4D Seismic to Image a Thin Carbonate Reservoir During a Miscible CO$_2$ Flood: Hall-Gurney Field, Kansas, USA

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Introduction. Time lapse (TL) seismic monitoring has proven a valuable tool for reservoir management. If available in a timely, cost-effective manner, it can be incorporated into a dynamic reservoir management approach, specifically in terms of assessing sweep efficiency through constraining reservoir simulations, quantifying compartmentalization, and enhancing the placement of infill-wells. Thus cost-effectiveness, rapid turnaround time, and sensitivity of the seismic response to subtle changes in reservoir properties evident in production data are critical assets of a robust and economic TL-seismic application. Successful applications of TL seismic monitoring has been predominantly offshore—Gulf of Mexico and North Sea—in thick clastic reservoirs characterized as low technical risk. Changes in TL seismic images as a direct result of enhanced oil recovery operations in low compressibility, "stiff," carbonate reservoirs are so small that distinguishing reservoir fluid changes from background noise on seismic attribute maps is challenging at best and many times impossible. Reservoirs predicted to produce weak TL anomalies associated with enhanced oil recovery (EOR) operations are classified as high-risk cases and languish in what has been designated the "stretch portfolio" of time-lapse application in reservoir management.

Significant reservoir heterogeneity and high rock frame stiffness complicate the use of 4D-seismic monitoring of fluid changes in carbonate rocks during EOR or carbon dioxide (CO$_2$) sequestration activities. As well, background noise and residual differences in time, phase, amplitude and frequencies after cross-equalization represent obstacles to all 4D-seismic monitoring projects. For this application, the key to successfully monitoring the movement of miscible CO$_2$ injected into a shallow (900 m) thin (3.6-6 m) carbonate reservoir was a high-resolution approach. This approach concentrated on repeatability during acquisition and processing, and use of amplitude envelope 4D-horizon attributes. Amplitude envelope values were extracted from the baseline and three monitor surveys acquired at approximately two-month intervals during the first eight months of a DOE-sponsored EOR pilot study in an Upper Pennsylvanian shelf carbonate reservoir in central Kansas. Production data and reservoir simulations compared to seismic images provided a measure of the effectiveness using TL-seismic to detect weak anomalies associated with changes in fluid concentration.

Revealing TL-anomalies using a nonlinear color bar was instrumental in increasing interpretation confidence in areas with change. Assignment of a single color to all values above and below a progressively decreasing range of values while searching the data for spatially significant textural differences between the baseline and monitor datasets highlights areas that otherwise would not be distinguishable from noise due to the coarseness of the scale. These textural differences are relatively stable over a range (two-three color steps) of scanned levels, further advancing the suggestion of production and/or EOR effects. Production simulation, production data, and seismic consistency in multiple surveys solidified the relationship between these textural changes and reservoir response to CO$_2$ injection. Our approach, called parallel progressive blanking (PPB), proved sensitive to weak time-lapse signatures that otherwise would have been concealed by noise and remnants of balancing/cross-equalization techniques.

The 4D-seismic interpretation approach applied here allows better focusing of color scales within the critical textural-difference range on time-lapse attribute maps, thereby

enhancing apparent resolution within the critical range. Below the temporal resolution in thin heterogeneous stiff reservoirs, signatures of reservoir change are encoded in and interfered with main events. Small changes in fluid saturation will manifest themselves as subtle spatial changes in texture rather than monotonically increasing or decreasing horizon attributes. The following is a case study demonstrating successful use of the PPB approach to track the CO_2 flood bank in a thin carbonate formation in the Hall-Gurney field, Kansas, USA. Production data from wells and field simulations provide evidence of the viability of the PPB approach when searching for weak TL anomalies. As will be shown later in this paper, this approach is also aiding our efforts analyzing these high-resolution data to distinguish subtle seismic characteristics and associated trends related to depositional lithofacies and geometries and structural elements of this carbonate reservoir that impact fluid character and EOR efforts.

Hall-Gurney field: Development phase and geological setting. Primary production in the Hall-Gurney field began in 1931 and was followed by extensive waterflooding during the 1950s and 1960s (Figure 1). Waterfloods reached their economic limits in the 1970s and 1980s. Bypassed and stranded oil has been postulated to represent a significant resource accessible through CO_2 miscible flooding techniques. The target of the current EOR-CO_2 miscible flood is a thin (3.6-6 m-thick), carbonate formation (Plattsburg) "C zone" within the Lansing-Kansas City (L-KC) groups in this central Kansas field. The C zone is part of a sequence of Upper Pennsylvanian cyclic deposits classically termed cyclothems. Modern wireline logs and core data from the recently drilled CO_2 injection well (CO2I#1) and well No. 16 validate previous general reservoir models based on data from mid-century development of this field but, importantly, also show previously unrecognized reservoir complexity. The CO_2 target C zone is composed of as many as three stacked, shallowing-upward cycles that are contained within a single higher-order shallowing-upward sequence that formed in response to sea-level fluctuations over a broad Kansas shelf.

Reservoir rocks in the C zone are oolitic grainstones that were originally deposited as shallow marine coarse-grained ooid sands concentrated on bathymetric highs on the shelf. Subaerial exposure and meteoric water percolation in the shallow shelf setting commonly caused ooid dissolution, resulting in oomoldic grainstone textures. The dissolution of ooids along with fracturing and crushing (providing connectivity between ooid molds) resulted in the oomoldic grainstones being the principal reservoir rock type (lithofacies). Each of the stacked cyclic deposits within the C zone is characterized by vertically increasing porosity and permeability resulting in vertical heterogeneity. Previous study of well log and core data indicate lateral lithofacies changes resulting in lateral heterogeneity.

