[PS]A New Tool for High-Resolution Sedimentological Imaging of Deepwater Clastic Reservoirs*

R. Laronga[1], G. R. Kear[1], A. Kumar[1], P. Vessereau[1], R. Bloemenkamp[1], and T. Zhang[1]

[1]Schlumberger Limited, London, United Kingdom (laronga1@slb.com)

Abstract

We introduce for the first time in this paper a new high-definition full-coverage wireline formation-imaging tool and illustrate its direct relevance to the identification of depositional environment in deepwater wells drilled with nonconductive synthetic-base drilling fluids (NCM).

Literature documents the use of borehole images to interpret depositional environment in deepwater clastics, with the best examples coming from wells drilled with conductive water-base fluid (WBM), where high-definition, full-coverage images are easily acquired. Channel, proximal or distal levee, crevasse splay, proximal or distal lobe, slope, and basin floor are distinct environments that have been readily identified from such images based on an association of detailed sedimentological observations.

Today NCM fluids dominate deepwater, and even the most successful NCM-adapted formation imager has had interpretive limitations.

We field-tested a new high-definition full-coverage formation-imaging tool for NCM fluids, based on a new measurement principle. A recent version provides over 90% coverage via 192 microelectrodes (3mm by 5mm), resulting in images like those acquired in WBM. Further, the chosen physics result in a more natural response to formation texture.

Based on a review of images from the field test, it is clear that nearly every area of borehole image interpretation is improved in NCM compared to previous technology. Even simple determination of structural dip benefits greatly because the new tool is significantly more sensitive to bedding. Tabular nature of sandstones and lamination in shale that were previously invisible are revealed. Resolution allows to evaluate each contact for planarity, and lapping or crosscutting relationships are more likely to be spotted. Ripples are observed in individual cm-scale sands within levee deposits. Slumps from a few cm to several meters are clear where previously this was an expert's judgment call. Conglomeritic formations such as traction deposits or debris flows that were previously unrecognizable are now 'photographically' imaged.

Deepwater geologists interpreting these images now have a full range of core-like observations upon which to base their conclusions. The depositional environment and depositional axes so derived from these images give operators a valuable input to realistically constrain the distribution of reservoir facies in 3D models, aiding pragmatic field development or enhanced oil recovery plans.

A New Tool for High-Resolution Sedimentological Imaging of Deepwater Clastic Reservoirs

R. Laronga, G.R. Kear, A. Kumar, P. Vessereau, R. Bloemenkamp, and T. Zhang; Schlumberger

Abstract

We introduce for the first time in this paper a new high-definition full-coverage wireline formation imaging tool and illustrate its direct relevance to the identification of depositional environment in deepwater wells drilled with nonconductive synthetic-base drilling fluids (NCM).

Literature documents the use of borehole images to interpret depositional environment in deepwater clastics, with the best examples coming from wells drilled with conductive water-base fluid (WBM), where high-definition, full-coverage images are easily acquired. Channel, proximal or distal levee, crevasse splay, proximal or distal lobe, slope, and basin floor are distinct environments that have been readily identified from such images based on an association of detailed sedimentological observations.

Today NCM fluids dominate deepwater, and even the most successful NCM-adapted formation imager has had interpretive limitations.

We field-tested a new high-definition full-coverage formation imaging tool for NCM fluids, based on a new measurement principle. A recent version provides over 90% coverage via 192 microelectrodes (3mm by 5mm), resulting in images like those acquired in WBM. Further, the chosen physics result in a more natural response to formation texture.

Based on a review of images from the field test, it is clear that nearly every area of borehole image interpretation is improved in NCM compared to previous technology. Even simple determination of structural dip benefits greatly because the new tool is significantly more sensitive to bedding. Tabular nature of sandstones and lamination in shale that were previously invisible are revealed. Resolution allows to evaluate each contact for planarity, and lapping or crosscutting relationships are more likely to be spotted. Ripples are observed in individual cm-scale sands within levee deposits. Slumps from a few cm to several meters are clear where previously this was an expert's judgment call. Conglomeritic formations such as traction deposits or debris flows that were previously unrecognizable are now 'photographically' imaged.

Deepwater geologists interpreting these images now have a full range of core-like observations upon which to base their conclusions. The depositional environment and depositional axes so-derived from these images give operators a valuable input to realistically constrain the istribution of reservoir facies in 3D models, aiding pragmatic field development or enhanced oil recovery plans.

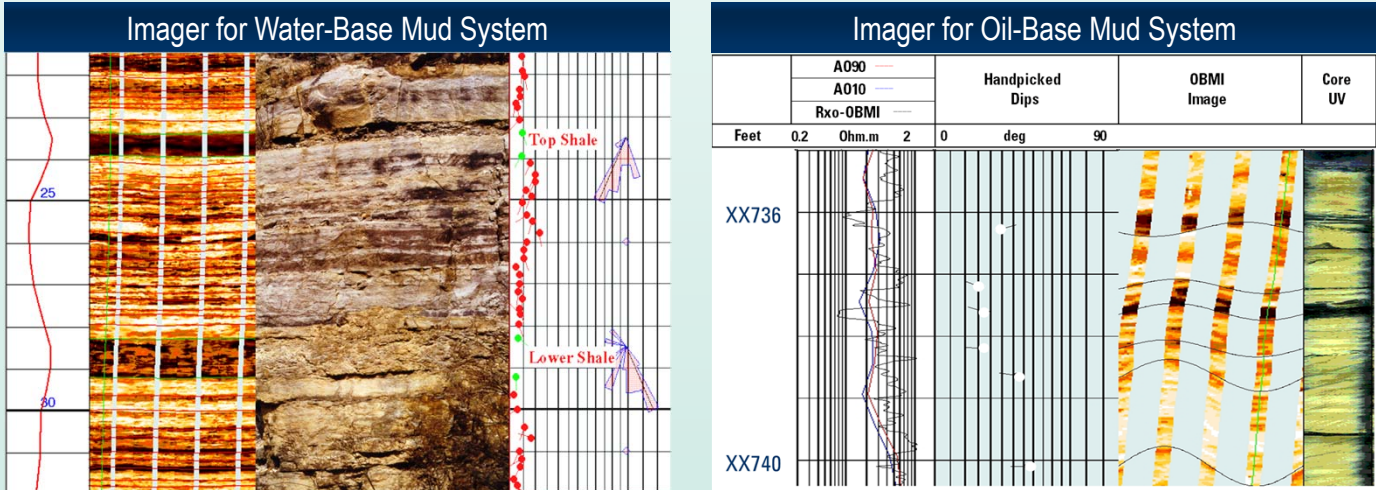## What's a microelectrical image?

