New Technology in Geothermal Developments

Future Developments in Geothermal Energy

Discovery of new (blind) high temperature resources at <3 km depth
Enhanced or engineered geothermal systems (EGS)
Exploitation of deep hydrothermal resources at >3 km depth
Geopressured resources (e.g. abandoned oil-gas fields)
Utilization of ground sourced heat pumps (heating, air conditioning)
Improved efficiency in steam gathering systems
Advances in drilling and well logging methods
Novel power cycles (e.g. Kalina cycle)
Mineral recovery (precious & base metals)
Subsurface heat recovery

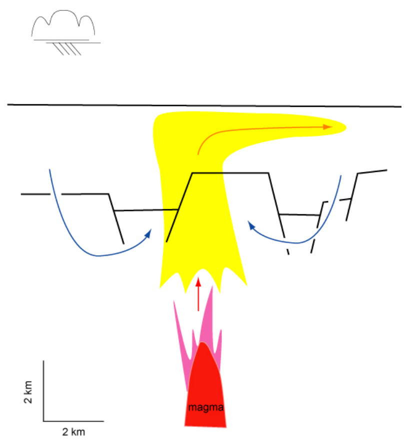
Topics Covered in this Presentation

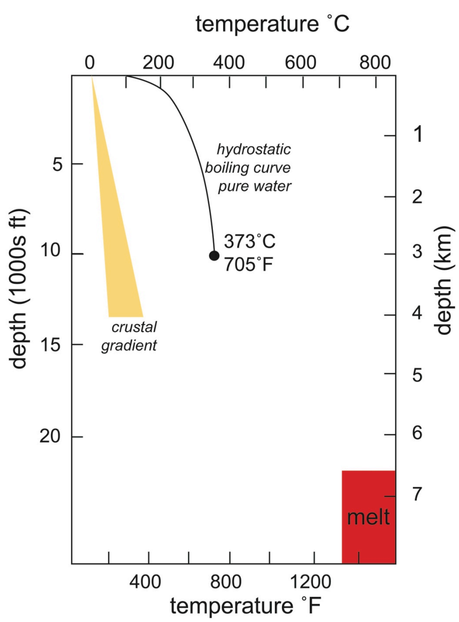
New exploration methods: blind resources at <3 km depth

Enhanced or engineered geothermal systems (EGS)

Magmatic hydrothermal resources

Geothermal energy for mines & hydrocarbon production



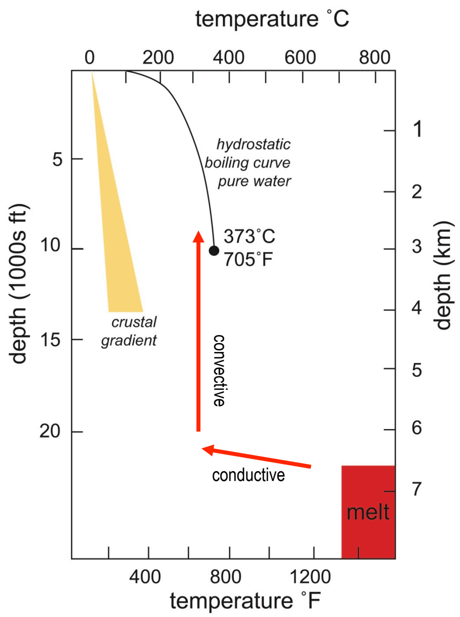


Normal crustal gradient:10 to 30°C/km

Hydrostatic boiling curve

Intruding magma: >650°C

Conductive & convective heat transfer



Normal crustal gradient:10 to 30°C/km

Hydrostatic boiling curve

Intruding magma: >650°C

Conductive & convective heat transfer

Essential ingredients for sustainable heat transfer

Permeability structure (i.e. faults, fractures, interconnected pore space)

Temperature gradient

Fluid supply (heat carrier)

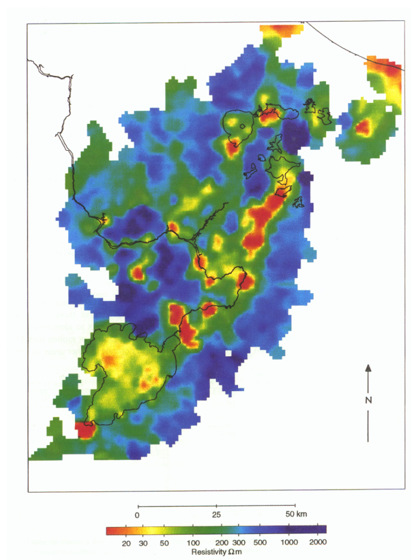
Conventional Exploration Methods (e.g. NZ)

Geology: hot springs, volcanic-seismic activity, country rocks, hydrothermal alteration, fault-fracture networks

Geochemistry: fluid compositions, aqueous-gaseous geothermometers, fluid flow

Geophysics: gradient wells for heat flow, electrical methods for conductive clay alteration (shallow), seismic methods to determine fluid flow

Conventional Exploration Methods



Central TVZ: DC apparent resistivity (Stagpoole and Bibby, 1998-GNS Science)

Image Permeability Structure

Combination of electrical and seismic geophysics methods

Dense array of geophones (surface & shallow borehole)

