IMPLEMENTING A NOVEL CYCLIC CO2 FLOOD IN PALEOZOIC REEFS

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ABSTRACT

Recycled CO_2 will be used in this demonstration project to produce bypassed oil from the Silurian Dover 35 pinnacle reef (Otsego County) in the Michigan Basin. We began injecting CO_2 in the Dover 35 field into the Salling-Hansen 4-35A well on May 6, 2004. Subsurface characterization is being completed using well log tomography animations and 3D visualizations to map facies distributions and reservoir properties in three reefs, the Belle River Mills, Chester 18, and Dover 35 Fields. The Belle River Mills and Chester 18 fields are being used as type-fields because they have excellent log and/or core data coverage. Amplitude slicing of the log porosity, normalized gamma ray, core permeability, and core porosity curves is showing trends that indicate significant heterogeneity and compartmentalization in these reservoirs associated with the original depositional fabric of the rocks.

Digital and hard copy data continues to be compiled for the Niagaran reefs in the Michigan Basin. Technology transfer took place through technical presentations regarding visualization of the heterogeneity of the Niagaran reefs. Oral presentations were given at the Petroleum Technology Transfer Council workshop, Michigan Oil and Gas Association Conference, and Michigan Basin Geological Society meeting. A technical paper was submitted to the Bulletin of the American Association of Petroleum Geologists on the characterization of the Belle River Mills Field.

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The permeability slice data range is 0 to 30 millidarcies with values greater than 30 md reset to 30. The contour interval for each slice is 4 millidarcies. The porosity slice data range is 0 to 36 percent. The contour interval for each slice is 4%. The data range for each gamma ray slice is 0 to 40 api units. The contour interval is 5 api units. All wells in the field have gamma ray curves through the reef. Gray lines are section boundaries and gray numbers are section numbers. North is toward the top of the slices. Large white dots are data control points on each slice and small white dots are other well penetrations. Slice numbers or elevation in feet above the reef base is displayed in yellow below the vertical scale bar.

Figure 9. Belle River Mills 3D reef presentation, showing permeability voxels 25 md and greater (green), porosity voxels 13% and greater (red), rock types (blues and green), and transparent crestal reef structure surface. View is looking northwest, 30 degrees above horizontal. The best permeability and porosity is located in the upper wackestone (dark blue, lower reef) and lower boundstone (light blue, mid-reef) rock types. The stromatolite rock type (medium blue, upper reef) generally has poorer quality permeability and porosity. Storage and deliverability capacities of this gas storage reservoir could be optimized using this type of 3D visualization analysis. Vertical exaggeration is 10X. Six inset tomography images show the core permeability, core porosity, and gamma ray at two levels in the reef – in the wackestone and upper boundstone. Inset (upper right) model shows color-filled top of reef structural contours and landgrid overlays with no vertical exaggeration. Also shown is the trace of a potential horizontal well designed to encounter the best permeability areas based upon the tomography and 3D-imaging.

Figure 10. Structure map of Chester 18 Field in Otsego County, Michigan. Red circles indicate the vertical wells which have core data, the Shell Jaruzel 1-18 and the Shell Vinecki-Samkowiak 4-18 wells (refer to figures 12a and 12b for log and core description for the 4-18 well).

Figure 11. Chester 18 Well Log Tomography slices. Color Scale is in percent porosity with a Contour Interval of 2 phi for Log Porosity slices, and Color Scale is in API units with a Contour Interval of 4 api for Gamma Ray slices. Slice number is feet above reef base or below reef top.

Figure 12a. Type log for Chester 18 30N-2W, Otsego County, Michigan, Shell Vinecki-Samkowiak 4-18 (KB 1330). Depth ranges on right correspond to the core descriptions given in Figure 12b.

Figure 12b. Core descriptions and correlation to log curves of type log for Chester 18 30N-2W, Otsego County, Michigan, Shell Vinecki-Samkowiak 4-18 (refer to Figures 10 and 12a).

1.0 EXECUTIVE SUMMARY

Goals and Results

The primary goals of this project are to:

1. Demonstrate through a field trial that significant quantities of by-passed hydrocarbons can be recovered from pinnacle reefs using a novel CO2 cycling technology. The CO2 will come from nearby Antrim gas processing facilities resulting in the added benefit of the CO2 being sequestered rather than vented to the atmosphere.

2. Use log-curve tomography to develop a 3D digital model of a pinnacle reef.

3. Inventory the Michigan Basin for abandoned or shut-in reefs that are suitable candidates for similar recovery efforts. Compile pertinent engineering and geological characteristics in digital format.

4. Pass the results, economics, and data obtained from the demonstration project along to small independent producers via an aggressive technology transfer program.

<u>Field Demonstration</u>

We began injecting CO2 into the Niagaran reservoir in the Dover 35 field in Otsego County, Michigan on May 6, 2004 using the Salling-Hansen 4-35A well (Figures 1, 2, and 3). The field demonstration project was shifted three miles to the west to the Dover 35 Niagaran Field from the Charlton 6 Field based upon CO2 availability and flooding schedules. The change in the demonstration well site was previously approved by the DOE. Contract negotiations between our industry partner (Jordan Exploration Company, LLC) and the CO2 supplier (Core Energy, LLC) have reached completion. The State of Michigan and the Environmental Protection Agency have inspected facilities and have issued orders granting our industry partner's application to begin the project.

Figure 3 is a location map for the Dover 35 Field area. The Salling-Hansen #4-35A (northwest well in field, blue triangle, Michigan permit number 29995) is being used to inject recycled CO2 from the Dover 36 and/or Dover 33 fields and/or compressed Antrim waste CO2 into the uppermost Dover 35 Niagaran reservoir. Injection rates are less than anticipated into the 4-35A well and are approximately 2 MMCF per day versus the anticipated 5 MMCF per day. Figure 4 shows the daily CO2 injection amounts into the 4-35A for the first 82 days of injection; facility downtime resulted in several time frames of zero CO2 injection. The Salling Hansen #1-35 (northeast well in field, Michigan permit number 29236) is currently being worked over to convert the well to a CO2 injection well (expected activation date is July 29, 2004) to increase injection rates into the reservoir. The Pomerzynski #5-35 (southeast well in field, Michigan permit number 37324) is expected to respond to the CO2 injection and repressurization of the reservoir in six to nine months. [The Pomerzynski #2-35 (southwest well in field, Michigan permit number 29374) is permanently abandoned and cannot be re-entered.]

Analogs

Amplitude slice animations and 3D models and visualizations have been completed that show the distribution of the gamma ray, core porosity and core permeability amplitudes in the Belle River Mills reef. A technical paper describing this work is in review with the Bulletin of the American Association of Petroleum Geologists.

Significant progress has been made modeling the Chester 18 and the Dover 35 Fields and preliminary well log tomography animations of the gamma ray and porosity have been created.

Data Compilation

Engineering data is currently being compiled for Niagaran reefs in the Michigan Basin from hard copy records of the Michigan Department of Natural Resources. A digital production database from January 1982 through July 2003 has been manipulated to create a digital report of the production for all Niagaran Fields.

A separate digital database has been created from the Michigan Tech well databases showing wells that were cored in the Niagaran in the Michigan Basin. A similar spreadsheet listing wells with Niagaran cores in the Michigan Basin is located on the Michigan Basin Core Research Laboratory web site at Western Michigan University [http://www.wmich.edu/geology/corelab/corelab.htm]. The Michigan Department of Natural Resources historical paper copy pressure reports for the Niagaran Reef trend have been obtained and initial (virgin) reservoir pressure data from these reports is being entered into a pressure database.

New Findings

One new key finding is that the distribution of the log porosity in the Dover 35 and Chester 18 Reefs appears to be similar to the distribution of the core porosity and core permeability in the Belle River Mills reef. In addition the gamma ray distribution trends in all three reefs appear similar although the Dover 35 field is relatively small (only 4 well penetrations) in comparison to the other fields. These are important observations and are significant because it means we may be able to use well log tomography visualization techniques to map the distribution of permeability and porosity in reefs without core data (most Niagaran Reef wells have at least a gamma ray and porosity log curve). By scaling the areal distribution of this relationship (calibrated with additional analogs) we may be able to predict the likely distribution of the permeability and porosity in the Dover 35 Field as well as other reefs.

Another key finding that has emerged from the continuation of our 3D visualization work during the reporting period is that it appears that the best permeability and porosity in the Niagaran Reefs are not necessarily coincident. In other words, *high permeability does not always indicate high porosity nor does low permeability always indicate low porosity.* It appears that the distribution of permeability and porosity in the reefs is controlled by the original depositional fabric of the carbonate rocks (i.e., vuggy, pinpoint, moldic fabrics, among others) and that subsequent diagenesis has only partially modified this original depositional and rock property fabric (i.e., dolomitization of the original limestones has not completely removed this original fabric).

A third key finding is that high-resolution images of the larger multi-well Niagaran Fields can be obtained using well log tomography. In comparison, 3D seismic is more costly and does not achieve the high resolution found in the well log curves; together 3D seismic and well log tomography can yield high vertical resolution and high lateral resolution reservoir images. Tomography of the Belle River Mills and Chester 18 fields shows that these fields are really composed of five and two individual reefs or carbonate sediment production centers, respectively, that have coalesced to form what has been called a single reef field. Reservoir engineering data from previous studies by the operator in the case of the Chester 18 Field supports the interpretation of two distinct reefs or pressure/production compartments. The gamma ray, core porosity, and core permeability amplitude slicing at Belle River Mills show five areal subdivisions to the field.

Lessons Learned

We have learned that there is no substitute for capturing, performing rigorous analysis and visualizing the various types of Niagaran reef reservoir data. 3D visualization and well log tomography of the core permeability, core porosity, and gamma ray log data have revealed new observations about the distribution of important reservoir properties in the reefs that impact producibility and economics for these producing and gas storage reservoirs.

We have also learned that flexibility must be maintained by all parties to optimize the timelines for flooding the best and most accessible reefs first (e.g., changing of demonstration project to Dover 35 from Charlton 6) to insure optimum economics and recovery. We also learned that negotiations for a CO2 supply contract using waste gas from Antrim processing facilities can become very involved from a legal and contract perspective and take longer than expected.

Applications

The results of the 3D visualizations and well log tomography of the Belle River Mills and Chester 18 type fields has been applied using well data to the Dover 35 field.

Well log tomography is showing that the reservoir properties of the Niagaran reefs in the Michigan Basin vary both horizontally and vertically. These variations in permeability, porosity, and connectivity of the reservoir rock must be considered to insure that enhanced recovery operations including CO2 injection, horizontal well placement, and gas storage facilities are designed appropriately. It appears likely that previous interpretations of reservoir and production engineering data, suggesting that many Niagaran reefs deplete uniformly, are incorrect.

Reefs in the Devonian Traverse Group in the Michigan Basin and in many stratigraphic intervals in other U.S. basins are logical targets for application of 3D visualization and well log tomography to assist in the determination of the viability of secondary or tertiary recovery projects and CO2 sequestration. Our recent results in combination with the technical literature on world-wide reefs suggest that most reef reservoirs may have undrained reservoir compartments.

Future Work

The initial demonstration injection well (4-35A) is being studied to determine if further reservoir analysis could assist in determining a means to increase injectivity. The 1-35 well is being recompleted as an injection well. The potential addition of this well as an injector is expected to boost CO_2 injection rates to re-pressurize the reef. The demonstration production well (5-35) will produce oil and eventually CO_2 that will be recycled. Surface facilities will be modified to handle two injection wells. As the project progresses the operator could decide to drill a new producing well in the reef.

The 3D visualization and well log tomography techniques applied to our type-reef fields will be applied in more detail to the Dover 35 reef and vicinity during the next six month project period. Well, field, and reservoir data will continue to be gathered for other Niagaran reefs in the Michigan Basin to identify likely candidates and the potential for future CO_2 injection and sequestration projects in the Niagaran reefs.