Fig 1. At left: standard WBM microelectrical image acquired in a research well 15m behind the photographed outcrop. Sedimentary features as small as 5mm are reproduced in remarkable detail (after Hansen, 2000). At right: standard NCM-adapted microelectrical image compared to UV lighted core photo in a deepwater sandstone (after Cheung, 2001). There is an obvious difference in the level of detail and interpretability between the two images.

Making high-resolution 'photorealistic' images of the formations penetrated by a wellbore is not a simple matter of lowering a camera into the well, since the majority of drilling fluids are opaque. While various solutions have been tried, none have been so successful as microelectrical imaging, first introduced by Ekstrom in 1986. In this technique, a wireline logging tool features multiple arms that maintain a set of measurement pads in close proximity to the borehole wall. An array of small measuring electrodes emit a measuring current into the formation that is proportional to the formation conductivity in front of each electrode. Data are mapped into a false-color image honoring the tool and borehole geometry.

There are a few very important characteristics of this technique. Formation resistivity is a parameter that may vary by up to seven orders of magnitude, providing excellent dynamic range that may even reveal features that cannot be seen by the human eye. The spatial resolution of such images is determined by the electrode size (5 – 20 mm) and sampling rates. Most often the pads do not cover 100% of the circumference of the borehole, resulting in gaps in the processed image. This attribute is commonly referred to as coverage.

Historical application to deepwater clastics

During the 1990's some of the early deepwater wells of the Gulf of Mexico were drilled with water-base mud and high-resolution image logs equivalent to that of figure 1 acquired. The applications of such images were well-summarized by Hansen (2000) and can be short listed as:

1. Determination of structure, especially for deep subsalt wells.

2. Identification and quantification of thin-bedded low-resistivity pay.

3. Classification of facies, based either on depositional or petrophysical characteristics.

4. Identification of depositional environment.

5. Constraint of the reservoir model.

Applications 3, 4, and 5 above demand the best of both the imaging tool and the interpreter to be reasonably achieved. In particular, images of the highest-possible resolution and circumferential coverage are required. The latter becomes particularly important as large boreholes (12.25 in and larger) have become common in deepwater wells.

The assemblage of image details that can be useful to determine the depositional environment are not discussed here, but are well-documented by Hansen (2000), and Davis (2010) among others. The figures below reproduced from Hansen's paper demonstrate how various elements of deepwater slope systems may present when top-quality, high-resolution images are acquired in a WBM drilling environment.
These examples are noteworthy because the subject of this paper is an imager that aims to produce the same level of photorealism in an oil-base NCM environment.
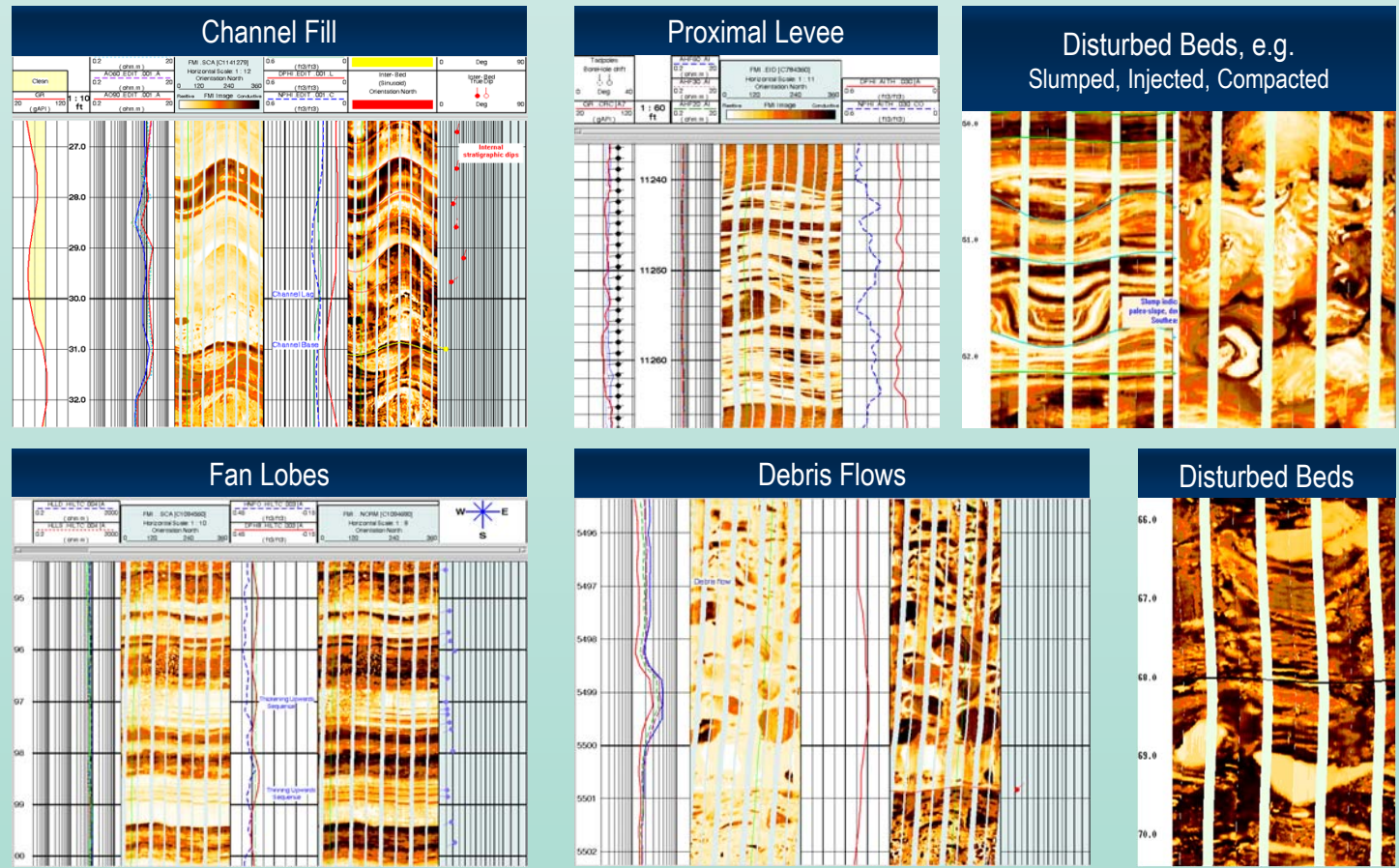

