3D Seismic Proves Its Value in Bakken Geosteering*

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Abstract

Improved geosteering performance has been hailed publicly by WPX Energy management as a key driver in achieving lower well costs in the Williston Basin. Geosteering errors in the basin were reduced by 90% from mid 2012 to early 2013. This impressive improvement is in part attributable to the use of advanced processing of 3D seismic data. Using 3D seismic for geosteering applications requires (1) resolving the Bakken interval, a well documented challenge in the Williston Basin, and (2) accurately converting seismic surfaces to depth, an easy task filled with hidden problems.

Resolving the Bakken interval is the most critical and arguably the most difficult objective for 3D seismic data in the Williston Basin today. 130 square miles of 3D data were reprocessed rigorously at the front end so that high-frequency "extender" (HFE) approaches had a chance to produce stable and geologically plausible results. Upper Bakken, Lower Bakken and Three Forks horizons were mapped using the HFE volume, providing higher confidence geosteering surfaces.

Converting to depth with HFE 3D seismic shed light on another important challenge with creating accurate geosteering surfaces: well tops, and their accuracy. Careful examination of both logging procedures and depth calibration of wireline versus MWD/LWD tools must be performed. Examples can be shown that this issue is more the culprit for depth conversion inaccuracies than uncertainty in seismic velocities. Additionally PSDM comparisons are available to take advantage of carefully vetted well tops and meticulous seismic velocity determinations.

Background

Upon taking over operations, WPX brought geosteering in-house and hired geologists to geosteer under the management of the drilling department. WPX drilled 47 wells under that structure in 2011 and 2012, and one out of every three wells on average had a geosteering error. A geosteering error is defined as steering instructions that placed the well in the Upper or Lower Bakken shale, resulting in a sidetrack or TD'ing short--or, in the case of a Three Forks lateral when the well enters the Lower Bakken shale or the second bench costing time, money, or lateral length. Geosteering errors were defined that way to distinguish them from directional errors, where drilling may have gone out of zone but not because of geosteering instructions.

Geosteering errors were hitting the bottom line hard. An internal study done in early 2013 included a cursory look at costs, and the impact of a geosteering error on well cost was significant. To make matters worse, wells with one geosteering error had greater than a 50% chance of having at least one more geosteering error and/or a directional error. Because of the compounding effects of errors, the directly related costs and mounting indirectly related costs, wells with steering errors were estimated to average about 60% more drilling days and 60% higher drilling capital than wells with no geosteering or directional errors. Well cost and other directly related metrics, including lost time and delayed production, were not sustainable. In August. 2012. senior management moved geosteering from the Drilling Department to the Geology Department in Denver and also moved the Drilling Department from Tulsa to Denver. Since that transition, geosteering errors have been reduced by 90% with a geosteering error now occurring in only one of every thirty wells.

How did WPX get there? This article focuses on the use of 3D to improve geosteering performance, but of equal importance in the turnaround were increased accountability, clearer communication with the Drilling Department, and creating an integrated geologic approach.

Geology

The Williston Basin is a northwest-southeast-oriented, sedimentary intracratonic basin that formed approximately 450 million years ago (Figure 1). Oil and gas are produced from numerous carbonate and clastic reservoirs ranging in age from Early Paleozoic to Cenozoic (Figure 2). Some structural anticlines within the basin, notably the Nesson, Cedar Creek, Antelope, Poplar, Billings, and Little Knife anticlines (Figure 1), have dips of up to 3^{o}; the majority of the basin has regional dips between 0.1^{o} and 1^{o}. The Forth Berthold Indian Reservation (FBIR) is within a region of gentle dips and is the subject area for this article (Figure 3).

The Bakken petroleum system (Figure 2) on the FBIR consists of multiple reservoirs: the middle Bakken containing silty carbonates and dolomitic siltstones and mudstones, and the silty dolomites and dolomitic mudstones of the first, second, and lower benches of the Three Forks. WPX drills and operates lateral wells in the Middle Bakken and upper benches of the Three Forks.

Method to Resolve the Bakken

WPX uses Paradigm, a geosteering software that allows one to create a 3D model of the area the well is going to traverse. The inputs to the model are depth surfaces derived from seismic and well control data. The second iteration of 3D seismic processing WPX utilized had radon and post-stack spectral balancing applied; a step beyond the post-stack spectral whitened volume WPX was first using. The radon did a good job of removing multiples and reducing noise and the spectral balancing enhanced the magnitude of the weak high frequencies. This product began to resolve the Bakken interval, which meant that there was a chance for the “HFE” processing to work (Figure 4).

This survey was then reprocessed rigorously at the front end so that high-frequency “extender” (HFE) approaches had a chance to produce stable and geologically plausible results. The goal of HFE processing is to enhance spatially the higher frequencies of the seismic data. Although the workflow for HFE processing falls in the normal spectrum of 3D seismic processing, there needs to be more focus on conditioning the gathers carefully for a cleaner stack so that a geologically meaningful frequency enhanced volume results.

The HFE process is applied post-stack, and based on two assumptions commonly used in seismic processing: first, the seismic wavelet is stable and stationary over a time window, and second, the geology can be approximated by a sparse, random spike sequence. HFE shapes the spectral content of the data, shifting the higher frequencies to have more total power than the lower frequencies when compared with the input data. Algorithmically, a sparse spike solution using L1 minimization is obtained first, and then a wavelet extracted from the data is convolved with this spike sequence. The extracted wavelet is "blued" to increase the higher frequency power (Kappius, 2014).

Figure 5 shows the amplitude spectrum of the intermediate volume (radon with spectral balancing) and two versions of the frequency enhanced volumes. Successful application of HFE requires diligence through collaborative efforts of the interpretation and processing teams. When the final HFE process is parameterized, critical QC at the reservoir interval is required as it is very easy to create a non-geologic response. It took two iterations of adjusting the HFE frequency-power parameters to produce a volume that tied with well data. The first iteration was very ringy in nature, and the synthetic had a poor tie; the lower and higher frequencies were boosted in the second version, eliminating the ringy character and tied better to well control. This successful product was created by careful integration of quality processing, highly accurate well log integration, and interpretive control during the application of HFE. Our success here proves there is much value left to be extracted from seismic volumes, beyond the resolution limits currently considered acceptable.

The new HFE volume allowed us to map the upper and lower Bakken horizons and faults, in addition to the Three Forks, providing higher confidence geosteering surfaces. The presence of small faults (5-20 ft of vertical separation) and the validity of the volume was questioned until WPX cored its first well in the basin. The cored well was planned and permitted as WPX received the HFE volume in-house; as the data was interpreted, a fault was mapped cutting-out part of the Three Forks section. The decision was made not to change the position of the well as this was the golden opportunity to validate the HFE volume.

The FMI run in the cored well confirmed a fault in the deeper portion of the Three Forks striking WNW-ESE, as mapped. Even with this ground truth confirmation, there is still some question as to what is real and what is noise; that interpretation is ongoing. When a lateral cuts a mapped fault, it is not always possible to interpret a fault in the lateral GR log. Identifying a fault in the lateral depends on having a sufficiently deep profile of the section where the well was landed, cutting the fault at an angle that allows for identification, and traversing sufficient section after the fault has been cut to determine that the well was in fact in a different stratigraphic position. Because of these uncertainties in GR interpretation, it is not always possible to tie a fault picked on seismic back to the lateral well log.

Time-to-Depth Conversion

Converting to depth with HFE 3D seismic shed light on another important challenge in creating accurate geosteering surfaces: well tops and their accuracy. Careful examination of both logging procedures and depth calibration of wireline versus MWD/LWD tools must be performed. Examples can be shown that this issue is more the culprit for depth conversion inaccuracies than uncertainty in seismic velocities.

The PSDM workflow chosen has two major components: the tomographic velocity update loop and the “VelWell” calibration. VelWell is Sterling’s proprietary module that vertically shifts the PSDM stack volume to match the well top picks made on logs (Kappius, 2014). It took five passes of the tomographic inversion to update the migration velocity field, each pass at progressively finer spatial and depth sampling to get the best isotropic velocity field for imaging via the tomographic loops. Even with this refined velocity field, the seismic volume does not match the vertical positioning of events in well logs that requires VelWell (Kappius, 2014). VelWell was applied to the HFE time volume that resulted in the final PSDM volume WPX uses to interpret the Bakken interval in depth.

Creating the final PSDM product took several months and multiple iterations working closely with Sterling to evaluate each volume, then to identify and solve problems as they arose. Along with the velocity field and well tops, horizons are the last critical piece to constrain VelWell. The horizons serve as a guide for adjustments to the velocity field in VelWell. Seven horizons were used and their corresponding formation tops had to be examined, adjusted for consistency and fit with the wavelet. Velocity perturbations are done all at once and required interaction with the processor to determine what is geologically reasonable.

VelWell is extremely sensitive to the adjustment of well tops; small errors in top picks are immediately visible in a VelWell volume. One example of how meticulous one needs to be when picking/tying tops for PSDM conversion can be demonstrated with the Greenhorn limestone. The Greenhorn is a regionally pervasive limestone unit with great variability at the top of the section. The most consistent pick was found to be at the base of a shale above the Greenhorn. The new pick did not correspond to the peak that had been mapped in the seismic; therefore the horizon had to reinterpreted at the zero crossing above the peak.

After the formation tops were repicked for consistency and horizons reinterpreted VelWell was rerun, careful examination of this volume led WPX to the conclusion that something still was not “right.” Structures appeared to be much more dramatic and exaggerated, violating the one degree max dip that we generally see in the area, and faulted areas became more confused and distorted. This inferior product from the vetted tops led to the examination of logging procedures and depth calibration of MWD/LWD tools.

Because the PSDM process requires the most accurate well tops possible, each well on the 3D had to be carefully scrutinized for log calibration accuracy. Open-hole wireline stretch is not a new problem, and in North Dakota where only one well per square mile is required to have an open-hole logging run, WPX only had a handful of wells on the 3D that fell into this problem category. Unless it is in an old vertical well, open-hole logs do not go deeper than the Lodgepole because of the prohibitively high build rate of the laterals drilled in the Bakken and Three Forks. If the shift necessary to correct for wireline stretch is complicated, the tops from the shallow portion of the logs may not be used for control in the PSDM processing. Formation tops deeper than Lodgepole in lateral wells require the use of MWD/LWD or CBL logging runs.

MWD/LWD logs are depth- calibrated every time a trip is made in the hole providing the opportunity to identify and correct for issues such as pipe tally error when it happens. Because of this redundancy the decision was made to hold MWD/LWD logs as ground truth and shift CBL logs with respect the MWD/LWD. Depth shifting the CBL required a review of the CCL data to check to make sure distance between joints was consistent and that there was not a complex depth shift already applied to the log. The raster image must also be checked at this time to see if any shifts were made. After shifting the CBL to the MWD/LWD based on log character, the shoe and liner tie-ins were also checked against the shifted CBL log to help quantify the bulk shift.

Once each well has been evaluated to have consistent tops and accurately shifted logs, a series of average velocity maps (Vavg) must be constructed at each horizon level that is being used in VelWell. Determinations must be made for how to deal with Vavg points that do not follow regional trend. For example, anomalously high or low Vavg “bulls-eyes” in the overlying Permian-Jurassic section can be real as they are related to sudden structural changes caused by salt movement.

Conclusions

WPX Energy has demonstrated bottom-line value in applying 3D seismic data as a geosteering tool when proper attention has been paid to seismic processing and depth conversion.

Citation

Kappius, Russ, personal communication, January, 13, 2014.

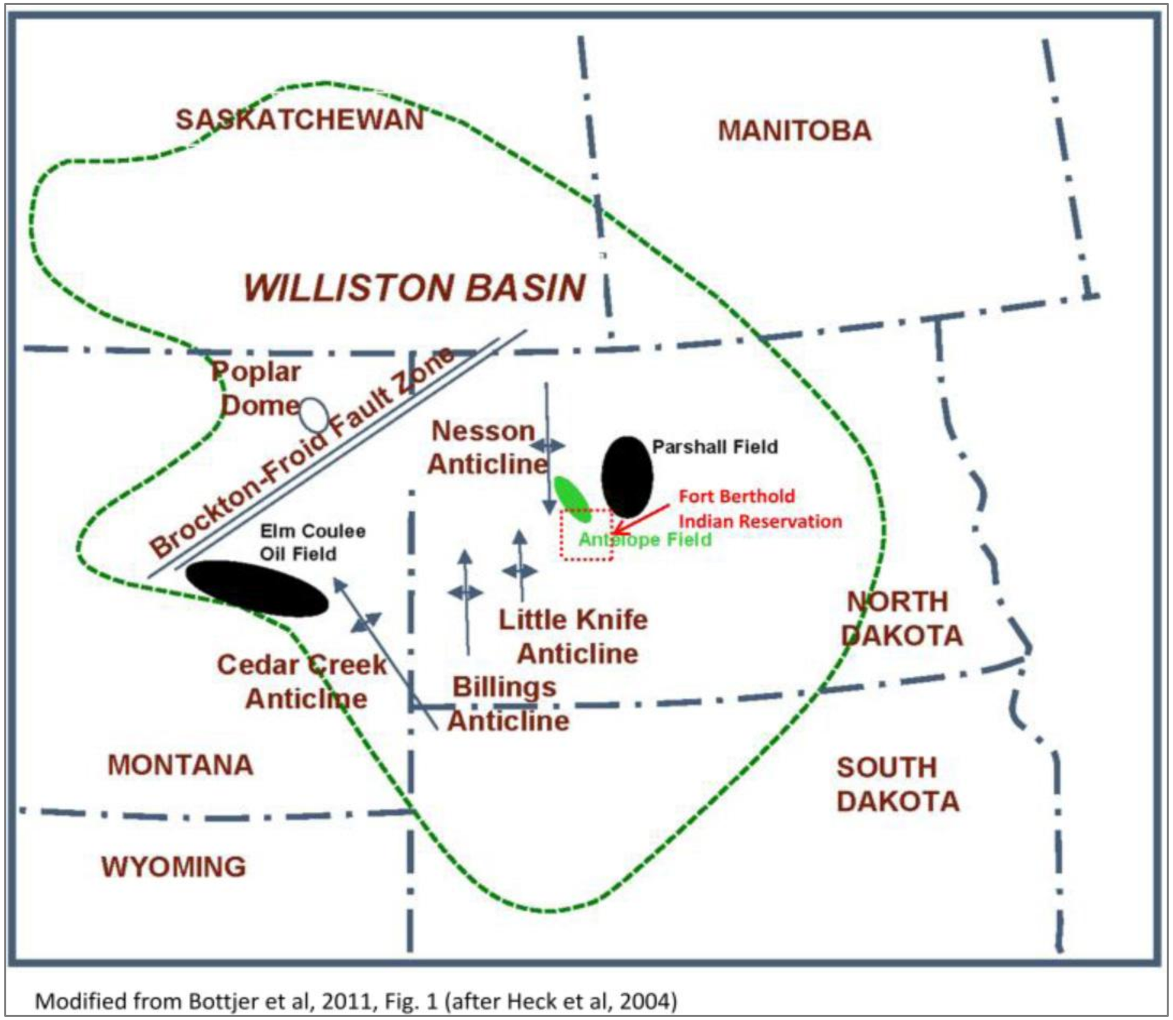

Figure 1. Regional map of the Williston Basin, showing the locations, types, and orientations of the major structural elements.

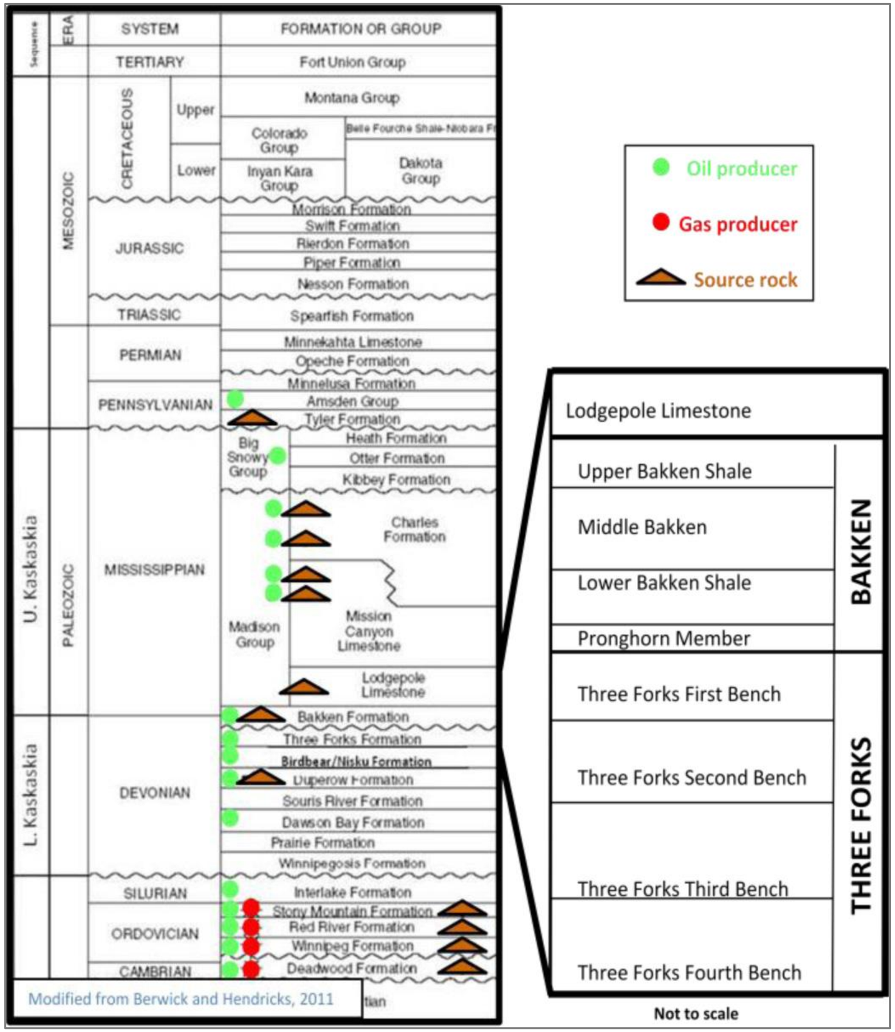

Figure 2. Stratigraphic column from the Williston Basin identifying oil (green) and gas (red) producers, the major source rocks (brown), along with an expanded stratigraphic column showing the Bakken and Three Forks formations and their members.

