IMPLEMENTING A NOVEL CYCLIC CO2 FLOOD IN PALEOZOIC REEFS

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PRINCIPAL AUTHORS:

JAMES R. WOOD, MICHIGAN TECHNOLOGICAL UNIVERSITY, HOUGHTON, MI

W. QUINLAN, JORDAN EXPLORATION COMPANY LLC, TRAVERSE CITY, MI.

A. WYLIE, MICHIGAN TECHNOLOGICAL UNIVERSITY, HOUGHTON, MI

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NAME AND ADDRESS OF SUBMITTING ORGANIZATION:

MICHIGAN TECHNOLOGICAL UNIVERSITY
1400 TOWNSEND DRIVE
HOUGHTON, MI. 49931

ABSTRACT

Recycled CO2 will be used in this demonstration project to produce bypassed oil from the Silurian Charlton 6 pinnacle reef (Otsego County) in the Michigan Basin. Contract negotiations by our industry partner to gain access to this CO2 that would otherwise be vented to the atmosphere are near completion. A new method of subsurface characterization, log curve amplitude slicing, is being used to map facies distributions and reservoir properties in two reefs, the Belle River Mills and Chester 18 Fields. The Belle River Mills and Chester18 fields are being used as type-fields because they have excellent log-curve and core data coverage. Amplitude slicing of the normalized gamma ray curves is showing trends that may indicate significant heterogeneity and compartmentalization in these reservoirs.

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 the log curve amplitude slicing technique and a booth at the Midwest PTTC meeting.

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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.

Contract negotiations between our industry partner (Jordan Exploration Company, LLC) and the CO2 supplier are nearing completion. We expect to begin demonstration well operations and to lay the CO2 supply pipeline, the product flow line, and begin injecting CO2 in the third quarter of 2003. The shut in St. Charlton-Zeimet #1 (Michigan permit number 35209) will be plugged back from existing production perforations in the lower portion of the reef to a zone in the upper portion of the reef where the CO2 will be injected. We expect to begin drilling the new horizontal production well in the fourth quarter of 2003. The production well will be placed in the best reservoir rock in the lower regions of the reef stratigraphically where the vertical well (now the CO2 injection well) was originally completed.

Modeling of two Niagaran reef reservoirs is underway. The Bell River Mills Field located in the southern reef trend in St. Clair County, Michigan was selected as a type-field because it has excellent well log coverage and core coverage, and rock descriptions of the core have been published. The Chester 18 Field was chosen as the second type-field for modeling because it is located in the northern reef trend in Otsego County approximately five miles to the west of the Charlton 6 Field demonstration site and also has excellent log curve coverage. Log curve amplitude slicing of the gamma ray curves in these two fields has been completed and the remaining log curves are presently being digitized for additional modeling work. The core analysis data from the 35 cored wells in the Bell River Mills Field has been located and entered into a digital database. Amplitude slices can now be created of the porosity and permeability distribution in the reef. The logs for the Charlton 6 Field and vicinity are presently being digitized. Approximately 100 digital well log curve files (LAS files) were obtained from a Michigan operator for the northern reef trend. These digital files are being edited and quality controlled and along with the digital well log data captured for this demonstration project will form the basis for a digital Michigan Basin Niagaran reef well log database.

Engineering data is currently being compiled for Niagaran reefs in the Michigan Basin. The Michigan Department of Natural Resources production database through 1998 has been manipulated to create a digital report of the production for all Niagaran Fields. So far a separate digital database has been created from the Michigan Tech well databases showing wells that were cored in the Niagaran in the 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]

New Findings

One key new finding has emerged during the reporting period. It appears high-resolution images of the larger multi-well Niagaran Fields can be obtained using log-curve tomography. Tomography of the Belle River Mills and Chester 18 Fields shows that these fields are really composed of two to five individual reefs (or carbonate sediment production centers) that have coalesced to form what has been called a one 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 are each showing five areal subdivisions to the field.

Lessons Learned

We are learning 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. Ways to reduce the time required to secure these contracts will need to be considered when expanding this demonstration project to other Niagaran reefs in the Basin in the future.

Applications

The results of the log curve amplitude slicing of the Belle River Mills and Chester 18 Fields will be applied using well data in several other medium size Niagaran fields near the demonstration site as well as to the Charlton 6 field.

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 log curve amplitude slicing to assist in the determination of the viability of secondary or tertiary recovery projects and CO2 sequestration. Log curve amplitude slicing is showing that the reservoir properties of the Niagaran reefs in the Michigan Basin vary both horizontally and vertically. These variations in porosity, permeability, and connectivity of the reservoir rock must be considered to insure that enhanced recovery operations including CO2 injection and horizontal well placement are designed appropriately. It appears likely that previous interpretations of reservoir and production engineering data suggesting that many Niagaran reefs deplete uniformly are incorrect. Our recent results suggest that most reefs may have undrained reservoir compartments.

Future Work

The demonstration injection well (St. Charlton-Zeimet #1) will be plugged back to a shallower position in the reef and CO2 injection will begin to re-pressurize the reef. The demonstration production well will be drilled into the best porosity in the basal portion of the reef using available data including 3D imaging and tomographic modeling of the Charlton 6 reef using log curve amplitude slicing. Surface facilities for handling the CO2 supply, CO2 injection, and the produced hydrocarbons and CO2 will be constructed and placed into operation.

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 CO2 injection and sequestration projects in the Niagaran reefs.