The vertical and lateral heterogeneity in reservoir properties (permeability/pressure barriers or sealing discontinuities) has been suggested as an explanation for the differences between observed and predicted production data associated with CO_2 injection. Wellhead measurements suggest the most pronounced anomaly within the demonstration area is between the CO_2I#1 and No. 13 wells (Figure 1). Standard reservoir simulation models based on well bore geology (including cores), historical production data, and pre-injection test data indicated communication problems but failed to accurately predict the response of well No. 13. The synergy between geophysicists overseeing the TL-monitoring of the CO_2 flood and the reservoir management team engineering the production scheme proved crucial for reconciling and upgrading the reservoir simulation to respect both the production data and changes observed on TL-monitoring data. Arrival of CO_2 at production well No. 12 was generally consistent with

models of the flood completed prior to commencing the EOR program. However, the advance of CO_2 toward well No. 13 was much slower than predicted and a matter of concern to production engineers and investors. Evident from pre-flood production and seismic data was a fluid barrier (discontinuity) between wells CO2I#1 and No. 13 and an additional barrier south of well No. 18. Key to improving the reservoir simulations were detailed adjustments in permeability and increasing the number of model layers, both characteristics derived from geologic and seismic models. Unraveling the localized variability in the reservoir was necessary to economically produce this field.

TL-Horizon map interpretation: Parallel Progressive Blanking (PPB) approach. The PPB concept is based on the observation that differencing alone will not recover reservoir anomalies if the magnitude of change in seismic response is less than the amplitude of non-repeatable background noise. Using PPB, changes in reservoir seismic signature can be revealed at levels far below what has conventionally been demonstrated. Background color is assigned to all values above and below a progressively changing range while focusing the full color spectra to enhance spatially significant textural differences between the two datasets. The PPB approach can be illustrated (Figure 2) by placing a very weak TL anomaly over a TL attribute profile from a seismically innocuous area (blue). Because the (below noise fluctuations) amplitude of change is low, textural differentiation is a more feasible approach than differencing the baseline survey (green) with a TL dataset (blue). PPB highlights weak reservoir signatures (texture), suppresses background noise, and focuses the highest resolution components of the color scale on the critical range of attributes.

The PPB method is an alternative to TL-map differencing when targeting low signal-to-noise TL anomalies and can be described succinctly using the following expressions.

$$B(x, y) = S_T(x, y) + N_b,$$

where $B(x,y)$ is the baseline survey attribute horizon map and $M_1(x,y)$ is a monitor survey (acquired at some later time) attribute horizon map

$$M_1(x, y) = S_T(x, y) + S_{TL}(x, y) + N_m,$$

where N_b and N_m are random noise in baseline attributes and TL attributes respectively, and S_{TL} is the change in attributes due to a change in physical properties. The anomaly (S_{TL}) is not distinguishable over the background signal/noise levels on difference maps ($B-M_1$), when $N_b - N_m$ is equal to or greater than S_{TL}. The extremely subtle S_{TL} imprinted on the S_T, combined with the non-geologic, highly variable N_m results in textural differences between baseline and monitor horizon attributes at "optimum" PPB-level. This textural change is only observable when PPB-levels for the baseline horizon are selected near background levels. Intrinsic with this approach is the need to suppress background noise so a larger color range is available within this critical variability range of TL and baseline attribute maps.

Time-lapse seismic monitoring of Hall-Gurney EOR-CO$_2$ flood. Distinguishing changes in fluid on TL-seismic data from carbonate reservoirs is difficult due to complex geologic variability that is commonly characteristic of these rock types. Thus, a carbonate reservoir setting, such as at the Hall-Gurney field, is the ideal place to evaluate the PPB interpretation approach. The PPB approach for identifying weak TL anomalies was applied to three pilot, high-resolution TL 3D-seismic datasets (with about a two month survey-to-survey interval). These data were acquired for monitoring the miscible EOR-CO_2 flood in the shallow (depth of about 900 m) thin (3.6-6 m) oomoldic carbonate reservoir C-zone in the Hall-Gurney field.

Heterogeneity of petrophysical properties established by production data (pressure and fluid measurements), small size of the reservoir, and small change in impedance (less than 10% estimates from Gassmann modeling) after replacement of reservoir fluids with CO_2 all predict difficulty monitoring the EOR-CO_2 flood with TL-seismic techniques.

With the expected small change in seismic response relative to the change in fluid during the CO_2 flood at the Hall-Gurney field, the PPB method seemed like a perfect fit (Figure 2). Since this method does not involve differencing, PPB can be applied to amplitude envelope maps of baseline and monitor data without equalization operations. Unlike differencing, PPB allows more control (determining the PPB range and scale segmentation) on the part of the interpreter, placing a more significant emphasis on matching display characteristics with the geologic setting. We selected the amplitude envelope or reflection strength seismic attribute because of its insensitivity to small uncompensated phase differences between baseline and TL-datasets. Advancement (Figures 3b, c, d, e) of the injected CO_2 plume was successfully monitored using the PPB technique and verified against independent production data. Seismic data quality is good; the seismic horizon of interest within the L-KC group is pronounced and can be confidently interpreted across the entire in-line slice. Data were acquired specifically focusing on this thin zone and therefore reflections outside this target window are of lesser quality (Figure 4).

