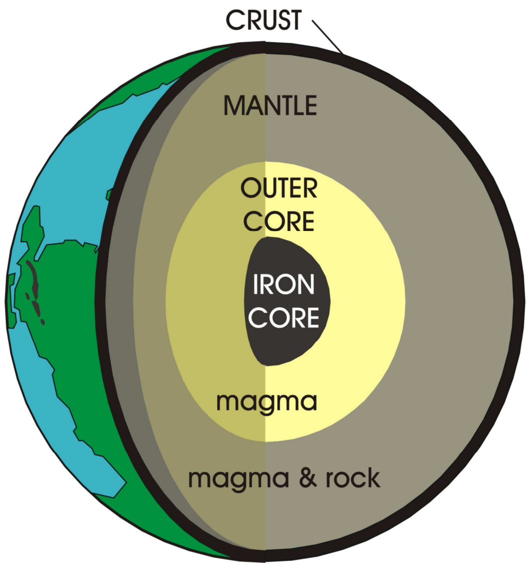
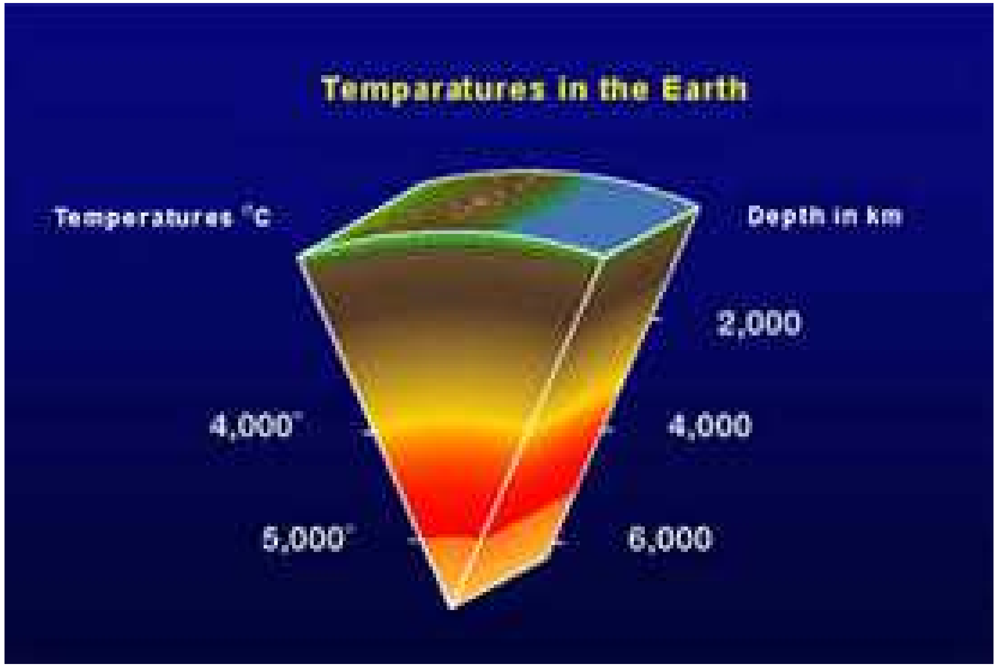
Geothermal Energy

- **Geothermal energy** consists of the thermal energy generated and stored in the earth's crust. In practice depends in part on the type of application.
- 5-10% was produced when Earth was created millions of years ago
- Most comes from the decay of radioactive material such plutonium and uranium
- Planet is made up of different layers with different temperatures (solid inner core, liquid outer core, mantle and crust)
- Temperatures 10-20 meters are constant 25ºC year round

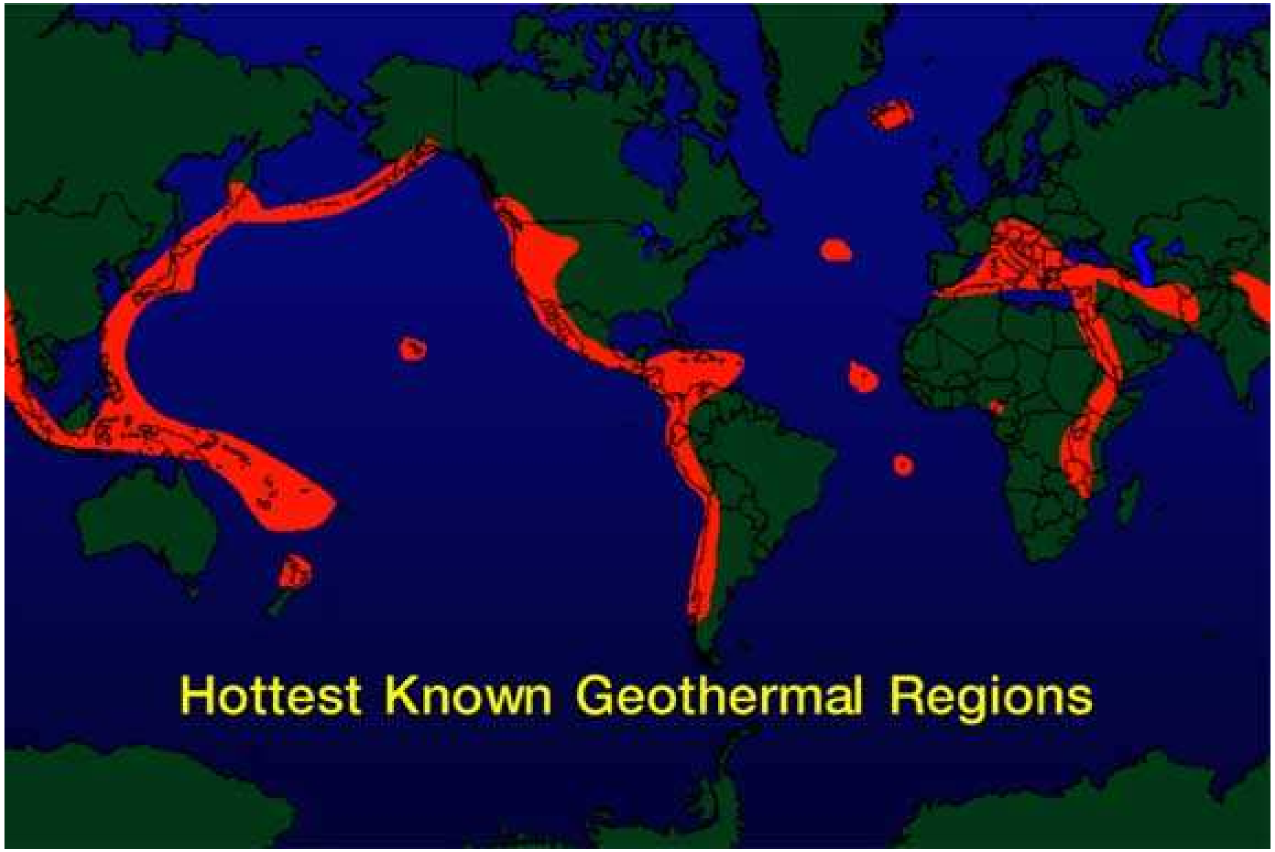


Geothermal resource



Heat has been radiating from the center of the Earth for some 4.5 billion years. Temperatures close to the center of the Earth, ~6437.4 km (~4,000 miles) deep, hover around 9932° F (~5,500° C), about as hot as the sun's surface.

Heat flows through the crust of the earth at a rate of 0.65W/m2 under the continents and 0.101W/m2 through the ocean floor. The resulting thermal temperature gradients range from 25º and 30º / km.



Local and regional geologic and tectonic phenomena play a role in determining location and quality of a particular resource. Regions with higher than normal heat flow are associated with tectonic plate boundaries and recent volcanic events.

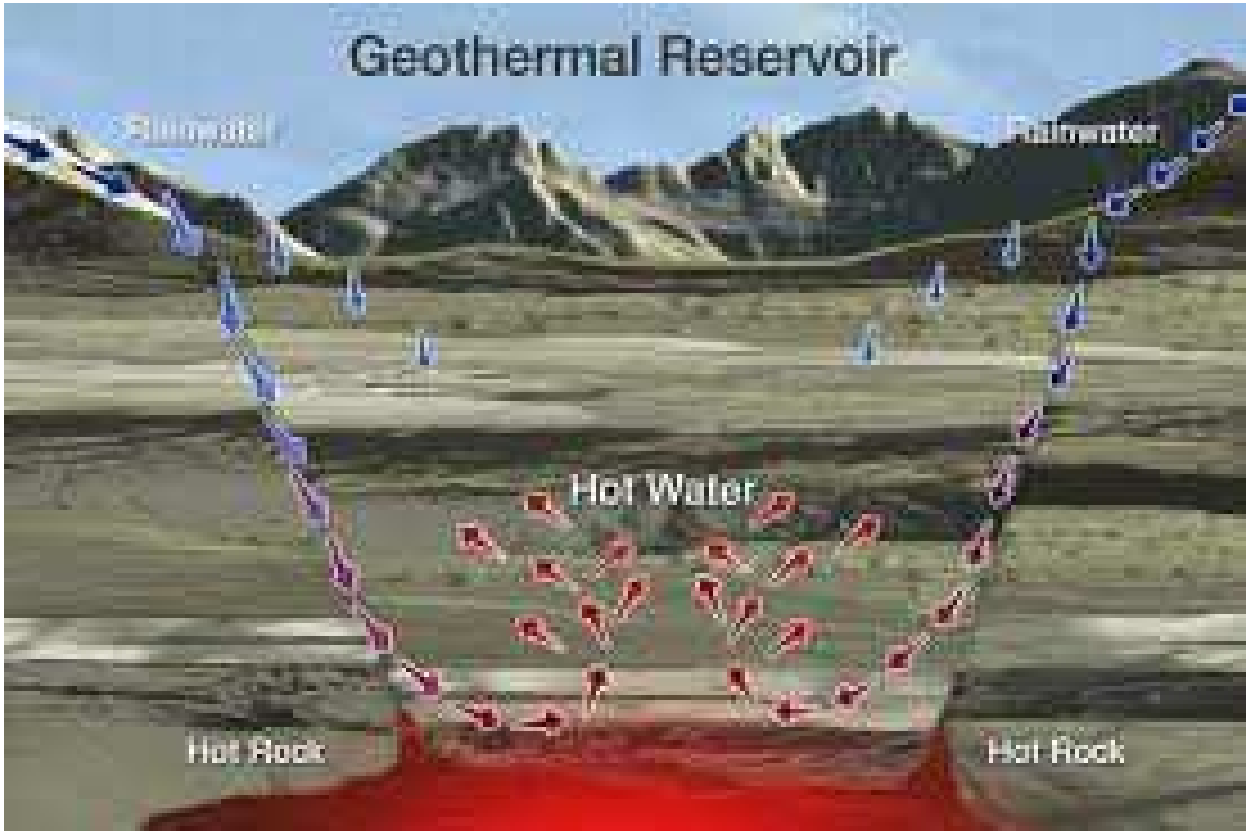
Iceland, New Zeland, Japan (plate boundaries)

Yellowstone National Park or Lardello field (recent Volcanism)

Many areas have accessible geothermal resources, especially countries along the circum-Pacific "Ring of Fire," spreading centers, continental rift zones and other hot spots.

