FROM HYDROTHERMAL TO ENHANCED GEOTHERMAL SYSTEMS

Geomechanical Considerations in Geothermal Drilling

John McLennan

University of Utah

Imperial Valley in the 1970s

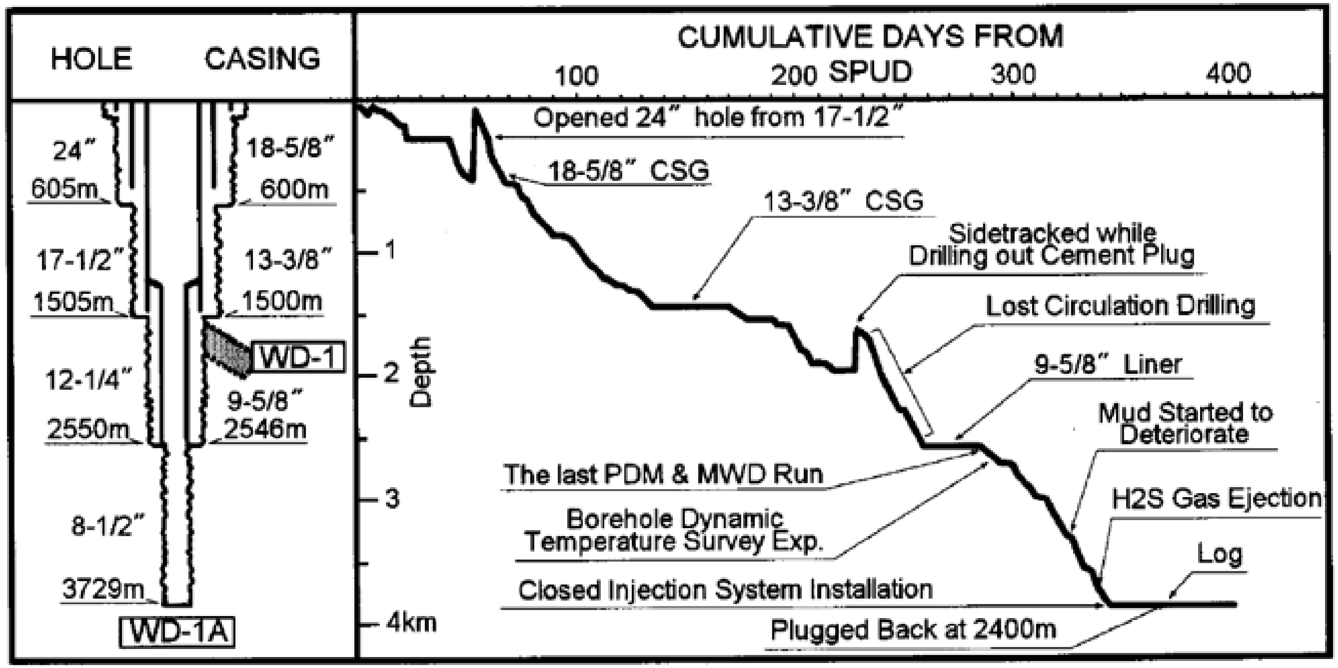
Problems Experienced

- Lost Circulation
- Hole enlargement
- Sloughing shale
- Excessive torque and drag
- Stuck pipe
- Surveying
- Difficulty in getting logging tools to bottom
- Difficulty in breaking circulation after trips

H.E. Zilch, H.E., Otto, M.J., and Pye, D.S. The Evolution of Geothermal Drilling Fluid in the Imperial Valley, SPE 21786.

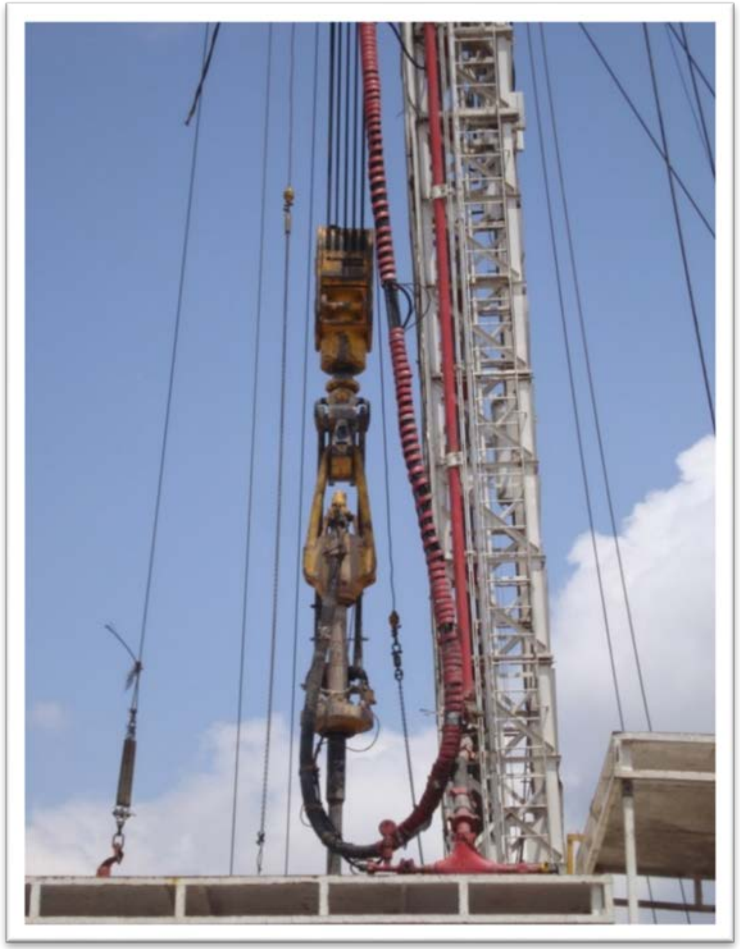
Kakkonda Well WD-1A (Japan)

- Eleven trajectory correction runs (last at 2600 m) at 350°F
- TD at 3729 m in July 1995
- Temperature of 500°C
- With cooling seals of tricone bits would survive (using top drive)
- Drilling mud degrade
- CO_2 produced, also H_2S



How Are Geothermal Operations Different?

- **Temperature:**
  - Average temperature greater (production intervals from 160°C to above 300°C)
- **Mechanical Characteristics:**
  - High strength (240+ MPa compressive strength), high modulus, abrasive (quartz often above 50%)
- **Natural Fractures:**
  - Highly fractured (centimeter)
- **Formation Fluids:**
  - Often contain corrosive fluids
  - Some have very high solids content[total dissolved solids (TDS) [in some Imperial Valley brines is above 250,000 ppm]



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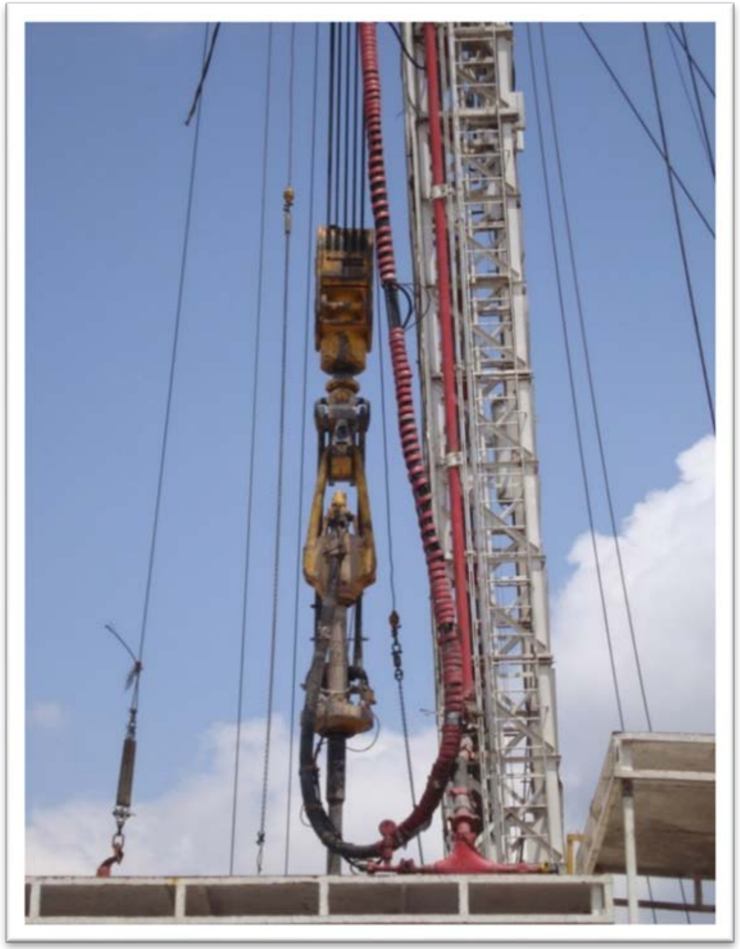
How Are Geothermal Operations Different?

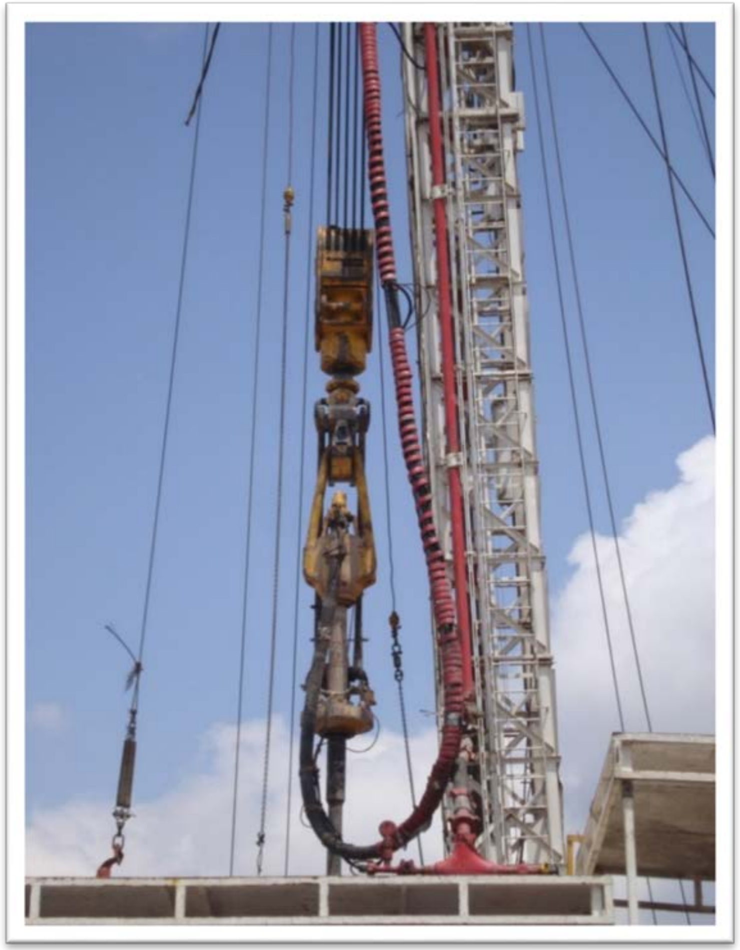
- Temperature
- Mechanical Characteristics
- Natural Fractures
- Formation Fluids
- High Production Rates Required
  - Large Diameter Casing
- May Need to Reach Significant TVD
  - Extensive and Hot Drilling and Completion
- Often Underpressured
  - Lost Circulation (Also Natural Fractures)



Well Cost Drivers

More expensive (cost/depth) than onshore oil and gas drilling:

1. Special tools and techniques required for harsh downhole conditions.
2. Large diameters: produced fluid (hot water or steam) intrinsically low energy density, large flow rates and large casing required.
3. May require more casing strings to achieve a given depth in a geothermal well
4. Uniqueness: even in same field, wells more different than oil and gas wells in same field, learning curve from experience is less useful



Temperature

Temperature

- Depth and temperature of geothermal resources vary considerably
- Several power plants, (e.g., Steamboat Hills, Nevada and Mammoth Lakes, California) operate on lower-temperature fluid (below 200°C) produced from depths of approximately 330 m
- The Geysers produce dry steam (above 240°C) and are typically 2,500 to 3,000 m deep.
- Extreme cases - exploratory well with a bottomhole temperature of 500°C at approximately 3,350 m in Japan
- Experimental holes into molten rock (above 980°C) in Hawaii and Iceland

Implications of High Temperature

- Reduce drill bit and drilling jar performance
- May preclude use of mud motors and directional MWD
- Adversely effects drilling fluid and cementing slurry properties
- Reduces performance of blow out prevention equipment
- Increases potential for reservoir fluid flashing to steam resulting in flowback or blowout from shallow depths

Temperature: Effects on Tools

- Temperature effects on downhole drilling tools and muds improved by refinement of seals and thermal expansion processes
- Fluid temperatures in excess of 190°C (370°F) may damage components such as seals and elastomeric insulators.
- Bit bearing seals, cable insulations, surface well control equipment, and sealing elements must be designed and manufactured with these temperatures in mind
- Geomechanical Considerations: Bit Performance and ROP

Temperature: Thermal Expansion of Casing

- Expansion:
  - Buckling and Casing Collapse
- Contraction:
  - Cooling In Injection Wells, or Thermal Cycling
  - Damage And Eventual Tensile Failure Of Casing. It
- Complete Cement Sheath on All Casing Strings:
  - Support and Stability
  - Shields Against Corrosion on Outside of Casing
  - Surface Expansion Spools
- Adequately Addressed for Wells Below 260°c (500°F).
- Above Operating Temperatures Of 260°c (500°F) …..
- Geomechanical Considerations: Stress, Cement, Cyclicity

Temperature: Drilling Fluid & Mud Coolers

- Surface "mud coolers": Commonly used to reduce temperature of drilling fluid before pumped back down hole.
- Regulations: Usually require mud coolers when return temperature exceeds 75°C (170°F).
- High drilling fluid temperatures in the well can cause drilling delays after a bit change. "Staging" back into well may be required to prevent bringing to surface fluid that may be above boiling temperature under atmospheric conditions
- Geomechanical Implications: Thermal Cycling and Generation of Thermal Stresses in Casing, Openhole and Effects at the Bit Face

Drilling Induced Fractures

Temperature Change

- **Time-Dependent**
- **Temperature perturbation propagates into formation**
- **For a conduction only scenario**

$$\sigma'_{\theta\theta} = \left[\frac{\beta E \Delta T}{1-\nu}\right]\left[\left(\frac{1}{2\rho} - \frac{1}{2} - ln\rho\right) I_0^{-1} - \left(\frac{1}{2} - \frac{1}{2\rho}\right)\right]$$

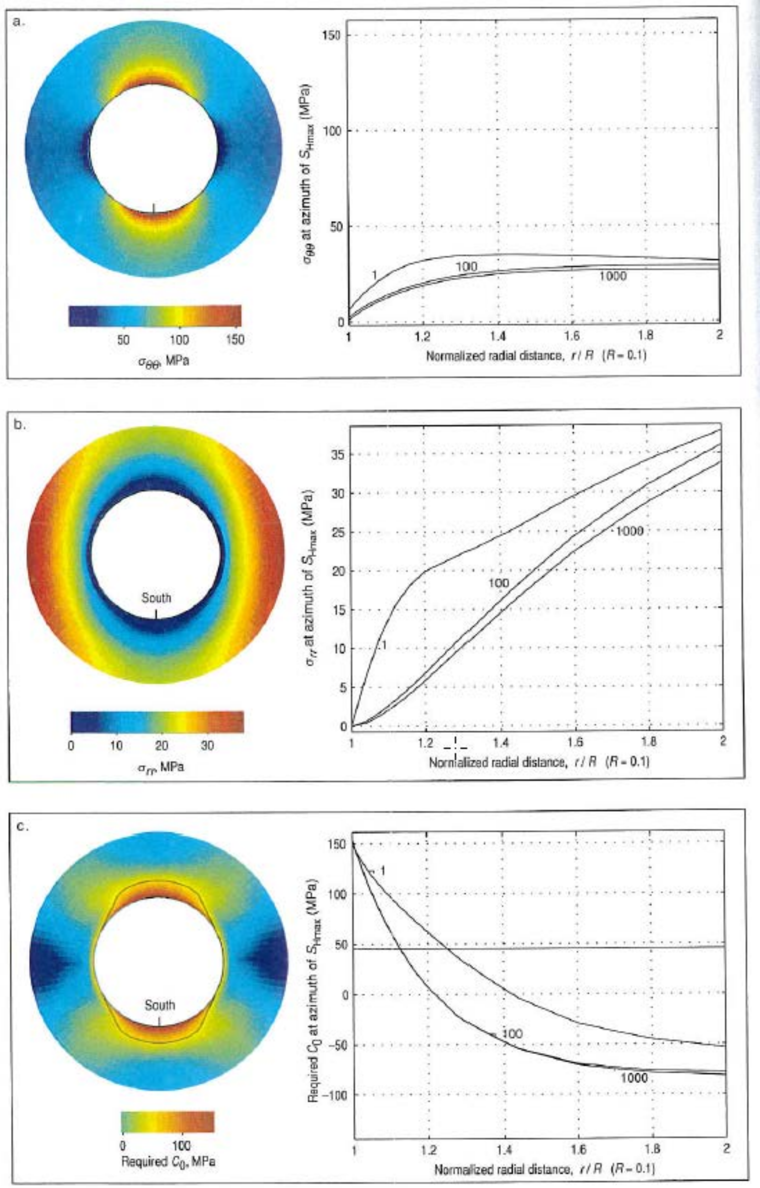
$$\sigma'_{rr} = \left[\frac{\beta E \Delta T}{1-\nu}\right]\left[\left(-\frac{1}{2\rho} + \frac{1}{2} - ln\rho\right) I_0^{-1} - \left(\frac{1}{2} - \frac{1}{2\rho}\right)\right]$$

$$I_0^{-1} = \frac{1}{2\pi i}\int_{-\infty}^{0+} \frac{e^{[4\tau z/\sigma_2]^z}}{z ln z} dz$$

- **For steady state:**

$$\sigma'_{\theta\theta} = \frac{\beta E \Delta T}{1-\nu}$$

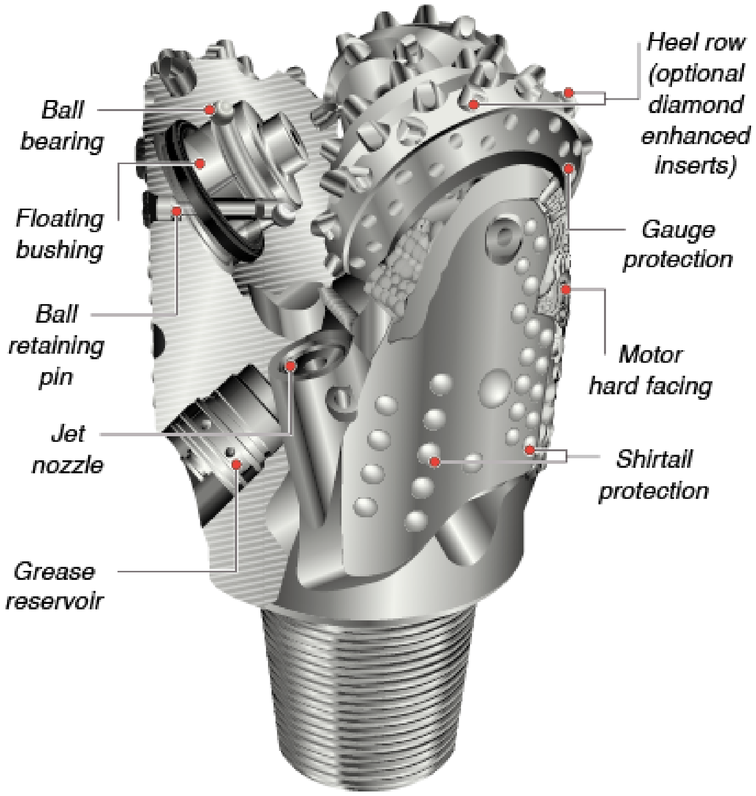
β is the linear coefficient of thermal expansion



Drill Bits

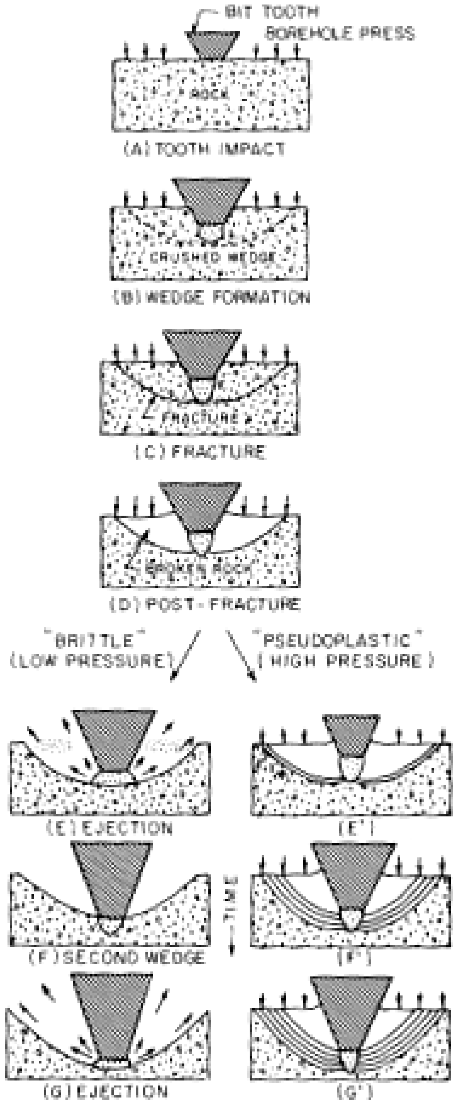
Historical Perspective

- Unocal Geothermal, Phillips Petroleum (now part of ConocoPhillips), Chevron, and others.
- From oil, gas, mining, and water well drilling practices
- Some modification of traditional methods:
  - Muds, coolers, bit design and selection
- Problems:
  - Rapid bit wear, especially in heel row (or gauge)
  - Corrosion of drill pipe during air drilling,
  - General corrosion - wellheads and valves



Roller Cone Bits

- Since 1950's, R&D for roller-cone bits has alternated between better bearings and more durable cutting structures
- Roller cones dominate geothermal drilling because of durability
- Drag bits provide shearing action - more efficient than roller-cone bits.
- Drag bits with polycrystalline-diamond-compact (PDC) began to be widely used in early 1980's for ability to drill faster and last longer in soft to medium formations.
- Do not have moving parts, so temperature limitations on bearings, seals, and lubricants not a factor.
- Historically, PDC bits have not had acceptable life in hard or fractured formations, and great deal of work has been done to extend use to harder rocks