Validation and assessment. Integrating TL-seismic interpretations with production data helps equilibrate results with real reservoir characteristics and allows more meaningful geologic and engineering models. For example, pressure maps, fluid composition, and flow rates of fluids between wells are all types of information that can be incorporated. Our mapping of the EOR-CO_2 injection in Hall Gurney field using 4D seismic data has honored

- solvent "CO_2" breakthrough in well No. 12 (Figure 3c);
- inter-well testing indications of a pressure communication/permeability barrier between Well No. 13 and Well CO_2;
- reservoir simulation-based prediction that solvent "CO_2" will move northward from CO_2 injection well;
- lower cumulative oil production observed in well No. 13 than previously projected for the reservoir simulation period (8 months) studied here; and
- material balance calculations integrating reservoir architecture inferred from core measurements and reservoir injection data and production data.

Geological and engineering calibration of seismic similarity and lineaments. Based on well logs, core, and production data, it is envisioned that the depositional environment for the C zone in the Hall-Gurney field area was that of a tidally dominated ooid shoal complex, which other studies have shown to be a common depositional motif for similar cyclothemic strata throughout the Pennsylvanian in Kansas. An important aspect of our ongoing efforts is focusing on details of seismic attributes associated with the C zone that appear to be showing depositional lithofacies and structural elements resolved at an unprecedented scale (e.g., Figures 5 and 6). Relatively few published land-based 3-D seismic surveys have focused on oolitic reservoir systems. Those that have been published are at the typical industry resolution and result only in larger scale delineation of general shapes on the order of tens of meters. The data in our study allow resolution of the Hall-Gurney oolite shoal complex in the C zone at a scale of approximately 5 meters. Studies in the Modern and ancient show that ooid shoal depositional environments are complex in regard to lithofacies distribution. Although seismic similarity facies maps in our study (Figure

5) are averaged over a thickness of approximately 5 m and reflect several stacked oolitic deposits, they are providing a level of detail that can be more closely related to features observed within individual oolitic shoal complexes as documented from the Modern (Figure 5c) and other ancient examples. The seismic attribute, "similarity," in our study was calculated and an optimum sliding median window (five samples) selected to average over, outputting a five-sample average value for every time sample. Similarity areas ("seismic facies") with higher (dark and light blue) similarity are correlated with better reservoir properties (higher permeability), whereas lower similarity areas (golden to red) are correlated with lower reservoir quality (lower permeability). The similarity changes are interpreted as representing heterogeneity within the C zone carbonate unit rather than heterogeneities within the encasing material. In looking at the similarity patterns on Figure 5 and comparing with Modern examples (Figure 5c), it is not unreasonable to interpret sinuous to linear, isolated pod-shaped, and apparent parabolic features on the similarity map as reflecting small scale depositional features within an ooid shoal depositional system, with blue areas representing ooid-dominated shoals (good reservoir quality) and golden to red areas representing inter-shoal depositional environments and differing lithofacies characterized by poorer reservoir quality. After about a year of monitoring the CO_2 flood using 3D-seismic surveys with about two month survey-to-survey time lapse, the expansion of the CO_2 bank is strongly influenced by the elongated NE-SW trending higher similarity areas.

In addition to depositional lithofacies patterns, it is apparent that structural elements, including lineaments, contribute to heterogeneity in Hall Gurney field and may have influenced the location of depositional lithofacies. Curvature attribute seismic lineaments (Figure 6) trending NNE-SSW play an important role in the interconnectivity between areas with higher similarity (higher permeability paths). Unlike the timely (according to initial reservoir simulation) and predicted response in well No. 12, the poor (lagging) response of well No. 13 to CO_2 injection can be attributed to both its location relative to areas of lower similarity and being close to perpendicular to the CO_2-injection well relative to both the dominant lineaments (NNE-SSW) and the trend (NE-SW) of higher similarity and better reservoir property facies. Our ongoing studies are focused on further detailed geologic and attribute studies to delineate the relative contributions of depositional facies and structural elements at finer scales to better understand reservoir heterogeneities that are important to EOR efforts.

Discussion and conclusions. The PPB approach, though it is difficult to automate, was very effective at mapping a weak TL anomaly that otherwise would have been difficult, if at all possible, to map using TL-differencing. It is qualitatively efficient to apply PPB in situations where weak TL imprints are unlikely to be pronounced relative to background on difference maps. To reveal subtle TL anomaly textures, selecting a small, optimum range of high-resolution colors is essential to the successful application of PPB. It is also critical to avoid applying severe equalization methods that might subdue significant parts of TL signatures indicative of reservoir changes.

By avoiding non-repeatable noise differencing and by color resolution focusing/sliding (Figure 3a) to optimize the scale resolution within the range of variability on an attribute map, the PPB approach does preserve/enhance TL-textural imprints. Additional quality control is provided by the baseline attribute map to which PPB has also been applied in a manner that preserves maximum similarity between baseline and monitor surveys in areas where no reservoir change is expected.

A real positive aspect of applying PPB is the high cost-effectiveness of mapping TL-EOR anomalies based on a non-inversion or "direct" seismic data attribute; in this case normalized amplitude envelope or reflection strength. From this perspective the processed data are not as influenced by the interpreter as is the case with results based on inversion attributes.