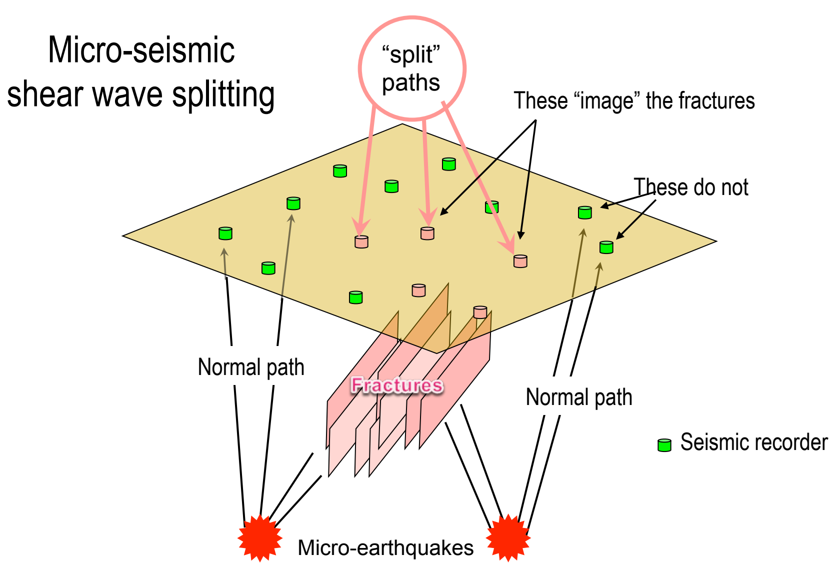
Dense array of magneto-telluric coils (surface)

Image active fluid flow-fracture networks

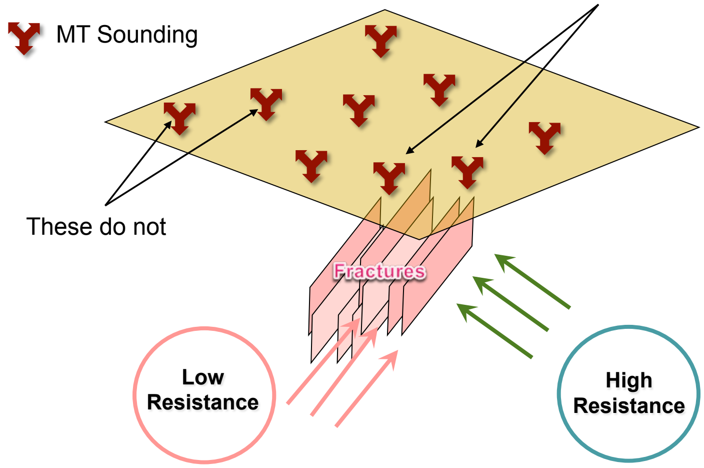
Identify drill targets

Enhance well production

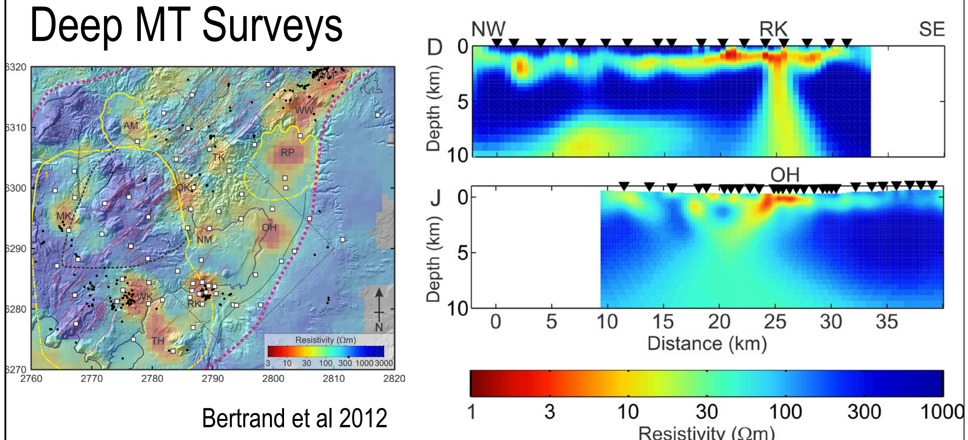
Examples: brownfields exploration-Olkaria, Kenya & Krafla, Iceland—IESE, University of Auckland



Magneto-telluric



Deep MT Surveys



Bertrand et al 2012

large-scale magneto-telluric surveys reveal deep resistivity structure and possibly the outline of the hydrothermal plume

Engineered Geothermal Systems (EGS)