(© 2000 Geothermal Education Office)

Scientists estimate that **42 million megawatts** (MW) of power flow from the Earth's interior, expected to remain for billions of years to come, ensuring an inexhaustible supply of energy. Since the heat emanating from the interior of the Earth is essentially limitless, geothermal energy is considered a renewable resource.[1] That is one of its big advantages.



Geothermal system that can be developed for beneficial uses requires heat, permeability, and water. When the rising hot water and steam is trapped in permeable and porous rocks under a layer of impermeable rock, it can form a geothermal reservoir.

Prince Piero Ginori Conti proved the viability of geothermal power plant technology in 1902, at the dry steam field in Larderello, Italy. The geothermal field has produced continuously since then, except for a brief period during World War II, and is still producing today.

First Geothermal Power Plant, 1904, Larderello, Italy

Prince Ginori Conti and the 10-kW experimental power plant, Larderello (courtesy of ENEL)

Other developments: steam fields and hot water systems

Drilling a Wairakei, New Zealand, 1950s (courtesy of Ian Thain)

First power plant at The Geysers, USA, early-1930s (courtesy of Geothermal Resources Council).

Modern 110-MW plant at The Geysers, California. The Geysers is the world's largest geothermal field, containing 22 geothermal plants, drawing steam from 35o wells

Cerro Prieto Geothermal field (covers an area of approximately 15 km2) located in South Mexicali, North Mexico

The power station features four plants, comprising of 13 units. The first plant was commissioned in 1973, while the fourth plant was commissioned in 2000. Installed capacity of 720MW and future plans for expansion

Makban Geothermal Complex, Philippines

World's fourth largest biggest geothermal power facility, with an output capacity of 458MW, comprising 6 power plants, covering 700ha (commenced operations in 1979)

Iceland : **Five major *g*eothermal power facilities currently generate 25% of the country's total electricity production. In addition geothermal heat meets heating and hot water requirements of 87% of all buildings**

Countries Generating Geothermal Power as of May 2012

Country	Installed Capacity (MW)
United States	3,187
Philippines	1,904
Indonesia	1,222
Mexico	958
Italy	883
New Zealand	768
Iceland	661
Japan	535
El Salvador	204
Kenya	202
Costa Rica	208
Nicaragua	124
Russia	82
Turkey	93
Papua New Guinea	56
Guatemala	52
Portugal	29
China	24
France	16
Ethiopia	7
Germany	7
Austria	1
Australia	1
Thailand	0.3
Total	11,224.3

As of early 2012, GEA (Geothermal Energy Association) identified ~11,224 MW of energy on line at geothermal power plants in 24 countries around the world

Additionally, at least 78 countries utilize geothermal direct use applications

Geothermal Resources

Hydrothermal Systems

Geopressure Systems

Hot Dry Rock (EGS)

Magma Systems

Natural Hydrothermal Systems

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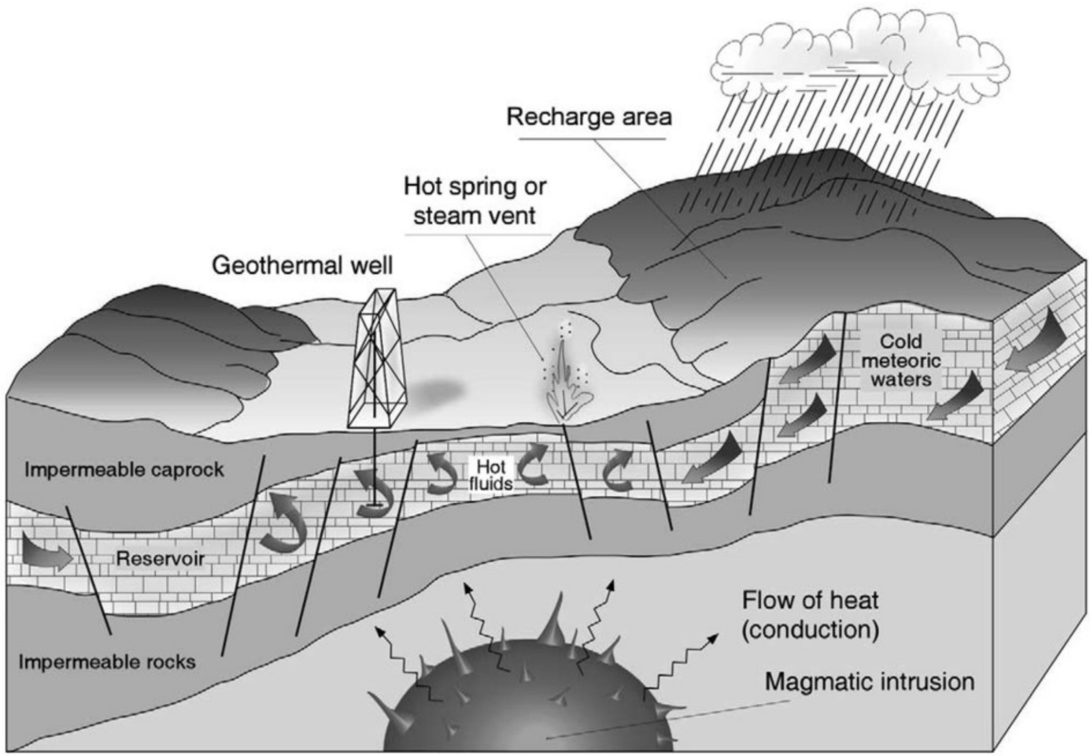
Systems that spontaneously produce hot fluids.

- Source heat (usually magnetic intrusion at depth)
- Formations with enough permeability to allow fluid mobility
- Adequate supply of indigenous fluid (water or steam)
- Sufficient contact surface
- Time for fluid to be heated
- Return path to the surface

Frequently located in or near zones of recent volcanism and tectonism. Water or steam in hydrothermal systems is usually of meteoric origin, typically located at depths of 1-4km at temperatures of 350C. Water falls as rain or snow, percolates downward through sediments or fissures until it comes to a heat source. There it is heated rises toward the surface where it usually appears as geysers, hot springs, fumaroles.

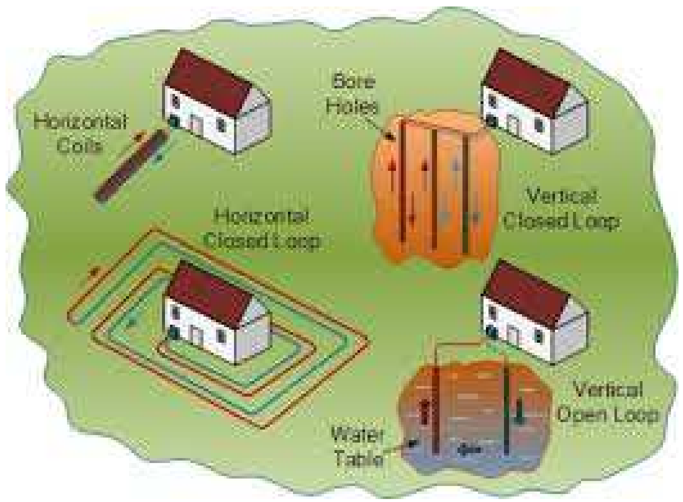


Source: Barbier (2002, *Renewable and Sustainable Energy Reviews* 6, 63–65, http://www.sciencedirect.com/science/journal/13640321)

Hydrothermal resources are used for different energy purposes depending on their temperature and how deep they are.

Low Temperature: "Direct Use" or Heating

When the temperature of a hydrothermal resource is 50°c-100°c, it can be used directly in spas or to heat buildings, grow crops, warm fish ponds, or for other uses. Most of the people in Iceland use geothermal heat for their public buildings, schools, and homes. In the United States, geothermal heat pumps are used in 45 states to heat and cool homes and buildings



High Temperature: Producing Electricity

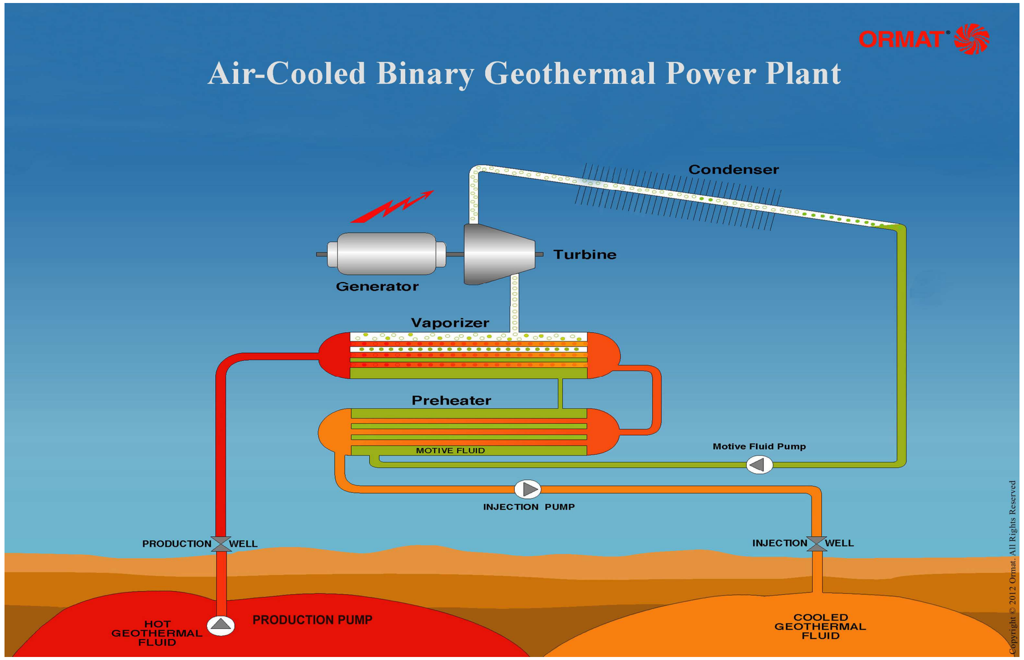
When the temperature of a hydrothermal resource is around 150^{o}C and up, it can be used to generate electricity. Two main types of hydrothermal resources are used to generate electricity:

- dry steam (vapor-dominated) reservoirs, and
- hot water (liquid-dominated) reservoirs.

Dry steam reservoirs are rare but highly efficient at producing electricity. The Geysers in California is the largest and best known dry steam reservoir. The steam is obtained by drilling wells from 7,000 to 10,000 feet deep. In a dry steam reservoir, the natural steam is piped directly from a geothermal well to power a turbine generator. The spent steam (condensed water) can be used in the plant's cooling system and injected back into the reservoir to maintain water and pressure levels.

Hot water geothermal reservoirs are the most common type. In a liquid-dominated reservoir, the hot water has not vaporized into steam because the reservoir is saturated with water and is under pressure. To generate electricity, the hot water is piped from geothermal wells to one or more separators where the pressure is lowered and the water *flashes* into steam. The steam then propels a turbine generator to produce electricity. The steam is cooled and condensed and either used in the plant's cooling system or injected back into the geothermal reservoir.

A **binary cycle** power plant is used when the water in a hot water reservoir is not hot enough to flash into steam. Instead, the lower-temperature hot water is used to heat a fluid that expands when warmed. The turbine is powered from the expanded, pressurized fluid. Afterwards, the fluid is cooled and recycled to be heated over and over again.



