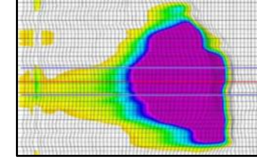
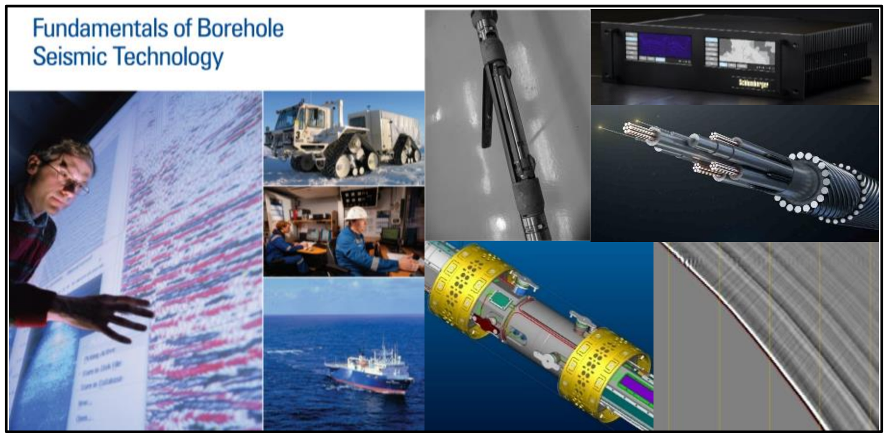
NORWEGIAN PETROLEUM DIRECTORATE
50 years

FORCE



# NPD FORCE Geophysical Methods Group

## *LWD Seismic While Drilling technology*



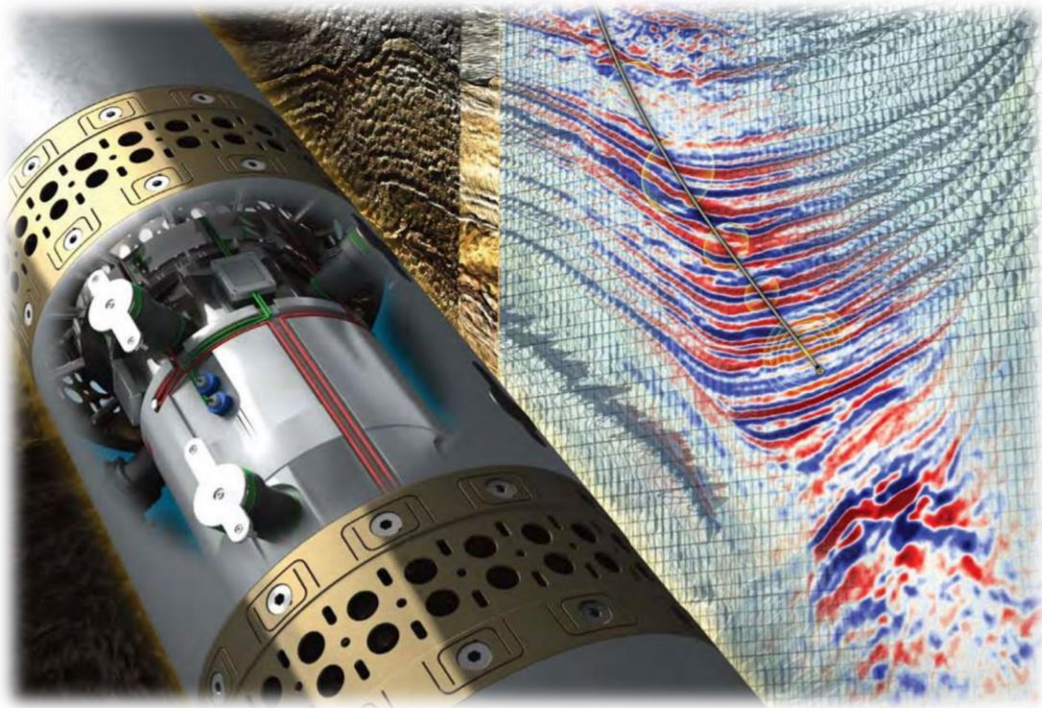

***By:*** *Neil Kelsall (LWD Domain Geophysicist)*

Schlumberger

Stavanger, 04-Oct-2022

# Agenda

- Seismic While Drilling
  - What is it?
  - How does it work?
  - Overcoming challenges in a drilling environment
- Review examples of different applications
- Potential new application



# Seismic While Drilling

- Length: ~ 14 ft
- Pressure Rating: 23k – 30k PSI
- Any Hole size > 8 3/8”
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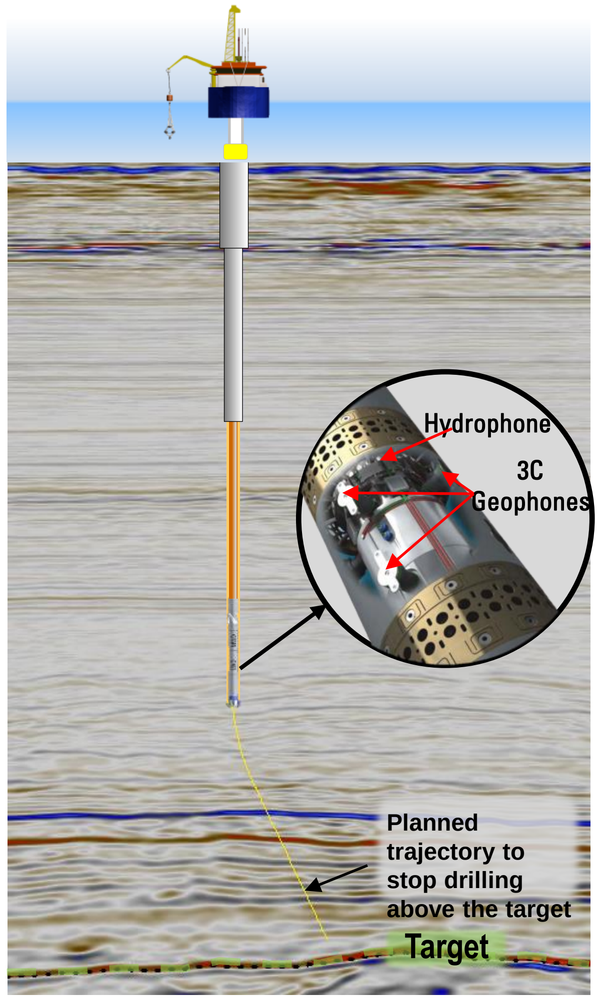

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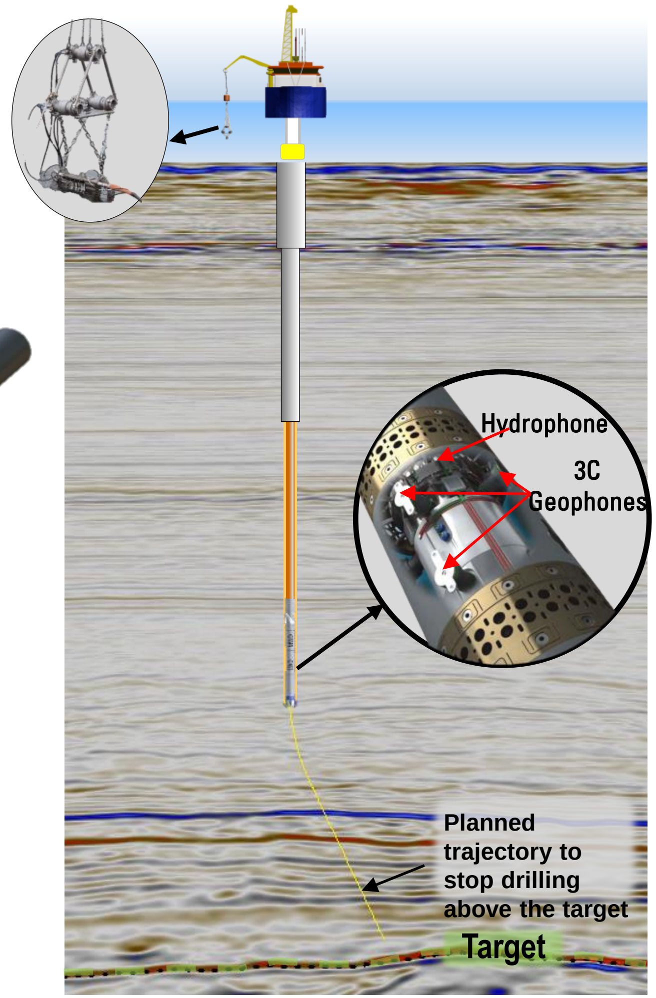

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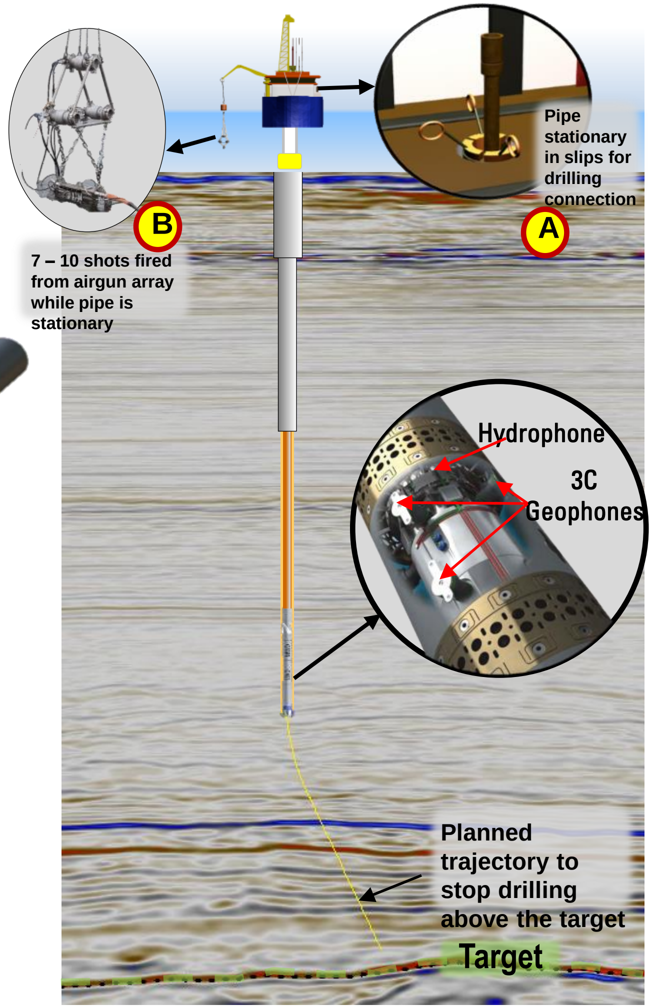
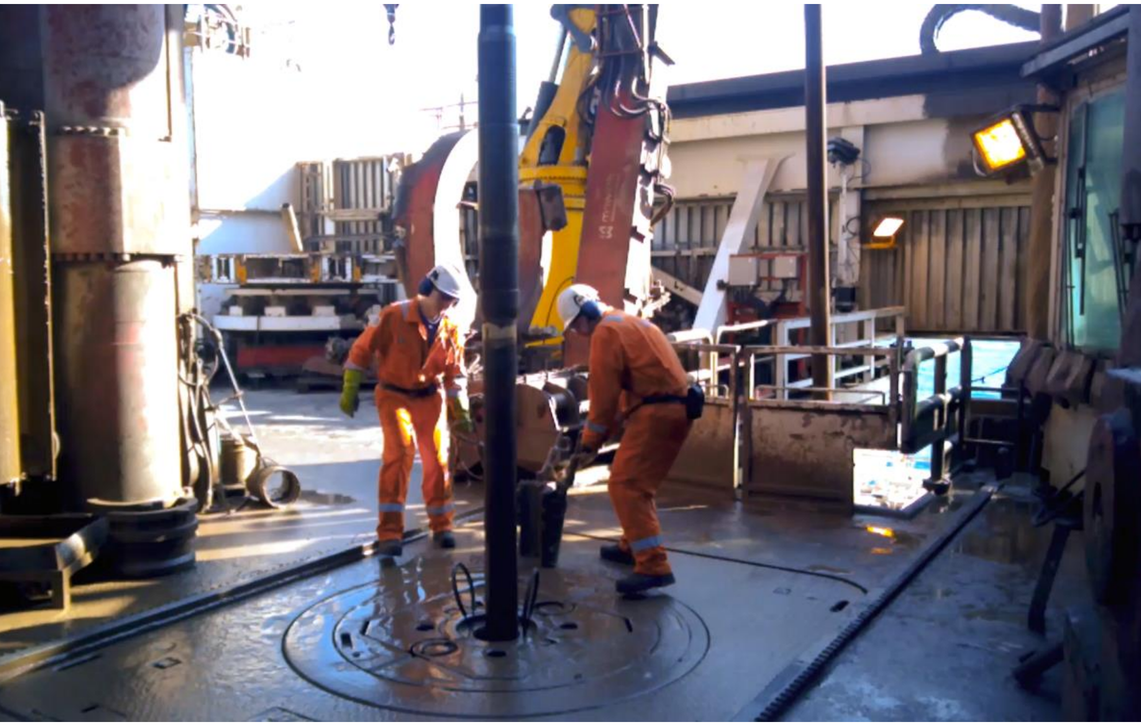
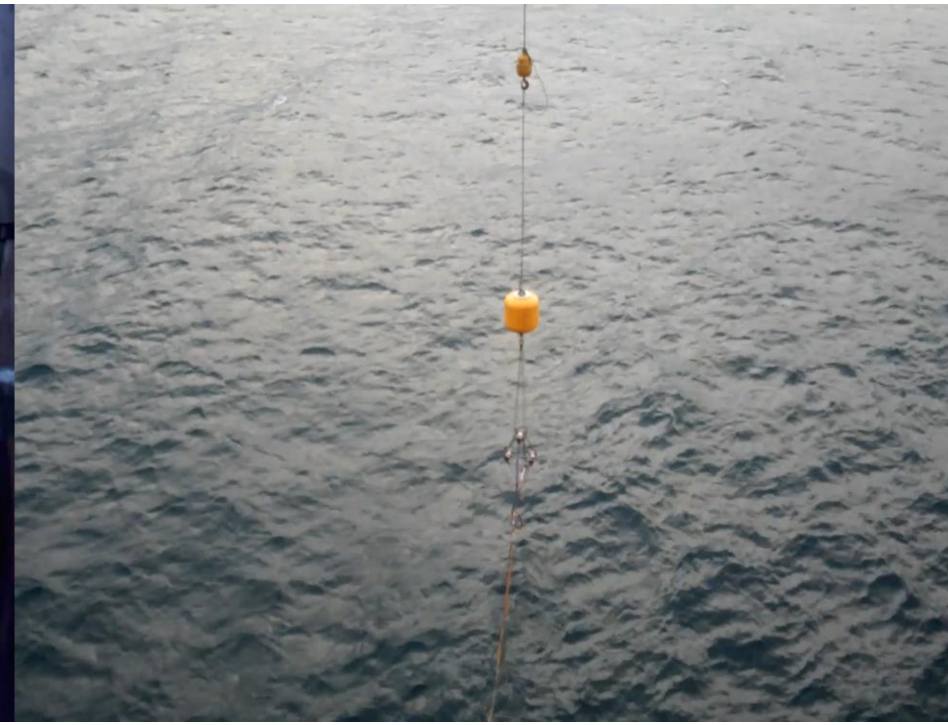


# ZERO RIG TIME FOR NORMAL DRILLING ACQUISITION



4 x Playback Speed



4 x Playback Speed when shooting

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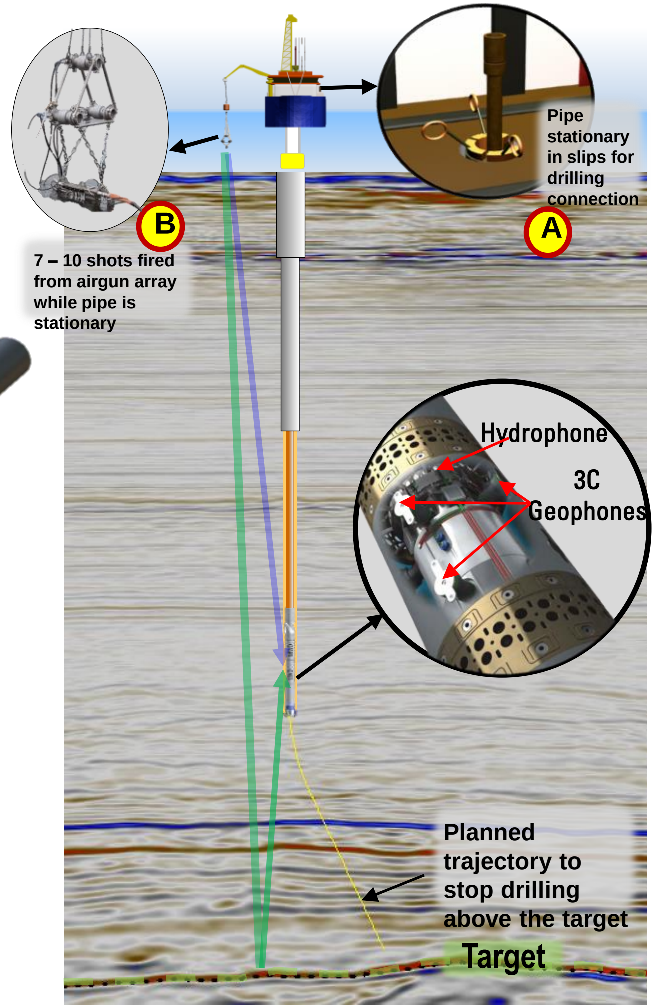

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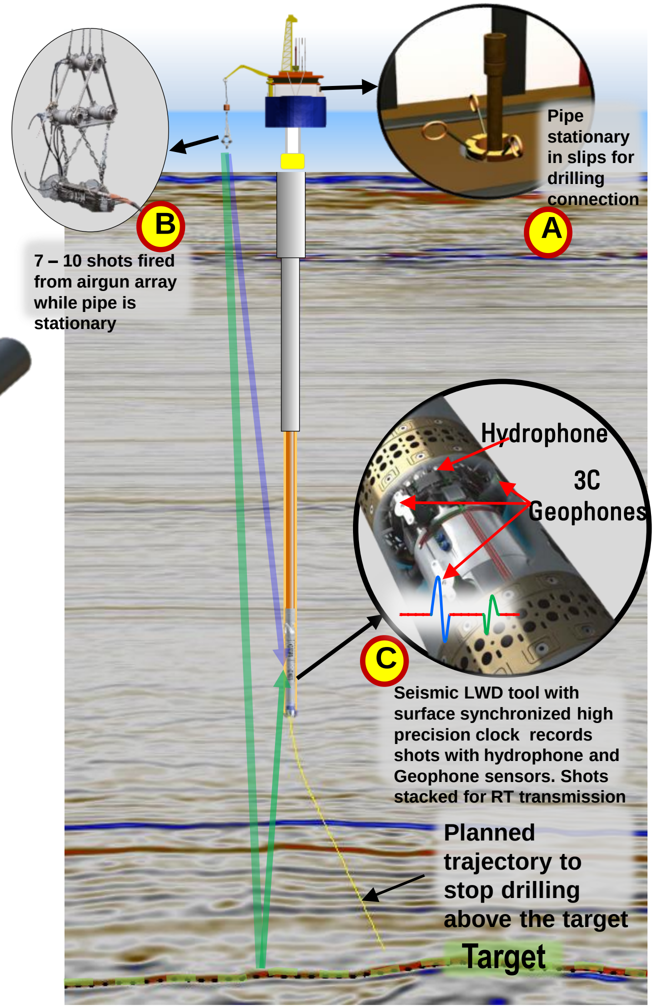




Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

# Seismic While Drilling

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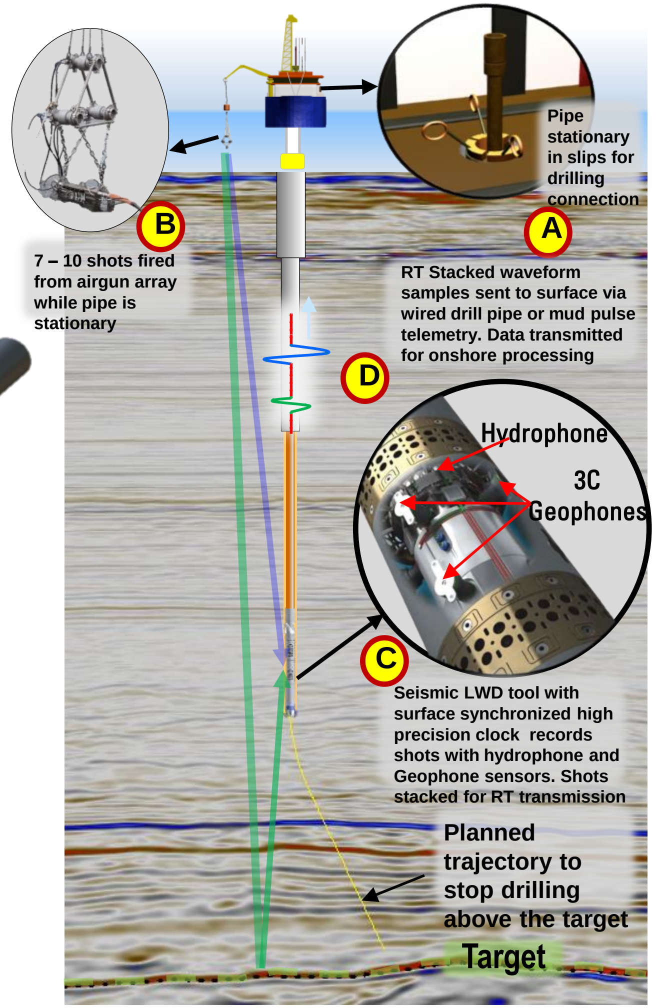

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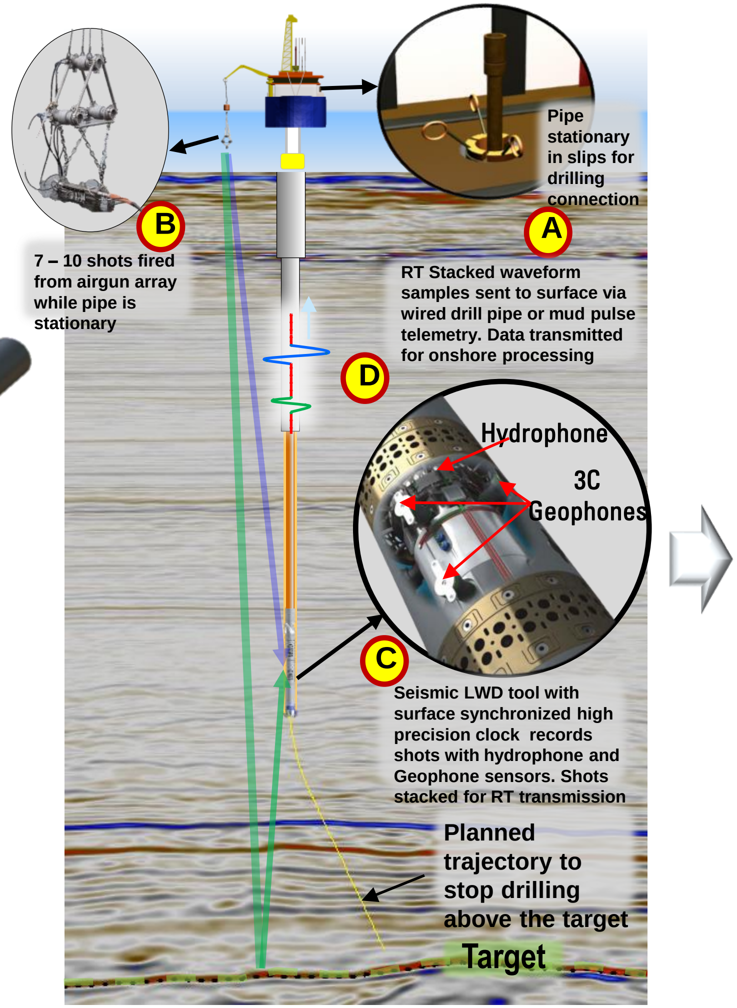
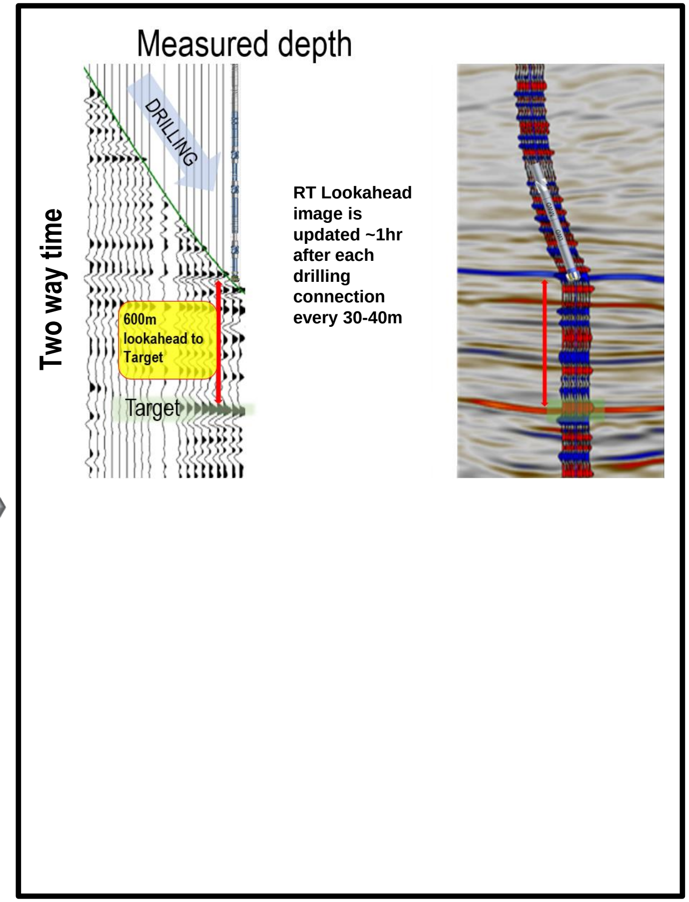



Real Time Lookahead VSP




OTC-30811-MS • Safe Landing Of A Deviated Well With A Rig Source VSP Using RT Lookahead Seismic Technology • Neil Kelsall et al

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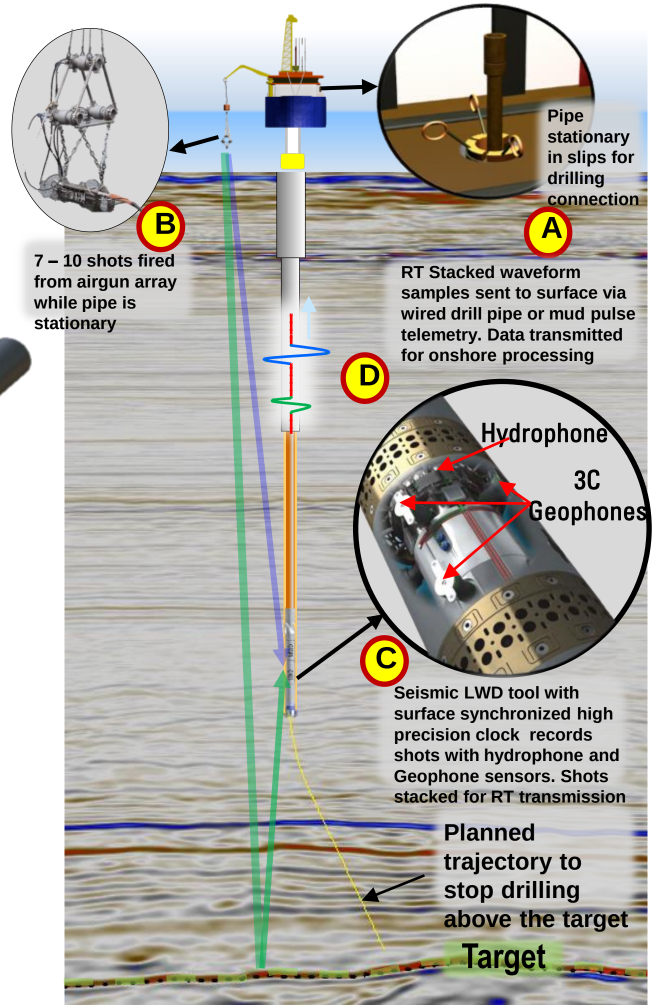
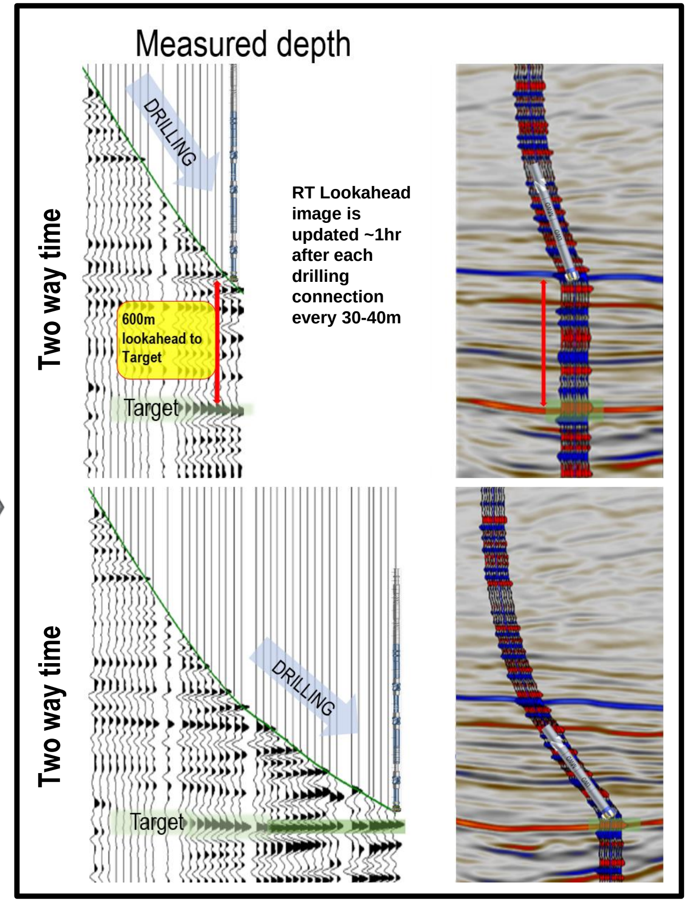


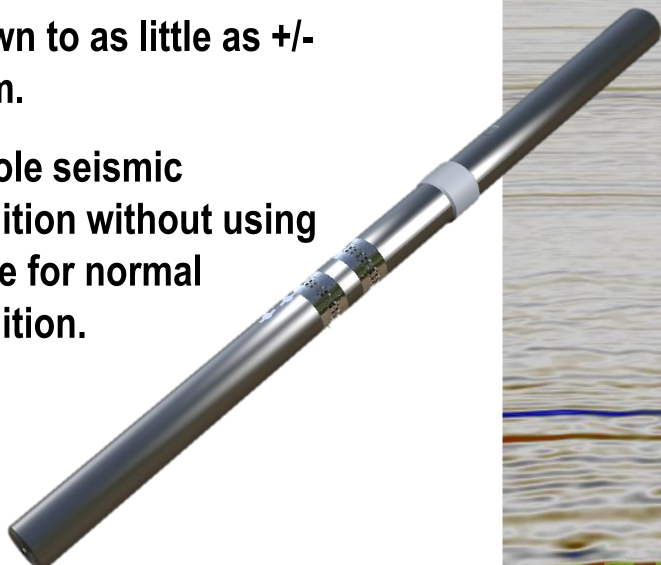

**Real Time Lookahead VSP**

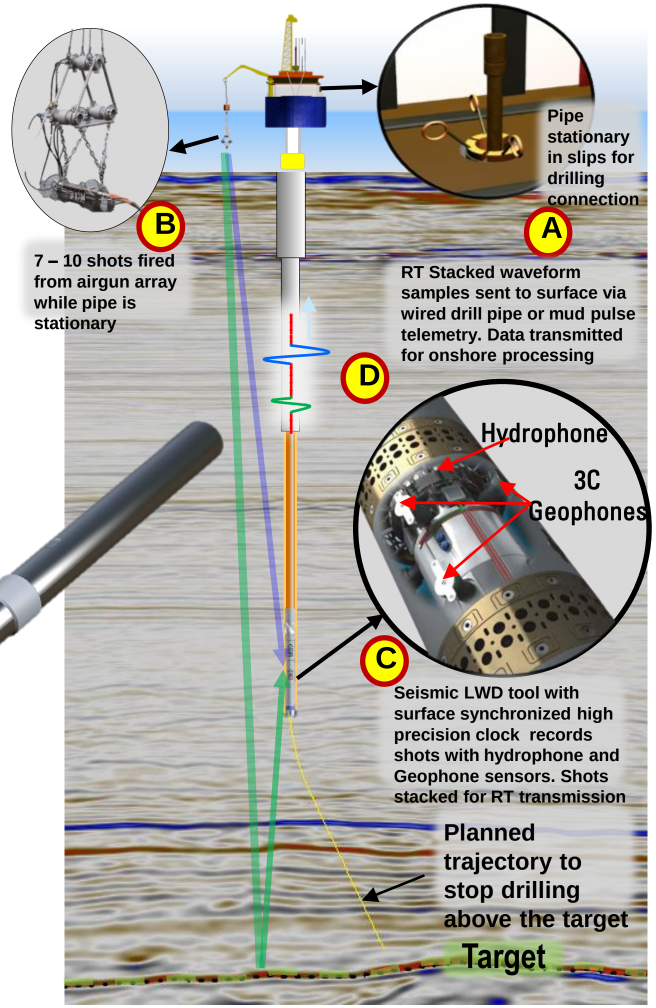



OTC-30811-MS • Safe Landing Of A Deviated Well With A Rig Source VSP Using RT Lookahead Seismic Technology • Neil Kelsall et al

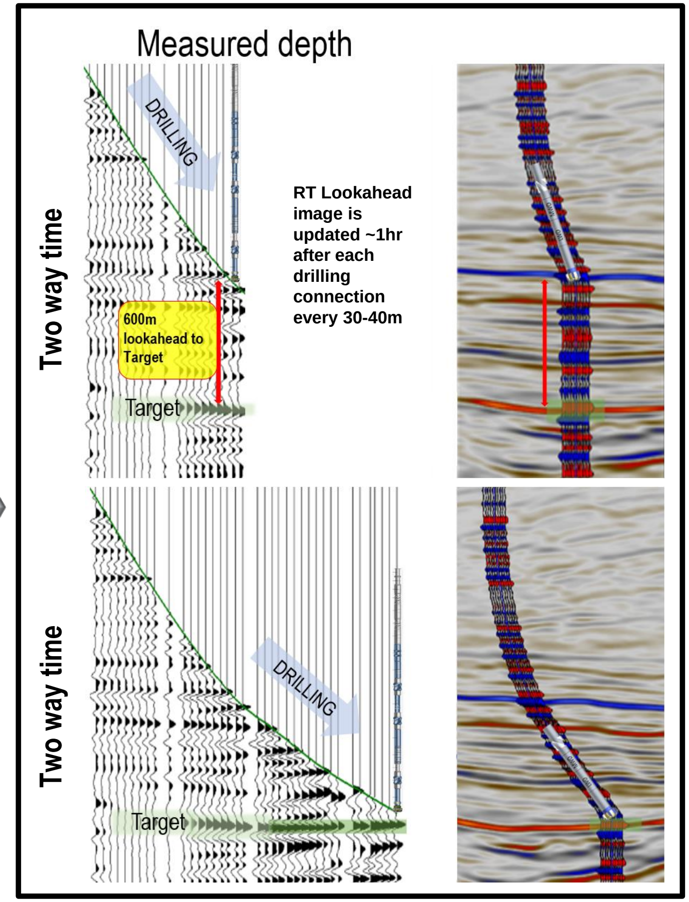
# Seismic While Drilling

- The only technology that can provide over 100m of lookahead while drilling:
  - Depth uncertainty reflectors ahead reduced down to as little as +/- 10m.
- Borehole seismic acquisition without using rig time for normal acquisition.

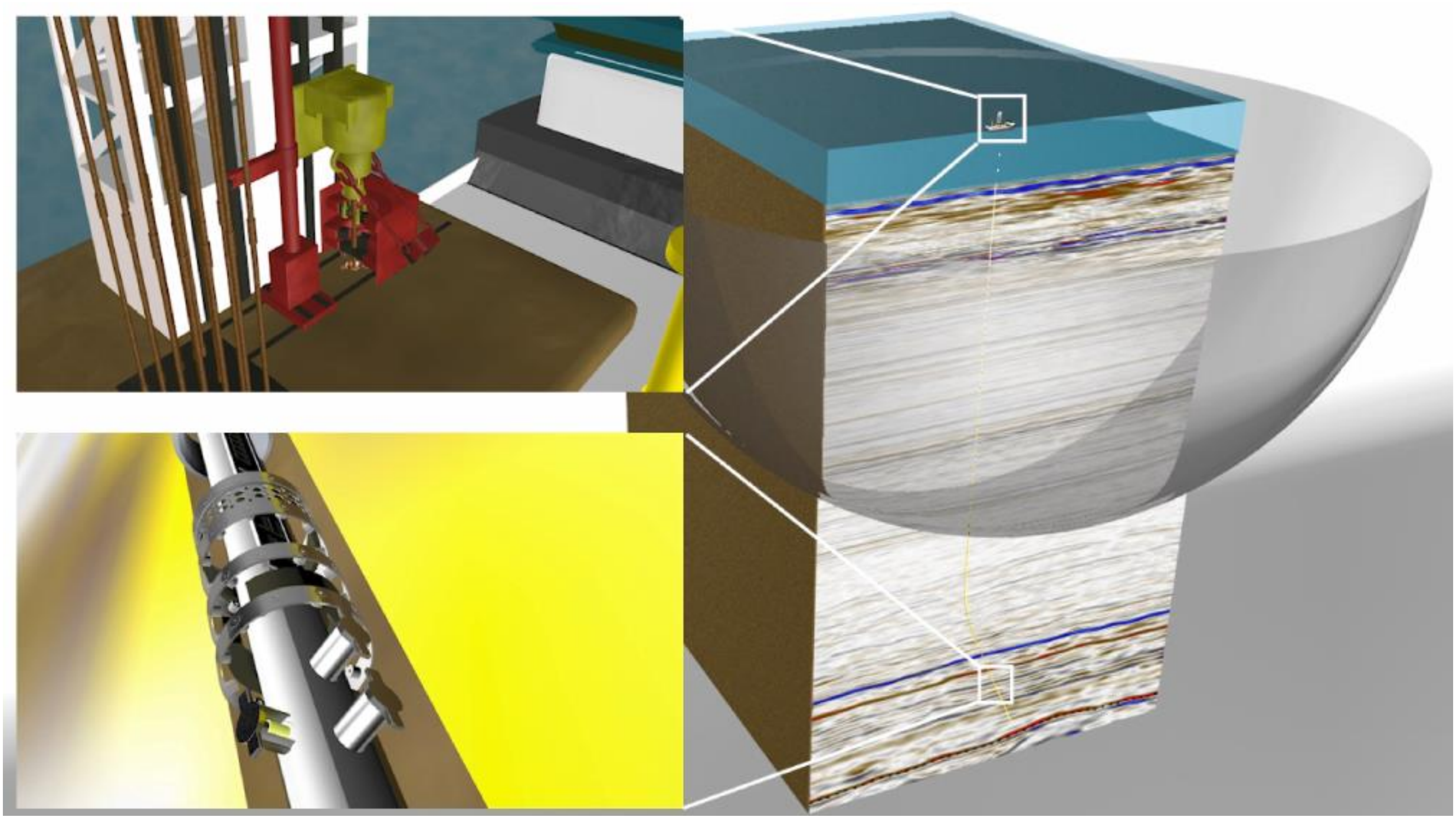





Real Time Lookahead VSP



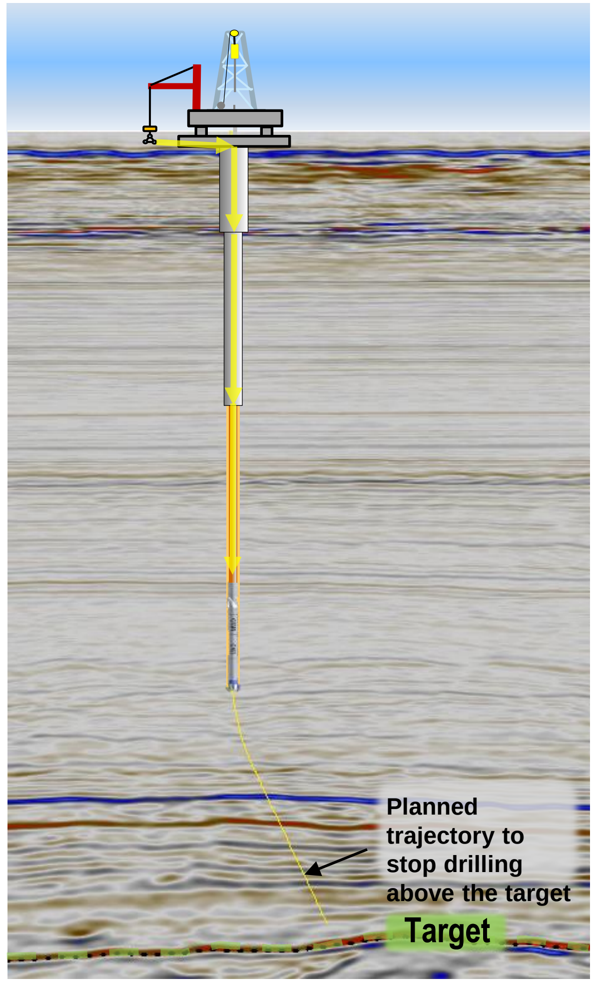

OTC-30811-MS • Safe Landing Of A Deviated Well With A Rig Source VSP Using RT Lookahead Seismic Technology • Neil Kelsall et al



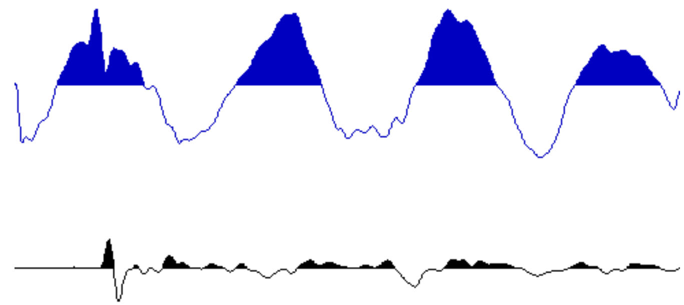
# ACQUISITION CHALLENGES

**Noise Types:**

- Vibration through pipe and casing




**Raw RT waveform acquired with noise**



**Raw RT waveform acquired without noise**

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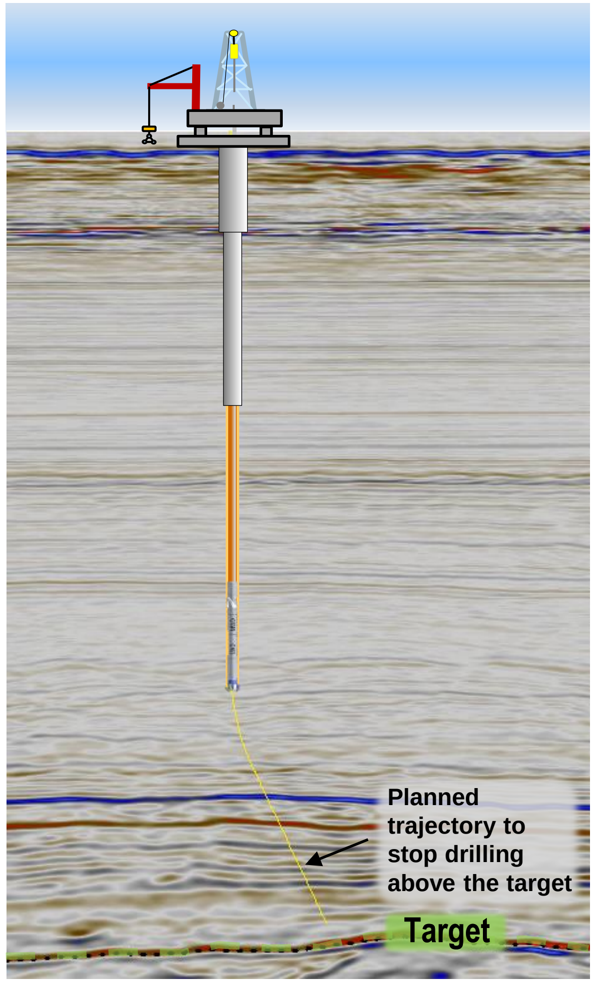
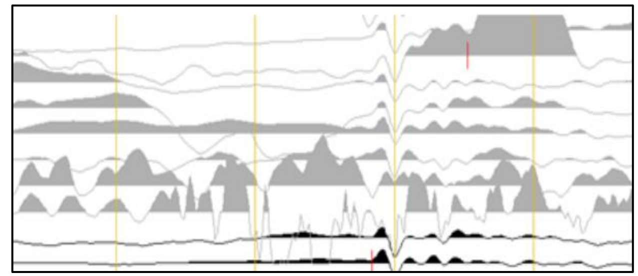
**Noise Types:**