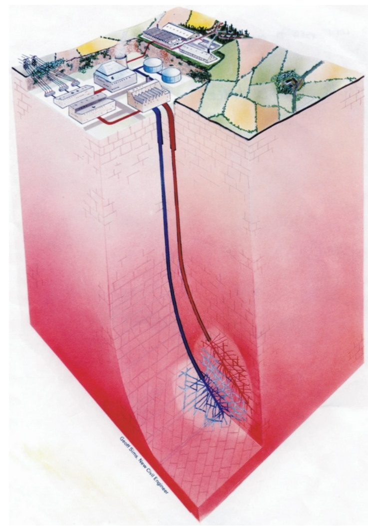
Deep hot rock

Induce fracture permeability

Inject fluid to advect thermal energy to surface

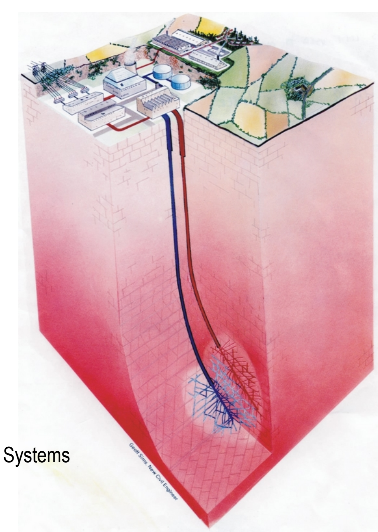
35 years of R&D (USA, Japan, Europe, Australia)

New investment in resource development



EGS Research Advances*

Directional drilling
Fracture systems in >1 km^3 of rock
Control of rock fracture apertures
Stimulation & fluid flow controls
Continuous fluid flow >25 kg/s
Seismic monitoring/management
Extraction of thermal energy
Small scale electricity generation
Concept proven



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

USA Resource Potential

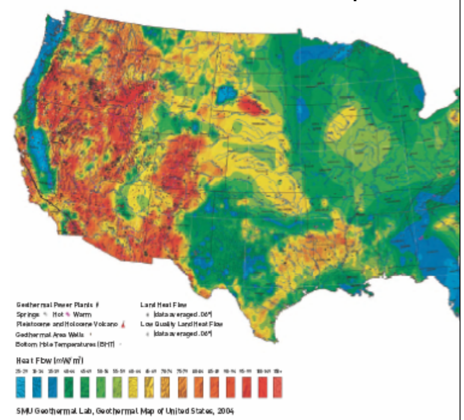
USA Heat Flow Map

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

2% Recovery 0.28 x 10^6 EJ

Total consumption 100 EJ
(2005)

EJ=10^{18} joules

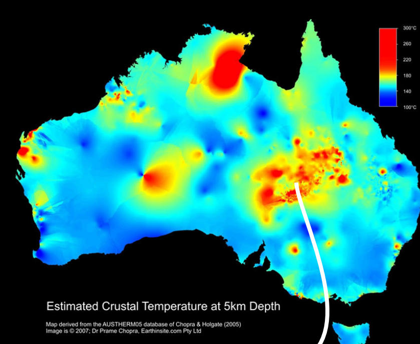


Blackwell & Richards 2004

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

EGS Sites

Fenton Hill (USA)
Rosemanowes (UK)
Hijiori-Ogachi (Japan)
Soults-sous-Forêts (France)
Basel (Switzerland)
Cooper Basin (Australia)



Cooper Basin, Australia

Prospect area 2000 km^2

Hot granite beneath 4 km sedimentary rk

3 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 constructed but not connected

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

Soults-sous-Forêts (France)

Upper Rhine Graben (border w/Germany)

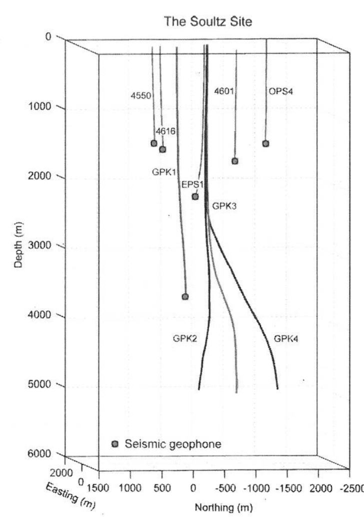
4 wells: 2 to 5 km depth, ~200°C

Temperature gradient: 40°C/km

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

Induced seismicity causes delays

1.5 MW power plant commissioned 2008



Majer et al. 2007 Geothermics

Soults-sous-Forêts (France)

Upper Rhine Graben (border w/Germany)

4 wells: 2 to 5 km depth, ~200°C

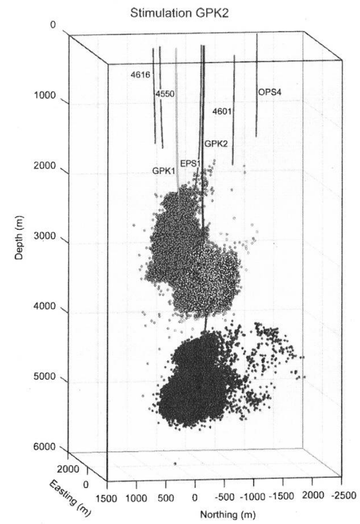
Temperature gradient: 40°C/km

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

Induced seismicity causes delays

1.5 MW power plant commissioned 2008

18 l/s @ 164°C production 2010
24 l/s @ 159°C production 2011



Majer et al. 2007 Geothermics

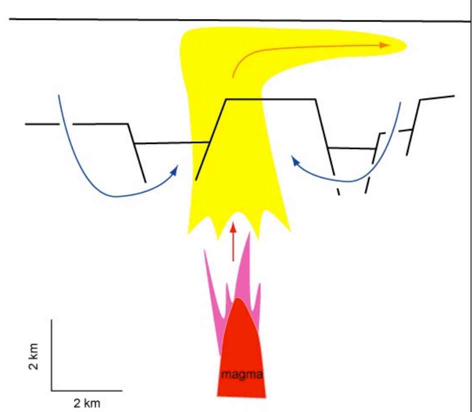
Deep Geothermal Resources

Deep drilling to near super critical conditions

Significantly increased power output per unit fluid mass (high enthalpy)