The unprecedented resolution of 5 m is allowing detailed imaging of geologic features of the C zone. Similarity maps show sinuous to linear, isolated pod-shaped, and apparent parabolic forms with differing reservoir (permeability) quality that are consistent with small scale depositional features that occur within ooid shoal complexes. Lithofacies changes associated with these similarity patterns could be a major factor controlling observed heterogeneity within the C zone. Curvature attribute seismic maps indicate the presence of lineaments affecting the C zone that also appear to play an important role in reservoir character and impact EOR efforts. The likely interplay of lithofacies patterns and structural elements (lineaments) in controlling reservoir character and production patterns associated with the CO2 EOR effort is demonstrated by the movement of the CO_2-bank, which appears to be influenced by the elongated NE-SW trending higher similarity "seismic facies" areas (better reservoir properties) as well as the NNE-SSW lineaments, which provide interconnectivity among the higher similarity areas.

Suggested reading.

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Lumley, D.E., R.A. Behrens, and Z. Wang, 1997, Assessing the technical risk of a 4-D seismic project: *The Leading Edge*, v. 16, n. 9, p.1287-1292.

Figure Captions.

Figure 1. Map showing 10+-acre flood pattern for the DOE-sponsored CO_2 miscible flood in the Hall-Gurney Field.

Figure 2. Schematic of the PPB approach of revealing below-background TL anomalies.

Figure 3. (a) "Optimum" PPB color scale applied to baseline and TL amplitude envelope horizon attribute. Normalized amplitude envelope maps from four surveys: (b) baseline (November 2003), (c) first monitor (January 2004), (d) second monitor (April 2004), and (e) third monitor (June 2004). Spatially and temporally persistent anomalous feature (dashed blue circle) on all surveys.

Figure 4. Typical seismic line from the third monitor survey showing interpreted time horizon of L-KC top.

Figure 5. Similarity "seismic facies" map. (a) Highest similarity shown in blue and lowest similarity shown in red. The better reservoir properties occur in blue areas as demonstrated by preferred (faster) EOR-fluid movement in those areas and generally in a SW-NE trend. Well No. 13 has had delayed response as a result of being separated from a CO_2 injection well (yellow) by lower (golden-red) quality reservoir properties. The distribution and geometries associated with similarity seismic facies patterns are suggestive of a complex ooid shoal depositional motif, which is supported by oolitic lithofacies being the known reservoir in this interval (image ~ 0.75 mi. square). (b) Same as (a) but with time structural map (upper map) showing highest areas in red and lowest areas in blue. (c) Modern oolite shoal examples. A) Southern part of Eleuthera Island in the northern Bahamas. Dark blue is deep water and light blue is shallow-water platform area. Oolite shoals (lightest color) near the edge of platform are curved, elongate bodies that are dissected by tidal channels. NASA Photo ID: STS066-88-056. B) A portion of the Tongue of the Ocean (dark blue, bottom left) and the Bahamas Bank (light blue). Oolite shoals near the edge of the bank are elongate and parabolic in shape. NASA Photo ID: STS005-37-839. C) Joulter's Cay area of the Bahamas showing ooid shoal complex (light gray areas) dissected by tidal channels. Note pod-shapes of some bodies (from Harris, 1994).

