Applications of Generative Topographic Maps on Post-stack Data to Enhance Carbonate Reservoir Characterization

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Summary

Carbonate reservoirs provide numerous complications for accurate reservoir characterization and management. A seismic survey acquired in the Fall of 2019 over a Silurian (Niagaran) pinnacle reef gas storage reservoir is utilized to investigate the applicability of unsupervised machine learning techniques on volume attributes generated on angle stacks to enhance facies identification in seismic data. Utilizing the full angle stack currently provides the best result on this dataset, as the seismic facies classification workflow reveals the morphology of the reef core and peritidal facies.

Introduction

The Michigan Basin was a prolific hydrocarbon producer throughout the mid to late 20th century. Niagaran (mid-Silurian) pinnacle reefs were widely produced throughout the basin. Following production, many of these reefs were converted to storage reservoirs for natural gas and carbon sequestration. Despite the widespread production, few stratigraphic models of the internal structure and facies distribution of the reefs has been done. Rine et al. (2017) provides a core and log-constrained facies model for Niagaran reefs along the southern trend in the Michigan Basin and illustrates that the reefs are composed of distinct, predictable lithofacies.

Carbonate reservoirs, especially those that have undergone dolomitization, are characterized by a high degree of vertical and lateral heterogeneity (Pranter et al., 2005). Well data provides excellent vertical constraint on the distribution of reservoir properties, however provide little spatial constraint.

