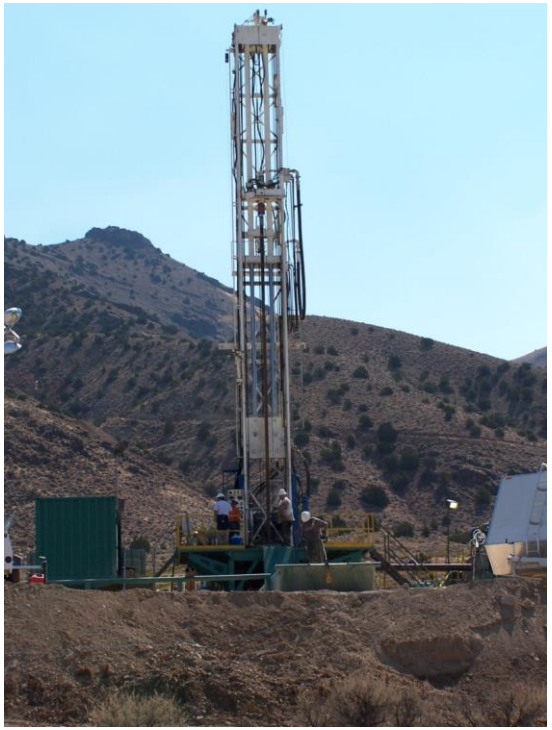

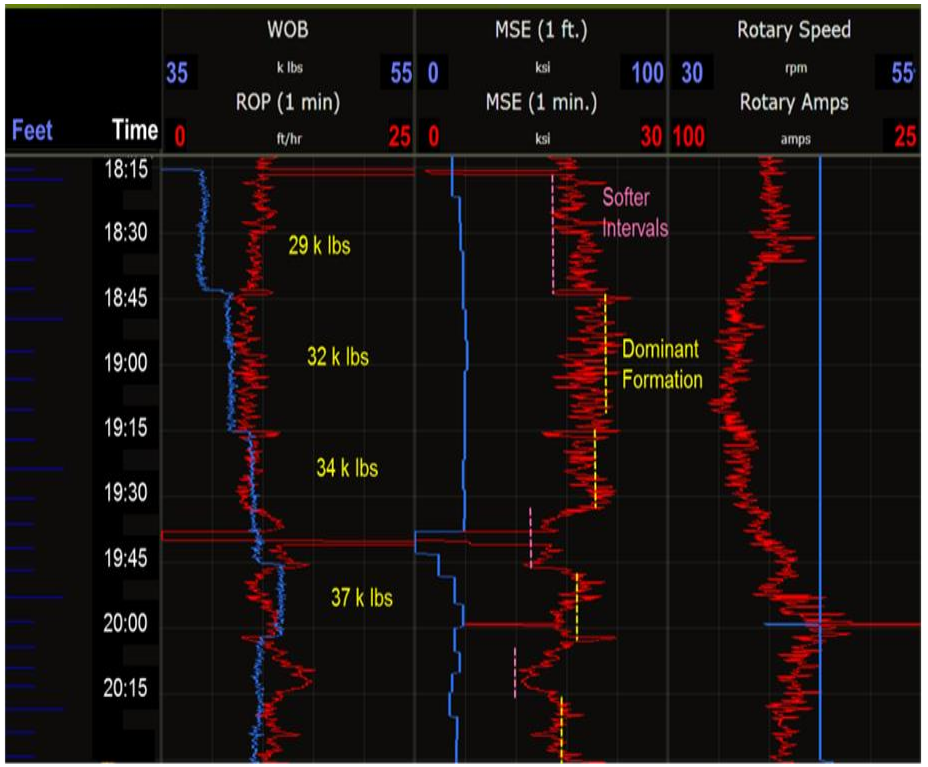

Evaluation of Emerging Technology for Geothermal Drilling and Logging Applications

Project Officer: Eric Hass / Lauren Boyd

Total Project Funding: $375,000

May 13, 2015

Steve Knudsen / Doug Blankenship

Presenter: Doug Blankenship

Sandia National Laboratories

High Temperature Tools, Drilling Systems

Project objective

- Like all projects in this track, the global intent is to lower the cost of geothermal wells
  - Necessary for Hydrothermal / EGS / and Low Temp
- Development and adoption of new geothermal drilling technology is hampered by the sheer lack of development activity in comparison to other drilling sectors
  - Size of industry impacts adoption and qualification for numerous reasons
- Where possible - leverage what others have done

Project objective (cont.)

