Seismic-Based Porosity Prediction in the Silurian Niagaran Formation Reefs of Northern Michigan: An Integrated Case Study

Allen Modroo and Wayne Goodman, Core Energy LLC, Traverse City, Michigan; Doug Paul and Amber Padilla, SeisWare Inc., Houston Texas*

Summary

Identifying Lower Silurian Niagaran (Guelph) Formation reefs with 3D seismic in the Michigan Basin has been very challenging from the onset of the use of this technology. Gaining experience in recognizing diagnostic seismic signatures and refining processing flows has led to the ability to define these structures far more reliably. While production can be very prolific, the heterogeneity encountered within individual reefs has led to many poor producers and dry holes due to lack of primary porosity, compartmentalized reservoirs, and/or salt occlusion. The objective of this study was to integrate seismic and geology to better predict porosity distribution. A combination of near angle (0-15º) stacks and high resolution processing was used to create a seismic volume in which various attributes were correlated with well porosities. Coherence, spectral decomposition, wavelet analysis, and Rock Solid Attributes were cross plotted against the well properties. Areas identified as having porosity from each analysis were combined to generate predicted distribution of porosity across the reef. A High Angle Lateral well was subsequently drilled into this predicted porosity to test this hypothesis, with successful results. The same methodology will be further tested on a different reef. Seismic acquisition has been completed and processing is underway. Drilling is anticipated to be completed prior to October, 2014.

Introduction

The Lower Silurian Niagaran (Guelph) Formation in Northern Michigan consists primarily of various shallow water facies of marine carbonates, including discrete pinnacle reefs in the uppermost Niagaran/Guelph that grew on a gentle ramp along the basin margins. The uppermost Niagaran is overlain by the bedded carbonates, salts, and anhydrites of the Upper Silurian Salina Group (Figure 1). Production occurs within the Guelph reefs which developed atop the underlying Lockport Dolomite, or White Niagaran, carbonate complex. Particularly in reefs nearest the carbonate platform/margin that rims the basin, these reefs are commonly dolomitized. The Niagaran is directly overlain off-reef by the A-1 Evaporite (bedded salt with minor bedded anhydrite), and over-reef, where minimal anhydrite or no evaporites at all were deposited, by the A-1 Carbonate, or Ruff Formation, which itself is often a part of the reservoir. The A-1 Evaporite serves as a primary lateral seal of the reef on its flanks; top seal is generally provided by the younger A-2 Evaporite (salt with minor anhydrite), which underlies the low-energy, low-porosity Salina A-2 Carbonate and sits atop Ruff Formation (A-1 Carbonate) over-reef reservoir rocks. (Huh 1973; Charbonneau 1990; Gupta of Battelle 2014).

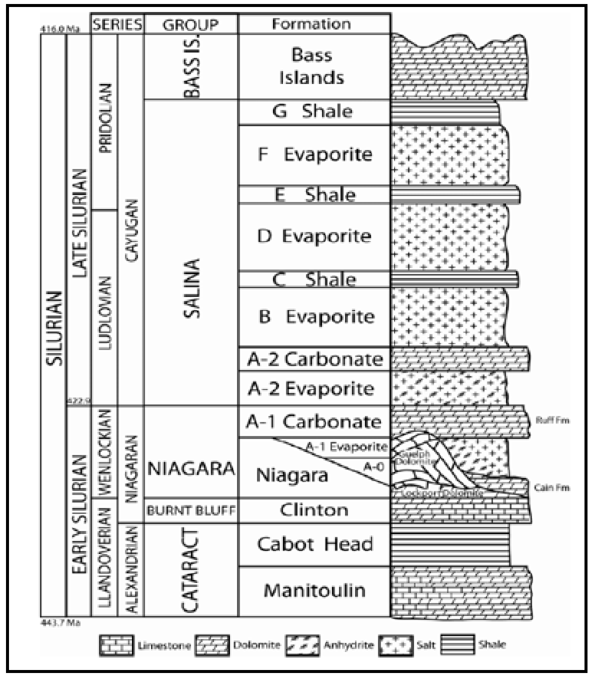


Figure 1: General Stratigraphy of the Silurian Niagaran Reef System and adjacent rocks (Ritter 2008 from Cercone 1984)