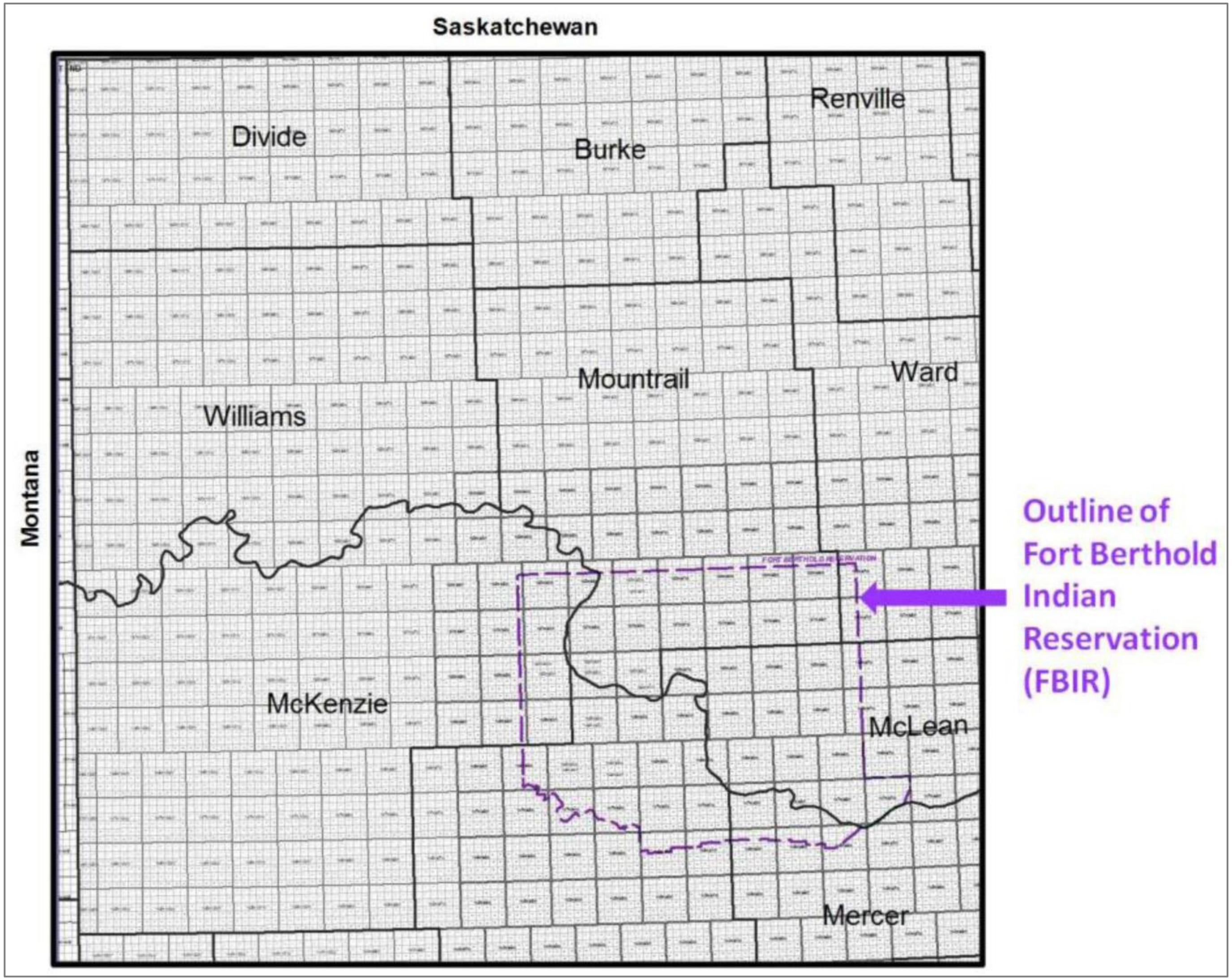

Figure 3. Base map of northwestern North Dakota, showing the location of the Fort Berthold Indian Reservation

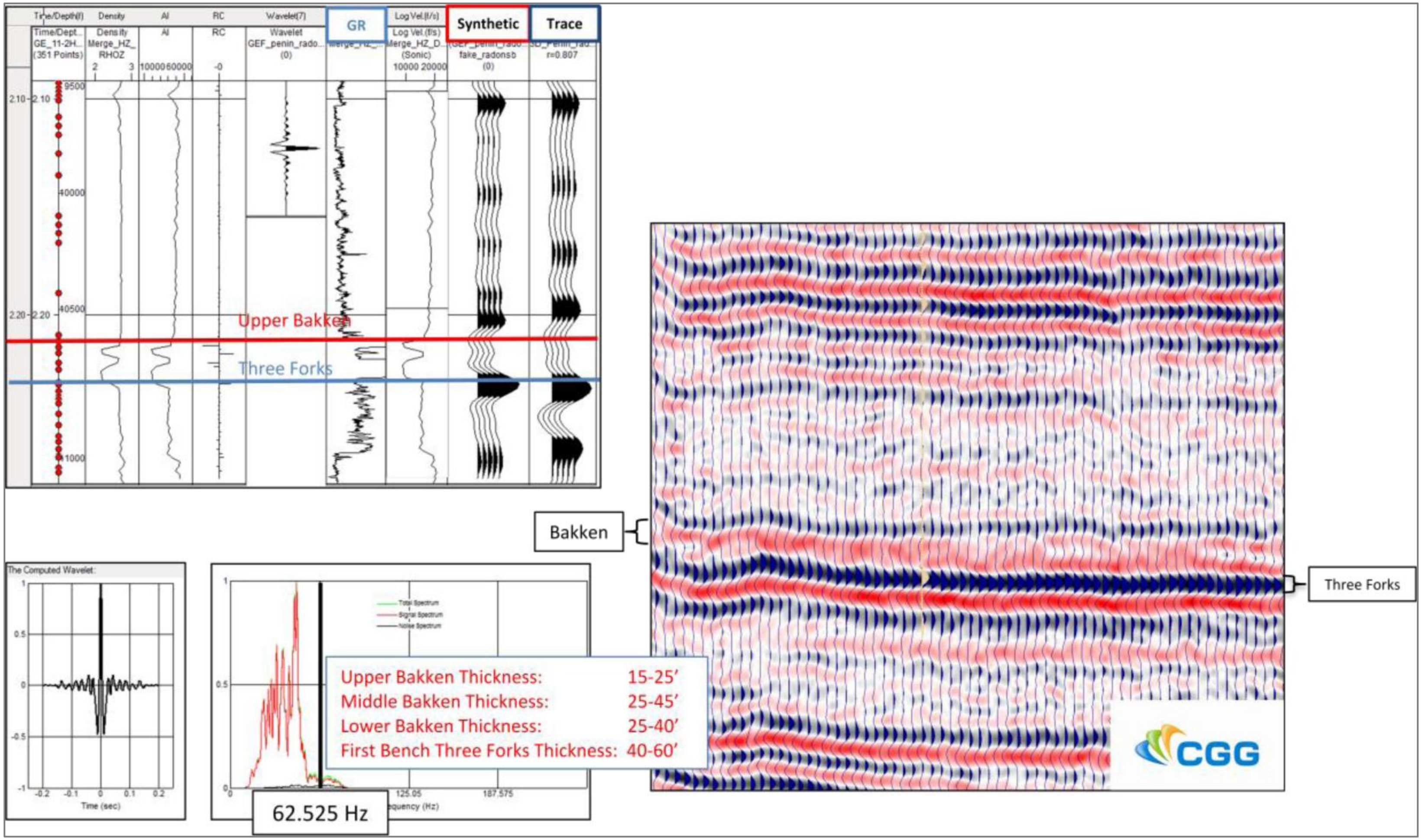

Figure 4. Transect through pre-stack time-migrated volume with radon and post-stack spectral balancing. Synthetic shows slight break-out of the upper and lower Bakken shales.

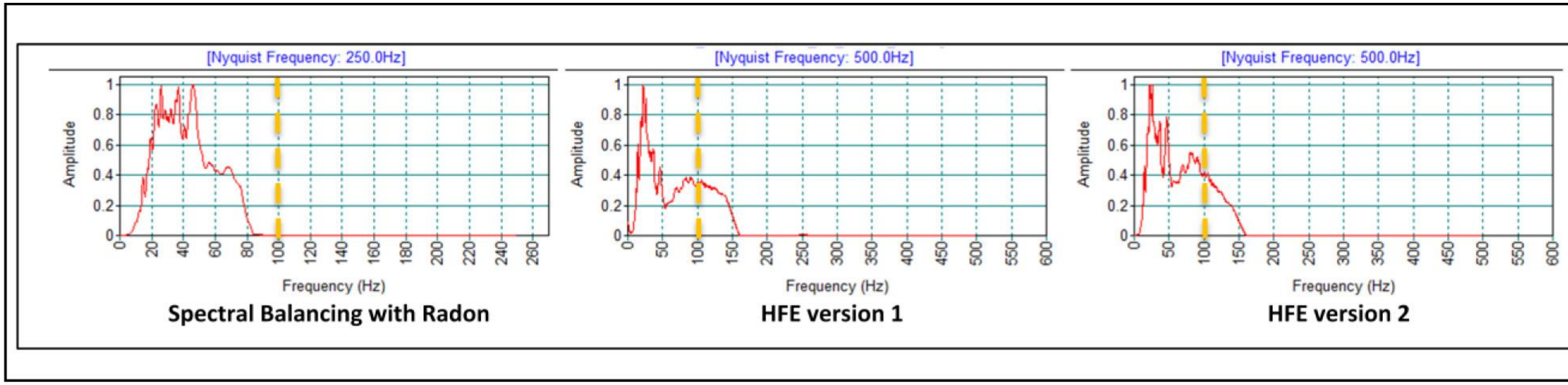

Figure 5. Left spectrum from radon- and spectral-balancing volume: middle and right spectrums from HFE volumes. Final selected product is on the right.

SLIDES of PRESENTATION

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2014 AAPG Rocky Mountain Section
Denver, Colorado

2014

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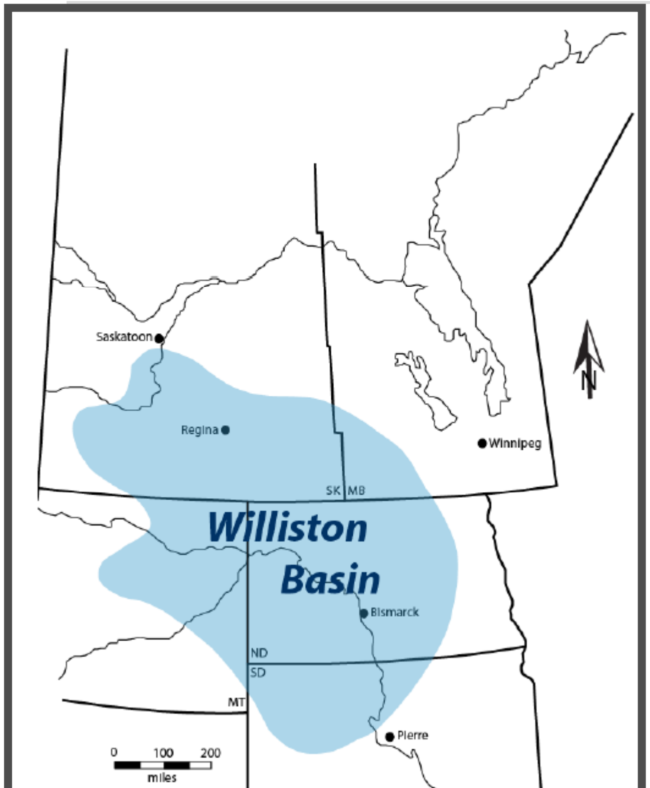
WPXENERGY

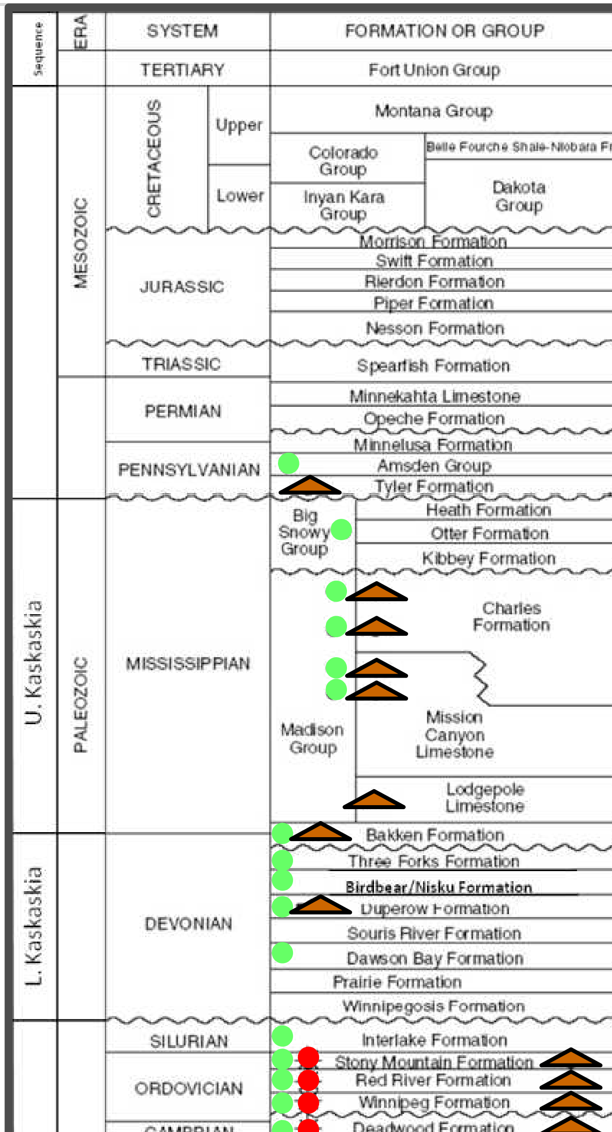
Outline

- **Introduction to the Williston Basin**
- Background and motivation for the talk
- 3D processing history
- Converting time to depth
- Conclusions

Williston Basin stratigraphic column



Modified from LeFever



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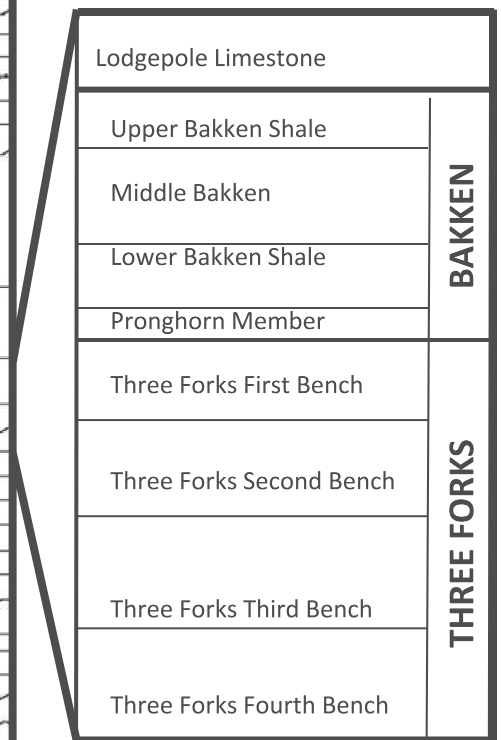
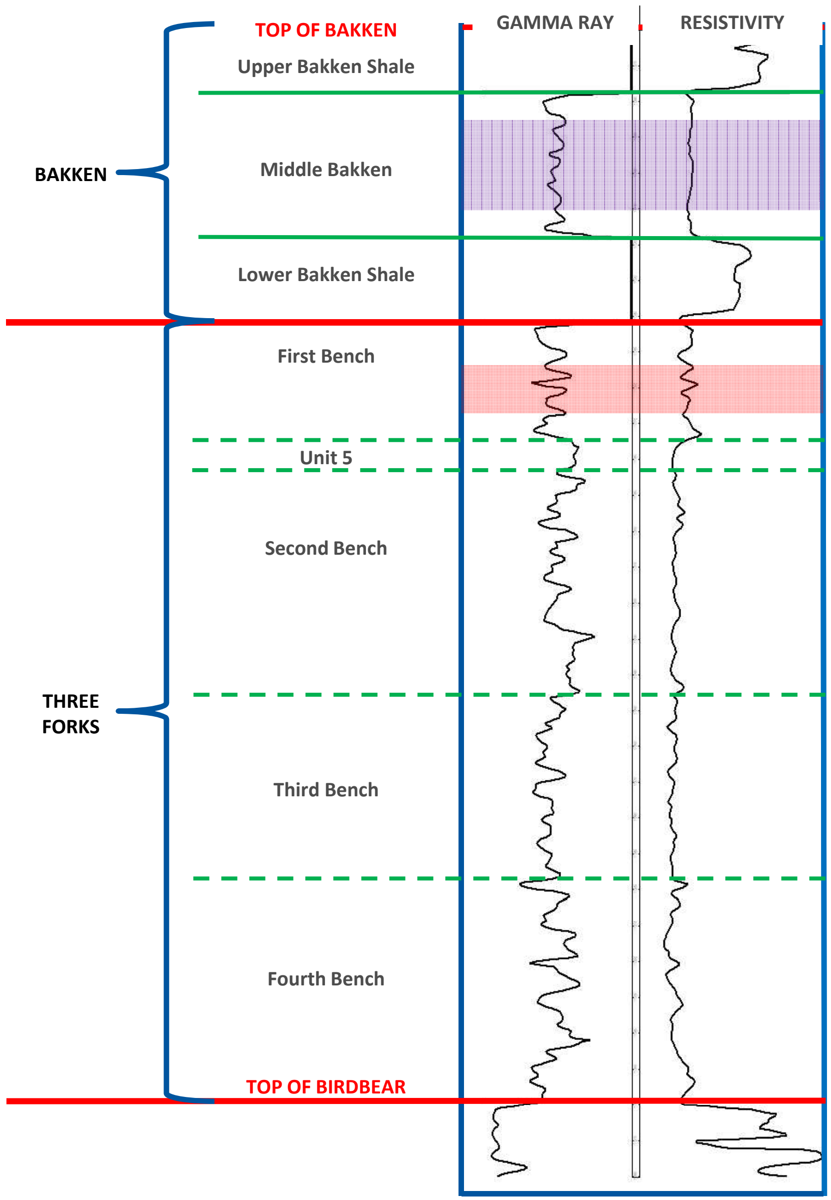