- Purposefully identify technologies and processes in comparable drilling industries that can provide benefits in the near-term
  - Oil & Gas obvious, but include mining, construction, …
- Includes investigation of processes as well as technology
  - Not just better improved technologies but learnings as well
- Technologies and processes investigated must be successful in other industries
  - What can be adopted, with or without modification for geothermal conditions

Relevance/Impact of Research

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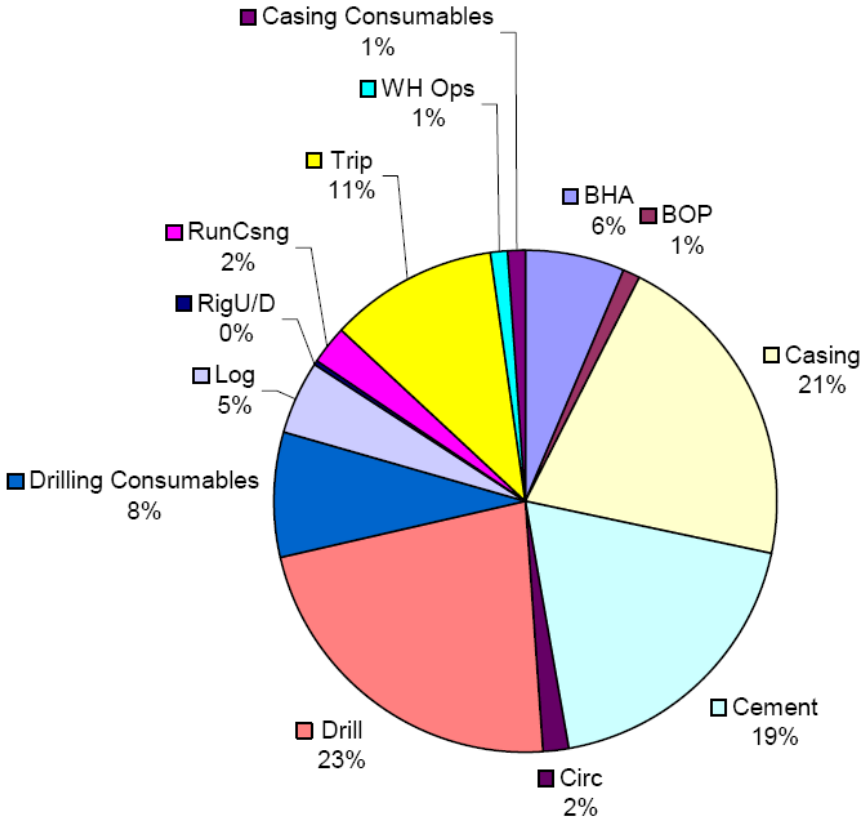
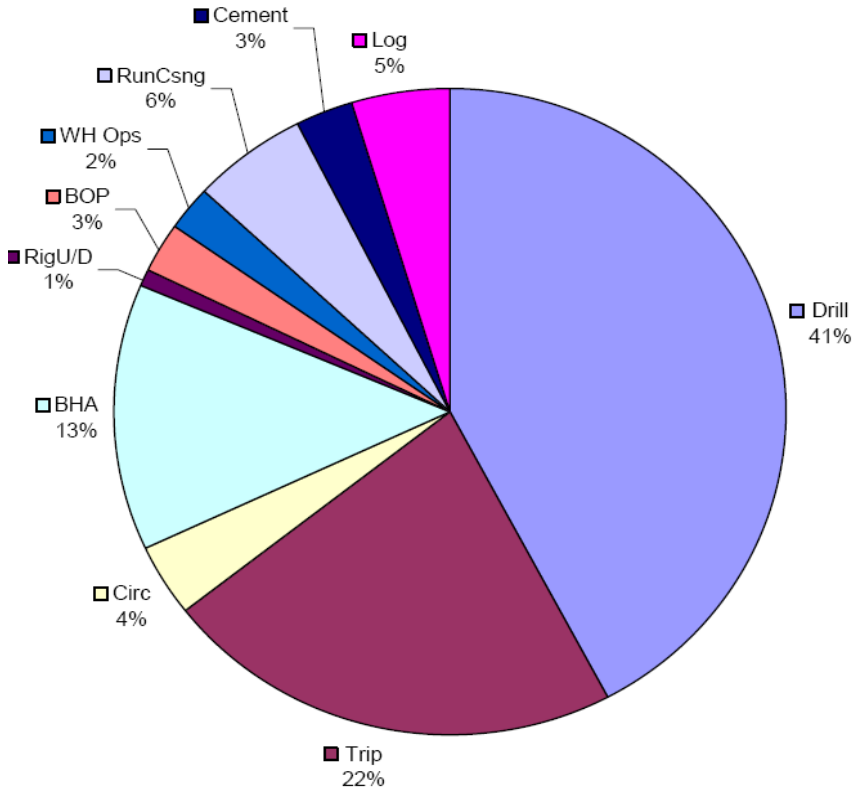
Many Opportunities to Target, But No "Silver Bullets"



Well cost (%) breakdown by task.



