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# MASTERTHESIS

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# An Optimization Study of Current Drill Bit Technology for the Troll Field, Norway

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## 1.1 Preface

This post-graduate thesis is written in Norway at Smith Bits, a Schlumberger Company, in collaboration with the University of Stavanger. The thesis is motivated by Smith Bits in order to map geology, current drill bit technology and possible improvements regarding drilling efficiency at the Troll field, Norway. Special thanks are given to Product Engineer Alberto Caycedo, Associate Professor Helge Hodne, North Sea Manager Christian Utvik, Technical Service III Engineer Rene van der Laan, Mgr Senior Engineer Peter Kleimeer, Technical Service II Engineer Erik Sundfør, Hansini Kothare, and the Sales Department.

## 1.2 Object

*The objective of this study is to optimize current drill bit technology at Smith Bits to find the most applicable Polycrystalline Diamond Compound (PDC) bit for the 8 ½" section on Troll. Focus is laid on Troll West and the interbedded Sognefjord formation.*

## 1.3 Abstract

In the current study geology, drill bit technology and drilling challenges at the Troll Field are mapped.

It has been established that the Troll Reservoir Formation consists of unconsolidated shallow marine sandstone with highly dense calcite cemented intervals. However the occurrences of calcite cemented intervals are difficult to predict. The intervals can cause breakage to the PDC cutting structures, along with undesired high local doglegs, and low penetration rates.

Sophisticated and advanced simulation software was used to simulate and create a similar drilling environment for the targeted 8 ½" section on Troll. Several PDC bits were simulated to determine the most optimum PDC cutting structure for Troll Drilling.

The newest iteration of the Smith Bits 8 ½ " MDSi716LUVPX, with 5" gauge pad length, was found to be the most applicable for drilling the 8 ½" section on Troll.

# CONTENTS

# 2. INTRODUCTION

## 2.1 Background

The Troll Field is operated by Statoil. For several years Statoil has been satisfied with the bit and steerable system packages provided by Baker Hughes. Due to this, the Troll Bit Market has been difficult to penetrate. In 2012, Statoil opened a new tender on Troll. Statoil is now developing the gas reserves. To develop the gas reserves, a large drainage area is required. Therefore, most of the upcoming wells will be drilled with 2 to 3 sidetracks from existing wellbores, where the 8 ½" section of each sidetrack will consist of several thousand meters of horizontal drilling. The vendor, who is able to deliver a bit that can penetrate the whole 8 ½" section in a safe and efficient manner, will achieve priority in upcoming wells.

## 2.2. General

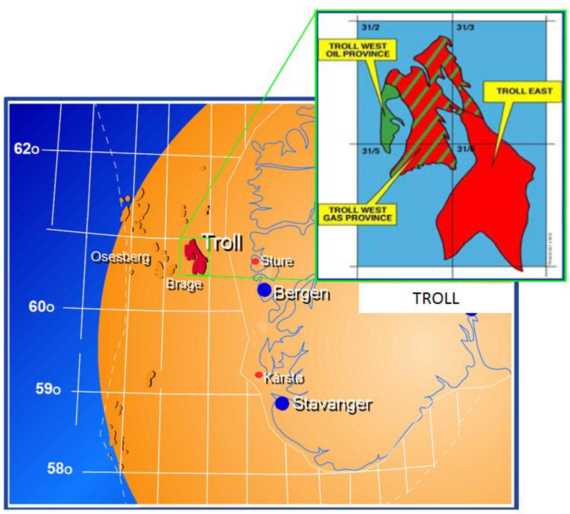


**Figure 1:** *The Troll field is located in the North Sea near the west coast of Norway. The field is divided into three provinces Troll West Oil Province (TWOP), Troll West Gas Province (TWGP) and Troll East. Re-illustrated from "Success factors in Troll Geosteering, OTC 17110.*[5]

The Troll Oil and Gas Field is located on the North-Western edge of the Horda Platform, at the Eastern margin of the Viking Graben, in 300-350 meters of water [1], approximately 1400-1500 meters below seafloor [29]. It was discovered in 1979 [14], but due to technological challenges at that time, the field was not developed before early 1990's [29]. The field lies in Norwegian Blocks 31/2, 31/3, 31/5 and 31/6, covering an area of approximately 780km$^2$, see Fig. 1. The accumulation of hydrocarbons is contained within a series of North-Easterly and South-Westerly tilted fault-blocks. The field contains a major gas cap overlying an oil rim of variable thickness. The accumulation is believed to be filled to a spill-point in the South-East corner of Block 31/6, see Fig. 2. [1] The Troll field contains about 40% of total gas reserves on the Norwegian Continental Shelf (NCS), and represents the very cornerstone of Norway's offshore gas production [23, 25].

The North-Easterly and South-Westerly tilted fault blocks divide the Troll Field into three pressure communicating hydrocarbon bearing structures [1], see Fig. 1 and 2.

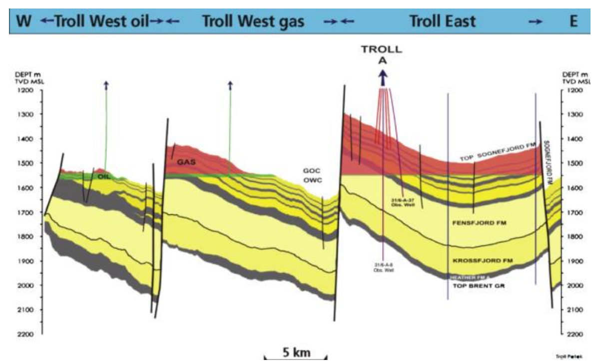


**Figure 2:** *Cross-section of the three fault blocks, dividing Troll into Troll West Oil Province (TWOP),Troll West Gas Province (TWGP) and Troll East..*[20]

**Troll West, divided in two:**

- a South-Western Oil Province with initial oil column thickness of 22-26m, with a small gas cap on top
- rest of Troll West is considered as an aerially larger gas province with gas column up to 200 meters

**Troll East**

- major gas accumulation with narrow 1-4m oil column

The hydrocarbon communication between Troll East and Troll West is restricted to two relatively narrow corridors, see Fig. 1. [5]

**Plan of Development**

The field has been developed in three stages:

*Stage 1: Develop gas reserves in Troll East.*
Troll A, shown in Fig. 3, is a purpose built platform to extract the natural gas on Troll. The platform is 472 meters high, where 369 meters is below sea level.

**Figure 3:** *Purpose built concrete platform, Troll A, attached to seabed.* [23]

*Stage 2: Develop oil reserves in Troll West.*
For development of the oil reserves in Troll West, two semisubmersible production units were built, shown in Fig. 4.

**Figure 4:** *Two semisubmersible production units, Troll B with both production and drilling facilities and Troll C with production facilities, also used for producing the Fram field.* [23]

*Stage 3: Develop the gas reserves in Troll West.*
Troll is now in its final and last stage. Currently (January 2012), four rigs are drilling in Troll West, mainly Vest Venture, Stena Don, Songa Trym and Transocean Leader, represented in Fig. 5. Today the field is operated by Statoil. [14, 23, 24]

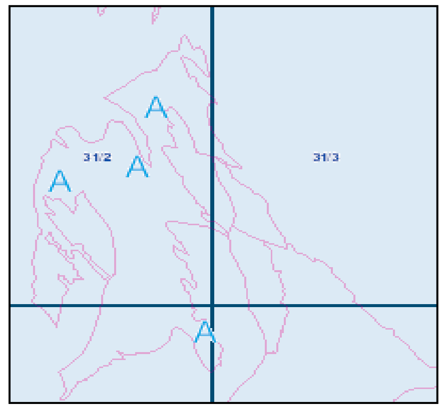


**Figure 5:** *Currently active rigs on Troll West. The blue letter "A" represents the location of active rigs.* [30]

# 3. RESERVOIR GEOLOGY OF THE TROLL FIELD

## 3.1 Depositional Environment

The reservoir interval of Troll lies within the Middle to Upper Jurassic Viking Group sands, consisting of the Fensfjord, Middle Heather, Sognefjord and Upper Heather formations [1], see Table 1.

| CHRONOSTRATIGRAPHY | | LITHOSTRATIGRAPHY | |
|---|---|---|---|
| PERIOD | STAGE | GROUP | FORMATION |
| QUATERNARY | | NORDLAND | |
| UPPER TERTIARY | PLIOCENE | NORDLAND | |
| | MIOCENE | | |
| LOWER TERTIARY | OLIGOCENE | HORDALAND | |
| | EOCENE | | BALDER |
| | PALEOCENE | ROGALAND | SELE |
| | | | LISTA |
| | | | MAUREEN |
| UPPER CRETACEOUS | | SHETLAND | |
| LOWER CRETACEOUS | | CROMER KNOLL | |
| UPPER JURASSIC | RYAZANIAN PORTLANDIAN KIMMERIDGIAN | VIKING | DRAUPNE |
| | | | U.HEATHER |
| | OXFORDIAN | | SOGNE-FJORD / MID. HEATHER |
| MIDDLE JURASSIC | CALLOVIAN | | FENSFJORD |
| | BATHONIAN | | KROSS-FJORD / LOWER HEATHER |
| | BAJOCIAN | BRENT | TARBERT |
| | AALENIAN | | NESS |
| | | | ETIVE |
| LOWER JURASSIC | TOARCIAN | DUNLIN | DRAKE |
| | PLIENSBACHIAN | | COOK |
| | SINEMURIAN | | U.AMUNDSEN |
| | | | JOHANSEN |
| | | | L.AMUNDSEN |
| | HETTANGIAN | | STATFJORD |
| TRIASSIC | RHAETIAN | | |
| | | HEGRE | |

**Table 1:** *Stratigraphic summary of the Troll Area.* [1]

The Viking Group represents a period of incremental transgression over the earlier Jurassic sediments. The depositional environments gradually change from paralic (deposits lay down on the landward side of coast; deltas, shoreline-shelf systems, and estuaries) and marginal-marine (beaches, deltas, estuaries, tidal mud and sand flats), to higher energy conditions in Late Jurassic times. The sediment supply during this period was most likely from coastal distributaries located east of Troll.

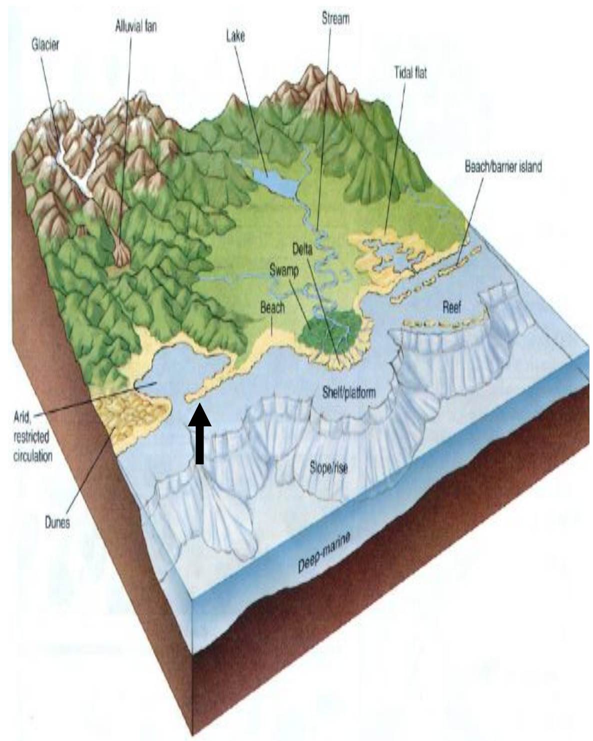


**Figure 6:** *Different depositional environments. The mountains are the source area for clastic sediments, eroded by glaciers and other processes. The Sognefjord formation is believed to be formed by spit barriers. The spit barrier system is marked with an arrow in the figure.* [18]

The Lower Heather Formation comprises of fine micaceous siltstones. The Lower Heather Formation is overlain by coarse sandstones of the Krossfjord Formation. The Krossfjord Formation is overlain by the Fensfjord Formation where more variable coarsening upwards sequences are found. Shore face progradation is observed here. During the latest Callovian and early Oxfordian times, a marked increase in transgressive activity led to deposition of the micaceous sands and silts of the Middle Heather Formation. The Middle Heather Formation was deposited on top of the Fensfjord Formation. The Middle Heater Formation is overlain by Southwards- and Westwards-advancing coarse, clean, transgressive sands. This sand is successively off-lapped by Westward prograding shore face sand facies of the Sognefjord Formation. The Sognefjord formation is believed to be deposited as a spit system, and is the principal hydrocarbon bearing interval of Troll, see Fig. 6 and 7. [1] The "Spit Barrier" represents excellent permeability and porosity. [6]

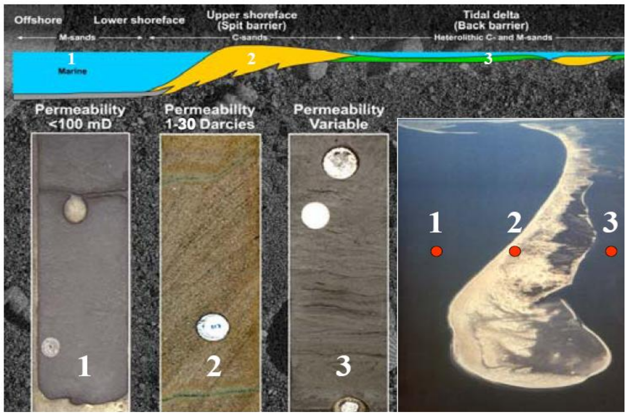


**Figure 7:** *Modern analogue of the depositional environment in the Troll area during late Jurassic time. The Sognefjord formation is believed to be deposited as a spit system* [6]

The Draupne Formation is deposited after the Sognefjord Formation, but is not found in all parts of the field due to erosion in Early Cretaceous times. Therefore, Creteaceous to Tertiary shales and silts can be found resting on the Upper Jurassic in the Western part of the Field. [1]

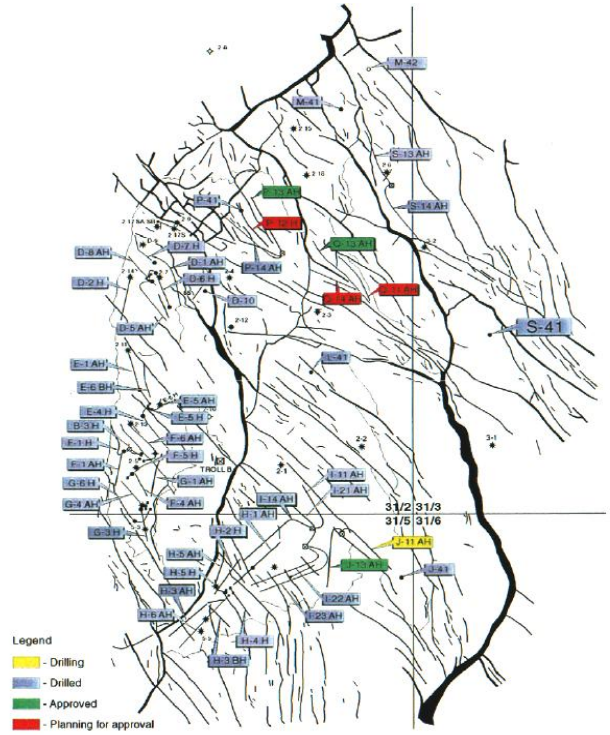


**Figure 8:** *Illustration of the complex faulted structure of Troll West.* [4]

## 3.2 Structure

The Troll field is a structural trap produced by the multiphase faulting due to extensional and oblique slip plate movement. The structure and complexity is illustrated in Fig. 8 and 9. The major fault structures were formed in the Triassic, creating easterly dipping mega blocks over this area. Northward movement of the Viking graben created a series of NE-SW faults during the Middle to Upper Jurassic, which influenced the Viking Group deposition. Early Cretaceous/Late Kimmerian rift-related movements occurred up to and including Aptian times. This resulted in a series of unconformities and imposing a conjugate set of N-S and NW-SE-trending faults. During this period, earlier faults were reactivated due to regional graben subsidence. During Tertiary times, stress releases between the down-warping graben and the Horda platform imposed a NW-SE fault component and developed a hinge zone through block 31/2. [1]

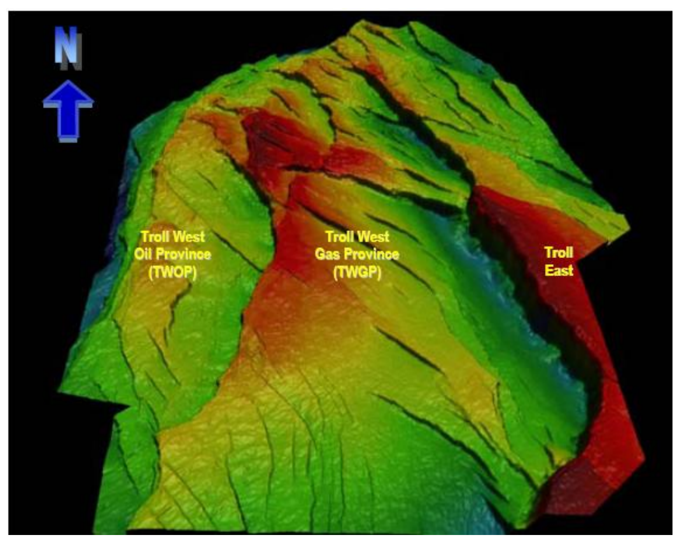


**Figure 9**: *3D illustration of Troll West.* [28]

## 3.3 Reservoir

The reservoir is sealed by cap-rocks from Late Jurassic claystones in the East, to Paleocene claystones in the West. The dominant source rock is the organic rich Draupne Formation (Kimmeridge Clay). [1]

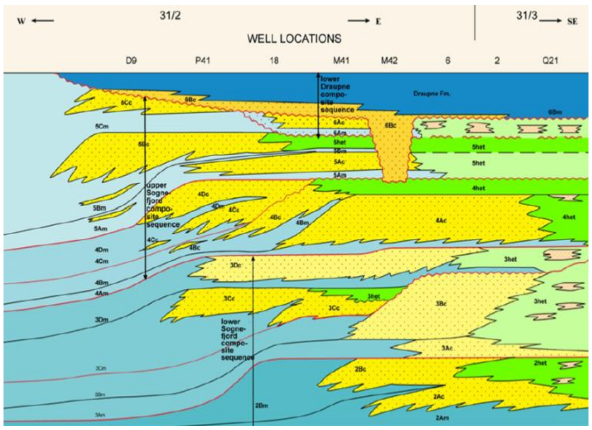


**Figure 10**: *Sequence stratigraphy of Troll West along an east-west transect across the northern part of the field. The middle and bottom arrow represents the Sognefjord formation. The nomenclature of the different bodies describes the subdivisions of the different sands. To the left the sand pinch out, to the right sands interfinger with micaceous sands and silts.* [6]

### *3.3.1 Reservoir Division*

The reservoir can be roughly subdivided into three zones, shortly described below:

**Zone 1:**
Combines the Sognefjord and Middle Heather formations, see Fig.10. This zone contains more than 90% of the hydrocarbons in place.

*Middle Heather*

- 19-26% porosity, permeability of 10mD, gross thickness of 15-110m.

*Sognefjord*

- 25-34% porosity, permeability around 1 D, gross thickness 24-160m.
- Is called Sognefjord due to the fact that the sand is believed to be deposited from the Sognefjord fluvial system, approximately 130 mill years ago [29], see Figure 11.

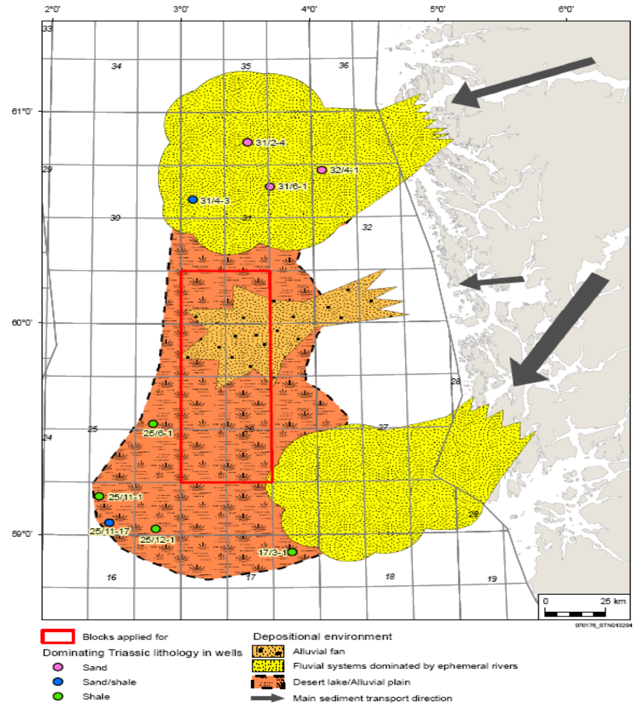


**Figure 11:** *The northern most arrow represent the most likely depositional source for the Sognefjord formation.* [3]

Sognefjord and Middle Heather have undergone six depositional cycles, each marked by rapid rise in sea level. A depositional cycle consists of low energy, giving distal, fine micaceous sediments. These sediments coarsen upwards into medium to coarse sand sequences. These represent a shore face progradation of a complex sand-body across the shelf. In western parts of Troll West, clean sands pinch out, and towards east, interfingers with micaceous sands and silts, see Fig. 10. [1]

**Zone 2:**
Zone 2 is equivalent to the Fensfjord Formation. It has 23-30% porosity, and a gross thickness of 110-290 meters. It comprises of stacked series of small, coarsening upward units, passing from micaceous siltstones to fine sandstones and medium to coarse sands. [1]

**Zone 3:**
Zone 3 is represented by Krossfjord and Lower Heather. [1]

### 3.3.2 Sand Types

It is common to divide the reservoir sands into Mica-sands (M-sands) and Clean-sands (C-sands), dependent on the amount of mica-content. Mica content will give Gamma Ray (GR) readings. In general, 60-75 American Petroleum Institute (API) units are used to differentiate between M- and C-sands. In Fig. 12 the resistivity profiles for the different sands are illustrated. The C-sands are often called clean sands with "non-presence" of mica, typically upper shore face spit barrier sand bodies, see Fig. 7. These sand bodies can be 3-45 meters thick, with medium to coarse-grained unconsolidated sands. The permeability of the spit barrier sand bodies ranges from 1D-20D. The M-sands have poorer quality, and represent finer grained micaceous deposits. Typical deposits are offshore-lower shore face marine deposits, or back-barrier tidal deposits. [6]

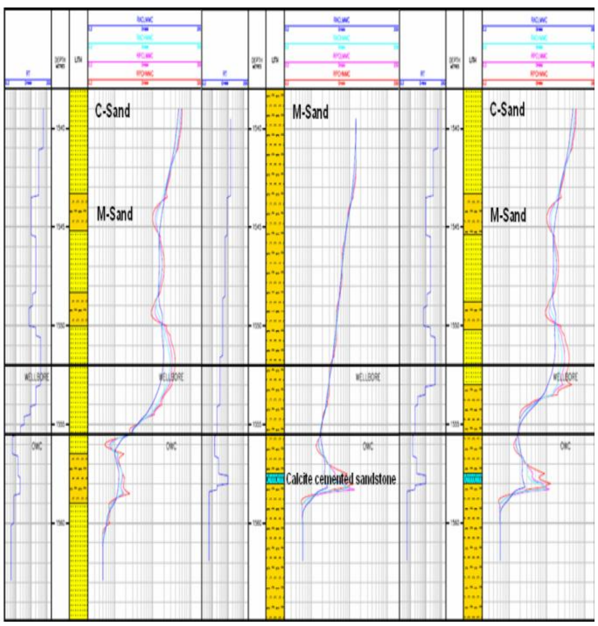


**Figure 12:** *Resistivity profiles from the different sand qualities and calcite cemented intervals on the Troll Field.*[6]

### 3.3.3 Calcite Cemented Sandstone

All over, tightly calcite cemented sandstone intervals are recognized throughout the reservoir sequence. These are present in different amounts and are difficult to map. [6] The shape of individual concretions may vary widely. They may occur as nodules or layers, layers of strata bound concretions, scattered concretions or patchy calcite, see Fig. 13-16. The lateral extent can vary widely, from meters to kilometres, and the thickness is typically from 10 cm up to 2 m. [7] The bulk density readings for the most dense calcite cemented sandstone, during logging while drilling, are usually between 2.67-2.69 g/cc [6].

**Figure 13:** *Scattered concretions.* [7]

**Figure 14**: *Calcite-cemented concretions and developing layer.* [7]

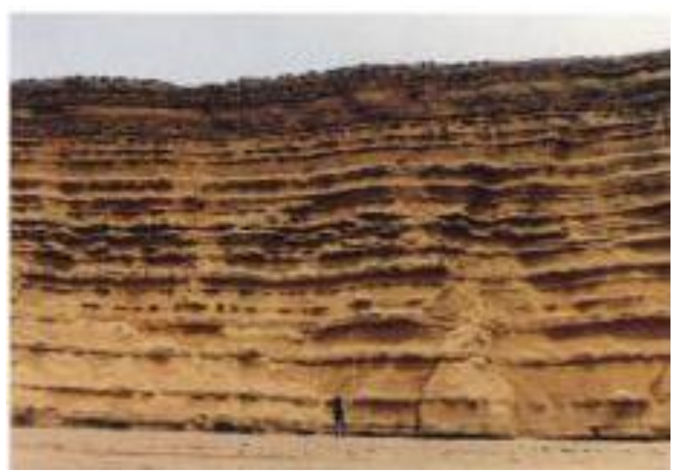

**Figure 15:** *Laterally extensive continuously calcite-cemented layers.* [7]


**Figure 16:** *Patchy calcite cementation merging downwards to form an almost pervasively cemented interval.* [7]

According to the study done by O. Walderhaug and P.A.Bjørkum [7], a calcite cemented interval is not expected to be found in shallow marine sandstone due to lack of viable transport mechanisms for significant amounts of dissolved calcium carbonate. The only significant source of calcite cement is usually biogenic carbonate (e.g. skeletal grains), which is consequently considered to be the dominant source of calcite cement within shallow marine sandstones. [7]

Calcite cement is believed to be formed when the fairly unstable aragonite or high Mg-calcite is allowed to dissolve and create a source for calcite cement as burial proceeds from overlying sediments.[7] Cement will then form and bind the framework grains of the calcite cement source together within the pores of the sandstone. Cement is a secondary mineral that forms after deposition, and during burial of the sandstone. These cementing materials may either be silicate minerals or non-silicate minerals, such as calcite. Calcite cement is the most common carbonate cement, and is an assortment of smaller calcite crystals. [21, 22] The formation of calcite cement is believed to be completed at temperatures below 70˚C. Below 70-80˚C the quartz cementation will become significant. [7]

The growth and geometry of the calcite cement can be summarized in three factors listed below. For a more detailed description, it is recommended to read the study done by Waldehaug and Bjørkum [7]:

- *Concentration of biogenic material* (e.g. determines what type of geometry will form)
- *Fluid flow during compaction of a sedimentary basin* (e.g. the fluid flow in between pores within sandstone will determine how fast and in what direction the calcite cement is allowed to grow. This will also influence the geometry of the calcite cemented sandstone)
- *Siliclastic supply* (e.g. a period with little siliclastic supply will allow the biogenic material to be more concentrated, hence allow more calcite cement to form).

Calcite cement normally forms pervasively cemented intervals where all porosity is filled by calcite cement. The biogenic source material will be transported until there is no source material left (if the process is not disrupted by uplift, subsidence or other activity that will affect the process). Because of this, presence of calcite cement between the calcite cemented intervals are seldom to be found. Its occurrence is difficult to predict since it is dependent on the original distribution of biogenic carbonate within the sandstone. The calcite cement itself will not act as flow barrier, but may affect the total flow in a reservoir if present in larger quantities. [7]

### 3.3.4 Mapping of Calcite Cemented Intervals

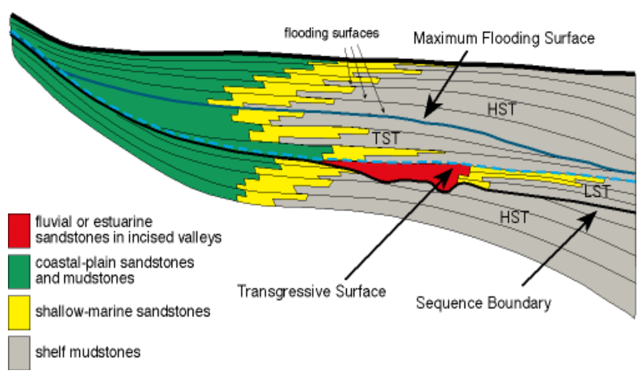


**Figure 17:** *Example of MFS, shift from retrograde to prograding sequence. The sediments become finer grained as moving towards right in the figure.*[20]

Geostatistical analysis shows that 10% of the reservoir formation is calcite cemented [8]. Calcite cementation has been found to occur within all sequences and lithologies in the reservoir. The frequency and occurrence is independent of depth and stratigraphy.[12] A study related to sequence stratigraphy and facies development of the Troll field by K.Gibbons et.al.[8], showed that theoretically the calcite cemented intervals are more likely to occur in correlation with Maximum Flooding Surfaces (MFS). See Fig. 17. A MFS represents the change from a retrograding to prograding parasequence patterns [20]. It has also been shown, according to the study done by Eva Helle Simmenes [9], that there are correlations with respect to energy conditions, grain size, and calcite cemented intervals.

### *3.3.5 Chalk and Calcite Cemented Sandstone*

Chalk is fine-grained limestone composed largely of microscopic calcite plates called coccoliths. The coccoliths are derived from a group of planktonic algae, the coccolithosphores [10]. Chalk cementation is formed of similar elements as the calcite cemented sandstone. The difference being that the calcite cemented sandstone is formed by larger shells in smaller quantities, in periods with little siliclastic supply. During formation, the calcite cement fills the sandstone pores, reducing the porosity [7]. As for chalk, huge coccolithic accumulation on the seafloor allows the chalk to be formed in several hundred meters of thick bands [10]. The porosity is determined by the chalk itself and is a direct function of the burial depth. Chalk has, as the calcite cemented sandstone, low permeability.

### *3.3.6 Hardness of Reservoir*

A Drill Bit Optimalization System (DBOS) study was done in order to map the hardness and confirm the occurrences of calcite cemented sandstone intervals on Troll. DBOS is an optimalization system that helps to find optimum bit selection for a specific formation by calculating the Unconfined Compressive Strength (UCS) of the formation from the GammaRay log, Sonic log and Composite/mud log. The unconfined compressive strength is the very sole base of the whole DBOS analysis, and represents the hardness of the rock. The reason for using unconfined compressive strength is that it relates more to the bit performance of the bit in that confinement condition.
Six DBOS-plots for Troll were correlated as shown in Fig. 18.

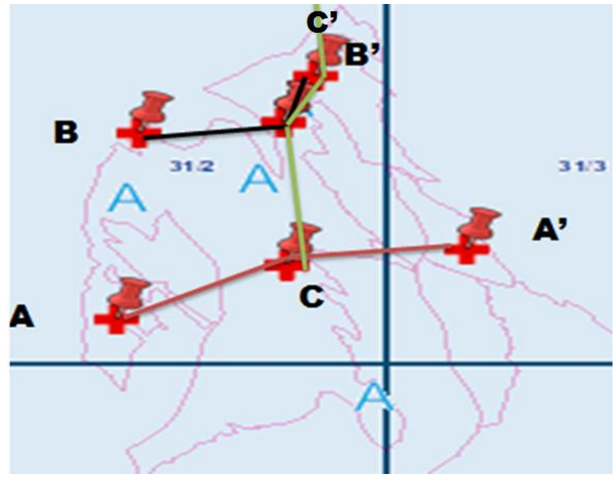


**Figure 18:** *Correlation of DBOS-plots, Troll West; A-A', B-B' and C-C', Appendix 1.*

The study pointed out that the field is quite homogenous in terms of hardness of sandstone, approximately 1000 - 3000psi UCS (Unconfined Compressive Strength). The hardness of the calcite cemented sandstone varied from 15 000 - 30 000psi UCS, where most of them were located around 15 000 - 20 000psi, see Fig. 19. Following standards were used to classify the hardness of the different formations in psi:

| | | |
|---|---|---|
| Ultra soft | <1000 | psi |
| Very soft | 1000-4000 | psi |
| Soft | 4000-8000 | psi |
| Medium | 8000-17000 | psi |
| Hard | 17000-27000 | psi |
| Very hard | >27000 | psi |

The study confirmed that the calcite cemented sandstone intervals are present all over the field, but vary in quantity and hardness. Hence, some areas of Troll are easier to drill than others. For more information see Appendix 1.

As described in Section 3.3.4, several studies have been done with respect to mapping the calcite cemented intervals. Due to the formation and random occurrence, the calcite cemented intervals are difficult to predict. Most likely it should be possible to produce a calcite prognosis for an upcoming well bore, due to several years of drilling on Troll. A prognosis would then exist in the hand of the operator (Statoil). It was concluded that no more effort should be put into trying to map the calcite cemented intervals, but on how to handle the interbedded formation in Troll West with respect to drilling.

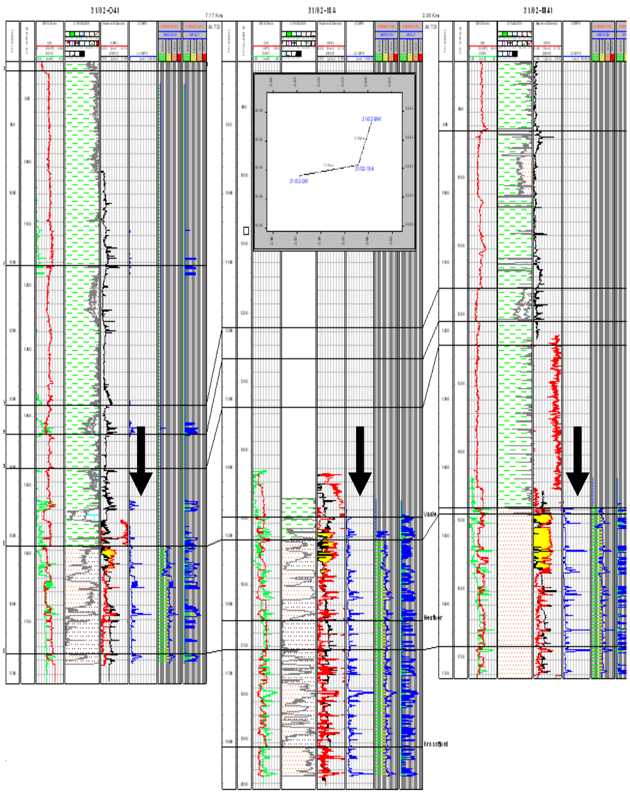

**Figure 19:** *Outcrop of DBOS correlation of well O41, 18A and M-41 (C-C' correlation) showing the UCS for the reservoir.The arrows marks the columns with UCS (unconfined compressive strenght), all showing UCS peaks from 15000-30000psi. Note the variation in quantity and amplitude of the UCS, see Appendix 1 for higher resolution.*

# 4. RESERVOIR GEOLOGY OF THE GJØA FIELD

## 4.1 Gjøa – Analogue to Troll

Gjøa is believed to be analogue with Troll in regards to formation type and characteristics. Gjøa is located in block 35/9 and 36/7, approximately 45 kilometers North of Troll [26], see Fig 20.

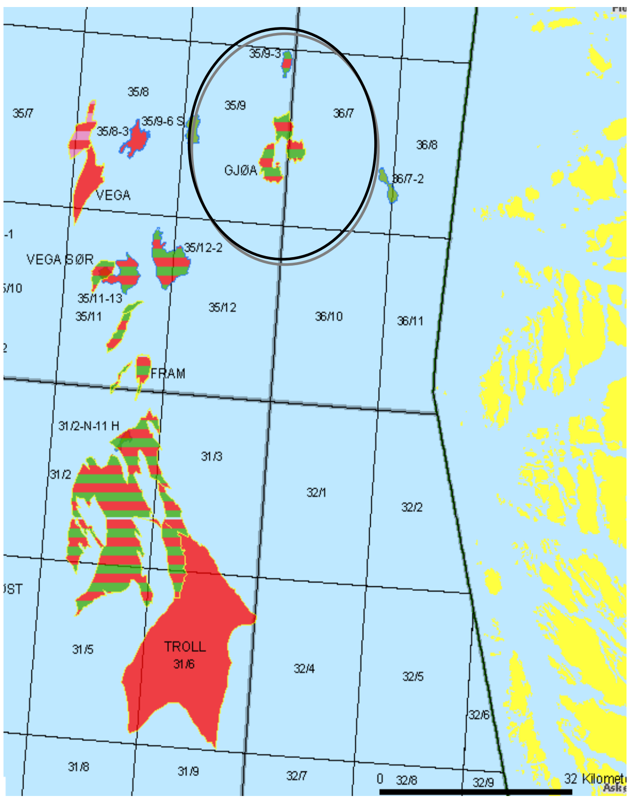


**Figure 20:** *Gjøa location in relation to Troll.* [26]

## 4.2 Depositional Environment

The Gjøa reservoir was deposited in a similar environment as Troll. The reservoir formations consist of Jurassic sandstone, represented by the Viking, Brent and Dunlin groups. The Upper Jurassic sediments belong to the Viking Group, which have been subdivided in 5 formations: Heather, Krossfjord, Fensfjord, Sognefjord and Draupne. These formations form the main reservoir. All formations in the Viking Group, except Draupne, are believed to be deposited under shallow marine conditions, similar to the Troll depositional conditions, with prograding sand ridges. The sand ridges migrate to the west at an active shore face. The Draupne formation contains deep marine turbiditic sandstones at the bottom. [34]

Massive sandstone bodies occur in the Gjøa reservoirs, especially within the Fensfjord formation. The Gjøa massive sandstones are described as alternating with cross-bedded sandstone, interpreted as tidal sand wave deposition on the shore face. They have a sharp base and top, several meters in thickness and tubes are abundant throughout the entire massive sandstone. [34]

The cross-bedded sandstones of the Gjøa field have porosities in the range of 0.15-0.25, and permeability ranging from 50-1000mD. The massive sandstone bodies have around 0.25 in porosity and more than 1D in permeability. Thus, the massive sandstone of the Gjøa field provides excellent reservoirs. [34]

As for Troll, hard sandstone intervals are recognized throughout the reservoir sequence, mainly in the Sognefjord and Fensfjord formation. The hard intervals were thought to be tightly cemented, calcite-rich sandstone intervals since the reservoir formations and depositional environment were similar. The sandstone with calcite cemented sandstone for Troll and Gjøa is illustrated by core photos from the Norwegian Petroleum Directorate (NPD) in Fig. 21.

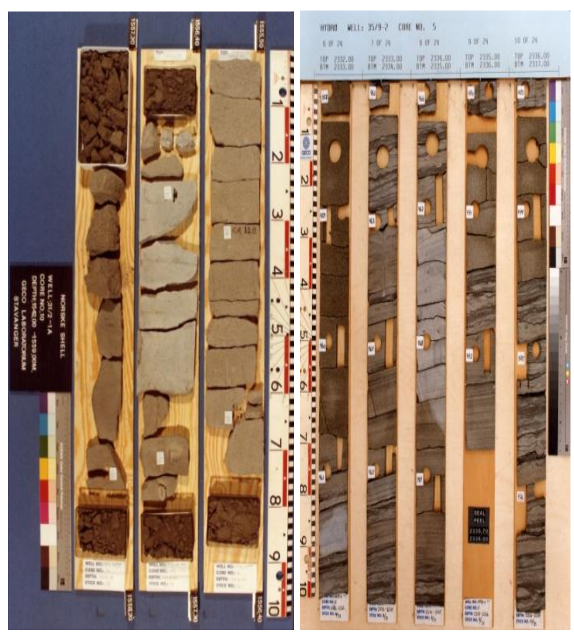

**Figure 21:** *Core photos from the NPD. Here Gjøa formation is to the right, and Troll to the left. Both formations are showing cemented intervals.* [26]

## 4.3 Structure

Gjøa is a structural trap, produced by the multiphase faulting caused by extensional and oblique slip plate movement [32]. Gjøa has undergone many of the same cycles as Troll. A general picture of the structure is given in Fig. 22 and 23:

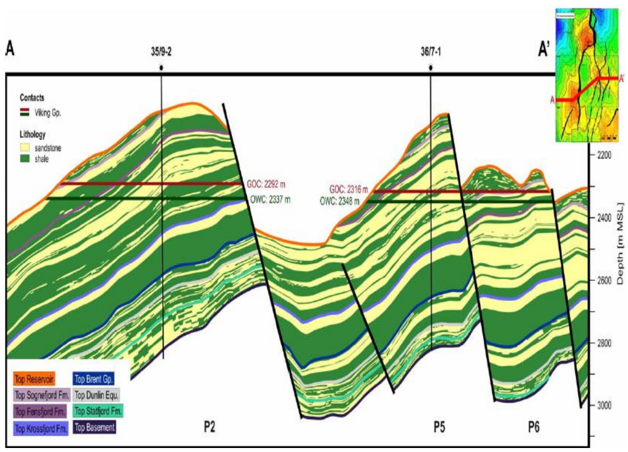


**Figure 22:** *Gjøa – W-E profile.* [32]

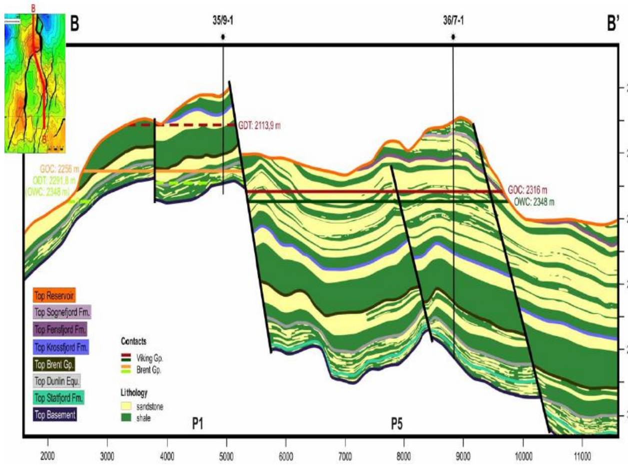


**Figure 23:** Gjøa - *N-S profile.* [32]

## 4.4 Hardness of Reservoir

A DBOS study was previously done on Gjøa for three wells; these wells were correlated with two wells on Troll. The aim of the study was to confirm if both the Gjøa sands and calcite cemented intervals could be similar to those located on Troll. The study showed that the Gjøa reservoir formation, mainly Fensfjord and Sognefjord, could represent a good analogue for Troll reservoir formation. Gjøa shows the same hardness of the calcite cemented sands, and indicates local occurrences all over the field, as for Troll, see Fig 24. Gjøa has a deeper burial depth, approximately 2300 meters TVD (True Vertical Depth), making the sandstone harder, approximately 6-9000 psi. The assumed calcite cemented sandstone has a range in hardness from 15000-30000psi, where most of them are located in-between the interval of 15000-250000 psi, more detailed results can be seen in Appendix 2.

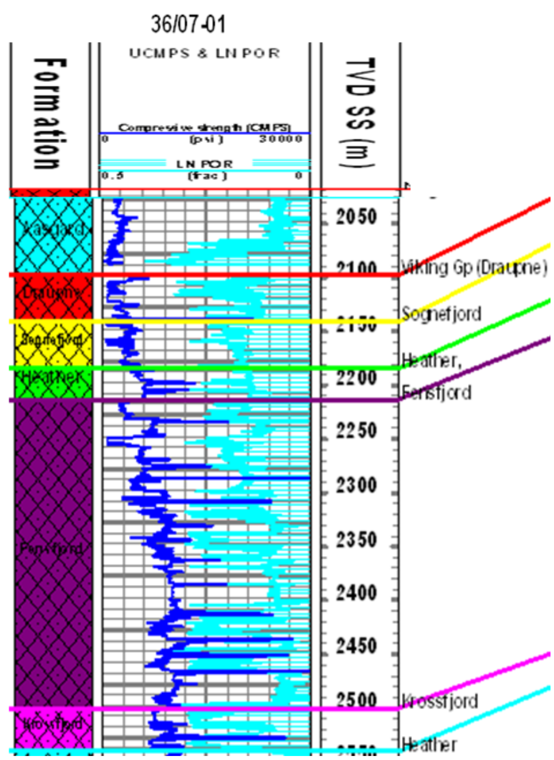


**Figure 24**: *Outcrop of the UCS for Gjøa well 36/07-01, scale is from 0 to 30 000 psi for the UCS. The UCS is the darkest line. Calcite cemented sandstone have a range in hardness of 15 000psi to ~30 000psi. See Appendix 2 for details.*

# 5. BASICS OF PDC TECHNOLOGY

## 5.1 General

In general, we have two types of bits; Polycrystalline Diamond Compound Bits (PDC) and Roller Cone Bits (RC). Since most of the upcoming wells on Troll are to be drilled as a sidetrack from an existing wellbore with PDC bits, the RC bits will not be elaborated.

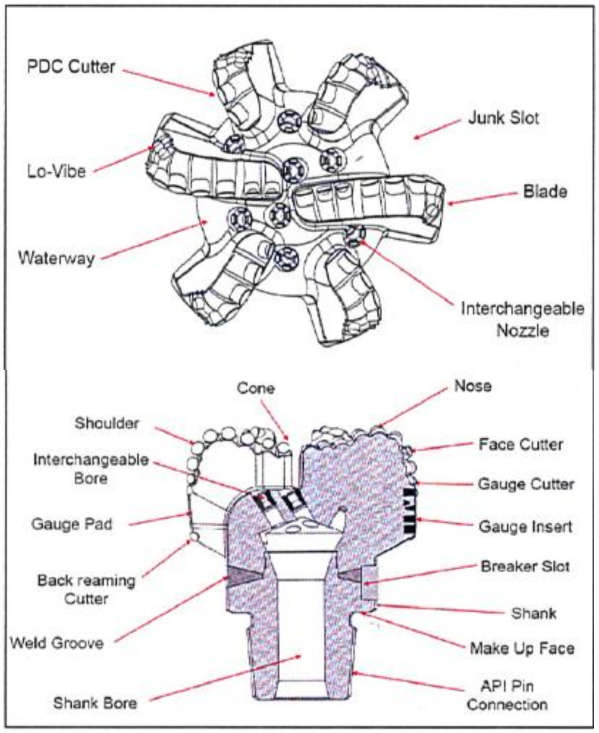


**Figure 25:** *General PDC bit setup.* [32]

A PDC bit is a fixed cutter designed bit that shears the formation with a continuous scraping action, see Fig. 26. The PDC bit, with its nomenclature, is illustrated in Fig. 25. The PDC bit rotates as one piece and contains no separately moving parts. In the early years of PDC technology, the main application area was for relatively soft, non-abrasive rocks. During later years, improvements were made both in cutter technology and design, giving the PDC bit a wider range of applications. [32]

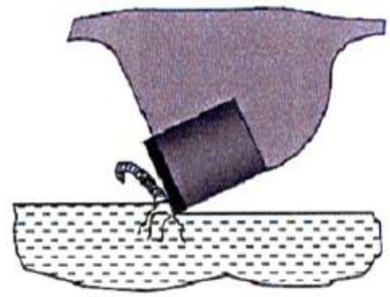

**Figure 26:** *Shearing action from PDC-cutter.* [32]

## 5.2 PDC Design

Several factors contribute to making the optimum PDC design for a specific drilling application. The main factors are:

**Matrix Design**

*Materials:* The bit body can be made up of steel or tungsten carbide. A steel body will be more impact resistant than a tungsten carbide body, but less wear resistant. The tungsten carbide body design is usually termed "matrix". [32]

*Bit profile:* The bit profile has a direct influence on bit stability, steerability, cutter density, durability, ROP, cleaning, and cooling. Drilling environment and application needs to be matched to the profile. In general, 4 bit profile types are used: [32]

- Flat
- Short parabolic
- Medium parabolic
- Long parabolic

*Blade count:* When applying weight on bit, the force the weight creates is distributed on the respective blades (and on to the cutters). A 5 bladed bit will have higher force per blade than for a 7 bladed bit, and a 7 bladed bit will have more cutters than a 5 bladed bit. [32]

*Blade geometry:* Two types of blade geometry are used, straight or spiral shown in Fig. 27. [32]

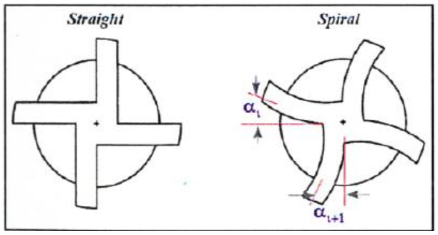


**Figure 27:** *Spiral versus Straight blade layout.* [32]

With straight blades, the cutter radial forces are summed up as a whole on the gauge. With spiral blades, only a component of each radial force is used, and the net effect on gauge is less than that of straight blades. Lower gauge stresses reduce the chance of a bit to pivot about its gauge. This reduces the damaging vibrations that result from such pivoting. [32]

*Blade Layout:* The blade layout can either be symmetrical or asymmetrical. With symmetrical layout, the angle between consecutive blades is equal. The symmetry repeats and amplifies vibrations. In an asymmetrical layout, the angle between any consecutive blades is different. This will break down the harmonics and make the elapsed time between signals maximized. [32]

### Cutter Technology Design

In general, PDC cutters are made by pressurizing graphite at high temperatures together with a catalyst material (cobalt) in a belt press, to form diamond grit. The particle size of the graphite is predetermined since it will affect the diamond grit. The diamond grit is placed into a refractory metal can, with a tungsten carbide substrate placed on top. This is mechanically sealed and placed within a graphite heater tube. The assembly is placed in the diamond press and the sintering process is commenced. At approximately 1000ksi and 1400˚C, diamond to diamond bonding occurs. The cobalt from tungsten carbide substrate sweeps through the diamond grit catalyzing the bonding process. The cobalt also bonds with the tungsten carbide substrate creating one integral component. The current cutter technology at Smith Bits is the ONYX cutter. The ONYX cutter is manufactured by a two-step High Pressure High Temperature (HPHT) process, where the cutter is subjected to leaching (explained below). The manufacturing process will not be elaborated in detail because of confidential information. [32] Different design options within cutter technology are:

*Leaching:* Leaching is to expose the diamond cutting surface to powerful acids; this will remove some of the cobalt phase by an etching process. By doing this the diamond degradation is reduced and thermal resistance increased, hence the cutter is more resistant. [32]

*Cutter edge bevel:* Cutters have cutter edge bevel that is ground into the cutter after it is manufactured. They have the advantage of increasing the impact resistance of a cutter. [32]

*Cutter Size:* The larger the size of cutter, the larger the area it will cover in its borehole trail. 19 mm cutters on an 8 ½" PDC bit will make the cutting structure more aggressive than with an 8 ½" PDC bit with 13 mm cutters. The forces on a 19mm cutter will be larger than for a 13mm cutter. The choice of cutter size depends on environment and type of application. [32]

*Diamond table / Tungsten Carbide - Interface:* The interface between diamond table and tungsten carbide insert prevents separating the diamond table from the tungsten carbide insert. Different shapes of the interfaces exist, depending on type of environment and drilling application. [32]

### Cutting Structure Design

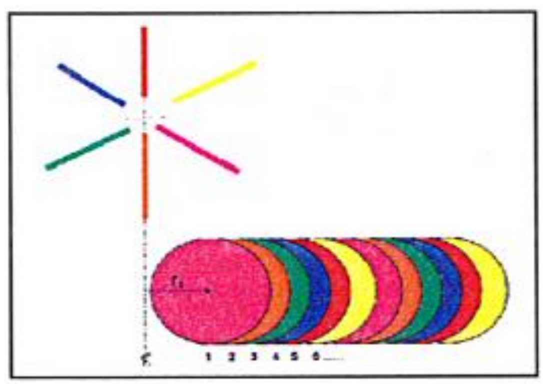


**Figure 28:** *Single set layout.* [32]

Bit behavior and drilling efficiency are directly influenced by the cutter arrangement. The two major cutting structures are single set layout or plural set layout. A single set layout has one PDC cutter in each radial position, illustrated in Fig. 28. The plural set layout has more than one PDC cutter in each radial position. The plural cutter arrangement generates more pronounced ridges as compared to a single set. Formation ridges are illustrated in Fig 29. The shape and size of the formed ridges have considerable effect on bit stability and to a certain extent penetration rate. The plural cutter arrangement offers greater resistance to off-center movement as compared to a single set. [32]

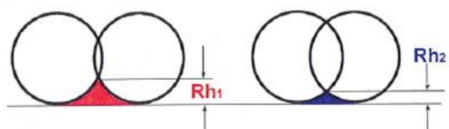


**Figure 29:** *Illustration of formation ridges.* [32]

For the single set layout, forward spiral or reverse spiral cutter arrangement is being used. In forward spiral, cutters advance outward radially, in a clockwise direction, illustrated in Fig.30. In reverse spiral, cutters advance outward radially, in a counterclockwise direction. The forward spiral is more difficult to stabilize than the reverse spiral. [32]

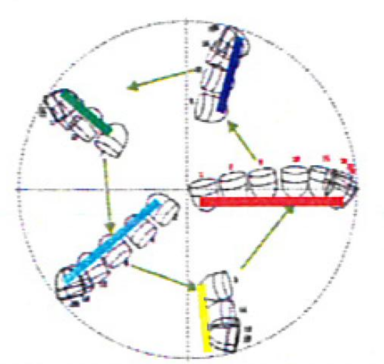

**Figure 30:** *Reverse spiral set up.* [32]

**Other design options**

*Orientation of cutter* – How the cutter is oriented in the vertical and horizontal planes relative to the blade. [32]

*Cutter exposure* – the depth of cut can be controlled by placing a knuckle feature, also called "Lo-Vibe", behind the cutter, illustrated in Fig. 31. The height of the feature determines the depth of cut. This feature can improve bit stability on specific bit areas.

*Back up cutters* – If the bit will be exposed to heavy wear, extra cutters can be added behind the primary cutters. These are termed back up cutters and will increase the wear resistance of the PDC bit. [32]

*Hydraulics* – the hydraulics, meaning flow speed through nozzle bores and total flow area (TFA) is determined by the type of drilling application (hole cleaning, balling). [32]

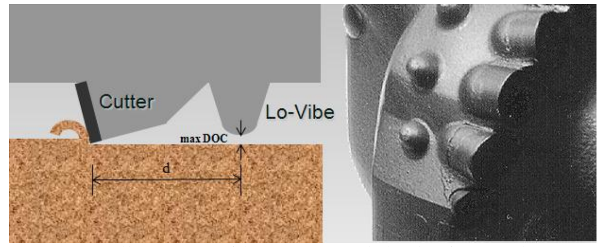


**Figure 31***: Illustration of how to control depth of cut with a Lo-vibe feature behind cutter.* [32]

**Force Balancing**

As the bit drills, the WOB is distributed over the cutters, and the total torque is generated from all the circumferential forces on cutters. All radial and circumferential forces are summed up to determine the magnitude and direction of the resultant imbalance forces. It is desired to lower the imbalance forces. This will make the PDC bit more resistant towards initiation of bit vibration. [32]

The design options described in this section (5.2) can all be played with to reduce the total imbalance force and promote bit stability.

**This thesis does not incorporate a new design, but uses the existing bit technology present at Smith Bits.**

## 5.3 Smith Bits PDC Nomenclature

All drill bit vendors have different nomenclature to describe their PDC bits. Smith Bits has the following nomenclature shown as an example below:

8 ½" MDSi616

8 ½" = the diameter of bit in inches
M = matrix
D = directional certified through IDEAS
S = backup cutters
i =IDEAS certified
616 = 6 blades with 16 mm cutters

Behind 8 ½"MDSi616, additional feature letters are written. These are very well described in Smith Bits own product catalogue. [31]

## 5.4 Smith Bits BOM – Bill of Material

Each bit has a specific Bill Of Material (BOM). The BOM represent the cutting structure, internal features and cutter types. If changes to design, cutters or features are done, it is documented in Smith Bits own data directory, and in the BOM itself.

## 5.5 IADC dull grade code

After a bit is run, it will be given a dull grade. The nomenclature of the code is shown in Table 2. It represents the wear to the bit.

| T | | | | B | G | REMARKS | |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| CUTTING STRUCTURE | | | | B | G | REMARKS | |
| Inner Rows (I) | Outer Rows (O) | Dull Char. (D) | Loca-tion (L) | Brng. Seal (B) | Gauge 1/16 (G) | Other Dull (O) | Reason Pulled (R) |

**Table 2:** *IADC dull grading code.* [2]

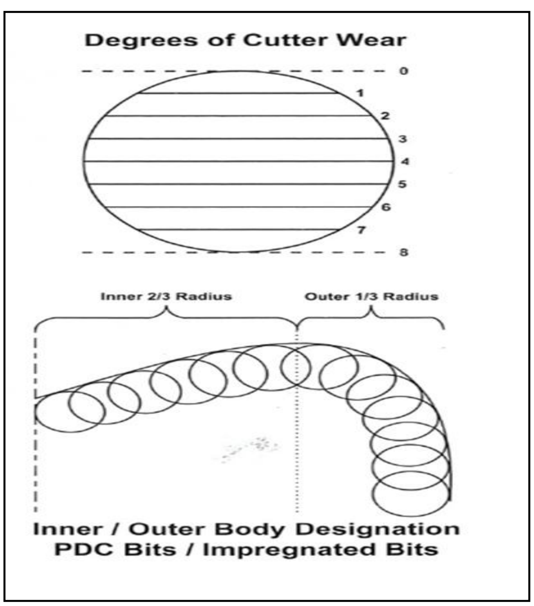


**Figure 32:** *Degrees of cutter wear and classification of inner and outer.* [2]

The first 4 letters in the dull grade code represents the wear of the cutting structure. Column 1 and 2 represent the inner and outer cutting structure, illustrated in bottom of illustration in Fig. 32. The inner and outer is graded from 0-8 where 0 represents no wear, illustrated in top of Fig.32.