Not to scale

- Oil producer
- Gas producer
- Source rock

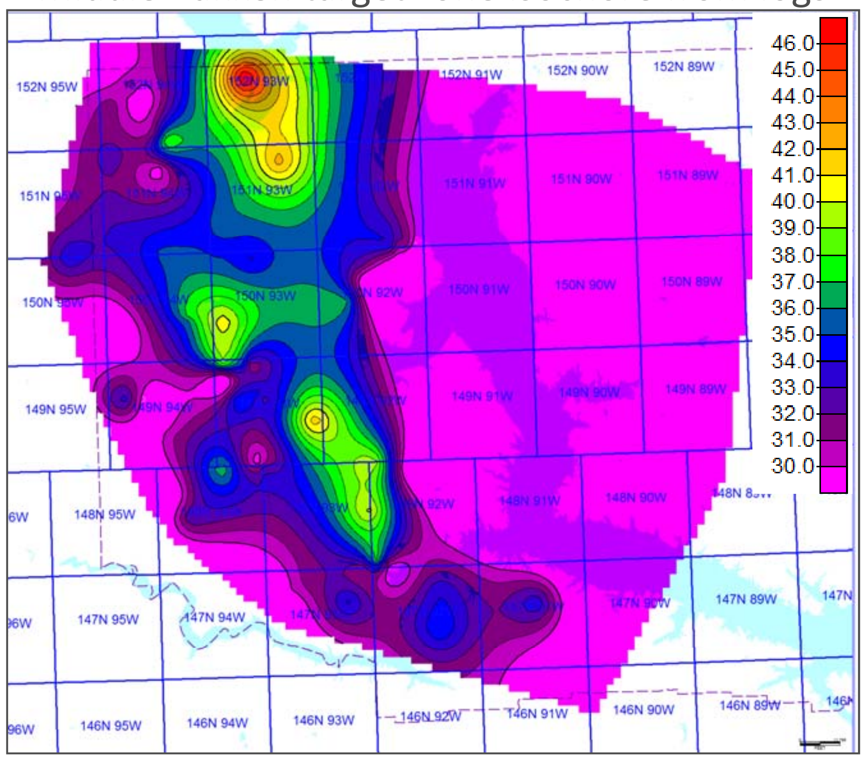
Williston Basin stratigraphic column



target zone for geosteering

target zone for geosteering

Middle Bakken target zone isochore from logs



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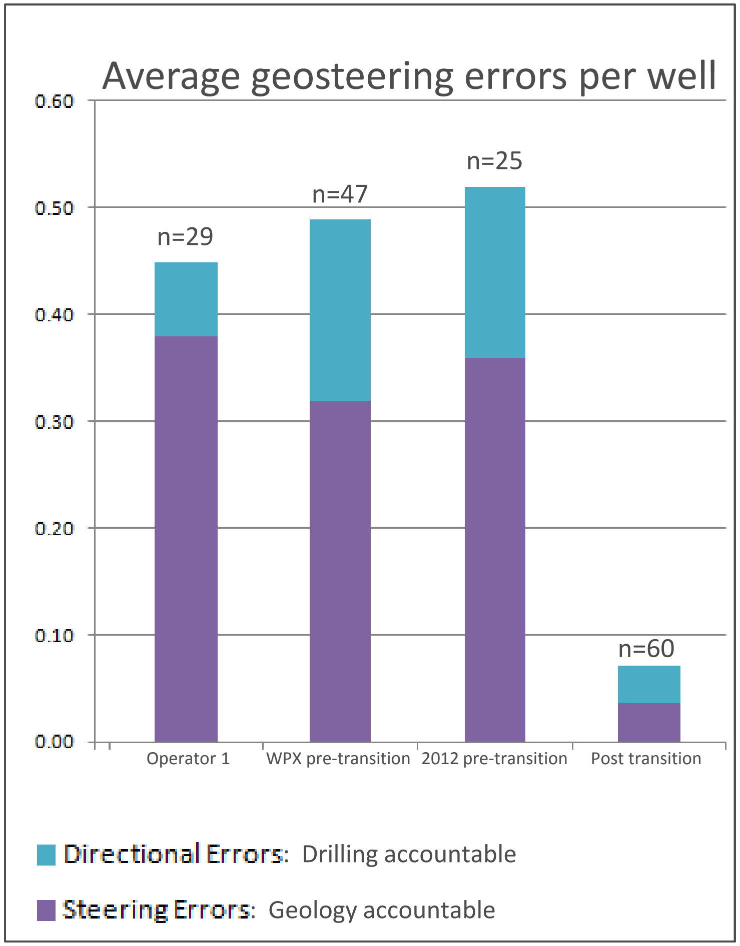
Background and motivation for the talk



A geosteering error is defined as a steering instruction that in the case of a Middle Bakken lateral placed the well in the Upper or Lower Bakken Shale.

Errors Were Hitting Bottom Line Hard

Alongside other factors

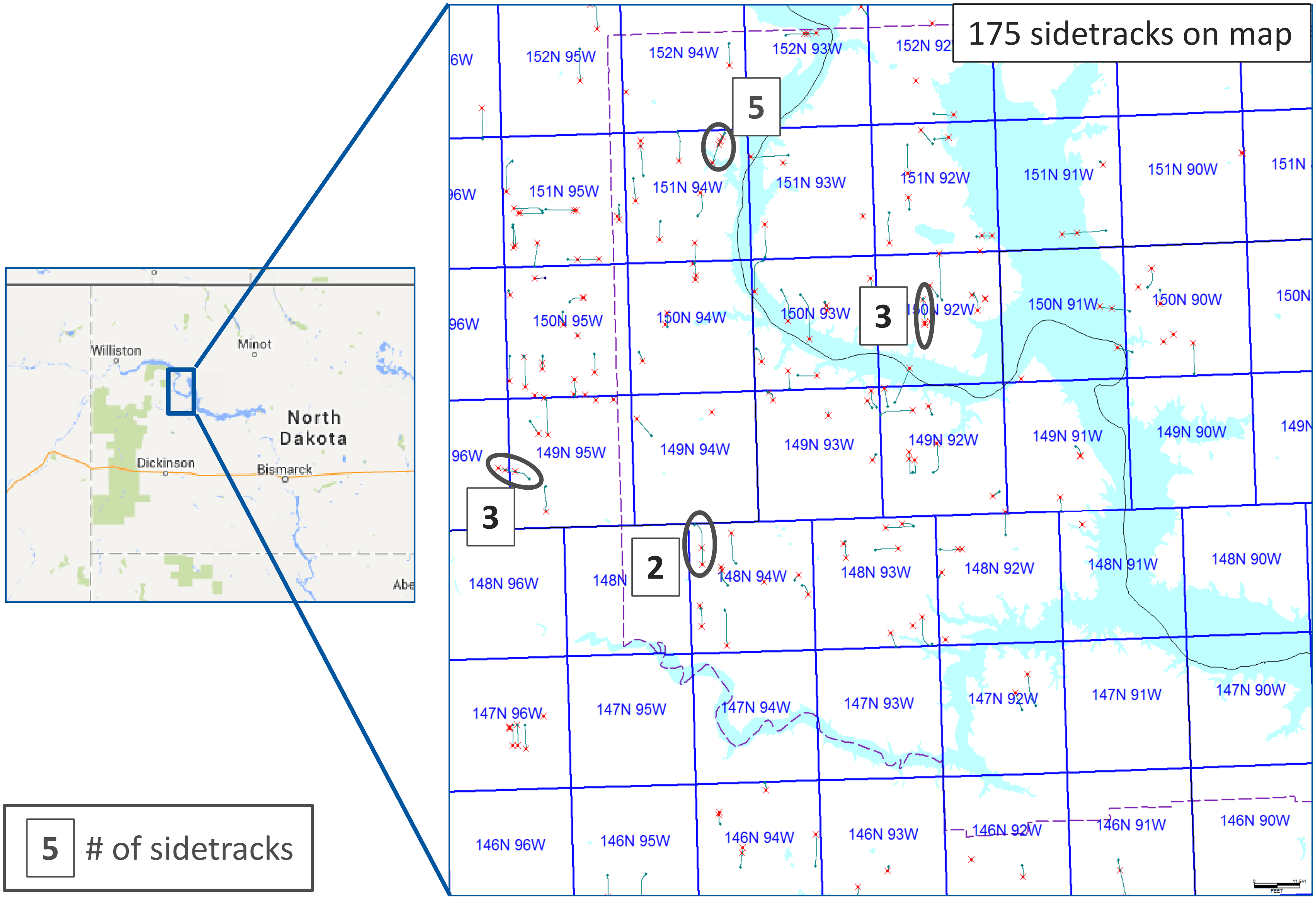
- **Drilling capital**
  - Wells with steering errors estimated ~60% higher than error free wells
- **Drill days (days spud to TD)**
  - Wells with steering errors estimated ~60% higher than error free wells
- **Other directly related metrics, including completed lateral length lost, delayed production was not sustainable**

Steering and Directional Performance

August 2012: Geosteerers transitioned from Drilling in Tulsa to Geology team in Denver

- **90% reduction in steering errors**
- **Helped drive 75% reduction in directional errors**

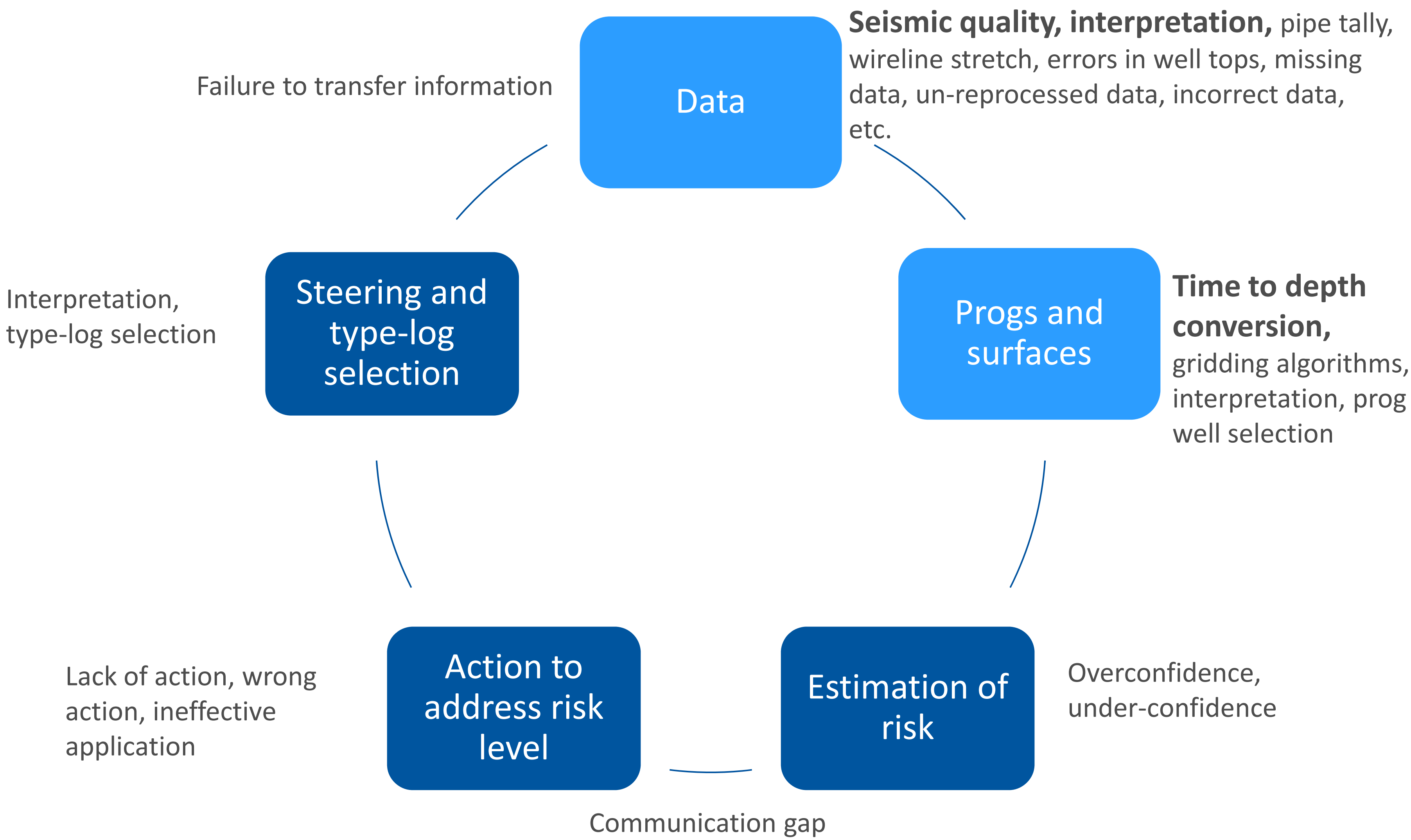
Shale strikes not just a WPX problem




Republic Plaza is 2 miles from where this photo was taken
Middle Bakken is about four stories thick (yellow bar)
Bryant
28 th
STOP

How did we get the 90% reduction in geosteering errors?

Cycle of Learning



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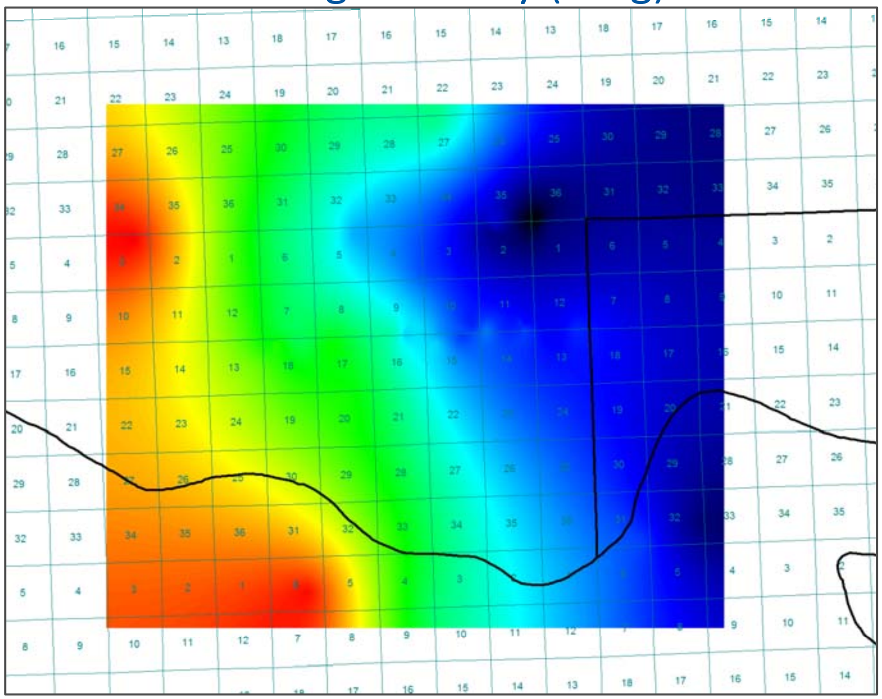
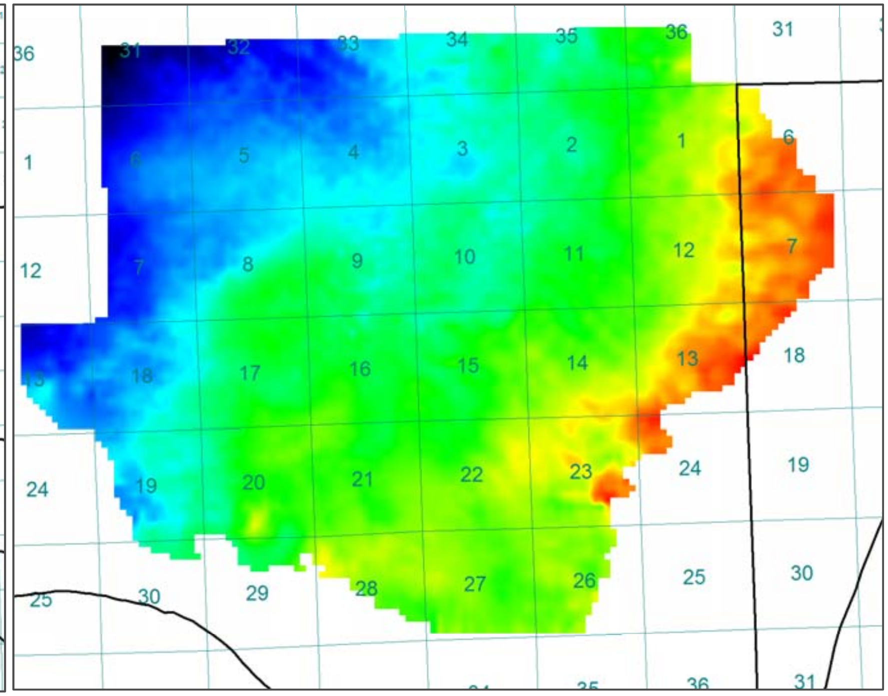
3D processing history: Converting to depth for geosteering