Uncertainties regarding permeability and production of deep fluid

Examples: Krafla, Iceland
Kakkonda, Japan



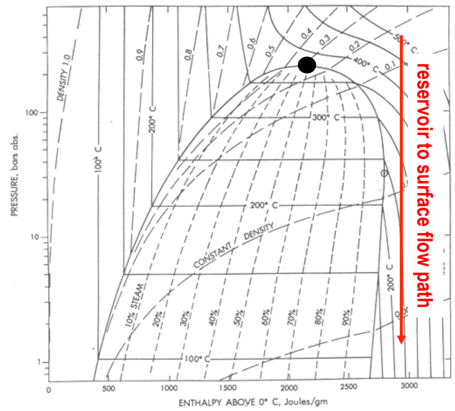
Attributes of water near critical point

bouyancy forces and heat transport reach maxima

viscous drag minimized

convective heat transfer 70 times conductive heat transfer

heat transfer requires “abnormal” permeability-near magma intrusion



Enthalpy-Pressure Plot-Pure Water

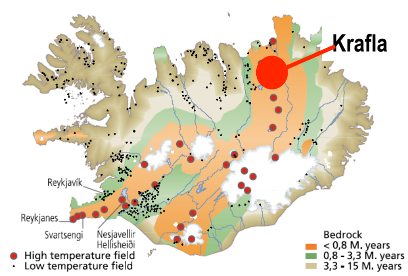
Krafla, Iceland

60 MWe production from existing steam field

New well 3.5 to 5 km depth, >450° C

Drill within seismogenic zone where brittle fracturing could enhance permeability

Rift setting: Deep tectonic fracturing influences magma emplacement & fluid flow



Map: Icelandic National Energy Authority & Ministries of Industry & Commerce, 2006

Krafla, Iceland

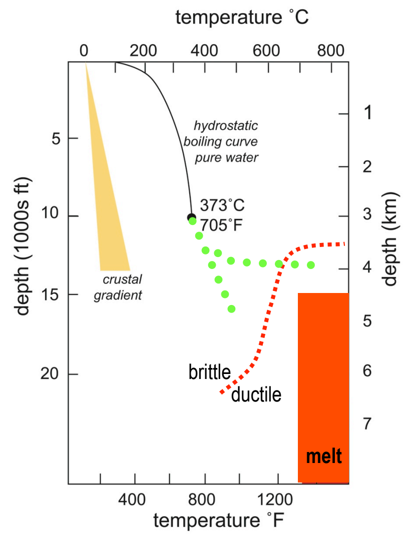
Super critical conditions require shallow intrusion of magma (confirmed by S-wave attenuation)

Existing wells to 2500 m follow hydrostatic boiling point for depth

Anticipate possibility of shallow supercritical conditions (e.g. Nesjavellir, 1985)

Target brittle rocks on the edge of intrusion

Option to penetrate ductile zone



Krafla, Iceland

Drilling began late 2008

After winter break, drilling recommenced March, 2009

Late April to Late June, 2009, drilling problems encountered

24 June, 2009, fresh magma intrudes into hole

May, 2010 onward, intermittent flow testing, production of superheated steam (10 kg/s, 3200 kJ/kg, 140 bar) ~25-35 MWe

Krafla IDDP Site (photo: http://www.iddp.is/)

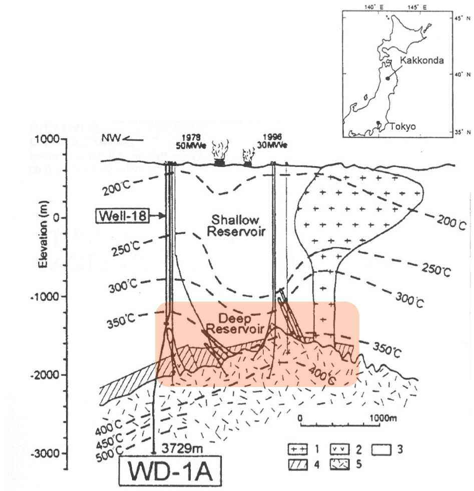
Well closed July, 2012 maybe permanently due to well damage

Kakkonda, Japan

WD-1a drilled to 1500 m (1994) & extended to >3700 m (1995)

Search for deep hot reservoir in young granite (previous drilling experience)

Deep exploration driven by competition with spa resorts/ national parks



Kato et al. 1998 (Geothermics)