Column 3 in the dull grade code represents dull characterization, meaning the type of wear, see Table 33. Column 4 is location of wear, see Fig. 3. Column 5 represents the bearing of a roller cone, graded to be effective or not effective. In a PDC dull grade, it will be represented by an X, since the PDC is a fixed body design with no sealing parts. Column 6 represents the wear in gauge area, and is measured with a gauge ring. The amount of wear is described as 1/16 of an inch (e.g. 2 means 2/16 of an inch). Column 7 represents other dull characteristics and column 8 the reason bit was Pulled Out of Hole (POOH), see Table 4.

**DULL CHARACTERISTICS**

| | |
|---|---|
| BF — Bond Failure | LN — Lost Nozzle |
| BT — Broken Teeth / Cutters | LT — Lost Teeth / Cutters |
| BU — Balled Up Bit | NR — Not Rerunable |
| CR — Cored | OC — Off Center Wear |
| CT — Chipped Teeth / Cutters | PN — Plugged Nozzle / Flow Passage |
| DL — Cutter Delamination | RO — Ring Out |
| ER — Erosion | RR — Rerunable |
| HC — Heat Checking | SP — Spalled Cutters |
| JD — Junk Damage | WO— Washed Out Bit |
| LM — Lost Matrix | WT — Worn Teeth / Cutter: |
| | NO— No Dull Characteristics |

**Table 3:** *Different dull characteristics.* [2]

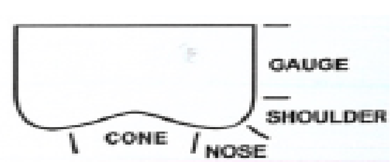


**Figure 33:** *Location Designation.* [2]

| | | |
|---|---|---|
| BHA | — | Change Bottom Hole Assembly |
| CM | — | Condition Mud |
| CP | — | Core Point |
| DMF | — | Downhole Motor Failure |
| DP | — | Drill Plug |
| DSF | — | Drill String Failure |
| DST | — | Drill Stem Testing |
| DTF | — | Downhole Tool Failure |
| FM | — | Formation Change |
| HP | — | Hole Problems |
| HR | — | Hours |
| LIH | — | Left in Hole |
| LOG | — | Run Logs |
| PP | — | Pump Pressure |
| PR | — | Penetration Rate |
| RIG | — | Rig Repair |
| TD | — | Total Depth / Casing Depth |
| TQ | — | Torque |
| TW | — | Twist Off |
| WC | — | Weather Conditions |
| WO | — | Washout in Drill String |

**Table 4**: *Reasons pulled out of hole.* [2]

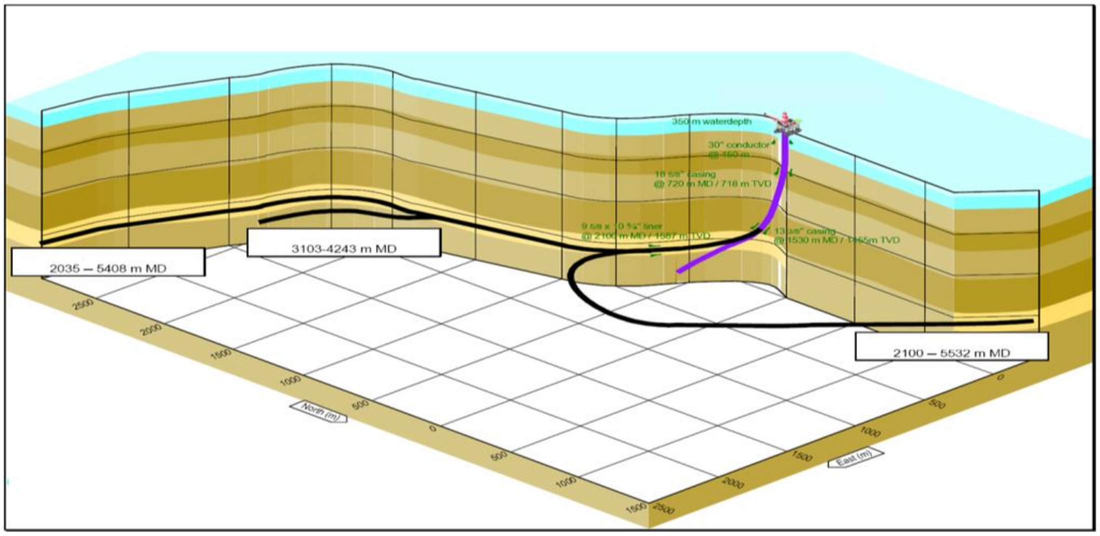


**Figure 34:** *Typical Troll well profile with long horizontal section and several junctions. Re- illustrated from "Troll Oil Drilling"; OTC17112.* [13]

# 6. DRILLING THE TROLL FIELD

Typical for Troll is a long horizontal section of 3000-4000 meters, as shown in Fig. 34. Usually 3 sidetracks are drilled from one wellbore. The long horizontal 8 ½" section indicates the importance of durability to the PDC bit. In Norway, the rig cost is around 3-4 millions NOK. If the bit has to be retrieved, the planned drilling can be postponed with 15-20hours or more, giving loss in revenues for the operator.

## 6.1 Troll Story

Historically, three major factors have contributed to make Troll development possible, listed shortly below [11]:

**1. Horizontal drilling** – development of the Rotary Steerable Systems pioneered by Baker Hughes during the 1990's, enabling them to control the toolface in the narrow TVD interval of the relatively shallow unconsolidated sands of Troll [12]. The end product has been their Autotrak, push-the-bit-technology, which is currently being used at Troll. [13] Nowadays several steerable systems are available at the market.

**2. MLT (multilaterals)-technology** – allowing several sidetracks in one well, making reservoir drainage more efficient. [13]

**3. Durable and stable PDC bits –** Hughes Christensen (now Baker Hughes) has done several improvements with respect to durable and stable PDC bits for Troll applications, which have given them a product that can be steered, give high ROP in the unconsolidated sands and handle the somewhat randomly occurring calcite cemented intervals. [13]

Due to this development in technology, Troll has become a simpler field to drill wells in compared to the early 1990's. The low abrasive unconsolidated sands give high Rate of Penetration (ROP), and when using recommended drilling practices, mainly for Revolutions per Minute (RPM) and Weight on Bit (WOB), the calcite cemented intervals can be overcome.

## 6.2 Challenges – Sognefjord formation

### *6.2.1 Vibrations and Low Penetration Rates*

As mentioned in Section 3.3.3, tightly calcite cemented sandstone intervals are recognized throughout the reservoir sequence. Well data from 8 wells with high quantities of calcite cemented intervals were investigated. The wellbore names are given in Appendix 9, where the well logs are presented. A calcite cemented sandstone was considered to be equal or above 2.6 g/cc in bulk density. At this value the ROP was lowered significantly. The quantities of calcite cement in each well were calculated based on the 2.6g/cc bulk density criteria. The calculations showed variation in amount of calcite cemented sandstone drilled, from 50 up to 200 meters. This confirms that the quantity of calcite cemented sandstone varies, as described in section 3.3.6.

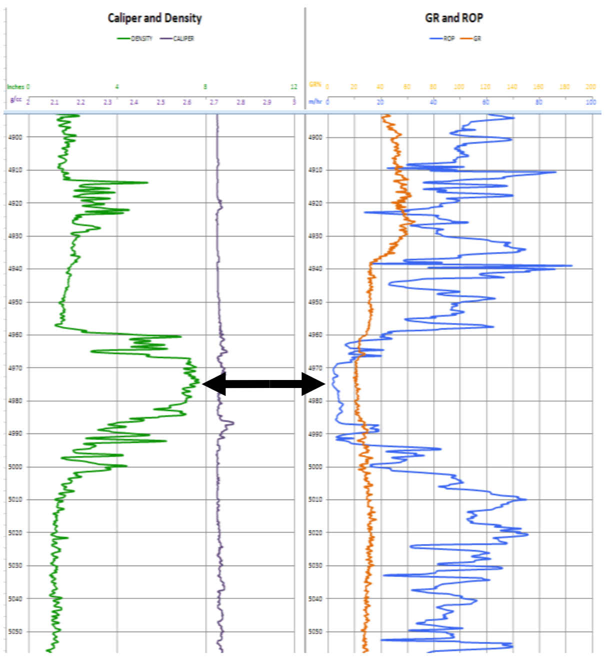


**Figure 35:** *Example showing the effect of drilling through a high density calcite cemented sandstone in well 31-2-F-1-BY1H. Note the density increase and ROP decrease, marked with a two headed arrow in the figure.*

The well data showed that in the loose unconsolidated sands, ROP typically range from 50-100m/hr. For the calcite cemented sandstone, the ROP is lowered down to 2-5 m/hr giving slow progress, see Fig. 35.

The calcite cemented sandstone give high torque values, inducing risk of torsional oscillations, stick slip, whirl and even lateral vibrations. This can cause breakage to PDC cutting structure and BHA. [11]

Several studies have been done, pioneered by Baker Hughes, in collaboration with Norsk Hydro (now Statoil Hydro), on how to achieve higher penetration rate and less vibration when drilling through the calcite cemented sandstone. [11, 12] The results have been to optimize the design of PDC and BHA, and to control the drilling parameters [11, 12, 13]. The drilling practice at Troll is described in Section 8.2.4. Inconsistent choice of drilling parameters, mainly WOB and RPM, is believed to induce vibrations. It has been shown crucial to have close communication between the optimization engineers, drillers, and drilling supervisors. This ensures efficient utilization of the information available from the down-hole environment to provide safe and efficient drilling. [15]

### *6.2.2 High local doglegs and extended gauge length*

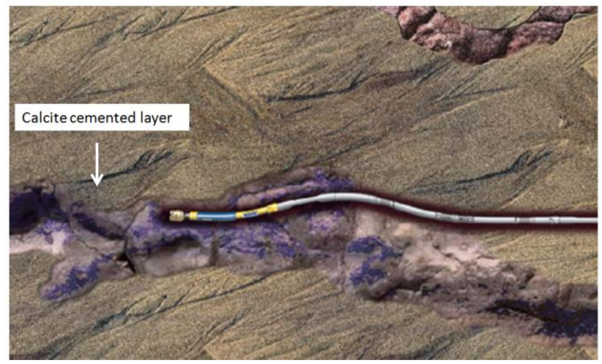


**Figure 36**: *High local dogleg can occur while drilling in sandstone with presence of calcite cemented intervals. Illustration re-illustrated from "Real-Time BHA Bending Information Reduces Risk when Drilling Hard Interbedded Formations".* [16]

Depending on the dip angle, and the orientation of the calcite cemented sandstone surfaces; the bit can be deflected aside into the more drillable loose sand. As re-correcting well path, a high local dogleg can be created, see Fig. 36. [16] This can introduce stress to the BHA-assembly and create problems staying in the narrow True Vertical Depth (TVD) interval as drilling ahead. Later, during completion, it can cause a premature landing of completion equipment. This has been improved by:

- introducing optimum Drilling Practices for the interbedded Troll formation[12]
- survey bending stresses [16]
- survey near bit inclination [16]
- stiffen the BHA [15]
- elongate the gauge pad of the bit [16]

An elongation of the gauge pad section of a PDC bit will make the bit less affected by deflecting off from the planned well path, as drilling into calcite cemented sandstone. [16] The elongation will affect the steerability, but not make the bit unsteerable.

# 7. PDC PERFORMANCE - TROLL FIELD

## 7.1 DRS – Drilling Record System and Round Tuit

Troll drilling records, including bit dull grades, are uploaded into Smith Bits own Drilling Record System (DRS). The DRS is a database that helps you filter and extract desired data. The DRS Troll data was entered in an Excel based program called RoundTuit. The RoundTuit helps you filter the extracted DRS data, and do analysis with respect to run distribution and bit performance. DRS and Round Tuit were used to produce the performance plots in section 7.2 and 7.4, (Appendix 3 and 4).

## 7.2 Troll Performance Study

This study was done to point out overall trends and bit technology used on the Troll Field by different drill bit vendors. It is a guideline to help finding the optimum bit for Troll drilling. Detailed descriptions are given in Appendix 3.

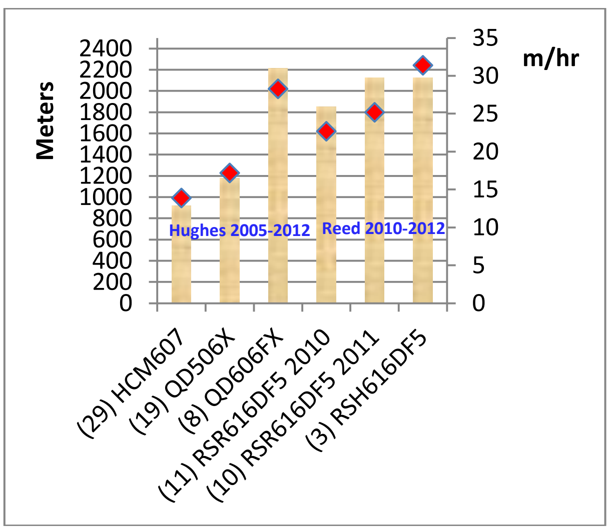


**Figure 37:** *8 ½" section ROP and length performance. Hughes to the left, Reed to the right: Red dots represent ROP, columns represent drilled interval. The current bits used are the QD606FX (Hughes Christensen), and RSH616DF5 (Reed Hycalog). The brackets in front of each bit notation represent number of relevant runs representing the above length interval column and ROP dot. See appendix 3.*

The current drill bit - vendors for the 8 ½" section are Hughes Christensen and Reed Hycalog. Due to the development in drill bit technology and drilling practices in recent years, bits now drill further, give higher ROP and show less wear. This is displayed in Figure 37, 38 and 39.

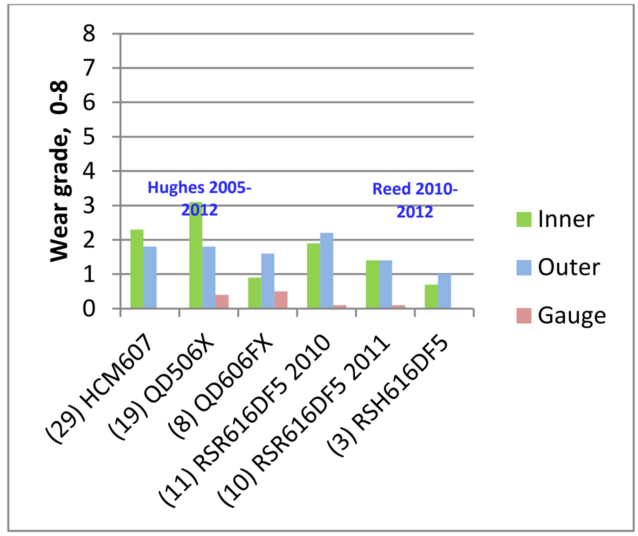


**Figure 38:** *8 ½" section wear to inner, outer and gauge section given in IADC dull grade classification. Baker Hughes is presented to the left and Reed Hycalog to the right. The current bits used are the QD606FX (Hughes Christensen), and RSH616DF5 (Reed Hycalog). The brackets in front of each bit notation represent number of relevant runs representing the above length interval column and ROP dot. See appendix 3.*

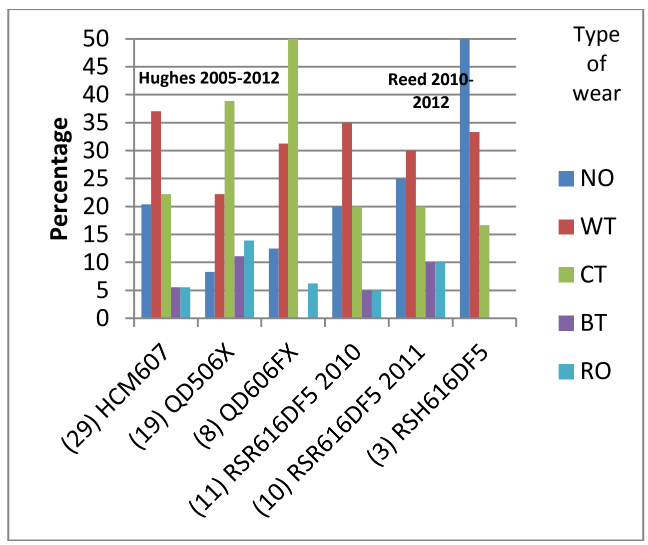


**Figure 39:** *Type of wear observed to cutting structure. Baker Hughes is presented to the left and Reed Hycalog to the right. The current bits used are the QD606FX (Hughes Christensen), and RSH616DF5 (Reed Hycalog) The brackets in front of each bit notation represent number of relevant runs representing the above length interval column and ROP dot. See appendix 3.*

Both Hughes Christensen and Reed Hycalog use a 6-bladed bit that has 16mm cutters with backup cutters.

## 7.3 Troll 8 ½" PDC Bit

Based on Section 6.2 and 7.2, an 8 ½" PDC bit for Troll should be:

*Durable and impact resistant*

- Handle runs up to 3-4000meters.
- Handle impacts running into calcite cemented sandstone intervals with high ROP.

*Efficient*

- Drill efficient in both hard calcite cemented sandstone and in soft unconsolidated sandstone.

*Stable*

- Prevent instability issues that can cause damage to cutting structure or BHA.

*Steerable*

- Be able to hold inclination and steer in horizontal direction (azimuth changes).

*Non-deflecting*

- Be able to maintain well path when drilling from sandstone into calcite cemented sandstone.

## 7.4 Gjøa Performance Study

As described in Section 4, the Gjøa reservoir geology is similar to the reservoir geology on Troll. Because of similar geology and well profiles in the 8 ½" section (see Appendix 3 and 4 for well profiles), the drilling environment was assumed similar.

The main drill bit vendors that have drilled in the 8 ½" section on Gjøa are Smith Bits, Reed Hycalog and Hughes Christensen. Reed Hycalog and Hughes Christensen use the same nomenclature for their products in the 8 ½" section on Gjøa as for Troll; the QD606FX (Hughes Christensen) and RSH616DF5 (Reed Hycalog).

**Note:** The RSH616DF4 and RSH616DF5 product from Reed Hycalog has a change from F4 to F5 from Gjøa to Troll. The change is believed to be related to the hard facing of the PDC bit.

It is assumed that Hughes Christensen and Reed Hycalog use similar products for Gjøa as for Troll. Smith Bits drilled on Gjøa in the 8 ½" section in 2009-2010 with the product 8½" MDSi716LUBPX. The performance by Smith Bits in the 8 ½" section on Gjøa could be similar to the performance it would give in the 8 ½" section on Troll.

A comparison study of the different drill bit vendors was done. The aim was to compare Smith Bits, Reed Hycalog and Hughes Christensen under a similar drilling environment. The drilling environment was thought to be similar if wellbores were drilled in the same area or as sidetracks from the same wellbore. Two sidetracks drilled from the same wellbore were found, one representing Smith Bits and one representing Hughes Christensen, located on the D-template on Gjøa. Most of the Reed Hycalog runs were drilled from the C template and could therefore not be compared. The wellbore names used for comparison were 35/09-D01Y01H and 35/09-D01Y02H. A comparison plot with ROP and drilled interval was implemented. The result is presented in Fig. 40. The comparison shows that the 8 ½" MDSi716LUBPX can be a candidate for similar Troll drilling applications.

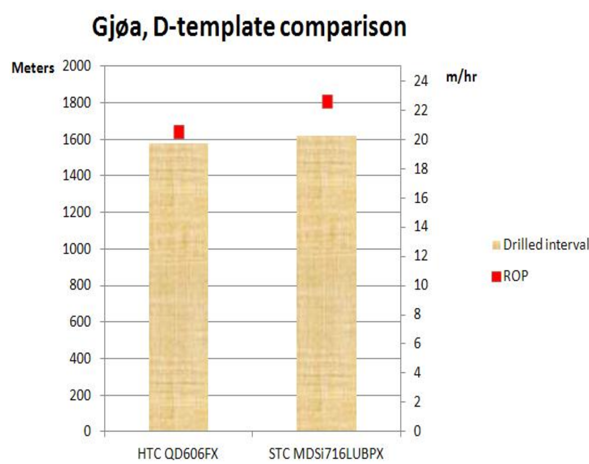


**Figure 40:** *Comparison of Hughes Christensen (left) vs. Smith Bits (right) in similar drilling environments. Dot represents ROP, column represents drilled interval. (Appendix 4).*

Further, an overall performance study was done for Gjøa, similar to the Performance Study done for Troll, described in Section 7.2. The focus is laid on the 8 ½" section and is presented in detail in Appendix 4.

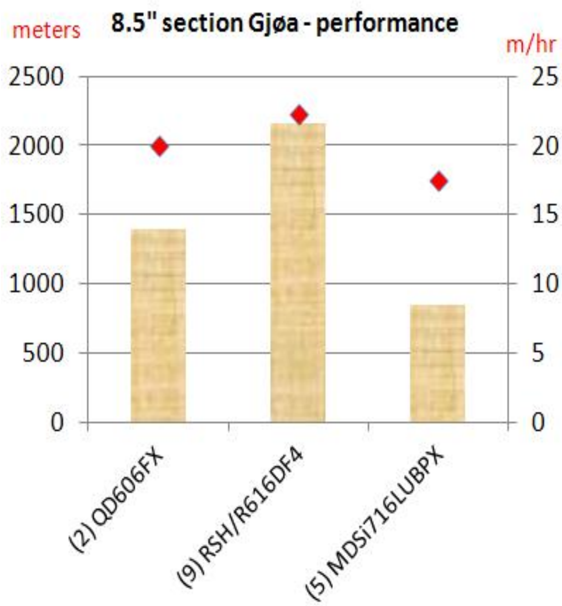


**Figure 41:** *Gjøa bit performances comparison. From left to right: Hughes Christensen (left), Reed Hycalog (middle) and Smith Bits (right). Brackets presents number of relevant runs from 2009-2012. For details, see appendix 4.*

The result, given in Figure 41, show that Reed Hycalog has higher ROP and longer footage drilled compared to Hughes Christensen and Smith Bits.

### 7.5 New iteration of the 8 ½" MDSi716LUBPX

In 2011, Smith Bits proposed a new iteration of the PDC bit; 8½" MDSi716LUBPX. The new iteration was optimized for the 8 ½" section to overcome the relatively lower performance compared to other drill bit vendors, as described in Section 7.4, Fig. 41. The design was optimized for Chalk Drilling. So far, the 8 ½" MDSi716LUBPX has shown an increase in penetration rates and higher rates of stability, see Appendix 5. The calcite cemented sandstone was similar to the chalk, as explained in Section 3.3.5. The 8½" MDSi716LUBPX is therefore thought to be a good candidate for Troll drilling.

# 8. IDEAS – INTEGRATED DYNAMIC ENGINEERING ANALYSIS SYSTEM

IDEAS is a simulation software used to design, test and analyze bit performance in specific applications. The software predicts how several different bit designs will perform in particular formation types, with a specific drive type, under various operating parameters, with specific BHA configuration and specific well paths. It allows the user to virtually drill in the same interval multiple times with different bits and then choose the most appropriate bit and BHA combination for the specific application. The main focus areas are stability, (in order to prevent vibrations), and drillability (rate of penetration and directional tendencies).

Each formation will be given a rock file in the IDEAS system. The rock file represents shear tests for different sizes of the PDC-cutters at different confining pressures. For each formation listed in IDEAS, a specific cutter test exists.

## 8.1 IDEAS Simulations

Three simulation studies were done;

**Study 1**

Aim:

- Find the most analogue formation for a calcite cemented interval
- Find the most stable bit in proposed formations, drilling in one formation at the time

**Study 2**

Aim:

- Find the most stable bit when drilling with shift in formations.

**Study 3**

The 2 first studies held WOB and RPM constant. The implementation of the 8 well logs described in Section 6.2.1 and 8.2.4 show that WOB and RPM fluctuate. To create a more realistic scenario, the third study incorporated fluctuating weight with constant RPM, and fluctuating RPM with constant WOB. Study 3 was based on the results found in study 1 and 2.

Aim:

- Create a more similar Troll drilling environment by fluctuating drilling parameters, mainly WOB and RPM, when simulating drilling with shift in formations.

## 8.2 IDEAS Parameters

### 8.2.1 Formation types

For Troll, both the calcite cemented sandstone and the unconsolidated loose sandstone should be included in simulations.

*Sandstone*

IDEAS does not contain rock files for sandstones with unconfined compressive strength below 5000 psi. Therefore, Colton Sandstone with 5000 psi UCS was used. It was thought to be the best analogue for Troll Sandstone of the existing rock files in the IDEAS library.

*Calcite Cemented Interval*

For the calcite cemented interval, the Carthage Marble with 15 000psi UCS was chosen according to the study done by Harald Fiksdal et.al. [12]

In 2011, Smith Bits did studies on the two Chalk Formations; Tor and Hod, in the North Sea. Different types of Chalks were compared with Norwegian Petroleum Directorate (NPD) cores from different blocks in the North Sea that contained the Tor and Hod formations. The study incorporated depositional environment, sea temperatures, and porosity. According to the study, the Northern Ireland chalk, called the Ulster White Limestone Formation, was the most similar chalk. The results from the Chalk Study done by Smith Bits was compared with the results from the Fiksdal et al. study [12], mainly with respect to porosity and unconfined compressive strength values, see Appendix 6 (Permeability values of the Ulster White Limestone Formation or Carthage Marble were not present in Smith Bits IDEAS library). It was found that the members from the Ulster White Limestone Formation; GlenArm (17000psi UCS, 1-5% porosity) and Tanderagee (11000psi UCS, 15-20% porosity), could be similar formations for a medium hard and hard calcite cemented sandstone. Hence GlenArm and Tanderagee were included in simulations for Study 1 and 2.

### 8.2.2 Confining pressure

The confining pressure represents the hydrostatic head above the rock being drilled. IDEAS has the option to simulate at different confining pressures. For Troll the confining pressure is around 3000psi. Both 3000 psi and 6000 psi confining pressure was investigated. The aim to have higher confining pressure than field confining pressure was to see what effect it would have on the vibrations and ROP response. It was desired to have a stable product through all applications.

Colton Sandstone has no shear files in IDEAS at 6000 psi. For simulations with 6000 psi confining pressure, 9000 psi confining pressure was chosen for the Colton Sandstone.

### 8.2.3 Well path and simulation depth

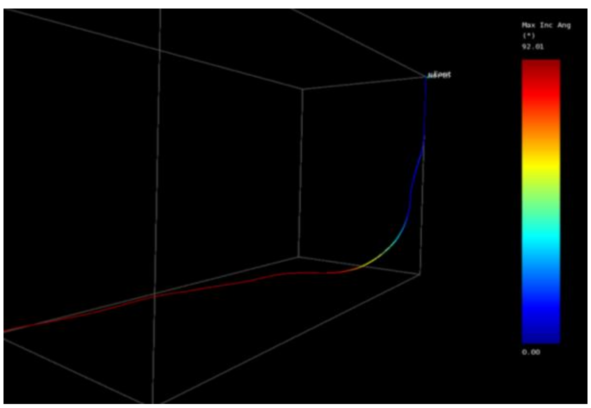

**Figure 42**: *IDEAS illustration wellbore NO 31/5-J-13 AY3H. Red represents 90 degrees, blue 0 degrees.*

A wellbore named 31/5-J13-AY3H, located south in Troll West, was chosen to be simulated on. The simulations were done with the same BHA assembly used for that specific well, see Appendix 7. The simulation measured depth (MD) was set to be 4420 meters. The well is illustrated in Figure 42.

### 8.2.4 Drilling Operating Parameters

As mentioned in section 6.2.1, 8 wells were investigated with respect to drilling parameters and logging parameters, example shown in Fig. 43. It was found that typical operating parameters for Troll range were from 2 to 15 tons and 80-180 RPM. For simulations in Study 1 and 2, the WOB was set from 5 to 17.5 tons with intervals of 2.5 tons, and 80 to 180 RPM with intervals of 20.

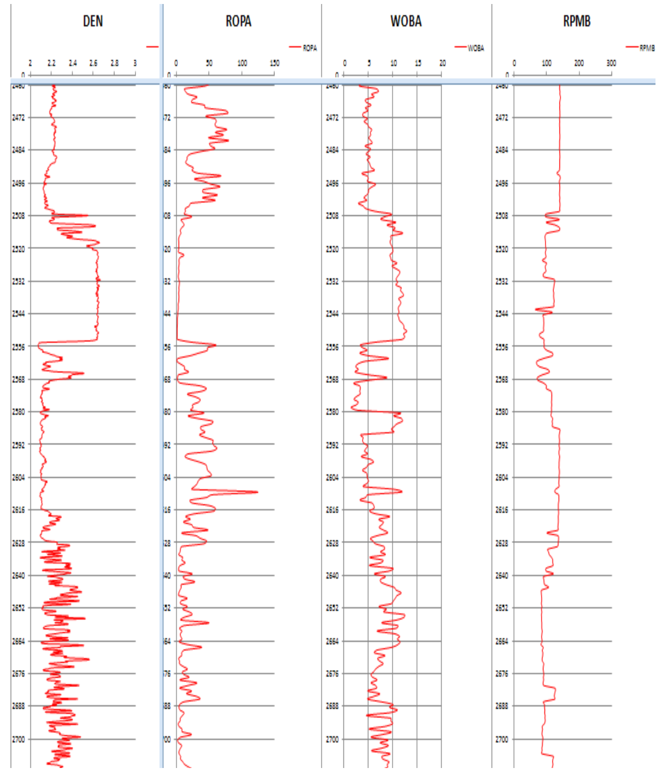


**Figure 43:** Drilling parameters from well 31/2-M-14-BY3H. At ~2500meters MD a calcite cemented interval where encountered. Note the ROP reduction. The WOB is increased and RPM decreased to establish depth of cut in the calcite cemented sandstone. For more details see Appendix 9.

In the sandstone, the RPM is usually around 120-130 with WOB from 2-5 tons. For the calcite cemented sandstone the WOB is from 9-12 tons with 80-90 RPM. In the rest of the thesis these operating parameters will be termed “sandstone drilling parameters” and “calcite cement drilling parameters”. When drilling from sandstone into a calcite cemented interval, the common approach is to lower the RPM and increase the WOB until a certain depth of cut into the dense formation has been established. Usually the WOB is increased from 2-5 tons to 10-12 tons and RPM is decreased from 120-130 to 80-90. This is believed to reduce lateral vibration (whirl) at the soft rock / hard rock interface, and reduce the amount of deflection. When exiting the calcite cemented sandstone, the WOB is relaxed and the RPM is increased back to normal operating parameters for the sandstone. Variations do occur, but the approach in general is the same. This made the basis for Study 3.

## 8.3 PDC products used for simulations

### 8.3.1 Bit types

Simulations were done with 5, 6 and 7 bladed bits to find the most stable bit for the 8 ½" section. The 7 bladed bit was the newest iteration of the 8 ½" MDSi716LUBPX. The reason for selecting the Ferrari was on the basis of the performance seen in chalk and on Gjøa as described in Section 7.5. Since both Hughes Christensen and Reed Hycalog are currently drilling with a 6 bladed bit that contain 16 mm cutters, the 6 bladed 8½" MDSi616LBPX was included. The 5 bladed bit called 8 ½" MDSi516LBPX, was included in simulations. It was included since the quantity of wear to bits has decreased the later years on Troll. It will have a greater ROP potential, but will also be less wear resistant. The specific BOM for the 8 ½" MDSi516LBPX and 8 ½" MDSi616LBPX were picked on the basis of similar applications on the NCS. In the rest of the thesis the 8 ½" MDSi716LUBPX, the 8 ½" MDSi616LBPX and the 8 ½" MDSi516LBPX will be named 5 bladed, 6 bladed and 7 bladed bit, respectively.

### 8.3.2 Elongated gauge section

Study 1 and 2 included two different gauge pad lengths for the 5, 6 and 7 bladed bit. The gauge pad length was set to 2" and 5". The aim was to see how it affected the stability. The elongated gauge pad length was simulated on since it will reduce the risk of high local doglegs when drilling into calcite cemented sandstone, as explained in Section 6.2.2. The results are shown in Section 9.1.3. **(Note that in the appendixes, the 2" and 5" gauge pad length are named as G2 or G5 in the Bit Nomenclature. E.g; MDi616G2 means the 6 bladed bit with 2" gauge pad length, the MDSi716G5 means the 7 bladed bit with 5" gauge pad length).**

### 8.3.3 Restrictions for the GlenArm and Tanderagee Carbonates

IDEAS simulates the whole cutting structure, including back up cutters since they interfere with the formation when more WOB is applied. Usually the backup cutters for an 8 ½" 16mm cutter bit will be 13mm cutters. To do simulations, rock files (shear values) for both 16mm and 13mm must be present. GlenArm and Tanderagee Carbonates only have rock files for 16 mm cutters. To see what effect the backup cutters had, the 6 and 7 bladed bits were simulated in Carthage Marble with and without backup cutters. The result is seen in Appendix 8 and outcropped in Fig 44. The study shows that whether using backup cutters or not, it will have little effect on the vibrations (torque and lateral accelerations). This could be due to the main shearing action being performed by the cutting structure itself. Therefore, the backup feature for simulations in GlenArm and Tanderagee Carbonates was excluded.

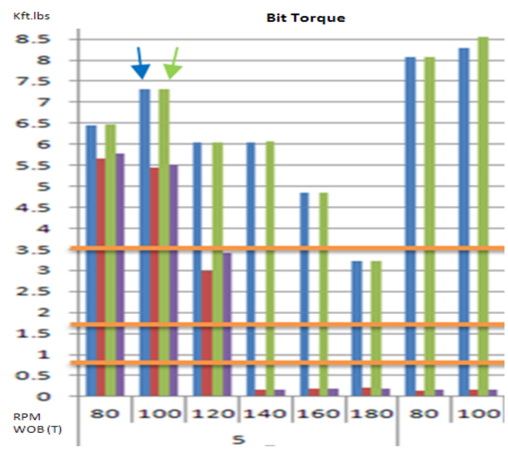


**Figure 44:** *Graph represents bit torque in Carthage Marble at 6000psi confining pressure of the 6 and 7 bladed bit without backup feature (blue and red) versus the 6 and 7 bladed bit with backup feature (green and purple). The blue arrow represents the 6 bladed bit without backup feature, and the green the 6 bladed bit with back up feature. Small differences are seen whether using backup feature or not.*

All of the current 5 bladed bits from Smith Bits have 13 mm cutters in the cone area. Because of this, simulations with the 5 bladed bit in Tanderagee and GlenArm Carbonates were excluded.

## 8.4 Output

Study 1 and 2 produced 3 plots for the respective WOB and RPM parameters; one for lateral accelerations, one for Δ bit torque, and one for ROP. The lateral accelerations are given as median values and the bit torque as "p90-p10" (the difference between the 90percentile and the 10percentile). The plots have thresholds for "low", "medium", "high", and "very high" lateral accelerations / Δ bit torque. The thresholds are based on research done by Smith Bits by comparing values seen in the field with values seen in simulations. Study 3 is displayed as "box and whisker" plots for lateral accelerations and Δ bit torque presented by the p5, p25, p50, p75 and p95. In addition, history plots/time based plots were produced, (explained in Section 9.3).

# 9. RESULTS

## 9.1 Study 1 – Results (Appendix 10)

### *9.1.1 Applicable IDEAS formations for Troll Drilling Simulations*

The Colton Sandstone gives lower ROP compared to the field ROP seen in the unconsolidated sandstone at Troll. This could indicate that it is either inappropriate for Troll simulations, or that the bits simulated do not have the ability to create high ROP for that low WOB. The Colton Sandstone with 5000 psi UCS will be harder than the unconsolidated 1000-3000psi UCS sandstone at Troll. To establish a certain depth of cut, more WOB needs to be applied. This could explain why low ROP is observed for low WOB in the Colton Sandstone.


**Figure 45:** *Lateral vibrations at bit for Carthage Marble, Tanderagee and GlenArm, from 5 to 17.5 tons, 80-180RPM. Note the increase in lateral vibrations for Tanderagee and GlenArm Carbonates compared to Carthage Marble Carbonate. (Appendix 10)*

The Carbonate types GlenArm, Tanderagee and Carthage Marble, show similar torque trends at bit, see Appendix 10. In general, GlenArm and Tanderagee show higher torque values than Carthage Marble. For the lateral accelerations, GlenArm and Tanderagee give higher amplitudes than Carthage Marble, shown in Fig. 45. All over, GlenArm shows the highest torque and lateral accelerations values.

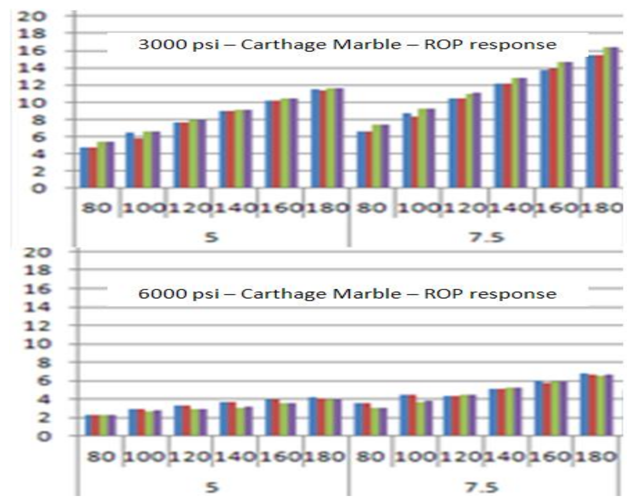


**Figure 46:** *ROP response at different confining pressures for Carthage Marble at 5-7.5 tons, 80 to 180 RPM. Note the difference in ROP response when confining pressure is increased, and compare it with GlenArm ROP response in Fig. 47. Each column represents a bit, mainly 6 and 7 bladed bit compared with short and long gauge, the y-axis is in m/hr see Appendix 10.*

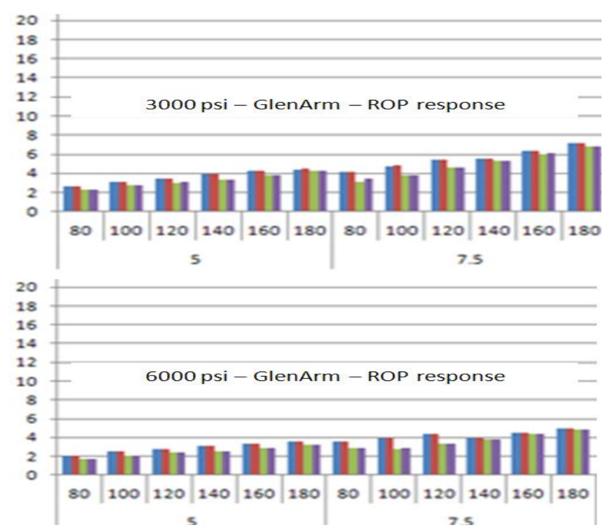


**Figure 47:** *ROP response at different confining pressures for GlenArm at 5-7.5 tons, 80 to 180 RPM. Note the low ROP difference as confining pressure is increased. Each column represents a bit, mainly 6 and 7 bladed bit compared with short and long gauge, the y-axis is in m/hr see Appendix 10.*

ROP response for the respective formations was compared. The Carthage Marble showed greater reduction in ROP compared to GlenArm and Tanderagee as confining pressure was increased. This is illustrated in Fig. 46 and 47 (here GlenArm and Carthage Marble are compared). The GlenArm and Tanderagee were less affected to increase in confining pressure.

A study done by TerraTek related to deep water drilling[17], shown in Fig. 48 and Table 5, show the effects increasing confining pressures have on the rock compressive strengths. The study shows that the higher the confining pressure, the higher the strength of rock. The strength of rock will affect the ROP. From the rock properties in Table 5, it could look like the permeability is one of the factors affecting the rock strength under confining pressure. E.g. the Crab Orchard Sandstone has higher permeability than the Carthage Marble and Mancos Shale (50 and 100 times higher). A theory could be that the confining pressure is allowed to pressurize more of the pores in the Sandstone than in the Carbonate types mentioned, giving it higher compressive strength and hence lower the ROP. This could again explain why lower ROP changes are seen for the carbonates GlenArm and Tanderagee when changing the confining pressure, indicating that the Carthage Marble has higher permeability. Calcite cemented sandstone will have low permeability since the calcite source fills the pores within the sandstone, as explained in Section 3.3.3, making it less affected to confining pressure. Therefore, the proposed carbonate GlenArm is thought to be a better analogue for calcite cemented sandstone due to the low change observed in ROP when changing confining pressure. Further, if the above mentioned assumption is correct, the GlenArm Chalk will represent a more realistic drilling simulation scenario than the Carthage Marble.

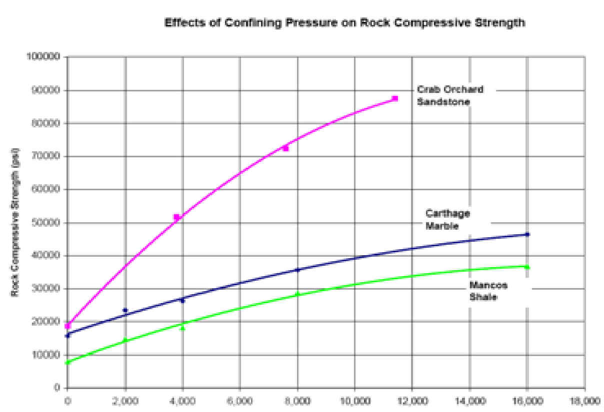


**Figure 48:** *The figure show rock properties of Carthage Marble, Crab Orchard Sandstone and Mancos Shale and how the confining pressure affects the rock strength. The differences in permeability could explain the behavior rock strength* [27]

| Rock/Attribute | Property |
|---|---|
| **Carthage Marble** | |
| Bulk density | 2.65 g/cm³ |
| Unconfined compressive strength | 16,000 psi |
| Porosity | 1.4% |
| Permeability | 0.002 md |
| **Crab Orchard Sandstone** | |
| Bulk density | 2.47 g/cm³ |
| Unconfined compressive strength | 19,000 psi |
| Porosity | 7.0% |
| Permeability | 0.1 md |
| **Mancos Shale** | |
| Bulk density | 2.54 g/cm³ |
| Unconfined compressive strength | 9,800 psi |
| Porosity | 17.9% |
| Permeability | <0.001 md |

**Table 5:** *Rock properties from the TerraTek Study, Fig. 48.* [27]

**Note:** Rock properties, mainly permeability and bulk density, are not available for the Carbonates GlenArm, Tanderagee, and Carthage Marble in IDEAS rock file library.

### 9.1.2 Bit Stability

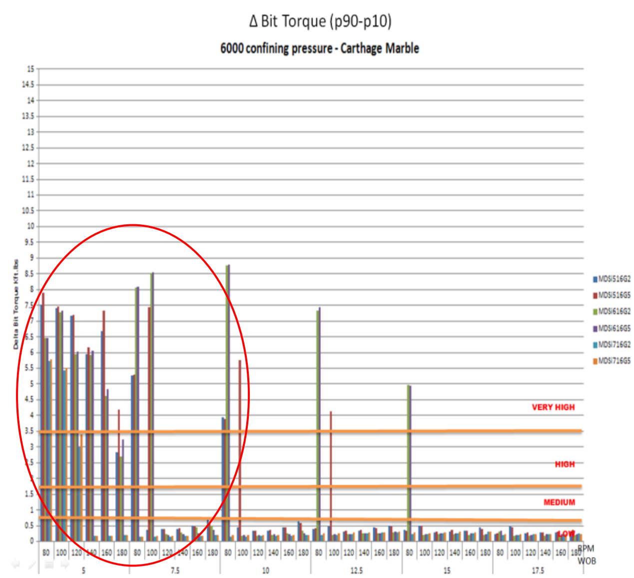


**Figure 49:** *Carthage Marble at 6000 confining pressure, ΔBit Torque (p90-p10). At 5 and 7.5 tons with low RPM, the 5 and 6 bladed bits give undesired torque values .The 5 bladed bit is represented by the two first columns on each RPM node, the middle two columns on each RPM node represent the 6 bladed bit. The two last columns on the RPM node is the 7 bladed bit. It is recommended to look into Appendix 10 for higher resolution.*

The 5 bladed bit was only run in Carthage Marble and Colton Sandstone, as explained in Section 8.3.2. It had the highest ROP potential but showed higher rates of both lateral accelerations and Δ bit torque than the 7 bladed bit. In general, when looking at Carthage Marble and Colton Sandstone, both the 5 bladed and 6 bladed bit show higher lateral accelerations and Δ bit torque than the 7 bladed bit. The difference in Δ bit torque for the respective bits in Carthage Marble at 6000 psi confining pressure is illustrated in Fig. 49. Since the trend showed that lateral accelerations and Δbit torque increased for the 6 and 7 bladed bit when simulating in GlenArm and Tanderagee, the same trend was assumed to be seen for the 5 bladed bit.

From Study 1, when considering all four formations, the different WOB and RPM parameters, and the respective confining pressures, the 7 bladed bit gives the best performance.

### 9.1.3 Extended Gauge Length

As described in Section 6.2.2, the gauge pad length was investigated. The effect of a 5" gauge pad length compared to a 2" gauge pad length showed, from Study 1 and 2, that the 5"gauge pad contributed to making the bit slightly more stable in terms of lateral movements. In terms of Δ bit torque, the trend shifted depending on simulation drilling parameters. The difference between a long gauge and short gauge pad length was low, indicating that the main reason for using a long gauge pad should be to prevent undesired doglegs.

## 9.2 Study 2 – Results (Appendix 11)

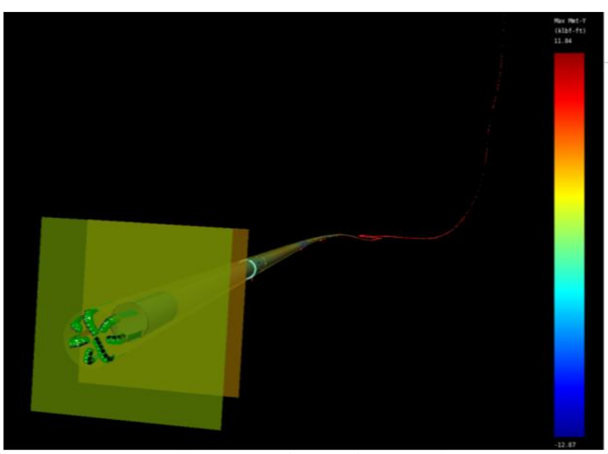

**Figure 50:** *IDEAS illustration of going from one layer into another, as done in study 2 and 3.*

Shift in formations were simulated, illustrated in Fig. 50. From study 1, it was found that the higher the confining pressure, the higher the overall vibrations. Therefore, a higher simulation confining pressure can contribute to uncover instabilities for the different bit types. The confining pressure was set to 6000 psi. As explained in section 8.2.2, the confining pressures used for the Colton Sandstone was set to 9000 psi. A shift in formation, with shift in confining pressure, is unrealistic. The simulation was still thought to contribute to uncover possible instabilities.

The "shift in formation" simulations gave higher undesired Δbit torque values. This could indicate that a shift in formation could be a source to vibrations like stick slip. In terms of lateral accelerations, only small differences were observed when comparing drilling simulations in single formations from study 1, with shift in formations in Study 2. There was a small tendency of seeing slightly higher torque and lateral accelerations when simulating drilling from either of the Carbonates into the Colton Sandstone than compared to the opposite.

When comparing the Δbit torque and lateral accelerations for the 5, 6 and 7 bladed bit, with typical sandstone or calcite cement operating parameters, the 7 bladed bit is the most stable.

## 9.3 Study 3 – (Appendix 12)

The aim was for Study 3 was to create a more realistic drilling scenario on Troll, as described in Section 8.1. Study 1 and 2 pointed out that the 7 bladed bit, with a 5" gauge, was the most applicable for Troll drilling of current PDC bit products at Smith Bits. The GlenArm Chalk was found to be the most similar formation as for calcite cemented sandstone. It gave similar ROP response during simulations as the ROP in a calcite cemented sandstone during drilling. As mentioned in Section 9.1.1, the ROP response in Colton Sandstone simulations indicated that it was too hard. Since no other rock files with low UCS were available, it was decided to use the same sandstone in Study 3. Therefore, the 7 bladed bit, the GlenArm Carbonate and Colton Sandstone was used in Study 3. Study 2 used unrealistically high confining pressure and shift in confining pressure. To create a more similar scenario to the actual drilling on Troll; the confining pressure was set to 3000psi, see Section 8.2.2. The study incorporated drilling with sandstone drilling parameters, ~120 RPM and ~3 tons, from Colton Sandstone into GlenArm Carbonate. Then with calcite cement parameters, ~90RPM and ~10 tons, from GlenArm Carbonate into Colton Sandstone. Both cases drilled 2 feet; 1 foot with GlenArm Carbonate and 1 foot with Colton Sandstone. The reason for using the same drilling parameters through the whole interval is because there will always be a certain time lag during drilling. E.g. when drilling into hard calcite cemented sandstone, it will take a certain time for the driller to change from sandstone drilling parameters to calcite cement drilling parameters. This is seen in figure 43, where the parameters are changed in a dynamic way. Therefore it was of interest to map the effect of using sandstone parameters in calcite cemented sandstone and calcite cemented sandstone parameters in sandstone. The drilling simulations were divided in two; one with WOB fluctuations and constant RPM, and one with RPM fluctuations and constant WOB. Simulations were also done without fluctuations to map the effect of WOB and RPM fluctuations.

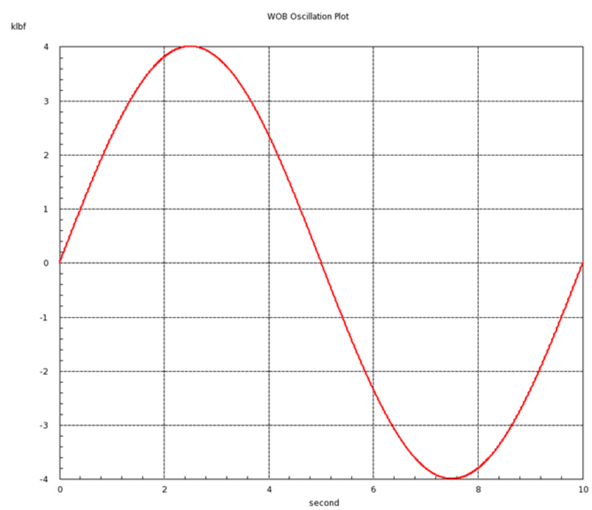


**Figure 51:** *For Study 3 a sinusoidal curve was used to perform the fluctuating RPM or WOB. Here WOB with plus/minus 2 tons over a 10-second-time-period is displayed.*

The WOB and RPM fluctuation was implemented as a sinusoidal curve in IDEAS. In Fig. 51 the WOB fluctuation is displayed. The sinusoidal curve was set to have a time period of 10 seconds. The range for WOB and RPM was set to be ±2tons and ±20RPM. The sinusoidal curve was believed to give a more realistic WOB and RPM distribution than a sudden increase or decrease of 2 tons or 20 RPM.

The results of Study 3 are displayed in Fig. 52 and 53, see Appendix 12.

### *9.3.1 Fluctuating WOB and RPM simulations results*

<u>*WOB fluctuations:*</u>

The simulations showed that when WOB fluctuated, the Δbit torque range and lateral accelerations range increased for all cases, except for Colton Sandstone into GlenArm Carbonate, see Fig 52 and 53. The decrease in torque range from Colton Sandstone into GlenArm Carbonate simulation can have several explanations. The most logical is that when drilling in GlenArm, the PDC bit will be more stable at high WOB than for low WOB (compare torque range in GlenArm in Fig.54 (high WOB) with Fig 56 (low WOB)).

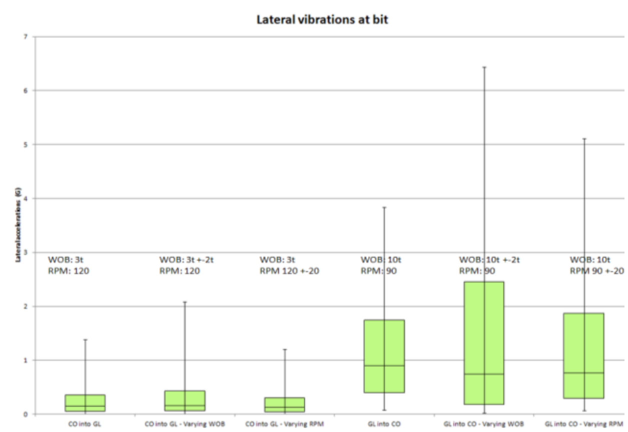


**Figure 52:** *Box and whiskers plot for Lateral Vibrations at Bit. Here shift in formations (Colton and GlenArm) with and without varying WOB and RPM is displayed, presented by p5, p25, p50, p75 and p95.*

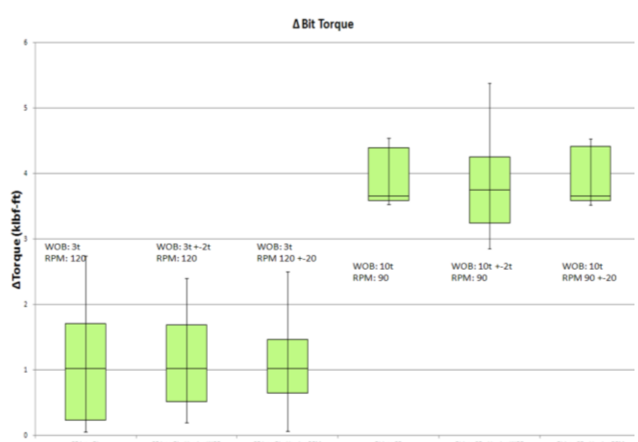


**Figure 53:** *Box and whiskers plot for Bit Torque at bit. Here shift in formations (Colton and GlenArm) with and without varying WOB and RPM is displayed, presented by p5, p25, p50, p75 and p95.*

When the Δbit torque range increases, the system will be more destabilized, giving higher risks of destructive vibrations like stick slip. The increase is illustrated in Fig. 52, when simulating from GlenArm Carbonate into Colton Sandstone. Both the Δ bit torque range and lateral acceleration range increases. The increase in both lateral acceleration and Δbit torque was highest when using calcite cement drilling parameters (high WOB). This could indicate that more vibrations are expected to be seen for a high WOB scenario as compared to a low WOB scenario.

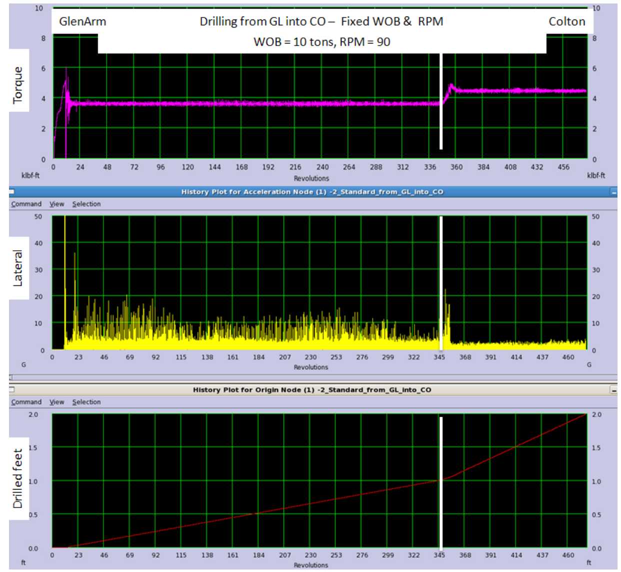


**Figure 54:** *History plots from GlenArm into Colton without varying weight with 10 tons and 90 RPM, the shift is marked with a white line. Bottom graph displays revolutions (x-axis) vs. feet (y-axis). Clearly see a shift in ROP as entering the sandstone at approx 350 revs. Middle graph displays revolutions versus lateral accelerations. Top graph displays revolutions versus bit torque. See Appendix 12 for more detailed description.*

*RPM fluctuations:*

The effect of fluctuating RPM was low compared to the WOB fluctuation. Only small changes were observed, see Fig. 52 and 53. In general the RPM variations had higher influence on lateral accelerations at high WOB compared to low WOB. For Δbit torque, the RPM fluctuation showed little effect.

Both RPM and WOB will affect the forces acting on cutters in different ways. The WOB affects the depth of cut, and the RPM affects the rotation velocity of cutters. Since the effect of fluctuating WOB was higher than RPM fluctuations, the WOB was believed to have a greater influence to create vibrations than the RPM. When WOB shifts over shorter time periods, the depth of cut will vary; hence the forces on cutters will vary. This can cause the system to be imbalanced, inducing risk of vibrations.

For all simulations in Study 3, described in figure 52 and 53, history plots were made. A history plot describes the vibrations over time, in this case over revolutions. Figure 54-57 illustrates the effect of WOB fluctuations. The RPM fluctuations are displayed in Appendix 12.

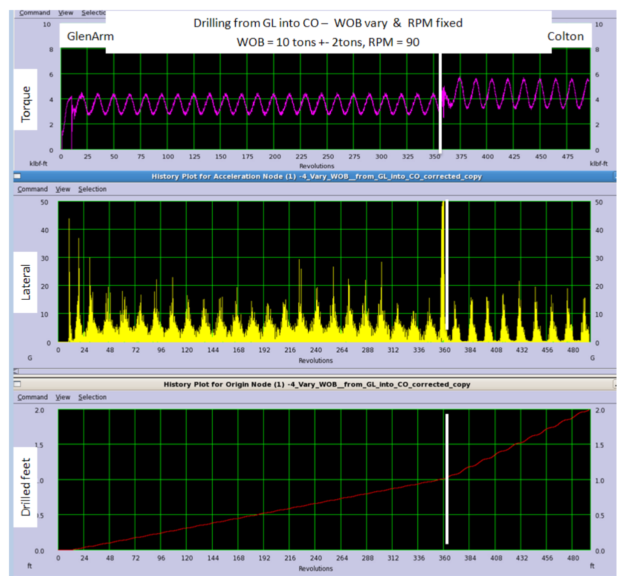


**Figure 55:** *History plots from GlenArm into Colton with varying weight with 10 tons and 90 RPM, the shift is marked with a white line. Bottom graph displays revolutions (x-axis) vs. feet (y-axis). Clearly see a shift in ROP as entering the sandstone at approx 350 revs. Middle graph displays revolutions versus lateral accelerations. Top graph displays revolutions versus bit torque. See Appendix 12 for better resolution.*

*GlenArm into Colton – fluctuate WOB history plots*

From Fig. 54 and 55, the effect of weight variation is easily seen; here 10 tons and 90 RPM were used. The Δbit torque and lateral accelerations will fluctuate as WOB is fluctuated. This can induce risk of undesired vibrations like stick slip. Every time the weight is low, the lateral accelerations increase and torque decreases, see appendix 12 for better resolution. The effect of weight variations are also seen in bottom graph in Fig 55, where the ROP increases as WOB is increased.