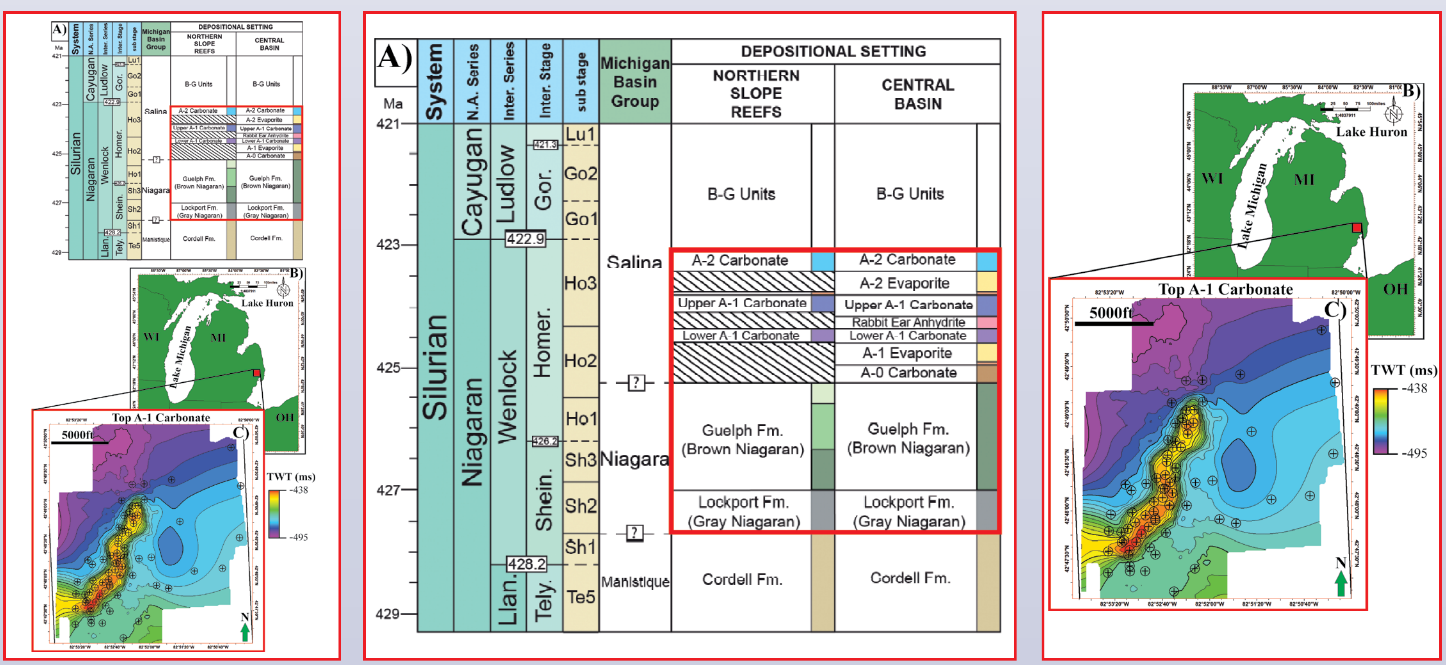

Figure 1: A- Chronostratigraphic chart for the Michigan Basin (After Rine et al., 2017). B- Overview map of the study area. C- TWT structure map of the A1 Carbonate displaying the structure and well locations of the Ray Reef study area.

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To better understand the spatial distribution of quality reservoir facies, a recently acquired three-dimensional (3-D) seismic survey over Ray Reef, a reef in the southern reef trend, is integrated with tightly-spaced well log and core data. A suite of volume attributes was generated on the full-angle stack and far-angle (20-30°) stack. Generative Topographic Maps (GTM) were then run on each volume for seismic facies classification.

Both core and log data from intersecting wells were then incorporated to map out facies within favorable reservoir zones to target for storage within the pinnacle reef complex. Following the analysis of the GTM, the resulting facies classification volumes will be used as constraints for geostatistical reservoir models to enhance reservoir management.

Field Description

Geologic Setting

The Michigan Basin is an intracratonic basin that exhibits unusual circular symmetry and is bounded by a continuous structurally stable area, and covers an area of 316,000 km^2. The Silurian reefs occur in the upper Niagaran Guelph Formation, also known as the Brown Niagaran, which rims the circular Michigan Basin. The reefs are presently buried at depths of 900 to 2000 ft. Individual reefs have average widths of approximately 1000 ft and average heights of 300 ft. Reef development was concentrated in two parallel lineaments on the northern and southern margins of the basin, basinward of wide spread shelf-edge reef complex.

The lithostratigraphy of the reefs is well established *(Figure 1a)*. Silurian reefs overly the Lockport Formation (informally called the "Gray Niagaran"), which is described as a micritic carbonate mudstone. Reefs are laterally encased unconformably by the thin limestones and evaporites of the Silurian Salina Group. Reefs along the southern reef trend have undergone extensive dolomotization. Haynie (2009) provides a well-based geostatistical model of petrofacies in Ray Reef, and defined favorable petrofacies as those with greater than 5 % porosity and permeability greater than 1mD. Overlying facies within the Upper A1 Carbonate and the upper portion of the reef core were proposed as the highest quality reservoir, and the stromatolitic cap facies (underlying the Upper A1 carbonate) and bioherm facies were identified as poor reservoir facies. The reef core is characterized by an abundance of fair to favorable reservoir facies, with an irregular, but consistent distribution. This model can be greatly improved by incorporating new stratigraphic models and observations made in 3-D seismic For gas storage, the target zones are the reef core in addition to conglomerate debris deposits located on the flank of the reef complex.

Data Description

In this study, a 3-D survey with an area of approximately 10 mi2 acquired in 2019 was used to analyze the internal structure of a Niagaran reef along the southern reef trend *(Figure 1c)*. The survey was cropped to the limits of the reef for efficient attribute generation *(Figure 2a)*. The survey has a 1 millisecond sample rate and two second record length, and a line spacing of 55 ft for both inlines and crosslines. Three volumes were available: a PSTM full stack volume, a near angle stack of 0-10 degrees, and a far angle stack of 20-30 degrees. Due to high amounts of noise in the angle stacks, these were omitted from the study. Vertical resolution within the reef interval is approximately 50 ft. The morphology of the reef matches that of the proposed model *(Figure 2b,c)*, however the seismic data fails to properly image the margins due to the steep dips. It is also important to note that as the reef exhibits velocity pull-up at the margins *(Figure 2c)*. At the time of acquisition, Ray Reef was at near full storage capacity, as it had 64.5 bcfg out of a total storage capacity of 65.4 bcfg.

A total of 81 wells are present within the study area. Of these, 15 are cored and have whole-core derived gamma ray, permeability, porosity, water and oil saturation logs. 7 wells have sonic logs and 6 have density logs. The remaining wells provide GR, resistivity and neutron logs. Average absolute open flow (AOF) measurements for 40 active storage wells were also made available by Consumers Energy.

