[PS]Second Bone Spring Borehole Image Derived Depositional Facies Characterization: Case Study from the Delaware Basin, West Texas*

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Abstract

The Bone Spring Formation is a Permian deposit characterized by a variety of facies, from well-layered fine-grained basinal turbiditic deposits to coarser grained flow deposits, to slumps and complex mass transport deposits. This case study focuses on integration of conventional core analysis and routine and advanced wireline logs including nine borehole image logs, all acquired within a 20 miles radius from the core. Core analysis included lithofacies, identification of sedimentary and/or biologically and/or chemically induced structures. The borehole image logs were analyzed for fracture distribution, identification of sedimentary facies, and their variation in the vertical and lateral space. A lithofacies catalog (mudstone, carbonate-rich mudstone, thick bedded silt, and thick bedded carbonate-rich silt) was produced and applied to all the nine wells by comparison between core, borehole images and advanced spectroscopy log available in one well. From the analysis of the borehole images, the structure is consistently gently dipping to the WNW with a rotation to the SE in the Southern most well. This is justified by the presence of a major fault, dissecting the basin into two parts. This major fault is also coincident with a rotation of the in situ max stress from E-W to WNW-ESE. Natural fractures show a strike bi-modal distribution: NE-SW and WNW-ESE. The southernmost well shows a different result with a NW-SE predominant and a NE-SW secondary trend. The presence of interpreted open fractures increases towards the West of the study area. Facies analysis on the borehole image highlighted the presence of laminations, dewatering structures, mud clasts, intense bioturbation, large concretions, oblate concretions, pyrite, patchy cement, cross laminations and highly deformed facies. Newly applied technologies allowed the quantification of laminations from high-resolution image data. Laminations frequency and thickness can give indications on sedimentary energy and provides information on the depositional settings. The variation on lamination thicknesses and densities supported in the identification of facies. The different depositional environments interpreted from this dataset are deep basin, distal turbidite lobe, and distributary channels. The integration between core and image logs helped propagate the facies and depositional environment interpretation from expensive cored wells to much more cost-effective logs datasets and it helped also in reducing wellbore risk.

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POSTER ABSTRACT

The Permian-aged Bone Spring Formation of the Western US Permian Basin is a mixed succession of siliciclastic and calcareous sediment gravity flow deposits. It is comprised of fine grained turbidites/calciturbidites, slumps, mass flow deposits, and coarser-grained debrites (Thompson et al., 2018). This case study focuses on the integration of conventional core interpretation with routine and advanced wireline logs. The dataset includes nine high-quality resistivity image (FMI) logs, all within a twenty-mile radius of the core.

The core provided calibration for the resistivity image analysis. Lithology, facies, facies associations, sedimentary structures, and natural fractures made up the interpretation set. The objective was to tie these core properties to the FMI and routine wireline logs for the purpose of extrapolating rock and fracture intensity properties to uncored areas both vertically in the core well and laterally in offset wells.

From the borehole image analysis, the geologic structure in the northern Delaware Basin consistently dips to the WNW with at rotation to the SE in the southern-most well. This rotation is coincident with the presence of a major E-W Mid-Basin Fault (MBF) that bisects the Delaware. The MBF is also coincident with a rotation of the *in situ* maximum stress from E-W to its north to WNW-ESE to its south.

Natural fractures show a bimodal strike direction: NE-SW and WNW-ESE. The southernmost well is again different; it has primary NW-SE and secondary NE-SW trends in fracture orientation. The presence of interpreted open fractures increases towards the west of the study area.

Core and spectroscopy log data (Lithoscanner) were combined to identify the following lithofacies:

Mudstone
Carbonate-rich mudstone
Thickly bedded silt
Thickly bedded carbonate-rich silt

Detailed comparison of core data to resistivity images showed the that following textural elements are identifiable in the images:

Laminations and cross laminations
Slumps and deformed beds
Mud clasts
Large and oblate concretions
Hybrid event beds
Patchy cement
Pyrite

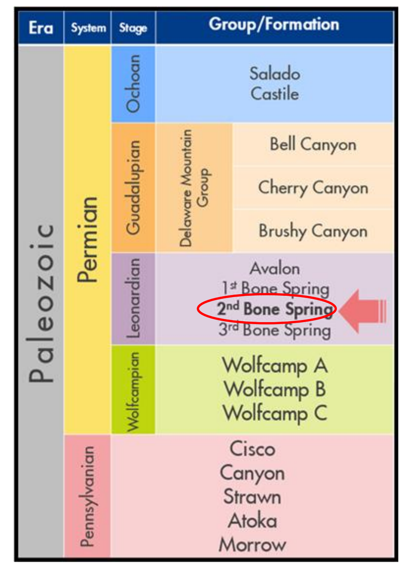
Newly created and introduced technologies allowed the identification and quantification of laminations from the high-resolution resistivity image data. Lamination frequency and lamination thickness can give indications of sedimentary processes and environments of deposition. The variations in lamination thickness and lamination frequency in conjunction with other textural characteristics underpinned the identification of facies.

From the facies and facies associations, different depositional environments were interpreted from the dataset:

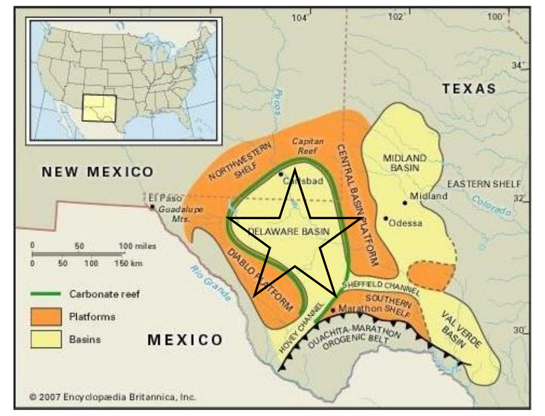
On-axis turbidite lobe
Off-axis turbidite lobe
Turbidite lobe fringe

The integration of core, routine wireline logs and high-resolution resistivity image logs helped propagate the interpretations of facies and depositional environment away from expensive cored wells to much more cost-effective log datasets.

SIMPLIFIED STRATIGRAPHIC COLUMN



DELAWARE BASIN LOCATION MAP



The wells subjects of this case study are located in the Delaware basin, one of the largest oilfield in West Texas and SE New Mexico.

☆ Wells general location

PROJECT WORKFLOW

This study comprises three different milestones: 1) data collection and processing, 2) detailed sedimentological facies description, and 3) multi-well facies correlation. This study also outlines observations regarding lateral facies variation observed in borehole images acquired in a lateral well. The end-goal — facies correlation — addresses the complexity of intermixed facies throughout the focus area and helps improve reservoir delineation as compared to a simple correlation using basic open hole logs.

The project entailed processing and analyzing borehole image data for sedimentary facies, depositional environments, and stratigraphic orientations (sediment dispersal, paleo-current, and paleo-slope) of intervals over the Bone Spring Formation. Indicators for sediment distribution, such as channel orientation, were sought in the stratigraphic dip data (structural dips removed). Given the distal positon of the wells, though, few observations were made. High resolution electro-facies were carefully tied with the conventional core facies analysis in the validation well. A facies scheme was obtained from the correlated well and used as a basis for the rest of the wells in the study.