Figure 6. Seismic lineaments map. The main trend of lineaments, shown in gold, is NNE-SSW.
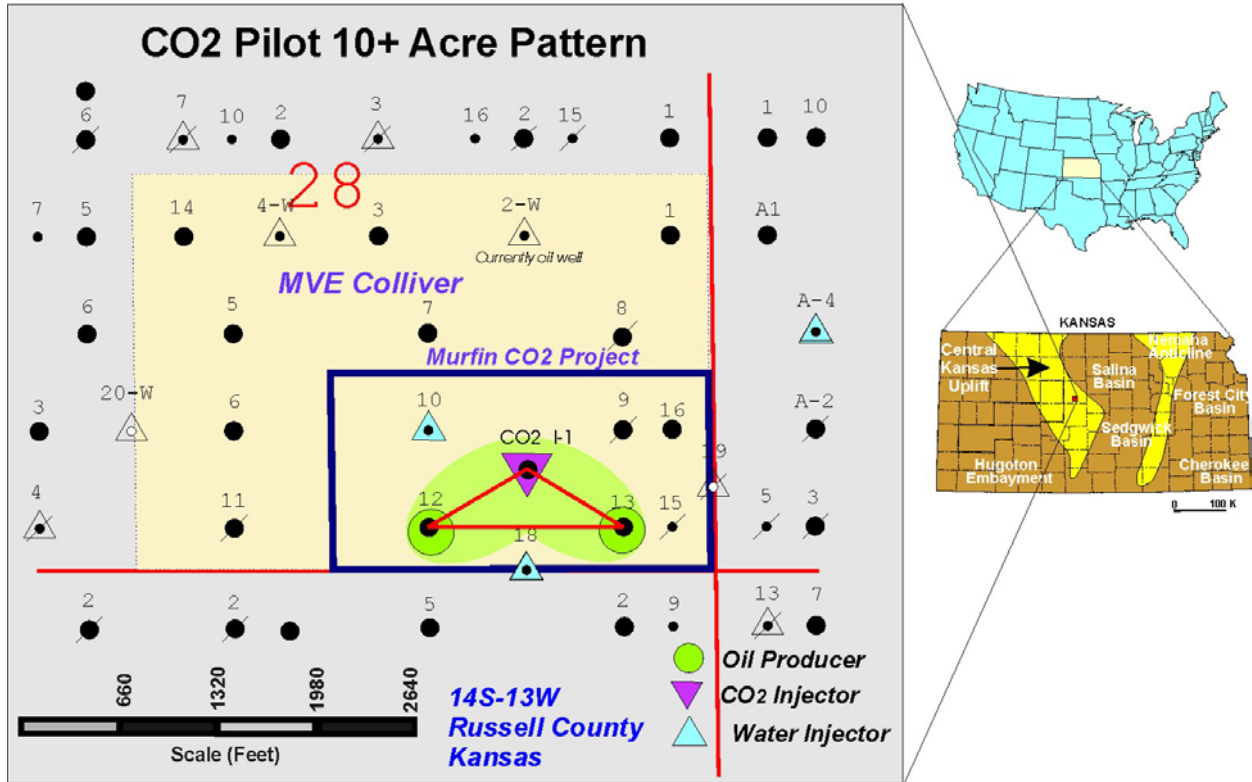
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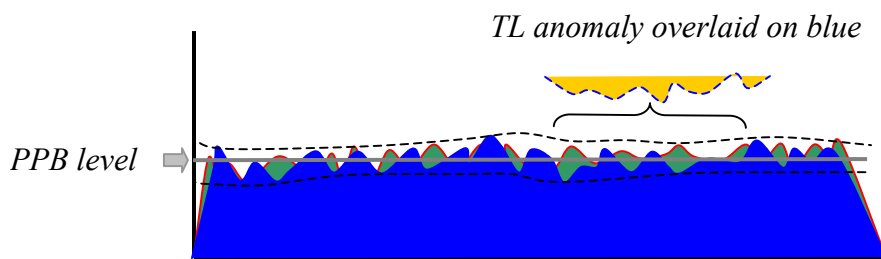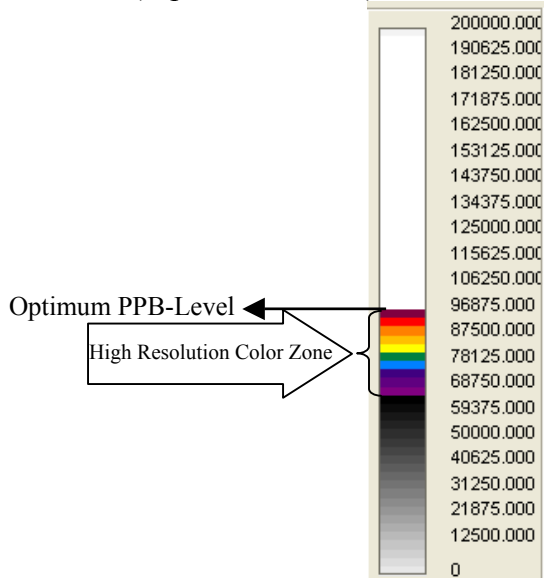