Fig. 2. Image examples of deepwater facies acquired in WBM drilling fluid (modified after Hansen, 2000).

Why is oil-base mud (NCM) a challenge?

By the late nineties, virtually 100% of deepwater wells were drilled with oil- or synthetic-base NCM. The non-electrically-conductive nature of these drilling fluids rendered the conventional high-resolution imager useless, and images such as those contained in figure 2 could no longer be acquired in deepwater reservoirs.

A microresistivity imager with specialized physics adapted for the NCM environment was first introduced by Cheung in 2001 and represented a major industry breakthrough. Yet the physics challenges and complex electronics imposed a number of limitations, most notably:

- Larger sensor aperture (10 mm) and resulting lower resolution.
- Fewer sensors (20) and resulting lower coverage.
- Reduced sensitivity to high-apparent-dipping (wellbore parallel) features.
- Shoulder and horn effects at strongly contrasting boundaries.
- Non-photorealistic response to heterogeneous formations.
- High sensitivity to clay dehydration cracks, sometimes overprinting the image.

The coverage issue was partially addressed by running two tools in a string with an angular offset. The other issues have never been satisfactorily addressed. Yet until now, this imaging tool remains a standard part of the formation evaluation program for most deepwater wells, as there has not been an alternative.

Since the NCM-adapted imager and the standard imager for WBM are in principle never run in the same hole section, it is difficult to make comparison between the two except on specifications (below) and gut feeling. Bourke (2011) came up with a novel way by comparing both imagers to core seperately in 11 wells each, and found that approximately six times the number of surfaces could be interpreted from WBM images. This does not bode well for image sedimentologists, and it is clear that the industry needs higher-spec images in NCM.

More recently, Laronga (2012) discussed running an improved tool for WBM in wells drilled with OBM, but noted not to expect success in formations having relatively low resistivity—normally the case in deepwater. For this reason the authors have been working quietly for many years on a new imaging tool to achieve robust, high-specification images in any environment drilled with NCM. It's ambitious specifications are given in table 1 below and compare favorably to the industry standard WBM imager:

TABLE 1	Std NCM Imager	WBM Imager		New Hi-Spec NCM
Number of sensors	20 / 40*	192		192
Sensor aperture	10 mm (elongate)	5 mm (circular)		5 mm h x 3 mm w
Vertical sample rate	5 mm	2.5 mm		2.5mm
Coverage in 8-in hole	32% / 64%*	80%		97%