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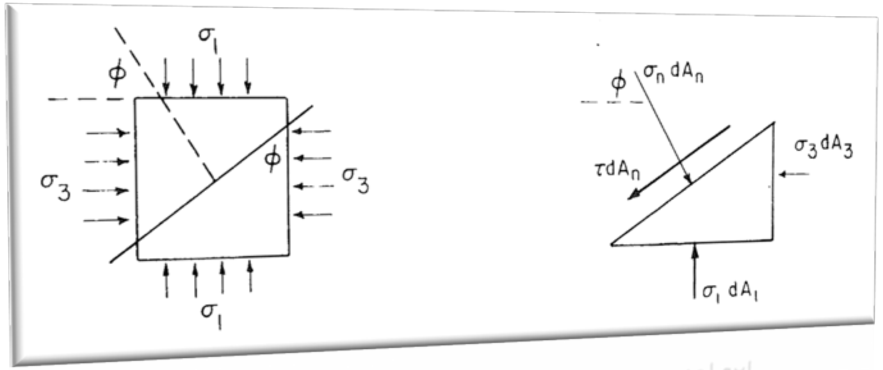

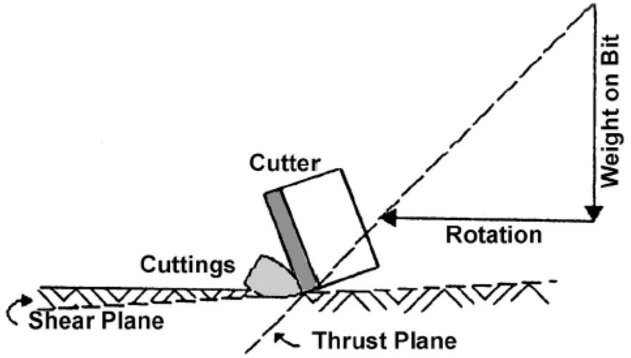

Resolutions

- Wear of bit bearing, improved design of heel row and cutting structure reduced with tougher and more robust, tungsten carbide roller cone journal bearing bits, PDC coatings
- Rapid wear of cutting structure reduced with more wear resistant tungsten carbide cutters and occasional use of polycrystalline surfaced inserts to improve wear resistance
- **Cutting structure wear rates in fractured, abrasive formations still a problem, and bit life in deep geothermal drilling still limited to less than 50 hours in many applications.**

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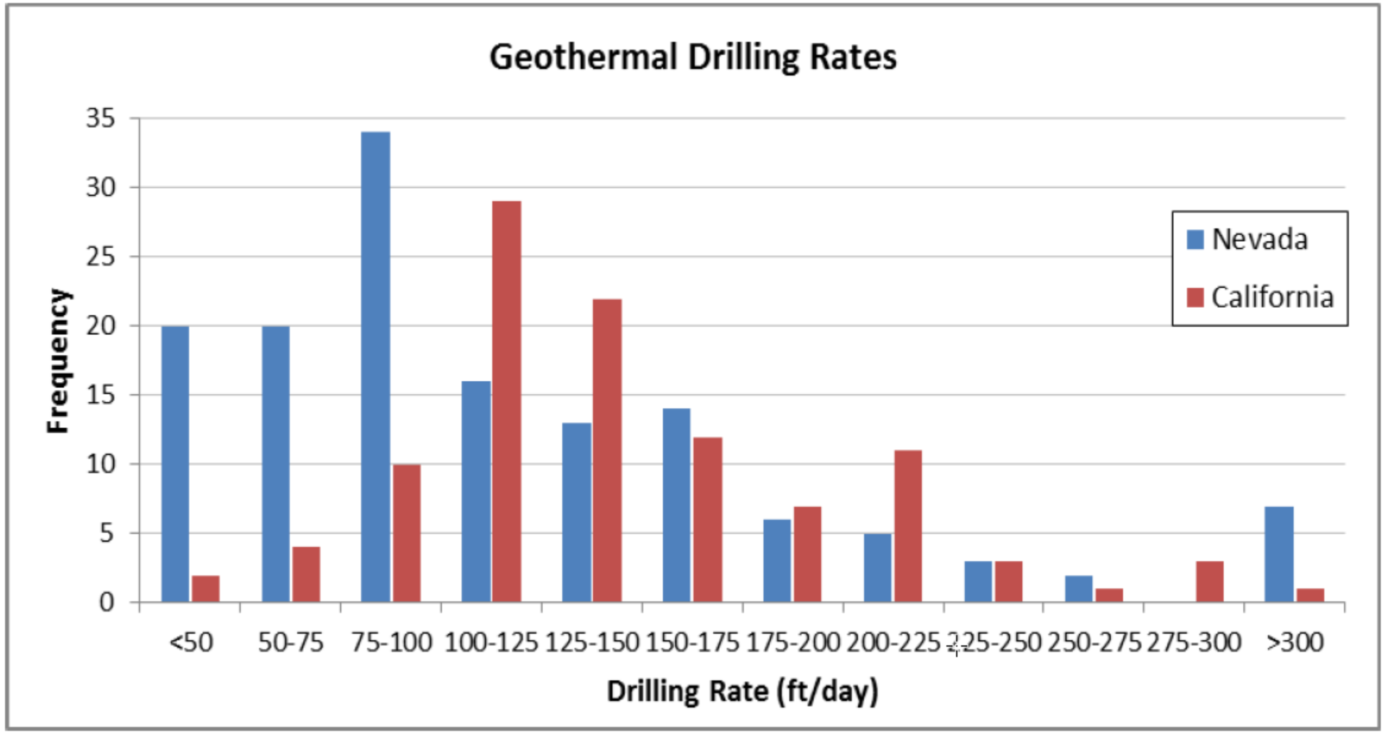
Daily Drilling Rates (ft/day) in United States

	Mean	Median	n
California	144.8	131.5	105
The Geysers	125.3	111.7	31
Salton Sea	155.6	139.8	71
Nevada	119.3	93.8	140
Combined	130.2	118.6	245

Frone, Z., and Boyd, L. 2018. Baseline Metric for Domestic Geothermal Drilling Rates, GRC Transactions, Vol. 42.

Daily Drilling Rates (ft/day) in California and Nevada

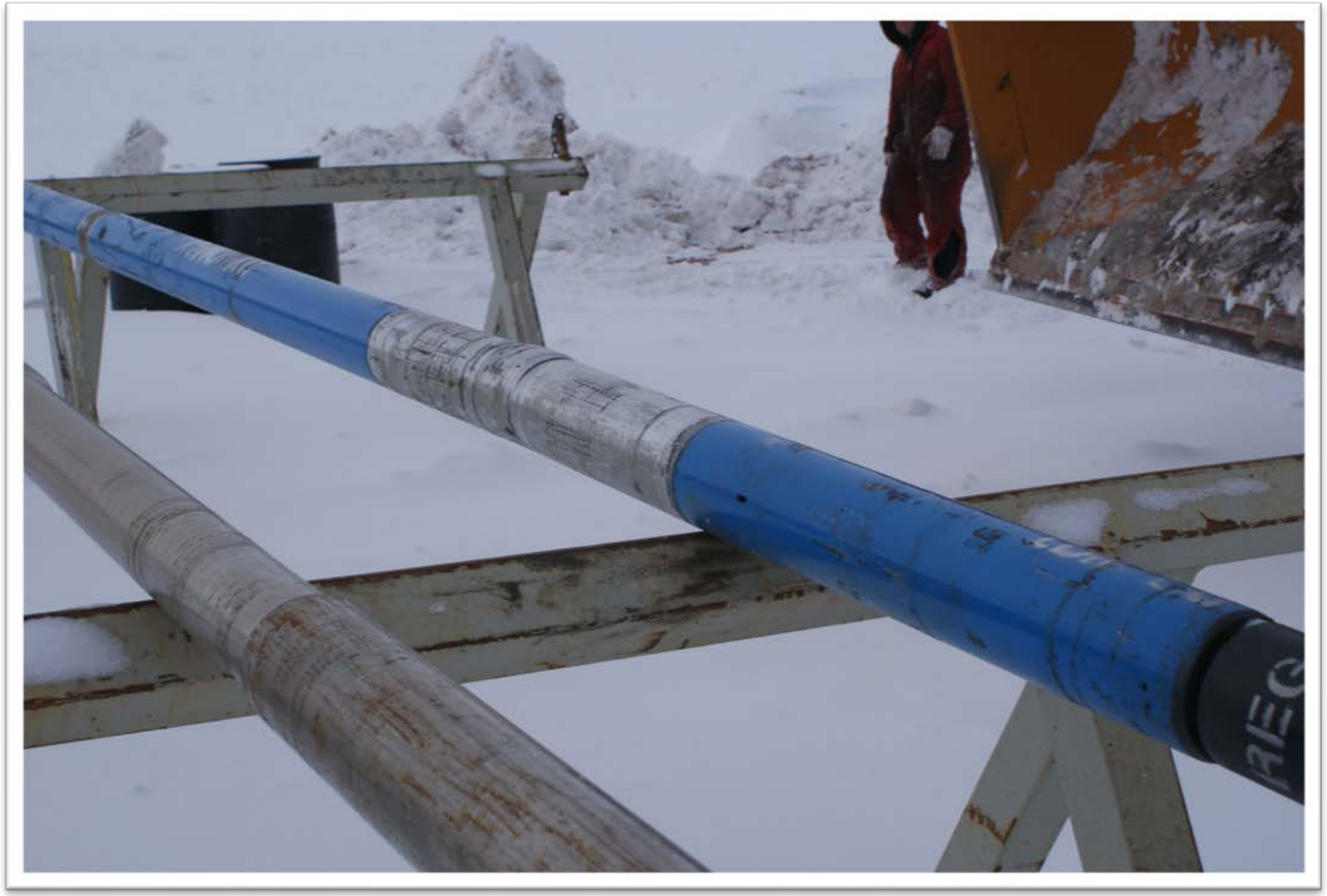


Frone, Z., and Boyd, L. 2018. Baseline Metric for Domestic Geothermal Drilling Rates, GRC Transactions, Vol. 42.

Bit Performance

- Not always easy to optimize performance with a new bit design drilling an unfamiliar formation.
- Parameters that can be changed for any bit/formation combination are rotary speed, weight on bit (WOB), and hydraulics (combination of jet size and flow rate) and it often takes some experimentation.
- Factors that most affect bit and tool life are lithology, drilling parameters (including well path), and bottom-hole assembly design.
- **WE WILL COME BACK TO THIS**

BHA and Directional Drilling



Vibration Control

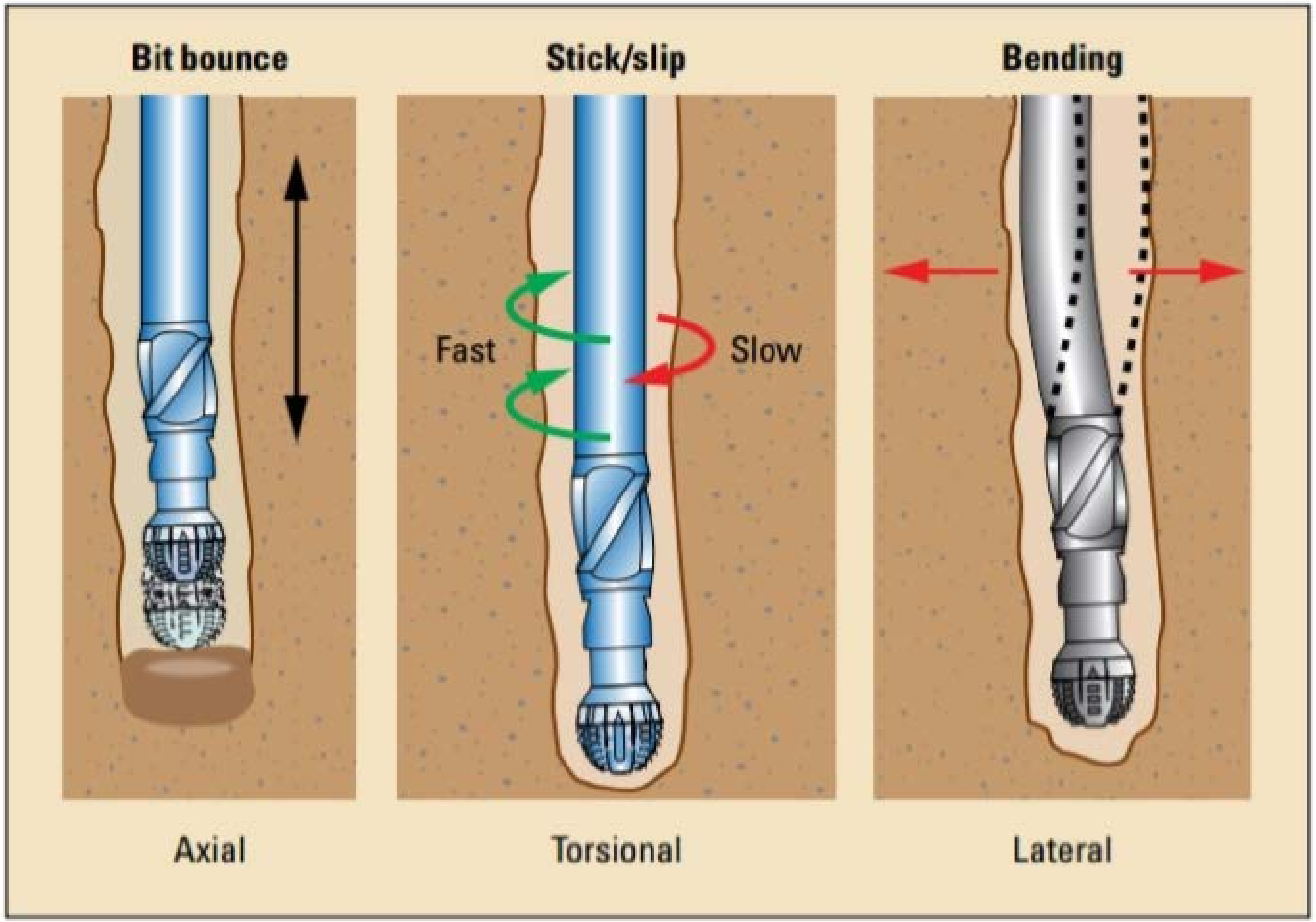
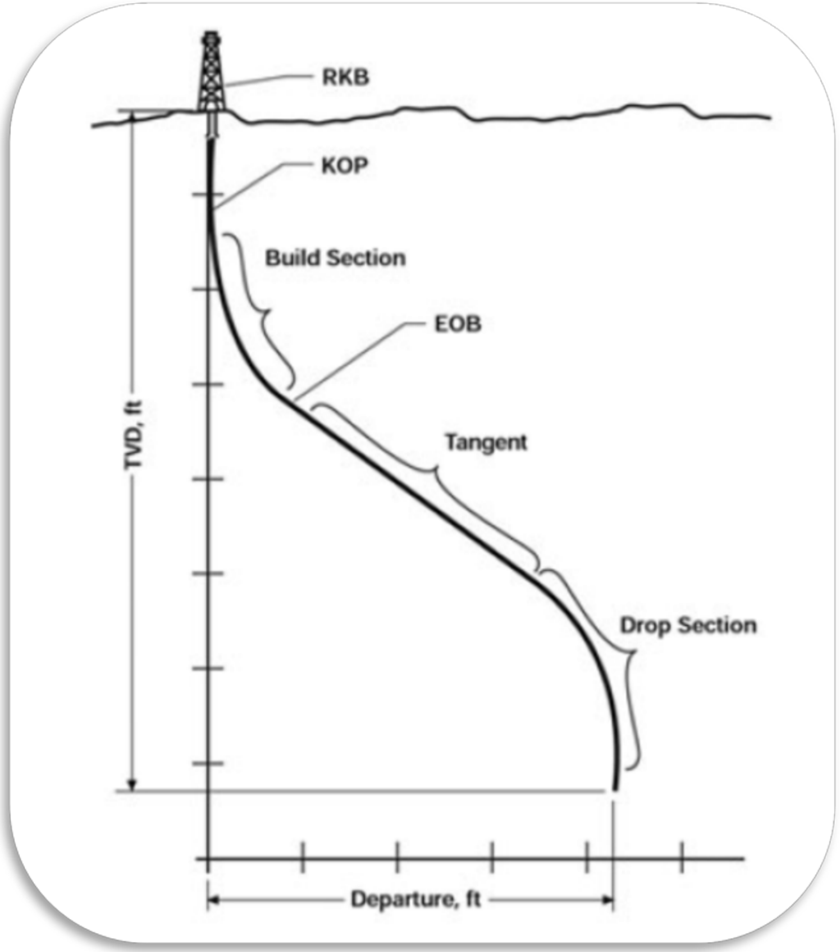


Figure 5: Three different types of vibrations acting on the drillstring (Slb 2010).

Directional Drilling

- Cover a greater portion of resource and intersect more fractures
- Reduced footprint
- Tools adapted for geothermal use
- HIstorically, directional equipment not well suited to high temperature downhole environment
- High temperatures, especially during air drilling, caused problems with directional steering tools and mud motors.
- Positive displacement downhole motor, combined with a realtime steering tool
- Still limitations on temperatures



Directional Drilling

- Cut across as many structures as possible,
- Lithology includes, trachyte, pyroclastics, tuff and syenite.
- Build-hold (J) directional well profile is most common in geothermal application, however in Menengai the build-hold-drop (s) profile popular

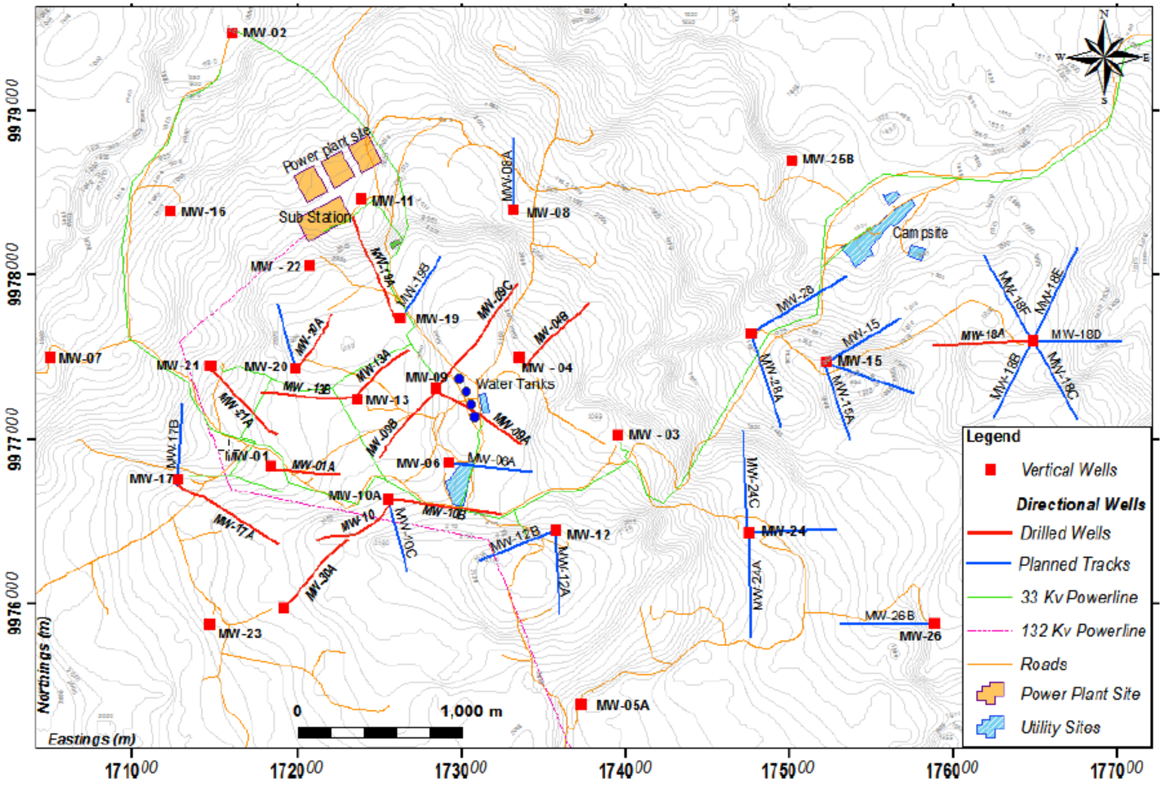


Figure 2: Directional well map of Menengai

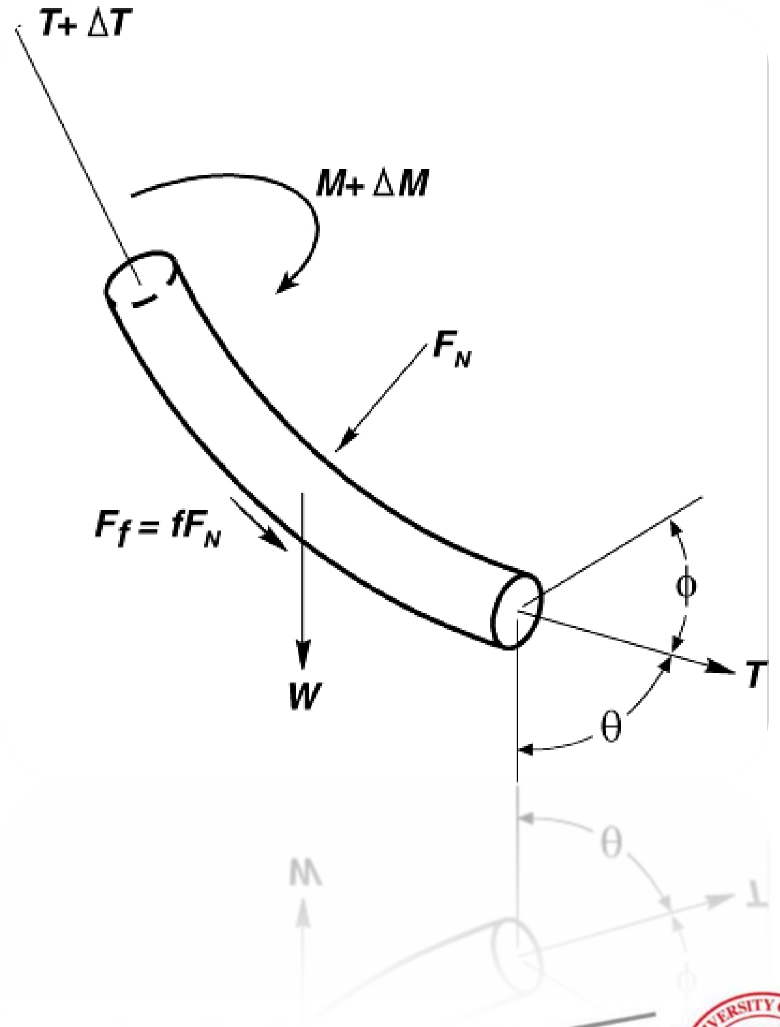
GRC Transactions, Vol. 41, 2017 Case Study of Geothermal Directional Drilling: The Menengai Geothermal Field Marietta Mutonga and Kamau Mungai Geothermal Development Company, Ltd. – GDC

