8_1 Exploration and Characterization - Drilling

Recap:

1. Geophysics provides 3D view of the reservoir/site at high granularity
2. Uses only proxies for permeability and temperature - and no samples or p,T,x measurements
3. Geophysics low cost but only slightly reduces investment risk

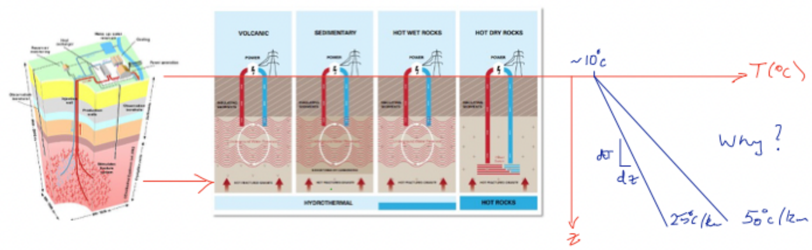
Movies: (GSHP Installation) https://www.youtube.com/watch?v=IMO9jvwlHFg

West Flank Coso: https://www.osti.gov/servlets/purl/1455367/

Resources: WG9

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
Therefore prospect for:
- (i) High Mass_rate/permeability/overpressure - define fast flow paths, and
- (ii) High T at shallow depth

Less crucial in "engineered" systems - "EGS" and "GSHP"

Scientific Questions:

2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

1. How do we locally define the reservoir and the distribution of:
   - A. Temperatures - as shallow as possible
   - B. Permeable pathways - as distributed as possible or high flow rates

   .... by direct access.....

DRILLING

1. Soil - Trenching/Augering/Tricone drilling
2. Rock - Tricone drilling/Core drilling

Table 1. Advantages and Disadvantages of Auger, Rotary, and Cable Tool Drilling

Type	Advantages	Disadvantages
Auger	• Minimal damage to aquifer • No drilling fluids required • Auger flights act as temporary casing, stabilizing hole for well construction • Good technique for unconsolidated deposits • Continuous core can be collected by wire-line method	• Cannot be used in consolidated deposits • Limited to wells less than 150 ft in depth • May have to abandon holes if boulders are encountered
Rotary	• Quick and efficient method • Excellent for large and small diameter holes • No depth limitations • Can be used in consolidated and unconsolidated deposits • Continuous core can be collected by wire-line method	• Requires drilling fluids, which alter water chemistry • Results in a mud cake on the borehole wall, requiring additional well development, and potentially causing changes in chemistry • Loss of circulation can develop in fractured and high-permeability material • May have to abandon holes if boulders are encountered
Cable Tool	• No limitation on well depth • Limited amount of drilling fluid required • Can be used in both consolidated and unconsolidated deposits • Can be used in areas where lost circulation is a problem • Good lithologic control • Effective technique in boulder environments	• Limited rigs and experienced personnel available • Slow and inefficient • Dificult to collect core

Source: EPA (1989).

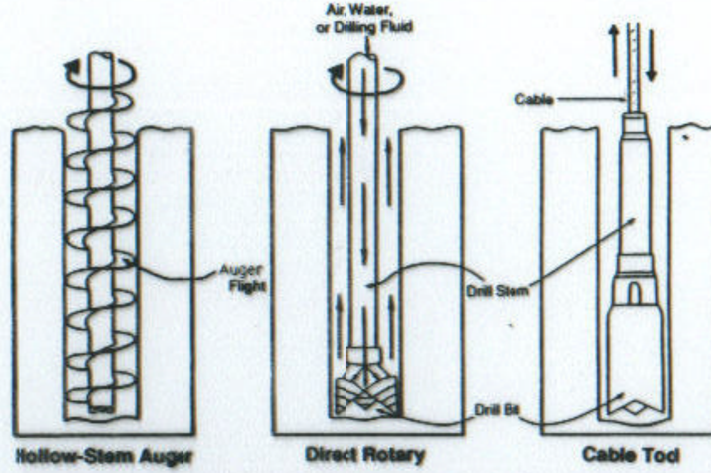


Figure 2. Illustration and advantages and disadvantages of auger, rotary, and cable tool drilling. *Source:* EPA (1989).

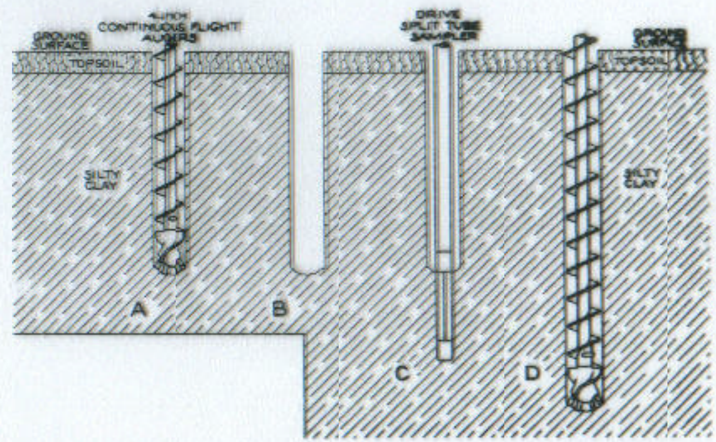


Figure 3. Continuous flight auger drilling. A. Advance auger to sampling interval; B. Remove flight augers; C. Advance split-spoon sampler; D. Advance auger to next sample interval. *Source:* University of Missouri, Rolla (1981).

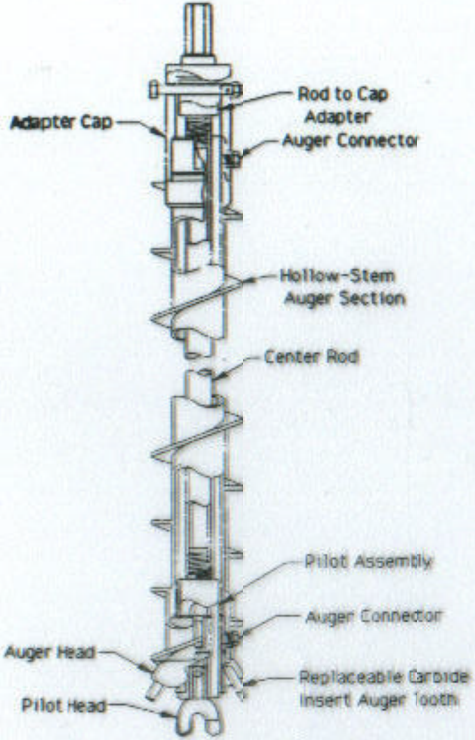


Figure 5. Components of a consolidated mining equipment hollow-stem auger. *Source:* University of Missouri, Rolla (1981).

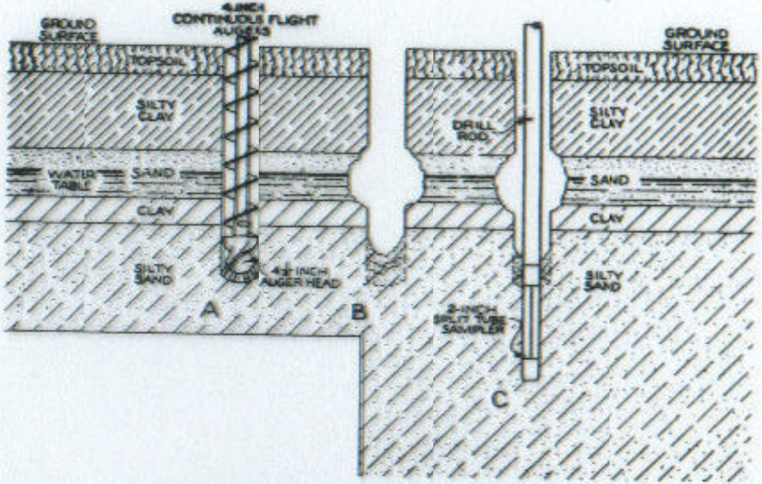


Figure 4. Continuous flight auger drilling though caving material. A. Auger to sample interval; B. Saturated sand stratum flows causing borehole to "bell"; C. Sampler must advance through sand "flow" slough to sample in-place silty sand. *Source:* University of Missouri, Rolla (1981).