A step-by-step description of the workflow is as follows:

- Prepare image to manually pick all relevant primary and tectonic structures.
- Identify structural features such as faults (orientation, throw, drag, etc.), fractures, unconformable surfaces, bedding surfaces, etc.
- Identify and classify image dips and interpret near-wellbore structure related to rock texture (i.e. slumped beds, bioturbated intervals, massive silts, etc.).
- Describe and interpret all fracture types (open, closed, partly open, mineralized, partly mineralized) and their relationship(s) to the structural interpretation.
- Analyze in-situ present day stress field using borehole breakout and drilling induced fractures.
- Interpret variation in lithology, texture, reservoir characteristics, and image lithofacies of sedimentary packages.
- Integrate the core facies with image log facies and create a facies scheme to be deployed to offset wells with image logs.
- Identify lateral variations observed from the horizontal wellbore.
- Post facies and rock structures on map for regional context.

CASE STUDY BACKGROUND

The Leonardian Bone Spring Formation of West Texas and South east New Mexico is composed by 4 units (Avalon, First, Second and Third Bone Spring and is representing one of the original targets of the unconventional resources development. The above mentioned Units are quite challenging to characterize both geologically and petrophysically, utilizing standard log sets.

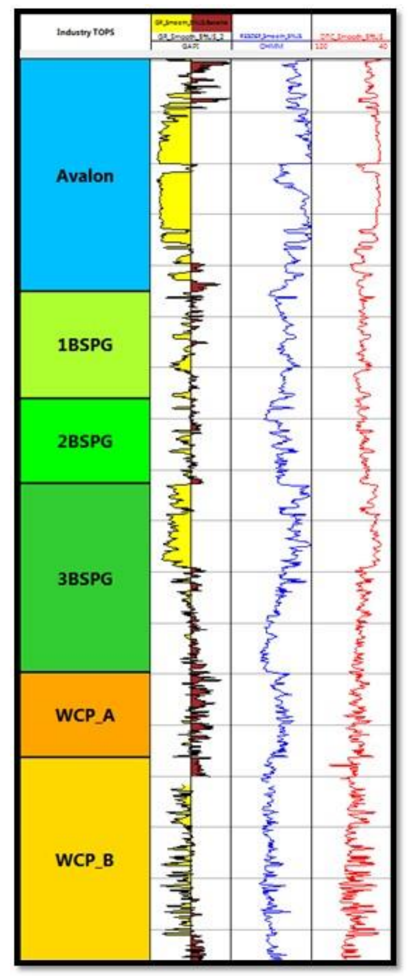
During Leonardian time, basinal depositional processes dominated area of Loving, Ward and Reeves counties (Texas), while to the east and West in Texas, as well as Northward in New Mexico, slope and shelfal deposits are predominant. Major submarine fan complexes are deposited by turbiditic and mass flows which push deep into the basin. Conventional hydrocarbon accumulations are found proximal to the slope in channel sands/overbank deposits, while distal silts are the unconventional reservoirs, with horizontal developments.

The Bone Spring in the study area is approximately 3000 ft thick, with a very heterogeneous succession of basinal turbiditic siltstones and shale intermixed with mass flow deposits and hemipelagic. The primary targets are historically the low resistivity turbiditic silts, while the interbedded shales may be rich or lean in organic matter. Carbonate-rich layers—including diagenetically cemented silts—are common. This type of vertical and lateral heterogeneity adds complexity which is better resolved with a conventional core, which is an expensive operation and add wellbore risks into the wells operations. Assessing changes in rock facies with utilization of advanced logging could be a cost-effective solution. The objective of this project was to better understand the Bone Spring silt plays and help quantifying the heterogeneity of the basinal Bone Spring Formation across the Delaware basin. The workflow involved the analysis of the whole core and the integration with the micro resistivity image logs from the vertical well and produce and validate the detailed facies identification; subsequently the detailed facies was propagated to other wells with no core acquisition. With this, we would be able to map facies variations and petrophysical parameters tied to facies across the basin.

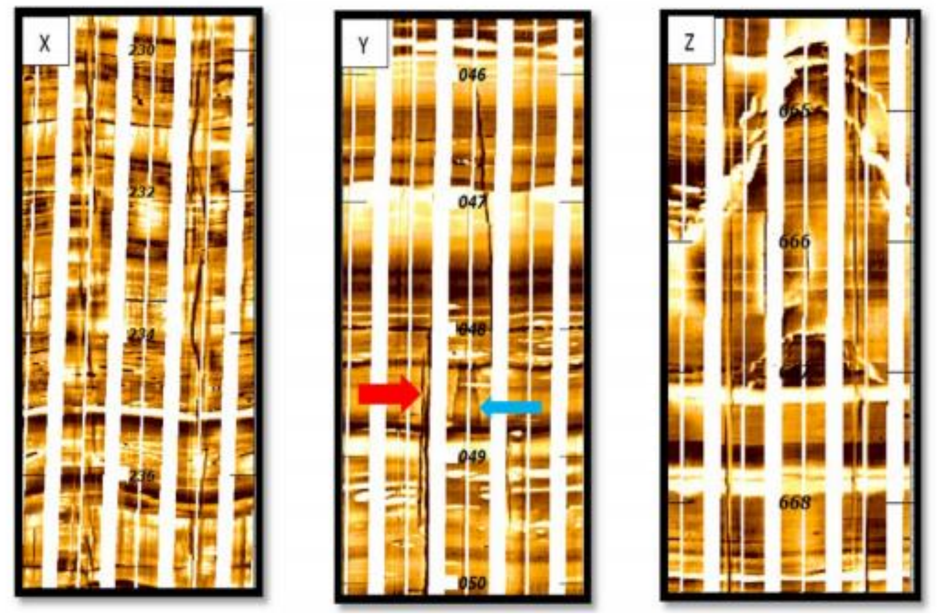
The dataset includes a vertical continuous whole core from the Second Bone Spring unit and well logs over the entire Bone Spring Formation .

The image data revealed details not discernable on the triple combo because of the different resolutions. The core was described in detail, as were fractures. Thin sections were used to aid the visual core description and check interpretation. Seven additional vertical image logs covering the Bone Spring Formation across the study area were used to push facies interpretation away from the conventionally cored well. Additionally, a single resistivity image in a lateral wellbore was acquired and is discussed further below.

REPRESENTATIVE LOG SECTION OF LEONARDIAN AND UPPER WOLFCAMPIAN IN THE DELAWARE BASIN



Representative Log section of the Leonardian and upper Wolfcampian in the Delaware Basin. Track 1 is stratigraphy; Track 2 is Gamma Ray; and Track 3 Resistivity; Track 4: Sonic.



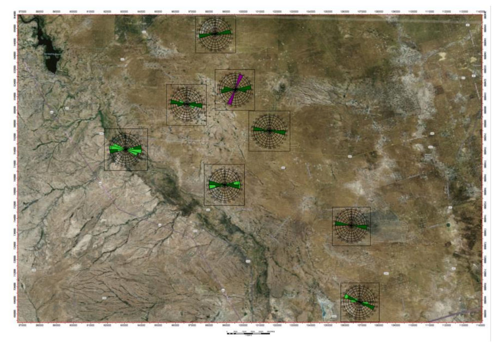
Bore hole resistivity image log with fracture examples. (X) An example of a typical drilling induced fracture, sub-vertical with 180 degrees spacing between the two traces. (Y) A conductive fracture trace (dark, vertically oriented in mid-image, red arrow) is shown together with a resistive trace located at 048.5 ft (blue arrow). Both these fractures are defined as lithology bound as they do not engage the borehole fully and clearly end at formation boundaries (visible on the snapshot for the resistive fracture only). (Z) Examples of resistive continuous fractures (light colored), fully crossing the borehole and showing a complete sinusoid on the image.