Technology Transfer

An invited presentation was made at the U. S. Geological Survey in Reston, VA in December, 2003 on our regional mapping and fault delineation work. An article was published in the February 9, 2004 issue of the Oil and Gas Journal that highlighted our regional sample attribute mapping and fault delineation work. The annual planning meeting for our industry partners was held in Tampa, FL in early March 2004. Regional maps were posted for viewing by operators from the basin at the PTTC core workshop on March 19, 2004 in Mt. Pleasant, MI. Regional maps were also posted in a booth at the Michigan Oil and Gas Association's Annual Oil Conference on April 22, 2004 in Gaylord, MI and an oral presentation was made highlighting opportunities for exploration in the Michigan Basin. We participated at the Michigan Basin Geological Society Annual Field Excursion from April 30 to May 2 with a presentation on our basin-scale well log tomography and by attending several of the field stops in the Traverse and Dundee carbonates. Presentations were also made at the monthly northern SPE meeting in April, 2004 and at the monthly, MBGS meeting in May, 2004.

A paper was submitted to AAPG titled, "Well Log Tomography and 3D-Imaging of Core and Log Curve Amplitudes in a Niagaran Reef, Belle River Mills Field, St. Clair County, Michigan, U.S." on June 9, 2004 and is in review.

Results and presentations from a portion of this technology transfer are available on the internet at *http://www.geo.mtu.edu/~aswylie/indxhtml.htm* while our main subsurface visualization web page (*http://www.geo.mtu.edu/svl/)* is being updated and expanded.

2.0 EXPERIMENTAL

2.1 Log Data

2.1.1 Log Data Capture

Paper copies of the well logs for the Dover 35, Charlton 6, Belle River Mills and Chester 18 Fields and surrounding area were obtained from the files at Michigan Tech and scanned to create tagged image format (tif) digital images using the commercial Neuralog software and a 36-inch scanner. Neuralog software was used to digitize the gamma ray and/or transit time (sonic), bulk density, neutron, and resistivity log curves for each well; the resistivity curves were not captured for Belle River Mills due to their vintage and low vertical resolution. Log ASCII Standard 2.0 (LAS) files were output from the Neuralog software to use in log curve amplitude slicing and cross sections.

2.1.2 Gamma Ray Normalization

We have found that well log curves have to be normalized to eliminate variability due to log tool types, log tool sensitivity, or log calibration between wells over time (see Neinast and Knox, 1974; Shier, 1997; Collins, 1998). Histograms and mean and standard deviations were computed for each of the 60 gamma ray curves using the bottom 100 feet of the Salina B salt (all wells penetrate this unit) to check for tool calibration errors, operator and tool vintage errors, and to low side normalize the gamma ray curves. Log curves from a group of wells were then selected (qualitatively) where the means and standard deviations for this interval were very similar to create a type histogram to use to normalize the remaining log curves that were deemed in error or in need or correction. Approximately 10 wells needed to have the gamma ray curves shifted. One well could not be corrected and was removed from the data set. A high-side gamma ray normalization was attempted using the Salina C Shale but was abandoned as unnecessary after reviewing preliminary statistics.

2.2 Core Data Capture

Paper copies of core analysis reports for the 34 cored wells in the Belle River Mills field were obtained from the Western Michigan University Core Repository through an exhaustive search of their files. Most of the core was analyzed using the whole core method but some plugs were utilized especially through broken core intervals. A spreadsheet was then created for each and the permeability, permeability at 90 degrees, porosity, water and oil saturation, and grain density (where available) measurements were entered into the spreadsheet. A one-foot sample increment was used for the core data and samples at tenths of feet were moved to the nearest even depth increment without losing samples. The null value (-999.2500) was used to denote missing samples or samples that were not analyzed. 7000 millidarcies (md) was the maximum permeability due to equipment measurement limits; 0.01 md was used for all permeability measurements reported as less than 0.01 md. Trace oil saturation amounts (tr) in the original core report were assigned a value of 0.1 for the oil saturation. The core data were then converted to LAS files for use with cross sections and loaded to an Access database for well log tomography and data preparation for 3D visualization.

2.3 Production Data Capture

Digital monthly production data records from January 1982 through June 2003 were obtained from the Michigan Department of Natural Resources in a series of MS Access data files and then recombined into one composite MS Access database. This database contains field names and monthly oil, gas, natural gas liquids, and water production volumes among other data elements. These data can be used to create monthly decline plots for wells, production units, and fields. If the field went on line post January 1982 these data can be summed to determine cumulative production for the field for the period January 1982 through June 2003.

Historical monthly production records prior to January 1982 are not available in digital format from the State of Michigan at this time. Therefore, hardcopy annual reports from 1932 through 1984 were obtained with annual production data. We are beginning the process of entering the annual production from the hardcopy reports into our digital production database. This will enable us to create historical decline plots for Niagaran fields to use to analyze the performance of individual wells and groups of reservoirs. At this time, cumulative production can be taken from the final hardcopy report (1984) and in combination with the digital data records can be used to determine field level cumulatives.

2.4 Data Processing for 3D Visualization

In an effort to keep the cost of 3D visualization low, we decided to use the Rockware suite of software. Specifically, Rockworks2002 is capable of excellent 3D manipulation, visualization, and animations and is low cost at around $500 (http://www.rockware.com/). The key step with the program is the data preparation or data processing to place the various types of data (i.e., logs, tops, locations, etc.) into the required Rockworks formats for loading into the program. A routine has been developed whereby the well and log data is first manipulated in an MS Access database and then used to populate the Rockworks2002 spreadsheet loader; however, when file length exceeds spreadsheet limits a series of ASCII text files must be used to load the data into the program. Drawbacks to the program are that all data must be reloaded each time new data is added to a project and the 3D visualization module of the program performs slowly when one foot sample increment log data is loaded for an entire project; a subset must be used to decrease processing and redraw times (Rockworks will release a new version in March 2004 that may correct some of these issues).

2.5 Well Log Tomography

Well log tomography also known as log curve amplitude slicing (Wylie and Huntoon, 2003; Wylie, 2002) is a form of tomography that utilizes the full vertical resolution of geophysical well log curves. Amplitude slices represent *approximate* time lines when the interval under analysis is bounded by unconformities or other chronostratigraphic surfaces and show the inferred distribution of lithofacies at the time of deposition. Computer animation allows visualization of changes in the distribution of lithofacies between successive slices or timelines. The distribution of other reservoir properties including porosity, permeability, and water saturation can also be visualized using the technique. The software used to create the tomographic animations includes MS Access, Golden Software Surfer, JASC Paintshop Pro Animator, and an in-house Visual Basic program.

In the case of the Niagaran reefs, only one chronostratigraphic surface is used. The base of the reef (or estimated base of the reef) in each well penetrating a reef is being used to establish one approximate time surface. Bottom-up slicing is then applied utilizing both reef and/or non-reef well penetrations to visualize the distribution of any particular log curve amplitude or other regularly sampled (in depth) reservoir property such as core permeability or core porosity measurements.

3.0 RESULTS AND DISCUSSION

3.1 Dover 35 Field

Reservoir characterization of the Dover 35 Field is under way. Well logs in the field and vicinity have been digitized and historical production data is being gathered from the Michigan Department of Environmental Quality hard copy records. Figure 5 shows a structural cross section through the 4 wells in the field with the A2 Carbonate, A1 Carbonate, Brown Niagaran, and Gray Niagaran correlations. Variability in the Neutron Porosity amplitudes between the four wells (blue curve, track 2, Figure 5) indicates significant vertical and lateral heterogeneity exists in the reef carbonates. Preliminary well log tomography animations of the neutron porosity and gamma ray amplitudes in the four wells appear to validate the high vertical heterogeneity in this single reef reservoir (Figure 6). We intend to incorporate the borehole compensated sonic log curves and the resistivity log curves from the four wells in the field into our reservoir model during the next reporting period.

Initial CO2 injection into the 4-35A well was in the uppermost portion of the Niagaran reservoir, and injection rates have been lower than expected (approximately 2 MMCF per day actual versus 5 MMCF per day expected). We are working with our industry partner to identify the cause of this reduced injectivity. It is unclear at this time if the problem is mechanical or reservoir related or a combination of both. Our industry partner is recompleting the Salling-Hanson #1-35 as an injector in order to increase CO2 injection into the reservoir. Consideration has been given to adding additional perforations at lower positions in the reservoir to improve injectivity. However, at this time, our industry partner prefers not to perforate either the 4-35A or the 1-35 injection wells deeper in the reservoir because of potential productivity losses related to gravity drainage. Dover 35 recovered 952,000 barrels of oil from primary production, and we estimate 242,000 barrels of additional oil will be recovered as a result of the CO_2 flood.

3.2 Belle River Mills Field

The Belle River Mills Field was discovered in 1961 and has been well-studied (Katz and Coats, 1968; Gill, 1973, 1977a, b, 1985; Balogh, 1981). Approximately, 54 wells have been drilled in the reef and an additional 20 well penetrations are nearby (Figure 7). Most of these wells have gamma ray log curves. Thirty-four wells in the field were extensively cored during the timeframe of the field's original development and its conversion to a gas storage reservoir in 1965. Laboratory measurements on these cores provide approximately 6000 measurements of core permeability and core porosity in and adjacent to the reef reservoir. The excellent gamma ray log and core data coverage in combination with the rock type and facies interpretations of Gill (1973; 1977a, b; 1985) make the Brown Niagaran reservoir in this field a prime candidate for the application of well log tomography on a limited-scale. The objective of this analog study was to see if trends observed in the log and core data in the reservoir could shed new light on the internal architecture and reservoir properties of this and other pinnacle reefs. In brief, the answer was, "yes", the technique did result in new observations on the permeability and porosity architecture of the reef. More importantly, in combination with 3D-imaging techniques, the study resulted in a "type" Silurian pinnacle reef that can be used as a benchmark to study other less well-characterized pinnacle reefs in the Michigan basin and perhaps set a model for the application of well log tomography and 3D-imaging to reef studies world-wide.

3.2.1 Well Log Tomography

Four representative core permeability slices are shown in Figure 8 (left images). These slices are map view images of the distribution of permeability in the wackestone at 125 feet above the base of the reef, in the boundstone 200 and 250 feet above the base of the reef, and in the basal stromatolite at 324 feet above the base of the reef. The patterns in these four slices show three to four 'centers of permeability' that are likely related to the original depositional fabric of the carbonate rocks. These 'centers of permeability' most probably represent individual biohermal mounds and carbonate boundstone reefs that coalesced to form what is called the Belle River Mills Field. These four slices as well as the full tomography animation (viewable on the aapg.org website using DataShare) further indicate that the permeability is very heterogeneous varying both vertically and horizontally in the reef reservoir. Later dolomitization of the original rock types of the Niagaran reef was insufficient to eliminate the original depositional, rock and pore fabrics. In contrast, diagenetic processes control the permeability distribution in the dolomitized Leduc carbonate buildups in the deep Alberta basin of Canada (Mountjoy and Marquez, 1997).

The distribution of core porosity in the Belle River Mills Field is also shown in Figure 8 (center images). These slices are map view images of the distribution of porosity in the wackestone at 125 feet above the base of the reef, in the boundstone 200 and 250 feet above the base of the reef, and in the basal stromatolite at 324 feet above the base of the reef. These porosity slices are at the same levels in the reef as the permeability slices shown on the left in Figure 8 and therefore, can be used to compare the distribution of porosity relative to the distribution of permeability in the reef. The patterns in the slices show three to four 'centers of porosity' in the four images. At the scale of the whole Belle River Mills Field, these 'centers of porosity' correspond with the 'centers of permeability' and serve to reinforce the interpretation that the field is composed of individual carbonate mounds and boundstone reefs that coalesced. At a smaller scale, it is apparent there are areas with high porosity and low permeability (for example compare porosity and permeability slice 125 in Figure 8). Other areas of the reef have both high porosity and high permeability (for example compare porosity and permeability slice 250 in Figure 8). The full porosity slice animation is viewable on the aapg.org website using DataShare.

