

Application of Time-Lapse Seismic Monitoring for the Control and Optimization of CO₂ Enhanced Oil Recovery Operations

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ABSTRACT

The “Application of Time-Lapse Seismic Monitoring for the Control and Optimization of CO₂ Enhanced Oil Recovery Operations” project is investigating the potential for monitoring CO₂ floods in carbonate reservoirs through the use of standard p-wave seismic data. This project will involve the use of 4D seismic (time lapse seismic) to try to observe the movement of the injected CO₂ through the reservoir. The differences between certain seismic attributes, such as amplitude, will be used to detect and map the movement of CO₂ within the reservoir. This technique has recently been shown to be effective in CO₂ monitoring in EOR projects such as Weyborne.

The project is being conducted in the Charlton 30/31 field in northern Michigan Basin which is a Silurian pinnacle reef that has completed its primary production. This field is now undergoing enhanced oil recovery using CO₂. The CO₂ flood was initiated the end of 2005 when the injection of small amounts of CO₂ begin in the A1 Carbonate. This injection was conducted for 2 months before being temporarily halted in order for pressure measurements to be conducted.

The determination of the reservoir’s porosity distribution is proving to be a significant portion of this project. In order to relate the differences observed between the seismic attributes seen on the multiple surveys and the actual location of the CO₂, a predictive reservoir simulation model had to be developed. From this model, an accurate determination of porosity within the carbonate reservoir must be obtained. For this certain seismic attributes have been investigated.

The study reservoirs in the Charlton 30/31 field range from 50 to 400 acres in size. The relatively small area to image makes 3-D seismic data acquisition reasonably cost effective. Permeability and porosity vary considerably throughout the reef, thus it is essential to perform significant reservoir characterization and modeling prior to implementing a CO₂ flood to maximize recovery efficiency.

Should this project prove successful, the same technique could be applied across a large spectrum of the industry. In Michigan alone, the Niagaran reef play is comprised of over 700 Niagaran reefs with reservoirs already depleted by primary production. These reservoirs range in thickness from 200 to 400 ft and are at depths of 2000 to 5000 ft. Approximately 113 of these Niagaran oil fields have produced over 1 million bbls each and the total cumulative production is in excess of 300 million bbls and 1.4 Tcf. There could potentially be over 1 billion bbls of oil remaining in reefs in Michigan much of which could be mobilized utilizing techniques similar to those employed in this study.

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INTRODUCTION

Evidence concerning an increase in global warming due to the emission of greenhouse gases has become more prevalent throughout the scientific community in recent years. Potential methods for combating this trend include the removal of these greenhouse gases and their sequestration in underground reservoirs. CO₂ has been identified as a major greenhouse gas that is contributing to global warming.

Permanently removing and storing CO₂ underground will be a costly and lengthy task, particularly if it is to be performed only by the various governments around the world. This process can be accelerated if it is demonstrated to be of economic advantage to companies in the private sector. This will encourage a more active participation in this process by various industries.

CO₂ has been used within the petroleum industry for a number of years as an agent for secondary and tertiary recovery of hydrocarbons. Injection of CO₂ into oil-bearing reservoirs has resulted in a more efficient sweeping of the remaining oil and boosting the ultimate recovery from older fields. However, determining the path taken by the injected CO₂ has been problematic. Consequently, it is believed that pockets of unswept reservoir often exist and significant quantities of oil have been left behind.

The ability to image where CO₂ has been injected into an underground reservoir would not only identify any remaining space for the sequestering of additional CO₂ could occur but would also identify unswept portions of the reservoir where more oil reserves remain to be recovered. This knowledge would increase the economic advantage to petroleum industry companies and encourage drilling of additional wells for not only the recovery of these extra oil reserves but also the injection and sequestration of additional CO₂.

The overall objective for this project is to determine if advanced geophysical methods, such as 4D seismic surveys, can be used to identify those portions of an oil-bearing reservoir that have been flooded with CO₂, as well as those portions that remain unflooded. The reservoir chosen for this study is the Charleton 30/31 Field, a Niagaran reef field in the northern Michigan basin.

This study site offers a unique opportunity to demonstrate the potential gains associated with combining an environmental solution with an industry economic objective. The Antrim Shale trend in the northern Michigan basin produces CO₂ as an unwanted byproduct during the production of natural gas from this formation. The deeper, Niagaran reef trend contains a large number of isolated reef reservoirs that have been depleted through primary recovery methods. The trends of these two geologic formations overlap in the study area providing the perfect opportunity to demonstrate the sequestering of the CO₂ byproduct gas from the Antrim Shale into the Niagaran reefs and its concurrent use in the tertiary recovery of needed oil from these reefs.