Directional Drilling

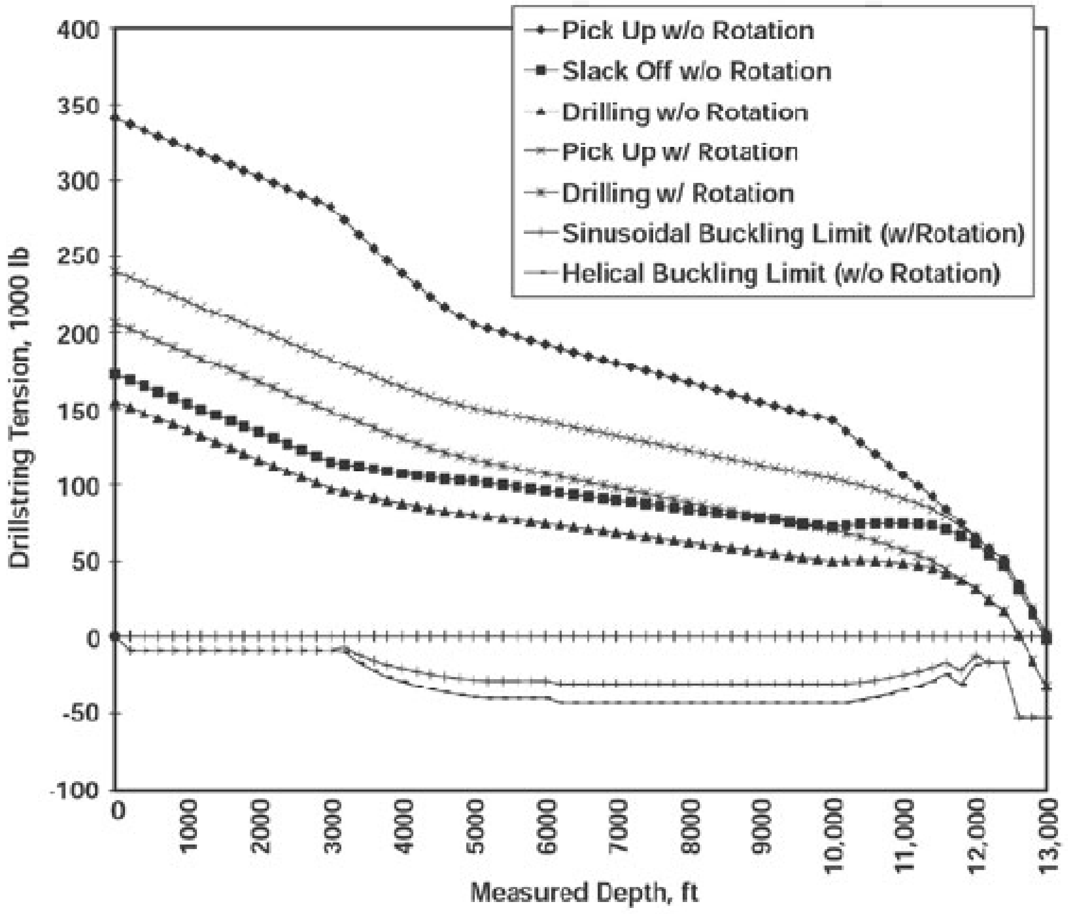
- Neither positive-displacement motors nor steering and measurement-while-drilling (MWD) tools operate reliably at high temperature, so most corrections are done at depths where the formation is still cooler than 175°C
- Kick-offs in higher temperature formations can be done with whipstocks if they can be oriented with high-temperature survey instruments
- High-temperature turbines have been demonstrated
- High-temperature positive displacement motors (PDM)
- Motors often fail on trips back into the hole if no circulation
- The ability of a top-drive unit to circulate while tripping into or out of the hole is a significant advantage for this operating method. High-temperature electronics for steering tools can also be a problem, but technologies exist for operating unshielded electronic components above 260°C
- What are the geomechanical considerations?

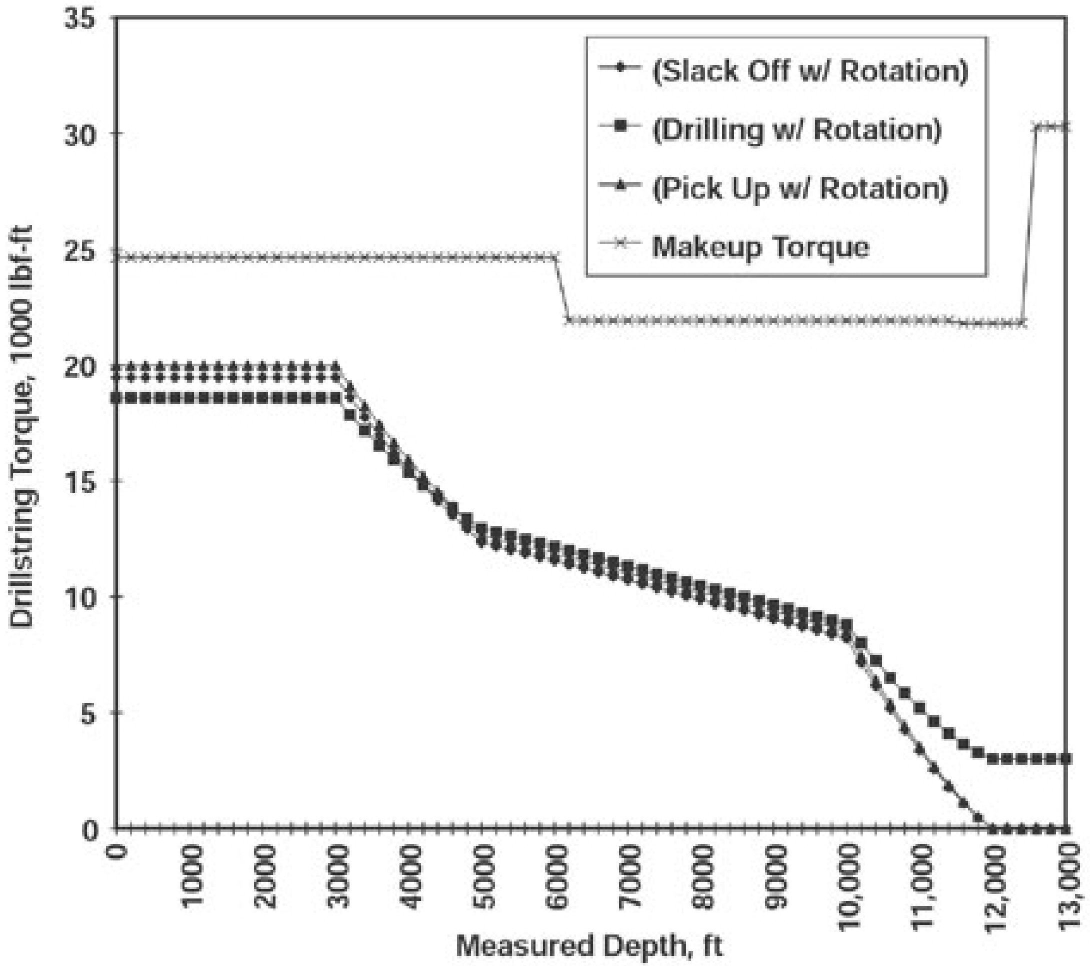
1. Torque and Drag

- Downhole motors sometimes restrict drilling parameters, such as WOB and hydraulics
- Motors can also be the mechanical weak point in a BHA, which is important when drilling through aggressive formations.
- Drill string will experience increased torque and drag
- How do we avoid excessive directional changes and micro-doglegs?



1. Torque and Drag





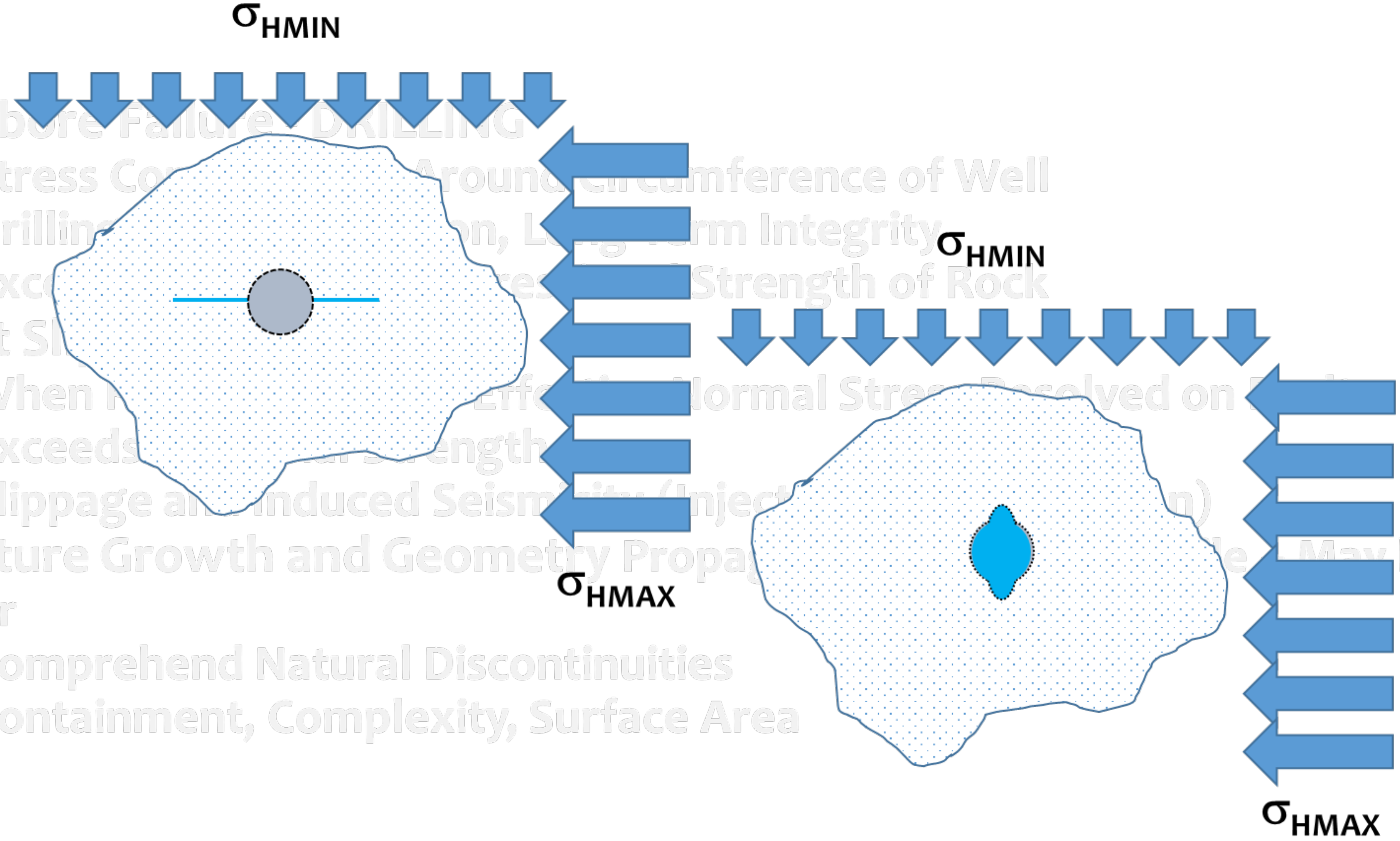
2. Wellbore Stability

Case Study - Humeros Geothermal Field, Mexico, Mexico

- High-enthalpy andesite, one liquid dominant with hydrostatic pressures, between 1150 m and 1800 m and temperatures from 290°C and 330°C. The second, steam dominant, reservoir has steam-static pressures and temperatures ranging between 300°C and 400°C, and is located at depths between 2100 m and 2800 m.
- Narrowing, wash-outs, break-outs, fracturing, hole collapse
- Circulation losses encountered while drilling in fractured formations, where drilling fluid pressure exceeds the fracture pressure
- Wellbore instability might lead to stuck pipe and even loss of hole
- Underbalanced and MPD are advocated

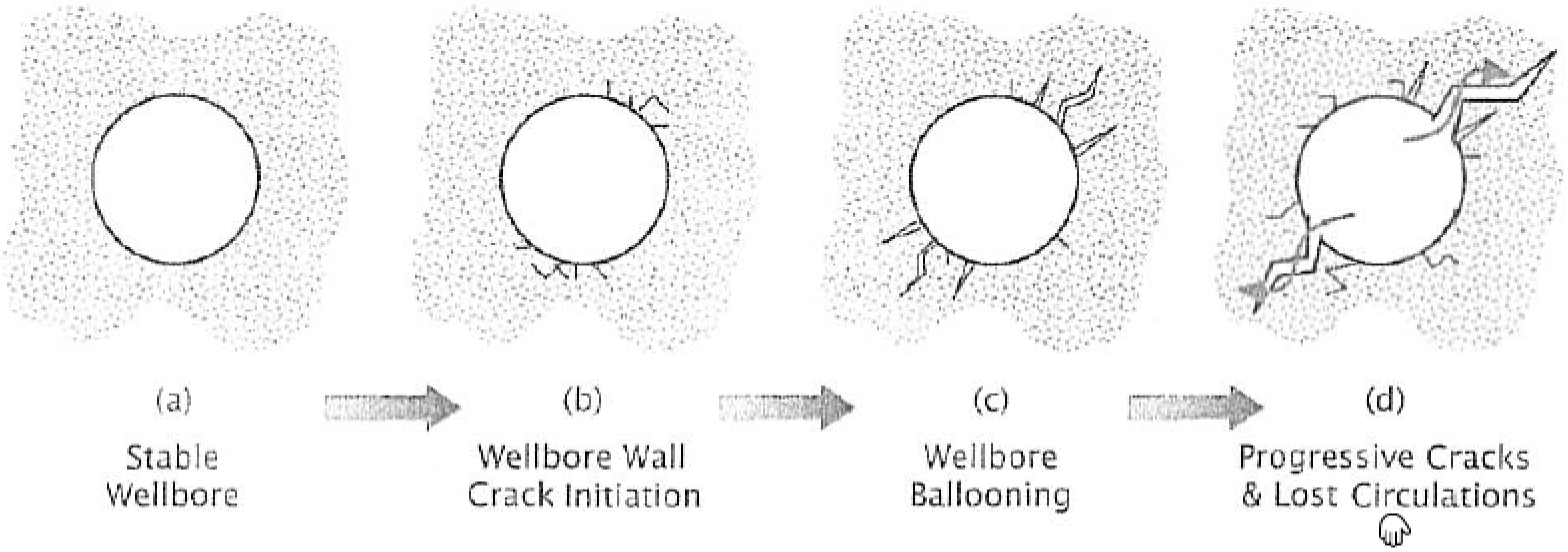
Kruszewski, M., Ramirez, M., Wittig, V., Sanchez, M., Bracke, R. 2018. Drilling and Well Completion Challenges in the Los Humeros Geothermal Field, Mexico, GRC Transactions, Vol. 42.

Why is Stress Important?



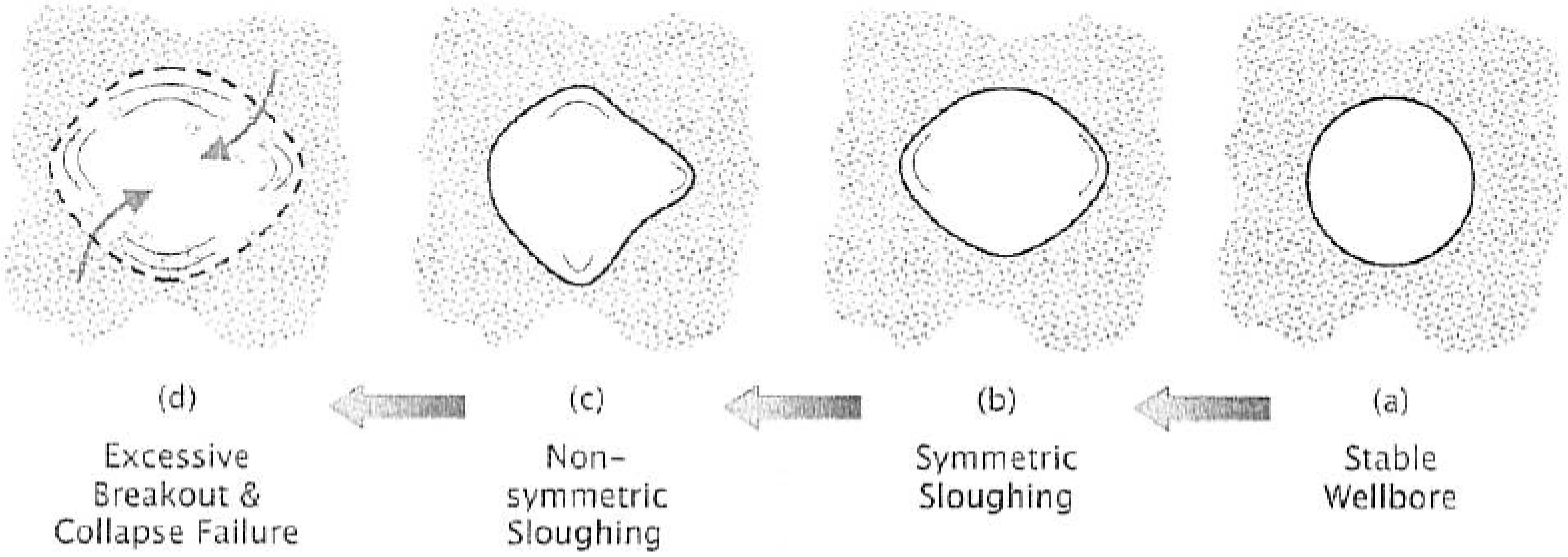
Wellbore Fracturing Pressure

- **Fracturing initiates after rock stress at the wellbore wall changes from compression to tension and any available tensile strength is overcome**
- **As wellbore pressure increases, the circumferential stress σ_θ decreases and eventually becomes tensile**



Wellbore Collapse Pressure

- Collapse (or symptoms) occurs as wellbore pressure is decreased
- As wellbore pressure decreases, the circumferential stress σ_θ increases, the radial stress reduces at the same rate and shear stress increases – collapse can occur because of high shear



Underbalanced Drilling

$$\sigma_\theta < \frac{1}{1 - tan\phi}[2c' - 2P_0 tan\phi + P_{wc}(1 + tan\phi)]$$

- **We calculate:**

$$P_{wc} = \frac{1}{2}(3\sigma_x - \sigma_y)(1 - sin\phi) - c'cos\phi + P_0 sin\phi \ for \begin{cases} \sigma_x < \sigma_y \\ \theta = 90° \end{cases}$$

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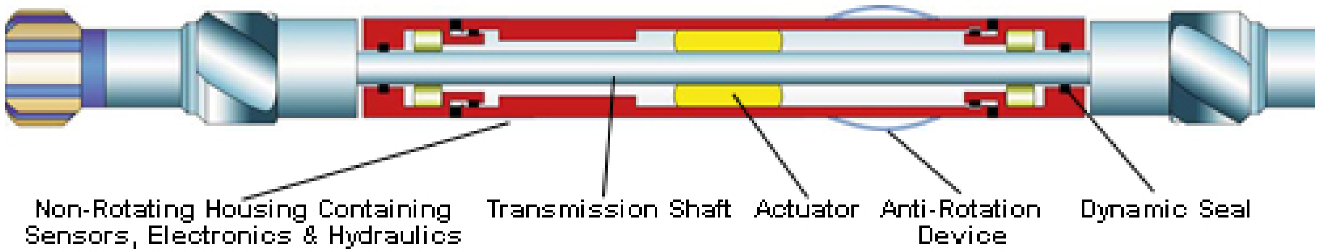
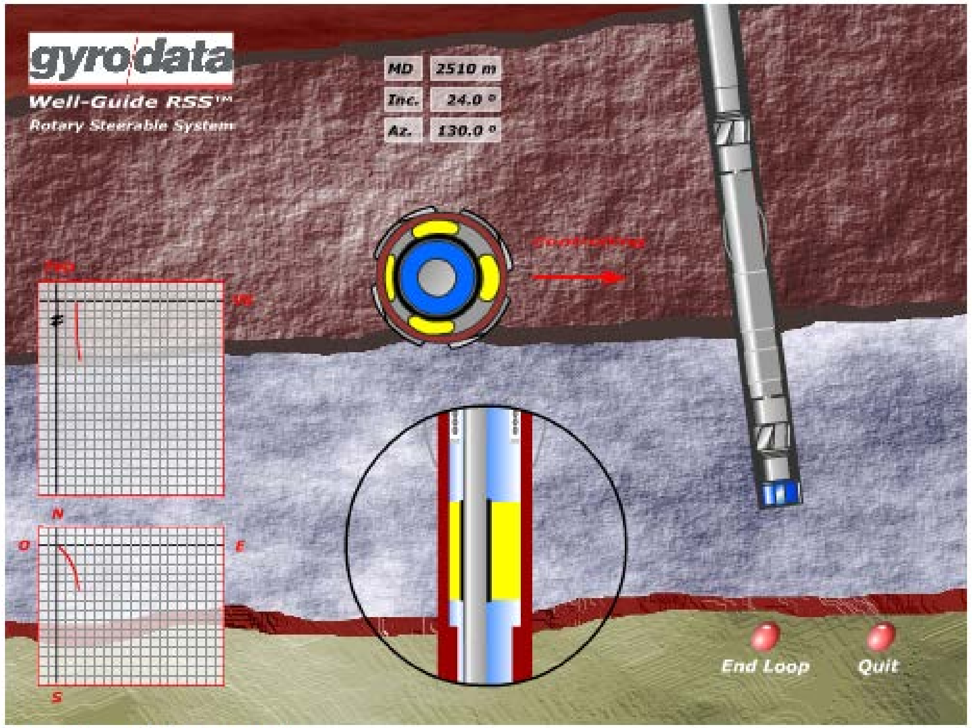
$$\sigma_\theta = \sigma_x + \sigma_y - P_w - 2(\sigma_x - \sigma_y)cos2\theta - 4\tau_{xy} sin2\theta$$

Rotary Steerables



- A rotary steerable system drills directionally with continuous rotation from surface
- No need to slide to hold angle
- Continuous rotation transfers weight to the bit more efficiently, which increases the rate of penetration (ROP).
- Rotation also improves hole cleaning
- Continuous rotation and better hole cleaning reduce the chance of mechanical and differential sticking of the drill string.