When exiting GlenArm into Colton, a spike in vibrations is seen for both with and without WOB variation. This correlates with study 2 where slightly more vibrations were seen as exiting the calcite cemented sandstone, see section 9.2. The formation shift without WOB fluctuations, from GlenArm Carbonate into Colton Sandstone, produces a lateral acceleration peak. When WOB is fluctuated, this peak is amplified. Values of this order are undesired.

*Colton into GlenArm – fluctuate WOB*

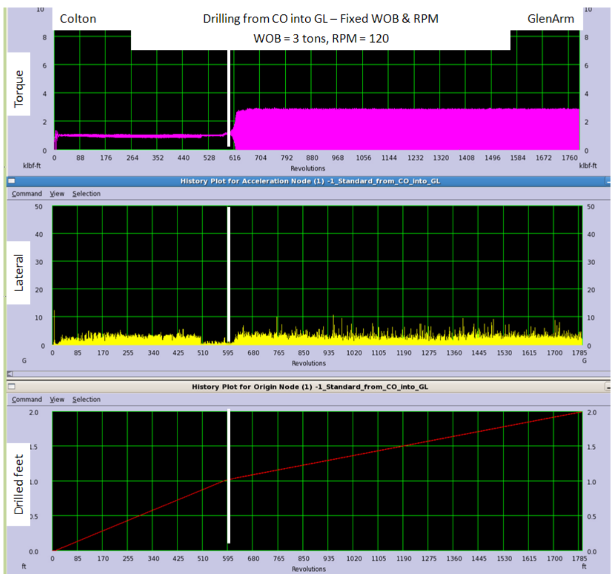


**Figure 56:** *History plots from Colton into GlenArm without varying weight with 3 tons and 120 RPM, the shift is marked with a white line. Bottom graph displays revolutions (x-axis) vs. feet (y-axis). Clearly see a shift in ROP as entering the sandstone at approx 350 revs. Middle graph displays revolutions versus lateral accelerations. Top graph displays revolutions versus bit torque; note the change as entering GlenArm when having incorrect parameters for calcite cemented sandstone. See Appendix 12 for better resolution.*

The history plots for Colton Sandstone into GlenArm Carbonate, illustrated in Fig. 56 and 57, show similar lateral acceleration trends as seen from GlenArm Carbonate into Colton Sandstone. The WOB fluctuation created the 7 bladed bit to become slightly more stable in terms of Δbit torque, as explained in the beginning of this section (9.3.1.). During a low WOB period as drilling in GlenArm, the progress is very low, see bottom plot in Fig. 57. This implies that to penetrate GlenArm, high WOB is needed.

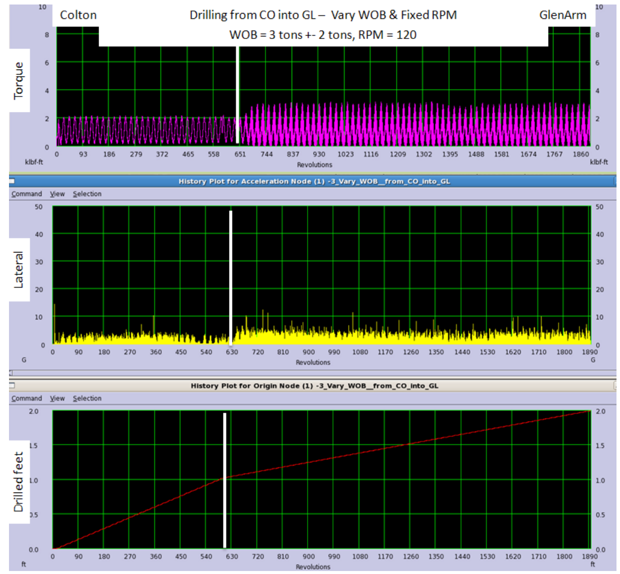


**Figure 57**: *History plots from Colton into GlenArm with varying weight with 3 tons and 120 RPM, the shift is marked with a white line. Bottom graph displays revolutions (x-axis) vs. feet (y-axis). Clearly see a shift in ROP as entering the sandstone at approx 350 revs, also note the poor approach in GlenArm when having low weight. Middle graph displays revolutions versus lateral accelerations. Top graph displays revolutions versus bit torque. See Appendix 12 for better resolution.*

### 9.3.3. Troll Drilling Parameters

Study 3 illustrates the effect of using “sandstone drilling parameters” in calcite cemented sandstone, and “calcite cement drilling parameters” in sandstone. This is shown in Fig.56 and Fig 54 when comparing the torque in GlenArm at 3 tons and 10 tons. The torque range increases when using “sandstone parameters” in calcite cemented sandstone, which again induces risk of stick slip. This confirms that the drilling approach used on Troll, described in Section 8.2.4, is a good approach to achieve progress through the interbedded formation on Troll, both with respect to efficiency and stability. It confirms that the incorrect use of WOB and RPM induces vibrations, as mentioned in Section 6.2.1.

## 9.4 Summary Results

Study 1 and 2 pointed to GlenArm Carbonate being the most similar rock to simulate on for calcite cemented sandstone for Troll applications. Study 3 points out the importance of using correct drilling practices on Troll to keep the vibrations at a low level. From study 1, 2 and 3, the 8 ½” MDSI716LUBPX was found to be the most applicable PDC bit for Troll applications.

# 10 DISCUSSION

## 10.1 DRS Study

The DRS study displayed in section 7.2 for Troll show that some of the datasets used are really narrow, and would not be representable for the whole field. E.g. the latest Reed Hycalog runs are only represented by 3 runs giving high ROP and long drilled interval. Still, no information on amount of calcite cemented sandstone drilled, or how long the section was planned to be, is to be found.

## 10.2 IDEAS

The simulations done in IDEAS are only simplified versions of drilling. The results produced are indications of what is going on down hole and should never be thought of as expected field values. Despite this, the simulations show similar trends as a real drilling case. Therefore the result can be thought to be highly relevant for understanding the Troll drilling environment.

## 10.3 What is causing vibrations?

In the end, it is difficult to distinguish what really is causing vibrations. E.g. when a bit is worn, the forces between the cutters are imbalanced and the bit may induce vibrations. It is known from drilling experiences around the world that; well path, BHA contact points, local curvature, over gauged hole, poor drilling practices, fluctuating drilling parameters (ref. study 3)) and improper bit choice, all can contribute to destabilize the drilling system and induce vibrations[15]. When considering all these factors, it is understood that the drilling environment is complex.

Still, by reducing vibrations created from the PDC cutting structure, the down hole environment will become more stable and other factors that cause vibrations can be detected.

# 11. CONCLUSION

- Troll consists of unconsolidated shallow marine sandstones with highly dense calcite cemented intervals. The unconfined compressive strength for the sandstone was found to be 1000-3000 psi, and for the calcite cemented intervals 15000-20000 psi. The study confirms that the occurrences of calcite cemented intervals are difficult to predict. The calcite cemented intervals can cause breakage to the PDC cutting structure, along with undesired high local doglegs, and low penetration rates.

- The Gjøa Field is similar to the Troll Field with respect to petroleum geology. The drill bit experience on Gjøa can be transferred to Troll.

- When drilling on Troll, the drilling parameters, mainly WOB and RPM, will fluctuate. The IDEAS simulations showed that fluctuating drilling parameters can induce vibrations. The WOB fluctuations were found to have higher risk of inducing more severe vibration rates than the RPM fluctuations.

- The IDEAS simulations showed that incorrect drilling practices can induce vibrations. IDEAS confirmed that the drilling practices on Troll are good drilling practices.

- The GlenArm Carbonate, with 17000 psi unconfined compressive strength and 1-5% porosity, is the most similar rock to simulate on for calcite cemented sandstone for Troll applications.

- The IDEAS simulation software was able to capture a drilling scenario similar to the actual drilling in the 8 ½” section on Troll. The newest iteration of the 8 ½” MDSi716LUBPX was found to be the most applicable bit for Troll drilling.

- The main reason for using an elongated gauge pad section should be in order to reduce the amount of deflection created by drilling into calcite cemented sandstone.

- A bit for the 8 ½” section on Troll needs to be durable, impact resistant, drill efficient in both calcite cemented interval and sandstone, be stable, be steerable, and not deflect from well path when a calcite cemented interval is encountered.

# ABBREVATIONS

| | | |
|---|---|---|
| PDC | – | Polycrystalline Diamond Compound |
| DBOS | – | Drill Bit Optimalization System |
| ROP | – | Rate of Penetration |
| NCS | – | Norwegian Continental Shelf |
| IDEAS | – | Integrated Dynamic Engineering Analysis System |
| WOB | – | Weight on Bit |
| RPM | – | Revolutions per Minute |
| RC | – | Roller Cone |
| BOM | – | Bill of Material |
| GR | – | Gamma Ray |
| UCS | – | Unconfined Compressive Strength |
| MFS | – | Maximum Flooding Surface |
| NDP | – | Norwegian Petroleum Directorate |
| BHA | – | Bottom Hole Assembly |
| TFA | – | Total Flow Area |
| HPHT | – | High Pressure High Temperature |
| IADC | – | International Association of Drilling Contractors |
| API | – | American Petroleum Institute |
| POOH | – | Pull Out of Hole |
| TVD | – | True Vertical Depth |
| TD | – | True Depth |

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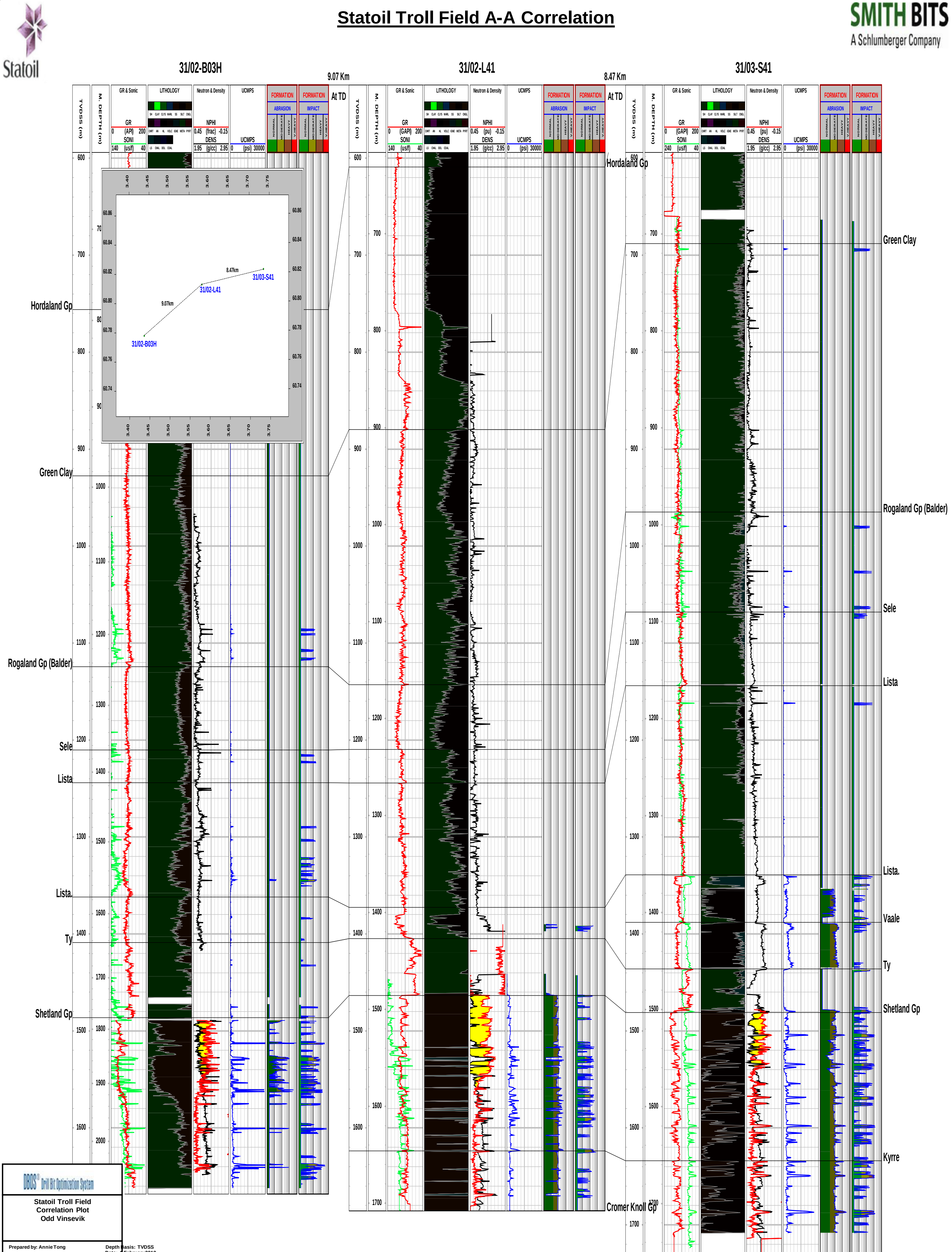
# Appendix 1-12

# APPENDIX 1
# DBOS
# TROLL CORRELATION

# Statoil Troll Field A-A Correlation



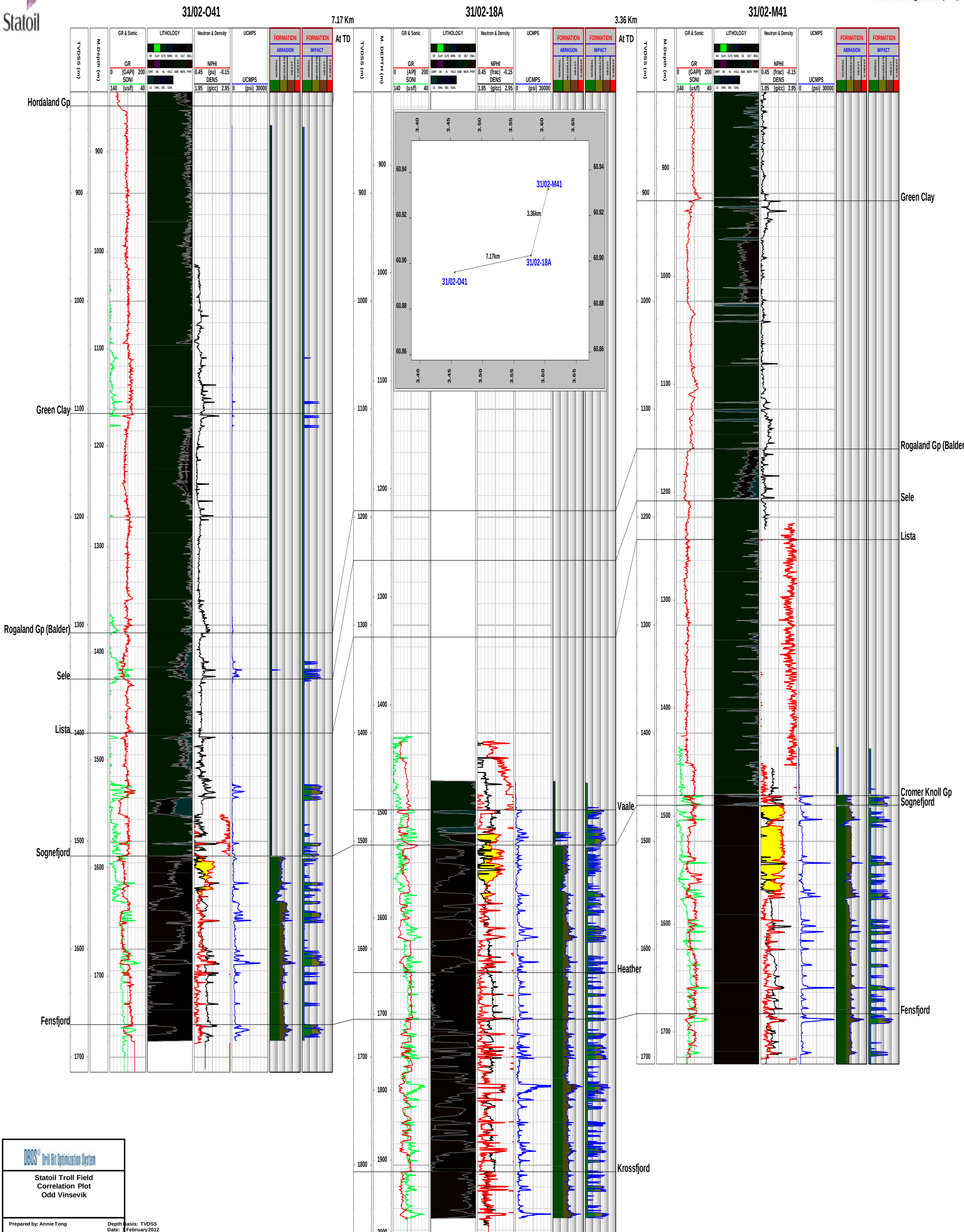

DBOS® Drill Bit Optimization System

Statoil Troll Field
Correlation Plot
Odd Vinsevik

Prepared by: Annie Tong

Depth Basis: TVDSS
Date: 1 February 2012

# Statoil Troll Field B-B Correlation



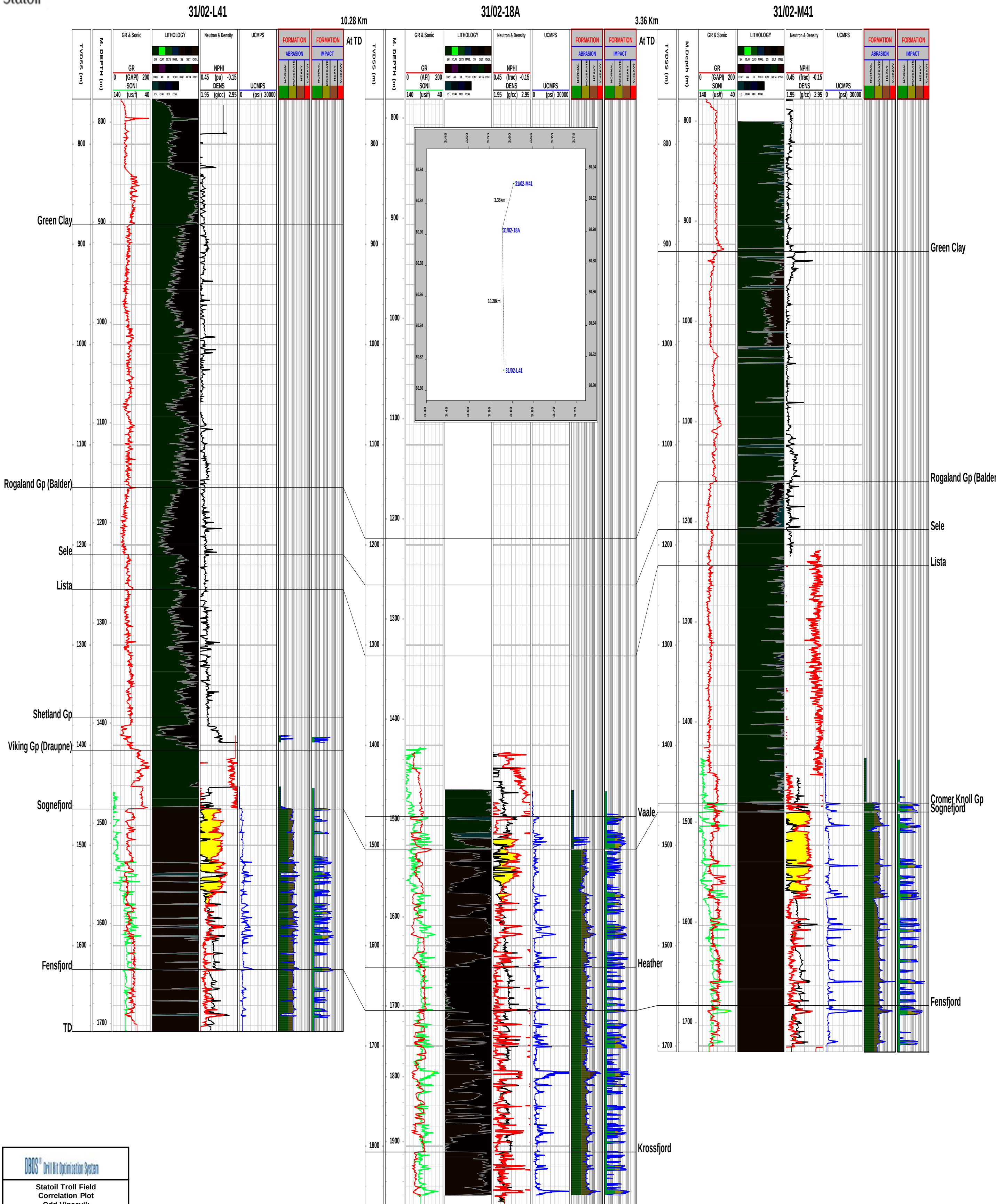

DBOS Drill Bit Optimization System

Statoil Troll Field
Correlation Plot
Odd Vinsevik

Prepared by: Annie Tong

Depth Basis: TVDSS
Date: 1 February 2012

# Statoil Troll Field C-C Correlation



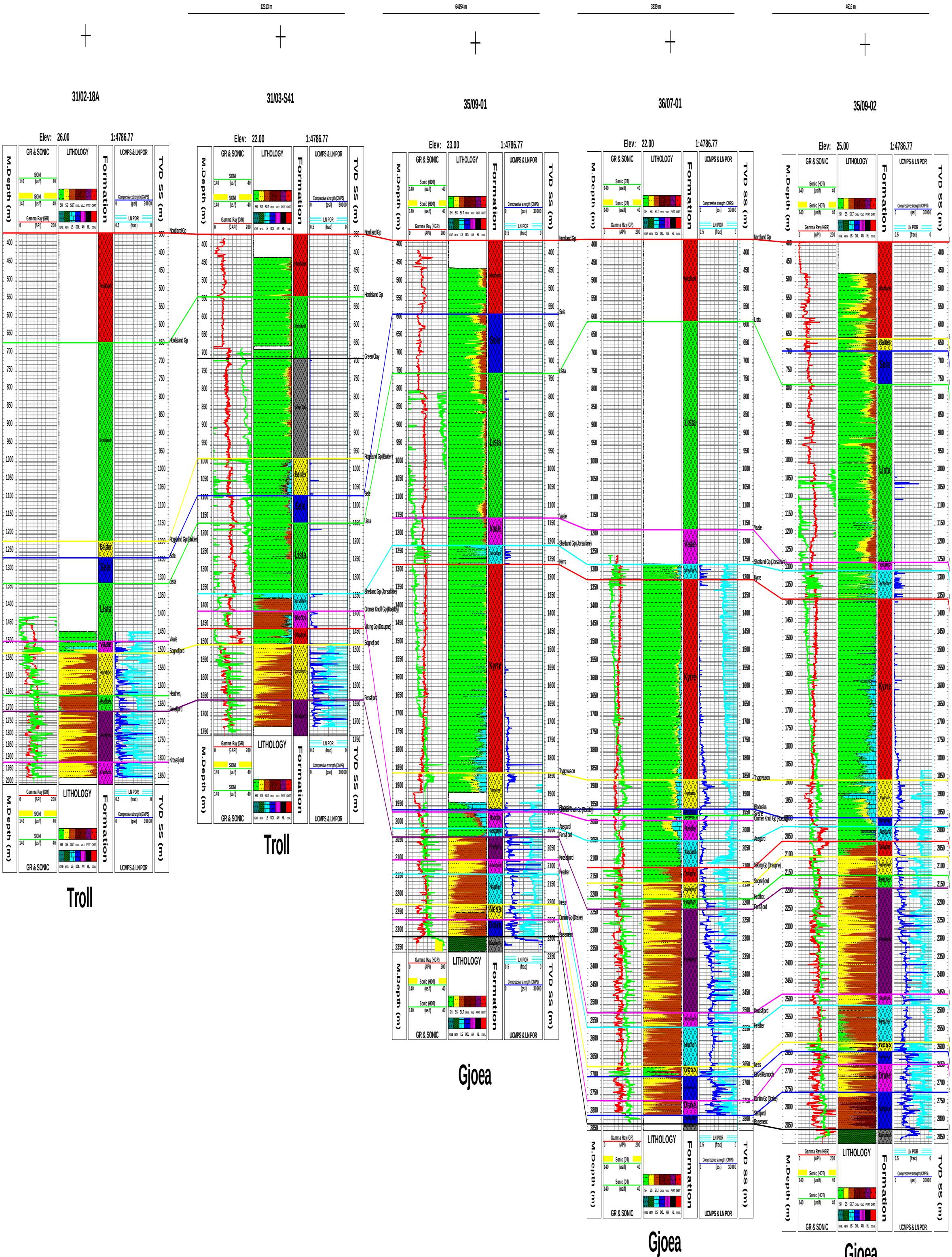

DBOS Drill Bit Optimization System

Statoil Troll Field
Correlation Plot
Odd Vinsevik

Prepared by: Annie Tong

Depth Basis: TVDSS
Date: 1 February 2012

# APPENDIX 2
# DBOS
# GJØA-TROLL
# CORRELATION

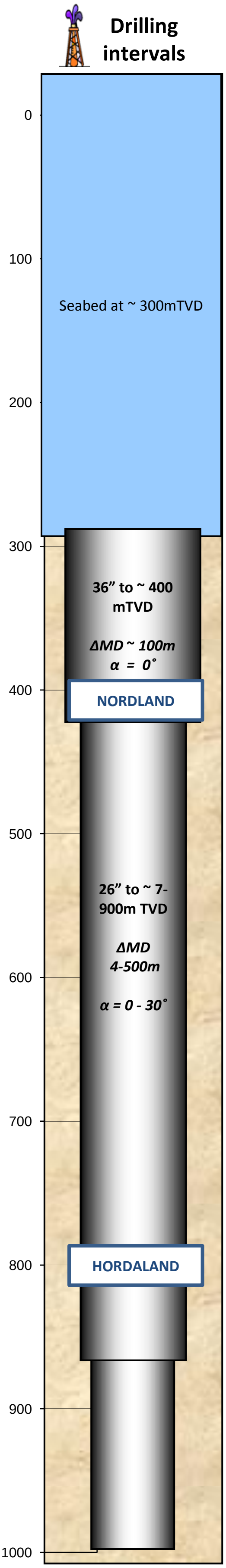



STATOIL

SMITH BITS
A Business Unit of Smith International, Inc.

# APPENDIX 3
# GENERALIZED TROLL WELL AND PERFORMANCE PLOTS

# Generalized Troll Well and Bit Technology




**For better understanding of this Appendix, it is recommended to read Section 5.5.**

**Note:** Formation tops, well path, drilled intervals, parameters and dullgrades are approximate and should be used as a guideline. The extracted data used (from DRS) were filtered on a minimum drilled interval and amount of hours run (e.g. 8.5" section minimum 200 meters and 5 hrs). Reasons for pulling out of hole which not were related to bit performance were excluded, e.g. WC is not relevant for bit performance. The data was filtered from 2005 to present. The focus was laid on the majority of bit types and trends.

This research was done with both excel raw data and RoundTuit. RoundTuit does not have the ability to filter on wells etc, and also if dataset is incomplete from DRS, the missing data will not be included for the present bit. Therefore, to overcome these errors, manually filtered raw data was used in combination with Round Tuit. In this sheet the trends are pointed out, note that the ROP's, dulls etc are based on calculating the median.

## Explanation of tables (note 36" and 26" section will vary)

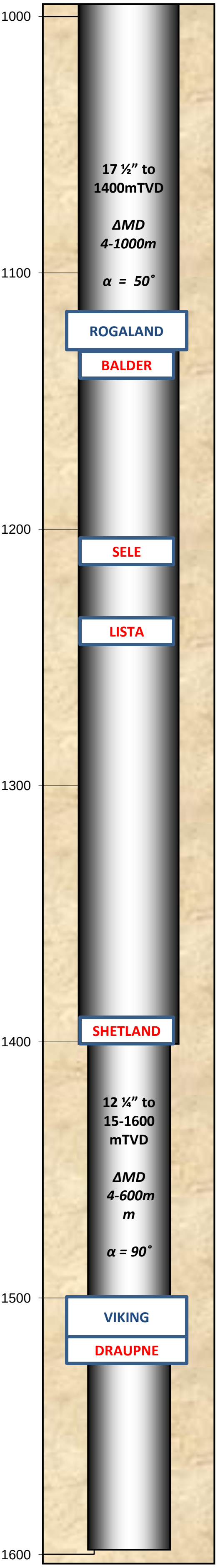
| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>Seawater/Waterbased/Oilbased<br>**Mud weight:**<br>Given in specific gravity | Information about the section. | The optimum bit type presented. Here the IADC code is given and nomenclature explained.<br><br>HTC = Hughes Christensen (Baker Hughes)<br>HYC = Reed Hycalog |
| | *Typical Parameters:*<br>WOB = weight on bit<br>RPM = rounds per minute<br>TFA = total flow area | In this column information about the dullgrades are given, and if it is mostly new applications or rerunned applications that are used. |
| **Technology** | In these two columns the different technologies used are shown, respectively on vendors and bit types. **These data are the dataset for the different graphs presented in the end of Appendix 3.**<br>ROP = rate of penetration<br>dMD = drilled intervall<br>dMD per tooth/cutterwear = presents the amount of drilled interval per calculated unit tooth wear (e.g. The interval drilled from a grade 0 to a grade 1).<br>POOH = pulled out of hole. | Dull = inner-outer-gauge-dull characterization<br>Dull characterisation represents the most occurring characterisation, both the "Characterisation column" and "Other column" in the IADC code is included here.<br>The nomenclature is not explained here, for interested readers it is recommended to read the product catalogue for the different vendors. |

## 36" Section

| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>SW<br><br>**Mud weight:**<br>1,03 | 1) Vertical section<br>2) Potential boulders | SHO – staged hole opener and 17.5" bit |


## 26" Section

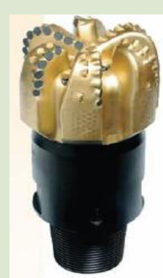
| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>WBM/SW<br><br>**Mud weight:**<br>1.03-1.1 | 1) Usually a straight section, may start to build angle up to 20-30<br>2) Easy section to drill<br><br>Formations: Nordland and beginning of Hordaland group. | HTC bit: GTXCMP03DX<br>IADC: 415X RTR<br><br>**GTX** series, tungsten carbide inserts<br><br>**CMP03** – **C**onical shape inserts, **M**-technology, **P**yramid compacts, **03** = cutting structure<br><br>**DX** – diamond gauge compacts |
| | *Typical Parameters:*<br>WOB: 5-25<br>RPM: 70-180<br>ROP: 25-30<br>TFA: 1.0-1.2 | Dull: 0.8 - 1.0 - 0.2 - WT to TD.<br>Seals: Good condition (no failures)<br><br>Revolutions: 150Krev.<br>295meters drilled per toothwear<br>Both new and rerunnable bits used. |

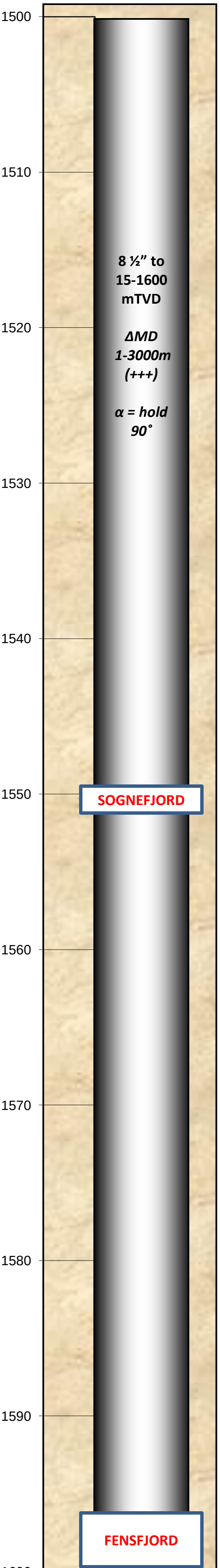



## 17 ½" Section

| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>WBM<br><br>**Mud weight:**<br>1.30 | 1) Builds angle to 50˚-60˚, want to land the 12 ¼" horizontally.<br>2) Soft unconsolidated formation.<br>Formation: Hordaland grp, Rogaland grp | **HTC : QD606X/HCM606**<br>IADC M323<br><br>QD: Quantec technology<br>HC: Genesis technology<br>6: 19 mm cutters<br>06: 6 blades<br>X: single row of backup cutters |
| | *Typical Parameters:*<br>WOB: 10-20<br>RPM: 120-160<br>TA: 1.48-1.55 | Majority of wear located in nose (N), rest is found to be all over (A) and in shoudler (S) area.<br>Both new and rerunnable bits used. |
| **Technology** | **HTC: Quantec QD606X (2009-present)**<br>ROP = 28.3 m/hr<br>dMD = 681m<br>dMD per unit cutter wear: 192 meters .<br>Dull: 1.6-1.8-0.6-CT | **HTC: Genesis HC606 (2005-2008)**<br>ROP =20.4 m/hr<br>dMD =777m<br>dMD per unit cutterwear: 277 meters.<br>Dull: 1.3-1.5-0.2-NO/WT |

## 12 ¼" Section

| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>WBM<br><br>**Mud weight:**<br>1.25-1.3 | 1) Is landed horizontally (~90˚), ready for the 8 ½" hold section.<br>2) Soft unconsolidated formation, but some local low density peaks/ medium hard stringers may occur in the Lista formation according to DBOS.<br>3) If section is landed in Sognefjord, calcite cemented sandstone may occur causing low PR (penetration rates).<br>4) Of 41 runs 5 bits were POOH due to PR.<br><br>Formation: Rogaland grp, Viking grp. | **HTC: QD 507X**<br>IADC M323<br><br>QD: Quantec<br>5: 16mm cutters<br>X: single row of backup cutters |
| | *Typical Parameters:*<br>WOB:10-20<br>RPM: 100-150<br>TFA:0.9-1.1 | More breakage in this section compared to 17 ½" section.Mostly new bits are used to this application (a few reruns). |
| **Technology** | *HTC: Quantec QD506X/507X (2009-present)*<br>**QD506X**<br>ROP = 11.7m/hr<br>dMD = 444m<br>dMD per unit cutterwear = 148m<br>Dull: 1.3-1.7-1.3-WT/CT<br><br>**QD507X**<br>ROP = 16.3m/hr<br>dMD = 524m<br>dMD per unit cutterwear= 234 m<br>Dull: 0.9-1.4-0.4-NO<br><br>**In general QD:**<br>ROP = 15.4 m/hr<br>dMD = 516m<br>dMD per unit cutterwear = 212m<br>Dull:1.0-1.4-0.7-NO/WT/CT<br> | *HTC: Genesis HCM/HCR 606/607 (2005-2008)*<br>**HCM/R606**<br>ROP = 14.0<br>dMD = 567<br>dMD per unit cutterwear = 227m<br>Dull: 1.5-1.0-0.3-CT/NO/WT<br><br>**HCM/R607**<br>ROP = 10.0 m/hr<br>dMD = 562m<br>dMD per unit cutterwear = 180m<br>Dull: 1.6-1.5-0.3-WT/NO<br><br>**In general HC:**<br>ROP = 14.0<br>dMD = 574m<br>dMD per unit cutterwear = 217m<br>Dull: 1.4-1.2-0.3- NO<br> |



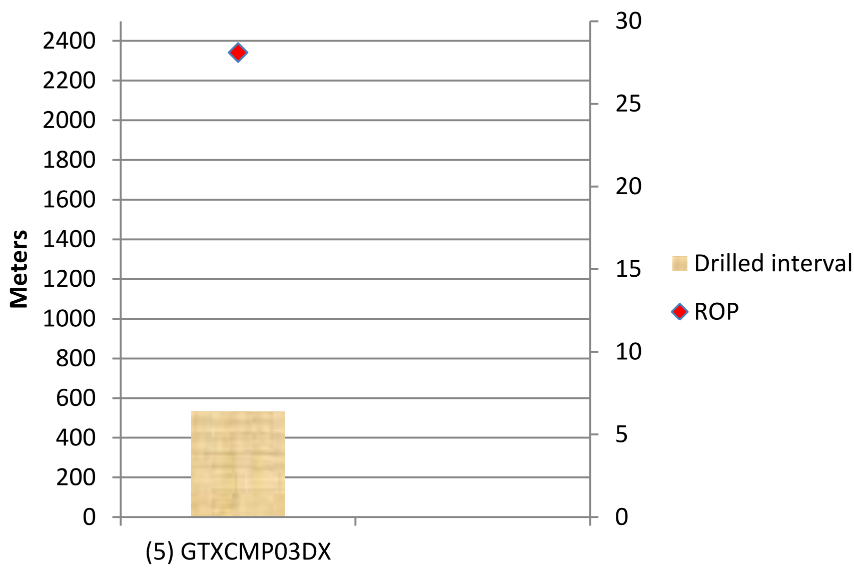

| 8 ½" Section | | |
|---|---|---|
| **General Info** | **Information** | **Bit type** |
| **Mud Type:**<br>WBM – drill in fluid<br><br>**Mud weight:**<br>1.07-1.13<br><br>**BHA type:**<br><br>**Steering:** | 1) Horizontal section, holds at 90˚.<br>2) Calcite cemented sandstone occurs, give high density readings .<br>3) Drill bit needs to be durable, stable and steerable, must not deflect from wellpath when hitting high density calcite cemented sadnstone<br>4) Risk of pulling bit due to breakage caused by stringers.<br>5) Several long 8 ½" sections from motherbore, typically 3 MLT.<br><br>Formation: Viking grp. – mainly. Sognefjord formation | **HTC: QD606FX**<br>**IADC: M323**<br>QD:Quantec technology<br>6: 19mm cutters<br>06: 6 blades<br>FX: Force series, one row with backup cutters<br><br>**HYC: RSH616DF5**<br>**IADC: M422**<br>RS: Rotary Steerable<br>H: Helios cutter technology<br>6: 16 mm cutters<br>06: 6 blades<br>D: diamon back up cutters<br>F5: hardfacing related |
| | Parameters: | Dullgrades are more varied due to the precense calcite cemented sandstone, more chippage/breakage observed.<br>New bits per run. |
| | WOB: 3-15<br>RPM:80-180<br>TFA: 0.78-1.03 (long runs with 1.03) | |
| **Technology**<br><br> | **HTC (2005-present)**<br>**Genesis HCM607 (2005-2008)**<br>ROP = 13.9m/hr<br>dMD = 921m<br>dMD per unit cutterwear = 222m<br>Dull: 2.3-1.8-0.0-WT (CT)<br><br>TOTAL 61 relevant HC-runs:<br>21/61 POOH due to PR<br>23/61 had major wear in N (both chippage and breakage)<br><br>**Quantec QD506X (2009-2010)**<br>ROP = 17.2m/hr<br>dMD = 1181m<br>dMD per unit cutterwear = 242m<br>Dull: 3.1-1.8-0.4-CT (WT)<br><br>**Quantec QD606FX (2011-present)** drilled from G,D,X,S templates<br>ROP = 28.3m/hr<br>dMD = 2215m<br>dMD per unit cutterwear = 906m<br>Dull: 0.9-1.6-0.5-CT (WT)<br><br>Total 18 relevant QD-runs:<br>6/18 runs had wear in nose (N). (rest had A,M and some minor in S.)<br>6/18 POOH due to PR. | **HYC (2008-present)**<br>Have been using several types of the RS-family bits. Now drill with the RSH616DF5<br><br>**RSR616DF5 (2010-2011)**<br>ROP = 22.7 m/hr<br>dMD = 1853 m<br>dMD per unit cutterwear = 446 m<br>Dull: 1.9-2.2-0.1-WT/CT (NO)<br><br>**RSR616DF5 (2011-present)**<br>ROP = 25.2<br>dMD =2128<br>dMD per unit cutterwear = 764m<br>Dull: 1.4-1.4-0.1-NO/WT (CT)<br><br>**RSH616DF5 (2011-present)**<br>ROP = 31.4m/hr<br>dMD = 2128m<br>dMD per unit cutterwear = 1277m<br>Dull: 0.7-1.0-0.0-NO<br><br>Total 38 relevant RS-runs:<br>8 POOH due to PR<br>Wear is mainly in N, then A/G/S. |

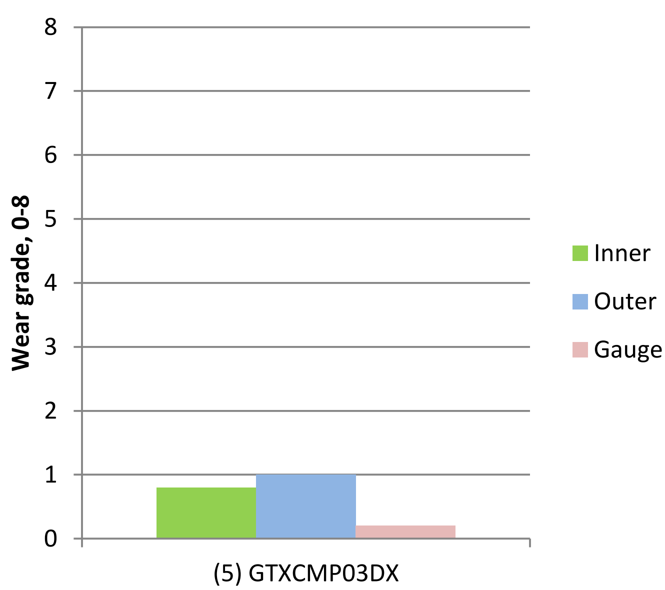
Explanation of graphs:
The graphs uses the base presented above. For each section the nbr of relevant runs is presented infront of its respective bit type, e.g. (8) QD606X. In general there are 3 type of graphs.

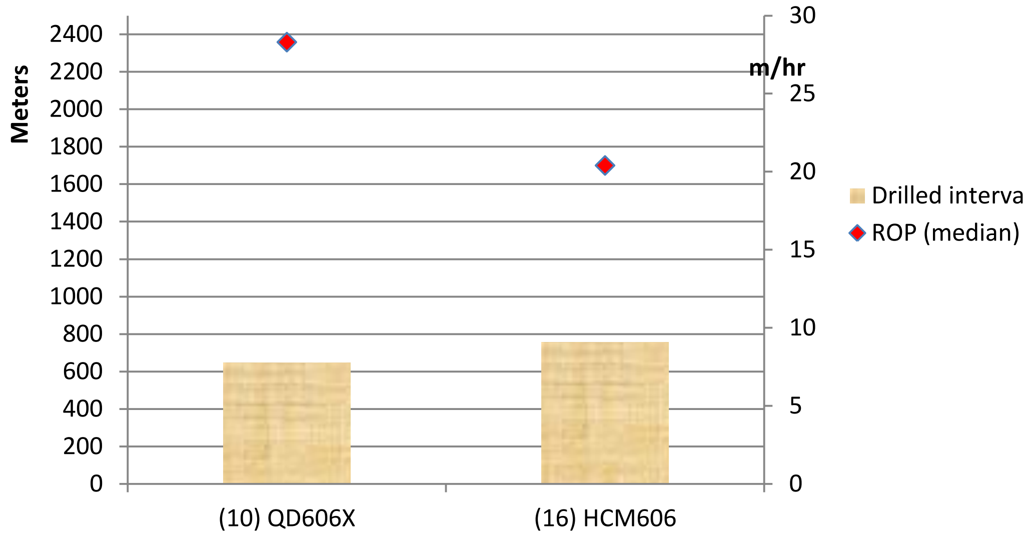
Graph 1: ROP vs drilled interval, giving the median drilled interval and median ROP for the respective products
Graph 2: Location of wear in terms of inner, outer and gauge, standarized to a 0-8 grade.
Graph 3: Occurrence of different types of wear for the different products. Note that both CH and O in the IADC dull grade code are included in this graph.

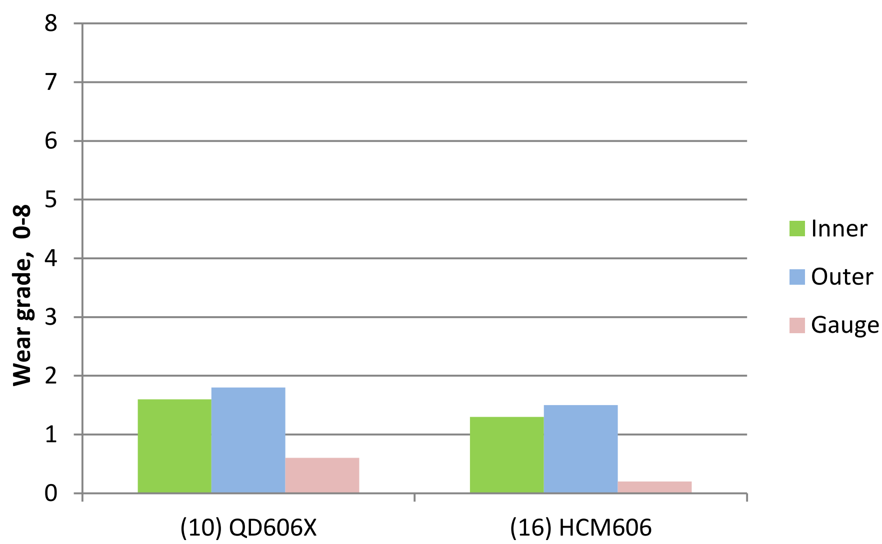
Best performance runs are also presented with respect to ROP and drilled interval in 8.5” section. One good ROP run in the 12.25” section is also presented, length is irrelevant since this section dont have long interval requirements before reaching TD.

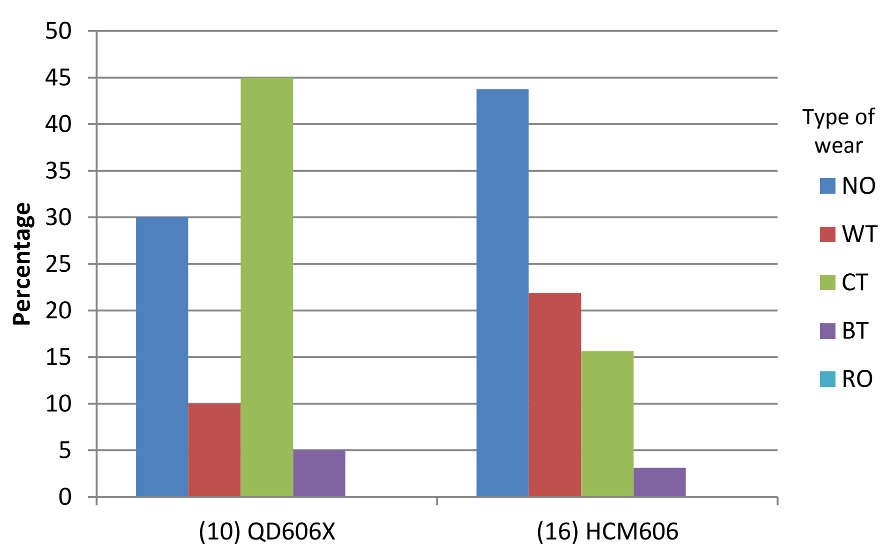
## 26” Section – Overall Performance

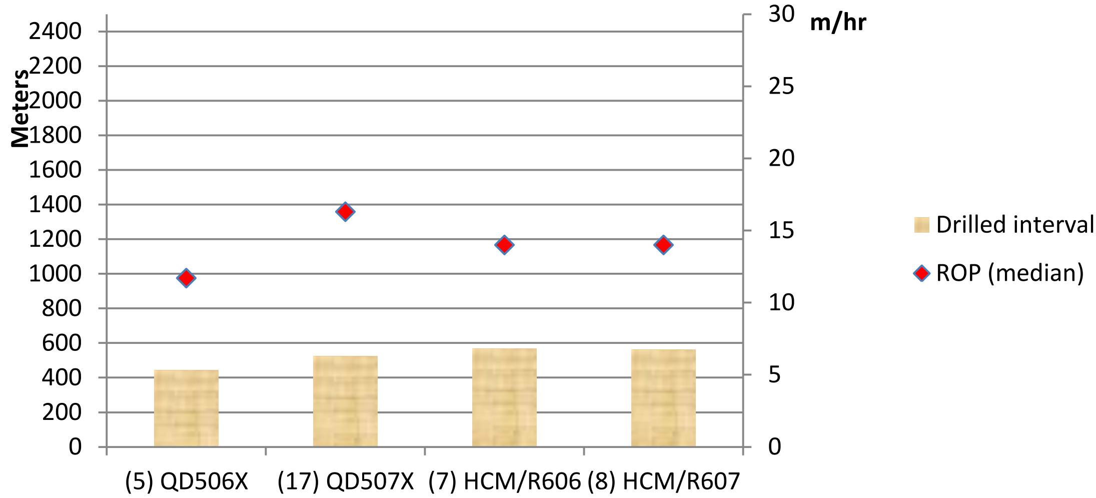


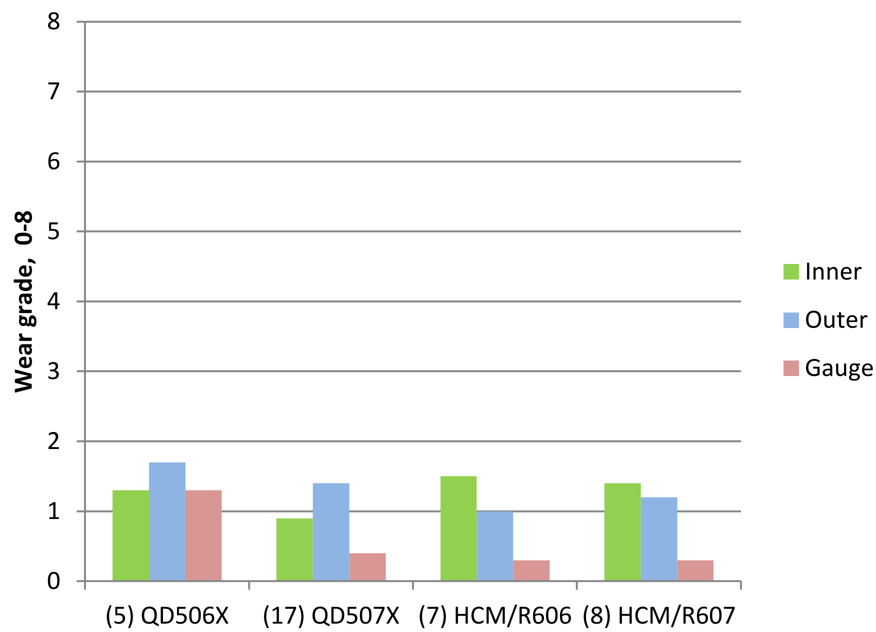



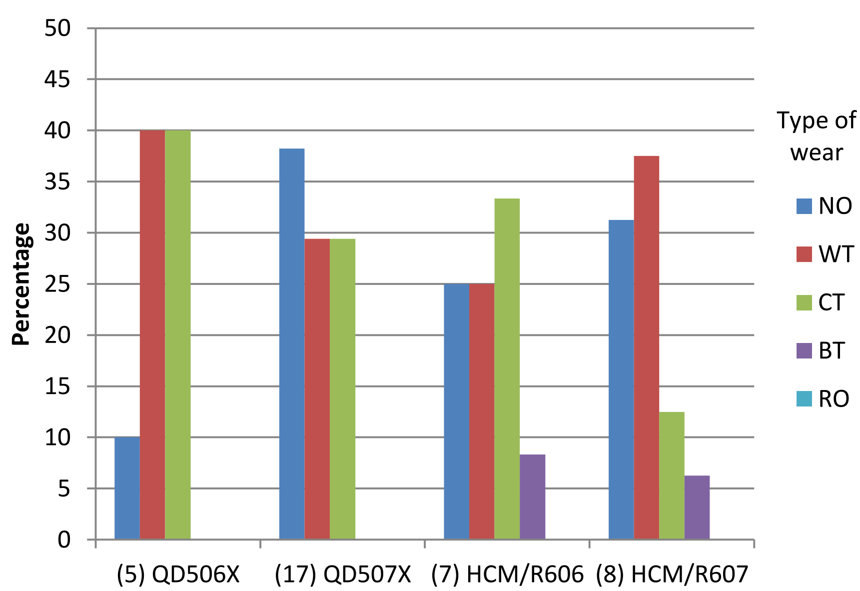

Meters
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
m/hr
30
25
20
15
10
5
0
Drilled interval
ROP (median)
(10) QD606X
(16) HCM606

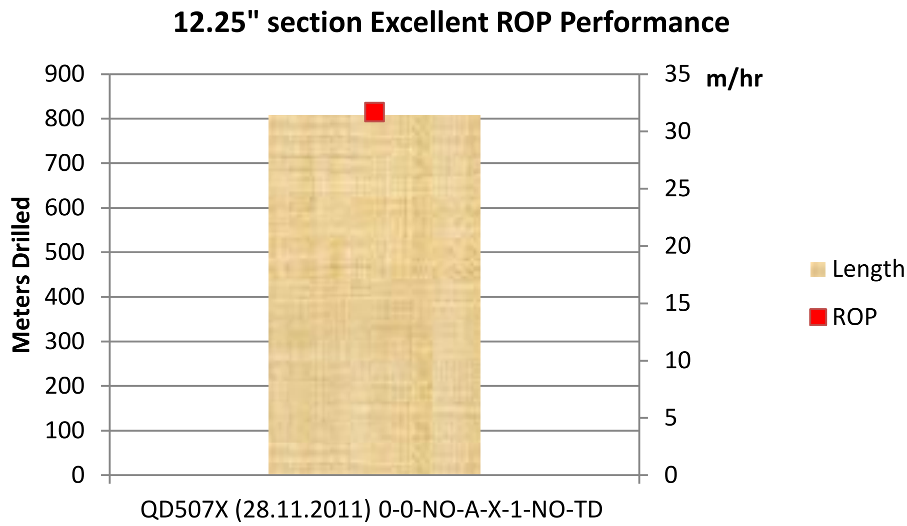

Wear grade, 0-8
8
7
6
5
4
3
2
1
0
Inner
Outer
Gauge
(10) QD606X
(16) HCM606

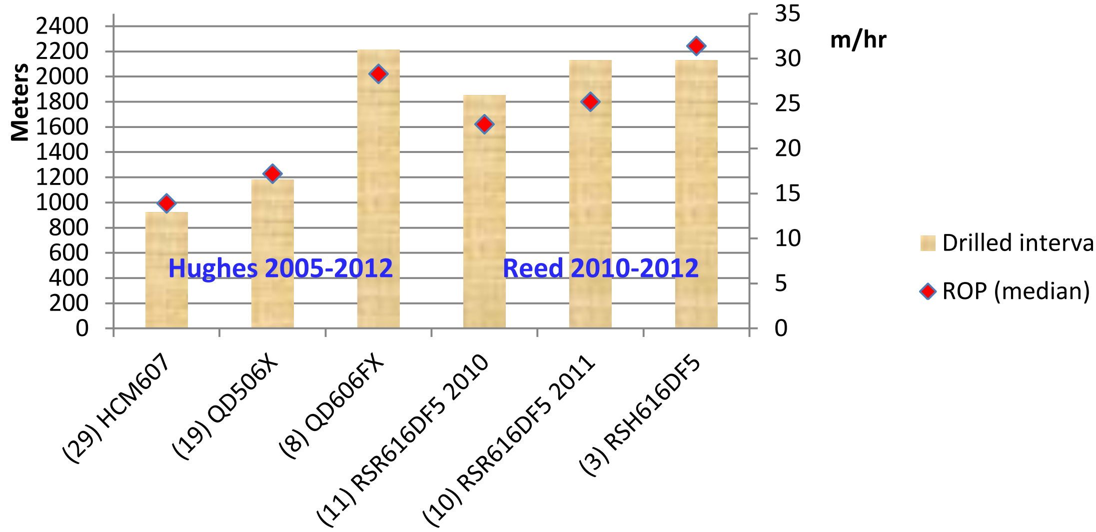

Percentage
50
45
40
35
30
25
20
15
10
5
0
Type of wear
NO
WT
CT
BT
RO
(10) QD606X
(16) HCM606

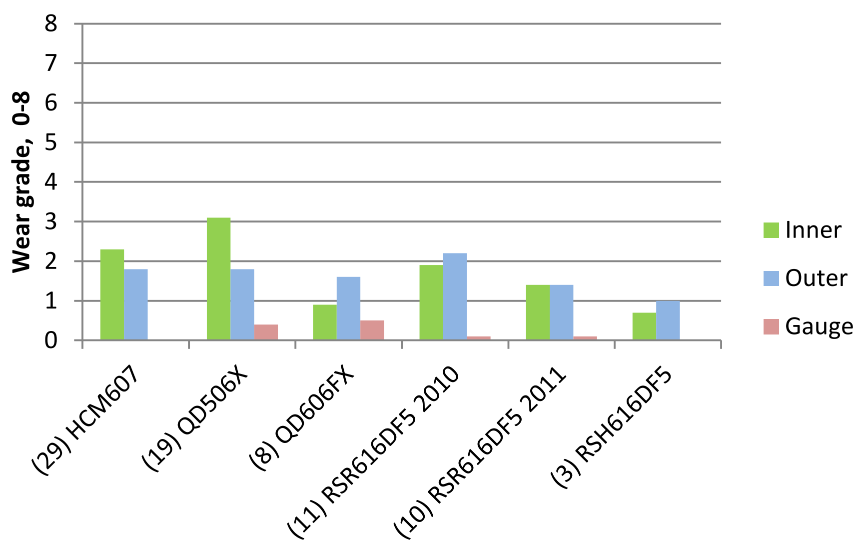

Meters
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
30
25
20
15
10
5
0
m/hr
Drilled interval
ROP (median)
(5) QD506X
(17) QD507X
(7) HCM/R606
(8) HCM/R607