- Vibration through pipe and casing
- **Pipe movement due to rig heave**




**Raw shot data with pipe motion**



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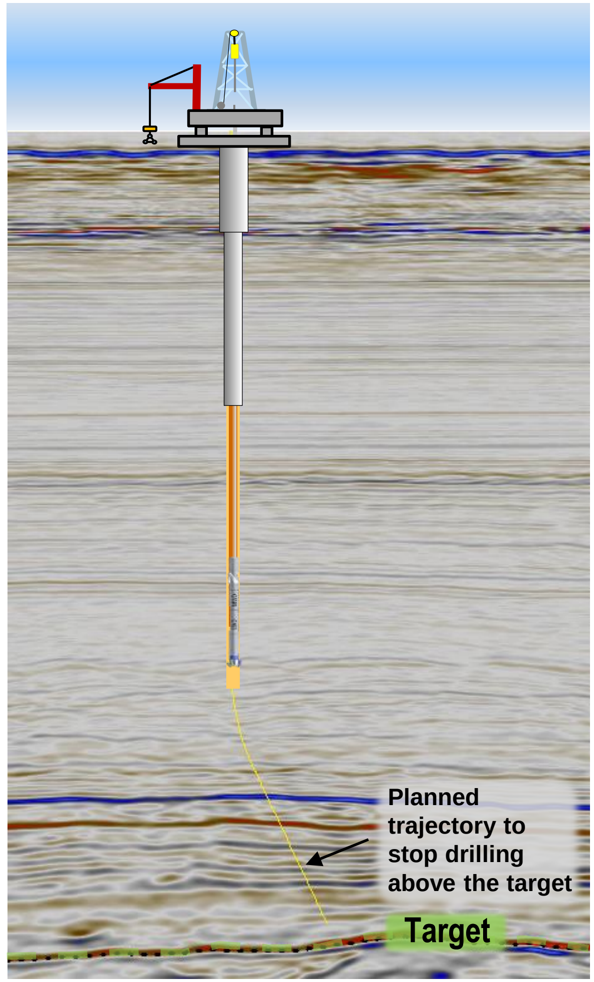


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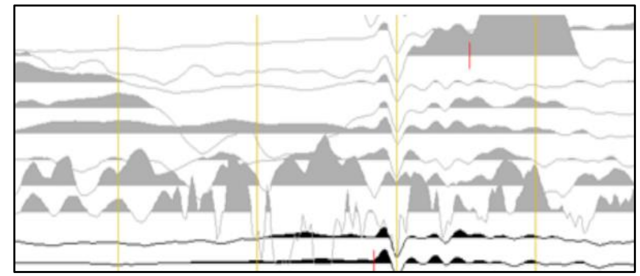

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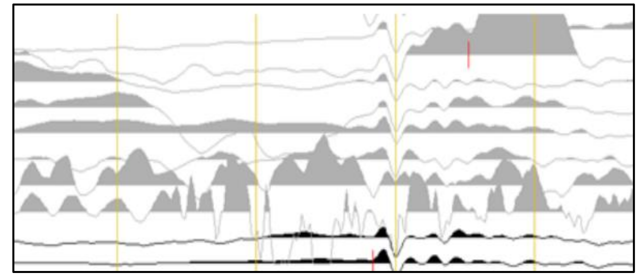

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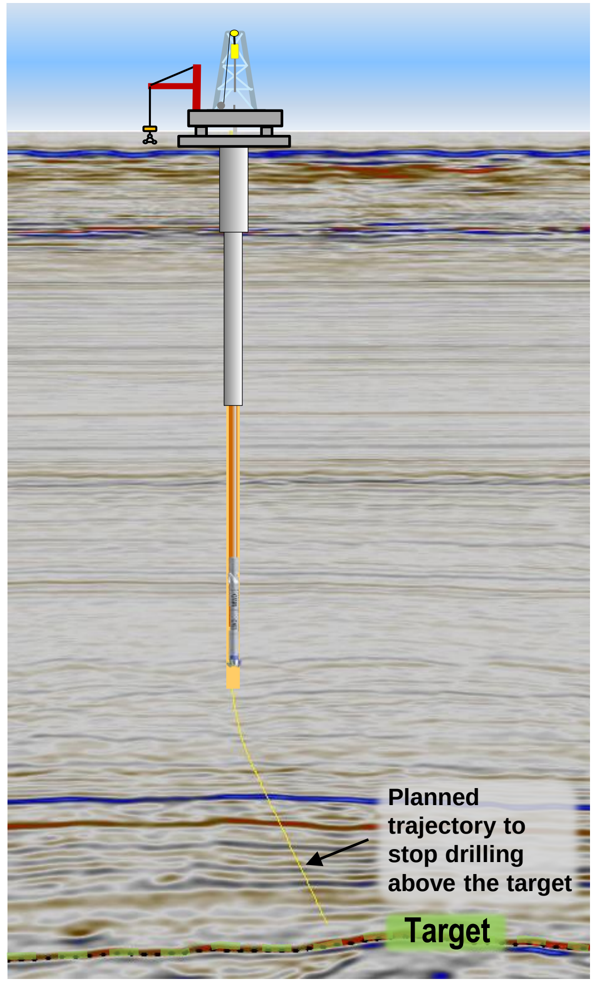


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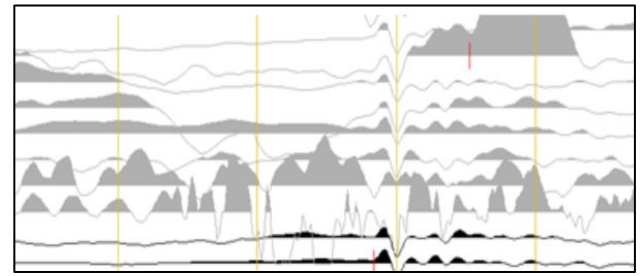

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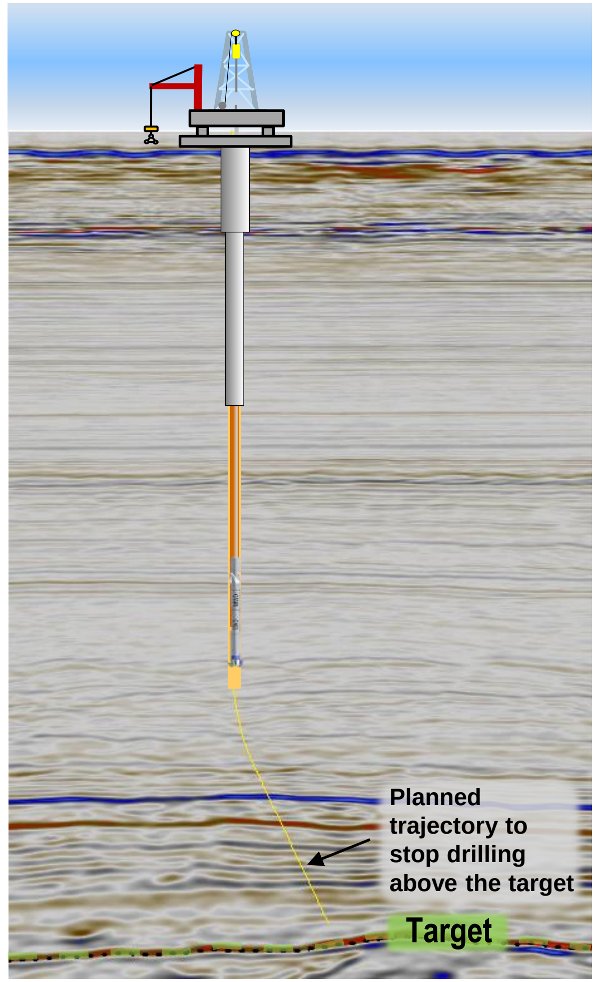
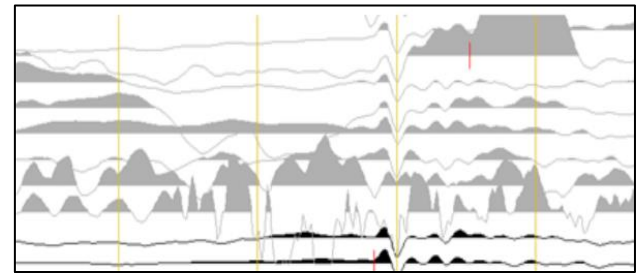
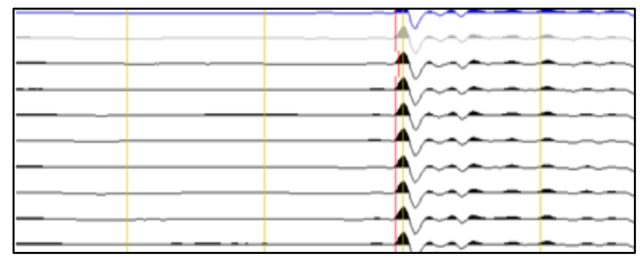


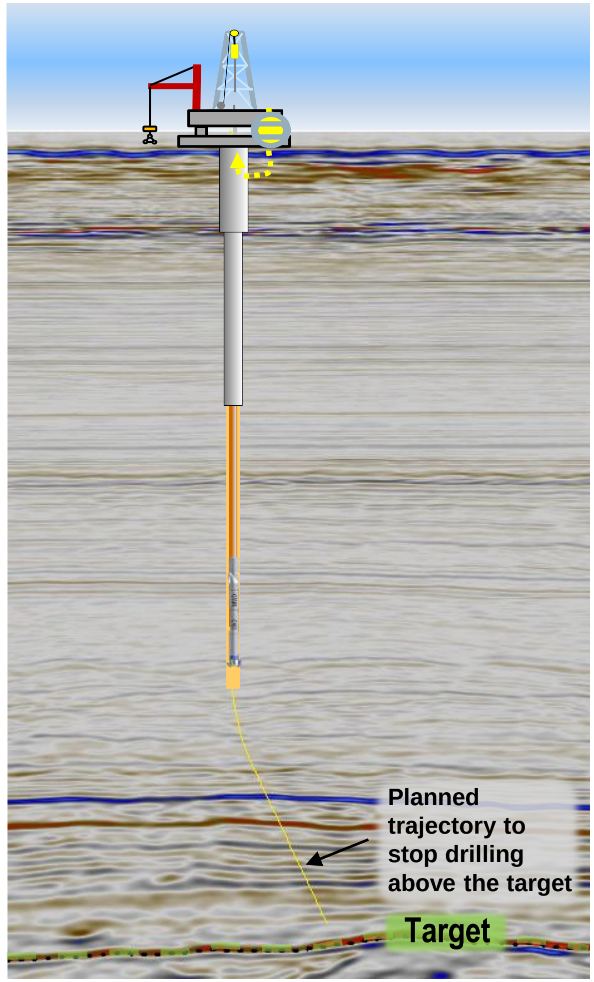

**Raw shot data with pipe motion**





**Raw shot data without pipe motion (Active heave compensation engage**

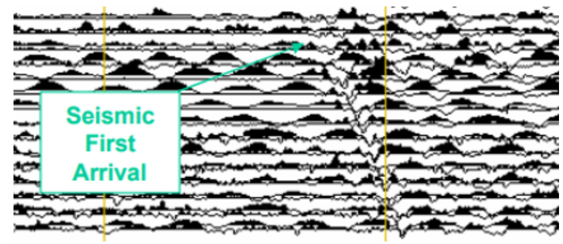
# ACQUISITION CHALLENGES




**Noise Types:**

- Vibration through pipe and casing
- Pipe movement due to rig heave
- **Riser Boost pump noise**

**Raw shot data with boost pump noise**



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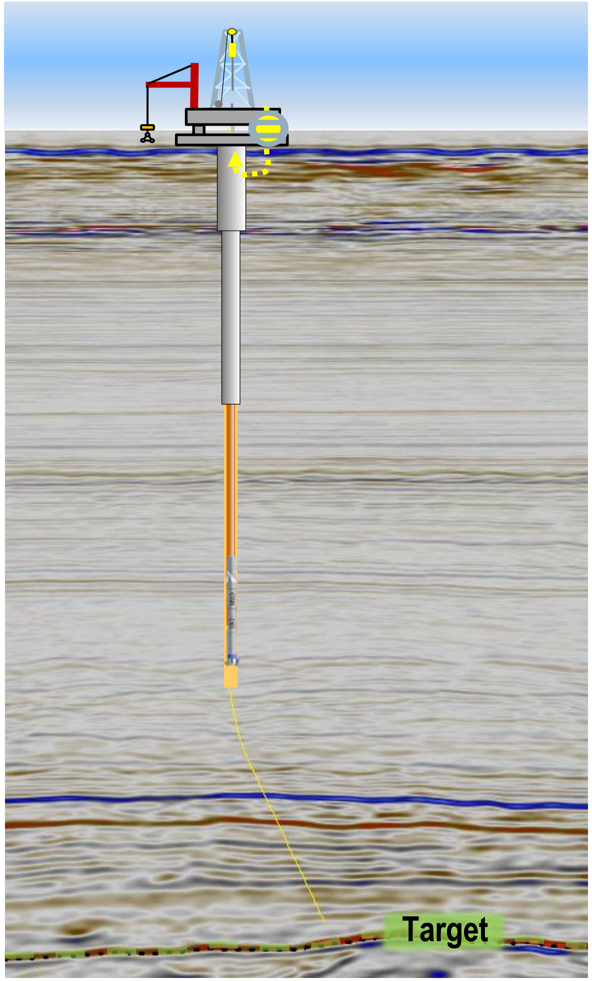
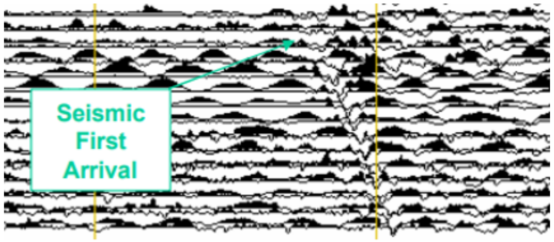
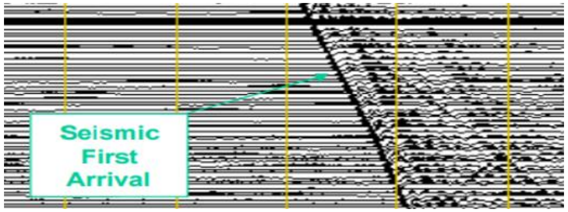



Raw shot data with boost pump noise



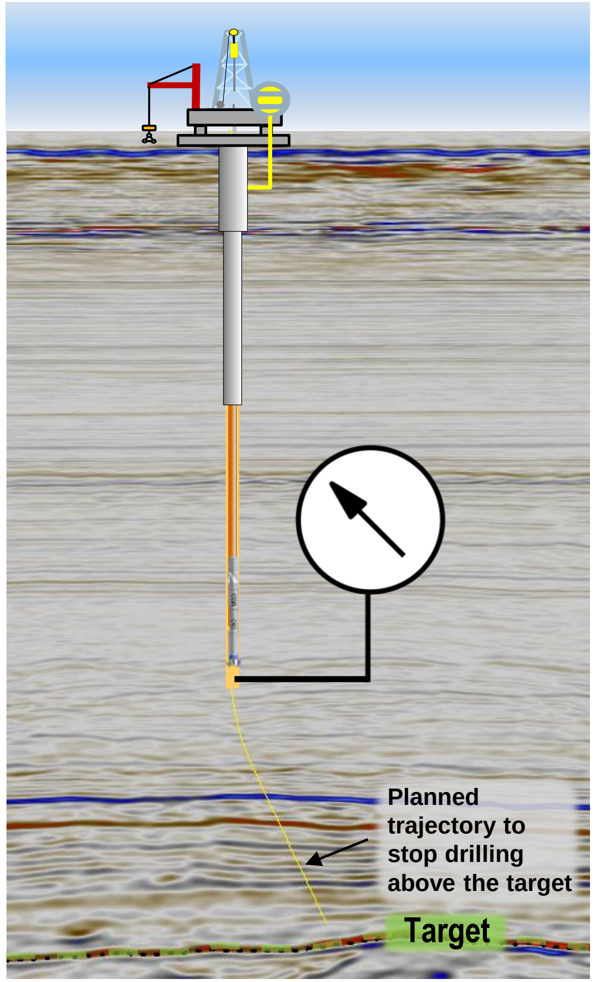



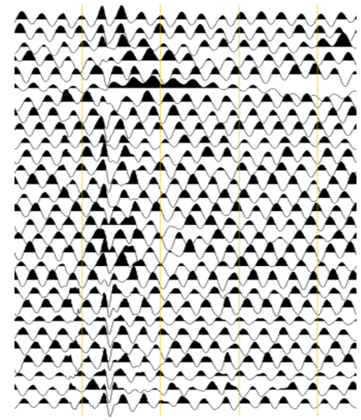

**Raw shot data without boost pump**

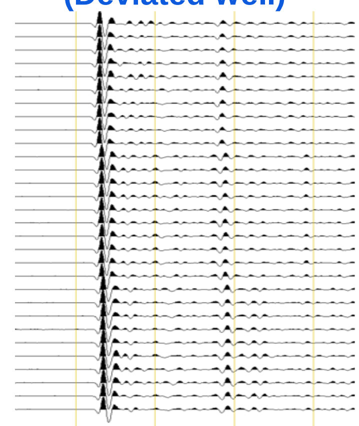
# ACQUISITION CHALLENGES

## Noise Types:

- Vibration through pipe and casing
- Pipe movement due to rig heave
- Riser Boost pump noise
- **Managed Pressure Drilling System**

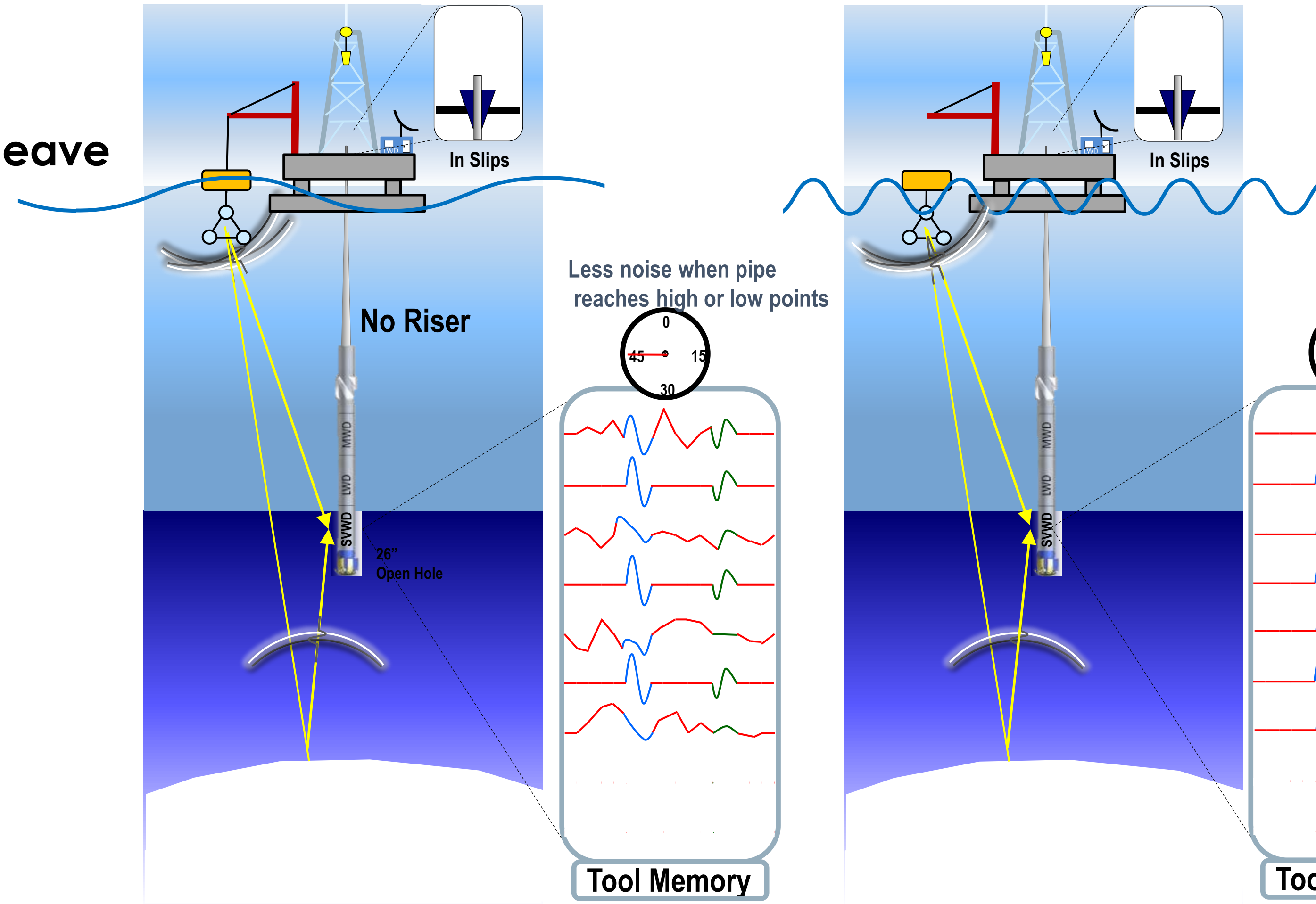


# SOLUTIONS TO ACQUISITION CHALLENGES

- **Rig Heave**



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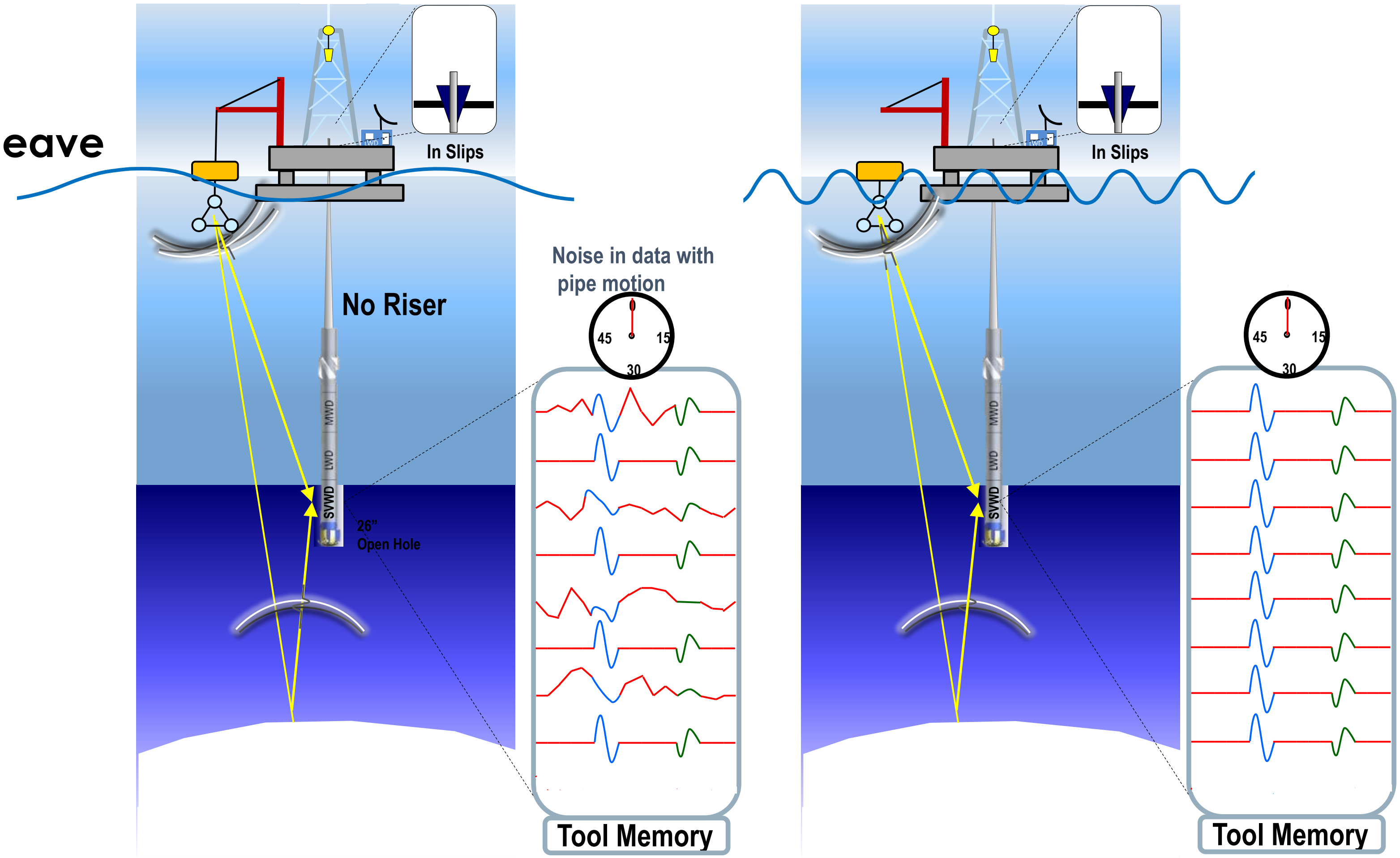

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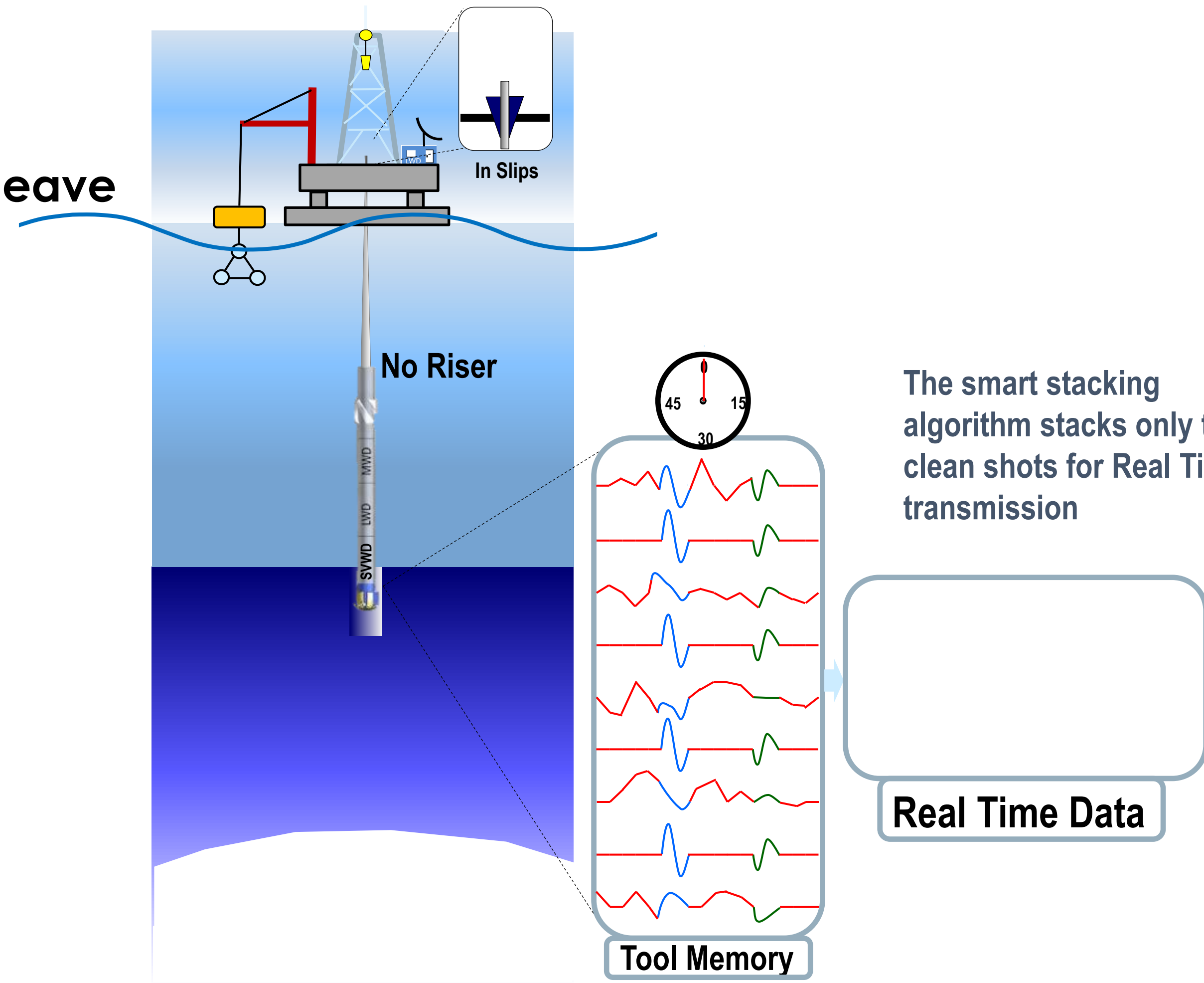


The smart stacking algorithm stacks only the clean shots for Real Time transmission

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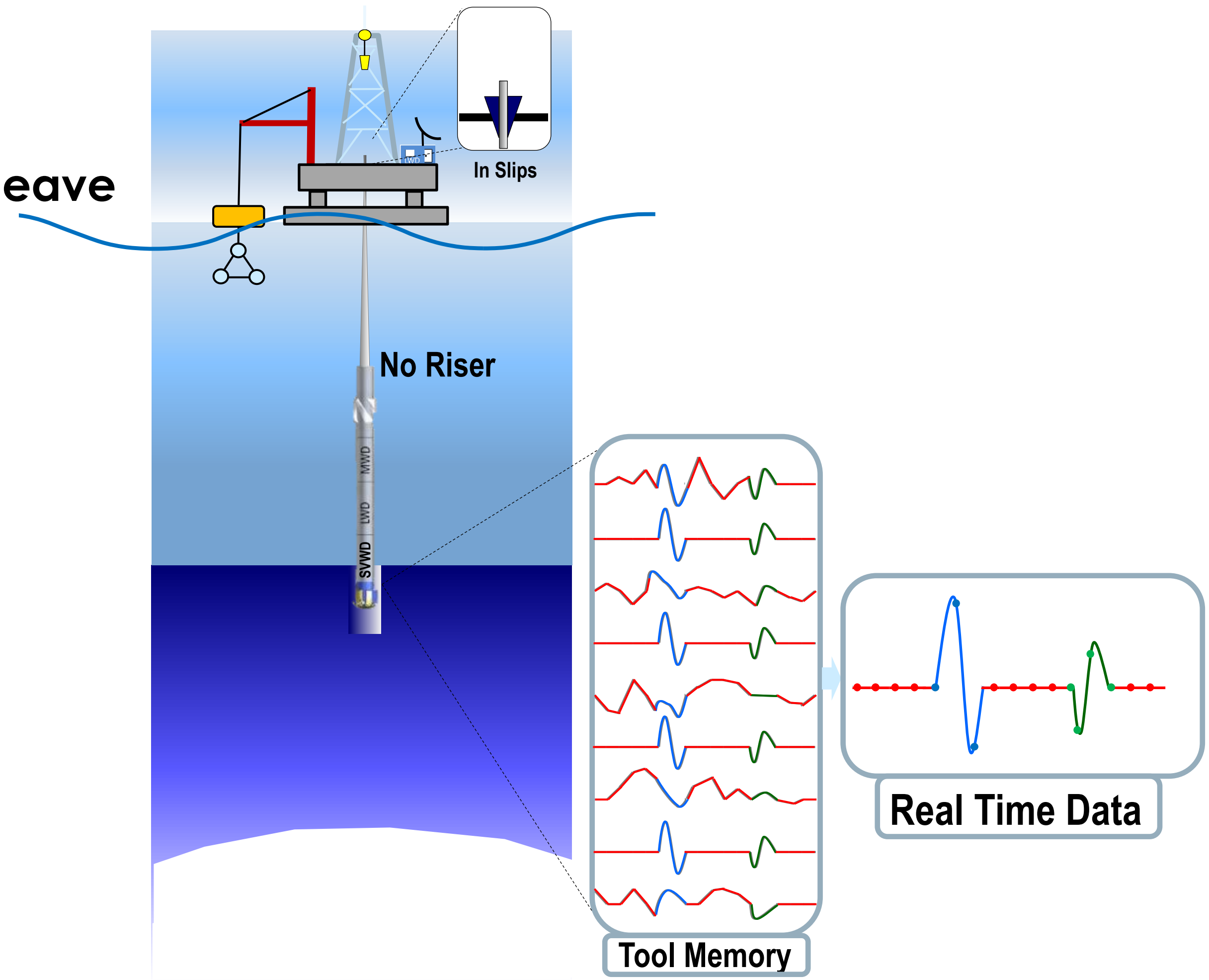

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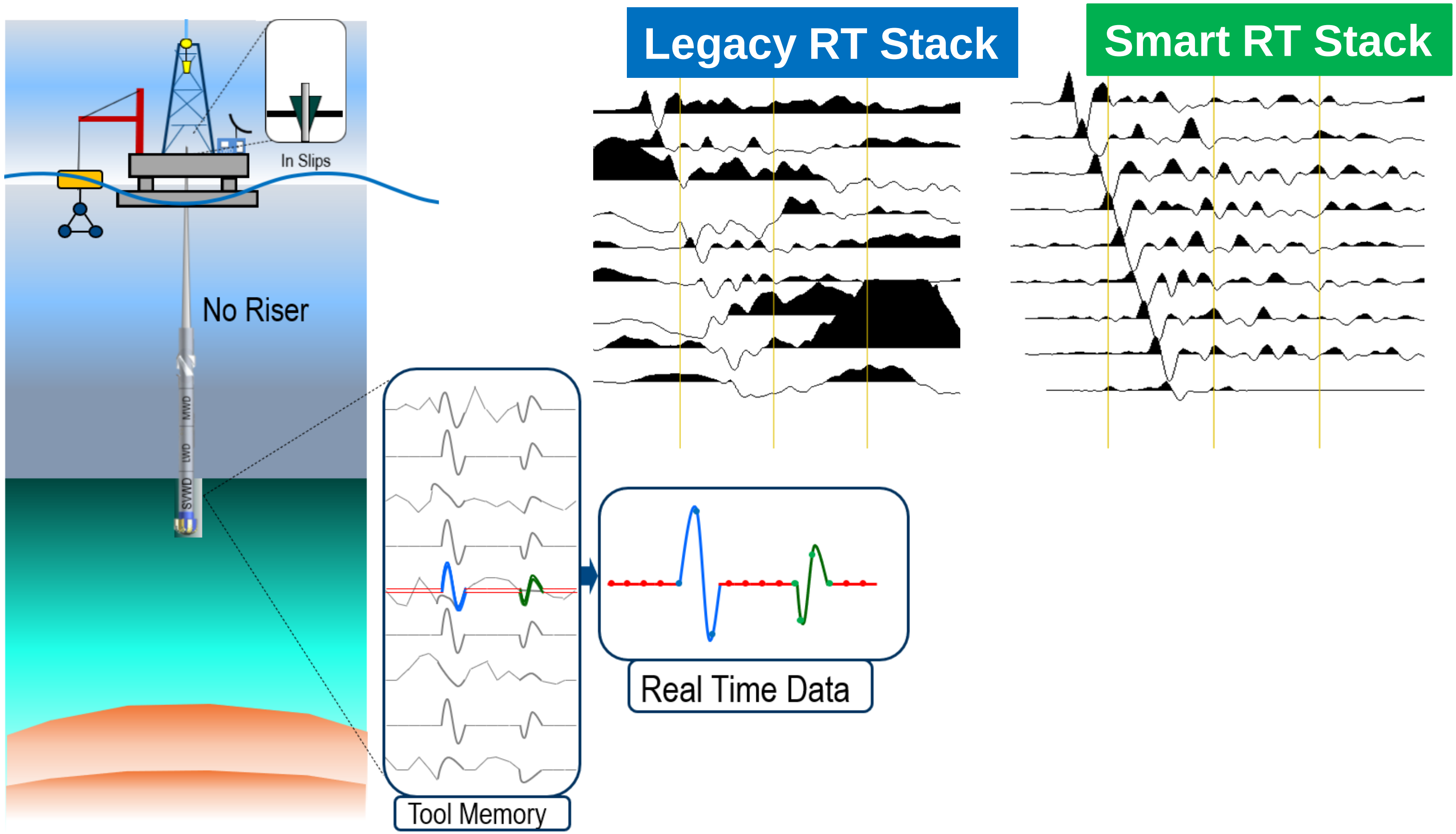

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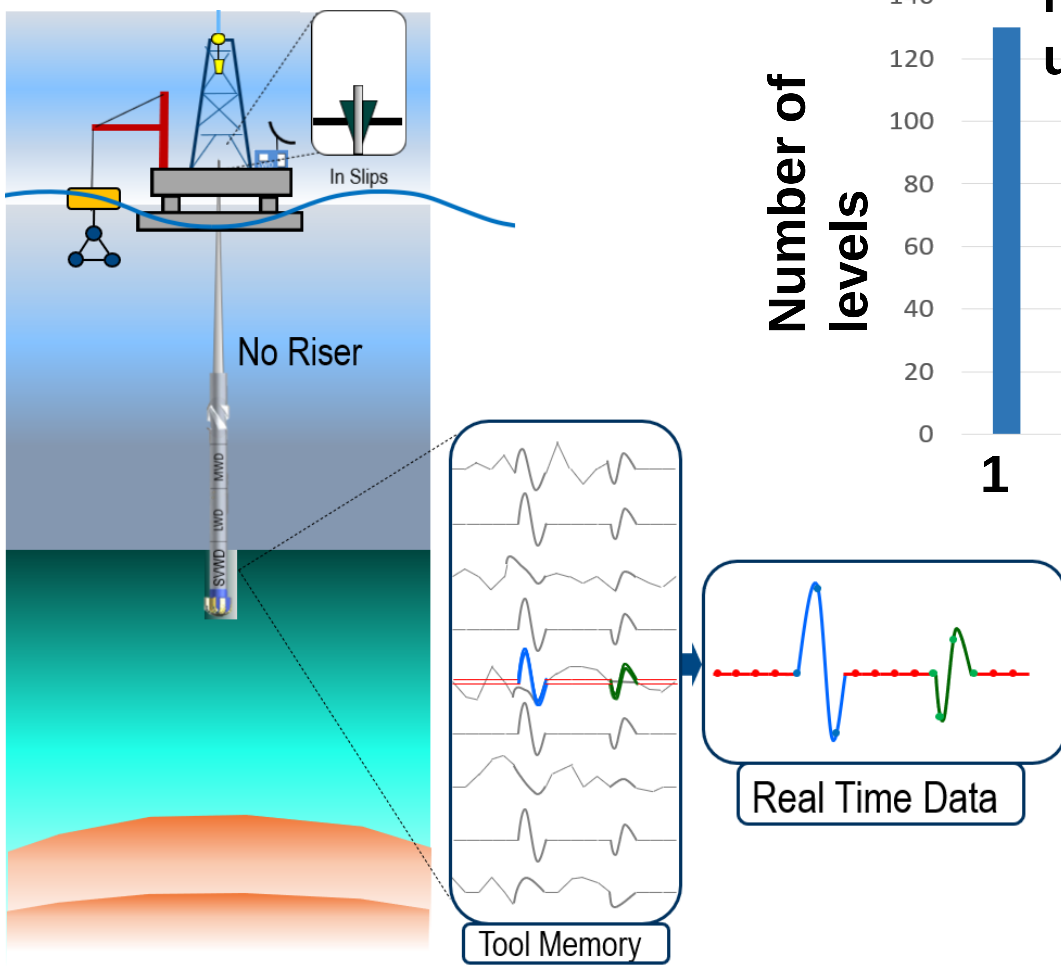
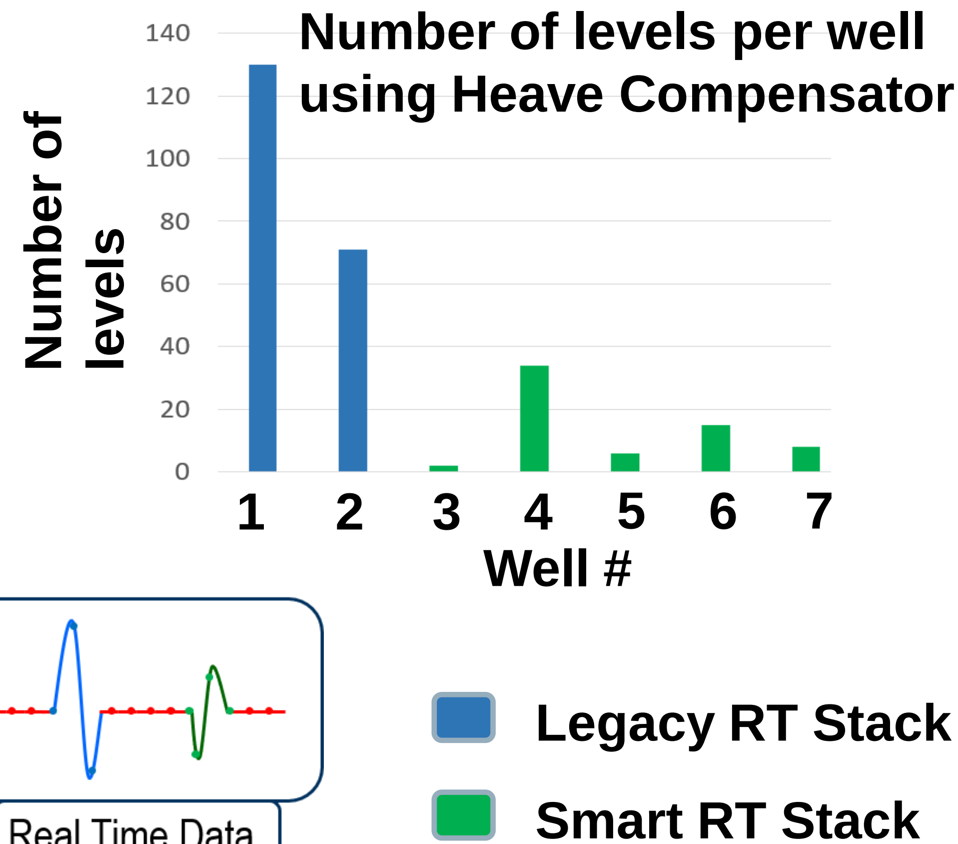
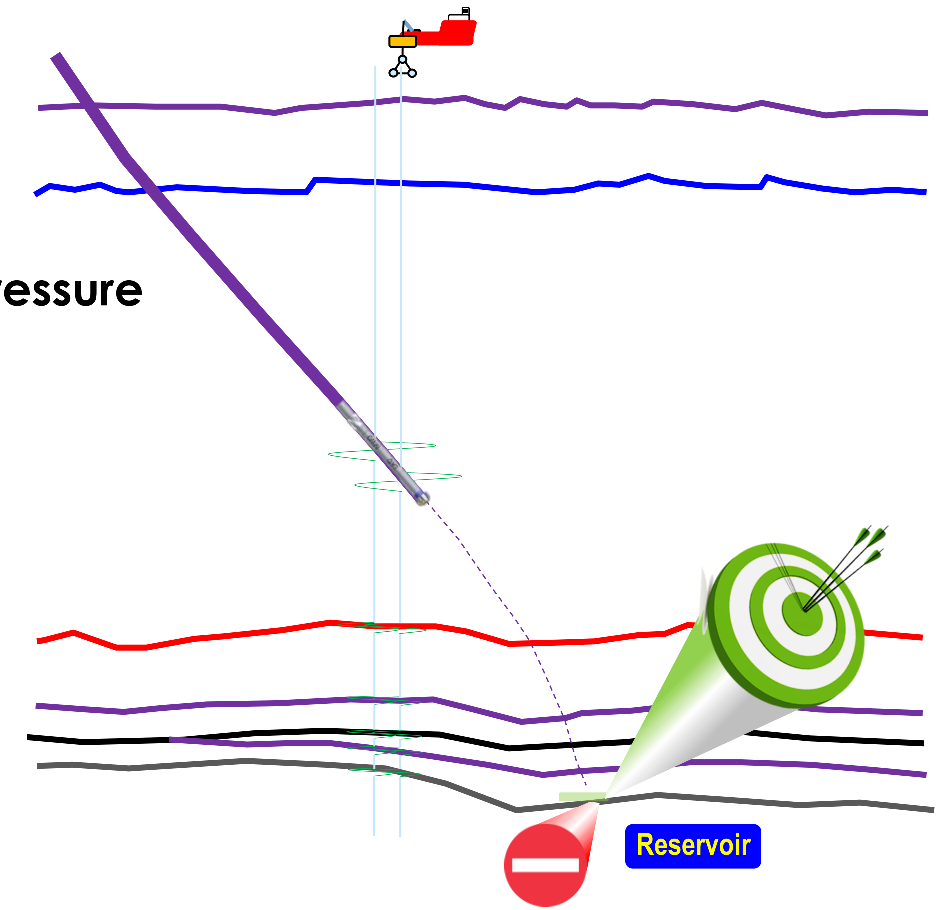