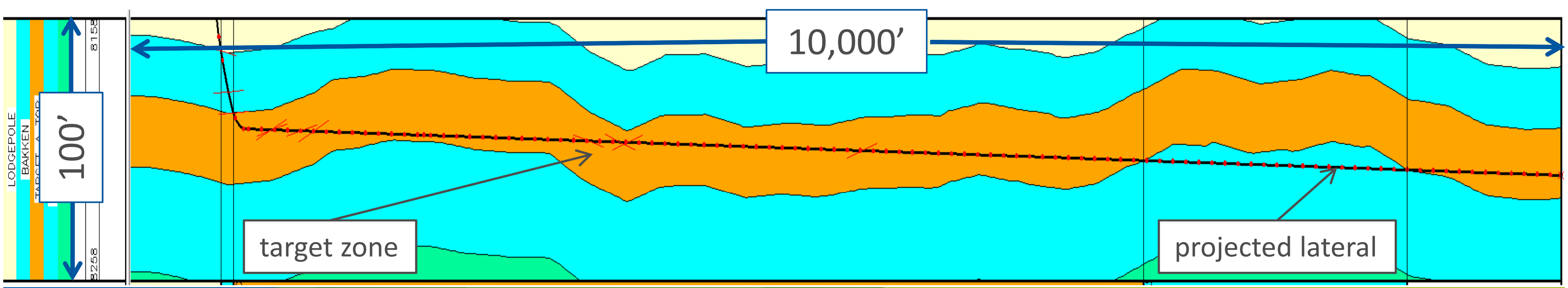
Average Velocity (Vavg)



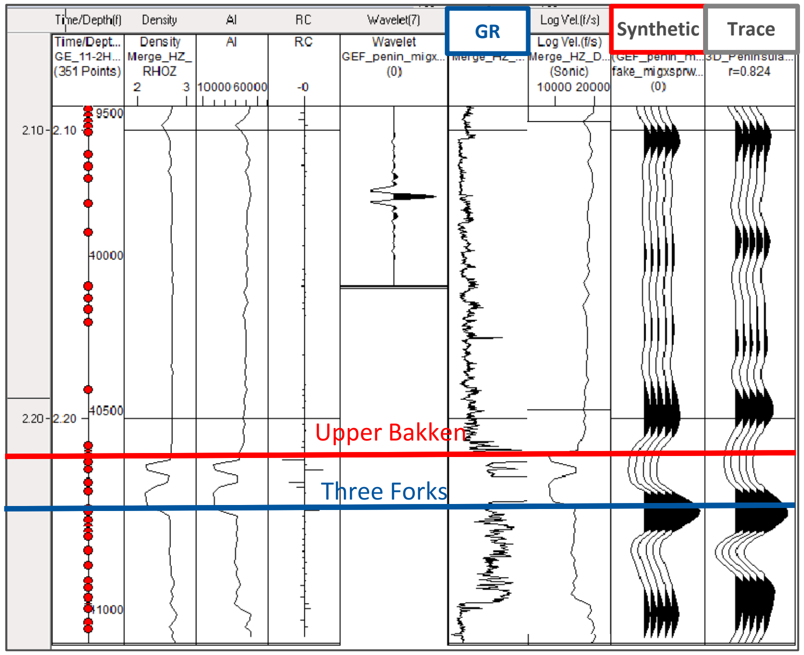
Time



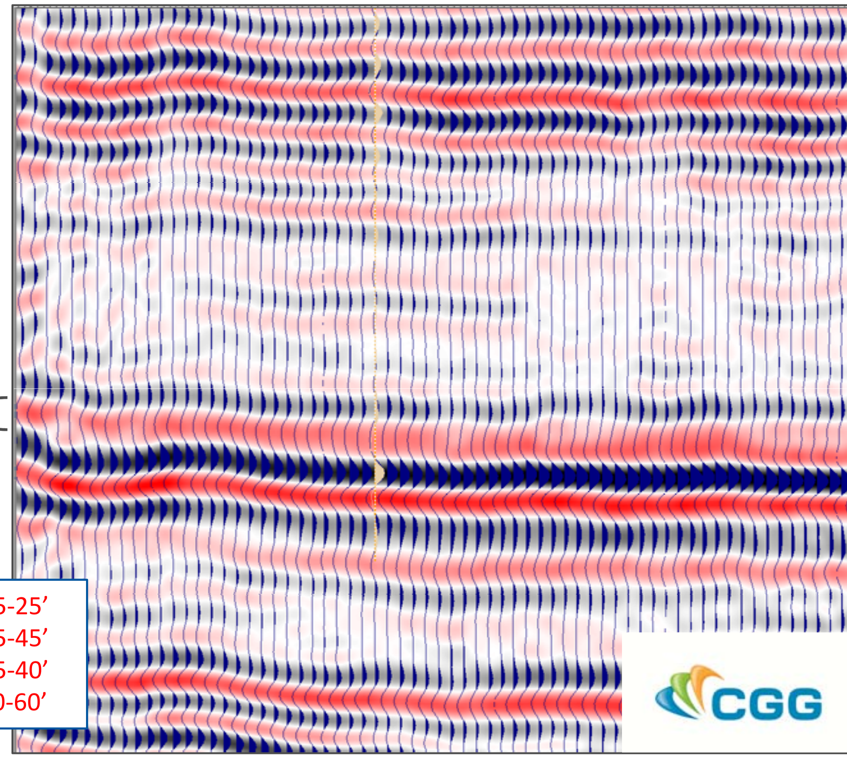
(Vavg*Time)/2=Depth

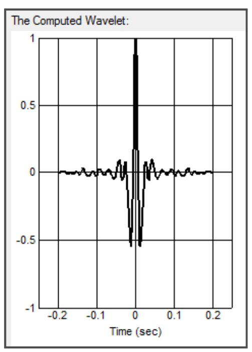


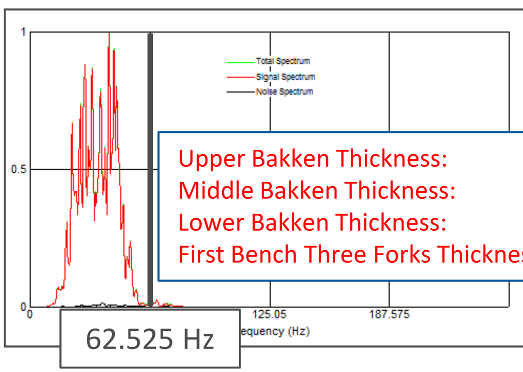
3D processing history: Processing progression - Post Stack



- Basic processing flow
- Spectral Whitening 6-84Hz
- Post Stack Spectral Balancing



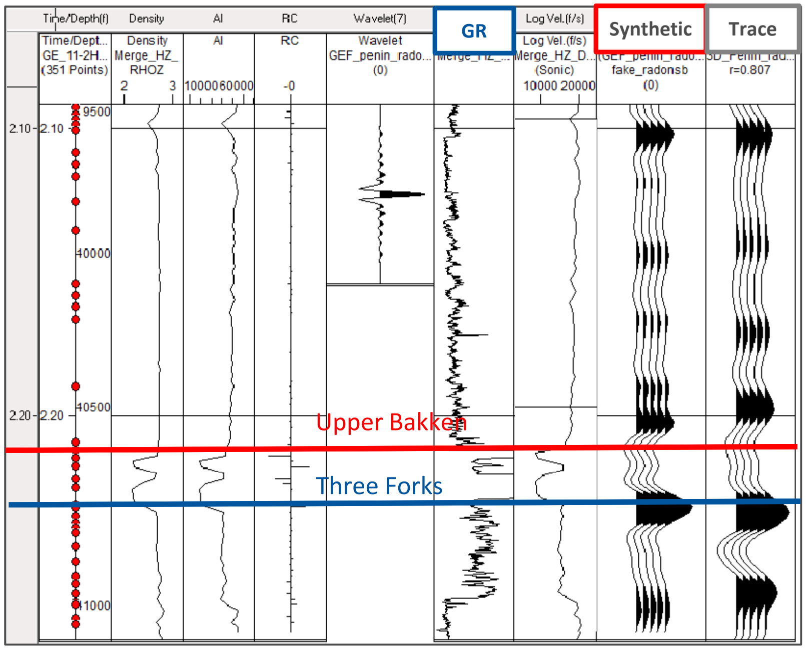


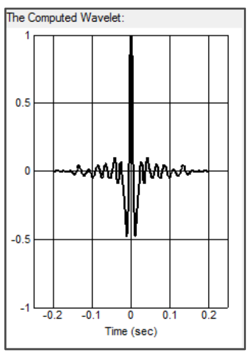


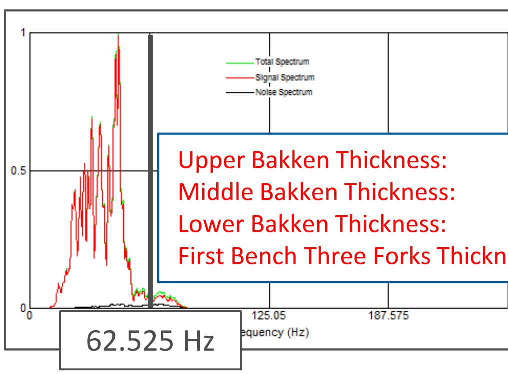
Upper Bakken Thickness:	15-25'
Middle Bakken Thickness:	25-45'
Lower Bakken Thickness:	25-40'
First Bench Three Forks Thickness:	40-60'

3D processing history: Processing progression - Pre Stack Time Migration

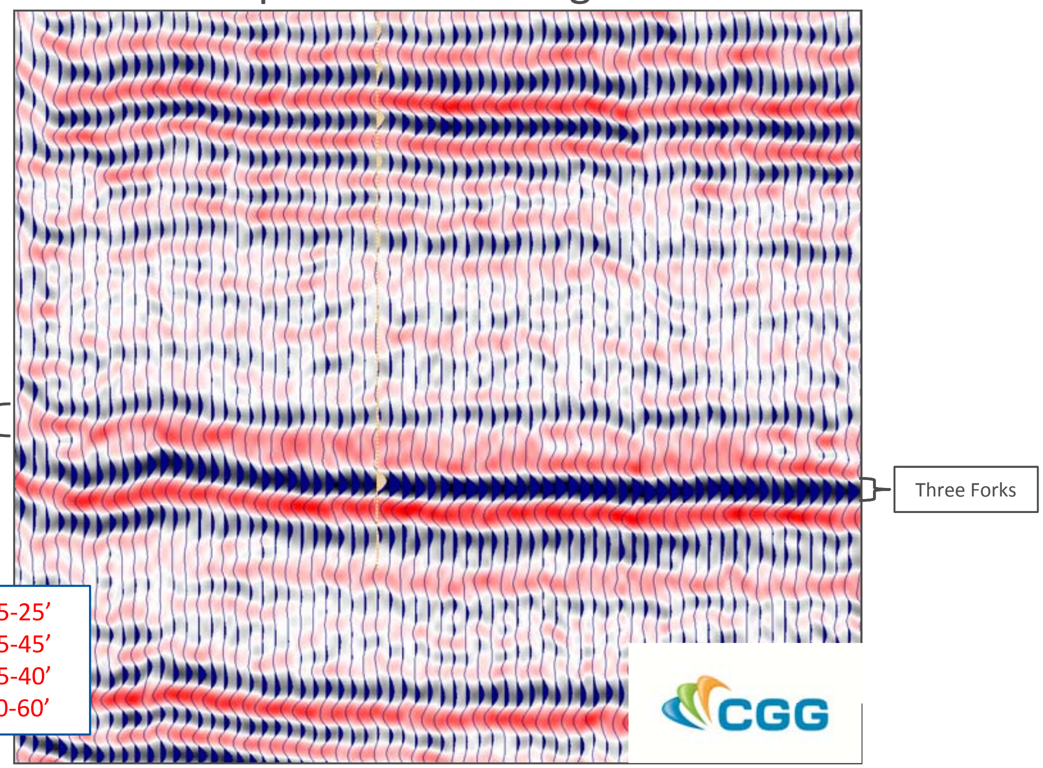
- Spectral Whitening 6-84Hz
- PSTM Kirchhoff Migration
- Residual Velocity Analysis
- Radon Filter, Horizon Based
- Post Stack Spectral Balancing



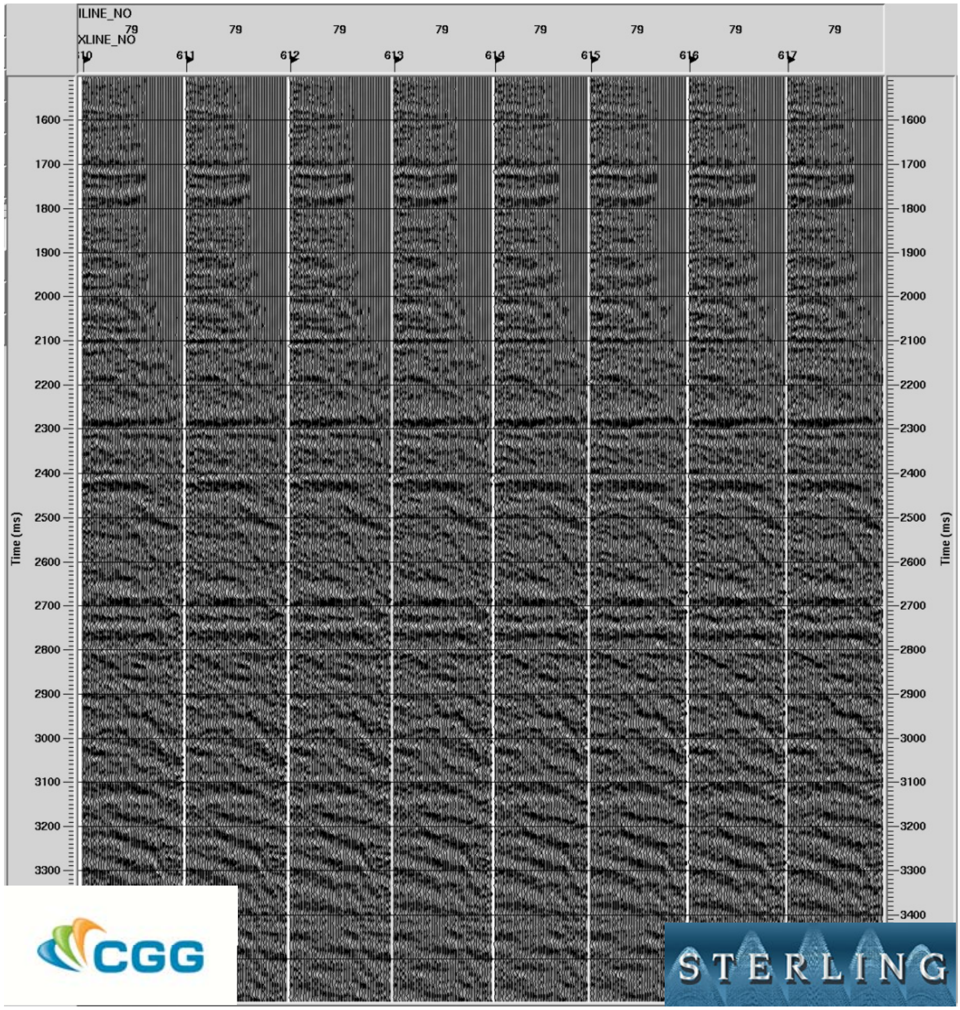




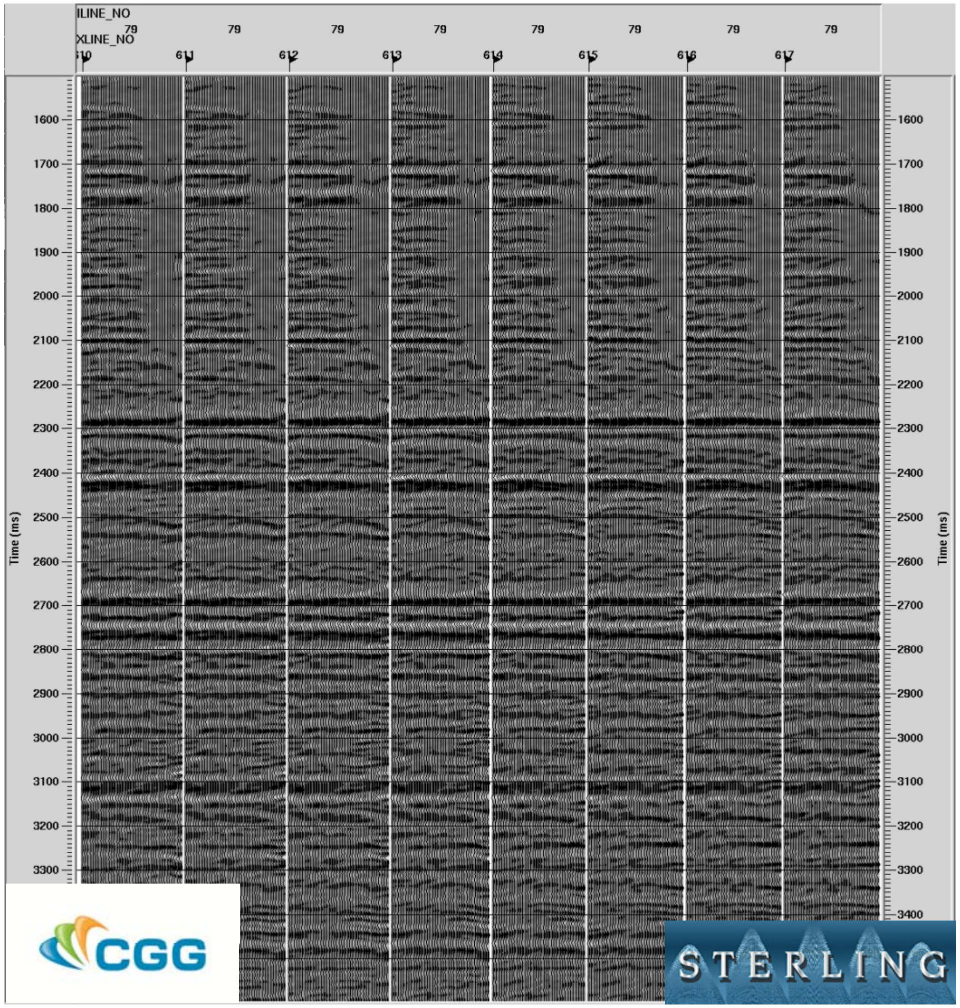
Upper Bakken Thickness: 15-25'
Middle Bakken Thickness: 25-45'
Lower Bakken Thickness: 25-40'
First Bench Three Forks Thickness: 40-60'