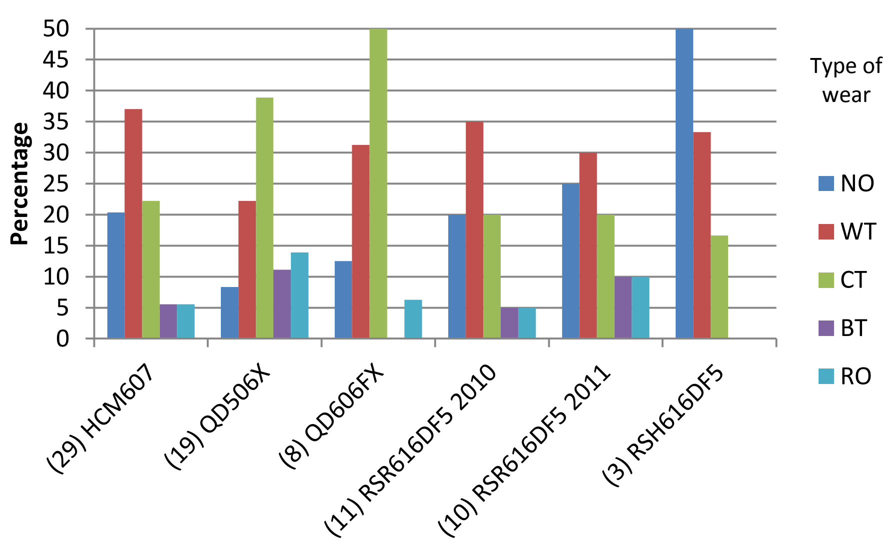

Wear grade, 0-8
8
7
6
5
4
3
2
1
0
Inner
Outer
Gauge
(5) QD506X
(17) QD507X
(7) HCM/R606
(8) HCM/R607


Percentage
50
45
40
35
30
25
20
15
10
5
0
Type of wear
NO
WT
CT
BT
RO
(5) QD506X
(17) QD507X
(7) HCM/R606
(8) HCM/R607

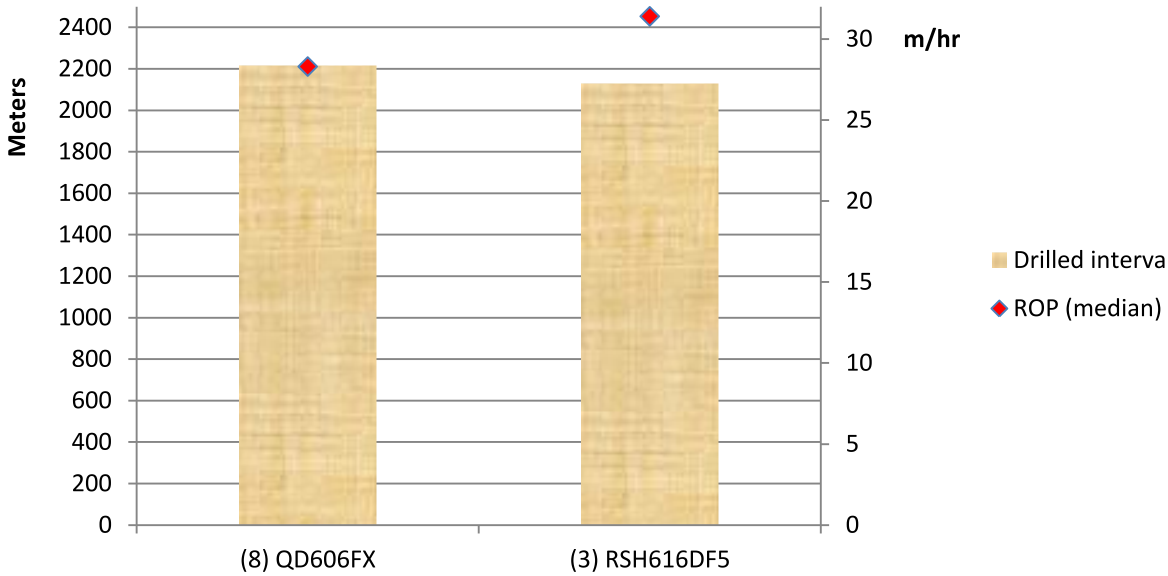

12.25" section Excellent ROP Performance
Meters Drilled
m/hr
900
800
700
600
500
400
300
200
100
0
35
30
25
20
15
10
5
0
Length
ROP
QD507X (28.11.2011) 0-0-NO-A-X-1-NO-TD

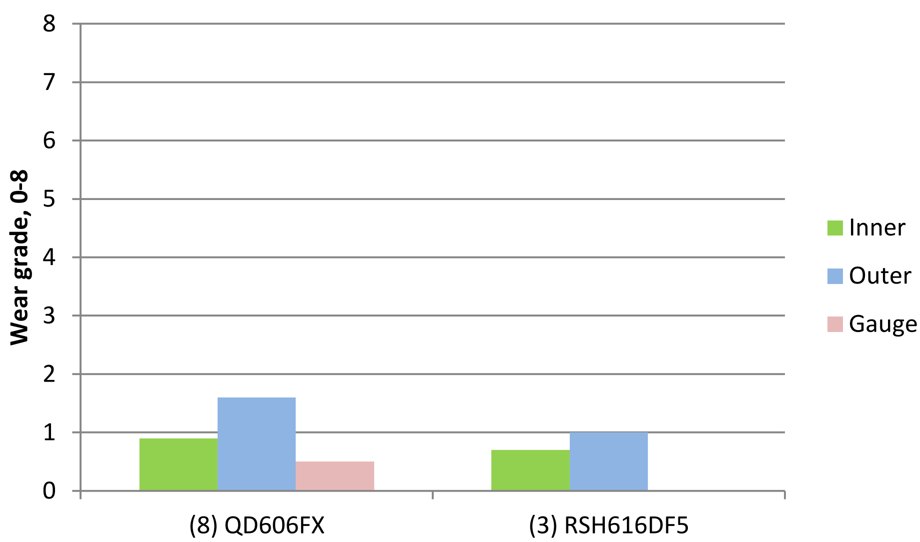

Meters
m/hr
Hughes 2005-2012
Reed 2010-2012
Drilled interval
ROP (median)
(29) HCM607
(19) QD506X
(8) QD606FX
(11) RSR616DF5 2010
(10) RSR616DF5 2011
(3) RSH616DF5

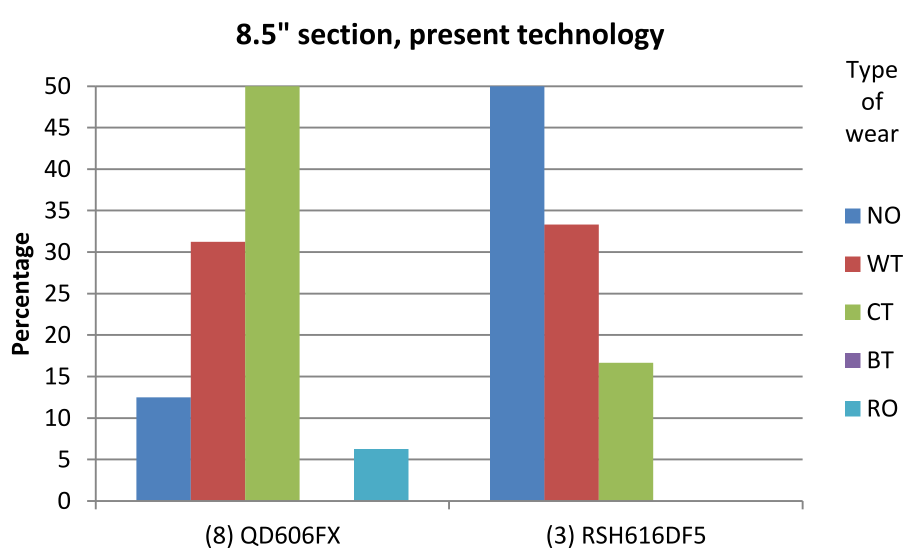

Wear grade, 0-8
Inner
Outer
Gauge
(29) HCM607
(19) QD506X
(8) QD606FX
(11) RSR616DF5 2010
(10) RSR616DF5 2011
(3) RSH616DF5

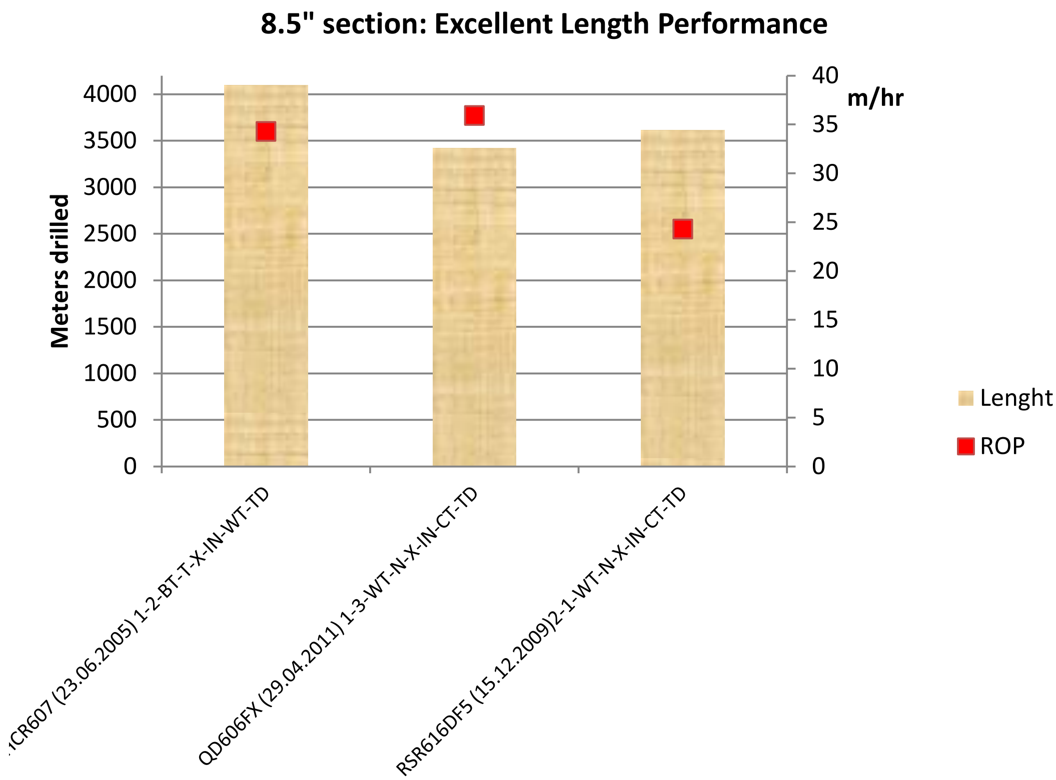

Percentage
Type of wear
NO
WT
CT
BT
RO
(29) HCM607
(19) QD506X
(8) QD606FX
(11) RSR616DF5 2010
(10) RSR616DF5 2011
(3) RSH616DF5

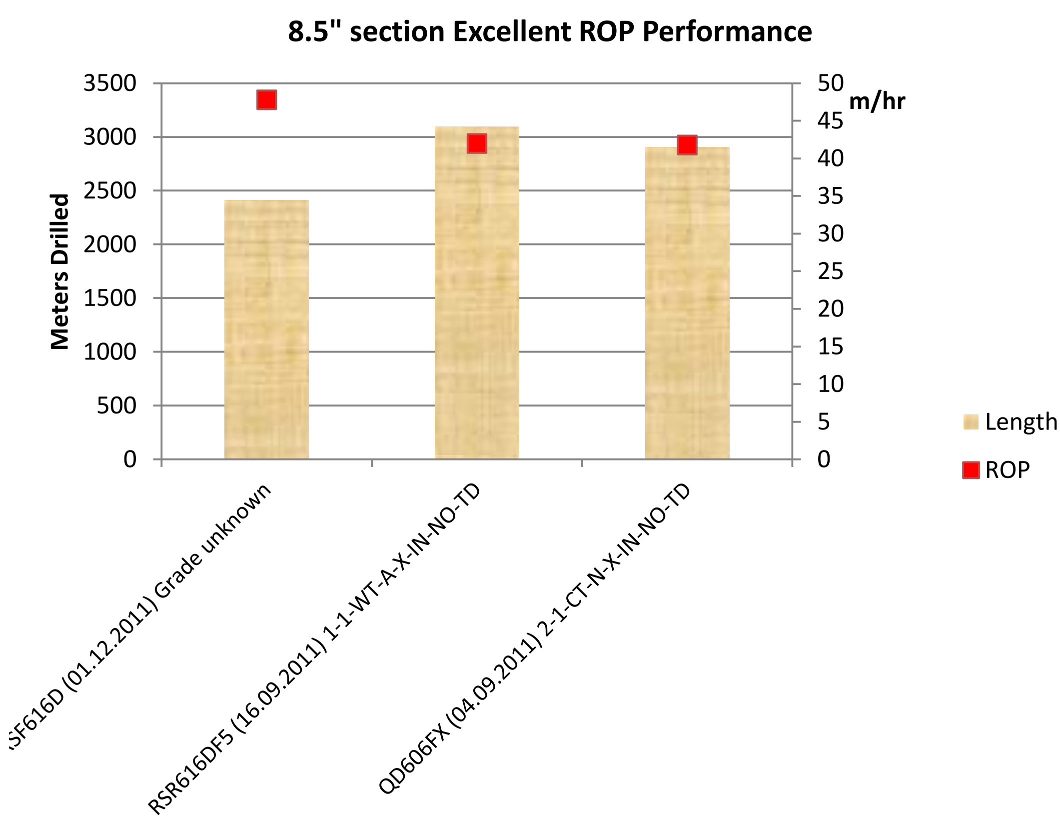
## 8.5" Section – Present Technology (2012)



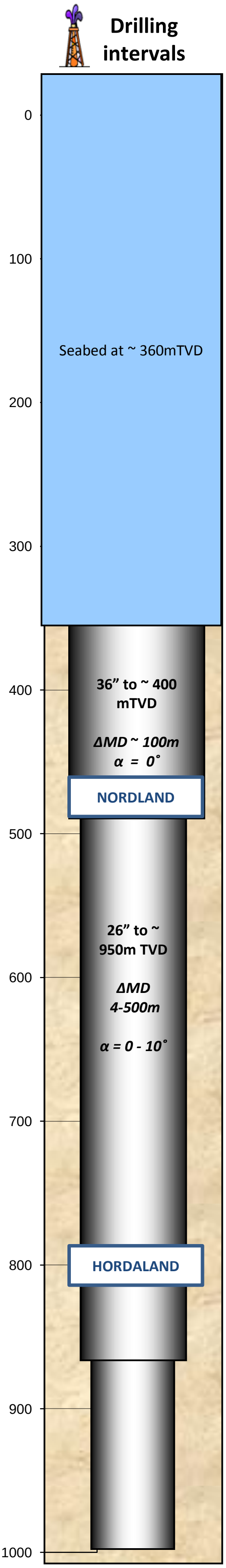

8.5" section: Excellent Length Performance
Meters drilled
4000
3500
3000
2500
2000
1500
1000
500
0
40
35
30
25
20
15
10
5
0
m/hr
Lenght
ROP
CR607 (23.06.2005) 1-2-BT-T-X-IN-WT-TD
QD606FX (29.04.2011) 1-3-WT-N-X-IN-CT-TD
RSR616DF5 (15.12.2009)2-1-WT-N-X-IN-CT-TD


8.5" section Excellent ROP Performance
Meters Drilled
3500
3000
2500
2000
1500
1000
500
0
50
45
40
35
30
25
20
15
10
5
0
m/hr
Length
ROP
SF616D (01.12.2011) Grade unknown
RSR616DF5 (16.09.2011) 1-1-WT-A-X-IN-NO-TD
QD606FX (04.09.2011) 2-1-CT-N-X-IN-NO-TD

# APPENDIX 4
# GENERALIZED GJØA WELL AND PERFOMANCE PLOTS

# Generalized Gjøa Well and Bit Technology (2009-2012)

SMITH BITS
A Schlumberger Company




**For better understanding of this Appendix, it is recommended to read Section 5.5.**

**Note:** Formation group tops are not accurate, only illustrating what groups are drilled. Well path, drilled intervals, parameters and dullgrades are approximate and should be used as a guideline. The extracted data used (from DRS) were filtered on a minimum drilled interval and amount of hours (e.g. 8.5” section minimum 200 meters and 5 hrs. Reasons for pulling out of hole which not were related to bit performance were excluded, e.g. WC is not relevant for bit performance. The focus was laid on the majority of bit types and trends.

This research was done with both excel raw data and RoundTuit. RoundTuit does not have the ability to filter on wells etc, and also if dataset is incomplete from DRS, the missing data will not be included for the present bit. Therefore, to overcome these errors, manually filtered raw data was used in combination with Round Tuit. In this sheet the trends are pointed out, note that the ROP’s, dulls etc are based on calculating the median since it will give a more respective picture of the trends.

## Explanation of tables (note 36” and 26” section will vary)

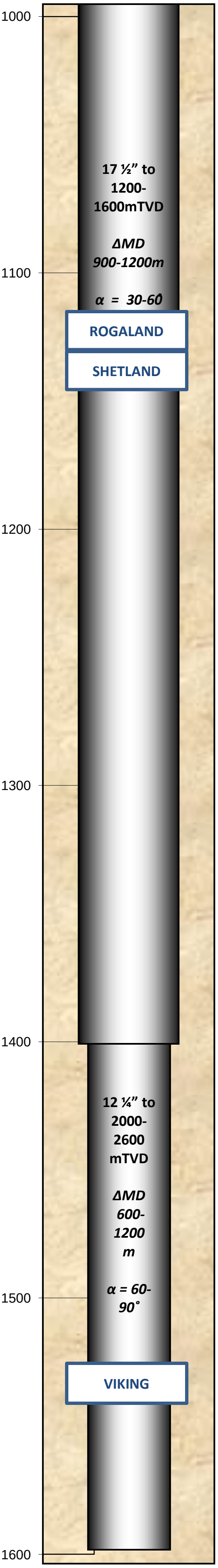
| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>Seawater/Waterbased/Oilbased<br>**Mud weight:**<br>Given in specific gravity | Information about the section. | The optimum bit type presented. Here the IADC code is given and nomenclature explained.<br><br>HTC = Hughes Christensen (Baker Hughes)<br>HYC = Reed Hycalog<br>STC/GEO = Smith Bits |
| | *Typical Parameters:*<br>WOB = weight on bit<br>RPM = rounds per minute<br>TFA = total flow area | In this column information about the dullgrades are given, and if it is mostly new applications or rerunned applications that are used. |
| **Other Products** | In these two columns the different technologies used are shown, respectively on vendors and bit types. **These data are the dataset for the different graphs presented later in Appendix 4.**<br>ROP = rate of penetration<br>dMD = drilled intervall<br>dMD per tooth/cutterwear = presents the amount of drilled interval per calculated unit tooth wear (e.g. The interval drilled from a grade 0 to a grade 1).<br>POOH = pulled out of hole. | Dull = inner-outer-gauge-dull characterization<br>Dull characterisation represents the most occurring characterisation, both the ”Characterisation column” and”Other column” in the IADC code is included here.<br>The nomenclature is not explained here, for interested readers it is recommended to read the product catalogue for the different vendors. |

## 36” Section

| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>SW<br><br>**Mud weight:**<br>1,03 | 1) Vertical section<br>2) Potential boulders | SHO – staged hole opener with 17.5” bit.<br><br> |

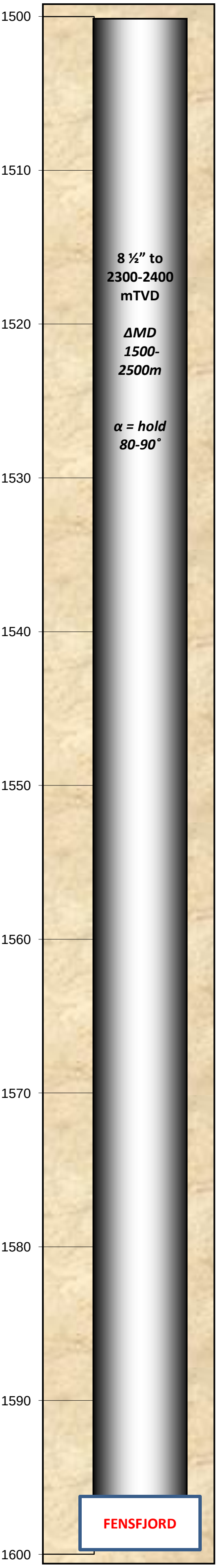
## 26” Section

| General Info | Information | Bit type |
|---|---|---|
| **Mud Type:**<br>WBM/SW<br><br>**Mud weight:**<br>1.03-1.1<br><br> | 1) Usually a straight section, may start to build angle up to 10˚<br>2) Easy section to drill<br><br>Formations: Nordland and Hordaland group. | HYC bit: T11<br>IADC: 115 RMR<br>ROP: 23.8<br>Dull: 1.5-1.3-0<br><br>STC bit: XR+<br>IADC: 115RMF<br>ROP: 15.9<br>Dull: 2.3-1.7-0.7 |
| | *Typical Parameters:*<br>WOB: 2-22<br>RPM: 20-200<br>TFA: 1.3 | Both NB and RR bits. No seal failures, a few examples of balling up (BU). The above given products will not be explained in detail. |




| 17 ½" Section | | |
|---|---|---|
| **General Info** | **Information** | **Bit type** |
| **Mud Type:**<br>WBM/SW/OBM<br><br>**Mud weight:**<br>1.03-1.26 | 1) Builds angle to 30-60˚,<br>2) Soft unconsolidated formation.<br>Formation: Rogaland grp, Shetland Group :Lista, Kyrre, Jorsalfaret, Vale | **GEO: MDi816LHSBPX**<br><br>M: Matrix<br>D: Directional certified<br>i: iDEAS certified<br>816: 8 blades w/ 16 mm cutters<br>L: Managed depth of cut<br>H: Anti balling<br>S: Short gauge length<br>B: Backreaming cutters<br>PX: Diamond enhanced gauge protection |
| | *Typical Parameters:*<br>WOB: 5-25<br>RPM: 70-180<br>TFA: 1.0-1.3 | Wear located mainly all over. Both NB and RR bits used. Both RC and PDC used, PDC seems to be the best application. Depends on formation. |
| **Other products** | **GEO: MDi816LHSBPX**<br>ROP = 25.8 m/hr<br>dMD = 1098m<br>Dull: 0.8-1.5-0.3 | **HTC: MXST03 (Rollercone)**<br>ROP = 16.7 m/hr<br>dMD =727m<br>Dull: 2.7-1.8-0.3 |

| 12 ¼" Section | | |
|---|---|---|
| **General Info** | **Information** | **Bit type** |
| **Mud Type:**<br>WBM<br><br>**Mud weight:**<br>1.25-1.3 | 1) Builds angle to 60-90˚<br>2) Possible calcite cemented sandstone may occur when drilling through Viking grp, especially Sognefjord and Fensfjord formation<br>Formation: Rogaland and Viking grp – mainly Kai, Draupne, Sognefjord, Fensfjord, Roedby, Tryggvason, Shetland, Aasgard, Heather, Blodøks | GEO: MDSi716LHBPX (12)<br>M: Matrix<br>D: Directional certified<br>S: Backup cutters<br>i: iDEAS certified<br>716: 7 blades w/ 16 mm cutters<br>L: Managed depth of cut<br>H: Anti balling<br>B: Backreaming cutters<br>PX: Diamond enhanced gauge protection<br><br>ROP= 17.5<br>dMD= 844<br>Dull: 0.7-1.2-0.1-WT |
| | *Typical Parameters:*<br>WOB:10-20<br>RPM: 100-180<br>TFA: 0.9-1.5 | Both new bits and RR used, depends on the prognosis of upcoming run. |
| **Other products** | *HTC: Quantec QD505HX (1)*<br>ROP = 17m/hr<br>dMD = 1362<br>Dull: 1-1-0-NO | *HYC: MSR716MB2C (1)*<br>ROP = 10.5<br>dMD = 778<br>Dull: 1-1-0-NO |

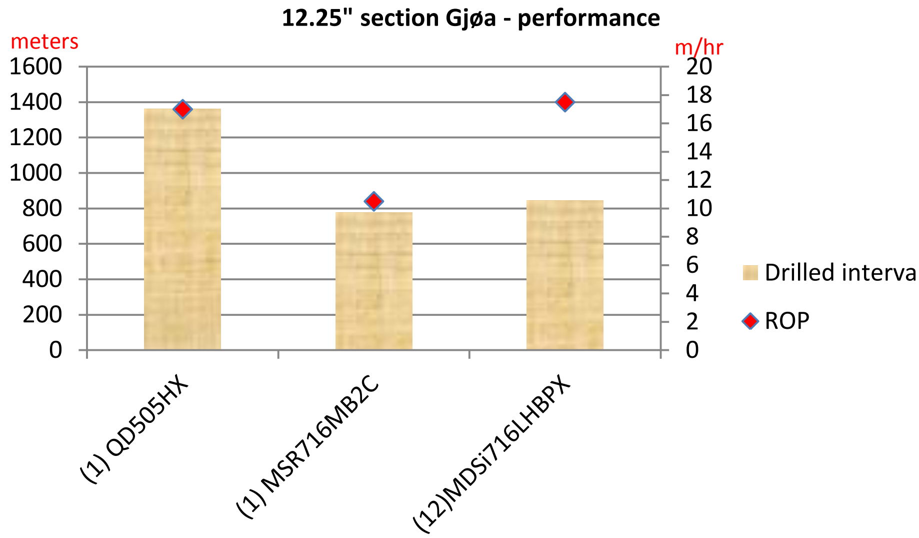


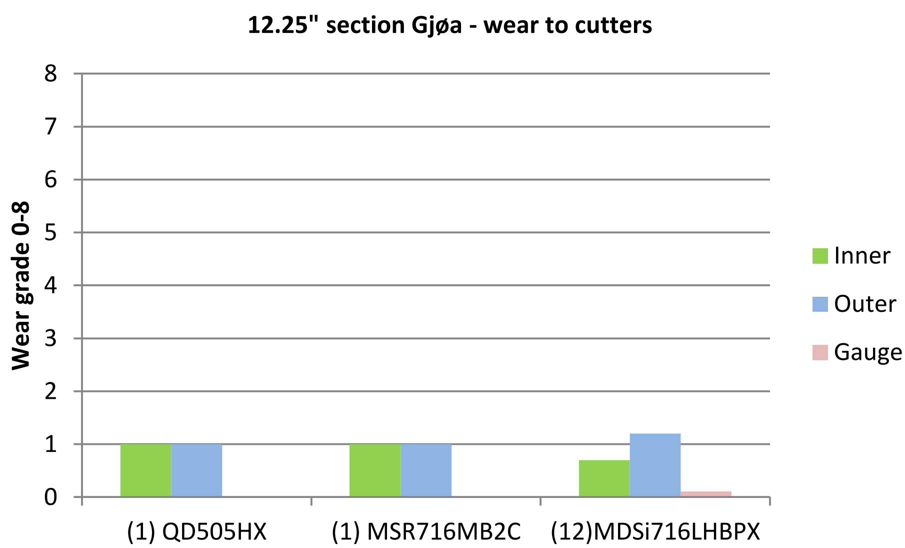

| 8 ½” Section | | |
|---|---|---|
| **General Info** | **Information** | **Bit type** |
| **Mud Type:**<br>OBM/WBM<br><br>**Mud weight:**<br>1.15-1.30 | 1) Both horizontal and highly inclined section, holds at 80-90˚<br>2) Calcite cemented sandstone occurs.<br>3) Drill bit needs to be durable, stable and steerable, must not deflect from wellpath when hitting high density calcitic sandstone.<br>4) Similar to Troll.<br><br>Formation: Viking grp. – mainly Sognefjord, Fensfjord, Krossfjord formation. | **HYC: RSH/RSF 616DF4 (9)**<br>**IADC: M422**<br>RS: Rotary Steerable<br>H: Helios cutter technology<br>6: 16 mm cutters<br>06: 6 blades<br>D: diamon back up cutters<br>F4: hardfacing related<br><br>ROP = 22.3<br>dMD = 2159<br>Dull: 1.2-1.1-0.1-WT |
| | Parameters:<br><br>WOB: 8-15<br>RPM: 120-200<br>TFA: 0.56-0.75 | Dullgrades are more varied due to the calcite cemented stringers, more chippage/breakage observed, use new bits per run. |
| **Other products** | **GEO: MDSi716LUBPX (5)**<br>ROP = 17.5m/hr<br>dMD = 844m<br>Dull: 0.7-1.2-0.1-WT | **HTC: QD606FX (2)**<br>ROP = 20.0m/hr<br>dMD = 1389m<br>Dull:1.5-3.0-0.5-WT |

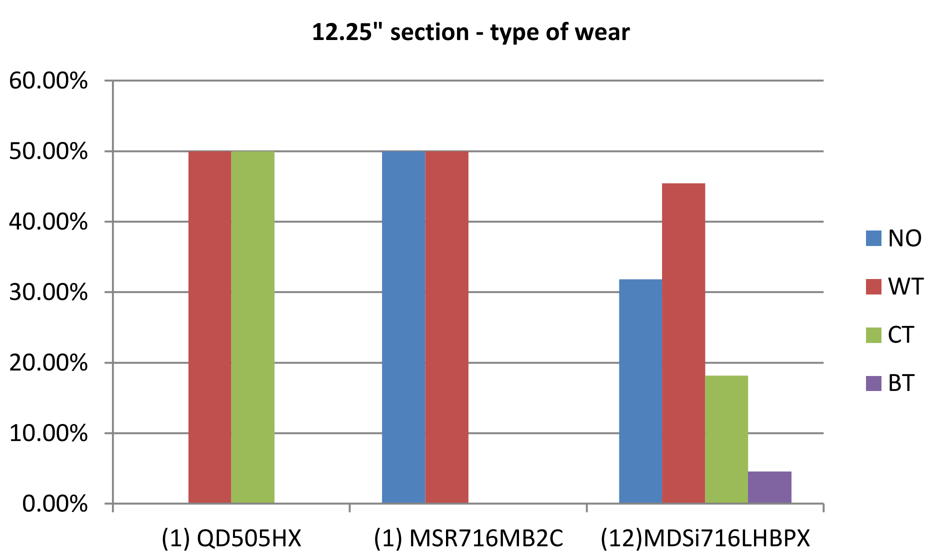
The last pages are graphs, shortly explained:
The graphs uses the base presented above. For each section the nbr of relevant runs is presented infront of its respective bit type, e.g. (8) QD606X. In general there are 3 type of graphs.

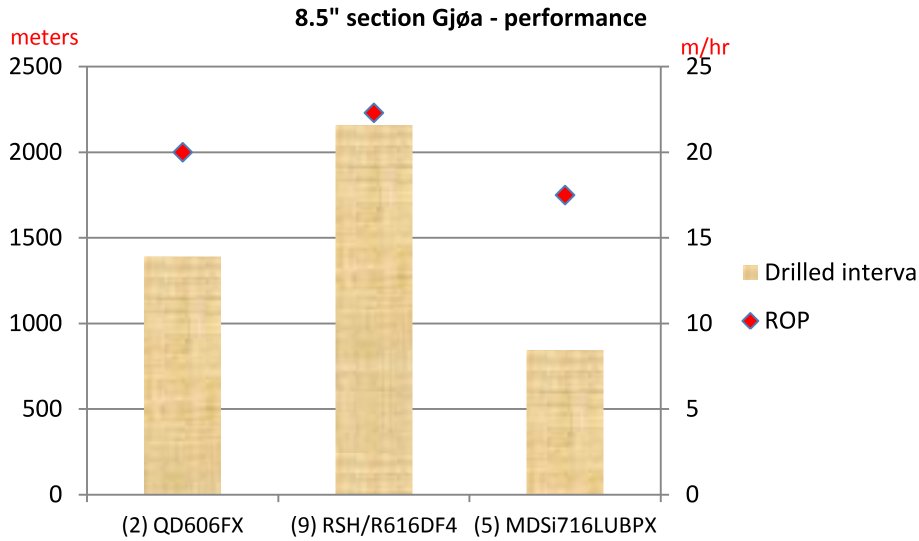
Graph 1: ROP vs drilled interval, giving the median drilled interval and median ROP for the respective products
Graph 2: Location of wear in terms of inner, outer and gauge, standarized to a 0-8 grade.
Graph 3: Occurrence of different types of wear for the different products. Note that both CH and O in the IADC dull grade code are included in this graph.

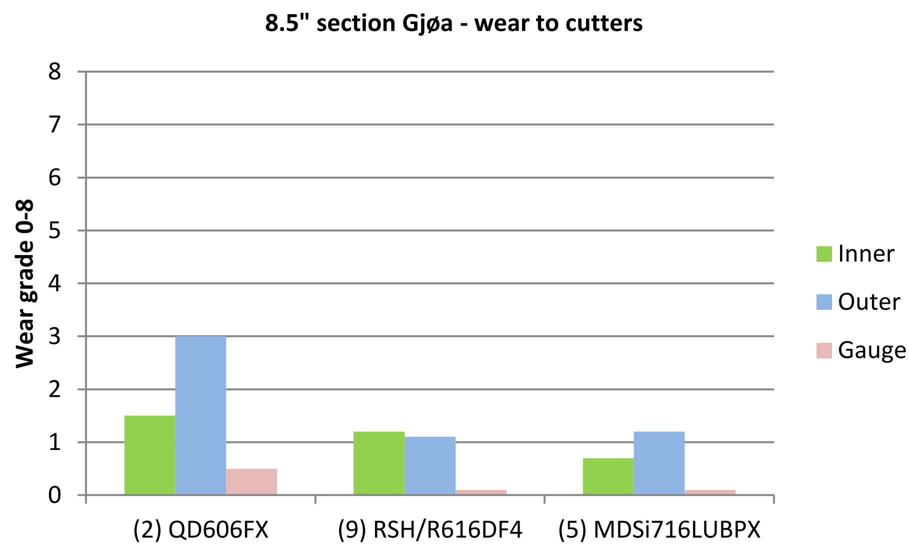
Comparisation Run of Smith Bits vs. Baker Hughes in the 8.5” section presented in the end.

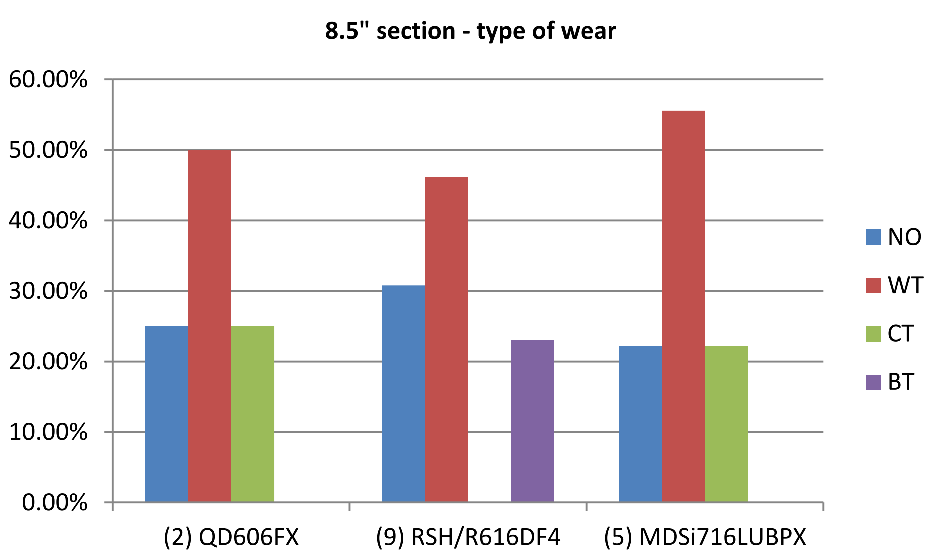

12.25" section Gjøa - performance
meters
m/hr
1600
1400
1200
1000
800
600
400
200
0
20
18
16
14
12
10
8
6
4
2
0
(1) QD505HX
(1) MSR716MB2C
(12)MDSi716LHBPX
Drilled interval
ROP


12.25" section Gjøa - wear to cutters
Wear grade 0-8
8
7
6
5
4
3
2
1
0
(1) QD505HX
(1) MSR716MB2C
(12)MDSi716LHBPX
Inner
Outer
Gauge

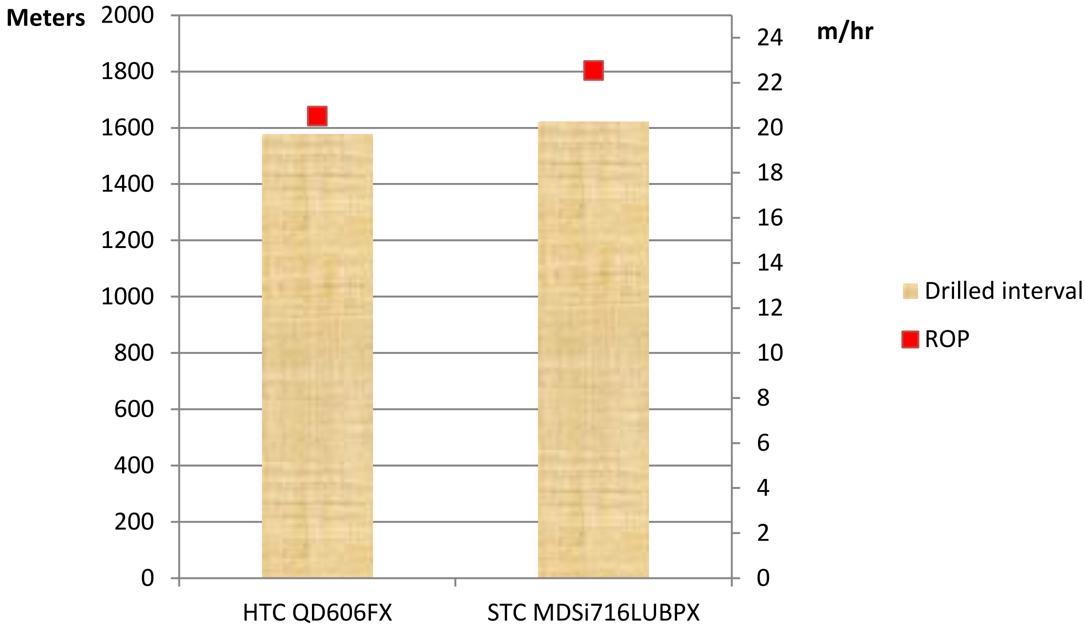

12.25" section - type of wear
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
(1) QD505HX
(1) MSR716MB2C
(12)MDSi716LHBPX
NO
WT
CT
BT


8.5" section Gjøa - performance
meters
m/hr
2500
2000
1500
1000
500
0
25
20
15
10
5
0
Drilled interval
ROP
(2) QD606FX
(9) RSH/R616DF4
(5) MDSi716LUBPX


8.5" section Gjøa - wear to cutters
Wear grade 0-8
8
7
6
5
4
3
2
1
0
Inner
Outer
Gauge
(2) QD606FX
(9) RSH/R616DF4
(5) MDSi716LUBPX


8.5" section - type of wear
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
NO
WT
CT
BT
(2) QD606FX
(9) RSH/R616DF4
(5) MDSi716LUBPX

# Gjøa, D-template comparison




Smith drilled from 35/09-D01Y01H (25.11.2010)
Hughes drilled from 35/09-D01Y02H (03.06.2011)
Same parameters for both runs (MW, WOB, etc)

Dullgrades:
STC MDSi716: 1-3-WT-S-X-1-CT-TD
HTC QD606FX: 2-3-WT-S-X-1-CT-TD

STC: ROP = 22.5, dMD=1621
HTC: ROP = 20.5, dMD=1578

# APPENDIX 5
# IMPROVED PERFORMANCE OF THE NEW ITERATION OF MDi716 (FERRARI)

# 8 ½" MDi716LUBPX

## Performance Comparison

## Talisman, Varg Field, Norway

## April 2011



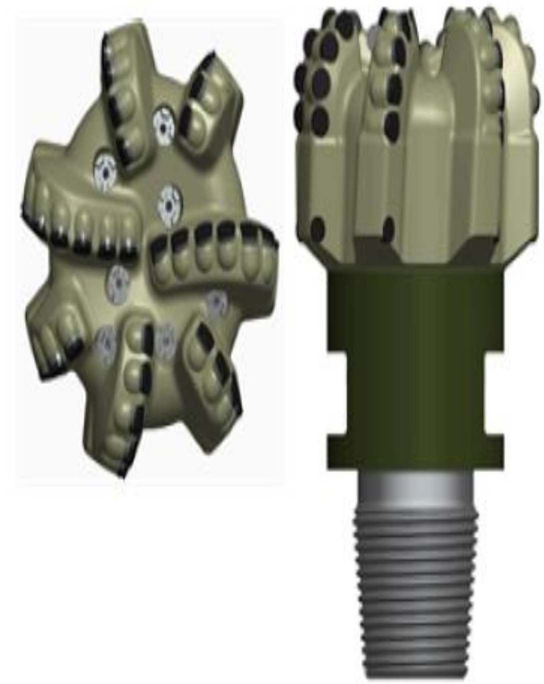
SMITH BITS
A Schlumberger Company

**8 ½" MDi716**

**BOM: 6425250001**

**Previous Design**

**8 ½" MDi716**



**BOM: 65024A0001**

**New Design**

- **The new design (65024A0001) is focused for steering modes with various RSS systems.**
- **The differences :**
  - **Profile change**
  - **Increased cutter aggressiveness**
  - **Increased Stability**
- **Designed for chalk drilling for Norway applications**

# 8 ½" MDI716LUBPX DIRECT OFFSET COMPARISON

Well: 15/12-A-1A
64867A0001
JD6501

- Drilled 1108 mt @ 12.6 mt/hr
- Depth In: 2904 mt
- Depth Out: 4012
- Formations: Shetland Gp-Viking Gp
- Inc In: 64.3 deg / AZ In: 109.36
- Inc Out: 35.3 deg / AZ Out: 107.85
- TVD In: 2667 mt
- TVD Out 2998 mt
- Max DLS: 5.32 deg/30 mt
- Smith Dull: 0-2-BT-S-X-I-CT-TD

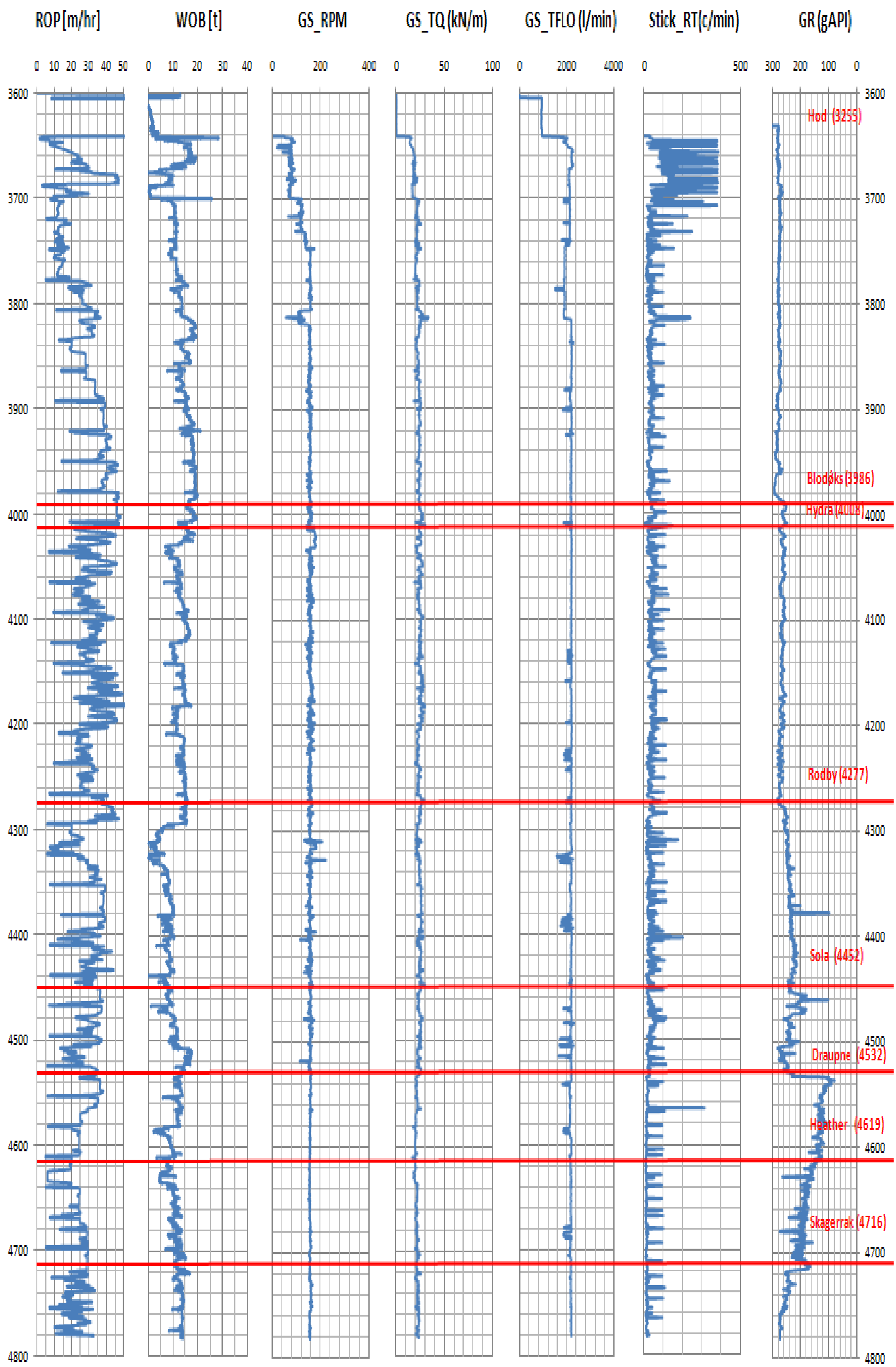
SLB DD Comments:
Xceed gave good responses both in build and drop. Severe stick slip was observed in shorter periods of time cured easy by reducing WOB.

Well: 15/12-A-12C
65024A0001
JE2197

- Drilled 1085 mt @24 mt/hr
- Depth In: 3697 mt
- Depth Out: 4782
- Formations: Shetland Gp-Viking Gp
- Inc In: 87.4 deg / AZ In: 160.5
- Inc Out: 65.8 deg / AZ Out: 158.6
- TVD In: 2597 mt
- TVD Out 3007 mt
- Max DLS: 3.46 deg/30 mt
- Smith Dull: 0-0-NO-A-X-I-NO-TD

SLB DD Comments:
No stickslip or vibration was seen in this run.

# 15/12-A-12C (New Design App)



# BHA Comparison

64867A0001 (1613 T487 TSP MB ):

**Serial#:** JD6501 (Well 15/12-A-1A)

65024A0001 (1613 ERD349 DEEP MB ):

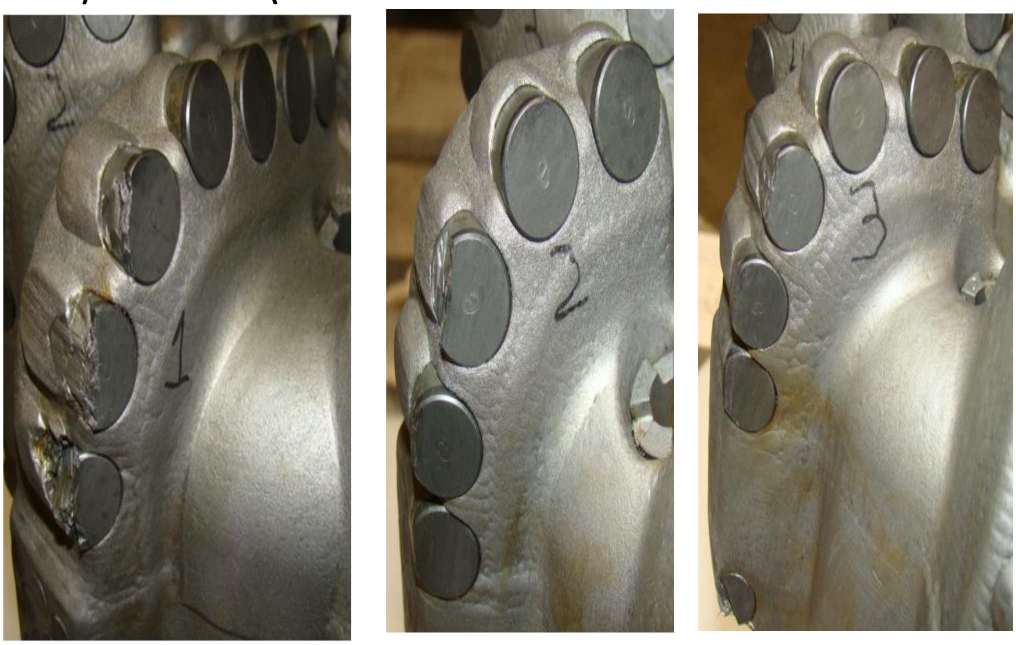
**Serial #:** JE2197 **(Well 15/12 –A12-C)**

| 15/12-A-1 A |
|---|
| **Description** |
| |
| 8 1/2 " Bit |
| Xceed 675 w/Dummy Float |
| EcoScope w/APWD |
| Telescope w/MVC Shock |
| Stethescope |
| X-over |
| Float Sub w/ Non ported float |
| 8 3/8" NM Roller Reamer |
| 2 x NMHWDP (2 joints) |
| 8 3/8" NM Roller Reamer |
| X-over |
| 2 x 5 1/2" FH VAM EIS HWDP |
| Hydraulic Jar w/X-overs |
| 2 x 5 1/2" FH VAM EIS HWDP |
| Jar Accelerator w/X-overs |
| 3 x 5 1/2" FH VAM EIS HWDP |
| X-over |
| 8 3/8" Steel Roller Reamer |
| X-over |
| |
| |
| |

| 15/12-A-12 C |
|---|
| **Description** |
| |
| 8 1/2 " Bit |
| Xceed 675 w/8 3/8" Stab & Dummy Float Vavle |
| EcoScope w/APWD w/8 1/4" Stabiliser |
| Telescope MWD |
| Stethescope w/8 1/4" Stabiliser |
| 8 3/8" NM In Line Stabiliser |
| seismicVISION 675 |
| sonicVISION 675 |
| 8 3/8" NM In Line Stabiliser |
| seismicVISION 675 |
| Float Sub w/ Non Ported float |
| 8 3/8" NM Roller Reamer 3-Point |
| 5" NMHWDP |
| 5" NMHWDP |
| 8 3/8" NM Roller Reamer 3-Point |
| X-over 4 1/2 IF Pin x 5 1/2 FH VAM EIS Box |
| 2 x 5 1/2" FH VAM EIS HWDP (2 joints) |
| 6 1/2" Hydraulic Jar w/ X-overs to 5 1/2" FH VAM EIS |
| 2 x 5 1/2" FH VAM EIS HWDP (2 joints) |
| 6 1/2" Accelerator Jar w/ X-overs to 5 1/2" FH VAM EIS |
| 2 x 5 1/2" FH VAM EIS HWDP (2 joints) |
| 5-1/2" FH VAM EIS DP |

# 8 ½" MDI716LUBPX Cutter Comparison

64867A0001 (1613 T487 TSP MB ):**Serial#:** JD6501 (Well 15/12-A-1A\0



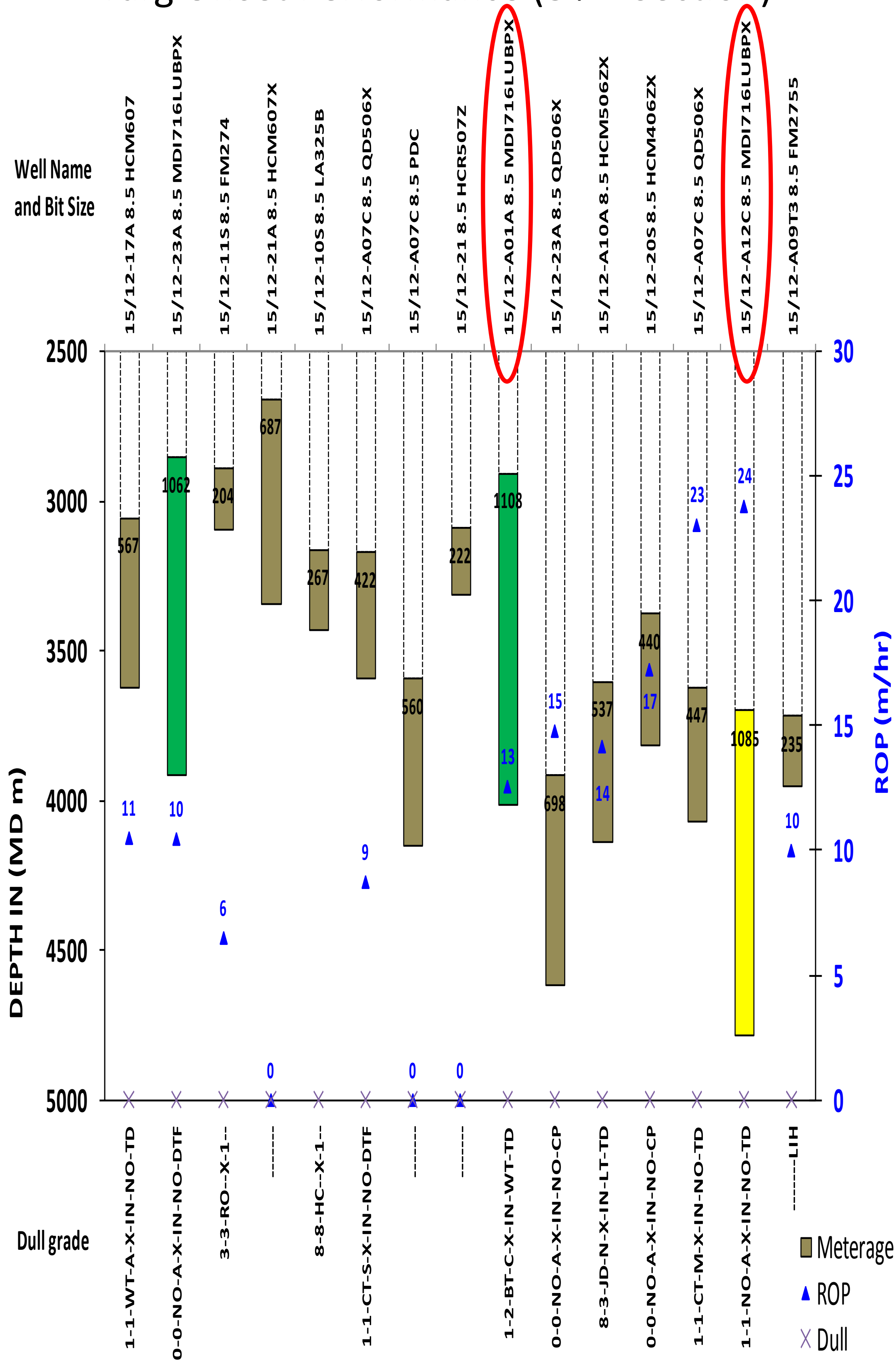

65024A0001 (1613 ERD349 DEEP MB ):**Serial#:** JE2197 (Well 15/12 –A12-C)

# 8 ½" MDI716LUBPX Cutter Comparison

64867A0001 (1613 T487 TSP MB ):**Serial#:** JD6501


65024A0001 (1613 ERD349 DEEP MB ):**Serial#:** JE2197 (Well 15/12 –A12-C)

# Varg Offset Performance (8 ½" Section)




- **The new design (65024A0001)**
  - **Improved ROP as per direct offset against previous BOM**
  - **Great stability drilling chalk ( 389 mt  of Hod formation)**
  - **Great stability through out the entire run**
  - **Highest ROP  per meter drilled as per Varg field 8 ½” offsets**
  - **Increased cutter durability as per previous version (BOM 6425250001)**

# APPENDIX 6
# CHALK STUDY SMITH BITS
# FIKSDAL ET AL RESULTS

# Chalk Outcrops Physical Characteristics (North Ireland Samples)

| Sample ID | As-Received Bulk Density ($g/cm^3$) | Effective Confining Pressure[1] (psi) | Porosity (%) | Effective Compressive Strength (psi) | IDEAS Tests |
|---|---|---|---|---|---|
| GL-2 (Glen Arm) | 2.429 | 0 | Low (1-5) | 17,175 | X (16 mm) |
| PR-1 (Portrush Cliffs) | 2.485 | 0 | Med (5-15) | 13,480 | |
| LB-1 (Larry Baine) | 2.498 | 0 | Med (5-10) | 14,400 | |
| TA-2 (Tanderagee) | 2.415 | 0 | High (15-20) | 11,150 | X (16 mm) |
| All tests conducted with pore pressure = 0 psi. | | | | | |

Fiksdal et al. Results – Rock strength from NPD cores with calcitic sandstone. The results shown below are re-illustrated from paper IADC/SPE 59110 *Application of Rotary Steerable System/PDC Bits in Hard Interbedded Formations: A Multidisciplinary Team Approach to Performance Improvement*. Harald Fiksdal, Norsk Hydro, Clive Rayton, Hughes Christensen OASIS, and Zvonimir Djerfi, SPE, Baker Hughes INTEQ. This paper was prepared for presentation at the SPWLA 49th Annual Logging Symposium held in Edinburgh, Scotland, 25-28th May, 2008.