# SOLUTIONS TO ACQUISITION CHALLENGES

- Rig Heave
- **Managed Pressure Drilling**



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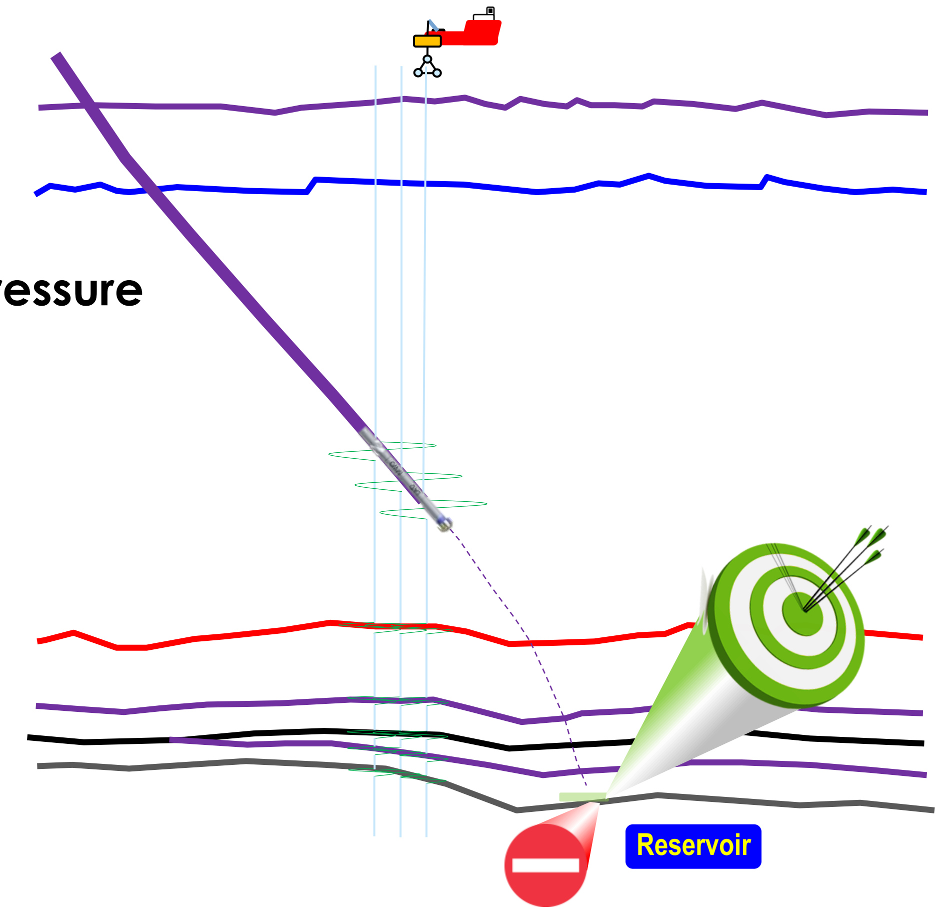

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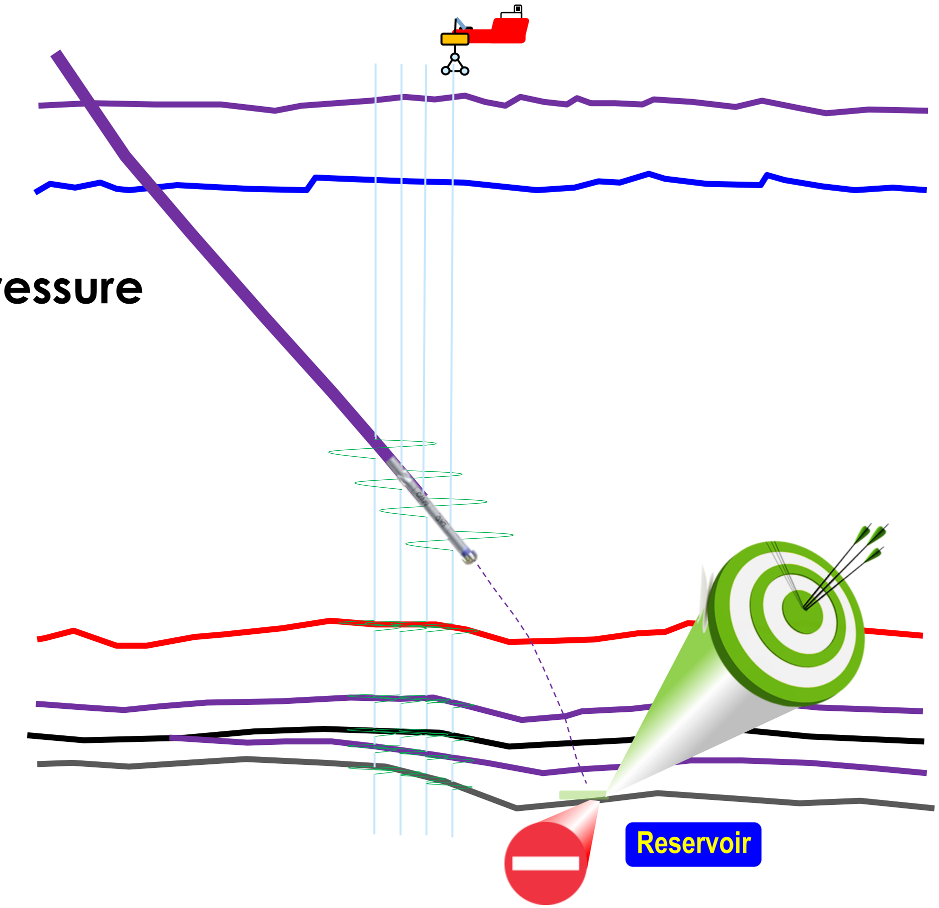

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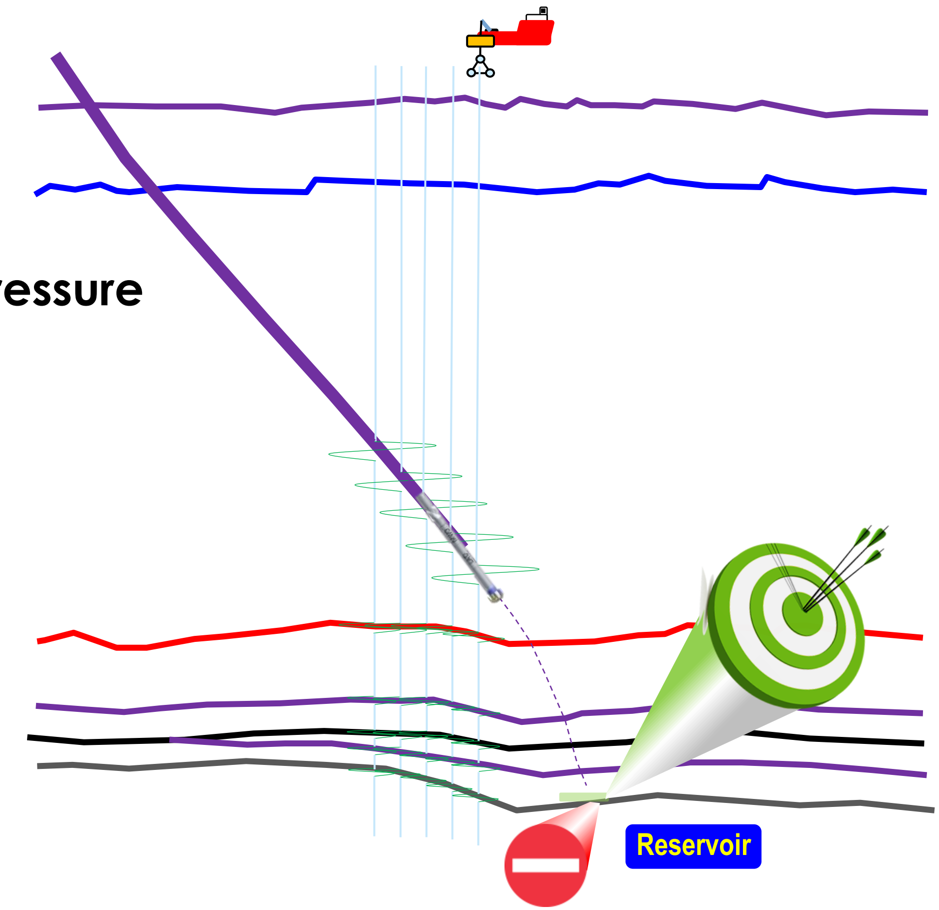

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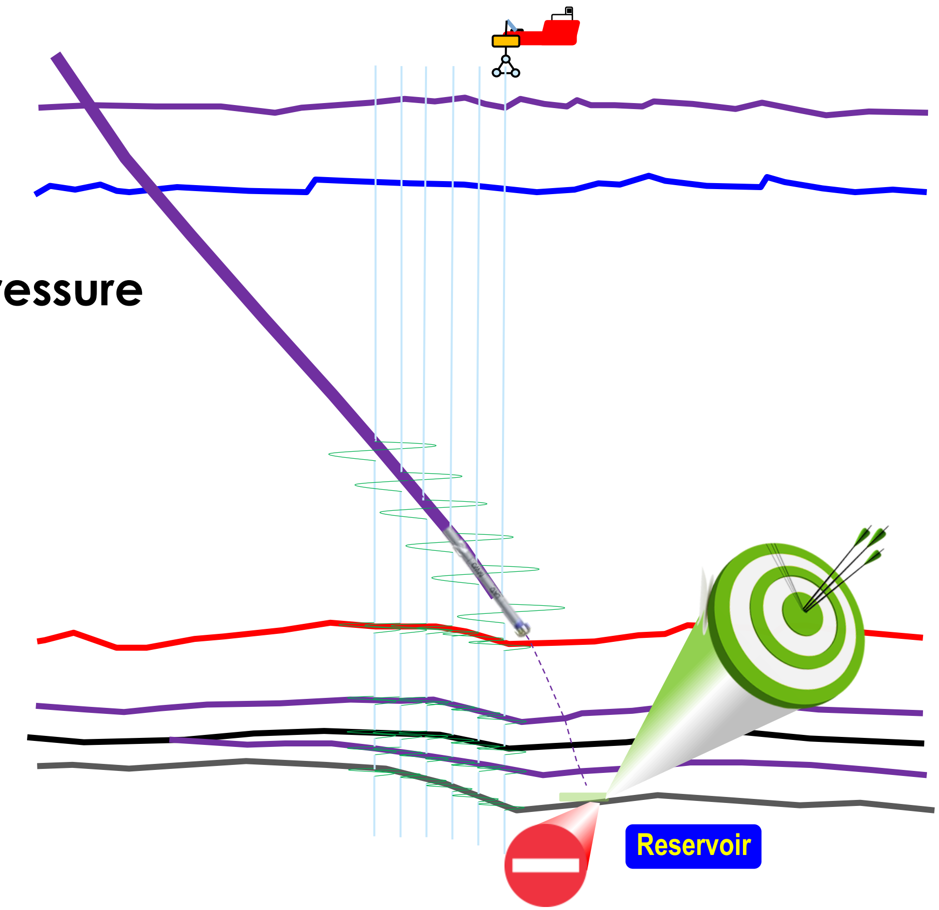

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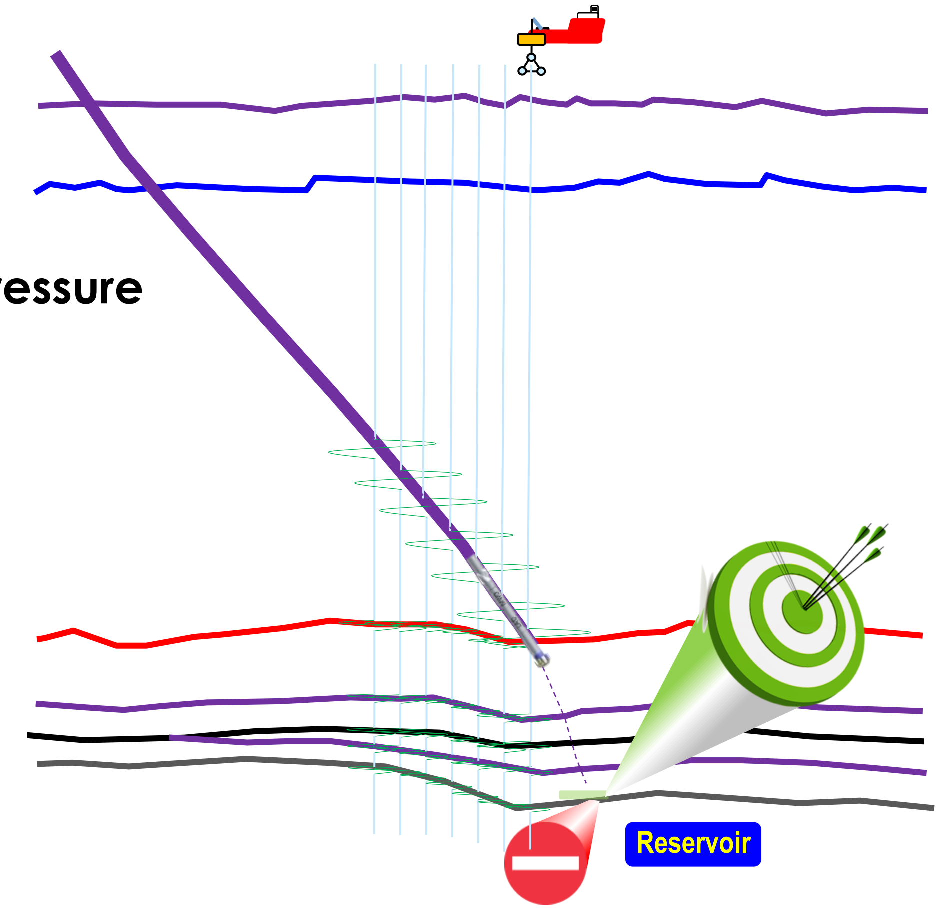

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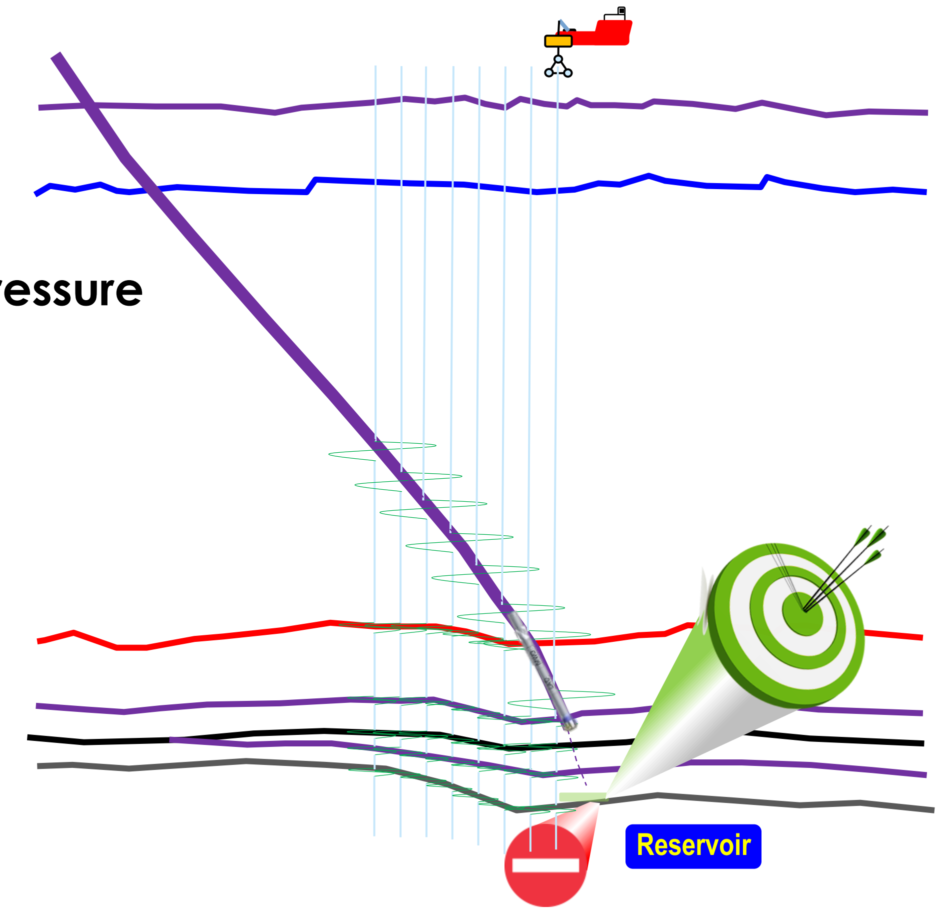

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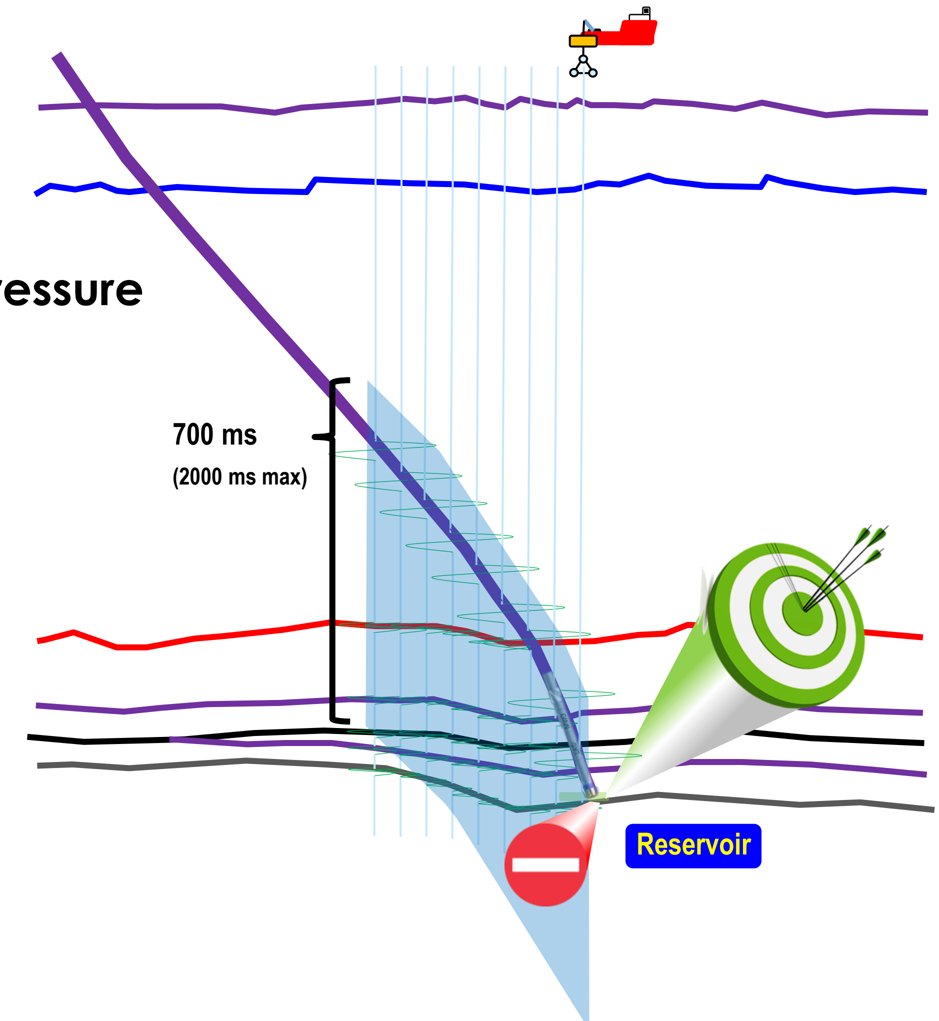

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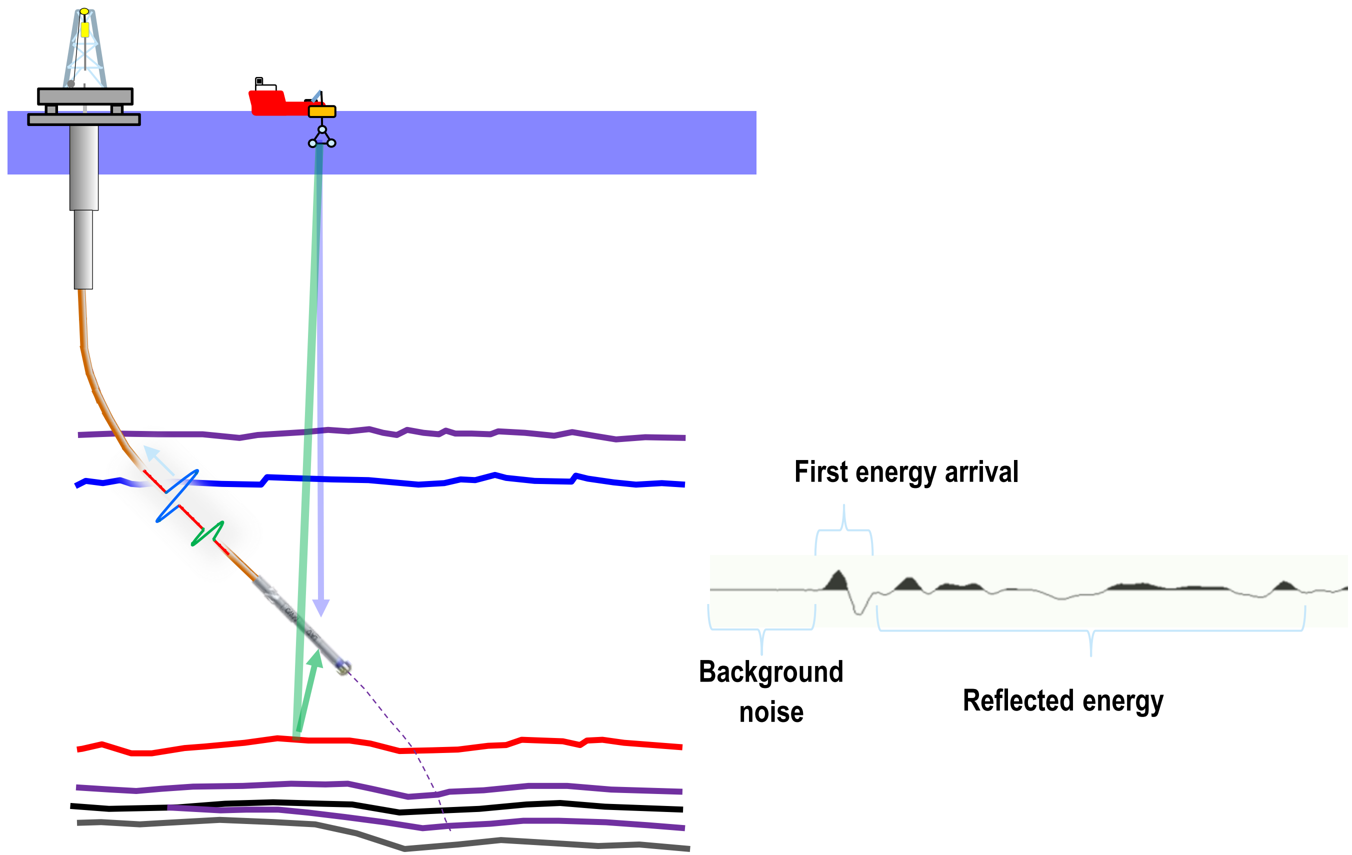

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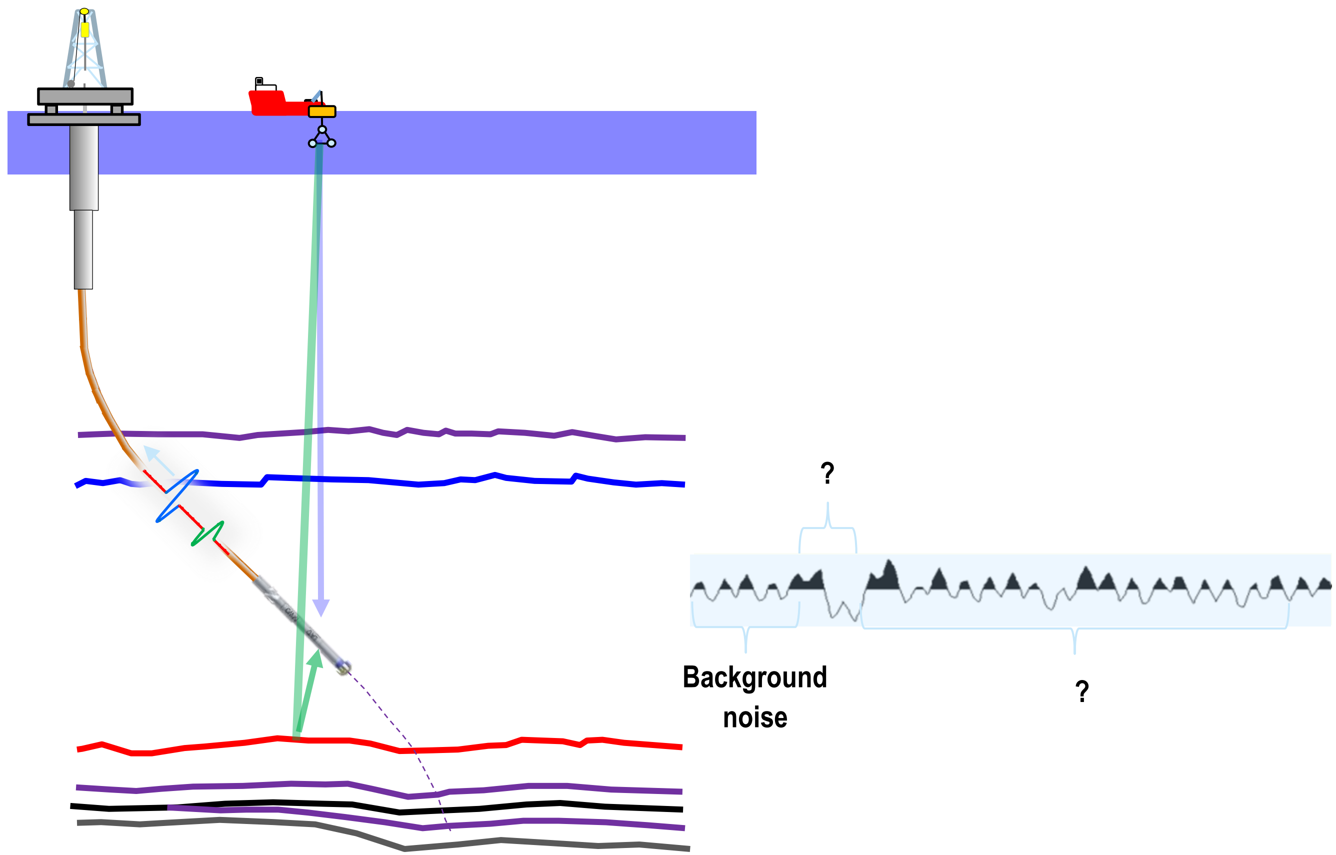

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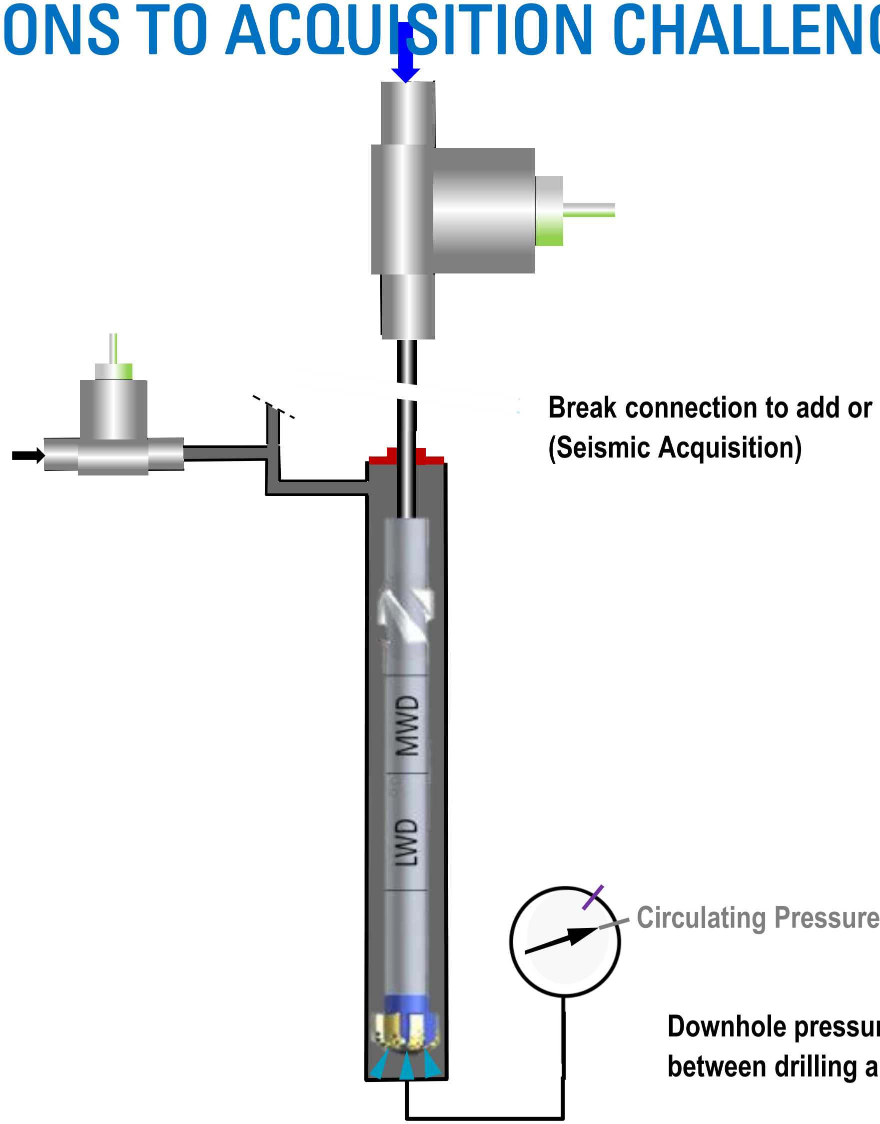
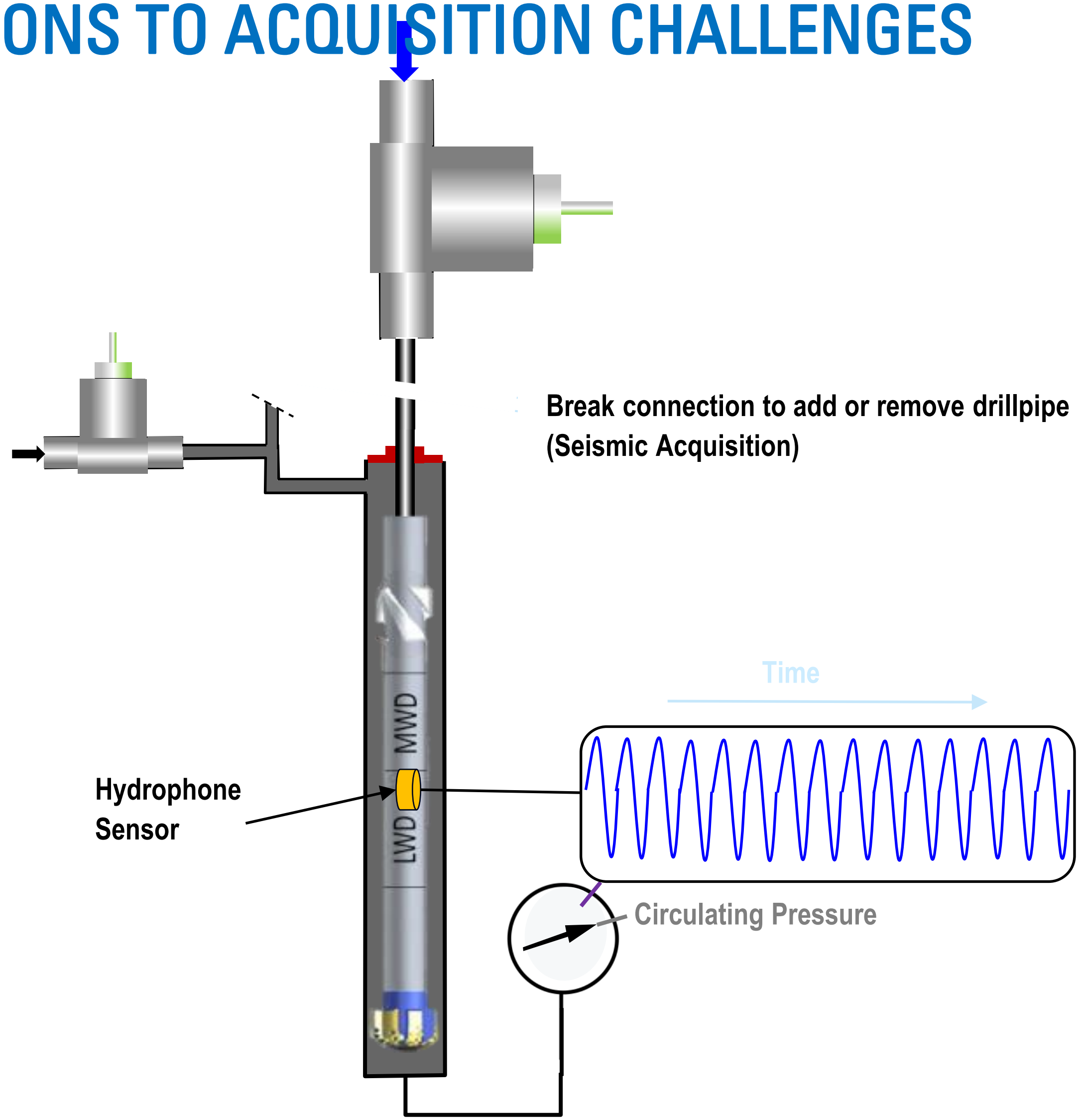



**Break connection to add or remove drillpipe (Seismic Acquisition)**

**Downhole pressure is CONSTANT between drilling and connections**

# SOLUTIONS TO ACQUISITION CHALLENGES

- Rig Heave
- **Managed Pressure Drilling**



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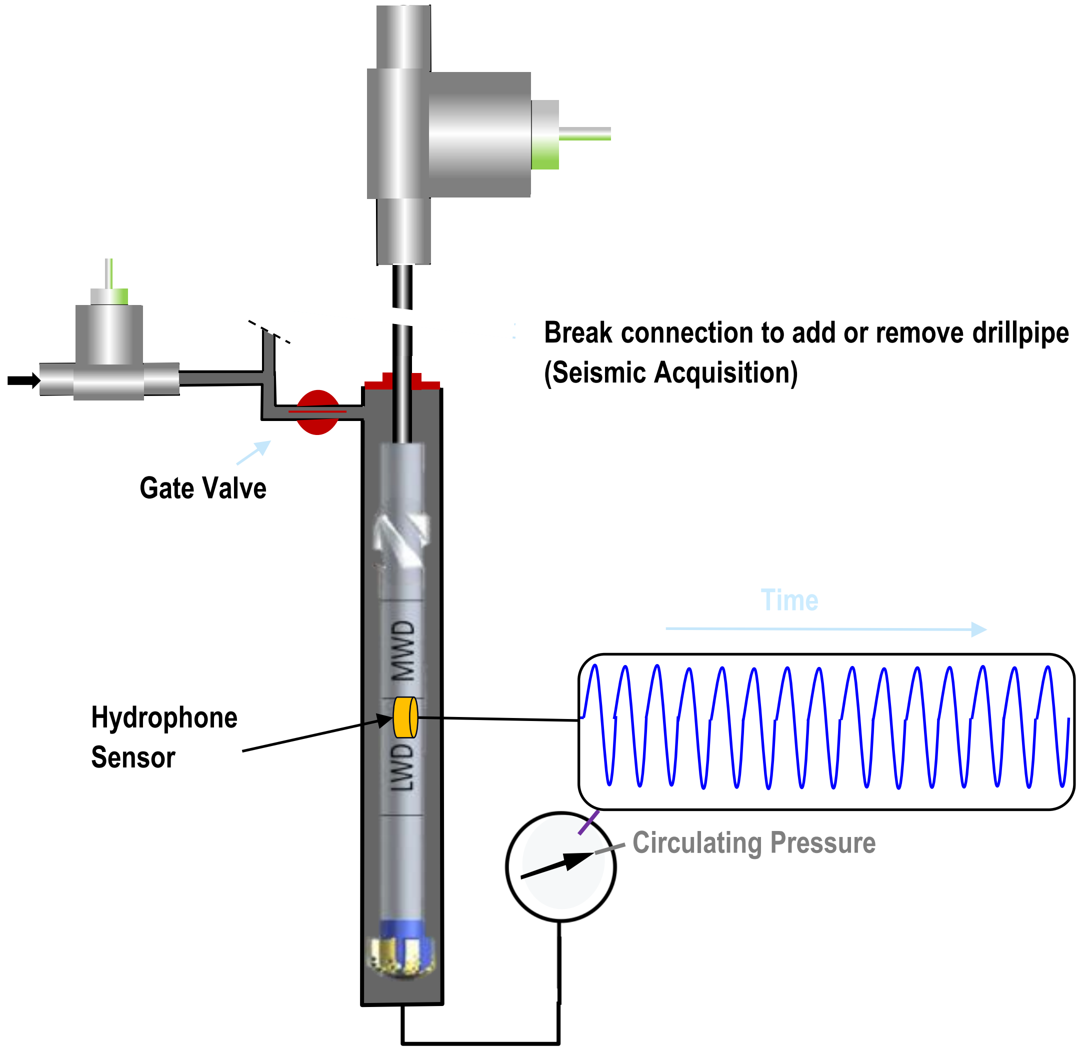

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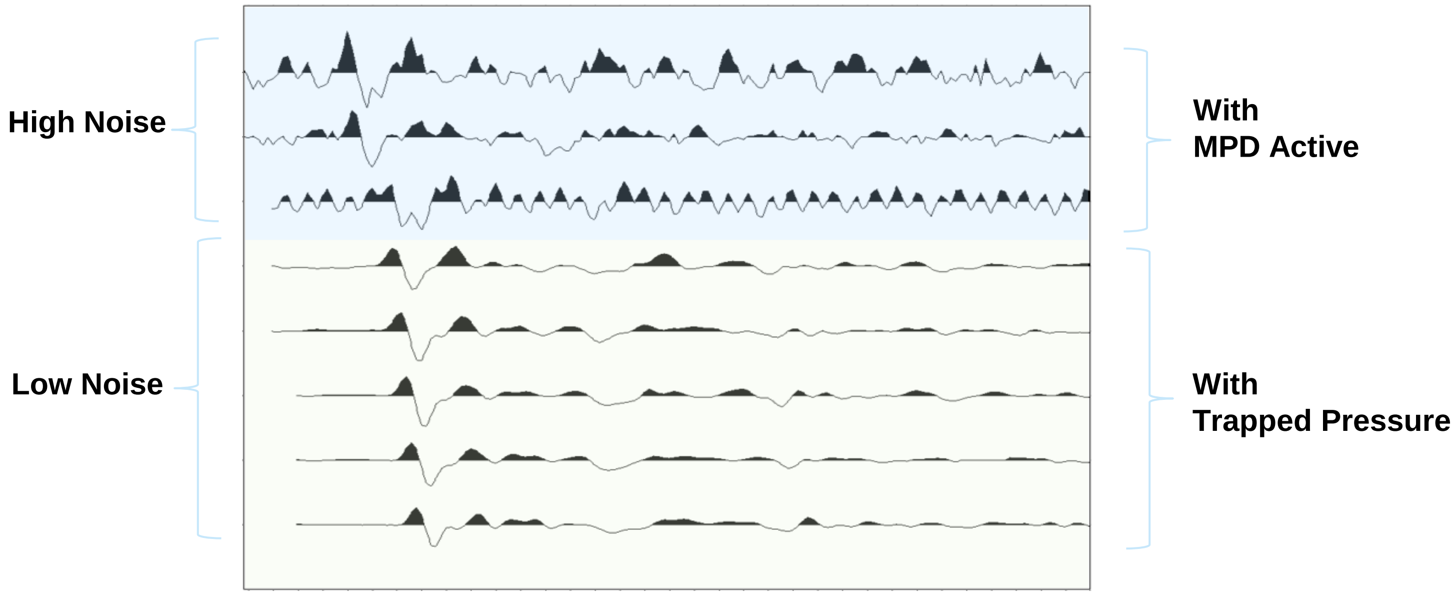
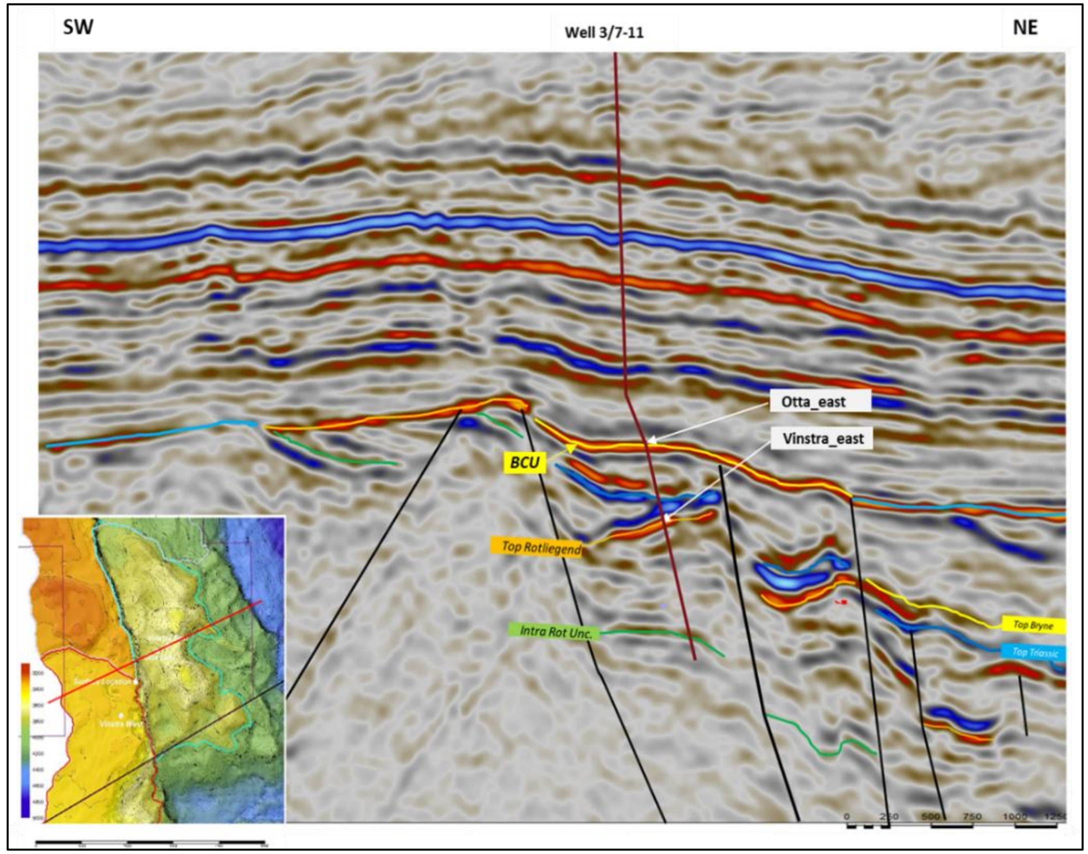