Well construction task time percentages.

Polsky, Y., et.al., 2008, *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report*, SAND2008-7866 (2008)

Scientific/Technical Approach

- Early project approach too focused on a “gadgets”
  - Redirected efforts
- Working group formed to decide project focus
  - Ormat Technologies
    - Ormat is an active partner and funding their participation internally
  - Engagement with Texas A&M
    - Fred Dupriest, TAMU / ExxonMobil retired
- Active monitoring of drilling has been shown to have real impact in the O&G sector
  - e.g., ExxonMobil “Fast-Drill” / “Limiter Redesign”
  - Applicable to the geothermal sector without adapting to conditions
- By monitoring drilling performance and understanding the data one can identify what is limiting performance

Mechanical Specific Energy Monitoring the Current Focus

Mechanical Specific Energy (MSE)

$$MSE = \left(\frac{F}{A}\right) + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right) in \cdot lb/in^3$$

Where

F = weight-on-bit (WOB)
A = area
N = bit rotation rate (RPM)
T = torque-on bit (TOB)
u = rate-of-penetration (ROP)

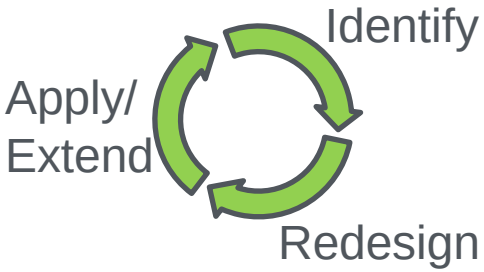
MSE is a measure of the efficiency of the drilling process, basically:

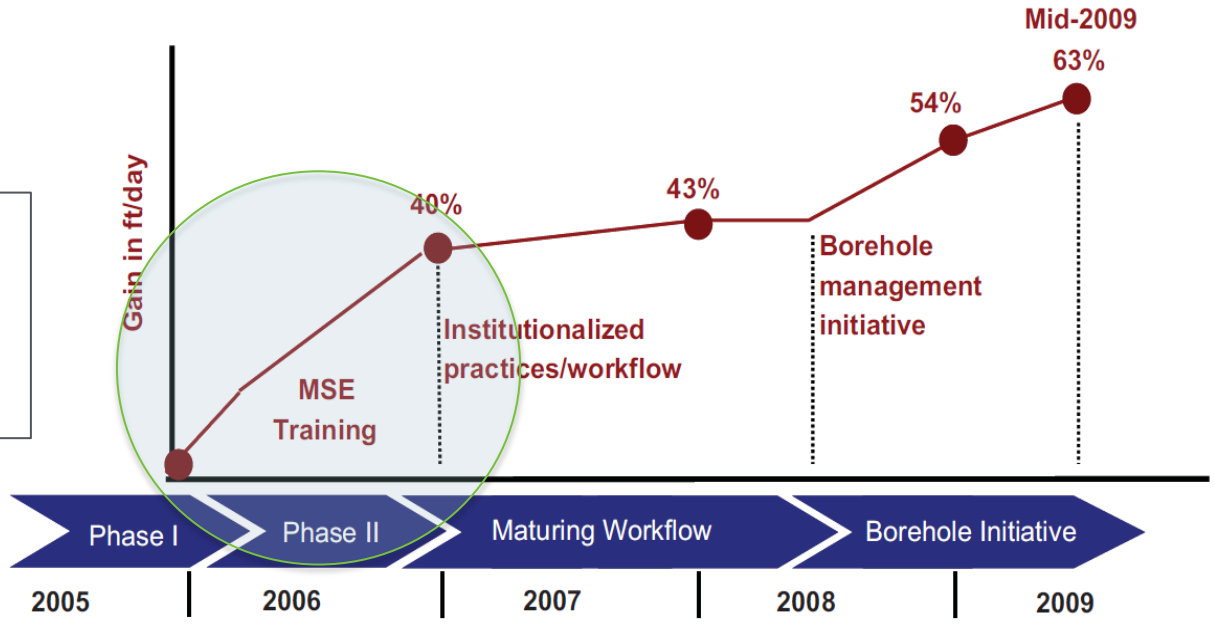
MSE = Input Energy / ROP

Scientific/Technical Approach

"Fast-Drill" workflow: **Identify, Redesign, Extend**

- MSE monitoring is used to identify bit related dysfunctions
  - Balling
  - Vibrations
  - Bit Dulling
- Borehole Quality Initiative tries to address other non-bit related limiters
  - Borehole instability