The targeted pinnacle reefs are typically quite small, ranging from 40 to 400 acres. The case study reef is approximately 110 acres in area, with a maximum height of approximately 400 feet. Seismic imaging of the reefs has always been very challenging, due to the steep dipping flanks, overlying carbonates of like velocities, and challenging surface statics that are in large part a function of regionally thick, varying lithology Quaternary glacial drift. Through both successful and unsuccessful drilling, early generation 2-D seismic began to yield a diagnostic signature representative of the reef's general structure and dimensions. Unfortunately, even successful cases of finding the reef did not always lead to successful wells. While some wells were very prolific and often have produced over a million barrels (successful wells in the play average over 400 MBOE ultimate recovery), others had much more limited porosity and produced limited amounts of hydrocarbons, or none at all, before being abandoned. Some wells were tight, particularly on the reef flanks largely due to salt occlusion, and on some reef crests, notably in areas where dolomitization was minimal.

The new challenge is to determine if it is possible to predict porosity distribution within the reef through seismic analysis. The objective of this paper is to outline the approach utilized to predict the porosity distribution at a specific reef and to discuss the results of a High Angle Lateral well drilled based on this premise.

The integrated approach to this problem consists of 4 main components:

1. Seismic Processing
2. Integrating Geological Data
3. Interpretive Seismic Analysis
4. Quantitative Analysis

The results of this study were used to derive an estimation of porosity distribution for the reef. A High Angle Lateral well was then planned and drilled to penetrate the porous zone. Its results will be discussed.

Seismic Processing

Surface statics have long been an issue in Northern Michigan. Coupled with the relatively small size of the reefs and steepness of their flanks, this makes imaging very difficult. One of the key challenges was to retain and enhance frequency while simultaneously improving signal to noise ratio. To provide a seismic volume with these characteristics, an FXY was run prestack. This was followed with a Cross Spread process which provided effective noise reduction. Angle stacks were also generated for near (0-15°), Mid (15-30°), and Far (30-45°). Qualitative analysis showed that the Near (0-15°) best imaged the reef flanks and also eliminated apparent multiples. HI RES frequency enhancement was then performed on the near volume, significantly enhancing the frequency. The original migration is compared to the Near Stack HI RES volume in Figure 2.

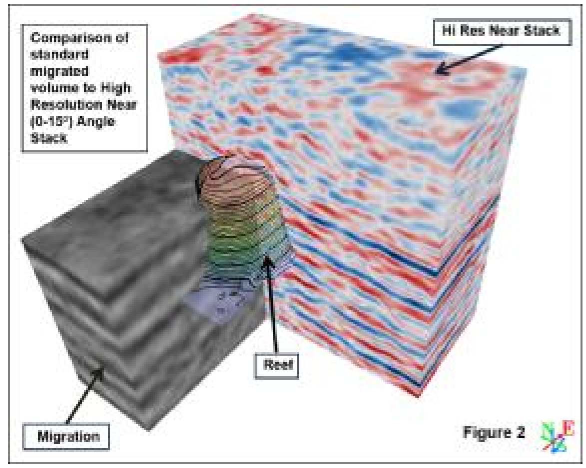


Figure 2

Integrating Geological Data

Prior to the drilling of the High Angle Lateral well, there were 6 wells that penetrated the subject reef and one adjacent off-reef dry hole just off its SE flank. Two wells are still producing, three were produced and abandoned, and one is an active CO_2 injector in a tertiary oil recovery program. Most of the early wells, drilled in the 1970's, had neutron logs (CNL, compensated neutron log, or SNP, sidewall neutron porosity log) that were used for porosity calculations. Various well properties, such as gross thickness, net thickness, average porosity, and phi-H, were calculated and mapped over the reef. These were analyzed and correlated with historical cumulative production. Sonic and density logs were limited, so the Faust's equation was used to develop pseudo-sonics and use in synthetics. The well responses were modeled and categorized to determine expected differences in seismic response among the following well types: good porosity, limited reservoir due to lack of primary porosity, and salt occluded porosity.