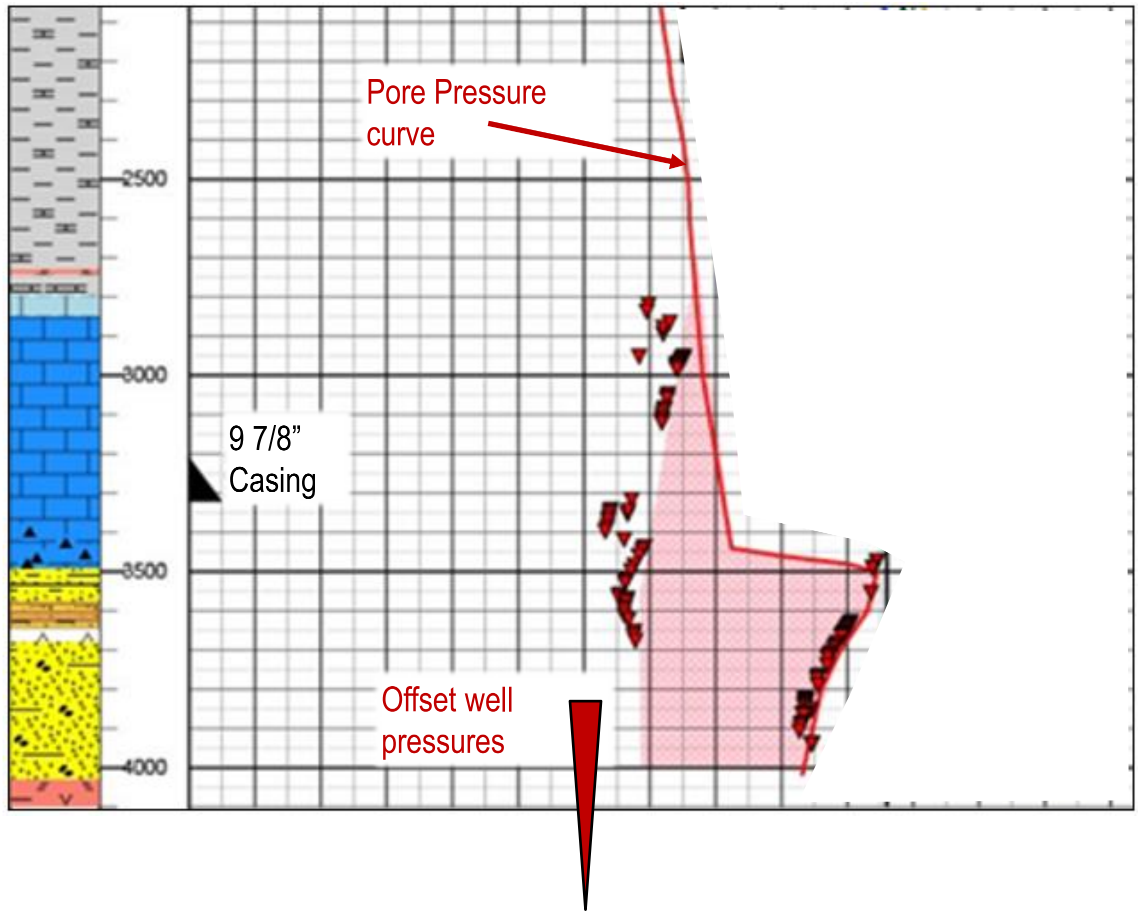
# SAFE WELL LANDING - DRILLERS OBJECTIVES

- Safely drill a deviated exploration well on time and budget
- Penetrate and log reservoirs in the Jurassic and Permian formations

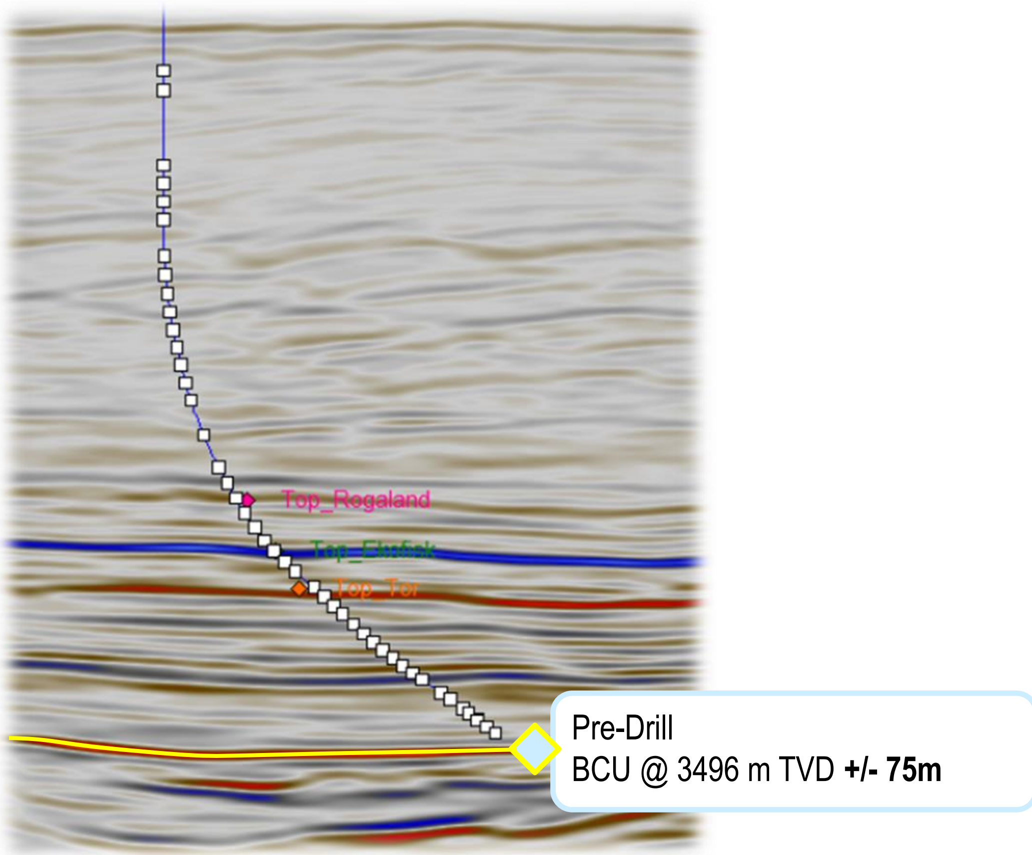


# DRILLERS CHALLENGES – PORE PRESSURE

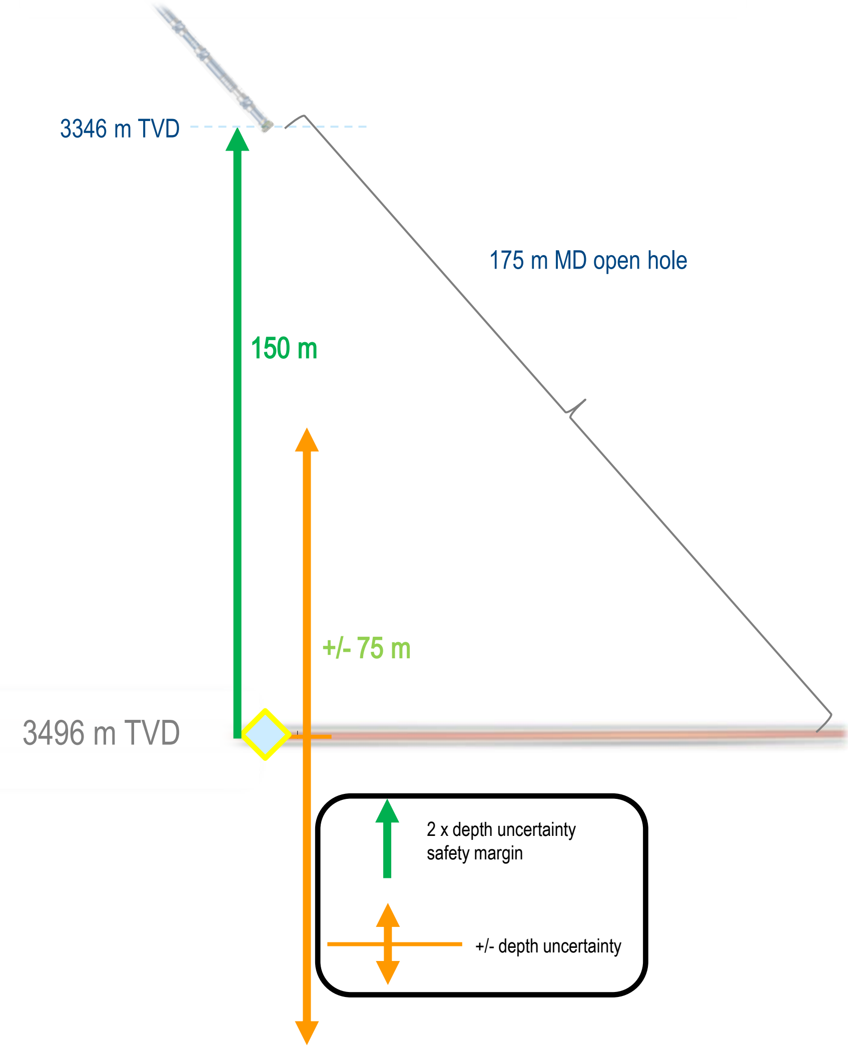
- Large pore pressure uncertainty below the Base Cretaceous Unconformity (BCU)
- 300 bar difference in pore pressure between offset wells within a few kilometers
- After the BCU will the pressure be a high case or a low case?
- Set 9 7/8" casing shoe close to the BCU to provide maximum well control



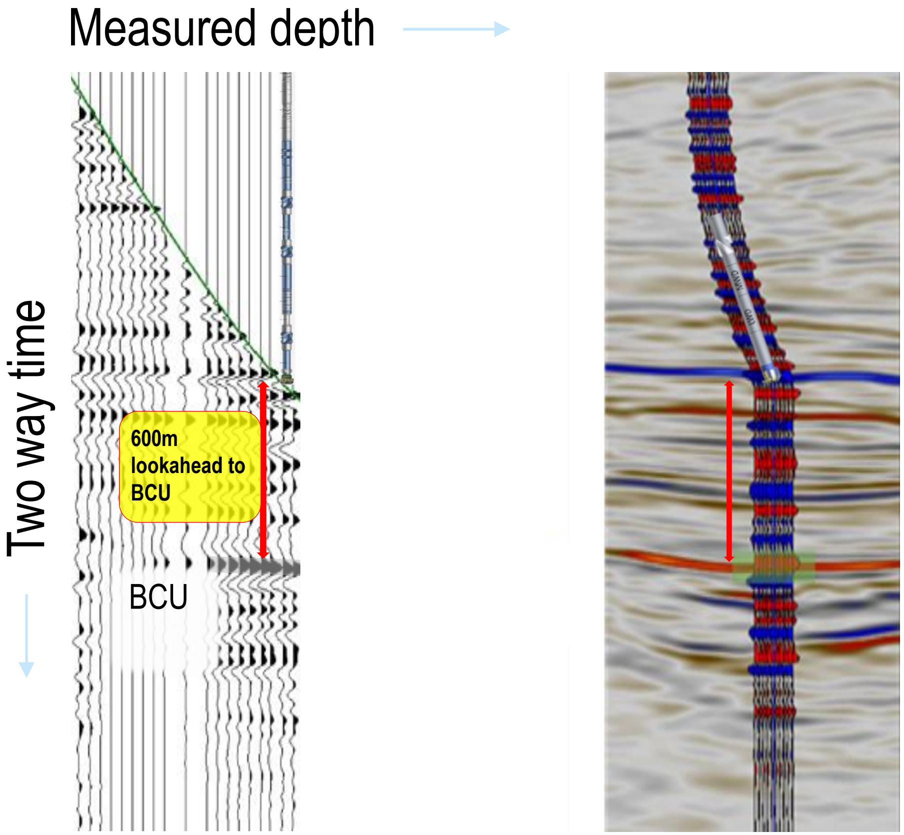
# DRILLERS CHALLENGES – DEPTH UNCERTAINTY




Need to set casing in close proximity to BCU for max kick tolerance safety



# LOOKAHEAD RESULTS



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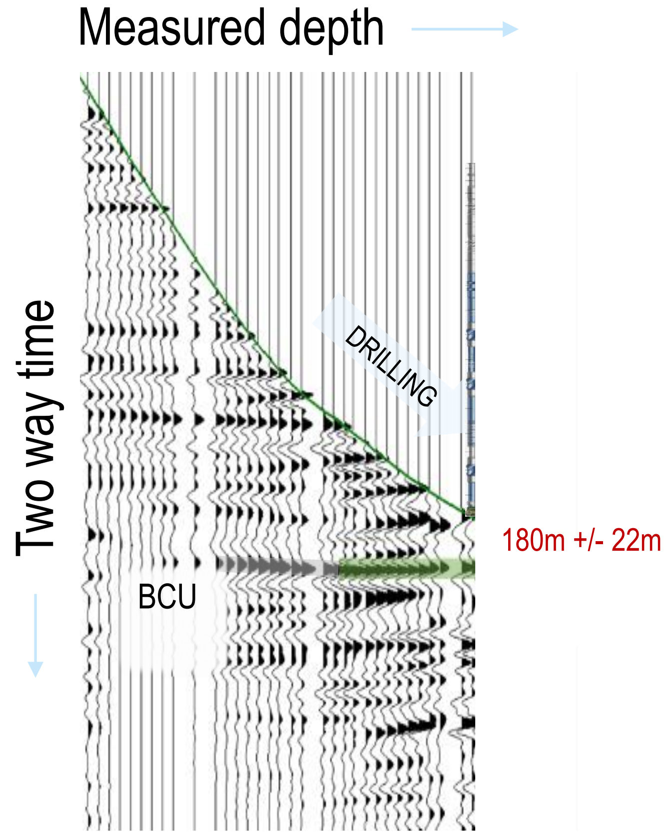


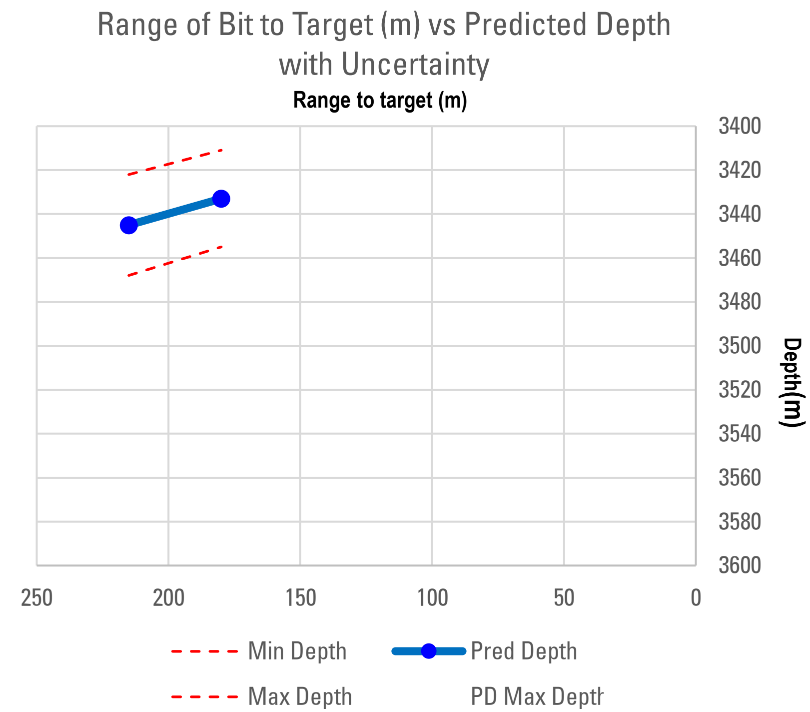

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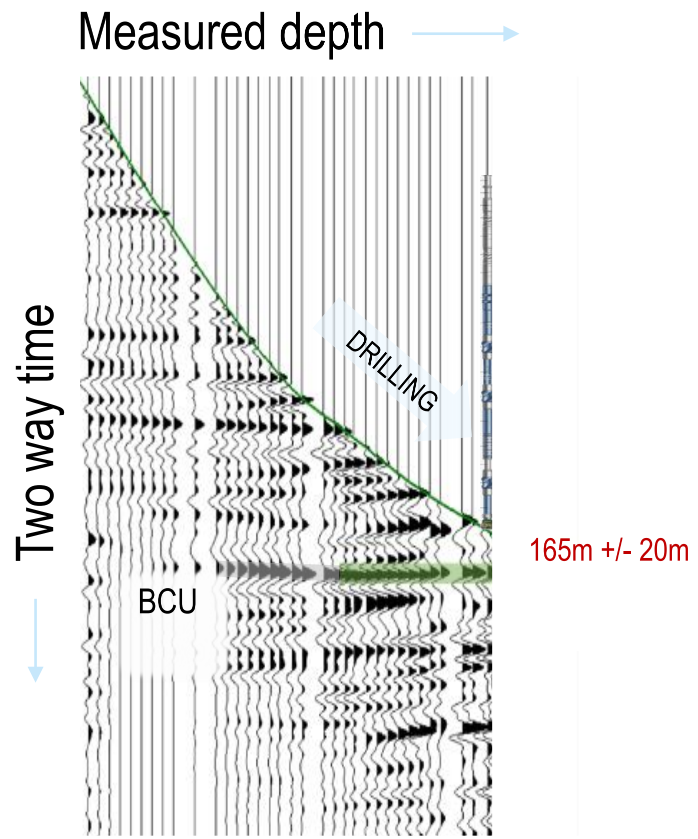


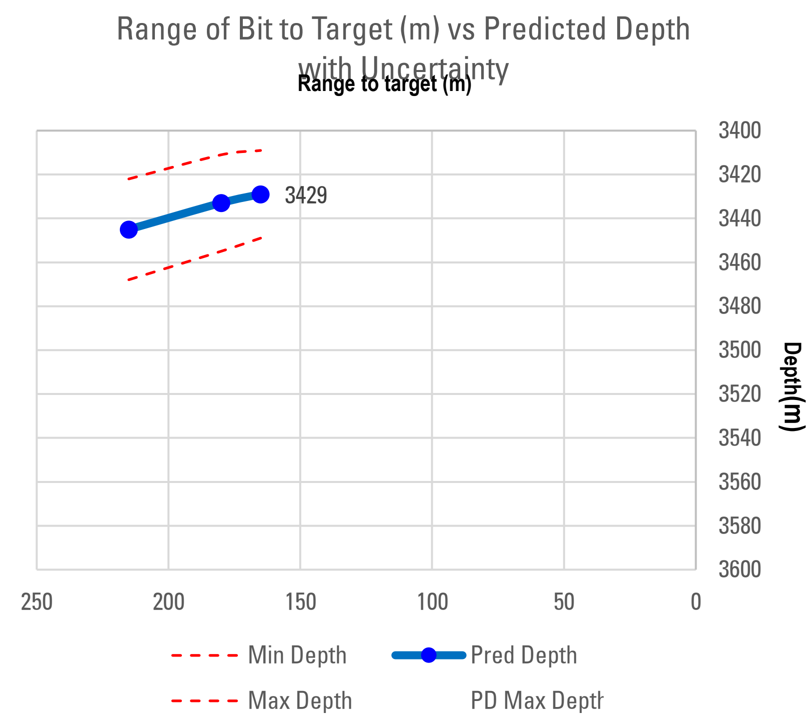

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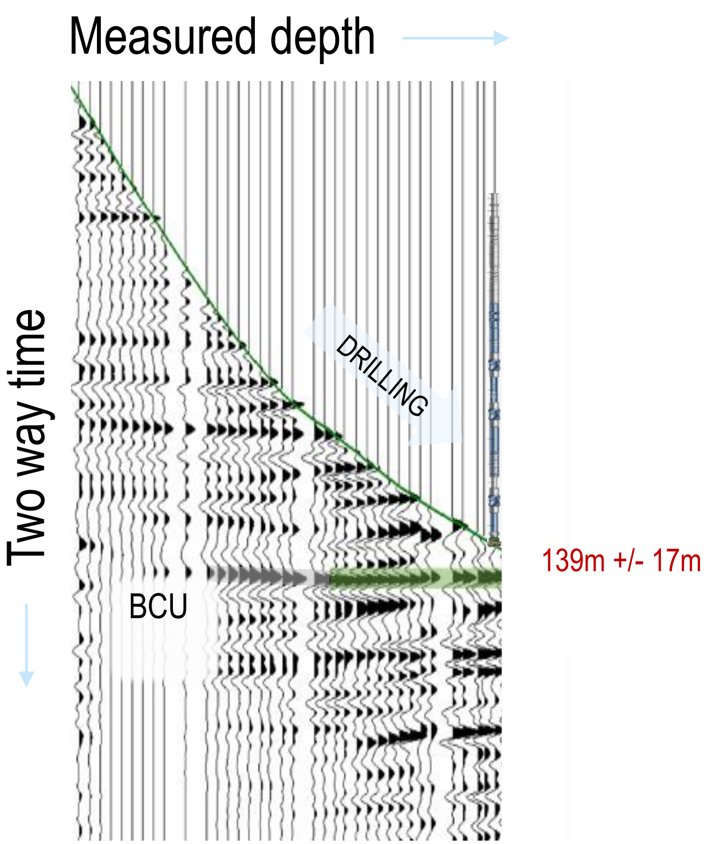


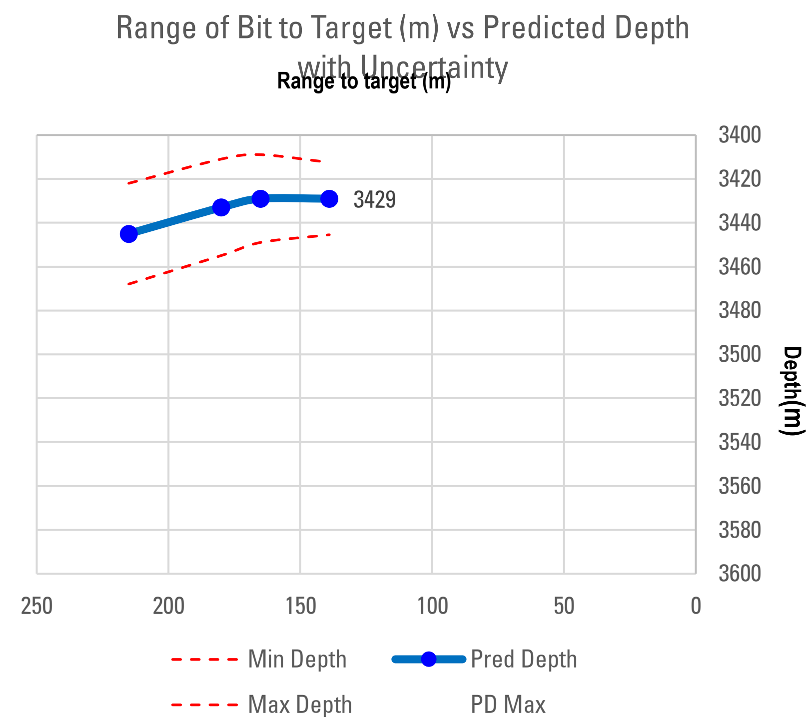

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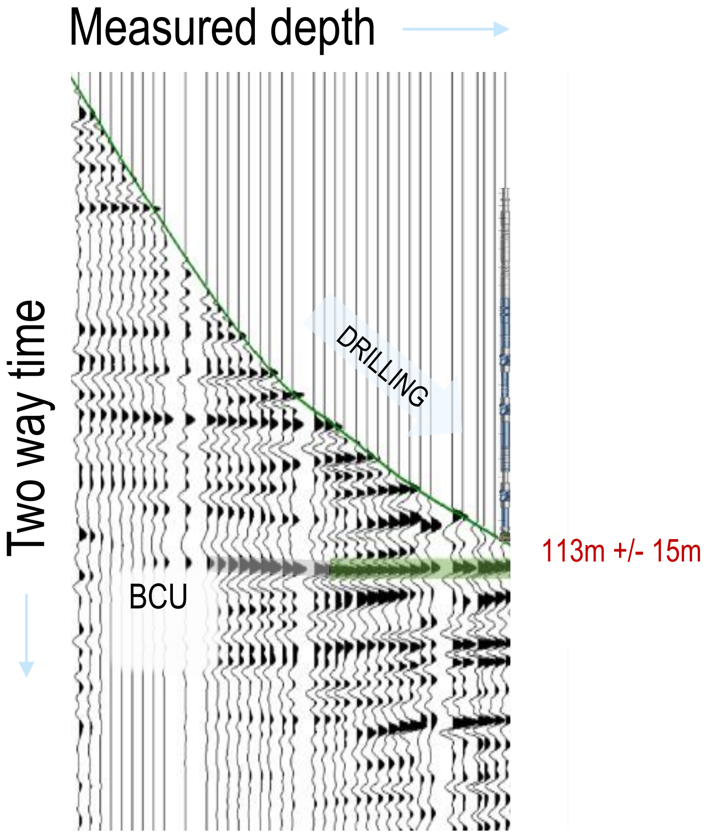


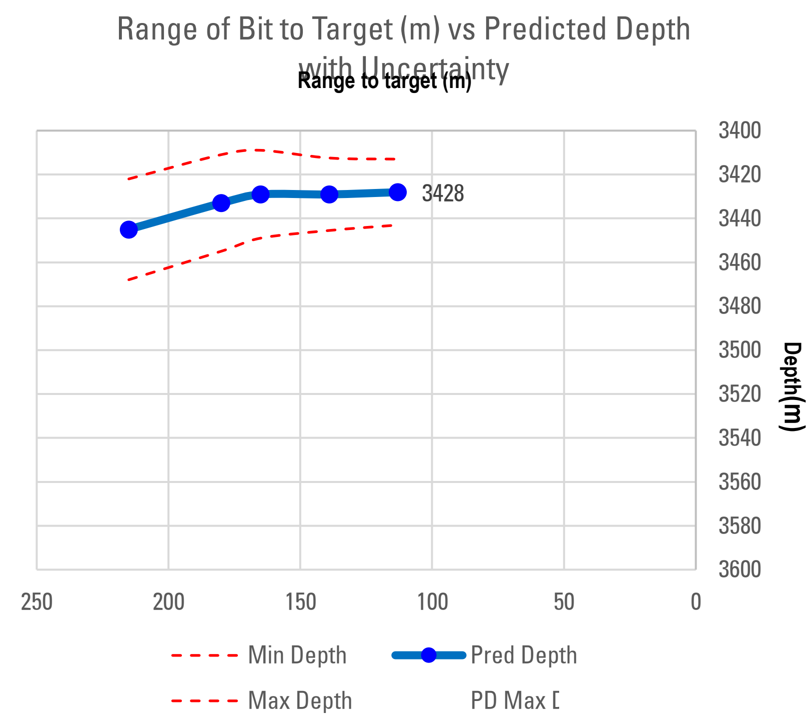

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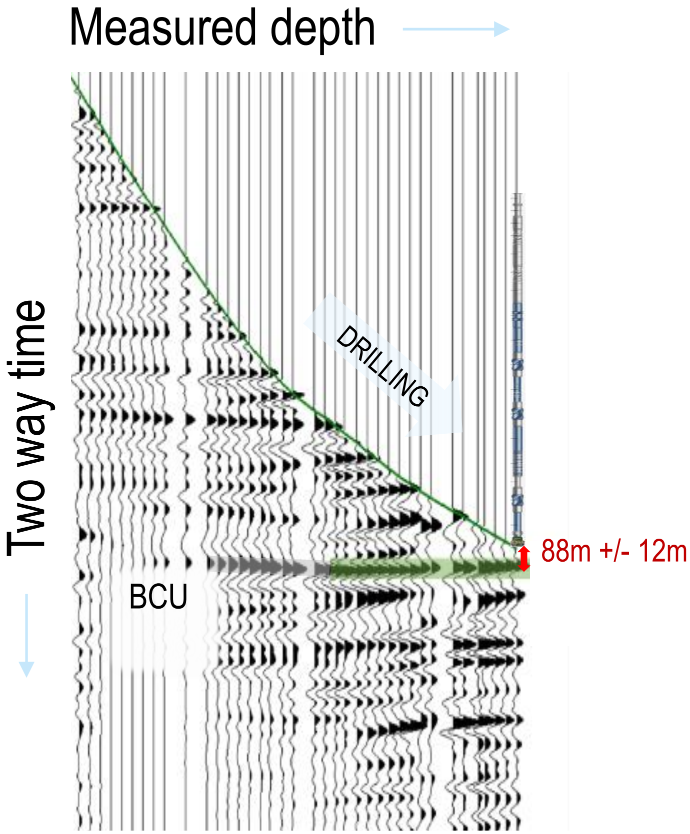


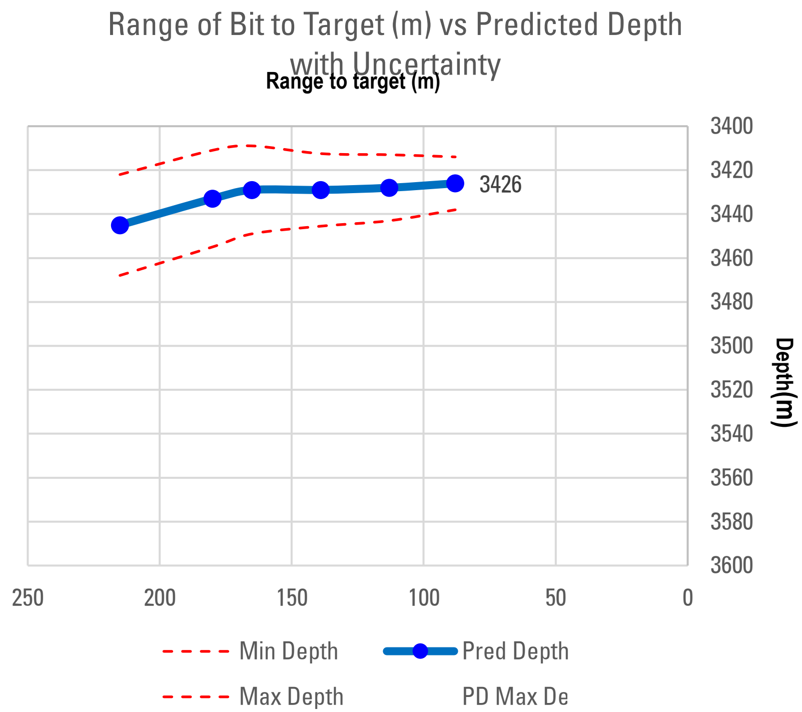

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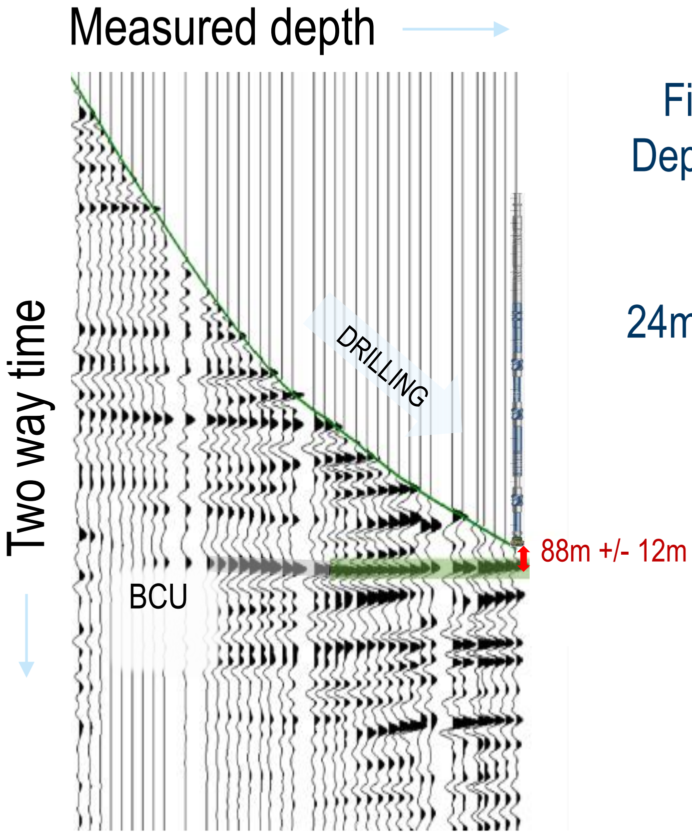
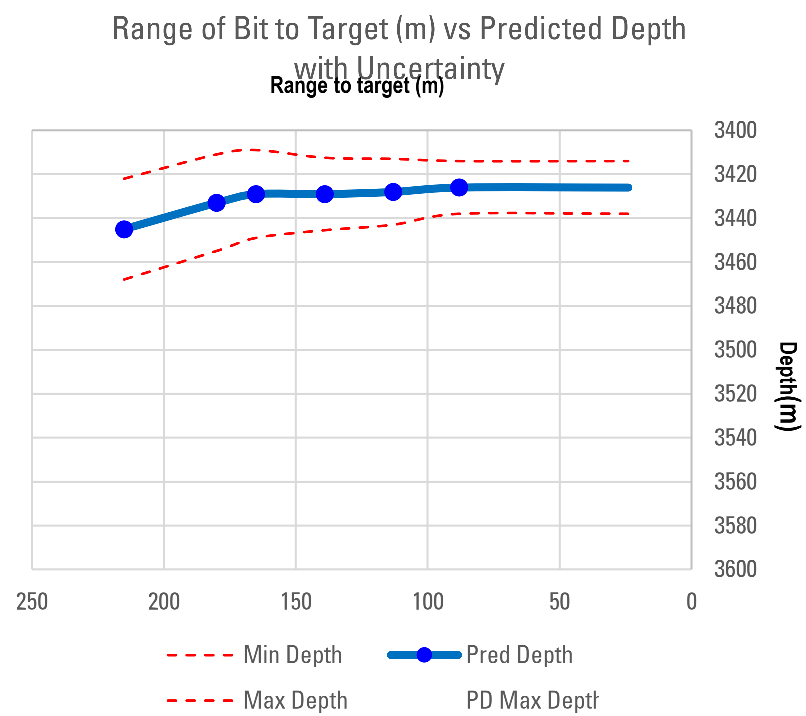



Final decision made on Depth of 12.25" section TD at 3402m TVD

24m above predicted target at 3426m TVD



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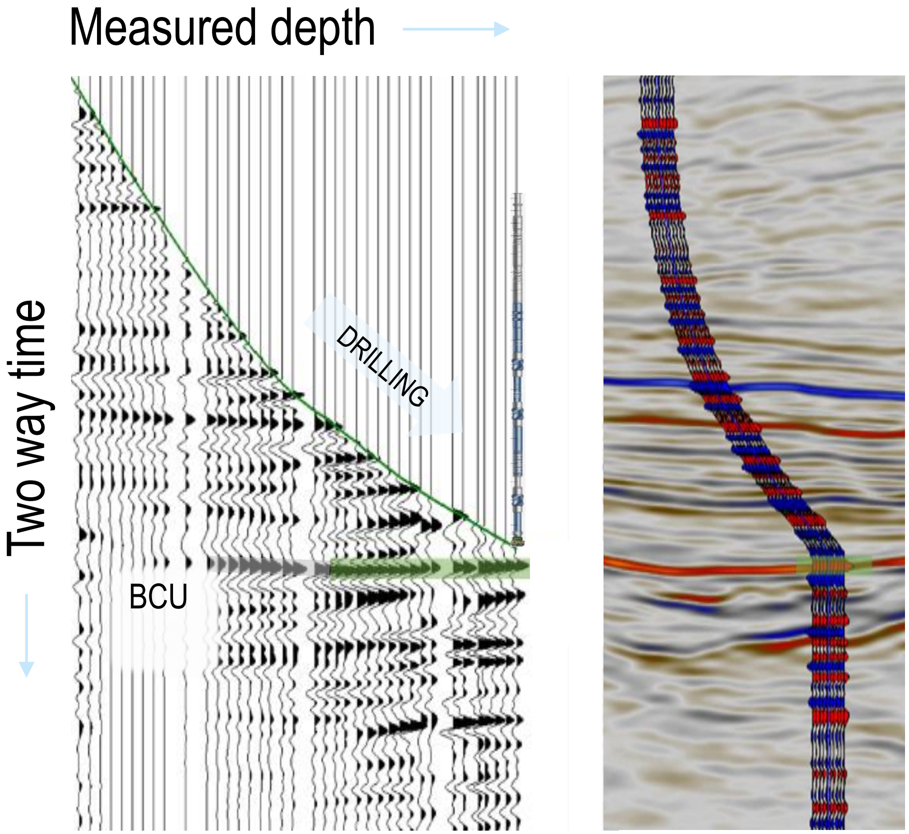


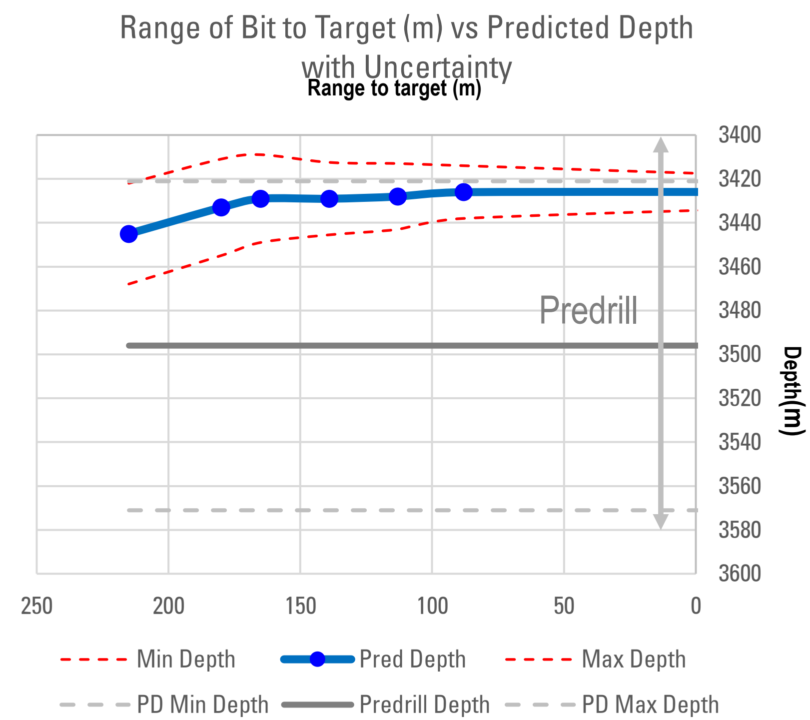

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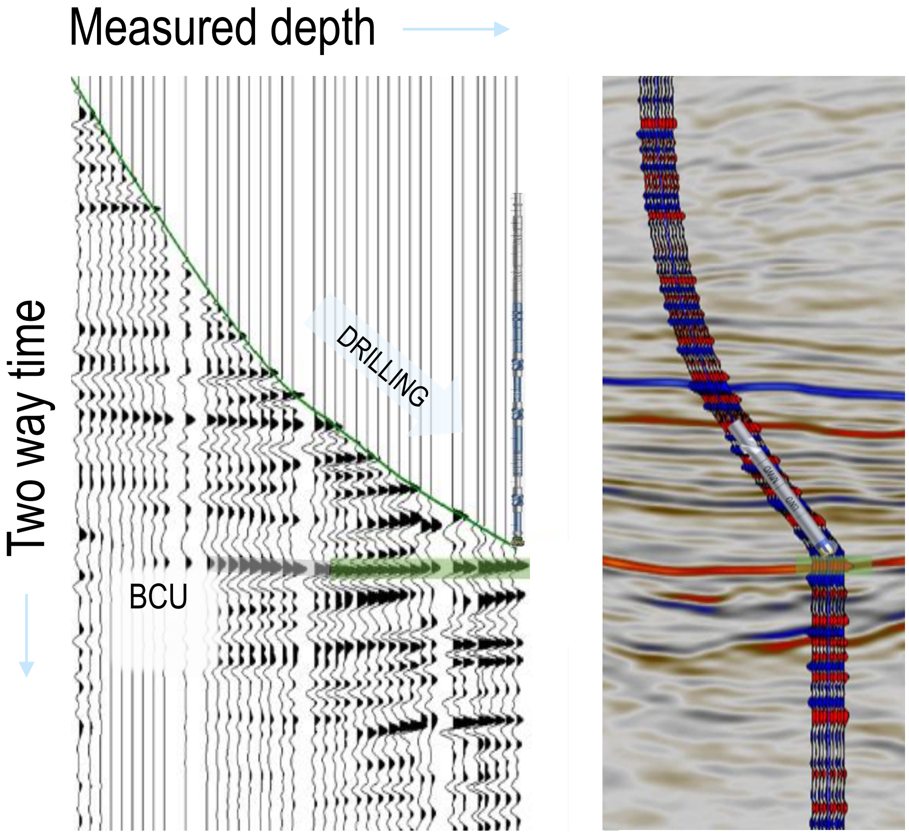