Geopressured Systems

Reservoirs characterized by pore fluids under high confining pressures and high temperatures with correspondingly large quantities of dissolved methane .
Temperatures typically range from 90°C to 200°C

Soft geopressure : Hydrostatic to 15.83 kPa/m
Hard geopressure: 15.83– 22.61 kPa/m (lithostatic pressure gradient)

Common Geopressured Geothermal Reservoir Structure

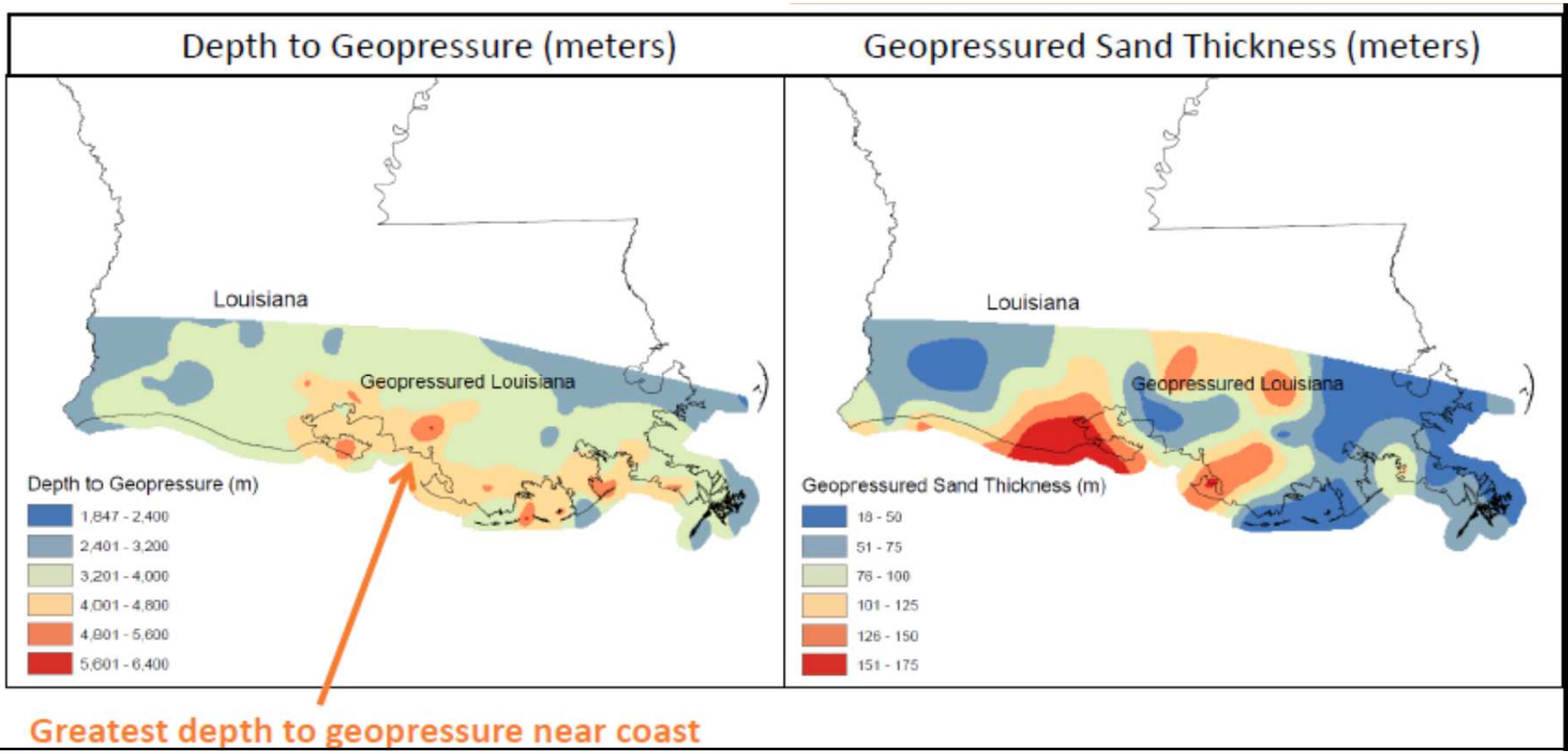
- Upper thick low permeability shale
- Thin sandstone layer
- Lower thick low permeability shale

Three Potential Sources of Energy

- Thermal energy (Temperature > 100° C – geothermal electricity generation)
- Chemical energy (natural gas)
- Mechanical energy (pressurized fluid)

Locations: Geopressured brine reservoirs are located along the Pacific coast, in Appalachia, beneath the Gulf of Mexico, and in other deep sedimentary basins in the United States.

Current Demonstration Project: Louisiana Geothermal, LLC, through a partnership with GeothermEx, Inc., Louisiana State University, and The Shaw Group, Inc. is currently working to demonstrate the commercial feasibility of geopressured-geothermal power development at the Sweet Lake Oil and Gas Field in Cameron Parish, Louisiana



Magma Systems:

Magma resource consists of rock that is partially or completely molten, encountered at accessible depths. Magma's high temperature make this resource extremely attractive for efficient generation of electricity.

Need for development of drilling and heat-extraction technology before heat can be extracted usefully from magma (equipment that can operate at temp of 700-1000C and depths of about 7km)

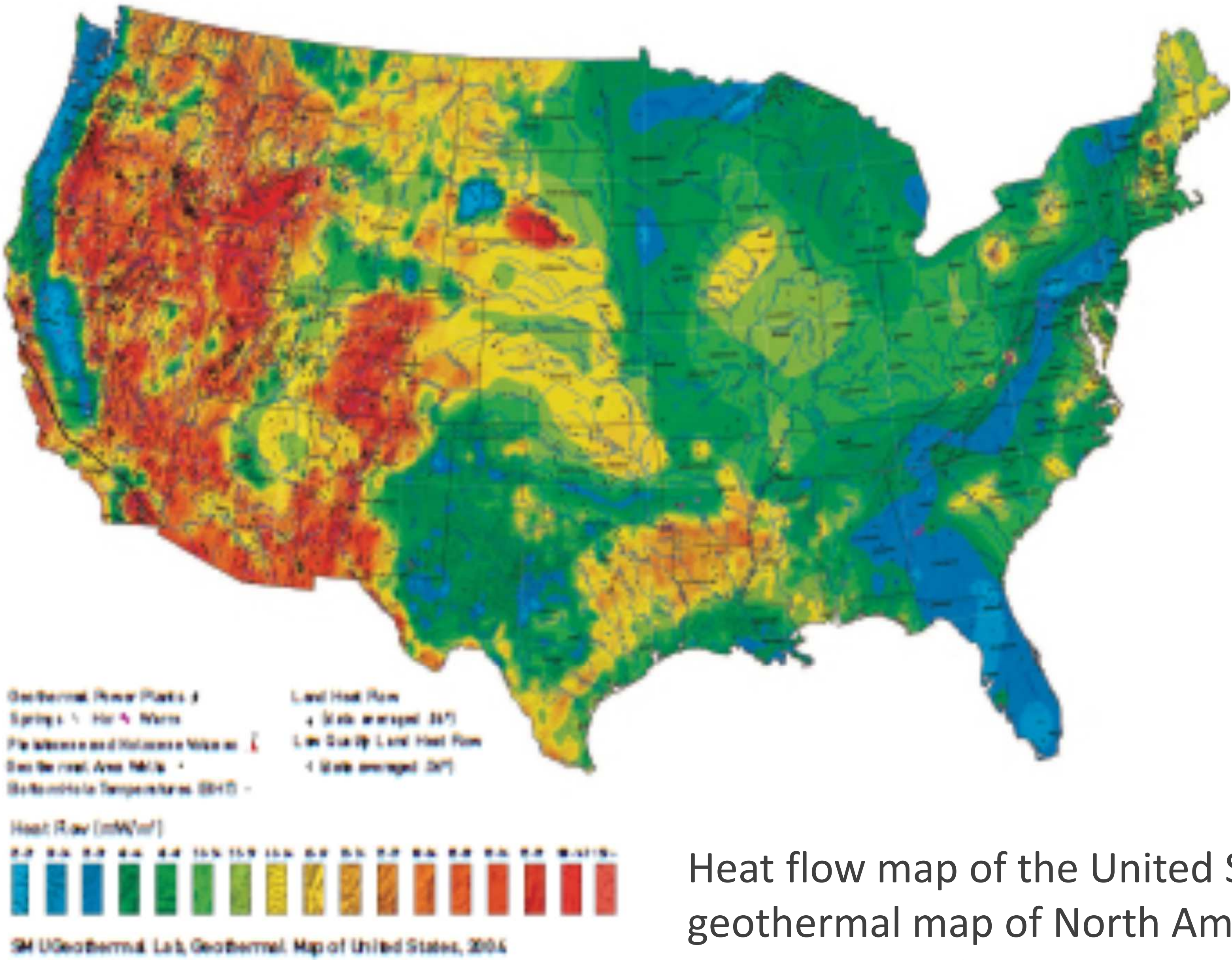
Main obstacle: find body of magma at drillable depths.

In 2009, a borehole drilled as part of the Icelandic Deep Drilling Project (IDDP), unexpectedly penetrated into magma (molten rock) at only 2100 meters depth, with a temperature of 900-1000 C.

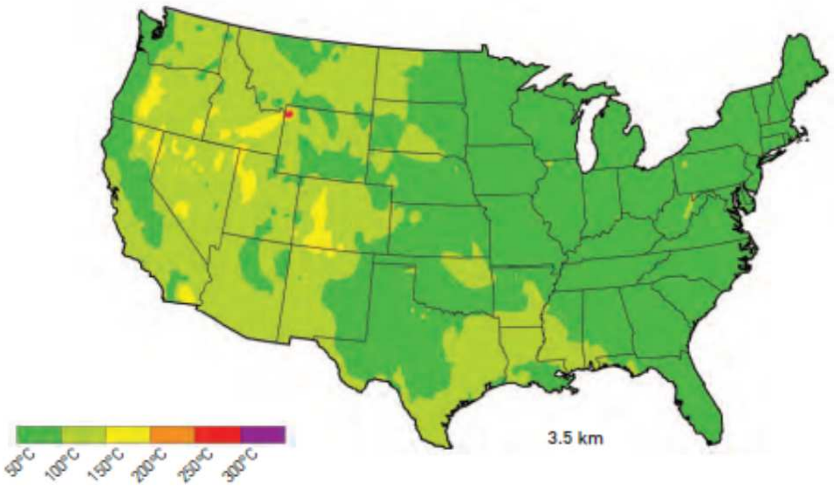
Flow test of the IDDP-1 well at Krafla (IDDP) world's first magma-enhanced geothermal system

Hot dry rock : Throughout most of the world, one more components of a hydrothermal reservoir is missing.