*in dual configuration and subject to regular tool movement

We have been testing prototypes of this tool for the last two years in over twenty wells. In this paper we present results of three wells, with an emphasis on the sedimentary and structural details that can be successfully resolved by the new tool, and on the comparison versus the legacy technology for NCM.
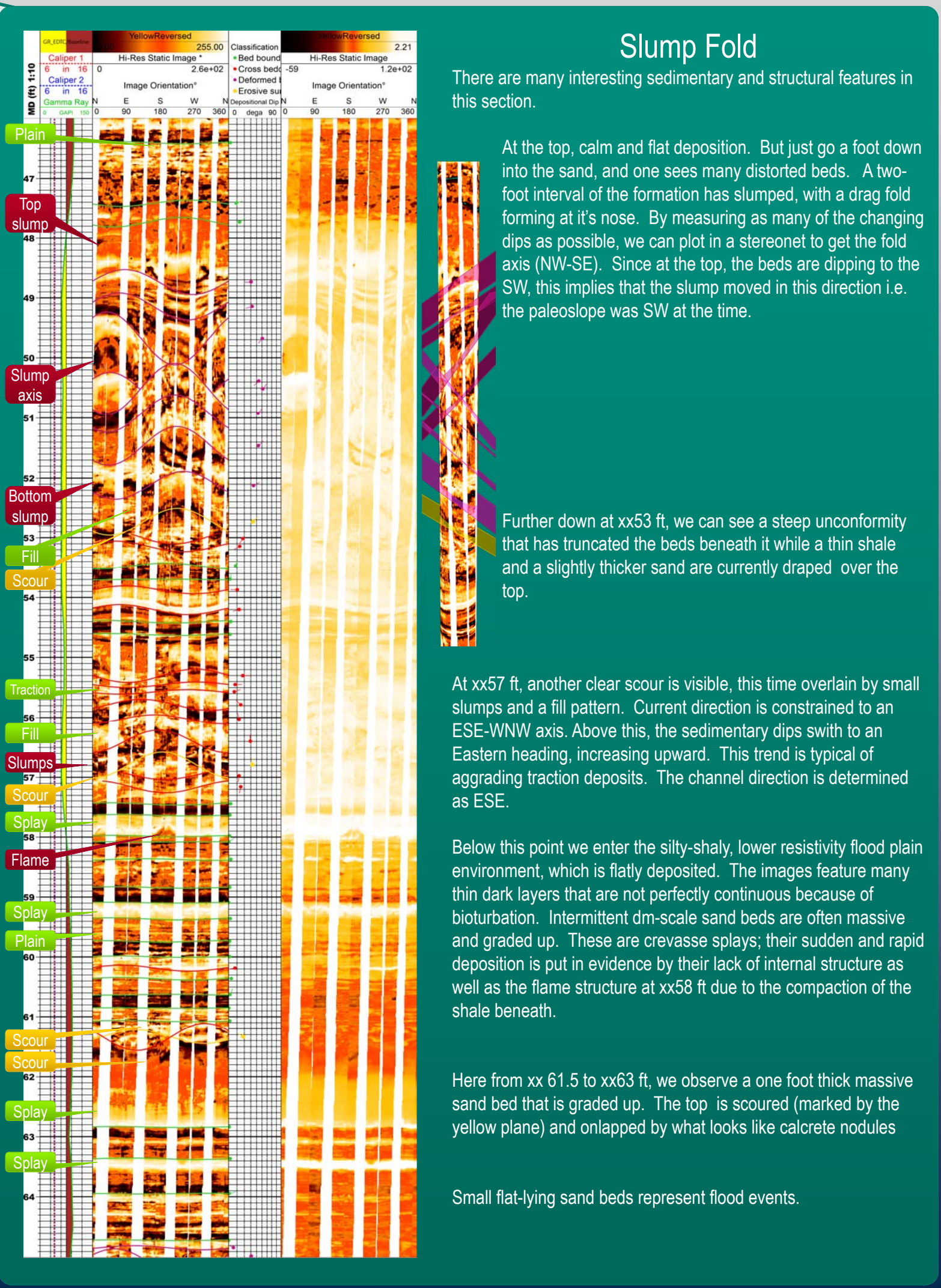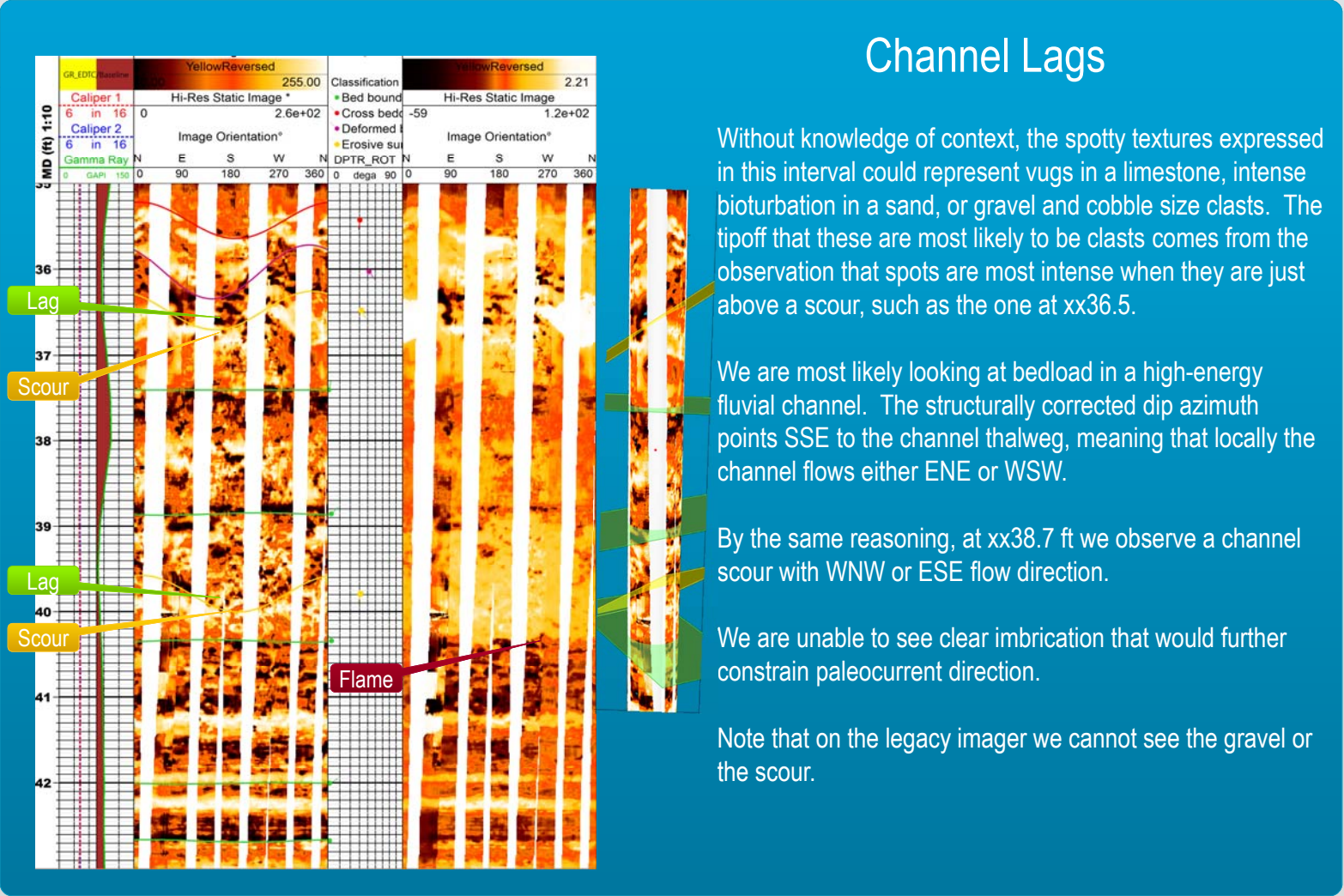
Experimental Prototype Field Test in OBM: Fluviodeltaic Environment, 8.5 in Borehole

