Mechanical Specific Energy (MSE) in Coring: A Tool to Understand the Drilling Mechanism and Coring Parameters Optimization for Improved Core Recovery*

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Abstract

The Mechanical Specific Energy (MSE) is not so well known in coring as compared to conventional drilling. Teale (1965) first defined MSE for the full face-bit as an amount to energy spent to remove unit volume of rock. Pessier and Fear (1992) introduced MSE in its expanded form in O&G industry. At present MSE has been used widely to understand the mechanism of drilling, evaluate efficient drilling, and diagnose the root cause of in-efficiency. MSE is also used real-time for drilling performance evaluation (Dupriest et al., 2005; Pessier et al., 2016). These processes have saved Billions of dollars in the O&G industry. However, the MSE concept has not been transferred to coring operations. Current work examines the use of MSE and its adaptation in coring processes. Limited data published were reviewed, re-analyzed, and finally compared with field example of MSE in coring thereby explaining the mechanism of coring, its usefulness in getting a better recovery, and the best bore-hole quality. The MSE for coring can be expressed as MSE = (W/A) + 2pi N.T / (A.R). Where, W, the weight-on-bit, and T, the torque are available from drilling rig through some mechanical loss. The rate-of-penetration is R, number of core-bit revolutions per minute is N and the core-bit kerf area (A) is given by coring diameter (OD-ID). The unit of MSE in metric unit is MPa or psi in imperial unit. The limited published data obtained from laboratory-based coring do not give the clear picture of coring operation. The re-processed data and a careful analysis shows that the depth-of-cut, DOC, is a better indicator of R and N, higher DOC results in lower MSE; stronger rocks ends up having higher MSE, and efficient coring zones could easily be identified. A similar and consistent result is obtained in the present work. The coring operation was conducted in a test well in Oklahoma; the rock types encountered were sand, shale and the basement granite. This paper will discuss the coring operations

results in detail. The role of axial and rotational energy will be analyzed and their influence on rock properties will be discussed. The efficient coring zone of linear weight-on-bit with DOC and torque with DOC will be presented and anomaly due to balling or undue vibrations will be discussed. Finally, the preliminary results show that the axial energy is proportional to hardness and rotational energy (nearly equal to MSE) is proportional to confined compressive strength.

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Mechanical Specific Energy (MSE) in Coring: A Tool to Understand the Drilling Mechanism and Coring Parameters Optimization for Improved Core Recovery

By

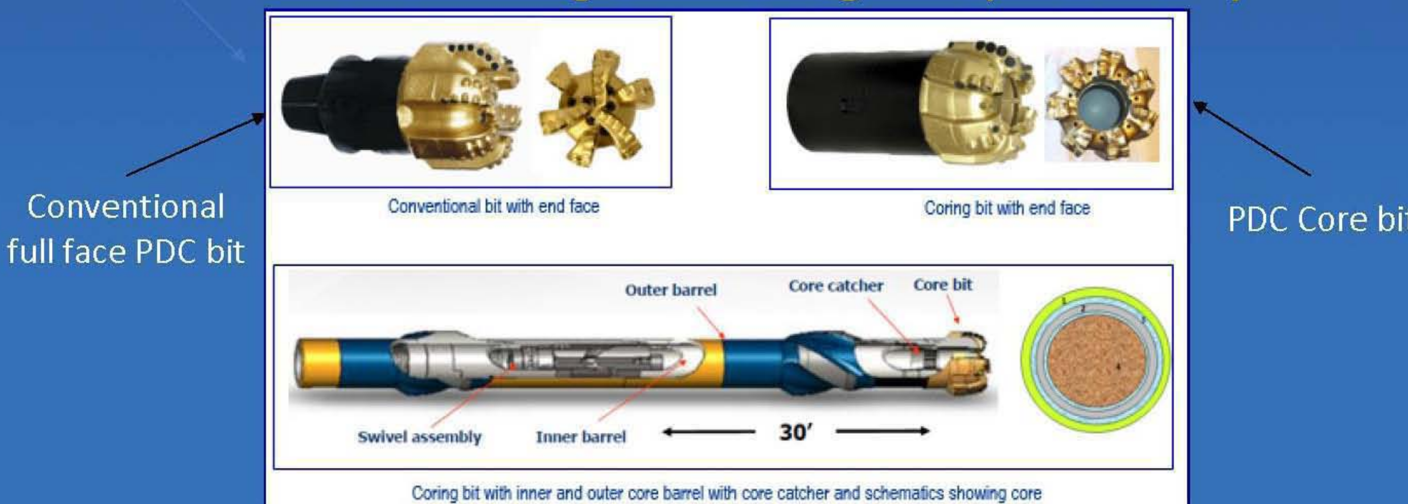
Umesh Prasad

OUTLINE

- Background on Coring Technology
- Introduction to Mechanical Specific Energy
- Glossary of Key Terms & Equations
- Drilling or Coring as Two-step Process
- Data obtained in Coring (Lab)
- Data obtained in Coring (Field)
- Discussions & Conclusions
- Acknowledgements

Background on Coring Technology

- **Conventional drilling /drill bits (say PDC bit) are almost the same as in Coring and coring bits (see below).**



Conventional bit with end face

Coring bit with end face

Coring bit with inner and outer core barrel with core catcher and schematics showing core

- Both the coring and conventional bits could be of three kinds, roller-cone (RC), Polycrystalline diamond cutter (PDC) bit and Impregnated diamond (Impreg) bits.

Presenter's notes: Traditionally, RC bit has very low durability due to limited load bearing capacity of the bearings in cones; the aggressiveness Mu is very low; it does not generate high Torque, thus rotating rotational power needed to drill is never a limiting factor; it utilizes a small component of installed capacity. It uses mostly crushing *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

mechanism. On the other hand, PDC generates very high torque, ROP is far more than tri-cone, and it draws more power from the installed capacity and at faster rates. However, variation in torsional oscillation is significantly higher, tubulars are always in fatigue limits, and thus controlled drilling mitigating dynamics issue is always the priority. This becomes more problematic in tortuous path where energy transfer is problem. Just as the PDC replaced the roller cone bits, PDC core bits also replaced both the rollercone or Impreg diamond core bits. The limitations of full PDC bits also apply to core bits. Mitigating vibrations in GOM coring operations resulted smooth drilling, RPM was increased, wall of the cores obtained was smooth, uninterrupted coring with breaks up to 3 ft straight, core was gauged with no evidence of vibrations (Sinor et al 1992, SPE 24587). Further anti balling features of additional fluid passage and higher flow rate also increased the ROP by three times, core run got doubled, and recovery increased from 80% to 93%.

Mechanical Specific Energy (MSE)

1. $Mechanical\ Specific\ Energy,\ MSE = \frac{W}{A} + \frac{2.\pi\ .RPM\ .T}{A\ .ROP}$

where, W = weight on bit, A = cross section area of drilling, RPM = revolutions per minute, T = torque, ROP = rate of penetration

1. $Coring\ Kerf\ Area,\ A = \left(\frac{\pi}{4}\right).\left(OD^2 - ID^2\right)$

where OD = outer-diameter of core bit, ID = inner diameter of core bit

3. $Depth\ of\ cut\ per\ unit\ revolution, DOC = \frac{ROP}{5\ RPM}$

DOC is a normalized parameter for speed of drilling when RPM is also changing in addition to W

4. $MSE = \frac{2.\pi\ RPM.T}{A\ .ROP}$

This is due to rotational energy; 99% of work while drilling.