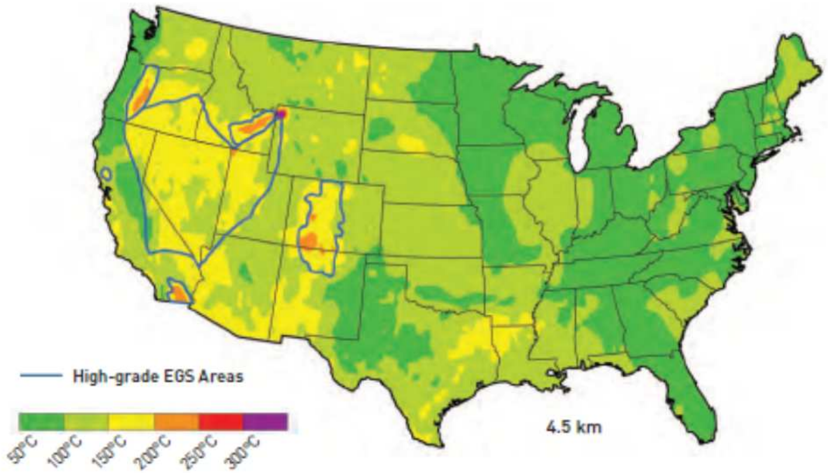
- The reservoir rock is often hot enough (>200^{o}C) but produces insufficient fluid for commercial heat extraction because
  - Low formation permeability
  - Or absence of naturally contained fluids
- In principle available everywhere just by drilling to depths sufficient to rock temperature useful for heat extraction:
  - > 150^{o}C for producing electricity
  - 50^{o}C-100^{o}C for direct heat use
- For base load electric power generation the depths required are:
  - 4-8km in low grade, low gradient regions
  - 2-5km for high grade, high gradient systems



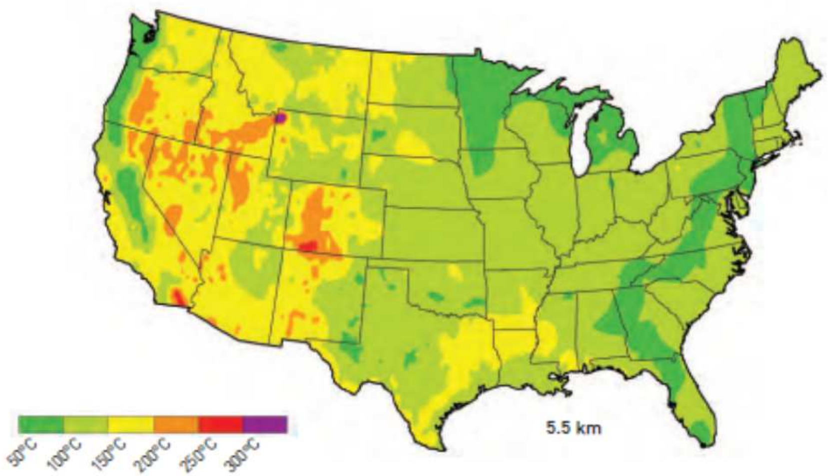
Heat flow map of the United States- subset of the geothermal map of North America (Blackwell and Richards, 2004)



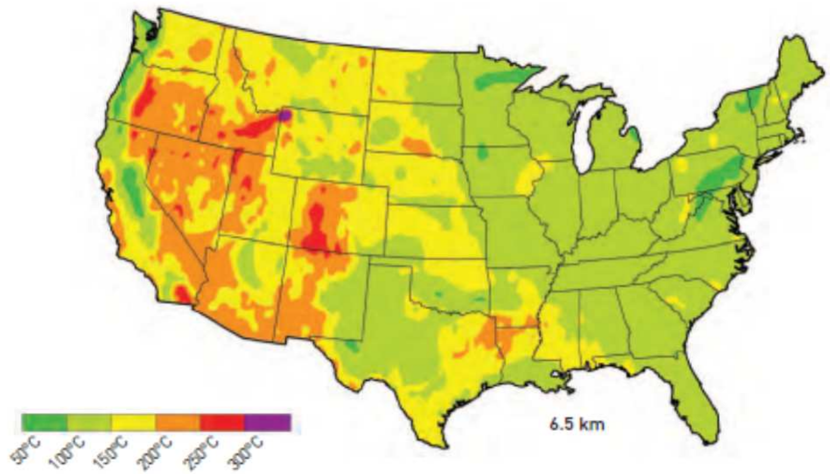
Average temperature at 3.5 km.



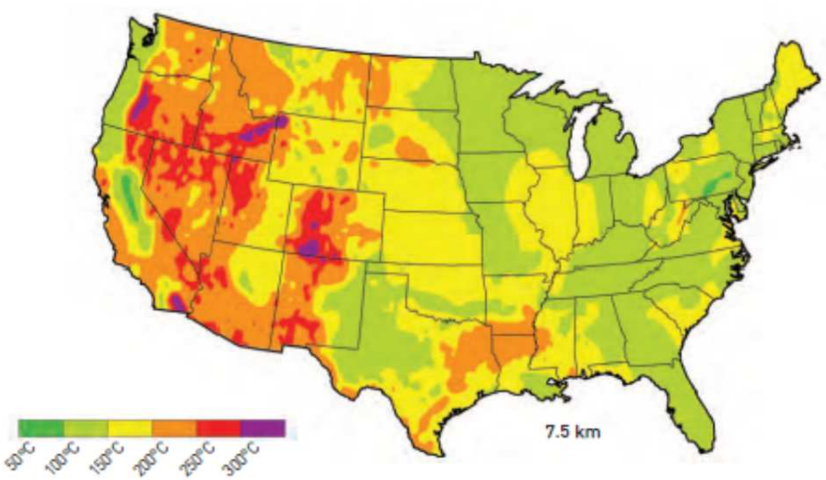
Average temperature at 4.5 km. Includes areas of special EGS interest outlined in blue.



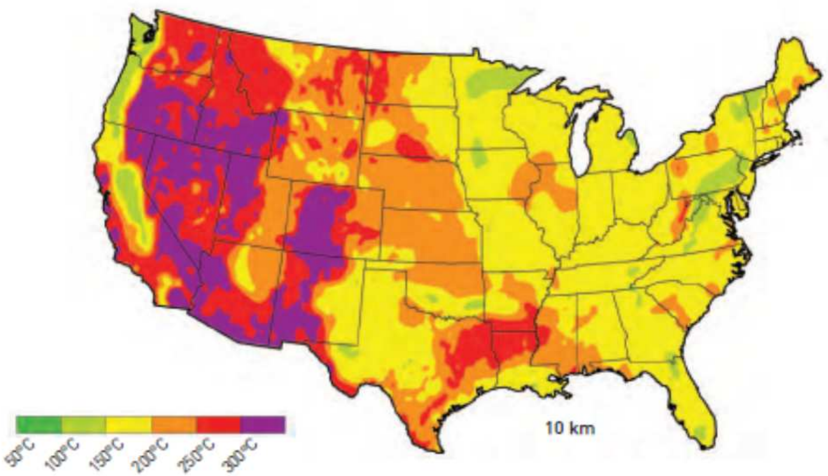
Average temperature at 5.5 km.



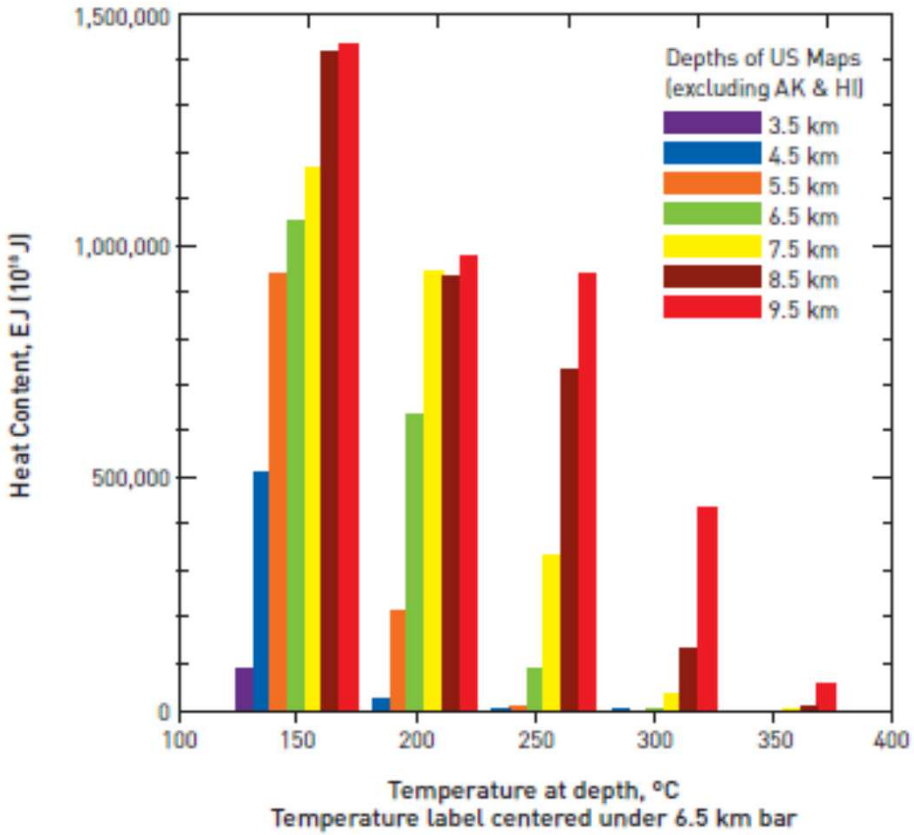
Average temperature at 6.5 km.



Average temperature at 7.5 km.



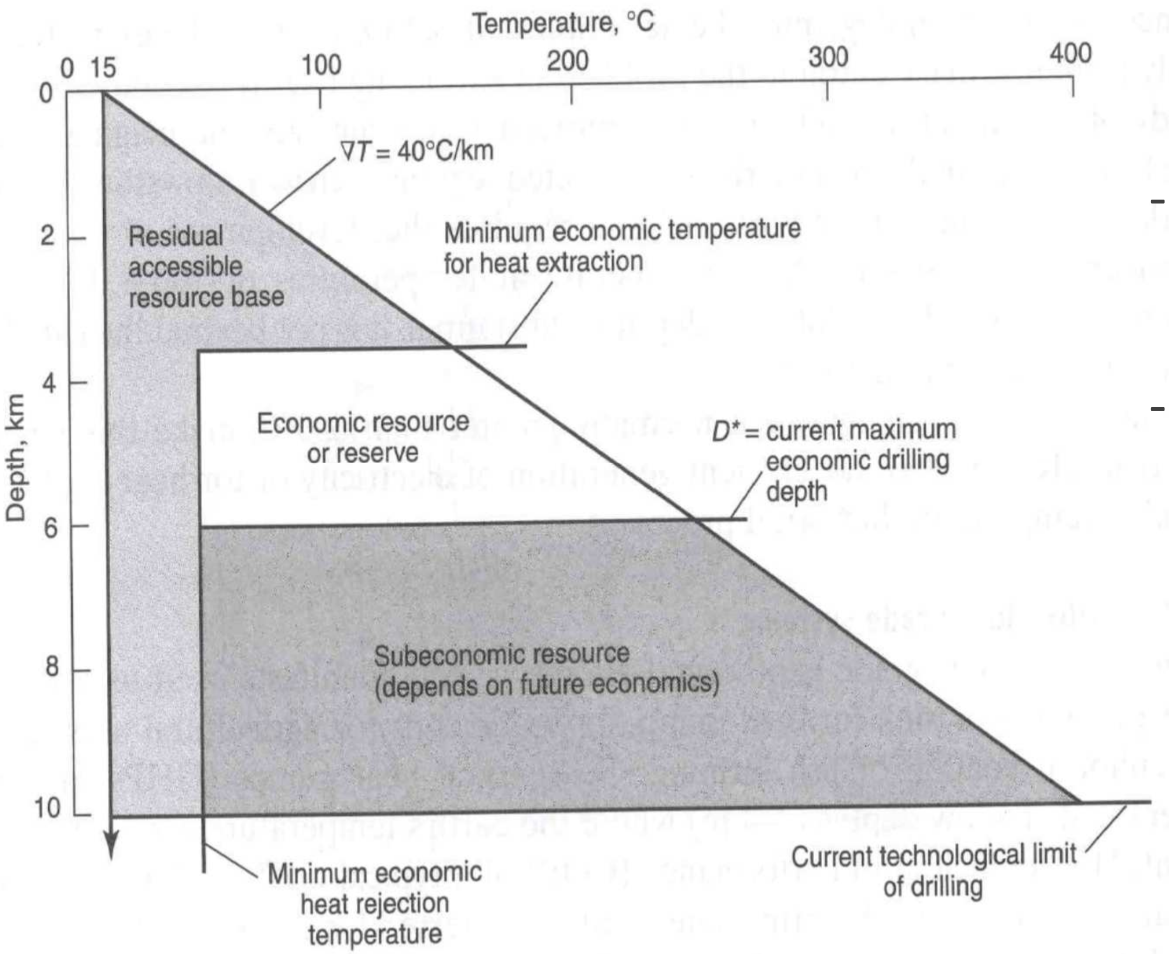
Average temperature at 10 km.