Methods

Well Data

Formation tops and interpreted seismic surfaces were provided by Consumers Energy. Wells containing

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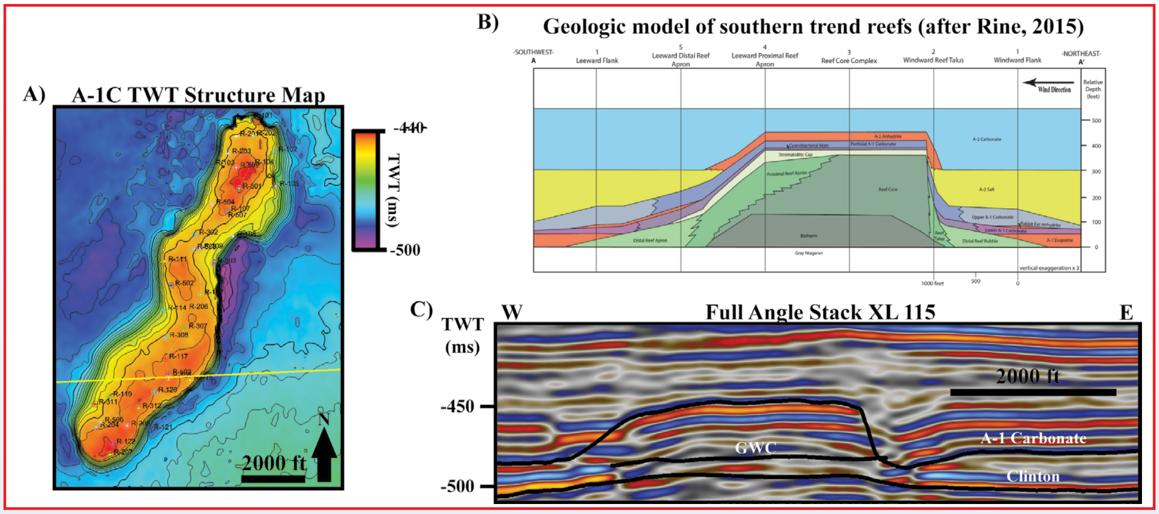
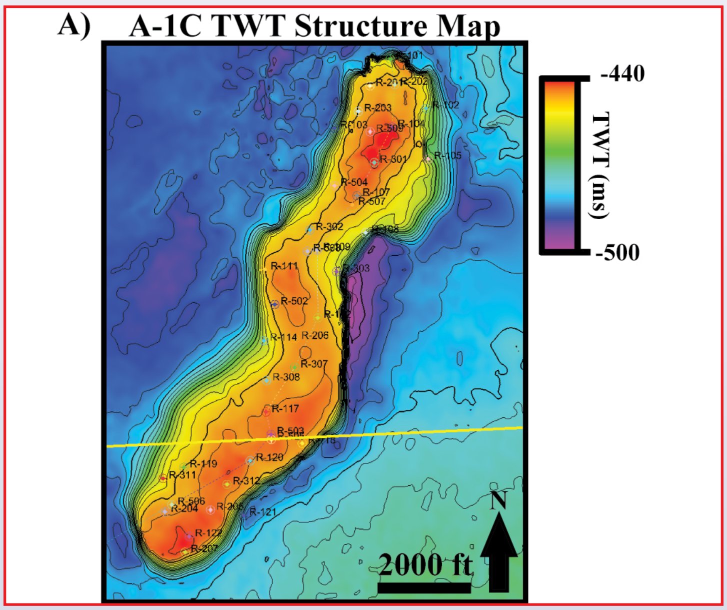
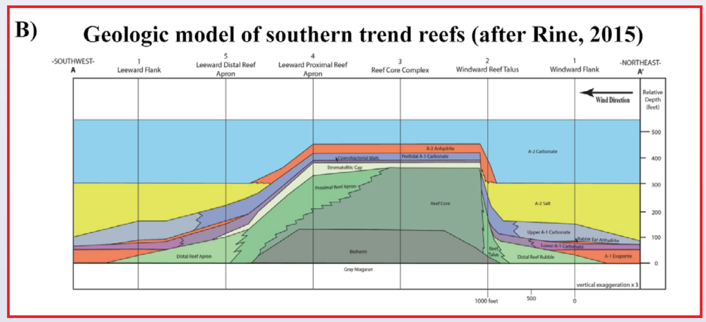
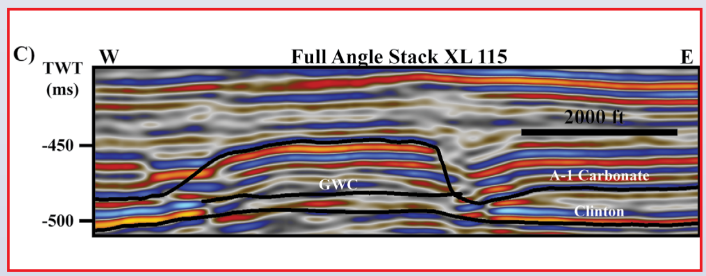
Figure 2: A- Zoomed in view of the A-1C TWT structure map. B- Geologic model for Niagaran pinnacle reefs along the southern reef trend proposed by Rine et al., 2017. C- Seismic amplitude section along XL 115 indicated by the yellow line in A.