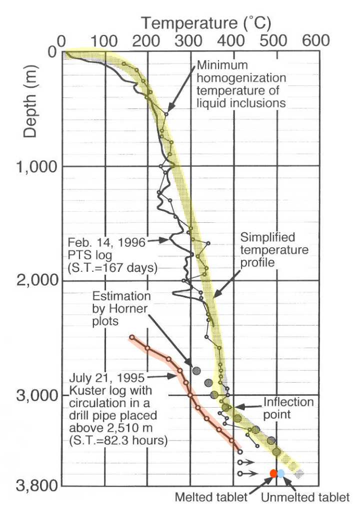
Kakkonda, Japan

Anticipated temperatures from previous drilling: ~400°C @ 4 km

Considerable drilling skill req'd to maintain drill track to target

Temperature measured with conventional tools down to 3500 m

Melting tablets required for BHT



Muruoka et al. 1998 (Geothermics)

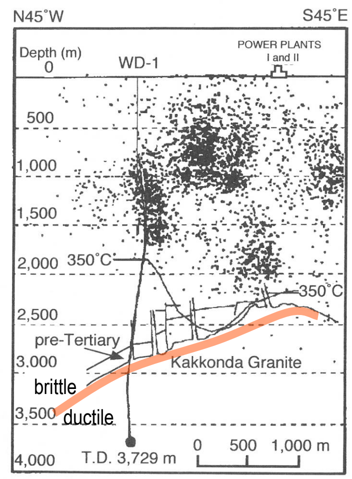
Kakkonda, Japan

Micro-seismicity restricted <2.5 km

Brittle-ductile transition penetrated

Deep rocks poorly permeable

Hypersaline fluid (39 wt % TDS)
Neutral pH-magmatic origin



Muruoka et al. 1998 (Geothermics)

Ladolam, Lihir Island, PNG

Small volcanic caldera host high temperature hydrothermal system

Gold mining operation (1300 t Au)

50 MWe geothermal power station

Geothermal drilling-discharge req'd for mining operation

Photo Lihir Mining Company

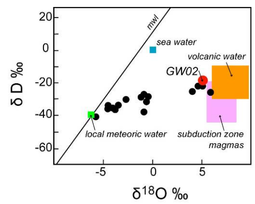
Ladolam, Lihir Island, PNG

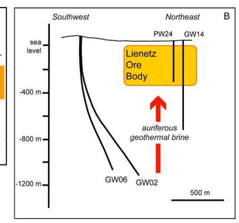
Drill tracks beneath shallow ore bodies

Geothermal fluid: ~8% TDS, neutral pH, magmatic origin

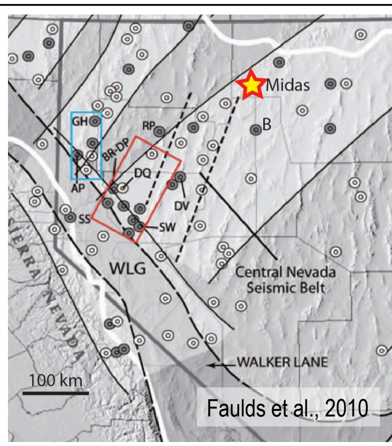
Environmental issues:

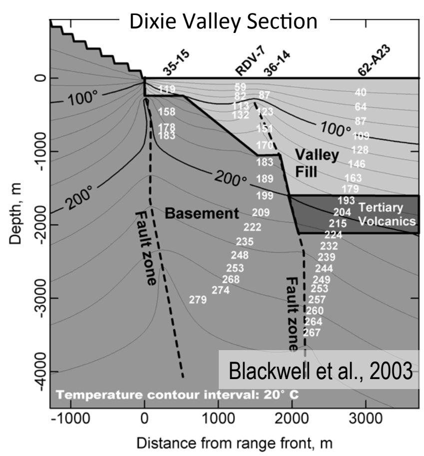
- hydrothermal eruptions
- H_2S gas

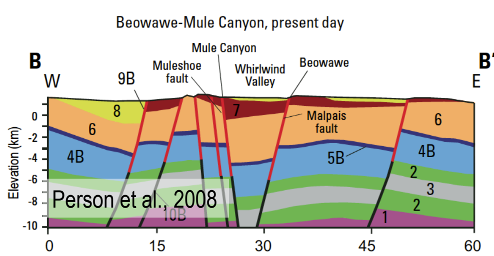




Simmons & Brown 2006 (Science)



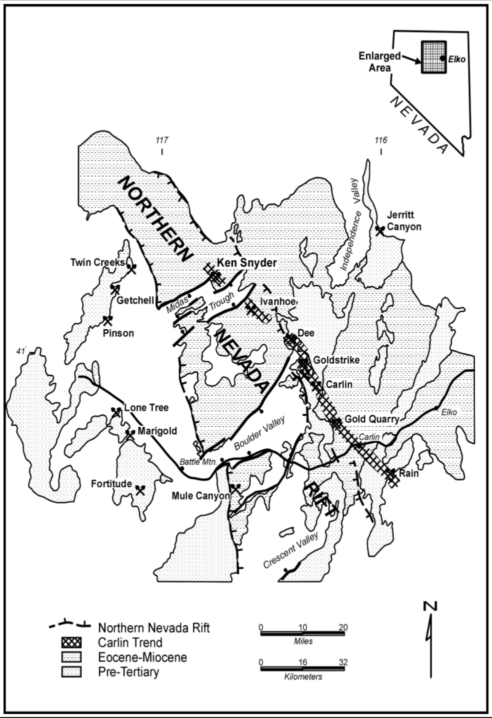


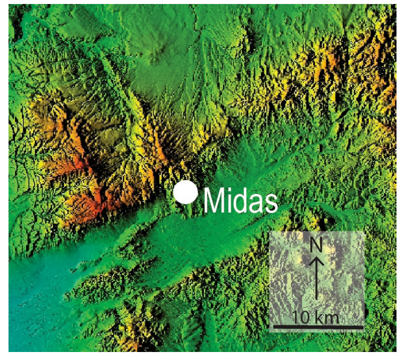


Regional Geothermal Trends

Midas is a new geothermal system.