Key Terms & Equations

5. $Depth\ of\ cut, DOC = \frac{2.\pi.T}{A\ .\ MSE}$

6. $Bit\ aggresiveness,\ \mu = \frac{36.T}{(OD-ID).W}$

7. Bit Efficiency $= \frac{Minimum\ MSE}{MSE\ obtained}$ = 0.125 – 0.35

8. $ROP\ *\ MSE = \frac{2.\pi\ RPM.T}{A}$ = k * Power

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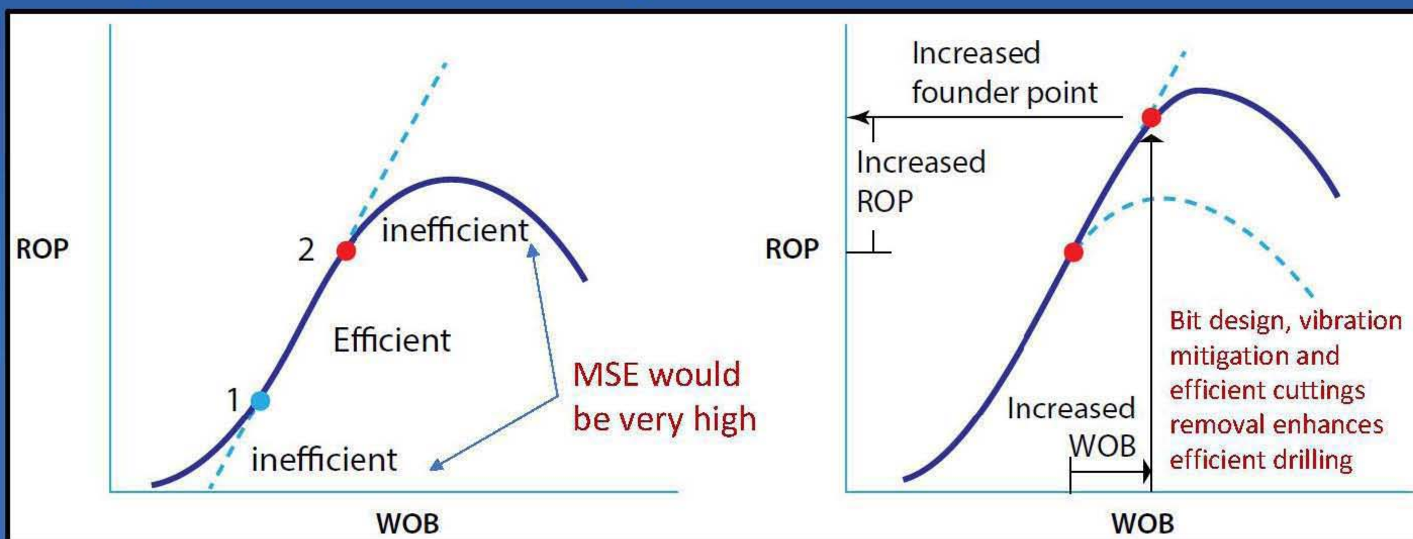
Key Terms & Equations



Efficient drilling is within the linear WOB & ROP stage
It gives lowest MSE before the founder point.

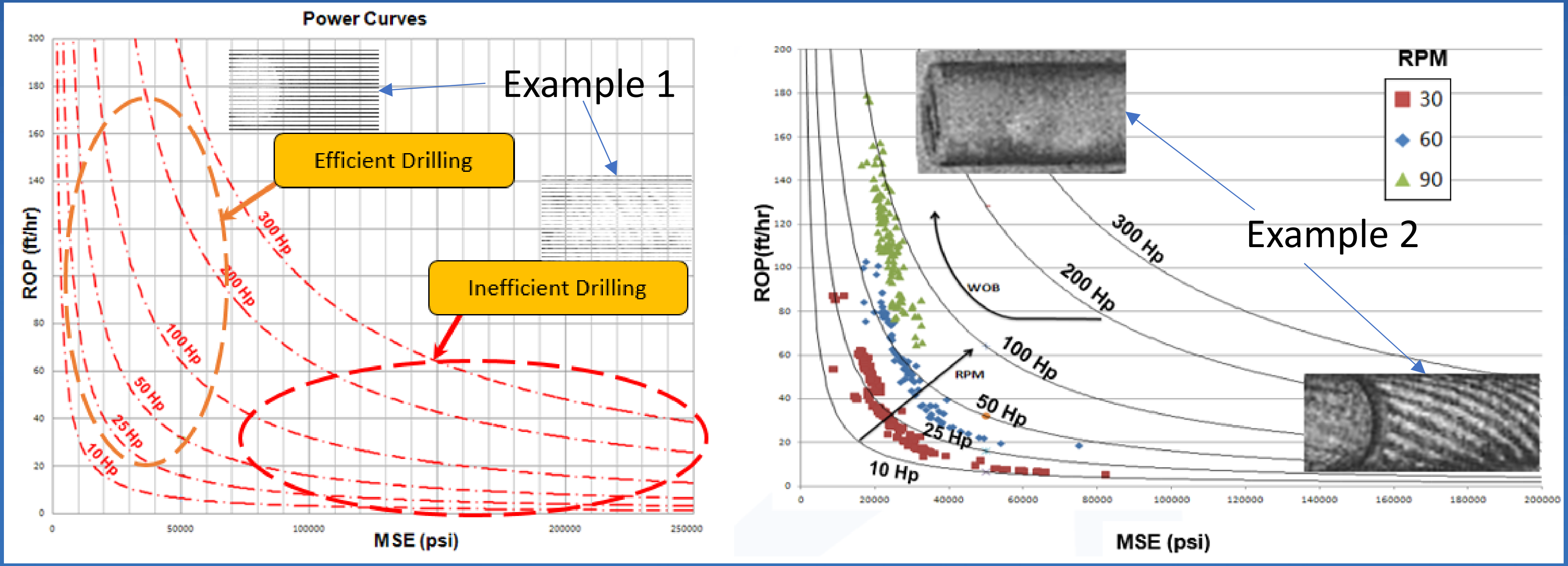
Sinor et al, 1992 [SPE 24587] have shown by mitigating vibrations and balling issues, the core was gauged, recovery to 93%, ROP thrice and core run twice.

Presenter's notes: At very low DOC, it is in a grinding mode, Stage 1, bit may also be buried in cuttings-bed. On the other hand, beyond "flounder or founder" point, Stage 2, bit balling, vibrations makes ROP-WOB non-linear. Bit translates only 30-40 % of input energy to useful ROP. In-between drilling is efficient, more the WOB there is a *(Presenter's notes continued on next slide)*

(Presenter's notes continued from previous slide)

proportionate increase in ROP; increase in HYDRAULICS will hardly change in ROP. Slope is nearly constant for the given bit, given rock and at GIVEN RPM. Lower SLOPE is for roller cone; higher slope is for PDC bits; its reflection of Aggressiveness, Mu. At founder point, its maximum ROP achievable using current system. The founder point is due to a) bit balling, b) bottom hole balling, and c) vibrations. If there is no founder then other parameter may limit the energy applications including solids handling capacity.