sonic logs were utilized to calculate time-to-depth relationships. These time-depth relationships were then extrapolated to nearby wells to tie well data to the seismic data. Neutron logs were converted to neutron porosity logs constrained by porosity values derived from whole-core measurements following the method described by Shier (1991) and Haynie (2009).

Seismic Attributes

Previous studies over southern Niagaran reefs investigating unsupervised machine learning techniques applied to seismic data have identified that frequency-based attributes have the potential to differentiate high and low porosity zones from volume attributes (Buist, 2020). A similar suite of volume attributes is generated on each volume. This included: Instantaneous frequency, cosine of instantaneous phase, and iso-frequency volumes output from spectral decomposition. Instantaneous phase is defined as the arc tangent of the ratio of the imaginary and real parts of the seismic trace (Tanner, 1971). It is independent of amplitude and is related to the propagation of the seismic wave front. It can be applied to analyze stratigraphic continuity and configurations. As instantaneous phase is a cyclic attribute, the cosine of the instantaneous phase is chosen avoid the cyclic values as the GTM algorithm will interpret the discontinuity in the phase at 90° and -90° as different values, when in reality they are zero crossings. With cosine of inst. Phase, zero crossings are represented by values of zero and correctly interpreted by the algorithm. Instantaneous frequency is the time derivative of instantaneous phase. Low instantaneous frequency values have been shown to correlate to high porosity zones within Niagaran reefs along the northern