Seismic Interpretive Analysis

Several different types of seismic analysis were performed on the Near (0-15°) High Resolution seismic volume. These included:

1. Seismic Zone Attributes - Horizon referenced, amplitude based analysis for the standard volume and derived seismic attributes.
2. Wavelet Analysis – Wavelets representative of the various well types were extracted and correlated throughout the volumes with the intent of categorizing facies distribution.
3. Coherence – Measure of dissimilarity of the seismic response in the reef. Differences were noted between porous and non-porous wells.

4. Spectral Decomposition – Analysis of contributing frequencies within the zone of interest leads to crisper seismic images through improving the signal to noise ratio.
5. Seismic Volume Attributes – A suite of attributes based on frequency, amplitude, and similarity were generated and compared to known geology. As an example, Relative Acoustic Impedance, among others, showed strong correlation with the well data.

Figure 3 is a three dimensional image of a wavelet analysis porosity prediction draped over the structure of the reef.

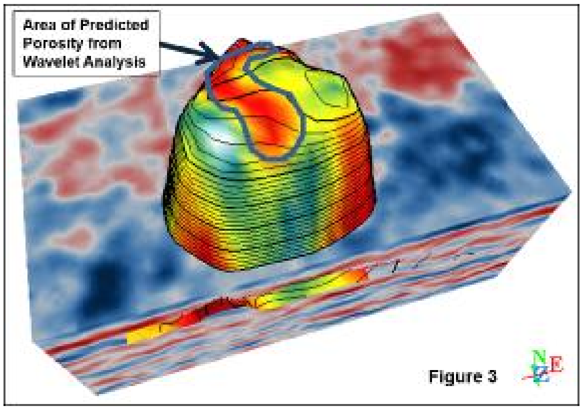


Figure 3

Quantitative Analysis

The qualitative observations made during the seismic analysis with respect to correlation with well data were then analyzed quantitatively. Individual correlative properties were cross plotted against the well derived values, most notably average porosity. The areas of predicted porosity for each seismic attribute type were captured. These predicted zones of porosity were then merged. The exact areas were quite variable, but a central zone was common to most. This was deemed to be the zone with the highest likelihood of porosity. The contributing seismic derived prediction maps were based on a wide variety of input. Coherence provided values between zero and one, while seismic amplitudes and attribute volumes, such as impedance, consisted of values in the tens of thousands, of which some were negative. In order to merge them in a meaningful manner, it was necessary to statistically normalize each contributing seismic property parameter. Once this was completed, the normalized composite property map was cross plotted against the average porosity at the wells. The linear regression solution to this correlation was then applied to the property map to create the composite seismic predicted porosity for the reef.

High Angle Lateral Well Planning and Results

In addition to predicting the porosity distribution within the reef, other considerations affecting the High Angle Lateral well location came into play. These included the present well locations and historical production therefrom. A second consideration was the EOR efforts, as active CO_2 injection is still occurring. The CO_2 has proven an effective drive mechanism, but it was important to avoid the CO_2 front. As a result, the well was drilled on a trajectory to intersect the predicted porosity in the northern portion of the reef, thereby reducing the risk of landing within a previously produced zone or an area swept by the CO_2 flood. The resultant well was High Angle Lateral for approximately 1000' and completed in a 500' zone at the distal end of the High Angle Lateral bore which had average porosity of about 10%, with some portions over 15%. Figure 4 shows the location of the High Angle Lateral well with respect to the seismic predicted porosity. The neutron porosity log shows the correlation with predicted porous portion in the northern portion of the reef.