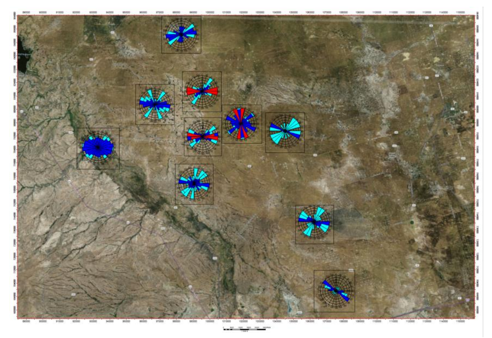
On left: Borehole image showing complex fracturing in a vertical study well. Depth increment is in feet.

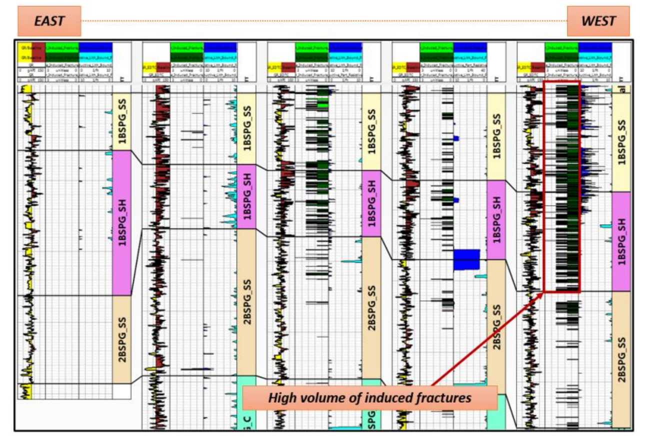
FRACTURES AND STRESS ANALYSIS

The nine borehole images were first interpreted to understand fracture occurrence, fracture attributes and stress direction. Fractures were differentiated between natural and stress-induced. Additionally, natural fractures were classified as resistive or conductive based on the electrical response on the image. Features have also been differentiated by looking at their morphology at the borehole wall, resulting in further definition of through-going and lithology bound fractures.

A detailed analysis of the stress induced features in the borehole image logs highlights the maximum horizontal stress orientation in the field as predominantly east-west. To the south, however, is a rotation of the maximum stress to the N70W-S70E direction. Stress orientation rotation was not observed vertically along any of the borehole images. Drilling induced fractures appear to concentrate in the First Bone Spring. A different drilling induced fractures density, though, is observed in the western boreholes. The processed images from these wells show a significant number of drilling induced fractures with abnormally large apertures when compared to the other image logs. We believe the occurrence of induced tensile fractures is closely related to varying pore pressure due to stratigraphic shallowing to the west. This regional trend is illustrated in the cross section below. Further geomechanical borehole modeling would be required for conclusive results, but these wells were drilled using similar mud weights leading to the belief that the frequency of tensile fractures is due to subsurface properties and not different drilling parameters. Wells far to the east, in contrast show fewer or no induced fractures. Natural fractures (both conductive and resistive) seem to be present sparsely through the full interval analyzed, but a clear increase in fracture density as we move towards the west in observed (see blue flag for conductive fractures, and cyan flag for resistive fractures in the third track of cross section below. An high fracture density in a given interval is not observed, however the strike trend of the natural fractures within the study area indicates a close match between the wells. Additionally, the analysis of the fractures reveals that they typically have high dip angle and thus are sub-vertical. This would explain the low occurrence in the pilot vertical wells. However an increased fractures density is observed in horizontal wells. A conjugated fracture system seems to exist: the primary set has a strike orientation of N 40 deg E to S 40 deg W direction of the secondary set is the N 80 deg W to S 80 deg E direction. A similar orientation between conductive and resistive fractures exist.



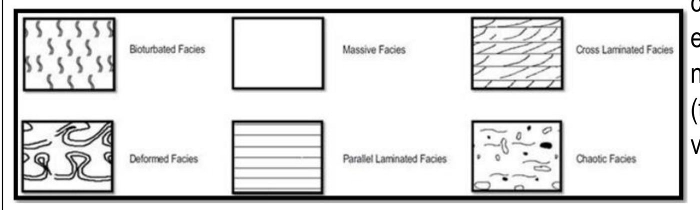




FACIES ANALYSIS FROM BOREHOLE IMAGES

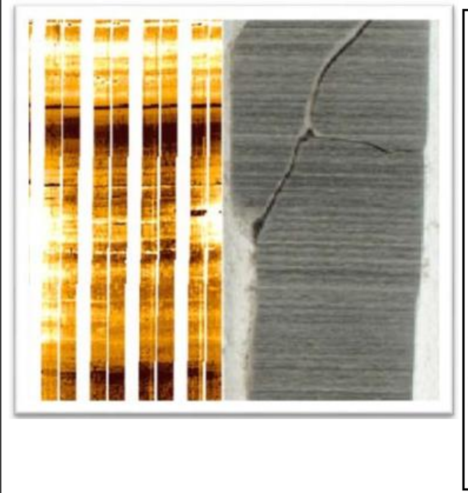
The second step in the borehole image analysis was understanding the facies variability observable in the images. This analysis benefited from the acquisition of a conventional core in the validation well and the tie between the core description and the image log interpretation. Several iterations in the facies catalog compilation were made to ensure that the core description was accurately reflected in the image log interpretations. Once the calibration with core was completed, the facies catalog was then used in offset image logs away from the cored well. The facies catalogue build began with the identification of first order lithofacies (Figure below). These are defined as lithology-based facies that were first identified on the cored well based on XRD mineralogy, thin section interpretation, and core description. This was then calibrated to an acquired elemental spectroscopy log. The acquisition of elemental spectroscopy logs in the other project wells allowed the first order lithofacies to be defined for each well in the study.

After defining our first order lithofacies, second order structures were described in the images. We defined second order structures as sedimentary features that are visible through both image acquisition and in the acquired conventional core. These are summarized in the below figure. The process of calibrating and comparing core to a borehole image log must take into consideration the difference in the resolution of the electrical measurement compared to core. Upscaling of the core lithofacies and features was necessary to allow the extrapolation of the lithofacies to image logs. Detailed core depth shifting (to the acquired wireline logs) was made to ensure accurate representation of core based observations.