**TABLE 1 - Rock Strength Test Results for Calcitic Sandstone Cores**

| Plug # | Plug orientation | Porosity % | Permability | Test # | Confining Pressure MPa | Failure MPa | Youngs Modulus MPa | Poissons Ration | Cohesive Strength ($SC_o$) MPa | Friction angle |
|---|---|---|---|---|---|---|---|---|---|---|
| 50-98 | HOR | 5.1 | 0.032 | mfx98029 | 5 | 90.0 | 39.5 | 0.13 | | |
| 50-98 | | | | mfx98029 | 10 | 110.0 | 28.9 | 0.27 | | |
| 50-98 | | | | mfx98029 | 15 | 156.4 | 25.6 | 0.36 | | |
| 50-98 | | | | | | **52.4 | | | 12.0 | 40.8 |
| 51-98 | VERT | 2.6 | 0.019 | uax98025 | 0 | *93.65 | 32.9 | 0.28 | | |
| 52-98 | VERT | 3.7 | 0.024 | uax98026 | 0 | *94.55 | 31.4 | 0.31 | | |
| 53-98 | VERT | 4.0 | 0.027 | mfx98030 | 5 | 79.5 | 27.4 | 0.34 | | |
| 53-98 | | | | mfx98030 | 10 | 104.0 | 27.3 | 0.35 | | |
| 53-98 | | | | mfx98030 | 15 | 130.3 | 26.0 | 0.55 | | |
| 53-98 | | | | | | **53.8 | | | 11.9 | 43.5 |
| 54-98 | HOR | 0.3 | 0.012 | mfx98031 | 5 | 132.0 | 55.3 | 0.02 | | |
| 54-98 | | | | mfx98031 | 10 | 160.0 | 50.9 | 0.20 | | |
| 54-98 | | | | mfx98031 | 15 | 183.1 | 49.6 | 0.41 | | |
| 54-98 | | | | | | **107 | | | 28.4 | 34.0 |
| 55-98 | HOR | 0.5 | 0.019 | uax98028 | 0 | *140.90 | 56.9 | 0.20 | | |
| 56-98 | VERT | 0.15 | 0.014 | uax98027 | 0 | *137.45 | 64.0 | 0.23 | | |
| 57-98 | VERT | 0.38 | 0.012 | mfx98032 | 5 | 92.0 | 40.0 | 0.20 | | |
| 57-98 | | | | mfx98032 | 10 | 115.0 | 39.0 | 0.25 | | |
| 57-98 | | | | mfx98032 | 15 | 127.3 | 35.5 | 0.28 | | |
| 57-98 | | | | | | **76.1 | | | 19.6 | 42.1 |
| 58-98 | VERT | 0.44 | 0.012 | mfx98033 | 5 | 115.0 | 55.9 | 0.13 | | |
| 58-98 | | | | mfx98033 | 10 | 136.0 | 50.9 | 0.32 | | |
| 58-98 | | | | mfx98033 | 15 | 165.5 | 50.0 | 0.35 | | |
| | | | | | | **88.3 | | | 22.0 | 37.1 |

* Uniaxial Compressive Strength (UCS) values from direct measurement (uax tests).

** Extrapolated UCS value from linear regression of confined multiple failure (mfx) test results.

# APPENDIX 7
# BHA DATA
# 31/5_J_13_AY3H

# BHA report

**Wellbore:** NO 31/5-J-13 AY3H

| Run no | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | Seq no: 1 | Conveyance: RIG | BHA description: AutoTrak, OnTrak, LithoTrak, TesTrak, CoPilot 8 1/2" section | | | | |
| | String component | Supplier | OD inch | ID inch | Length m | Acc length m | Comment |
| | BIT | Hughes Christensen | 8,500 | | 0,34 | 0,34 | |
| | AUTOTRAK | Baker Hughes Inteq | 8,500 | 2,000 | 2,17 | 2,51 | |
| | MWD STAB | | 8,375 | 2,250 | 1,31 | 3,82 | |
| | COPILOT | Baker Hughes Inteq | 7,000 | 2,250 | 2,26 | 6,08 | |
| | ONTRAK | Baker Hughes Inteq | 8,250 | 2,250 | 5,15 | 11,23 | |
| | MWD STAB | | 8,375 | 2,250 | 1,26 | 12,49 | |
| | BCPM | Baker Hughes Inteq | 7,000 | 2,000 | 4,94 | 17,43 | BCPM II |
| | FLEX SUB | | 7,000 | 2,250 | 2,19 | 19,62 | Non-magnetic |
| | LITHOTRAK | Baker Hughes Inteq | 8,375 | 2,250 | 3,02 | 22,64 | ORD2.6 |
| | LITHOTRAK | Baker Hughes Inteq | 8,250 | 2,250 | 2,78 | 25,42 | CCN II |
| | TESTRAK | Baker Hughes Inteq | 7,000 | 2,250 | 7,25 | 32,67 | |
| | STOP SUB | | 7,000 | 2,250 | 0,74 | 33,41 | Non-magnetic |
| | STAB STRING | | 8,250 | 2,250 | 1,98 | 35,39 | Non-magnetic |
| | FLOAT SUB | | 6,500 | 2,250 | 0,87 | 36,26 | |
| | HW DRILL PIPE | | 5,000 | 3,000 | 27,42 | 63,68 | |
| | JAR | | 6,500 | 2,250 | 9,51 | 73,19 | |
| | DRILL PIPE | | 5,000 | 4,276 | 3,26 | 76,45 | |
| | HW DRILL PIPE | | 5,000 | 3,000 | 44,98 | 121,43 | |
| | Remarks: Sensor for surface RPM not working properly. | | | | | | |

# APPENDIX 8
# VALIDATION STUDY

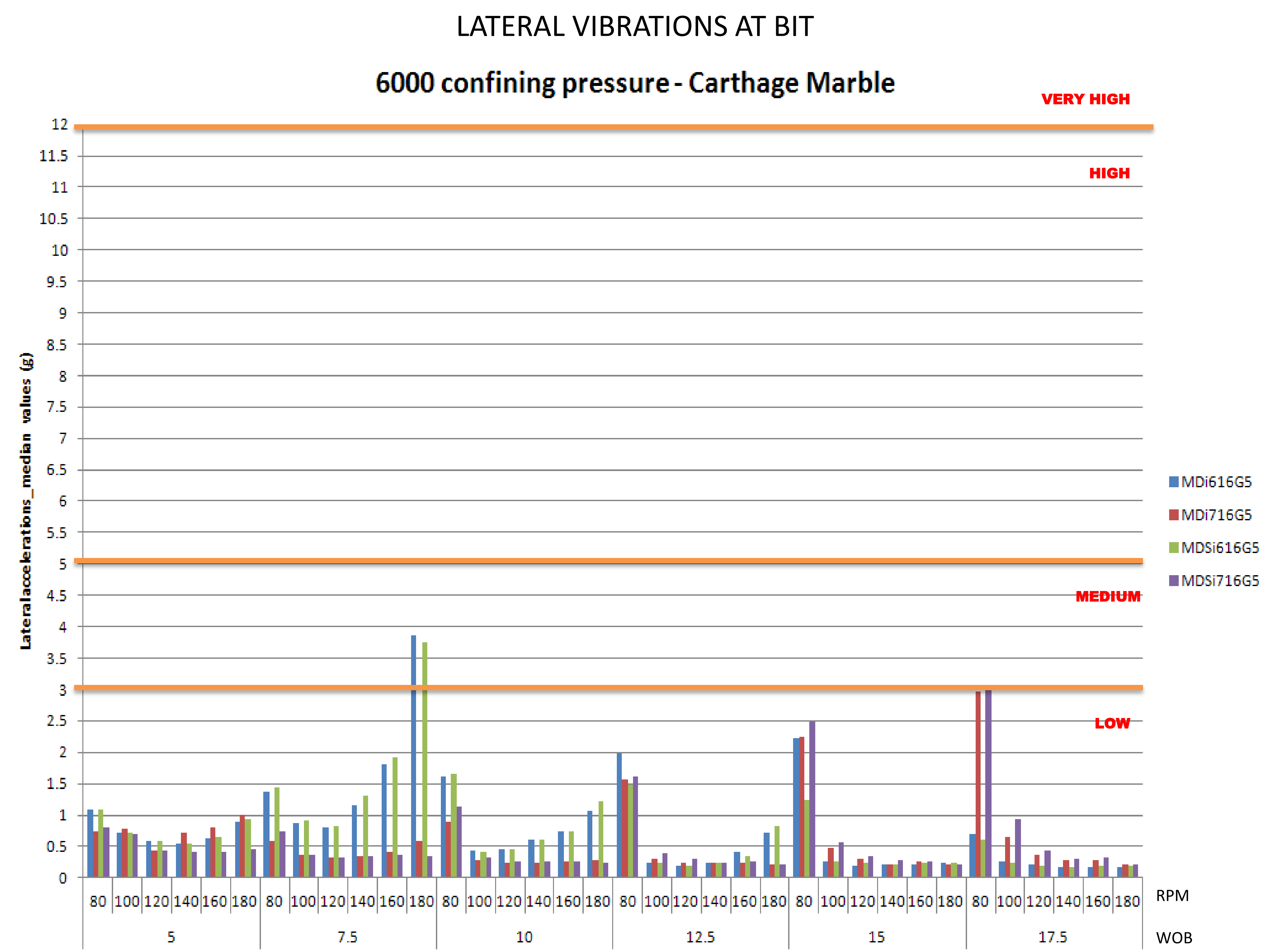
# WITH AND WITHOUT BACKUP CUTTERS

# IDEAS PROJECT RESULTS

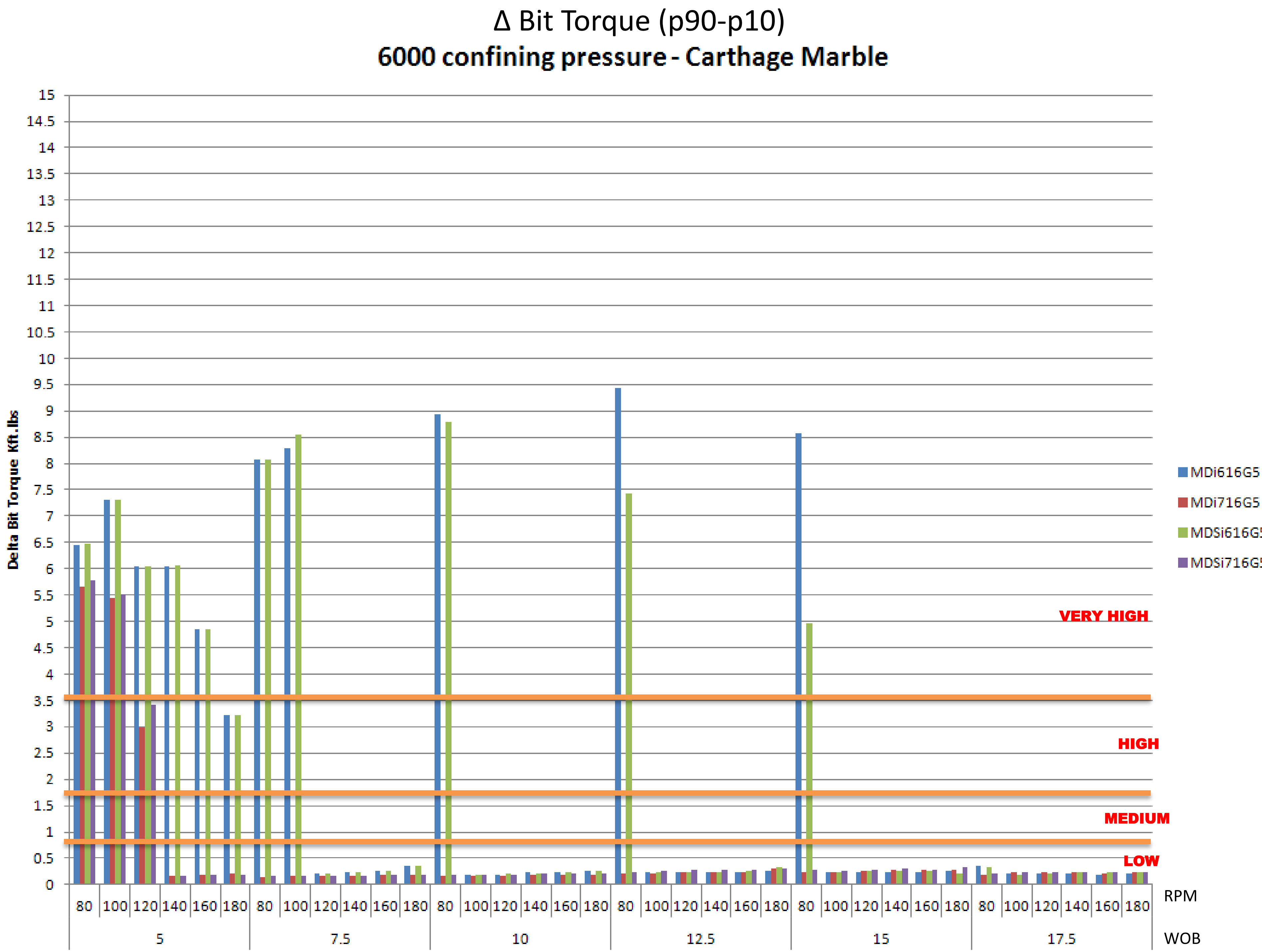
| | |
|---|---|
| OPERATOR: | Statoil |
| WELL NAME: | NO 31/5-J-13 AY3H |
| ORIGINATOR: | Odd Vinsevik |
| DATE: | 2012-3-1 |

## PROJECT DESCRIPTION:

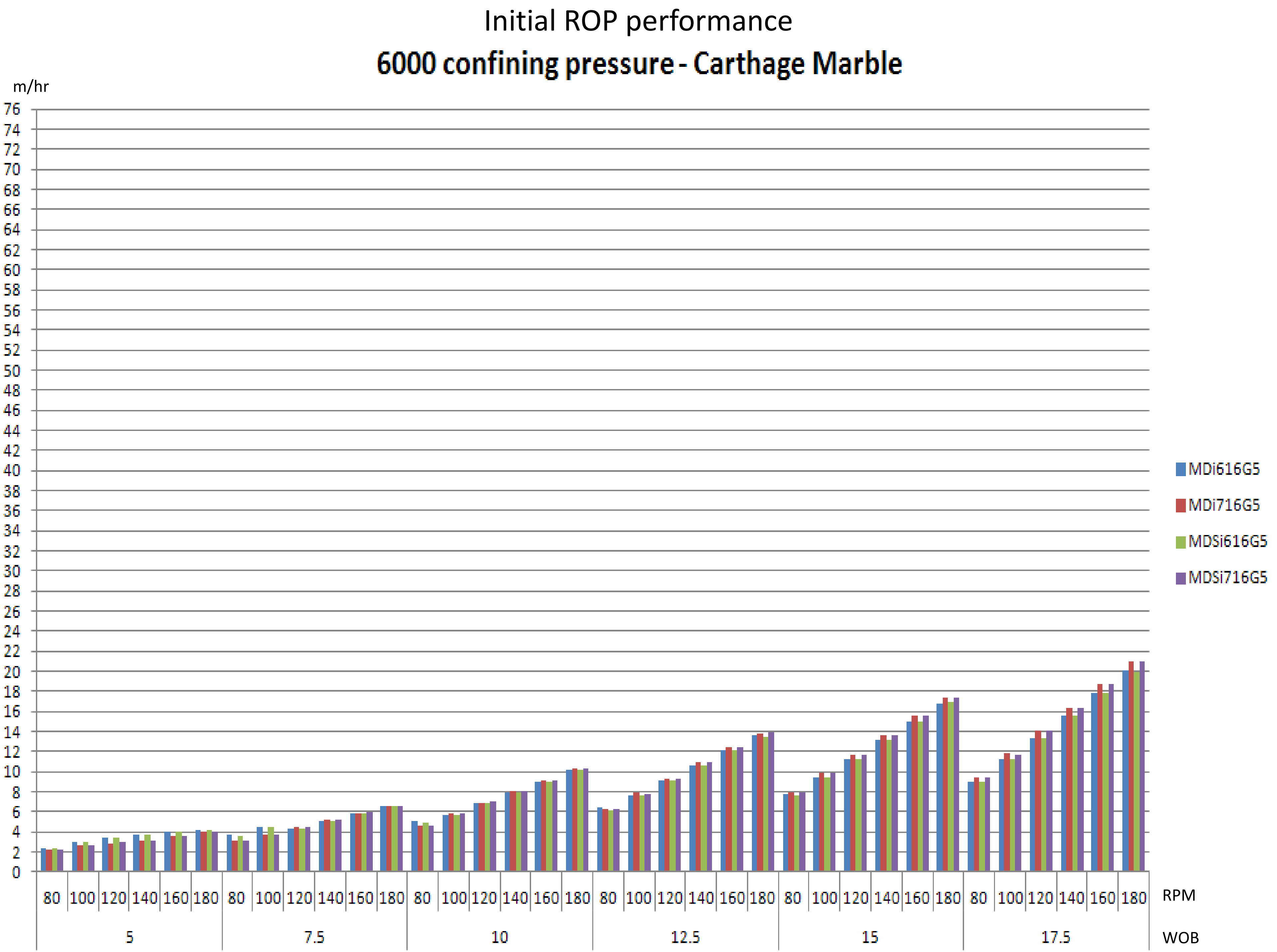
Analyse performance of MDSi 616_716 versus MDi616_716 in Colton sandstone and Carthage marble with 5” gauge.

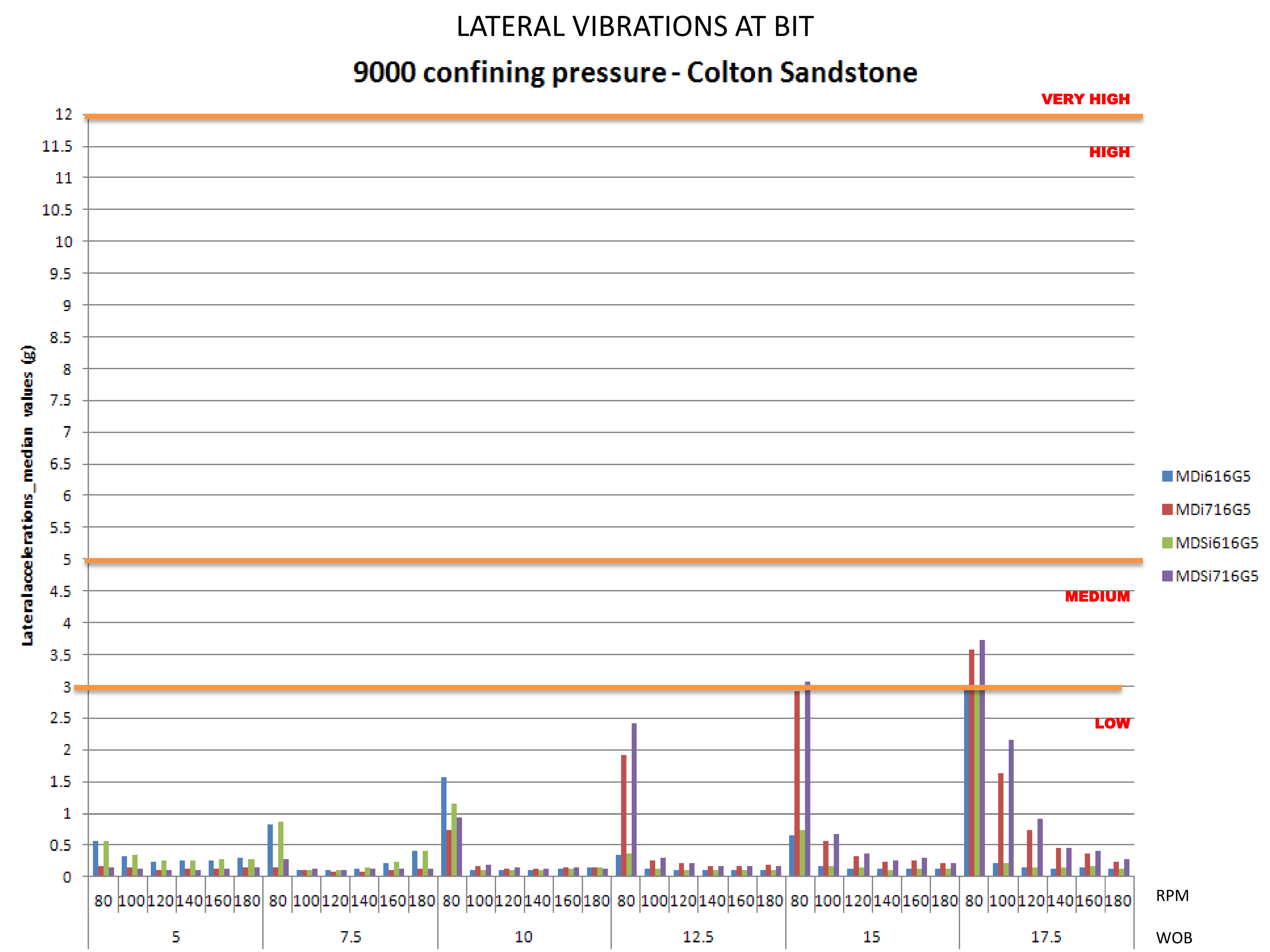


LATERAL VIBRATIONS AT BIT
6000 confining pressure - Carthage Marble
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5

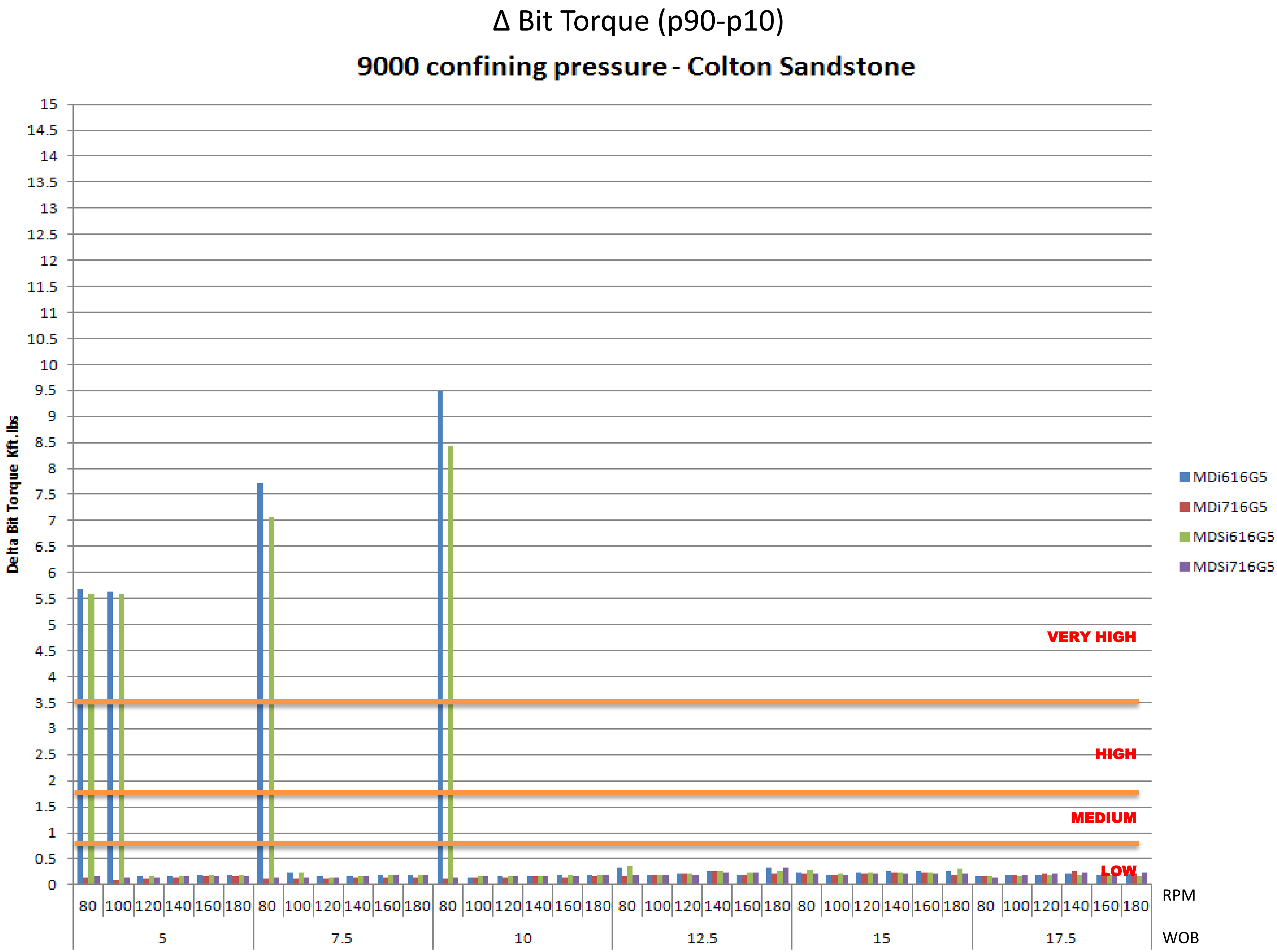


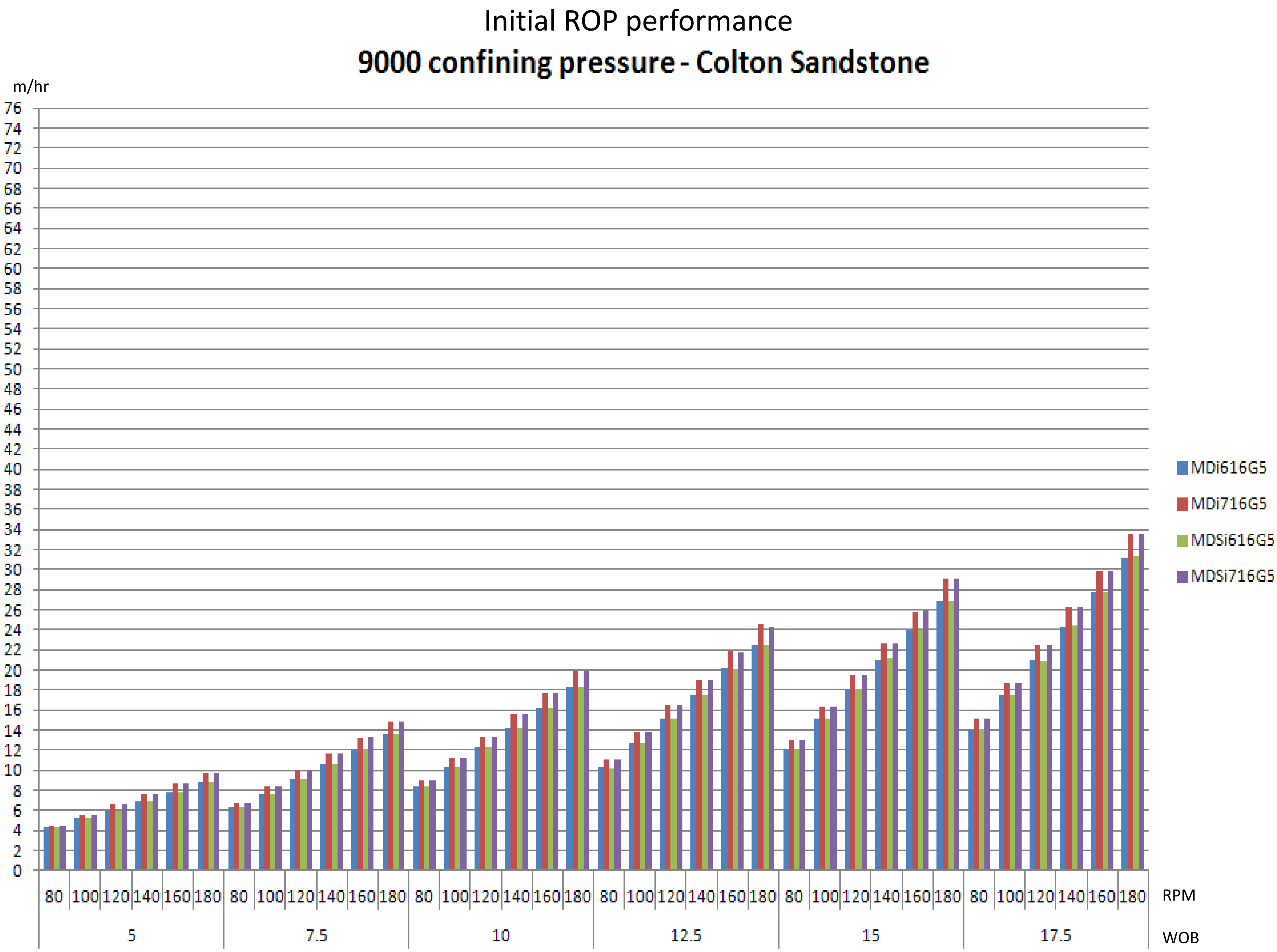
Δ Bit Torque (p90-p10)
6000 confining pressure - Carthage Marble
Delta Bit Torque Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5
80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB


Initial ROP performance
6000 confining pressure - Carthage Marble
m/hr
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5
RPM
WOB
80 100 120 140 160 180
5 7.5 10 12.5 15 17.5



LATERAL VIBRATIONS AT BIT
9000 confining pressure - Colton Sandstone
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5


Δ Bit Torque (p90-p10)
9000 confining pressure - Colton Sandstone
Delta Bit Torque Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB



Initial ROP performance
9000 confining pressure - Colton Sandstone
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB
MDi616G5
MDi716G5
MDSi616G5
MDSi716G5

# APPENDIX 9

# IMPLEMENTED WELL LOGS (ASCII INTO EXCEL)

# ONLY PRESENT DIGITALLY

Note to UiS;
the welldata can not be published under any means before the confidentiality agreement of the thesis is over (5 years). After this, the welldata are considered as official. For questions; contact Odd Vinsevik. The welldata is only present on CD.

Wellbores:

31/2-G1-BY1HT2,
31/2-G1-BY2H,
31/2-K12-BY1H,
31/2-M14-BY3H,
31/2-N13-AY2H,
31/2-O21-Y1H,
31/2-O21-Y1H,
31/2-O23-Y1H,
31/5-I21-BY1H

# APPENDIX 10
# STUDY 1

COLTON SANDSTONE
CARTHAGE MARBLE
TANDERAGEE
GLENARM

# IDEAS PROJECT RESULTS

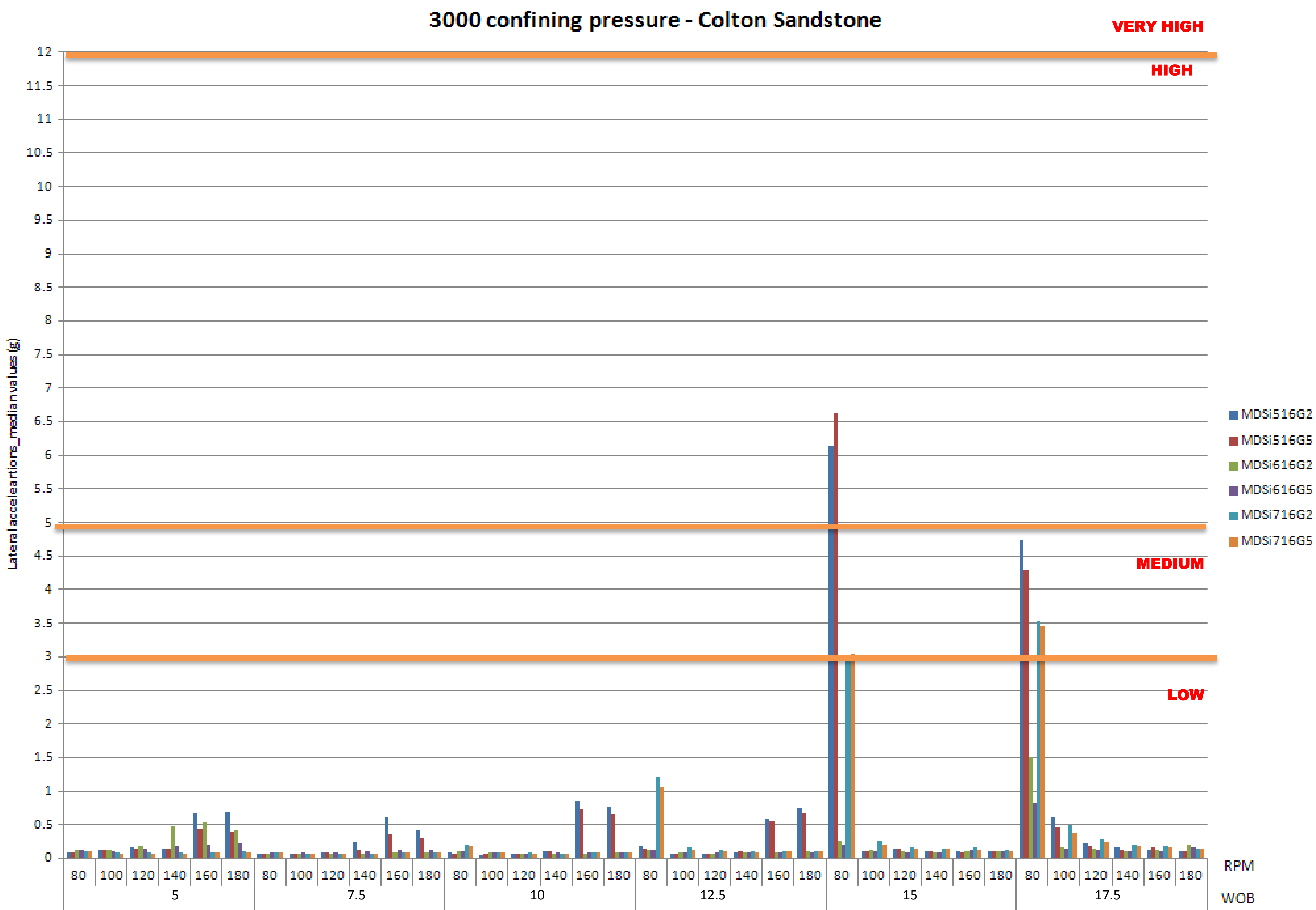
OPERATOR: Statoil
WELL NAME: NO 31/5-J-13 AY3H
ORIGINATOR: Odd Vinsevik
DATE: 2012-3-1

## PROJECT DESCRIPTION:

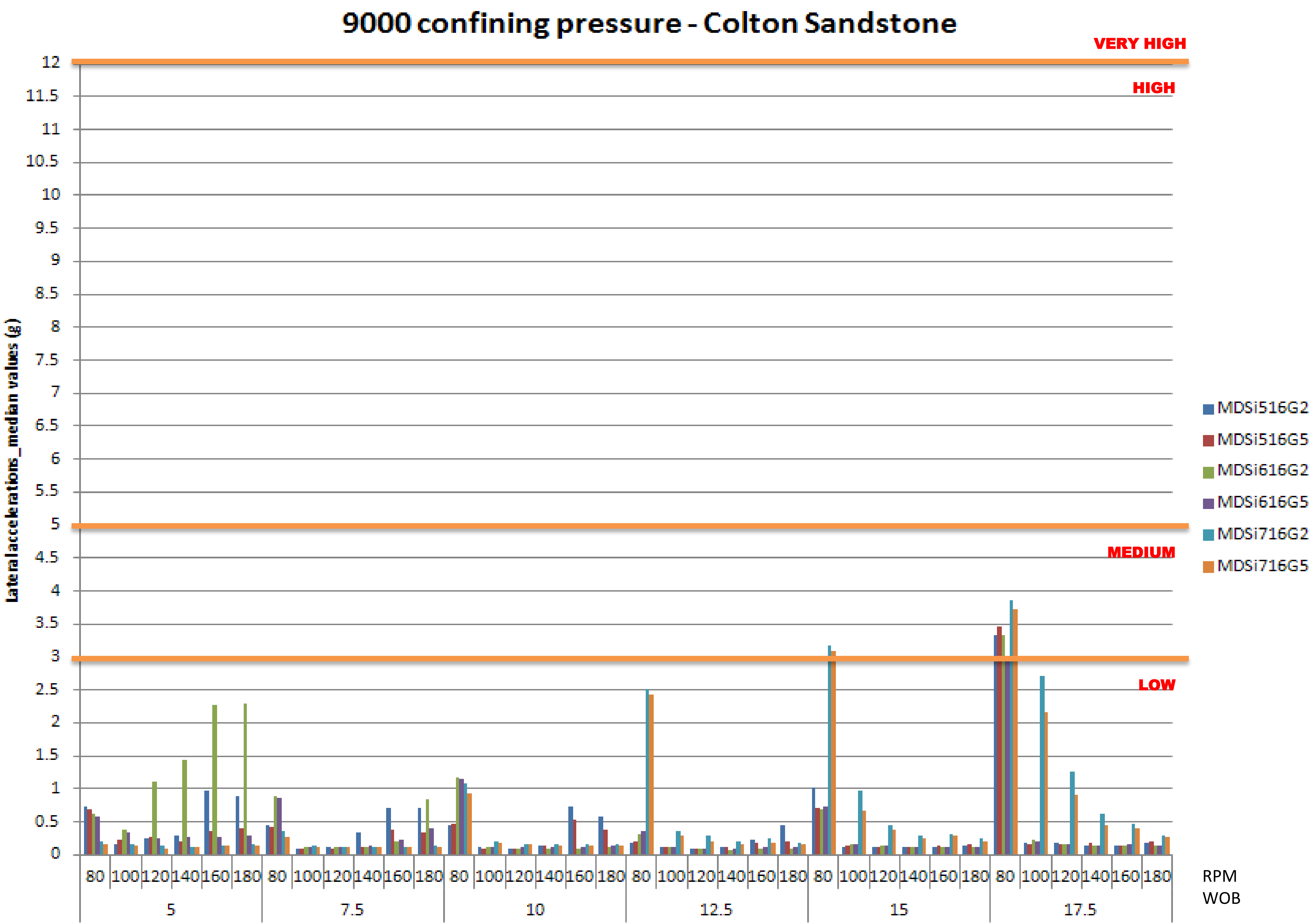
Analyse performance of MDSi 516_616_716 in colton sandstone at 3 and 6ksi confining pressure, with short and long gauge (2” vs 5”).

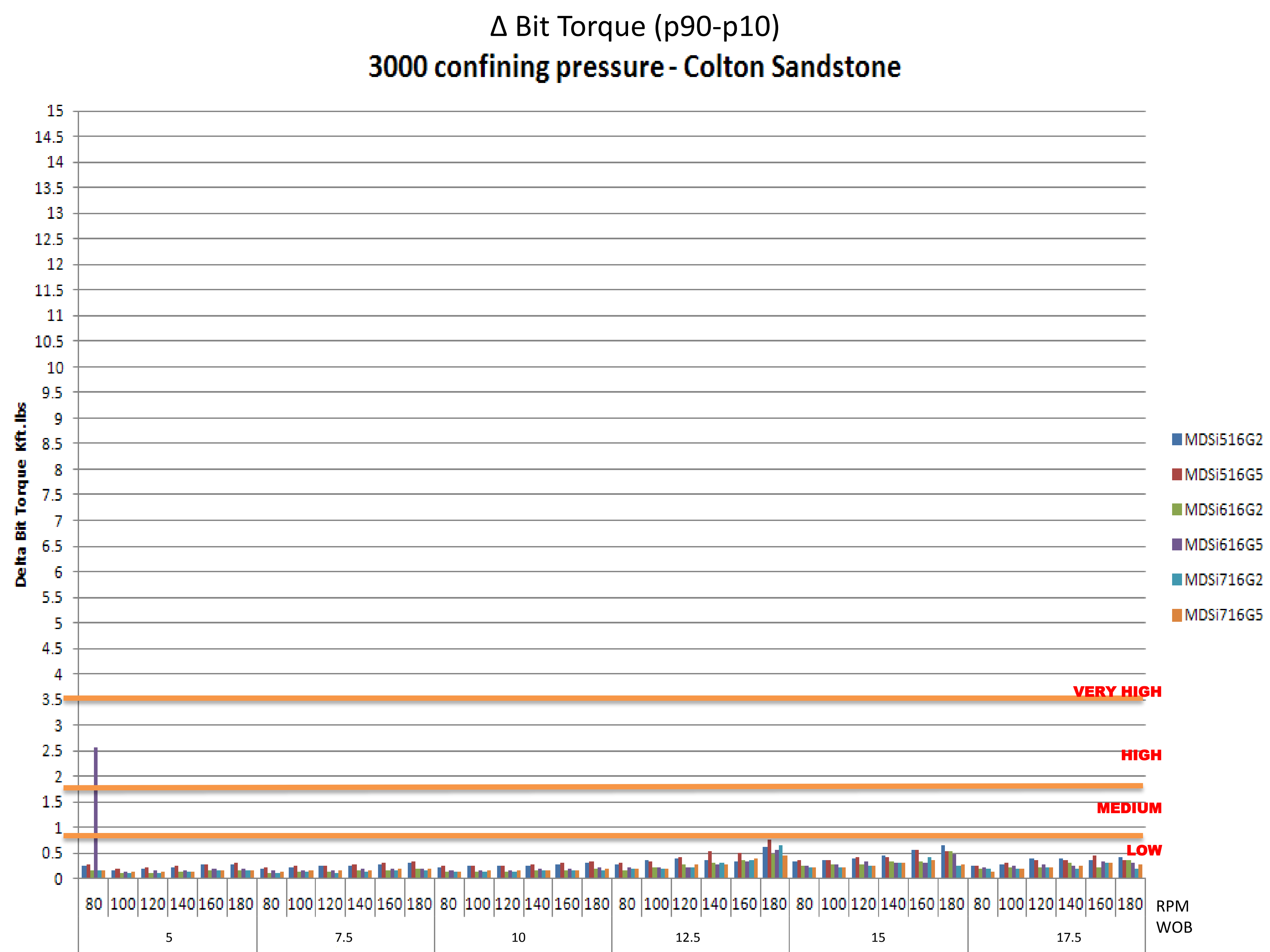
SMITH BITS
A Schlumberger Company

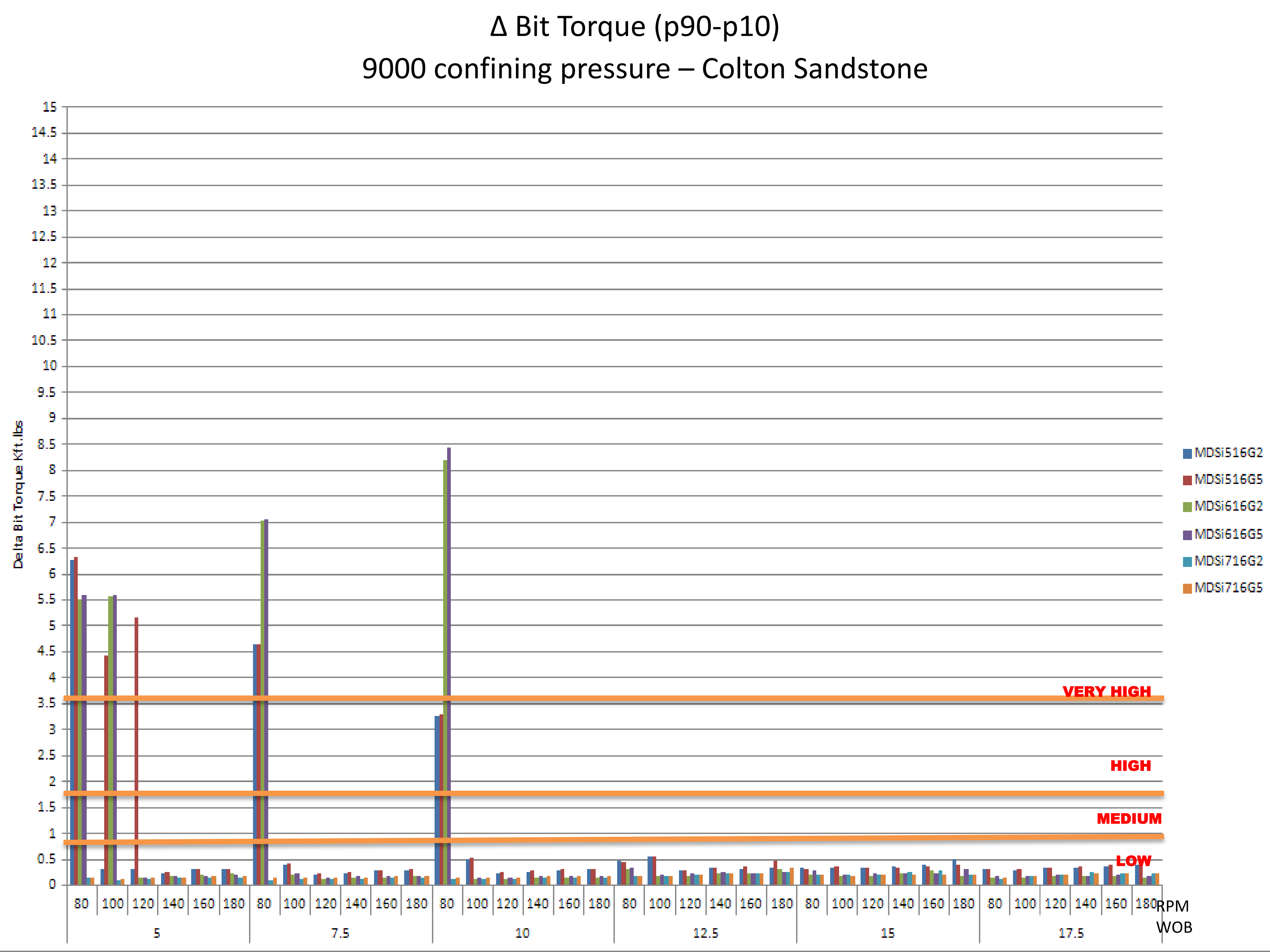
# LATERAL VIBRATIONS AT BIT



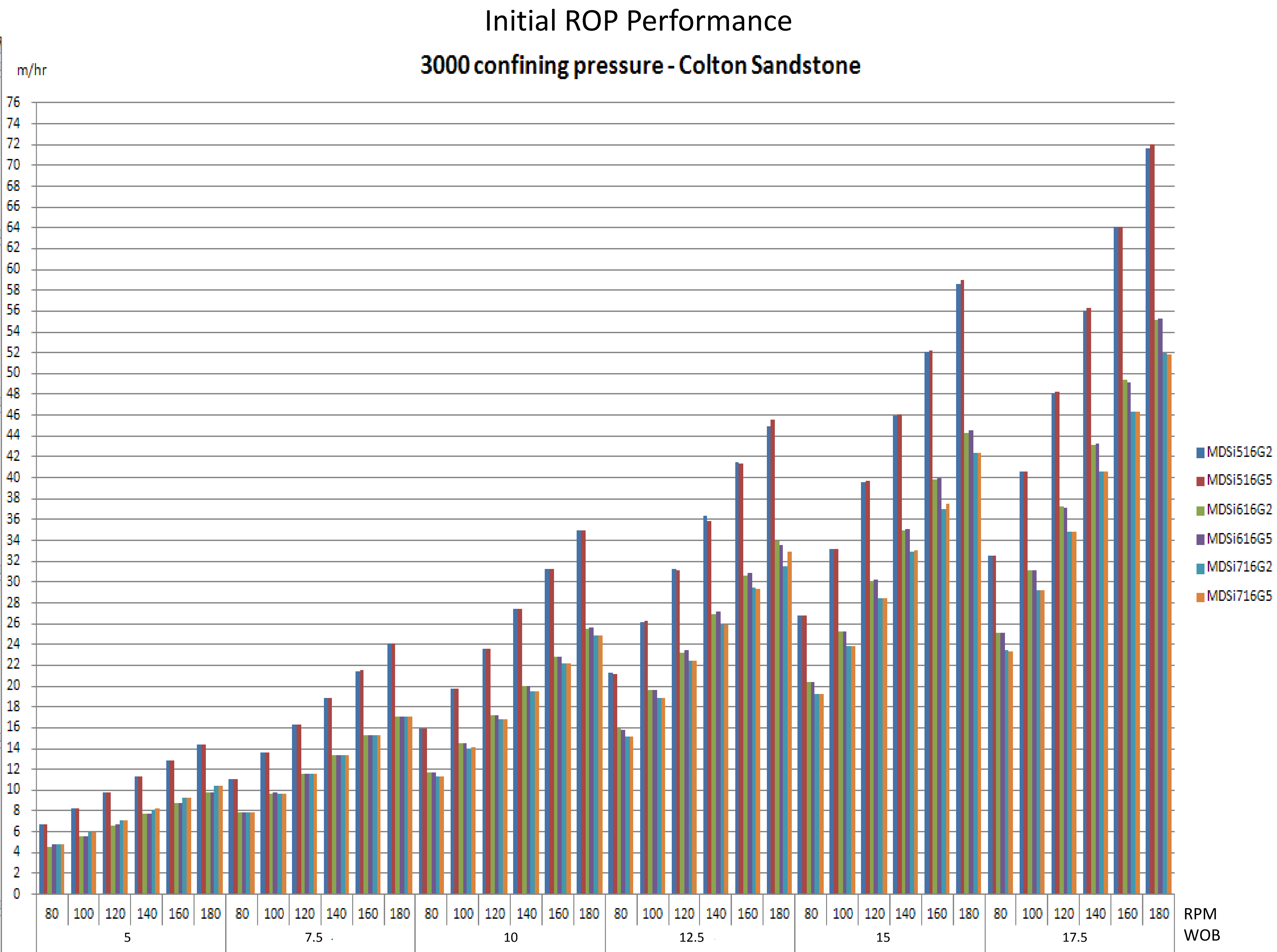
# LATERAL VIBRATIONS AT BIT

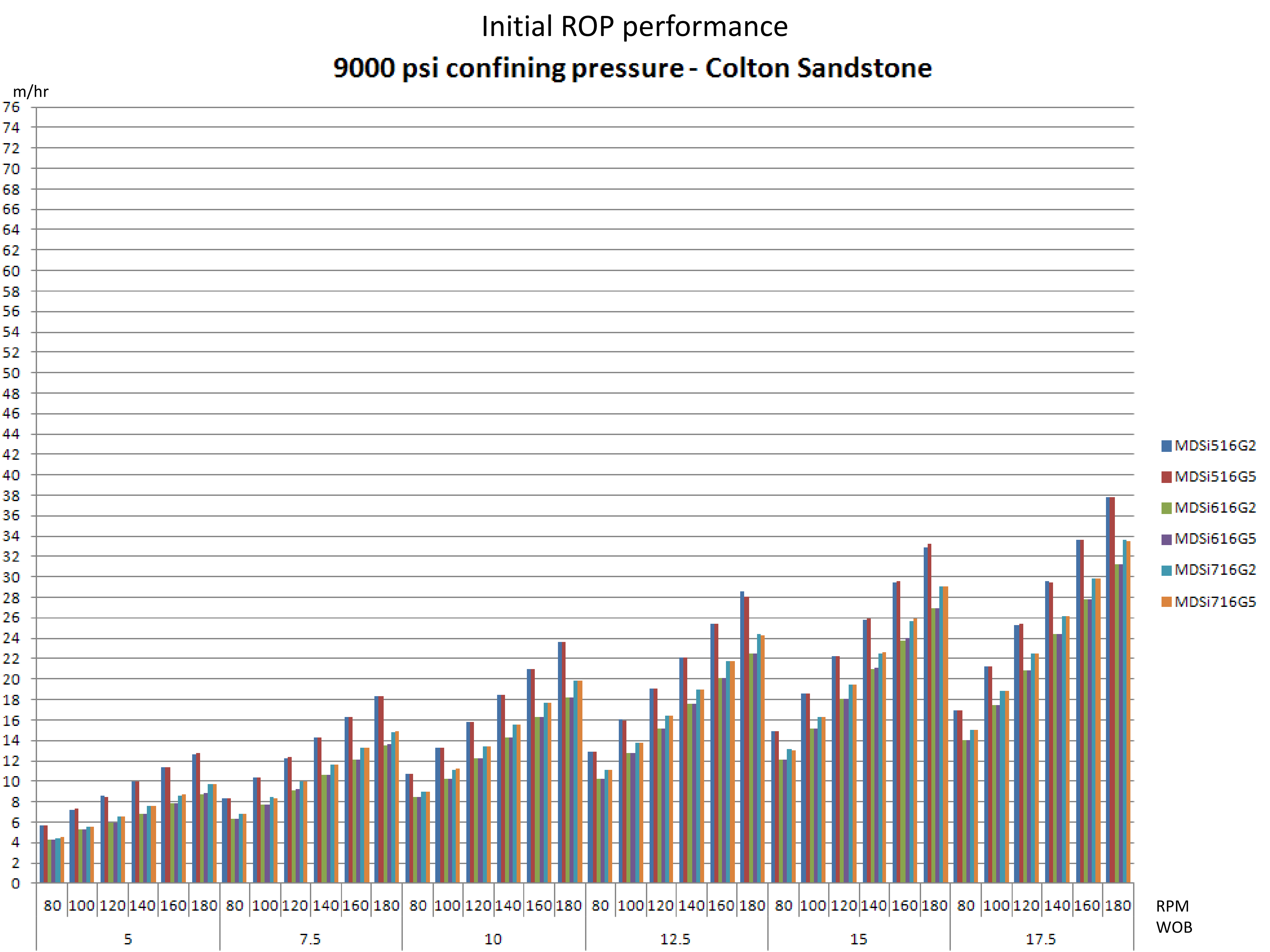



Δ Bit Torque (p90-p10)
3000 confining pressure - Colton Sandstone
Delta Bit Torque Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
5 7.5 10 12.5 15 17.5
RPM
WOB



Δ Bit Torque (p90-p10)
9000 confining pressure – Colton Sandstone
Delta Bit Torque Kft.lbs
VERY HIGH
HIGH
MEDIUM
LOW
RPM
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5


Initial ROP Performance
3000 confining pressure - Colton Sandstone
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
80 100 120 140 160 180
80 100 120 140 160 180
80 100 120 140 160 180
80 100 120 140 160 180
80 100 120 140 160 180
80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5

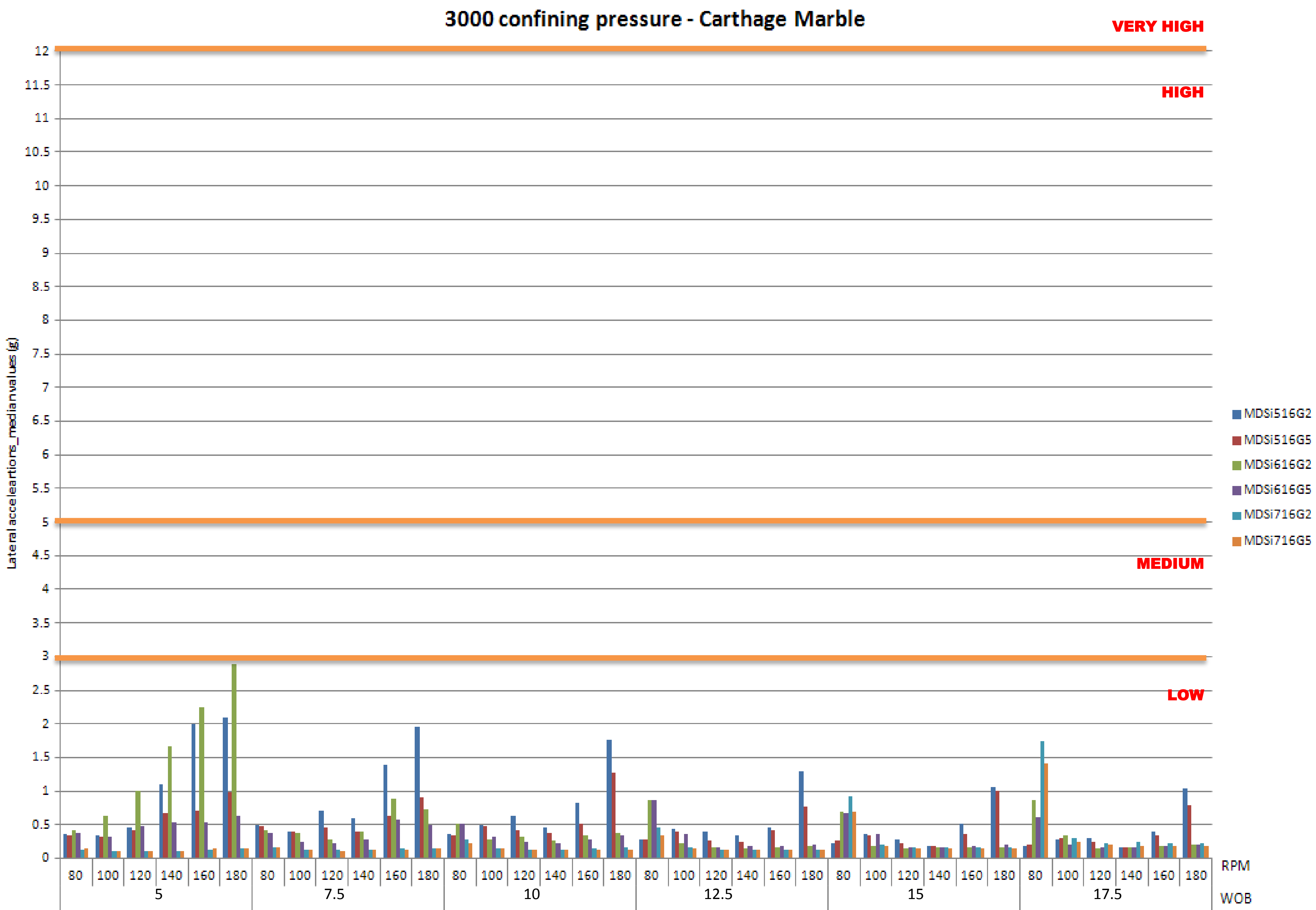

Initial ROP performance
9000 psi confining pressure - Colton Sandstone
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
WOB
5
7.5
10
12.5
15
17.5

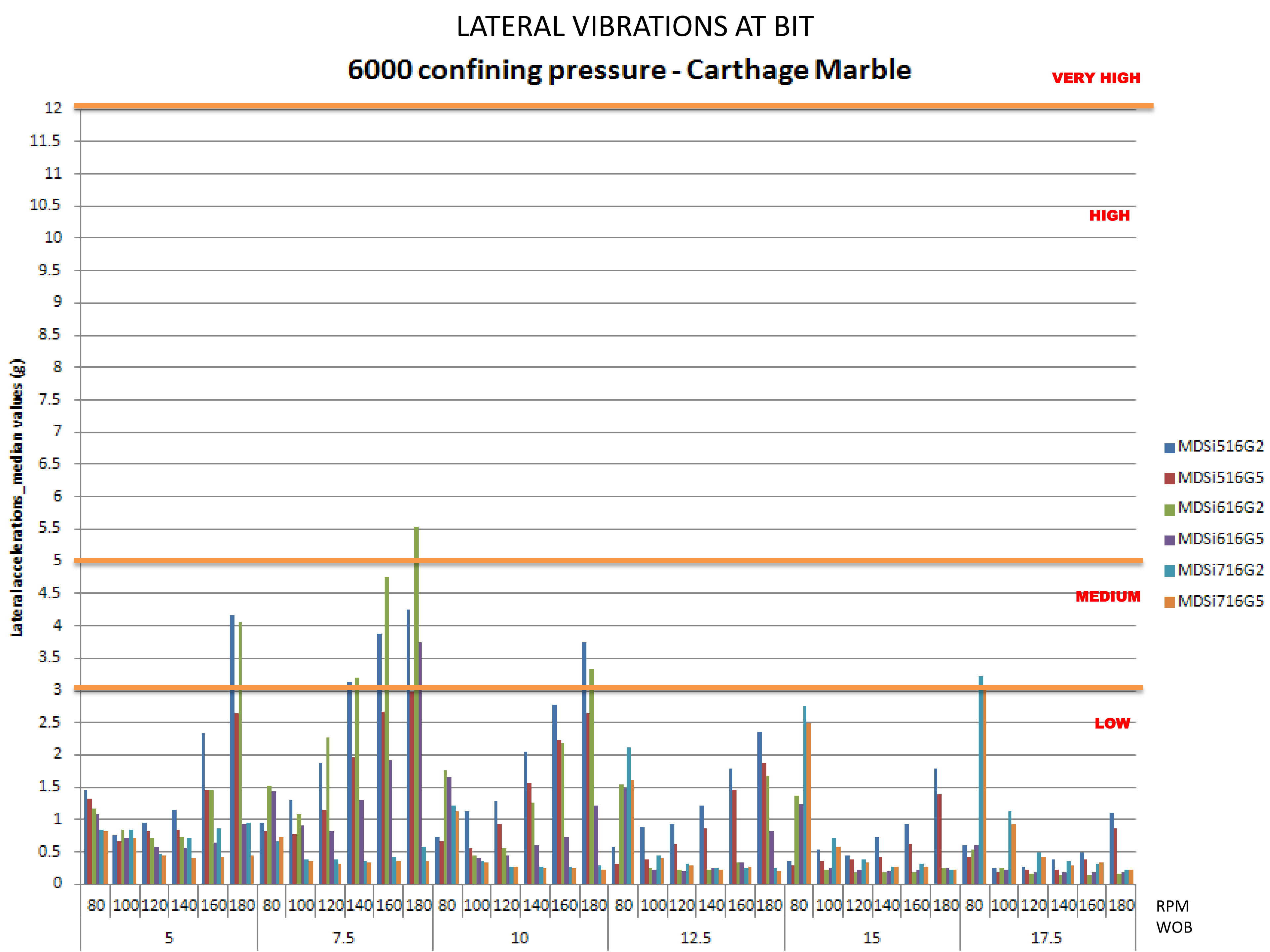
OPERATOR: Statoil
WELL NAME: NO 31/5-J-13 AY3H
ORIGINATOR: Odd Vinsevik
DATE: 2012-3-1

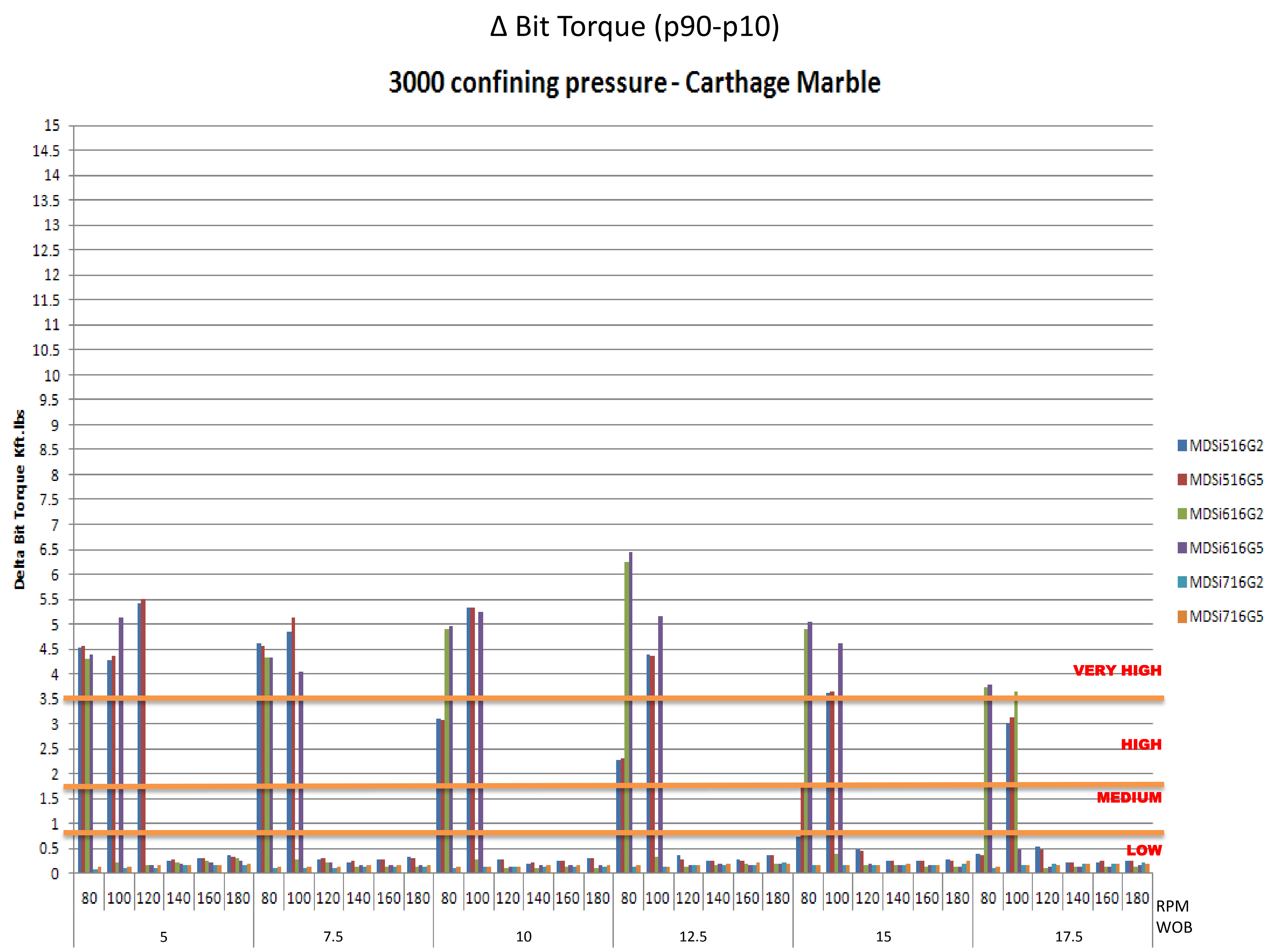
# PROJECT DESCRIPTION:

Analyse performance of MDSi 516_616_716 in Carthage marble at 3000 and 60000 psi, with short and long gauge (2” vs 5”).