Rotary Steerable Demonstration

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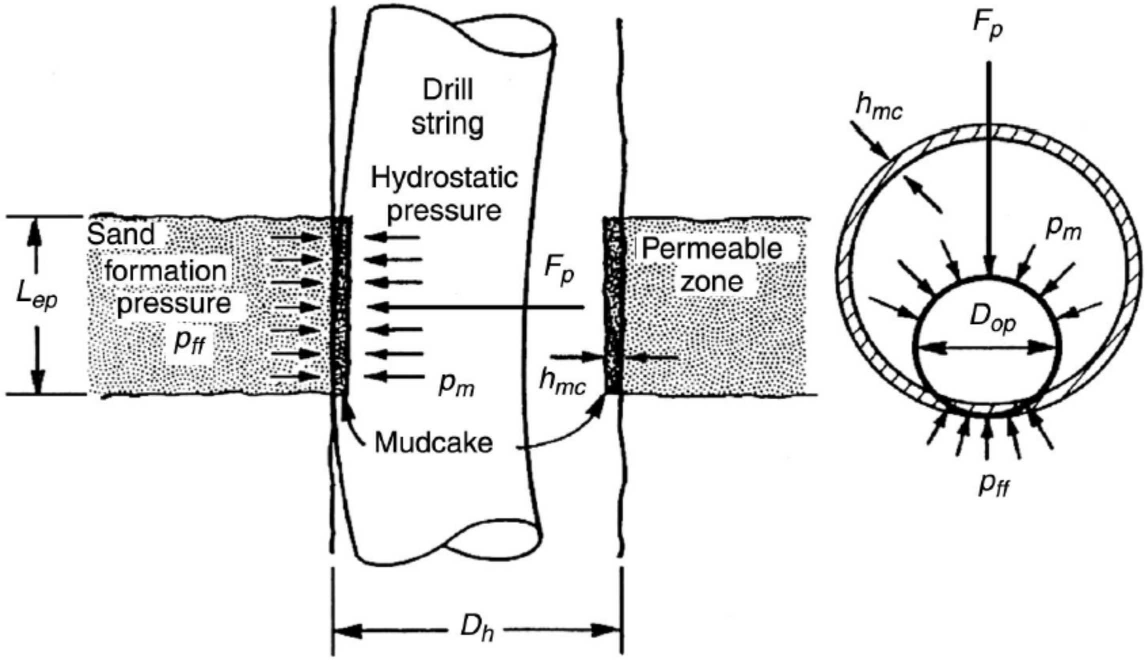
Lost Circulation



Lost Circulation - Consequences

- If drilling fluid fails to clean hole, cuttings can fall back on the BHA and stick drilling assembly
- Drilling fluid, especially high-temperature formulations, is expensive
- Production zone is usually a lost-circulation zone, may be difficult to cure lost circulation zone and preserve productive potential
- Can suddenly lower fluid level in a well. Decreasing the static head of drilling fluid in a hot formation can allow the formation fluids, gas, hot water or steam, to enter the wellbore, causing a loss of well control - in productive or non-productive zones

LCM

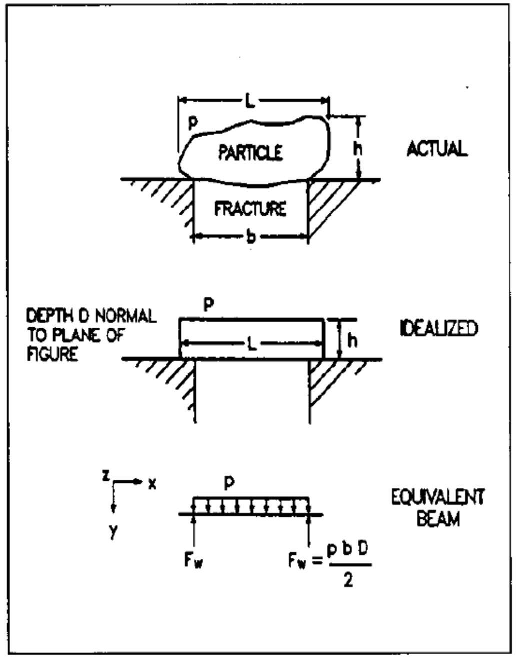


Fig. 1—Single-particle bridging at fracture entrance.

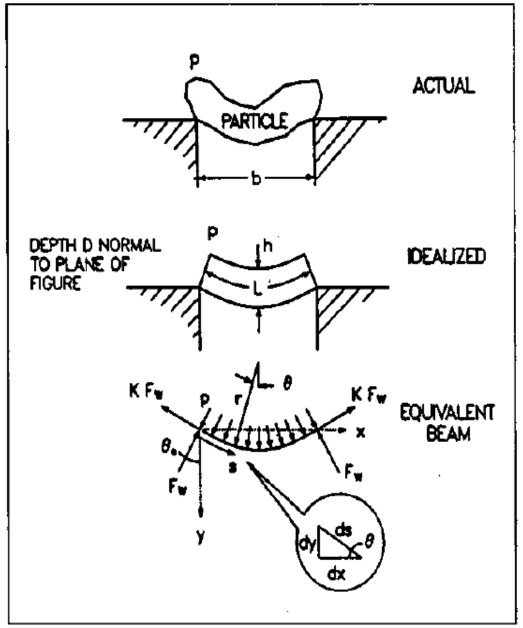


Fig. 2—Incipient failure of a single-particle bridge because of elastic deformation.

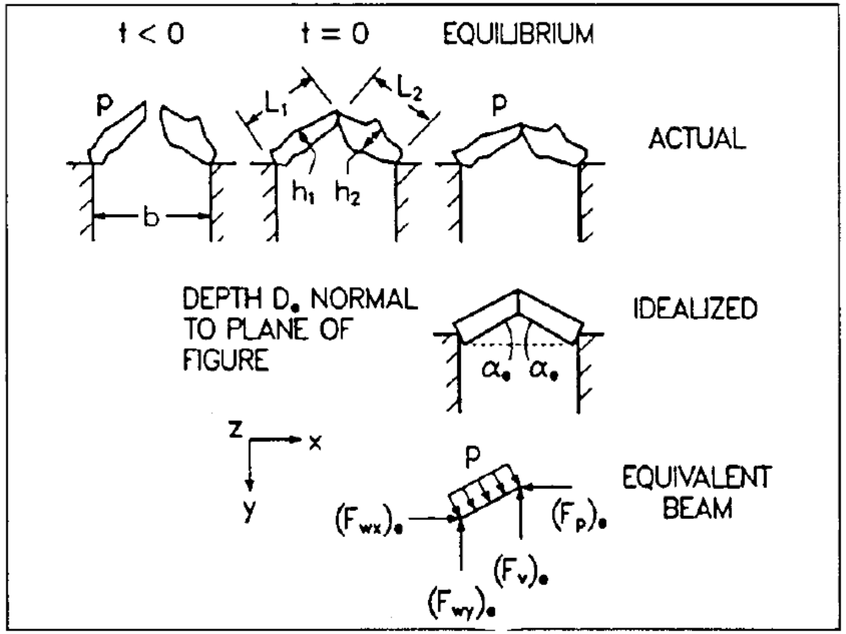
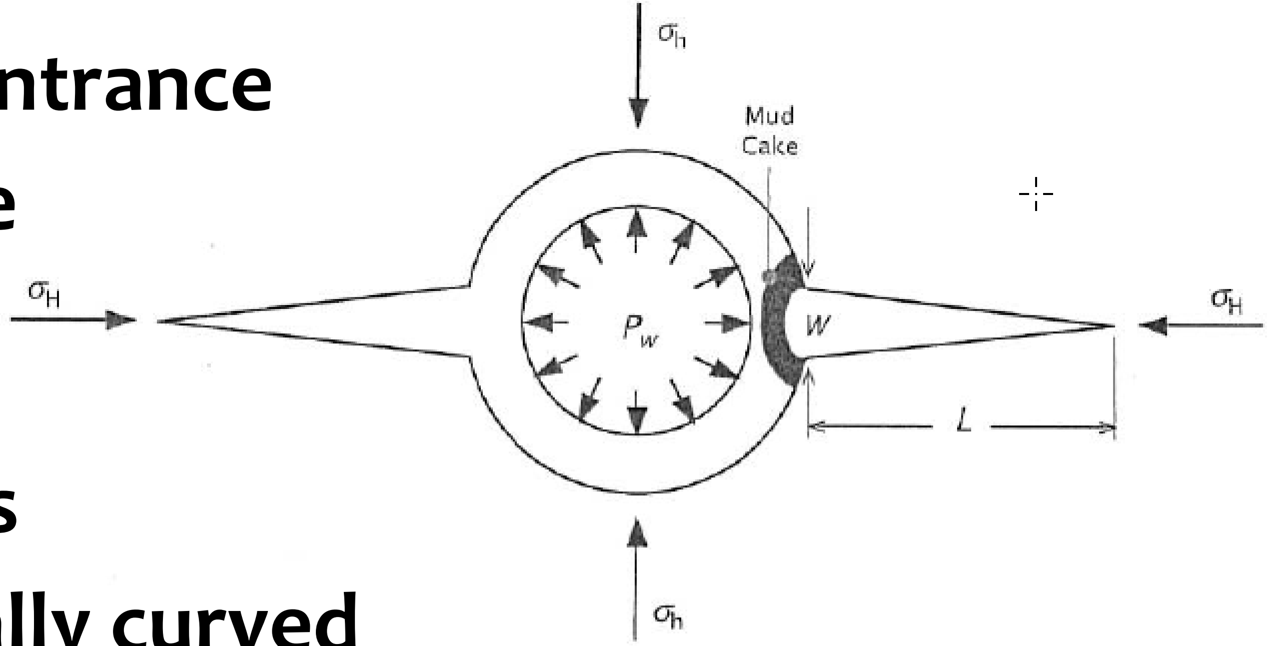


Fig. 4—Two-particle bridging at fracture entrance.

Interpretation of Leakoff Testing
Continuous Pumping

What Happens in the Post-Failure Regime

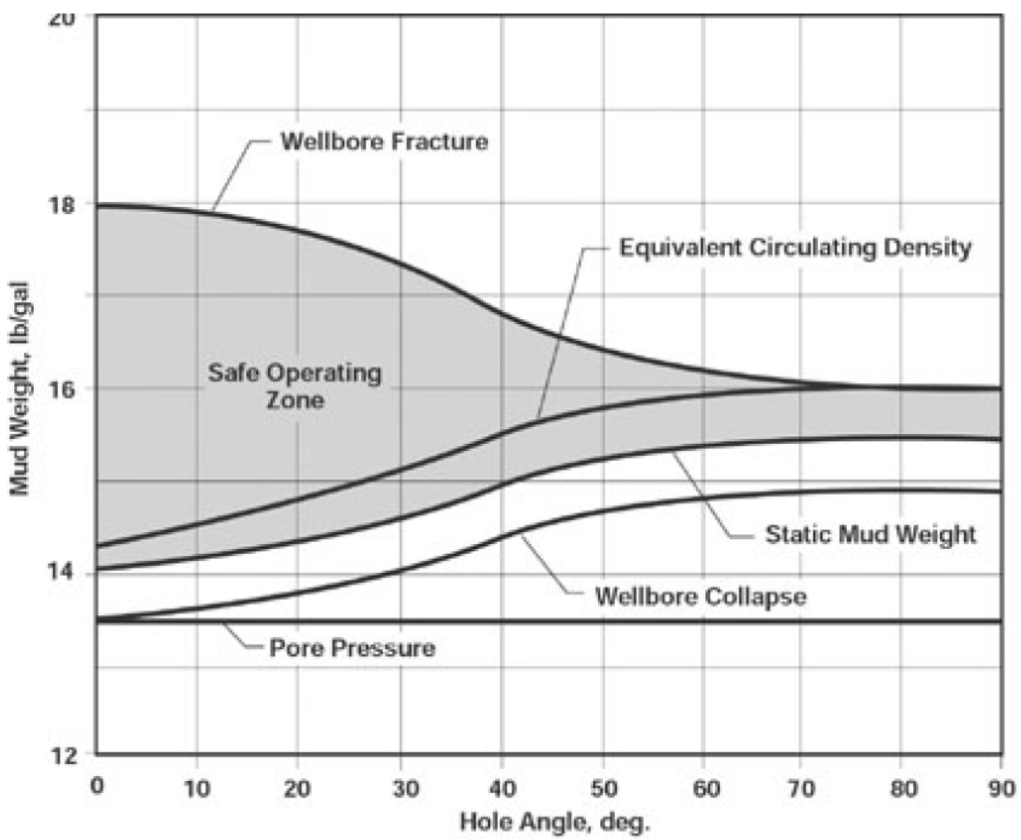
- At LOT point, fracturing occurs. Mud enters
- Stress bridge builds near entrance
- Prevents flow into fracture and allows pressure to increase
- Eventually bridge collapses
- Bridge needs to be nominally curved and maximum bridge pressure depends on particle strength



Drilling Fluids

Lightened Fluids

- Air, foam and aerated fluids from the lowest density to the highest density.
- Air can only be used where liquid production is minimal or non-existent. Foam will tolerate some water dilution, but not much, while aerated fluids can tolerate a significant amount of dilution.



Chemomechanical Effects

Gases

- Geothermal systems almost always contain dissolved or free carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gases
- Contribute to corrosion
- H_2S limits materials used for drilling equipment and for casing to the lower strength steels
- Higher strength steels will fail by sulfide stress cracking
- H_2S also presents substantial safety hazard during drilling process.
- What are the geomechanical implications?

Chemomechanical Effects on Producers and Injectors – Some Examples

- **Cove Fort:** pH 3 and H_2SO_4 condensed near surface, draining down and encountering formation – "runny" dolomite
- **Tiwi and Karaha:** vapor-dominated regimes and SO_2 – both sitting on volcanics - deep H_2SO_4 and HF – now drilling where nonvolcanic. Impacts components of BHA and WOB
- **Soultz sous Forêts:** Iron Oxidation – fluids oxidized strip out iron
- **Danang:** High gas contents – high CO_2 pressures, pressure built up and fatalities.
- **Salton Sea:** Inconel casing, pH 5 but so saline that you can't balance all hydrogen – big wells

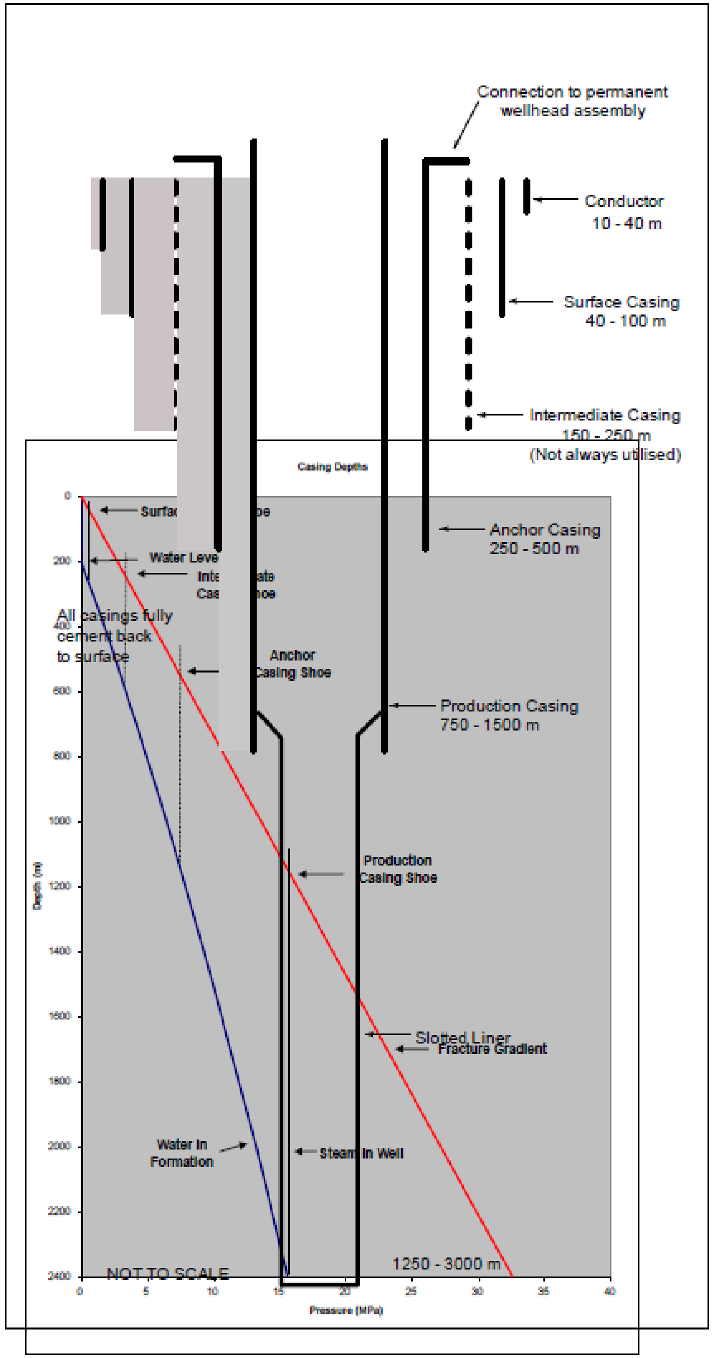
Chemomechanical Effects on Producers and Injectors – Some Examples

- **Roosevelt Hot Springs:** Use sulfuric to modify pH and keep silica in solution – changed to inhibitors but lost injectors, and binary plant
- Injectivity May Be a Premium Geomechanics Issue
  - Injectors in margins of field, impermeable rock and can't inject.
- **Coso**: Plugging for a few tens of meters
- **Raft River:** Excellent example of mitigation
  - Documented 20 gpm to 1736 gpm
  - Strategic stimulation, patient cold water injection
- Groundwater contamination from injectors?

Casing Program

Large Diameter Casing

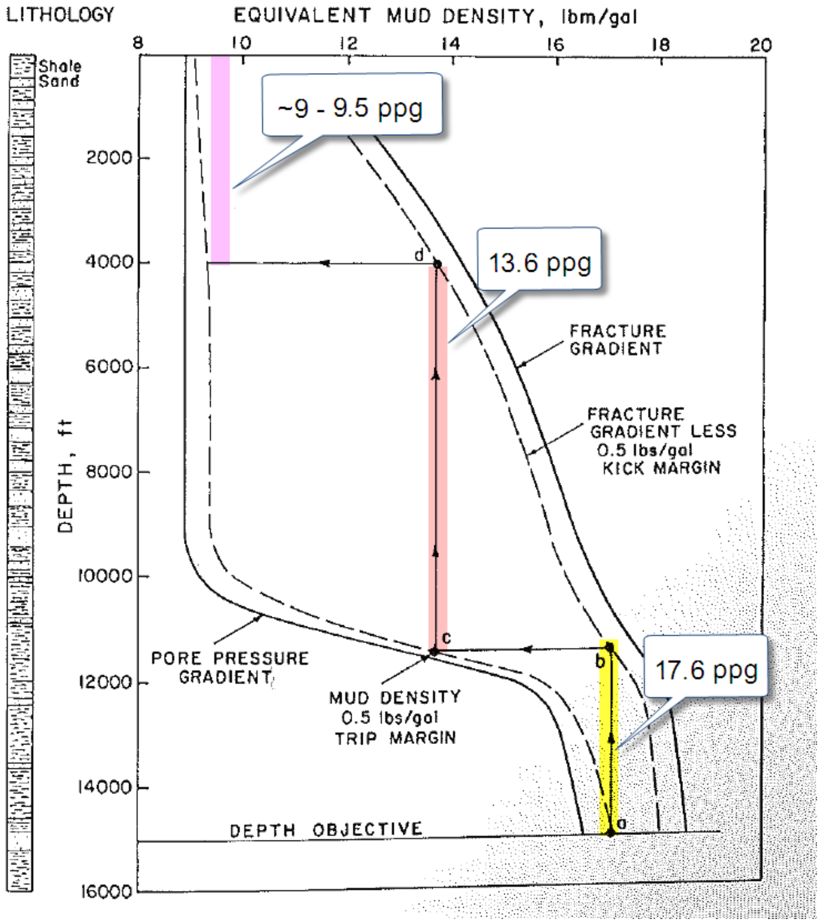
- Thermal efficiency converting geothermal steam/water to electricity is low (±20%)
- Large mass flows required, particularly in vapour dominated systems
- Require large diameter production casings, liners
- Typically ‘standard’ sized well will use API 9 5/8” production casing and 7” or 7 5/8” diameter slotted liner in an 8½” diameter open hole
- “Large” diameter well will use standard API 13 3/8” diameter production casing, with either 9 5/8” or 10¾” diameter slotted liner in a 12¼” diameter openhole



Casing Program

Depth of each string determined by:

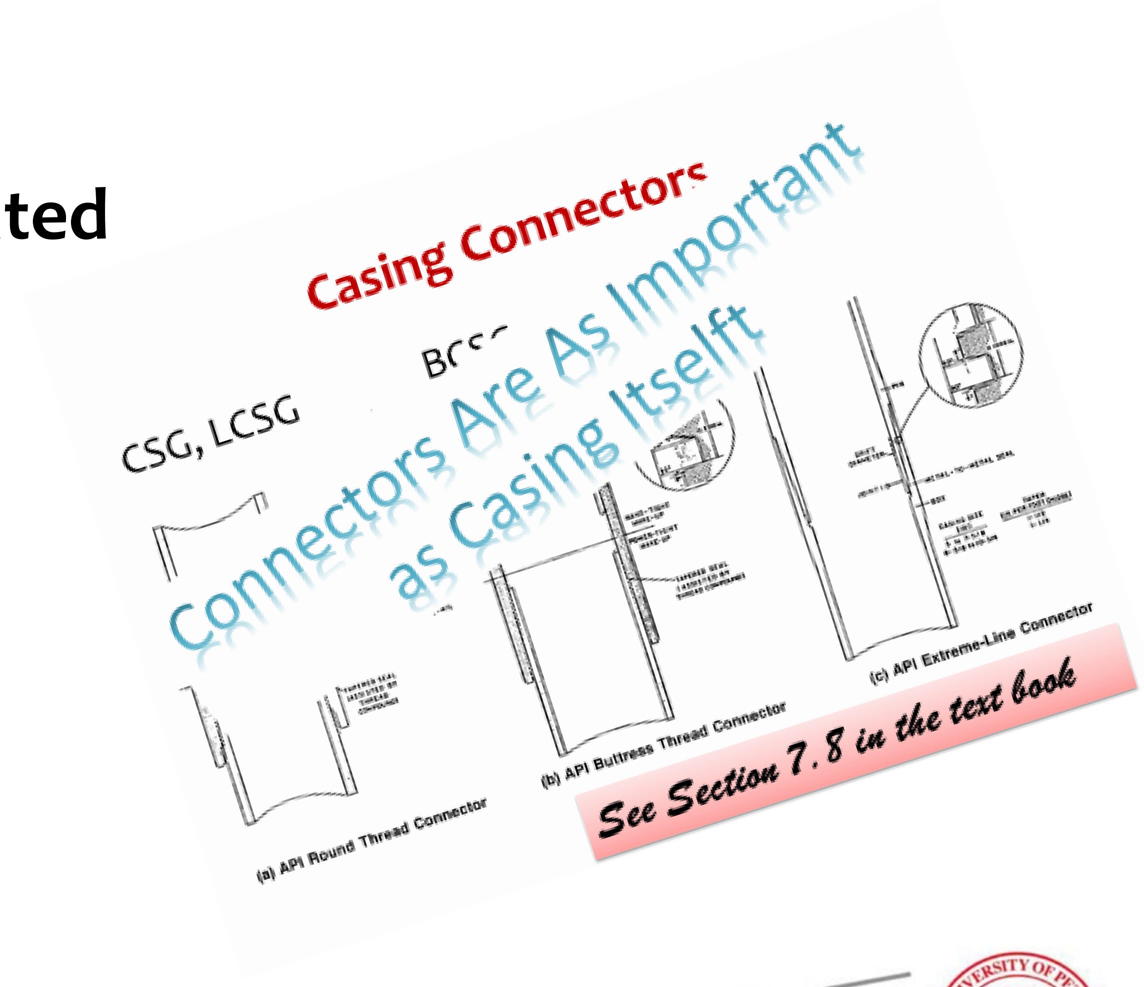
- Rock Properties (Fracture Gradient, Sloughing, Swelling, Unstable, Or Unconsolidated Formation)
- Stability Assessments
- Formation Pressure (Pore Pressure Much Less Or Much Greater Than Drilling Fluid Pressure)
- Well Control Considerations
- Regulatory Requirements