3D processing history: Gather panels



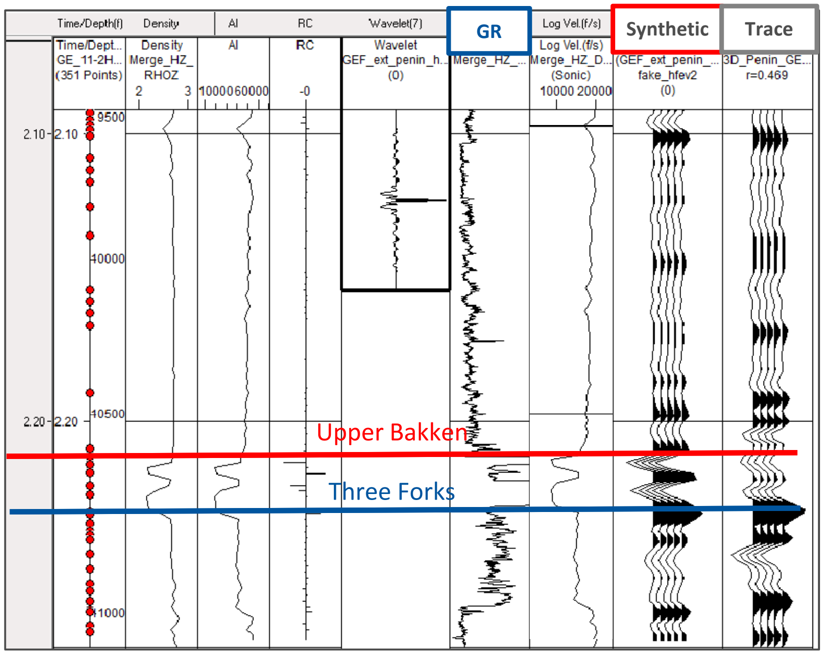
Before radon

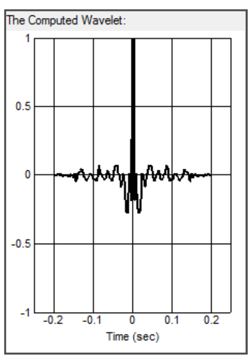


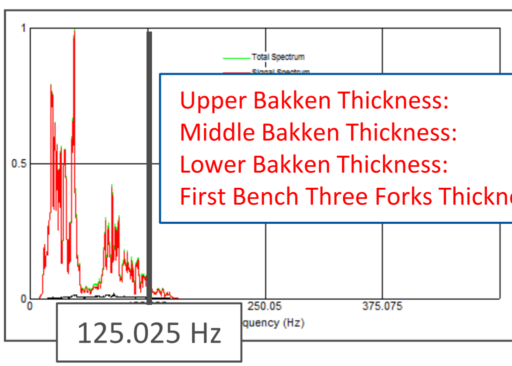
After radon

Processing progression: Pre Stack Time Migration High Frequency Extender

- Spectral Whitening 6-84Hz
- PSTM Kirchhoff Migration
- Residual Velocity Analysis
- Radon Filter, Horizon Based
- High Frequency Enhancement







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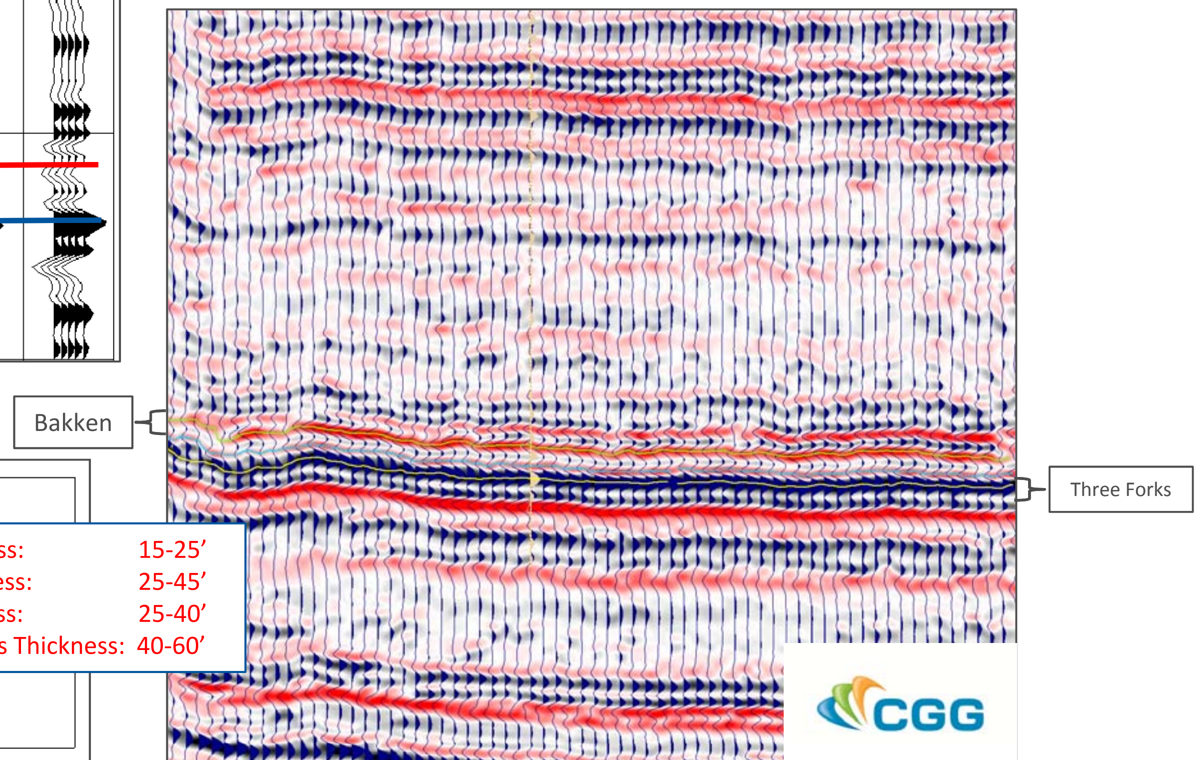
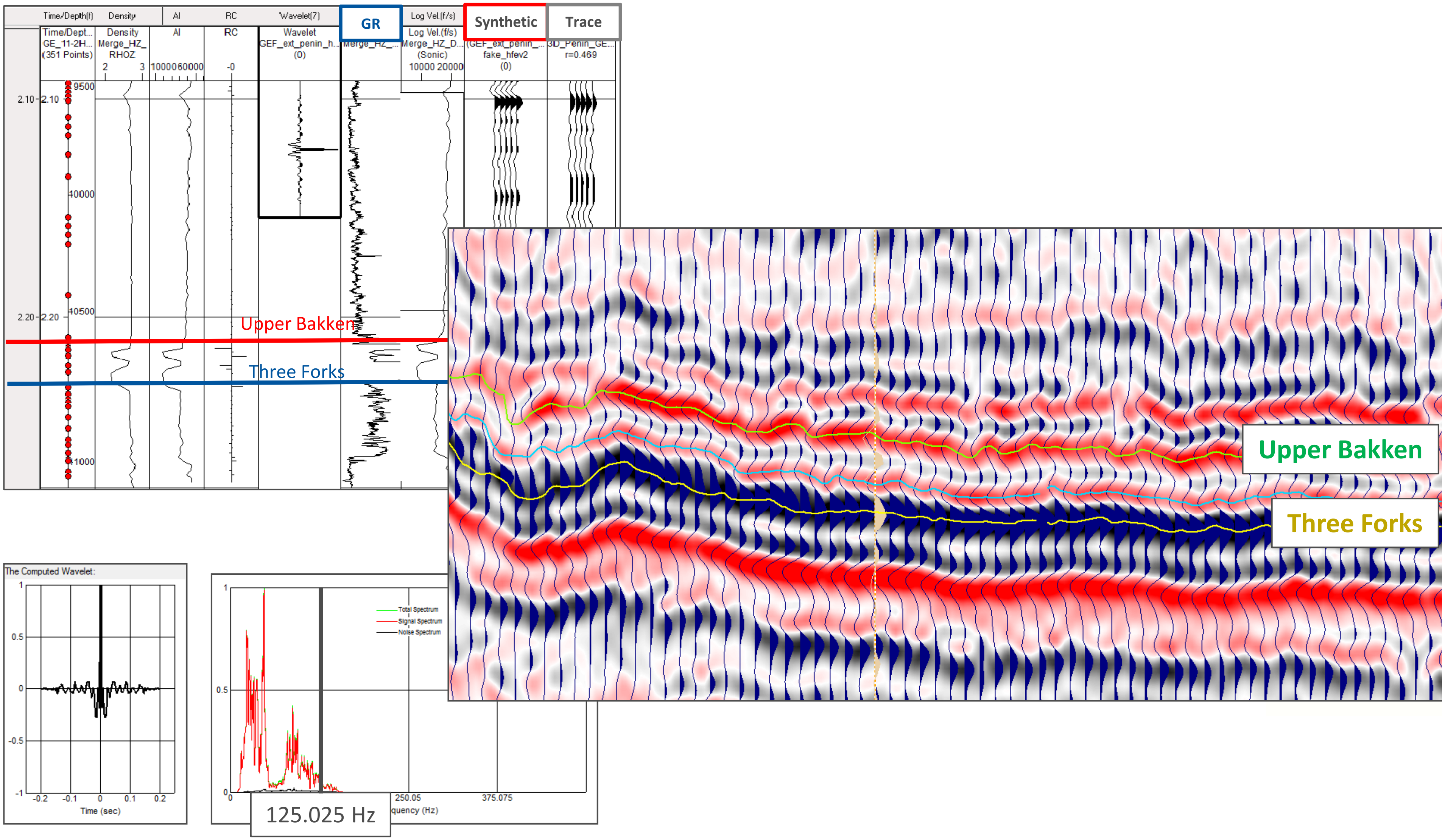
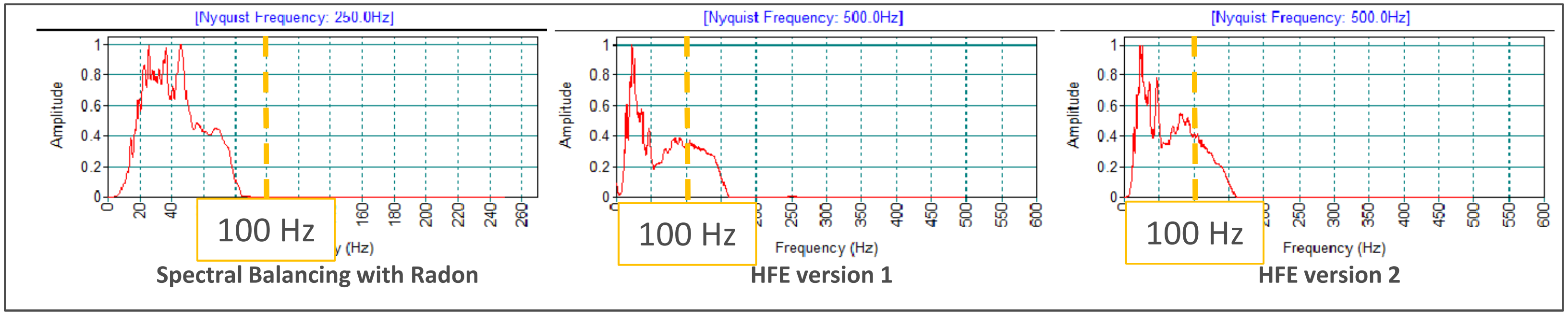
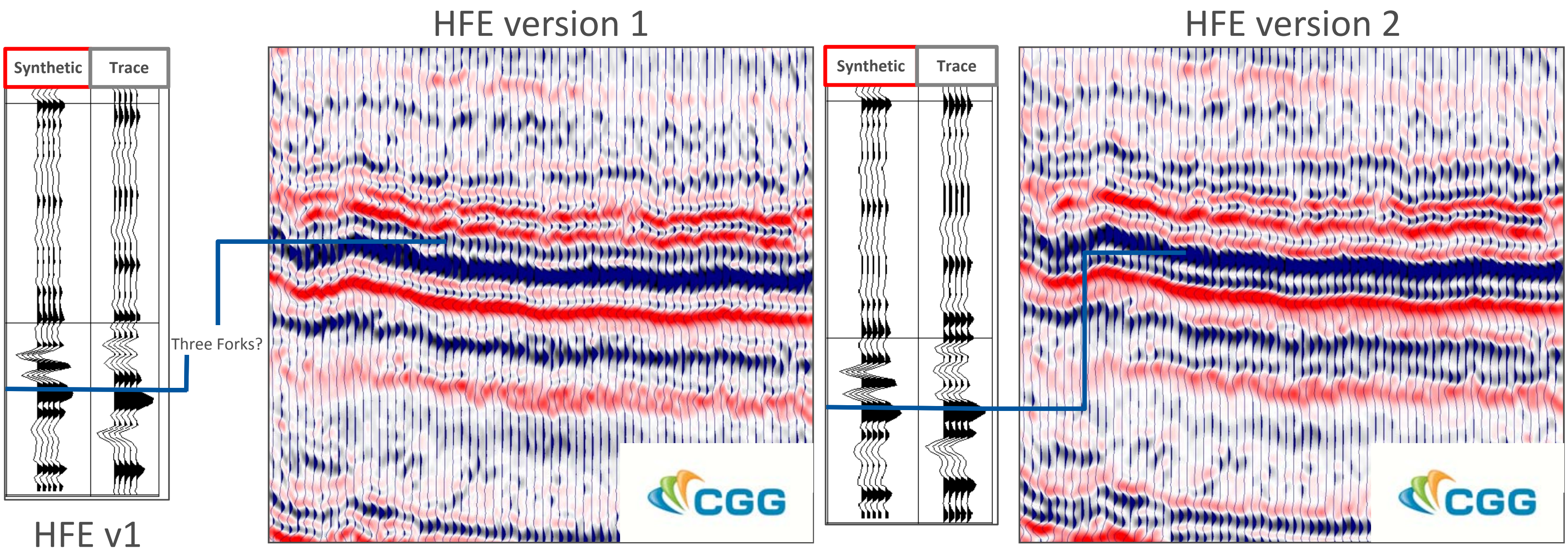