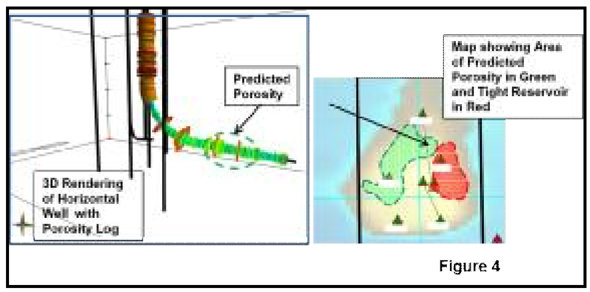


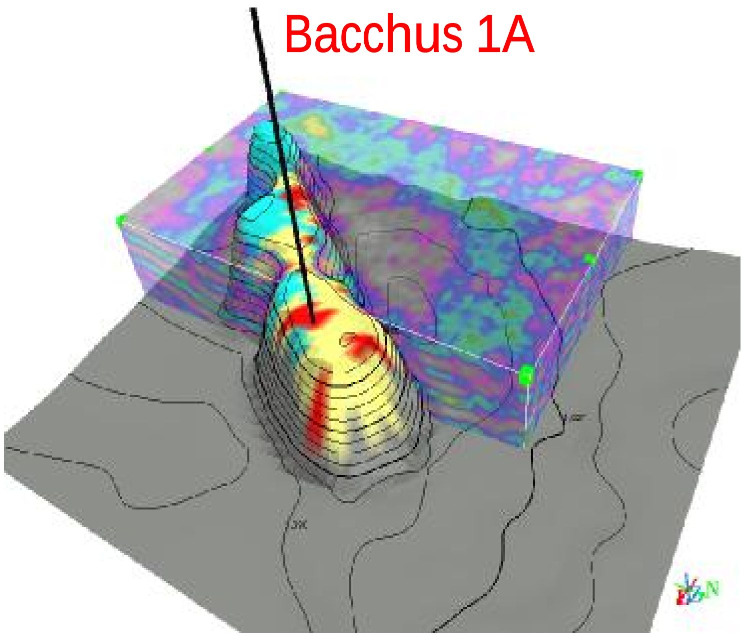
Figure 4

Discussion and Conclusions

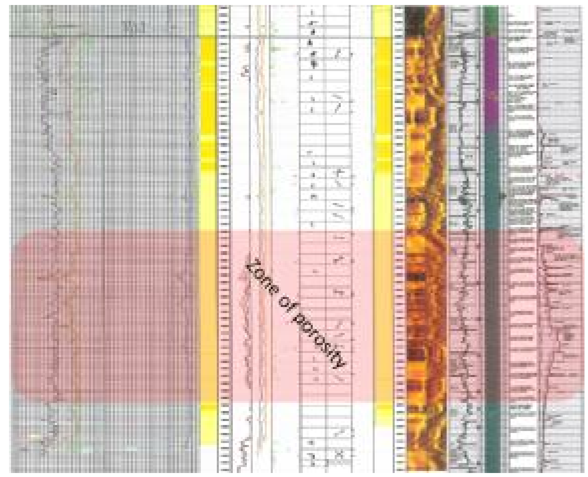
This approach proved successful in reducing the development risk of drilling field delineation wells and finding zones of higher porosity within the reef. By definition, a High Angle Lateral well will contact significantly more potential reservoir surface than vertical counterparts, so it was likely to encounter some porosity. In this instance, the porous portion of the well immediately upon reaching High Angle Lateral status was anticipated. It is, however, only one isolated example of this methodology. There are many variables that can affect the outcome, including the quality of the seismic and processing. The next challenge will be reproducing these results.

Next Steps

This approach was next be applied to the larger Bacchus reef which has less well control. Most notably there is no good producer on the reef. The same analyses were applied to Bacchus reef. The low angle high resolution seismic had bad signal to noise ration so our analysis were instead run on the filtered, migrated volume. Coherence revealed that the large reef was in fact, three separate pinnacles which grew together. Many of the dry holes on the reef were drilled in the inter pinnacle areas which are typically non porous. For wavelet analysis, an excellent producer from a nearby reef was utilized. For each analysis type, polygons were created and overlain to identify the most likely locations for porosity development. Two areas showed porosity in all analysis types and the Bacchus 1A location was proposed on the larger of these areas. The well was initially planned to be drilled in 2015 but due to the economic climate was postponed to Q2 2016.



The Bacchus 1A well finished drilling late Q2 2016. Logging revealed that the applied techniques did, in fact, identify a 70’ zone of porosity. Initial Production tests had rates of rates of about 250 BBL’s per day.



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