Histograms of heat content in EJ, as a function of depth for 1 km slices.
(US uses about 100EJ yearly in primary energy)
If you add all the bars you will obtain14million EJ which is much larger than what the US is using.

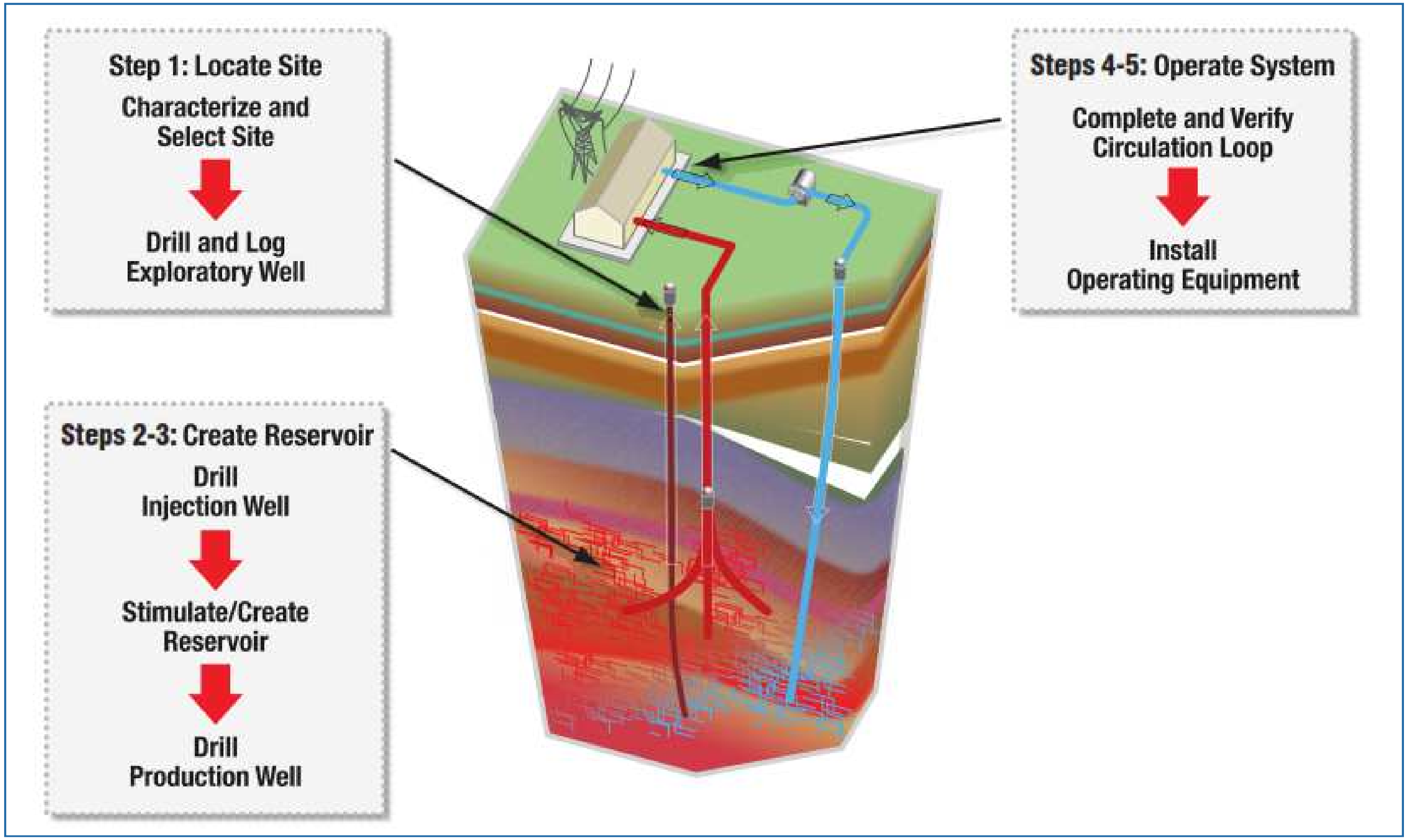
Geothermal Resource Size and Distribution

Factors that limit amount of energy that can be economically extracted



- Effective geothermal gradient. This largely determines the potential of an area.
- Minimum of 150°C is required to provide reasonable thermodynamic conversion efficiency
- Maximum economic drilling depth (~6km)

Enhanced or Engineered Geothermal Systems are engineered geothermal reservoirs formed by hydraulic stimulation of the rock mass



Benefits	Challenges
• Widely available • Ability to produce energy around the clock • Emits little to no greenhouse gas • Sustainable • Not dependent on climatic conditions	• High upfront costs: High investments for drilling and testing • Major uncertainties affecting EGS feasibility studies (reservoir creation, productivity, etc) • Need for technology research, development and demonstration (most technologies not fully yet adapted for use in EGS development) • Micro-seismicity (e.g. Basel, Switzerland)

Characterizing and Predicting

Efficiently and accurately locate target geophysical and geochemical responses, finding more viable and low-risk resource, and quantitatively infer their evolution under future engineered conditions

Accessing

Safe and cost-effective drilling, with reservoir integrity

Engineering

Create/construct desired subsurface conditions in challenging high-pressure/ high-temperature environments

Sustaining

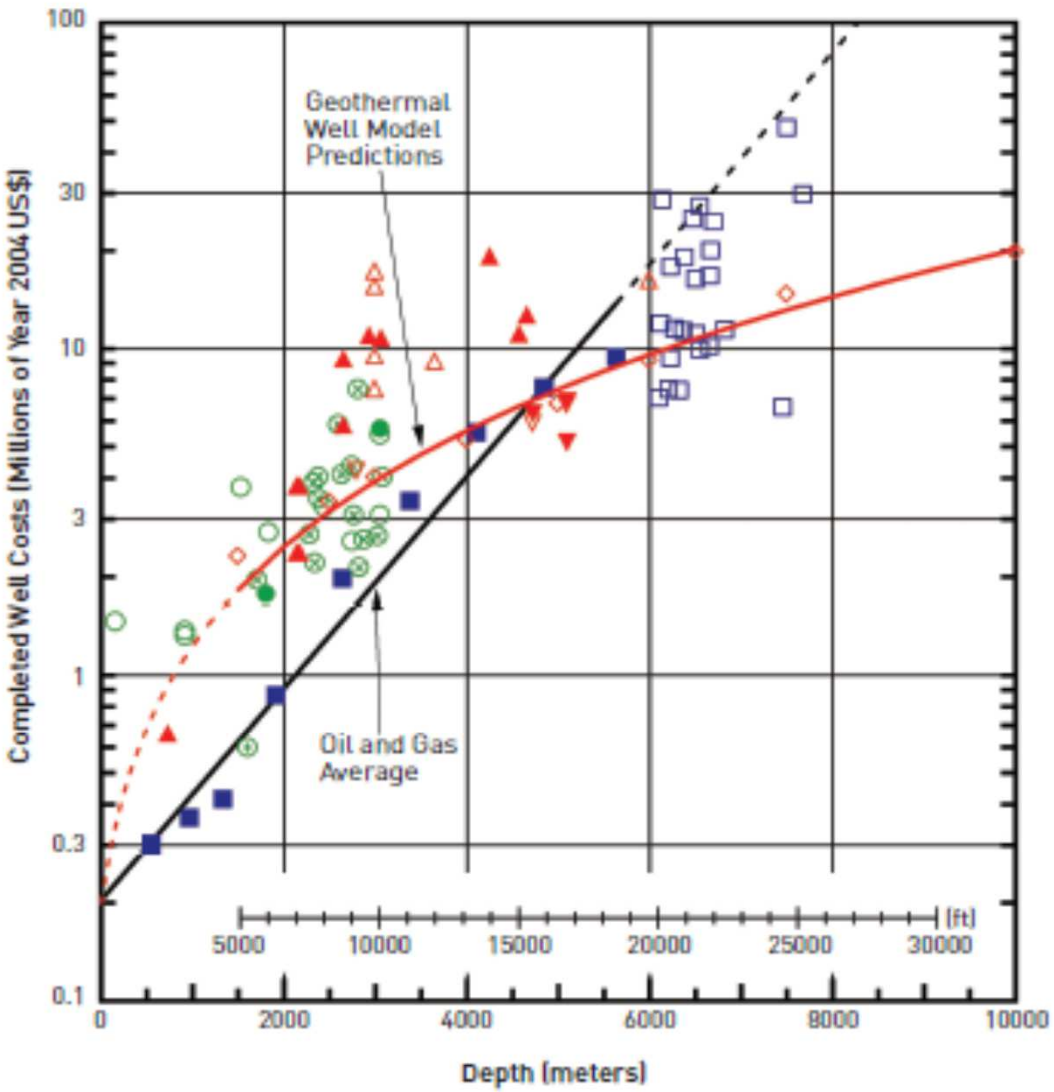
Maintain optimal subsurface conditions over multi-decadal or longer time frames

Monitoring

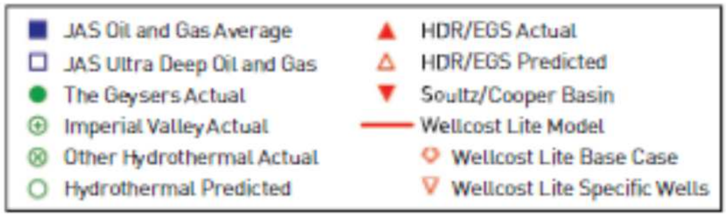
Improve observational methods and advance understanding of multi-scale complexities through system lifetimes

Drilling Technology and Costs

Exploration, production and injection well drilling are major cost components of any geothermal project (30%-60% total capital investment)



Source: interdisciplinary MIT study In 2006



1. JAS = Joint Association Survey on Drilling Costs.
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depths greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2000).
4. "Other Hydrothermal Actual" data include some non-US wells (Source: Mansure 2004).