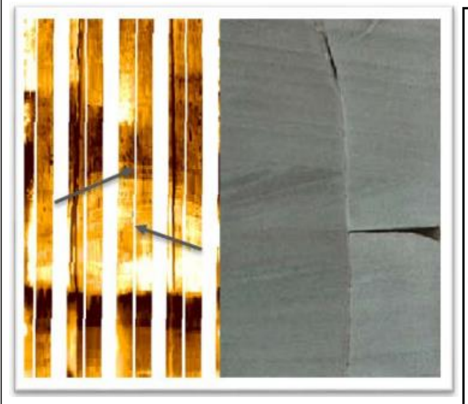
The rapidly changing facies seen in these wells makes it apparent that the depositional environment was dynamic over this time period. The major packages within the Bone Spring all show high vertical heterogeneity: the image logs acquired, and the core used to calibrate the facies catalogue, rarely show facies greater than 30 inches in thickness. The results of each well were analyzed and compared to see if any regional trend in the variation of facies could be highlighted. The facies distribution (within a well) was plotted in map view to highlight the presence or relative change of the individual facies around the field, potentially indicating variations in the depositional style. The distribution of lithofacies and second order structures is shown regionally on the right side picture. At field scale, it appears that the amount of mudstone increases from west to east. Also, we observed an increase in bioturbation as we move from north to south. The laminated facies appear to be constantly distributed in the field, while the chaotic facies are more common in the north part of the basin.

CORE TO IMAGE CALIBRATION AND COMPARISON : EXAMPLES OF DIFFERENT FACIES

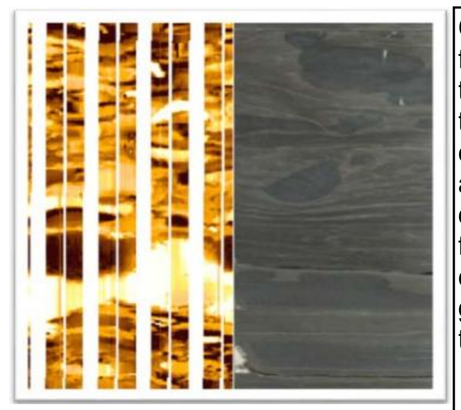


On left: parallel laminated Facies typically seen throughout the Bone Spring. They are characterized by planar sub-parallel laminations continuous around the borehole. The alternating laminae seen on the core photo are composed of lithologies with different electrical properties that generate the conductive/resistive contrasts seen in the borehole image.

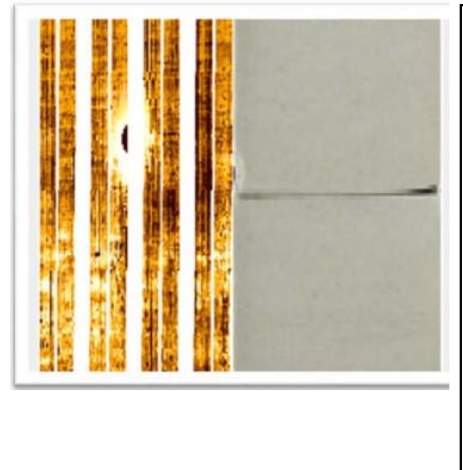
On left: Facies interpreted at the beginning of the project as bioturbated facies. This typical mottled appearance on the image has always been associated with bioturbation. Additional studies on the core highlighted instead these facies as not bioturbated by rich in Hybrid Event Beds. This additional information has been used in the on going project to better characterize these facies.



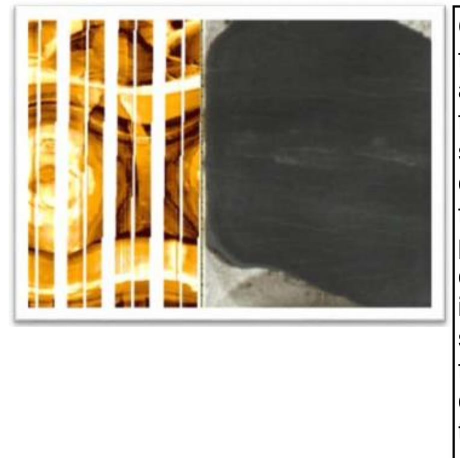
On left: short interval of cross laminations. These cross laminations can also be recognized on the image log; the black arrows indicate the crossing laminae. Typically, the cross laminations can be identified on the image log using dip picking in coarser-grained deposits (where deformed and slumped facies are not present).



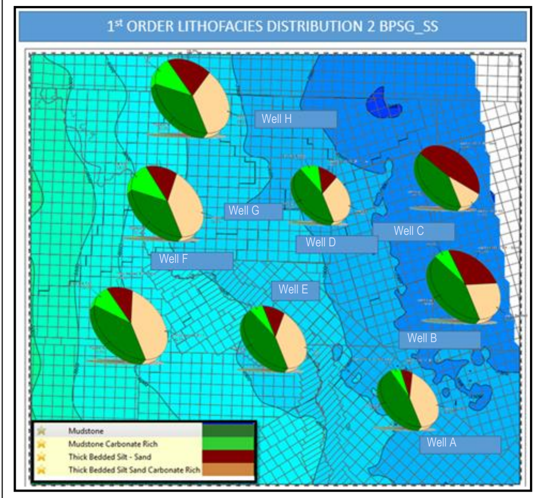
On left: example of a chaotic facies. In this type of deposition, a planar surface where the sediments were deposited cannot be distinguished and the clasts are randomly organized. This suggests different sources and/or different provenance. At times, grading can be observed in this facies.

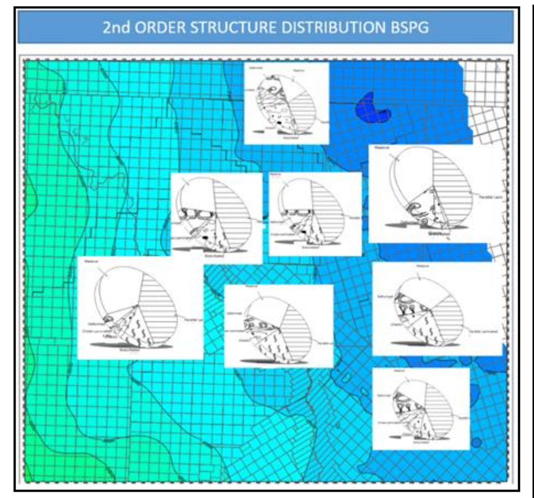


On left: example of a massive facies recognized in the core as homogeneous and the corresponding borehole image shows the absence of recognizable features. The dark round spot in the middle of the image represents a side wall core taken before the image log was acquired, providing additional value and context to the sample.



On left: example of a deformed facies. This is characterized by the presence of features associated with soft sediment deformation. On core these are described as flame structures, dish and pillar, load cast, and slump-contorted beddings. On the image, we can clearly observe micro fold hinges, flame structures, and load casts. The combination of these microstructures suggests rapid deposition.





On left: variation of first order lithofacies and second order structures over project area. Contours are TVDSS depth to top of bone Spring, increasing to the east. North is to the top of the map. Each square block is approximately 1 mile across.