Geothermal activity located on basin-bounding faults.

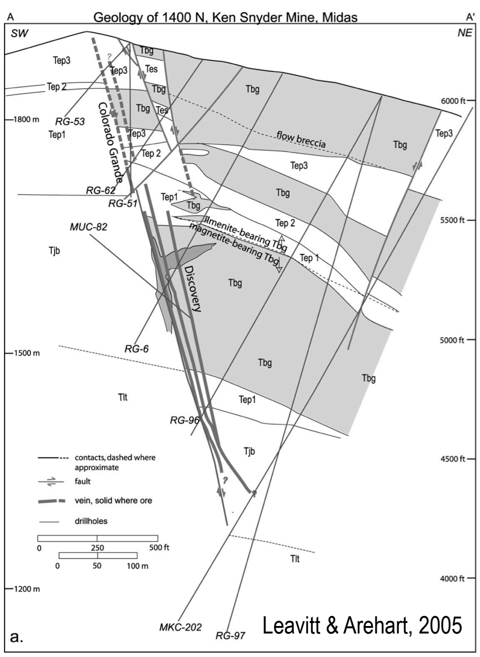




Midas Geolgical Setting

Volcanism, hydrothermal activity, and Au-Ag veins ores emplaced in the mid Miocene during NNR extension.

Rotation of the extensional regime produces the Midas trough in the late Miocene.

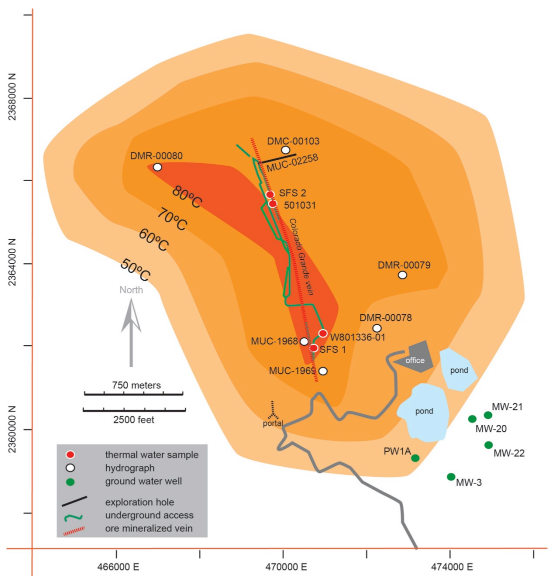


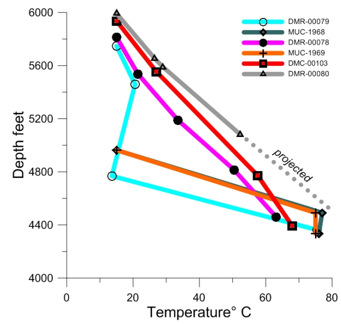
Midas Geological Setting

Epithermal gold-silver veins are hosted in steeply dipping faults that cross cut eastward dipping volcanic stratigraphy. Au-Ag mineralization is blind to the surface.

Hydrothermal alteration formed at the time of mineralization (~15 Ma), due to paleo-hydrothermal activity.

No modern hydrothermal alteration overprinting has been detected.

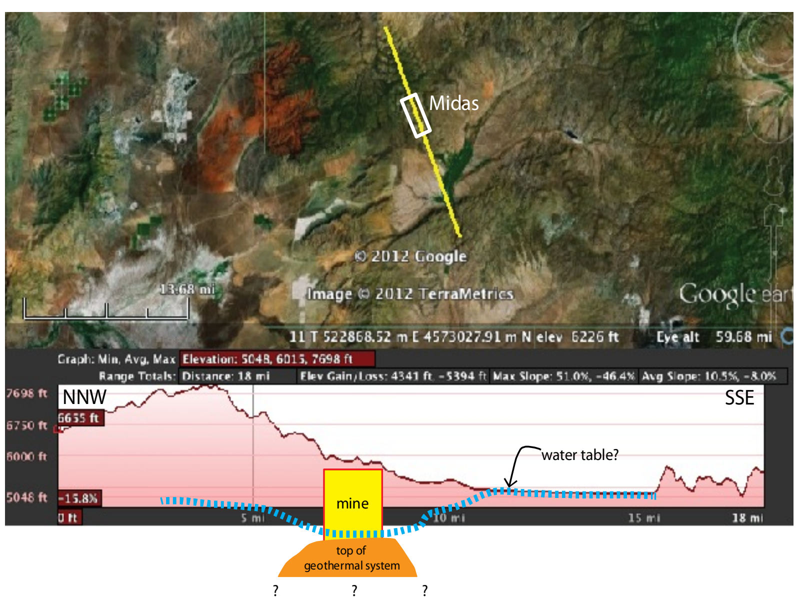




Thermal anomaly (~4500' elev)

Extent/continuity poorly known but covers several km^2 near the water table.