Processing progression: Pre Stack Time Migration HFE

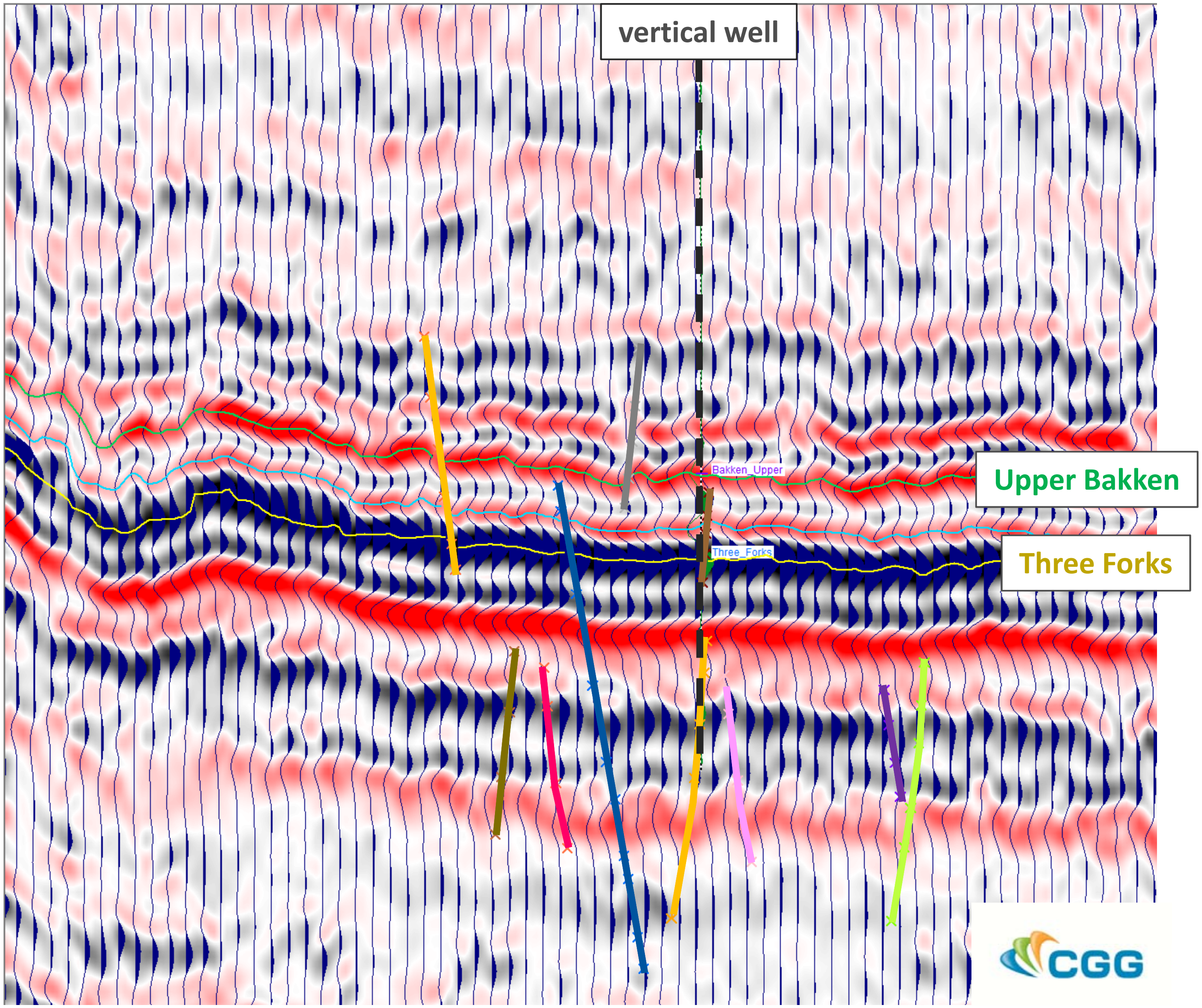


3D processing history: refining HFE volume

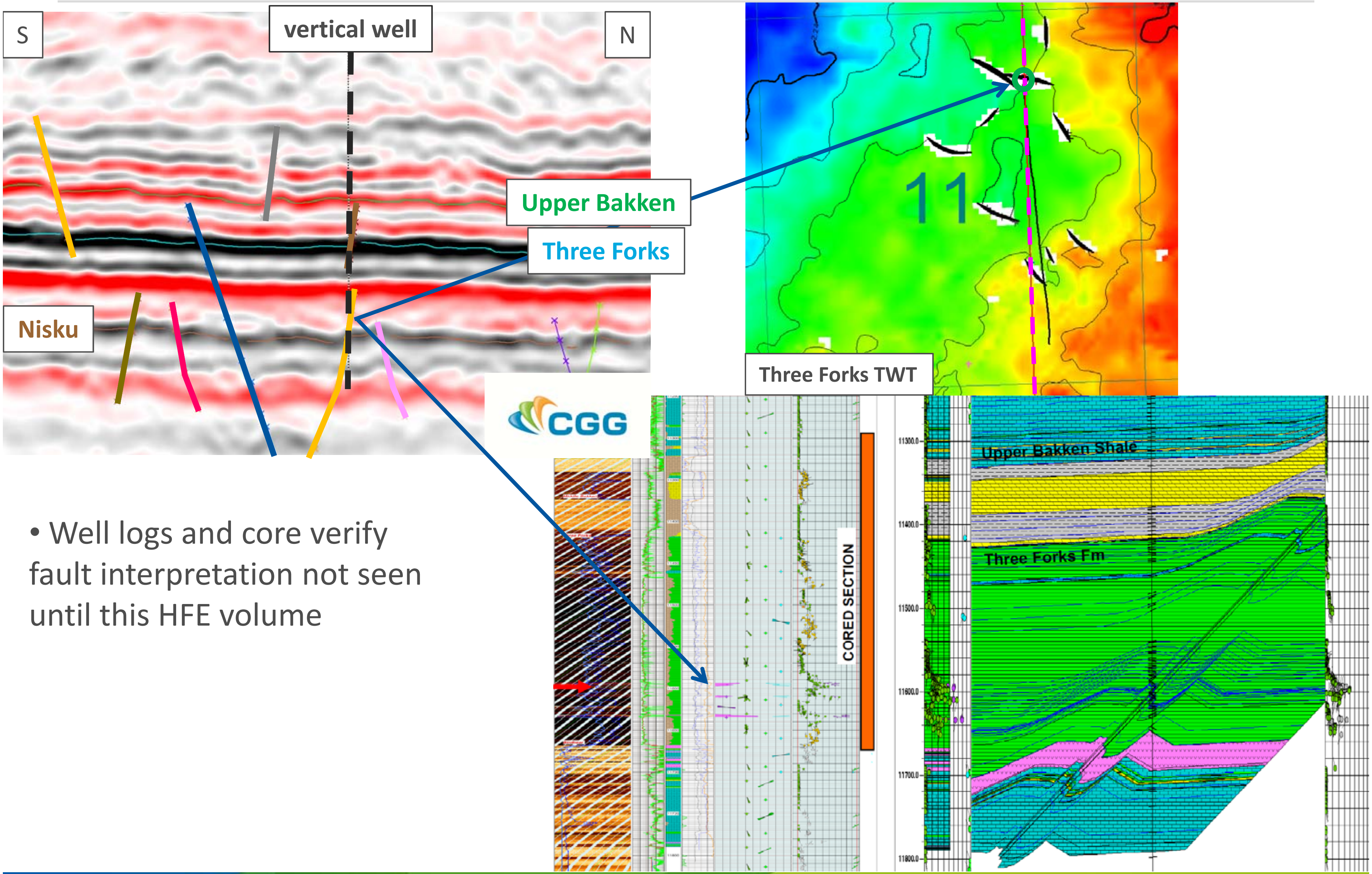




3D processing history: HFE



3D processing history: HFE



- Well logs and core verify fault interpretation not seen until this HFE volume

Outline

- Introduction to the Williston Basin

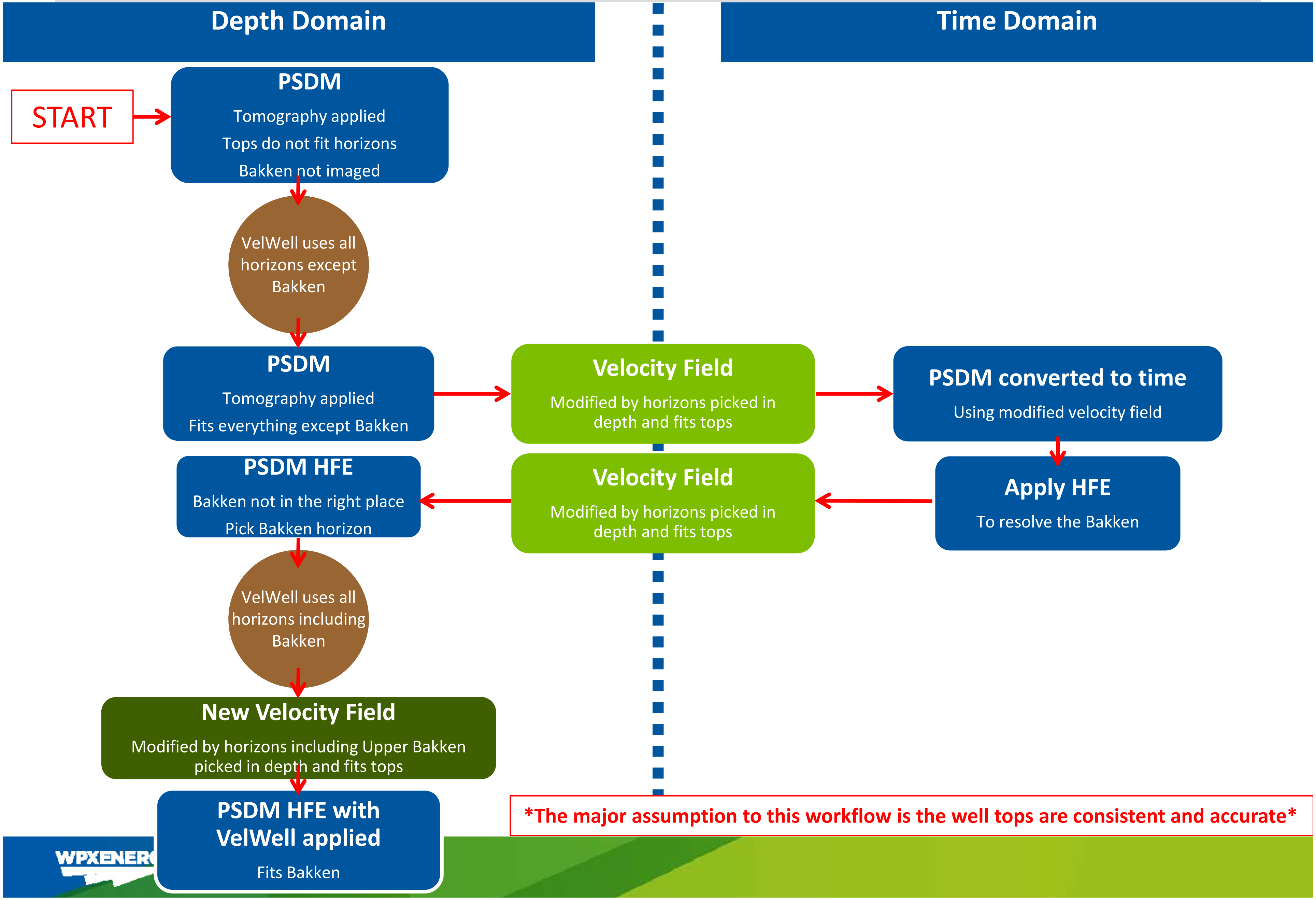
- Background and motivation for the talk

- 3D processing history

- **Converting time to depth**
    - **PSDM workflow**
    - Well tops and their accuracy
    - Depth calibration of CBL and MWD/LWD logs

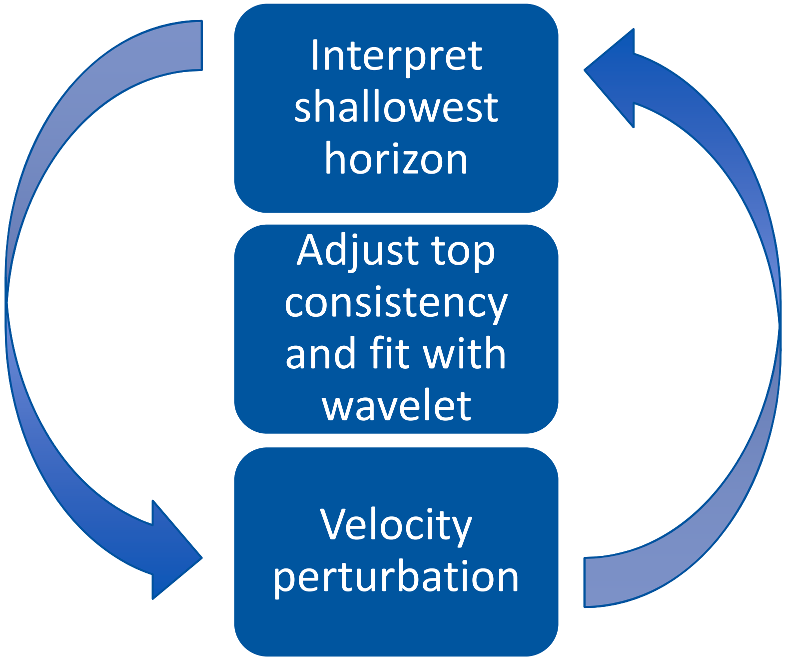
- Conclusions

Converting time to depth: Isotropic Depth Conversion



Converting time to depth

- After the tomo passes have converged on an answer the PSDM volume is interpreted at key horizons



- Go to second shallowest surface and repeat process of comparison to tops
- And so on down to last surface
- Provide fixed tops and interpreted horizons to processor

Outline

- Introduction to the Williston Basin
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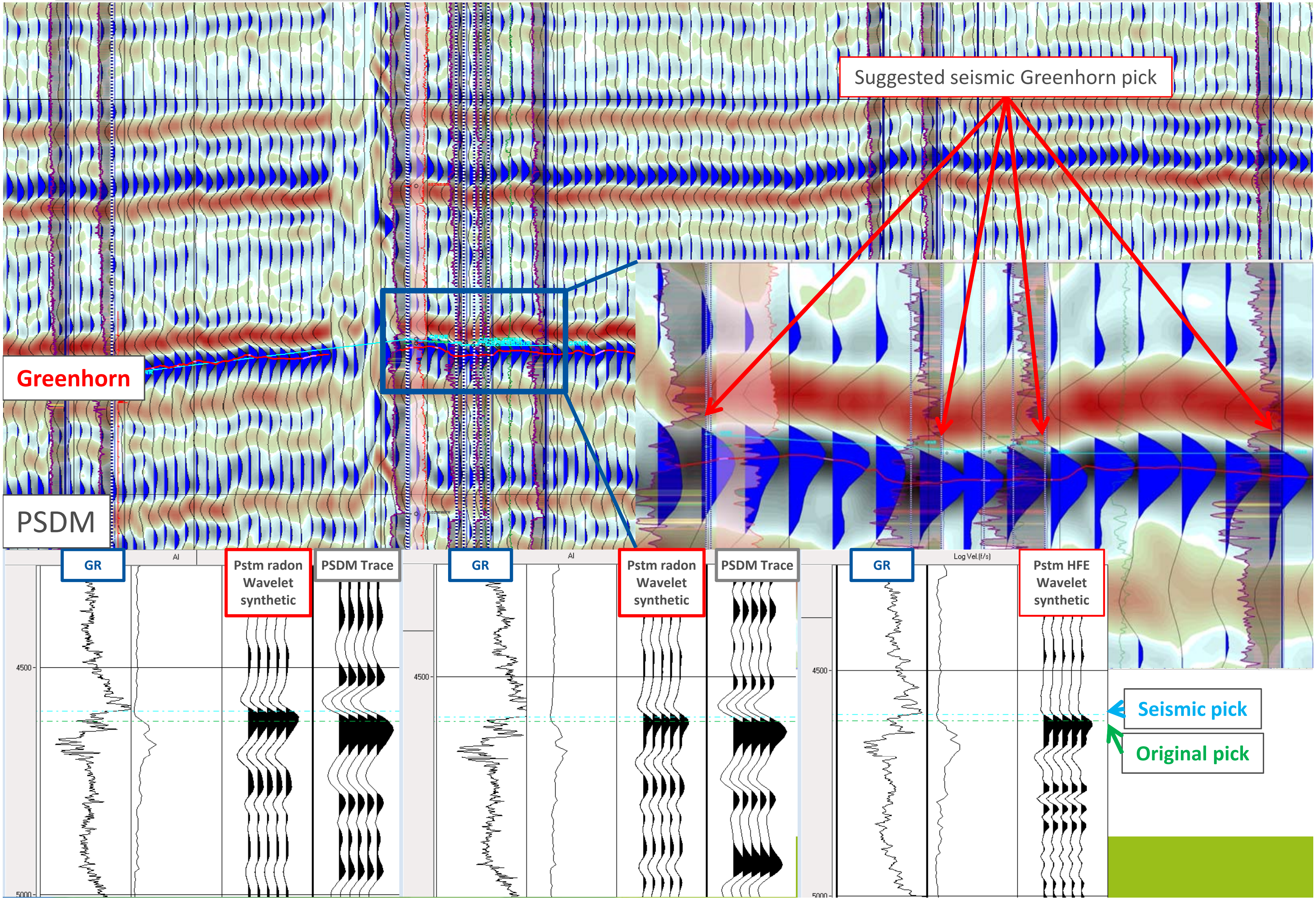
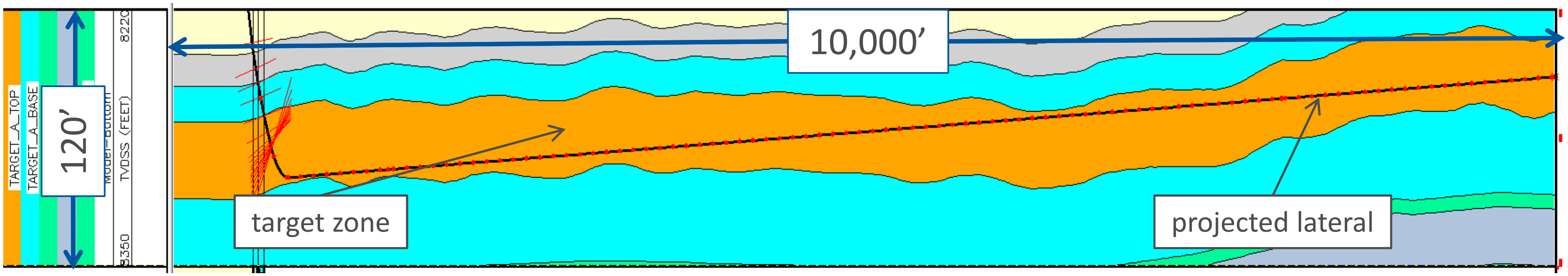
    - Depth calibration of CBL and MWD/LWD logs
- Conclusions