EXECUTIVE SUMMARY

The DOE project DE-FC26-04NT 15425, entitled “Application of Time-Lapse Seismic Monitoring for the Control and Optimization of CO₂ Enhanced Oil Recovery Operations” is being conducted in two phases. Currently the project is in phase I.

Phase I Project Tasks Completed:

This project is currently on schedule. Accomplishments to date include: data collection, forward modeling of acquisition parameters, acquisition of a 3-D seismic survey, basic seismic data processing, petrophysical log analysis, as well as geological and seismic data interpretation, and preliminary reservoir simulation. Preliminary well work within the Charlton 30/31 field has been performed in preparation for CO₂ injection. Currently, a seismic attribute analysis is being performed and correlations with rock properties, such as porosity, are being sought. Based on current data, a correlation is believed to exist between instantaneous frequency and porosities greater than 5%. Additionally, a depthed seismic volume was created during the last round of seismic processing and a wavenumber analysis was conducted. The results of this analysis appear to support the results from the previous frequency studies.

All well work-overs have been completed and CO₂ injection has commenced. Full reservoir simulations that include history matching have been performed. Additionally, advanced seismic processing to develop azimuthal attributes has been completed and an azimuthal velocity analysis has been conducted on this data set. A second, more detailed porosity volume has been developed and applied to the development of a more detailed reservoir simulation.

Phase I Project Tasks Remaining:

Additional analysis of these azimuthal attributes, such as amplitude versus azimuth, still need to be performed. From these attributes, fracture porosity and potential permeability indicators may be found. Additionally, fluid replacement modeling will be performed. The final reservoir simulation will be carried out to predict the CO₂ flow path. This information may then be used to plan which wells will be most effective as injectors and which ones will be producers. However, it must be noted that the current configuration of the various boreholes will be a primary influence on the final decision.

Phase II Project Tasks To Be Performed:

Acquisition of the second 3-D seismic survey is currently planned for late 2006 or early 2007. After acquisition and processing, the second survey will be interpreted to the same degree as the first survey and the difference mapping of various seismic attributes will be performed. Alterations to the reservoir model and simulation will be made as necessary based on this analysis. At some as of yet undetermined time in the future, a third 3D survey will be acquired and the procedure will be repeated, if warranted. The effect of the CO₂ sequestration in the reservoir and the potential impact on the extension of this type of program to other reservoirs of a similar type will be determined. It should be noted that it may be possible to add to or replace the third 3D survey with a multi-azimuthal VSP. The feasibility of this will be investigated further during phase II.

EXPERIMENTAL

* - this should describe, or reference all experimental methods being used for the research. It should also provide detail about materials and equipment being used. Standard methods can be referenced to the appropriate literature, where details can be obtained. Equipment should be described only if it is not standard, or if information is not available in the literature or other reference publications.

This project has been broken into two phases. Phase I of the study will characterize the reservoir through the use of advanced methods such as petrophysical, geophysical, geological, reservoir engineering, simulation, and surveillance technologies. These technologies are being employed to assess the likelihood that a CO₂ flood can be monitored. Phase II study will be to demonstrate the benefits of using advanced seismic acquisition, processing, interpretation methods, such as 4D seismic, for monitoring CO₂ flood front within the reservoir.

Project Tasks Completed During Phase I:

During Phase I the following tasks have been performed;

1. All previously existing data concerning the Charleton 30/31 Field was obtained and reviewed. This included: 3-D seismic data from an offset reef, well location data, borehole deviation survey data, all available well logs, well history and well marker tops data. A structural map of the top of the A1 Carbonate, based on well marker top data only, was also obtained. Older vintage 2-D seismic data was reviewed and found to be of such poor quality that it was not used.

The paper well logs were digitized and converted into industry-standard LAS format files. This existing data was loaded into a GeoFrame 4.04 project and examined for quality control purposes. The paper structure map on the top of the A1 Carbonate was digitized and duplicated within the GeoFrame project. Cross sections using the well logs were also generated through the reef.

2. A petrophysical well log analysis was performed on all available well logs and the data was quality controlled. The petrophysicist also generated porosity logs during this analysis.
3. Sonic, density and gamma ray logs were loaded into the AVolog application. Log blocking was performed and various rock properties, such as the shear velocity, were calculated.
4. All of this data was combined to build a 14 layer rock property model of the Charlton 30/31 Field within the 3-D modeling program Gemini. This model was then used for 3-D ray trace modeling in order to determine the optimum 3-D seismic acquisition parameters.
5. An approximately 2 1/2 square mile, dynamite source, 3-D seismic survey had previously been planned for acquisition at the Charlton 30/31 Field. The results from the

3-D ray trace modeling from Gemini were used to modify the acquisition parameters for this planned survey.