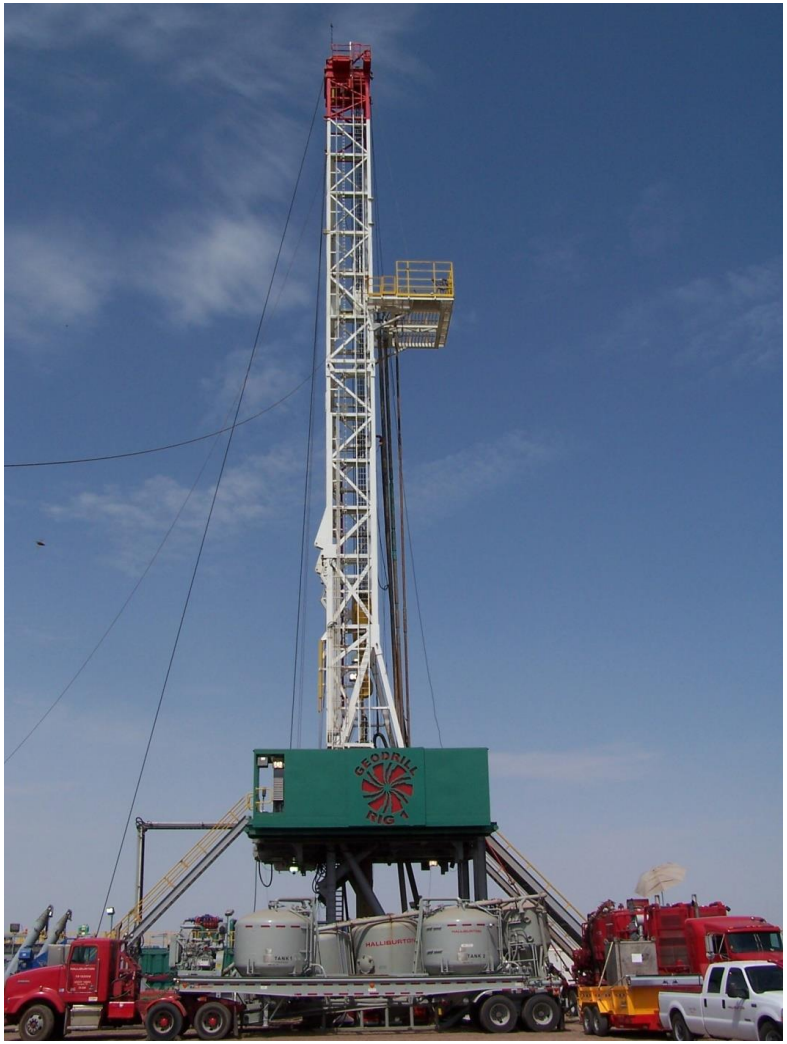




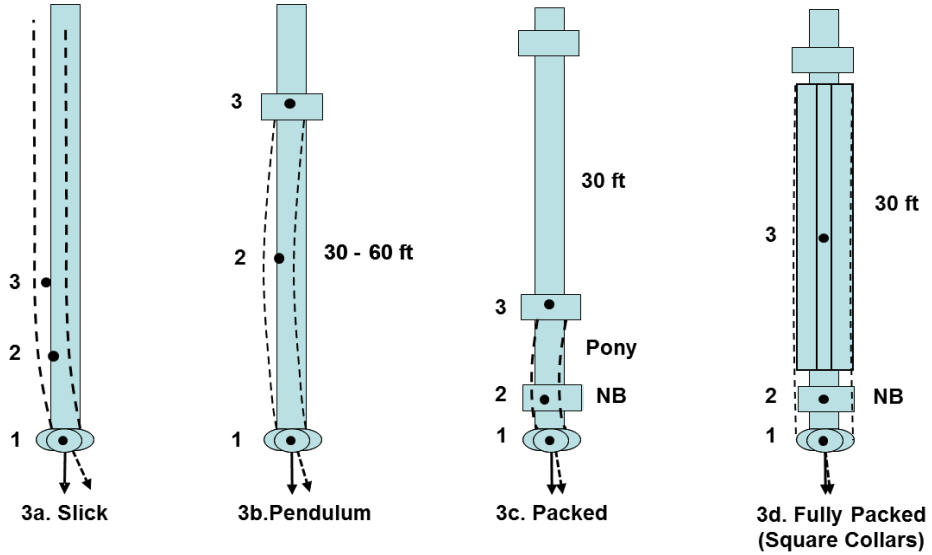
Dupriest F., et al., *Borehole-quality design and drilling practices to maximize drill-rate performance*, in *SPE Annual Technical Conference and Exhibition* 2011: Florence, Italy.