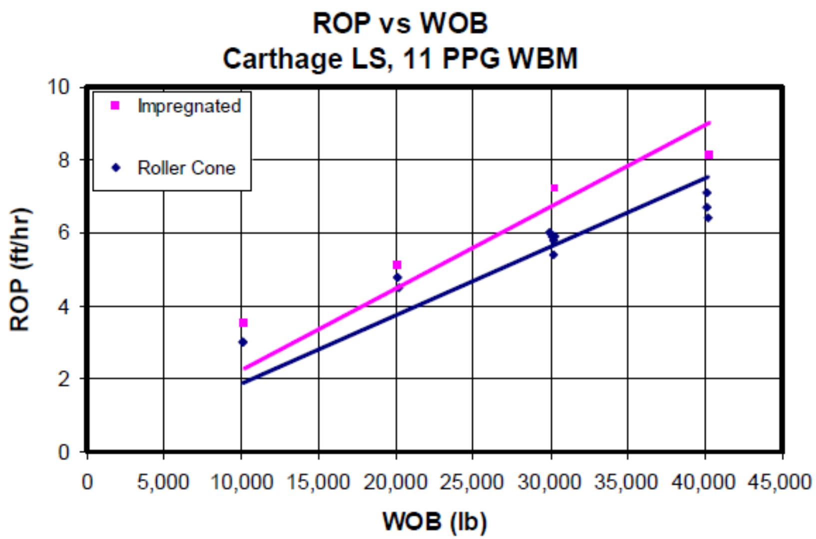
Key Terms & Equations

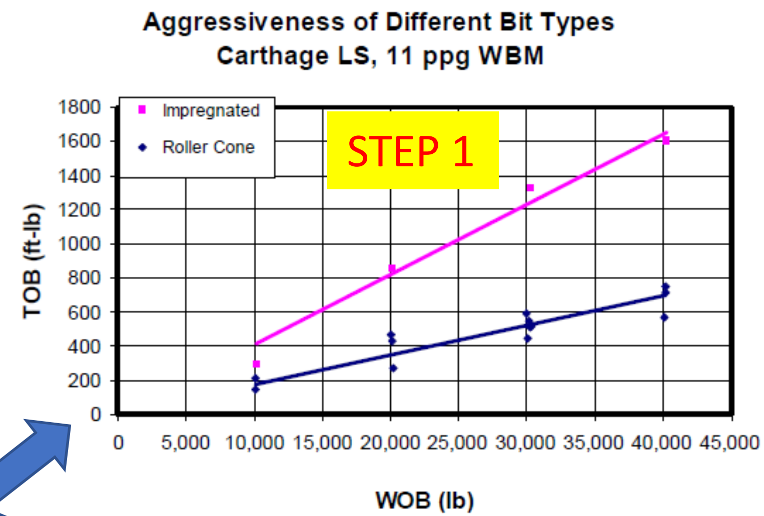


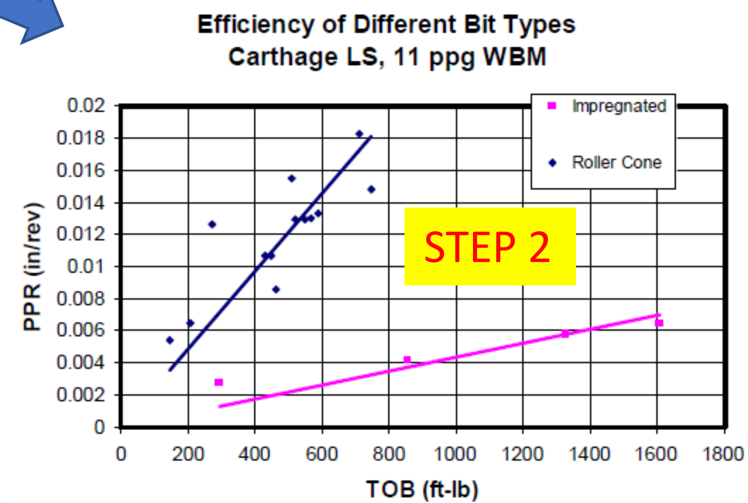
MSE & ROP are inversely related for a given rig-power (Eq. 8).

Two-examples of efficient and in-efficient cores (Sinor et al ‘ 1992)

Drilling or Coring as 2-Step Process

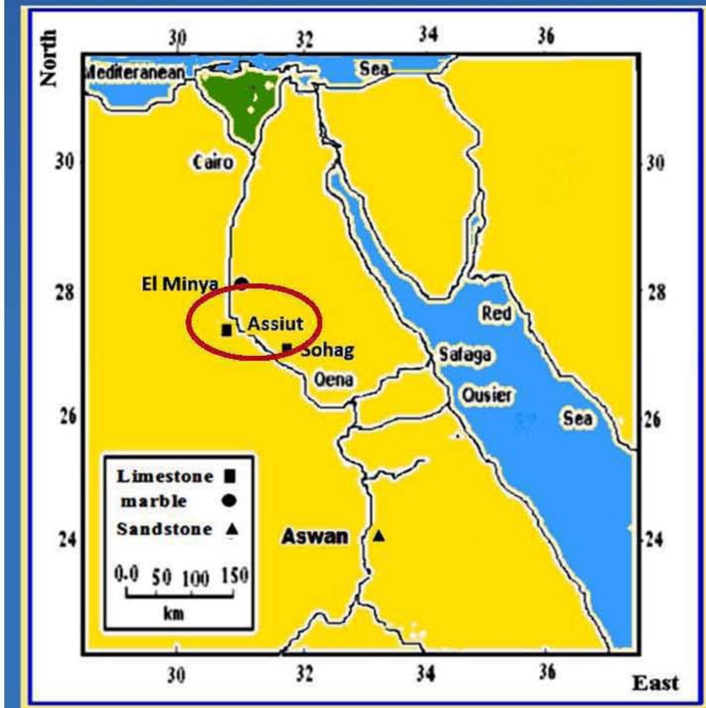






An example comparing performance of Impregnated and Roller cone bits. Both have ~ same ROP vs WOB trend (above). However, Figure above-right (STEP 1) shows Impreg bit highly aggressive. But figure-right (STEP 2) shows less aggressive bit gives more ROP thus roller cone more efficient.

MSE Data analysis in Coring (Lab)



Very limited data sets exists in literature elaborating. One such lab data [Imbaby & co-workers] is re-analyzed here.

Igneous, Sedimentary, and metamorphic rocks from Assiut region of Egypt were selected and cored in Lab.

Rock blocks = 20 cm x 15 cm x 10 cm. Porosity = 6.8-12.9%, density = 2.1-2.4 g/cc, UCS = 138-259 MPa

Core Bit = Impreg diamond ID-40, OD-45 mm.

WOB = 15 - 480 kg force.

RPM = 300 - 1000. At other series 1200.

Although, drilling fluid with a range mud-weight and viscosity were used which decreased the ROP and increased the MSE but were not discussed in this work.