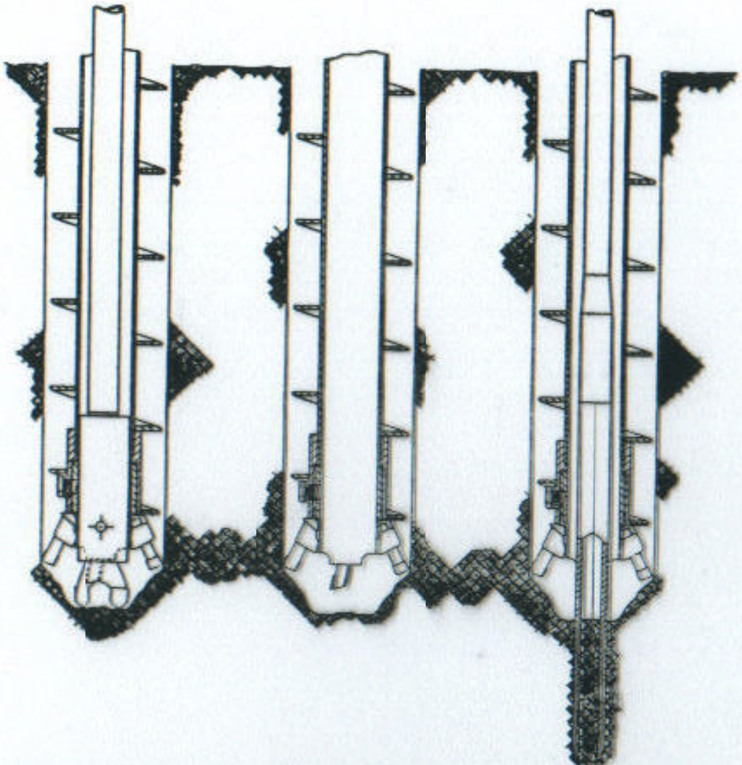


Figure 6. Driving a soil sampler through the hollow-stem auger. *Source:* University of Missouri, Rolla (1981).

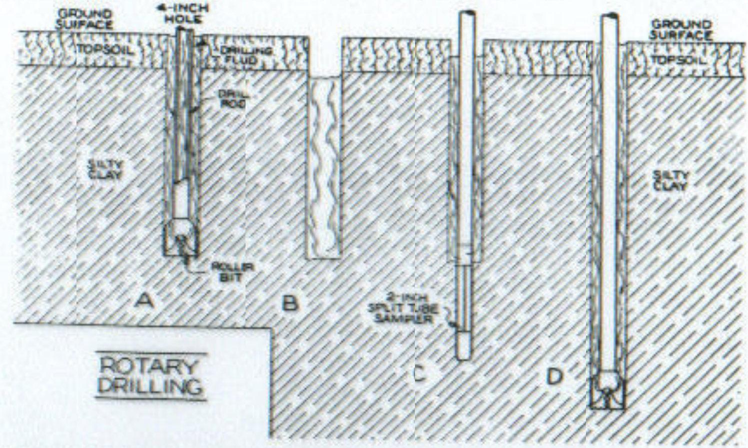


Figure 7. Rotary drilling. A. Mud rotary drilling advance to sampler interval; B. Drilling mud holds borehole walls up; C. Split-spoon sampler advanced; D. New drill rod attached and borehole advanced. *Source:* University of Missouri, Rolla (1981).

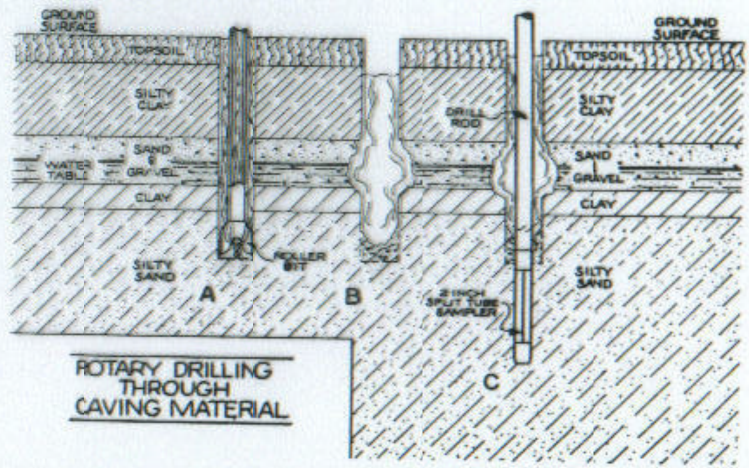
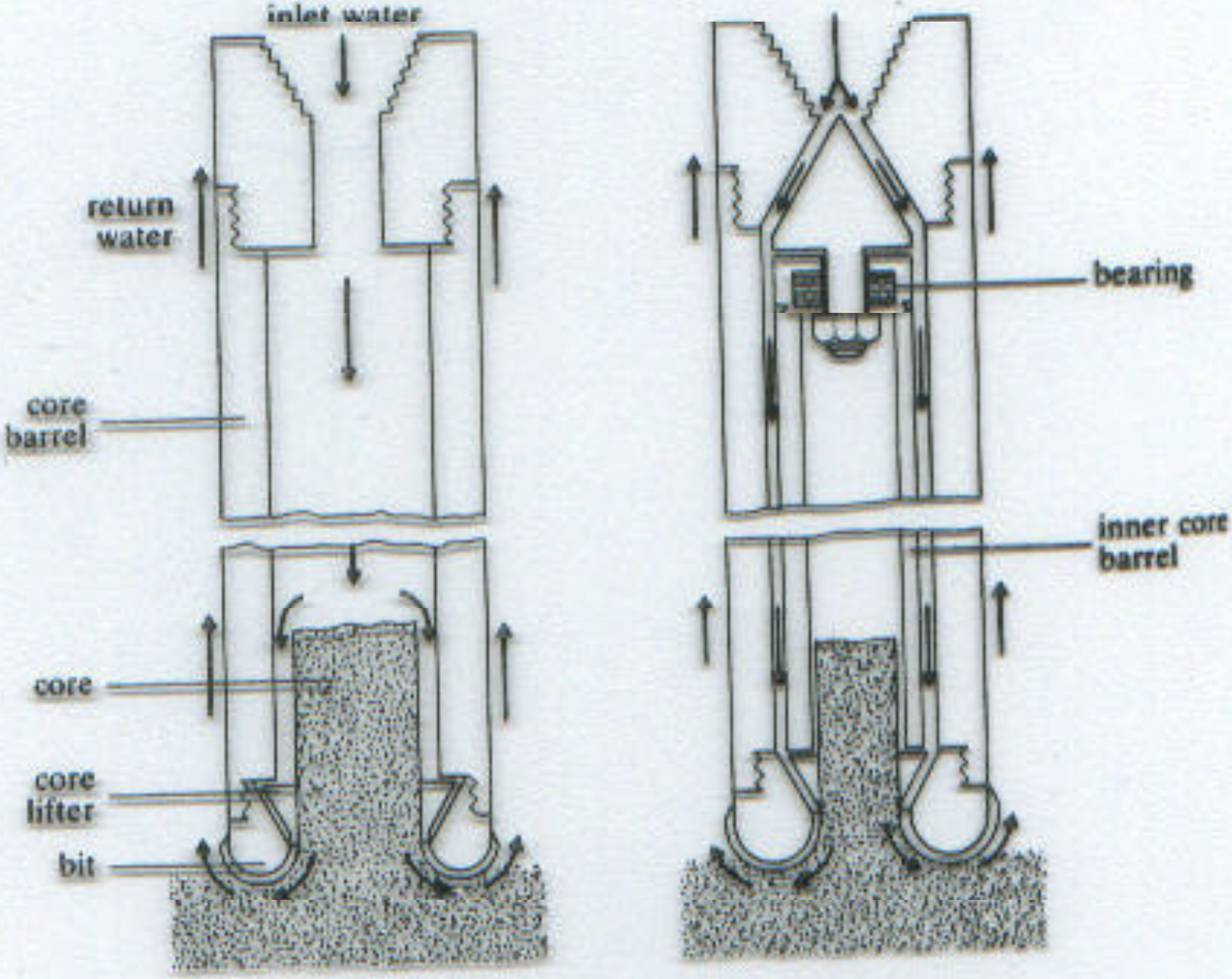