Accomplishments, Results and Progress

- Ormat began monitoring MSE and displaying / transmitting information on selected rigs in FY13
- MSE training conducted for drilling and exploration personnel
- Test of active MSE control of drilling activities conducted on at McGinness Hills geothermal field
- Results reviewed and published



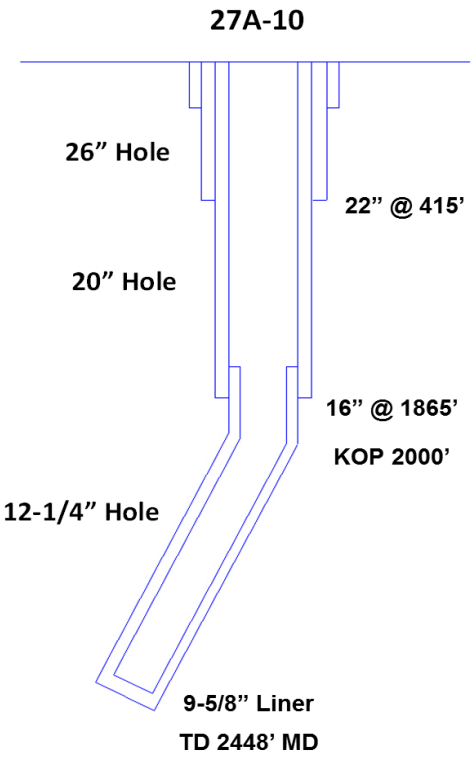
Accomplishments, Results and Progress



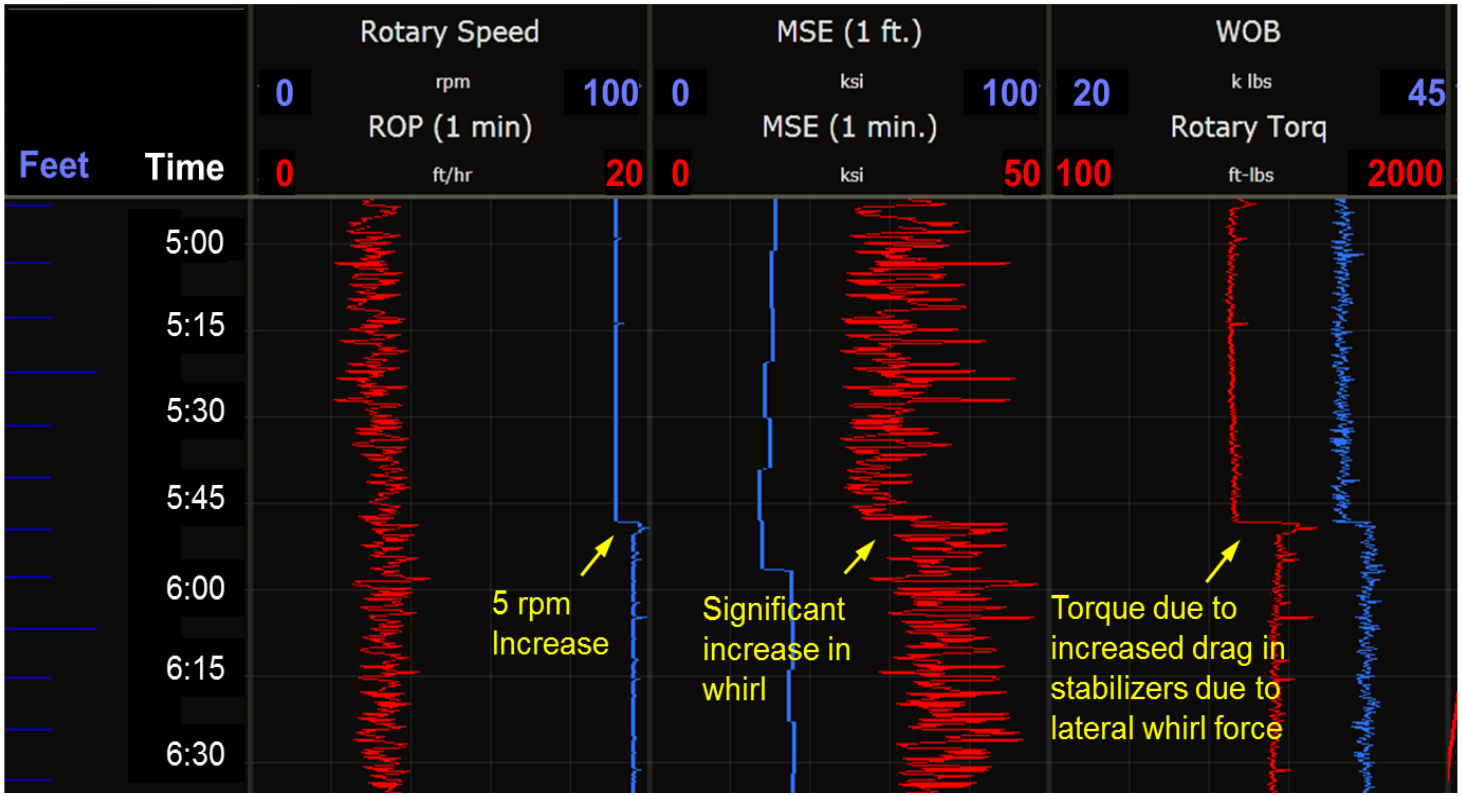
Four common categories of assemblies used in straight holes