Comparison to industry standard OBM-adapted imager
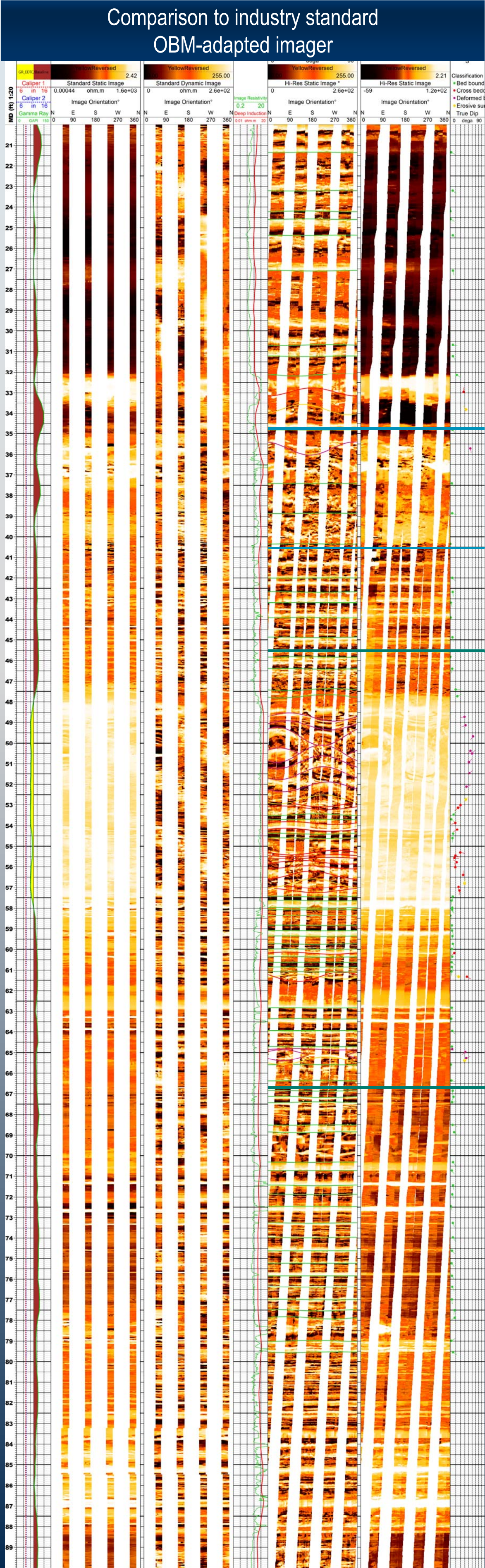
Experimental prototype wireline tools, even those designed specifically for deepwater applications, are most commonly tested first in the land operating environment to mitigate risk before being attempted on a costly deepwater operation. This well was drilled targeting sands in a fluviodeltaic environment which can feature many sedimentary structures that are also common to deepwater slope environments.

Although we have always planned on having eight pads and nominal coverage of 97%, the experimental prototypes that we operated for the first two years of field testing had only four pads giving 40% nominal coverage. To overcome this, we present a section where we have non-overlapping data from two passes, and as such we are able to synthesize an image having excellent coverage, resembling that of the full-coverage version of the tool shown on panels 4 and 5.
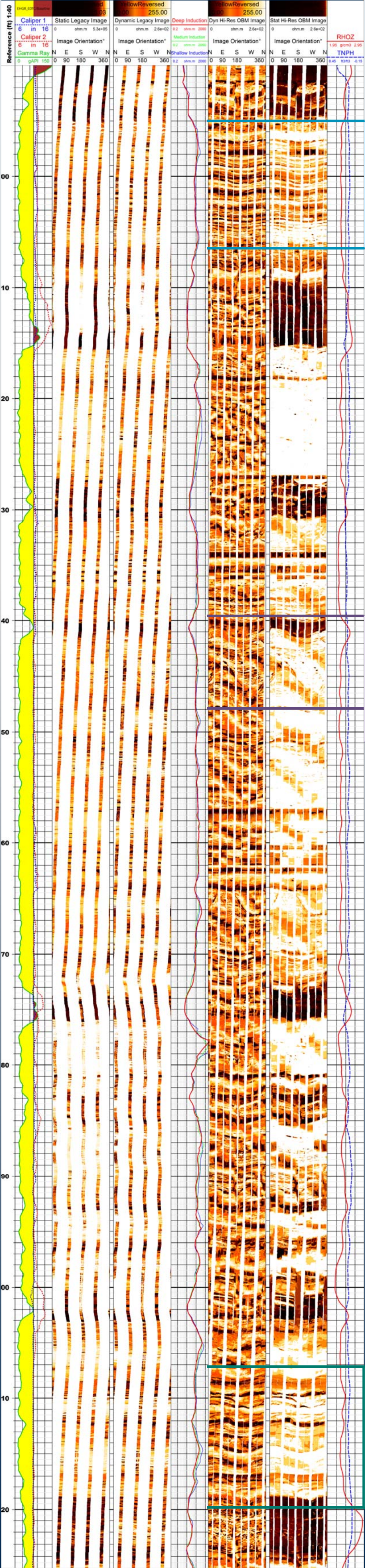
Channel Lags

Without knowledge of context, the spotty textures expressed in this interval could represent vugs in a limestone, intense bioturbation in a sand, or gravel and cobble size clasts. The tipoff that these are most likely to be clasts comes from the observation that spots are most intense when they are just above a scour, such as the one at xx36.5.

We are most likely looking at bedload in a high-energy fluvial channel. The structurally corrected dip azimuth points SSE to the channel thalweg, meaning that locally the channel flows either ENE or WSW.

By the same reasoning, at xx38.7 ft we observe a channel scour with WNW or ESE flow direction.

We are unable to see clear imbrication that would further constrain paleocurrent direction.

Note that on the legacy imager we cannot see the gravel or the scour.

Slump Fold

There are many interesting sedimentary and structural features in this section.

At the top, calm and flat deposition. But just go a foot down into the sand, and one sees many distorted beds. A two-foot interval of the formation has slumped, with a drag fold forming at it's nose. By measuring as many of the changing dips as possible, we can plot in a stereonet to get the fold axis (NW-SE). Since at the top, the beds are dipping to the SW, this implies that the slump moved in this direction i.e. the paleoslope was SW at the time.

Further down at xx53 ft, we can see a steep unconformity that has truncated the beds beneath it while a thin shale and a slightly thicker sand are currently draped over the top.