The rightmost slices in Figure 8 show the contoured amplitude of the normalized gamma ray curve in the wackestone, boundstone, and basal stromatolite at the same levels above the reef base as shown in the core permeability and core porosity amplitude slices. The four gamma ray amplitude slices contain significantly more data control points because the gamma ray curve is available in almost all wells in and adjacent to the Belle River Mills Field. A zero gamma ray boundary was used to constrain the gridding algorithm in order to compare these four slices with the permeability and porosity slices. Clearly, the gamma ray amplitude in wells outside the boundary of the reef is not zero but the stratigraphy does change from the thick Brown Niagaran of the pinnacle reef to the much thinner regional Brown Niagaran in off reef positions (5 to 20 api units is the range of the off reef Brown Niagaran); using a gamma ray boundary value of 5 or 10 api units would decrease the apparent amplitude transition near the edge of the reef. The greater density of control points in the gamma ray slices allows for more detailed patterns to be recognized in the gridding of the gamma ray amplitudes. It is unclear at this time exactly what the variation in the gamma ray amplitudes from well-to-well. One possible explanation is that the patterns in the slices could represent a central lagoon (blues) ringed by shoals or small islands (for example, Slice 324, yellows and oranges). The higher gamma ray amplitudes could represent original depositional variations and/or early diagenetic effects related to the water table typical of this type of environmental setting and described in the literature as occurring in the stromatolite rock type of the pinnacle reefs by Gill (1977a) and other authors (Huh et al, 1977; Mantek, 1973). Subsequent dolomitization of the reef did not completely eliminate these primary and early diagenetic variations.

The patterns apparent in the gamma ray amplitude slice sequence in Figure 8 (and in the full animation viewable on the aapg.org website using DataShare) could also indicate that a small increase in water depth (slice 125 to slice 200) occurred during the time of deposition of these rock types. This slight deepening in water depth resulted in the change from wackestone to boundstone rock type and the change from higher gamma ray amplitudes (yellows, slice 125) to lower gamma ray amplitudes (mostly blue, slices 200 and 250). Gill (1977a) postulated that subsidence and carbonate production rates played important roles in the change from wackestone to boundstone.

The comparison between the core permeability, core porosity, and gamma ray amplitude slices shown in Figure 8 is presented to demonstrate the similarity in the patterns observed in the contoured amplitudes of these three data types. Slice 125 shows a close parallelism between the distribution of core permeability amplitudes and the distribution of core porosity amplitudes at this level in the reef. In contrast, Slice 324 shows much lower core permeability amplitudes (less than 4 md) in the northern portion of the reef where the core porosity amplitudes remain above 8%. Three to five permeability and porosity centers or amplitude patterns representing centers of carbonate mound and/or reef growth may also be observed in the individual slices and slice animations. Comparing the patterns from the core permeability and core porosity slices with the gamma ray amplitudes for slice 324 (stromatolite) shows that the best permeability and porosity is located in the central or lagoon area (blues, low gamma ray, cleaner) of the coalesced reefs based upon using the higher gamma ray amplitudes as an indicator of shoaling/emergence. Gill (1977a) described the upper most rock type in the Belle River Mills Field to be stromatolite suggesting that either the boundstone reef grew to reach the water surface transitioning to shoals and/or islands (stromatolite rock type) or that the water depth decreased or a combination of reef growth and a decrease in water level took place.

3.2.2 3D-IMAGING

In order to visualize the location and distribution of the best permeability (25 md and greater) and the best porosity (greater than 13%), 3D models were created where these two different types of data could be displayed simultaneously (Figure 9). The porosity voxels greater than 13% were highlighted in a red color only along their edges and the permeability voxels 25 md and greater were displayed using a solid green color for the voxel. Figure 9 highlights the relationship between the permeability, porosity and the four rock types in the reef. Obvious in the figure is the high porosity and low permeability zone in the northern portion of the field that is predominantly composed of the boundstone rock type. This area of the reef reservoir is composed of mostly moldic-type porosity (Gill, 1977a). In some areas of the reef, high permeability reservoir is coincident with high porosity reservoir while in other areas of the reef high permeability reservoir is coincident with reservoir porosity below 8%. The best permeability and porosity are not always coincident, a conclusion that could be interpreted from core data cross plots but not apparent until the data are visualized in 3D space. Knowing the likely location of the best permeability and/or porosity in the reef reservoir and especially relative to each other could play an important role in the performance of this or other reef reservoirs.

Superimposing Gill's 13 lithofacies and 25 lithotypes on this 3D model would provide more detailed insights into carbonate rock fabric and pore type control on the distribution of permeability and porosity in the Belle River Mills Field. However, most Niagaran reef reservoirs do not have the core coverage necessary to determine the detailed distribution of rock types based principally on cores. Log curves must be used in most fields to infer and correlate rock types. Relationships established in the Belle River Mills Field between the distribution of core permeability and porosity and gamma ray amplitude based upon well log tomography and 3D-imaging may provide a new methodology for discerning carbonate rock and pore types in other reservoirs.

3.3 Log Curve Amplitude Slicing in the Chester 18 Field, Otsego County, Michigan

The Chester 18 Field is located in the northern reef trend (Figures 10), covers an area of about 600 acres, and was discovered in 1971 (Figure 23). The field has produced over 13.5 million barrels of oil (MMBO) and 11 billion cubic feet (BCF) of gas from 20 vertical and deviated wells from a depth of 5900 ft. Waterflooding was initiated in 1978 by converting eight of the producing wells to water injectors. Approximately 5.5 MMBO has been produced through secondary recovery. The field is currently producing 1880 BO, 21882 CFG, and 9500 BW per month (DNR, June 2003).

The porosity and gamma ray curves from 25 vertical and deviated wells in the Chester 18 Field and vicinity were scanned and digitized, but only the vertical wells were used in the well log tomography (Figure 11); the computer code to allow the use of log curve amplitudes in deviated wellbores is under development. No detailed stratigraphic analysis like the work of Gill has been completed for the Chester 18 Field and core was taken in only two of the vertical wells (Figure 10, black squares). However, the rock types described in these two cores correspond to the rock types of Gill.

The Shell Jaruzel 1-18 well (P.N. 28375) produced oil from a partially dolomitized mid-slope reef. 71 m of core were taken from the upper part of this 120 m high reef, including some of the overlying dolomitic A-1 Carbonate. The upper 17 m of core consist of A-1 Carbonate: leached dolomitic mudstones interbedded with stromatolites and oncolites. The upper 12 m of the reef itself also contain leached dolomitic mudstones, but these display small marine cements. Underlying this unit are very uniform crinoidal and coral/stromatoporoid wackestones and packstones with ubiquitous marine cements filling voids and coating grains. These rocks are disrupted by solution breccias at sporadic intervals, and some marine cements appear to be preferentially dolomitized (Cercone, 1984).

The Shell Vinecki-Samkowiak 4-18 well also produced oil from the Chester 18 reef. Figure 12a and 12b show the cored interval and core description relative to the log curves in the well from the Shell waterflood documentation supplied to the Michigan Department of Environmental Quality.

Only two wells penetrate the entire reef in the field and these were used along with non-reef wells to estimate the reef base in reef wells with shallower total depths. It was necessary to estimate tops for the reef base in order to place the gamma ray curves for these wells in the proper spatial (vertical) position relative to the reef base (null values were used to populate gamma ray amplitude values for those intervals below the actual total depth of the well for gridding).

Figure 11 shows represented log porosity and gamma ray slices through the reservoir. The slices show two carbonate depositional centers that are even more evident when the full animation is viewed. Production engineering data from the operator that was released to the State as part of the application for the waterflood project also suggested the Chester 18 Field was composed of two reservoir compartments. These results compare well with the three to five carbonate depositional centers observed in the well log tomography for the Belle River Mills Field

Additional work imaging other log curves (i.e., resistivity, sonic) using well log tomography and 3D visualization is planned for the Chester 18 Field.

4.0 CONCLUSION

The injection of CO_2 into the Niagaran reservoir in the Dover 35 field in Otsego County, Michigan began on May 6, 2004 using the Salling-Hansen 4-35A well. To date, over 4900 tons of CO_2 have been injected, approximately 10% of the anticipated capacity, and 2000 barrels of oil have been produced. The expected increase in oil production due to injection has not yet appeared, but was not expected until further injection.

Well log tomography and 3D imaging of the core permeability, core porosity and/or gamma ray and porosity curves for the Belle River Mills, Chester 18, and Dover 35 reservoirs is underway or has been completed. Results indicate significant heterogeneity exists in Niagaran reefs that could impact reservoir performance. This heterogeneity should be considered in the planning of primary, secondary, tertiary or gas storage projects in these types of fields.

The CO_2 injection phase of this project is now fully operational after a slow start due to well workovers and rehabilitating corroded pipe. It is anticipated that filling operations will now run for another 18-24 months, due in part to the slower injection rate. In most other aspects the demonstration is going well and hydrocarbon production is expected to increase over the next 12-24 months. In general, the project is now back on schedule and barring unforeseen problems, should run smoothly through the CO_2 injection phase.

The investigators will shortly request a no-cost extension of 24 months for this project to complete the injection and fully access the operations. The final report will compare this demonstration with the two previous CO_2 injection programs in nearby reefs. Work will continue on characterization of the Dover reefs and their look-a-likes.

5.0 REFERENCES

Balogh, R. J., 1981, A study of the middle Silurian Belle River Mills, Peters, and Ray pinnacle reefs from the Michigan basin: Ph. D. dissertation, Bowling Green University, 202 p.

Cercone, K. R., 1984, Thermal History of Michigan Basin: AAPG Bull., v. 68, n. 2, p. 130-136.

Collins, D. R., 1998, Visualization of subsurface geology from wireline logs in Digital Mapping Techniques '98 -- Workshop Proceedings: U. S. Geological Survey Open-file Report 98-487,< http://pubs.usgs.gov/of/of98-487/collins.html>, accessed September 30, 2002.

Gill, D., 1973, Stratigraphy, facies, evolution and diagenesis of productive Niagaran Guelph reefs and Cayugan sabkha deposits, the Belle River Mills gas field, Michigan basin: Ph. D. dissertation, University of Michigan, Ann Arbor, 275 p.

Gill, D., 1977a, The Belle River Mills Gas Field: Productive Niagaran reefs encased by sabkha deposits, Michigan Basin: Michigan Basin Geological Society, Special Paper No. 2, 188 p.

Gill, D., 1977b, Salina A-1 Sabkha cycles and the late Silurian Paleogeography of the Michigan Basin: Journal of Sedimentary Petrology, v. 47, p. 979-1017.

Gill, D. 1985, Depositional facies of Middle Silurian (Niagaran) pinnacle reefs, Belle river Mills gas field, Michigan Basin, southeastern Michigan, in Roehl, P. O., and Choquette, P. W., eds., Carbonate petroleum reservoirs: New York, Springer-Verlag, p. 121-139.

Huh, J. M., Briggs, L.I., and Gill, D., 1977, Depositional environments of pinnacle reefs, Niagara and Salina Groups, northern shelf, Michigan basin in Reefs and Evaporites-concepts and depositional models: AAPG Studies in Geology, no. 5, p. 1-21.

Katz, D. L. and K. H. Coats, 1968, Underground storage of fluids: Ann Arbor, Michigan, Ulrich's Books, 575 p.

Mantek, W., 1973, Niagaran pinnacle reefs in Michigan: Michigan Basin Geological Society Annual Field Conference Guidebook, p. 35-46.

Mountjoy, E. W., and X. M. Marquez, 1997, Predicting reservoir properties in dolomites: Upper Devonian Leduc buildups, deep Alberta Basin, in J. A. Kupecz, J. Gluyas, and S. Bloch, eds., Reservoir quality prediction in sandstones and carbonates: AAPG Memoir 69, p. 267-306.

Neinast, G. S., and C. C. Knox, 1974, Normalization of well log digitizing: The Log Analyst, v. 15, no. 2, p. 18-25.

Shier, D. E., 1997 A comparison of log response between different logging companies and different vintages of tools: The Log Analyst, v. 38, no. 3, p. 47-61.

Wylie, A. S., Jr., 2002, Log Curve Amplitude Slicing - Visualization of well log amplitudes for paleogeographic reconstruction of the Middle Devonian Traverse Group, Michigan Basin: Ph. D. dissertation, Michigan Technological University, Houghton, MI, 250 p.

Wylie, A. S., Jr. and Huntoon, J. E., 2003, Log Curve Amplitude Slicing - Visualization of Log Data for the Devonian Traverse Group, Michigan Basin, U. S.: AAPG Bulletin, v. 87, no. 4, p. 581-608.