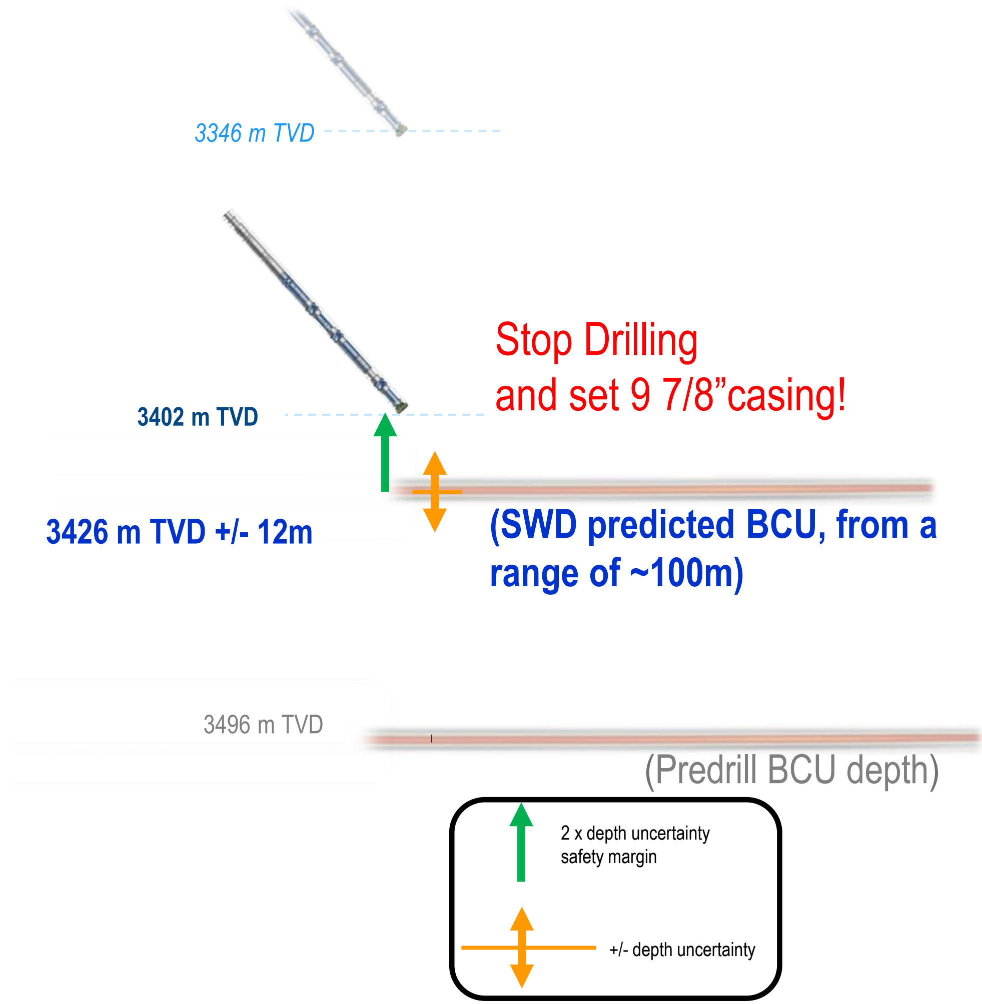

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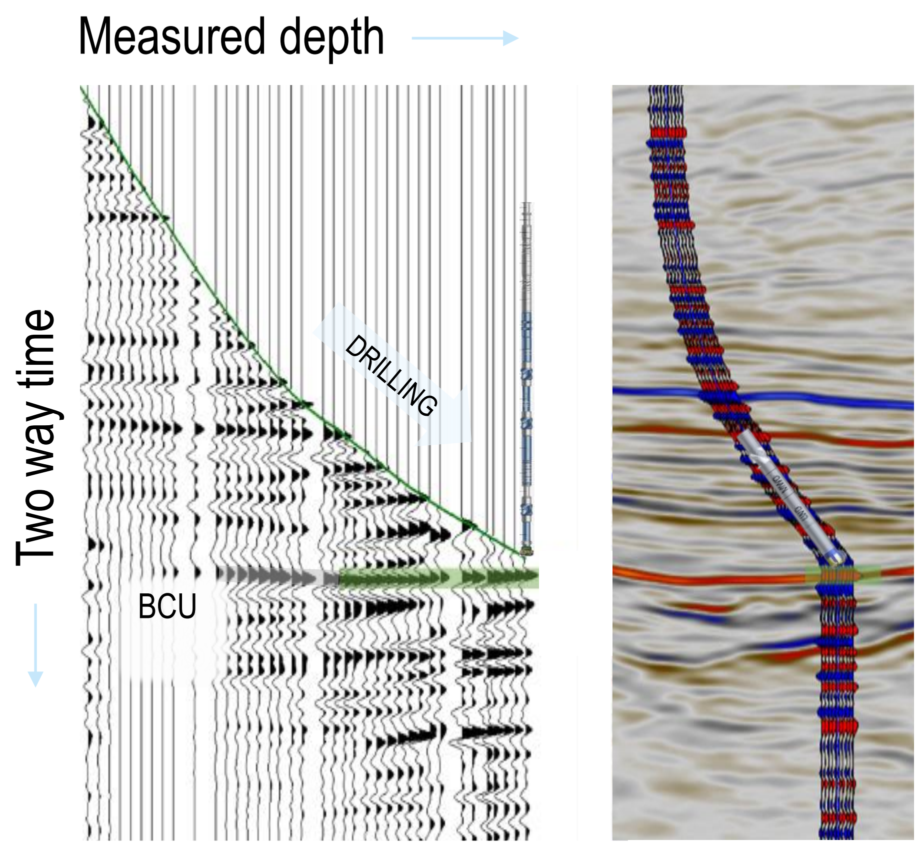
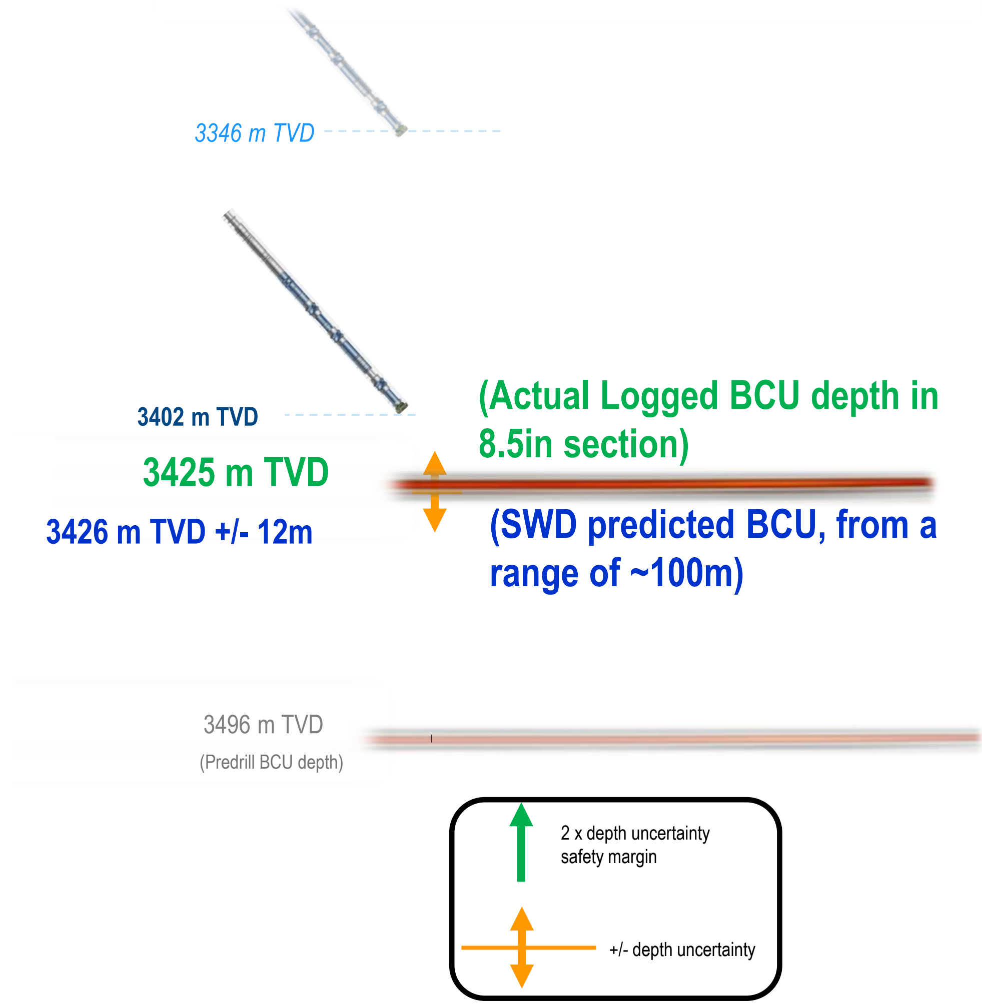
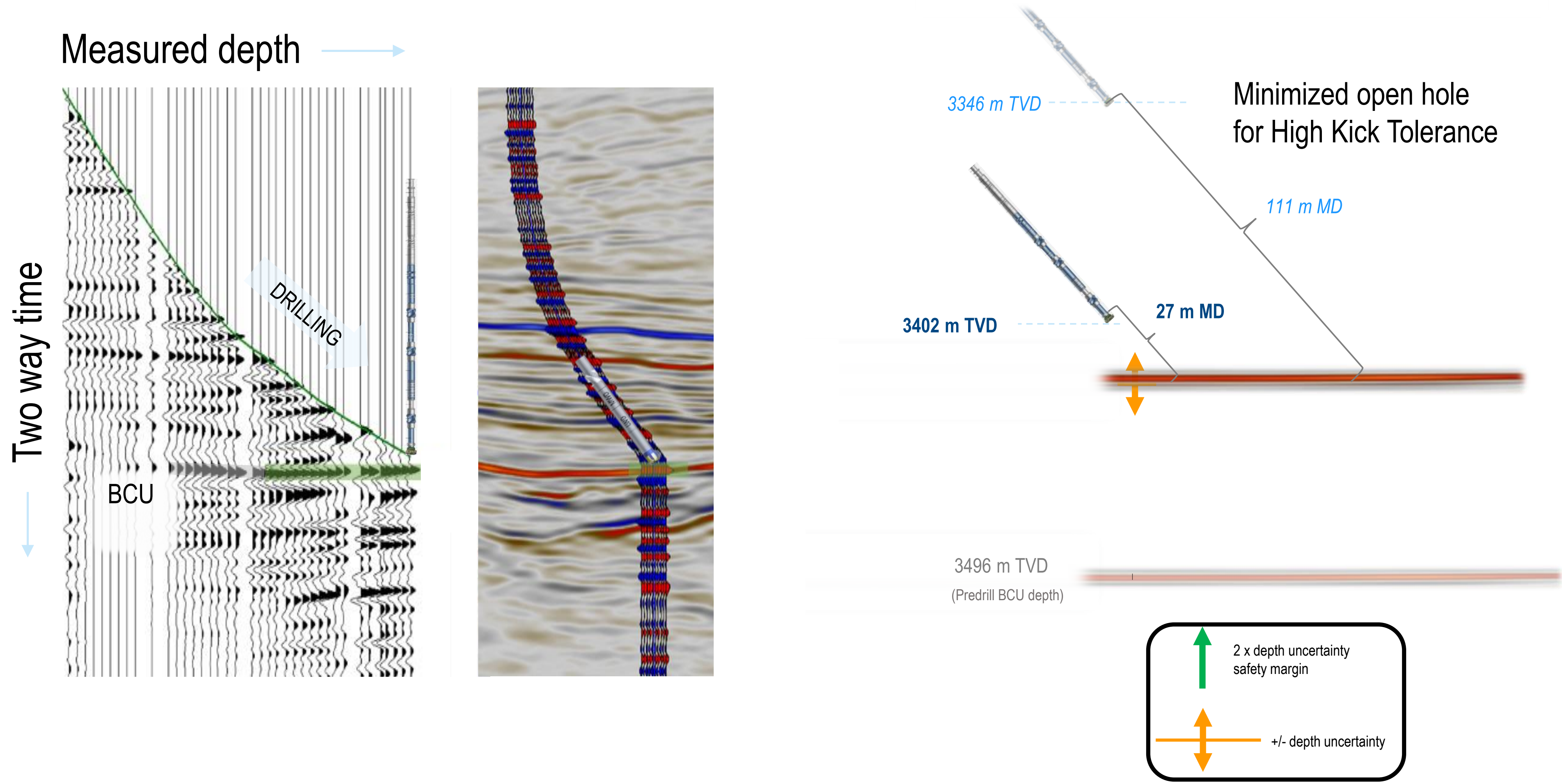


# LOOKAHEAD RESULTS

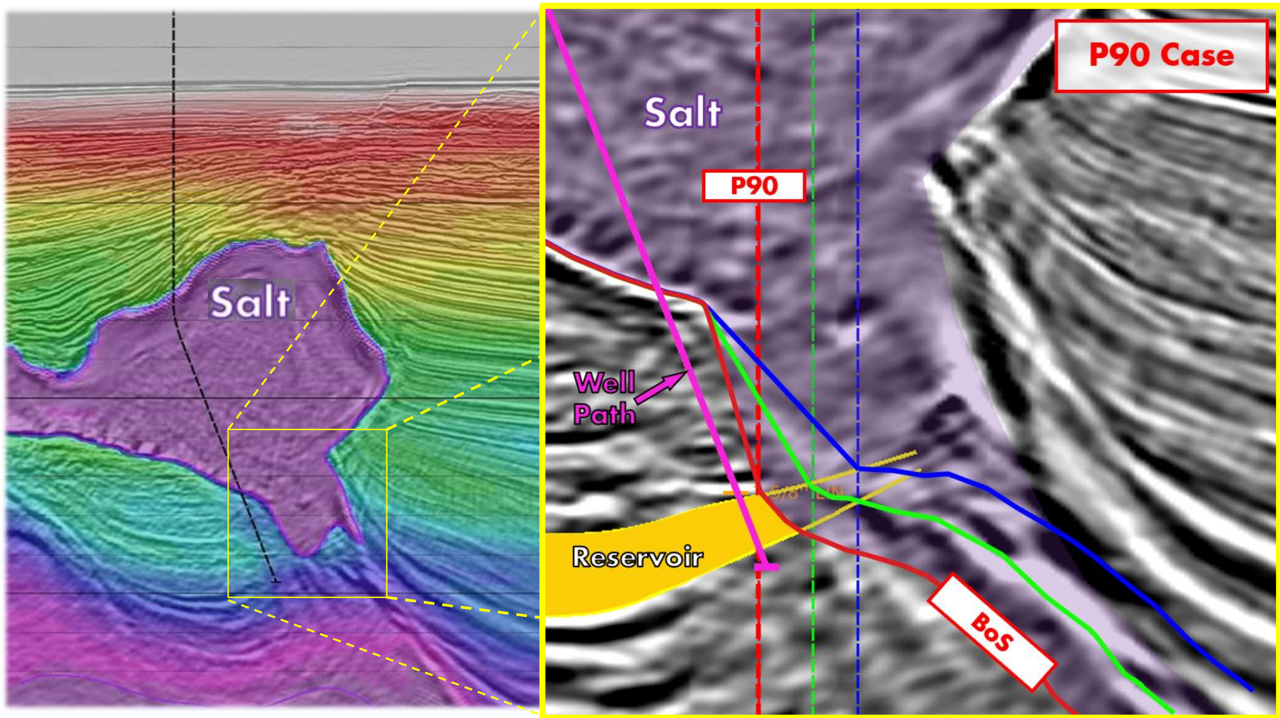


# LOOKAHEAD RESULTS

Norway 2019

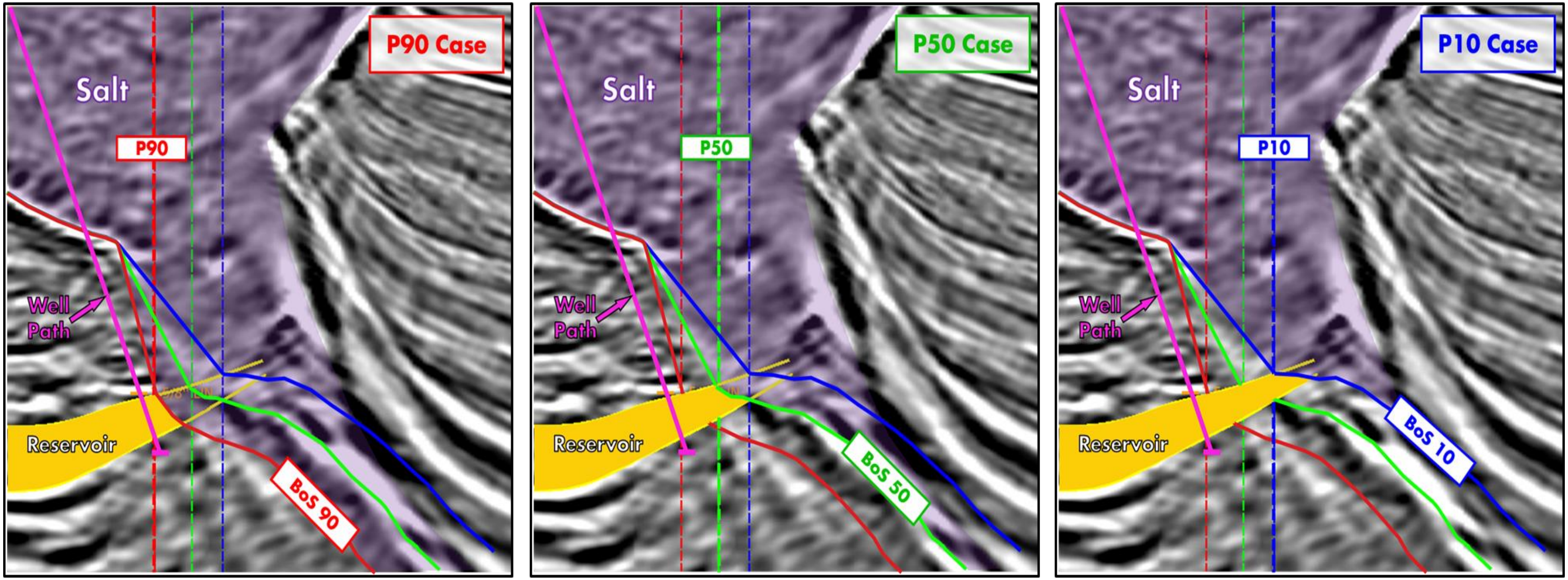
- Objective achieved
- Uncertainty reduced from +/- 75m to +/- 12m
- Optimum safety with a casing depth that gives maximum kick tolerance
- No rig time used for acquisition or data transmission – transparent to normal drilling operations.

# WHAT'S THE PROBLEM? WHERE IS THE SALT FACE?



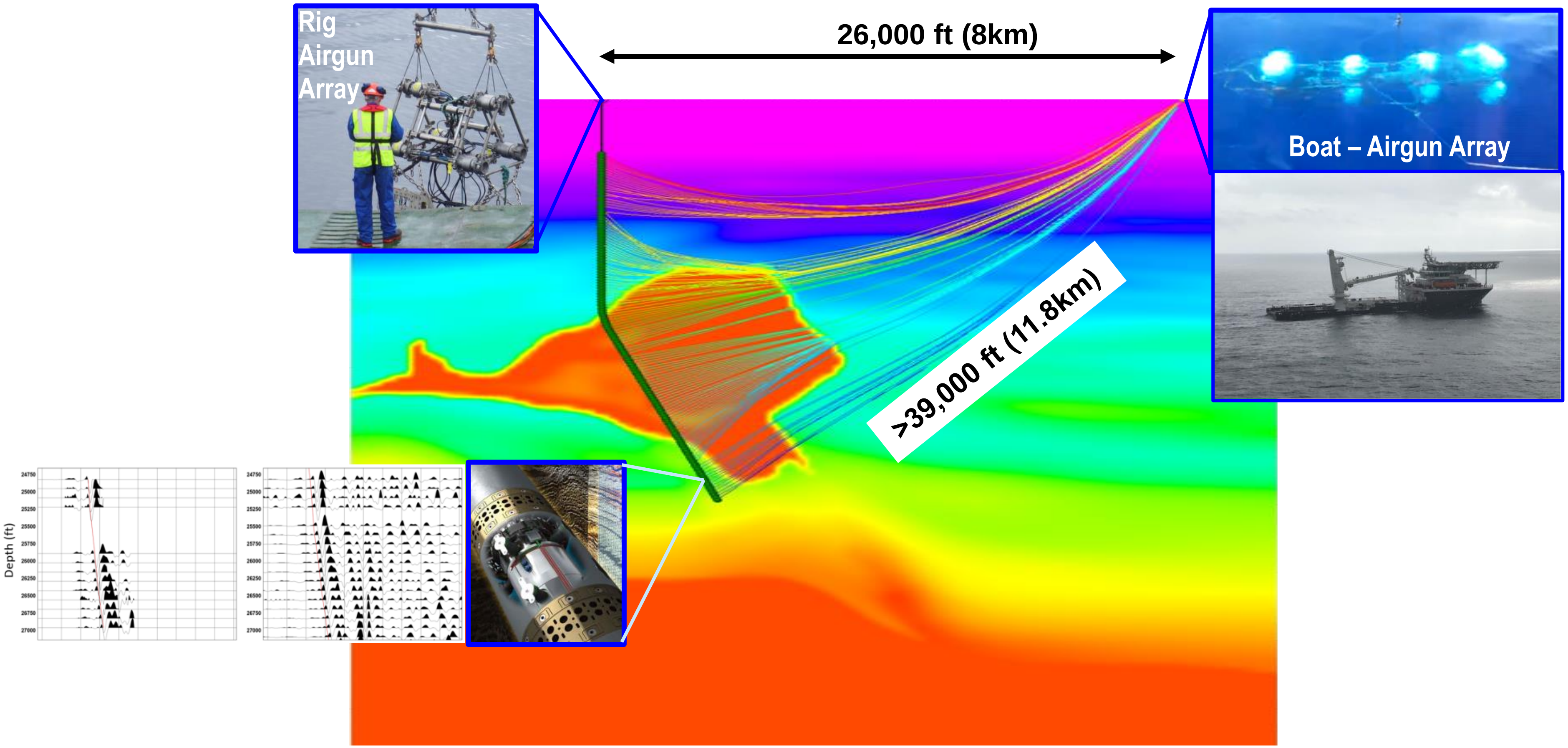
USA 2019

# WHAT'S THE PROBLEM? WHERE IS THE SALT FACE?

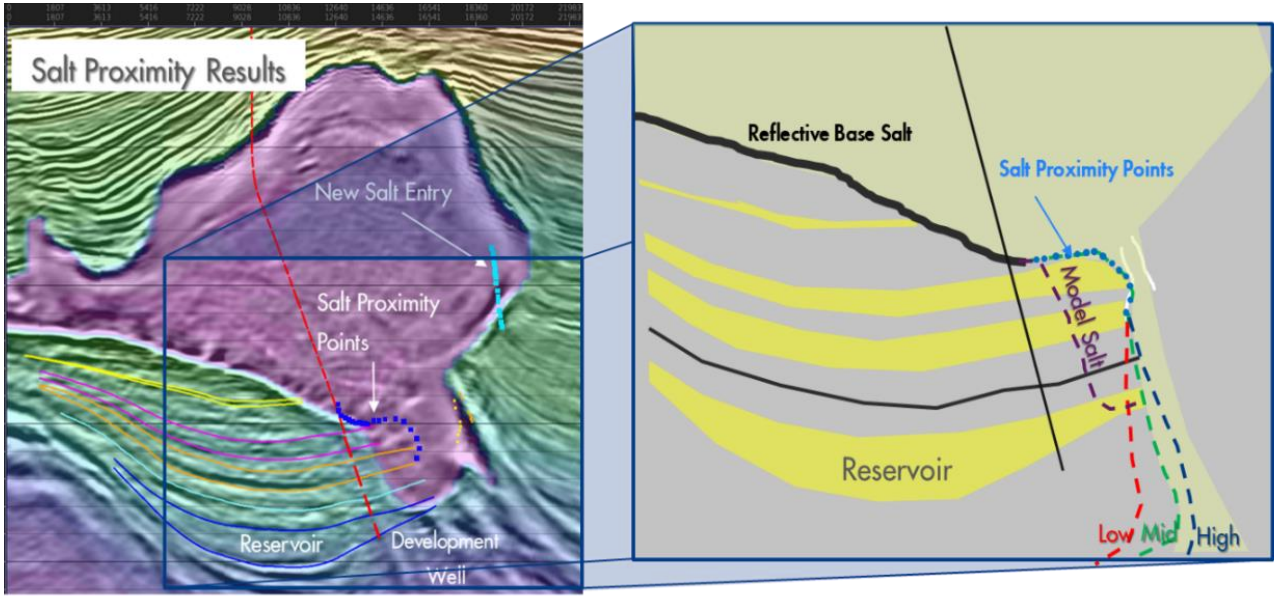


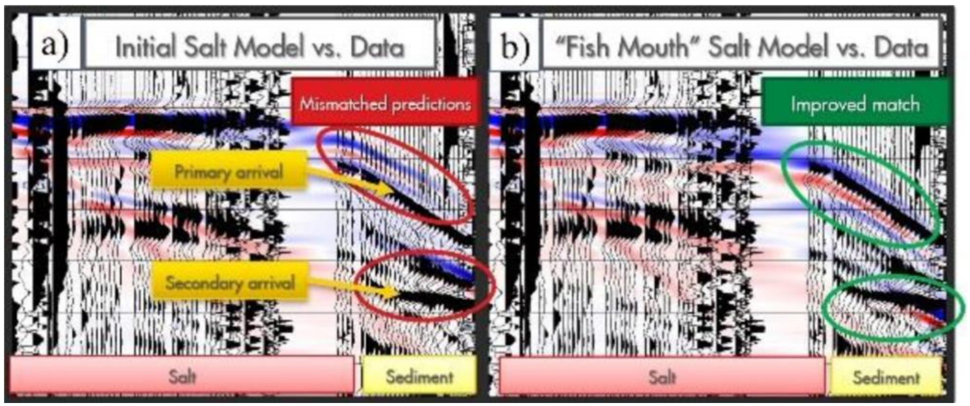
# SEISMIC ACQUISITION DURING DRILLING CONNECTIONS

USA 2019



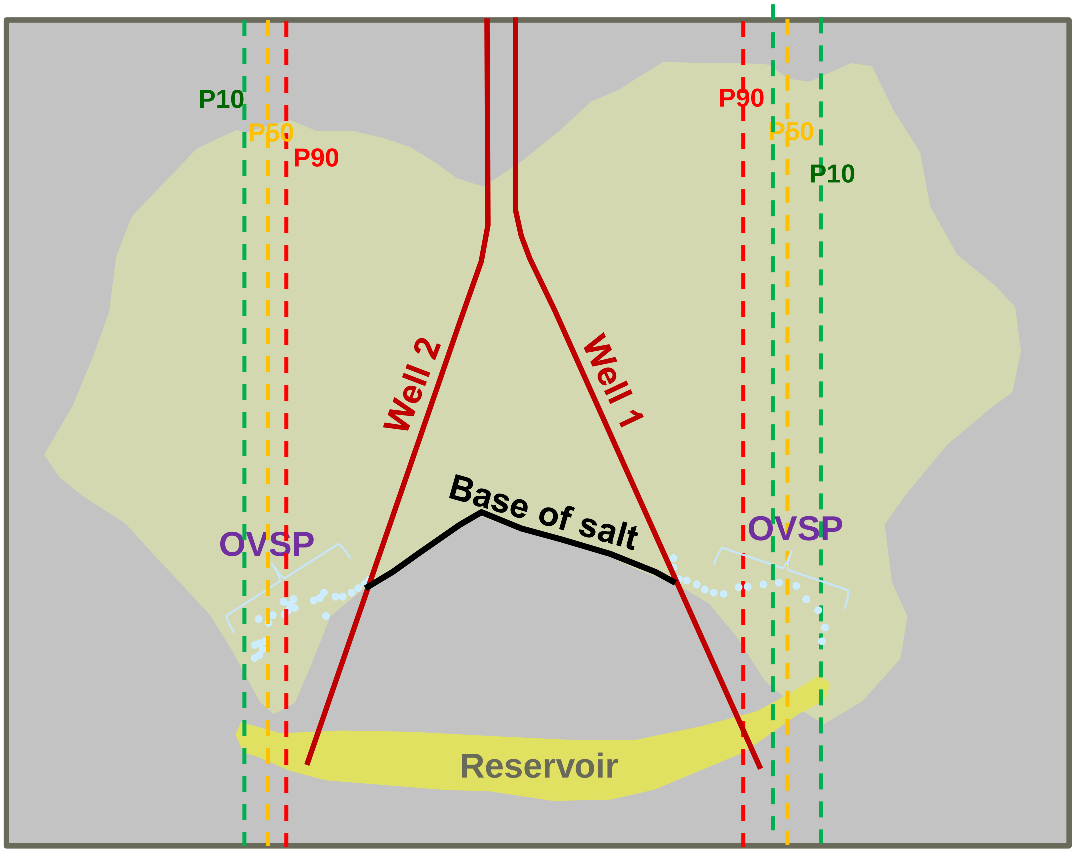
# SALT PROXIMITY SURVEY RESULTS



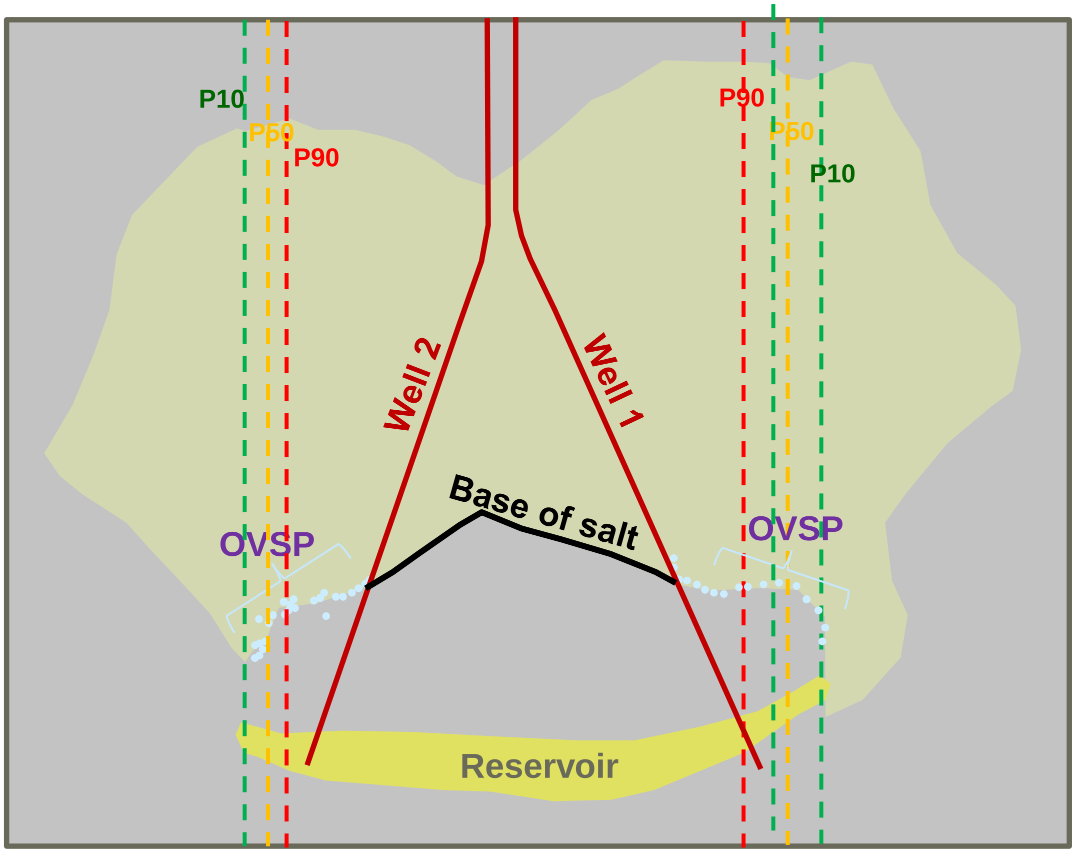




**Comparison of observed SWD-OVSP waveforms with Finite Difference modelling**

# WELL 1 + WELL 2 SALT PROXIMITY SURVEY RESULTS



# WELL 1 + WELL 2 SALT PROXIMITY SURVEY RESULTS



Shell

Schlumberger

# A Deepwater Salt Proximity Survey using Seismic While Drilling to Reduce Salt Positioning Uncertainty

EAGE

Kelsall N [2], Jensen B [1], Bayer J [1], Chen T [1], Li Y [1], Hayes R [2], Sayed A [2], Ali S [2], Goyal S [2]

[1]Shell Exploration and Production Company - Houston TX, USA
[2]Schlumberger - Houston TX, USA

## Introduction

In 2018 an operator acquired a Salt Proximity Survey while drilling a development well. The well is in a deepwater oilfield located beneath more than 4,000 feet of water, in the Gulf of Mexico, US. The field's main reservoir is a thick and highly pressured subsalt turbidite sand formation of Miocene.

The objective of the salt proximity survey was to help delineate the extent of the reservoir by mapping the intersecting salt flank with increased accuracy over the surface seismic image. Seismic imaging of highly dipping structures is challenging and made even more complex when located below a large salt body. Precisely locating the salt flank can significantly improve seismic imaging of such complex subsalt structures; thus, providing better characterization of reservoir geometry, properties, and consequently, resources.

A salt proximity survey allows for calibrating the subsurface model by measuring traveltimes, azimuth, and vertical angles of the refracted seismic signal from the surface to downhole receivers located near the salt flank. The traveltime and direction of the signal allow for mapping the salt exit points and delineating the salt flank location, enabling for more accurate placement of future wells. Three possible cases for identifying the salt flank location are shown in Figure 1.

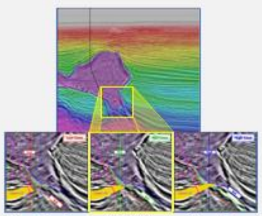


*Figure 1 Possible scenarios for the location of the salt face and the reservoir extent.*

## Method and Theory

Prejob vertical seismic profile (VSP) modelling with 3D ray tracing was necessary to establish the optimum location for positioning the seismic airgun array, which would provide the maximum spread of salt exit points for the planned well trajectory. Modelled traveltimes for zero-offset VSP (ZVSP) and offset VSP (OVSP) will enable for determining the record-time window by the SWD tool. One of these models is shown in Figure 2. The color coding indicates velocity and shows the expected ray paths from a seismic source located near the wellhead (rig source) and a source that is offset from the wellhead (vessel source) by approximately 5 mi.

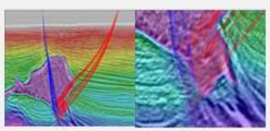


*Figure 2 (a) Ray-trace modelling, and (b) modelled salt exit points for rig source (blue) and vessel source (red)*

SWD uses logging-while-drilling (LWD) technology (Esmersoy et al., 2001) in which a seismic LWD tool is placed in the drilling bottomhole assembly (BHA) behind the drill bit. Borehole seismic data are acquired during when making drillpipe connections, which allow for acoustically quiet downhole conditions with no mud flow or pipe movement. Seismic shot data are recorded in the tool's memory and stack data from each series of shots can be transmitted from downhole to the surface via mud pulse telemetry (MWD) during drilling operations. This real-time stack data enabled quality control (QC) of the data being acquired and ensured the recorded data had a good signal-to-noise ratio (SNR).

Recording this dataset presented several challenges:

- First ultradeep (>28,000 ft) SWD survey below salt and a very large source offset (>26,000 ft). Good SNR?
- MWD bandwidth with complex logging BHA, including ultradeep resistivity look-ahead tools and high-rate of penetration (ROP) through salt.
- Short drillpipe connection time to acquire data due to efficient automated drillship.
- Large difference in traveltimes from rig source and vessel source and fixed recording window in downhole tool.

Careful planning between the operator and service providers allowed for overcoming these issues. The SNR could be improved by using a borehole seismic airgun array approximately four times the size of a conventional borehole source, which was composed of 12 guns with an air volume of 2,400 in.$^3$ and operating at 2,000 psi (see Figure 3 lower-right image). The airgun array required deployment from a vessel fitted with a fit-for-purpose crane (see Figure 3, lower left image)

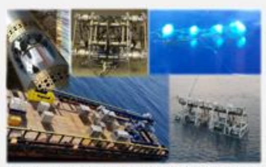


*Figure 3 (from top left clockwise) Seismic LWD tool sensors, 6-gun 1,500 in.$^3$ low-frequency airgun source, 12-gun 2,400 in.$^3$ vessel source and vessel deck with blue crane and seismic compressor equipment.*

MWD bandwidth can be managed by using the highest data transmission speed possible and by dividing the drilling run into phases. This procedure allowed for prioritizing the data transmission from the seismic LWD tool as it passes through salt and moves above the reservoir.

Data were acquired during the relatively short pipe connections during drilling and tripping operations, which provided time for 5 to 7 shots from both the rig and vessel source.

The recording window on the seismic LWD tool was fixed but the one-way traveltimes between the rig source and vessel source could have a difference of over 1500 ms. This condition was overcome using a patented technique (Kelsall, N. et al., 2017). The technique consists of independently varying the firing time of the rig source and vessel source such that the first-arrival energy is recorded in the downhole tools recording window (see Figure 4).


*Figure 4 Variable-time offset-to-surface firing time applied to vessel and rig seismic sources*

## Real-Time QC and Memory Data

Real-time stacked waveform data can be sent uphole from the recorded shots fired by the vessel source. A 300-ms waveform was transmitted to surface during drilling operations after each drillpipe connection had been made. As shown in Figure 5, the data showed a clear but complex signal with a good SNR.

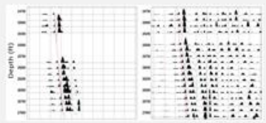



*Figure 5 (a) Hydrophone sensor data in real time during drilling and (b) from postrun memory data*

In addition to the hydrophone sensor data, three-component geophone data were also recorded together with tool orientation. The tool orientation was determined from the MWD directional toolface and the offset angle between the radial geophone sensors and the MWD tool reference point. Knowing the orientation of the tool was important to establish the direction of energy arrival for the salt proximity data processing.

The salt proximity data processing was performed using the postrun memory data and the hydrophone and three-component geophone data. The final results are shown in Figure 6, which provides a range of possible salt exit locations but with much less uncertainty than the predrill model. The observed primary arrival was significantly later than the predicted arrival from the predrill model. To calibrate the model to the observed data, the salt entry points and the shape of the salt structure were modified.

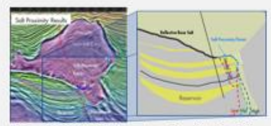



*Figure 6 (a) Salt proximity processing results and (b) updated salt root interpretation.*

## Conclusions

The salt proximity survey in this well successfully proved the concept for conducting such a survey using SWD with both a rig source and an offset vessel source. In addition, the survey proved that this survey method is even possible in some of the world's deepest wells using a large source offset.

Data were acquired during drilling operations and during pulling out without using additional rig time as required during a normal drilling run, increasing the efficiency and proving the economics of this acquisition method.

The key to the success of this complex project resulted from the detailed planning between the operator and the service providers. Teamwork and continual communications proved critical to assembling and mobilizing the large amount of equipment and specialized personnel to the precise place at the exact time followed by further careful communications during the data acquisition phase between onshore teams and offshore crews on both the rig and vessel.

The final results from the salt proximity survey data processing have proved to be valuable for the operator and partners by improving the reservoir model, firming up reserve estimates, and optimizing well placement for future wells in the development.

## References

Esmersoy, C., Underhill, W., and Hawthorn, A., 2001. Seismic Measurement While Drilling: Conventional Borehole Seismics on LWD. Presented at the 42nd SPWLA Annual Logging Symposium, Houston, Texas, USA, 17–20 June. SPWLA-2001-RR.

Kelsall, N., Will, M., Armstrong, P., Laraffie, P., 2017. Methods and apparatus for improved acoustic data acquisition. U.S. Patent 9638818

# Salt/Sediment proximity to delineate salt boundaries with P and PS waves using Seismic While Drilling in the Gulf of Mexico

*Jensen, B.*, J. Bayer (Shell E & P), Y. Li, T. Chen, and K. Matson (Shell International E & P)*

## Summary

Between 2018-2019, Shell acquired two VSP surveys in two deep water wells in the Gulf of Mexico (GOM) using a Seismic While Drilling (SWD) tool and both a rig source (ZVSP) and a boat source (OVSP). The major objective of the surveys is to delineate the salt-sediment boundary at the salt base and flank. We designed complex VSP surveys and executed them in an economic and effective manner. We developed a comprehensive analysis and processing method to integrate P wave sediment and salt proximities with converted PS salt proximity. We use the 2018 SWD-VSP survey to demonstrate how we define the salt boundary with the integrated results. Our results show that we can delineate the salt boundary with better accuracy and with a high degree of confidence. This successful VSP survey provides significant business and technical value.

## Introduction

Seismic While Drilling (SWD) is a downhole seismic method used for acquiring VSP data (Esmersoy et al., 2001; Underhill et al., 2001). A seismic tool package containing one hydrophone and one 3-component (3C) geophone is placed in the drilling BHA behind the drill bit while air-gun arrays fire at the surface. The VSP data is acquired during drill pipe connections which allows for acoustically quiet conditions downhole with no mud flow or pipe movement. SWD has widely been proved as a useful check-shot tool, but with limited application for salt proximity surveys (Rois et al., 2011). In 2018-2019, Shell carried out two SWD-VSP surveys with both rig and boat sources in two deep water development wells nearby in the GOM (Kelsall et al., 2019). A major objective of these surveys was to delineate the extent of the reservoir by mapping the intersecting salt flank with increased accuracy over the surface seismic image. We will demonstrate, using the 2018 VSP survey data, how to integrate drilling, sonic, and ZVSP check-shot data with the sediment and salt proximity surveys to delineate the salt boundary at the salt base and flank with increased accuracy and with a high degree of confidence.

## Data, Method, and Results

We carried out pre-survey VSP ray-tracing modeling (Fig. 1) with a rig and a boat source (ZVSP & OVSP) for both the salt and the sediment proximity surveys to delineate the salt boundaries. Accurately locating the salt boundary at salt flanks and the salt base is critical for updating velocity models, estimating reservoir size, minimizing drilling risks, and optimizing future well locations. Salt proximity is a seismic refraction method, which measures the P-wave first-arrival times and directions (azimuth and incidence angles) using 3C geophones placed in a well in sediment close to the salt. We apply 3D ray tracing in two velocity models (salt flood and sediment models) to calculate the salt exit points (e.g. Li et al., 2003a, b). For a well drilled inside of salt, we use a sediment proximity method (O'Brien, 2005) to determine the salt-sediment boundary using 3C geophones in the well and an offset seismic source at the surface of the sediment basin. The sediment proximity also measures the first arrival times, azimuth, and incidence angles. However, this method uses a sediment velocity model and a half-space salt velocity model to calculate the salt entry points, which define the salt top boundary.

In our SWD-VSP survey, one hydrophone and one 3C geophone are in an SWD tool on the BHA of the drill string and we fire two air-gun arrays of 1,500 cu. in. (ZVSP) and 2,400 cu. in. (OVSP) at the surface to acquire the VSP data inside and below the salt. This method enables us to integrate both salt and sediment proximities to delineate the salt boundaries. Using the SWD-OVSP data recorded inside the salt, we calculate the salt entry points via sediment proximity and use the results to calibrate the top of the salt. We then update the top of salt flood model and use this with the OVSP data recorded below the salt to calculate salt exit points at the salt base and flank, delineating salt proximity to the reservoir.

To minimize the velocity uncertainties of the salt and the subsalt sediment, we integrate the rig source (ZVSP) check-shot data, sonic P-wave velocity data (Fig. 2), and the Vp/Vs ratio from both the ZVSP and the sonic data to confirm and refine velocities in the salt and subsalt sediment. An average salt velocity of 14,822 ft/s from LWD sonic perfectly matches with that of the dirty salt model generated from the surface seismic data. Discrepancies between the observed and modelled ZVSP first arrival times are less than 0.1% from 17,000 ft depth to the base of salt (BoS). This discrepancy slightly increases to 0.2% from the BoS to 26,000 ft depth. At a depth of 28,000 ft, the discrepancy increases to 0.75%. We account for these observations when we refine and adjust the salt velocity and subsalt sediment velocity in the salt and sediment velocity models used for proximity surveys.