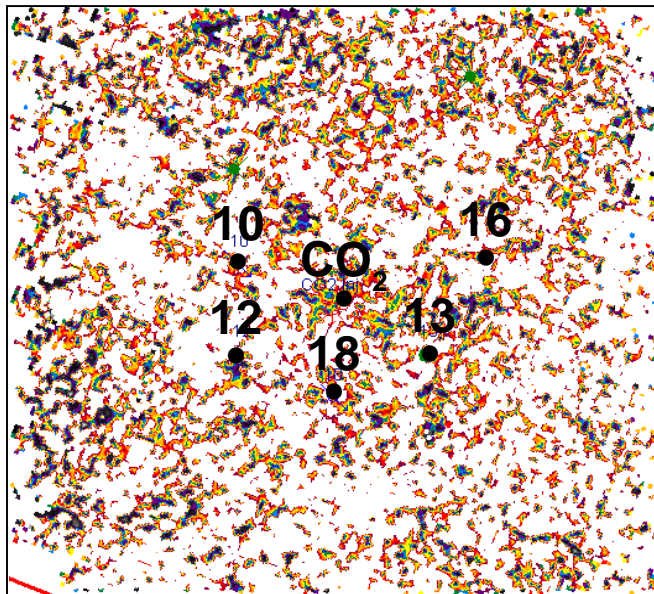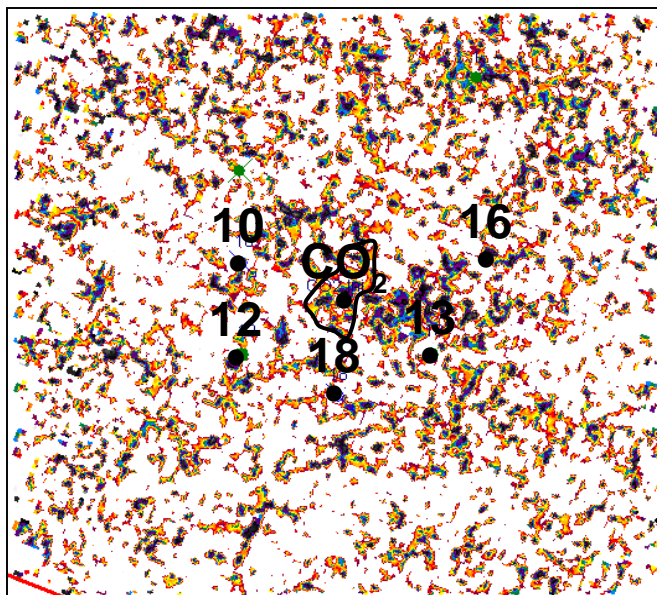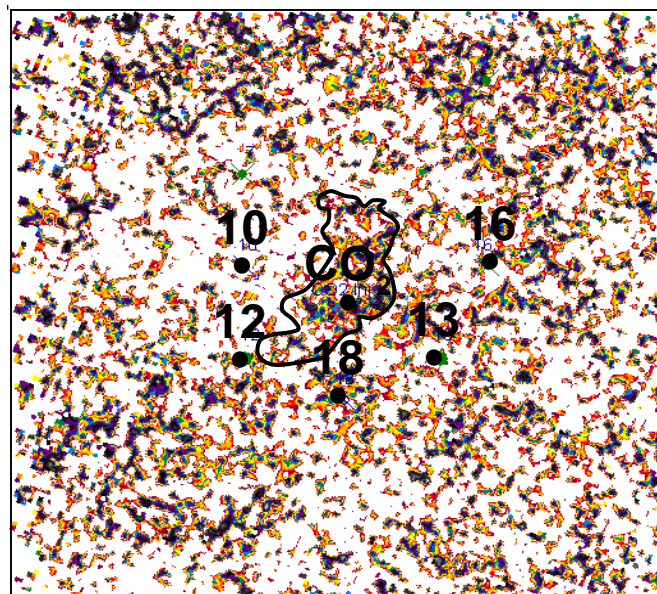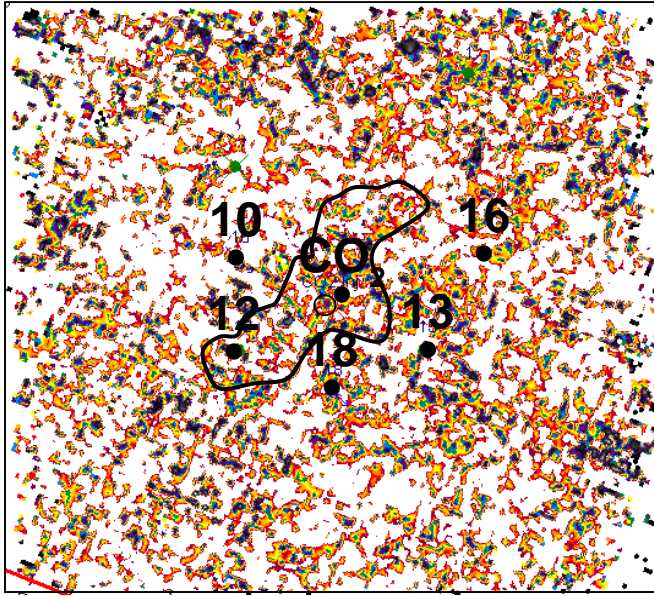Figure 2. Schematic of the PPB approach of revealing below-background TL anomalies.

Figure 3 a-e. (caption at bottom)

(a)

Optimum PPB-Level

High Resolution Color Zone

	200000.000
	190625.000
	181250.000
	171875.000
	162500.000
	153125.000
	143750.000
	134375.000
	125000.000
	115625.000
	106250.000
	96875.000
	87500.000
	78125.000
	68750.000
	59375.000
	50000.000
	40625.000
	31250.000
	21875.000
	12500.000
	0

(b)

(c)

(d)

(e)