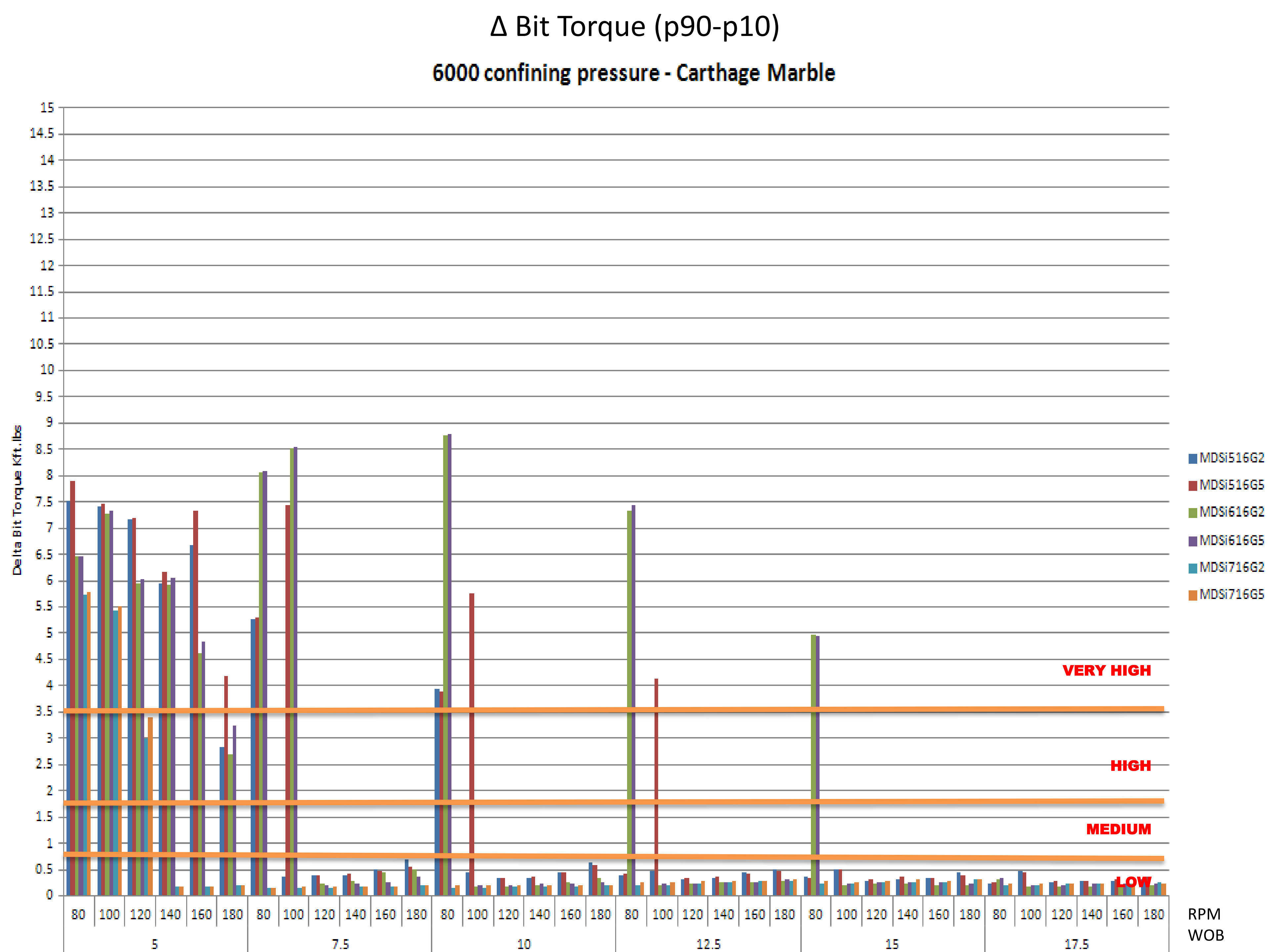
# LATERAL VIBRATIONS AT BIT

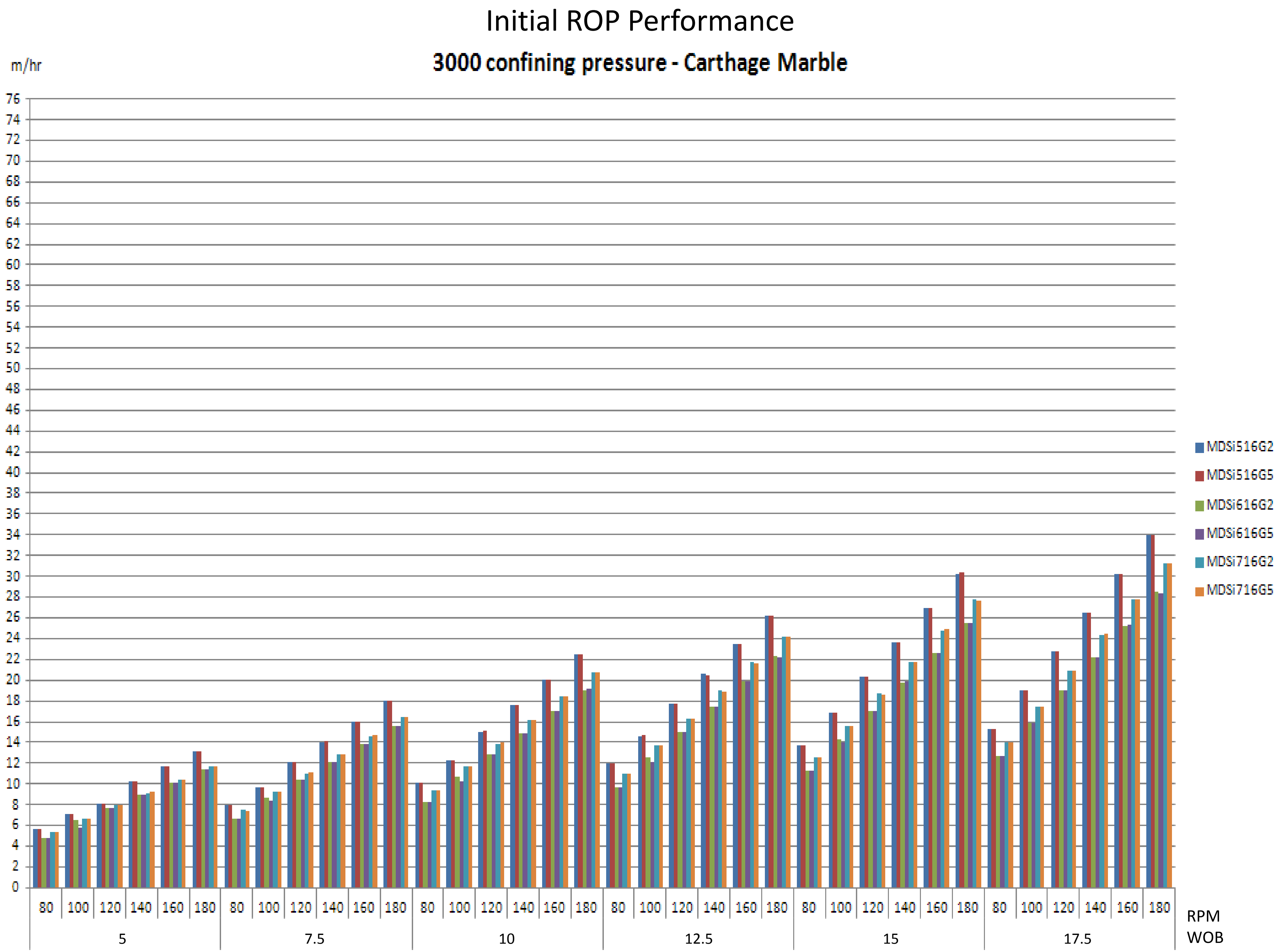



LATERAL VIBRATIONS AT BIT
6000 confining pressure - Carthage Marble
VERY HIGH
HIGH
MEDIUM
LOW
lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5



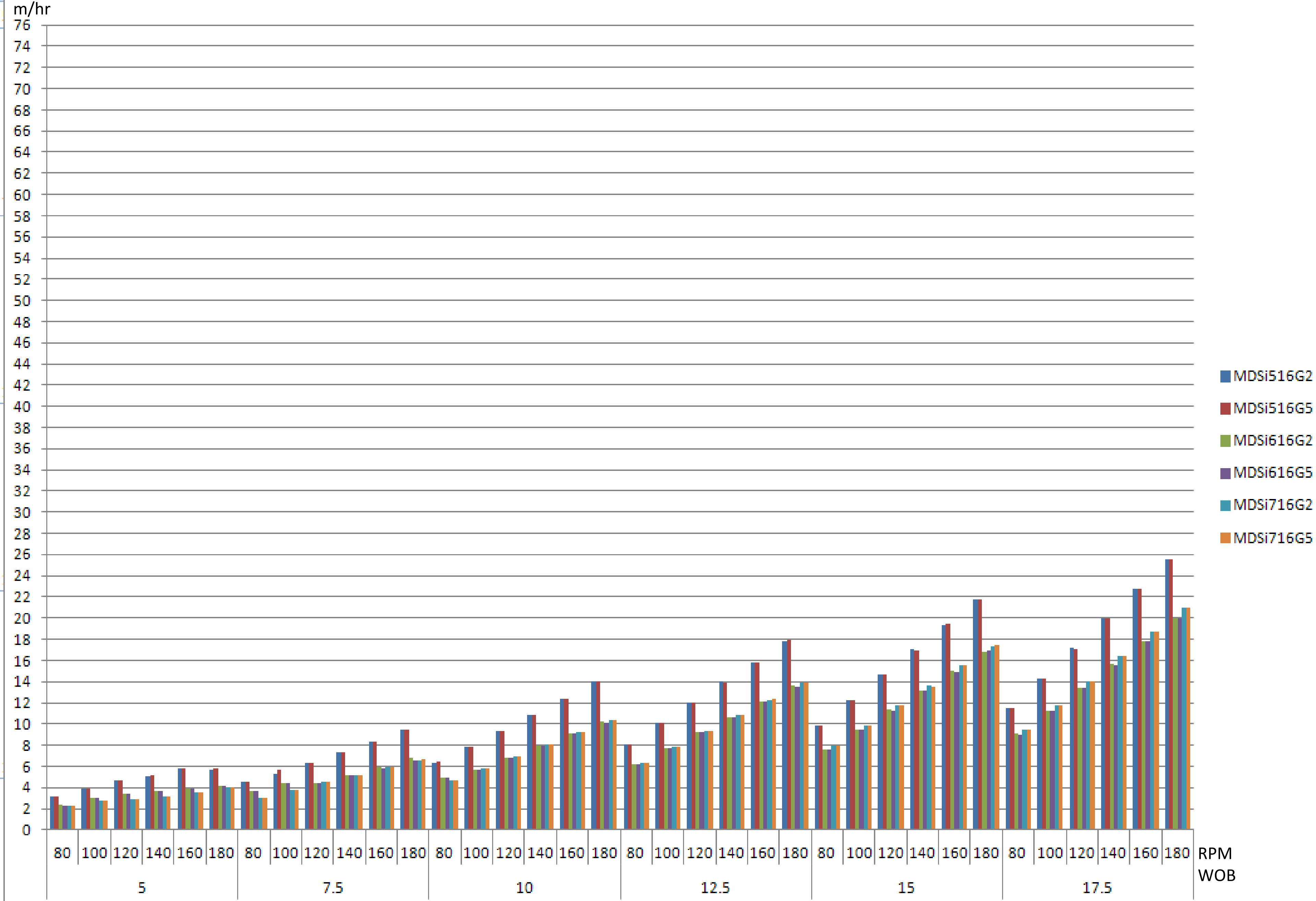
Δ Bit Torque (p90-p10)
3000 confining pressure - Carthage Marble
Delta Bit Torque Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
80
100
120
140
160
180
RPM
WOB
5
7.5
10
12.5
15
17.5
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5


Δ Bit Torque (p90-p10)
6000 confining pressure - Carthage Marble
Delta Bit Torque Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5 7.5 10 12.5 15 17.5
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5


Initial ROP Performance
3000 confining pressure - Carthage Marble
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
80
100
120
140
160
180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5

# Initial ROP performance

## 6000 psi confining pressure - Carthage Marble



| | |
|---|---|
| OPERATOR: | Statoil |
| WELL NAME: | NO 31/5-J-13 AY3H |
| ORIGINATOR: | Odd Vinsevik |
| DATE: | 2012-3-16 |

PROJECT DESCRIPTION:
Analyse performance of MDi616 vs MDi716 in Tanderagee Chalk with short and long gauge (2” vs 5”) at 3000psi and 6000psi

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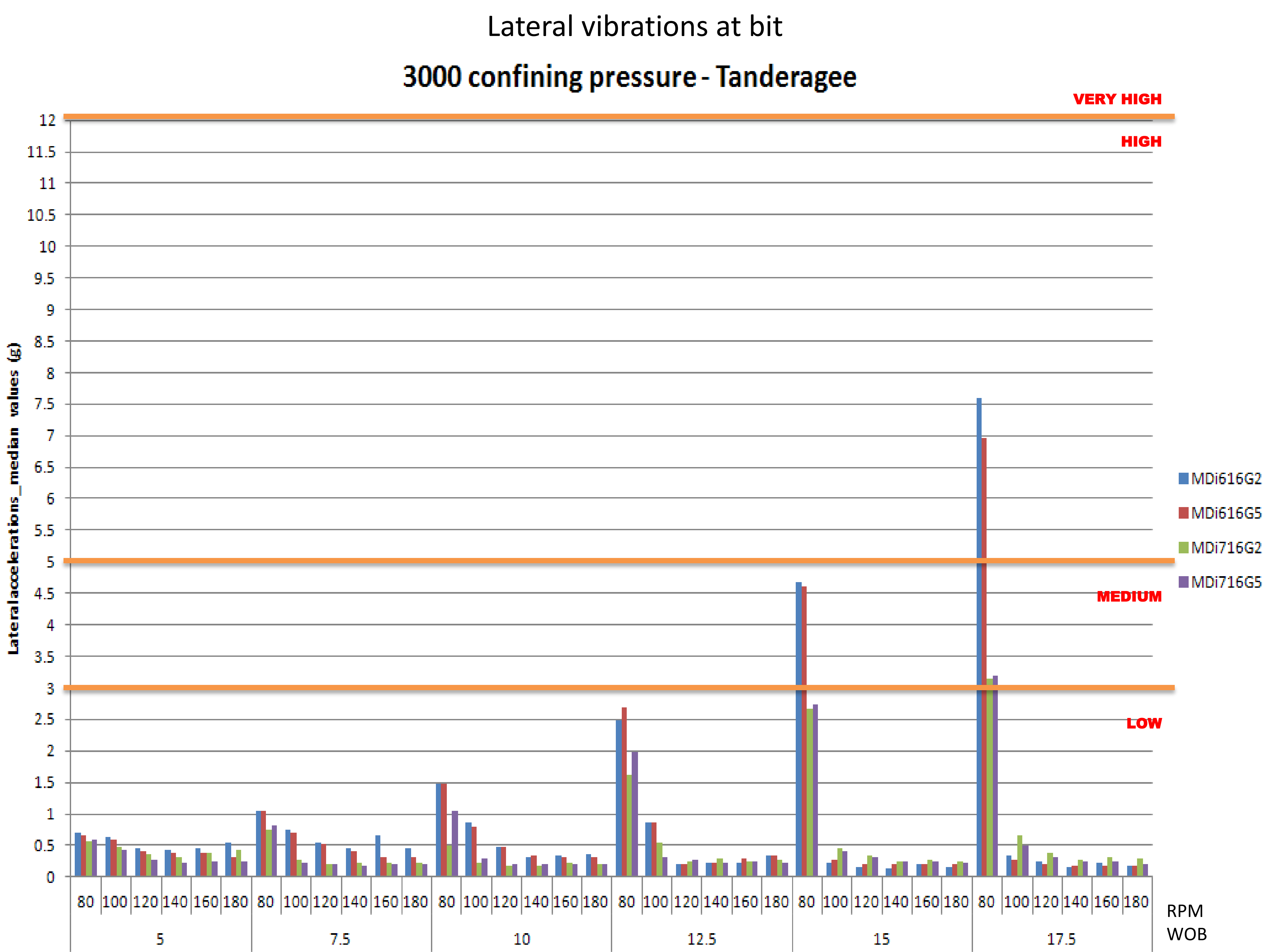
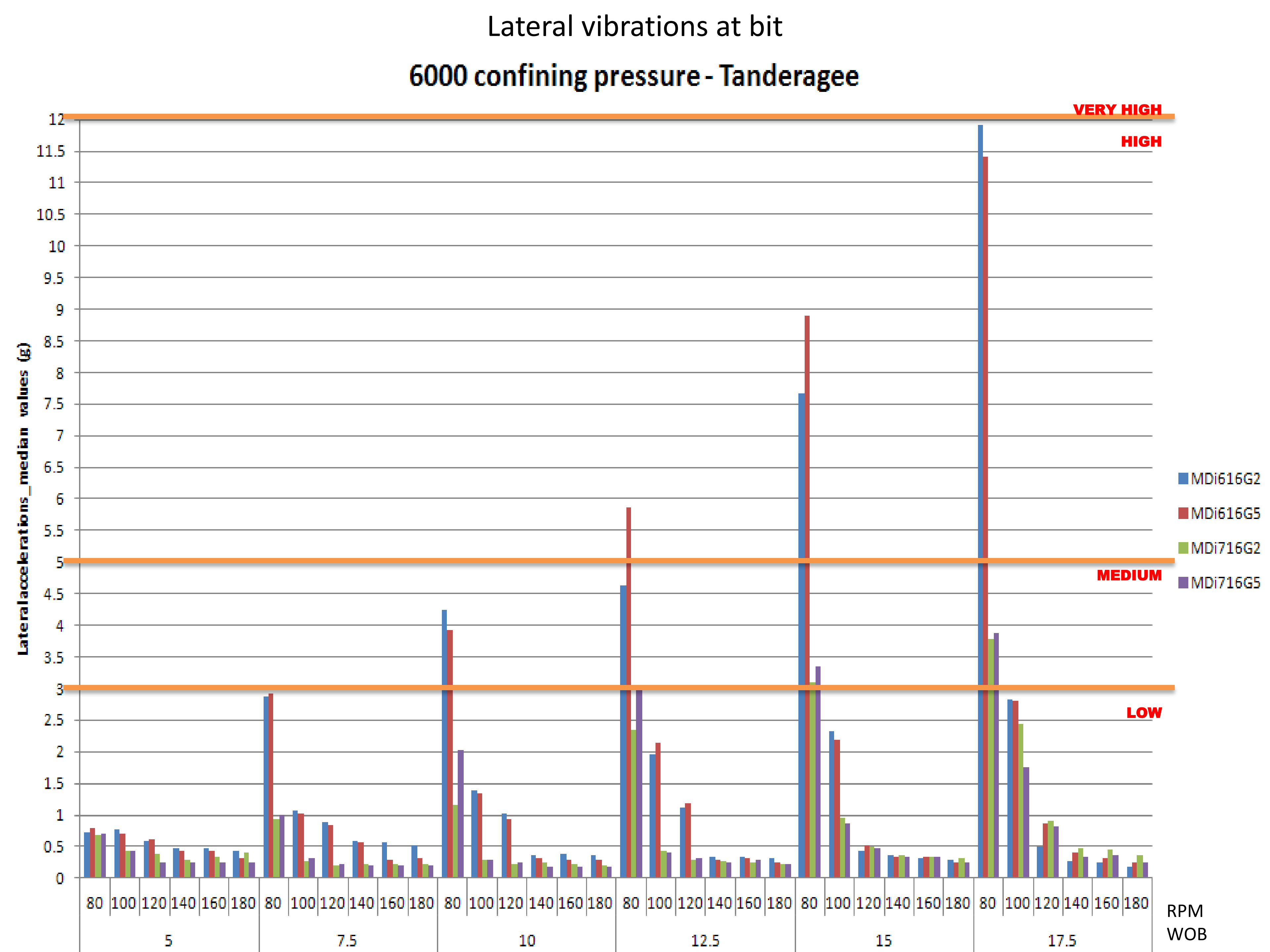
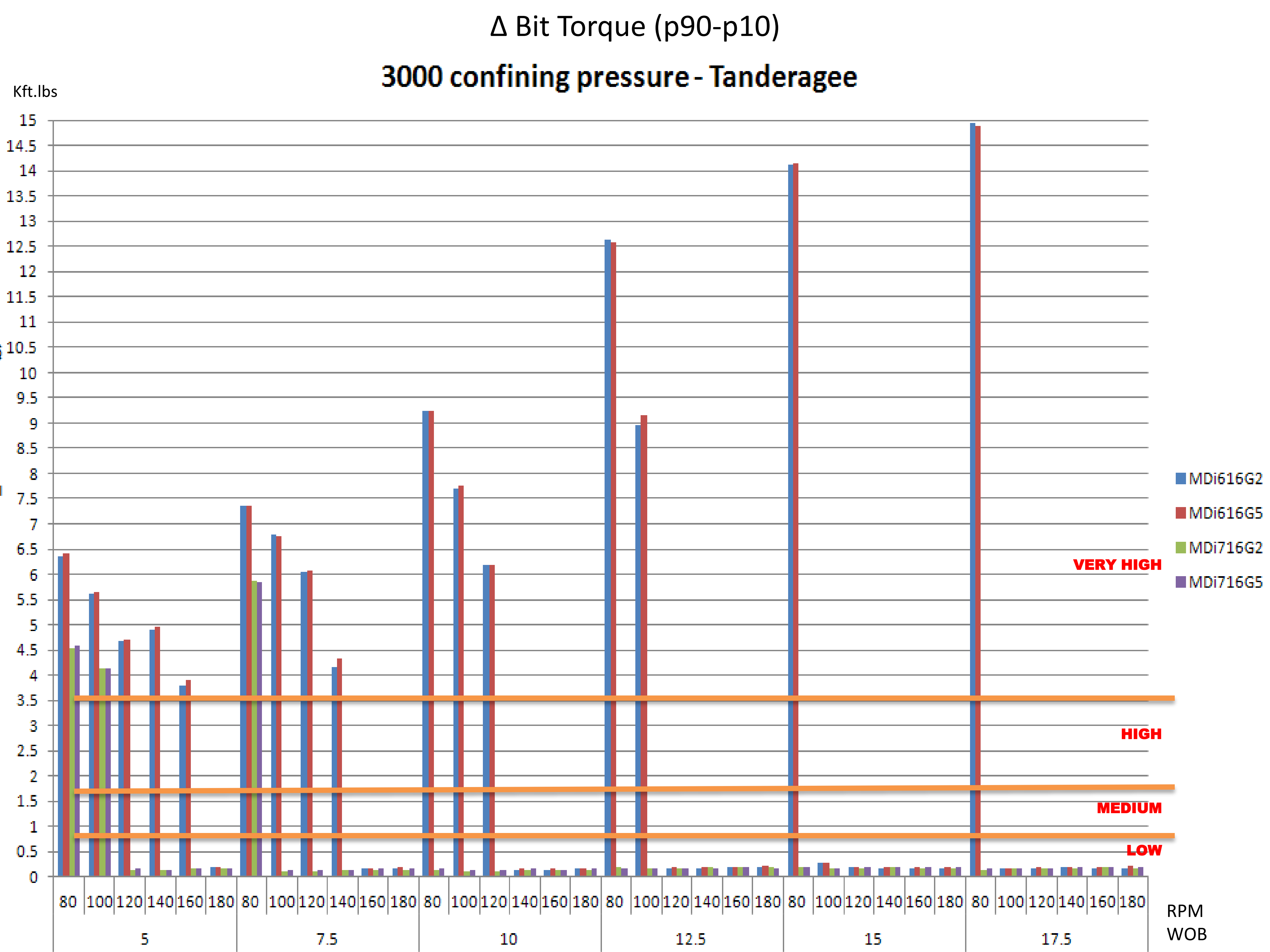


Lateral vibrations at bit
3000 confining pressure - Tanderagee
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB



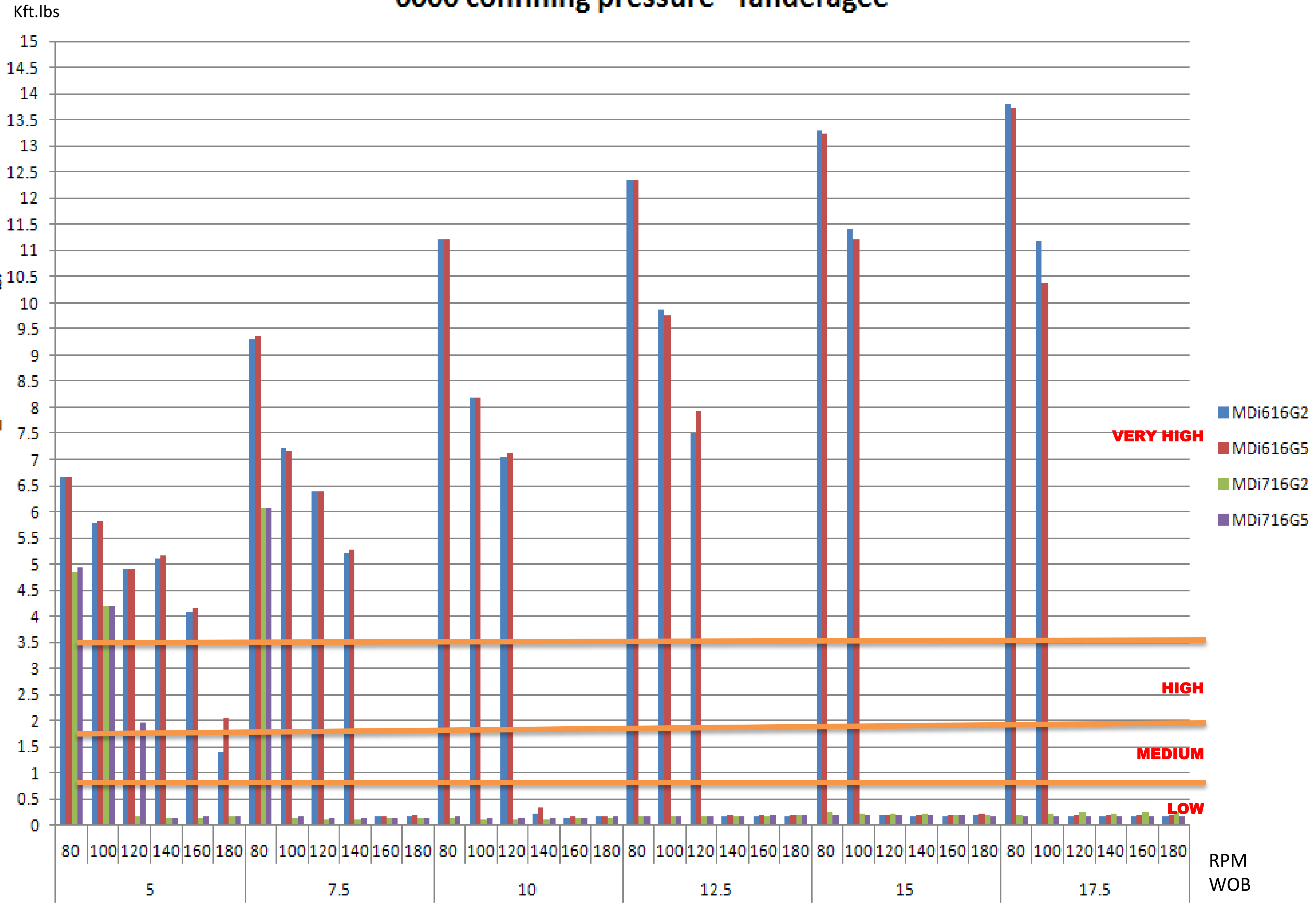
Lateral vibrations at bit
6000 confining pressure - Tanderagee
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

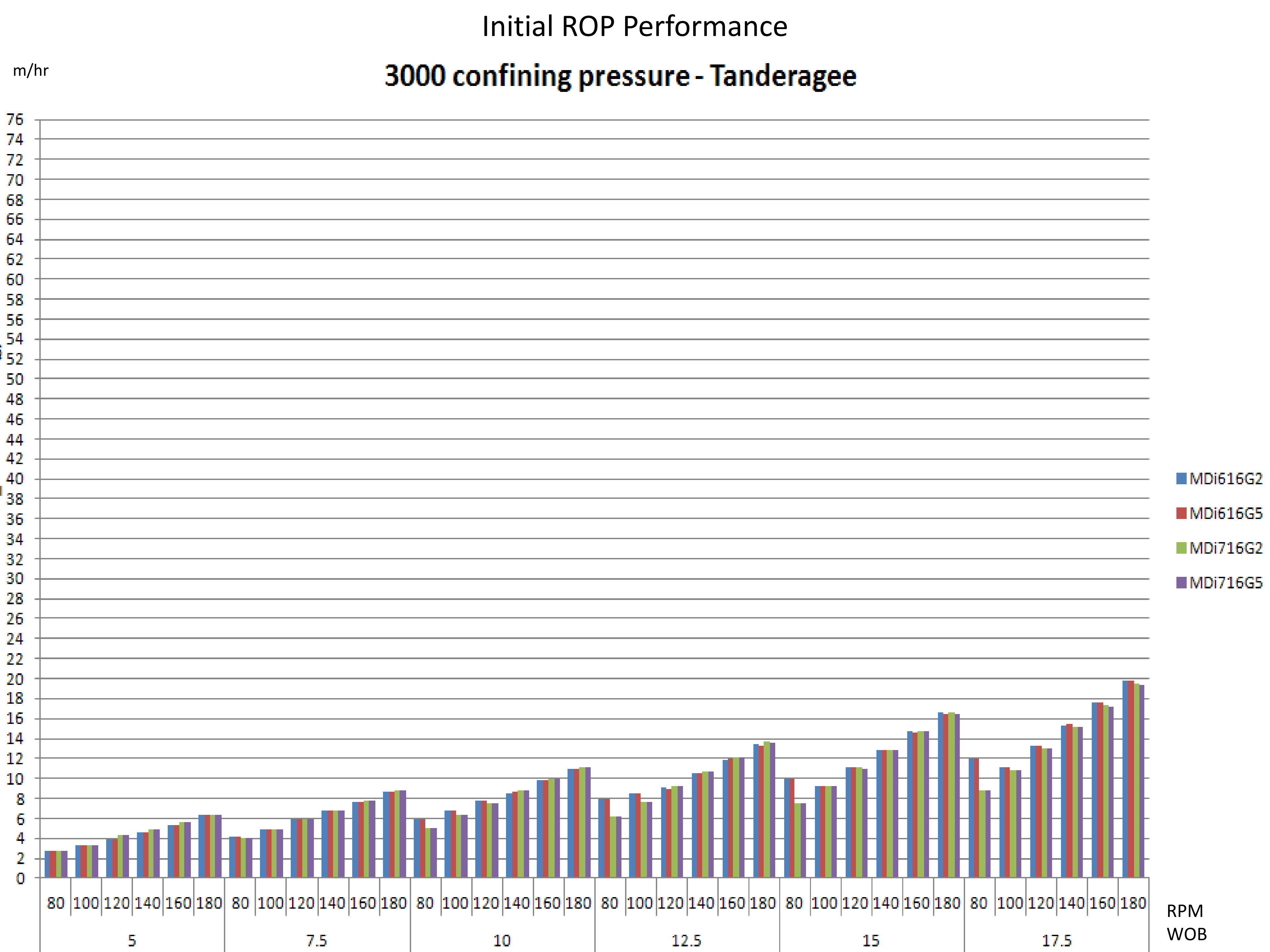


Δ Bit Torque (p90-p10)
3000 confining pressure - Tanderagee
Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

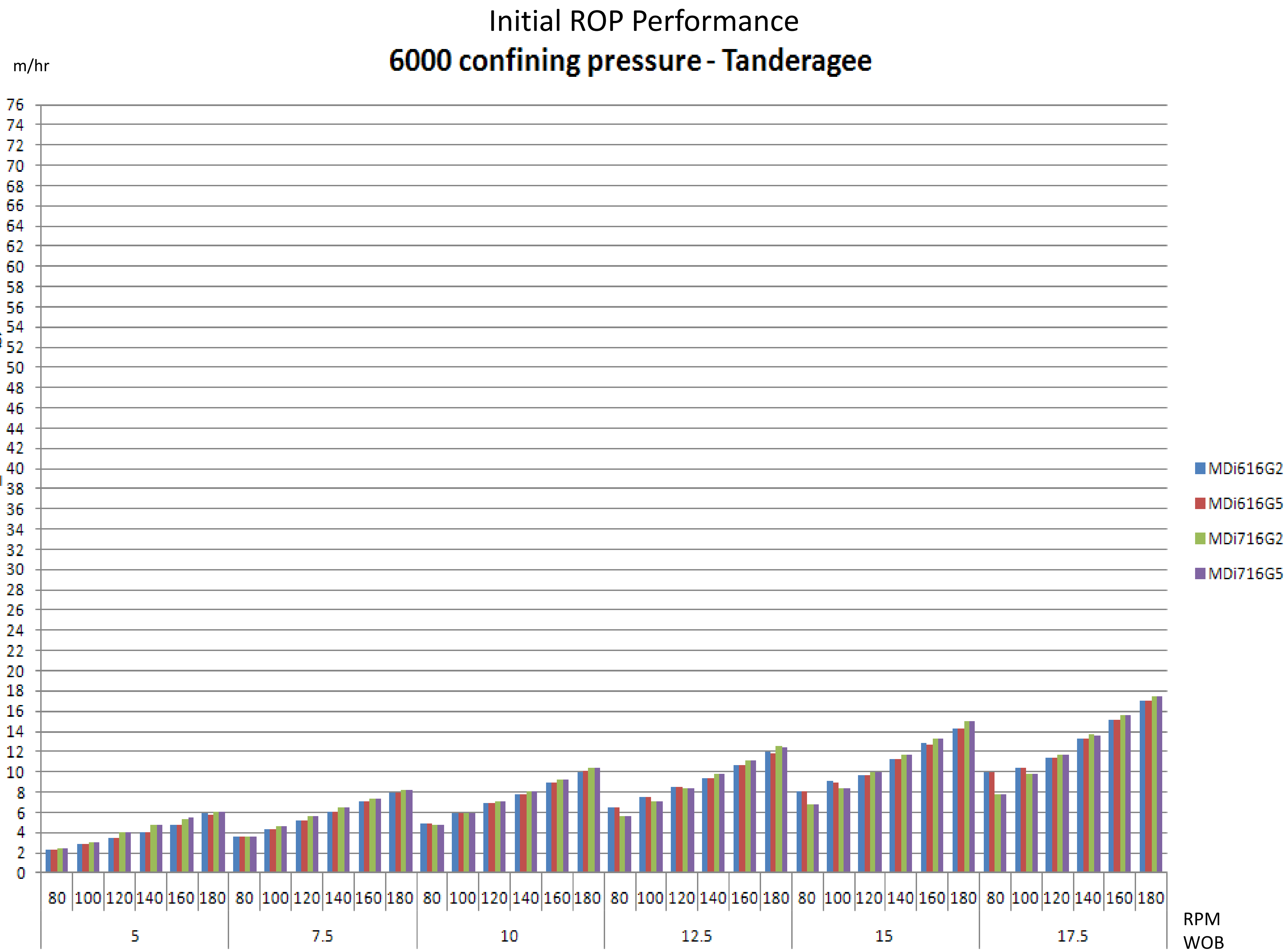
# Δ Bit Torque (p90-p10)

## 6000 confining pressure - Tanderagee





Initial ROP Performance
m/hr
3000 confining pressure - Tanderagee
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
80
100
120
140
160
180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDi616G2
MDi616G5
MDi716G2
MDi716G5

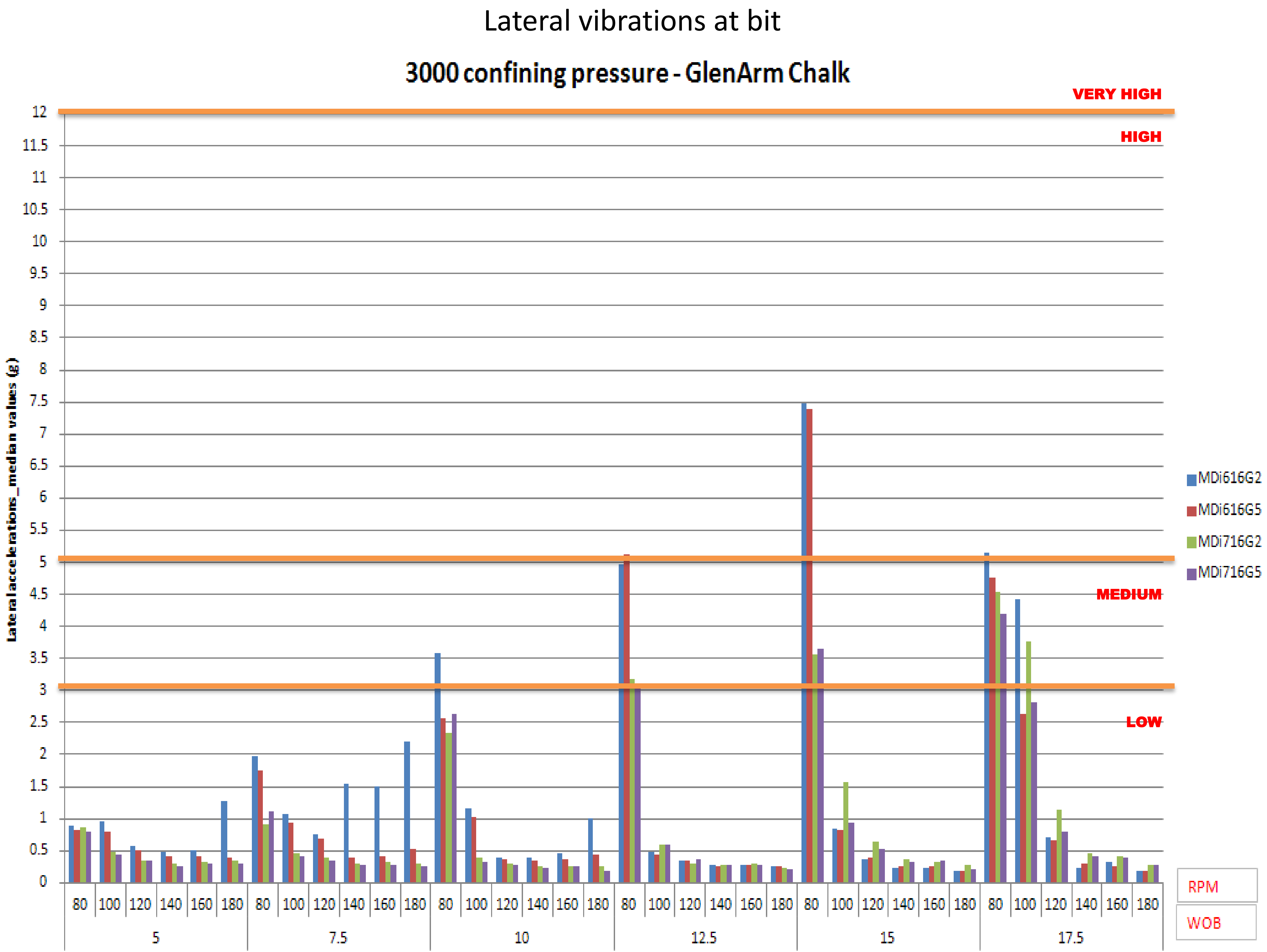

Initial ROP Performance
6000 confining pressure - Tanderagee
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

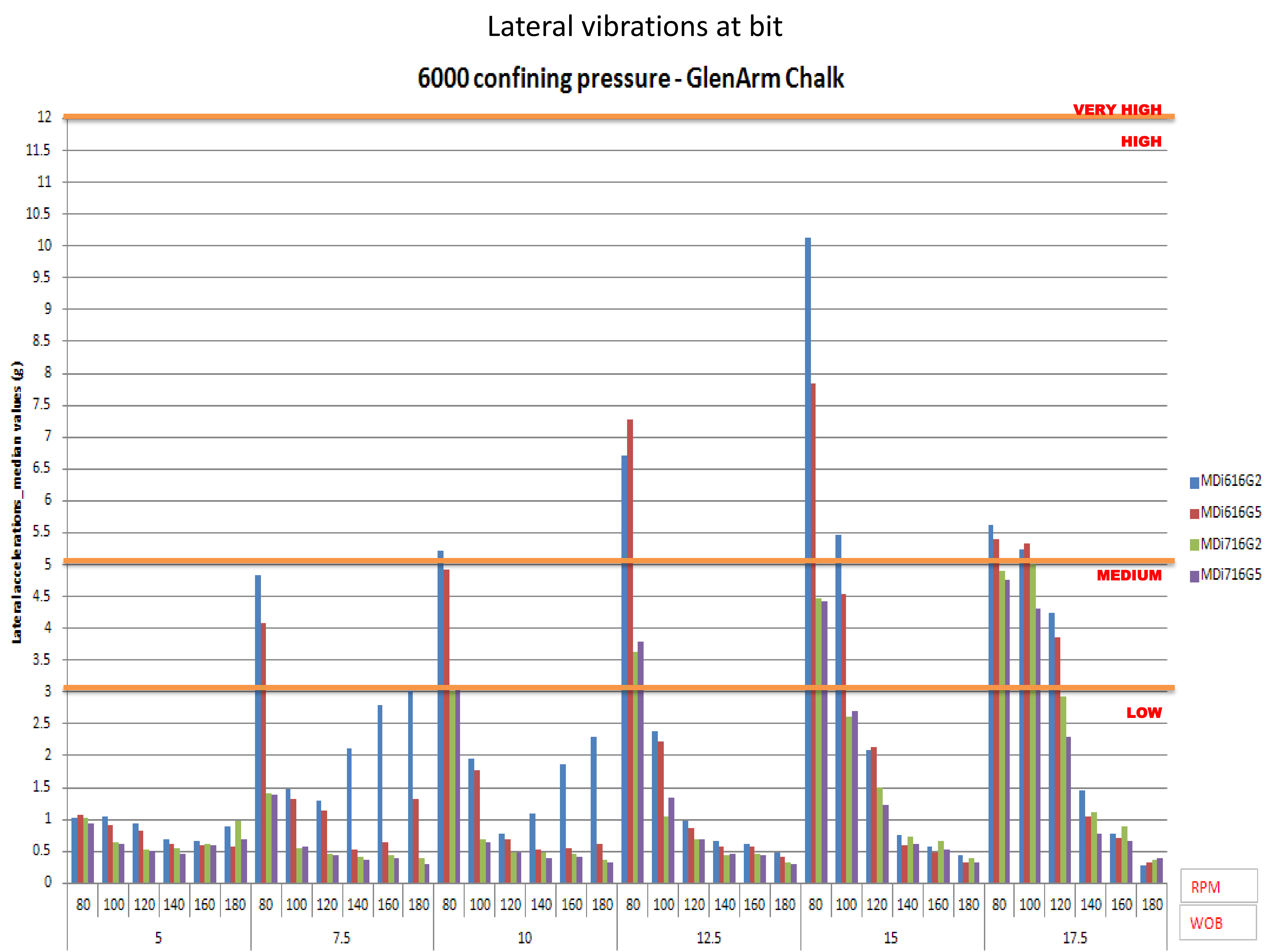
# IDEAS PROJECT RESULTS

OPERATOR: Statoil
WELL NAME: NO 31/5-J-13 AY3H
ORIGINATOR: Odd Vinsevik
DATE: 2012-3-16

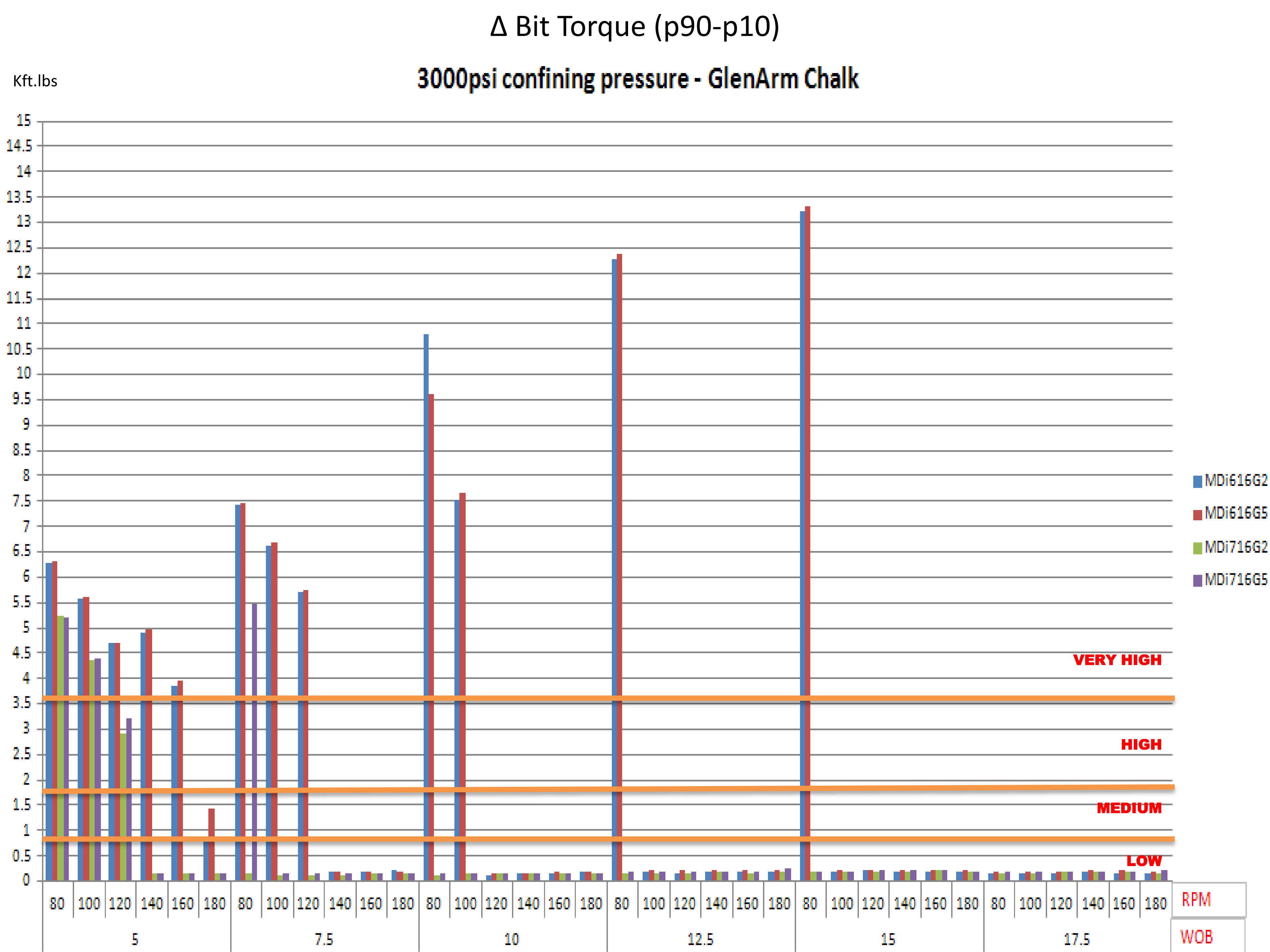
PROJECT DESCRIPTION:
Analyse performance of MDi616 vs MDi716 in GlenArm Chalk with short and long gauge (2” vs 5”) at 3000psi and 6000psi

SMITH BITS
A Schlumberger Company

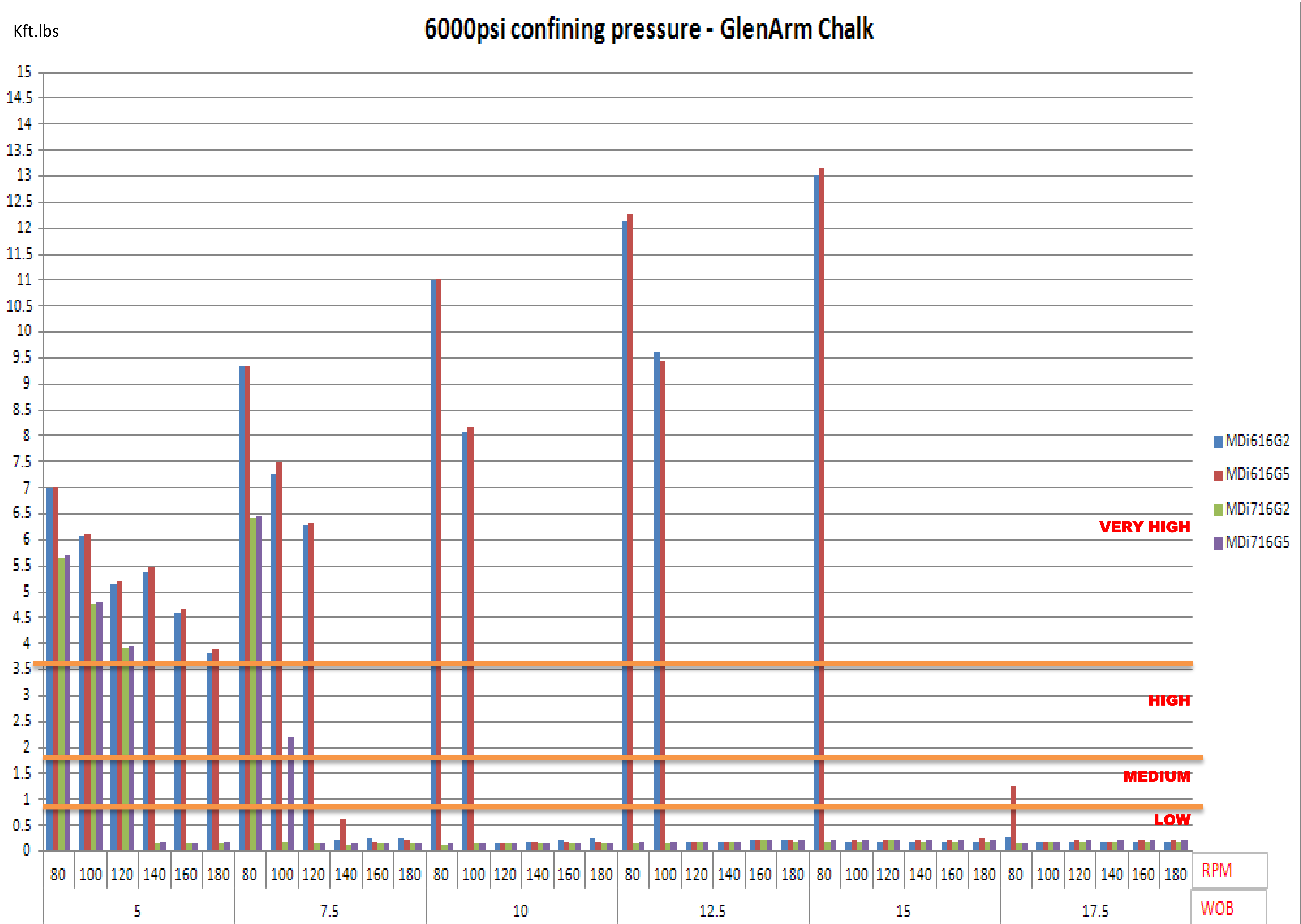

Lateral vibrations at bit
3000 confining pressure - GlenArm Chalk
VERY HIGH
HIGH
MEDIUM
LOW
lateral accelerations_median values (g)
MDi616G2
MDi616G5
MDi716G2
MDi716G5
RPM
WOB
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5