Well tops and their accuracy

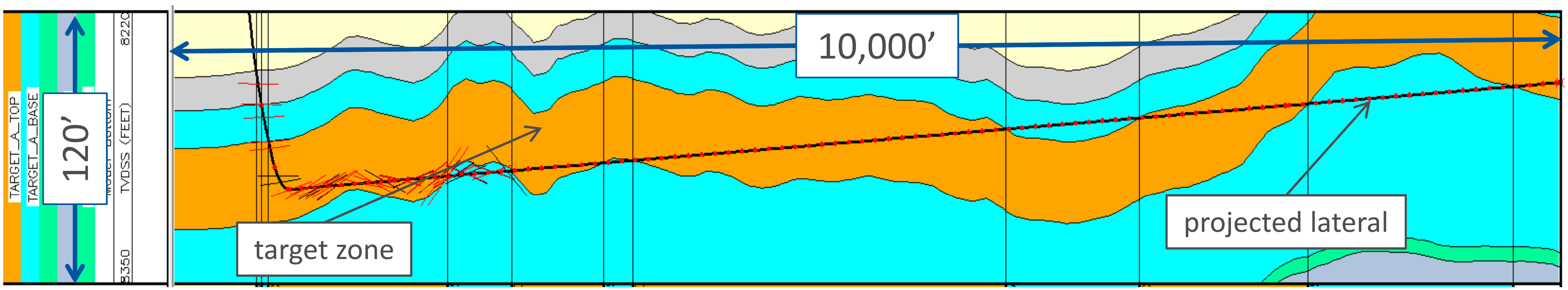


Well tops and their accuracy

PSTM HFE

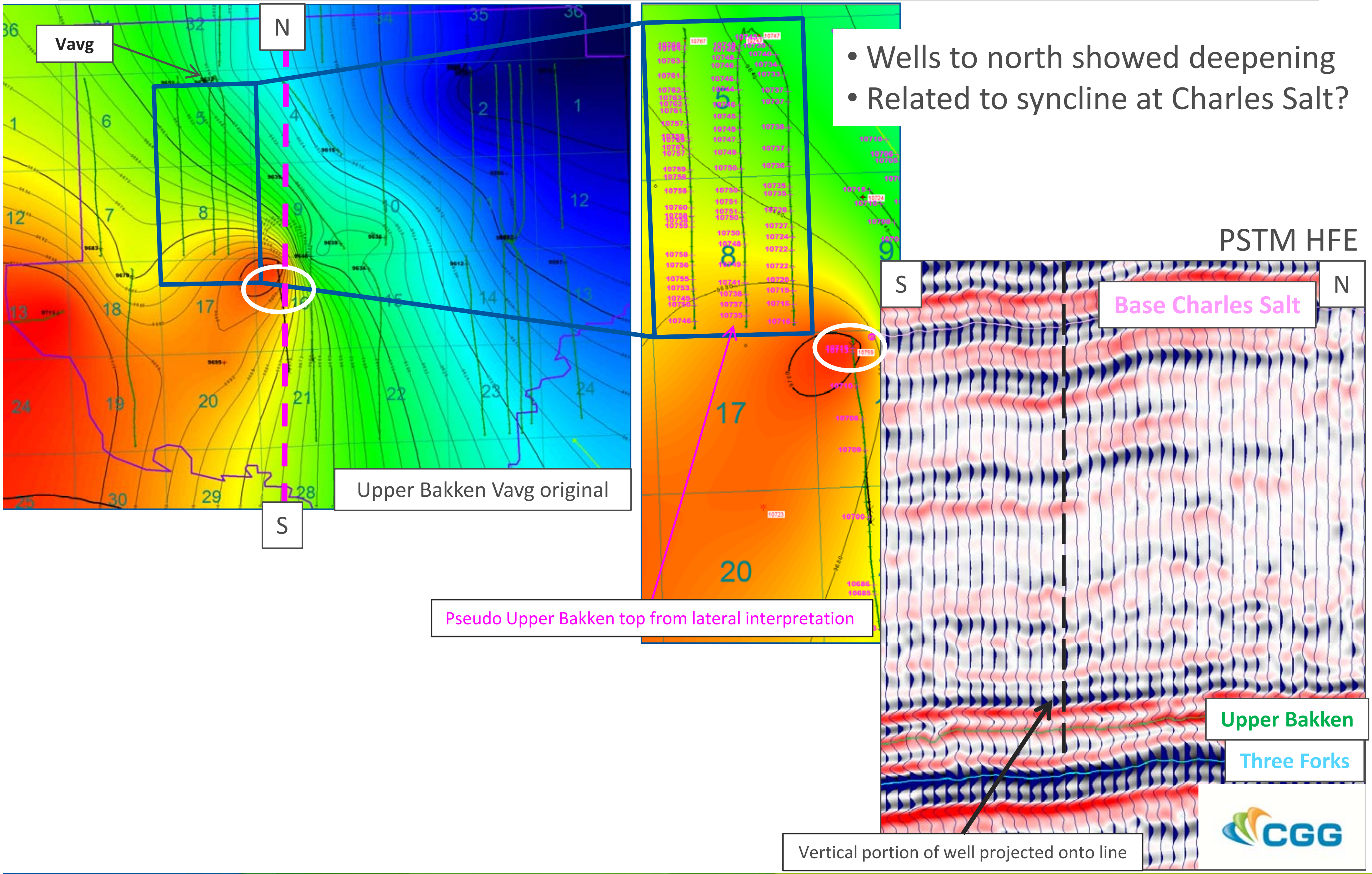


PSDM

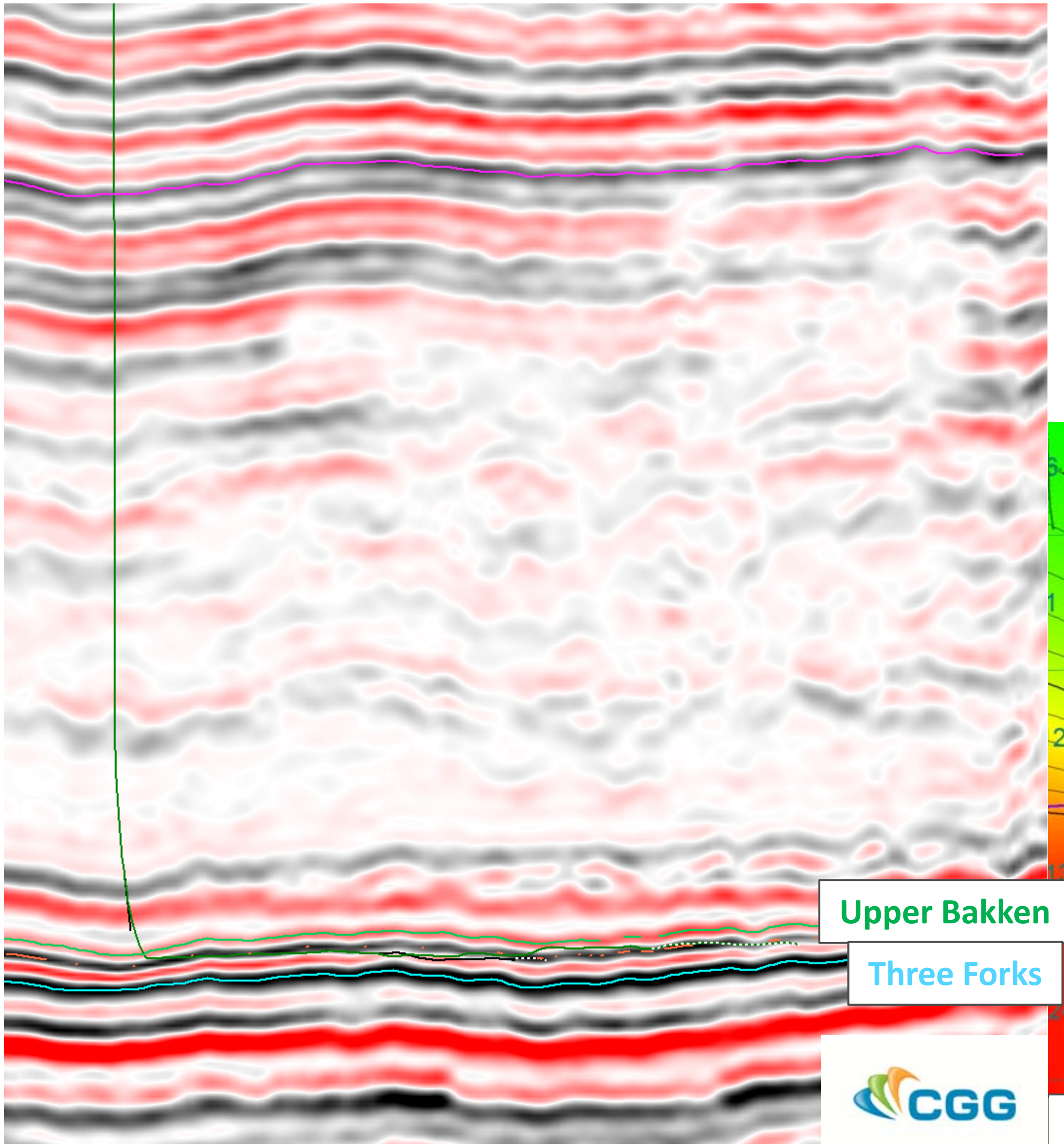


Well tops and their accuracy

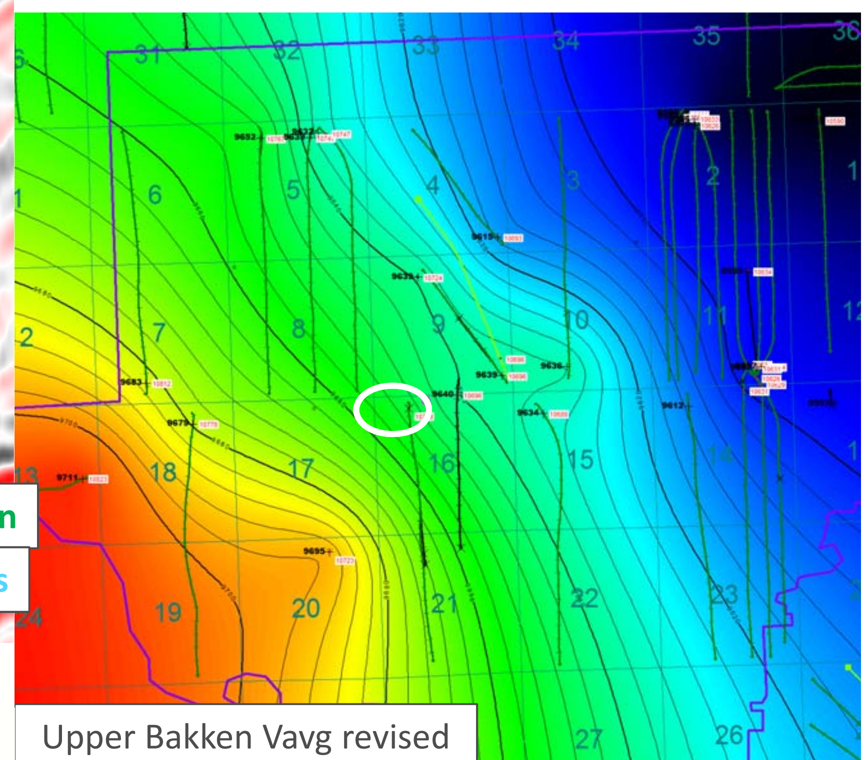
- Wells to north showed deepening
- Related to syncline at Charles Salt?



Well tops and their accuracy



- Error of 40 ft/sec is only 0.4%
- Puts the lateral in the Upper Bakken Shale



Well tops and their accuracy

- Error of 40 ft/sec is only 0.4%
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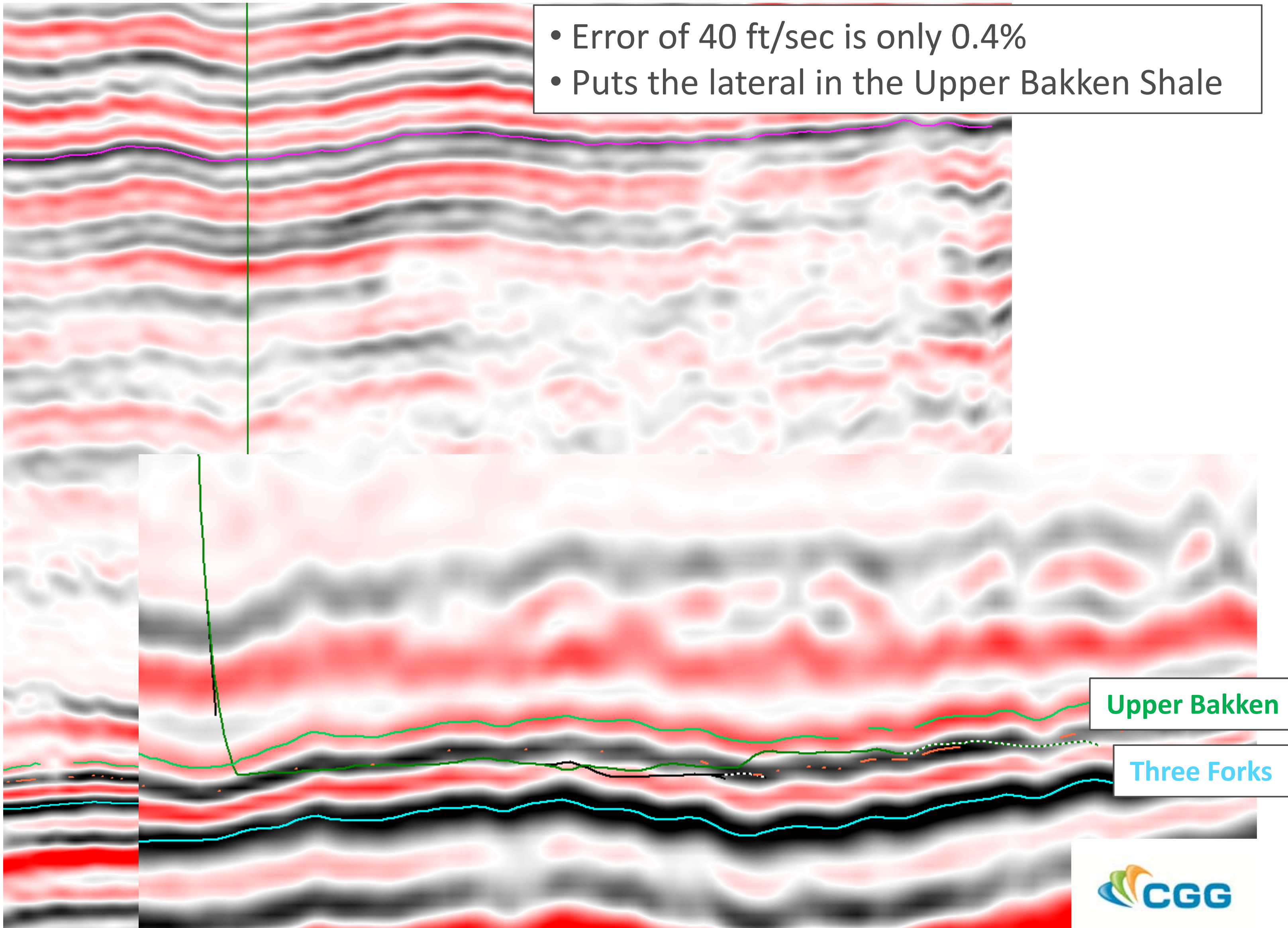
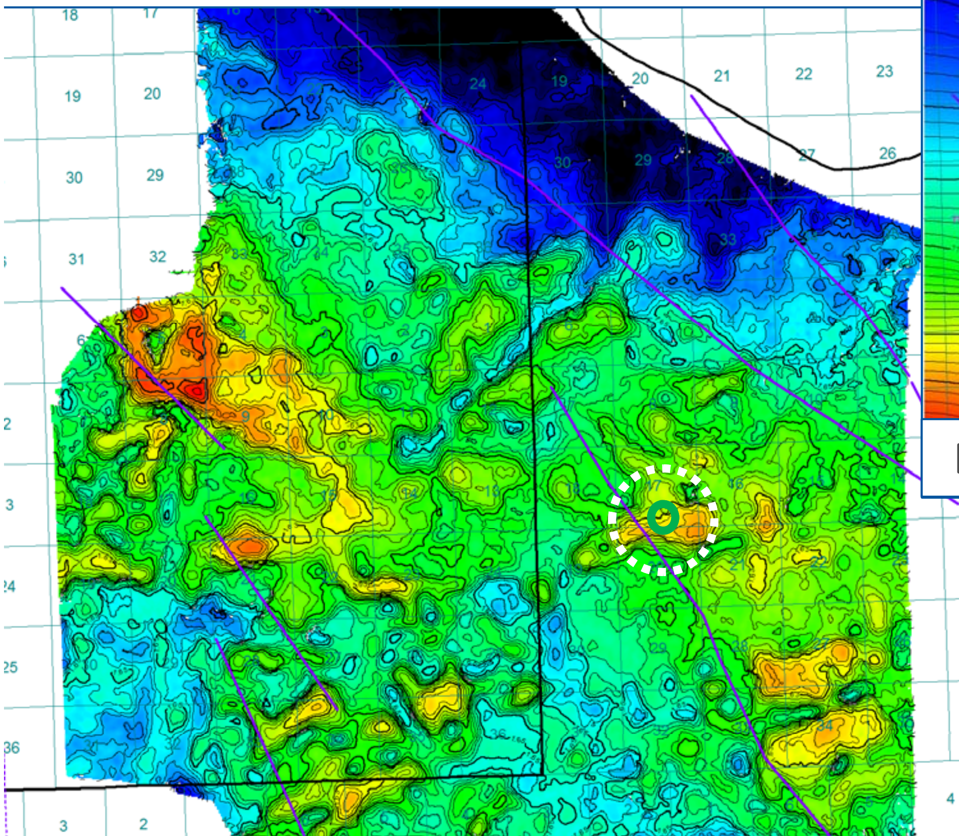
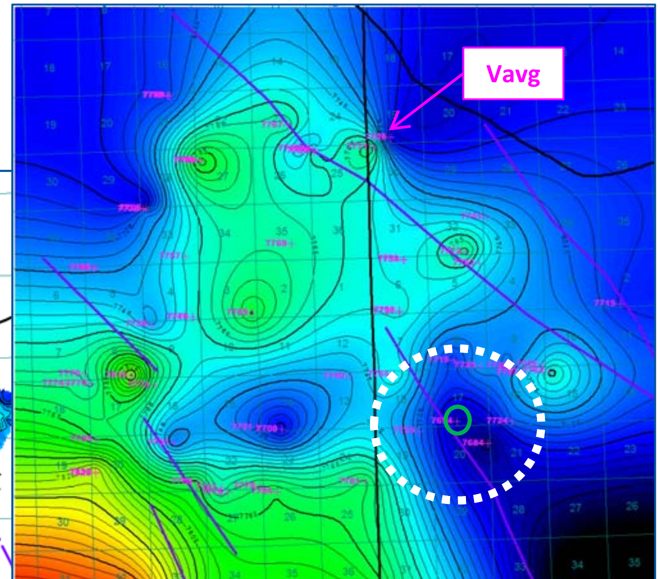