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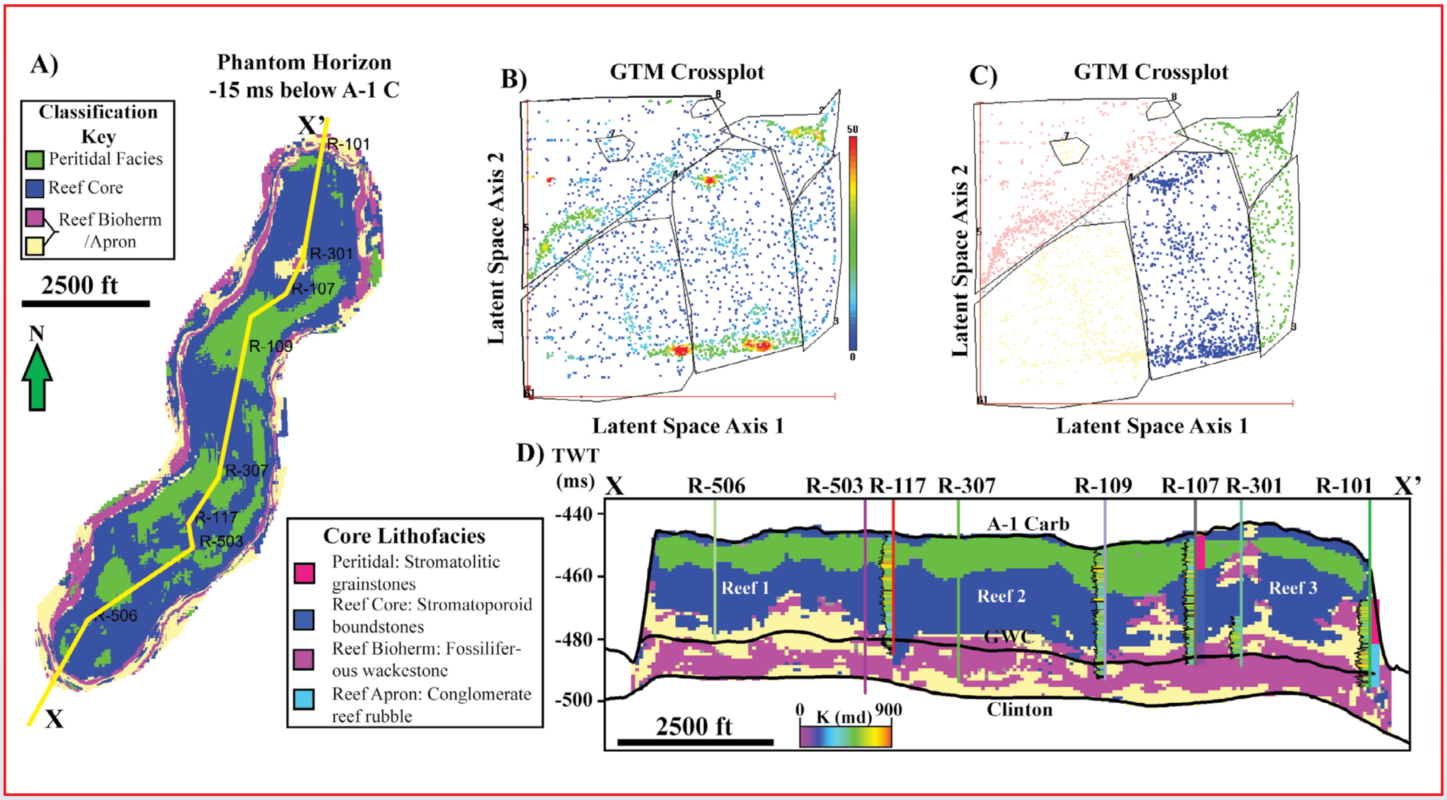