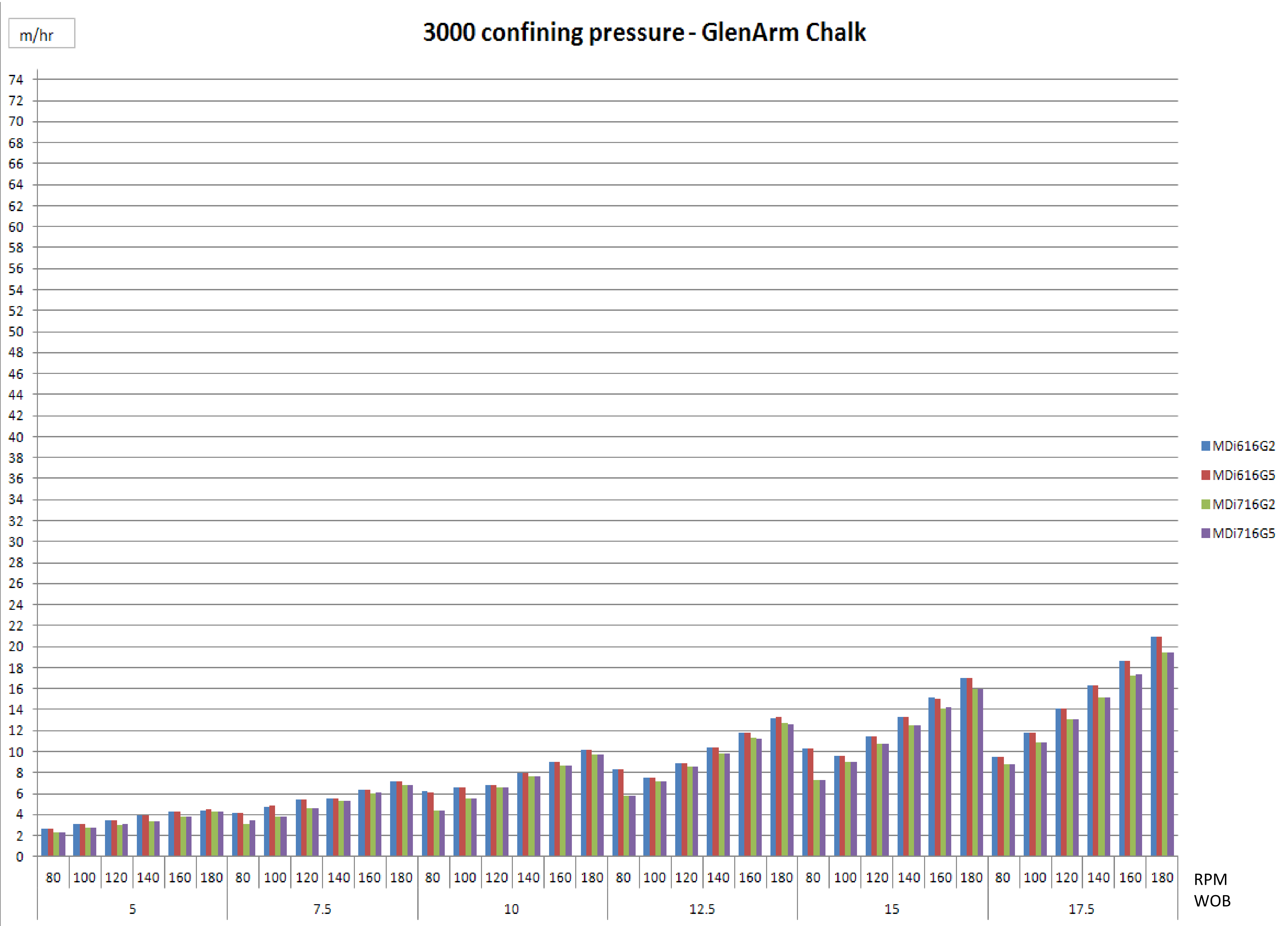
Lateral vibrations at bit
6000 confining pressure - GlenArm Chalk
lateral accelerations_median values (g)
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G2
MDi616G5
MDi716G2
MDi716G5
RPM
WOB
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5

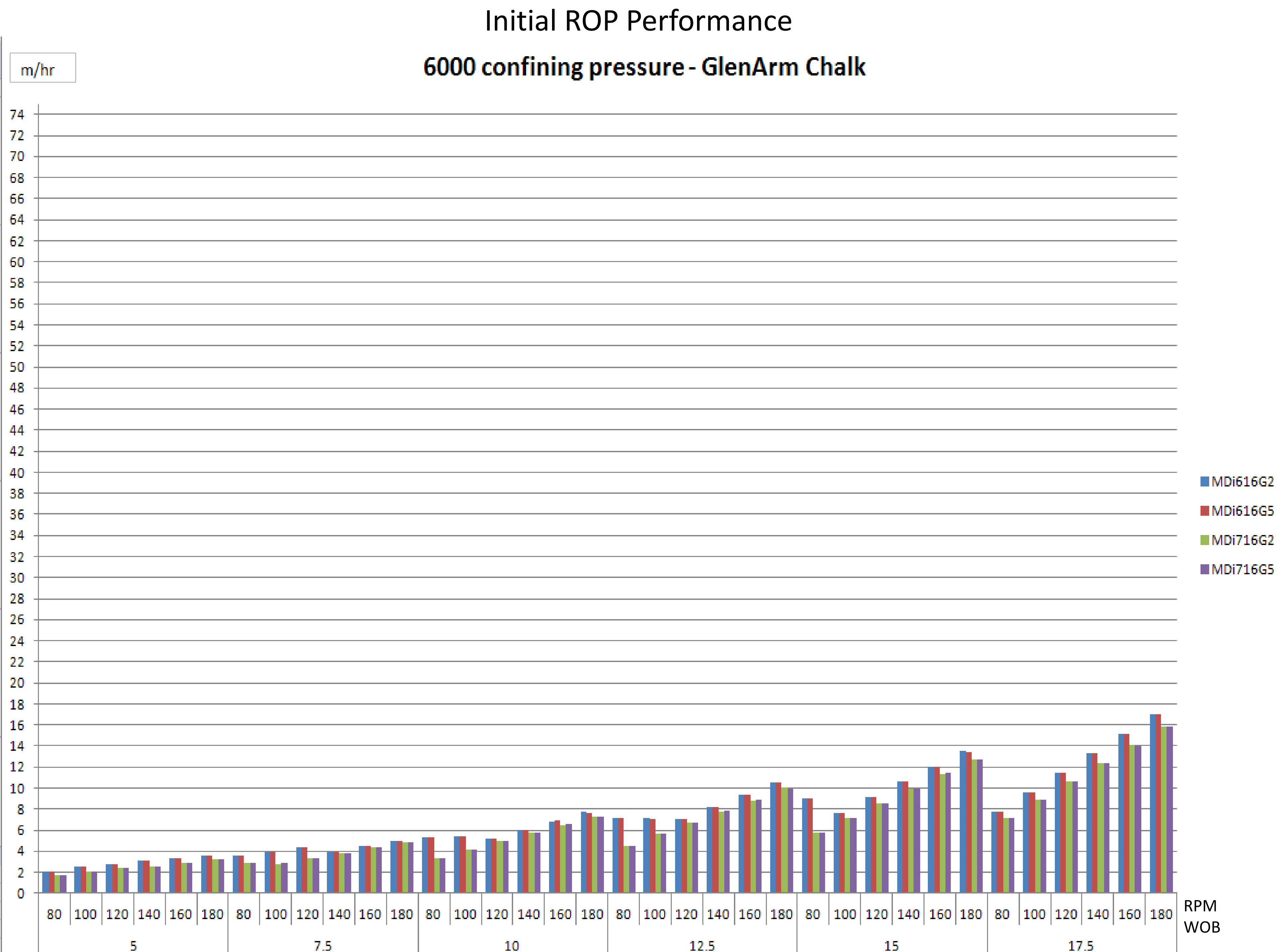

Δ Bit Torque (p90-p10)
3000psi confining pressure - GlenArm Chalk
Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5 7.5 10 12.5 15 17.5
WOB

# Δ Bit Torque (p90-p10)



# Initial ROP Performance





Initial ROP Performance
m/hr
6000 confining pressure - GlenArm Chalk
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
RPM
5
7.5
10
12.5
15
17.5
WOB

# APPENDIX 11
# STUDY 2

COLTON – CARTHAGE
CARTHAGE – COLTON

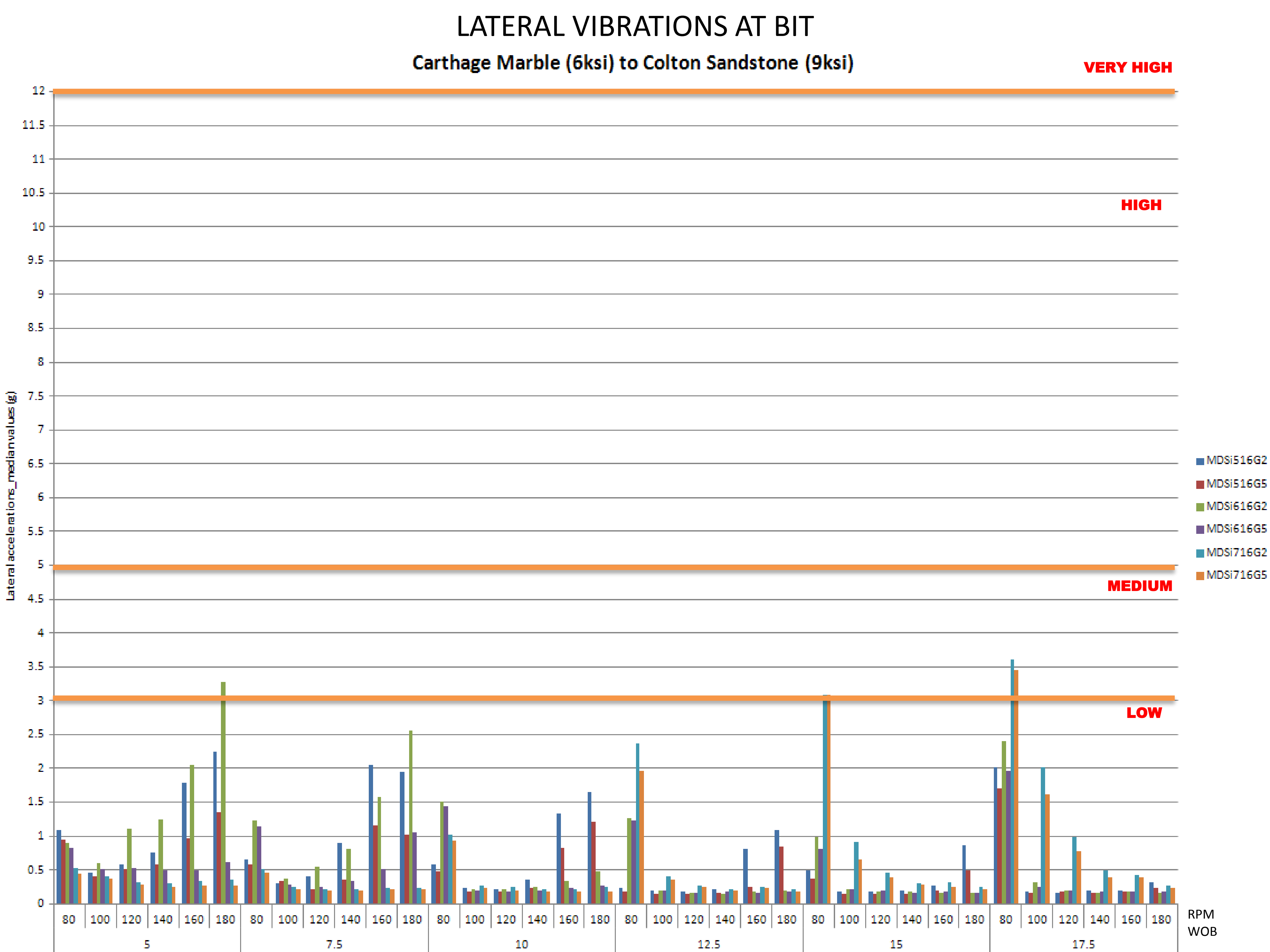
COLTON – TANDERAGEE
TANDERAGEE – COLTON

COLTON – GLENARM
GLENARM - COLTON

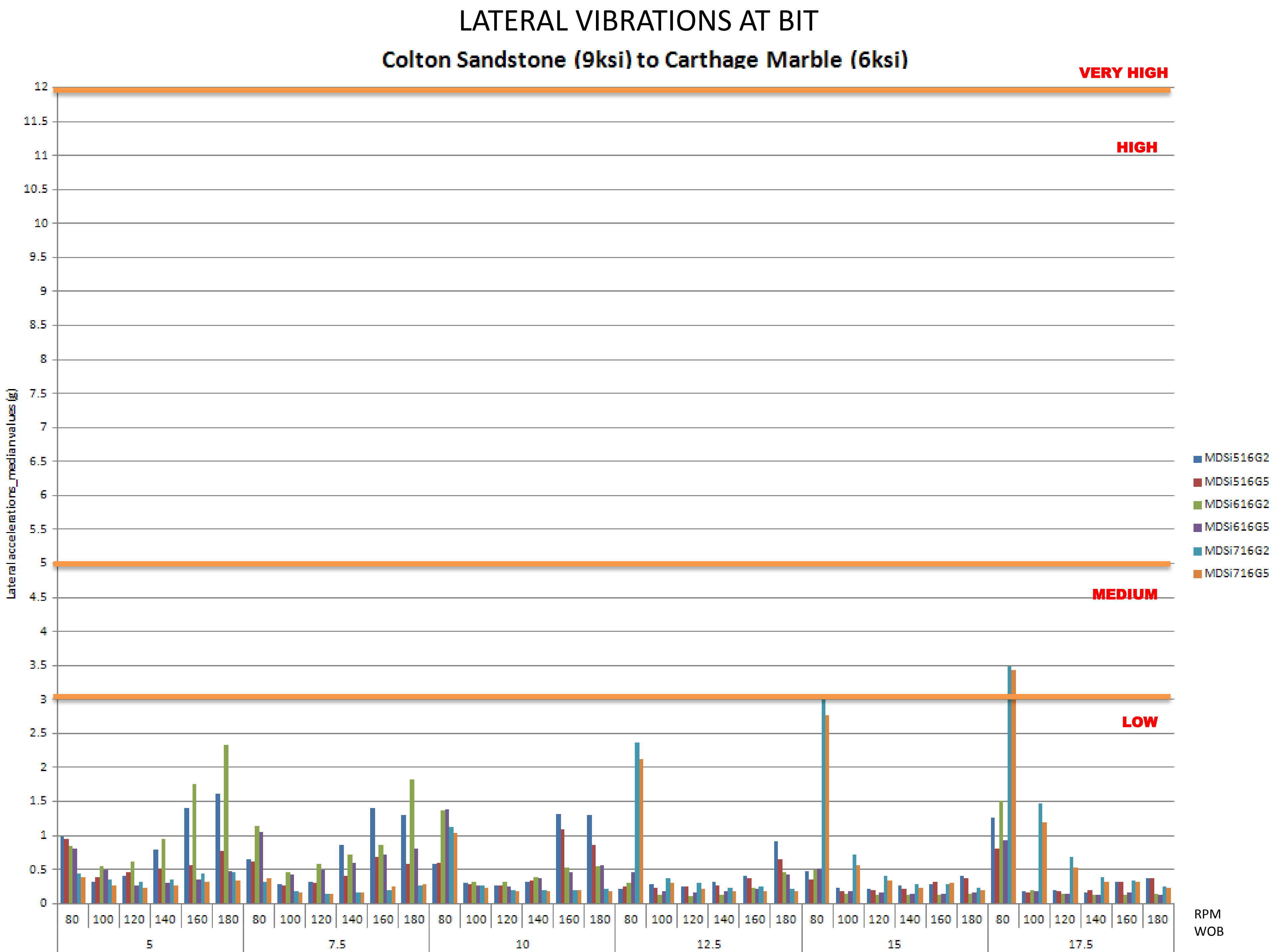
OPERATOR: Statoil
WELL NAME: NO 31/5-J-13 AY3H
ORIGINATOR: Odd Vinsevik
DATE: 2012-3-1

## PROJECT DESCRIPTION:

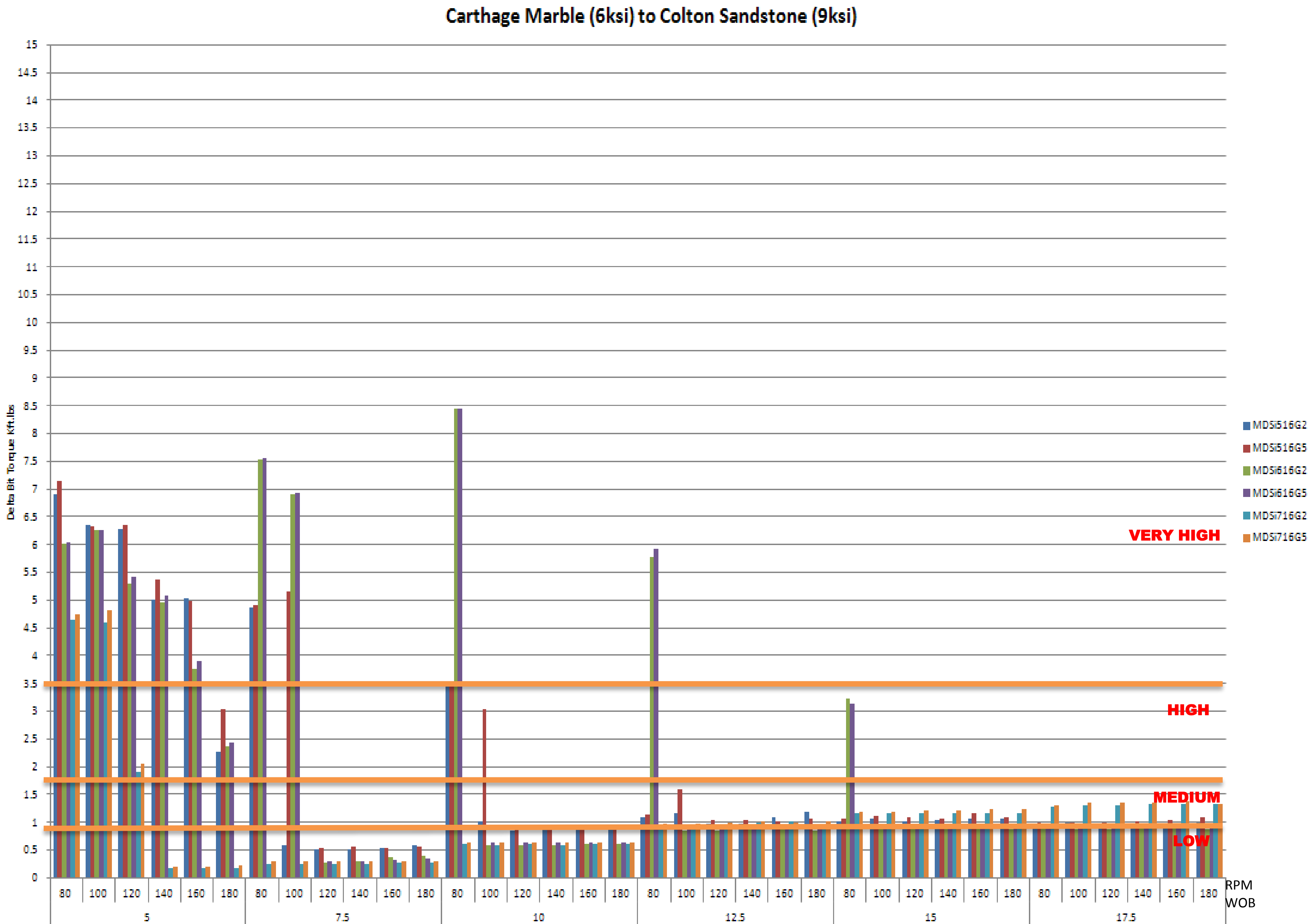
Analyse performance of MDSi 516_616_716 from Colton Sandstone (9000psi) to Carthage Marble (6000psi) visa versa, with short and long gauge (2" vs 5").



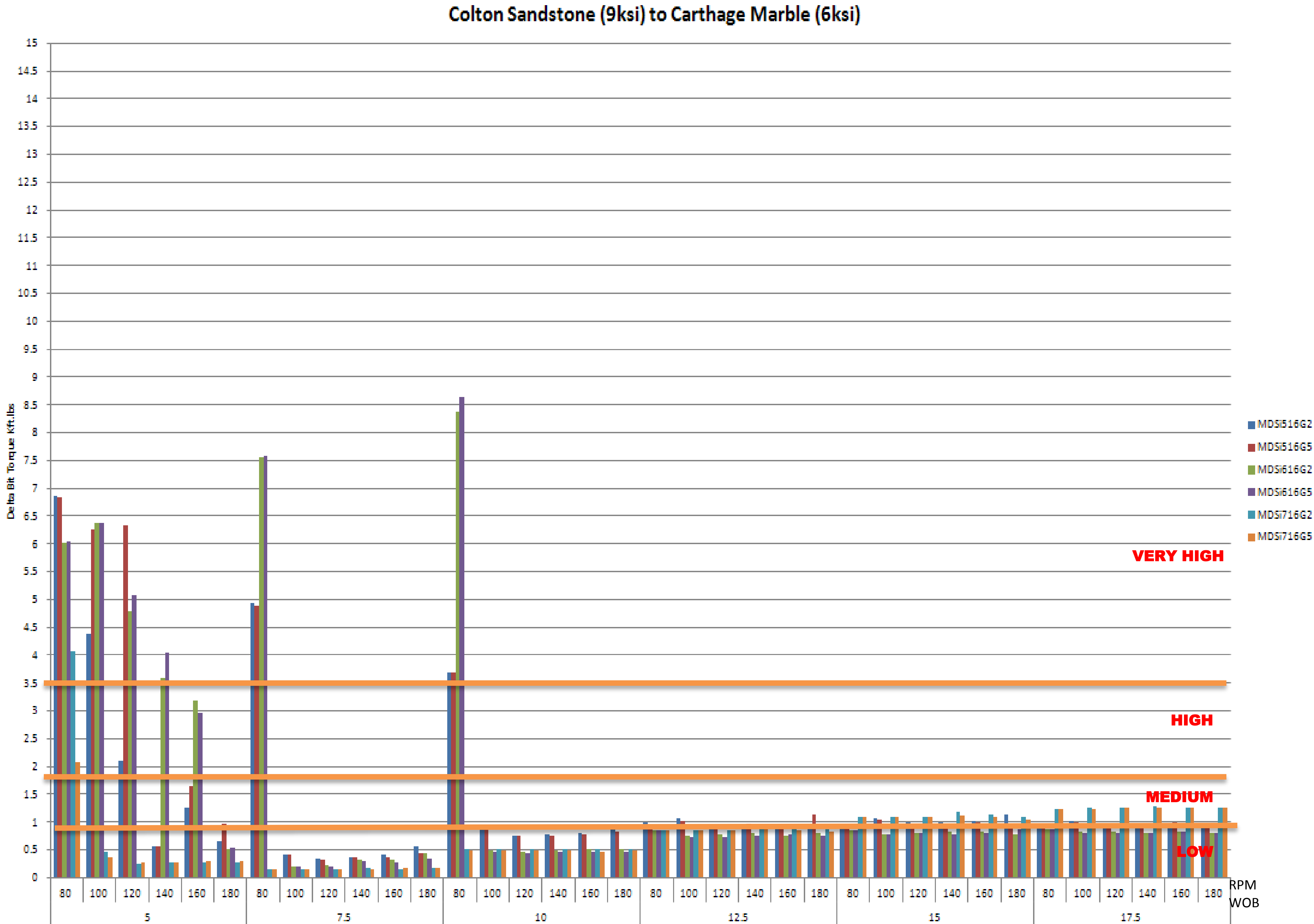
LATERAL VIBRATIONS AT BIT
Carthage Marble (6ksi) to Colton Sandstone (9ksi)
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5

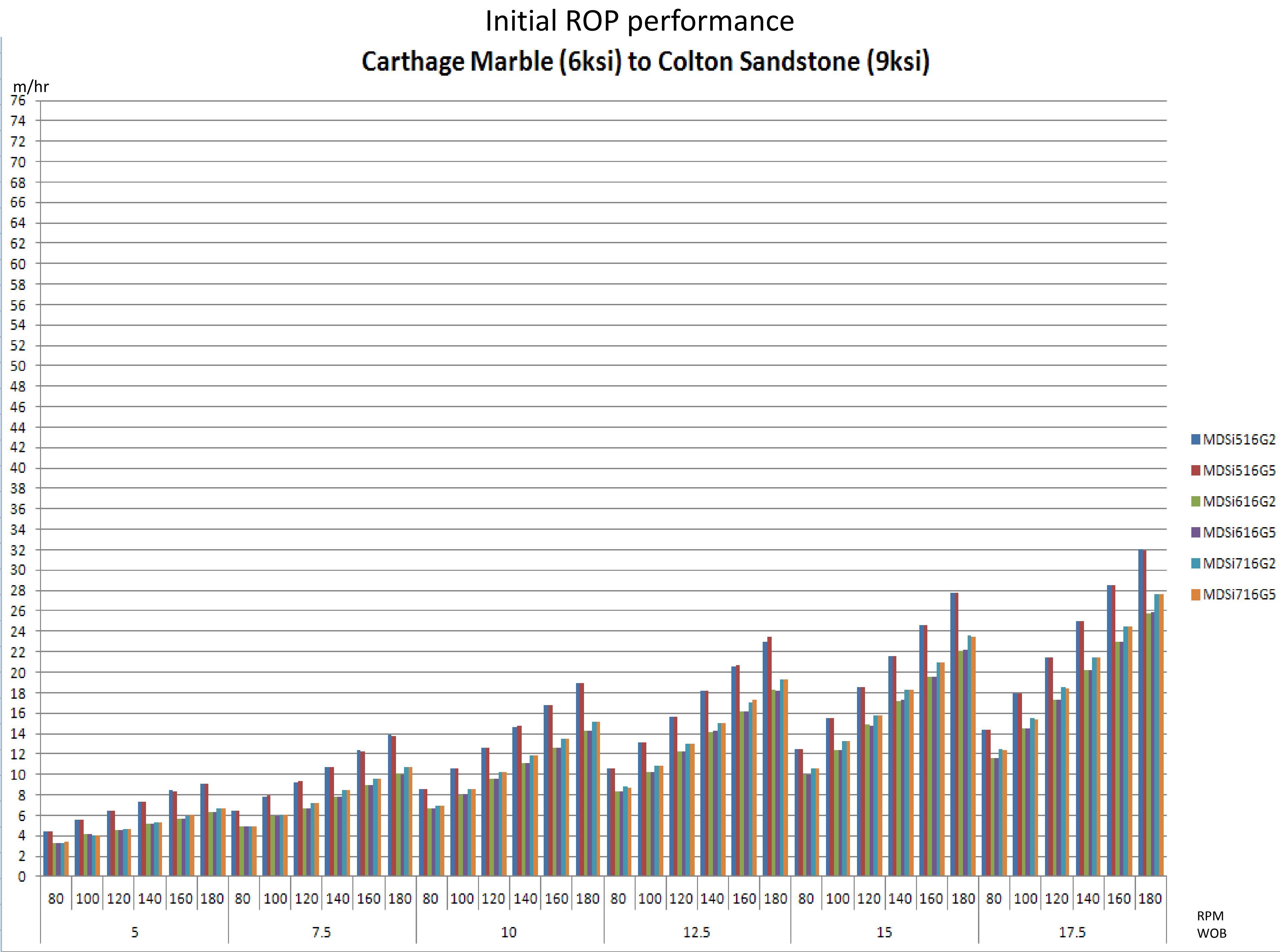

LATERAL VIBRATIONS AT BIT
Colton Sandstone (9ksi) to Carthage Marble (6ksi)
VERY HIGH
HIGH
MEDIUM
LOW
Lateral accelerations_median values (g)
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5
RPM
WOB
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5

# Δ Bit Torque (p90-p10)

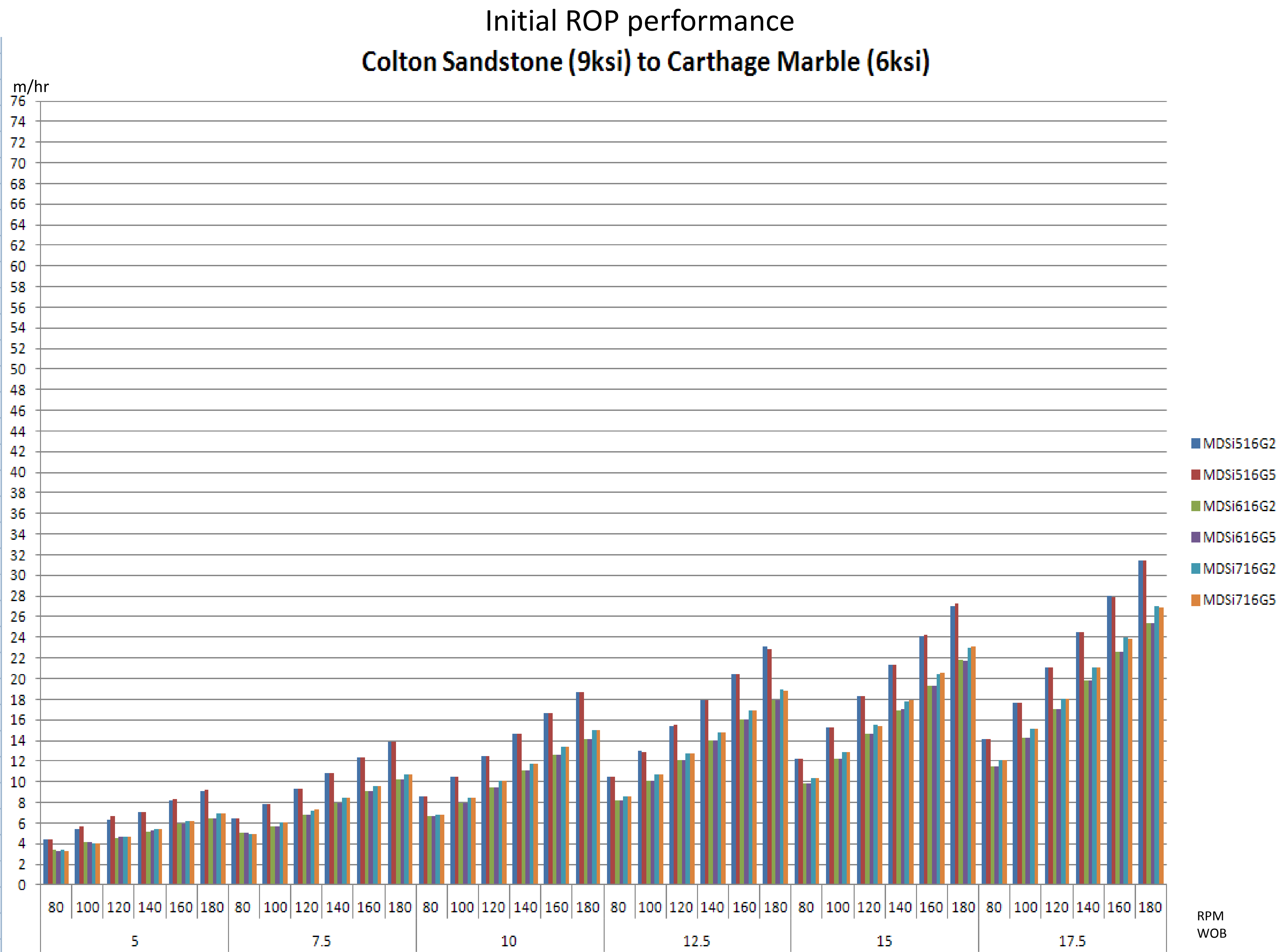


Δ Bit Torque (p90-p10)





Initial ROP performance
Carthage Marble (6ksi) to Colton Sandstone (9ksi)
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB



Initial ROP performance
Colton Sandstone (9ksi) to Carthage Marble (6ksi)
m/hr
MDSi516G2
MDSi516G5
MDSi616G2
MDSi616G5
MDSi716G2
MDSi716G5
RPM
WOB
80 100 120 140 160 180
5 7.5 10 12.5 15 17.5

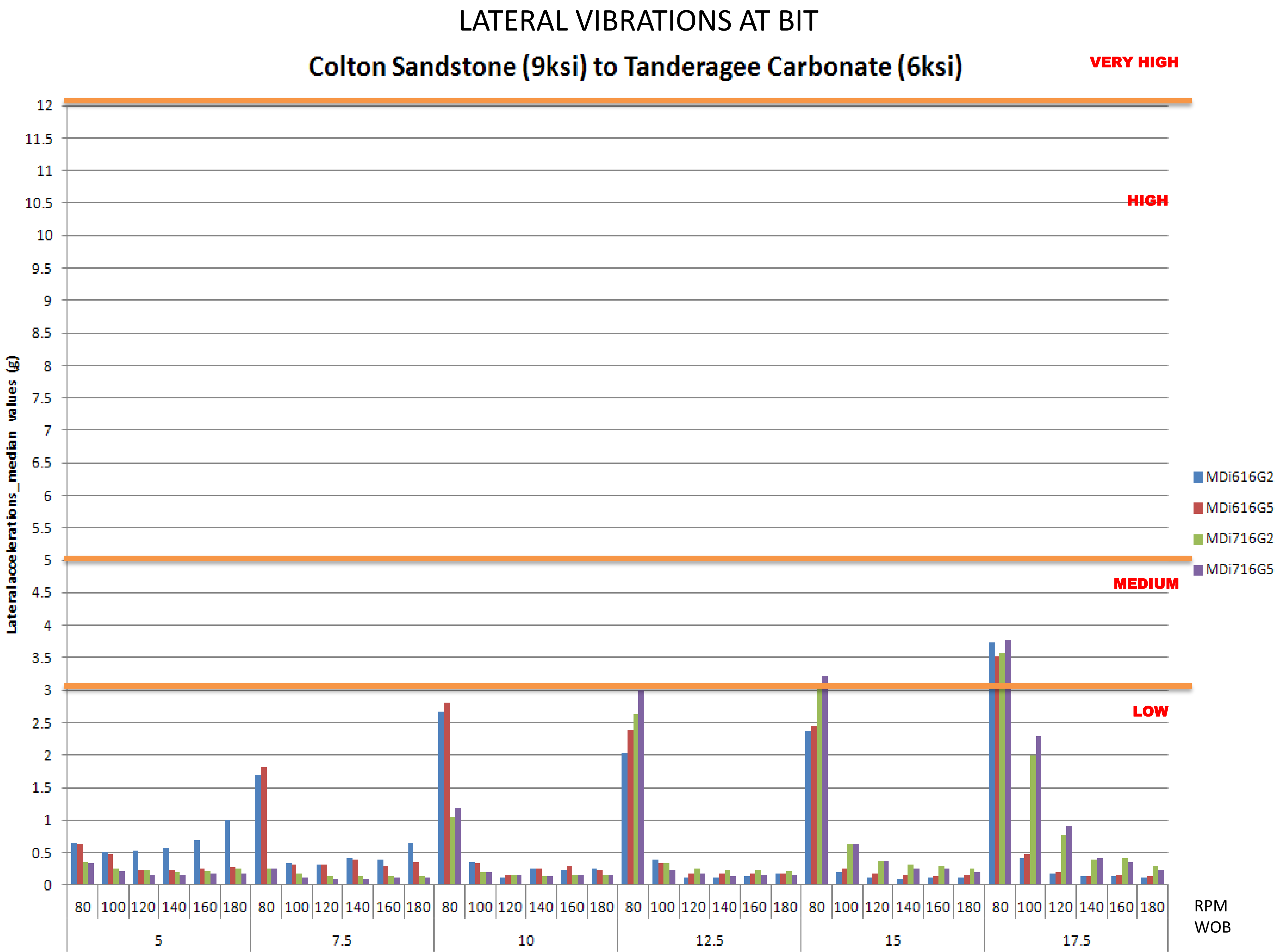
# IDEAS PROJECT RESULTS

OPERATOR: Statoil
WELL NAME: NO 31/5-J-13 AY3H
ORIGINATOR: Odd Vinsevik
DATE: 2012-3-1

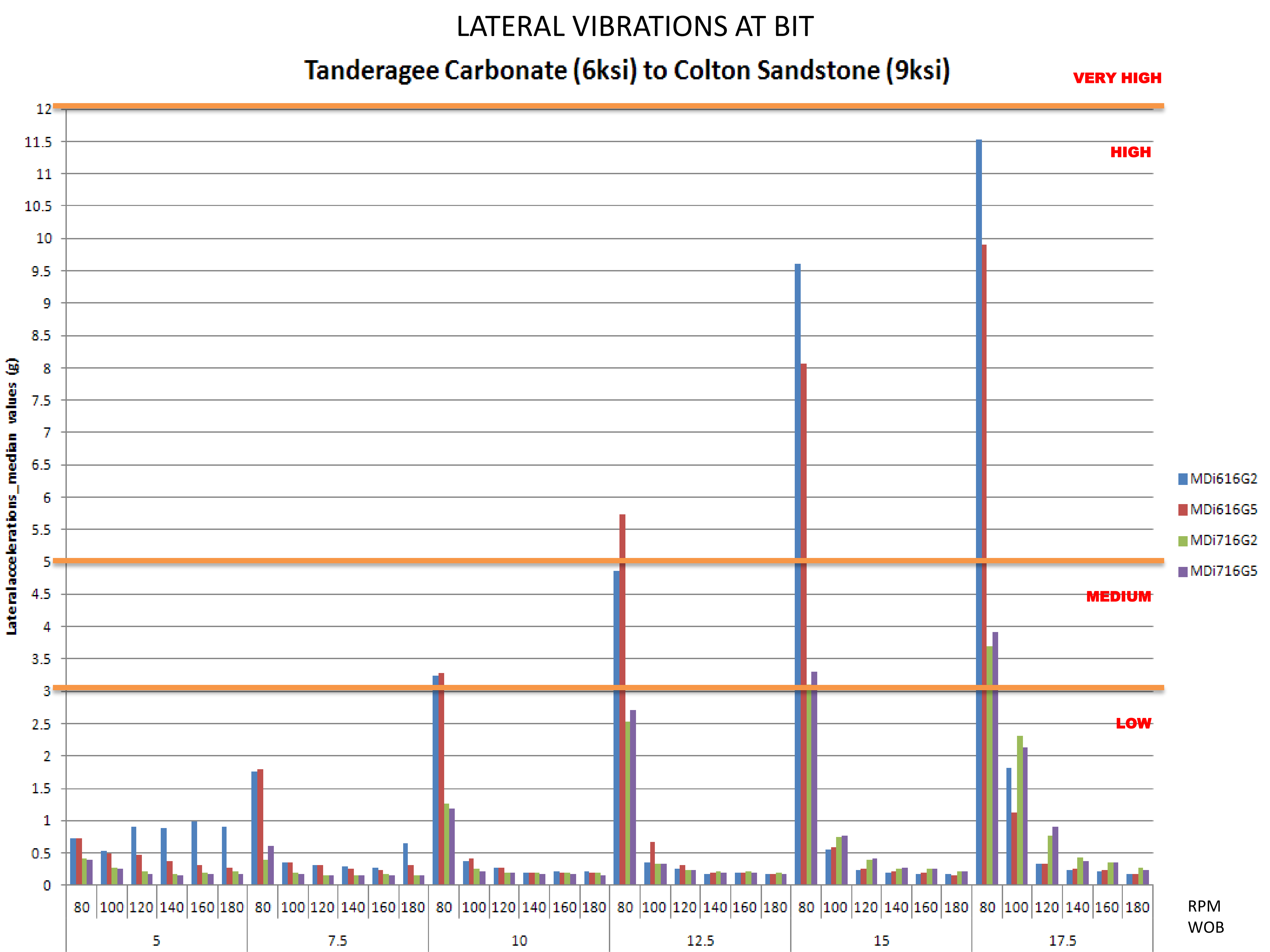
## PROJECT DESCRIPTION:

Analyse performance of MDSi 516_616_716 from Colton Sandstone (9000psi) to Tanderagee Chalk(6000psi), with short and long gauge (2" vs 5").

SMITH BITS
A Schlumberger Company



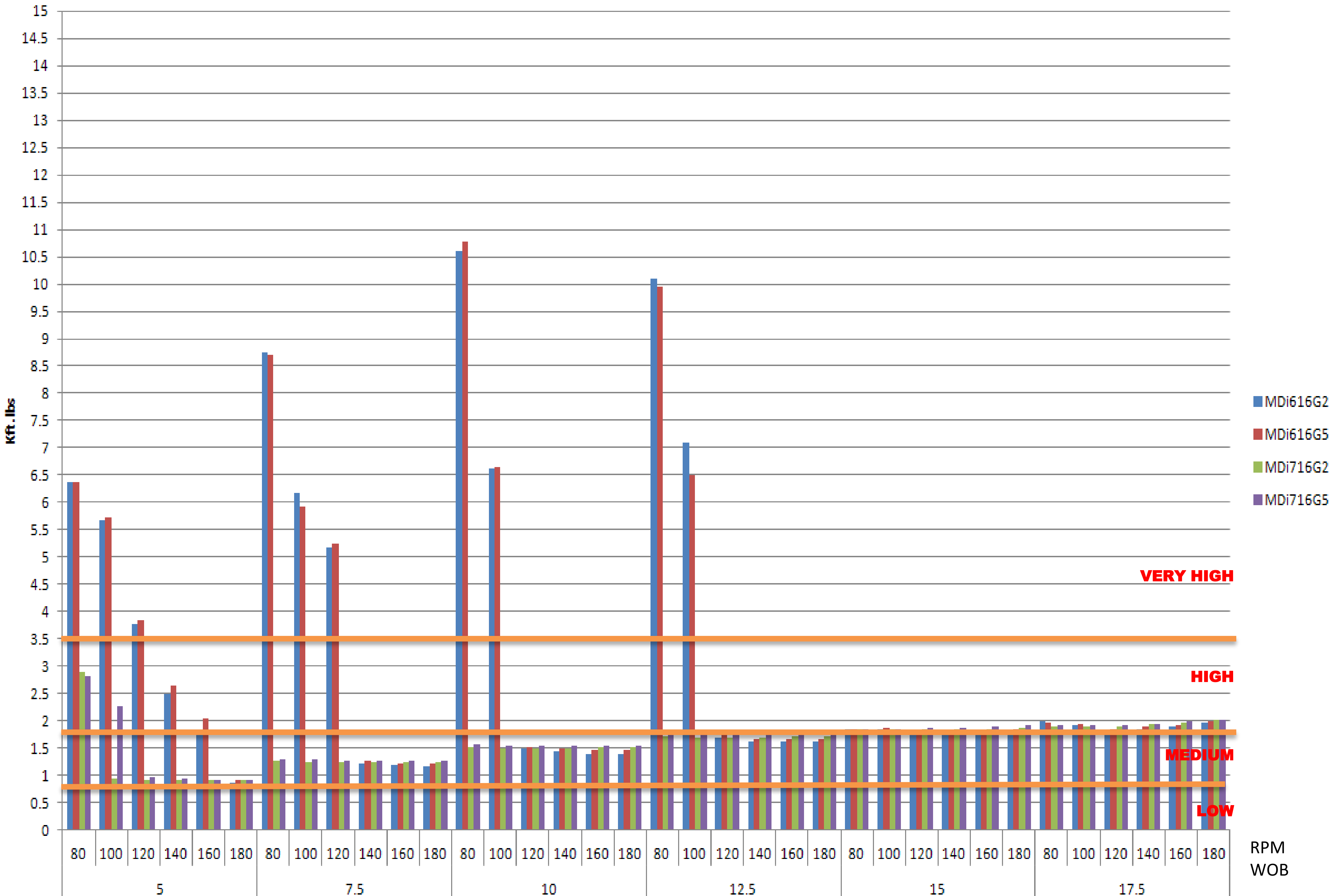
LATERAL VIBRATIONS AT BIT
Colton Sandstone (9ksi) to Tanderagee Carbonate (6ksi)
VERY HIGH
HIGH
MEDIUM
LOW
Lateralaccelerations_median values (g)
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

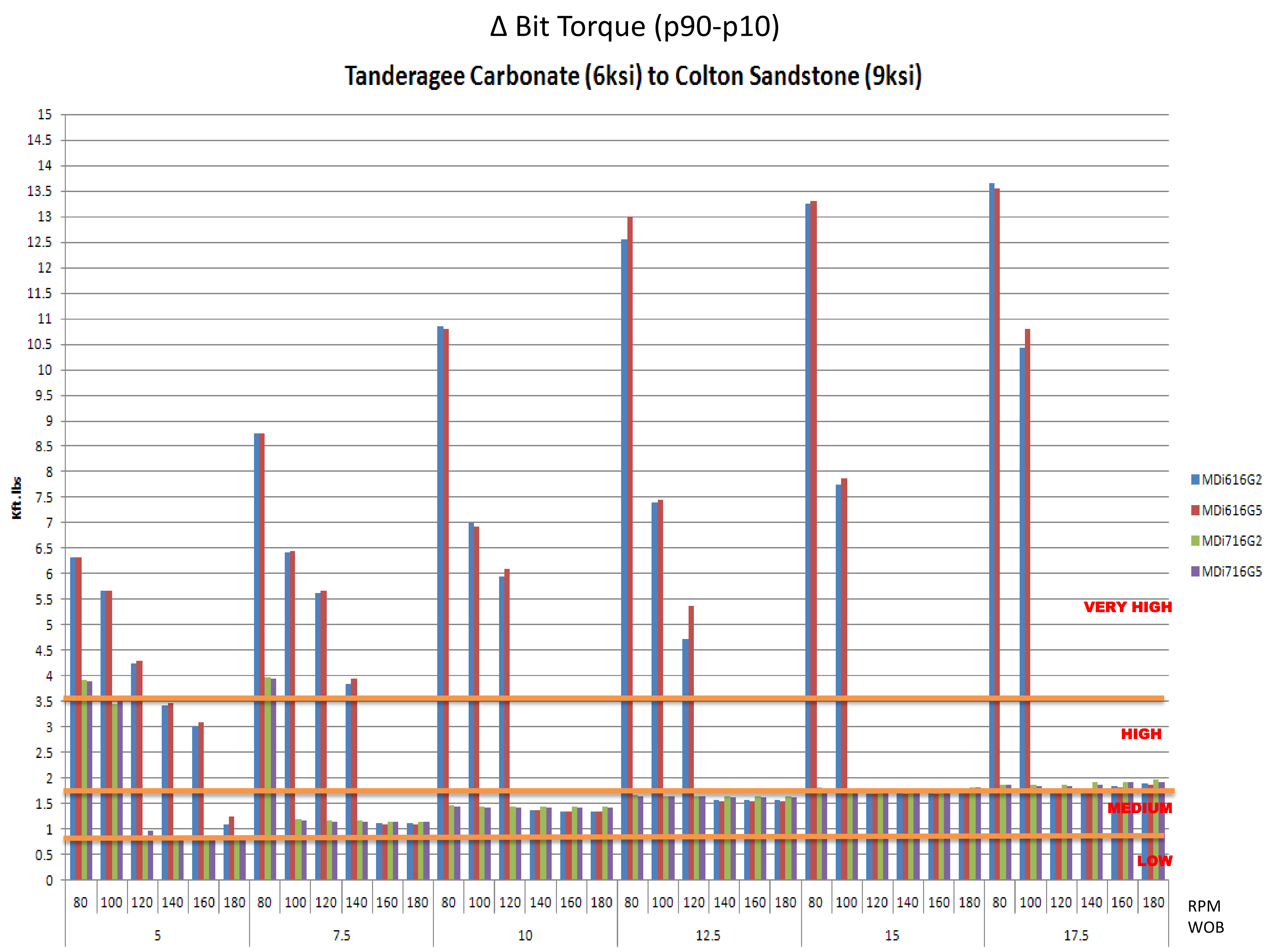


LATERAL VIBRATIONS AT BIT
Tanderagee Carbonate (6ksi) to Colton Sandstone (9ksi)
VERY HIGH
HIGH
MEDIUM
LOW
Lateralaccelerations_median values (g)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDi616G2
MDi616G5
MDi716G2
MDi716G5

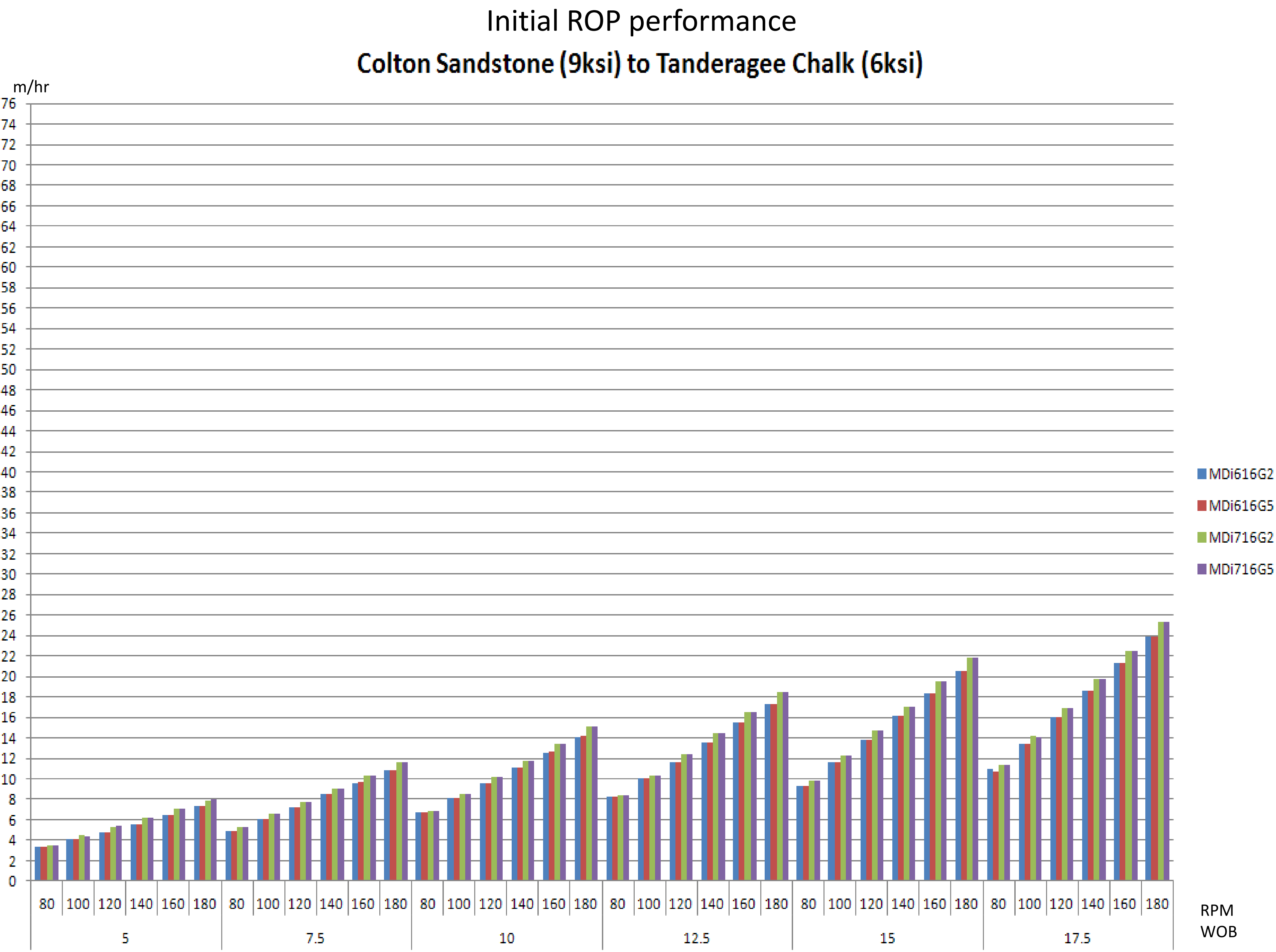
# Δ Bit Torque (p90-p10)

## Colton Sandstone (9ksi) to Tanderagee Carbonate (6ksi)

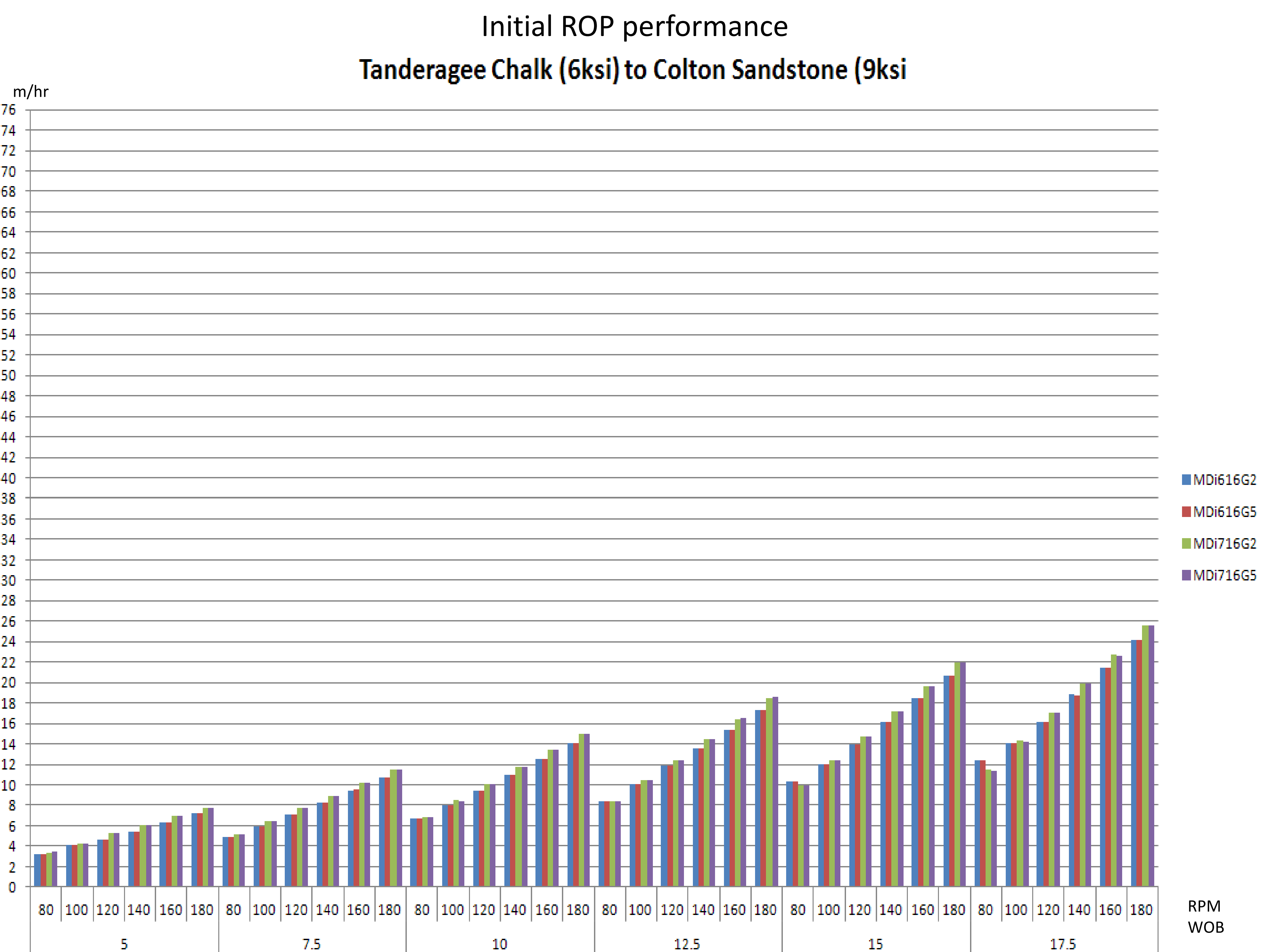




Δ Bit Torque (p90-p10)
Tanderagee Carbonate (6ksi) to Colton Sandstone (9ksi)
Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
VERY HIGH
HIGH
MEDIUM
LOW
80
100
120
140
160
180
RPM
5
7.5
10
12.5
15
17.5
WOB



Initial ROP performance
Colton Sandstone (9ksi) to Tanderagee Chalk (6ksi)
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB


Initial ROP performance
Tanderagee Chalk (6ksi) to Colton Sandstone (9ksi
m/hr
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

OPERATOR: Statoil

WELL NAME: NO 31/5-J-13 AY3H

ORIGINATOR: Odd Vinsevik

DATE: 2012-3-16

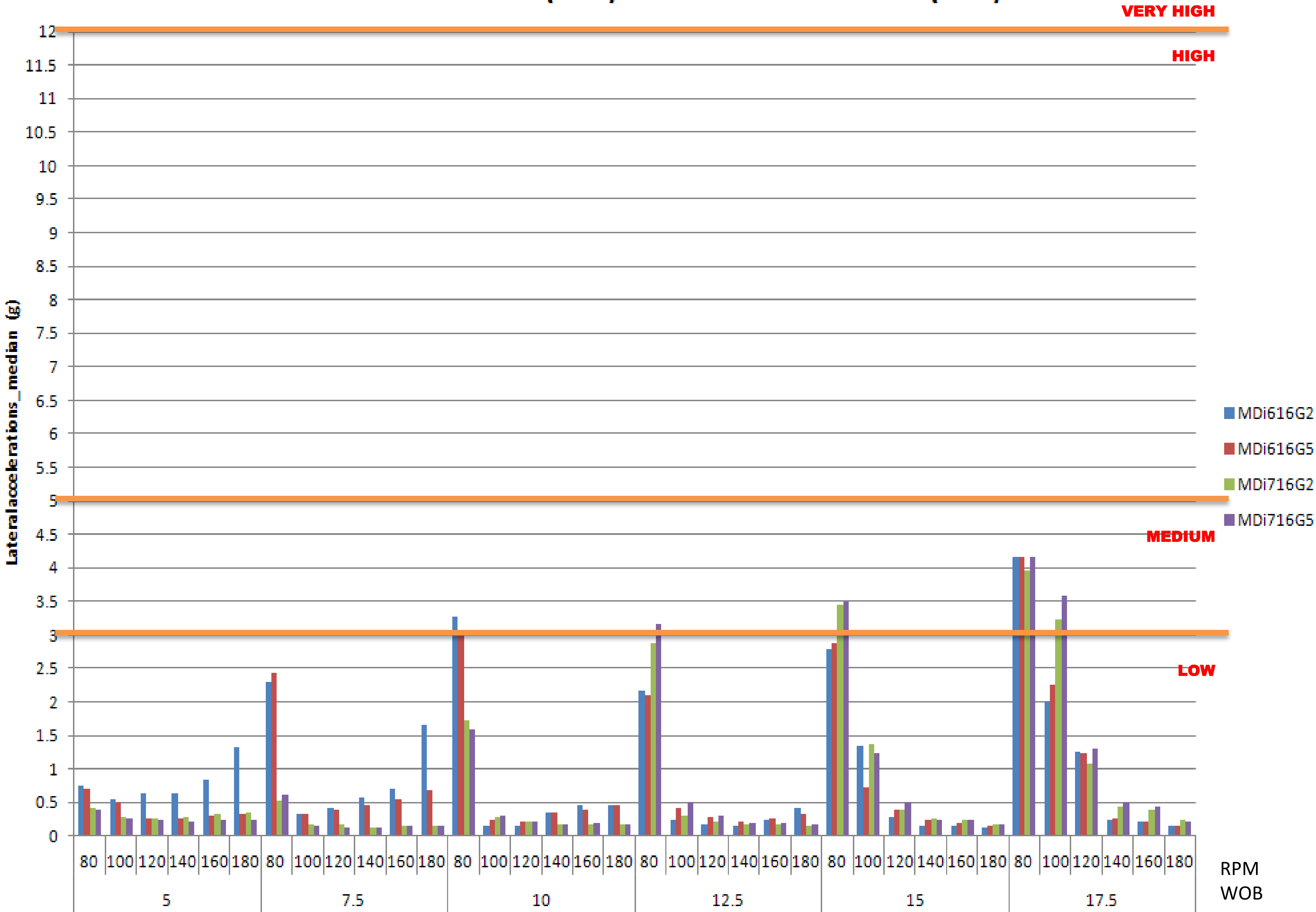
## PROJECT DESCRIPTION:

Analyse performance of MDi616 vs MDi716 in Colton Sandstone (9000psi) to GlenArm Chalk (6000psi) visa versa, with short and long gauge (2” vs 5”).

