Case Studies in Sub-seismic Resolution

by: Patricia Santogrossi

Geophysical Insights | Sr. Geoscientist

GEOPHYSICAL INSIGHTS

FROM INSIGHT TO FORESIGHT

Preface

This paper documents analysis resulting from the application of the Paradise® multi-attribute software on a portion of the Eagle Ford Trend in South Central Texas. The work was undertaken as part of a broader research project that would help to define a technology development roadmap for the Paradise platform. What follows is a compendium of four case studies that show readily interpretable resolution of geologic facies tracts and their disconformities in the Eagle Ford Group, underlying Buda, and overlying Austin Chalk formations. Most importantly, the use of multiple attributes will be shown to enable interpretation below classic seismic tuning. And, while the geologic setting and well logs used in this analysis are clearly unconventional, the principles outlined in this study are equally applicable to both unconventional and conventional resources alike. The full range of findings enabled visualization and characterization of explicit stratigraphic and structural details, though not all of which are depicted in the ensuing Briefs. It will be seen from in the following Briefs that the multi-attribute classification results provide an effective basis for more accurate and detailed mapping and calibrations, which are highlighted as follows:

- The Basal Clay Rich or Pebble Shale, which may be gas infused, can be mapped and separated from the Buda and Eagle Ford Shale targets;
- The Eagle Ford Shale interval consists of two distinct systems tracts, each of which is comprised of non-layer cake stratigraphy –
    - The updip high resistivity, regressive, downlapping carbonate-enriched margin is comprised of two red winning neurons 61 and 62,
    - The downdip clastic infill and transgressive onlap facies succeeds this deposition and is comprised of four onlap segments. Two of them - 53 and 54 - precede the episodic emplacement, perhaps by storms, of two distinct downdip geobodies, located still in the space in front of the carbonate margin. All of these elements are high resistivity facies.
    - The clastic fill continues to onlap the rest of the carbonate margin via the low resistivity facies of neuron 55 and 56.
    - All of this stratigraphy is then aggradationally overlain by ashy beds updip and by the same facies in lows downdip, likely produced by compaction of the clastic onlap wedge. These low resistivity ashy beds are identified by neurons 63 and 64.
- The gas-prone Upper Eagle Ford Marl can also be readily distinguished by unique neuron classification and by brilliant unconformity detection above and below these facies.

Table of Contents

First Steps in the Sub-seismic Resolution of the Eagle Ford

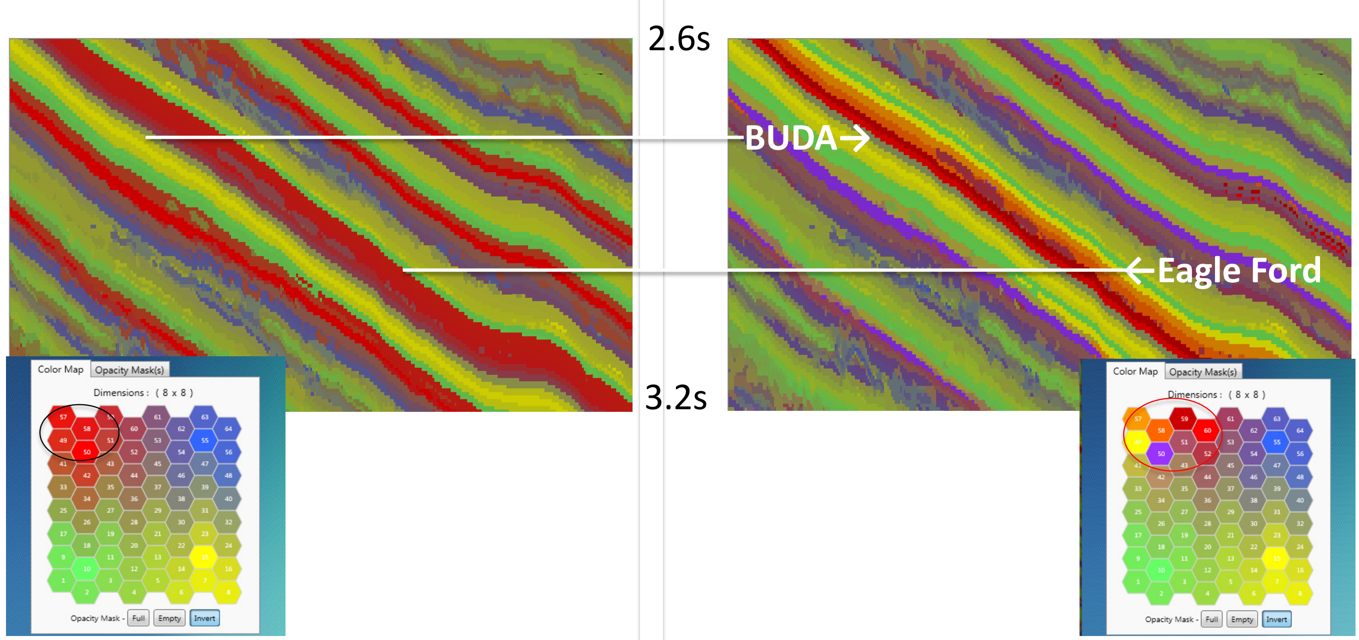
This and three companion Application Briefs (EF-2, EF-3, and EF-4) present details of an analysis and results from the application of Paradise® on a large 3D seismic volume from two counties in Texas focused on the eastern end of the Eagle Ford trend and its bounding formations: the underlying Buda and the overlying Austin Chalk. The results characterize remarkable resolution of stratigraphic and structural details in these three formations. Dramatically, these Application Briefs will show resolution of features below seismic resolution, a product of the analysis taking full advantage of multiple attributes simultaneously. While this and related Application Briefs are set in unconventional geologies, the principles outlined herein are applicable to both conventional and unconventional resource plays.

The analysis began by applying Principal Component Analysis (PCA) on 16 Instantaneous attributes. Instantaneous attributes calculate a value at each sample and inherently return higher frequency information. From the PCA analysis, nine attributes were run in Self-Organizing Maps (SOMs) and, of these, five were found to be most common in the Eagle Ford results. A brief description of the five types of Instantaneous attributes is as follows:

- **Instantaneous Phase is useful for the continuity/discontinuity enhancement.**
- **Normalized Amplitude aka Cosine of Instantaneous Phase returns the energy distinctly from each sample in the full trace.**
- **Relative Acoustic Impedance helps to resolve geobodies.**
- **Envelope or Total Energy of the entire reflected waveform, including Real Part of the reflected seismic that is measureable and the Imaginary Part which is not.**
- **Trace Envelope was found to occur only in both of the encapsulated geobody facies tracts.**