6. This first 3-D survey was acquired during March, 2004. Basic seismic data processing, up to and including pre-stack time migration, was performed on the data set.

7. The processed 3-D seismic data was loaded into the GeoFrame project constructed during step one of the project.

8. Seismic wavelet analysis was performed within GeoFrame's IESX module by extracting various wavelets from the vicinity of the wells within the 3-D survey. Statistical zero phase equivalent wavelets were first extracted over a long window and used to construct synthetics that were used for initial well to seismic ties. Once satisfactory character ties had been achieved, deterministic wavelets were extracted over shorter windows, including the Niagaran reef section. These deterministically based wavelets were used to construct the final well to seismic ties.

9. Blended seismic attribute analysis was conducted on the seismic volume. During this analysis, the attribute seismic variance was extracted multiple times using various parameters. The resulting variance volumes were subsequently blended with the seismic amplitude volume and examined. During this blending, only the high variance values were allowed to be opaque; mid range and low variance values were set to transparent, allowing the amplitude attribute to be viewed.

10. Interpretation of the reef's top and base, as well as many of the overlying formations, was performed and structure and isopach maps were created. During this interpretation, a number of relatively flat lying events were observed in various locations within the reef. These were interpreted, mapped and found to occur within a very small time range. One possible explanation for these events is that they represent the gas cap/fluid boundary. This will be investigated further as the project proceeds.

11. Preliminary average velocity data was used to convert the various time maps to depth. The structure surfaces were then transferred in CPS-3 binary format into the Eclipse reservoir simulation software.

12. The size of the seismic survey, as well as the survey's bin spacing, led to the decision that no upscaling would be performed for the reservoir simulation. This would allow a direct transfer of seismically determined properties into the reservoir simulator without any alteration to occur.

13. To facilitate the construction of a geologic model within the reservoir simulation software, time slices at every 2 ms interval were converted to depth, creating depthed isochron surfaces. Next, porosity values calculated from the well logs were averaged for the intervals between these depthed isochron surfaces.

14. Porosity maps for the intervals between the depthed isochron surfaces were created

using the well log data. These log based porosity maps were transferred to the Eclipse reservoir simulator in CPS-3 binary format.

15. A preliminary reservoir simulation was performed using the seismically derived structure for the reef and the well based porosity data.

16. A preliminary seismic attribute analysis was performed by extracting reflection magnitude data from the seismic volume. The reflection magnitude values were then compared with the well logs' derived porosity values in the vicinity of the various wells' boreholes. No definitive correlation between reflection magnitude and all porosity values was found. However, a possible correlation was noted between reflection magnitude and porosities greater than 6%.

17. Additionally, the instantaneous frequency seismic attribute was investigated. Production perforation zones within the various boreholes were found to occur within zones of low instantaneous frequency. Cross plots of porosity with instantaneous frequency reveal a trend similar to the one noted for reflection magnitude. A possible correlation exists between low instantaneous frequency and porosities greater than 5%.

18. Instantaneous frequency maps were generated for the same depthed isochron intervals as those used in the construction of the initial well log based porosity maps. .

19. These instantaneous frequency maps were used to condition the distribution of the log based porosity, resulting in porosity distribution maps conditioned by the seismic attribute. These new porosity maps were transferred into the Eclipse simulation software in CPS-3 binary format.

20. New reservoir simulation runs were performed. Production history matching was then conducted to confirm the accuracy of the porosity volume.

21. Azimuthal velocity analysis was performed on the azimuthal seismic volumes.

22. Four azimuth-limited seismic volumes were developed.

23. A depthed seismic volume was developed and interpreted.

24. The seismic attribute (depthed volume) wavenumber was investigated to determine if a relationship existed with porosity. This initially looked promising but was later discarded as not having a significant correlation with porosity.

25. A second, more detailed porosity volume was developed using tools available in the Petrel static model construction package.

26. The injection of small amounts of CO₂ began in the A1 carbonate in the northern portion of the reef at the end of 2005. This injection continued for approximately 2 months before being temporarily halted while reservoir pressure tests could be

performed.

27. The seismic attribute relative magnitude was investigated and found to have little, if any, correlation with porosity.

Phase I Project Tasks to be Completed:

1. A forward reservoir simulation based on the more detailed porosity volume will be used to predict where the injected CO₂ will flow within the reservoir. This is currently on-going.

Phase II Project Tasks to be Completed:

1. The second 3-D seismic survey is currently planned for late 2006. However, this will be dependent upon the length of the injection time indicated by the final reservoir simulation and the date when the injection is initiated. It is possible that the acquisition of the second 3-D seismic survey will take place in 2007.