Casing Program

Parameters That Determine Casing Requirements:

- Nominal Production Rate and Associated Casing Diameter
- Depth of Production Zone
- Expected Temperature
- Brine Chemistry
- Completion Type
- Well Trajectory
- Length of Individual Casing Intervals



Implications of Large Temperature Changes

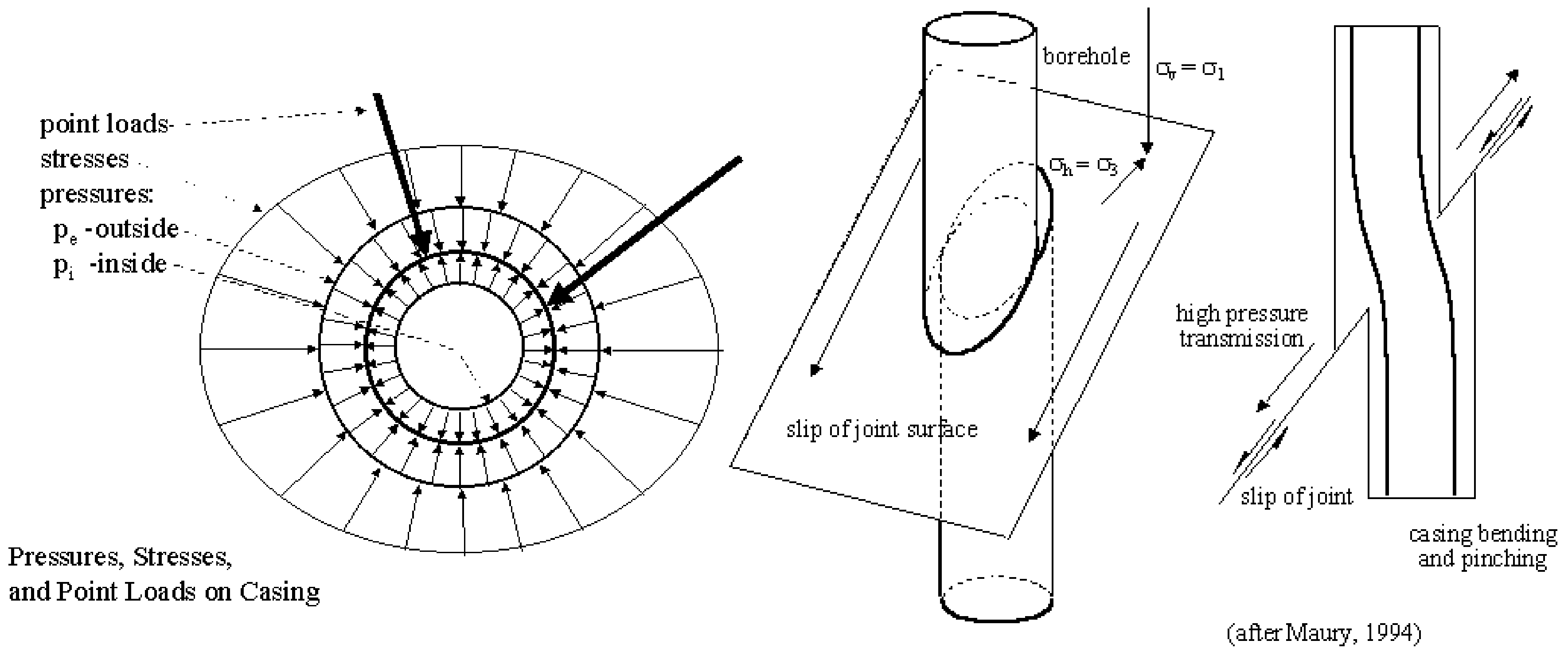
- **Precautions:**
  - To avoid entrapment of liquids between casing strings – which can exert extreme pressure when heated resulting in collapsed casing.
  - To ensure casing grade and weight, and connection type adequate for the extreme compressive forces caused by thermal expansion
  - To ensure casings completely cemented such that thermal stress uniformly distributed.
  - To ensure casing cement slurry designed to allow for adequate setting times and to prevent thermal degradation

Casing Design

- **Strength at Temperature**
  - Common casing materials lose strength at elevated temperature
  - More pronounced in higher grades
  - K-55 decreases from 388 MPa at 250°C to 359 MPa at 371°C
  - L-80 decreases from 632 MPa to 484 MPa over same range
  - Tolerate temperature change (low temperature when cemented).
- **Casing Availability**
- **Corrosion Resistance**
  - Almost all geothermal reservoirs produce H_2S.
  - Some geothermal reservoirs are quite saline
  - CO_2 common

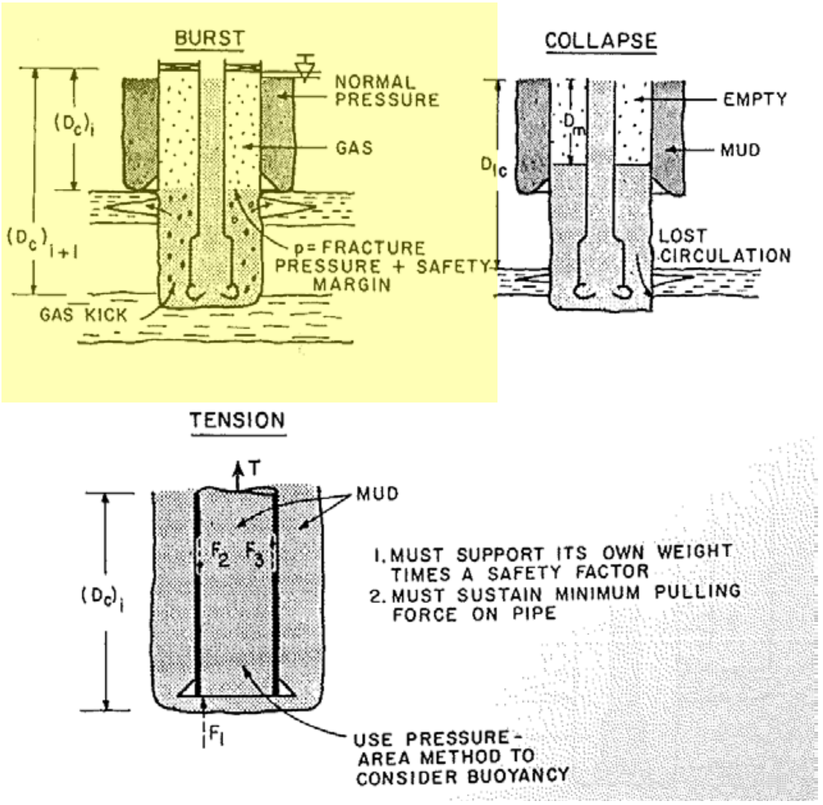
Casing Integrity?

- Movement along new or reactivated surfaces
- Casing can be shearing. Local concentration of loading associated with movement along such surfaces.



Generic Considerations:
Surface Casing (as an example)

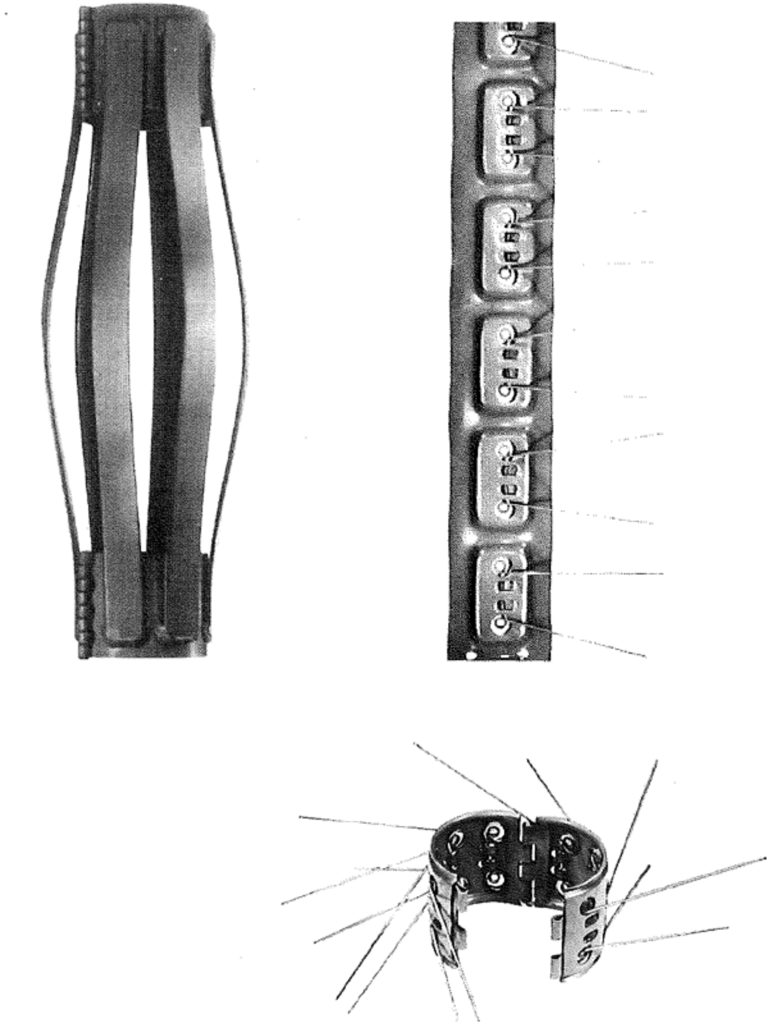
- Burst --- well control situation assumed to occur when circulating out a large kick
- Ensure that formation fracture pressure at casing seat exceeded before the burst pressure reached
- Assume all drilling fluid lost to fracture and there is only gas in the casing
- Resisted by external pore pressure



Cementing

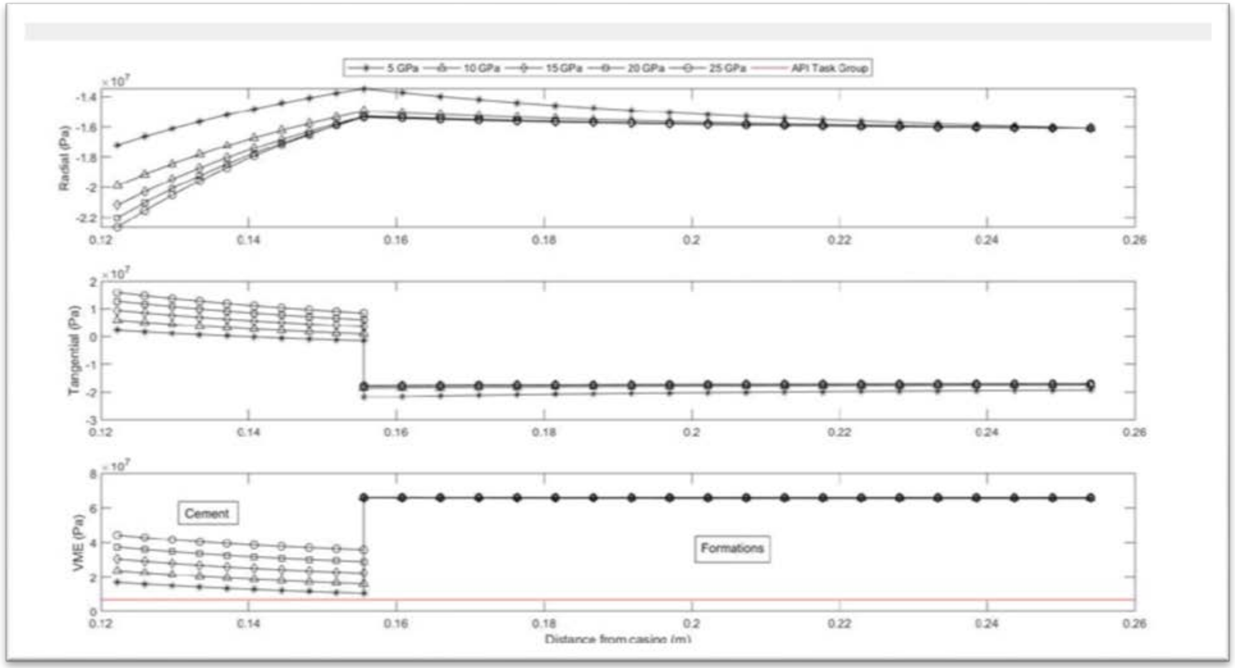
Cementing

- Portland cement conventionally used (sometimes calcium phosphates)
- Retarders
- Permeability and long term durability of the Portland /silica based cement improved with silica flour or similar
- New calcium phosphate refractory cements, resistant to several hundreds of degrees Celsius
- Lightweight blends often used
- Geomechanics considerations are lost circulation-related



Cement Damage

In one field: “In order to improve the cement design …, more elastic and flexible cements with higher Poisson’s ratio and lower Young’s modulus are advised. … by using more ductile non-Portland cement …, foamed cement blends, or …plasticizers such as liquid latex …”



Teodoriu C., Ugwu I., Schubert J., Estimation of Casing-Cement-Formation Interaction using a new analytical model, SPE EUROPEC/EAGE Annual Conference and Exhibition, 14-17 June, Barcelona, Spain 2010.

“Newer” Drilling Technology

Percussion Drilling

- Reciprocating downhole piston/anvil assembly to apply impact loading either to a conventional roller-cone bit or to a one-piece bit set with tungsten-carbide inserts
- Greater penetration rates
- Gage wear on the solid-head bits, necessity for accurate weight-on-bit control, difficulty fishing broken equipment and the requirement for air or foam drilling (unusable in mud drilling).
- Air hammers now been developed and used in field.
- Hydraulic Hammers?

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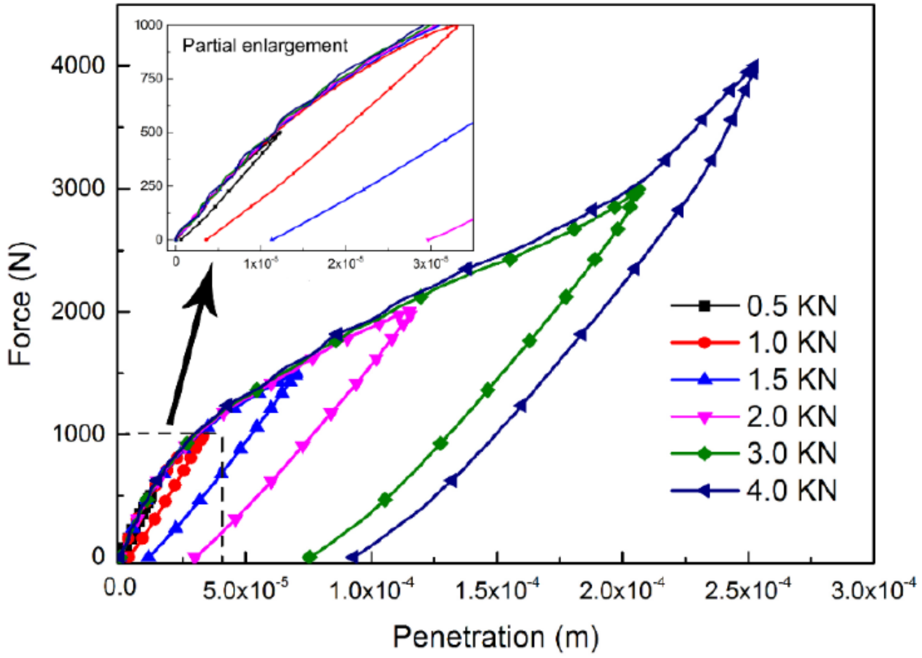
Percussion Drilling

- Penetration rate increases with impact frequency or dynamic loading amplitude in the low frequency range (200Hz)
- Simulated single tooth impacting rock and analyzed impact parameters on impact energy and rock damage.
- Rock damaged or broken under shock of impact force.

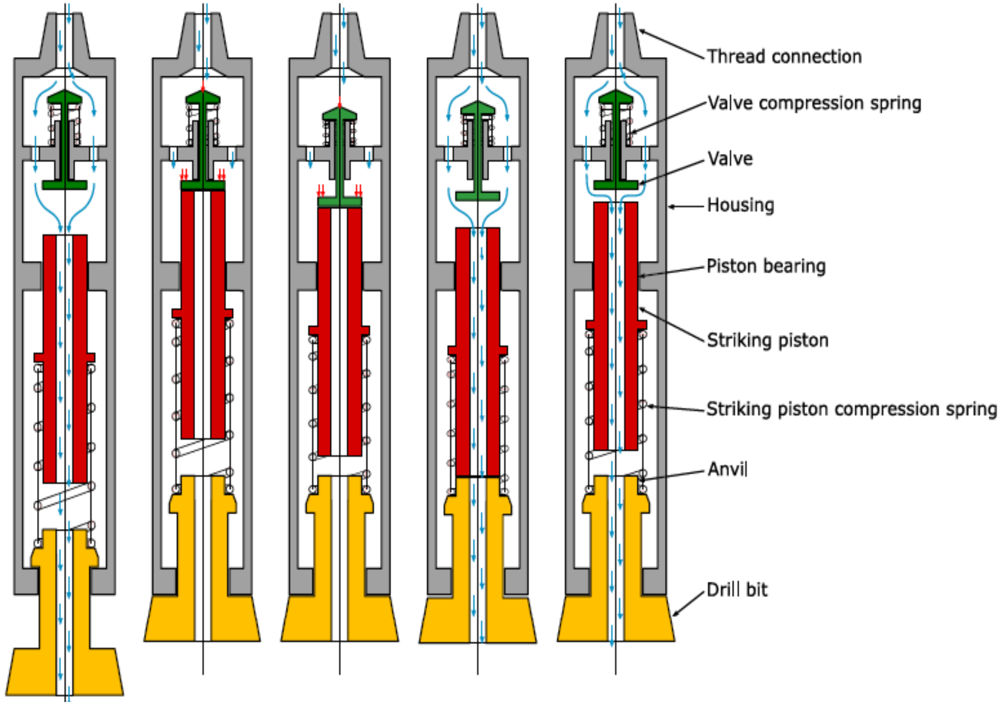


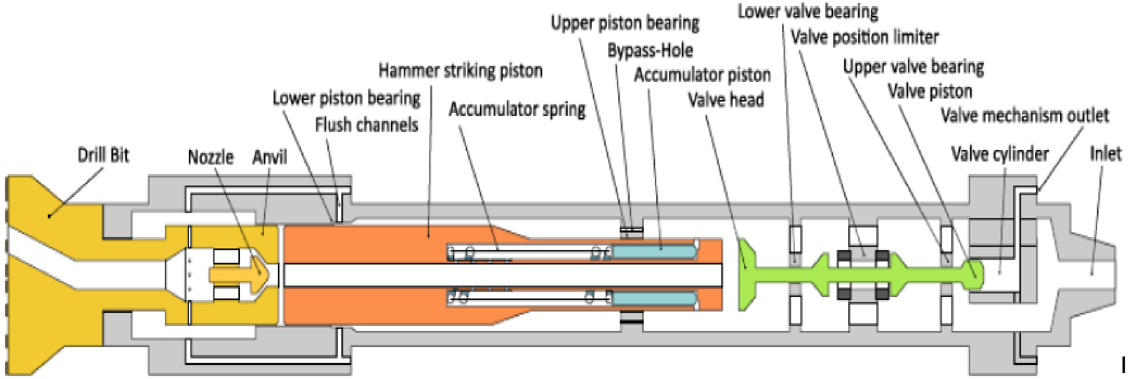
- Most of impact energy (work done by impact force on rock) can be used to damage and break rocks and little is dissipated in the form of elastic stress waves.

Song, H., Shi, H., Li, G., Ji, Z., Zhao, H., and Che, Y. 2018. Numerical Simulation and Experimental Research on Application of Percussion Drilling Technology in Geothermal Wells, GRC Transactions, Vol. 42.