Figure 1a **Default 2D ColorMap**

Figure 1b **Tweaked 2D ColorMap**



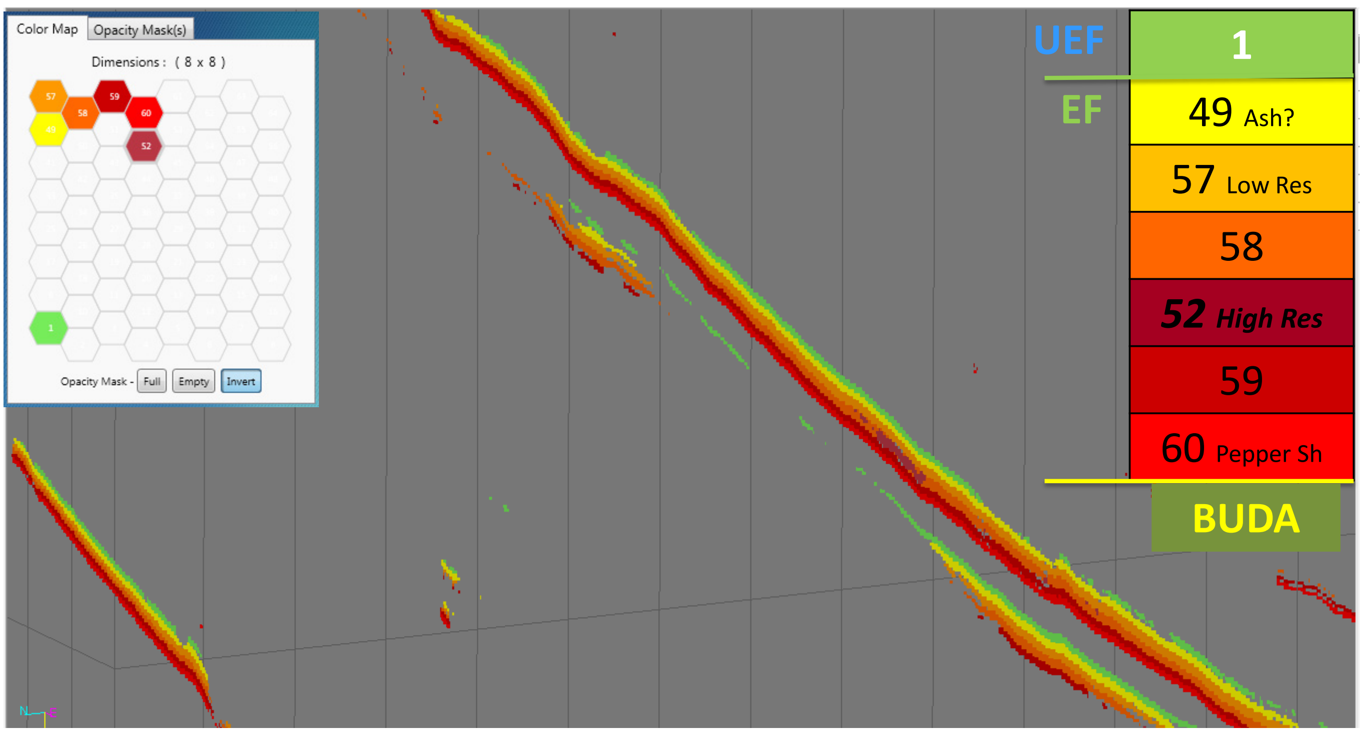
In addition to the above, Envelope 2nd Derivative, Instantaneous Frequency, and Thin Bed Indicator rounded out the nine suggested by the PCA. However, these three were less evident in the area investigated and were not found to be significant in the Eagle Ford Shale specifically.

The original PCA and SOM were run over a 1.5 to 3.2 sec. interval and a specific range of inlines and crosslines to capture the Eagle Ford's complete updip to downdip occurrence. Results were first viewed by use of the default Interactive 2D Colormap (**Figure 1a**), which is unique to Paradise. Note that the Eagle Ford is resolved but not uniquely distinguished until a few colors that were not specific to the Eagle Ford were changed in the Interactive 2D Colormap.

Figure 1b shows the result that helped confirm the near uniqueness of the Eagle Ford facies in the stratigraphy of the area.

The transparency function of the interactive 2D Colormap was then used to remove all neuron colors except those that represent the Eagle Ford shale and the overlying interface with the Upper Eagle Ford marl. This technique exposed other similar and sizeable objectives in the overall stratigraphic section. **Figure 2** reveals that filled scour structures carved into the top of the Georgetown and an uncalibrated zone, possibly Pearsall, share the facies characteristics of the Eagle Ford, which suggest these other formations also likely include similar organic-rich shale facies.

Figure 2



Detailed Sub-seismic Resolution in the Eagle Ford Shale and Identification of Under-explored Geobodies

This Application Brief is a companion to a series of four such Briefs. Please see Paradise® Application Brief EF-1 for an introduction to the project.

In **Figure 1a** on the left, a NW-SE seismic section across the location of Well #6 is comprised of a conventional amplitude seismic display with red/white/black 1D color scheme. The Figure shows the Austin Chalk – Eagle Ford Group – Buda stratigraphic interval resolved in roughly 3 peak/trough cycles. This sample was provided by the client. On it, amplitudes appear "boosted", which in the early days, say prior to the early 1980's, passed for continuity enhancement. Formations appear "continuous", yet any details are obscured rather than resolved and occur in the amplitude domain, where tuning, absorption, and other vertical "influence" effects are a legitimate concern.

The graphic on the right displays the results of a Self-Organizing Map (SOM) of multiple Instantaneous attributes colored by neurons of up to 64 classes (see Paradise Application Brief EF-1). A seismic interval from 10ms below the Buda to 100ms above the Buda or near to the top of the Austin Chalk was chosen for the SOM run. Shown clearly is the resolution improvement provided in Paradise when the interpretation interval is reduced to just the area of interest or to a few depositional sequences.

The results shown in **Figure 1b** reveal non-layer cake facies bands that include details in the Eagle Ford's basal clay rich shale, High Resistivity and Low Resistivity Eagle Ford shale objectives, the Eagle Ford ash, and the Upper Eagle Ford marl, which are overlain disconformably by the Austin Chalk.

The Basal Clay Shale (BCS) (**Figure 1b**) is distinctly resolved on top of the Buda (whose 10 ms are hidden by the shaded horizon as background) generally by the #1 neuron in dark gray. Its lithologic and neural uniqueness are concomitant with its distal detrital or pelagic emplacement after deposition of the underlying Buda carbonates. The BCS is distinct also from the overlying downlap of two red neurons (black arrow) and subsequent transgressive (white arrow) greyish-gold Eagle Ford High Resistivity organic rich facies.

Figure 1a

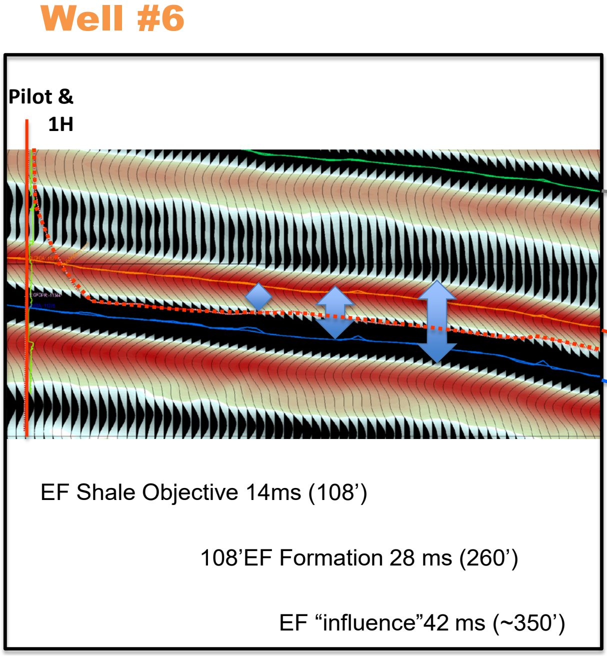
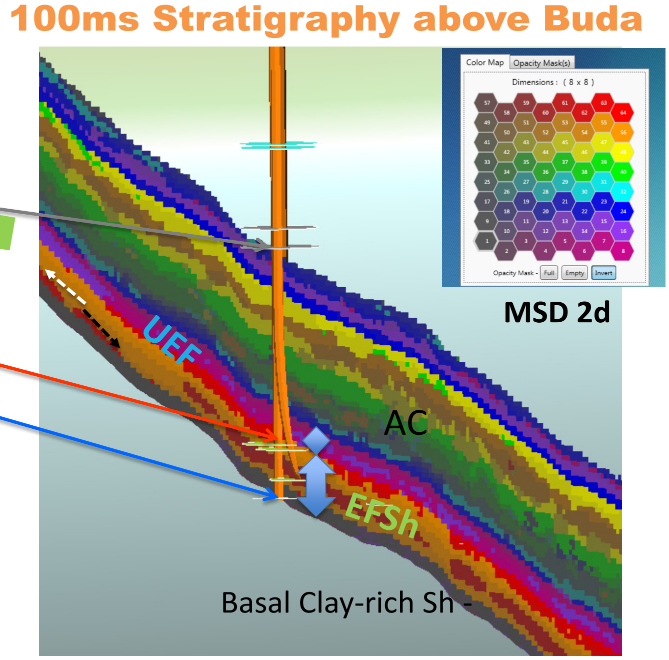


Figure 1b



A previously unknown, encapsulated, discontinuous core of <u>rust-colored</u> facies within the gold section of the Eagle Ford is also well resolved. This zone can be localized and its distribution understood by moving the top Eagle Ford horizon down to intersect the geobody shallow (**Figure 2a**) where its fairway is wide, and (**Figure 2b**) deeper where its fairway is narrower. Note that a change in the 2D ColorMap helped facilitate the geobody's extraction. This geobody can also be discriminated (**Figure 2c**) by selection of only its three neurons in the Paradise 2D Colormap. Calibration of this zone has proven it to be of the High Resistivity target reservoir type.