Figure 3. (a) "Optimum" PPB color scale applied to baseline and TL amplitude envelope horizon attribute. Normalized amplitude envelope maps from four surveys: (b) baseline (November 2003), (c) first monitor (January 2004), (d) second monitor (April 2004), and (e) third monitor (June 2004).
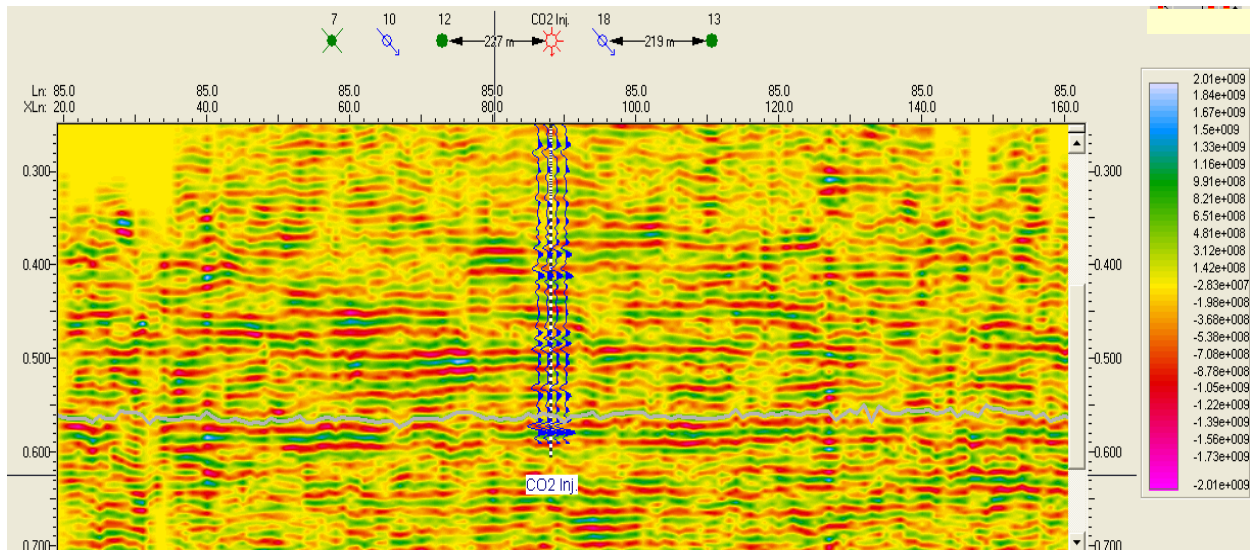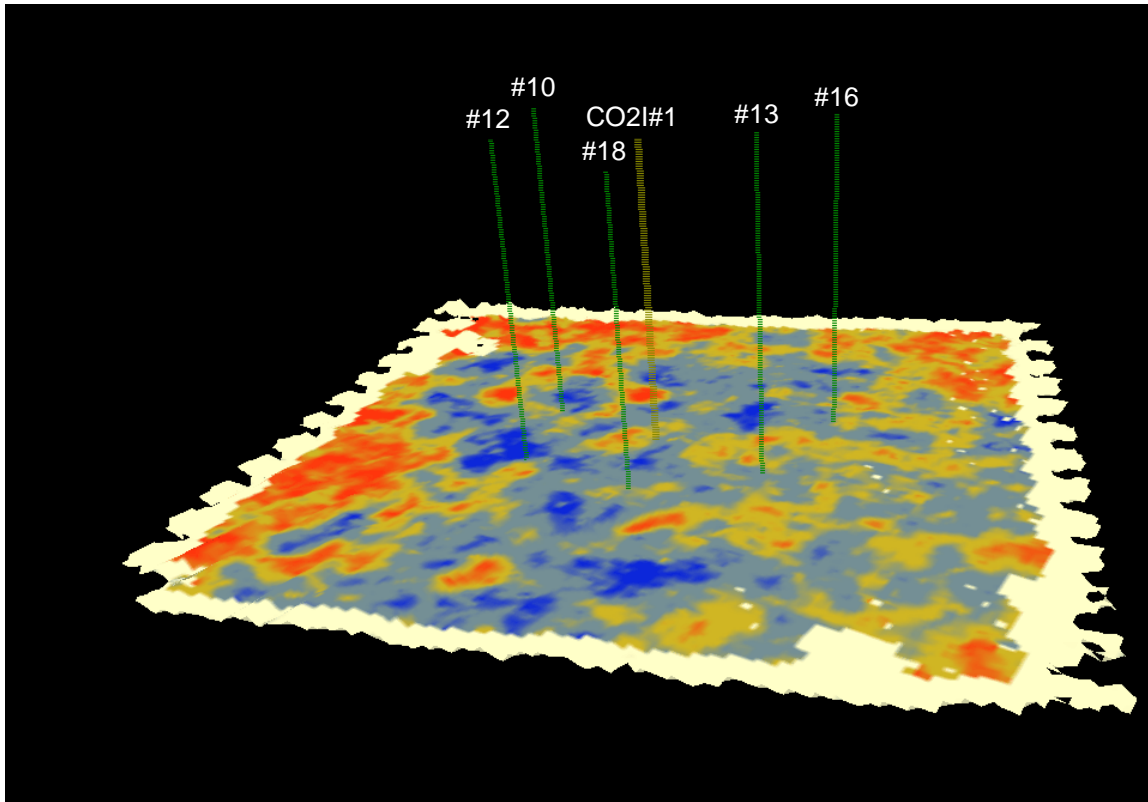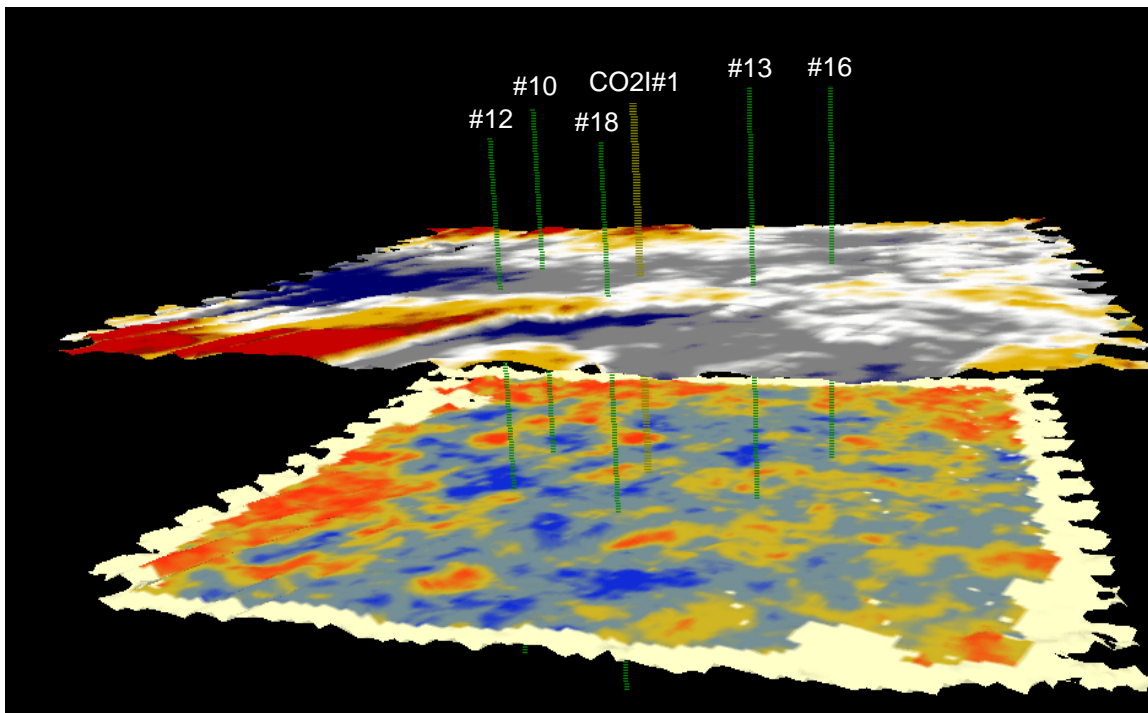

Figure 4. Typical seismic line from the third monitor survey showing interpreted time horizon of L-KC top.