Percussion Drilling

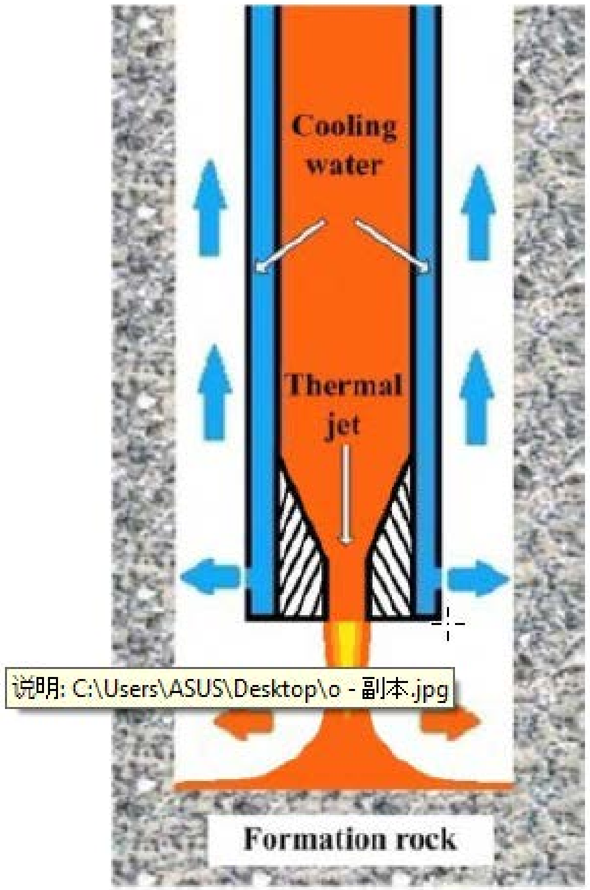
- GZB Germany
- Hydraulic Down the Hole (DTH percussion hammers powered by drilling mud
- Air-Powered Percussion Drilling is Common
- Hydraulically-Powered Hammers don't have depth limitations for lifting, wellbore stability …
- Available from Wassara and Hanjin but not compatible with drill fluid
- Convert hydraulic energy to percussive movement (air hammers rely on gas compressibility)
- Momentum transfer from hydraulic fluid to striking piston by interrupting fluid flow





Hydrothermal Jet Drilling

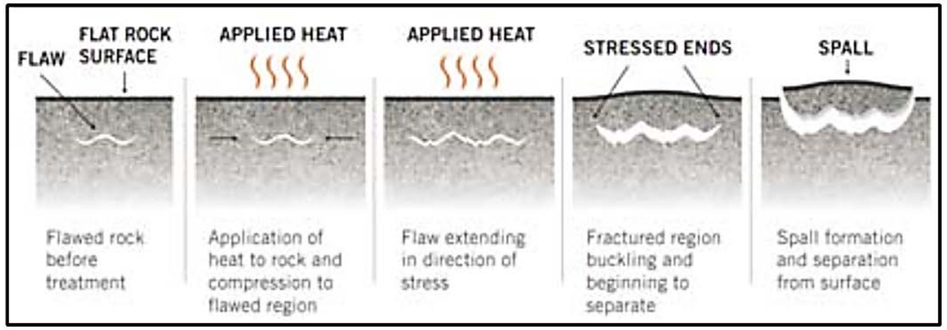
- Contact-free technology with coiled tubing used for continuous penetration
- Can reduce abrasion and tripping time.
- Fuel, oxidizer and cooling water are injected through respective channels in the coiled tubing to the downhole combustion chamber.
- Chemical reaction between the fuel and the oxidizer in the chamber is initiated by an electric spark.
- Reaction products, water and carbon dioxide, discharged from nozzle in BHA to impinge the rock.
- Cooling water flows out from the lateral outlet of coiled tubing and returns to the surface through the annulus



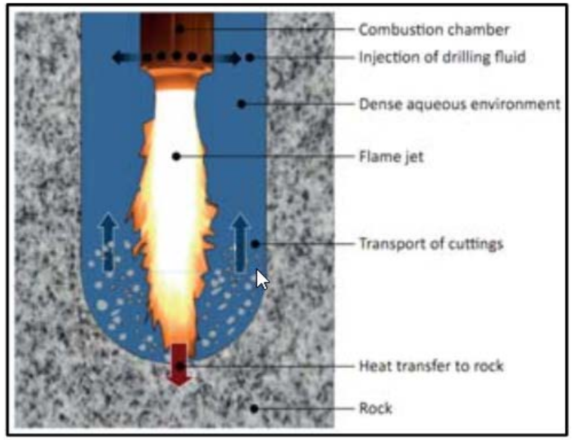
Numerical Analysis of the Two-material Downhole Flow Field in Hydrothermal Jet Drilling, Zehao Lyu, Xianzhi Song, Gensheng Li, Zhongwei Huang, Haizhu Wang, Xiaodong Hu,Yu Shi, GRC Transactions, Vol. 41, 2017

Hydrothermal Spallation

- **Thermal spallation drilling uses a large, downhole burner, much like a jet engine, to apply a high heat flux to the rock face. This drilling technology is based on thermal processes of rock spallation and fusion.**



Rauenzahn, R. M. (1986). Analysis of Rock Mechanics and Gas Dynamics of Flame-Jet Thermal Spallation Drilling. Doctoral Thesis, Massachusetts Institute of Technology.



Hydrothermal Spallation Drilling Technology: An Alternative Method of Geothermal Energy Development Mingbo Wang, Songyang Zhang and Gouemo Niangui Josue Edwin

Tobias Rothenfluh (2013): Heat Transfer phenomena of supercritical water jets in hydrothermal spallation drilling. PhD Thesis, ETH Zurich, Institute of Process Engineering.

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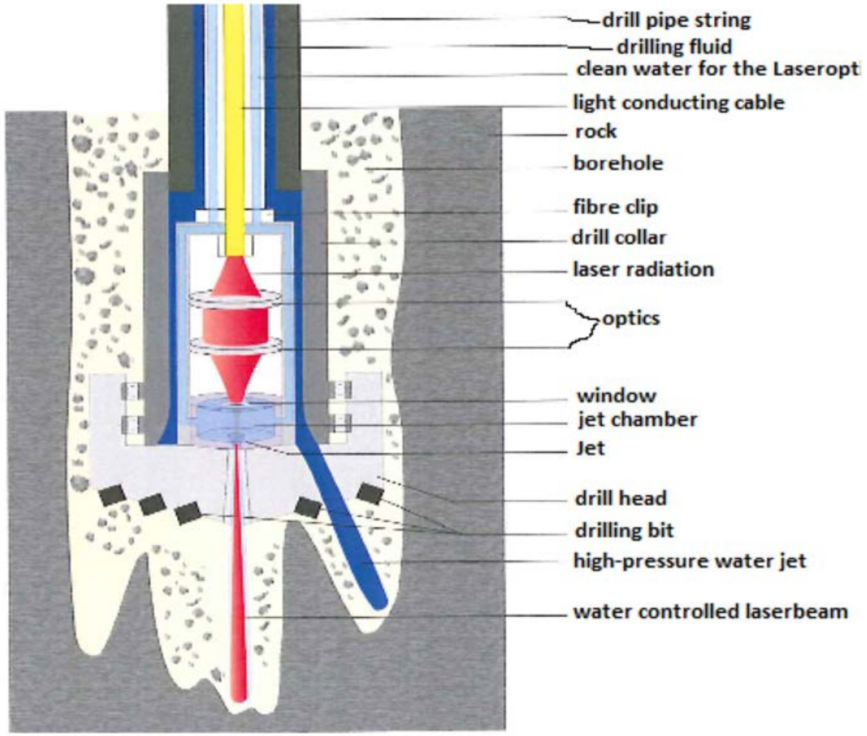
Laser Drilling

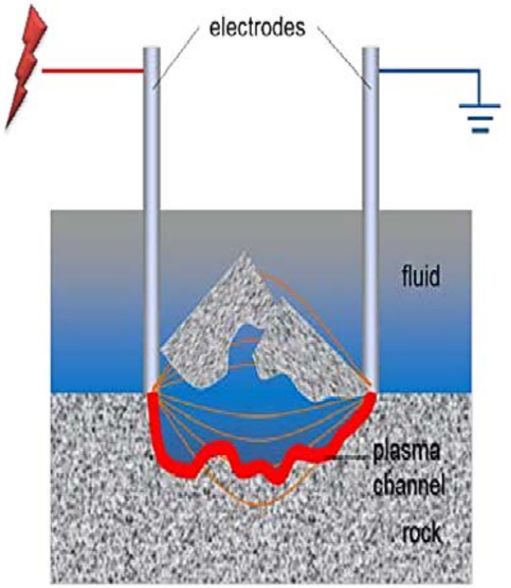
- Mechanically Assisted Laser Drilling
- Laser source of up to 30kW transfers energy to the bit face
- Addition of thermal load accelerative pulverization
- Thermal stresses

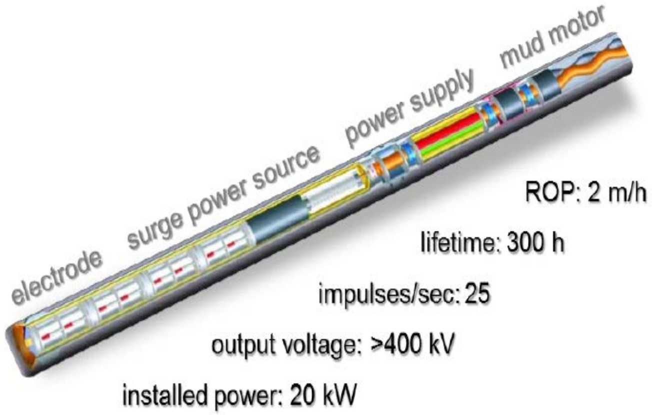


Newer Generation Drilling Technologies

Electro Impulse Technology (EIT)

- EIT – High Electric Voltage Impulses
- Generation of transient voltages in the range of 600 kV with a rise time of less than 120 to 150 ns.
- Discharge voltage causes stresses that surpass rock strength
- Conventional delivery system
- Driven by mud motor which powers the electrical generator





Thermal Shock Drilling

- Generate thermal-shock failure by depressurization, boiling and cooling to fracture or weaken rock
- Depressurization achieved by Venturi mechanism installed in a PDC bit.
- "Drilling mode" uses a conventional PDC bit drilling mechanism.
- In depressurizing mode, pressure reduced downstream of Venturi nozzle, vacuuming drilling fluid from suction line that leads center suction port.

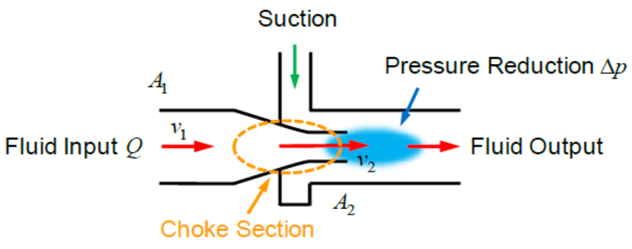
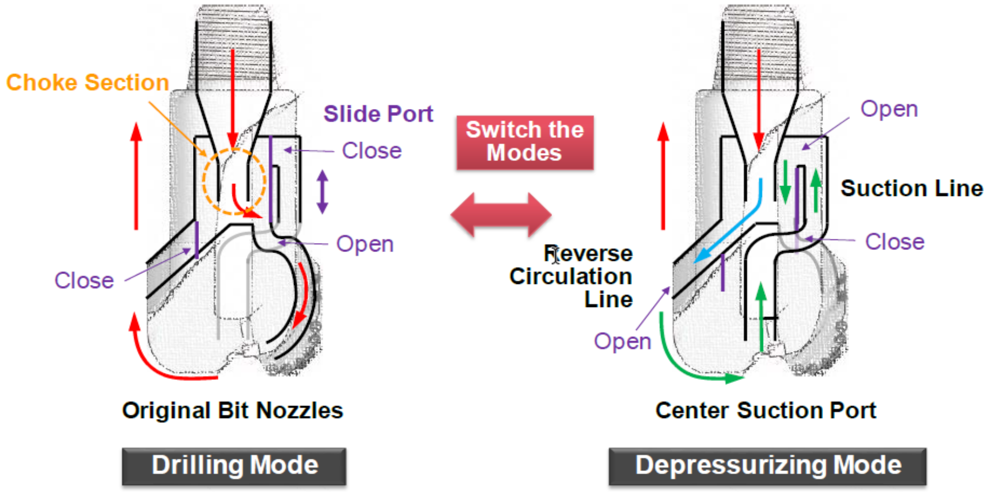
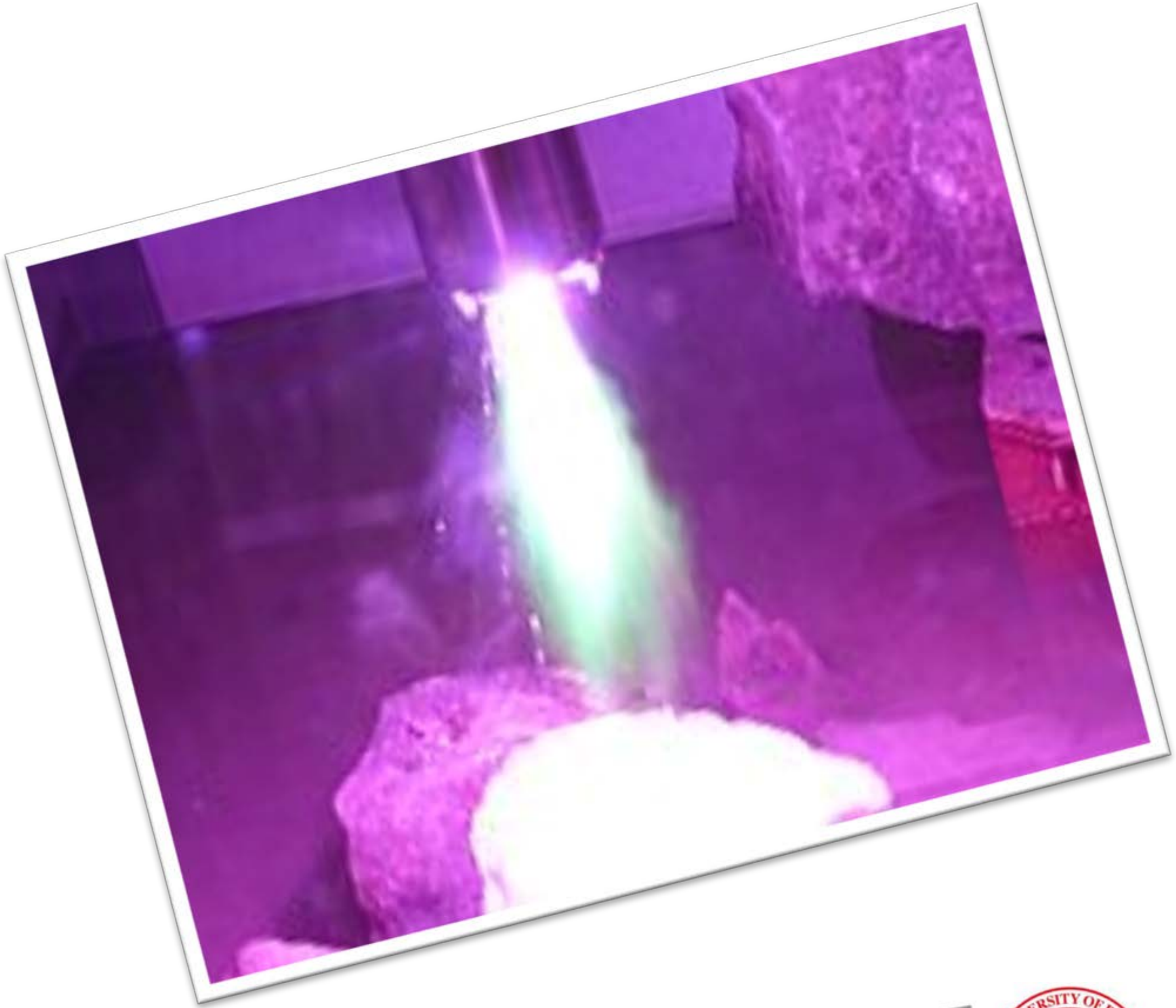


Figure 2: Principle of the Venturi effect.



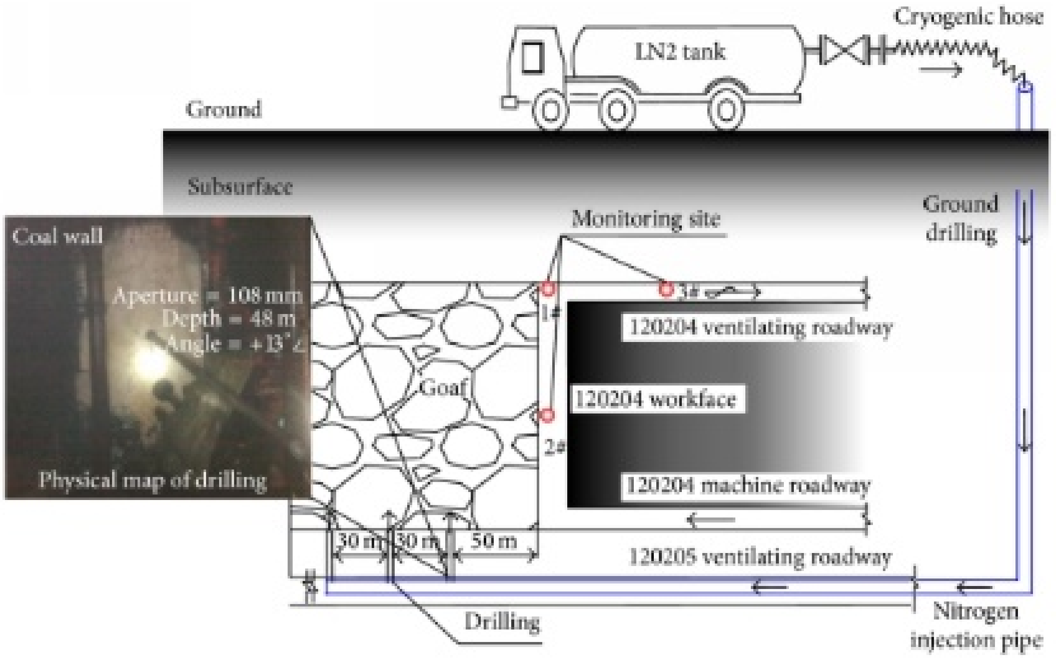
Electric Plasma

- Higher drilling energy efficiency
- Continuous drilling process without replacement of mechanical parts
- Constant casing diameter
- Effective transport of disintegrated rock



Drilling with Liquid Nitrogen

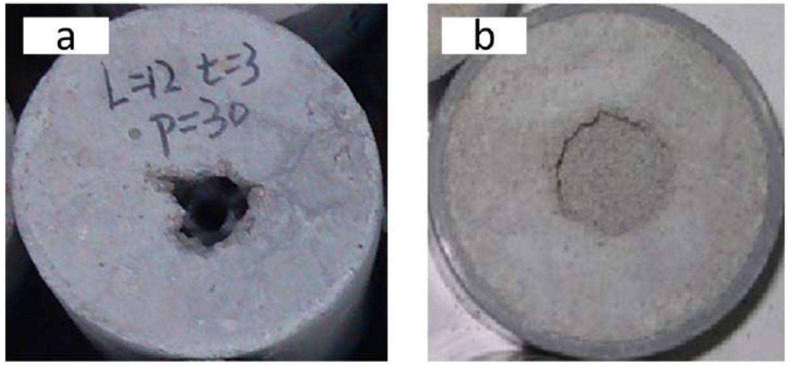
- LN_2 can be used as the drilling fluid
- Impinging on the rock surface through the nozzles on bit.

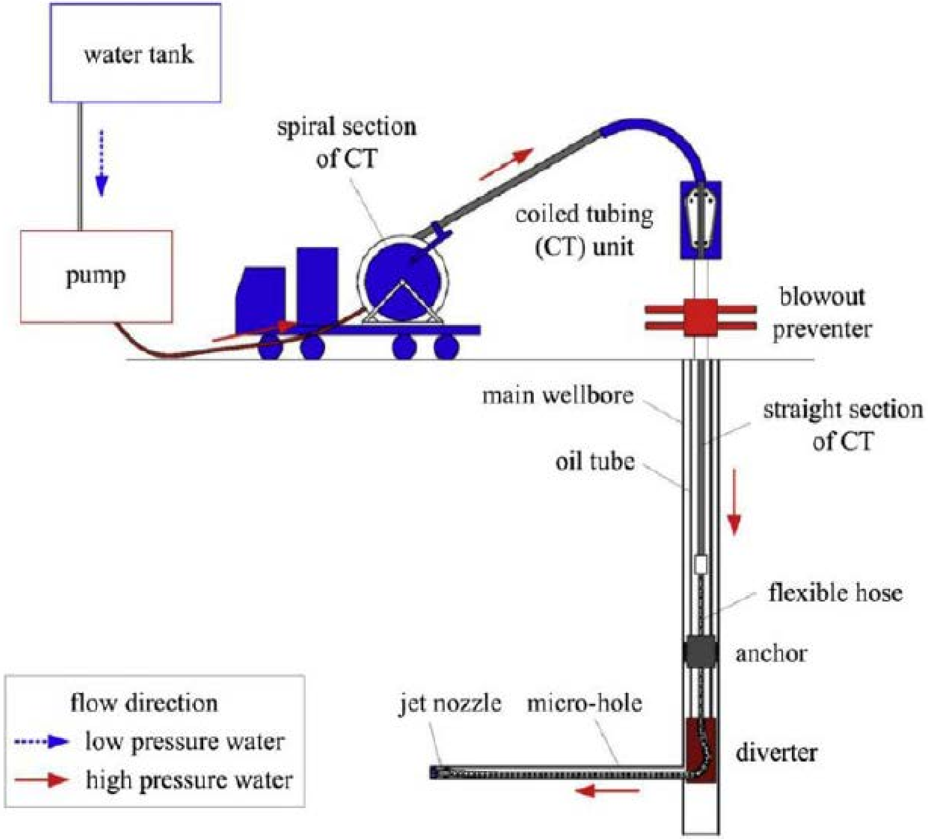


Li, R. Wu, L., and Huang, Z. 2018. Heat Transfer Study of Liquid Nitrogen Jet Impinging on Granite Rocks, GRC Transactions, Vol. 42.

Drilling with Abrasive Jetting

- Rotating Jet Method
- Abrasive Water Jet
- **Hydra-jet Lateral Drilling**



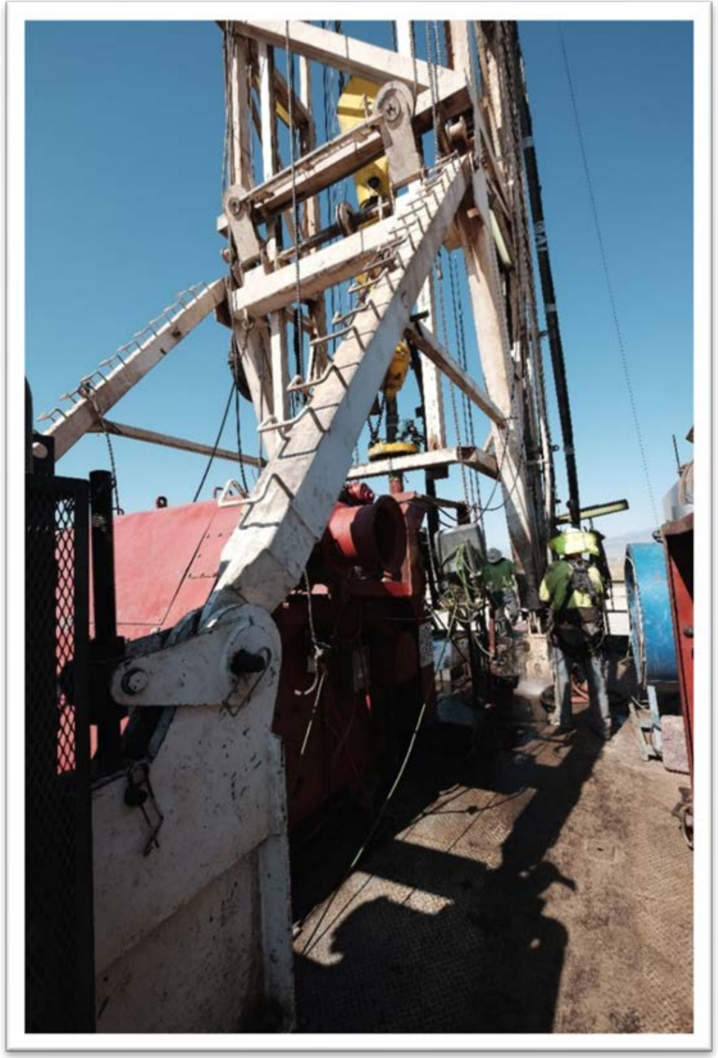


Huang, Z., Wu, X., Li, G., Zhang, S., and Zhang, H. 2018. The Hydra-Jet Methods for Oilfield Geothermal Production Enhancement, GRC Transactions, Vol. 42.