Presenter’s notes: Very limited data sets exist in literature elaborating coring process be it in lab environment or field. One such lab data (Imbaby, Boghdady & Biblawi, from Egypt) is re-analyzed. Igneous (pink and black granite), Sedimentary (five kinds of limestone) and metamorphic (white and black marble) from Assiut region of Egypt *(Presenter’s notes continued on next slide)*

(Presenter's notes continued from previous slide)

were selected and cored. Rock types were in the form of 20 cm x 15 cm x 10 cm brick shaped. The limestone ranged from 6.8-12.9% porosity, density 2.1-2.4 g/cc, UCS 138-259 MPa, and Tensile strength 17.1-27.4 MPa. The coring machine is a fixed laboratory type with core bit of thin walled impregnated diamond type with ID 40 m and OD 45 mm. Coring was carried out using various weights on bit of 15, 30, 45, 60, 75, 90, 120, 150, 180, 210, 300, 390, and 480 kg force. Rotation speeds (RPM) were 300, 400 and 1000. At other series of tests, even RPM of 1200. Although, drilling fluid with a range mud-weight (9-12 ppg) with viscosity in a wide range (30-50 sec/qrt) were used this decreased the ROP and increased the MSE but were not discussed in this work.

MSE Data analysis in Coring (Lab)

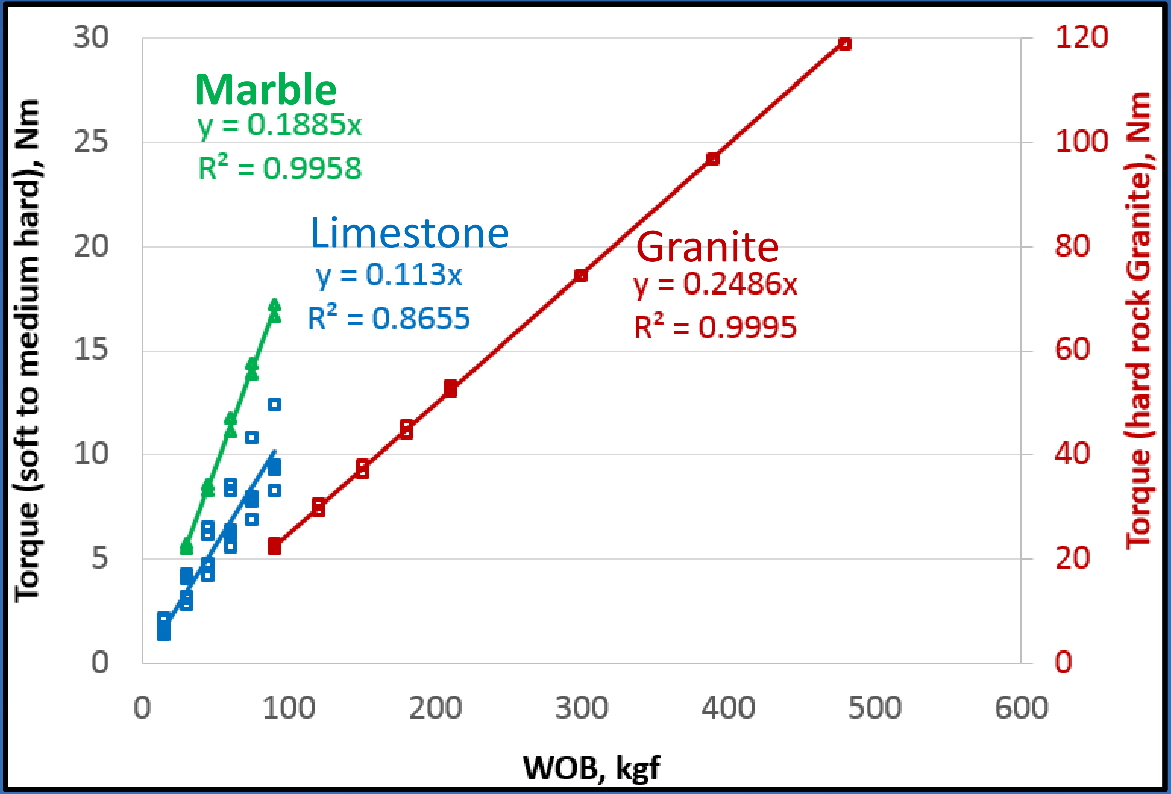
Step 1 of coring process: linear zone in WOB-Torque, its efficient drilling zone.

Step 1 of coring process: Stronger rocks allow less aggressiveness (μ).

At very low WOB, coring or drilling is in friction mode and thus in-efficient. The WOD-Torque may be non-linear.

At very high WOB, coring or drilling is also in-efficient as it Founders, stalls, generates vibrations and making rig unstable, WOB-Torque is non-linear.

Excess WOB may over-crush the rocks and cuttings removal may be in-efficient causing non-linear zone.



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MSE Data analysis in Coring (Lab)

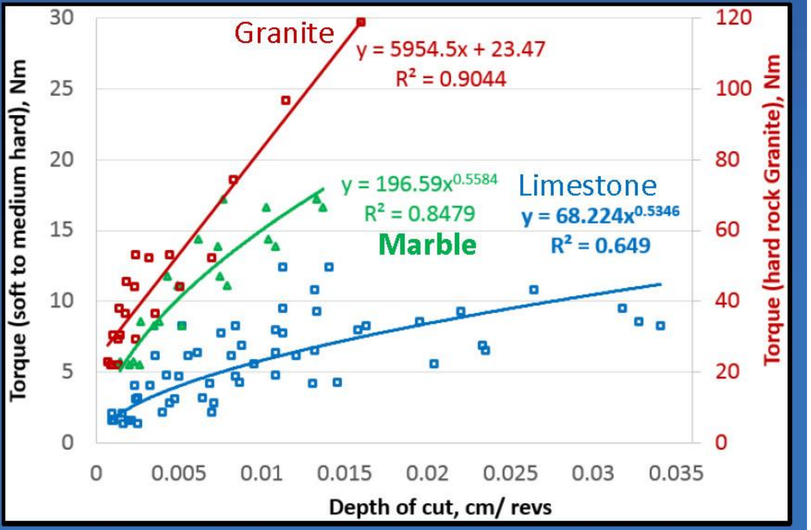
Step 2 coring process: If all the torque available is used to produce more ROP the coring is considered most efficient.

Step 2 coring process: DOC appeared better indicator of ROP when RPM changes.

WOB-ROP, or RPM-ROP, explain the coring process but mixes other things.

The slope of Torque with DOC is an indication of Mechanical Specific Energy (MSE), stronger rocks (granite) need more torque for unit DOC.

An in-efficiency in cuttings removal, bit wear, or vibrations, hampers the drilling or coring efficiency but not seen here.



Presenter's notes: WOB-vs.-ROP, RPM-vs.-ROP, or WOB-vs.-Torque explains the coring process but often mixing several things. Depth of cut (DOC) appeared better indicator of ROP when RPM changes. If all the torque available is used to produce more ROP, the drilling or coring is considered most efficient. The increase in ROP due to increase in WOB is widely discussed in the literatures but it complicates the analysis of drilling process. The slope of Torque with DOC is an indication of Mechanical Specific Energy (MSE), stronger rocks (granite) need more torque than weak rocks (marble) for unit DOC. An in-efficiency in cuttings removal, bit wear, or poor hydraulics hampers the drilling or coring efficiency.