6.0 FIGURES

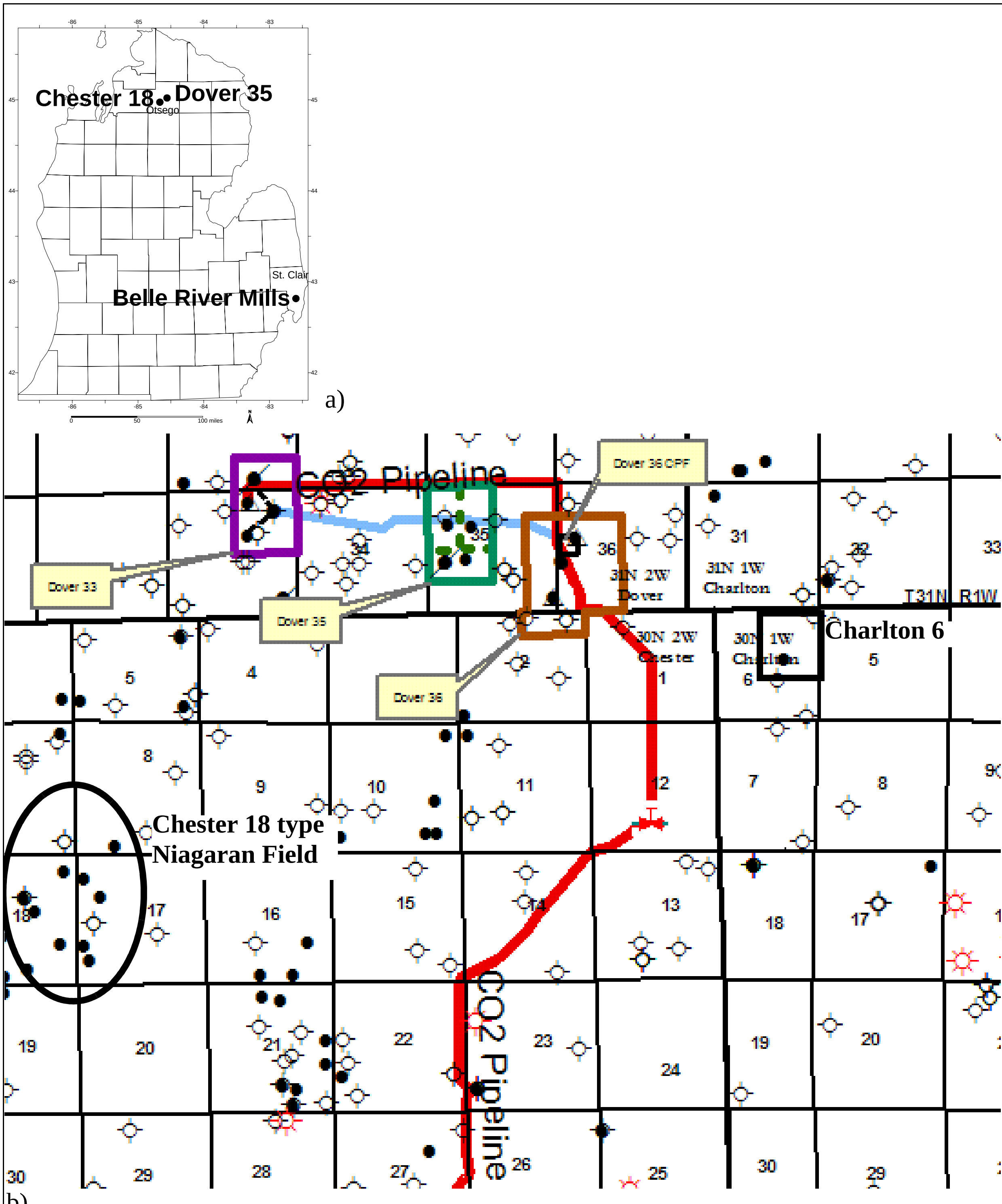
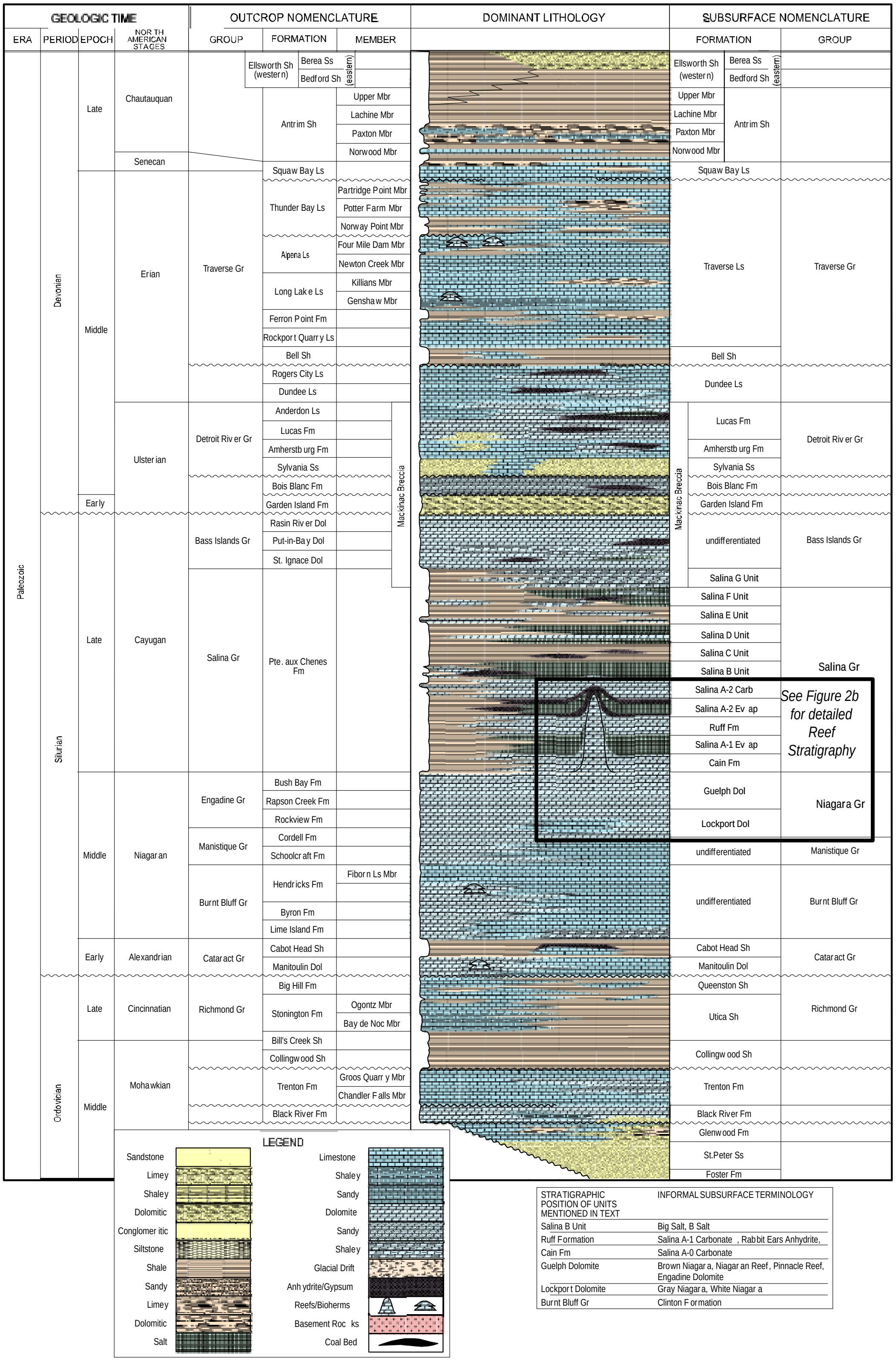


Figure 1. (a) Location of Dover 35, Chester 18 Fields in Otsego County, and Belle River Mills Field in St. Clair County, Michigan. (b) Location map for Dover 35 demonstration project area showing CO2 supply and distribution pipelines, old demonstration site, Charlton 6 and new demonstration site, Dover 35 (green outline).



STRATIGRAPHIC POSITION OF UNITS MENTIONED IN TEXT	INFORMAL SUBSURFACE TERMINOLOGY
Salina B Unit	Big Salt, B Salt
Ruff Formation	Salina A-1 Carbonate , Rabbit Ears Anhydrite,
Cain Fm	Salina A-0 Carbonate
Guelph Dolomite	Brown Niagara, Niagaran Reef, Pinnacle Reef, Engadine Dolomite
Lockport Dolomite	Gray Niagara, White Niagara
Burnt Bluff Gr	Clinton Formation

Figure 2a. Generalized stratigraphic column for the Michigan Basin.

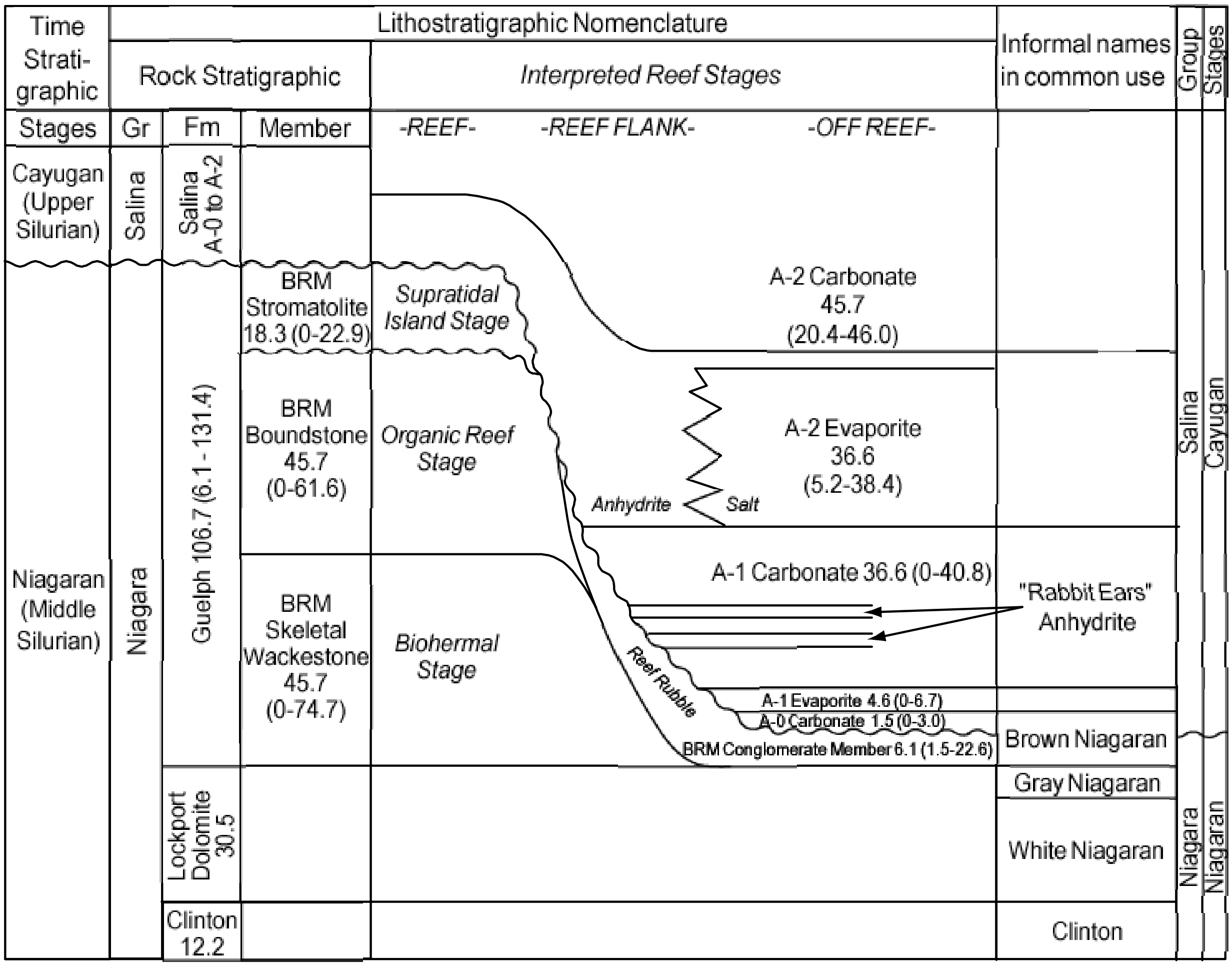


Figure 2b. Stratigraphic column showing subsurface nomenclature and correlations in the vicinity of the Belle River Mills Field (BRM), St. Clair County, Michigan as described by Gill (1977a) and reprinted with the permission of the Michigan Basin Geological Society. Average rock unit thicknesses and thickness ranges are shown in meters. Gill's subsurface nomenclature is followed in the text.