The Eagle Ford Ash (**Figure 1b**) lies above the gold and comprises a different red facies than the downlap; it is resolved as discontinuous and concave or low-seeking fill at the top of the Eagle Ford shale.

Lastly, the Upper Eagle Ford marl, in purple and magenta colors in **Figure 1b**, rather than showing simple layers, exhibits updip and downdip facies changes and features that may signify faults, fluid fill, and/or facies changes.

Figure 2a

Offset .012ms below Top EF Shale

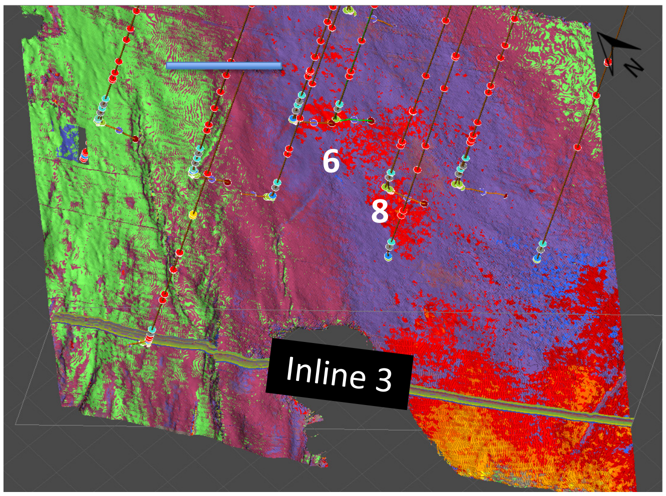


Figure 2b

Offset .016ms below Top EF Shale

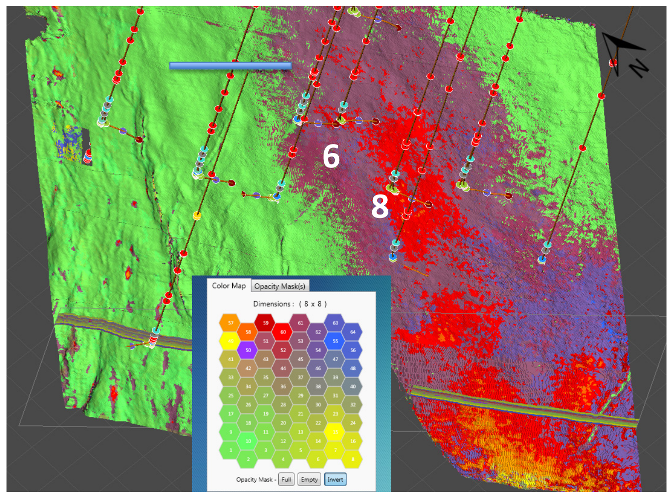


Figure 2c

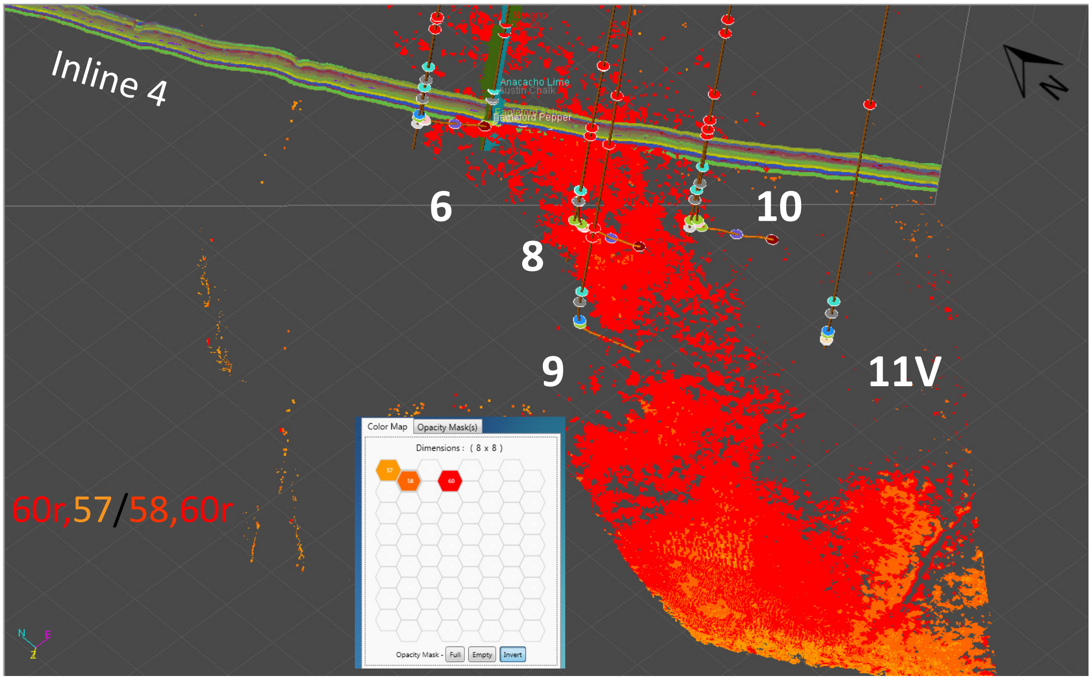
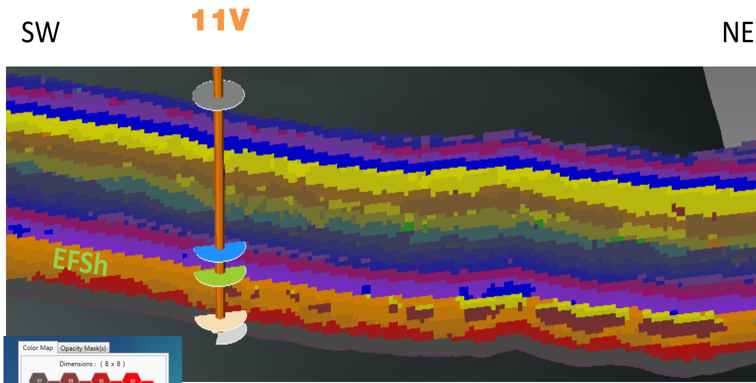
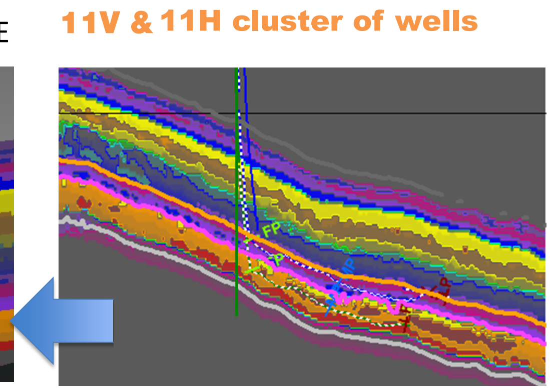