2. All of the analyses previously mentioned above will be performed on the second 3D seismic survey.

3. Additionally, difference mapping will be conducted between the first and second 3D volumes.

4. The actual distribution of the CO₂ noted by the difference mapping and the distribution predicted by the forward reservoir simulation will be compared.

5. The porosity volume developed using the seismic attributes will be validated.

6. Differences in the porosity volume indicated by the real and predicted CO₂ distribution will be investigated and the volume will be fine-tuned.

7. This adjusted porosity volume will be used to construct a new forward reservoir simulation to predict the spatial distribution of the CO₂ at some time period in the future, such as 1 year.

8. After that time period has elapsed, a third 3D survey will be acquired and the predicted CO₂ distribution will be validated.

RESULTS AND DISCUSSION

To date, the most important result that has been identified during this project has been a potential relationship between carbonates with porosity greater than 5% or 6% and the seismic attributes investigated so far, namely instantaneous frequency. Figure 1 shows a cross plot between the averaged porosity values within the reef's depthed isochron zones and their corresponding instantaneous frequency values. A trend can be noted in this data set for porosity values above 5%. Figure 2 shows the same data set but with porosity values below 5% removed. The trend is much more obvious and indicates that a

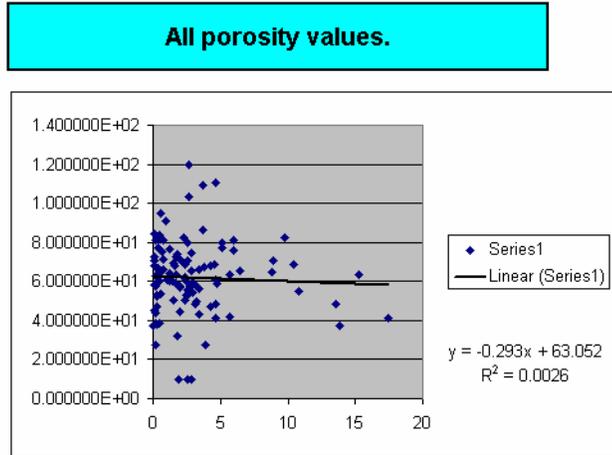


Figure 1: Reef's log porosity versus instantaneous frequency values – all data pairs.

With porosity less than 5% removed.

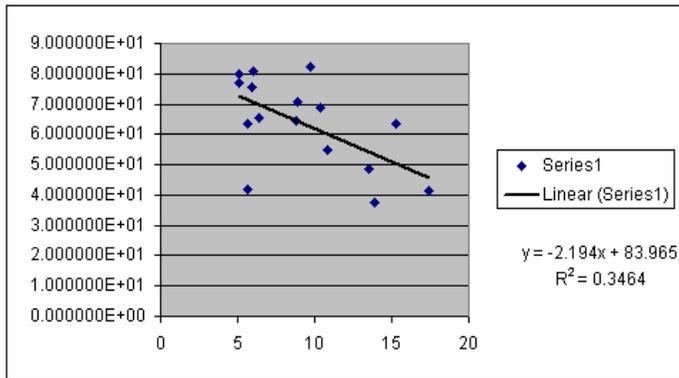


Figure 2: Reef's log porosity versus instantaneous frequency values – porosity values greater than 5%.

relationship exists between reservoir rock with greater than 5% porosity and the seismic data.

In an effort to confirm this trend, the instantaneous frequency volume and the well data were examined in more detail. Figure 3 shows the instantaneous frequency section for the survey's in-line 60. The synthetic seismogram, created during the well to seismic tie development, is also shown.

The location within the reef where the borehole was perforated was determined using this well to seismic tie. Perforation zones are generally within high porosity zones. Figure 3 shows that the zone perforated within the reef for the Charleton 1-30 corresponds to a strong low instantaneous frequency zone (in blue). Figure 4 shows the same display for the cross line 67. The same relationship of perforation interval for the Charleton 2-30 well aligning with a strong low instantaneous frequency zone (in blue) can be seen. Figure 5 shows the same display for the random line cut through the volume along the deviated borehole Charleton C2-30. Without a sonic log, a well to seismic tie could not be developed for this well. However, a similar time to depth relationship from the other wells was applied to this borehole. The same relationship of perforation interval aligning with a strong low instantaneous frequency zone (in blue) can also be observed here. This

suggests that the relationship described above is valid.