We acquire the 4C SWD data of the ZVSP and the OVSP in a "ping-pong" shooting style during a drilling trip in and trip out of the borehole to ensure enough depth coverage inside and below the salt for both proximity surveys. When the SWD tool is first tripped in at a shallow depth, we make test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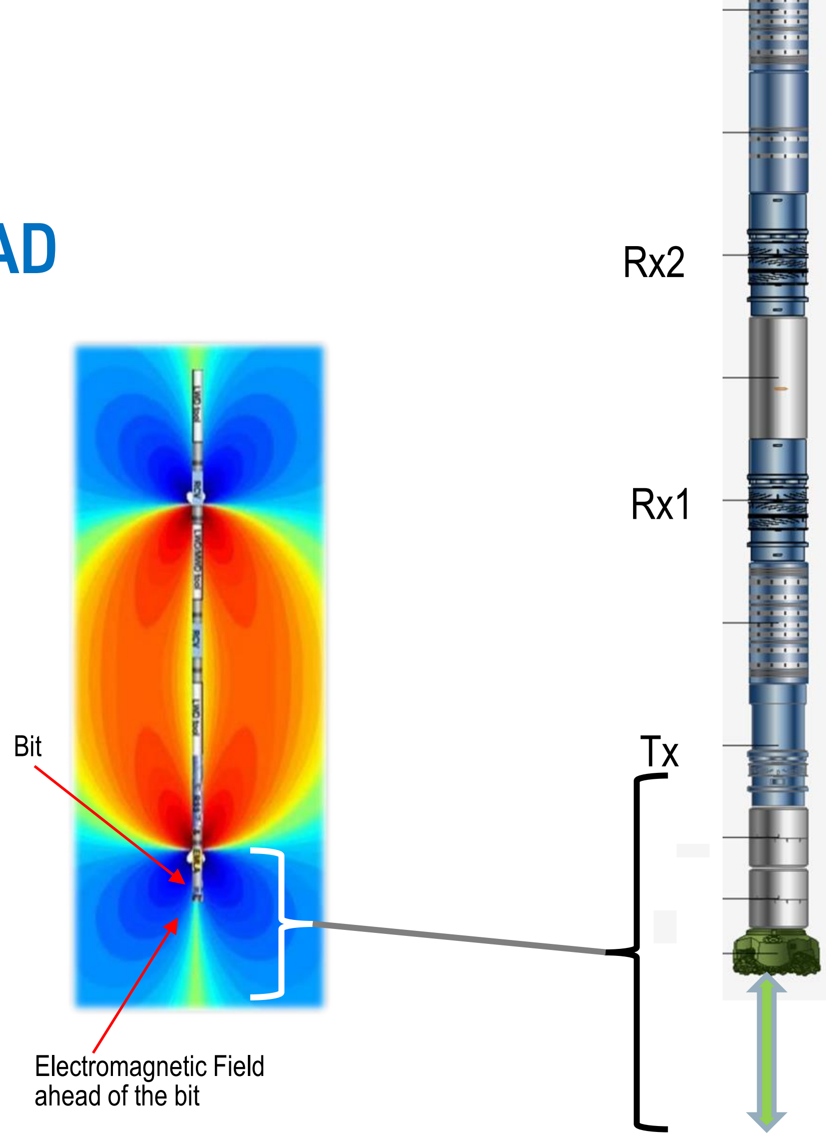
# SEISMIC + EM LOOKAHEAD / LOOKAROUND

# EM LOOKAHEAD

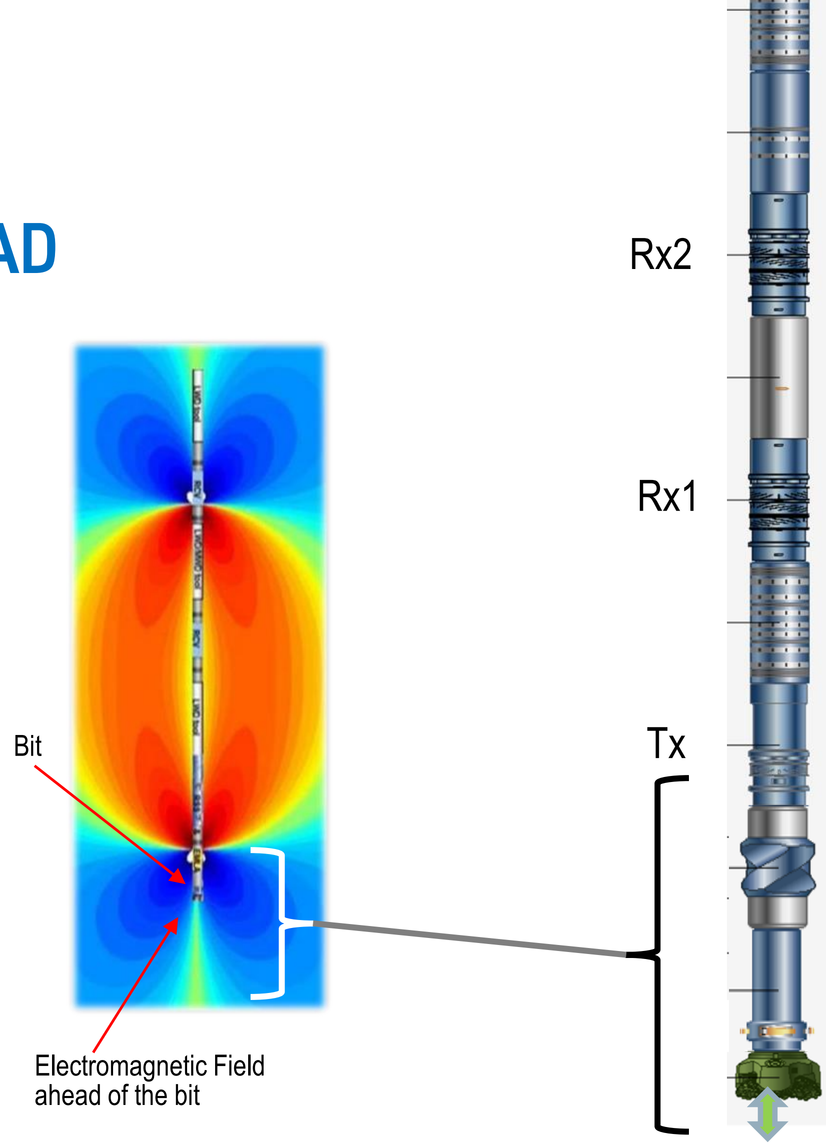



Lookahead range depends on:

- Resistivity contrast between formations
- Qty and spacing of Receivers in BHA (max 3)
- Distance between Transmitter and bit

Modelling can indicate lookahead range to expect for each environment

# EM LOOKAHEAD




Lookahead range depends on:

- Resistivity contrast between formations
- Qty and spacing of Receivers in BHA (max 3)
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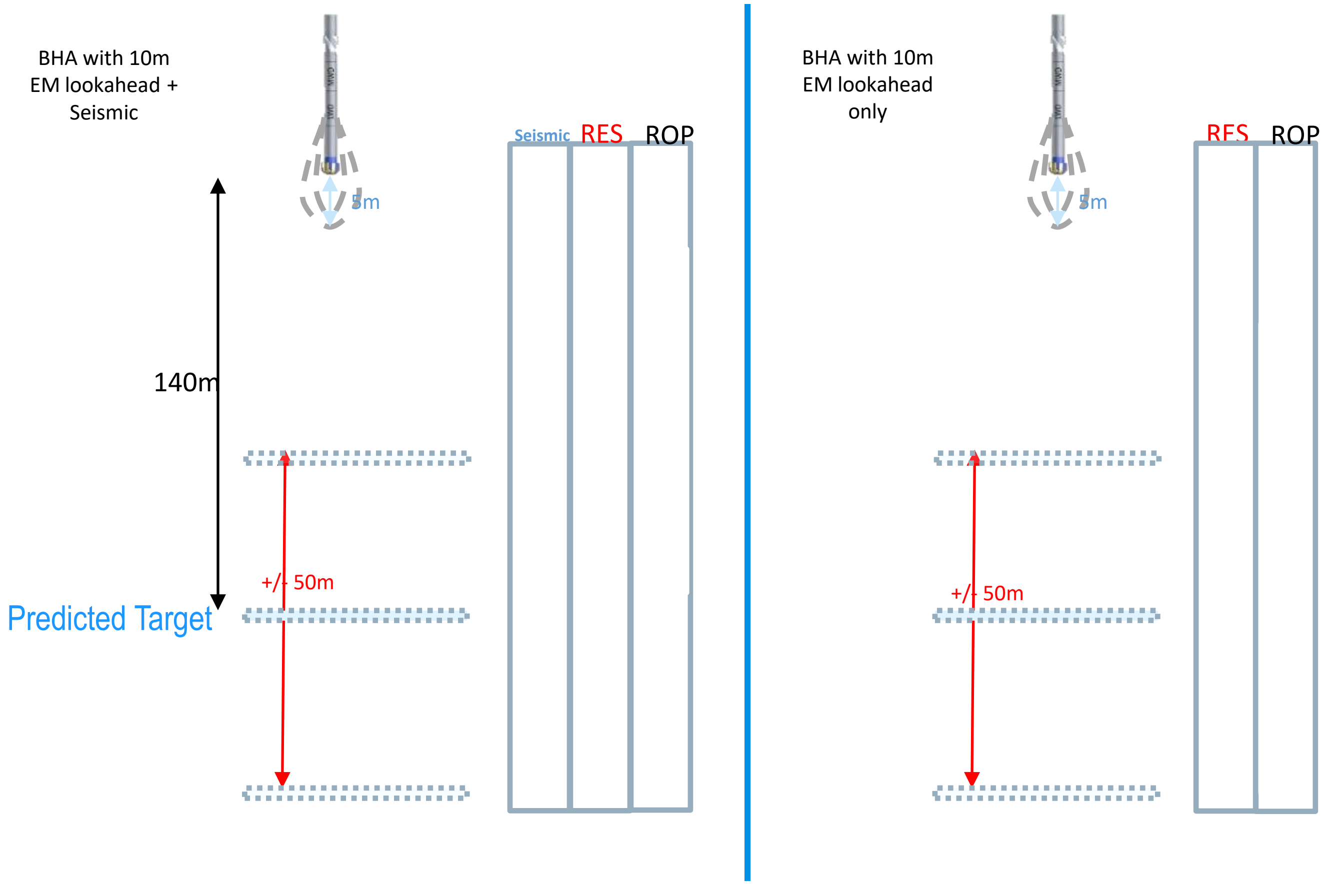
Modelling can indicate lookahead range to expect for each environment

# SEISMIC + EM LOOKAHEAD VS EM LOOKAHEAD ONLY



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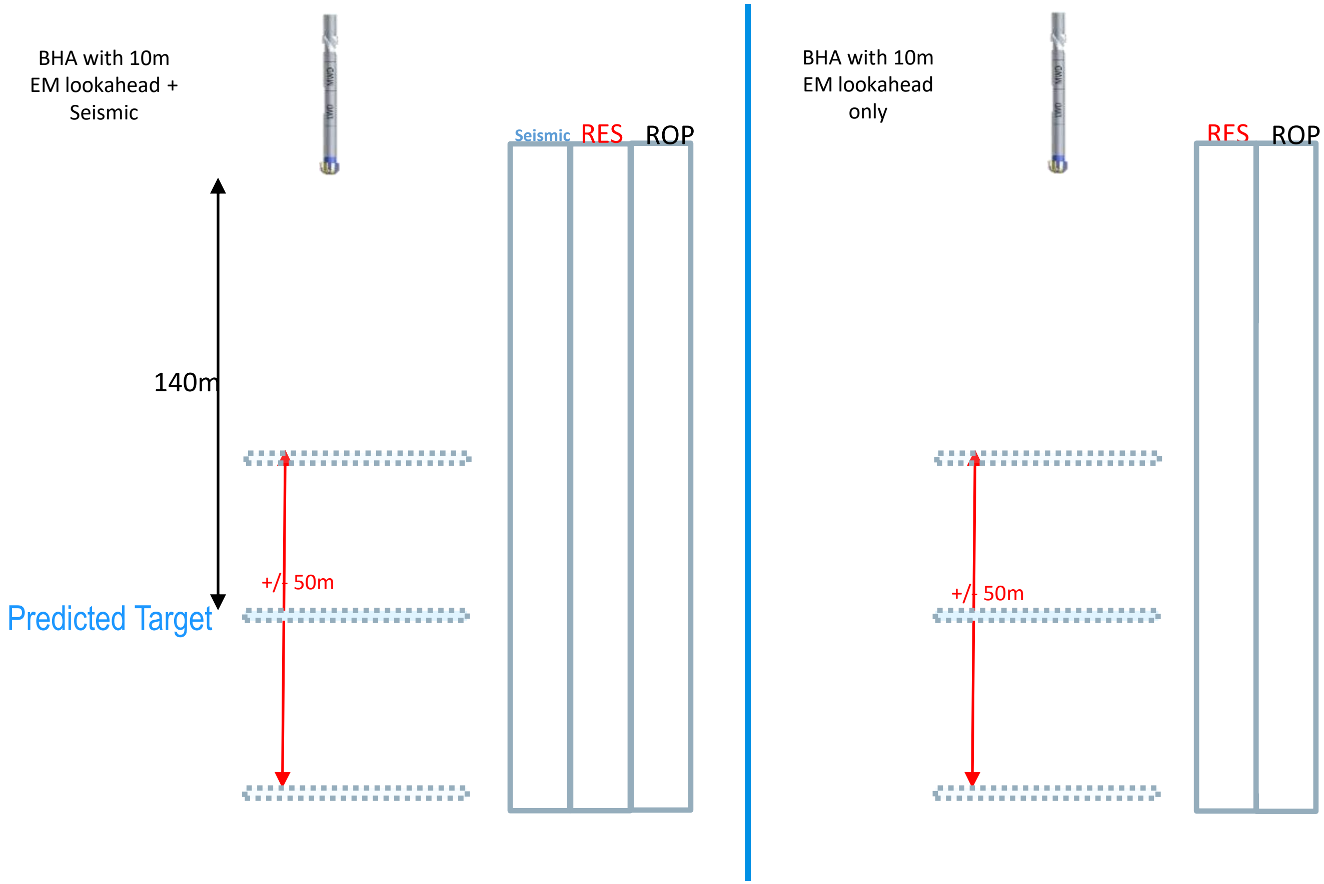

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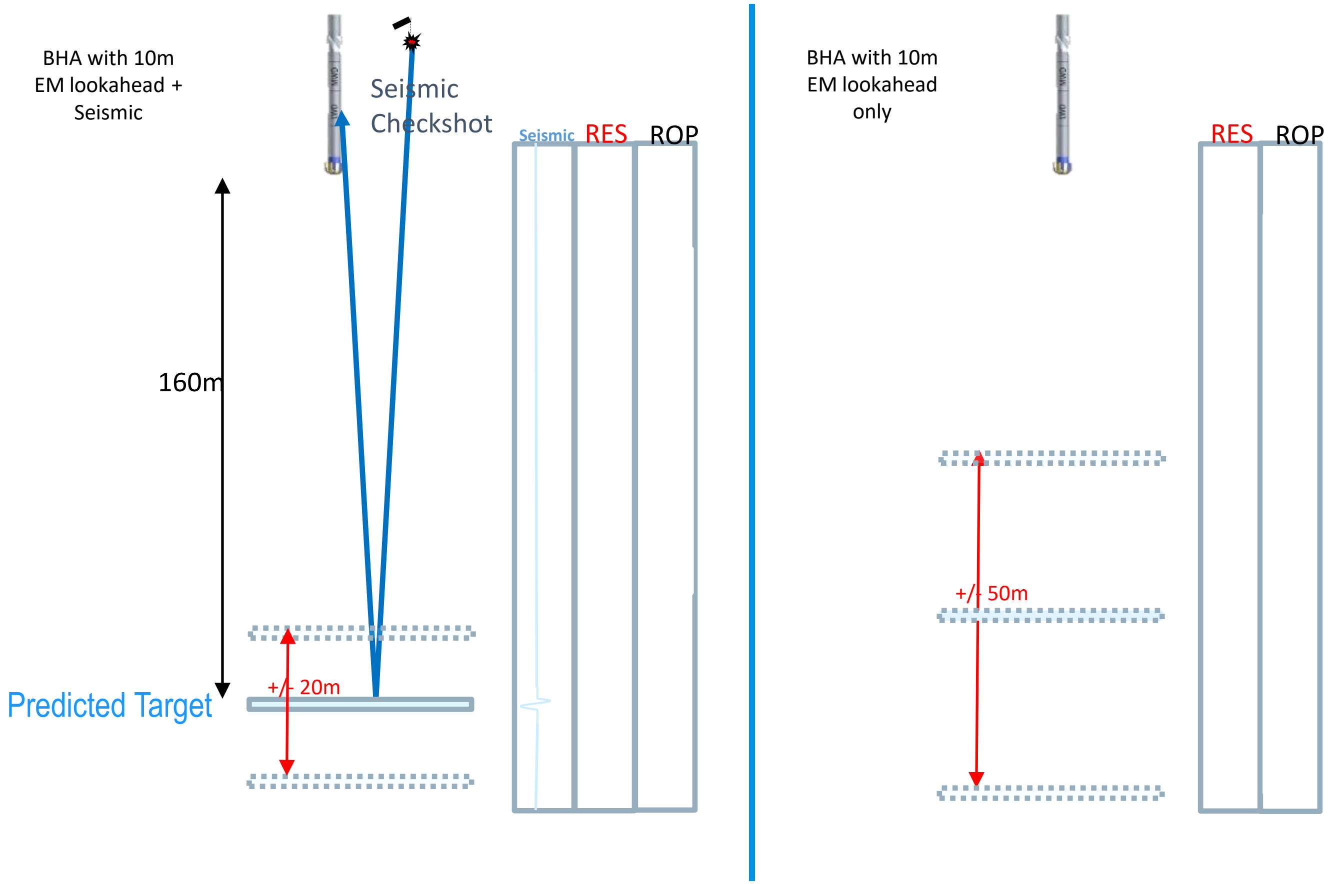
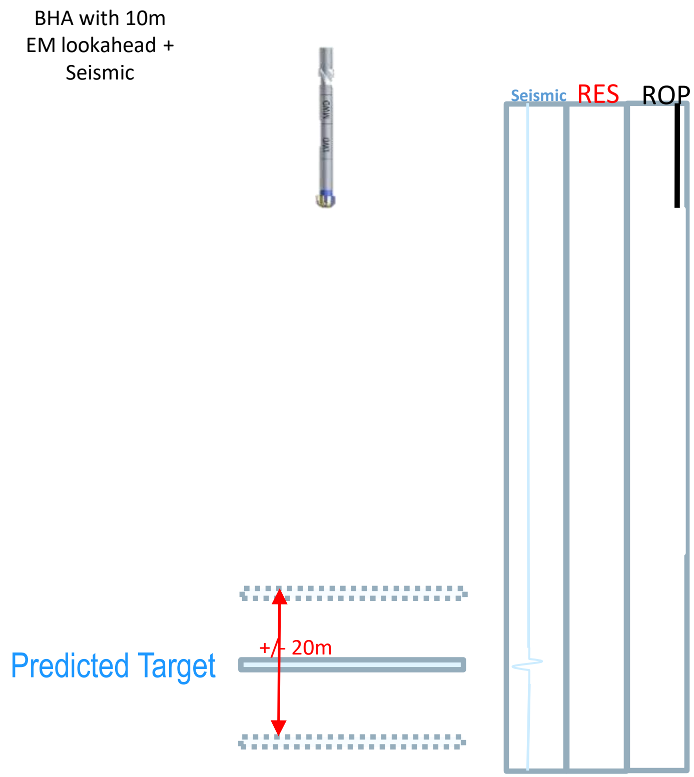
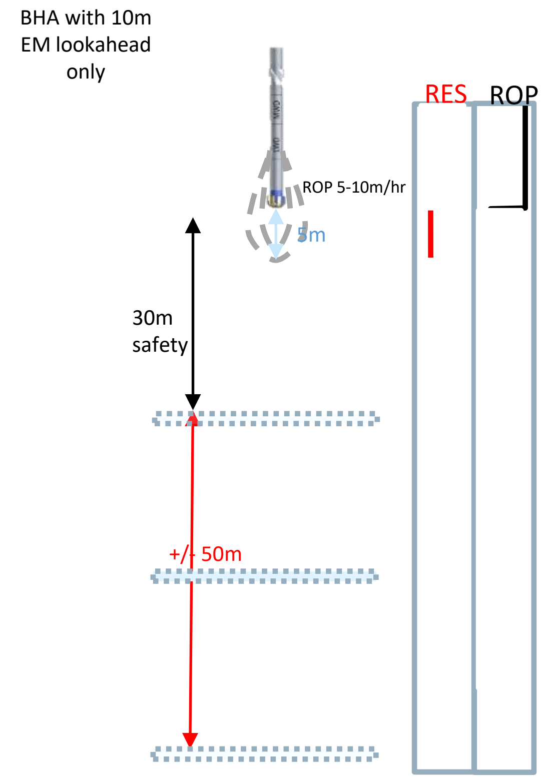


# SEISMIC + EM LOOKAHEAD VS EM LOOKAHEAD ONLY



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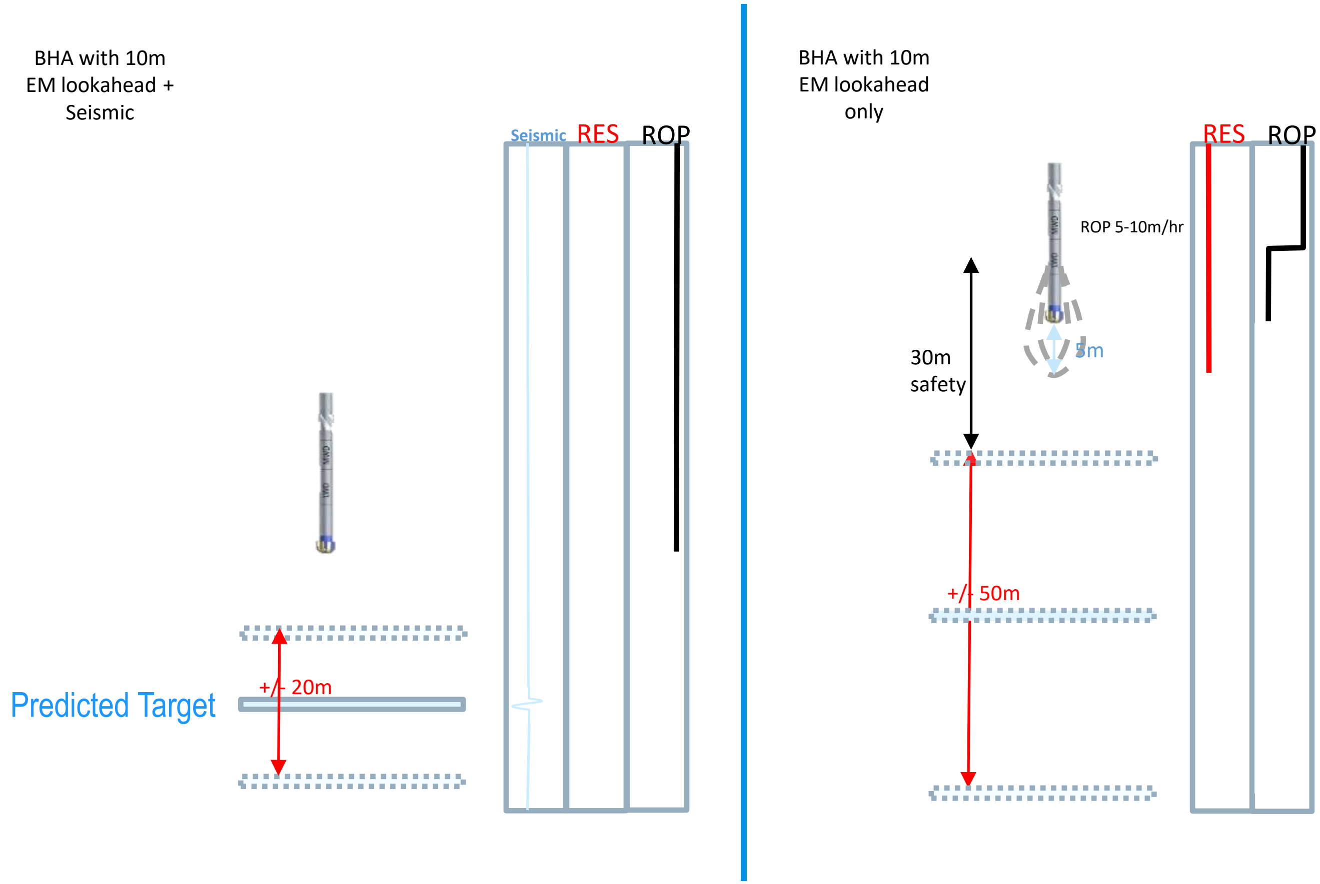

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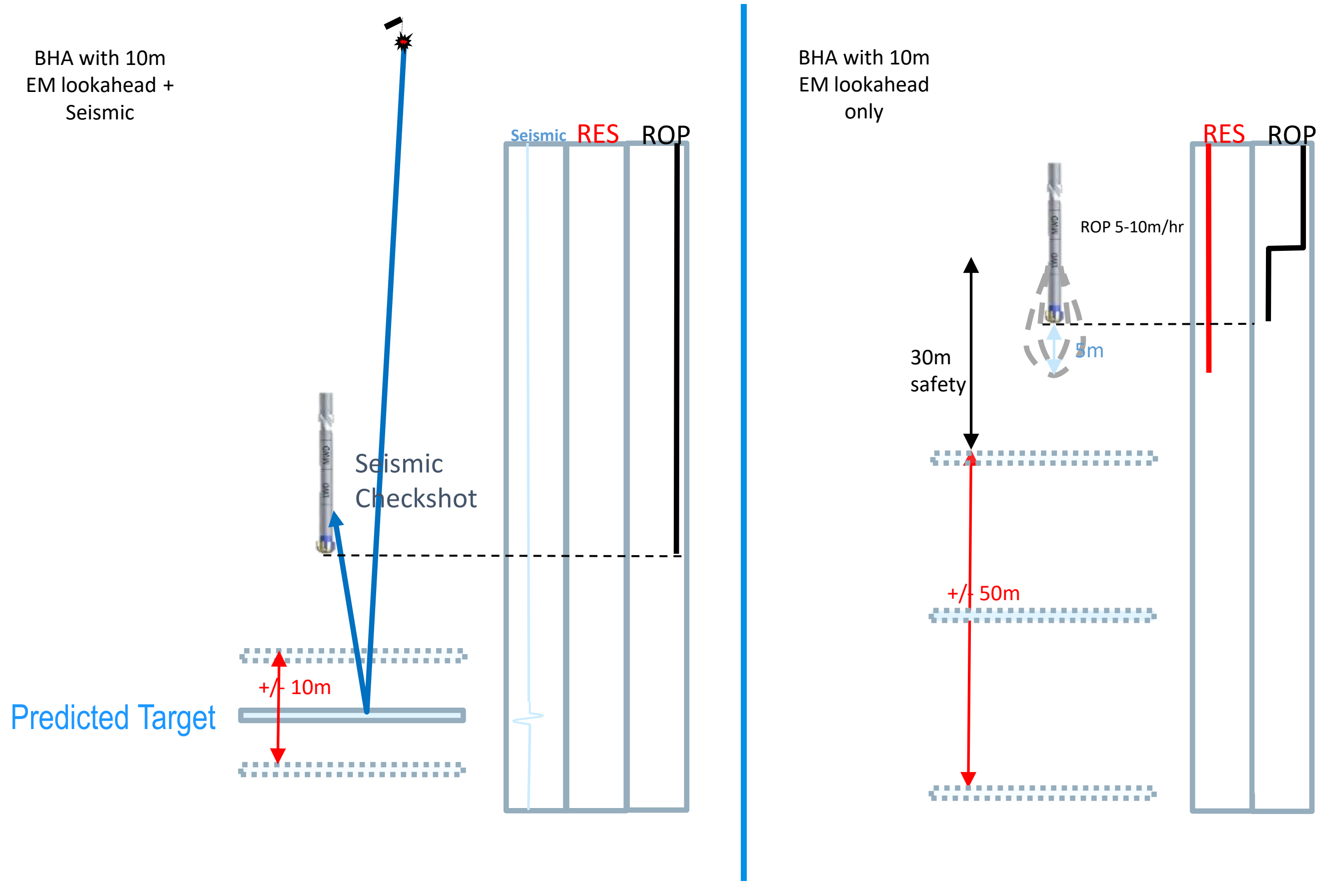

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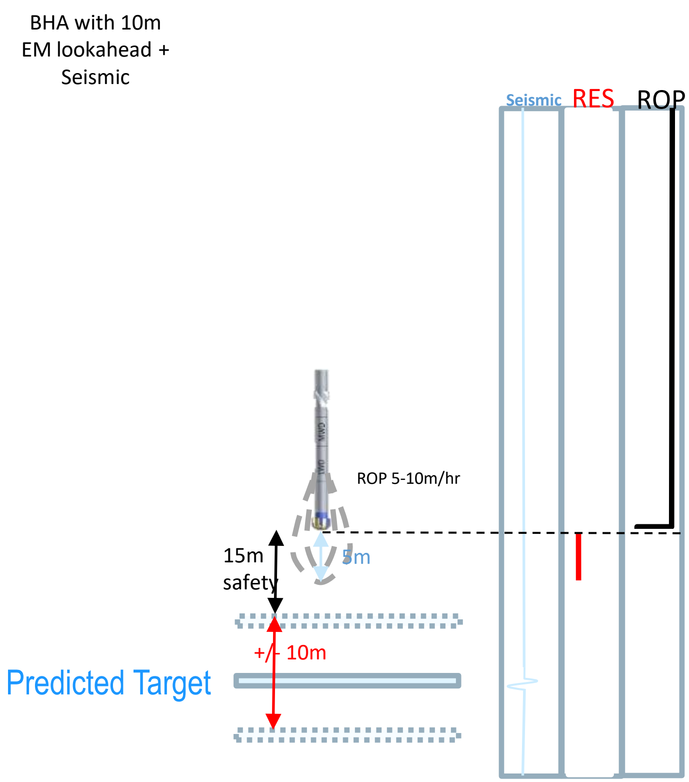
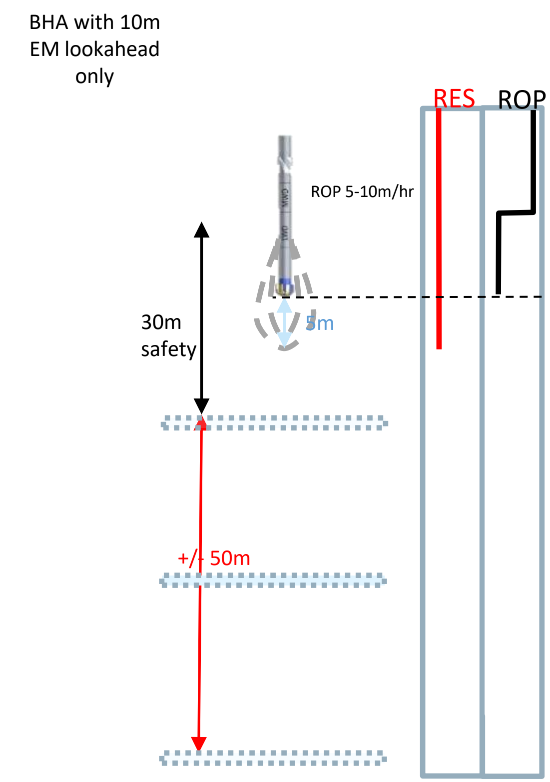
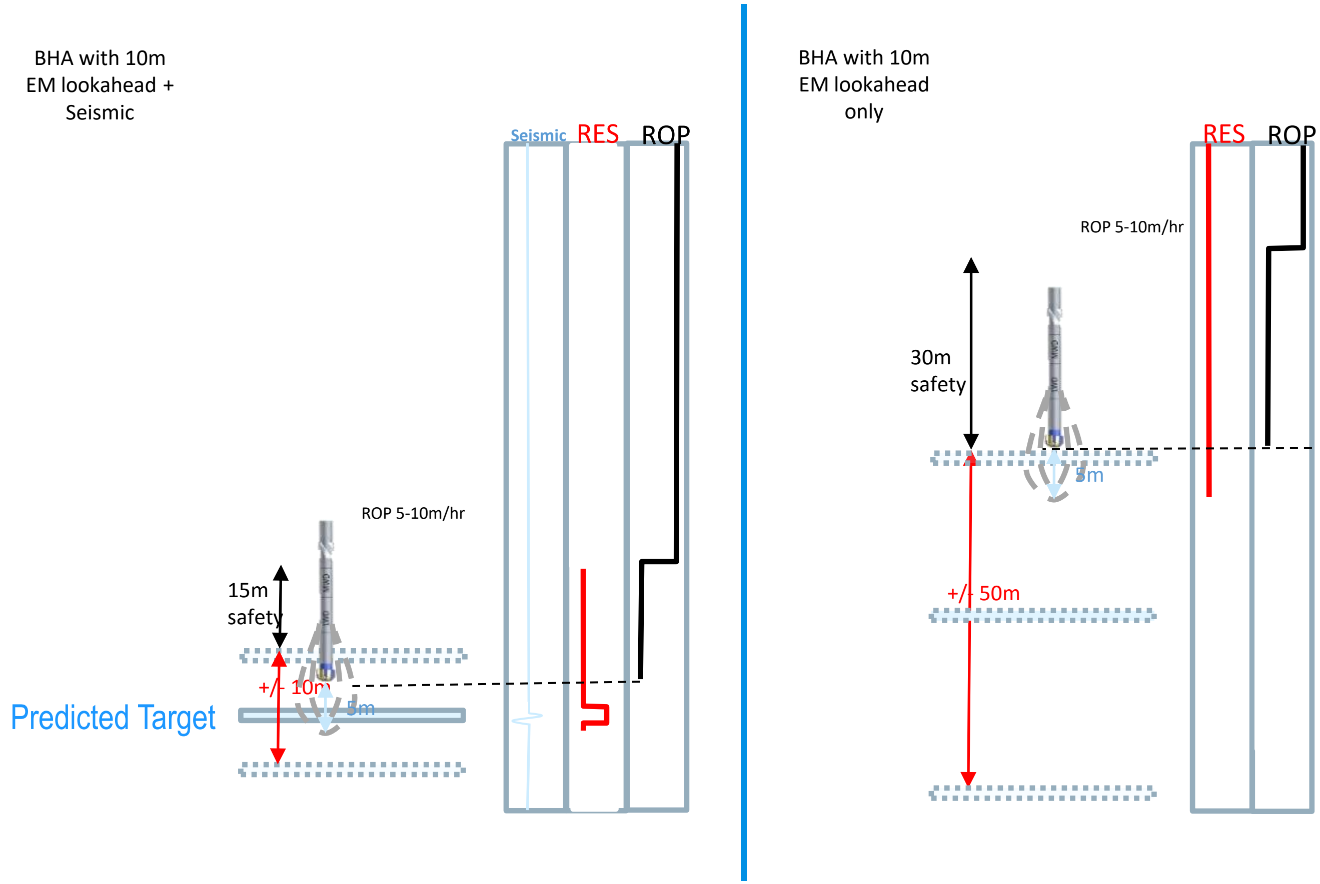
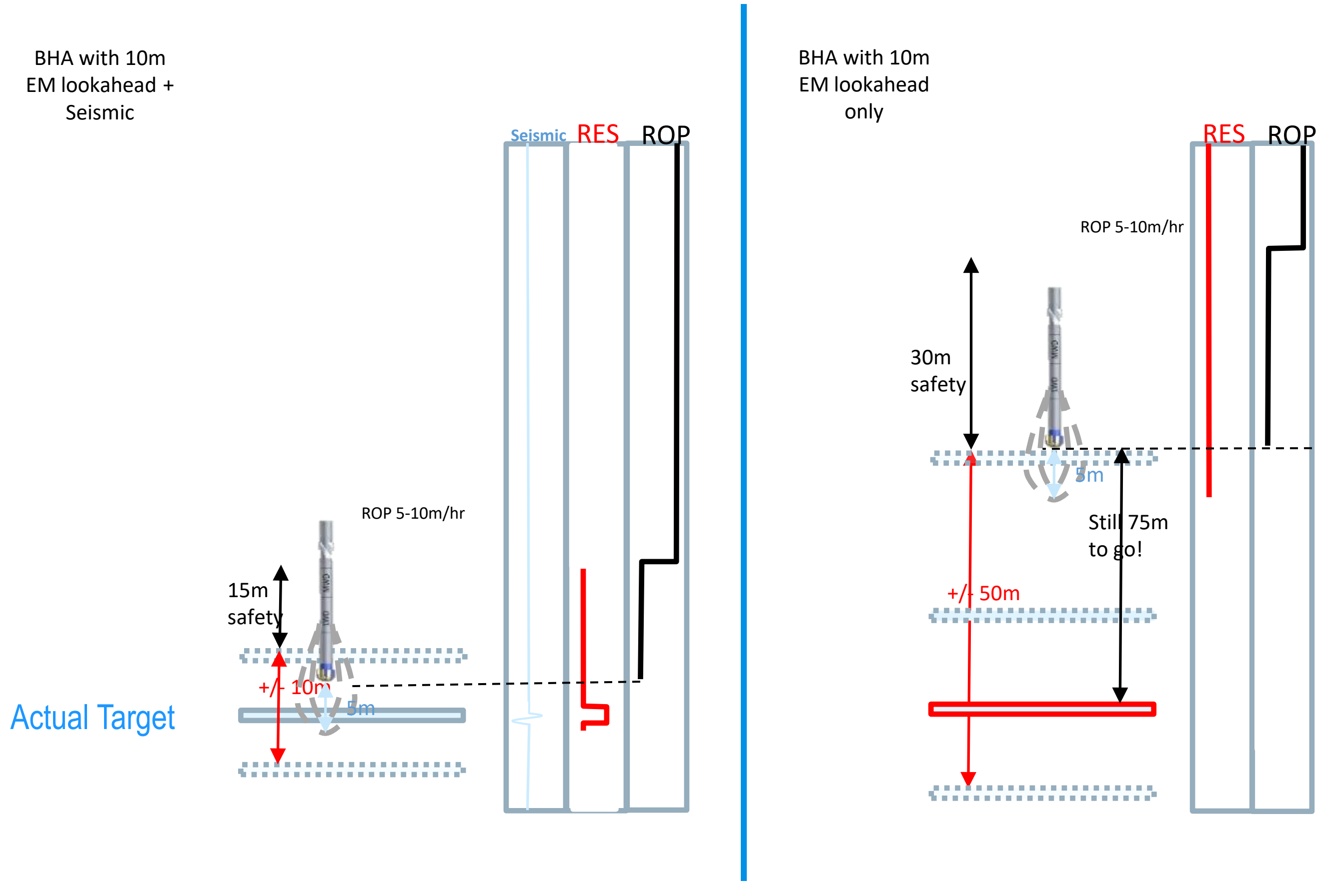


# SEISMIC + EM LOOKAHEAD VS EM LOOKAHEAD ONLY

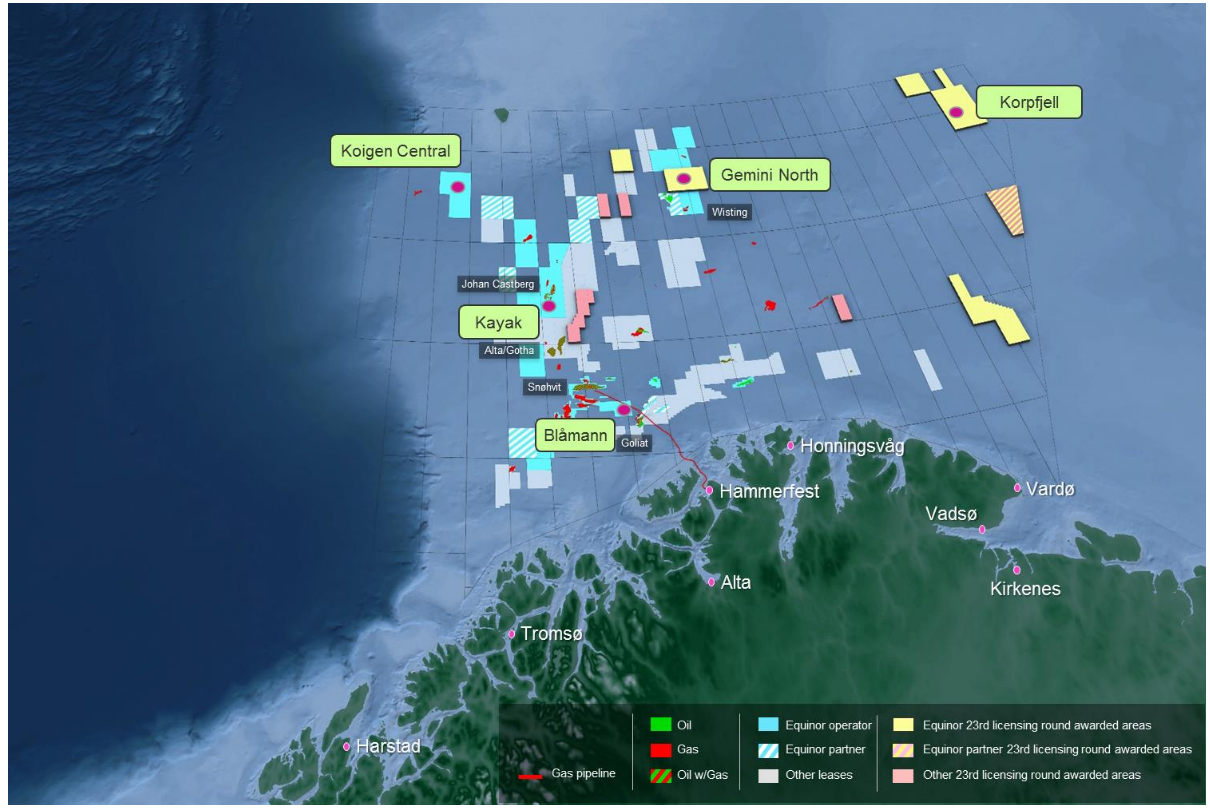


# SEISMIC + EM LOOKAHEAD VS EM LOOKAHEAD ONLY



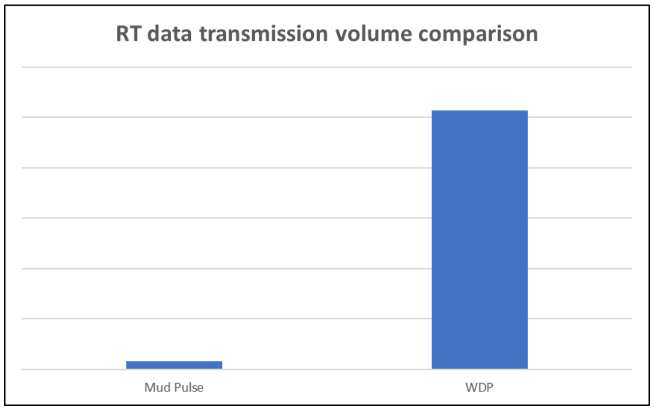
# SEISMIC+EM LOOKAHEAD

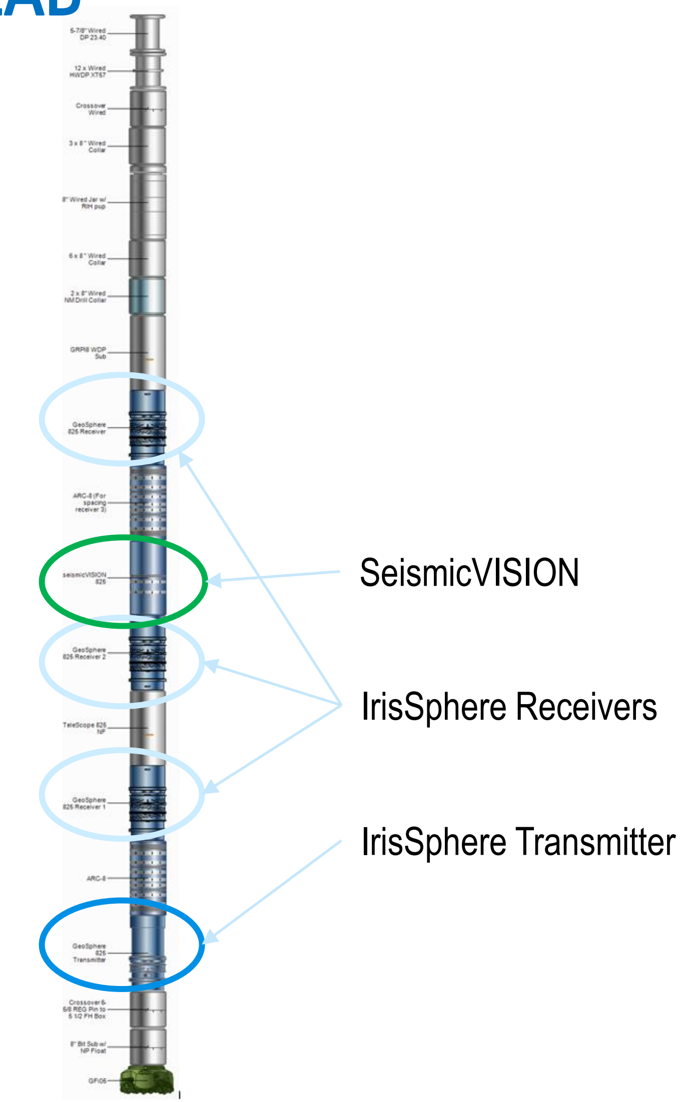
- Riserless drilling near artic
- Objective to safely drill close to reservoir top without accidental penetration
- Seismic + EM lookahead drilling BHA to mitigate risk