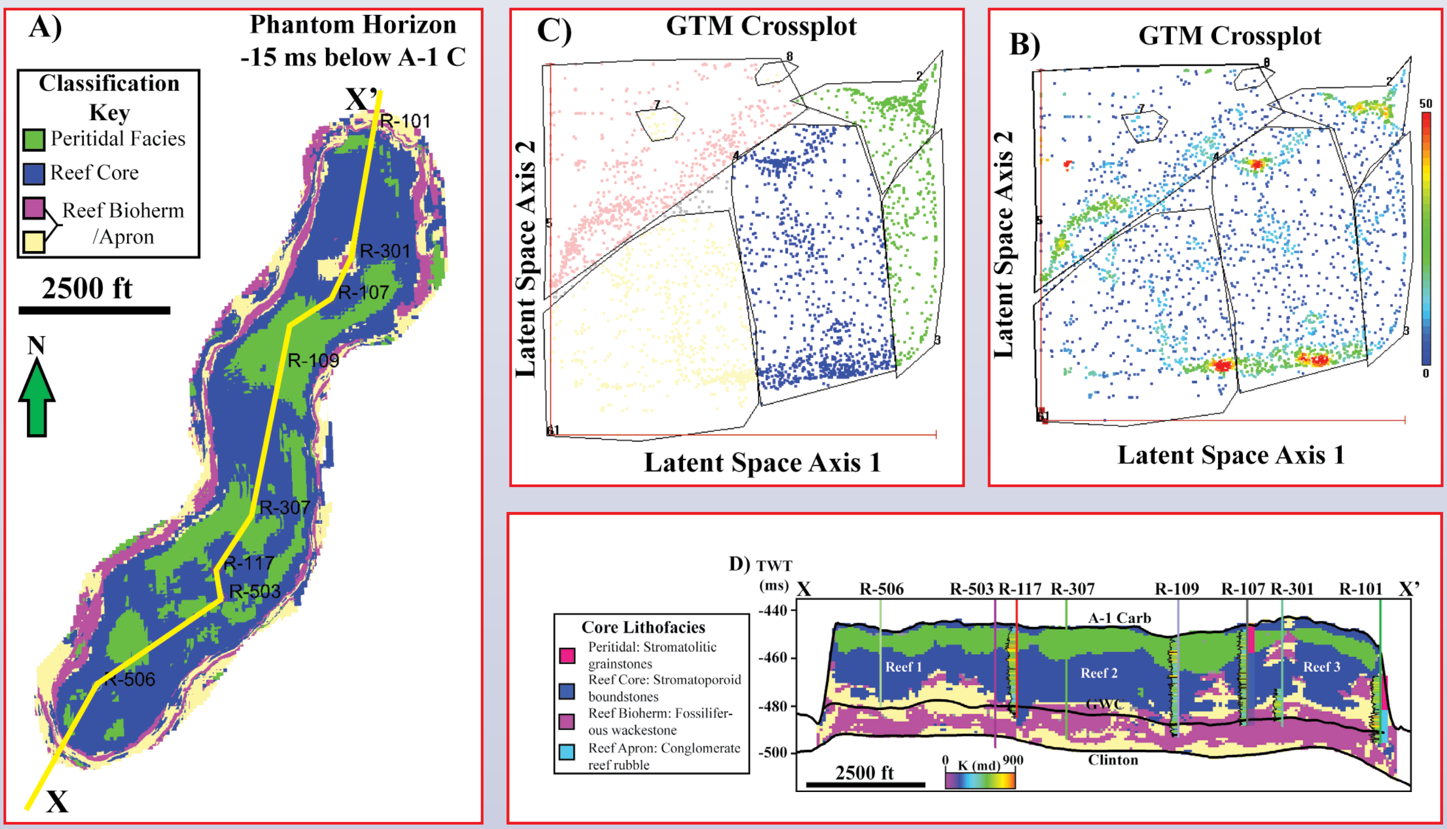

Figure 3: A- Phantom horizon 15 ms TWT below the A-1C horizon. B- GTM latent space axes cross plot with the data points colored by cluster density. The points represent the data shown in D. C- GTM latent space axes cross plot with the data points colored by class. D- Arbitrary cross section through the classified volume. Core-derived lithology and permeability logs are shown where available.

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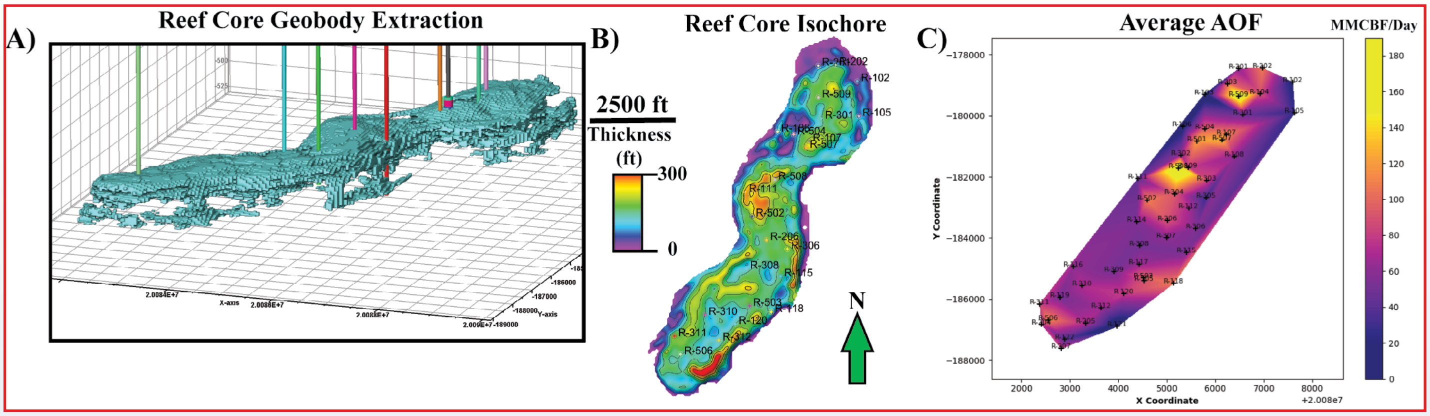
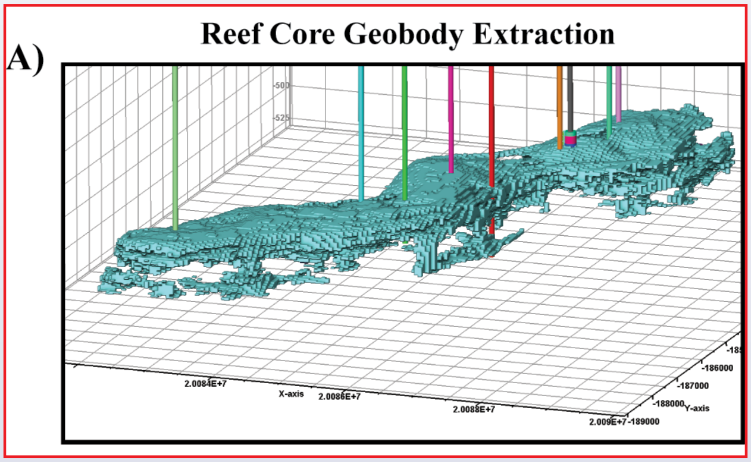