Shallow vertical temperature profiles suggest a gradient of >150°C/km; however, project to depth with caution.



Hydrological section showing the top of the Midas geothermal system.

Midas Summary

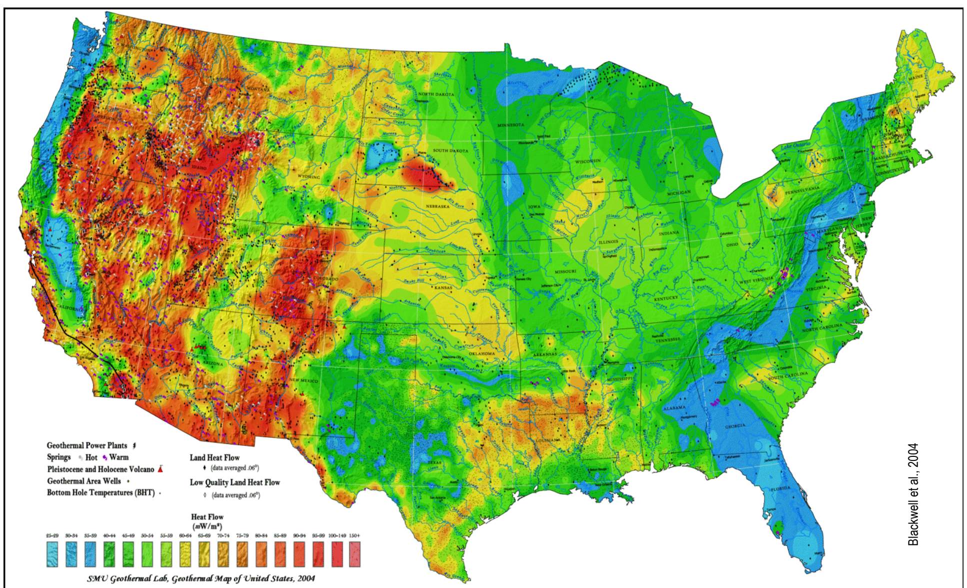
Underground development at Midas has revealed the top of a blind geothermal system, ~1000’ below the surface.

The thermal anomaly extends several km^2 with a maximum temperature of 85°C (185° F).

The chemistry of the waters suggest deep equlibration temperatures >130°C (>265° F), but the shallow mixing may be masking deep, hot temperature indicators.

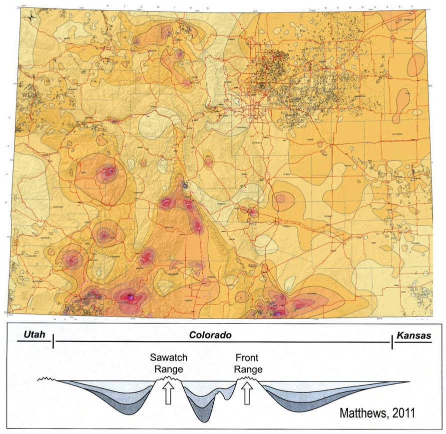
Midas shares geological similarities with Dixie Valley (63 MWe) and Beowawe (18 MWe).

Data compilation plus coordinated drilling activities that satisfy multiple objectives are recommended for advancing understanding of the resource.