# SEISMIC+EM LOOKAHEAD

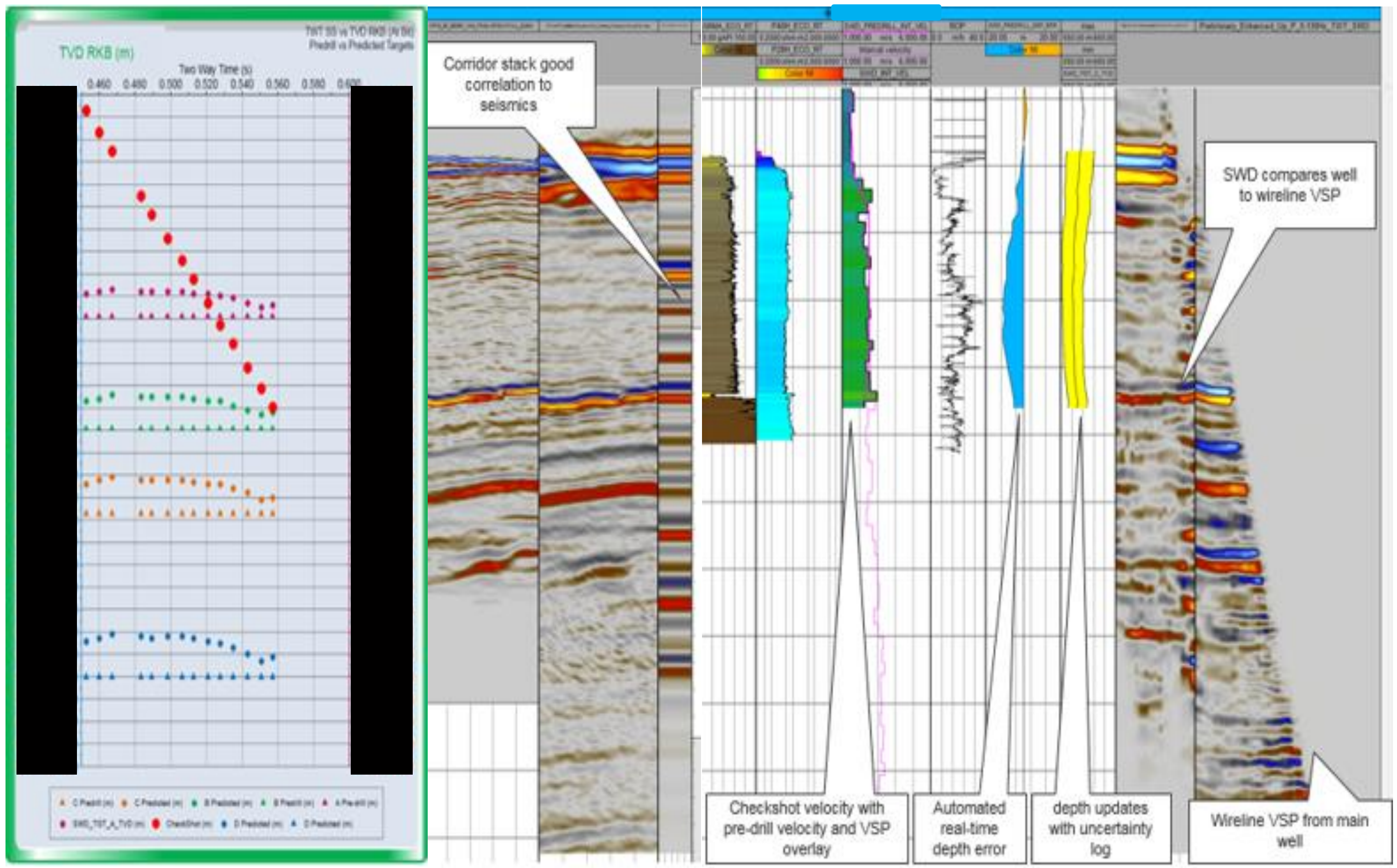
- ARC
- TeleScope
- IrisSphere w/3 receivers
- SeismicVision
- Wired Drill Pipe



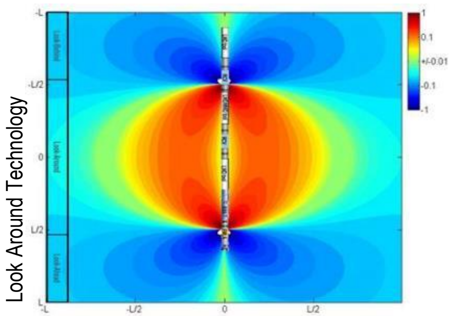



# REALTIME SEISMIC RESULT

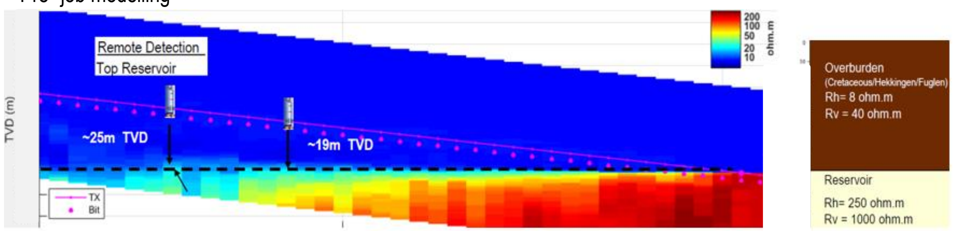
- Accurate RT Seismic Depth prediction

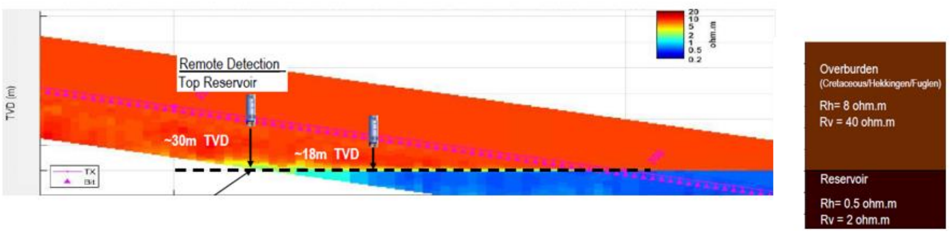


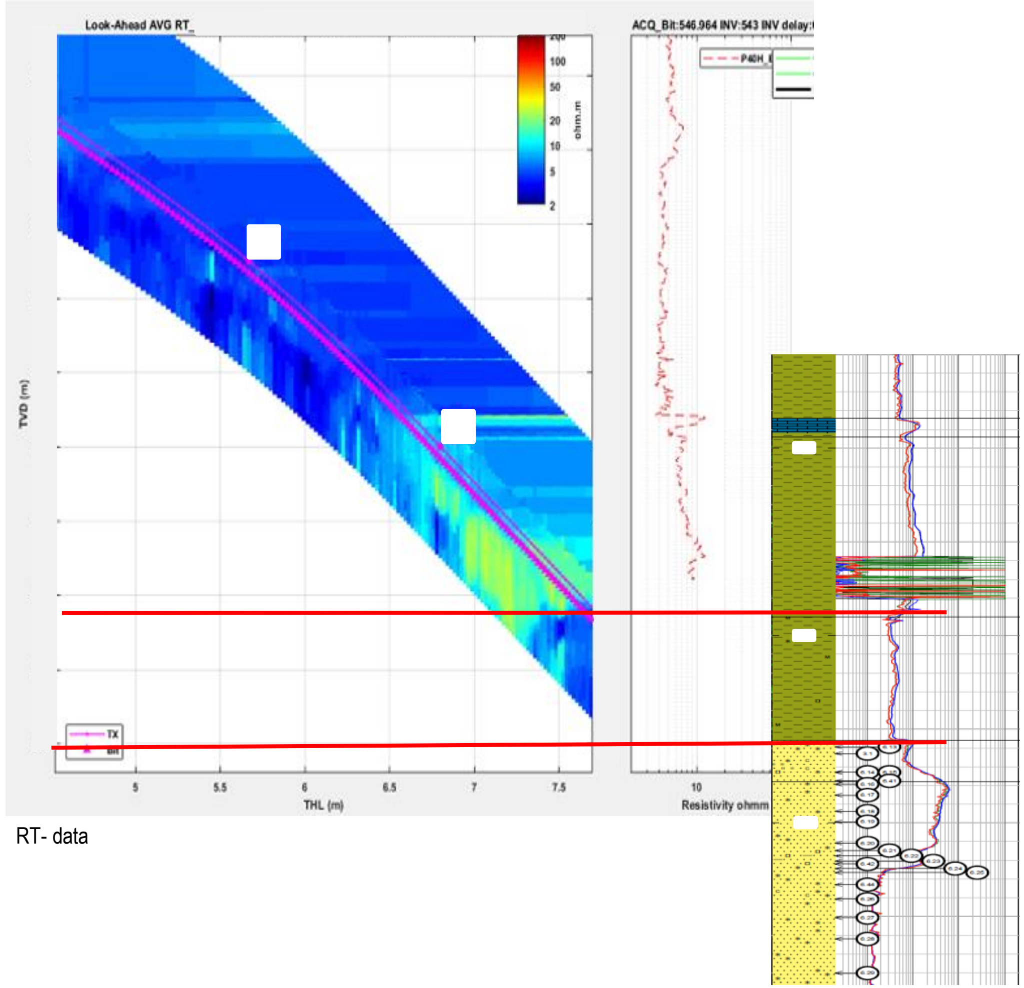
# EM LOOK AHEAD RESULT




Pre- job modelling

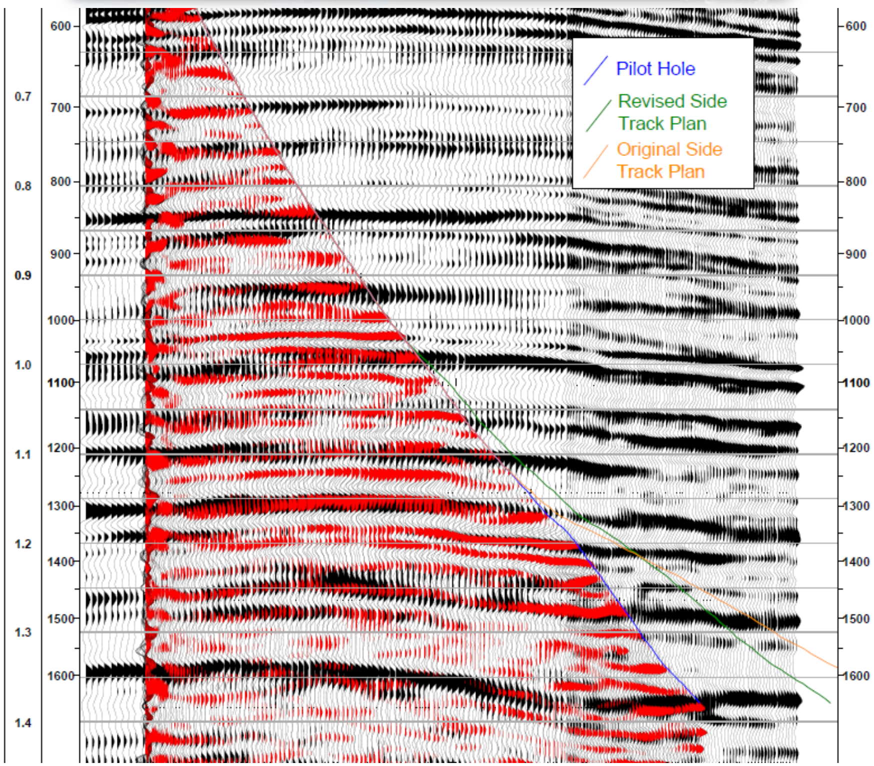


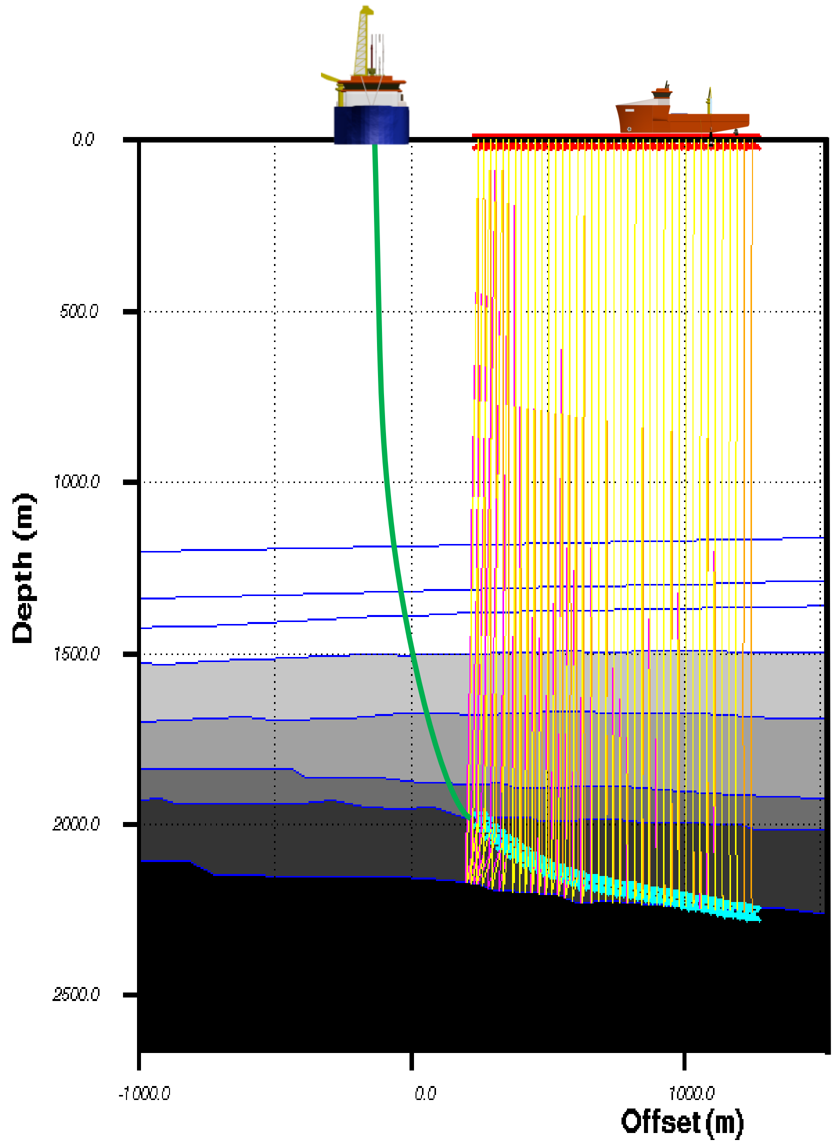




RT- data

# WALKABOVE VSP SURVEY WHILE PULLING OUT OF HOLE



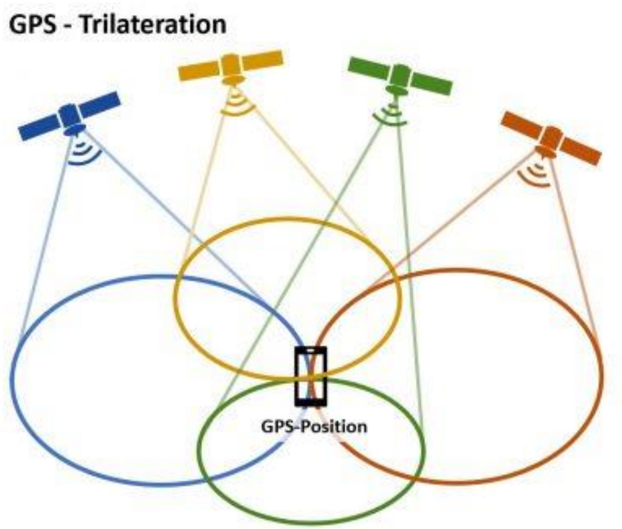



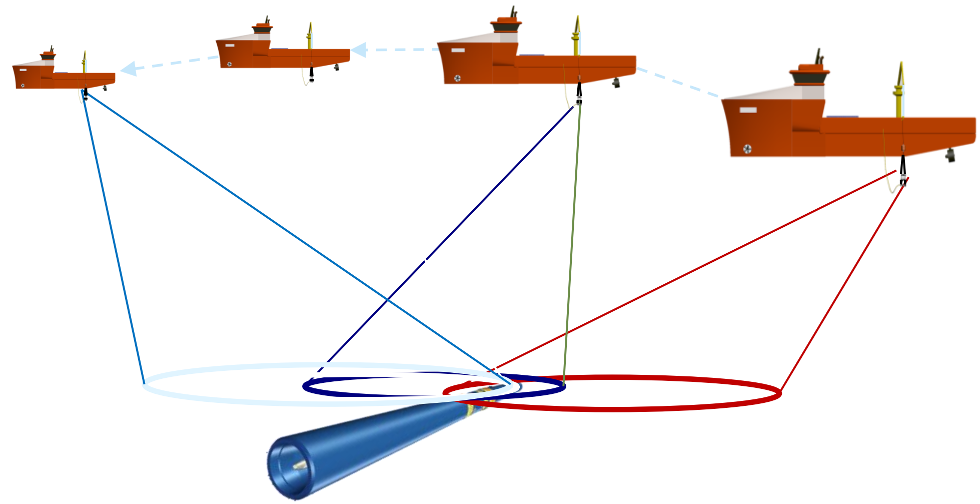


FORCE

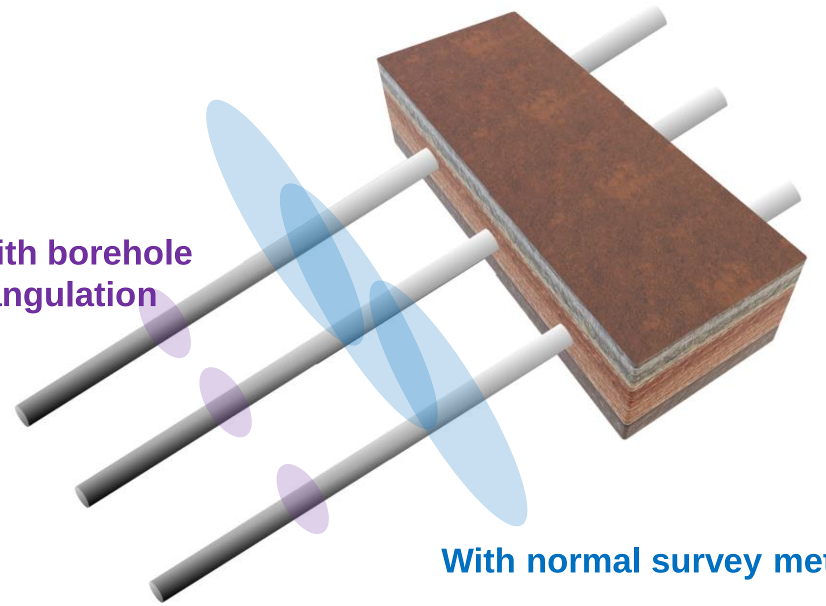
Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, 2022)*

# POTENTIAL SEISMIC WHILE DRILLING APPLICATION: “GPS FOR THE BHA”



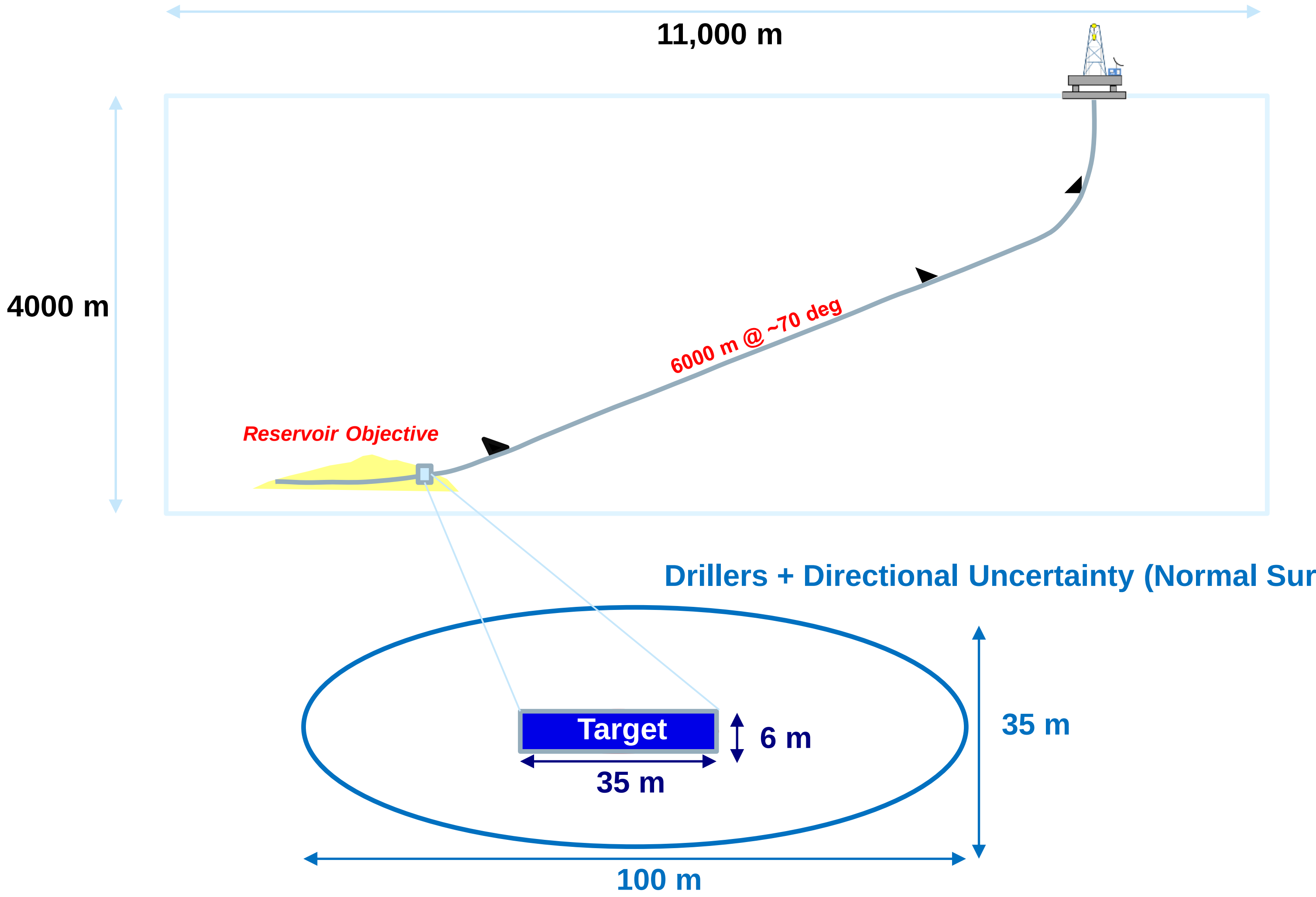



# MORE WELLS PER RESERVOIR?



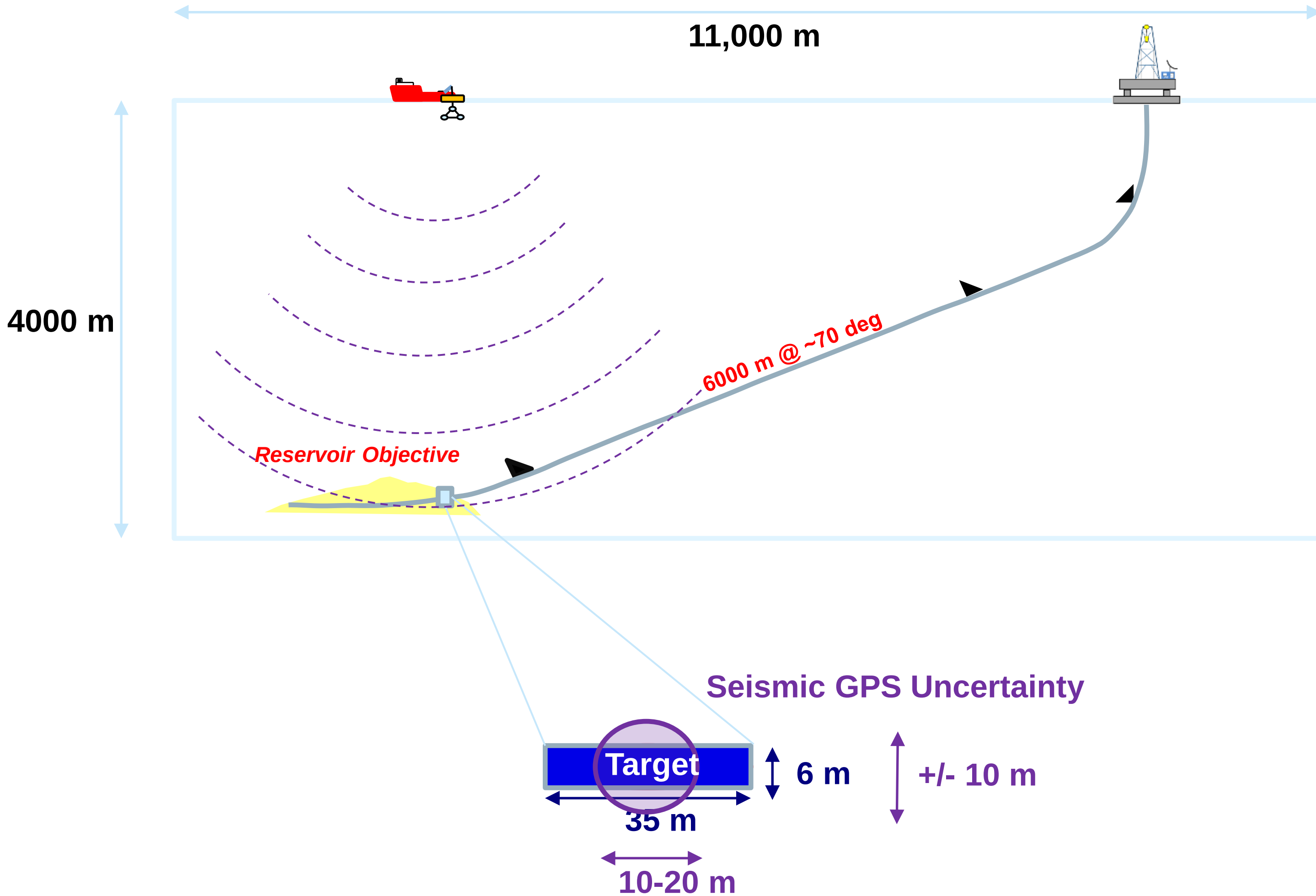
# "SEISMIC GPS"

- Lateral uncertainty reduced to 10-20m
- Reduced rig time for survey measurement vs Gyro
- Stationary pipe time < 5 minutes

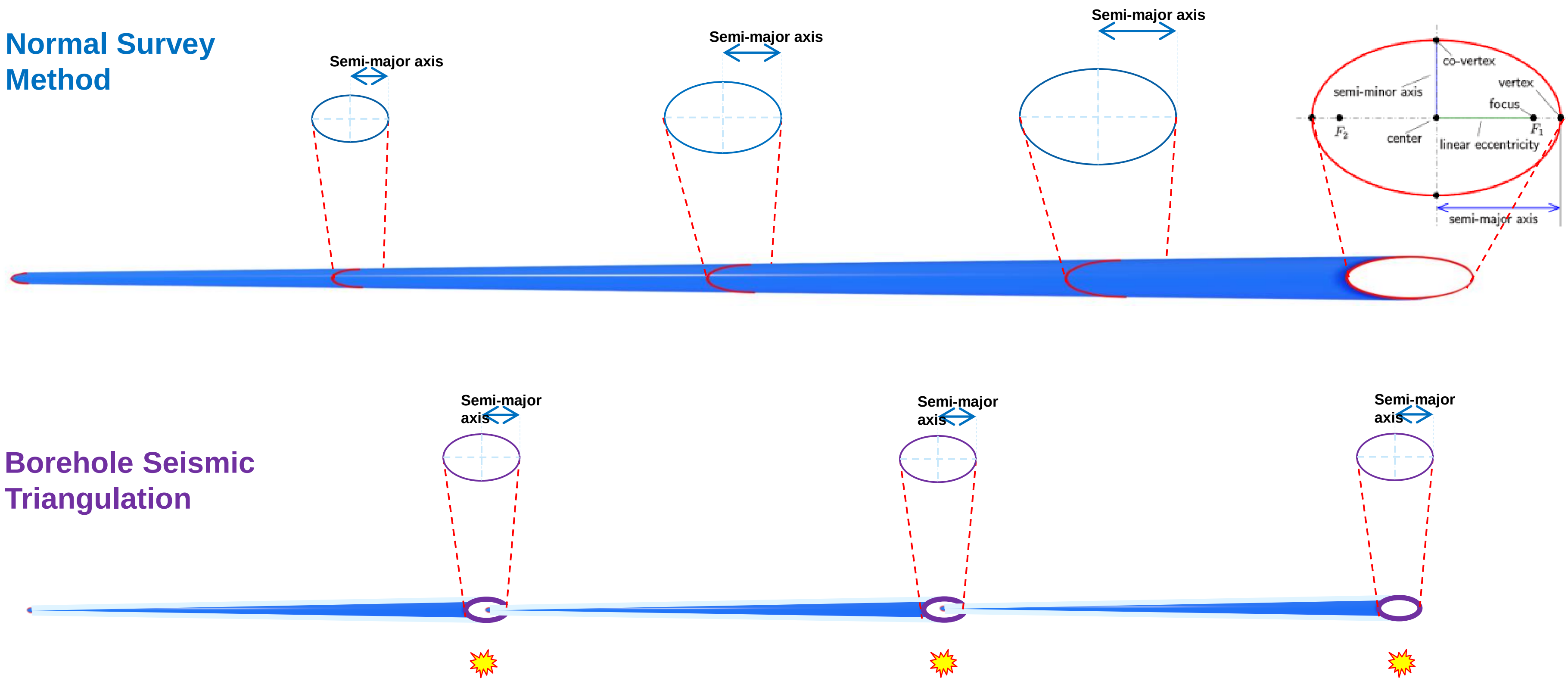


# "SEISMIC GPS"

- Lateral uncertainty reduced to 10-20m
- Well landing with VSP has reduced depth uncertainty to +/-10 m
- Requires velocity model
- Maybe not suitable in very complex geology

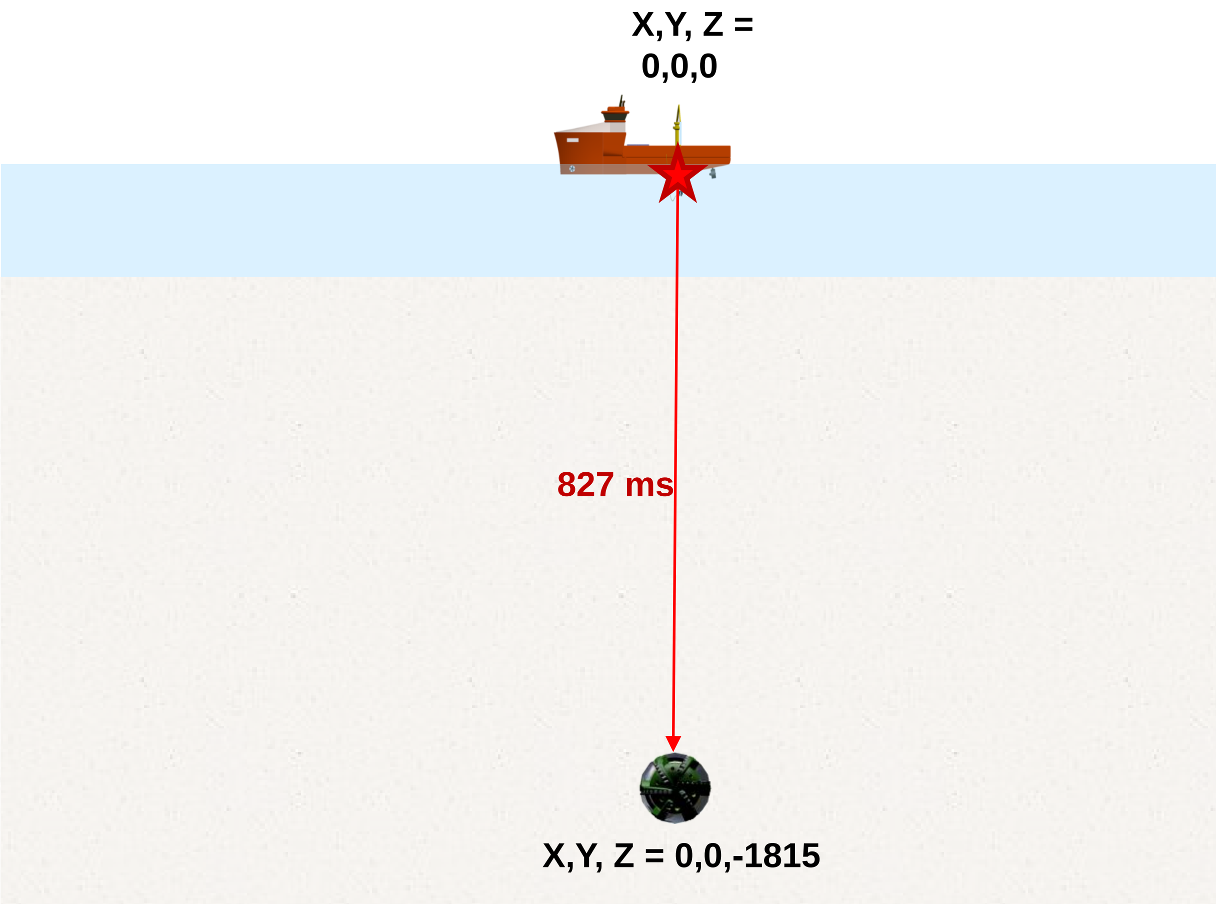


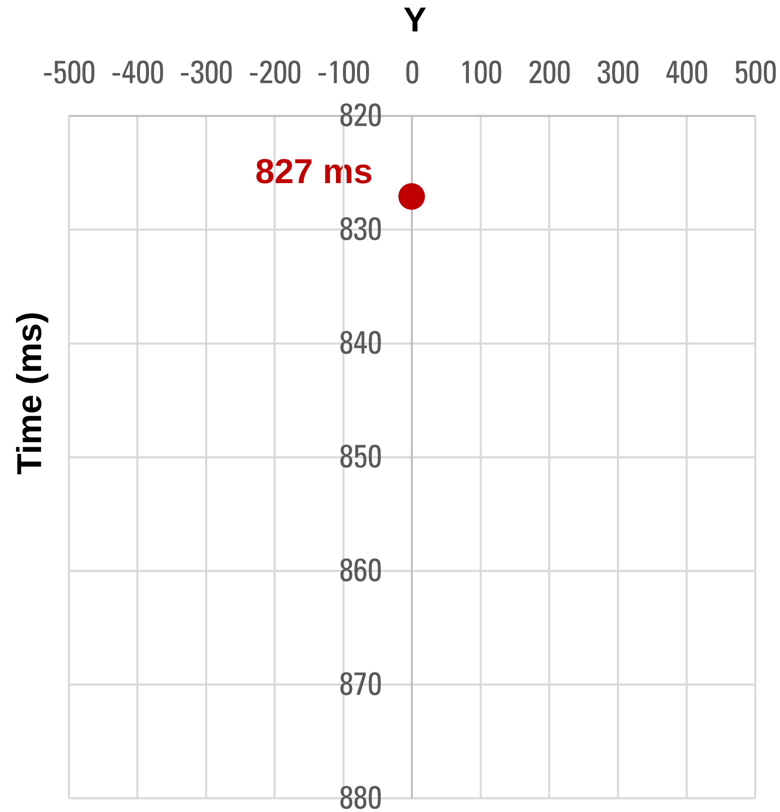
# LATERAL UNCERTAINTY OF WELLBORE POSITION




89

# LATERAL POSITION OF WELL FROM TRAVEL TIME



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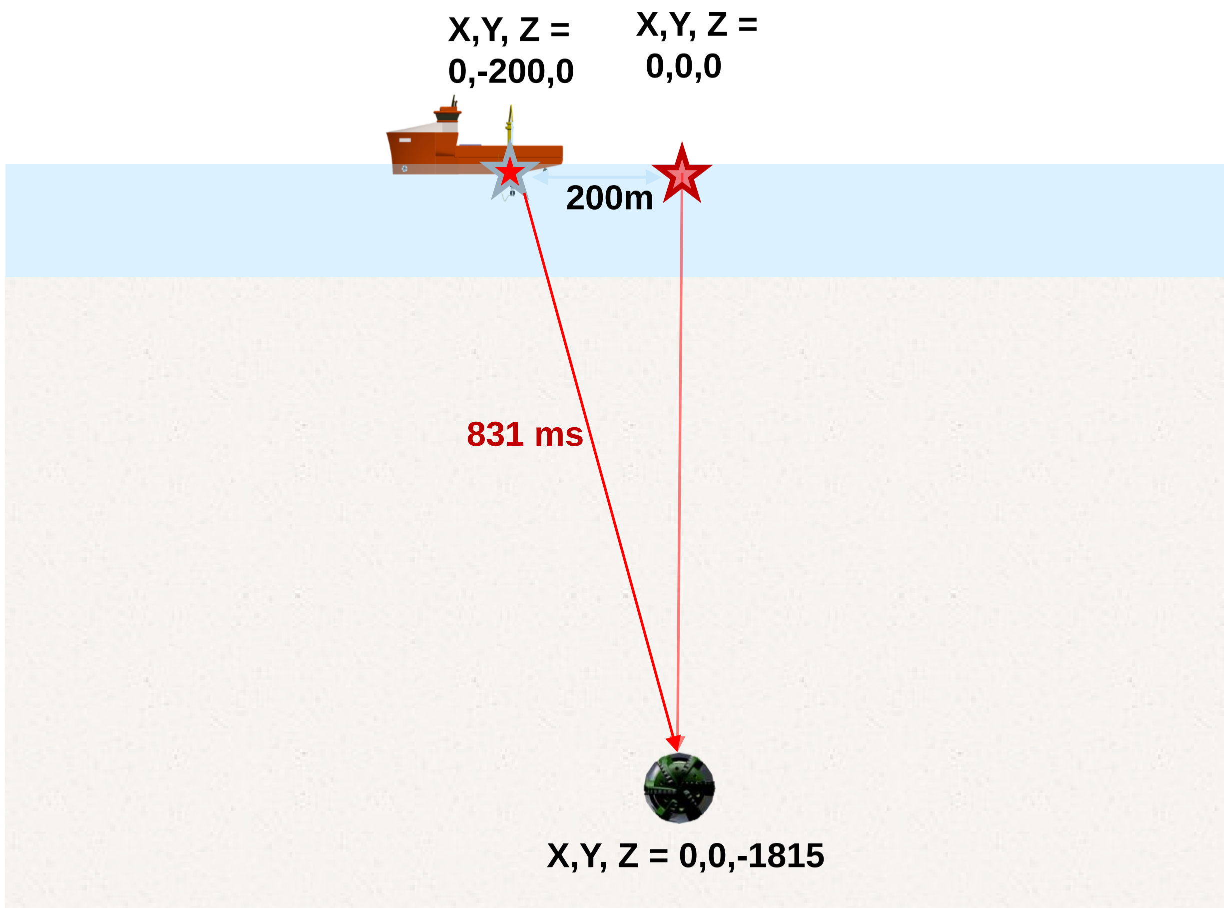


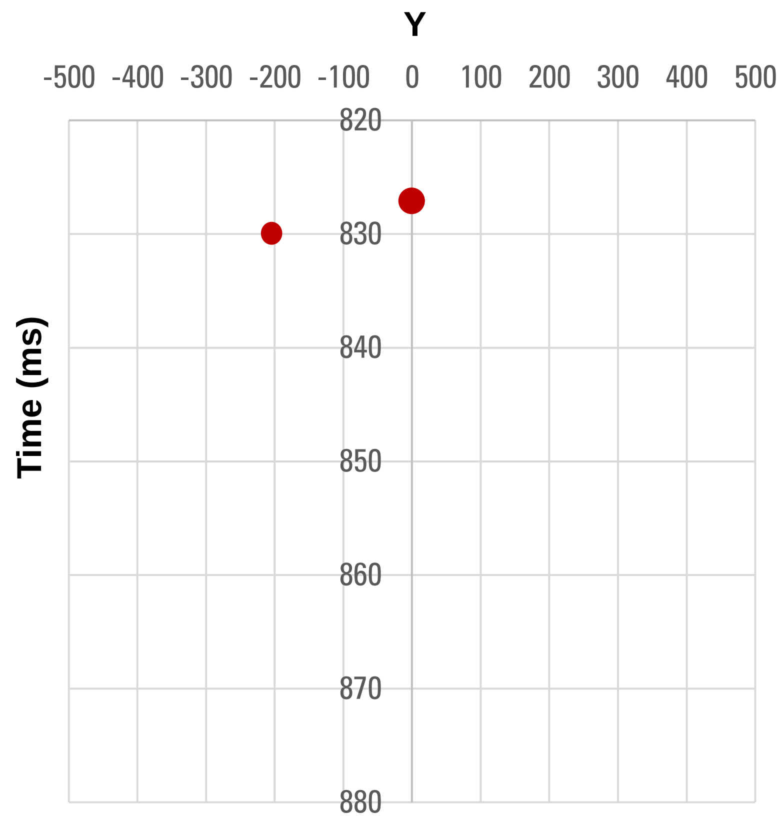

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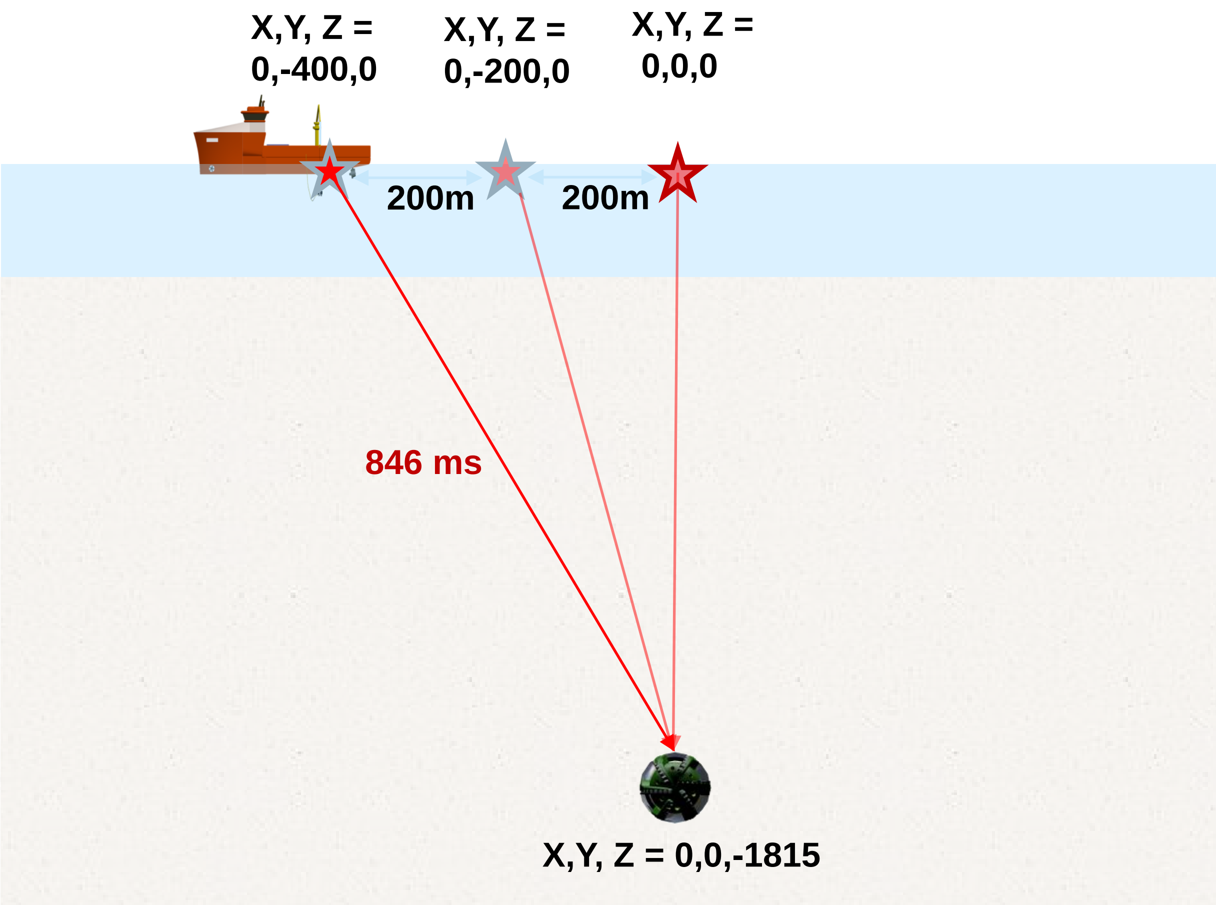