- Slick or pendulum used by partner with low WOB to hold vertical angle
- Improved efficiency required higher WOB but stiffer BHA
- Could stiffer BHA allow higher efficiencies and ROP yet maintain angle without undue problems?
- MSE monitoring allowed a safe evaluation

Focused on 20” vertical section – verticality critical



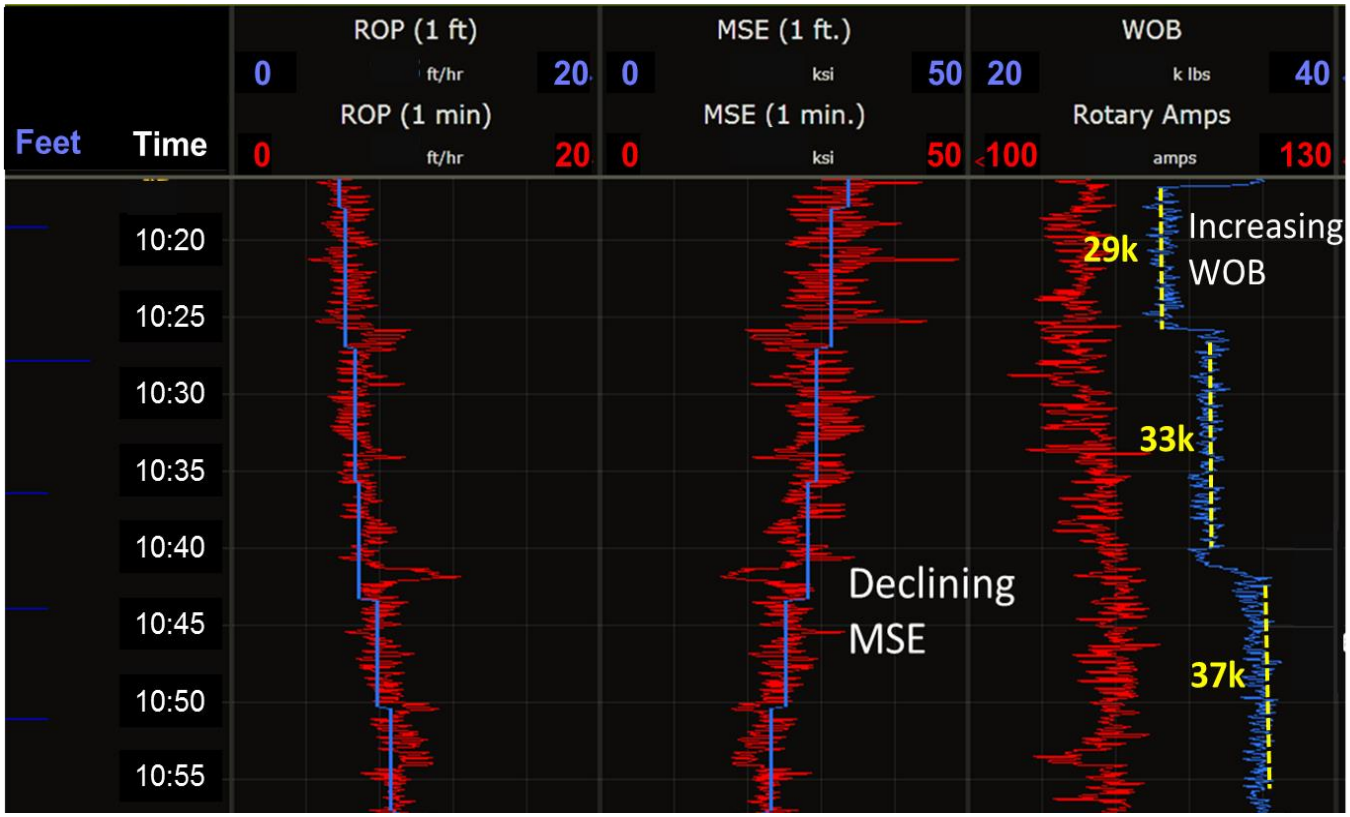
- Examples of benefits to MSE



RPM step test showing an increase in MSE following a 5 rpm change in rotating speed. Torque also increases, which