At xx57 ft, another clear scour is visible, this time overlain by small slumps and a fill pattern. Current direction is constrained to an ESE-WNW axis. Above this, the sedimentary dips swith to an Eastern heading, increasing upward. This trend is typical of aggrading traction deposits. The channel direction is determined as ESE.

Below this point we enter the silty-shaly, lower resistivity flood plain environment, which is flatly deposited. The images feature many thin dark layers that are not perfectly continuous because of bioturbation. Intermittent dm-scale sand beds are often massive and graded up. These are crevasse splays; their sudden and rapid deposition is put in evidence by their lack of internal structure as well as the flame structure at xx58 ft due to the compaction of the shale beneath.

Here from xx 61.5 to xx63 ft, we observe a one foot thick massive sand bed that is graded up. The top is scoured (marked by the yellow plane) and onlapped by what looks like calcrete nodules

Small flat-lying sand beds represent flood events.

A New Tool for High-Resolution Sedimentological Imaging of Deepwater Clastic Reservoirs

New Full Coverage Prototype in OBM, August 2013
# Shallow Marine Environment, 9.875 in Borehole

In July 2013, we fielded the latest version of the tool, on which the specifications of table 1 are based. Compared to the experimental prototype that acquired the images on panels 1 and 2, this new tool features an optimized button array, improved measurement electronics, and eight pads that give the highest nominal borehole coverage of any wireline microelectrical imager in the industry: a whopping 97% in an 8-in borehole.

The subject well for the first field test was drilled targeting sands in a shallow-marine environment that was believed to be wave-dominated. Significant carbonates associated with a platform or ramp are also present. As these data were acquired only ten days before the conference, the authors could not do a full interpretation in time for this publication. Nonetheless the examples below should give a good idea of what is possible with the new high-specification NCM imager.

Comparison to industry standard OBM-adapted imager

Crossbedded Sands
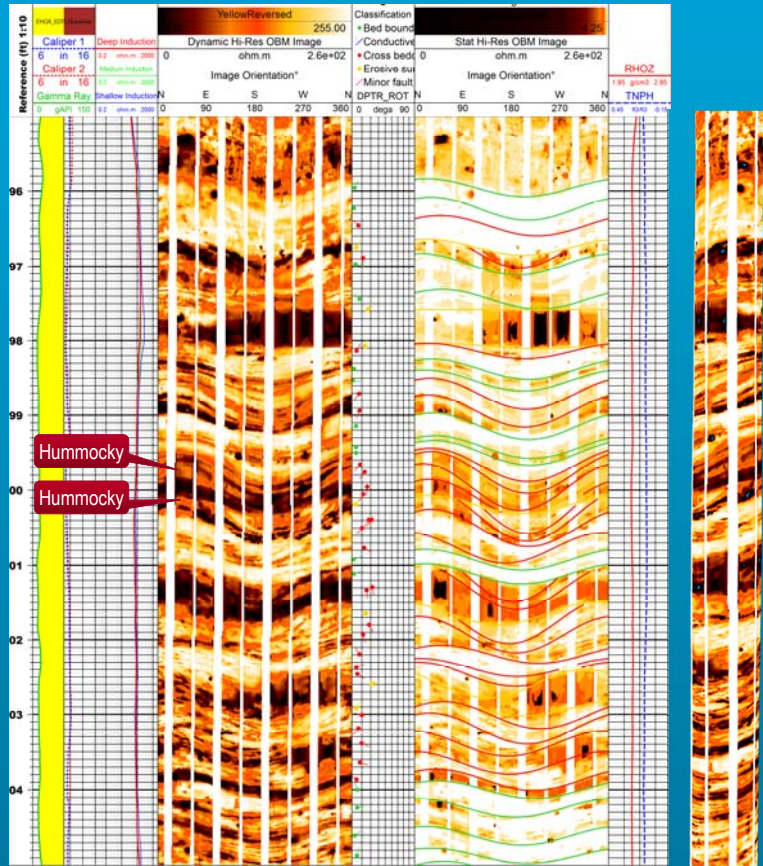
In this interval can be observed multiple sets of cross beds – even hummocky cross beds, which appear at xx99.6 ft and xx00.5 ft. Some of the dips from the sets of cross-beds show singular direction of flow – mostly southwest, whereas other sets of cross-beds show more than one direction of flow – mostly southwest and southeast, but occasionally also northwest or northeast. Some fecal pellets are also seen.

The high resolution images allow clearer visualization of rock features and very good definition of the beds associated with depositional features and more accurate dip determination. The complete interpretation is possible because of the complete images. These are lower shoreface sands.

Poor Hole Conditions
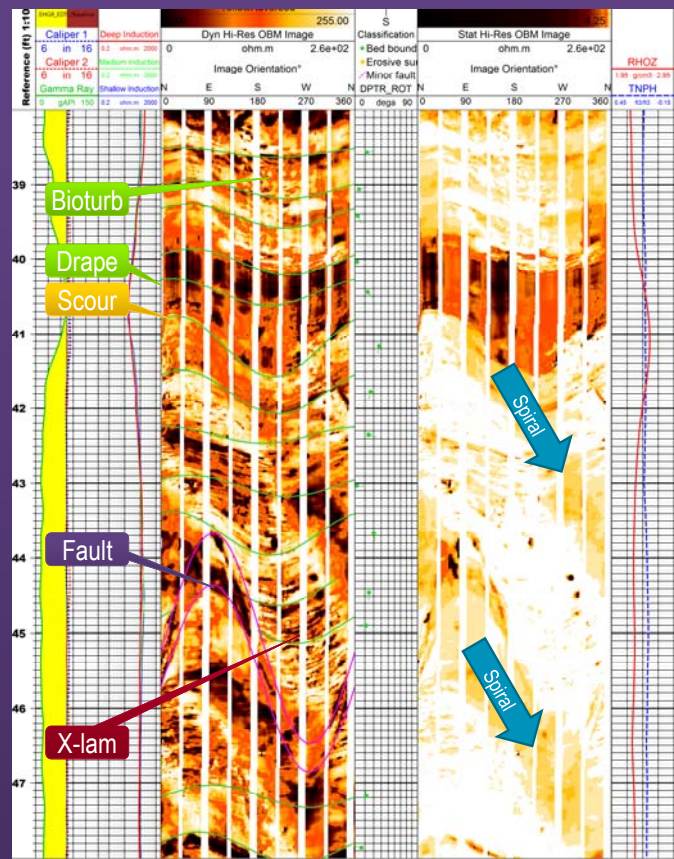
Spiraling of the borehole is clearly seen in this interval in the static image, even as the calipers show that the borehole is significantly rugose in most the overall section, with severe rugosity in places.