Figure 8. Rotary drilling through caving material. A. Rotary drilling advances borehole to below water table; B. Drilling mud holes borehole walls open to minimize "flow" and caving; C. Split spoon advanced at desired sample depth. *Source:* Unversity of Missouri, Rolla (1981).



inlet water
return water
core barrel
core
core lifter
bit
bearing
inner core barrel

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
HAND AUGERS – A hand auger is advanced by turning it into the soil until the bucket or screw is filled. The auger is then removed from the hole. The sample is dislodged from the auger, and drilling continues. Motorized units are also available.	• Shallow soil investigations (0 to 15 ft) • Soil samples collected from the auger cutting edge • Water-bearing zone identification • Contamination presence examination; sample analysis • Shallow, small diameter well installation • Experienced user can identify stratigraphic interfaces by penetration resistance differences as well as sample inspection • Highly mobile, and can be used in confined spaces • Various types (i.e., bucket, screw, etc.) and sizes (typically 1 to 9 inches in diameter) • Inexpensive to purchase	• Limited to very shallow depths (typically < 15 ft) • Unable to penetrate extremely dense or rocky or gravelly soil • Borehole stability may be difficult to maintain, particularly beneath the water table • Potential for vertical cross-contamination • Labor intensive
SOLID-FLIGHT AUGERS – A cutter head (≥ 2-inch diameter) is attached to multiple auger flights. As the augers are rotated by a rotary drive head and forced down by either a hydraulic pulldown or a feed device, cuttings are rotated up to ground surface by moving along the continuous flighting.	• Shallow soils investigations (< 100 ft) • Soil samples are collected from the auger flights or using split-spoon or thin-walled samplers if the hole will not cave upon retrieval of the augers • Vadose zone monitoring wells • Monitor wells in saturated, stable soils • Identification of depth to bedrock • Fast and mobile; can be used with small rigs • Holes up to 3-ft diameter • No fluids required • Simple to decontaminate	• Low-quality soil samples unless split-spoon or thin-wall samples are taken • Soil sample data limited to areas and depths where stable soils are predominant • Unable to install monitor wells in most unconsolidated aquifers because of borehole caving upon auger removal • Difficult penetration in loose boulders, cobbles, and other material that might lock up auger • Monitor well diameter limited by auger diameter • Cannot penetrate consolidated materials • Potential for vertical cross-contamination
HOLLOW-STEM AUGERS – Hollow-stem augering is done in a similar manner to solid-flight augering. Small-diameter drill rods and samplers can be lowered through the hollow augers for sampling. If necessary, sediment within the hollow stem can be cleaned out prior to inserting a sampler. Wells can be completed below the water table using the augers as temporary casing.	• All types of soil investigations to <100 ft below ground • Permits high-quality soil sampling with split-spoon or thin-wall samplers • Water-quality sampling • Monitor well installation in all unconsolidated formation • Can serve as a temporary casing for coring rock • Can be used in stable formations to set surface casing • Can be used with small rigs in confined spaces • Does not require drilling fluids	• Difficulty in preserving sample integrity in heaving (running sand) formations • If water or drilling mud is used to control heaving will invade the formation • Potential for cross-contamination of aquifers where annular space not positively controlled by water or drilling mud or surface casing • Limited auger diameter limits casing size (typical augers are: 6¼-in OD with 3¼-in ID, and 12-in OD with 6-in ID) • Smearing of clays may seal off interval to be monitored

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METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
DIRECT MUD ROTARY – Drilling fluid is pumped down the drill rods and through a bit attached to the bottom of the rods. The fluid circulates up the annular space bringing cuttings to the surface. At the surface, drilling fluid and cuttings are discharged into a baffled sedimentation tank, pond, or pit. The tank effluent overflows into a suction pit where drilling fluid is recirculated back through the drill rods. The drill stem is rotated at the surface by top head or rotary table drives and down pressure is provided by pull-down devices or drill collars.	• Rapid drilling of clay, silt, and reasonably compacted sand and gravel to great depth (>700 ft) • Allows split-spoon and thin-wall sampling in unconsolidated materials • Allows drilling and core-sampling in consolidated rock • Abundant and flexible range of tool sizes and depth capabilities • Sophisticated drilling and mud programs available • Geophysical borehole logs	• Difficult to remove drilling mud and wall cake from outer perimeter of filter pack during development • Bentonite or other drilling fluid additives may influence quality of ground-water samples • Potential for vertical cross-contamination • Circulated cutting samples are of poor quality; difficult to determine sample depth • Split-spoon and thin-wall samplers are expensive and of questionable cost effectiveness at depths > 150 ft • Wireline coring techniques for sampling both unconsolidated and consolidated formations often not available locally • Drilling fluid invasion of permeable zones may compromise integrity of subsequent monitor well samples • Difficult to decontaminate pumps
AIR ROTARY – Air rotary drilling is similar to mud rotary drilling except that air is the circulation medium. Compressed air injected through the drill rods circulates cuttings and groundwater up the annulus to the surface. Typically, rotary drill bits are used in sedimentary rocks and down-hole hammer bits are used in harder igneous and metamorphic rocks. Monitor wells can be completed as open hole intervals beneath telescoped casings.	• Rapid drilling of semi-consolidated and consolidated rock to great depth (>700 ft) • Good quality/reliable formation samples (particularly if small quantities of drilling fluid are used) because casing prevents mixture of cuttings from bottom of hole with collapsed material from above • Allows for core-sampling of rock • Equipment generally available • Allows easy and quick identification of lithologic changes • Allows identification of most water-bearing zones • Allows estimation of yields in strong water-producing zones with short "down time"	• Surface casing frequently required to protect top of hole from caving • Drilling restricted to semi-consolidated and consolidated formations • Samples reliable, but occur as small chips that may be difficult to interpret • Drying effect of air may mask lower yield water producing zones • Air stream requires contaminant filtration • Air may modify chemical or biological conditions; recovery time is uncertain • Potential for vertical cross-contamination • Potential exists for hydrocarbon contamination from air compressor or down-hole hammer bit oils
AIR ROTARY WITH CASING DRIVER – This method uses a casing driver to allow air rotary drilling through unstable unconsolidated materials. Typically, the drill bit is extended 6 to 12 inches ahead of the casing, the casing is driven down, and then the drill bit is used to clean material from within the casing.	• Rapid drilling of unconsolidated sands, silts, and clays • Drilling in alluvial material (including boulder formations) • Casing supports borehole, thereby maintaining borehole integrity and reducing potential for vertical cross-contamination • Eliminates circulation problems common with direct mud rotary method • Good formation samples because casing (outer wall) prevents mixture of caving materials with cuttings from bottom of hole • Minimal formation damage as casing pulled back (smearing of silts and clays can be anticipated)	• Thin, low pressure water-bearing zones easily overlooked if drilling not stopped at appropriate places to observe whether or not water levels are recovering • Samples pulverized as in all rotary drilling • Air may modify chemical or biological conditions; recovery time is uncertain