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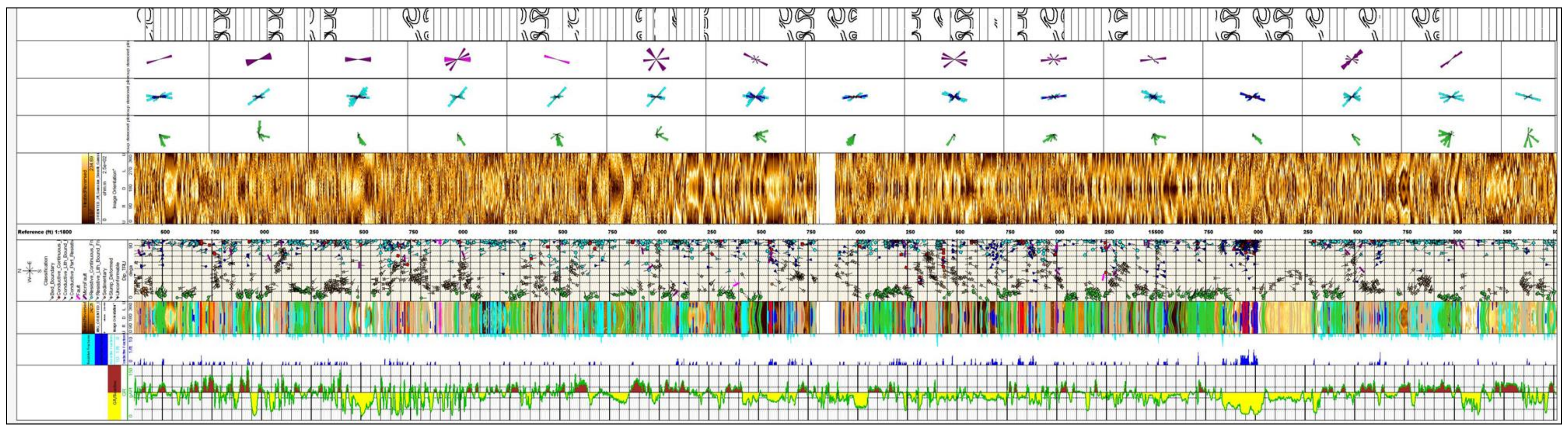
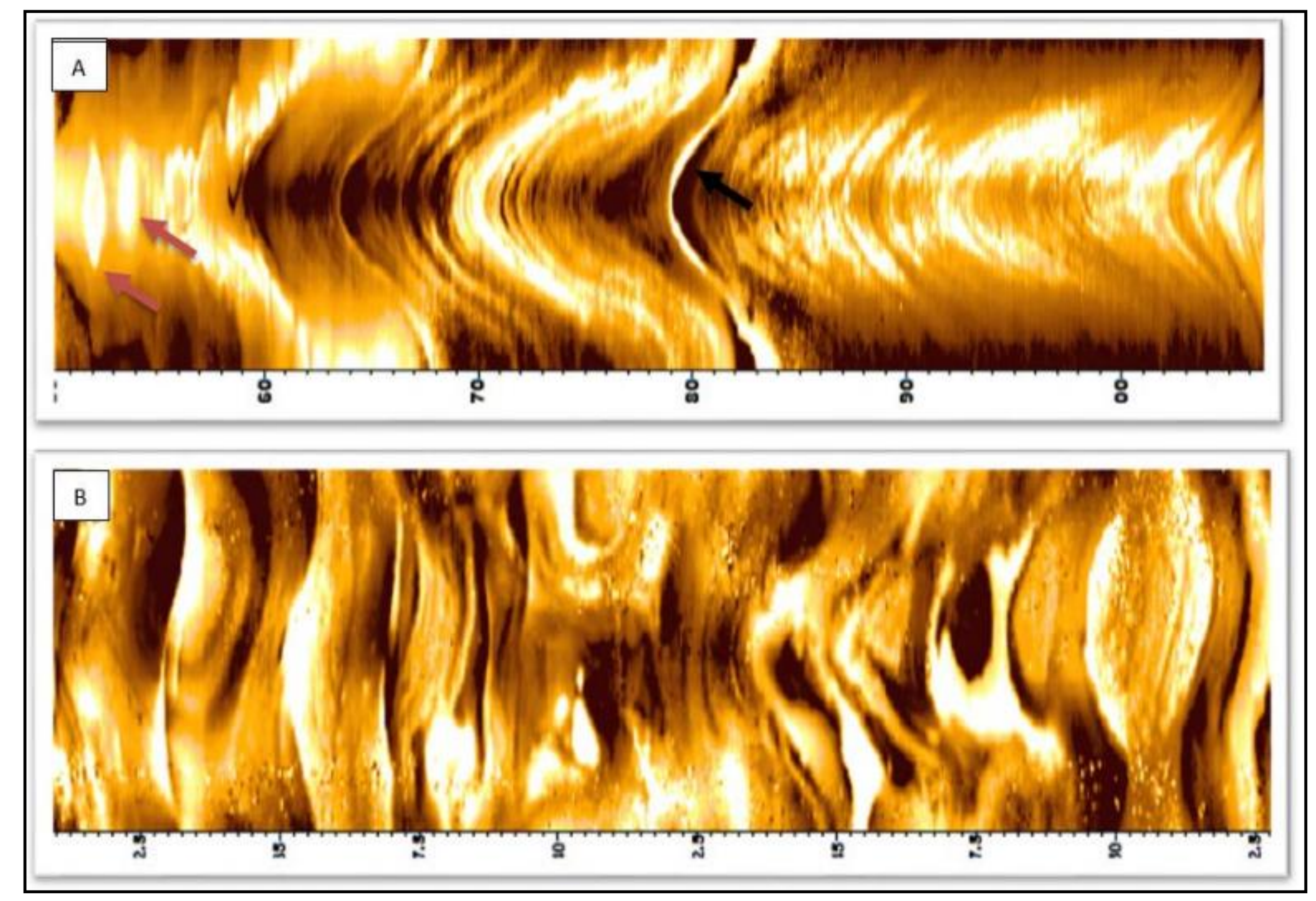
FACIES VARIABILITY IN THE LATERAL DIRECTION

An image was also acquired (via LWD) through a horizontal wellbore in the Bone Spring. The acquisition of these data was key in understanding how fracture distribution and facies vary laterally within the wellbore, potentially highlighting the importance of geosteering and keeping the well in the intended target. The same fracture interpretation performed on the vertical images was performed in this lateral wellbore. Fracture interpretation from lateral image logs is typically more difficult than with vertical logs; caution is advised as mixed stress orientations will add complexity to understanding fracture sets. Fracture density was significant throughout the lateral wellbore. It was rare to see even a 10-foot lateral zone without at least one conductive or resistive fracture; however, fracture density over shorter intervals in the wellbore was highly variable. This can potentially be used to group zones for an engineered completion strategy. It is unsurprising that the lateral well intersected more fractures than the vertical wells since the fractures are oriented near vertical. This suggests the existence of a significant fracture density throughout the project area that is not clearly demonstrable in vertical wellbores. Similar observations were made in other shale plays with similar datasets. A challenge of interpreting facies from a lateral image in near-horizontal beds is that the image is 'stretched' in comparison to a vertical image (Figure 17). A simple solution used to overcome this was to use a compressed scale overview, which does a better job highlighting the major laminated and massive facies. The slumps and deformation are instead more clearly seen at enlarged scales. The lateral image log can also be used to determine the facies within which the well is predominantly landed and the percentage of well that is in the target reservoir. Fractures and facies change may alter the completion strategy; for example, a massive, fractured facies could be treated differently than a chaotic, slumped deposit.