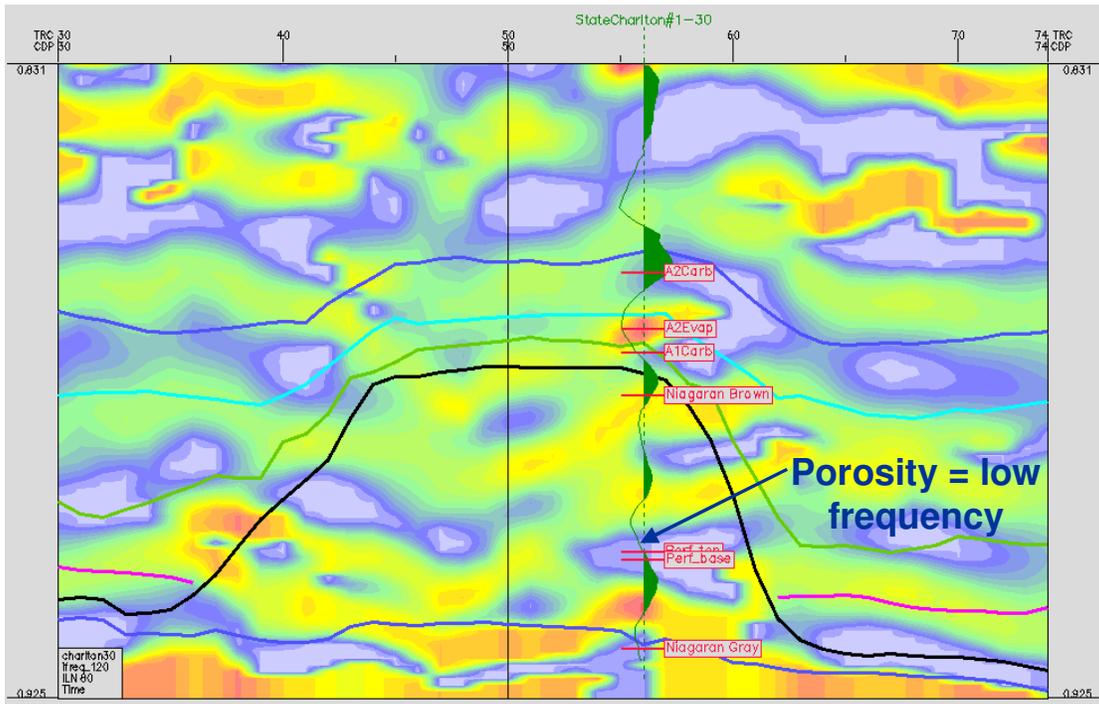


Figure 3: Instantaneous frequency section for in-line 60. Low frequency corresponds to the perforated high porosity zone.

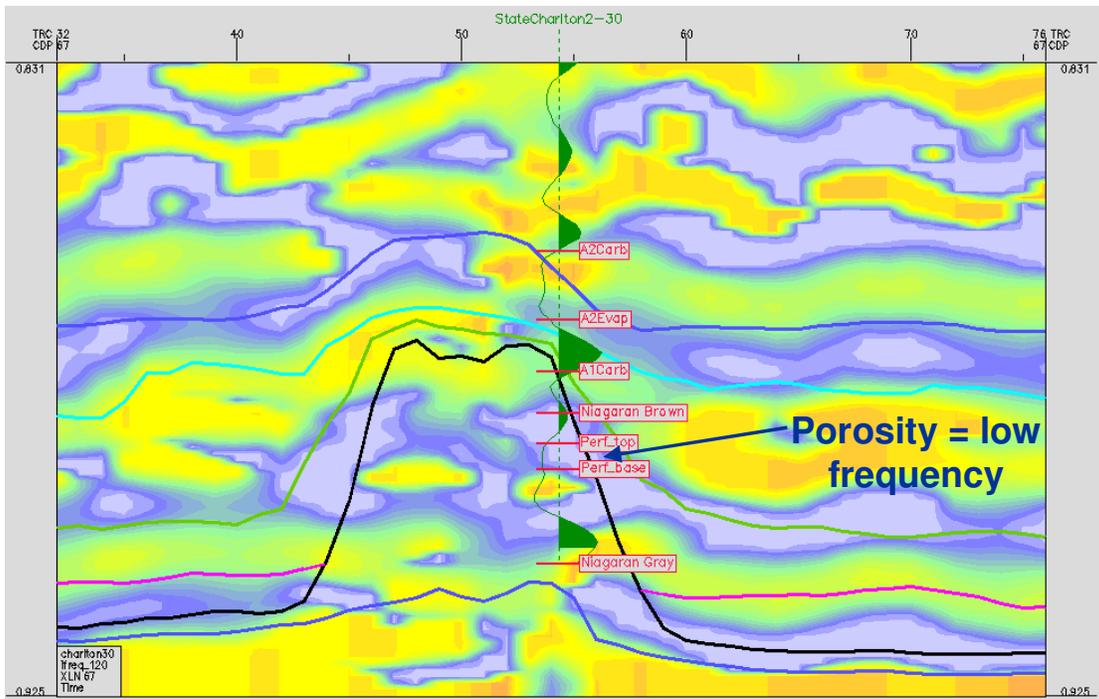


Figure 4: Instantaneous frequency section for cross-line 67. Low frequency corresponds to the perforated high porosity zone.