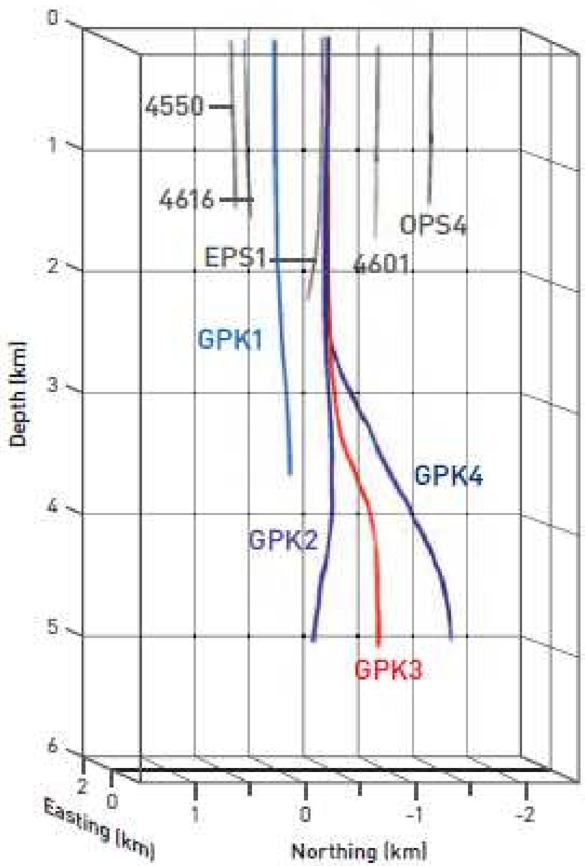
Current EGS drilling technology

The current state of the art in geothermal drilling is essentially that of oil and gas drilling, incorporating engineering solutions to problems that are associated with geothermal environments, i.e., temperature effects on instrumentation, thermal expansion of casing strings, drilling hardness, and lost circulation.

Advances in overcoming the problems encountered in drilling in geothermal environments have been made on several fronts:

- *High-temperature instrumentation and seals*
- *Logging (important diagnostic tool that is not yet fully developed in the geothermal industry)*
- *Thermal expansion of casing*
- *Drilling fluids/"mud" coolers*
- *Drill bits and increased rate of penetration (geothermal operations in harder, more fractured crystalline or granitic)*
- *Lost circulation. (drilling problem that arises when the circulation of the drilling fluid is interrupted and it does not return to the surface)*

Principal means of EGS reservoir creation will be hydraulic simulation to fracture the rock or open existing fractures. Hydraulic stimulation is a standard technology used in the oil and gas fields to enhance production. It has been applied to EGS projects with varied success.



Some EGS field experiments partly corroborated the ability to create EGS reservoirs, but the assumptions have not been corroborated by large, well documented field projects in a number of geological settings

DECISION ANALYSIS FOR EGS: OBJECTIVES

Challenge:

To develop economically viable and sustainable EGS systems.

Goal:

To assess the feasibility of EGS systems, and assess alternatives based on a quantitative and systematic risk assessment that includes uncertainties.

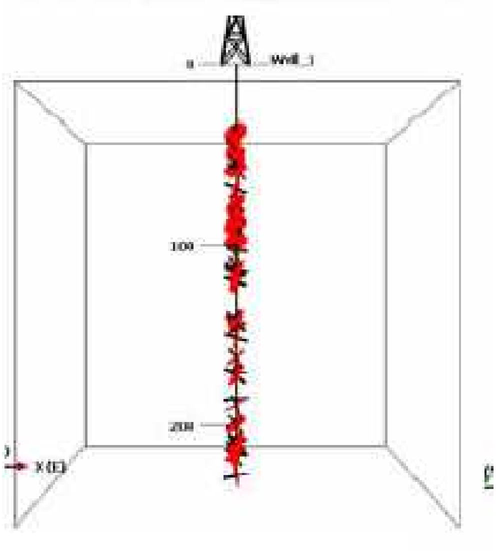
Risk defined by utility functions with different attributes such as monetary, time, environmental, safety, ...

Methodology that can be used by policy makers to make rational decisions for future use of EGS

Reservoir Characterization: Fracture characterization

Geological and geomechanical uncertainties

- ❖ Limited data because of accessibility and affordability
- ❖ Data source and type
  - 1D data (Boreholes)
  - 2D data (Face, Outcrop mapping)
  - 3D data (3D seismic data)



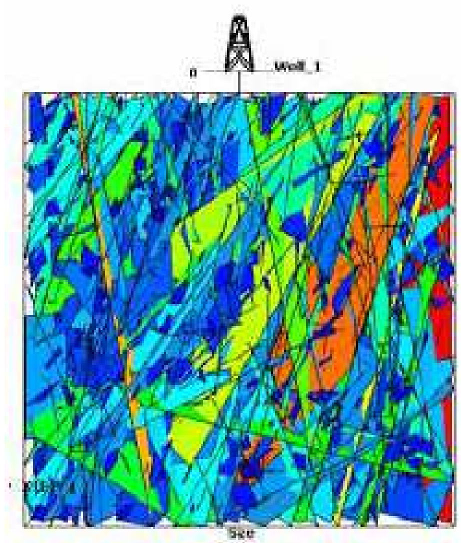
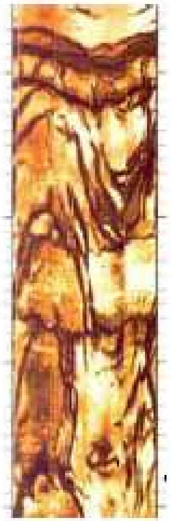
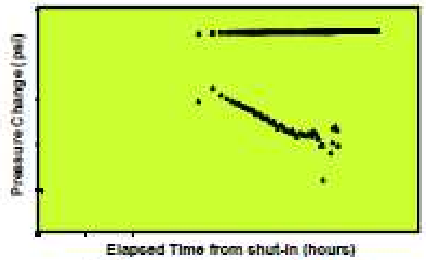


Image Logs



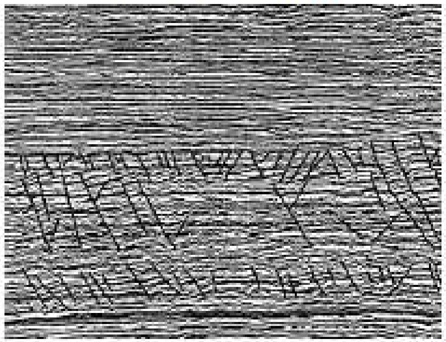
Outcrops

Well Test Data



Core

Seismic Sections



Risk Assessment Framework

Updating

State of Nature ⇄ Fracture Models

Other Models

Model(s) to represent the State of Nature

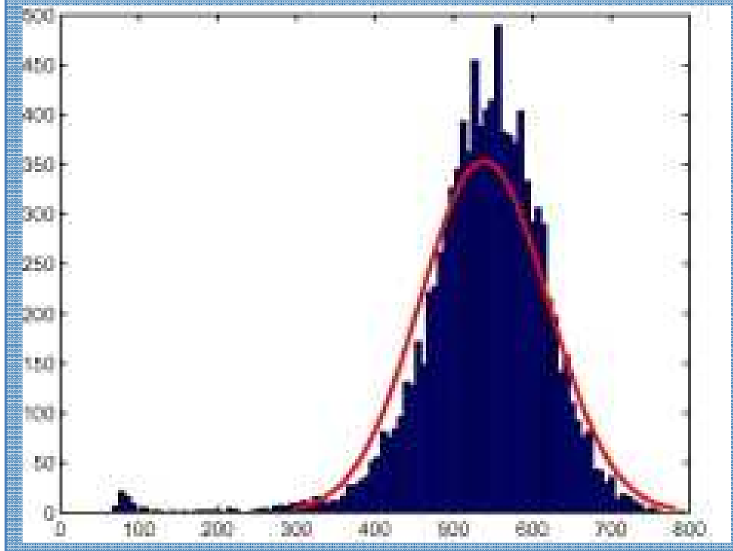
Model(s) to represent Processes

BENEFIT MODELING

Flow Model

Other Models

Flow rate distribution



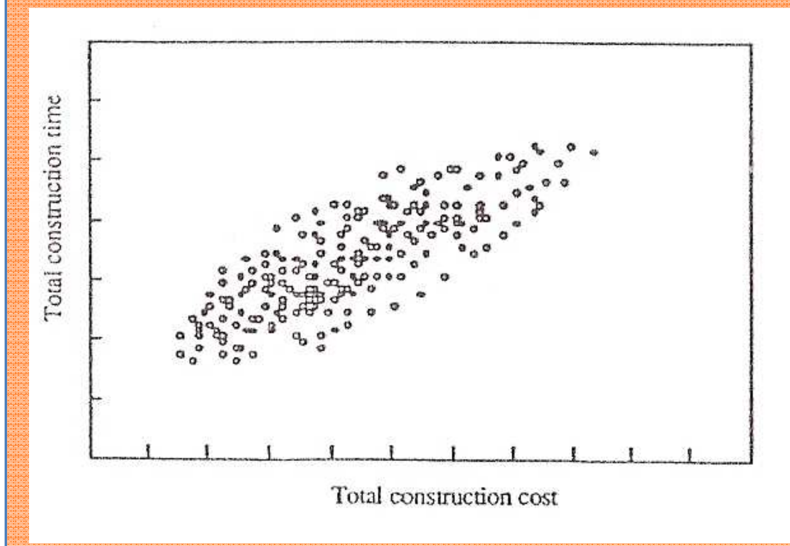
COST MODELING

Drill Cost and Time Model

Surface Operations Model

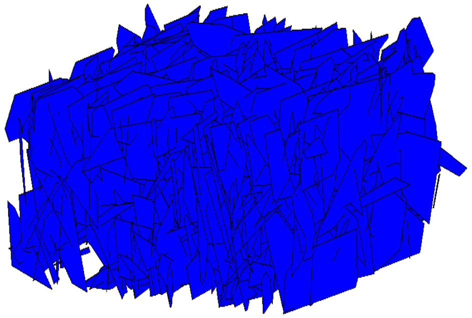
Other Models

Scatter Plot Time-Cost



Models used in Benefit Assessment

3D fracture pattern model GEOFRAC



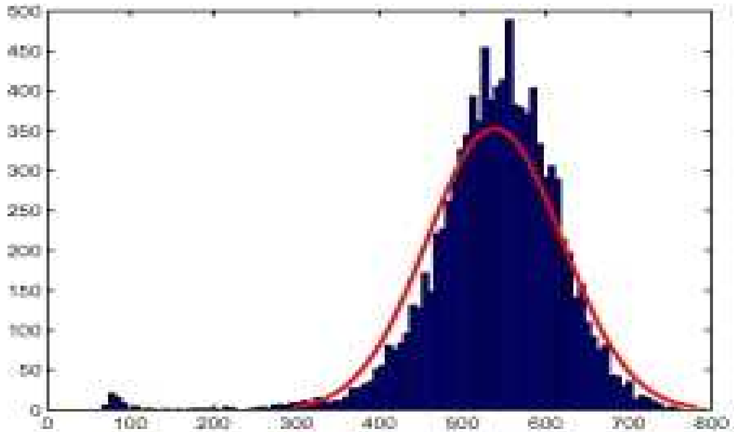
Circulation Model

Processes
Fluid properties
Well location and number
Reservoir pressure
…

State of Nature
Geological data
Type of rock
Fracture intensity
Fracture aperture
Fracture orientation
Permeability
…