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MSE Data analysis in Coring (Lab)

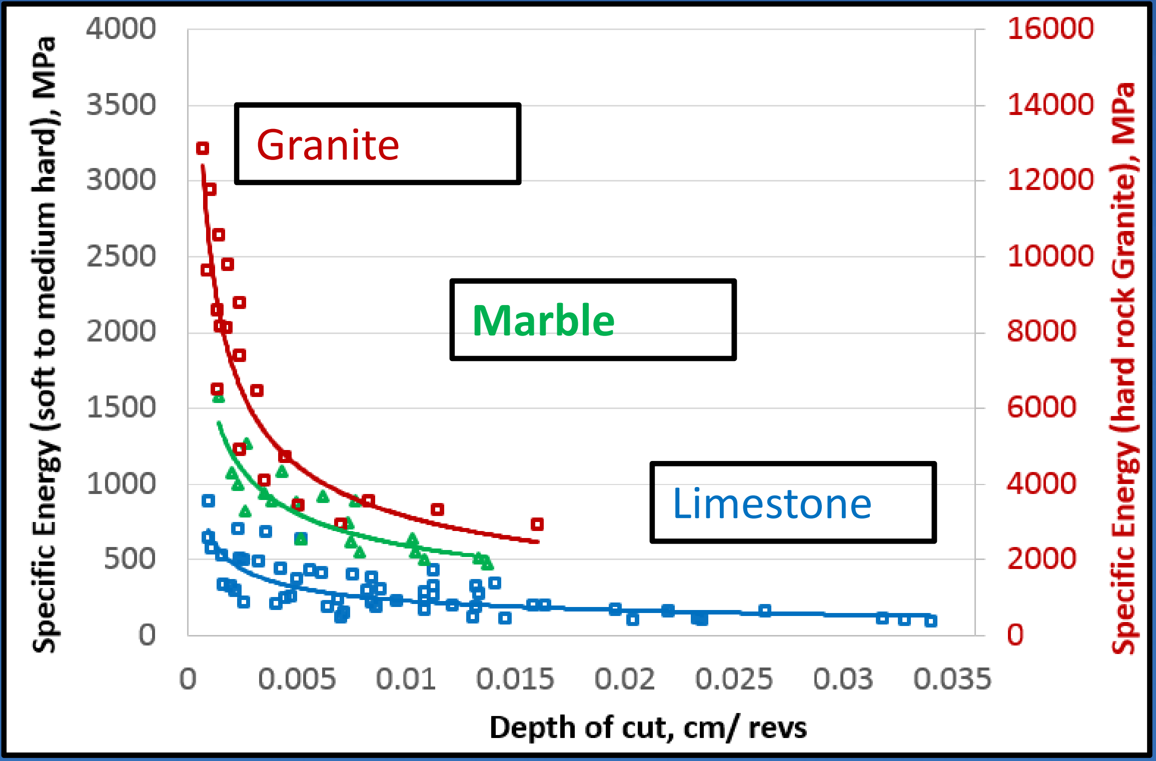
MSE)is found to be best indicator of coring efficiency.

The minimum MSE obtained appeared to be proportional to the strength or even the porosity.

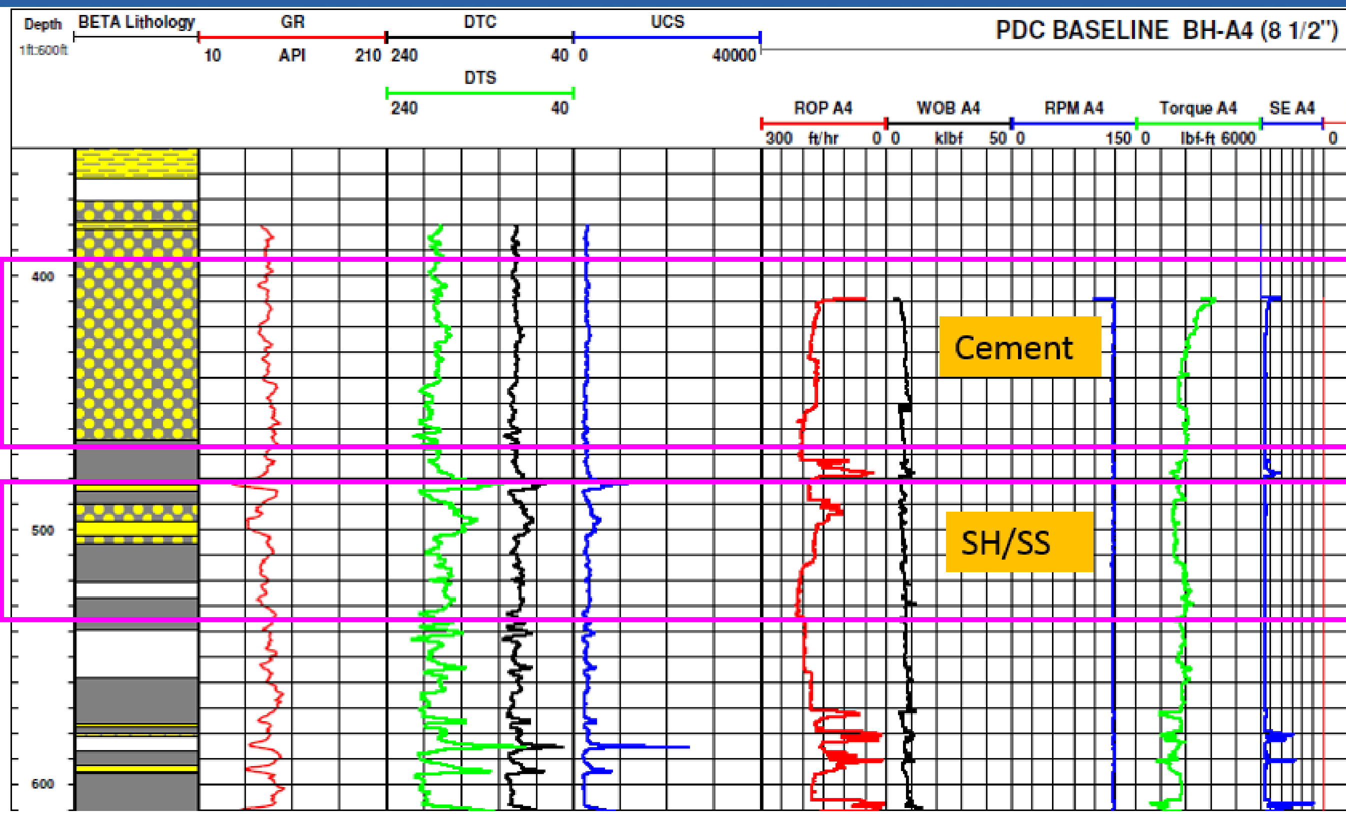
The minimum MSE is higher for stronger rocks (granite) and lower for weak rocks (marble & limestone).

The dimensionless index (UCS/MSE) is found to have limited use in coring when all the data is combined.

Mineral content, grain size, and anisotropy due to fracture or drilling orientation affected coring severely.