Figure 3a





NOTE: Seismic thickness is 100 ms

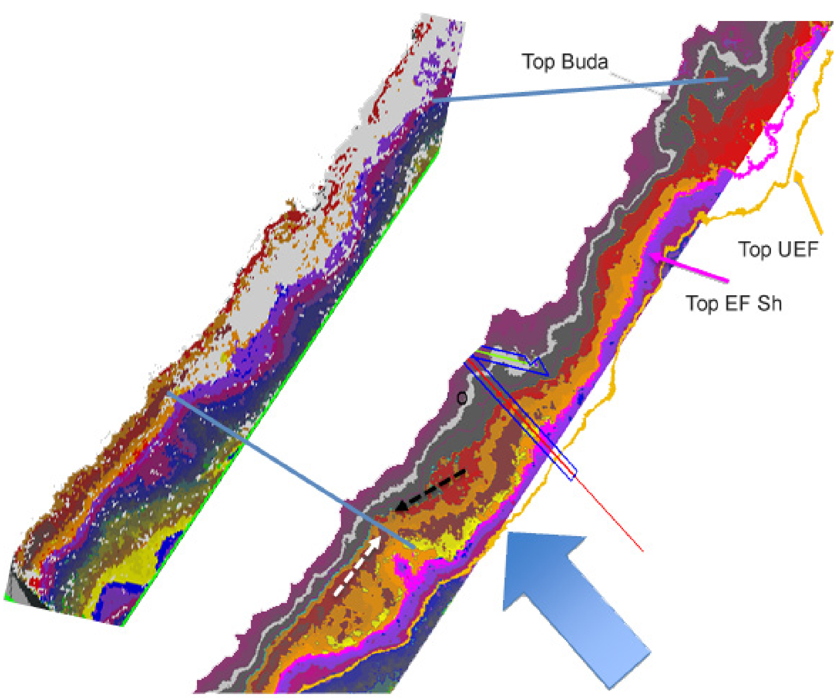
NOTE: Seismic thickness is 110 ms

MSD 2D

Figure 3a shows another geobody, which is highlighted by brown and yellow neurons, in the vicinity of the 11V calibration well and the cluster of associated horizontal wells. Note the concave upward shapes of the elements of the geobody. This geobody is stratigraphically above the Rust zone. Only one of the lateral boreholes appears to sample it as most of these wells targeted the Upper Eagle Ford marl.

Figure 3b is a time slice taken at 2.722 seconds and on the right is the SOM classification from Kingdom. Stratigraphic "up", the top of the Eagle Ford Group (gold marker) is to the right, and "down" to the Buda (gray marker) is to the left. Note that the Red lapout (black arrow) and the Rust geobody onlap (white arrow) both lie below Geobody 2. The left view shows the same slice from Paradise with the 10% probability filter on. This white overlay indicates that all of the Eagle Ford is rare or anomalous and is <u>likely</u>

Figure 3b
Time slice at 2.722s



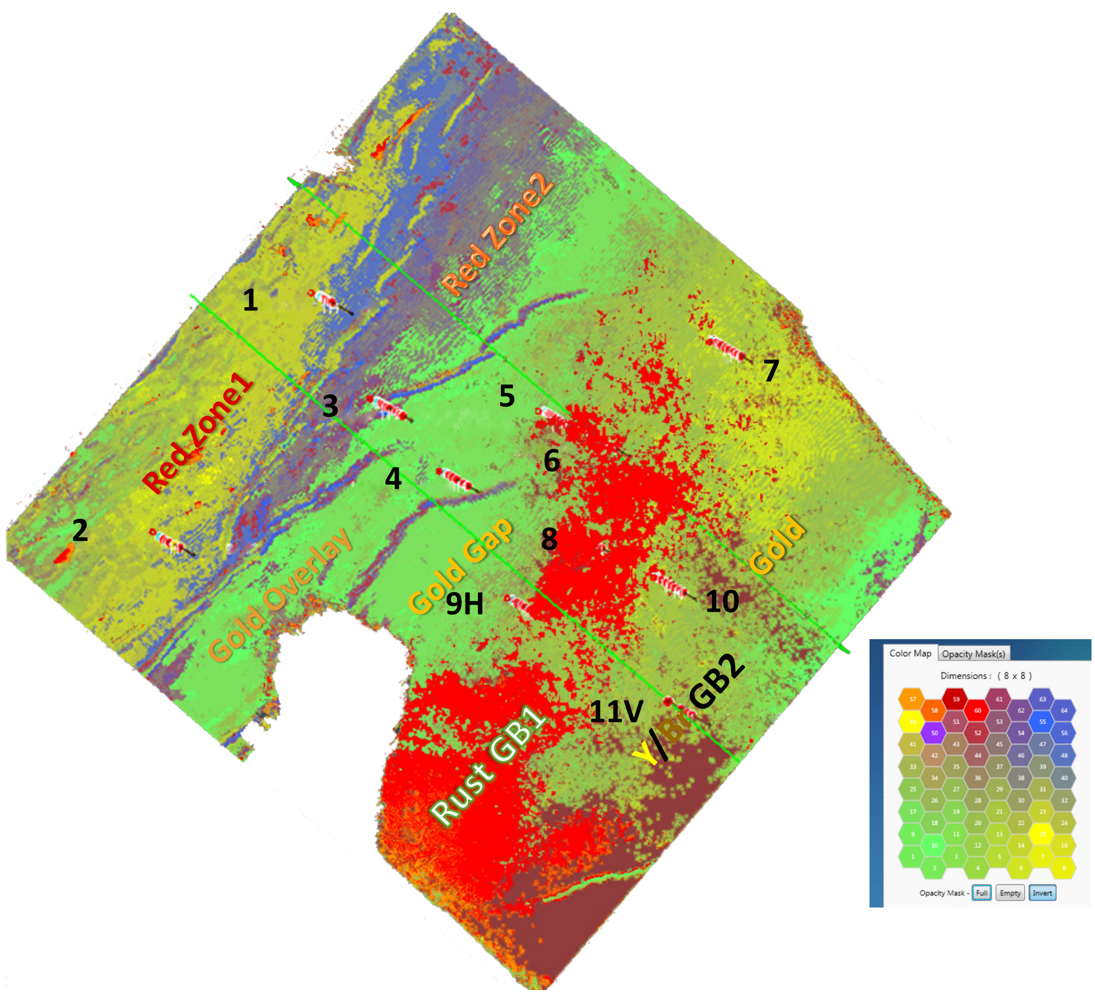
hydrocarbon rich. Note also the indication of a fault trace highlighted by the probability overlay as well as an offset of the two major pods of this geobody.

Figure 3c shows the extraction of the brown part of the geobody for a view of its distribution. The yellow was not shown as it is non-unique neural facies that also occurs in the Austin Chalk. A major fault is also clearly shown in this extraction.

Later studies indicate that both geobodies comprise their own unique neuron class and wells cluster when their geological and petrophysical characteristics are classified against other wells in the area (Source: still proprietary results of the research study).

Figure 3c

11V Wells



Resolution of Faults in the Eagle Ford

Prior to the analysis described in this and the related three Application Briefs (EF-1, EF-2, and EF-4), the client believed that the faults were not well resolved within the Eagle Ford on the base "amplitude" seismic survey or on views of a single similarity attribute. This brief demonstrates that faults can be readily resolved via analysis of multiple attributes simultaneously.