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
DUAL-WALL REVERSE ROTARY – Circulating fluid (air or water) is injected through the annulus between the outer casing and drill pipe, flows into the drill pipe through the bit, and carries cuttings to the surface through the drill pipe. Similar to rotary drilling with the casing driver, the outer pipe stabilizes the borehole and reduces cross-contamination of fluids and cuttings. Various bits can be used with this method.	• Very rapid drilling through both unconsolidated and consolidated formations • Allows continuous sampling in all types of formations • Very good representative samples can be obtained with reduced risk of contamination of sample and/or water-bearing zone • Allows for rock coring • In stable formations, wells with diameters as large as 6 inches can be installed in open hole completions	• Limited borehole size that limits diameter of monitor wells • In unstable formations, well diameters are limited to approximately 4 inches • Equipment available more common in the southwest U.S. than elsewhere • Air may modify chemical or biological conditions; recovery time is uncertain • Unable to install filter pack unless completed open hole
CABLE TOOL DRILLING – A drill bit is attached to the bottom of a weighted drill stem that is attached to a cable. The cable and drill stem are suspended from the drill rig mast. The bit is alternatively raised and lowered into the formation. Cuttings are periodically removed using a bailer. Casing must be added as drilling proceeds through unstable formations.	• Drilling in all types of geologic formations • Almost any depth and diameter range • Ease of monitor well installation • Ease and practicality of well development • Excellent samples of coarse-grained media can be obtained • Potential for vertical cross-contamination is reduced because casing is advanced with boring • Simple equipment and operation	• Drilling is slow, and frequently not cost-effective as a result • Heaving of unconsolidated materials must be controlled • Equipment availability more common in central, north central, and northeast sections of the U.S.
ROCK CORING – A carbide or diamond-tipped bit is attached to the bottom of a hollow core barrel. As the bit cuts deeper, the rock sample moves up into the core tube. With a double-wall core barrel, drilling fluid circulates between the two walls and does not contact the core, allowing better recovery. Clean water is usually the drilling fluid. Standard core tubes are attached to the bottom of a drill rod and the entire string of rods must be removed after each core run. With wireline coring, an inner core barrel is withdrawn through the drill string using an overshot device that is lowered on a wireline into the drill string.	• Provides high-quality, undisturbed core samples of stiff to hard clays and rock • Holes can be drilled at any angle • Can detect location and nature of rock fractures • Can use core holes to run a complete suite of geophysical logs • Variety of core sizes available • Core holes can be utilized for hydraulic tests and monitor well completion • Can be adapted to a variety of drill rig types and operations	• Relatively expensive and slow rate of penetration • Can lose a large quantity of drilling water into permeable formations • Potential for vertical cross-contamination

Table 9-3. Drilling methods, applications, and limitations (modified from Aller et al., 1989; GRI, 1987; Rehm et al., 1985; USEPA, 1987).

METHOD	APPLICATIONS/ADVANTAGES	LIMITATIONS
CONE PENETROMETER -- Hydraulic rams are used to push a narrow rod (e.g., 1.5-inch diameter) with a conical point into the ground at a steady rate. Electronic sensors attached to the test probe measure tip penetration resistance, probe side resistance, inclination and pore pressure. Sensors have also been developed to measure subsurface electrical conductivity, radioactivity, and optical properties (fluorescence and reflectance). Cone penetrometer tests (CPT) are generally performed using a special rig and a computerized data collection, analysis, and display system. To facilitate interpretation of CPT data from numerous tests, CPT data from at least one test per site should be compared to a log of continuously sampled soil at an adjacent location. References: Robertson and Campanella (1986), Lark et al. (1990), Smolley and Kappmeyer (1991), Christy and Spradlin (1992), Edge and Cordry (1989), and, Chiang et al. (1992).	• Efficient tool for stratigraphic logging of soft soils • Measurement of some soil/fluid properties (e.g., tip penetration resistance, probe side friction, pore pressure, electrical conductivity, radioactivity, fluorescence), with proper instrumentation, can be obtained continuously rather than at intervals; thus improving the detectability of thin layers (i.e., subtle DNAPL capillary barriers) and contaminants • There are virtually no cuttings brought to the ground surface, thus eliminating the need to handle cuttings • Process presents a reduced potential for vertical cross-contamination if the openings are sealed with grout from the bottom up upon rod removal • Porous probe samplers can be used to collect groundwater samples with minimal loss of volatile compounds • Soil gas sampling can be conducted • Fluid sampling from discrete intervals can be conducted using special tools (e.g., the Hydropunch™ manufactured by Q.E.D. Environmental Systems of Ann Arbor, Michigan)	• Unable to penetrate dense geologic conditions (i.e., hard clays, boulders, etc.) • Limited depth capability (depends on • Soil samples cannot be collected for examination or chemical analyses, unless special equipment is utilized • Only very limited quantities of groundwater can be sampled • Limited well construction capability • Limited availability

Table 1. Well-Drilling Selection Guide

Drilling Method	Drilling Fluid	Casing Advance	Type of Material Drilled	Nominal Drilling Depth, in ft 1_/	Nominal Range of Borehole Sizes, in in.	Samples Obtainable 2_/	Coring Possible	Reference Section
Power Auger (Hollow Stem)	None, Water, Mud	Yes	Soil, Weathered rock	<150	5 - 22	S, F	Yes	6.2
Power Auger (Solid Stem)	Water, Mud	No	Soil, Weathered Rock	<150	2-10	s	Yes	6.3
Power Bucket Auger	None, Water (below water table	No	Soil, Weathered rock	<150	18 -48	S	Yes	6.4
Hand Auger	None	No	Soil	<70 (Above Water Table Only)	2 - 6	S	Yes	6.5
Direct Fluid Rotary	Water, Mud	Yes	Soil, Rock	>1000	2 - 36	S, R	Yes	7.3
Direct Air Rotary	Air, Water, Foam	Yes	Soil, Rock	>1500	2 - 36	S, R, F	Yes	7.4
DTH Hammer	Air, Water, Foam	Yes	Rock, Boulders	<2000	4 - 16	R	Yes	7.5.1
Wireline	Air, Water, Foam	Yes	Soil, Rock	>1000	3-6	S, R, F	Yes	7.6
Reverse Fluid Rotary	Water, Mud	Yes	Soil, Rock	<2000	12 - 36	S, R, F	Yes	7.8
Reverse Air Rotary	Air, Water, Foam	Yes	Soil, Rock	>1000	12 - 36	S, R, F	Yes	7.7
Cable Tool	Water	Yes	Soil, Rock	<5000	6-8	S, R, F (F- Below Water Table)	Yes	8
Casing-Advancer	Air, Water, Mud	Yes	Soil, Rock, Boulders	<2000	2 -16	S, R, F	Yes	9
Direct-Push Technology	None	Yes	Soil	<100	1.5 - 3	F	Yes	10
Sonic (Vibratory)	None, Water, Mud, Air	Yes	Soil, Rock, Boulders	<500	4 -12	S, R, F	Yes	11
Jet Percussion	Water	No	Soil	<50	2 - 4	S	No	12
Jetting	Water	Yes	Soil	<50	4	S	No	12

1/ Actual achievable drilled depths will vary depending on the ambient geohydrologic conditions existing at the site and size of drilling equipment used. For example, large, high-torque rigs can drill to greater depths than their smaller counterparts under favorable site conditions. Boreholes drilled using air/air foam can reach greater depths more efficiently using two-stage positive-displacement compressors having the capability of developing working pressures of 250 to 350 psi and 500 to 750 cfm (particularly when submergence requires higher pressures). The smaller rotary-type compressors are only capable of producing a maximum working pressure of 125 psi. and produce 500 to 1200 cfm. Likewise, the rig mast must be constructed to safely carry the anticipated working loads expected. To allow for contigencies, it is recommended that the rated capacity of the mast be at least twice the anticipated weight load or normal pulling load. 2/ Soil = S (Cuttings), Rock = R (Cuttings), Fluid = F (Some samples might require accessory sampling devices to obtain.)