	MD(Feet	Incline(	Azimuth
71	7920.00	0.87	89.67
72	8010.00	0.78	88.30
73	8100.00	0.78	87.95
74	8190.00	0.79	95.40
75	8280.00	0.82	99.55
76	8370.00	0.77	102.99
77	8460.00	0.75	107.73
78	8550.00	0.74	115.03
79	8640.00	0.69	115.25
80	8730.00	0.71	116.00
81	8820.00	0.67	116.54
82	8910.00	0.62	111.41
83	9000.00	0.66	113.26
84	9090.00	0.63	113.69
85	9180.00	0.57	110.53
86	9270.00	0.56	97.81
87	9360.00	0.56	99.68
88	9450.00	0.57	101.94
89	9540.00	0.49	91.91
90	9630.00	0.44	85.15
91	9647.00	0.28	49.26
92	9681.00	0.94	159.45
93	9713.00	4.43	173.32
94	9744.00	7.39	175.63
95	9776.00	10.18	176.85
96	9808.00	13.45	176.97
97	9839.00	16.89	176.78
98	9871.00	20.30	177.92
99	9902.00	22.80	179.97
10	9934.00	25.47	181.59
10	9965.00	28.54	183.83
10	9997.00	31.80	184.81
[illegible]	[illegible]	[illegible]	[illegible]
10	10060.0	38.67	185.56
10	10228.0	38.67	185.56

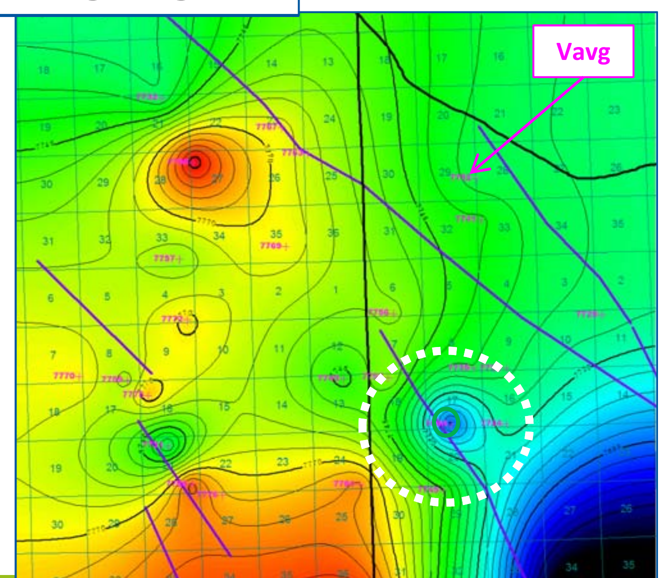
Well tops and their accuracy



Base of Rierdon TWT



Base of Rierdon Vavg original



Base of Rierdon Vavg revised

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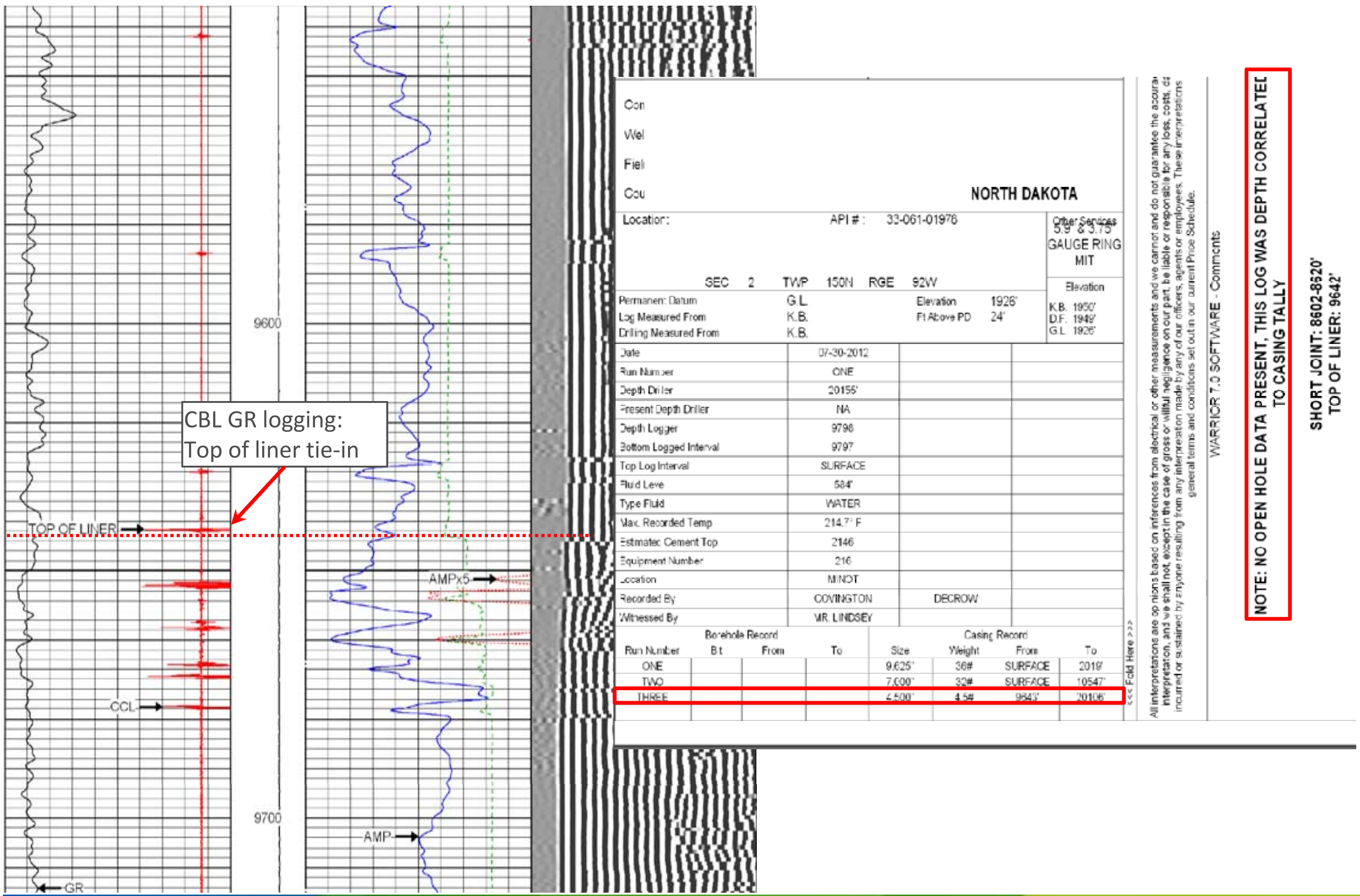
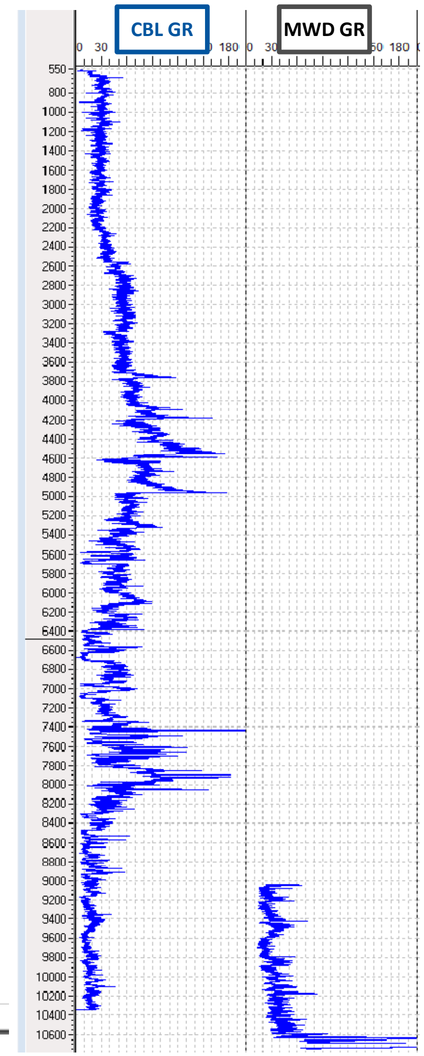
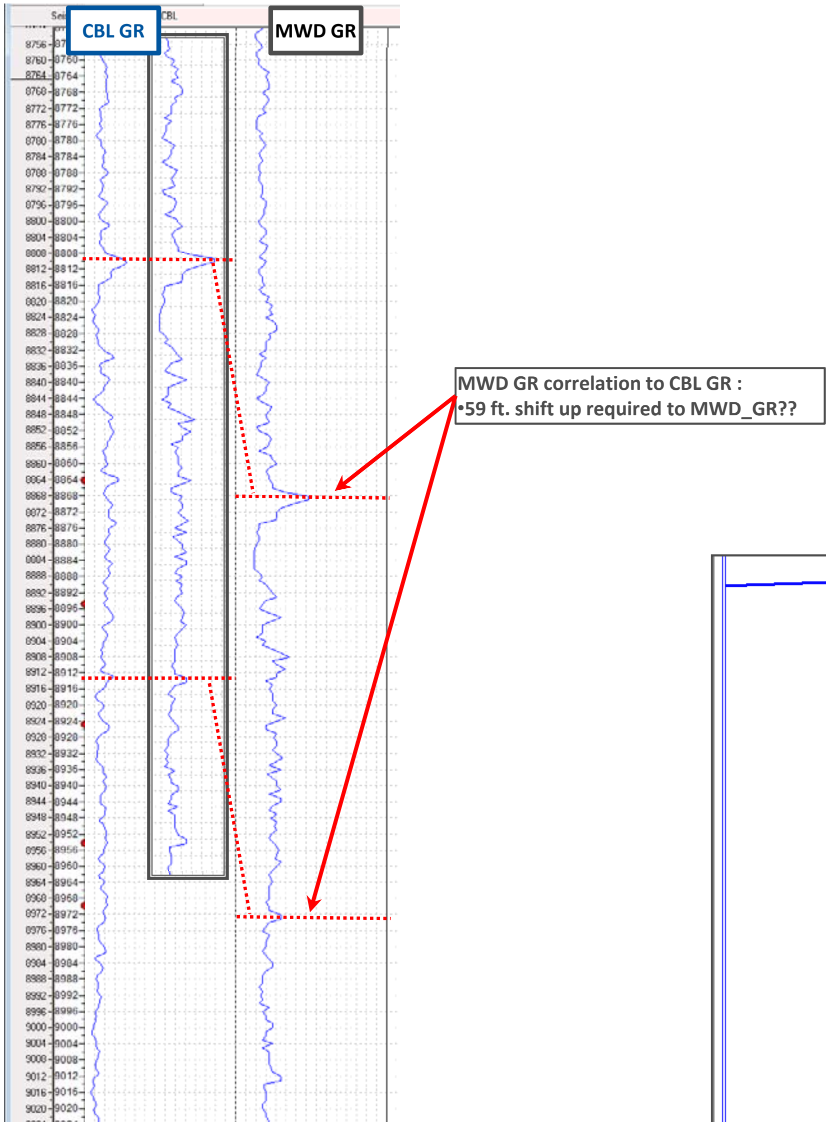
Depth calibration of wireline/CBL and MWD/LWD logs

- MWD GR logs turned on in Lodgepole due to time and cost constraints
- CBL GR run from KOP to surface usually months later





Depth calibration of wireline/CBL and MWD/LWD logs



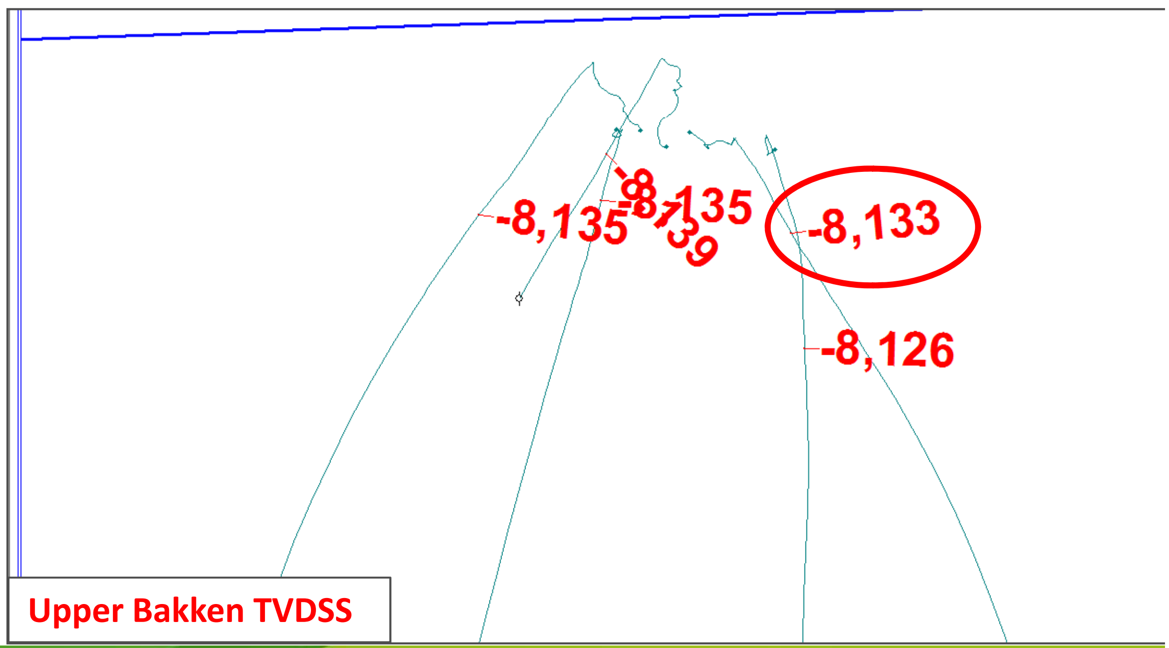
CBL has opportunity to be tied in with different markers at different depths

SHORT JOINT: 8602-8620'
TOP OF LINER: 9642'

One choice was to shift MWD GR to CBL GR

Posting TVDSS depths of Upper Bakken top does not suggest that MWD should be shifted to CBL

Shift CBL GR to MWD GR and shift all shallow tops!



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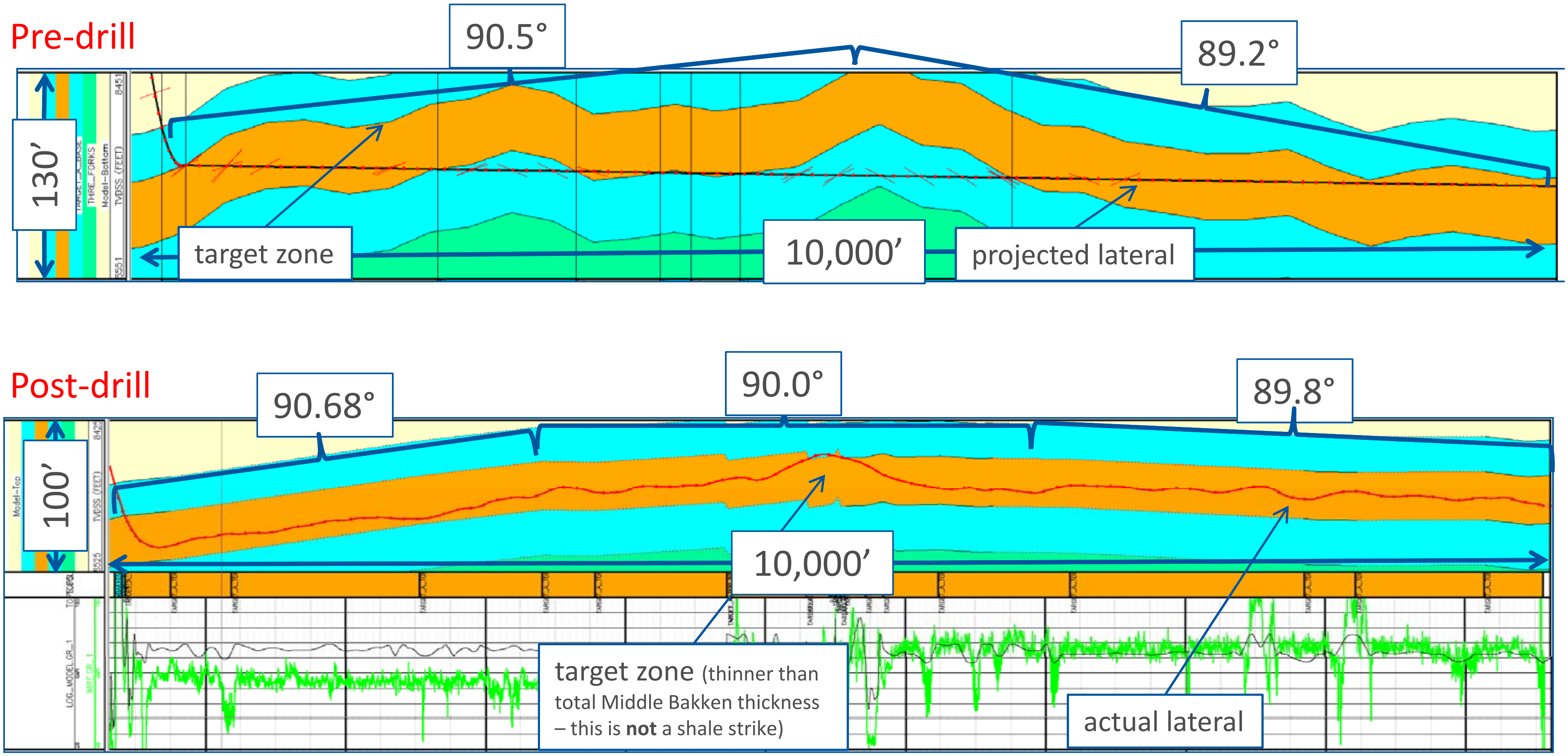
Conclusions



- Post drill surfaces modified by lateral GR interpretation

Thank you

WPX Energy

Hal Harper
Lee Steinke
Laura Wray
Jason A. Harms
John Frame
Simon Cole

STERLING

Rus Kappius
Steve Saindon

CGG

Rick Trevino