Principal Component Analysis in Paradise® was used initially to reduce an initial set of 25 geometric attributes to ten from the first two Eigenvectors. Five similarity attributes, which included Chaotic Reflection, Dip of maximum Similarity, Similarity, Smoothed Dip of Maximum Similarity and Smoothed Similarity, contributed the greatest variance to the result set according to the first Eigenvector. Curvature in the Dip and Strike Directions, Maximum Curvature, Mean Curvature, and Shape Index contributed the most variance within the second Eigenvector. For setting up the input to the Self-Organizing Map (SOM) process, a recommended work process uses the most prominent 2-5 attributes that contribute the greatest variance among each of the largest Eigenvectors which may number 1-4 or more. The combined contribution for the select set of attributes should comprise at least a cumulative 60% of the variance within the region of the PCA analysis.

A result illustrated in **Figure 1** is from a geometric SOM made from these ten attributes visualized as a "ghost" on the Top Eagle Ford horizon, which has then been pushed down into the High Resistivity Eagle Ford shale objective. The multiplicity of faults that can now be seen defied expectations. Well 3H's borehole encountered six faults while drilling, which now can be individually seen, were not anticipated from the use of a single similarity attribute display such as **Figures 2a** and **2b**.

Figure 1

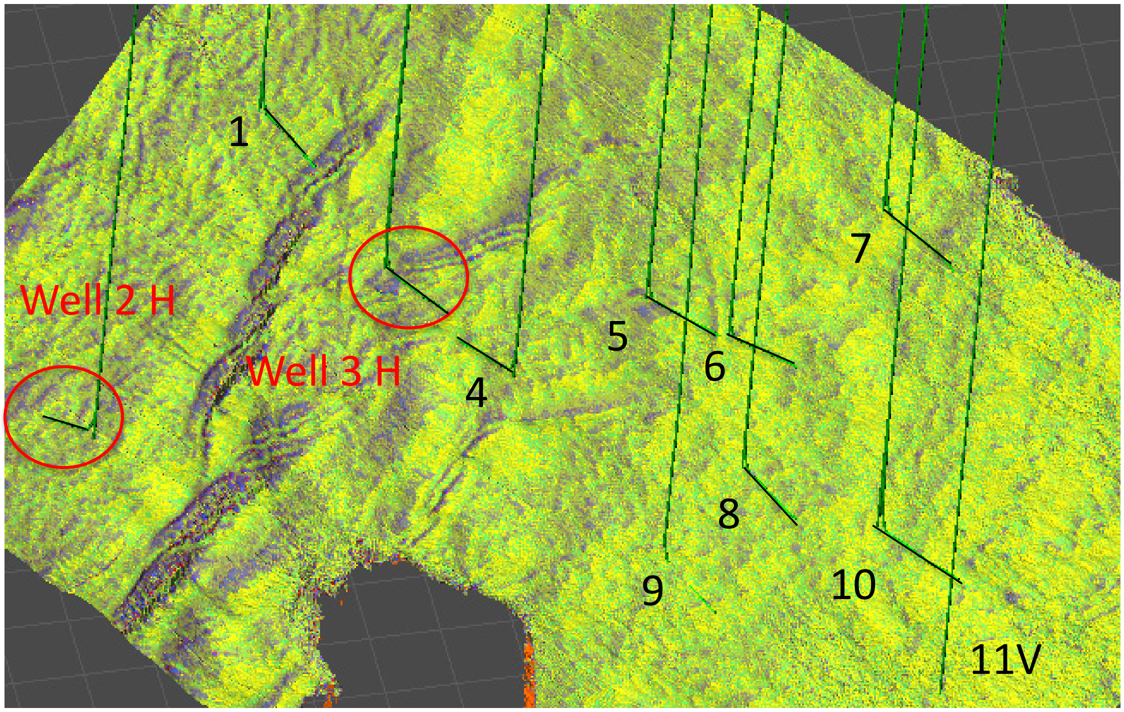
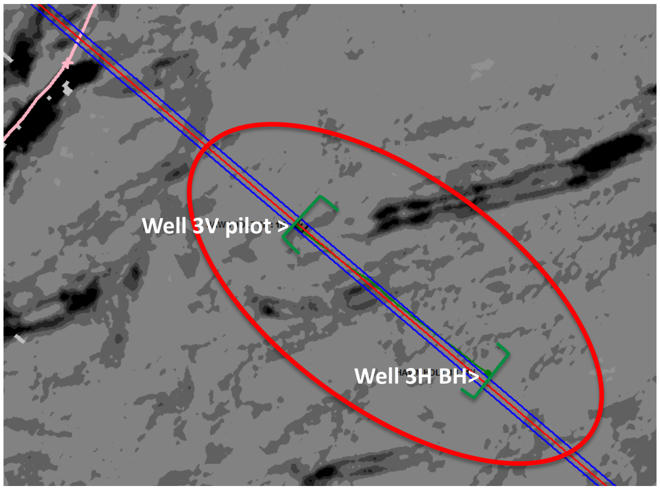
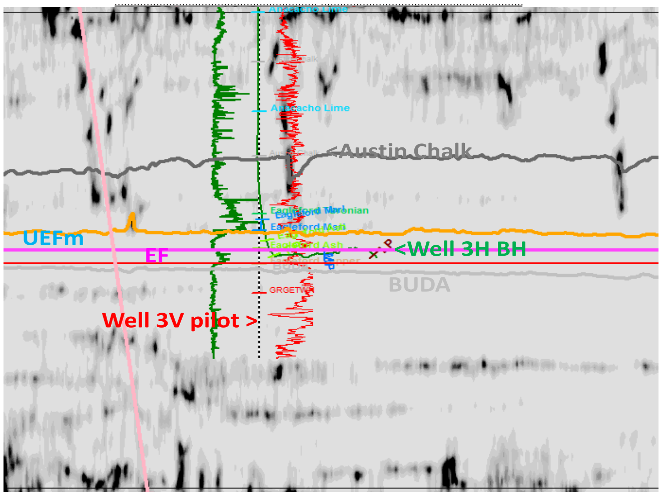


Figure 2a



NOTE: Poor fault image at well

Figure 2b



NOTE: No faults shown to offset Eagle Ford

Figure 3 shows results from the same Instantaneous SOM with the 2D Colormap formerly seen in Figure 2 in Paradise Application Brief EF-2 (PAB EF-2). The figure is from an inline that transects the downdip portion of Geobody 1, also shown there. The patterns seen in the neuron textures now reveal details in the structure of that body in the vertical section. Numerous offsets, including many that are compressional in nature, can be interpreted that were not evident at all in the original seismic data or with use of a single similarity attribute. The interpreted long pink fault in Figure 2b shows that faults may be interpreted on an instantaneous phase section with use of a poprietary 1D colorbar.

Figure 4 shows a close-up of a single compressional fault with remarkable detail in the offset in the Eagle Ford shale. For this view, the favored 2D Colormap for an 8x8 topology, i.e., 64 neurons, called Map Shade Dark, is in use (see also **Figure 1b** in PAB EF-2). Onlap of high resistivity greyish-gold facies are connoted by white left arrows. An underlying double red downlap is located by the black right arrow. Note that the former is evident as fill in the parting of the latter at the fault in the Eagle Ford. Offset is actually most subtle here in the Upper Eagle Ford marl.