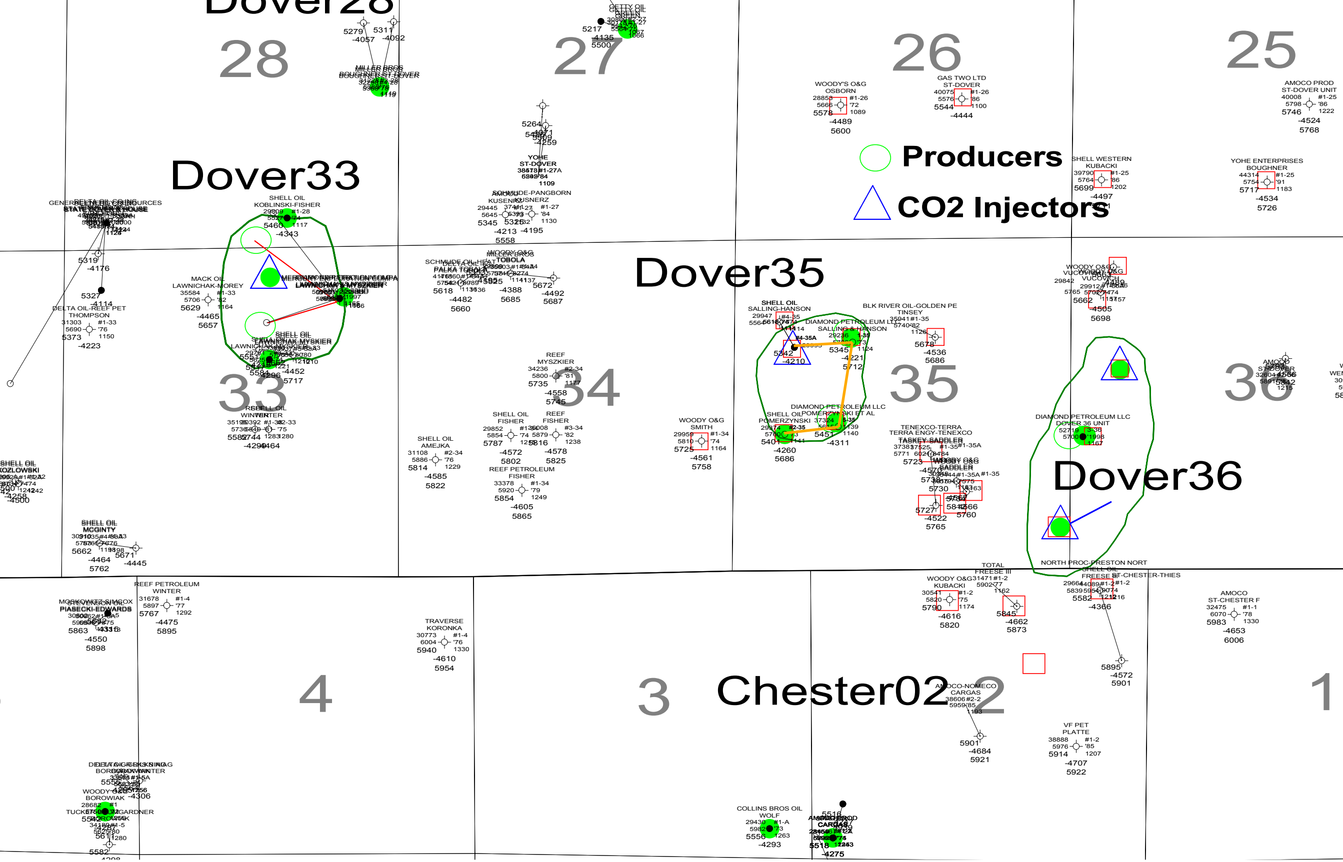


Figure 3. Location map for Dover 35 Field area. The 4 wells in the field are shown inside the green outline. The Salling-Hansen # 4-35 is the current CO2 injector well and the Pomerzynski #5-35 and Salling-Hanson #1-35 wells are the current producers in the demonstration project. Data posted around the well spots is operator, well name, well number, year drilled, KB, permit number, total depth, top Niagaran Brown measured and subsea depths, and top Niagaran Gray measured depth; small well spots are shallow Antrim wells. Section 35 is one square mile. North is towards the top of the map. Orange lines indicate the cross section shown in Figure 5.

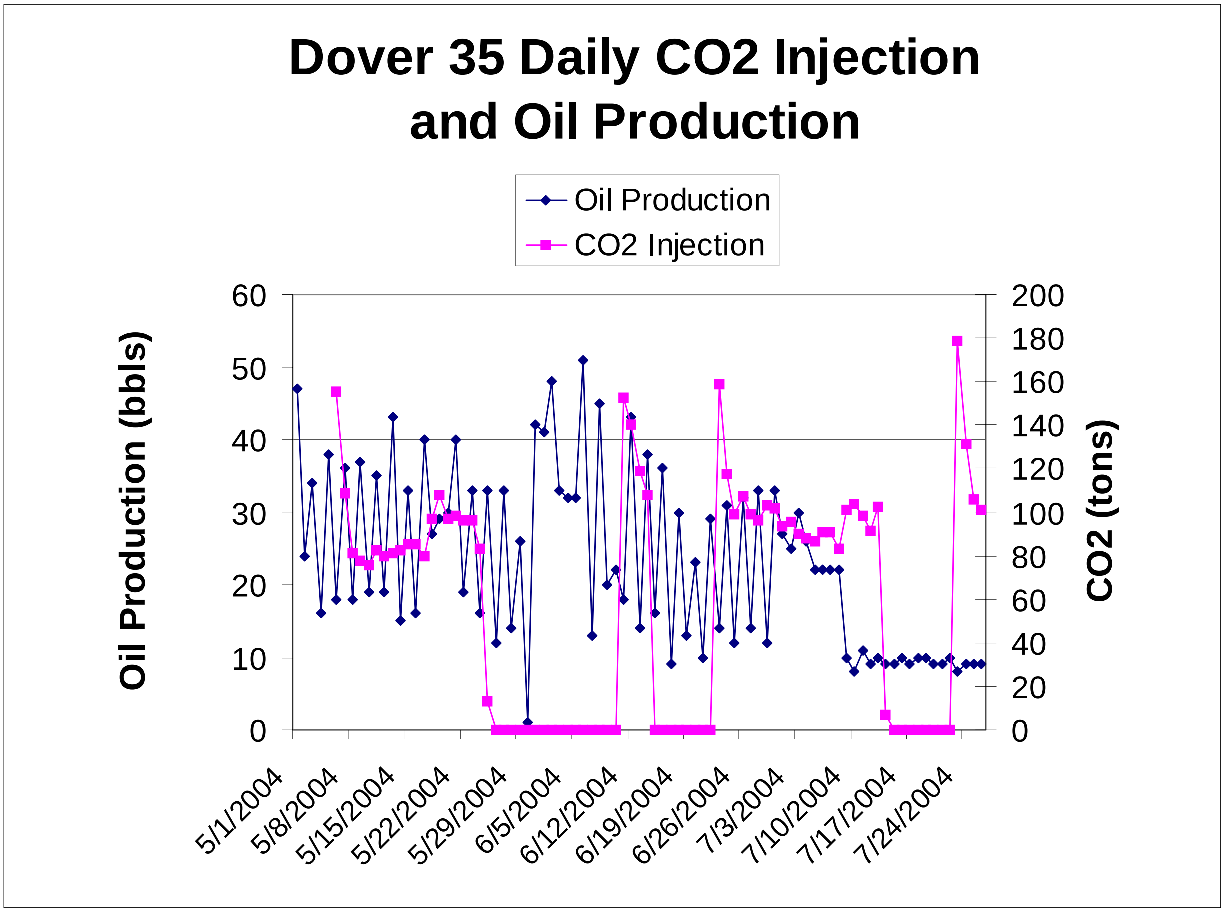


Figure 4. Dover 35 daily oil production and CO2 injection chart since injection began on May 6, 2004 through July 26, 2004. Facility downtime resulted in several time frames of zero CO2 injection.

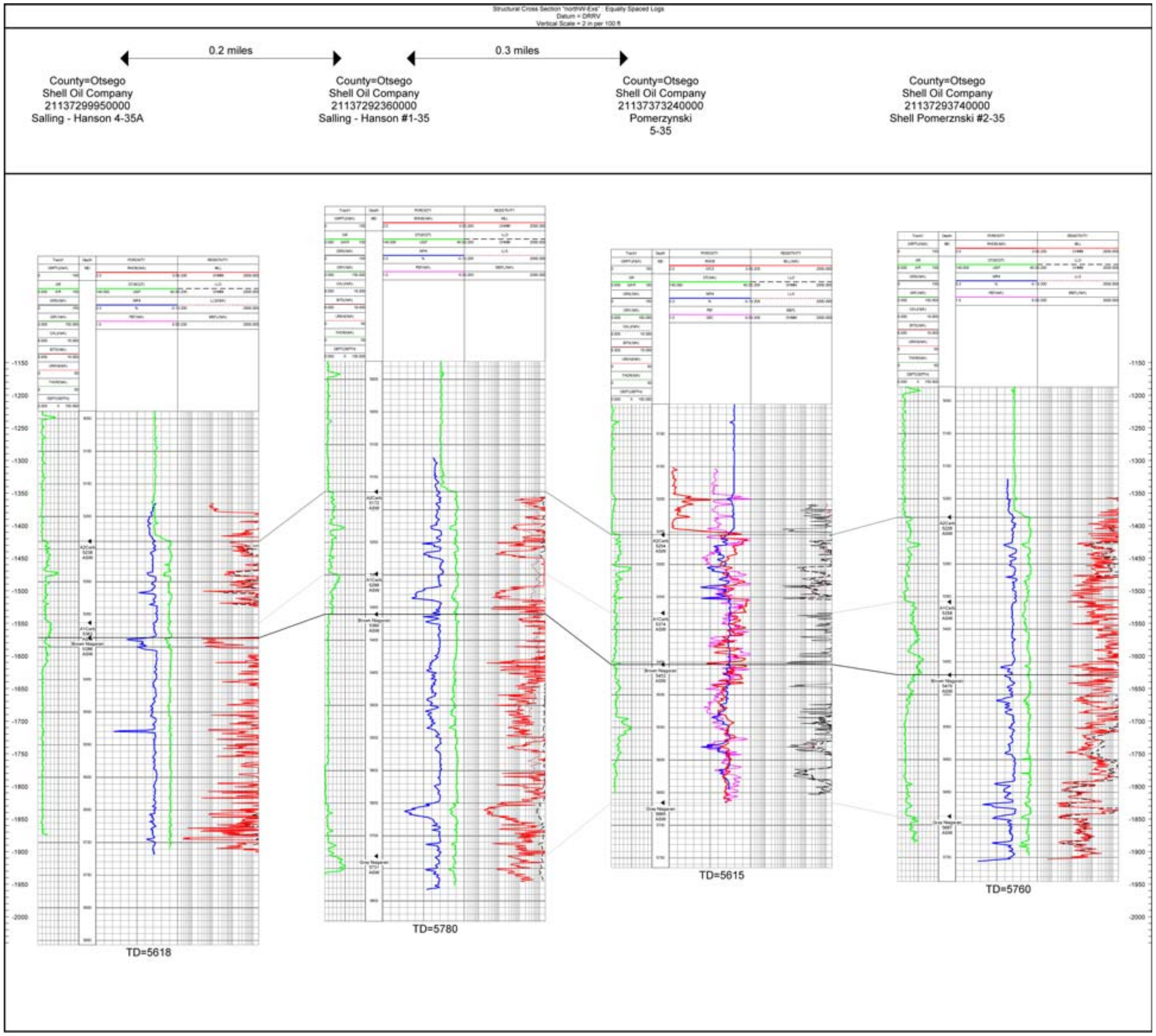


Figure 05. Structural cross section through the four wells in the Dover 35 Field in Otsego County, Michigan with the A2 Carbonate, A1 Carbonate, Brown Niagaran, and Gray Niagaran correlations. Cross Section lines are shown in Figure 3. CO2 is currently being injected into the Salling-Hansen #4-35A and the Salling Hansen #1-35 will become an injector well at the end of July, 2004.