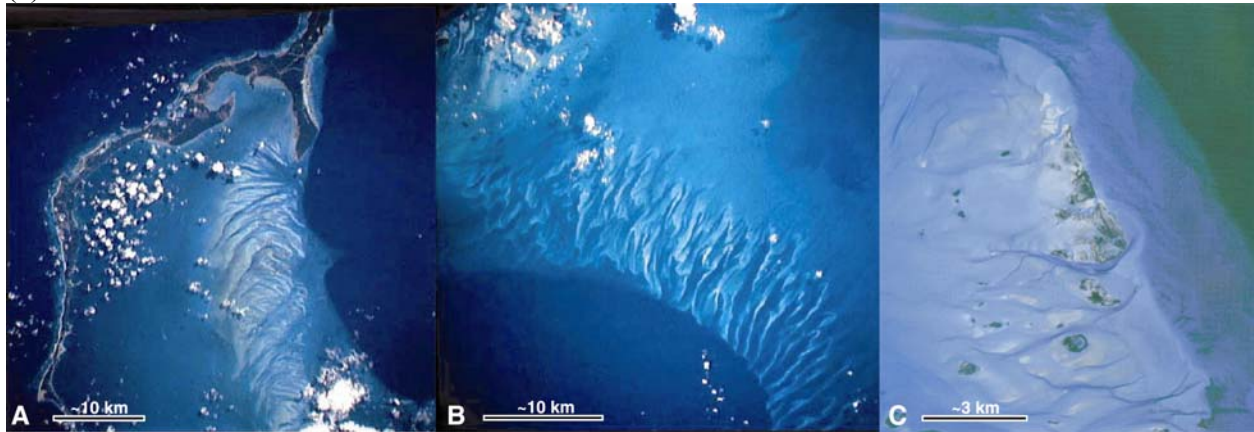Figure 5 a-c (caption at bottom)

(a)

(b)

(c)

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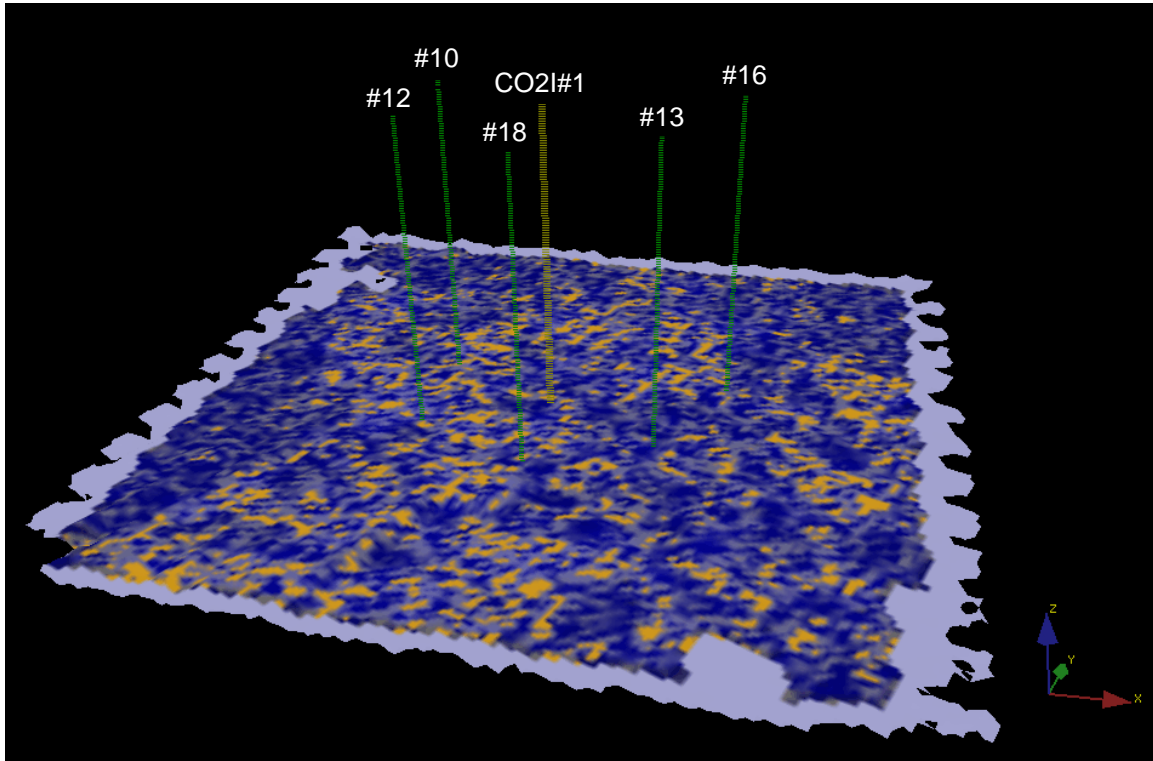
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