Figure 3

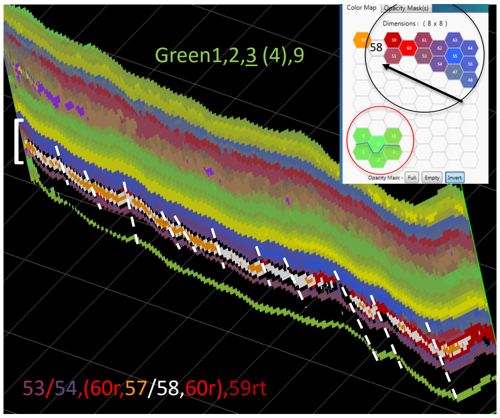
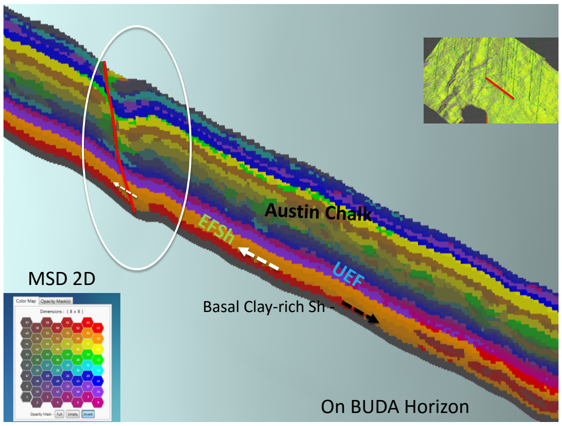


Figure 4



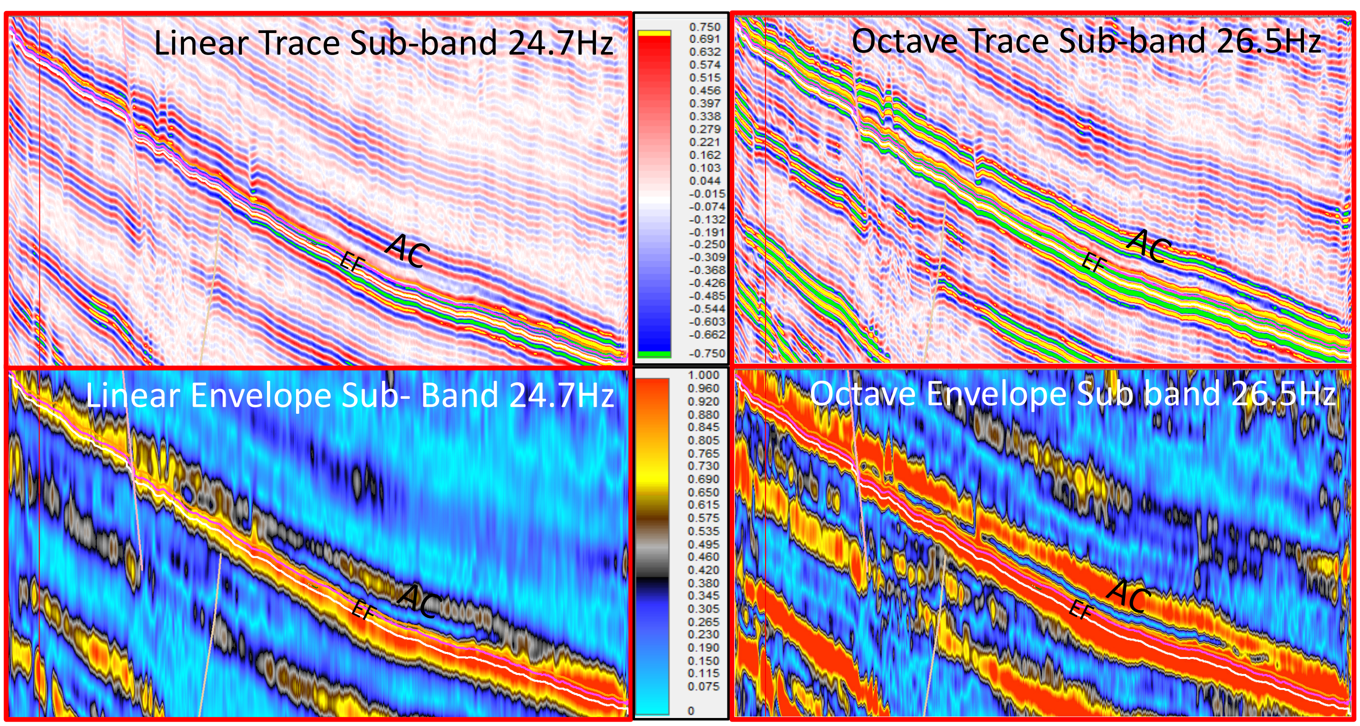
Stratigraphic and Structural Resolution using Instantaneous Attributes on Spectral Decomp Sub-bands

Spectral Decomposition (SD) is regarded as a useful tool for below-resolution seismic interpretation, reservoir thickness interpretation, and depositional structure enhancement. Amplitude components using Normalized Instantaneous attributes help quantify thickness variability more reliably. Phase components detect lateral discontinuities, both stratigraphic and structural, and also contribute to the segregation of various facies tracts. However, going beyond the visualization of one, two, or even three attributes at a time, this Application Brief describes the simultaneous analysis of multiple attributes using machine learning processes in Paradise®.

Initial steps were to take 20 sub bands from 8 to 85Hz. Run over the time interval of 1.5 to 3.2 seconds, the first three Eigenvectors yielded relatively low values for sub-bands 48.5 to 68.8Hz, moderate values for sub–bands 24.2 through 32.3Hz, and higher values for sub-bands 8 to 16.1Hz respectively. These results suggested a further look at the Linear/Octave Trace/envelope sub-bands from 12-50Hz. From these analyses, the Linear sub-band **24.7Hz** and the Octave sub-band **26.5Hz** stood out (**Figure 1**). The selections were based on the best resolution of the disconformity between the lower Austin Chalk and the Eagle Ford.

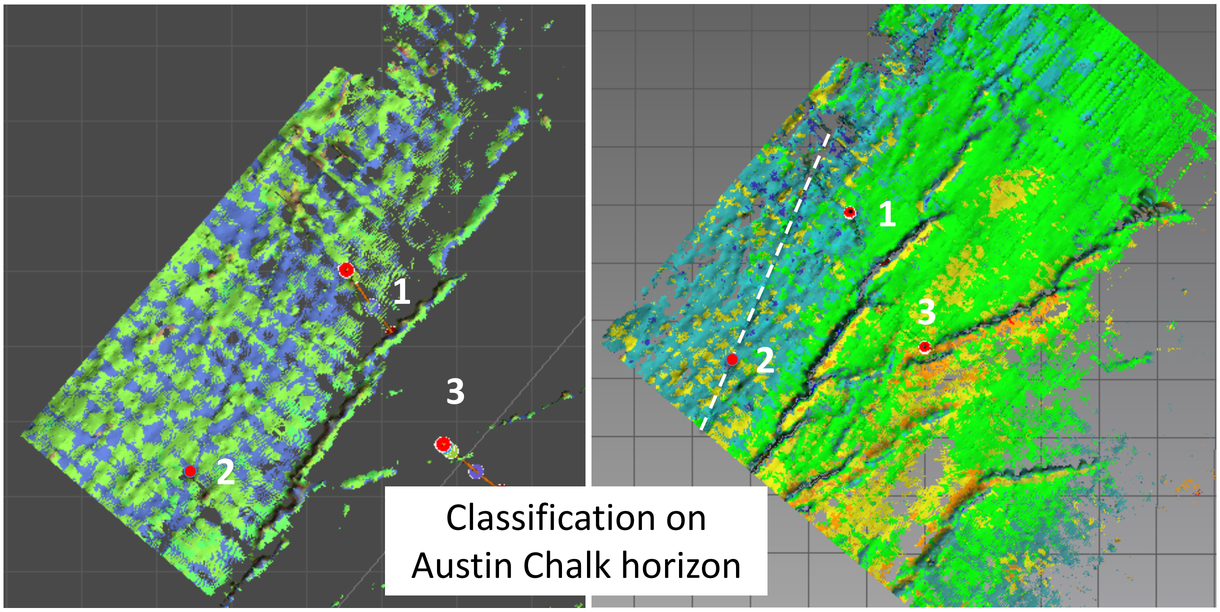
Instantaneous Principal Component Analysis (PCAs) and Self-Organizing Maps (SOMs) were applied using each of the two selected linear sub-bands as new base surveys. When the data in each case was delimited by area and by horizons (see Paradise Application Brief EF-2).