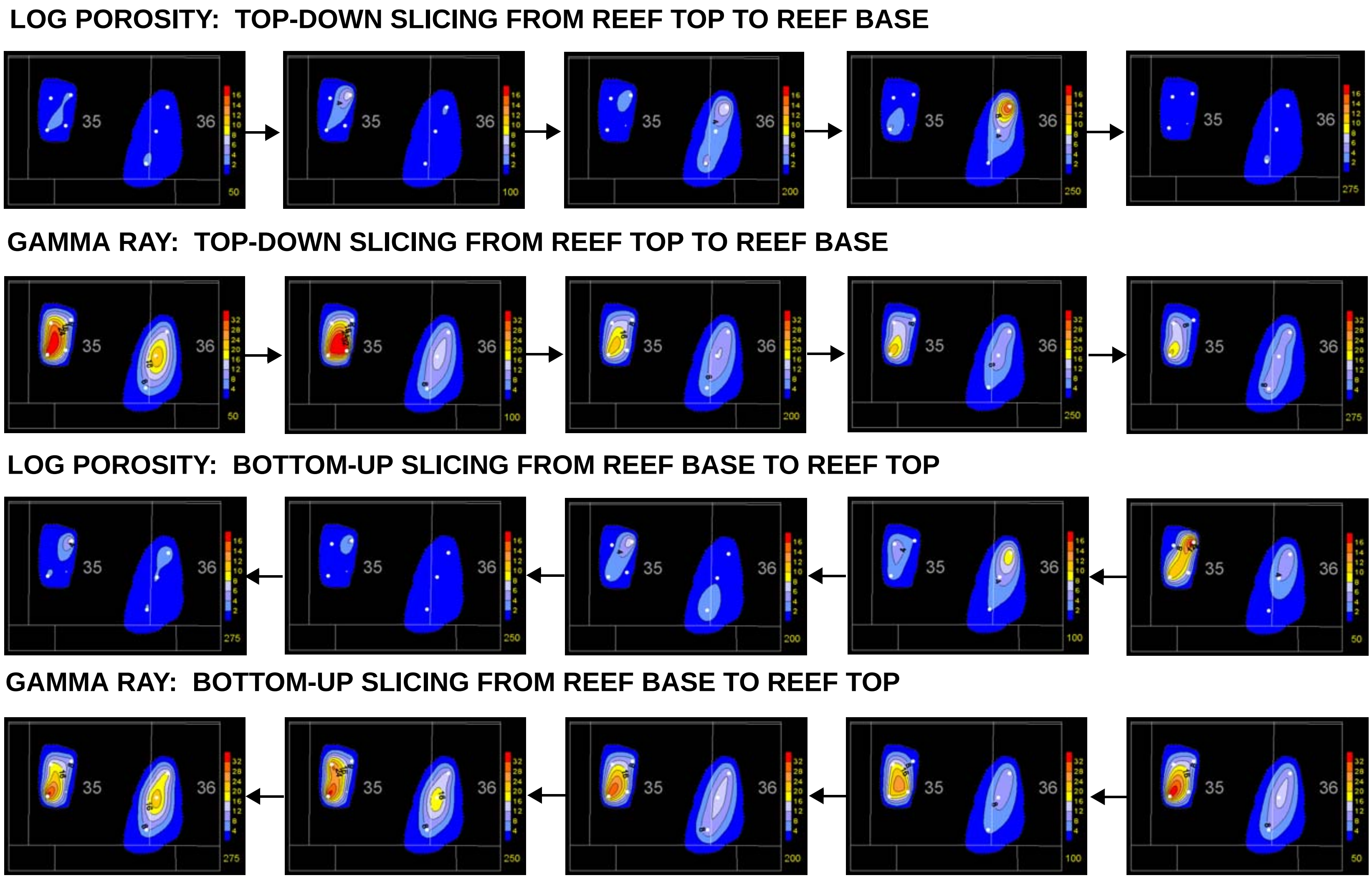


Figure 6. Dover 35 and Dover 36 Well Log Tomography slices. Color Scale is in percent porosity with a Contour Interval of 2 phi for Log Porosity slices, and Color Scale is in API units with a Contour Interval of 4 api for Gamma Ray slices. Slice number is feet above reef base or below reef top. North is toward the top of each map.

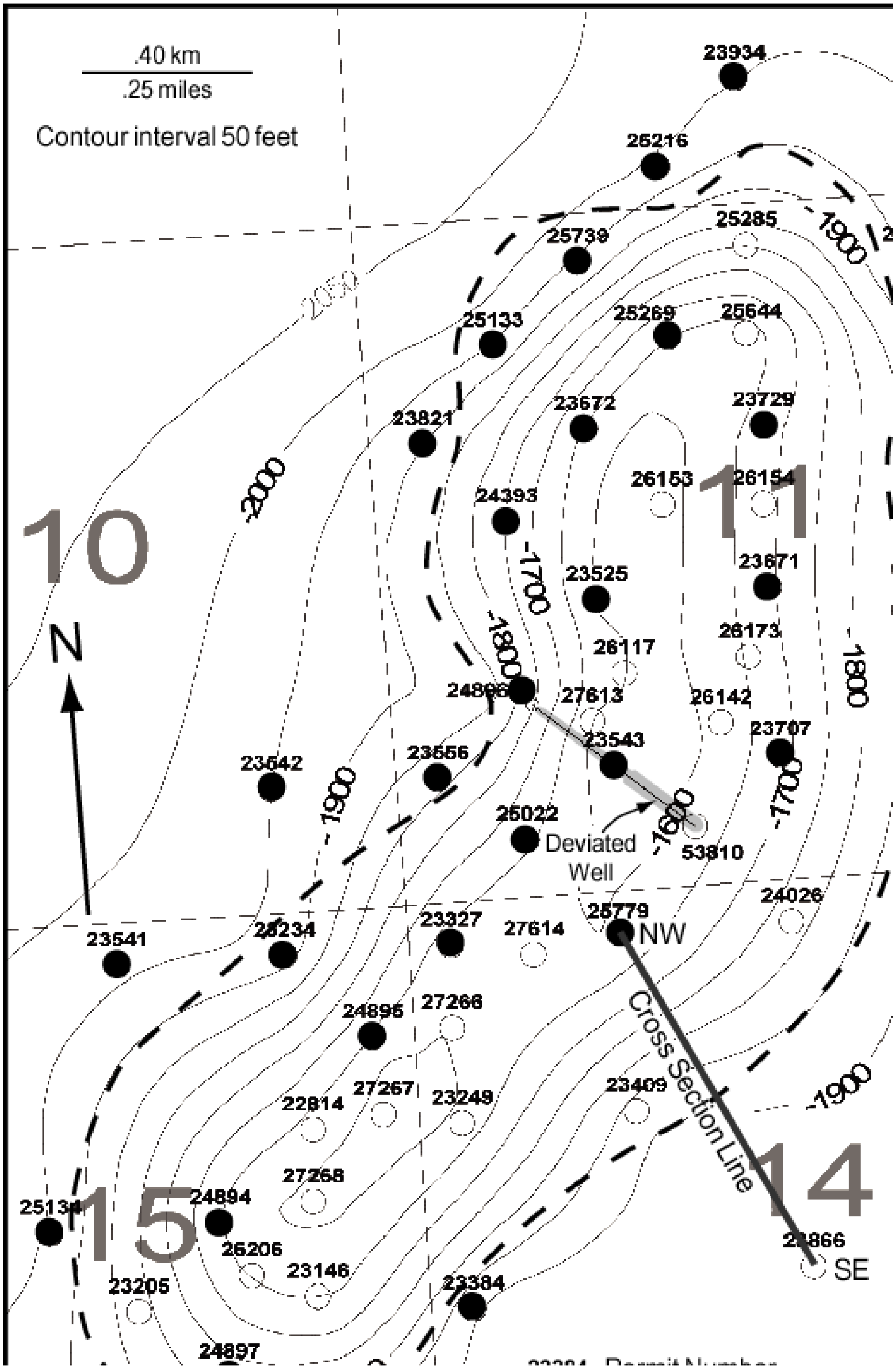


Figure 7. Belle River Mills top boundstone structure contour map (modified from Gill, 1977a) showing field extents. Maximum reef height is 400 feet above the non-reef Brown Niagaran. The contour interval is 50 feet. Black circles indicate cored wells.

Figure 8 (next page). Comparison of four bottom-up core permeability, core porosity, and gamma ray slices from the wackestone, boundstone and basal stromatolite in the Belle River Mills Field. Note the permeability and porosity amplitude trends are approximately equivalent to the trends observed in the gamma ray amplitudes. This is an important observation and is significant in that it means that the log curve amplitude slicing of the gamma ray curves only may be able to be used to visualize the approximate distribution of permeability and porosity in reefs without core data (most Niagaran reef wells have at least a gamma ray log curve) by utilizing the data from this benchmark reef. The permeability slice data range is 0 to 30 millidarcies with values greater than 30 md reset to 30. The contour interval for each slice is 4 millidarcies. The porosity slice data range is 0 to 36 percent. The contour interval for each slice is 4%. The data range for each gamma ray slice is 0 to 40 api units. The contour interval is 5 api units. All wells in the field have gamma ray curves through the reef. Gray lines are section boundaries and gray numbers are section numbers. North is toward the top of the slices. Large white dots are data control points on each slice and small white dots are other well penetrations. Slice numbers or elevation in feet above the reef base is displayed in yellow below the vertical scale bar.

	Core Permeability	Core Porosity	Gamma Ray
SLICE 324 basal STROMATOLITE			
SLICE 250 BOUNDSTONE			
SLICE 200 BOUNDSTONE			
SLICE 125 WACKESTONE			
	CI = 4 md	CI = 4%	CI = 5 api

