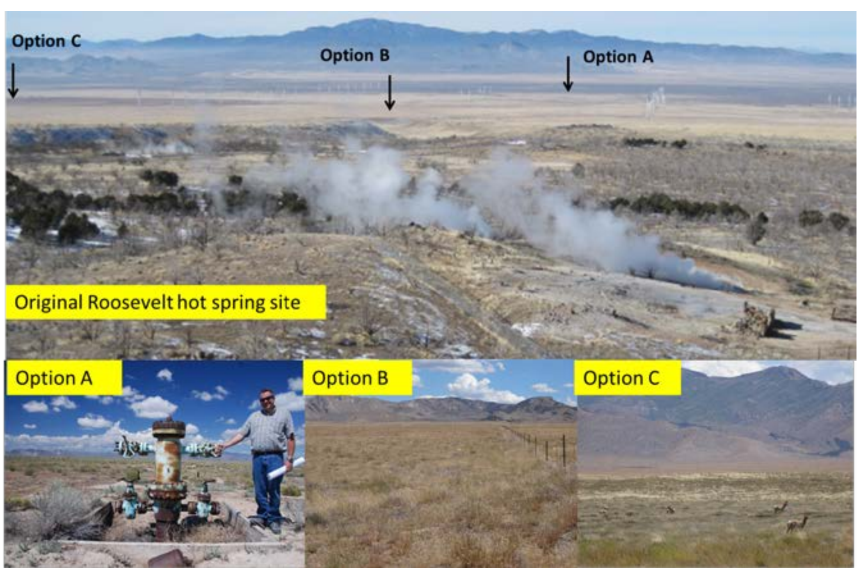
- Frontier Observatory for Research in Geothermal Energy (FORGE)
- Funding announcement for establishing & managing field lab
- Project comprises 3 Phases, with $31million allocated for I & II. Main objective is site selection from a starting pool of 10.
- Phase I—12 mos; Phase II—12-24 mos; Phase III—60 mos
- EGI, U Utah is leading a consortium to recommend a site in central Utah
- Ideal site: 175-225°C, 1.5 to 4 km depth, low permeability (~10^{-16} m^2), crystalline basement rocks
- Phase III includes drilling, stimulation, testing, using innovative tools, methods, & supporting science/engineering

DoE-FORGE





DoE-FORGE



DoE-FORGE

- Phase I funding for full scale proposal
- Phase II funding supports geoscientific & environmental investigations & proving site logistics
- Seismicity (natural/induced) are significant concerns
- Successful site selection will open new R&D opportunities for engineers & scientists
- Diverse range of physical & chemical problems related to engineering sustained heat & mass transfer for energy utilization largely involving water-rock interactions
- Differs from unconventional oil & gas development, because energy flows need to be sustained & uniform for electricity production

Summary

- Geothermal energy (heat from the Earth's interior) is utilized for thermal energy and electrical energy production.
- The resource is huge but low grade; the best/hottest resources are localized, dependent on geology.
- Conventional hydrothermal resources have been in production for ~100 yrs; but long payback period + financial risks due to uncertainty in fluid flow systems & resource assessment.
- Unconventional resources EGS-type resources are difficult to develop; i.e., how do you produce energy from a large volume (100-500 km^3), hot "dry" rock at 3-5 km depth?
- DOE FORGE represents new, big R&D support for an EGS field laboratory; new opportunity for advancing novel technologies. Utah test site is being proposed.