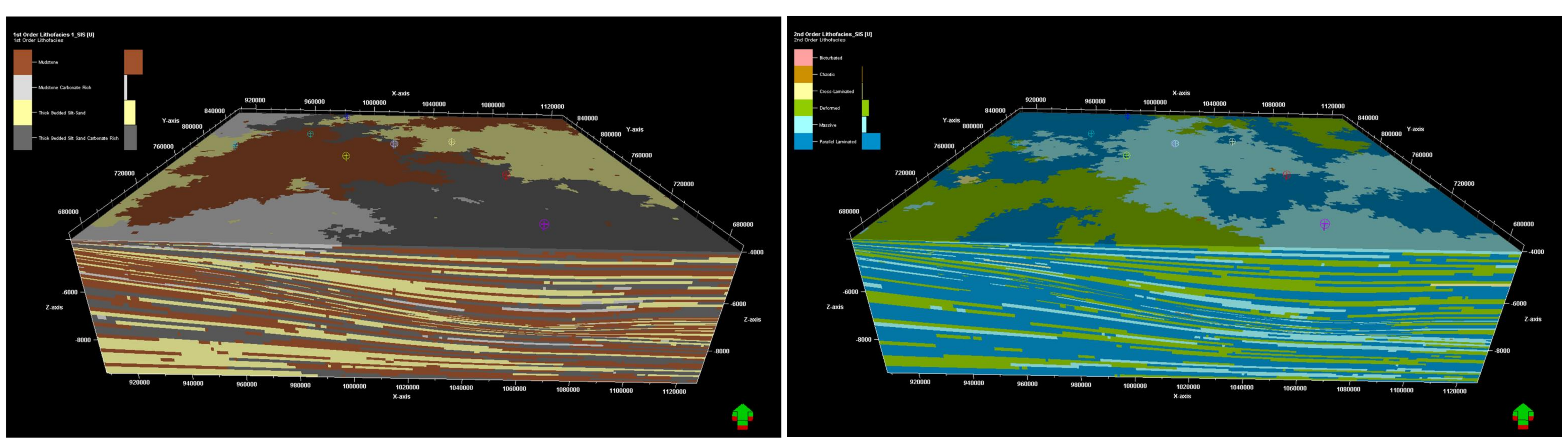


Above: Borehole images acquired in a lateral well to help with heterogeneity and facies variation.



Above: (A) Borehole image interpretation in the lateral studied well, showing similar facies as observed in the vertical well. This figure illustrates possible cross lamination with some reactivation surfaces (highlighted in black arrow). The red arrows indicate possible nodules or cemented features which were observed in the vertical wellbores. (B) Chaotic and slumped facies, rip-up mud clasts, load cast, and flame structures which were calibrated from the vertical wellbores. This may provide completion complexity.

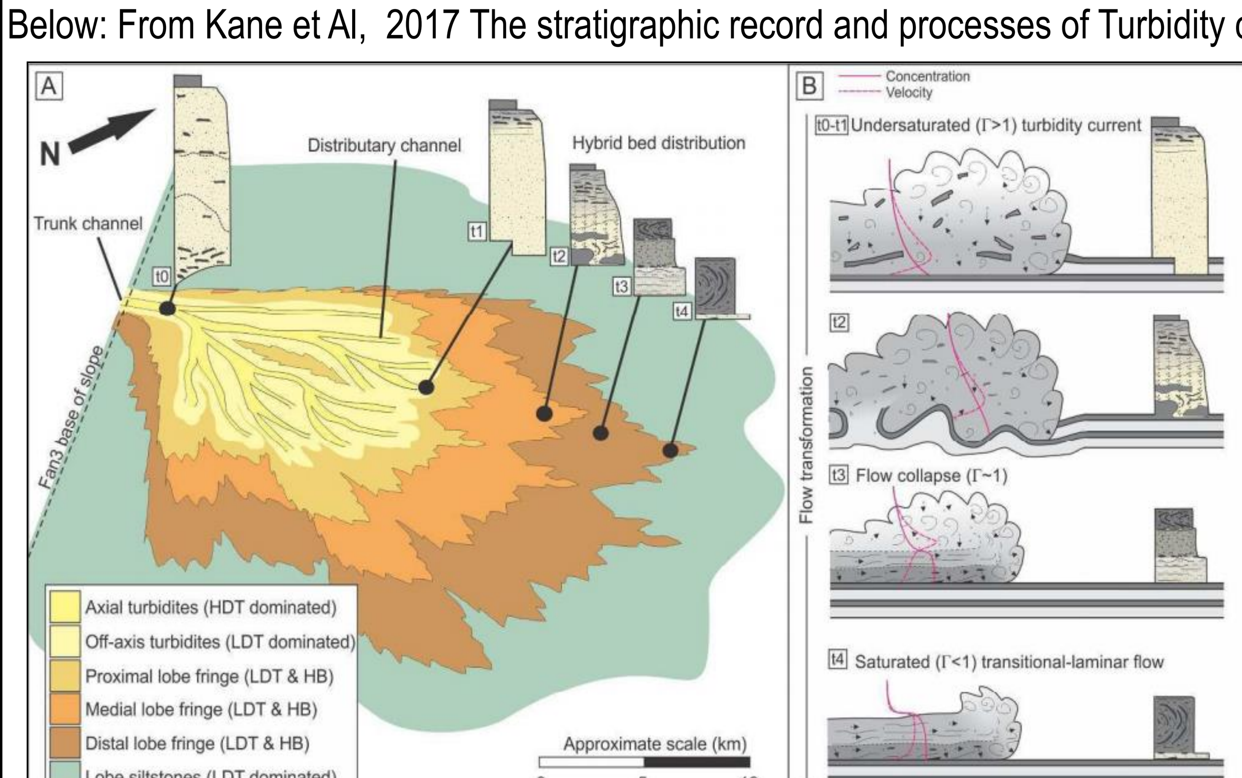
3D VISUALIZATION OF FACIES DISTRIBUTION IN THE 2ND BONE SPRING



Above: The 1st order lithofacies (left) and the 2nd order structures (right) were utilized to create a 3D facies model. Different approaches could be used to model such properties. In the given conditions it appeared that the sequential indicator simulation was providing better and more realistic results compared to the truncated gaussian simulation.

Sequential Indicator Simulation is a stochastic modeling technique dependent on the upscaled well log data, variogram, random seed, and frequency distribution of the upscaled data points. It is best used when the facies bodies are uncertain. TGS is a stochastic modeling technique dependent on upscaled well log data, variogram, random seed, and frequency distribution of upscaled data. It is best used in systems where there is a natural transition through a sequence of facies (i.e. carbonate environments and progradational fluvial environments).

Below: From Kane et Al, 2017 The stratigraphic record and processes of Turbidity current transformation across deep-marine lobes. Sedimentology, 64 (5).