should not occur with small changes in RPM unless they result in whirl, which causes increased lateral force and drag in the BHA.

Accomplishments, Results and Progress

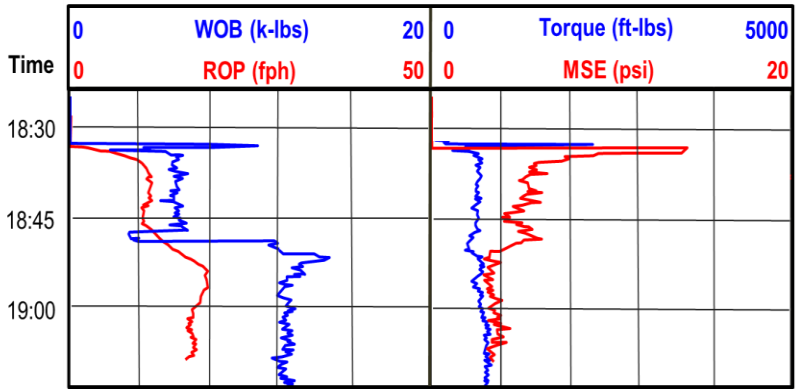
- Examples of benefits to MSE



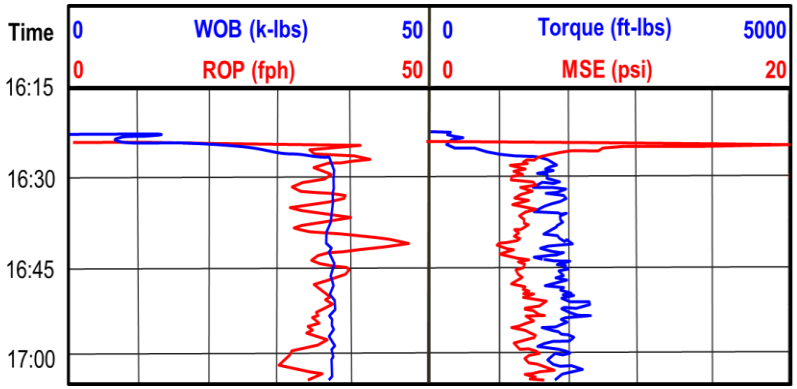
WOB step test showing MSE declining and rock cutting efficiency increasing with WOB. The driller's workflow is to continue increasing WOB unless the MSE rises, at which point he would return the parameter to the previous setting.