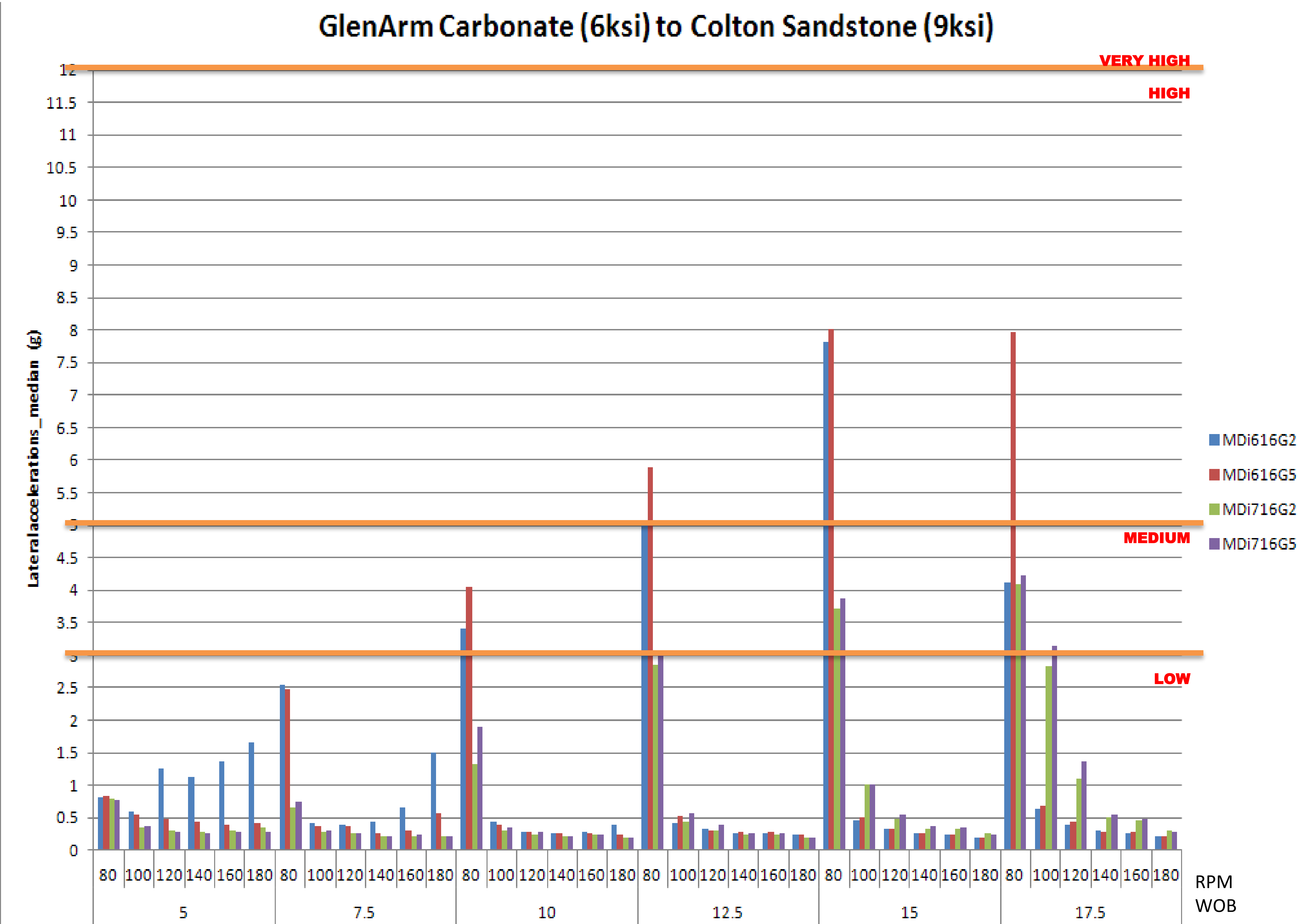
SMITH BITS
A Schlumberger Company

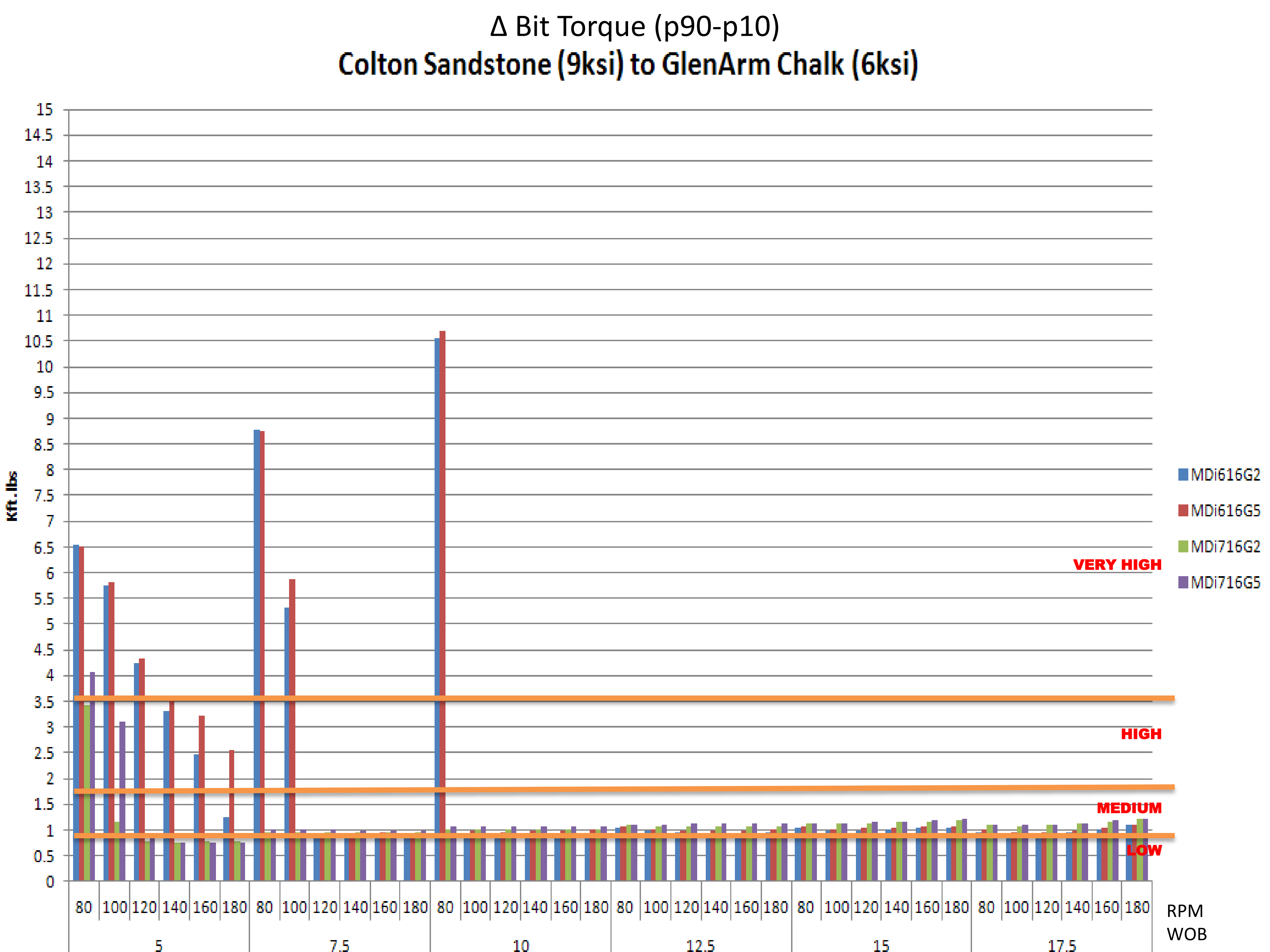
Lateral vibrations at bit

**Colton Sandstone (9ksi) to GlenArm Carbonate (6ksi)**

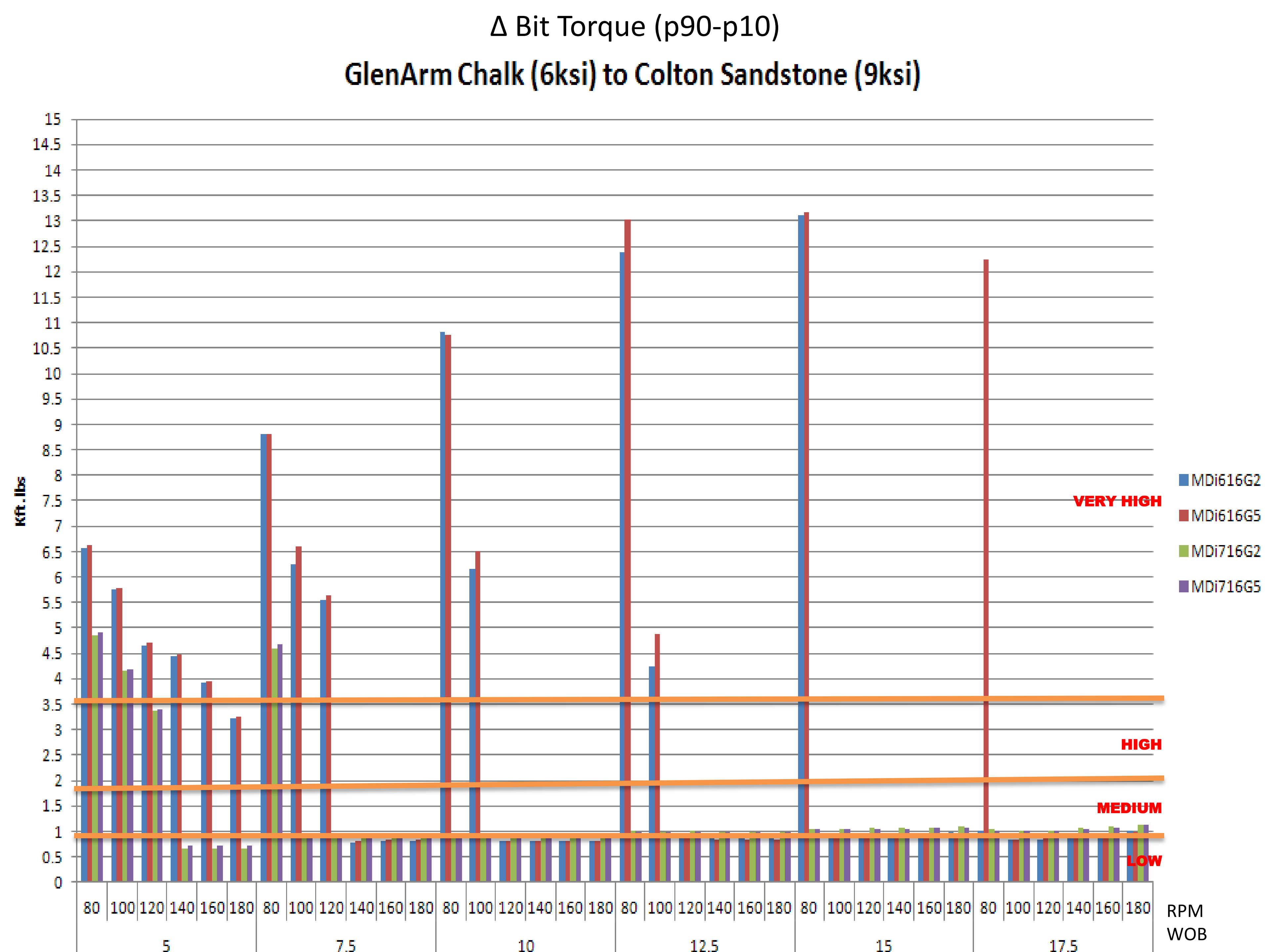


Lateral vibrations at bit

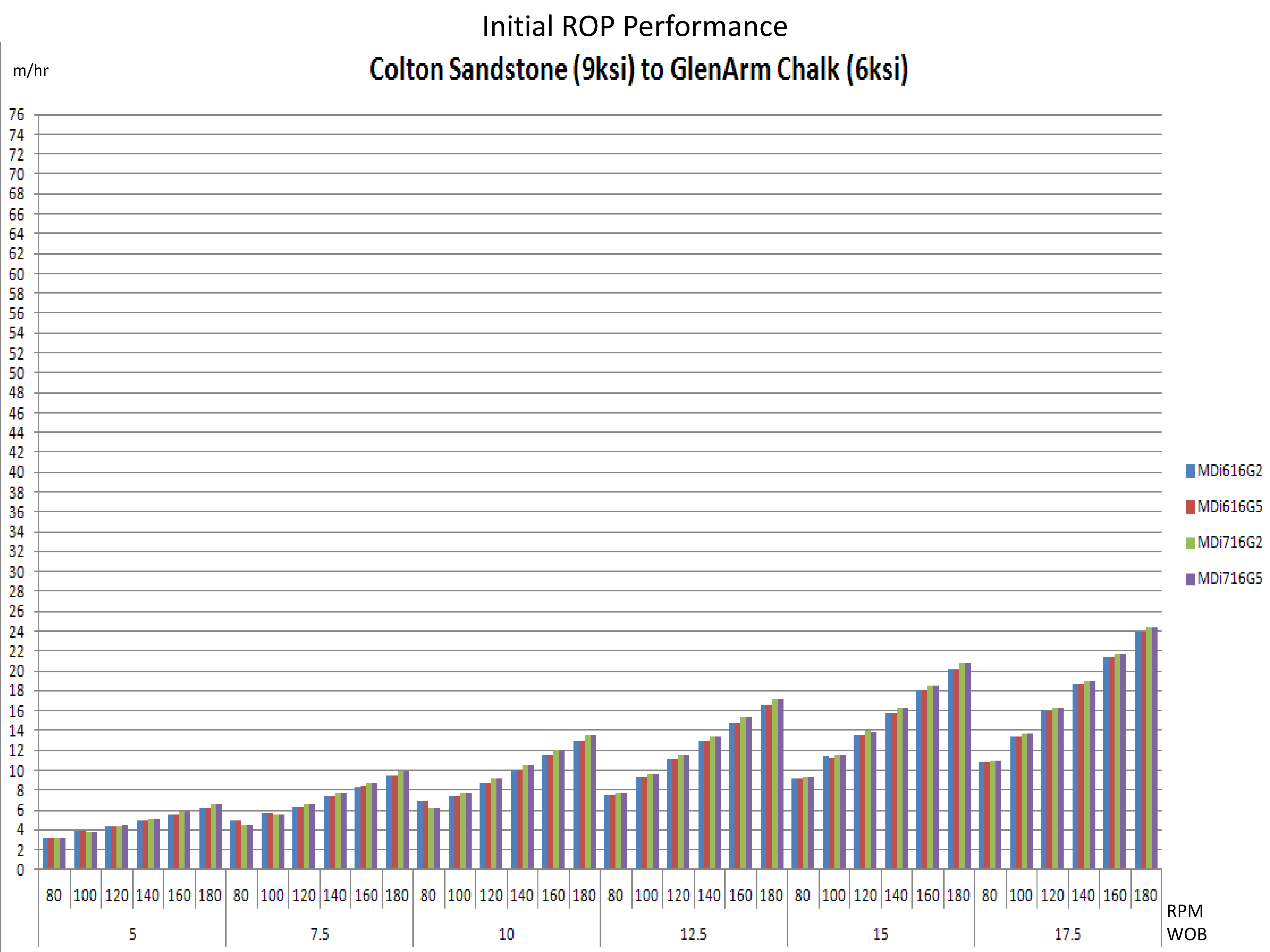




Δ Bit Torque (p90-p10)
Colton Sandstone (9ksi) to GlenArm Chalk (6ksi)
Kft.lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180
5
7.5
10
12.5
15
17.5
RPM
WOB

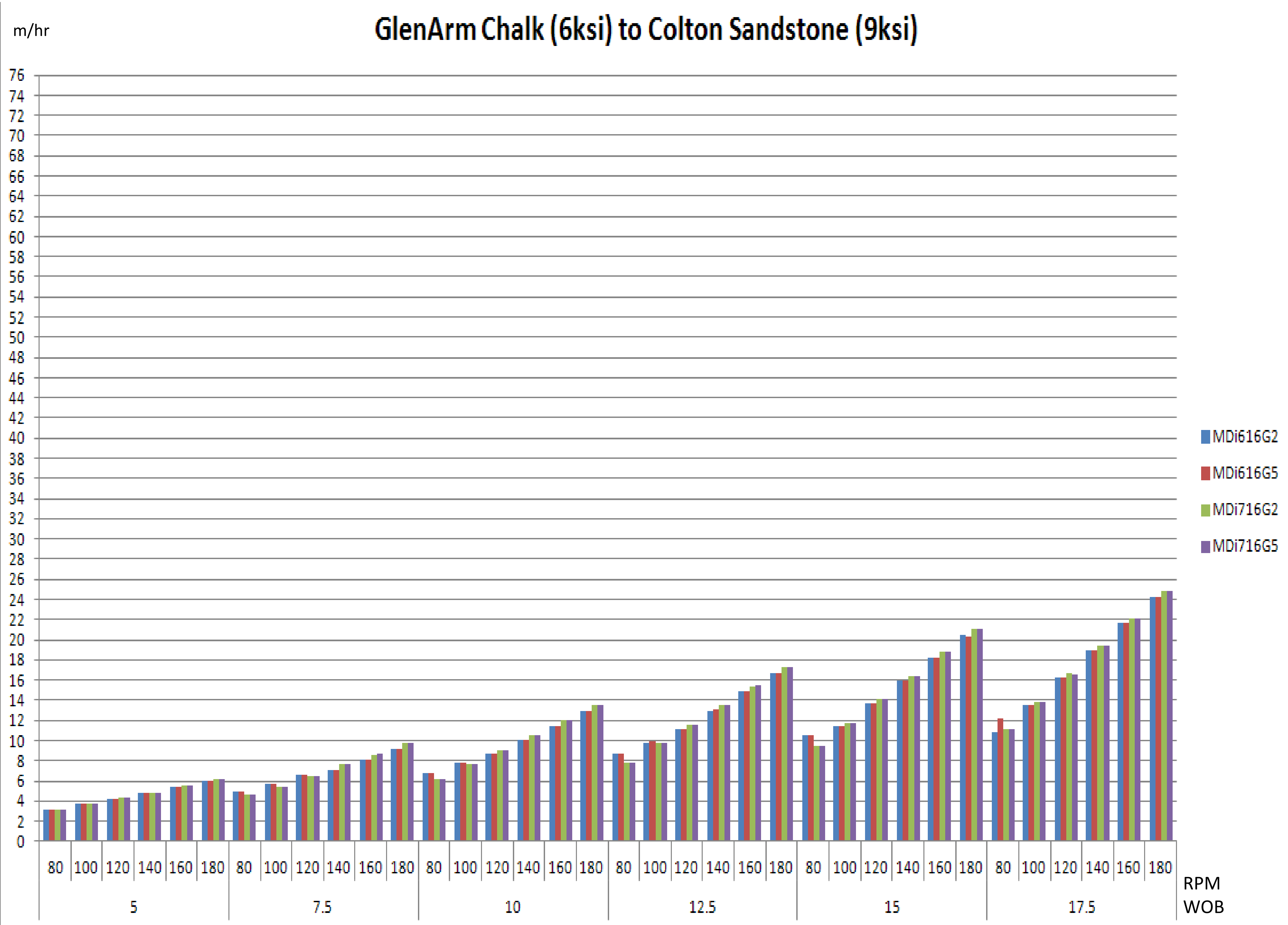


Δ Bit Torque (p90-p10)
GlenArm Chalk (6ksi) to Colton Sandstone (9ksi)
Kft. lbs
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
VERY HIGH
HIGH
MEDIUM
LOW
MDi616G2
MDi616G5
MDi716G2
MDi716G5
80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180 80 100 120 140 160 180
5 7.5 10 12.5 15 17.5
RPM
WOB



Initial ROP Performance
Colton Sandstone (9ksi) to GlenArm Chalk (6ksi)
m/hr
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
80
100
120
140
160
180
5
7.5
10
12.5
15
17.5
RPM
WOB
MDi616G2
MDi616G5
MDi716G2
MDi716G5

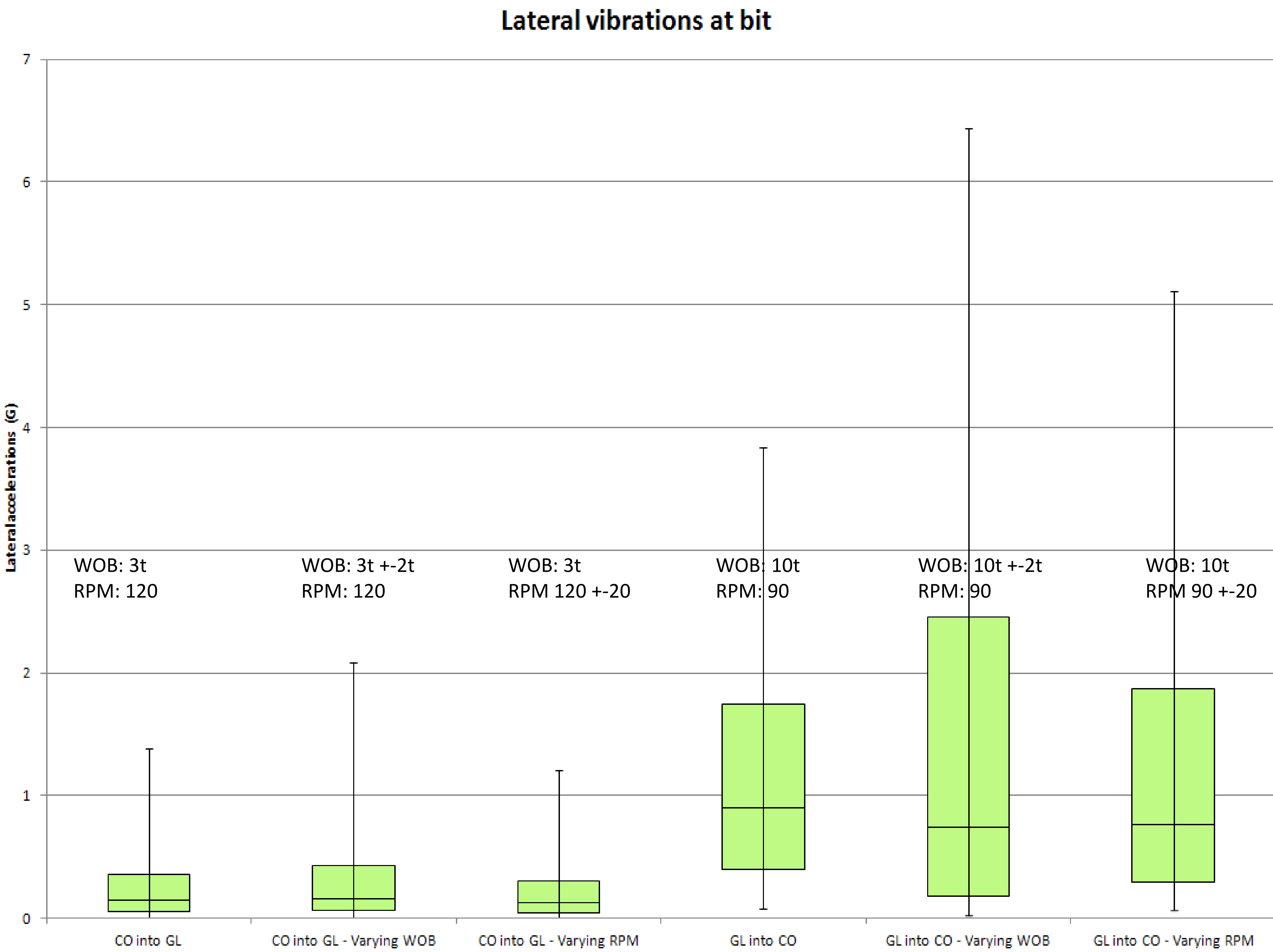
# Initial ROP Performance

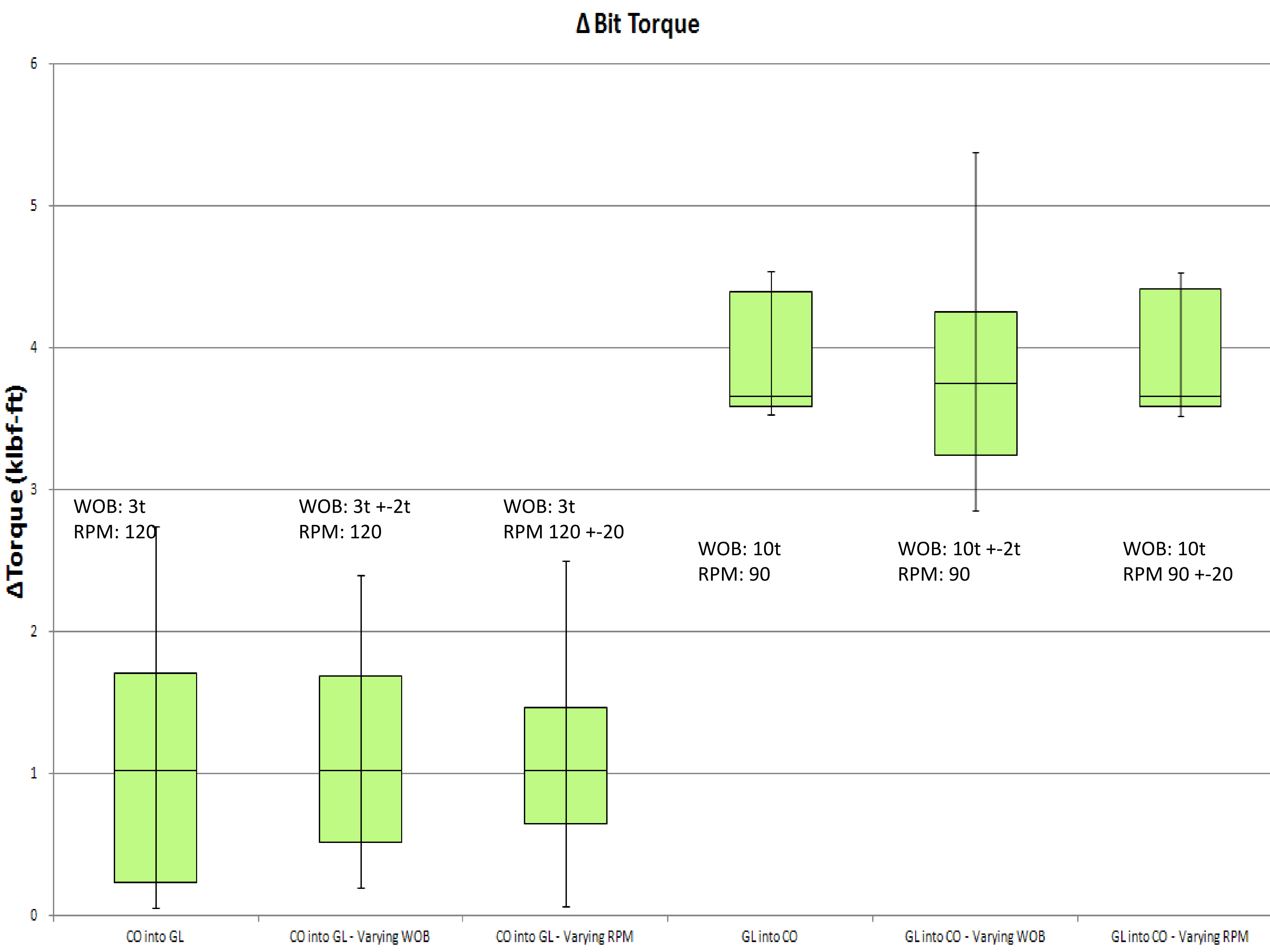


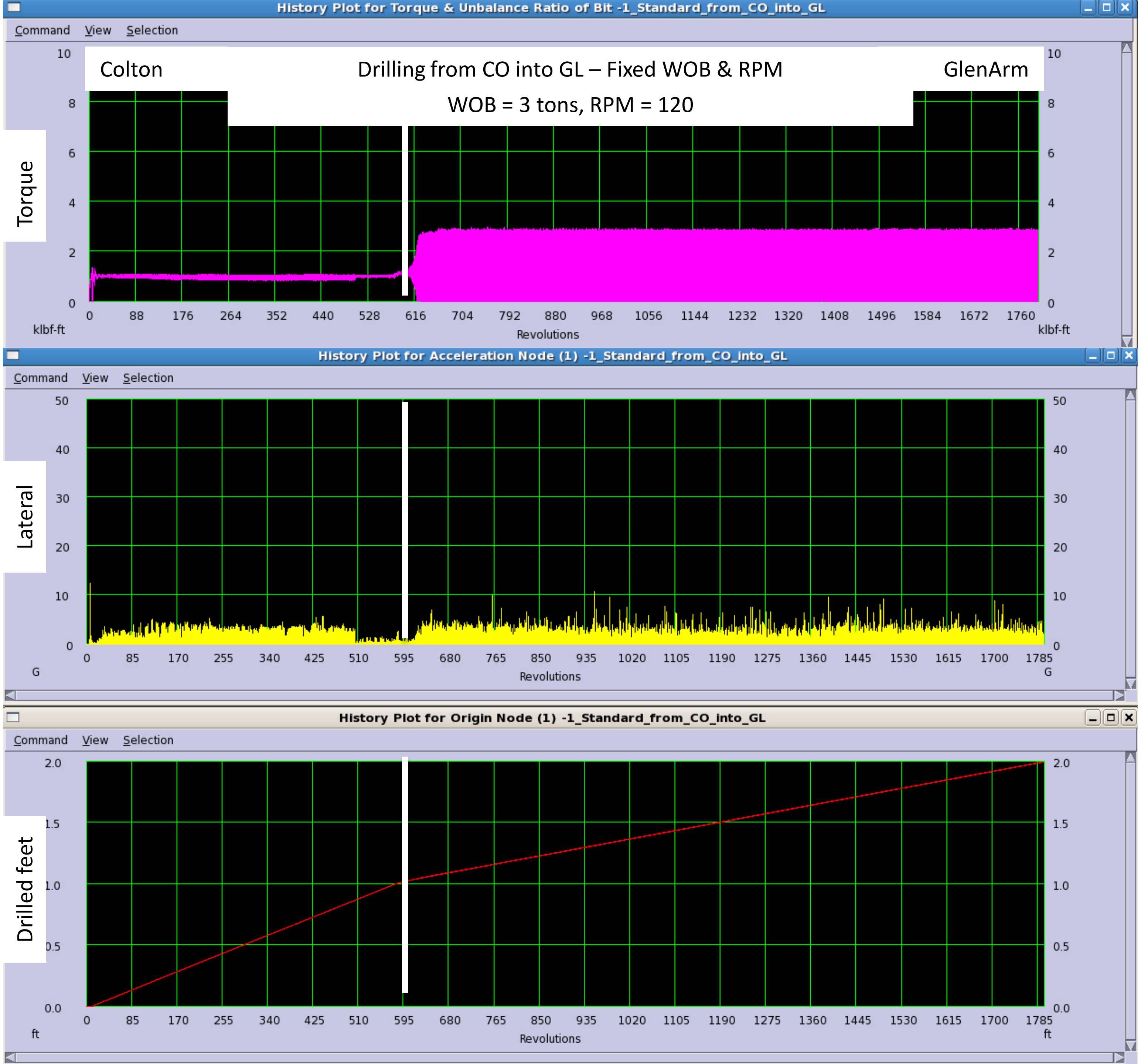
# APPENDIX 12
# STUDY 3

## COLTON TO GLENARM
## GLENARM TO COLTON

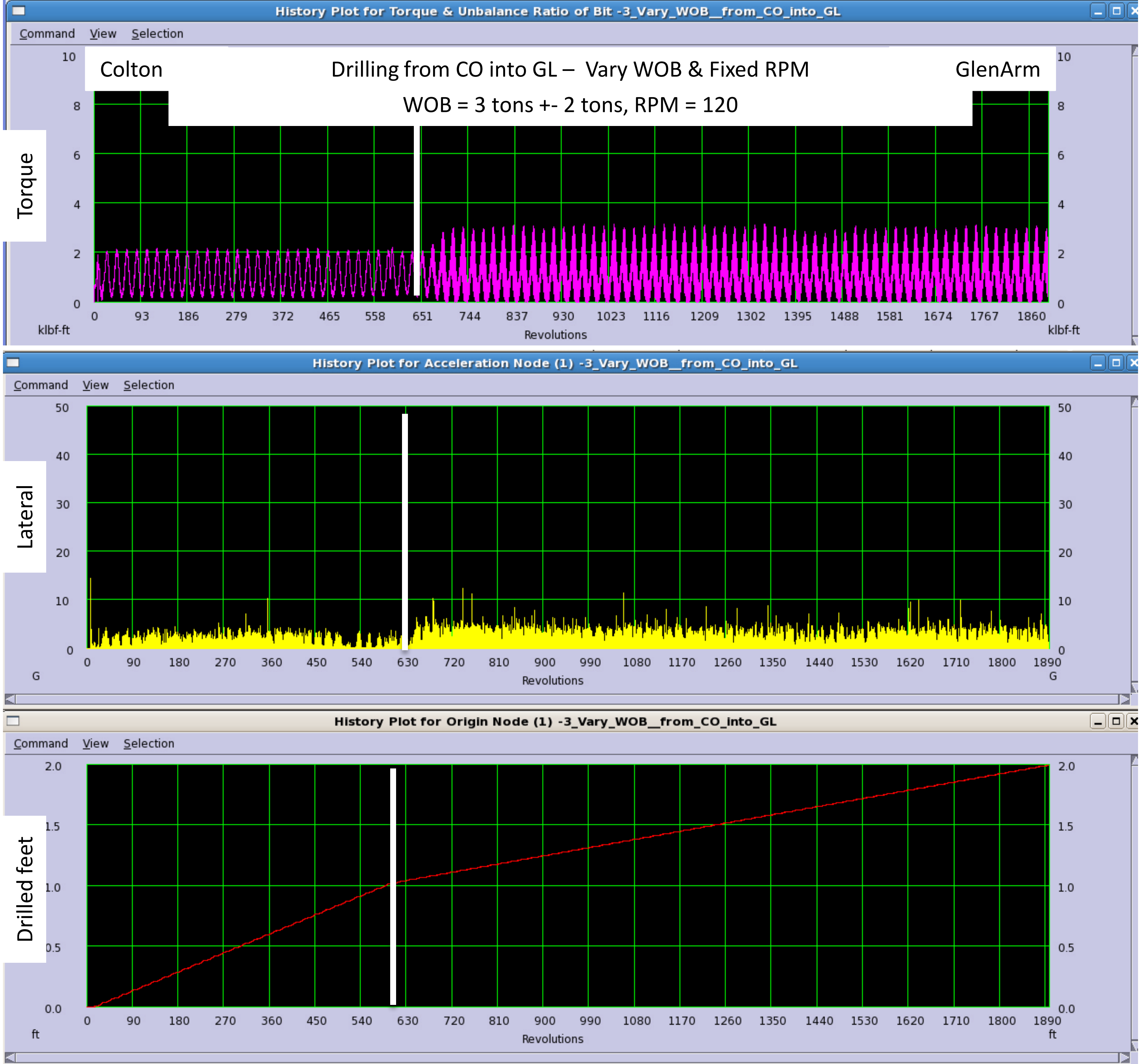
## FLUCTUATING WOB/RPM

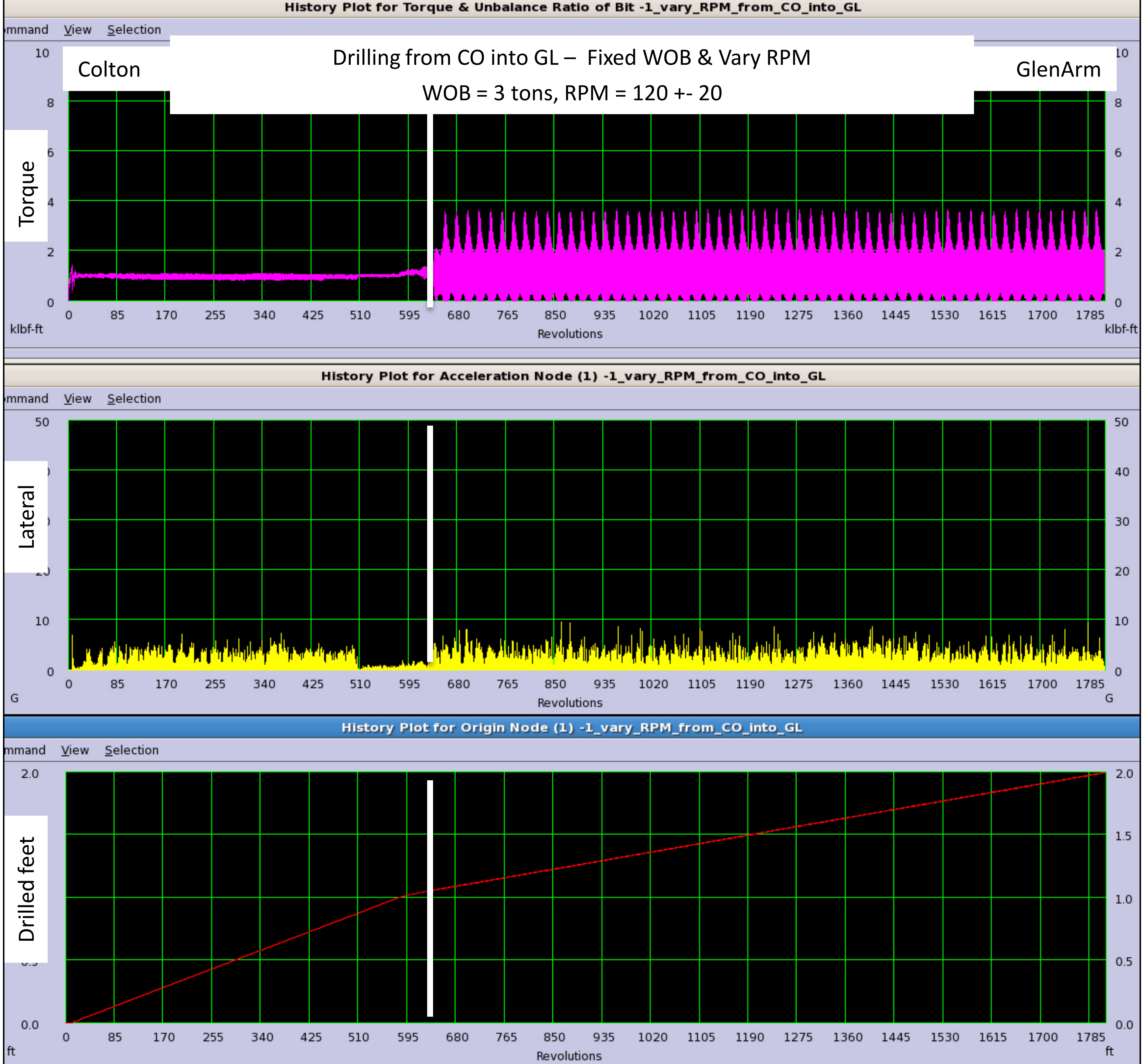

Lateral vibrations at bit
Lateral accelerations (G)
7
6
5
4
3
2
1
0
WOB: 3t
RPM: 120
WOB: 3t +-2t
RPM: 120
WOB: 3t
RPM 120 +-20
WOB: 10t
RPM: 90
WOB: 10t +-2t
RPM: 90
WOB: 10t
RPM 90 +-20
CO into GL
CO into GL - Varying WOB
CO into GL - Varying RPM
GL into CO
GL into CO - Varying WOB
GL into CO - Varying RPM

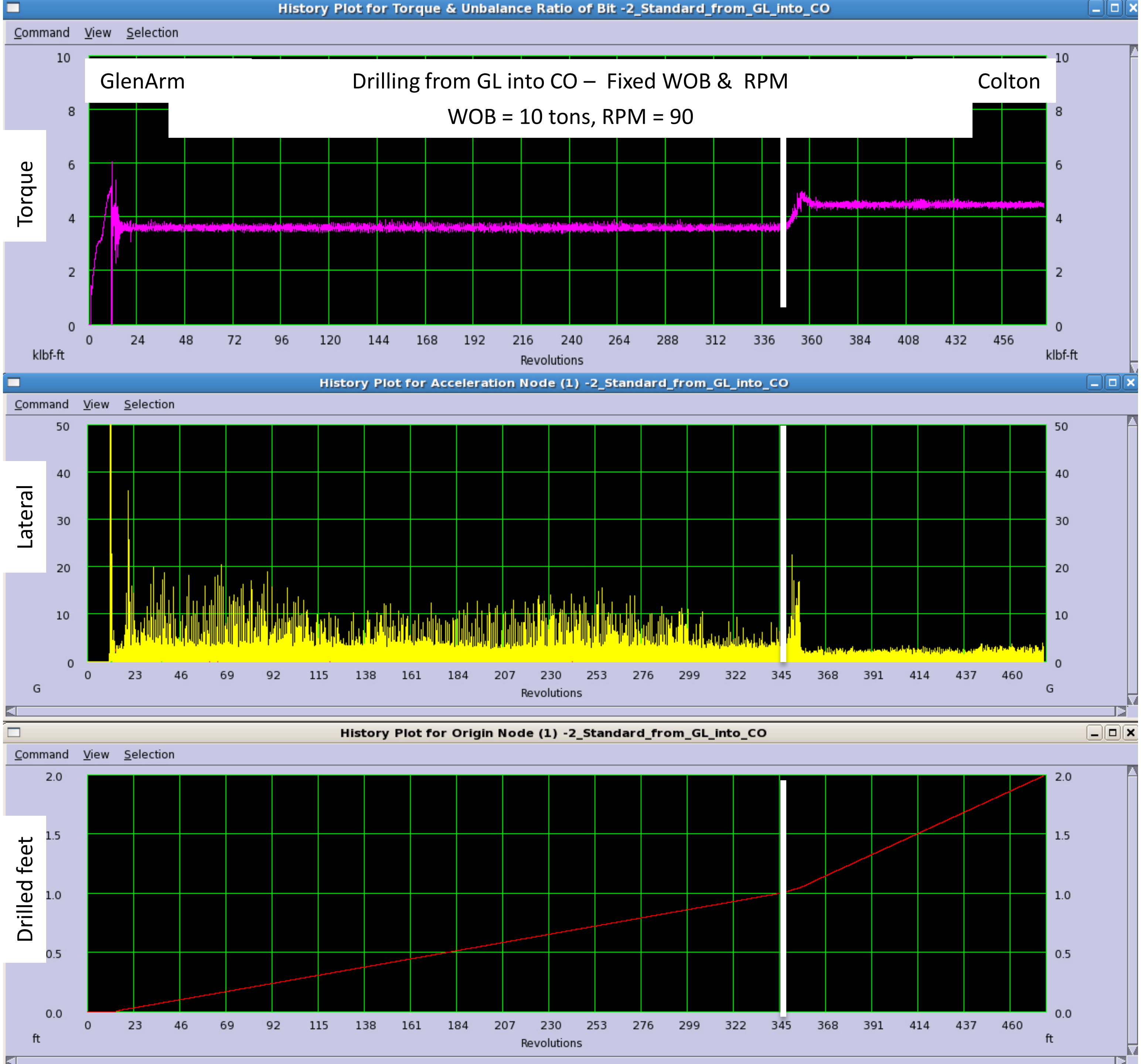

Δ Bit Torque
ΔTorque (klbf-ft)
0
1
2
3
4
5
6
WOB: 3t
RPM: 120
WOB: 3t +-2t
RPM: 120
WOB: 3t
RPM 120 +-20
WOB: 10t
RPM: 90
WOB: 10t +-2t
RPM: 90
WOB: 10t
RPM 90 +-20
CO into GL
CO into GL - Varying WOB
CO into GL - Varying RPM
GL into CO
GL into CO - Varying WOB
GL into CO - Varying RPM

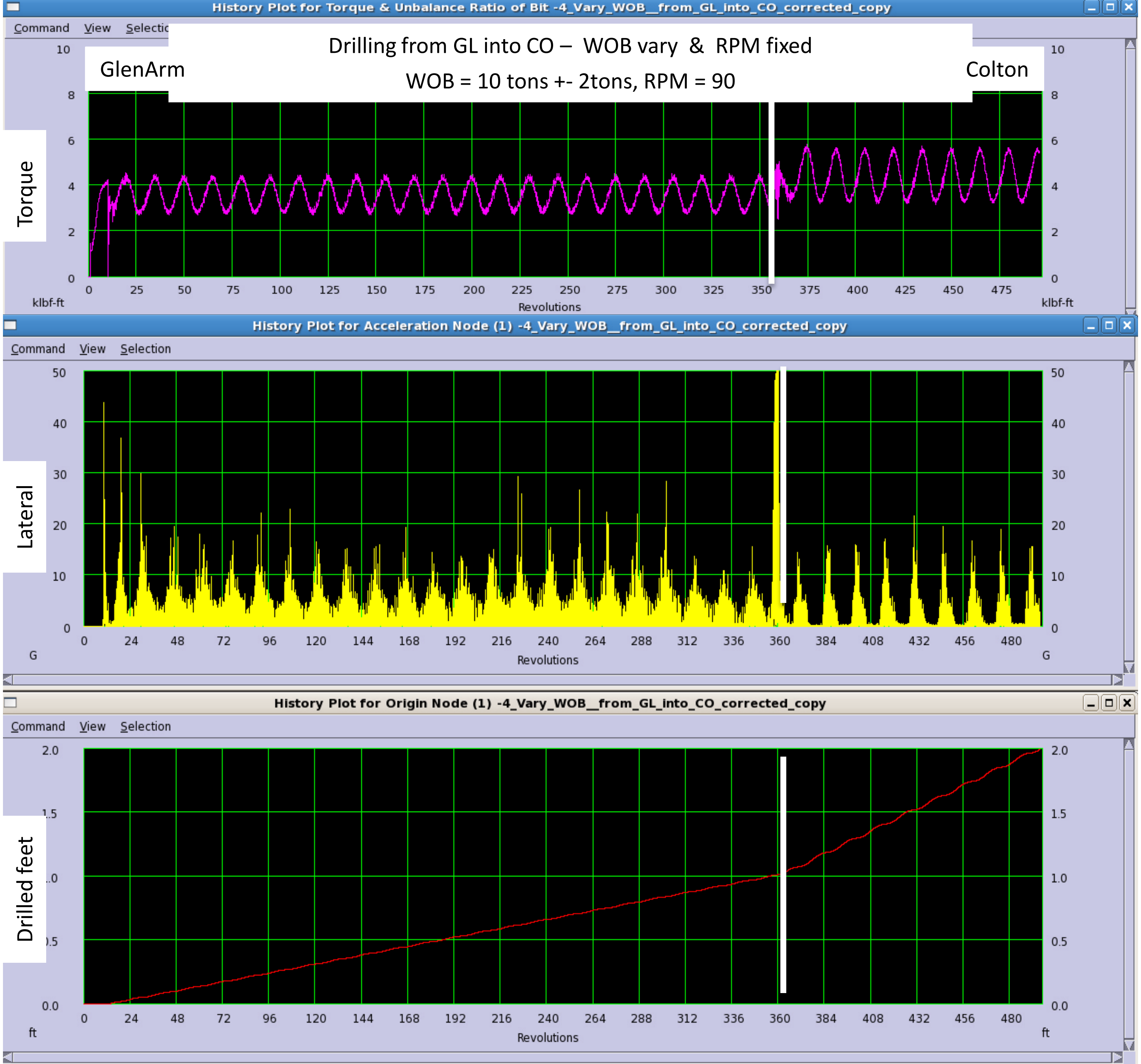


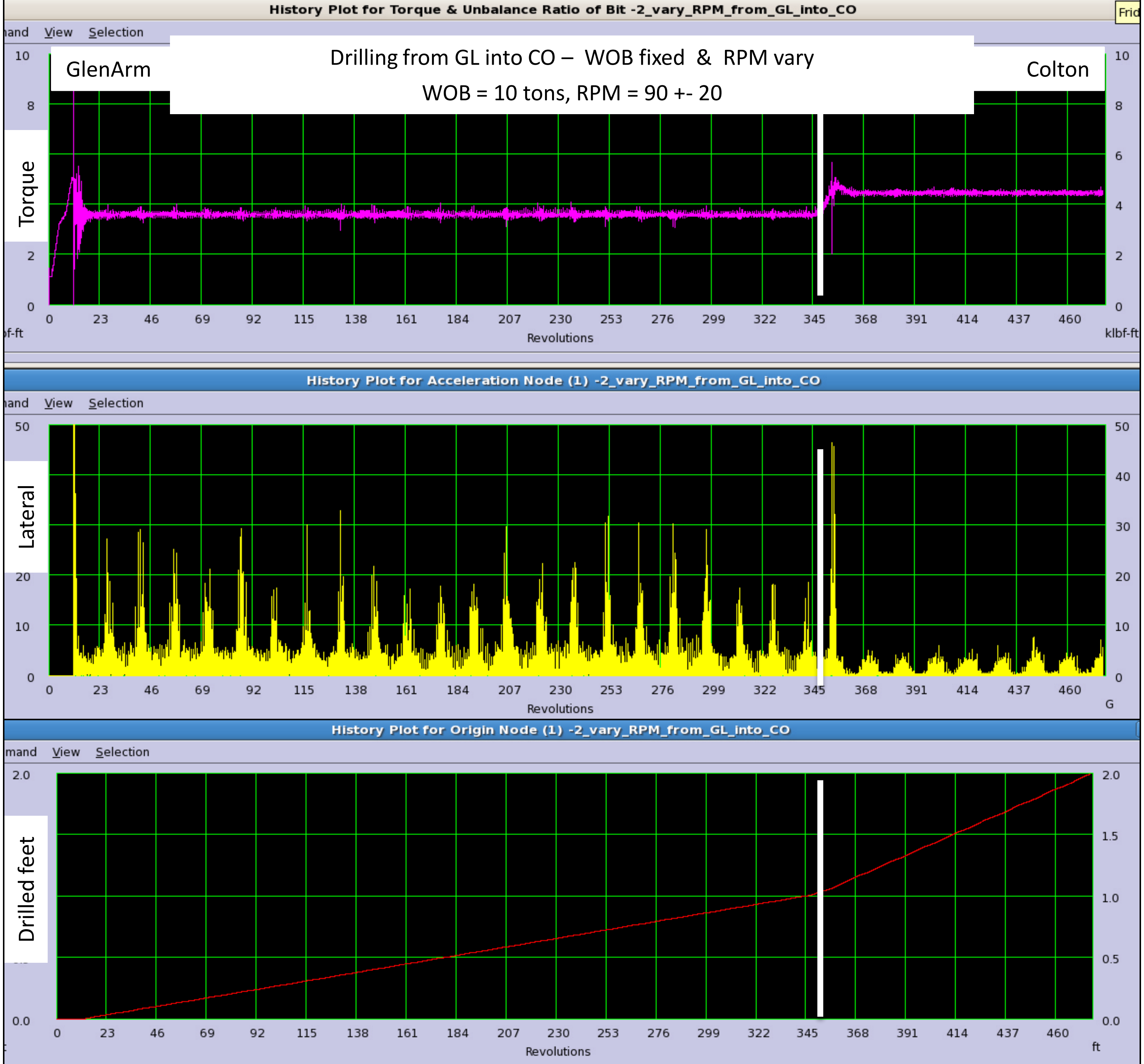
History Plot for Torque & Unbalance Ratio of Bit -1_Standard_from_CO_into_GL
Colton
Drilling from CO into GL – Fixed WOB & RPM
WOB = 3 tons, RPM = 120
GlenArm
Torque
klbf-ft
Revolutions
History Plot for Acceleration Node (1) -1_Standard_from_CO_into_GL
Lateral
G
Revolutions
History Plot for Origin Node (1) -1_Standard_from_CO_into_GL
Drilled feet
ft
Revolutions


History Plot for Torque & Unbalance Ratio of Bit -3_Vary_WOB__from_CO_into_GL
Command View Selection
Colton
Drilling from CO into GL – Vary WOB & Fixed RPM
GlenArm
WOB = 3 tons +- 2 tons, RPM = 120
Torque
0 2 4 6 8 10
0 93 186 279 372 465 558 651 744 837 930 1023 1116 1209 1302 1395 1488 1581 1674 1767 1860
klbf-ft
Revolutions
History Plot for Acceleration Node (1) -3_Vary_WOB__from_CO_into_GL
Command View Selection
Lateral
0 10 20 30 40 50
0 90 180 270 360 450 540 630 720 810 900 990 1080 1170 1260 1350 1440 1530 1620 1710 1800 1890
G
Revolutions
History Plot for Origin Node (1) -3_Vary_WOB__from_CO_into_GL
Command View Selection
Drilled feet
0.0 0.5 1.0 1.5 2.0
0 90 180 270 360 450 540 630 720 810 900 990 1080 1170 1260 1350 1440 1530 1620 1710 1800 1890
ft
Revolutions


History Plot for Torque & Unbalance Ratio of Bit -1_vary_RPM_from_CO_into_GL
Colton
Drilling from CO into GL – Fixed WOB & Vary RPM
WOB = 3 tons, RPM = 120 +- 20
GlenArm
Torque
klbf-ft
Revolutions
0 85 170 255 340 425 510 595 680 765 850 935 1020 1105 1190 1275 1360 1445 1530 1615 1700 1785
History Plot for Acceleration Node (1) -1_vary_RPM_from_CO_into_GL
Lateral
G
Revolutions
History Plot for Origin Node (1) -1_vary_RPM_from_CO_into_GL
Drilled feet
ft
Revolutions


History Plot for Torque & Unbalance Ratio of Bit -2_Standard_from_GL_into_CO
Command View Selection
GlenArm
Drilling from GL into CO – Fixed WOB & RPM
Colton
WOB = 10 tons, RPM = 90
Torque
10 8 6 4 2 0
0 24 48 72 96 120 144 168 192 216 240 264 288 312 336 360 384 408 432 456
klbf-ft
Revolutions
klbf-ft
History Plot for Acceleration Node (1) -2_Standard_from_GL_into_CO
Command View Selection
Lateral
50 40 30 20 10 0
0 23 46 69 92 115 138 161 184 207 230 253 276 299 322 345 368 391 414 437 460
G
Revolutions
G
History Plot for Origin Node (1) -2_Standard_from_GL_into_CO
Command View Selection
Drilled feet
2.0 1.5 1.0 0.5 0.0
0 23 46 69 92 115 138 161 184 207 230 253 276 299 322 345 368 391 414 437 460
ft
Revolutions
ft


History Plot for Torque & Unbalance Ratio of Bit -4_Vary_WOB__from_GL_into_CO_corrected_copy
Drilling from GL into CO – WOB vary & RPM fixed
WOB = 10 tons +- 2tons, RPM = 90
GlenArm
Colton
Torque
klbf-ft
Revolutions
History Plot for Acceleration Node (1) -4_Vary_WOB__from_GL_into_CO_corrected_copy
Lateral
G
Revolutions
History Plot for Origin Node (1) -4_Vary_WOB__from_GL_into_CO_corrected_copy
Drilled feet
ft
Revolutions


History Plot for Torque & Unbalance Ratio of Bit -2_vary_RPM_from_GL_into_CO
Drilling from GL into CO – WOB fixed & RPM vary
WOB = 10 tons, RPM = 90 +- 20
GlenArm
Colton
Torque
klbf-ft
Revolutions
History Plot for Acceleration Node (1) -2_vary_RPM_from_GL_into_CO
Lateral
G
Revolutions
History Plot for Origin Node (1) -2_vary_RPM_from_GL_into_CO
Drilled feet
ft
Revolutions