State of Nature
Fracture Network

Heat and Flow Rate distribution



Geothernal Energy…

Heat to Power conversion rates

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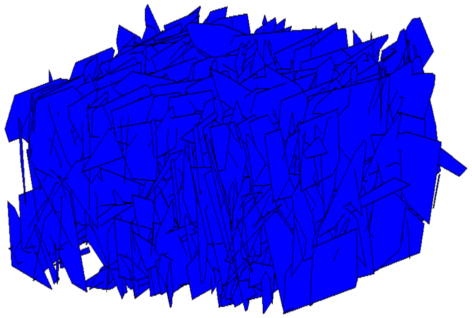
Models used in Cost Assessment

Representing the State of Nature

Fracture Network

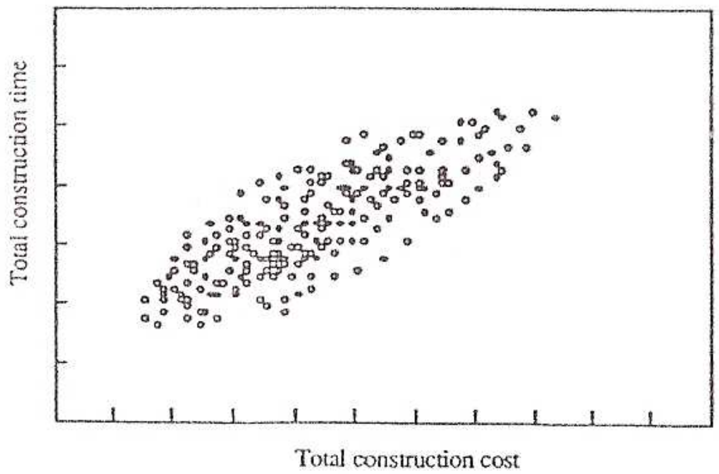


Surface Operations Model

Drill Cost and Time Model

Other Models

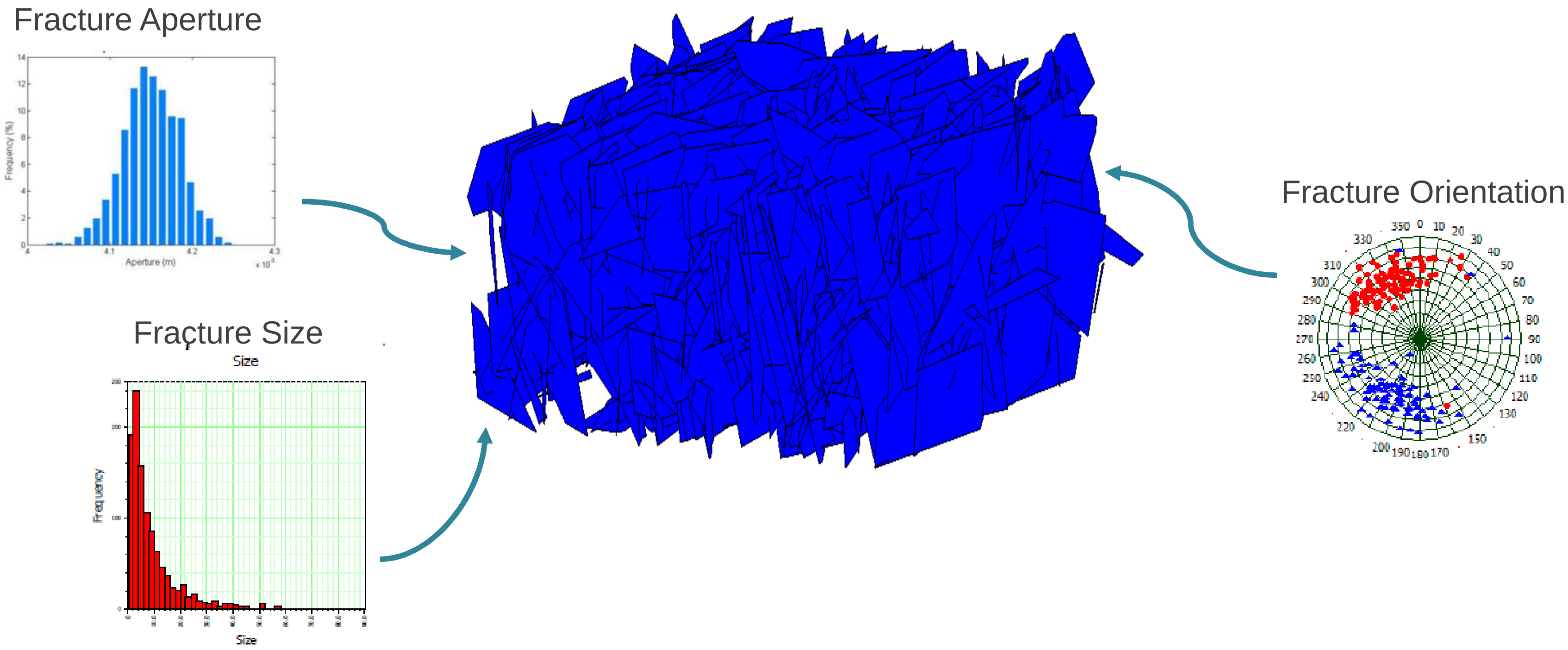
Scatter plot Time-Cost



Stochastic Fracture Pattern Models

Fracture Pattern Models or Discrete Fracture Network (DFN) Models:
Represent rock fracture (joints) in terms of their orientation, spacing, size, shape and aperture. DFN models range from deterministic to fully stochastic ones

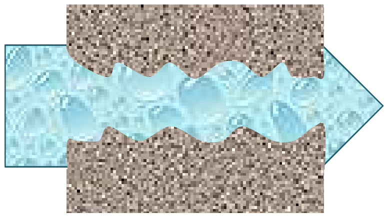
Stochastic Fracture pattern Models, e.g. GEOFRAC (3D stochastic fracture pattern model developed at MIT)



Major Advantage/ Strength : realistic model of the natural fractures, so that the natural fracture/hydraulic fracture interaction can be modeled explicitly and can consider geological uncertainties.

Flow Path Computation

Model Assumptions:
- Flow restricted to fractures (i.e. impervious rock)
- Laminar flow between parallel plates
- Fracture roughness (ε) taken into account through friction factor f
- Flow through "most likely" paths



Flow Rate (Parallel plates)

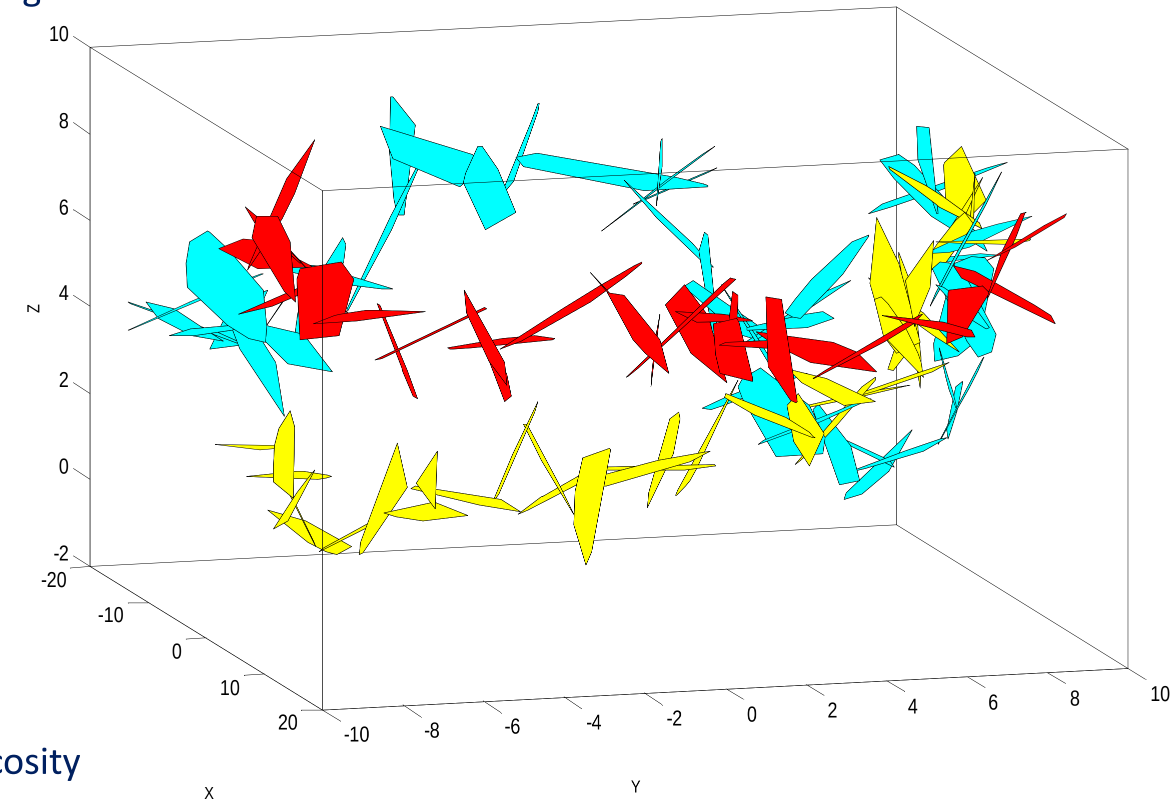
$$Q = \frac{wh^3 \Delta P}{12\mu \Delta L}$$

w: fracture width
h: aperture
ΔP: pressure gradient
μ: water dynamic viscosity
ΔL: fracture length

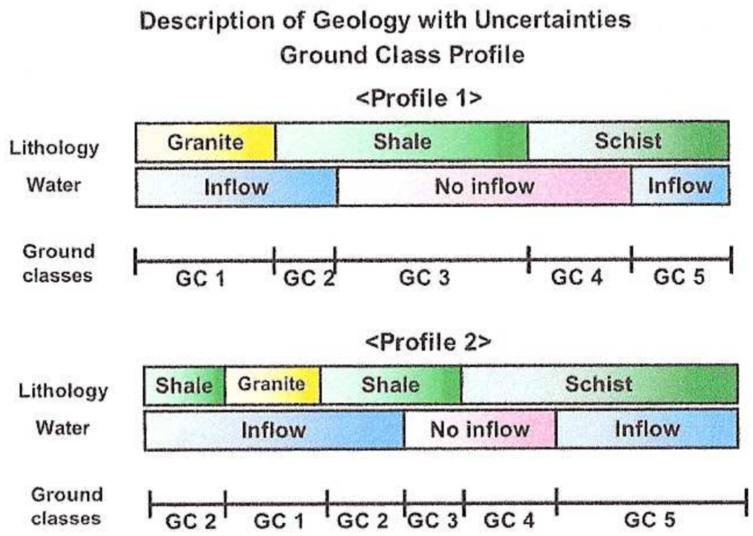
Fracture Roughness friction

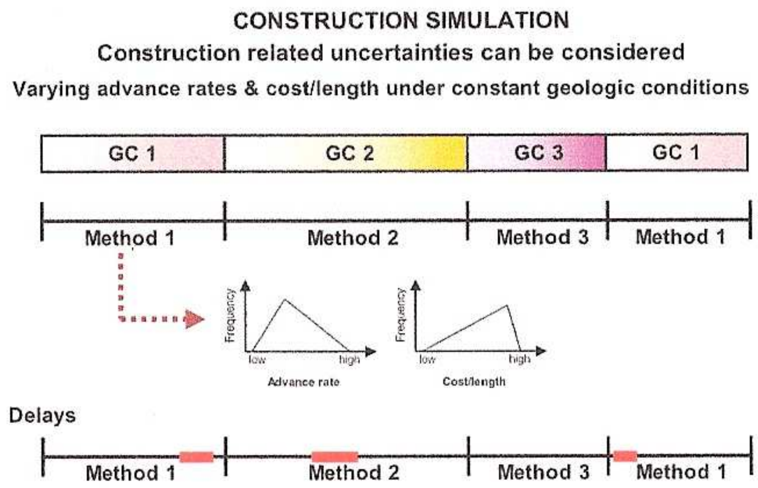
$$f = 1 + 3.1\left(\frac{\varepsilon}{h}\right)^{1.5}$$