ARMA-AAPG-SEDHEAT WORKSHOP

June 24 – 25, 2016

Drilling Challenges in Geothermal Reservoirs

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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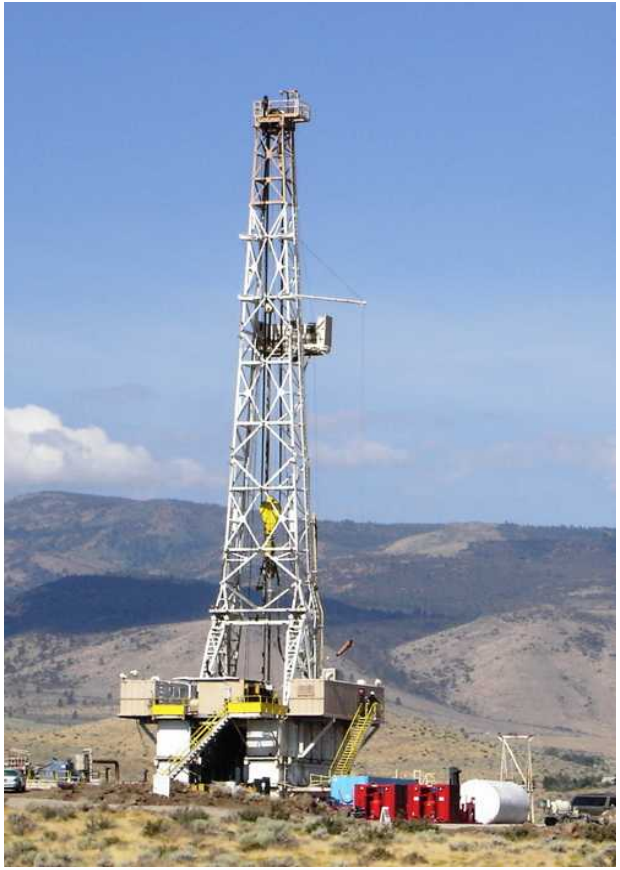
History

- First Oil Well in US – Drake's 1859

- First Geothermal Projects
  - Larderallo, Italy 1913
    - 250 kw, expanded in 1935
    - Sold electricity to the electric railway system
  - Geysers, USA 1921
    - 250 kw, just for use at the Geysers Resort
    - Commercially developed in 1962, PG&E sold into grid system
  - Wairakei, New Zealand 1958

Relative Size by Active Rig Count

- Oil and Gas Rigs Worldwide 1,448*
  - USA 424
  - Canada 69
  - International 955
- Geothermal Rigs Worldwide ~15-20



* From Baker Hughes Rotary Rig Count, June 2016

Geothermal Drilling vs O&G

- Hot
  - By definition
- Often
  - High matrix strength
  - Abrasive
  - Fractured
  - Underpressurized formations
  - Corrosive fluids
- Larger diameters
  - 12 ¼" dia. bottom-hole common

Drilling Costs can Exceed 50% of a Developer's Capital Investment

Different Purposes For Wells

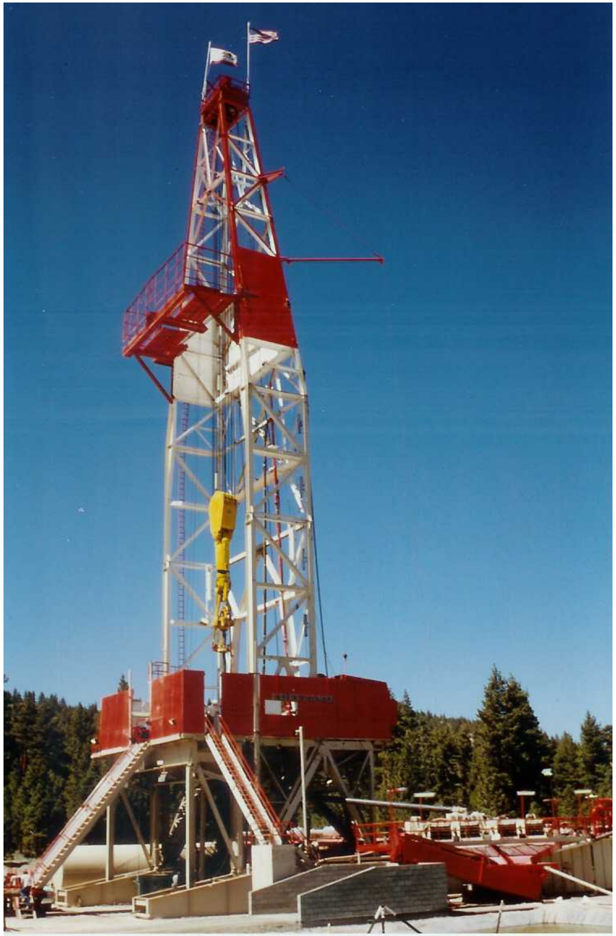
- Gradient Holes
- Test or Exploration Wells
  - Core Holes
  - Slim Holes
- Production Wells
- Injection Wells

Different Drilling Processes

- Cable Tool/Auger
- Continuous Coring
- Rotary
  - Mud
  - Air, Mist, Foam

Basic Components of the Drilling System

- Bits
- Drilling Fluids
- BOP
- Casing
- Cement



Bits in Geothermal

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- Used to extend the hole
  - Roller / Drag Bits (e.g., PDCs) /Hammers/Diamond Impregnated
- Roller bits most common in geothermal drilling
  - “Old” technology – Source of Howard Hughes fortune (Hughes Tool Company founded in 1909 by dad)
  - Durable in hard fractured formations but slow and inefficient rock reduction tool
  - Significant research over past couple decades (bearings, cutting structure, …) but footage/day remains low in geothermal.
- Bits are part of the bottom-hole-assembly
  - Collars / stabilizers / reamers/ jars / …

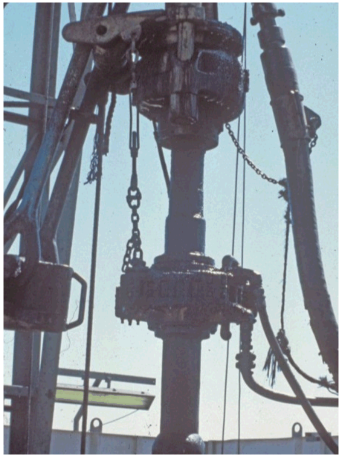
Rock Reduction in Broader Industry

- Polycrystalline diamond compact (PDC)
  - ~2/3 of world footage drilled with PDC's and all high $$$ O&G wells
  - Efficient, high performance tools
  - Viable for geothermal with recent advances
- Percussive hammers (air)
  - Extensive use in mining industry
  - Efficient, robust tool for hard rock limitations have been addressed
- High speed motors / turbines with impregnated diamond bits
  - Excellent results in O&G in drilling high strength rock

Rock reduction systems used in other industries can be applied to geothermal drilling to substantively improve daily drilling rates

Drilling Fluids

- A circulation system (fluid/pumps/cleaning)
  - Clean the hole of cuttings
  - Cool and clean the bit
  - Wellbore stability
  - Lubricate the drill string
  - Form filter cake
  - Well Control



Drilling Fluids in Geothermal

- Water-based muds
  - Bentonite primary viscosifier, polymers used but degrade at HT
  - Water uptake in solids greater at high temperatures, cleaning important
  - Mud coolers often used
- Air/Foam/Mist drilling common in geothermal
  - Prevents fouling of fractures
  - Probably not a big issues with EGS
- Clean water
  - Used with high lost circulation and drilling without returns