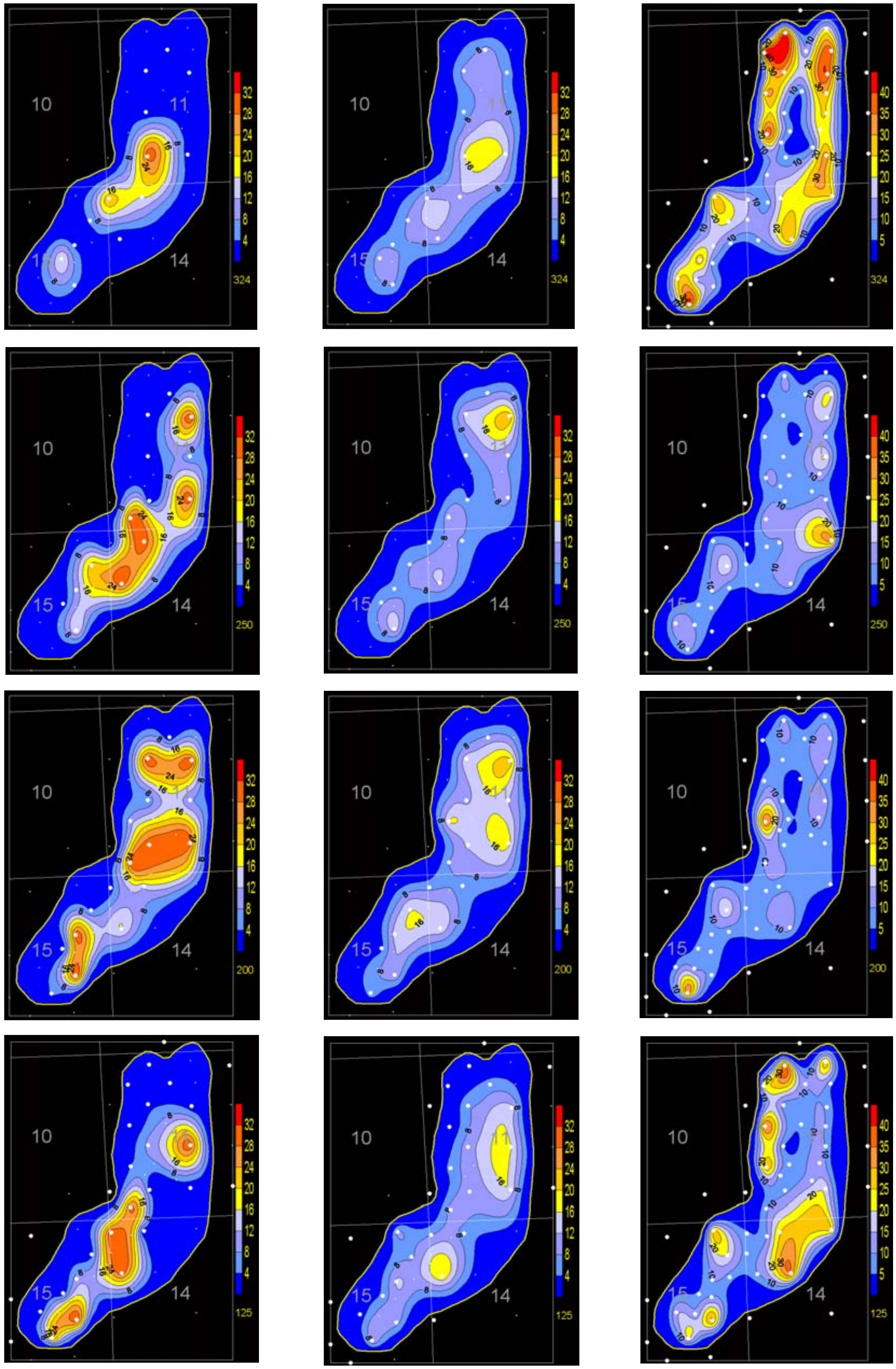
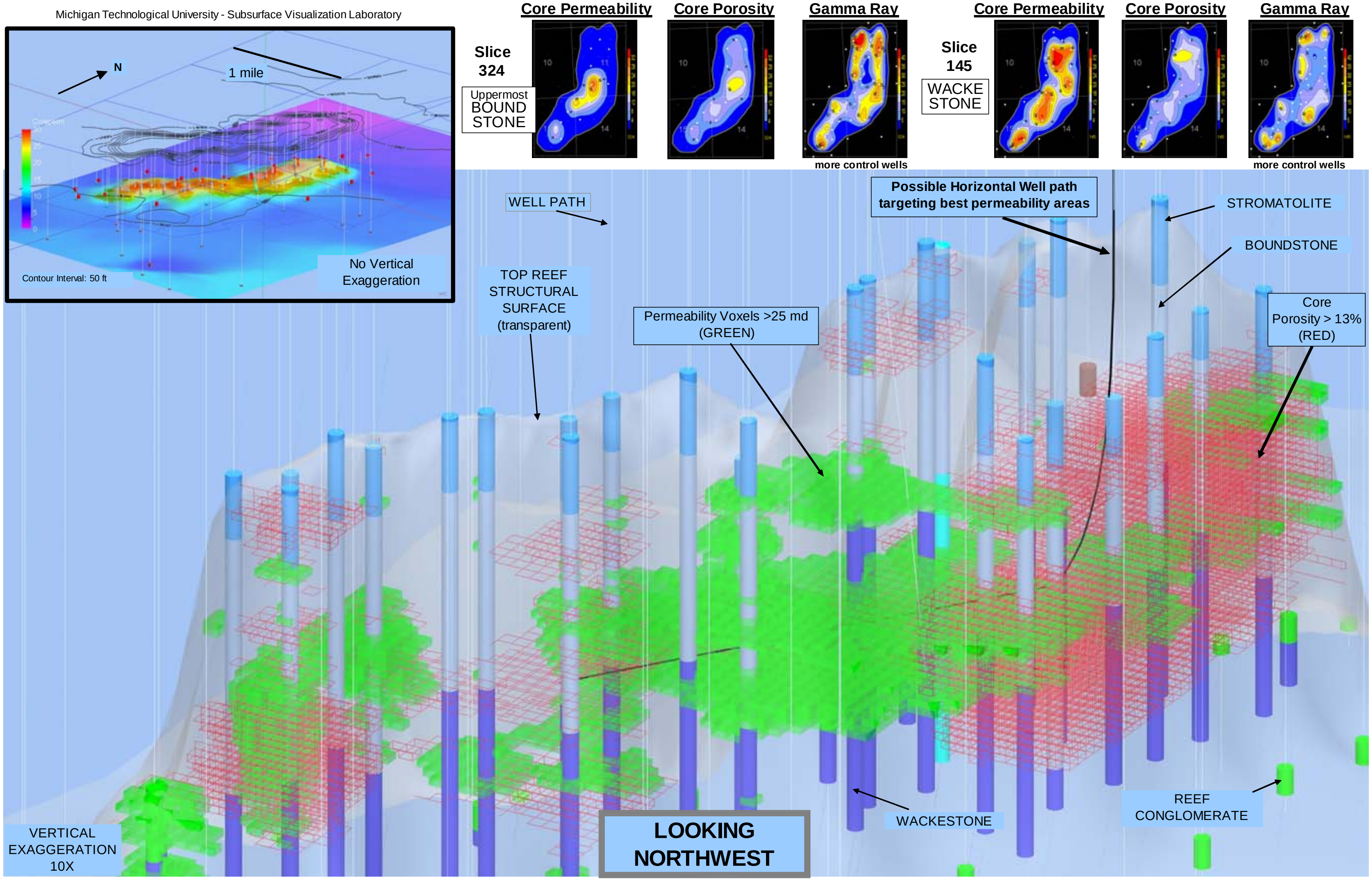


Figure 9 (next page). Belle River Mills 3D reef presentation, showing permeability voxels 25 md and greater (green), porosity voxels 13% and greater (red), rock types (blues and green), and transparent crestal reef structure surface. View is looking northwest, 30 degrees above horizontal. The best permeability and porosity is located in the upper wackestone (dark blue, lower reef) and lower boundstone (light blue, mid-reef) rock types. The stromatolite rock type (medium blue, upper reef) generally has poorer quality permeability and porosity. Storage and deliverability capacities of this gas storage reservoir could be optimized using this type of 3D visualization analysis. Vertical exaggeration is 10X. Six inset tomography images show the core permeability, core porosity, and gamma ray at two levels in the reef - in the wackestone and upper boundstone. Inset (upper right) model shows color-filled top of reef structural contours and landgrid overlays with no vertical exaggeration. Also shown is the trace of a potential horizontal well designed to encounter the best permeability areas based upon the tomography and 3D-imaging.


Michigan Technological University - Subsurface Visualization Laboratory
N
1 mile
Contour Interval: 50 ft
No Vertical Exaggeration
Core Permeability
Core Porosity
Gamma Ray
Core Permeability
Core Porosity
Gamma Ray
Slice 324
Uppermost BOUND STONE
Slice 145
WACKE STONE
more control wells
more control wells
WELL PATH
Possible Horizontal Well path targeting best permeability areas
STROMATOLITE
BOUNDSTONE
TOP REEF STRUCTURAL SURFACE (transparent)
Permeability Voxels >25 md (GREEN)
Core Porosity > 13% (RED)
WACKESTONE
REEF CONGLOMERATE
VERTICAL EXAGGERATION 10X
LOOKING NORTHWEST

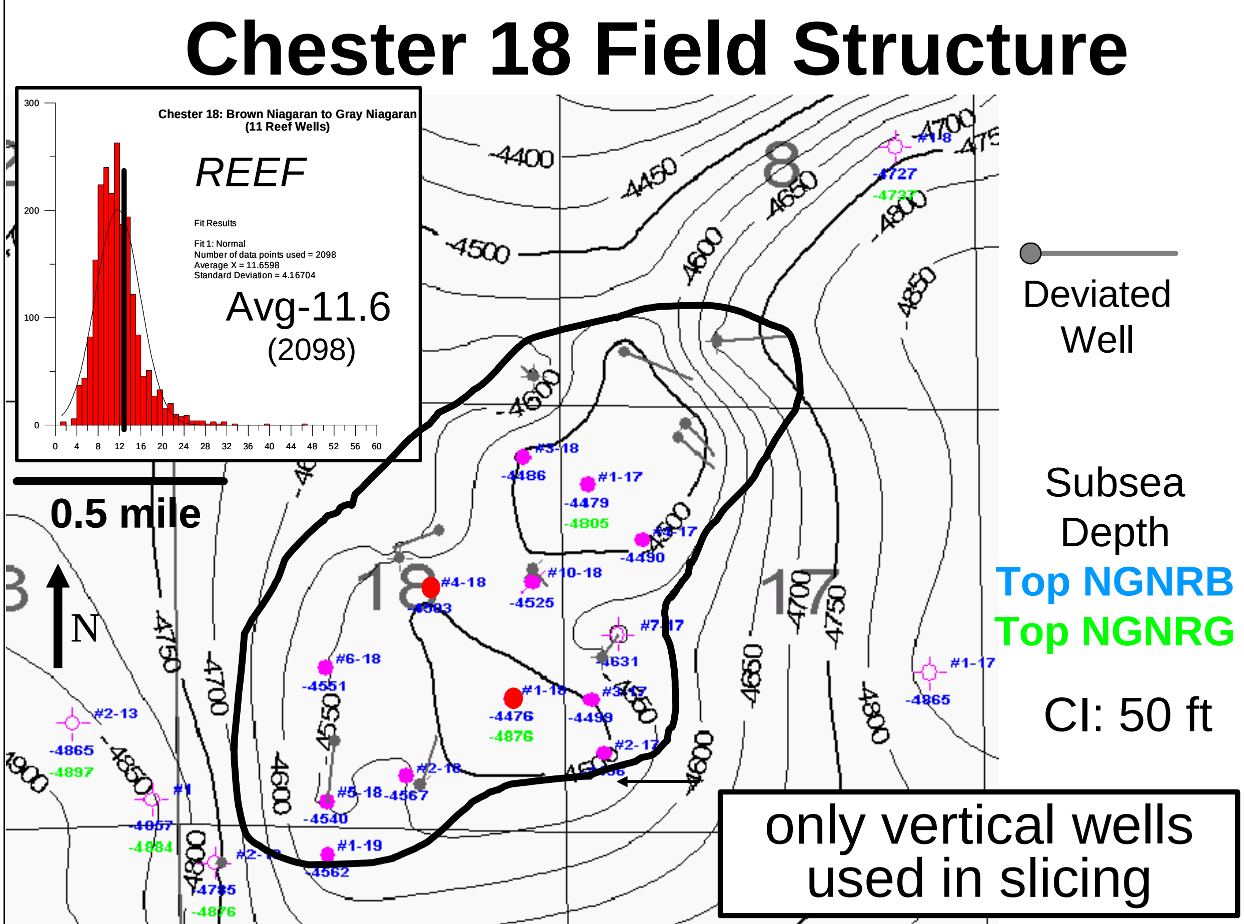


Figure 10. Structure map of Chester 18 Field in Otsego County, Michigan. Red circles indicate the vertical wells which have core data, the Shell Jaruzel 1-18 and the Shell Vinecki-Samkowiak 4-18 wells (refer to figures 12a and 12b for log and core description for the 4-18 well).