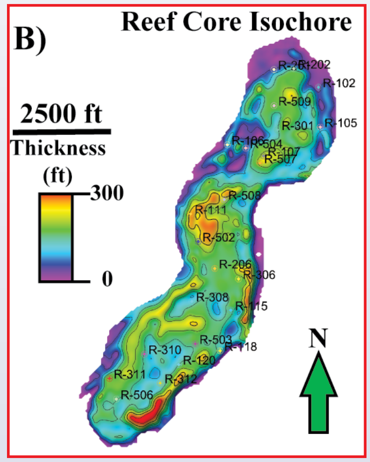
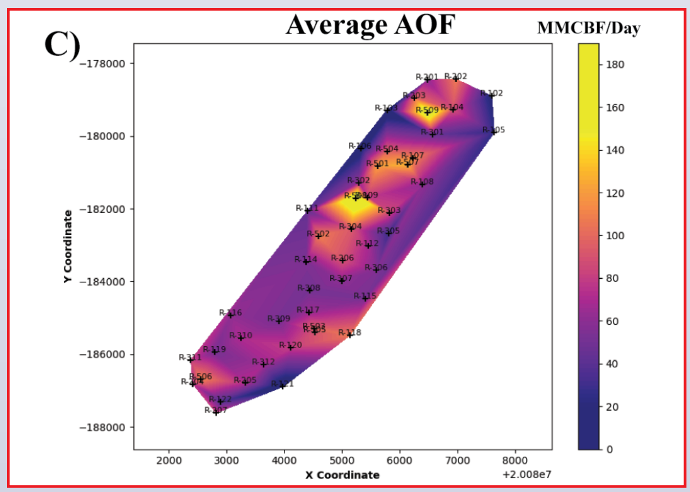


Figure 4: A- Reef core geobody extraction from the classified seismic volume. B- Isochore for the reef core faices. C- Average Absolute Open Flow (AOF) map of 40 active gas storage wells.



reef trend (Toole, 2012). Three iso-frequency cubes from spectral decomposition were also used as input. 24, 53, and 87 Hz frequency components were chosen based on their strong response in observed in the spectral domain, and these frequencies highlighted internal variations within the reef.