Blow Out Prevention Equipment – Well Control

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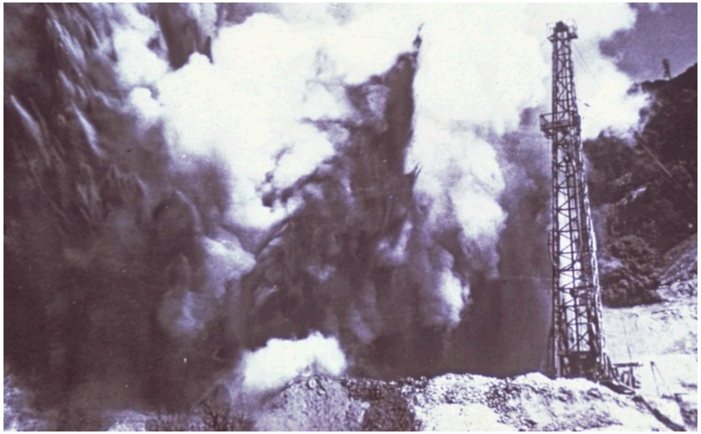
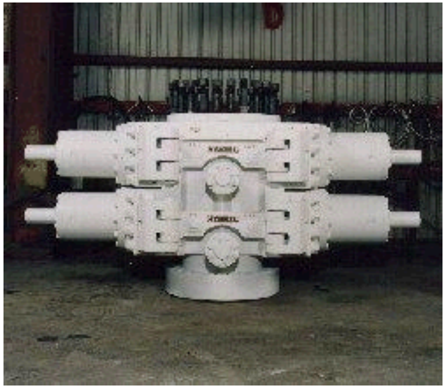
Blowout prevention equipment (BOPE) in geothermal drilling is necessary





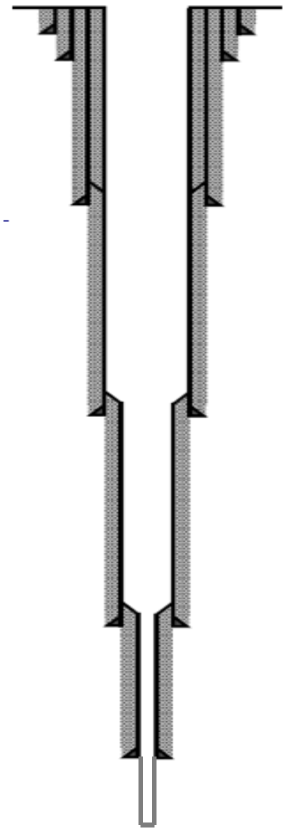
Blow Out Prevention in Geothermal

- BOPE is used to control "kicks" and potential outflow
  - Different components (rotating head, annual preventer, pipe rams, blind rams, shear rams)
  - Deepwater Horizon demonstrated why they are not called blow out stoppers
- Protects against unexpected steam or gas flow
  - Circulating hot water to surface which can flash
    - Higher temperatures or pressures than expected
  - Loss of drilling fluid in the well can result in flashing
    - Lost Circulation
- Some air drilled wells are advanced while producing

Mud is the first line of defense; BOPE and cemented casing are the second.

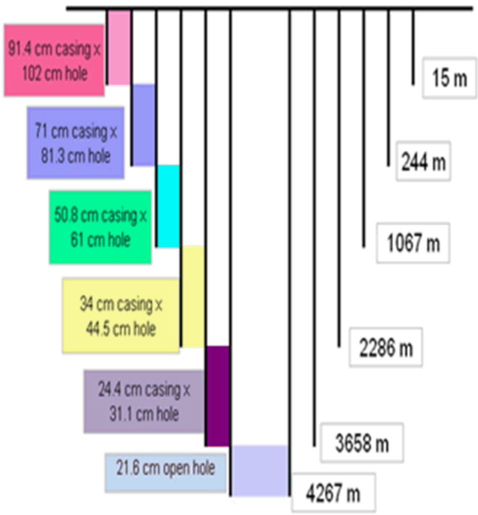
Casing and Cement

- Driven by Well Design
  - Well design is a bottom up process
- Casing and Cement
  - Provides aquifer protection
  - Part of the well control system
  - Isolates troublesome formations
  - Can define production zones
  - Provides fluid pressure control
- Geothermal casing is cemented to surface
  - Eliminates trapped water
  - Restrains unacceptable growth



Cement and Casing

- Casing and Cement need to
  - Retain strength at high temp.
  - Withstand corrosive fluids
- Cementing to surface often problematic
  - Inside out common
  - Outside in being used (reverse circulation)
- Geothermal specific cements have been developed by DOE
  - e.g., “ThermaLock”

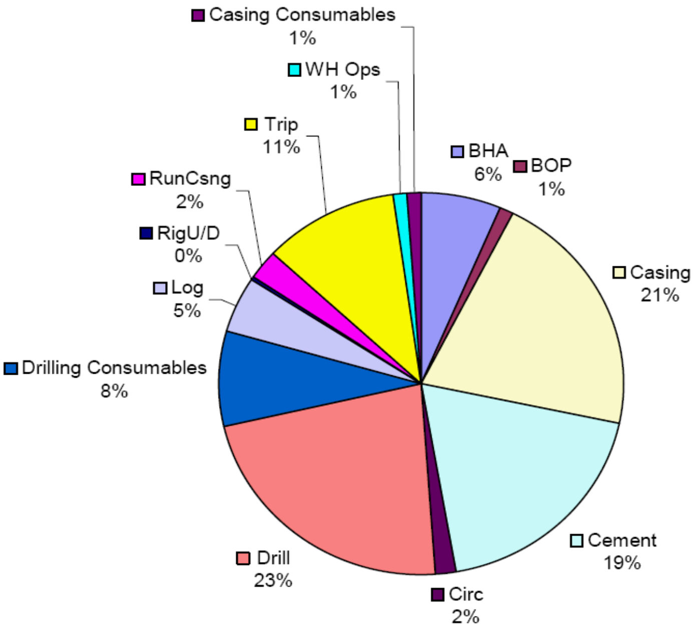


So what are Well Cost Drivers?

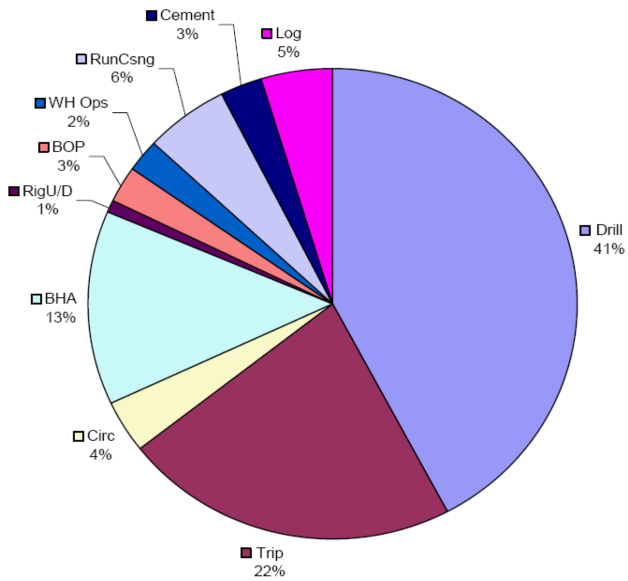
- An exercise
  - 6 km (20,000 ft) well
  - Analytical flow calculations performed to determine wells ability to meet MIT report recommended flow rates (80 kg/s @200 °C, 5 MWe)
  - ThermaSource Inc. performed “drilling on paper” exercise describing operational steps, tools, materials and costs
  - Drilling script provided by ThermaSource is subsequent basis for well construction analysis

SAND2008-7866 (2008)

EGS Well Construction Costs



Well cost (%) breakdown by task.



Well construction task time percentages.