MSE Data analysis in Coring (Field)



5386-5387 ft: Basement rock (pink granite) coring for which no logs were available

Geological settings, logs, coring bit and cores are shown

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MSE Data analysis in Coring (Field)

Coring data from field											Rock properties from Lab		
Core Run	Lithology	Core-cut, ft	Coring hrs	ROP, ft/hr	WOB, k-lbf	RPM	Torque Ft-lbf	DOC	Mu	MSE, kpsi	UCS, psi	YM, Mpsi	TS, psi
1	Cement Plug	10	0.08	123.5	4	60	3.19	0.412	0.798	13.32	2081	1.03	385
2	Cement Plug	10	0.08	123.5	4	60	1.61	0.412	0.403	6.77	1421	0.88	385
3	Cement Plug	10	0.09	106.0	4	69	1.59	0.307	0.398	8.92	1760	1.11	385
4	Cement Plug	10	0.12	83.3	7.7	60	1.93	0.278	0.251	12.03	2218	1.01	385
5	Cement Plug	10	0.14	71.4	5	58	1.44	0.246	0.288	10.09	2349	1.13	385
6	Cement Plug	20	0.35	57.1	4.9	58	1.48	0.197	0.302	12.93	1647	0.97	385
7	Shale/sand	10	0.20	50.6	4.55	60	1.66	0.169	0.365	16.92	3206	0.76	916
8	Shale/sand	4	0.95	4.2	7.6	62	1.1	0.014	0.147	140.90	3309	1.01	893
9	Shale/sand	8	0.15	53.3	4.1	60	1.7	0.178	0.415	16.41	3309	1.01	1119
10	Shale/sand	10	0.25	40	7.9	60	1.97	0.133	0.249	25.39	3309	1.01	951
11	Shale/sand	8	0.14	57.1	5.22	60	1.81	0.19	0.347	16.34	3309	1.01	934
12	Sandstone	11	0.22	50.0	5.75	58	1.625	0.172	0.283	16.22	12182	4.16	1899
13	Granite	2	4.42	0.5	10.67	65	3.43	0.001	0.321	4204.78	12581	6.41	3339

Coring data defines Step 1 & 2 coring process

Mu (μ) & MSE

Key rock properties

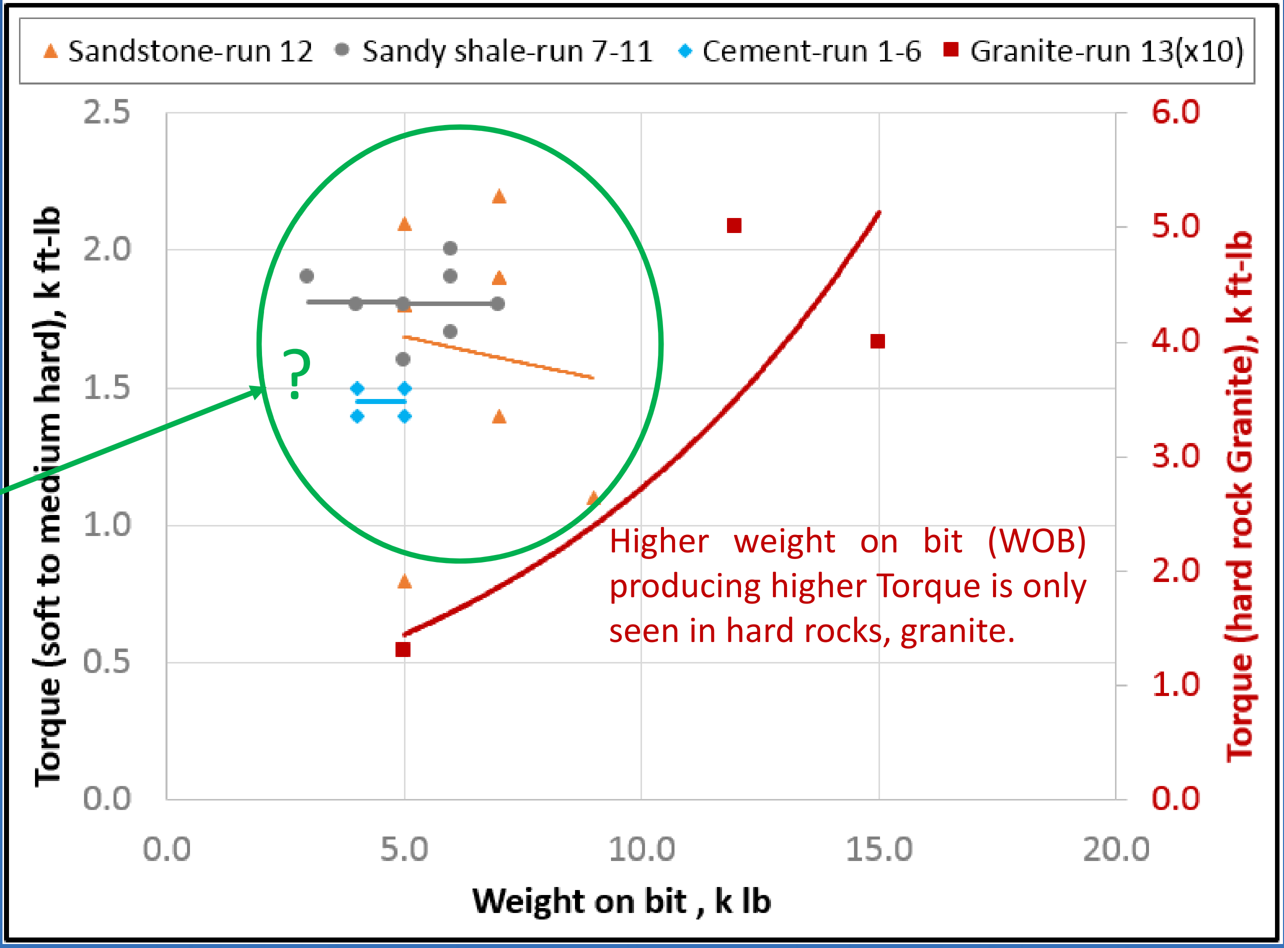
MSE Data analysis in Coring (Field)

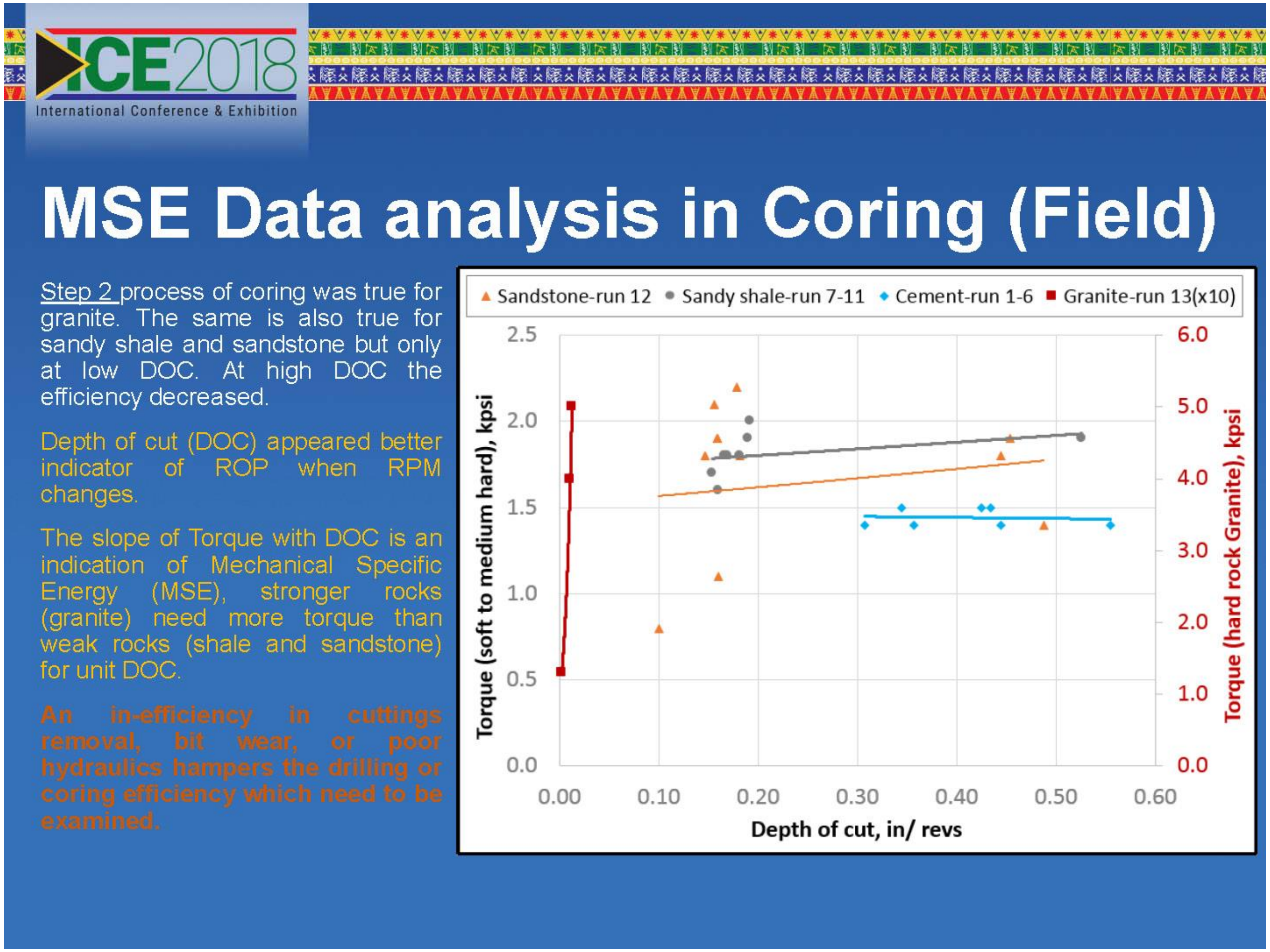
Step 1 process of coring seen only in granite.