As a spiral is not a plane, it does not appear as a sinusoid in the two-dimensionally displayed image, but rather as a diagonal band trending downward from left to right across the image and then wrapping back to the left side. This is most visible in the snapshot from xx42 ft downward; the darker band is the enlarged part of the hole.

At the same time, taking a close look at the images, they are not too badly affected by the rugosity (as often occurs with legacy imaging tools). The new imager is still able to resolve fine features such as bioturbation, thin beds, and small clasts, as well as bigger features such as scours and faults'.

Laminated, Crossbedded, and Faulted Sands
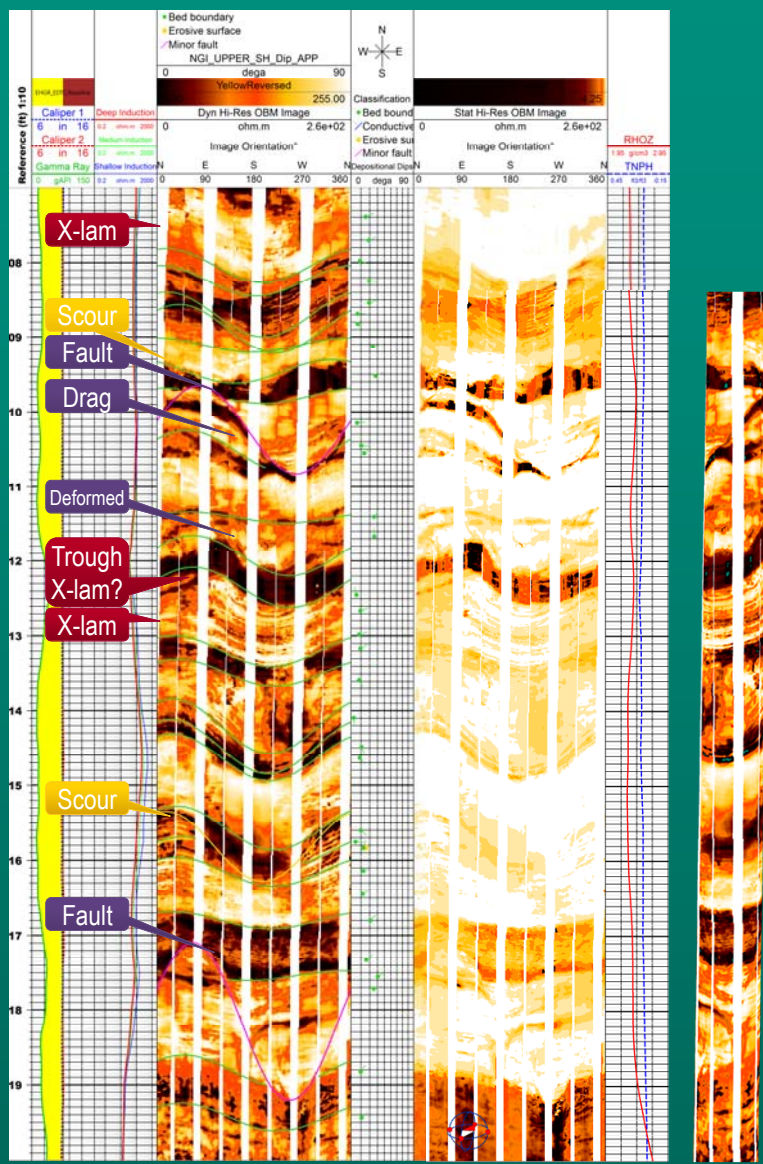
Sand appears to be a coastal deposit with episodes of high and low energy deposition. The basal part of the sand includes beach sands with fecal material and pyrite. The system then gains energy, and scouring with fill is observed with intermittent lower energy laminations and cross beds. The new images even make this kind of sub-inch resolution possible.

The rapid deposition also leads to syn-depositional faults and slips, as can be observed in the images at xx18 ft and xx 10 ft (pink). The high resolution along with a very high circumferential coverage afforded by the new images even in oil-base mud drilled holes allows a level of interpretation seen only in water-base mud drilled holes.

The crossbed from xx05-05.5 ft has a nonplanar top. This may be the result of a scour or due to rapid loading, but this particular geometry with an upward-pointing cusp represents a concave-upward surface which may indicate trough crossbedding. Such details are unobservable in the legacy NCM images.

A New Tool for High-Resolution Sedimentological Imaging of Deepwater Clastic Reservoirs

New Full Coverage Prototype in OBM, August 2013 Carbonate Section (Uninterpreted)