Phase	Drill	Trip	Circ	Drilling Consumabl	BOP	BHA	Casing	RunCsng	Casing Consumables	Cement	WH Ops	Log	RigU/D	Grand Total	Cost/ft
1 Surface	$109,728	$36,070	$6,278	$193,155	$81,620	$148,916	$170,000	$31,392		$258,171	$43,949	$130,813	$24,183	$1,234,276	$2,469
2 INT-1	$987,550	$203,561	$14,116	$582,450	$62,785	$153,840	$950,000	$94,177		$1,258,078	$75,341	$165,691	$12,557	$4,560,146	$912
3 PROD-1	$909,173	$309,909	$34,045	$354,380	$0	$291,501	$1,123,200	$94,177		$758,349		$200,569	$12,557	$4,087,861	$818
4 PROD-2	$1,786,996	$768,065	$132,817	$352,590	$0	$252,146	$705,600	$125,569		$577,114		$241,261	$6,278	$4,948,436	$707
5 PROD-3	$852,750	$833,203	$155,906	$185,492	$0	$264,786	$217,600	$125,569		$368,342		$270,326	$6,278	$3,280,253	$1,093
6 PL1-TB	$6,278	$100,455	$12,557		$81,620	$213,468	$1,128,000	$43,949		$690,428	$69,063		$6,278	$2,352,097	
General									$255,000					$255,000	
Grand Total	$4,652,477	$2,251,263	$355,720	$1,668,067	$226,024	$1,324,657	$4,294,400	$514,834	$255,000	$3,910,481	$188,354	$1,008,660	$68,132	$20,718,069	

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Well Cost Exercise

- Results consistent with proprietary drilling records
- Drilling, casing and cementing costs are obvious
- Other costs such as tripping and BHA handling are not trivial
- Task and consumable cost structure changes with depth and design
- Relative impact of new technologies and methods will be dependent on well specification
- Non-hole making tasks are significant cost drivers
  - Tripping and BHA handling are not trivial contributors

There is no economic silver bullet! Reducing well construction cost will require multiple focus areas

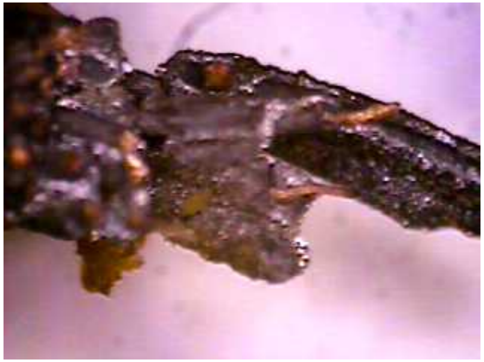
Geothermal in Sedimentary Systems

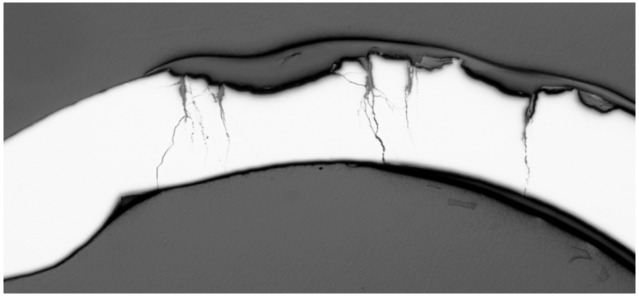
- Drilling will be closer to the O&G experience, but not the same.
  - Large diameter wells, High temperatures, Casing approaches, …
- Higher ROPS likely, but cost will be comparable
  - Many drivers on cost that are agnostic of application
  - Economic pressures will remain (leverage co-production?)
- Completion schemes will likely be different than "traditional" geothermal
  - Simple slotted liners may not be viable

High Temperature Challenges in Geothermal Drilling and Resource Exploration

High Temperature Failures

- A high temperature environment by itself can be a primary failure mode with electronic components, seals and circuit boards
- High temperature can also accelerate other failure modes
  - Intermetallic growth and voiding
  - Materials outgassing
  - Corrosion from wellbore fluids
  - Hydrogen darkening of optical fiber
  - Stress induced failures from CTE mismatch





Standard Open Hole Logging Tools

- Temperature, Pressure, Spinner (Flow)
- Spontaneous potential
- Resistivity (induction and laterolog)
- Gamma (total and U, K, Th spectrum)
- Gamma density (can include photoelectric factor)
- Sonic (porosity, stress estimate from dipole tool)
- Neutron porosity (can include formation sigma)
- NMR (pore size, porosity, permeability estimate)
- Borehole imagers (microresistivity and ultrasonic)

Other Logging/Monitoring Tools

- Cased Hole
  - Multi-arm caliper
  - Casing inspection (ultrasonic, EM and Hall effect imagers)
  - Cement Bond Log (sonic and ultrasonic)
- Seismic
  - Vertical seismic profile
- Fiber optic
  - Distributed temperature sensing (DTS)
  - Seismic

MWD/LWD

- Measurement While Drilling (MWD)
  - Pressure and temperate
  - Shock and vibration
  - Direction and inclination
  - RPM, weight on bit, torque on bit
  - Data is transmitted in real time (EM or mud pulse telemetry)

- Logging While Drilling (LWD)
  - Most of the open hole logging measurements
  - Measurements are stored for later download

Commercial HT Tools

- Most open hole logging tools are available in a HT versions up to 260°C
  - Dipole sonic tools, microresistivity imagers and NMR tools are the exception
  - Dewar heat shields are typically used above 177°C
  - Logging time can be between 4 and 12 hours

- MWD/LWD systems are typically limited to 180°C
  - Halliburton claims a 230°C system with directional, drill string dynamics, pressure and gamma information

Significant costs incurred if tools are run over their max temperature!

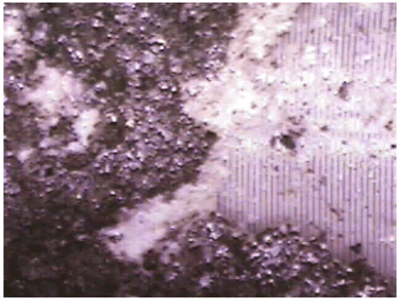
Electronics

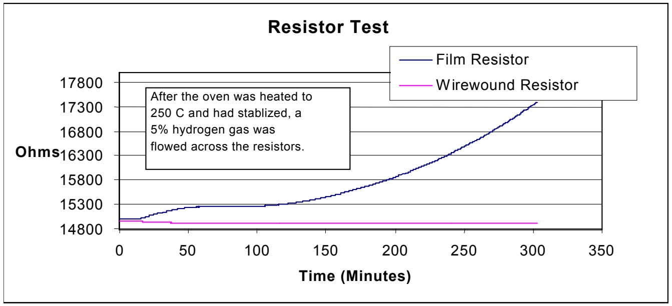
- Most commercial HT tools use automotive or MIL-SPEC components and heat shields
- High temperature SOI devices provide limited analog and digital capability up to 300°C
- SiC power devices and GaN RF devices offer additional functionality at temperatures exceeding 300°C
- Barriers to adoption
  - Cost
  - Component selection
  - Packaging
  - Everything else (solder, sensors, seals, cables…)

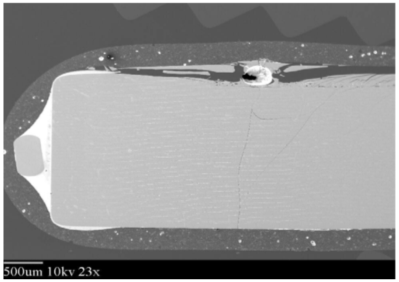
275°C Amplifier

Passive Components

- Wirewound resistors are typically used at high temperature
  - Become large as values increase
  - Coatings can degrade over time
- Metal film resistors can be susceptible to the downhole environment
- Only ceramic capacitors can be used above 225°C
  - Values are low for stable dielectrics
  - Fail shorted
- Currie Temperature becomes and issue for magnetic components as operating temperatures increase