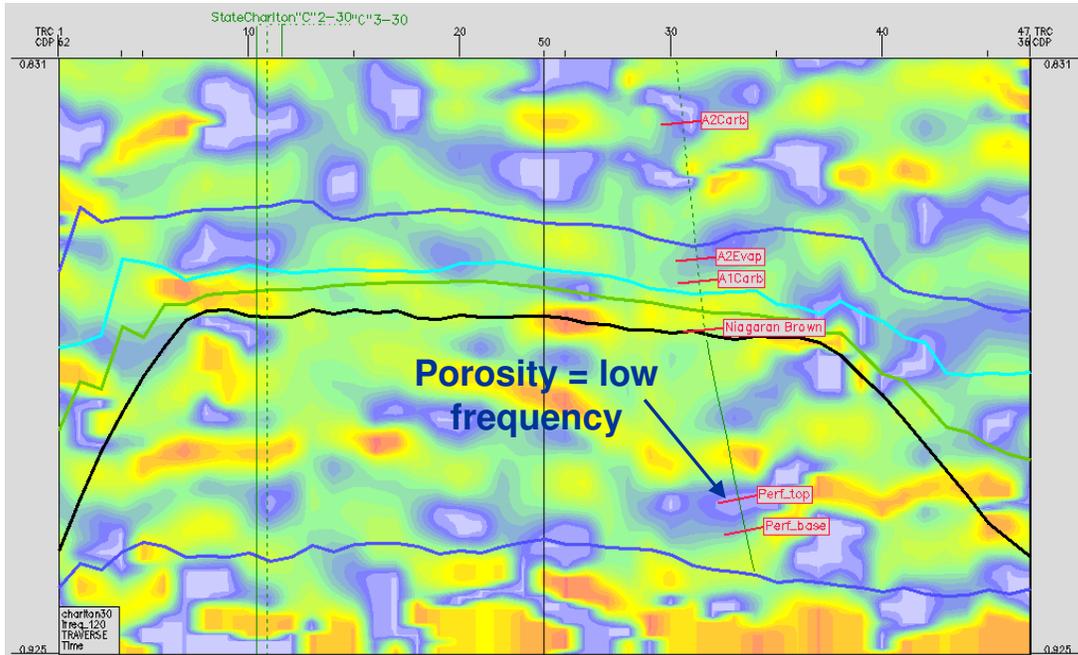


Figure 5: Instantaneous frequency section for random line along Charleton C2-30's deviated borehole. Low frequency corresponds to the perforated high porosity zone.

The seismically-derived porosity volume was tested in the field reservoir simulation and a good history match of the 25-year production history was obtained. This is shown in Figure 6. The simulation indicated that the porosity distribution was a good fit with field