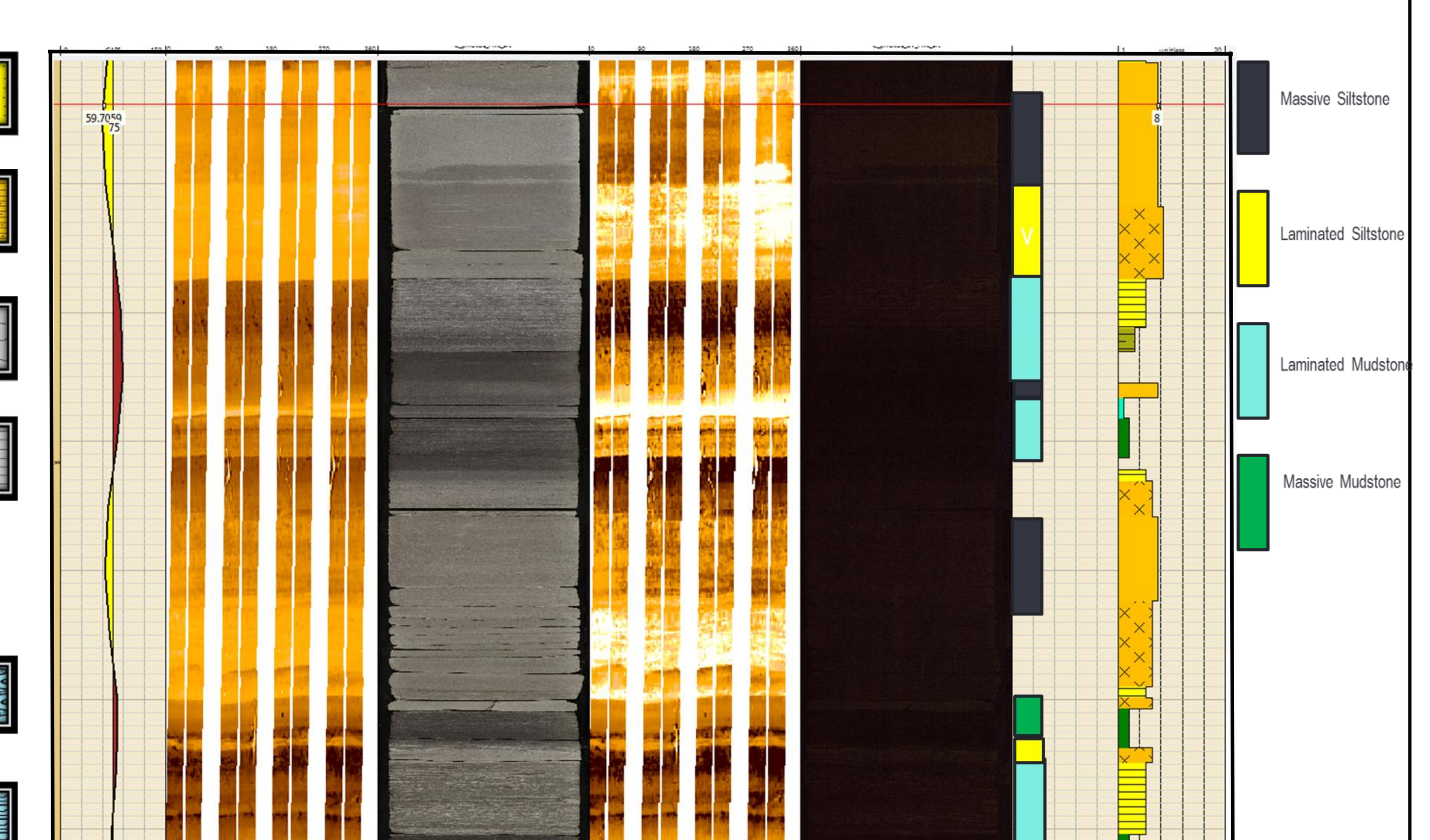
The cartoon on the side shows the conceptual model utilized in the description of the depositional environment for the facies described during this project. The occurrence of hybrid events beds has come to light in recent additional core studies and the alternans between those and low-density turbidite flow characterize the deposition in a deep marine fan environment. Distinguishing high density turbidites, from low density turbidites and hybrid event beds, allow the precise location of the deposit in the fringe (see picture on the left).

CONCLUSIONS AND WAY FORWARD

Effort is still on going in better understanding facies distribution in the 2nd Bone Spring and in the deeper Wolfcamp. These preliminary results have given new insight in the highly heterogeneous Bone Spring formation allowing mapping of the distribution of the facies aiming in a clearer regional understanding of the play. Even though not the main aspect of the project, understanding the distribution of fractures and the identification of the predominant fractures set can help in optimizing completion strategy, along with placement of horizontal wells relative to the regional stress direction. Tying the information related to facies to productivity allows a clearer identification of thin beds which are not highlighted by a triple combo solution, providing a more quantitative net and non-net thickness.

The on going studies performed on the acquired conventional cores lead to the revision of the facies model utilized so far and the description of new facies recognizable on the images. The newly adopted facies, and the on going project is focus on the Wolfcamp formation and adopt terminology and model described by Kane et al, and represented on the left side conceptual model picture.

Massive Siltstone
Laminated Siltstone
Massive Mudstone
Laminated Mudstone
Pseudo-Nodular Mudstone
Laminated Carbonate
Massive Carbonate



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Second Bone Spring Borehole Image Derived Depositional Facies Characterization: Case Study From the Delaware Basin, West Texas

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PETROPHYSICAL INTEGRATION:

Another key step in this process was tying petrophysical properties to image facies. Throughout the project, we found multiple ways for the image log interpretation to supplement other petrophysical logs, core analysis interpretation, and pay evaluation. In addition, by tying petrophysical properties to both the first order lithofacies
and the second order structures, we are able to better quantify the heterogeneity and productivity in a given area of the basin.

Figure on the right, shows an example type-log. There are multiple takeaways from this small section of the well through the integration of the image logs and other available petrophysical data.

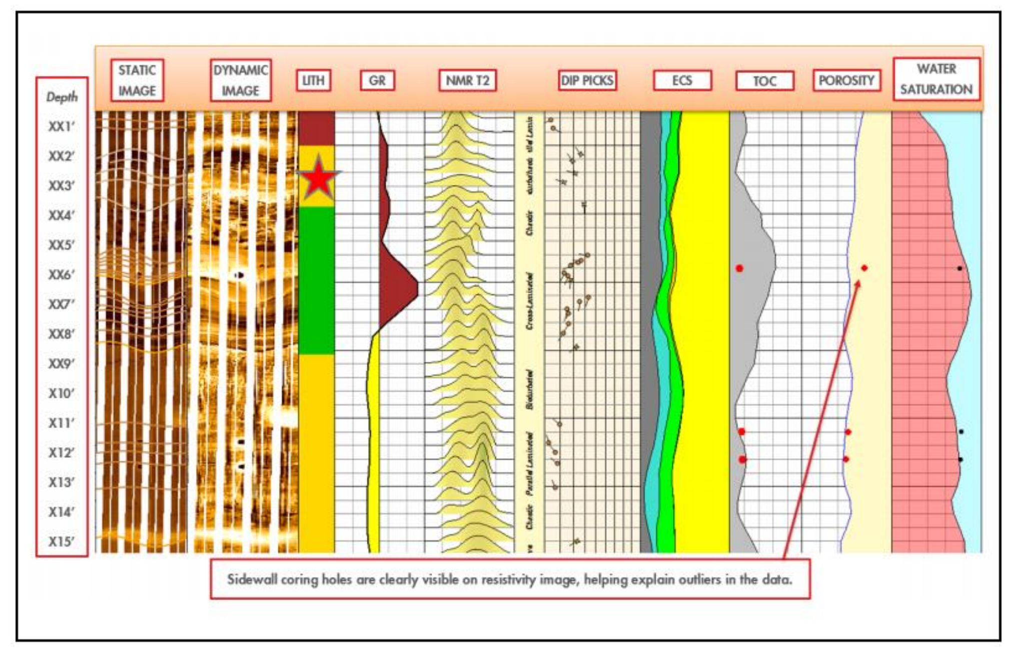
First, in this example, the sidewall core samples were taken prior to the image logging run. This allows the operator to identify the exact facies the sidewall core plug was taken from. This has been extremely useful in calibrating our petrophysical model to the core data, as we are able to identify lithofacies and structures that are significantly below the resolution of other logs. For example, at approximately XX6 feet in the type log, the sidewall coring hole can be seen. The TOC and porosity core data, however, does not match the modeled porosity and TOC from spectroscopy. Through the high resolution of the image log, we can see that the plug was taken from a small resistive (likely cemented) layer within the larger mudstone package. This package is much thinner (~1 to 2 inches) than the log resolution of the other tools, leading to the mismatch in predicted porosity and TOC from spectroscopy.