Accomplishments, Results and Progress

- Examples of benefits to MSE

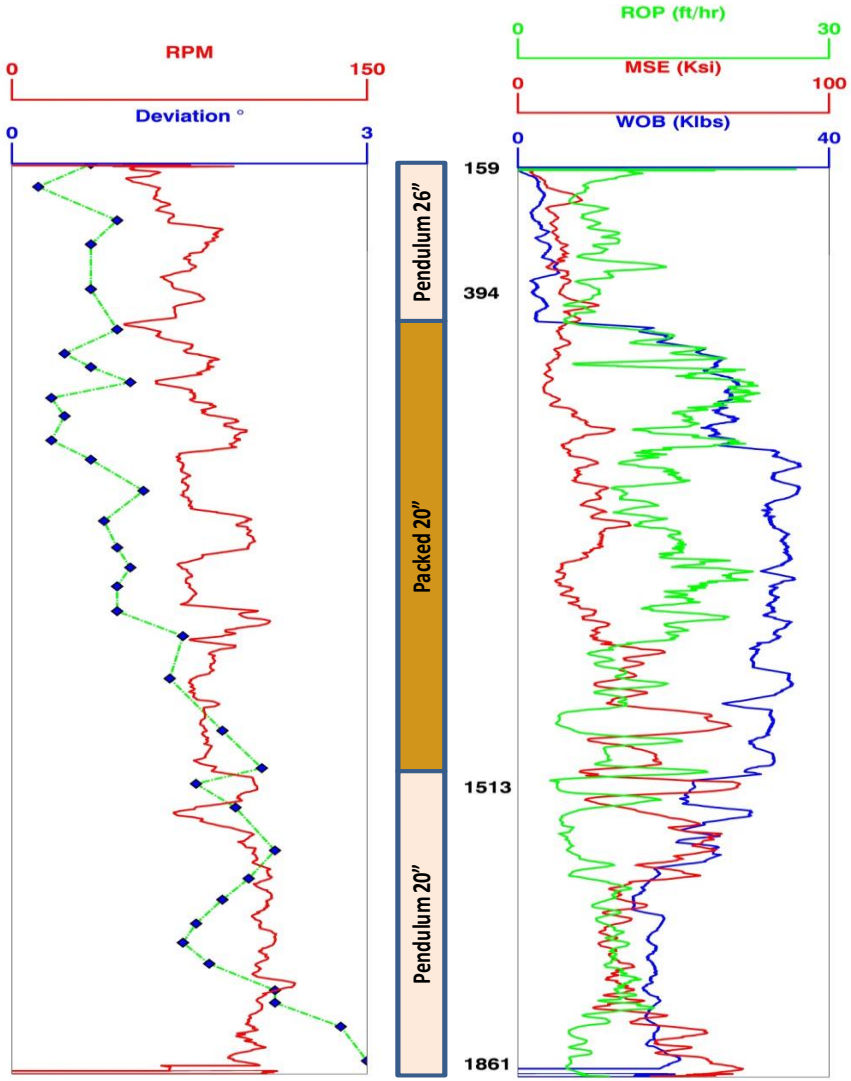


High MSE due to whirl as WOB is applied slowly in stages. DOC is inadequate to engage Region II of cutting structure, or to resist whirl in BHA.



WOB is applied in less than 60 seconds resulting in corresponding reduction in whirl.

Accomplishments, Results and Progress



14.5 ft/hr using MSE and packed assembly versus 7.8 ft/hr with pendulum while maintaining angle

26" surface hole with pendulum

Increased WOB consistently resulted in reduced MSE. Continued to raise WOB

Increased RPM resulted in increased MSE (BHA resonance). Returned to previous RPM

Loss of DOC due to increased rock strength resulted in higher MSE. Raised WOB

Attempted to increase RPM, but increased MSE indicated increased resonance

Frequent inclination surveys showed the angle was acceptable with 35K lbs through this depth. MSE step tests showed higher WOB was still needed

Lithology change (volcanic tuff to harder dactite) caused increasing inclination trend. Once desired angle was exceeded, it was necessary to trip for pendulum. The WOB for this assembly and formation should be limited to 30K lbs, which still allows high performance than pendulum

Lithology transitioned to softer formation (dactite to quartzite). Angle continued to build with pendulum until WOB was reduced to low value

MSE is reduced due to softer formation and higher DOC. Inclination tendency declined. ROP with packed might have been 2x higher

Increased formation strength increased inclination tendency. Low WOB with Pendulum in harder rock resulted in high MSE (bit whirl).

Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Complete MSE controlled drilling exercises on four geothermal wells.	Completed MSE monitoring on two wells and controlled drilling exercises on two additional wells	3/2014 (on schedule)
Complete preliminary evaluation of MSE drilling results. This first phase effort will demonstrate a >10% increase in daily drilling rates.	Completed preliminary evaluation of results. Exceeded 10% Improvement	6/2014 (On schedule)
Publish a SAND report and present results at the 2014 GRC annual meeting.	Results published through SPE (**14ATCE-P-2328-SPE)**	9/2014 (Paper published 10/2014)
Initiate fixed cutter / hybrid bit testing with an industrial partner	Pending – Due 6/2015 but may slip due to hole availability	

Future Directions

- Leveraging activities associated with a separate project, advanced bits will be deployed in concert with MSE efforts.
  - 12.25” PDC and 12.25” FuseTek Bits from NOV
  - 12.25 Kymera Bits from Baker-Hughes
- Publish results
- Planning with Ormat continuing

Milestone or Go/No-Go	Status & Expected Completion Date
Initiate bit testing with an industrial partner	6/2015 – Time may slip due to drilling schedules and needs
Evaluate results of tests using advanced bits and assess these results relative the ROP performance.	9/2015 - Time may slip due to drilling schedules and needs

Mandatory Summary Slide

- Technology development is absolutely needed, but not at the expense of leveraging learnings from other sectors.
- MSE based decisions from surface based measurements can improve drilling performance.
- There are no “silver bullets” – reducing drilling costs requires chipping away at all cost drivers
- Adoption of new practices is difficult and requires commitment from the stakeholders.
- This is a fun and rewarding project …..