Comparison to industry standard OBM-adapted imager
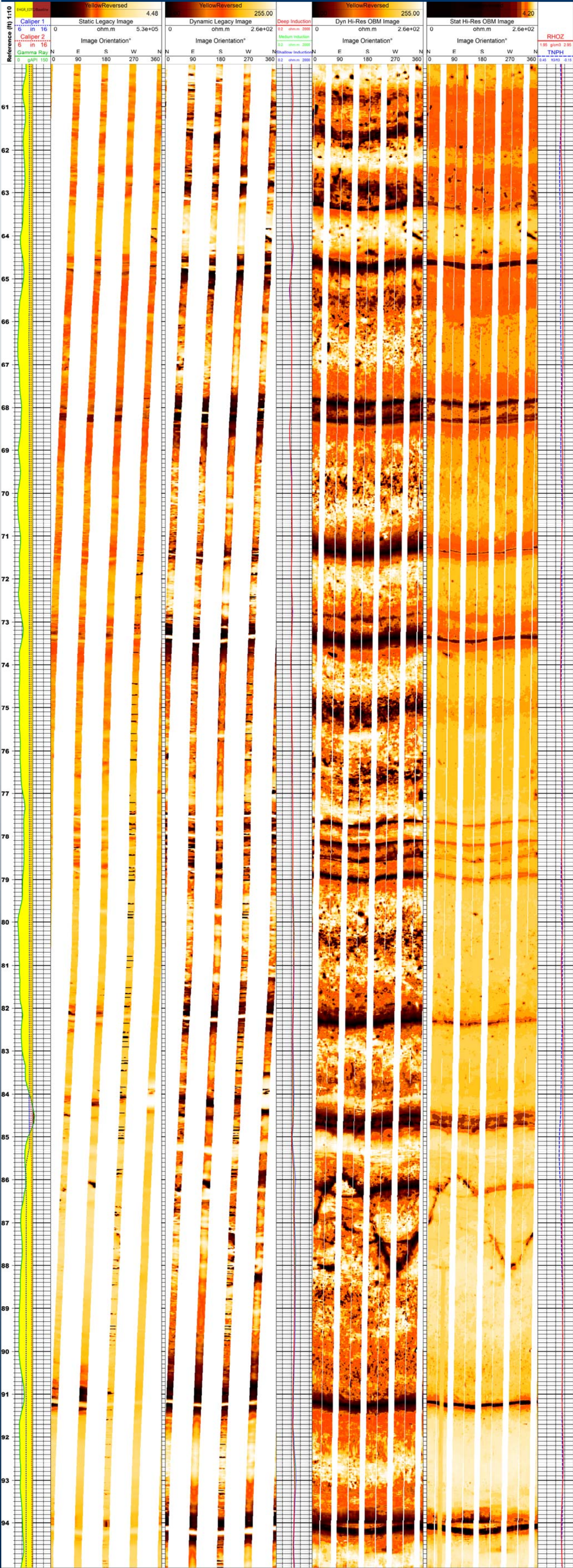
In the same well where the new full-coverage prototype was run (panel 4), significant limestone sections occur both above and below the target sand. Due to the afore-mentioned physics limitations of legacy NCM-adapted imager technology, hi-resolution photorealistic textures in carbonate rocks drilled with NCM have been an elusive target for the industry.

Because of the logging of the well only ten days ahead of this conference, the authors have not had time for any significant interpretation effort on these carbonates. We were successful in processing the images to provide the optimum example at the left, which, based on experience interpreting high-spec WBM images in carbonates, would appear to be consistent with possible grainstones, packstones, and wackestones deposited in a back-reef environment and having experienced grain-selective dissolution enhancement of porosity.

The other interval (not shown) produced a very credible boundstone or framestone texture consistent with a massive reef. So it can be seen that this new tool brings advances not only for clastic sedimentologists, but for carbonate experts as well.

Conclusions

A new microelectrical imaging tool designed for operation in any well drilled with nonconductive oil- or synthetic-base drilling fluid has been successfully developed and tested in a wide range of geologic environments, including the deepwater Gulf of Mexico.

The main specifications of this imager clearly match or exceed those of the industry standard microelectrical imager in use for wells drilled with conductive water-base fluid. Further details of the tool and measurement physics will be revealed in a future publication.

Although there is not yet a published comparison to core or outcrop, it is clear based on expert experience and based on analogs imaged in water-base fluid that the new tool is capable to produce images of similar quality and high-specification as those acquired in water-base fluid.

A world of previously undetectable sedimentary, structural, and diagenetic details can now be visualized in a photorealistic manner and interpreted by geologists in a natural and intuitive way. The performance of the new imager far exceeds that of legacy NCM-adapted imagers in nearly every way imaginable.

Like any type of borehole image, the features observed can have multiple possible explanations. Complementing the image with at least limited intervals of conventional core is highly recommended to validate the interpretations applied to a given reservoir.

Deepwater projects will stand to benefit the most from this promising new technology as the cost of poor decision-making is high, and demands a superb understanding of the reservoir geology.

Acknowledgements

References

Bourke, L.T., and Prosser, D.J., 2010, "An independent comparison of borehole imaging tools and their geological interpretability," paper GGG presented at the SPWLA 51st Annual Logging Symposium, Perth, Australia.

Cheung, P., Pittman, D., Hayman, A., Laronga, R., Vessereau, P., Ounadjela, A., Desport, O., Hansen, S., Lamb, M.; Schlumberger, Borbas, T., Wendt, B.; Conoco, , "Field Test Results of a New Oil-Base Mud Formation Imager Tool", paper XX presented at the SPWLA 42nd Annual Logging Symposium.

Ekstrom, M.P., Dahan, C.A., Chen, M.Y., Lloyd, P.M., and Rossi, D.J., 1986, "Formation imaging with microelectrical scanning arrays," presented at the SPWLA 27th Annual Logging Symposium.

Hansen, S.M., and Fett, T., 2000, "Identification and Evaluation of Turbidite and Other Deep Water Sands Using Open Hole Logs and Borehole Images," in *AAPG Memoir 72 / SEPM Special Publication No. 68: Fine-Grained Turbidite Systems* by Bouma, A.H. and Stone, C.G., eds.

Silva, I., Domingos, F., Marinho, P., Sonangol; Laronga, R., Khan, S., Schlumberger; 2003; "Advanced Borehole Image Applications in Turbidite Reservoirs Drilled with Oil-Base Mud: A Case Study From Deep Offshore Angola", paper AA presented at the SPWLA 44th Annual Logging Symposium.

Slatt, R.M., and Davis, R.J.; 2010; "Calibrating Borehole Image and Dipmeter Logs with Outcrops and Behind –outcrop cores: Case Studies and Applications to Deep-water Deposits," in *AAPG Memoir 92: Dipmeter and Borehole Image Log Technology* by Poppelreiter, M., Garcia-Carballido, C., and Kraaijveld, M.A., eds.