Mechanical Specific Energy and At-the-Bit Measurements – The Bit as a Laboratory

Mechanical Specific Energy

- Mechanical Specific Energy (MSE)
- Premise is conservation of energy.
- Energy and work input and expended to cut a volume of rock conserved in closed system.
- ROP is impacted by how much effective energy is actively applied to break and remove rock



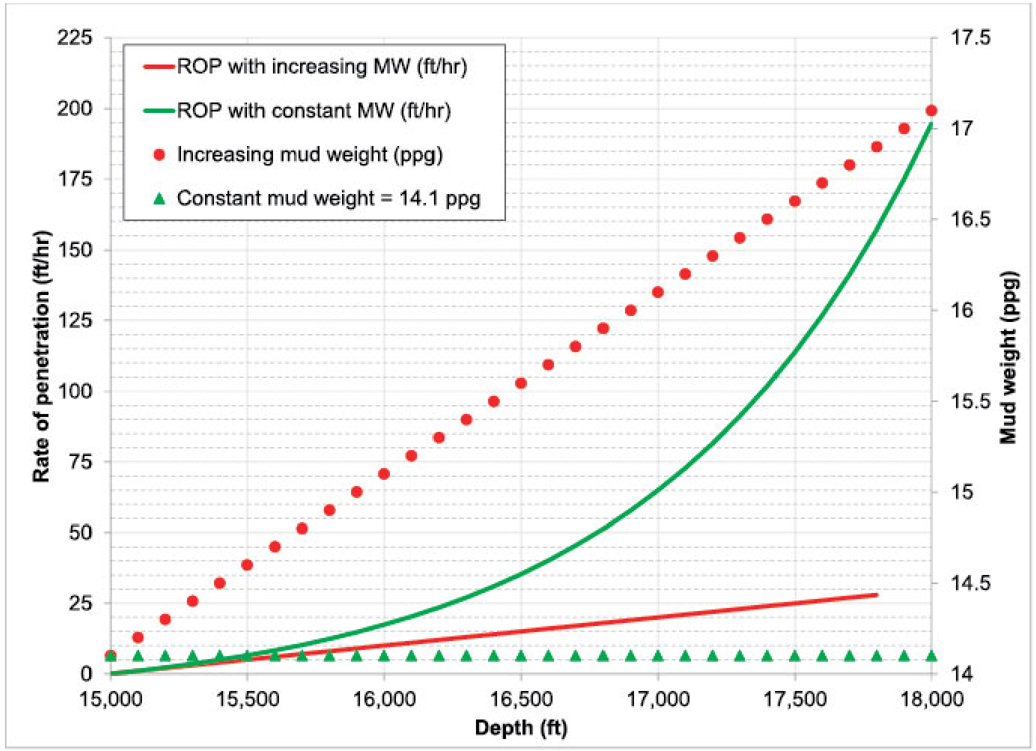
Mechanical Specific Energy

"Closed" System

- Energy From Top Drive Or Rotary Rig
- Energy From Circulation Of Drilling Fluids And Cuttings
- Losses - Friction, Drillstring Vibrations, Heat, Sound, Bit Balling
- Mechanical Disaggregation/ Removal Of Rock

Mechanical Specific Energy

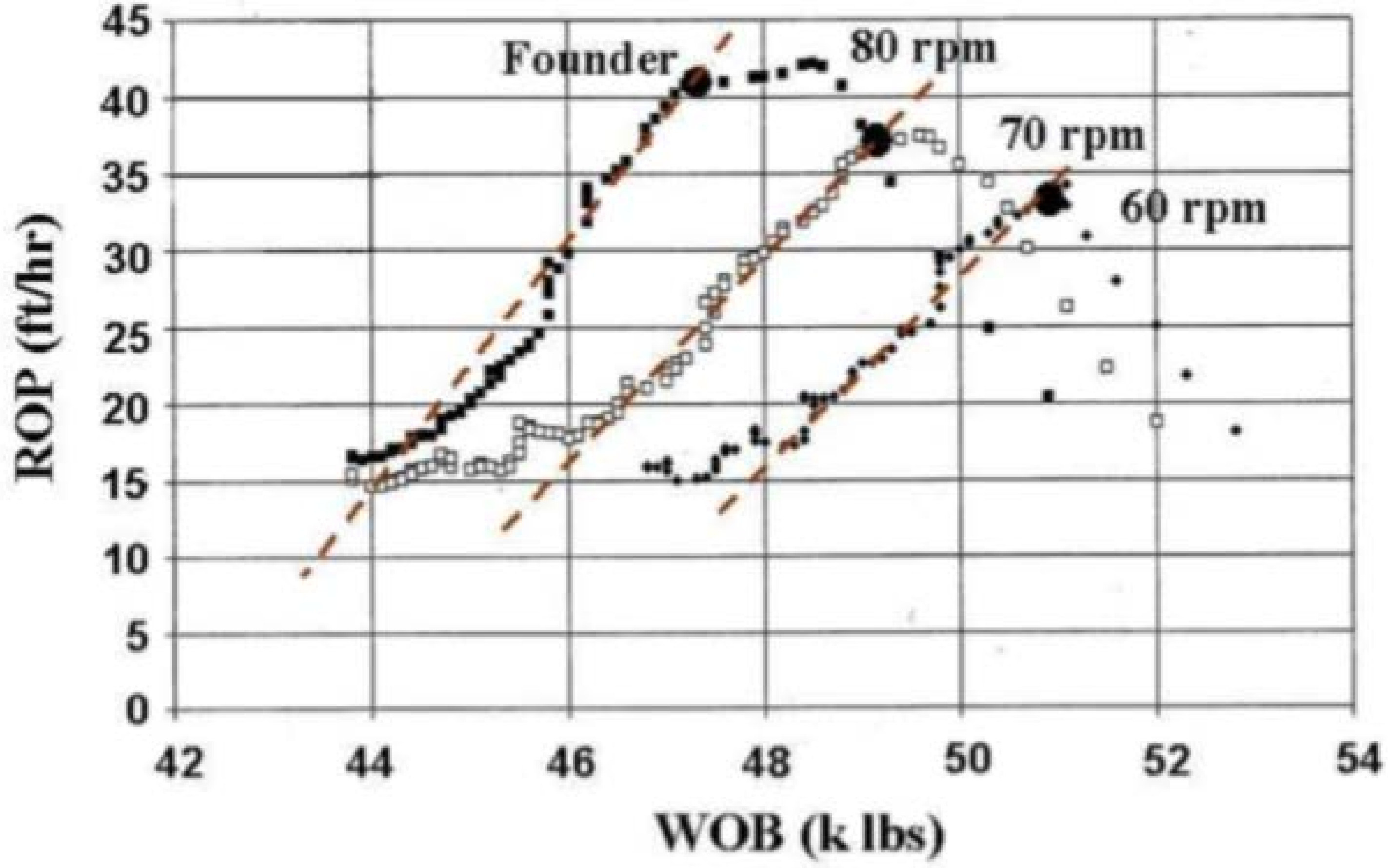
- Drillers interested in improving footage
- Widely used to improve performance and provide real time feedback
- Feedback loop to driller indicates operational issues, formation transitions
- ROP improvements attributed to adjusting drilling parameters (WOB and RPM) via bottomhole feedback



Mechanical Specific Energy

- Re-engineering technical limits that hinder performance - increasing top drive limits, altering bottomhole design specifications and redesigning bits
- Concurrent use of MSE and other at-the-bit measurements for inferring mechanical properties in real time

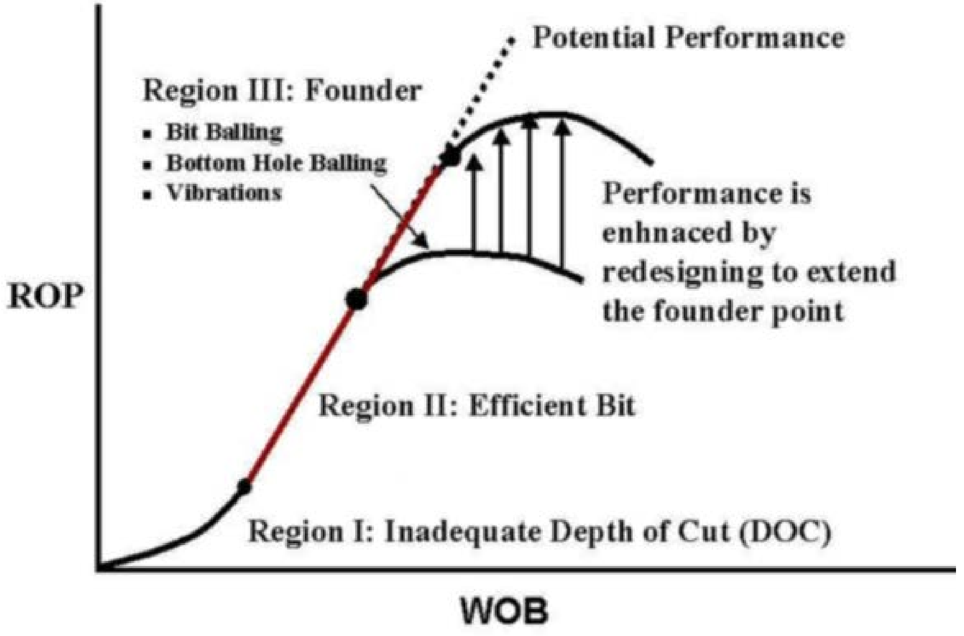
Parameters Governing ROP



After Dupriest and Koederitz, 2005

Three Regions of Efficiency

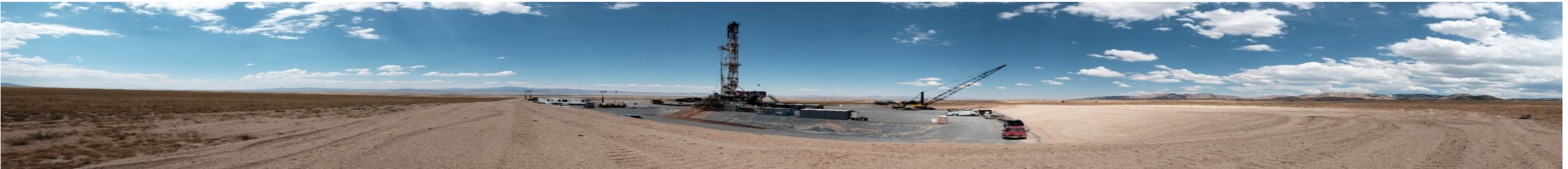
- Linear increase in ROP
- Bit works at maximum efficiency
- Increase in input energy results in proportional increase in ROP
- All systems exhibit
- Every system has limit
- Curve starts to flatten out, and increase in input energy no longer increases ROP
- Founder point of system



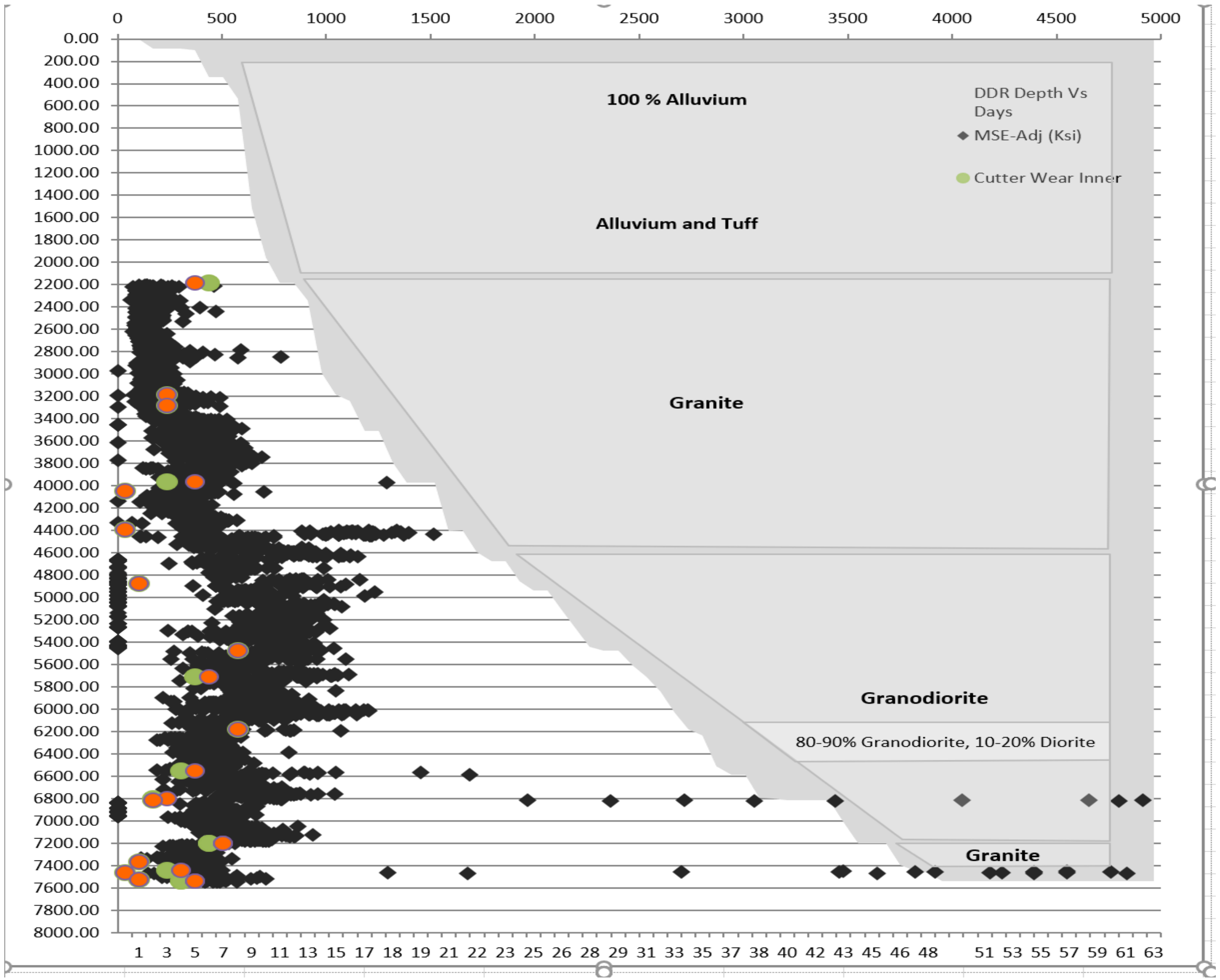
After Dupriest and Koederitz, 2005

FORGE Example Phase 2B Activities - Drilling

- Spud 17-1/2-inch on July 31, 2017
- Cement 13-3/8-inch casing on August 2, 2017 at 336 ft
- Cement 9-5/8-inch casing on August 7, 2017 at 2,172 ft
- TD at 7536 ft MD (7528 ft TVD) on Sept. 14, 2017
- Rig released on September 27, 2017



Drilling Program – MSE Expenditure



Why is the Torque So High?

IADC 647 Smith® FHI 30 Insert bit with outermost broken teeth

Why is the Torque So High?

PDC 7 bladed dual row 13 mm cutters showing outer damage – chipped teeth

Why is the Torque So High?

Polished Stabilizer

Energy Expenditure

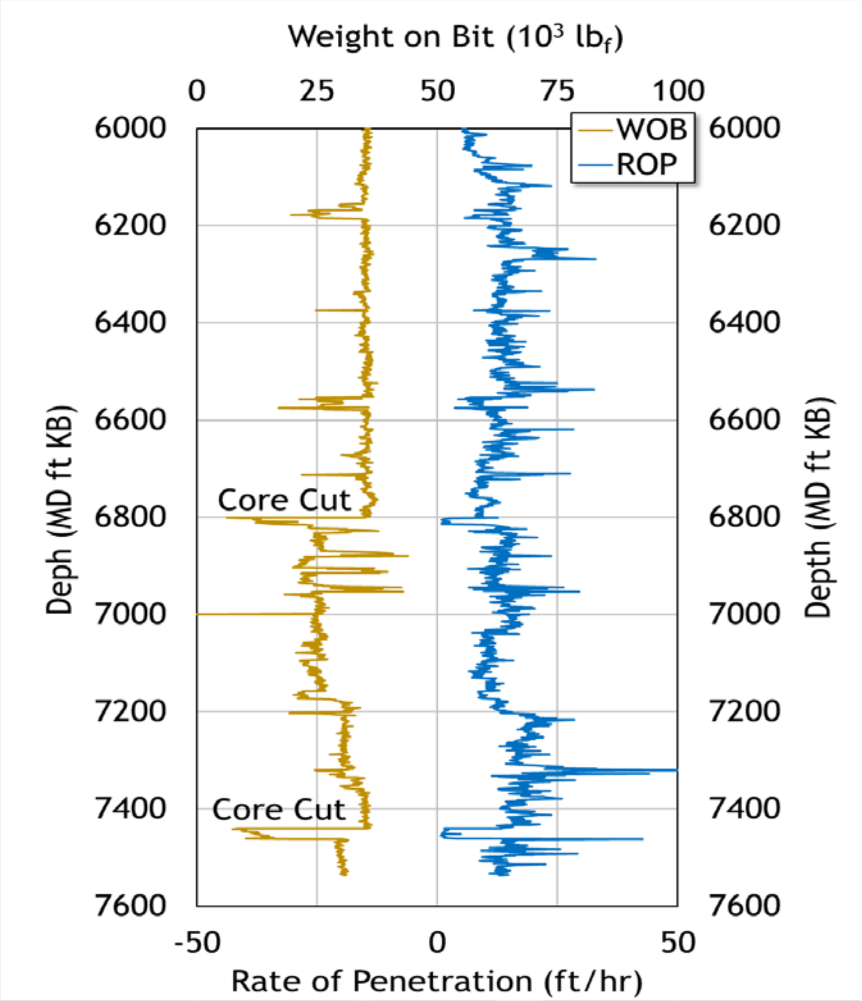
$$\mathrm{MSE} = \frac{480 \times \mathrm{T} \times \mathrm{RPM}}{\mathrm{d}_{\mathrm{bit}}^2 \times \mathrm{ROP}} + \frac{4 \times \mathrm{WOB}}{\pi \mathrm{d}_{\mathrm{bit}}^2}$$

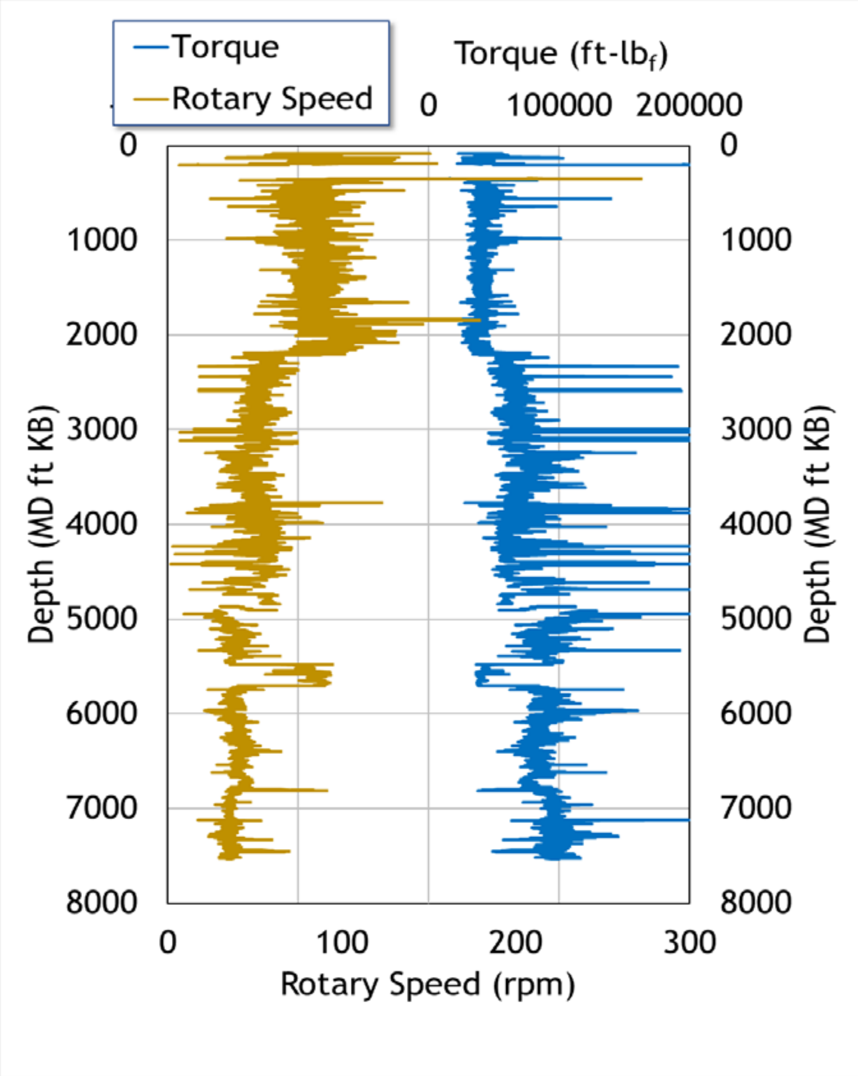
MSE	Mechanical Specific energy (psi)
T	torque (ft-lb_f)
RPM	revolutions per minute (1/minute)
d_{bit}	bit diameter
ROP	rate of penetration (ft/hr)
WOB	weight on bit (lb_f)