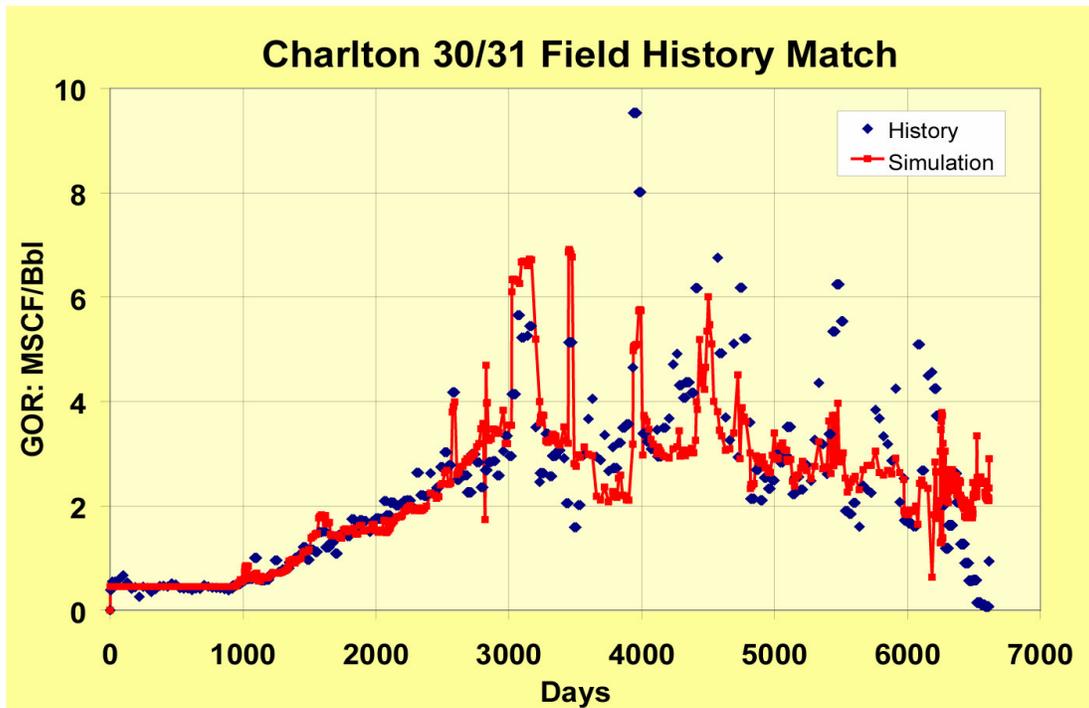


Figure 6: Results of production history match using the adjusted instantaneous frequency based porosity volume.

production performance. However, the simulation also indicated that the predicted overall pore volume was too high and had to be reduced to improve the history match, particularly regarding reservoir pressure. Reductions were systematically made to lower the porosity, and by inference permeability, in low porosity grid cells where the seismically-derived porosity may have been overestimated. This step was of primary importance in achieving the pictured history match of the field gas-oil ratio.

The simulation was created using a regular Cartesian grid with X-Y cell dimensions of 82.5 feet (25m). Figure 7 shows a screen capture of a perspective view of the simulation grid. The grid was oriented parallel to the 3-D seismic survey lines and is dimensioned to correspond with the bin spacing of the survey, thus minimizing the

Cross Section Through Porosity Perspective View Taken From The Reservoir Simulation

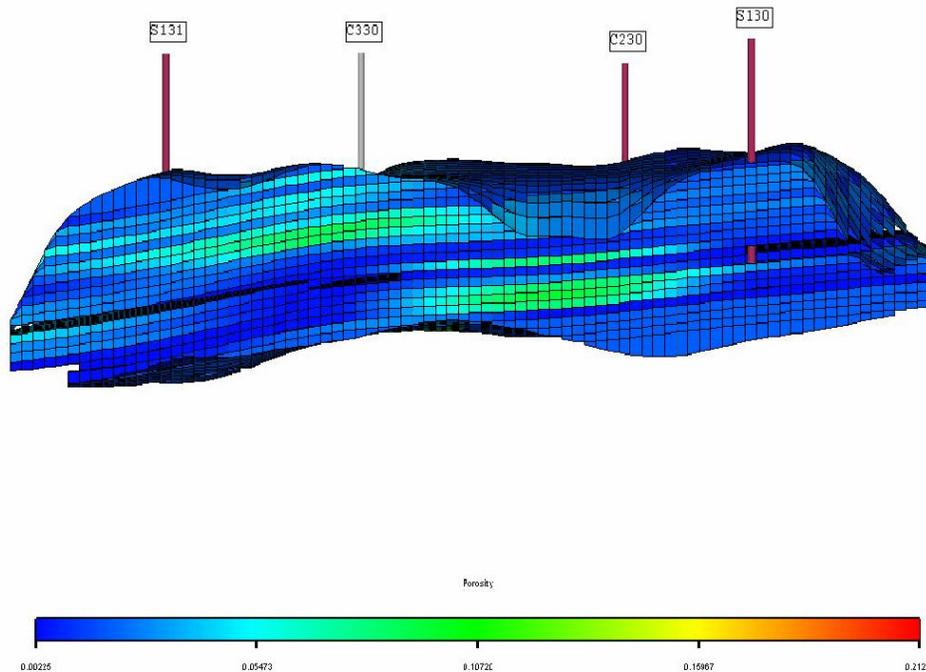


Figure 7: Cross section through a 3D perspective view of the reservoir simulation grid.

need for X-Y upscaling of the geologic model for simulation. Simulation layer thickness of approximately 18 feet corresponds to 2 milliseconds of seismic travel time, again to minimize the data averaging effects of upscaling. The resulting simulation grid has 34,000 active cells. Monthly historical oil rates for the original six production wells were inputted and the simulator calculated the corresponding gas rates and flowing pressures. There was no significant water production from the field. Given the lack of water production and the uncertainty of flowing bottomhole pressure estimates, calculated gas production, and the resulting GOR, are the best overall indicators of simulation performance.