This speaks further to the heterogeneity of the play and the need for high-resolution evaluation. The image log allows the operator to identify any potential pay and reservoir rock that may be below typical log resolution.

Conversely, the operator can also identify hard streaks and non-net intervals that may be missed in their evaluation.

An example of this is also shown in Figure on the side. The star indicates a thin zone – roughly 1 to 1.5 feet – that is described from the image as siltstone. However, as this zone is just barely at log resolution, the other logs do not fully respond to the lithology change. For example, the T2 distribution in the NMR shows a subtle shift to slower times, and the gamma ray response comes down relative to the TOC-rich surrounding mudstone. An operator would regularly miss this kind of thin-bed pay with even advanced logging tools, but it becomes more obvious when integrated with the resistivity image.

As mentioned earlier, another key use of the image log interpretation was tying the second order structures to critical petrophysical properties. This again allows us to understand what is driving the porosity, saturation, and TOC content – key parameters in determining productivity within the Bone Spring. Figure 19 shows an example of this work – again taken from the figure on the right log well.



ABOVE: Example of logview demonstrating potential missed pay and identification of coring locations.

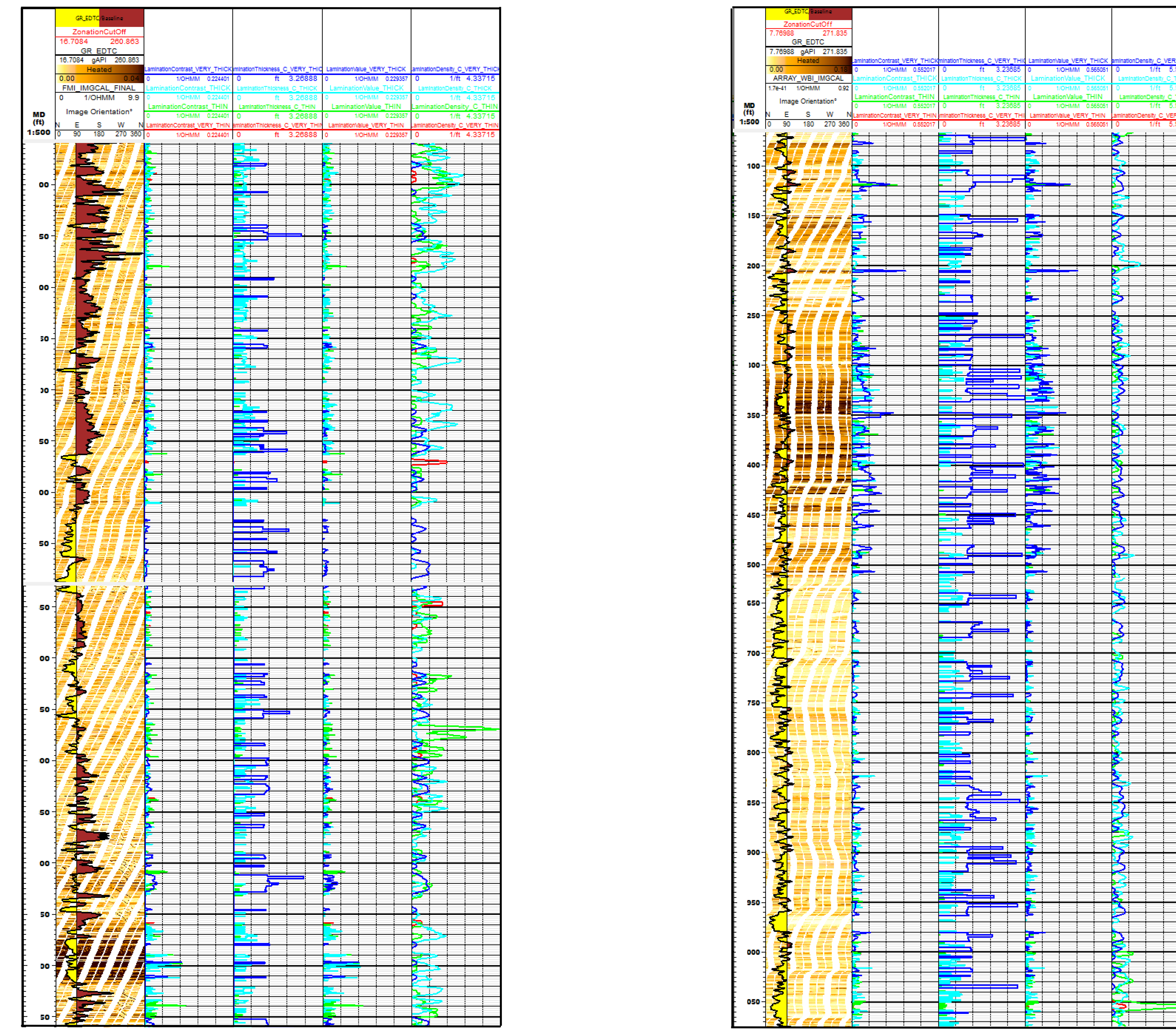
Structures	% of Focus Interval	Avg. Core Porosity	Avg. Core Water Saturation	Avg. Core TOC
Deformed	20%	green	yellow	green
Parallel Laminated	40%	yellow	yellow	yellow
Chaotic	10%	red	green	yellow
Cross-Laminated	10%	yellow	green	yellow
Bioturbated	5%	yellow	red	red
Massive	15%	green	green	yellow

ABOVE: Example of log view demonstrating potential missed pay and identification of coring locations.

This analysis makes it clear that reservoir properties can be mapped back to secondary structures; a process normally limited to whole core acquisition and description. We see that the massive beds tend to show the highest porosity and lowest water saturations, suggesting the massive beds would act as the best reservoir zone.

As expected, the bioturbated zones are very poor in quality and lead to degradation in reservoir quality – the TOC is extremely low and the water saturation increases significantly. Fortunately, in this example, the bioturbated beds make up a small fraction (~5%) of the total interval; however, understanding the distribution of the bioturbated beds can help an
operator land wells in the most productive zones.

LAMINATIONS ANALYSIS:



ABOVE: Examples of lamination analysis output in two samples wells analyzed in the project. Laminations are characterized from the borehole images for a better understanding of the stratigraphic environment and provides quantitative information that can be used as input also for well completion or reservoir characterization and in reservoir software. These laminations quantification can be utilized at a smaller scale to understend the cyclicity in the deposition.

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