<u>Generative Topographic Mapping (GTM)</u>

The Generative Topographic Mapping algorithm (Bishop et al., 1998) is a dimensional reduction technique, allowing interpreters to analyze multi-dimensional relationships between multiple seismic attributes in a two dimensional latent space. It was formulated as a probabilistic extension of the popular self-organizing map (SOM) algorithm that is commonly applied to seismic data. GTM addresses some shortfalls of the SOM algorithm, such as the inability to initialize framework parameters, and no measure of convergence of the algorithm. GTM represents the distribution of multi-dimensional data vectors by a 2-D deformed manifold that iteratively adjusts to best fit the data in data space. The probability of a data vector being represented by the 2D manifold can then be calculated. The AASPI algorithm extracts the x and y coordinates of the mean probability distribution of the data vectors in the latent space manifold as separate volumes, which can then be cross plotted for seismic facies classification. As only the reef complex itself is being target for gas storage, the GTM algorithm was limited spatially to only the reef complex and vertically between the top of the A-1 Carbonate and the top of the underlying Clinton formation.

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To relate the unsupervised classification to the geology, we begin by investigating the data corresponding to cored wells. For this study, the goal was to distinguish the target reservoir facies, the reef core, from the reef bioherm, and overlying peritidal facies. Using the Sound-QI software QI-Pro, investigation boxes are drawn at cored well location within the reef core *(Figure 2a)*. The data points which correspond to the investigation box are highlighted in the cross-section and user-defined polygons are then drawn around the data points while also honoring the natural clusters of the GTM output. Polygons are iteratively adjusted using in-context interpretation to appropriately correlate to other well locations. All data points within a polygon are assigned a single discrete value, or class, and a discretized SEG-Y volume is output by the software once a satisfactory classification is achieved. This workflow allows the interpreter to impose supervision on the unsupervised GTM algorithm.

Results

Facies Identification

The full angle stack classification is shown in *Figure 3*. A phantom horizon -15 ms below the top of the A-1 Carbonate displays the classified volume approximately through the top of the reef core *(Figure 3a)*. The crossplots of the two latent space axes volumes display the data corresponding to the cross-section shown below *(Figure 3d)*. Using the workflow described above, the polygons were initially centered about the clusters, and calibrated to the wells with core lithology logs. This resulted in a good match of the overlying peritidal facies and reef core complex at cored wells within the reef complex. However the reef bioherm is poorly discriminated from the reef apron and talus facies as seen in well R-101. There is also an anomalous classification of Bioherm/Apron facies in the upper section of well R-301. The arbitrary line through the reef reveals that Ray Reef is composed of three bioherms that likely amalgamated together through time.

Geobody Extraction

To quantify reservoir thickness away from well locations, a geobody extraction was done for the reef core seismic facies *(Figure 4a)*. To ensure an accurate extraction, the visible extents of the horizon probe used for the extraction was limited to avoid extraction of mis-classified facies at the top of the A-1 Carbonate horizon. Surfaces were then wrapped along the top and base of the extracted geobody. An isochron was calculated by subtracting the base surface from the top. Using the sonic log from well R-117, an average interval velocity of 19,500 ft/s was used to transform from TWT thickness to thickness in feet *(Figure 4b)*.

Well Flow Correlation

A map of average absolute open flow (AOF) was produced in Python. Values were interpolated between well locations providing a simple heat map of well flow (*Figure 4c*). It becomes apparent that the northern and central reef exhibit good flow performance, while the southern reef has average to low flow performance. Comparing the Figure 4c to the isochore created from the geobody extraction, we observe wells that encounter thicker intervals display better flow performance. As the reef core lithofacies is characterized primarily by vuggy porosity related to dissolution, wells that penetrate thicker intervals are more likely to encounter more porous zones.

Conclusions

Unsupervised classification of seismic facies was accomplished by applying generative topographic mapping to post-stack seismic attributes in a pinnacle reef gas-storage reservoir with vintage well control. The reef core and overlying peritidal facies were well classified which allows for quick mapping of their respective morphologies. The bioherm and flanking facies were difficult to discriminate. This may be attributed to the poor imaging of the flanks of the reef complex due to their steep dips and velocity pull-up. Quantification of reservoir thickness from seismic data was accomplished through extracting geobodies from the classified reef core facies, and applying a constant interval velocity.

Future Work

Future work to improve characterization of Ray Reef includes conducting AVO analyses on pre-stack gathers that were recently made available. Volume attributes produced from pre-stack inversion are

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directly related to elastic properties of the reservoir, such as porosity and fluid content. Using these results as input for the GTM, we expect the resulting classifications will improve our understanding of the reservoir properties.

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