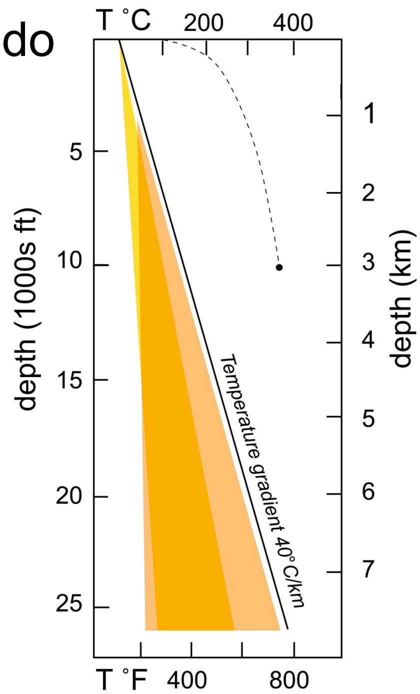


Blackwell et al., 2004

Deep Resource-Colorado



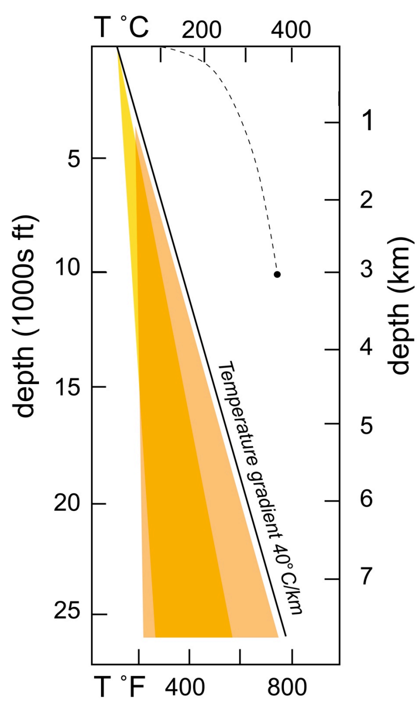
>240°C at 6 km depth



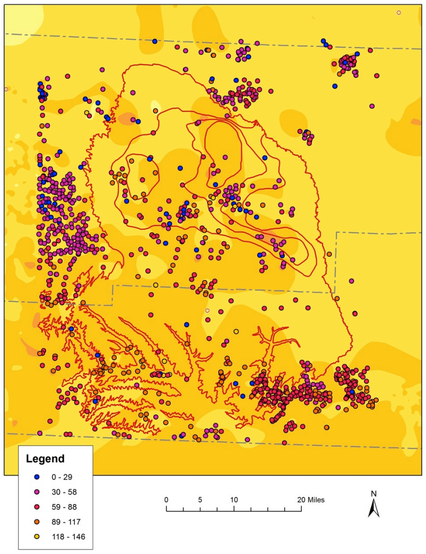
Deep Resource

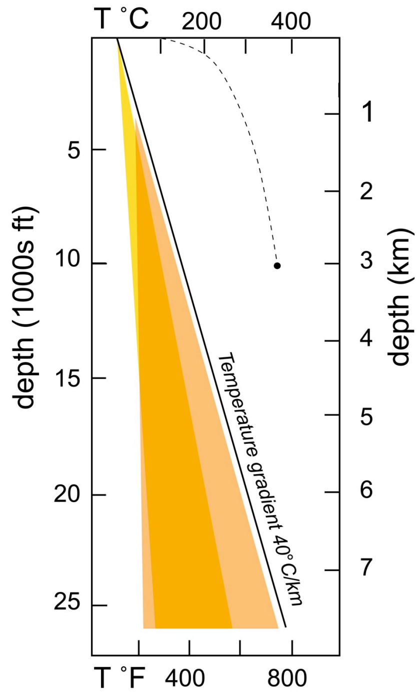
US Geol Survey

> Trillion barrels oil
< 1 km depth



Piceance Basin





Piceance Basin

T gradient >40°C/km

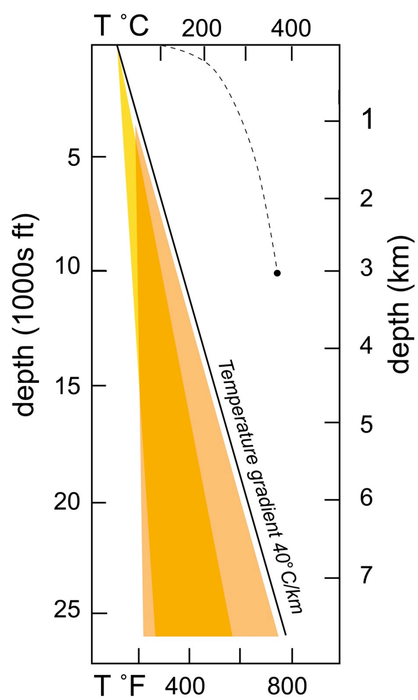
$[T_z - T_{z0}] = [300 - 200°C]$

2×10^{17} J/km^3

Hot rock volume >6000 km^3

70 $MW_{thermal}$/km^3 for a 100 years

Incentive for research



Oil recovery requires thermal energy

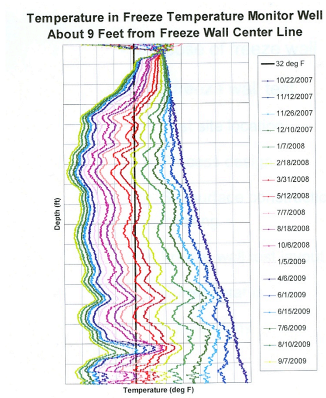
High demand for cooling & heating

>300°C required

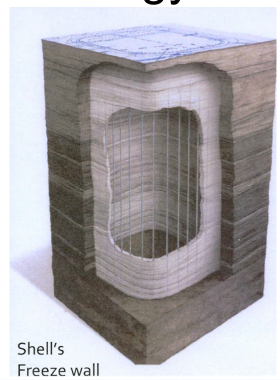
Water demand

Geothermal for preheating over long term

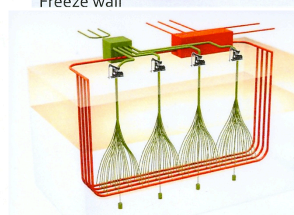
Time span ~100 yrs



Deeg et al., 2009, Johnson et al., 2009, 29th Oil Shale Symposium



Shell's Freeze wall



American Shale Oil CCR Process

Future Developments in Geothermal Energy

Diversity of R & D investment required

Main issues: permeability structure
sustained heat transfer

EGS remains a promising potential resource
New blind systems to be discovered
High thermal energy applications
Remote sites with high energy demands

Acknowledgements

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