Various MSE Equations

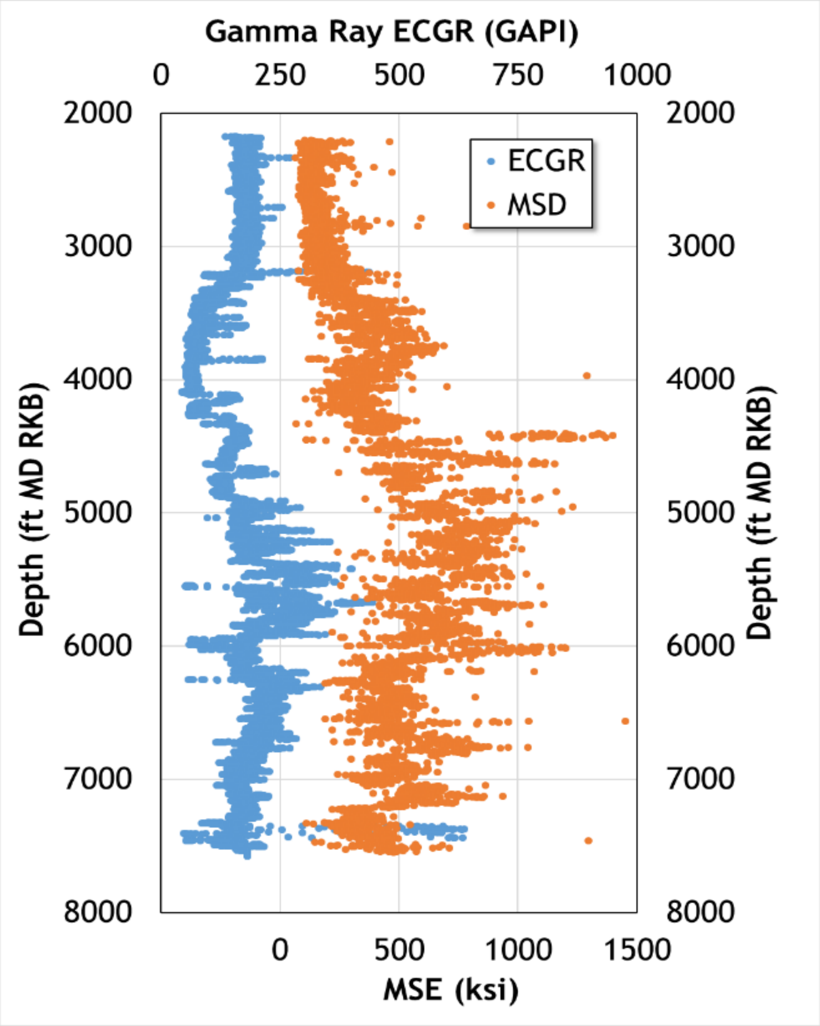
Channel Name	Calculation Type	Description
MSE_Dupriest $MSE_{psi} = \left(\frac{480 \times TOR \times RPM}{Dia^2 \times ROP} + \frac{4 \times WOB}{\pi \times Dia^2} \right) * 0.35 / 1{,}000$	Mechanical Specific Energy	This is the Wider Windows (UT) version of the standard basic Teale MSE Equation that was published in 1965 using surface torque and surface RPM. The MSEadj is (0.35*) multiplied to the Teale MSE Equation.
MSE_Pason $MSE[ksi]_{Downhole} = \frac{4 * WOB}{\pi * D^2} + \frac{480}{D^2} \frac{(N + Kn * Q) * ((T_{max} / \Delta P_{max}) * \Delta P/1000}{ROP}$ Standard Equation - Teale $MSE[ksi] = \left[\frac{40{,}000 \cdot WOB}{\pi D^2} + \frac{480{,}000}{D^2} \frac{(N + K_N \cdot Q \cdot 1000) \cdot ((T_{MAX} / \Delta P_{MAX}) \cdot \Delta P / 1000)}{ROP} \right] \times 0.14504$	Mechanical Specific Energy	MSE using a downhole motor for extra bit rpm and torque. NOTE: This equation must be updated for each BHA.
MSE_Hyd $MSE_{Simplified} = \frac{(550 \cdot 3600 \cdot \Delta P \cdot Q/1714))}{Area \cdot ROP} = \frac{550 \cdot 3600}{1714} \cdot \frac{Q}{Area} \cdot \frac{\Delta P}{ROP}$ MSE — Mechanical Specific Energy — psi Q — Total Mud Flow Rate — gal/min Area — Bit Area — inches² ΔP — Differential Pressure — psi ROP — Rate of Penetration — ft/hr	Mechanical Specific Energy Simplified using Hydraulics	MSE using surface hydraulic power input ((flowrate*differential)/1714) as the input power as opposed to mechanical power using ((torque*rpm)/5252).
DSE $DSE = \frac{WOB}{A_B} + \frac{120 * \pi * RPM * T}{A_B * ROP} - \frac{1{,}980{,}000 * \lambda * HP_B}{ROP * A_B}$ **SPE 116667** **Identifying Inefficient Drilling Conditions Using Drilling-Specific Energy** Miguel Armenta, SPE, Shell EPT-WT	Drilling Specific Energy	MSE defined as the work done to excavate and remove, underneath the bit, a unit volume of rock. Teal's original equation was modified to include a bit hydraulic-related term on the MSE correlation. DSE use the terms included on Pason MSE equation and adds a bit hydraulic-related term. The 1,980,000 is a unit conversion factor. There is also a dimensionless bit-hydraulic factor depending on the bit diameter. The ratio of bit hydraulic power and bit area is the bit HSI (hp/sqinch). ROP used here is the instantaneous ROP in ft/hr called "ROP - Fast.ft/hr". NOTE: This equation must be updated for each BHA.

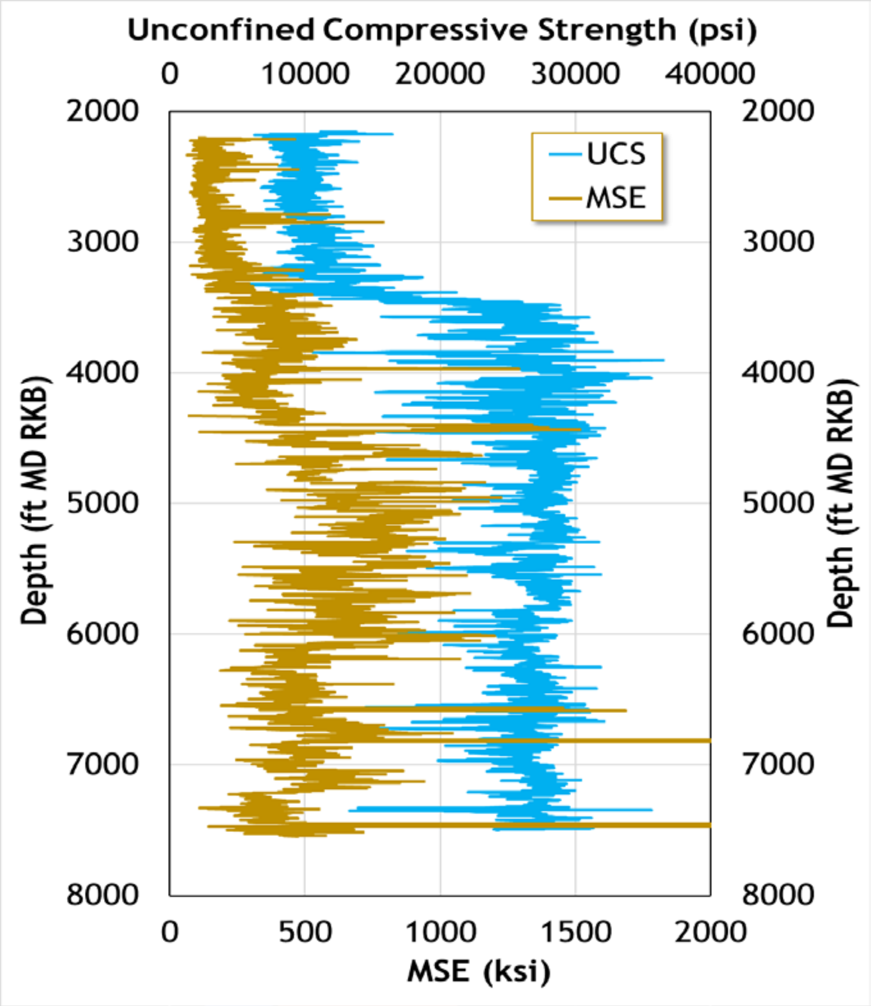
Drilling Parameters



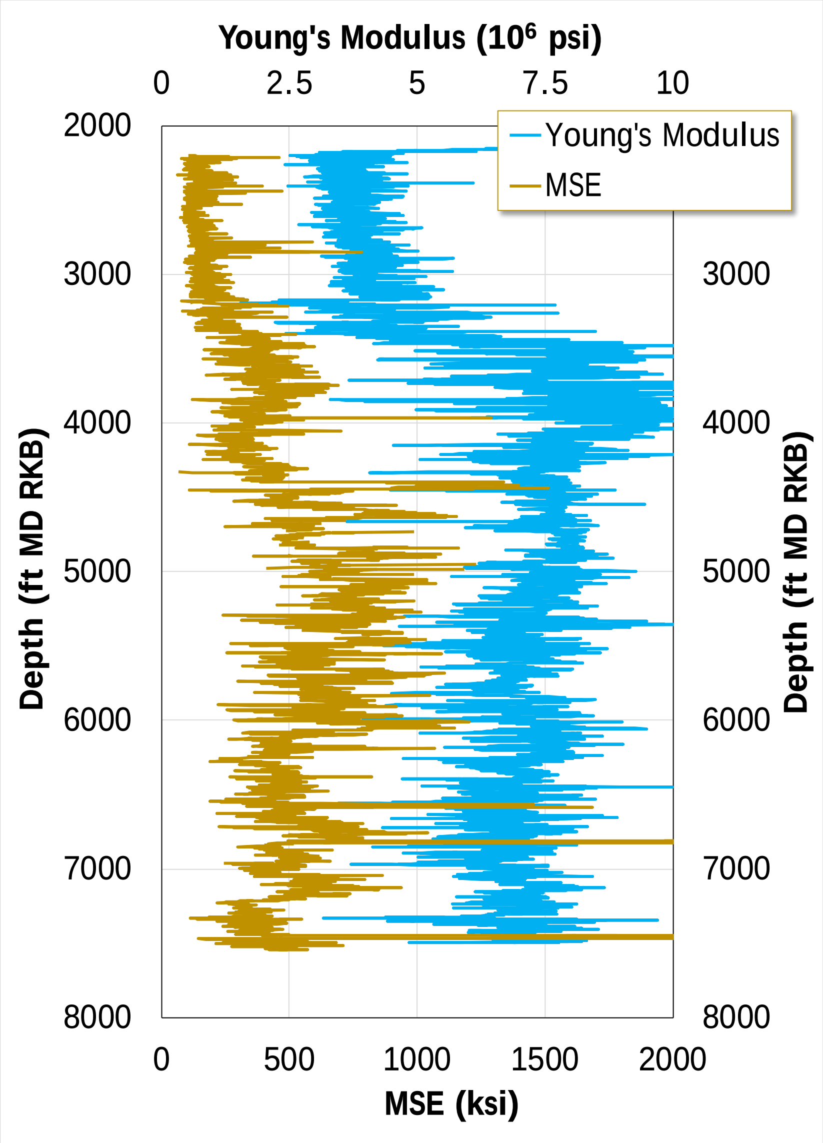


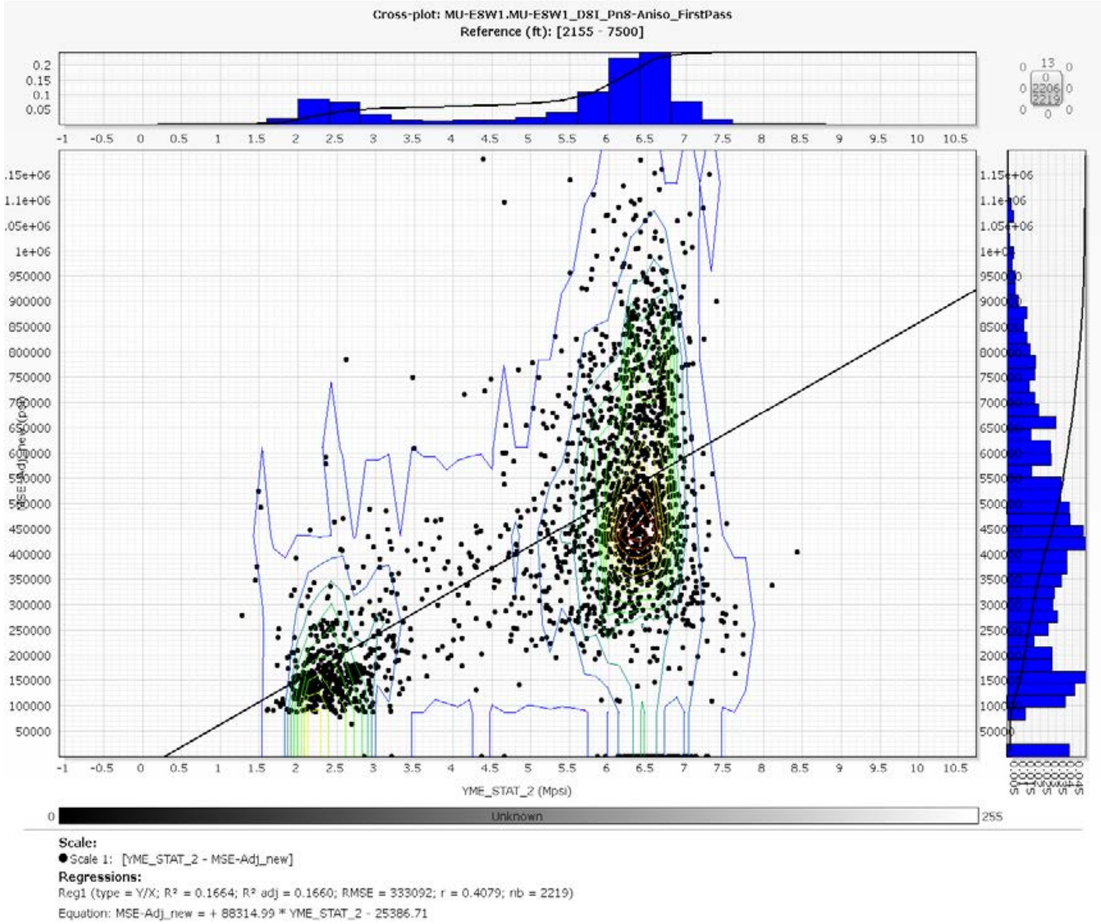
Unconfined Compressive Strength



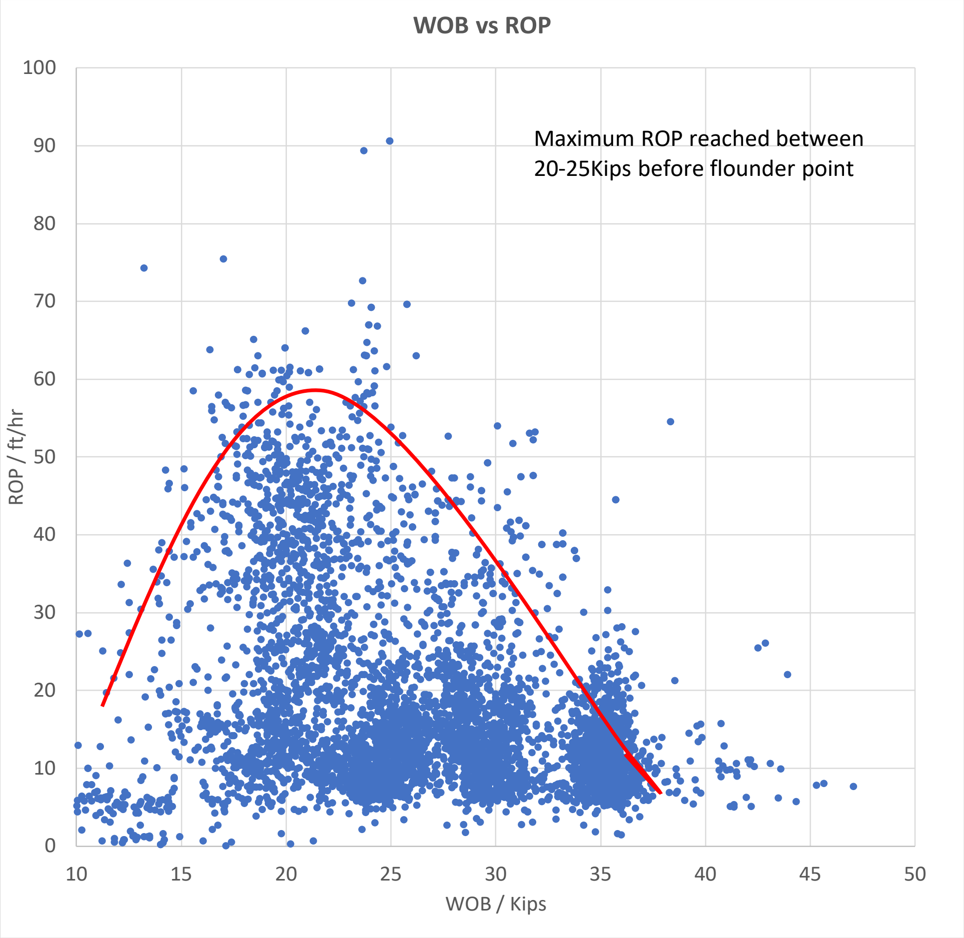


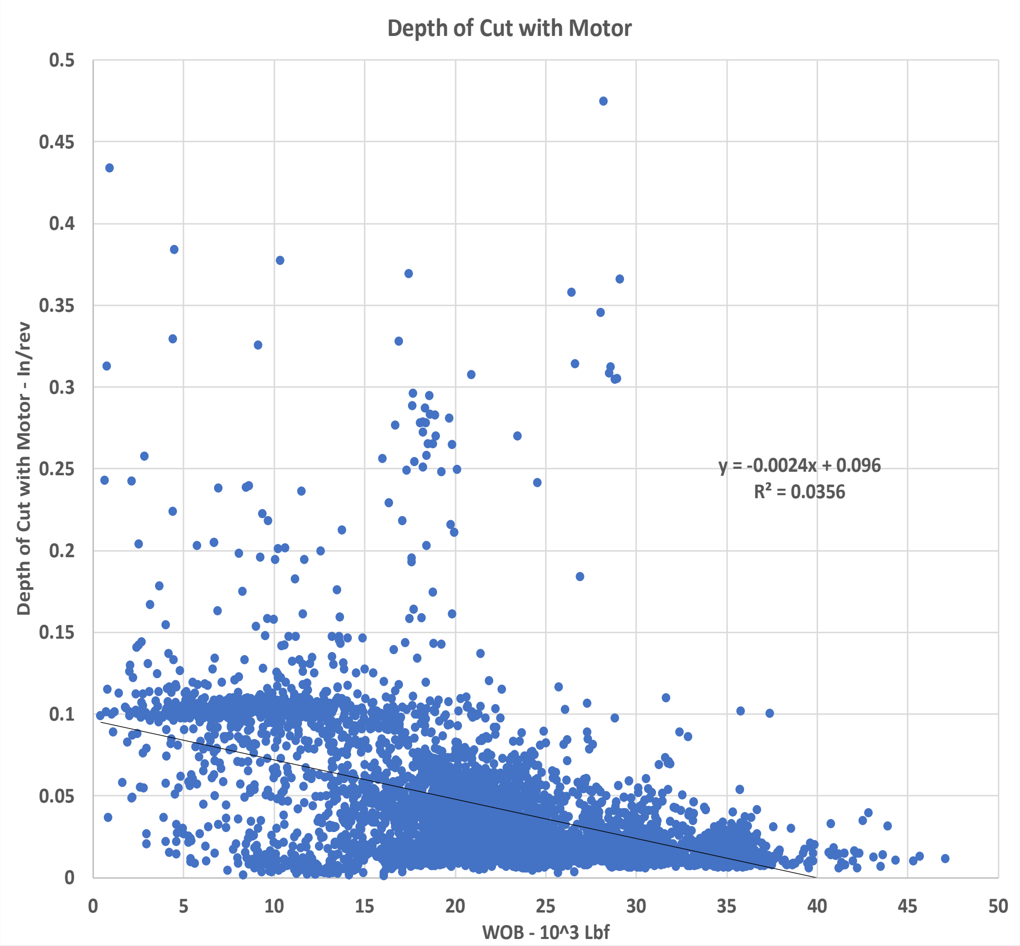
Young’s Modulus





Drilling Performance





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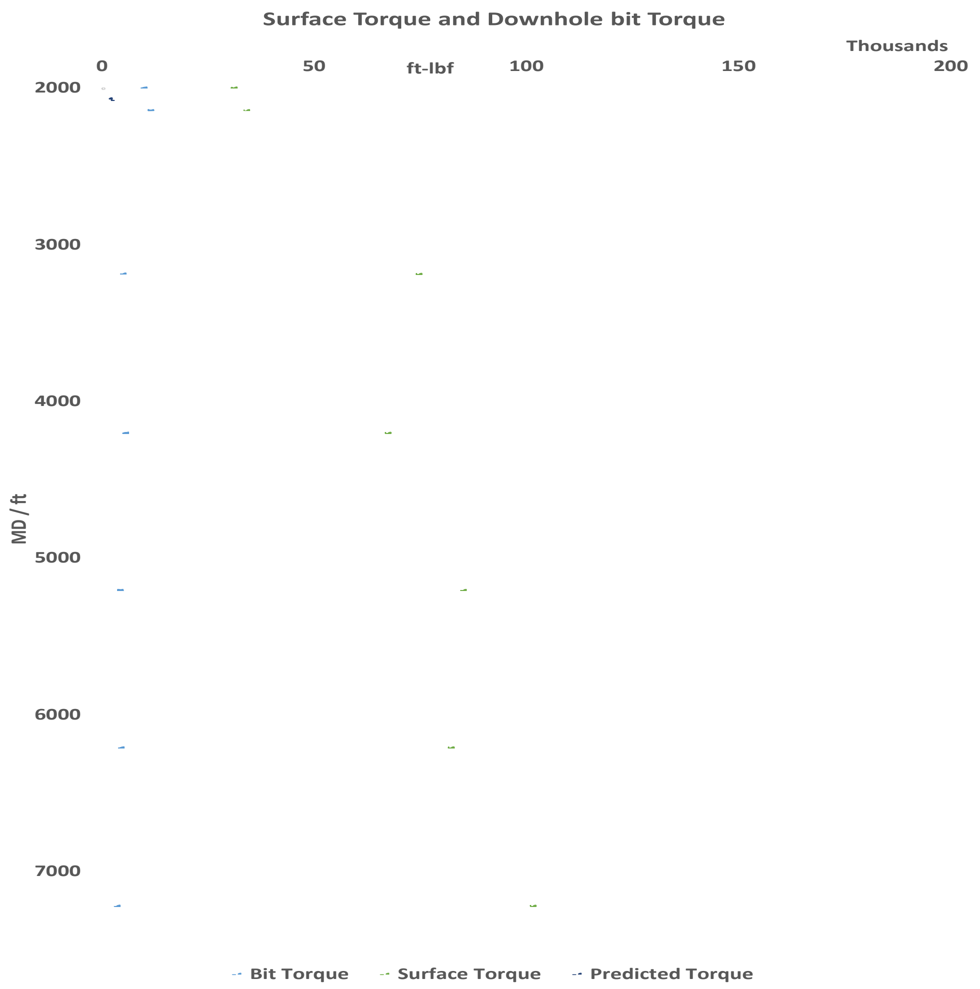
Drilling Performance



Significance of MSE

- Energy based measurements to predict and determine dynamic rock properties, ahead of in depth formation logging and determine variations from actual.
- Gather performance related lessons learned for changes in formation to apply in real time – drill off tests
- Optimize BHA by understanding drilling dynamics – BHA whirl, Stickslip, bit balling and Lithology changes
- Proactive stimulation (completions) modelling while drilling – Proppant, HP, Volumes, etc.

Geothermal Drilling in 2019

- Lost circulation
- Wellbore stability
- Excessive torque and drag
- Stuck pipe
- Measurements
- Difficulty in getting logging tools to bottom
- Difficulty in breaking circulation after trips
- ROP
- Motors
- Fully Using Information