Step 1 process of coring is not seen in weaker rocks due to pool of crushed bed, poor cuttings removal, worn bit, or vibrations.

Stronger rocks (only granite in this case) allowed high aggressiveness than in weak or porous rocks.

There is an opportunity to understand the coring mechanism including diamond and matrix used, extent of wear and hydraulics used.





Presenter's notes: Depth of cut (DOC) appeared better indicator of ROP when RPM changes. Torque vs. ROP was also used to analyze coring but is not shown here. If all the torque available is used to produce ROP, the drilling or coring is considered most efficient. This was true for granite. The same is also true for sandy shale and sandstone but only at low DOC. At high DOC, the efficiency decreased. The slope of Torque with DOC is an indication of Mechanical Specific Energy (MSE), stronger rocks (granite) need more torque than weak rocks (shale and sandstone) for unit DOC. An in-efficiency in cuttings removal, bit wear, poor hydraulics, or vibrations hampers the drilling or coring efficiency, which needs to be examined.

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MSE Data analysis in Coring (Field)

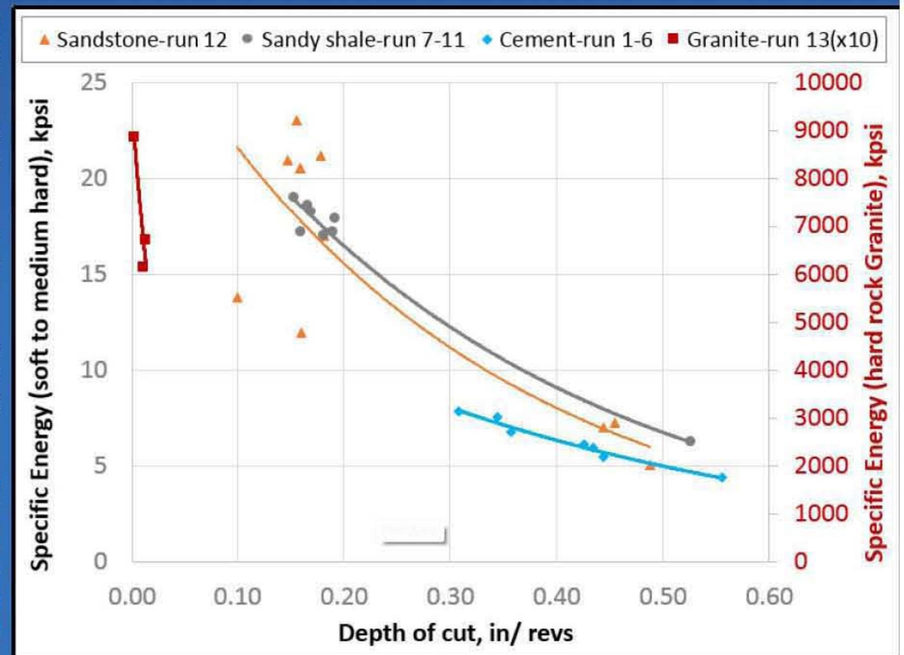
Mechanical Specific Energy (MSE) is found to be best indicator of coring efficiency.

The MSE decreasing with increase in DOC is expected and is consistent.

The minimum MSE is higher for stronger rocks (granite) and lower for weaker shale and sandstone.

At low DOC (may be in the beginning of coring), perhaps rubbing or friction grinding increased the MSE.

Rock mechanical properties including compressive strength (unconfined compressive strength, UCS; Young's modulus, YM, tensile strength (TS) and mineralogy were examined to explain the drilling process (next slide).