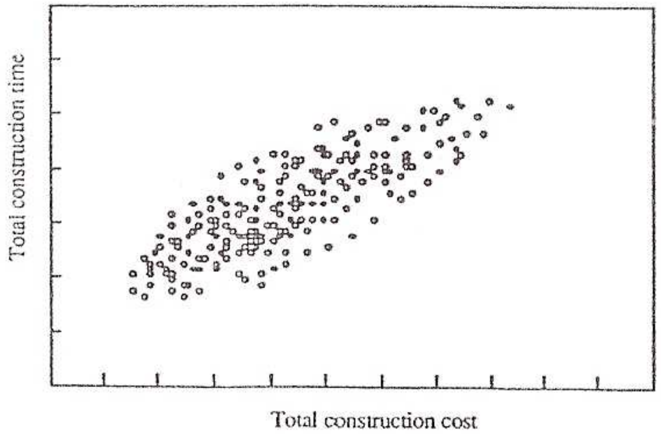
ε: fracture roughness
h : aperture



Existing Cost/Time Estimation Model

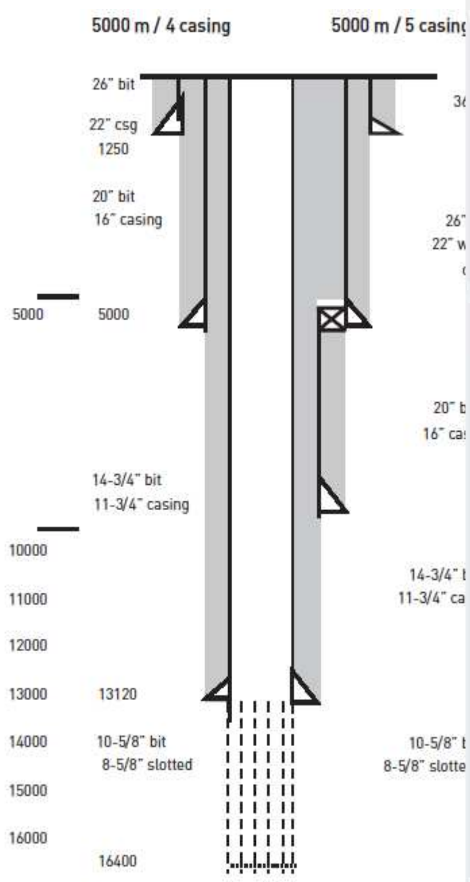




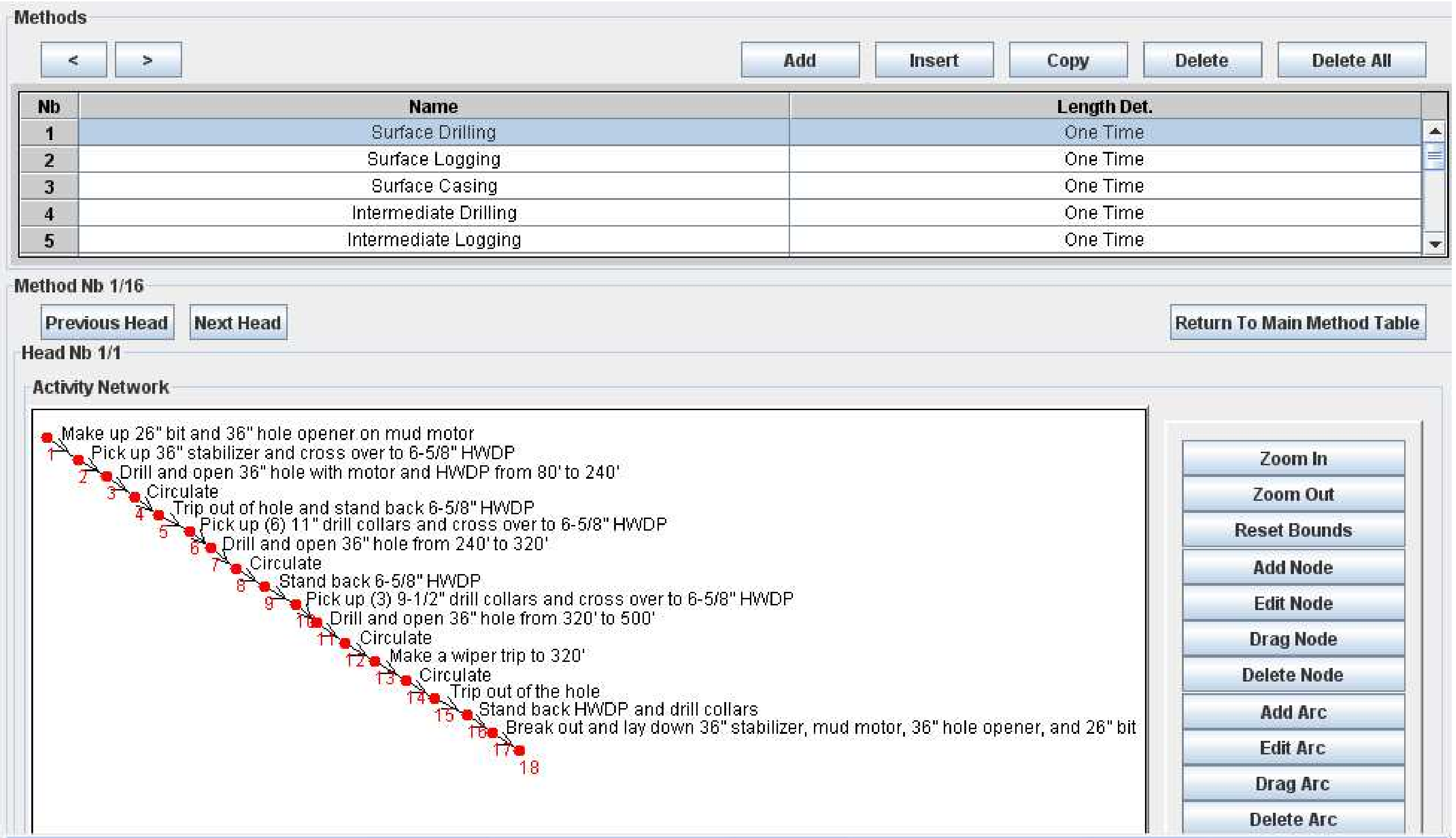


Drill Cost and Time Model

Prototypical well drawn from MIT Tester EGS Report

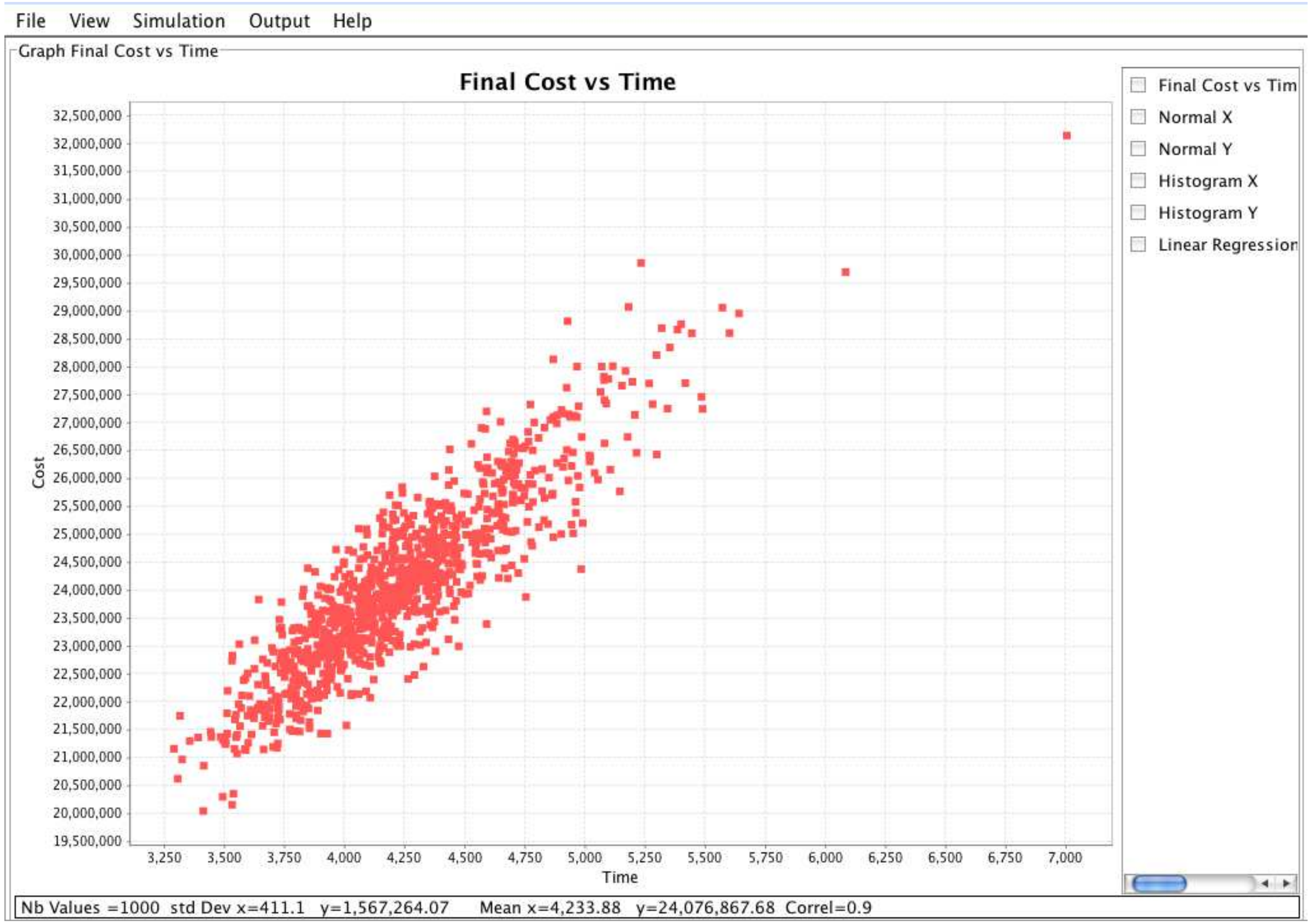


Snapshot of Drill Cost/Time Estimation model



Drilling Cost/Time Scattergram

(Dollars)



(hours)