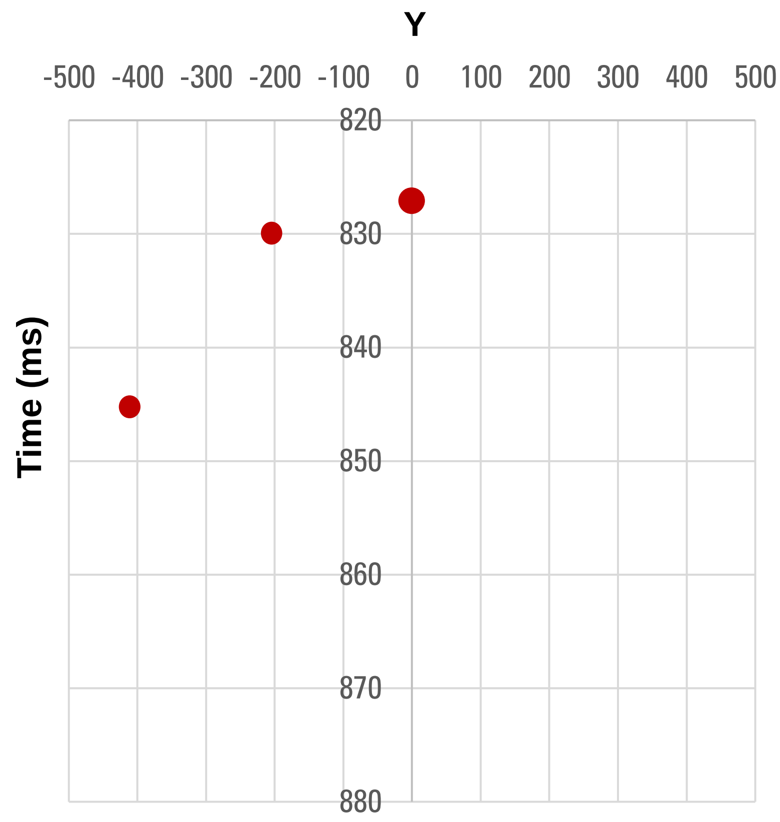

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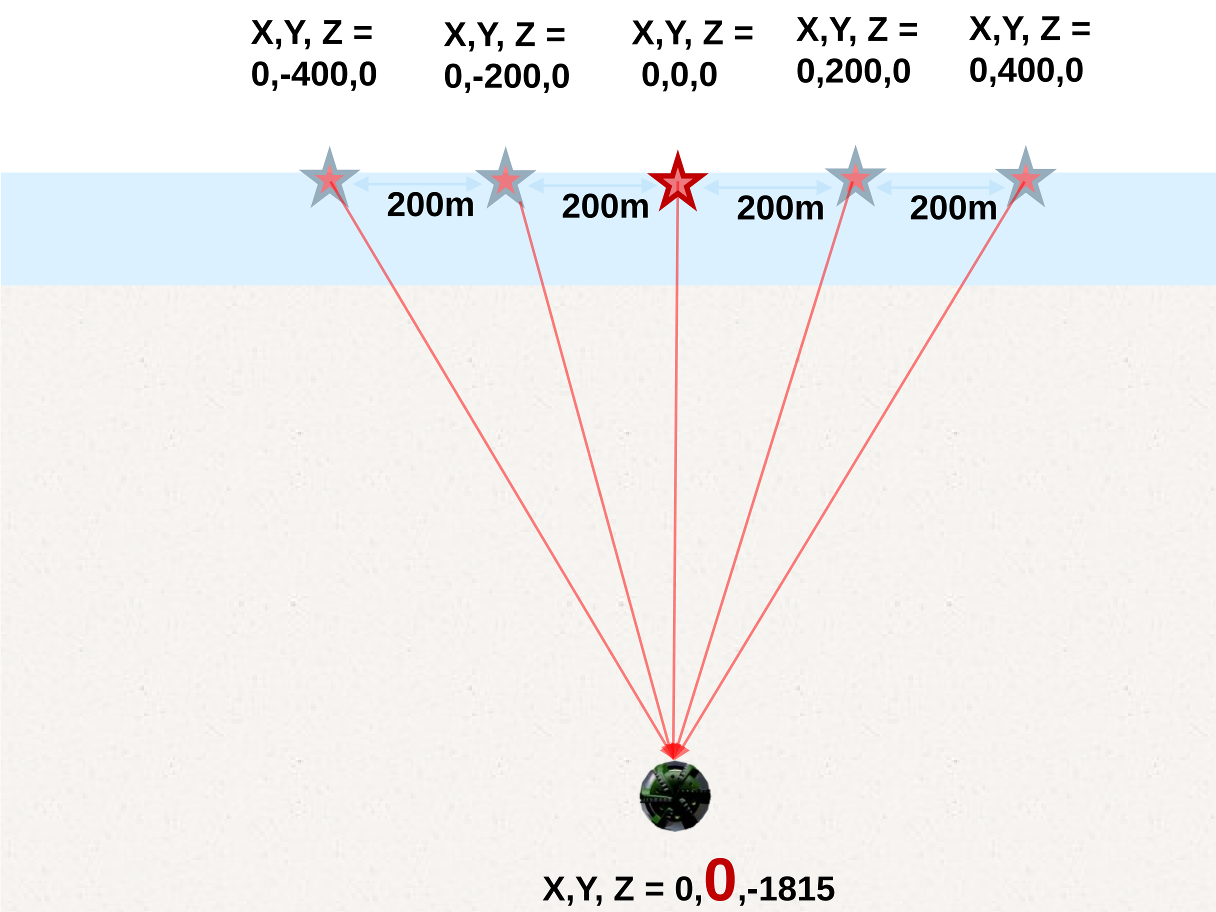


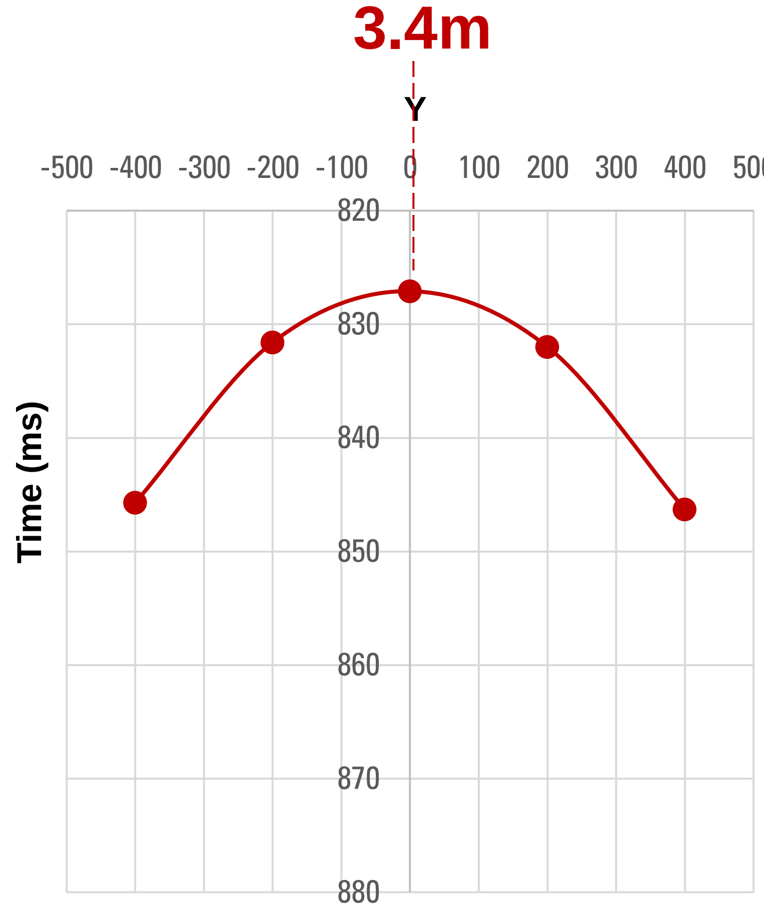

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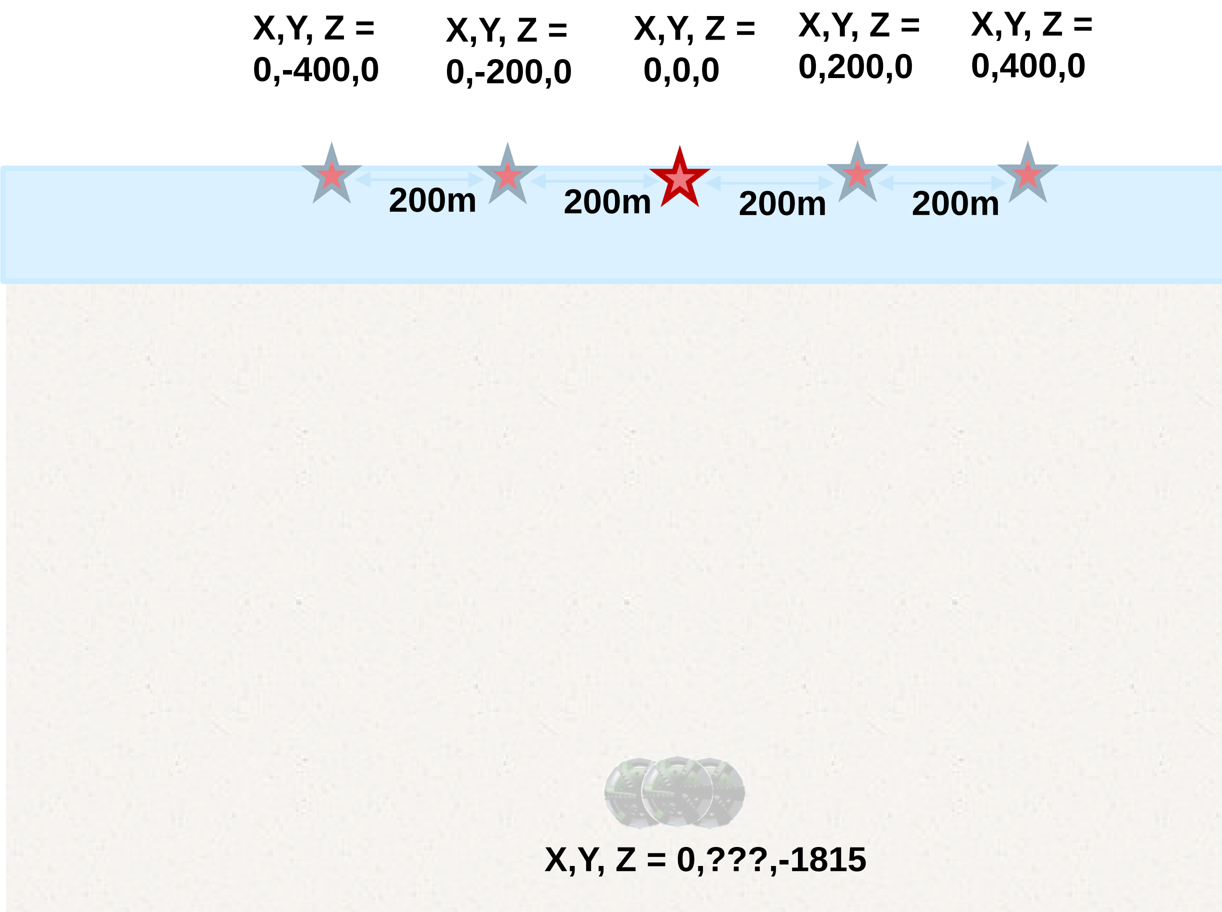

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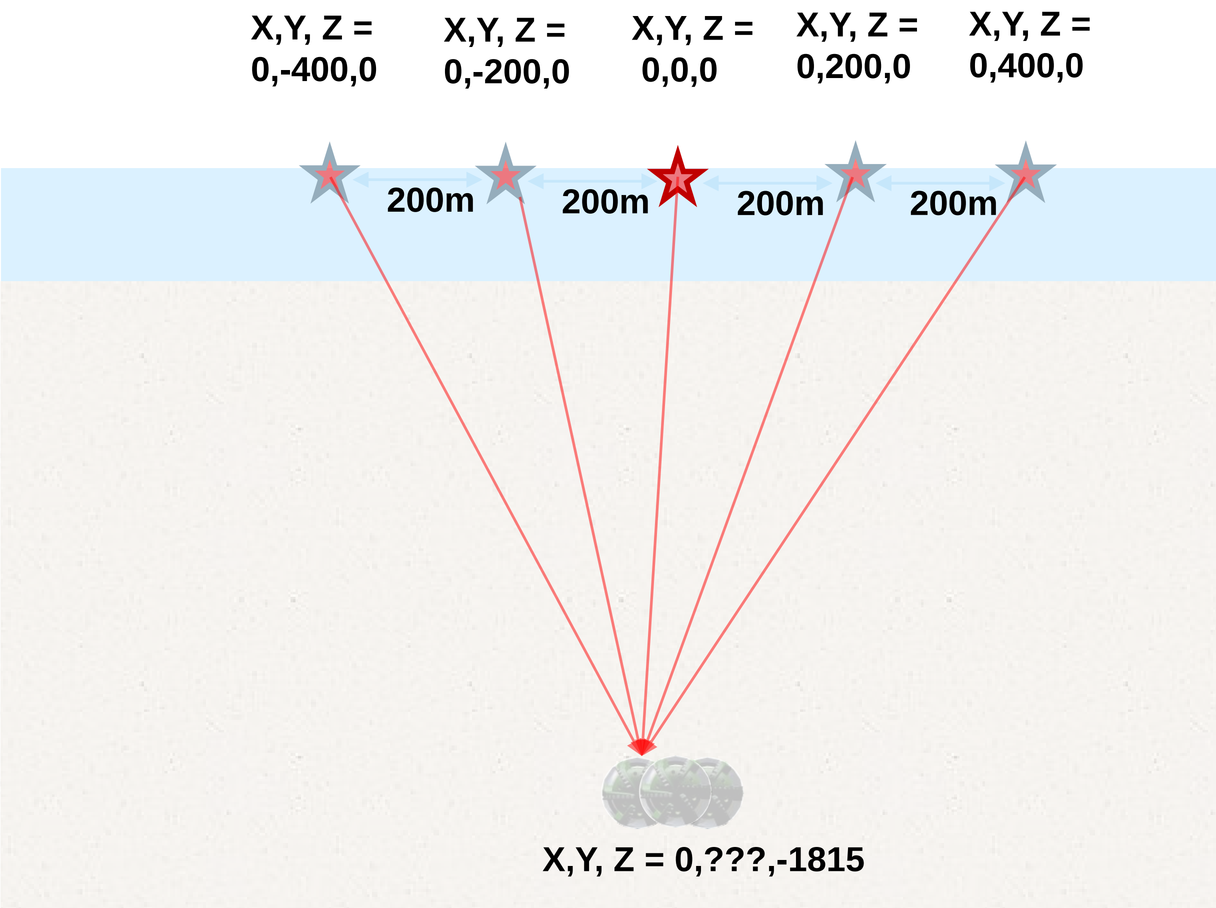


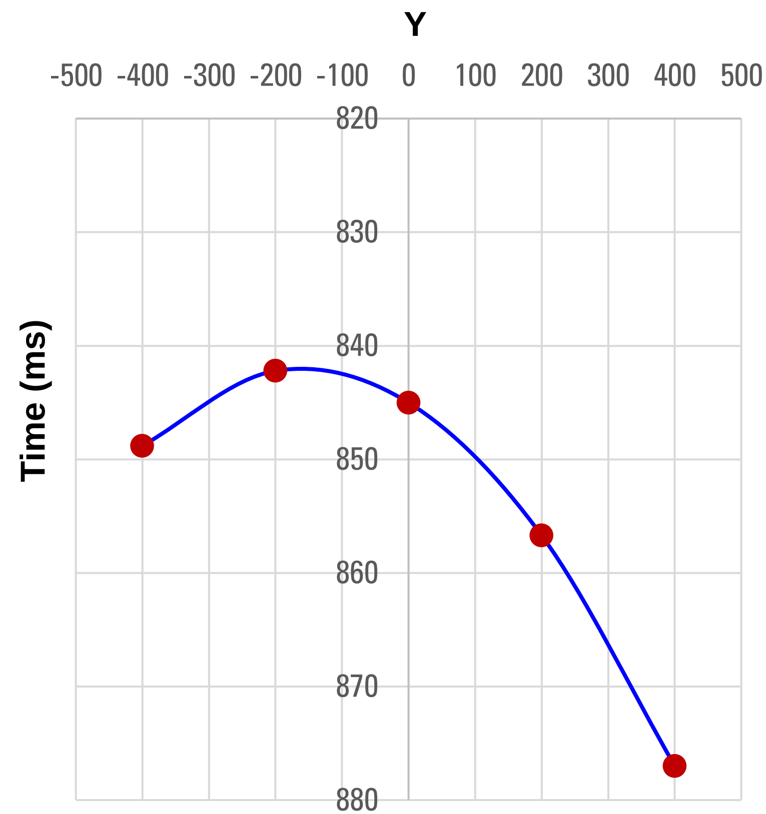

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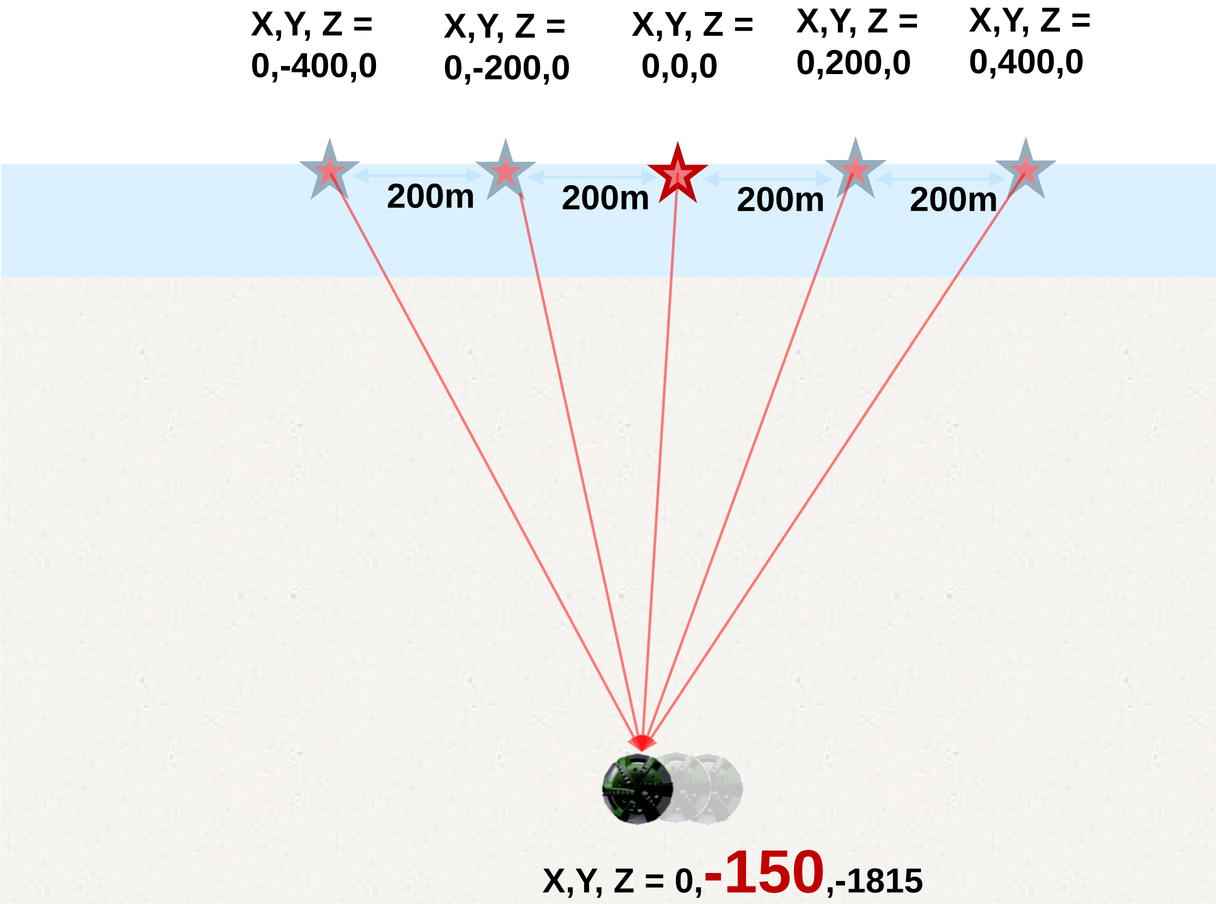


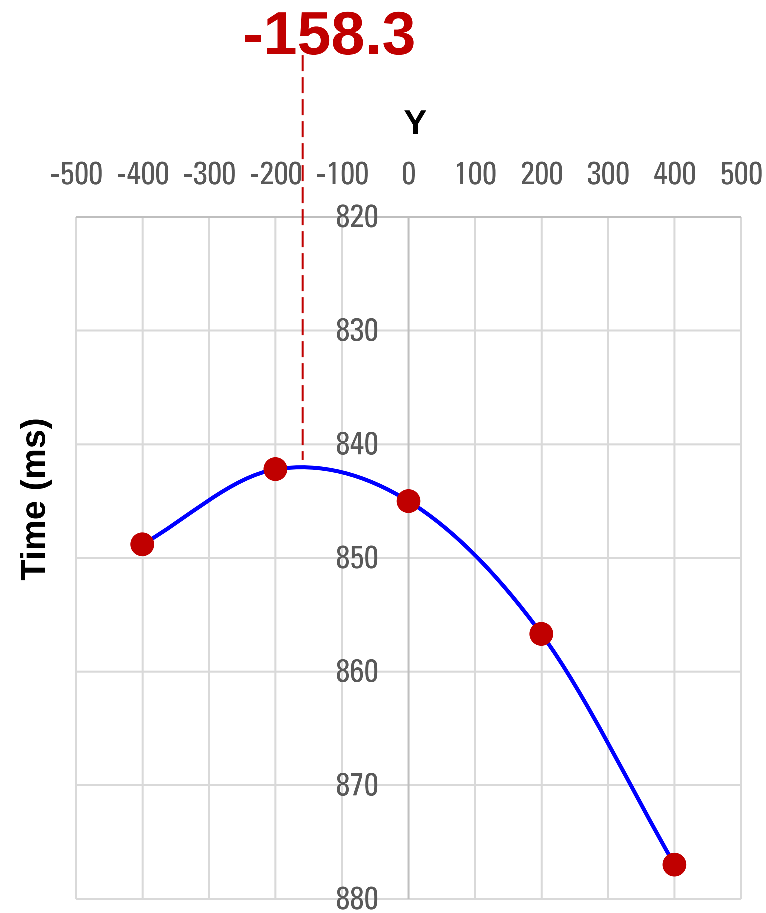

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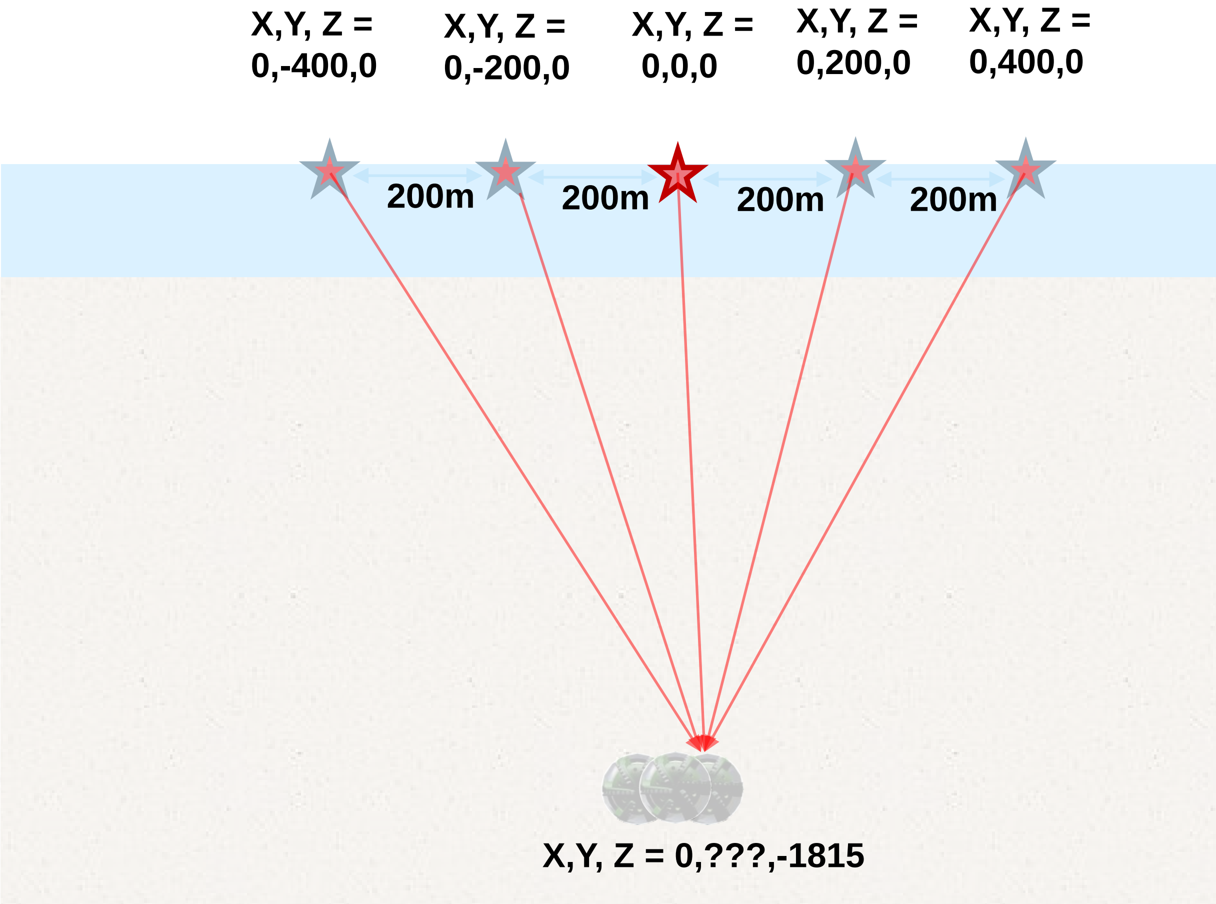


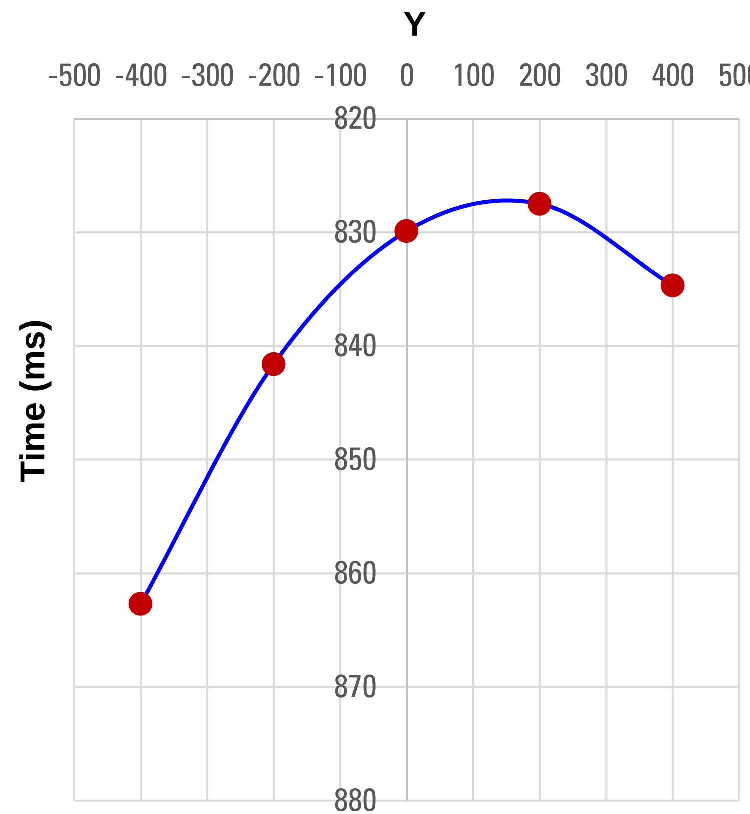

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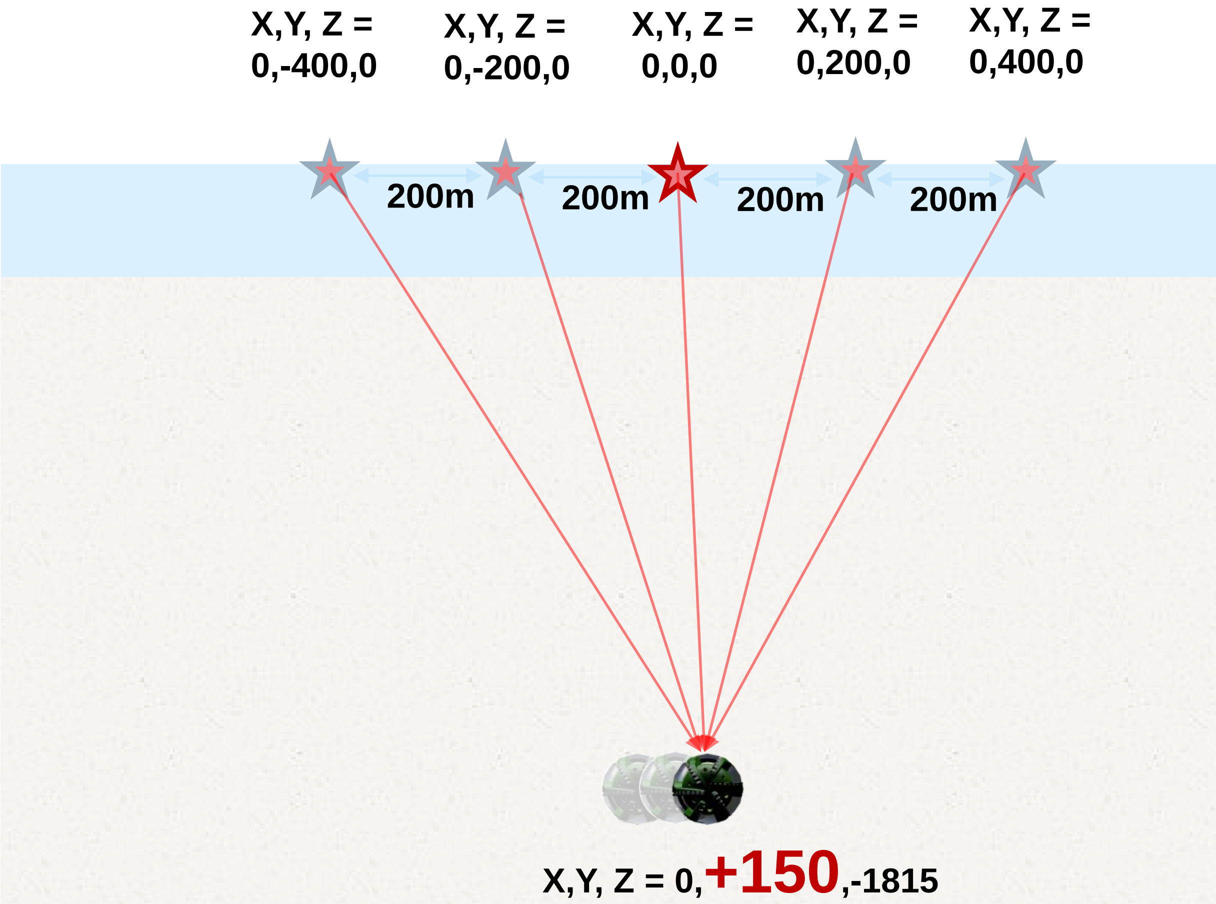


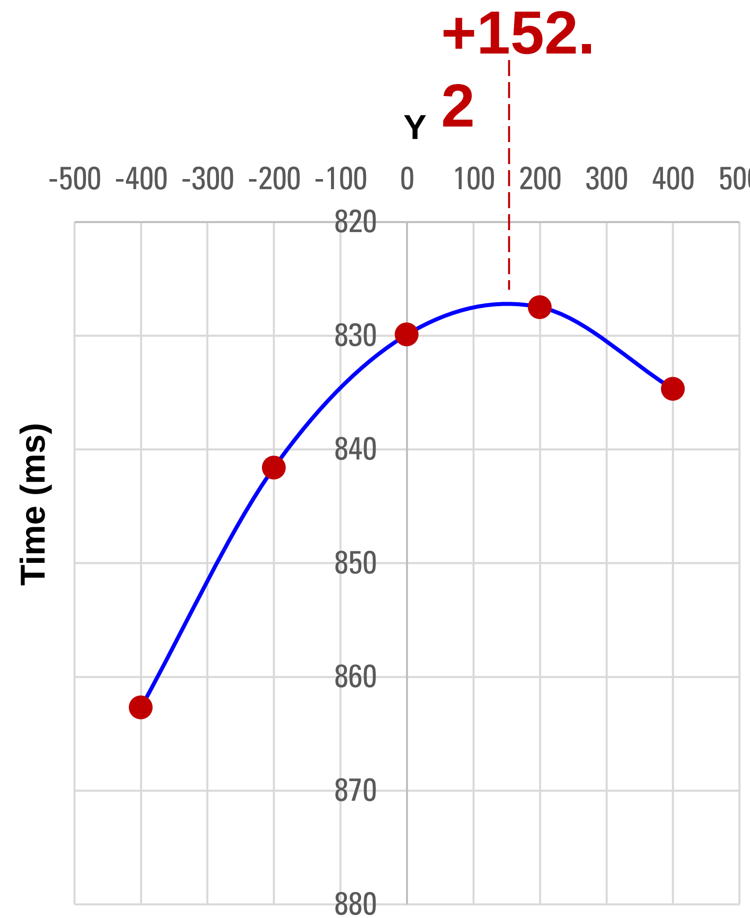

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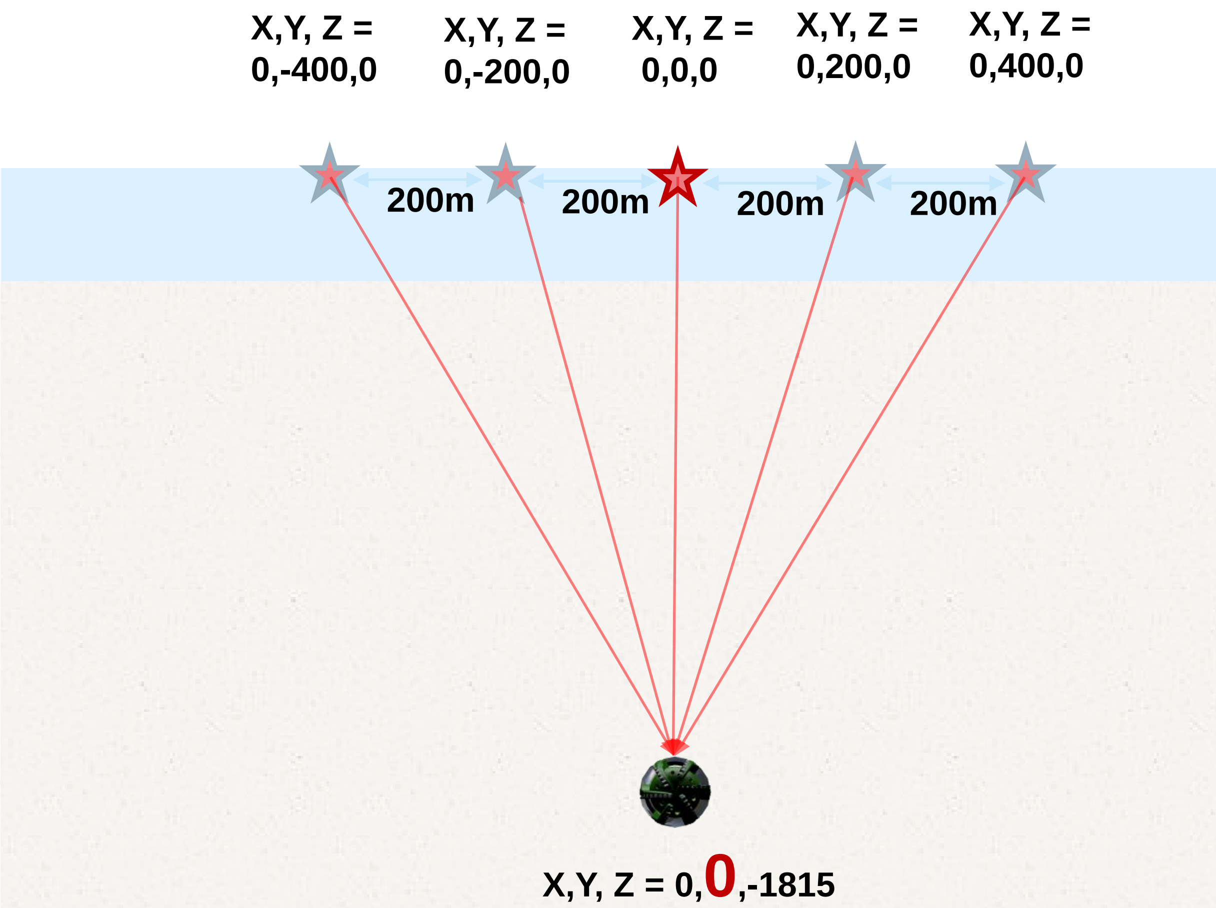
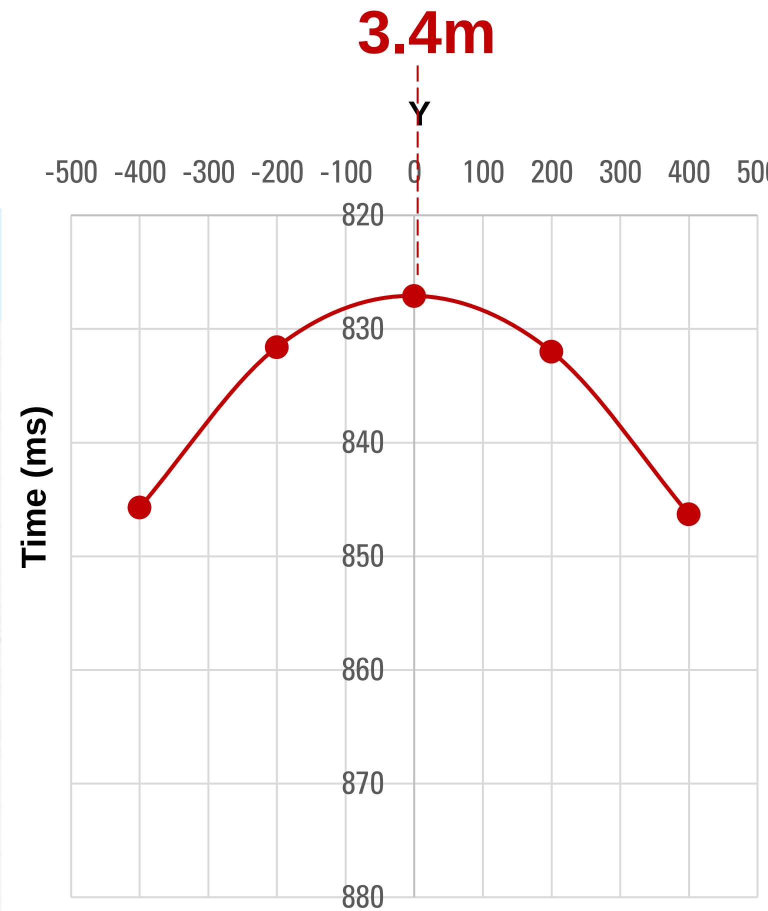
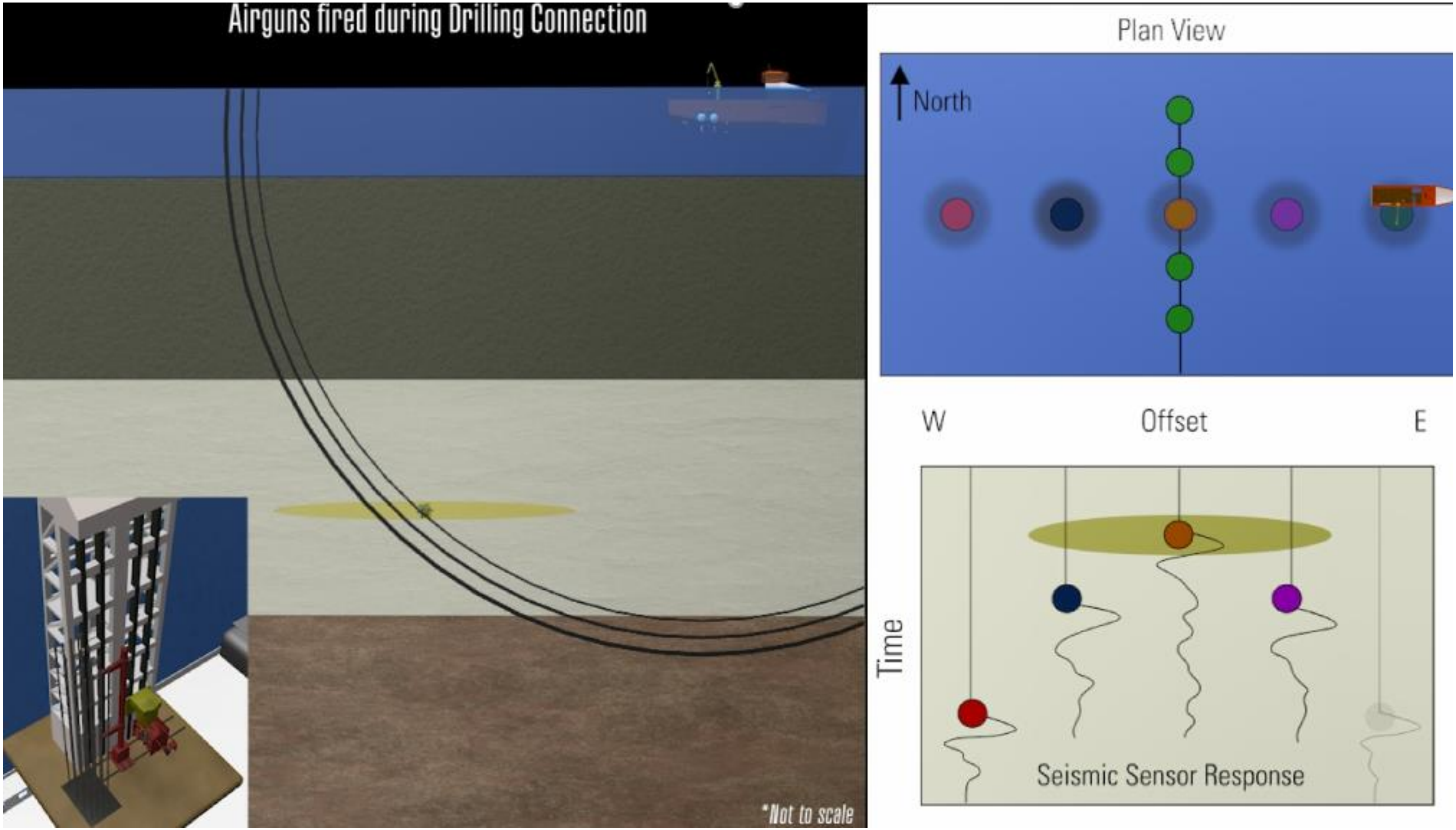


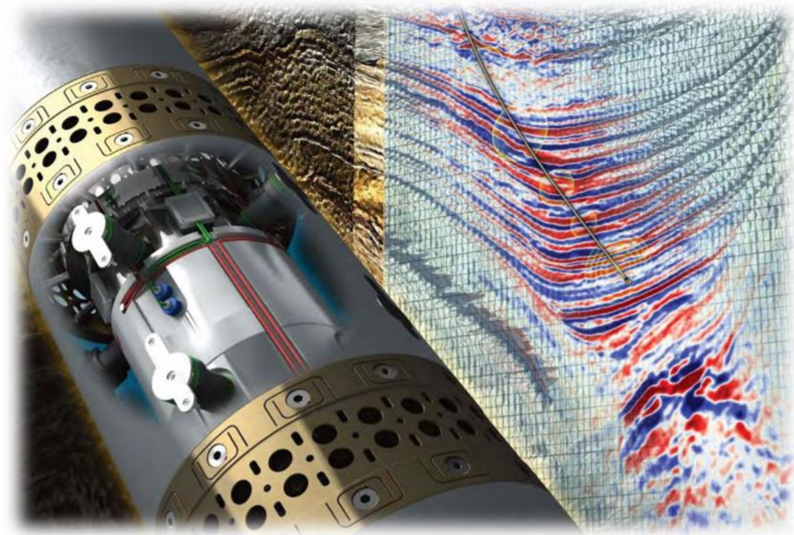




Airguns fired during Drilling Connection
*Not to scale
Plan View
North
W
Offset
E
Time
Seismic Sensor Response

# Recap

- Seismic While Drilling
  - What is it?
  - How does it work?
  - Overcoming challenges in a drilling environment

- Review examples of different applications
  - Efficient seismic checkshot / VSP acquisition
  - Well Landing
  - Highly deviated well conveyance
  - Geo-stopping – Look-ahead
  - Combination with EM look-ahead / look-around
  - Salt Proximity



- Potential new application
  - Reducing lateral wellbore position