Figure 1



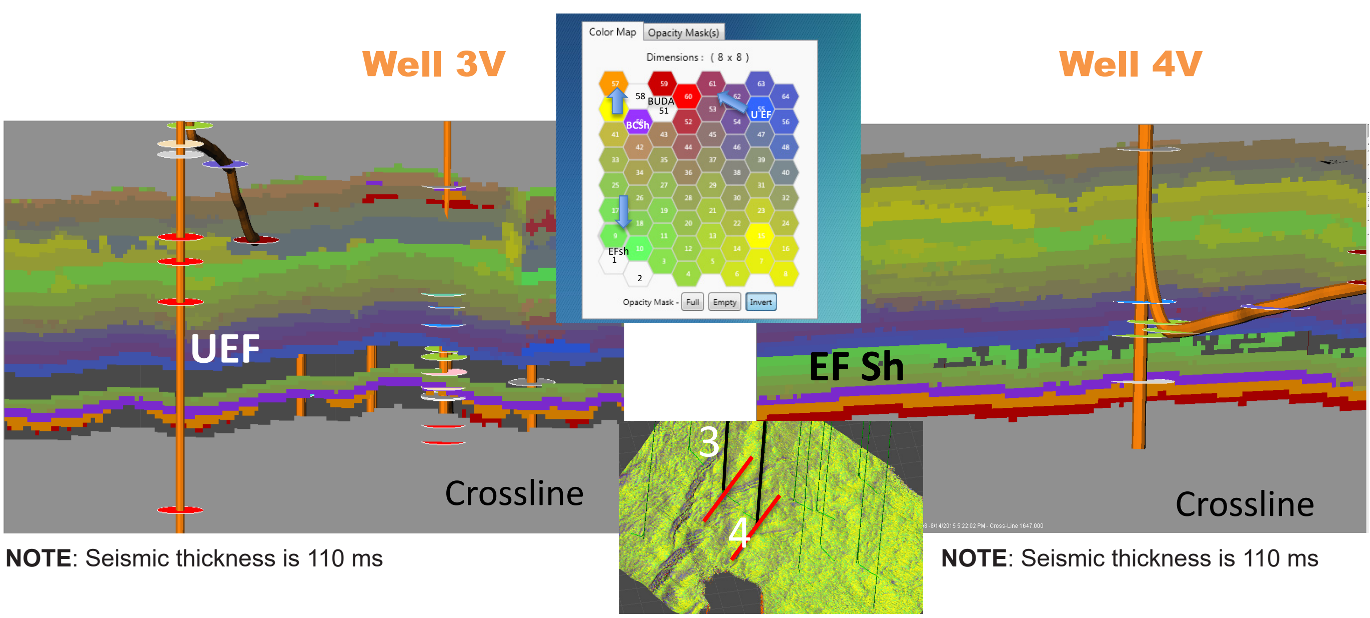
In Figure 2, the Instantaneous SOM results from Linear 24.7Hz (**Figure 2a**) and 26.5Hz (**Figure 2b**) were then ghosted onto the Austin Chalk top for comparison. A subtle SW–NE trending fault encountered in the #2 well, which had not been see using traditional methods, is resolved in **Figure 2a**; yet is a bit more subtle in **Figure 2b**.

Figure 2a **Figure 2b**



In **Figure 3**, the Instantaneous SOM result for the **Linear 24.7Hz** is displayed in SW to NE crosslines through two neighboring wells (see inset). It can be seen that stratal variations are rapid and subtle. In the Eagle Ford,when green neurons 1 and 2 are turned off, this action blanks out two continuous facies bands in the upper Eagle Ford at Well 3, and at Well 4 only a smattering of pixels are gone. Also in the right view, two additional semi-continuous green neurons 9 and 17 in the upper part of the Eagle Ford shale are present. Both views share the basal green bands of neuron 25 and 26.

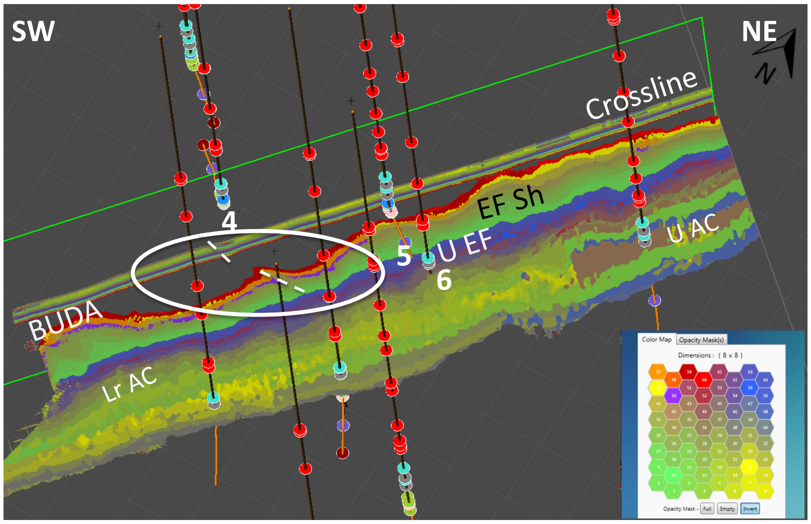
Figure 3



NOTE: Seismic thickness is 110 ms

NOTE: Seismic thickness is 110 ms

Figure 4



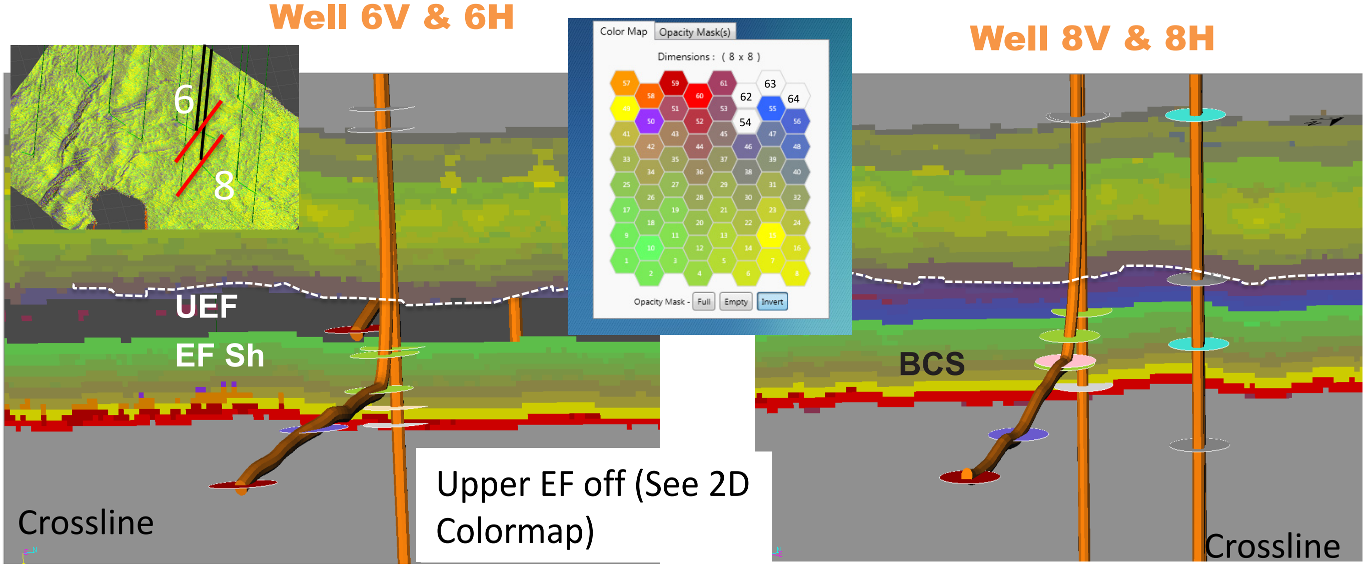
NOTE: Seismic thickness is 110 ms

The purple band in these views is the unique lithology of the Basal Clay shale (BCS), a presumed pelagic deposit. In the underlying Buda, scour shapes in neuron 57 and 59 (red) on the left contrast starkly with the continuous bands of both facies in the vicinity of Well 4. Neuron "facies" 51 and 58 at well 3, not present on the line over Well 4, have been turned off to enhance the appearance of the scours. The overall thickness of the Buda shown is only 10ms.