The history-matched simulation has been used to test several injection/production scenarios for Core Energy. These scenarios included operating at both above and below miscibility pressure, top-down and bottom-up displacement, north-to-south and south-to-north displacement. Alternatives for later additional drilling locations were also investigated to take advantage of areas that appear poorly swept by the four existing wellbores. Due to the geometry of the field's structure, the preferred development option was north-to-south flooding (at miscible pressure). The simulator was then used to further refine this scenario.

An update to the simulation is planned for 2006 which will include some recently discovered well data and early CO₂ injection history. During well tests conducted in 2006, it was discovered that the reef had previously been “dump flooded”. This term refers to the inadvertent flooding of the reef through the well bore perforations by formation waters from a shallower formation. In this instance acidic waters in the Dundee formation corroded the well casings to the point where water entered the well bore, descended the borehole to the open perforations and entered the Niagaran Brown formation. The Dundee formation has been used for a number of years as a water disposal zone for waters produced by the Antrim production.

The additional complication of these dump floods will be incorporated into the reservoir simulation. Additional updates will also be made as results from the 4-D seismic program become available.

CONCLUSION

The ability to determine where the high porosity zones occur within a carbonate reservoir through the use of seismic data alone would prove to be a major finding of the study. The implications for hydrocarbon exploration are obvious. A potential reservoir's hydrocarbon yield could be estimated and used in prospect prioritization and the best zones within a reservoir could be accurately targeted. For field development projects this technology could be used for more efficient field development planning and would result in a greater amount of hydrocarbons being recovered during a field's primary production.

For enhanced oil recovery projects, such as the Charleton 30/31 field, the impact of seismic-based porosity determination would be quite significant. High and low porosity zones within the reservoir could be mapped and used in reservoir simulations as is being done in this project. With this knowledge original hydrocarbons in-place could be estimated and a program to most efficiently sweep the remaining hydrocarbons in the reservoir could be designed.

The comparison of the predicted and observed CO₂ flood distribution within the reef will confirm if this relationship actually exists.

The results of the history-matched reservoir simulation support the relationship suggested in Figure 8. A relationship between lower instantaneous frequency and higher porosity

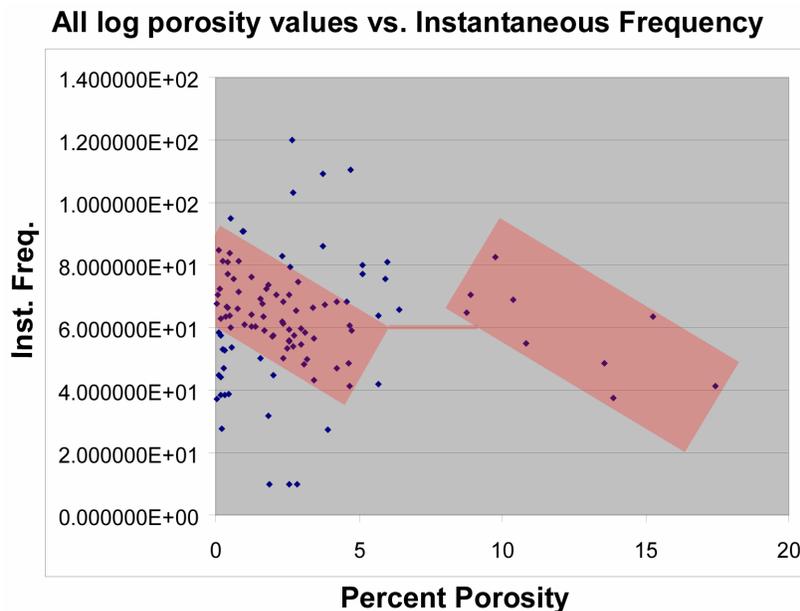


Figure 8: Cross plot of Instantaneous Frequency and log porosity.

exists in rocks with porosity values greater than 5%. Unfortunately, lower instantaneous frequencies can also be found in rocks with less than 5% porosity. Thus, when the

relationship is applied to the entire reef, rocks with porosities lower than 5% are artificially boosted to higher porosity values resulting in an overestimation of the pore volume for the reef, as indicated by the reservoir simulation.

Additional work is being conducted to distinguish the lower porosity zones from the higher porosity zones. This work will include comparing additional seismic attributes with the low instantaneous frequency zones. At least one well has also been planned to test a low instantaneous frequency zone in a nearby reef as part of this project.

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LIST OF ACRONYMS AND ABBREVIATIONS

GOR – Gas to Oil Ratio
CO₂ – Carbon Dioxide
VSP – Vertical Seismic Profile