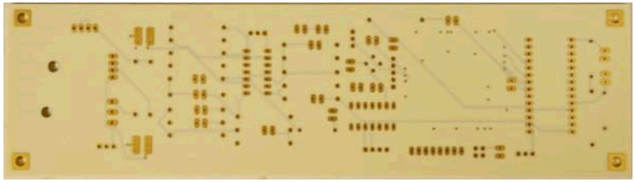






Packaging and Circuit Substrates

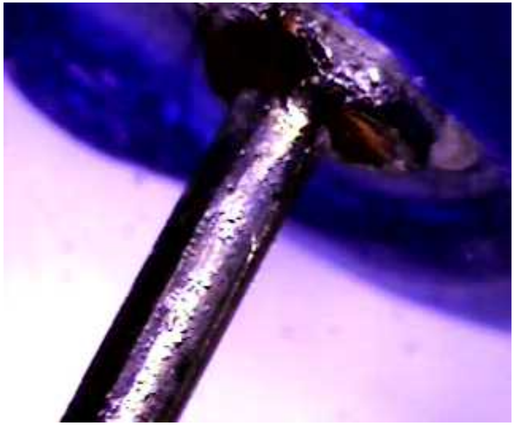
- Polyimide boards begin to fail above 250°C
- Ceramic boards show promise for applications above 300°C, but are difficult to manufacture for large aspect ratio boards (ex. 18” X 1”)
- Small multi-chip modules show promise for HT packaging
  - Die attach CTE mismatch must be solved for a wide range of systems
    - Die – Si, SiC, GaN
    - Substrate - Al_2O_3, AlN, Si_3N_4
  - Die bond pads must be matched to bond wire to avoid issues with intermetallic formation and Kirkendall voiding

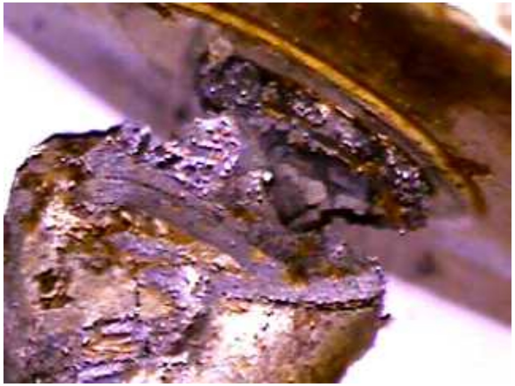


Hybrid Circuit in Metal Package (courtesy Quartzdyne, Salt Lake City, UT)

Solder and Wire

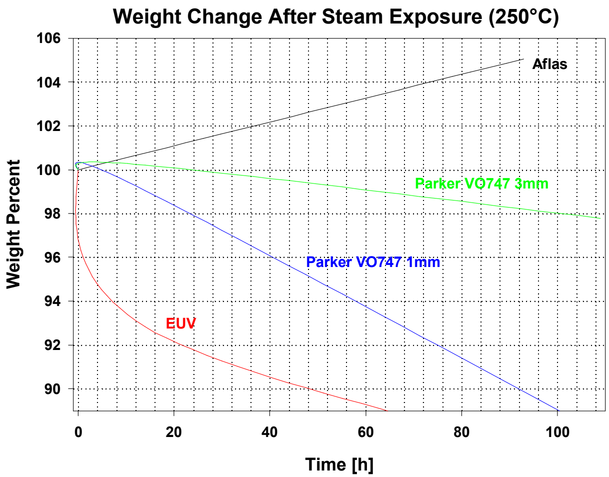
- Most HT solder alloys consist of high concentrations of Pb with either Sn or In
- High temperatures increase intermetallic growth rate
  - Cu-Sn, Au-Sn, Au-In
  - Leads to brittle failures and voiding
- AuSn solder can help, but is expensive and difficult to work with
- HT electronics assembly requires specialized tools





Seals and Insulation

- Polymers typically fail quickly in geothermal environments
  - Temperature, pressure, corrosive chemicals
- Seals are typically changed after a single HT logging run
- Insulation and encapsulants cannot be replaced easily
- Example materials:
  - Teflon
  - Kalrez
  - PEEK
  - Kapton



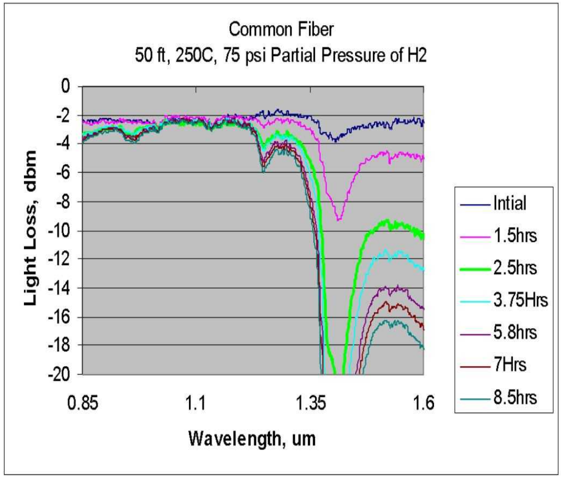
Sensors

- Pressure and temperature sensors are available up to 300°C
- Some accelerometers can function up to 275°C, but geophones are limited to ~200°C
- GM tubes and NaI crystals are limited to ~200°C
  - PM tubes available for 175°C
  - No commercial high temperature photodetectors

Widebandgap materials may provide a pathway to new high temperature sensor designs

Fiber Optics

- H_2 darkening is a major cause of fiber optic sensor failure in geothermal wells
- Fiber embrittlement is also an issue
- Pure silica core fiber and hermetic carbon coatings help at lower temps, but still fail at 300°C
- H_2 scavenging gels can be used, but also only buy a little more time



Special HT Considerations for MWD/LWD and Drilling Tools

- Downhole power for MWD/LWD systems is typically provided by mud driven generators and batteries
  - Batteries are not readily available between 200°C and 300°C
  - Supercapacitors may provide a solution
- Elastomeric seals in downhole motors begin to fail above 177°C
- Bearings in rollercone bits can fail at temperature
- Shock and vibration mitigation becomes difficult due to lack of reliable elastomers

Thoughts for Discussion

- Understand what kind of wells will be needed for EGS
  - Well construction, completion, reservoir construction and operations are all interrelated.
- Leverage technologies **and** practices employed by other industries.
  - What can be adopted or adapted to geothermal conditions
- Continue development of enabling technologies and known needs
  - Continue with the obvious

Thoughts - Understanding Needs

- Well field design
  - Number of wells (Injectors/producers)
  - Hole orientation
  - Extended reach directional drilling ("horizontal")
  - Multilaterals?
- Casing design
  - Cost reduction strategies
  - Identify tool/supply deficiencies
  - Optimize cementing practices
- Completions definition
  - What approach is needed to meet EGS needs and what is the state of the technology?
  - Should consider reservoir creation strategy, stimulation applications, production applications, intervention applications

Thoughts - Leveraging from Others

- Woo larger and similar industry service providers
  - O&G is obvious
  - Mining has similar mindset (lower margin)
- Adopt capabilities where possible
  - Active monitoring of drilling efficiency
  - Bit technologies
- Adapt to fit needs
  - Reverse circulation cementing
  - Expandable casing
- Look at wide bandgap development for power electronics, SSL and harsh environment sensing

Thoughts - Development Needs

Sandia National Laboratories

- Enabling Technologies
  - High temperature electronic components for logging and drilling tools
  - HT hard rock directional drilling tools
  - HT production and intervention tools
  - Improved telemetry (copper and fiber)
  - HT pumps
  - HT smart completions
  - HT H_2 tolerant fiber
- Known needs
  - Increase daily footage (not instantaneous ROP)
  - Leaner casing designs / new casing materials
  - Reduce tripping time
  - HT tools
  - Zonal Isolation

Application of Site Investigation to the West Flank of Coso FORGE Site

https://www.osti.gov/servlets/purl/1455367/