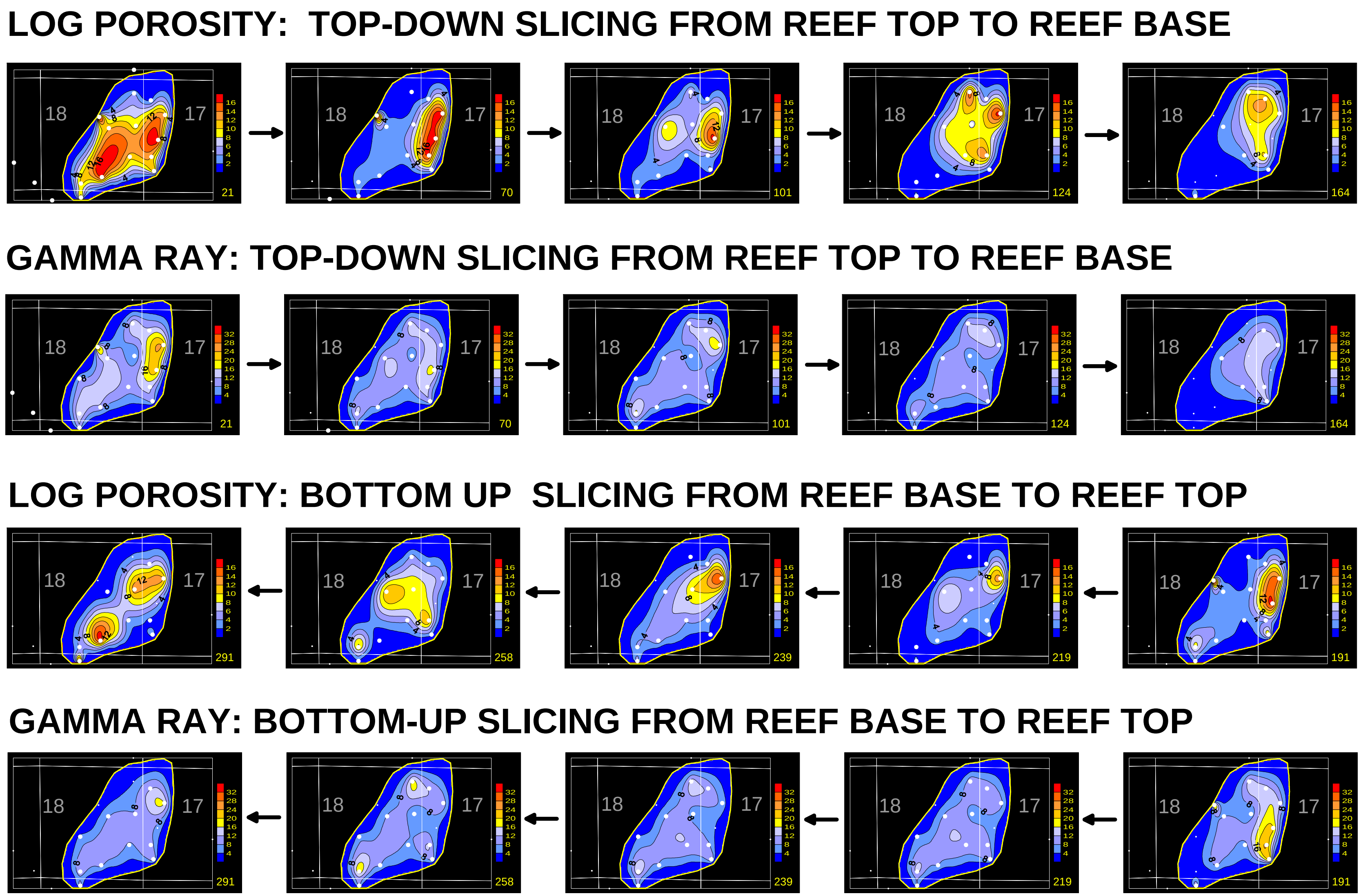


Figure 11. Chester 18 Well Log Tomography slices. Color Scale is in percent porosity with a Contour Interval of 2 phi for Log Porosity slices, and Color Scale is in API units with a Contour Interval of 4 api for Gamma Ray slices. Slice number is feet above reef base or below reef top.

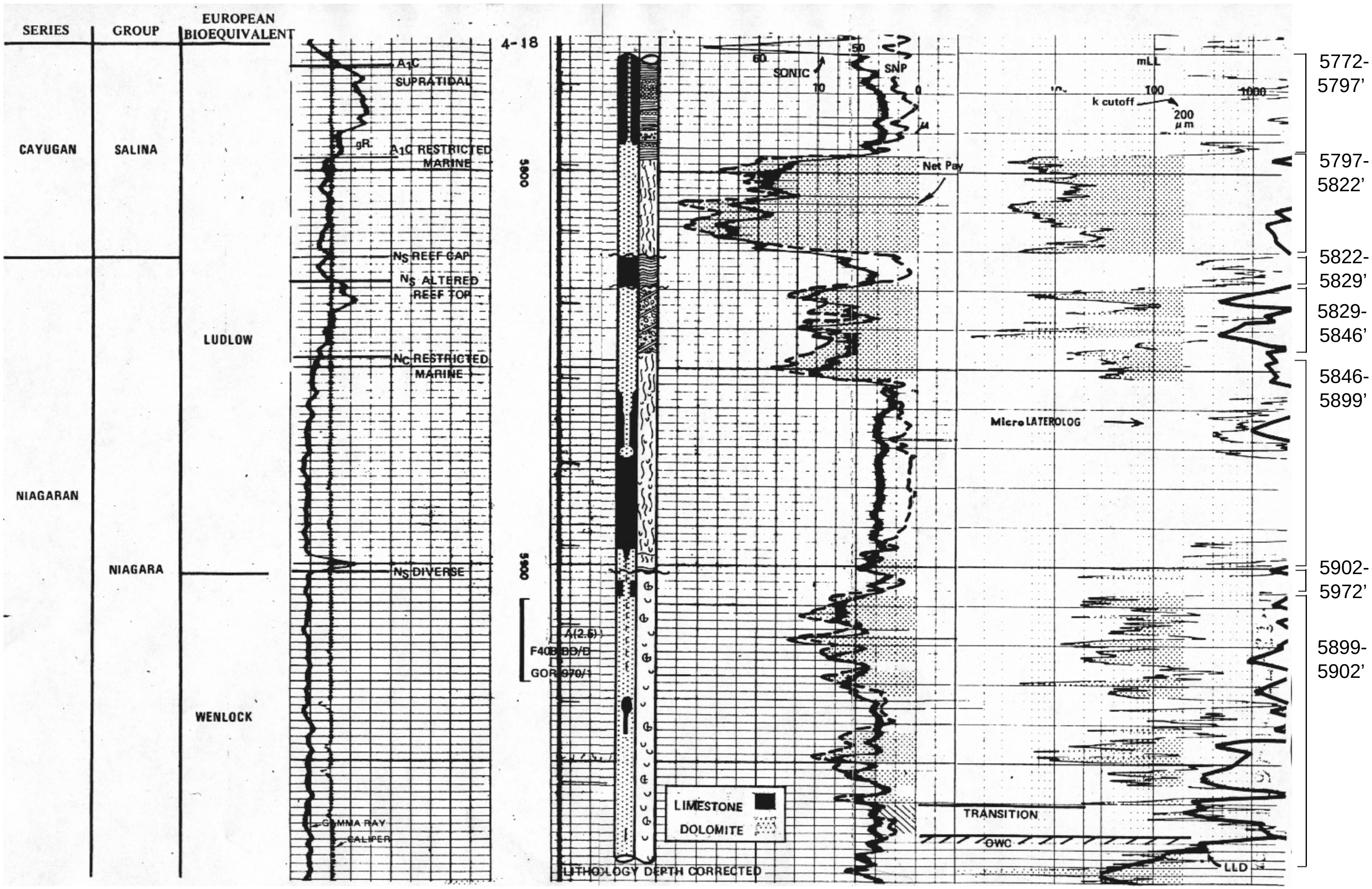


Figure 12a. Type log for Chester 18 30N-2W, Otsego County, Michigan, Shell Vinecki-Samkowiak 4-18 (KB 1330). Depth ranges on right correspond to the core descriptions given in Figure 12b.

TYPE LOG AND CORE DESCRIPTION FOR CHESTER 18 30N-2W
OTSEGO COUNTY, MICHIGAN
SHELL VINECKI-SAMKOWIAK 4-18
KB 1330

This core includes both the supratidal and restricted marine members of the Al carbonate, the restricted marine Niagaran reef, and approximately 70 feet of the diverse facies of the Niagaran reef. Core depths have been matched to correspond to the sonic log depths, normally by raising the core depth by three feet. However, much of the lower half of the core appears to be on depth with the sonic log. The SNP log overlays the sonic, and the MLL-LLD is on the right.

5772-97' A1 Carbonate-Supratidal
Algal stromatolite and fine-textured laminated mudstone with dessication features, alternating with lithoclastic-pelletoidal grainstone to packstone, coarse-grained and fairly well-sorted, mostly limestone. Lower 6 feet of the unit is dolomitized as are some of the clasts in the grainstone.

5797-822' Restricted Marine Al Carbonate

Fine to med1ium-grained sucrosic dolomite, massively bedded, probably a quiet water mudstone or pelleted wackestone. Rare fossils include small bracs and algal structures. Mottled texture due to variations in dolomite crystal size may reflect degrees of churning prior to lithification. Average crystal size decreases upwards as does porosity. A finely-structured vug system is common in the lower 15 feet of the unit and appears to grade upward into the intercrystalline porosity fabric. Bitumen is ubiquitous as adhering globules in the pore network, and severely reduces both effective porosity and permeability.

5822-29' latertidal lime mudstone and travertine Niagaran Cap

Lower three feet of this unit consists of intertidal-supratidal laminated mudstone, medium gray in color. Inorganic trivertine is gradually established in the middle of the unit and is light tan in color, concentric to uniform laminations with several slump features. Unit is very fine-grained limestone, without significant porosity. Contact of this unit with pisolite clastics is not present. This lithology in most wells is a hemispherical algal stromatolite.

5829'-46' Reef top sediments-Late Niagaran

Well-layered, coarse, poorly-sorted, dolomitized clastics, probably wackestone to packstone, at moderate depositional angle, containing many 1-2 cm. pisolites. These sediments were derived from reworked caliche on the reef surface and may have been weathered after deposition possibly in a topographic low in the reef surface. Scattered horizontal laminations near top of unit probably are altered intertidal to supratidal mudstones. Porosity from fine intercrystalline and pinpoint vugs as well as scattered primary intraclast vugs and several solution channels (5334 and 37').

5846-899' Restricted Marine facies of the Niagaran reef

A medium gray lime mudstone, poorly-churned and massively bedded, with numerous "scour" hiatus breaks near top of the unit. Irregular "birdseye" vugs, 2 mm. to 1 cm. in diameter are scattered to common and are normally filled with the first state fibrous marine calcite. Rare vugs result from incomplete calcite plugging. Several isolated leached vugs of large size are filled with spary calcite. Porosity in much of this interval approaches zero. In the upper 18 feet and lower 4 feet of the unit moderate leaching and partial dolomitization of the mud has produced fair to poor pinpoint to fine vuggy porosity which is not permeable except for upper 8 feet of unit. 5846-34' is more dolomitic with subtle laminations and fair to good, fine pinpoint porosity.

5899-902 Transgressive bioclastic grainstone

Gray argillaceous fine-grained dolomite siltstone, well-laminated, with several coarser-grained bioclastic detrital zones l cm. thick. Very tight. Similar gray sediment fills a vertical joint 2-3 feet below base of the zone. Could be lag sediment on possible exposure surface.

5902-72' Diverse facies of the Niagaran reef

Light to medium gray coral-crinoid dolomitized packstone to wackestone of normal marine environment. Fossil content includes finger corals, large crinoids, medium to large brachiopods and fragments of bryozoa, few in growth position, variable in abundance. Much variation in fabric due to differing fossil and mud content as well as degree of dolomitization and crystal size. Several zones are calcareous with partial dolomitization of mud matrix. Calcareous zones are tight. Reservoir rock consists of vuggy dolomite with porosity as fossil moldic and pinpoint to cm-sized tortuous vugs in the muddy matrix. Great variations in degree of leaching and dolomitization. Only in the coarser crystalline dolomite is there any matrix or intercrystalline porosity. Scattered leached-fracture porosity also present. Several thin argillaceous dolomite zones probably internal sediments deposited during leaching. Salt plugging evident in interval 5960-65 feet.

Figure 12b. Core descriptions and correlation to log curves of type log for Chester 18 30N-2W, Otsego County, Michigan, Shell Vinecki-Samkowiak 4-18 (refer to Figures 10 and 12a).