A time slice (**Figure 4**) in the area just downdip of the last figure shows detailed stacking variations across the upper Buda along its northern edge. Yellow neuron 49 facies come in above red 59 and underneath orange 58 of last figure, before the latter then the former laps out to the NE. A compressional fault is distinct in the time slice and is apparent throughout the vertical section in nearby crossline (circle). Probable karst features are apparent to the SW and NE in the uppermost Austin Chalk in both views.

At the dip position of wells 6 and 8 on the Instantaneous Spectral Decomp result set (**Figure 5**), the Upper Eagle Ford marl varies little in neuron sequence. With neurons 54, 62, 63, and 64 turned off across the #6 boreholes, the scour at the base of the Austin Chalk outlined by a white dashed line

Figure 5



NOTE: Seismic thickness is 110 ms

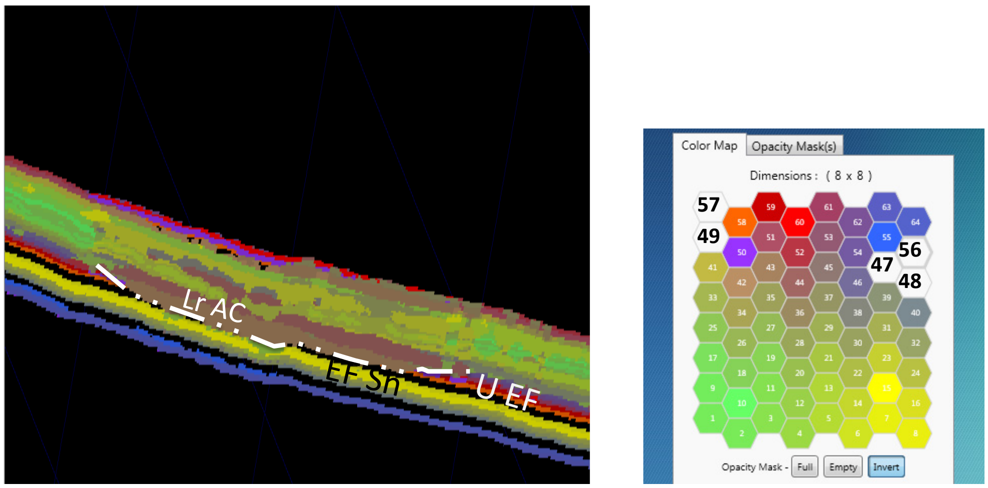
NOTE: Seismic thickness is 110 ms

can be seen to carve into marl neuron facies 46 and 54. In this dip position, the Basal Clay Shale (BCS) is lowest olive color.

Similar features of angular unconformity at the base of the Austin Chalk and phenomenal karsts can be seen on the Instantaneous SOM result for the **Linear 26.5Hz** result (**Figure 6a, b, c**) and are enhanced by the use of the interactive colormap. Corresponding neurons are turned off in the 2D Colormap in the upper left for the Upper Eagle Ford above the Eagle Ford shale and in the upper right for measures below the Eagle Ford shale. Note the absence of unconformity or any of the key stratigraphic features on conventional seismic display.

Figure 6a

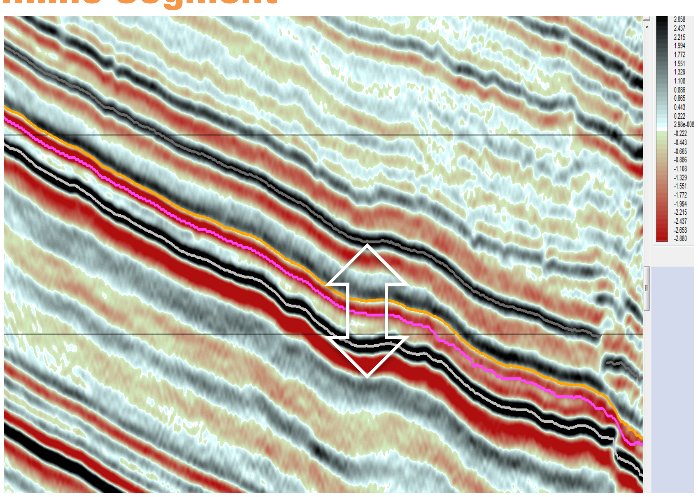
Inline Segment



NOTE: Seismic thickness is 110 ms

Figure 6b

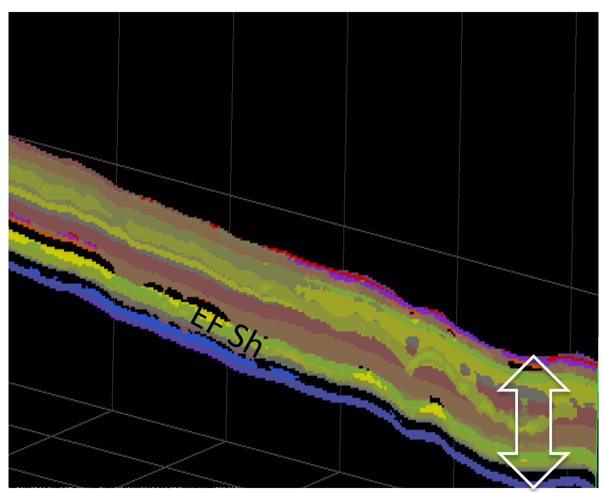
Inline Segment



NOTE: Seismic thickness is 110 ms

Figure 6c

Karst Feature or "Influence"?



NOTE: Seismic thickness is 110 ms

Patricia Santogrossi

Sr. Geoscientist | Geophysical Insights

Patricia Santogrossi is a geoscientist who has enjoyed 40 years in the oil business. She is currently a Consultant to Geophysical Insights, producer of the Paradise multi-attribute analysis software platform. Formerly, she was a Leading Reservoir Geoscientist and Non-operated Projects Manager with Statoil USA E & P. In this role Ms. Santogrossi was engaged for nearly nine years in Gulf of Mexico business development, corporate integration, prospect maturation, and multiple appraisal projects in the deep and ultra-deepwater Gulf of Mexico.

Ms. Santogrossi has previously worked with domestic and international Shell Companies, Marathon Oil Company, and Arco/Vastar Resources in research, exploration, leasehold and field appraisal as well as staff development. She has also been Chief Geologist for Chroma Energy, who possessed proprietary 3D voxel multi-attribute visualization technology, and for Knowledge Reservoir, a reservoir characterization and simulation firm that specialized in Deepwater project evaluations.

A longtime member of SEPM, AAPG, GCSSEPM, HGS and SEG, Ms. Santogrossi has held various elected and appointed positions in these industry organizations. She has recently begun her fourth three-year term as a representative to the AAPG House of Delegates from the Houston Geological Society (HGS). In addition, she has been invited to continue her role this fall on the University of Illinois' Department of Geology Alumni Board.

Ms. Santogrossi was born, raised, and educated in Illinois before she headed to Texas to work for Shell after she received her MS in Geology from the University of Illinois, Champaign-Urbana. Her other 'foreign assignments' have included New Orleans and London. She resides in Houston with her husband of twenty-four years, Joe Delasko.

GEOPHYSICAL INSIGHTS
FROM INSIGHT TO FORESIGHT

8584 Katy Freeway, Suite 400, Houston, TX 77024
Phone: 713.360.2507

www.geoinsights.com