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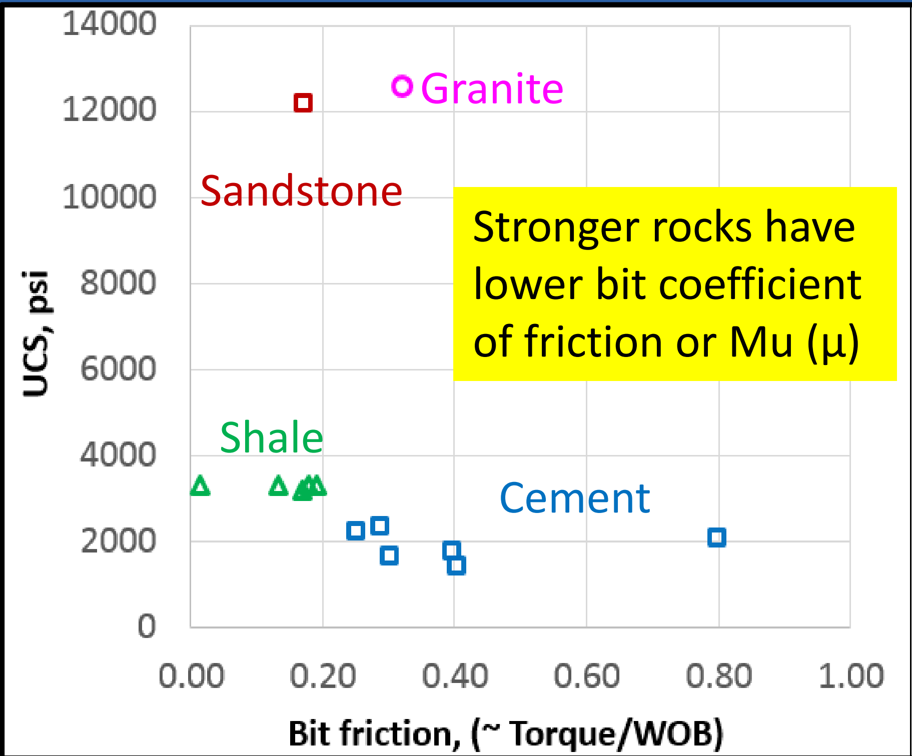
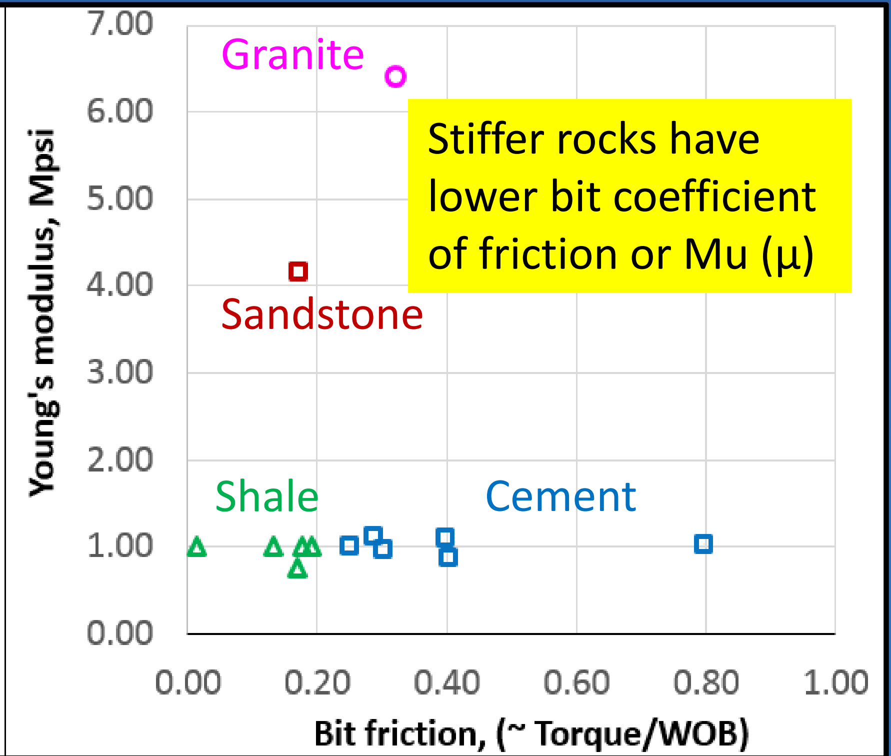
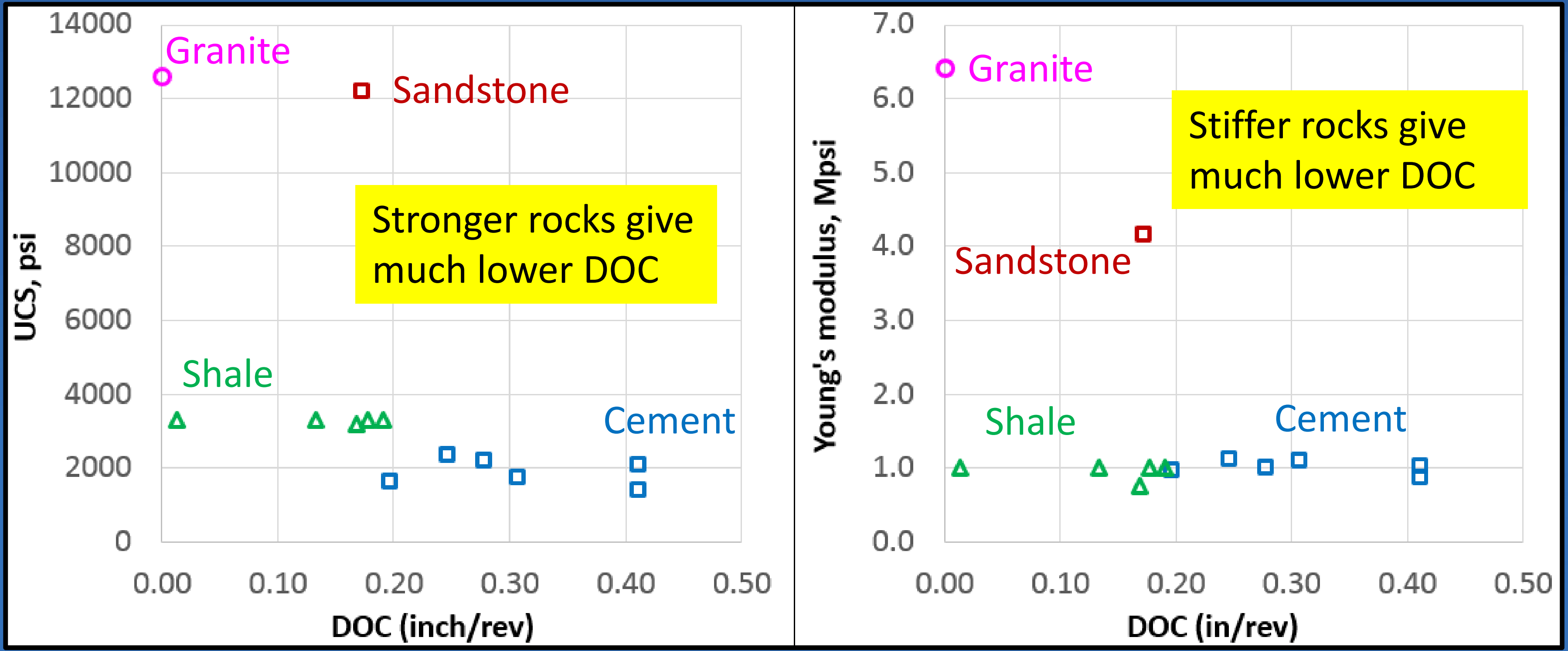
MSE Data analysis in Coring (Field)





Step 1 process of coring data compared with UCS & Young's modulus of elasticity for all the rock types

MSE Data analysis in Coring (Field)



* Depth of cut (DOC) indicates hardness or stiffness.
* Stronger or stiffer the rocks, lower is the DOC.
* Not enough data for granite and Sand

Discussions & Conclusions

Coring bits as compared to conventional drill bits are almost the same.

Both the coring and conventional bits could be of roller-cone (RC), Polycrystalline diamond cutter (PDC) bit and Impregnated diamond (Impreg) bits.

Proper choice of bits depends on rock types, the cutting mechanism used, the drilling environments given, and the drillability of the rock type.

A large body of works has been done on suitable drill bit selection data analysis for conventional drill bits; the same should apply to core bits.

However, not much work has been done in core bit selection or coring data analysis. Present work attempts to compile and analyze coring.

Discussions & Conclusions

Core bit data (in the lab environment) appeared to follow the conventional drilling of 2-step process.

1) WOB applied is used to generate Torque depending upon bit design and the environmental conditions, and it defines Aggressiveness (or μ)
2) Torque is used to produce rate of penetration (ROP); the ratio is ~ Mechanical Specific Energy (MSE) and it defines the efficiency of coring.

Role of rock mechanical properties (UCS and Young's modulus) were found to affect both Aggressiveness (μ) and MSE.

Present work of coring cement, shale, sandstone and granite indicated few anomalies in coring parameters; more work is needed for clarity.

Future work along the same direction would help mature data capture, data analysis and bit design which would lead to better core recovery, core quality, drilling efficiency, and reduce NPT.

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- Finally, previous work by authors and co-workers are duly recognized as references:

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