Technology Transfer

A technical paper on the preliminary slicing of the gamma ray log curves for Belle River Mills and Chester 18 Fields was presented at the Eastern Section Meeting of the American Association of Petroleum Geologist's meeting in Champaign, IL. A log curve amplitude slicing presentation was made to the Northern Section of the Society of Petroleum Engineers at a meeting in Traverse City, MI. A booth was set up at the Midwest PTTC horizontal well conference in Mt. Pleasant, MI in March, 2003 to show operators in the Basin log curve slicing animations and maps of the gamma ray curves for the Belle River Mills and Chester 18 Fields. A technical paper on the log curve amplitude slicing technique was published in the April 2003 issue of the Bulletin of the American Association of Petroleum Geologists.

2.0 EXPERIMENTAL

Log curve amplitude slicing is a form of tomography that utilizes the full vertical resolution of geophysical well log curves (Wylie and Huntoon, 2003; Wylie, 2002). 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. The distribution of other reservoir properties including porosity, permeability, and water saturation can also be visualized using the technique.

In the case of the Niagaran reefs, only one chronostratigraphic surface is being 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 porosity and permeability measurements.

2.1 Log Data Capture

Paper copies of the well logs for the 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 then utilized to digitize the gamma ray and/or transit time (sonic), bulk density, and neutron 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 (LAS) files were output from the Neuralog software to use in log curve amplitude slicing and cross sections.

3.0 RESULTS AND DISCUSSION

Extensive carbonate and evaporite deposition occurred during middle to late Silurian time when the Michigan Basin was located just south of the equator (Scotese and others, 1979, indicated the basin was located less than 30 S). The general stratigraphic nomenclature for the Silurian in the Michigan basin is shown in Figure 1. The basin is typically divided into three depositional settings during the middle Silurian Niagaran: 1) a shallow, basin-edge carbonate barrier reef or bank comprised of reef limestone, back-reef lagoonal deposits, patch reefs, and fore-reef lime mudstones and lime sandstones; 2) a gently sloping shelf, which includes the pinnacle reef belt and inter-reef micritic crinoidal limestones; and 3) a deep basin center with thinner deposits of dense, micritic, argillaceous limestones (Figure 2) (Mantek, 1973; Friedman and Kopaska-Merkel, 1991; Leibold, 1992). The upper Silurian Salina units lap out against and overlay the Niagaran reefs and represent sediments deposited in a hypersaline environment during the initial stages of a major craton scale regression in the late Silurian (Sanford, 1969; Sloss, 1963, 1969, 1982a). The precise temporal relationship of the Salina and underlying Niagaran is unclear. Some workers postulate the two units are partly contemporaneous while others conclude Niagaran deposition ended before the deposition of the Salina (Mesolella et al., 1974; Kesling, 1974; Droste and Shaver, 1977; Huh et al., 1977; Gill, 1979; Sears and Lucia, 1980; Leibold, 1992). Gill (1977) presented a concise picture of the Niagaran and Salina stratigraphic relationships in the Belle River Mills Field (Figure 3) that can be used in most areas of the basin.

3.1 Log Curve Amplitude Slicing in the Belle River Mills Field, St. Clair County, Michigan

The Belle River Mills Field covers an area of 1760 acres and was discovered in 1961 (Figure 4). The field produced over 21 BCF of gas from 30 wells before its conversion to a gas storage field in 1965. Gross distribution of reservoir facies and porosity zones in this Niagaran reef has been described based upon logs and cores (Gill, 1977). Belle River is currently operated by MichCon and has 47 BCF of working gas capacity and 29 BCF of base gas. All wells in the field area are vertical except for one horizontal well, the BRM 13HD-1 (permit number 53810, section 11, SENWSW), drilled in June 2000. Only the vertical wells were used in the log slicing.

A reef to non-reef, stratigraphic cross section is shown in Figure 5 for Belle River Mills. The Lockport Dolomite or Gray Niagaran top defines the base of the reef. The reef is divided vertically into biohermal (wackestone), organic (boundstone), and supratidal (stromatolitic dolomite) stages based upon Gill's core descriptions and formation tops. The cross section shows the change in the gamma ray curve character from reef to non-reef and how the lower Salina units pinch out against the reef. The reef rubble conglomerate that typically rings a reef at its base is also shown.

The gamma ray curves from approximately 60 wells in the Belle River Mills Field and surrounding area were scanned and digitized. Histograms and mean and standard deviations were computed for each gamma ray curve 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.

The normalized gamma ray curve amplitudes were divided into intervals using Gill's formation tops. Histograms were created of the gamma ray amplitudes for each of the intervals (Figure 6). Reef to non-reef slicing and use of non-reef gamma ray curve data was necessary to keep the gridding algorithm from creating incorrect contouring (spool ups) along the edges of the reef and map.

Another method used to limit the gridding algorithm and color fill to the edge of the reef was to use the Belle River Mills Field outline as a series of pseudo-wells equal to zero gamma ray amplitude. This provides a realistic limit for the gridding algorithm based upon the geology, likely reservoir properties, and extent of the reef. Belle River Mills Field is unique in that it has non-reef penetrations with log curves in close proximity. Many Niagaran reef fields do not have surrounding non-reef penetrations that can be used to constrain gridding, therefore, the use of pseudo-wells is necessary.

Using bottom-up slicing, 500 gamma ray amplitude slices were created through the Belle River Mills Field. Gamma ray slice 119 is shown in Figure 7. This slice is located 119 feet above the base of the reef (note horizontal bar on right of figure next to gamma ray curve shows the location of the slice). The slice shows three areas of higher gamma ray amplitudes separated by areas of lower amplitudes. We interpret this trend as indication of at least three separate carbonate depositional centers that coalesced to form what we call the Belle River Mills reef or field. Figure 8 shows six slices that depict patterns in the gamma ray amplitude that suggest the Belle River Mills field began to form as one large carbonate mound that continued to build into three to five carbonate depositional centers that coalesced or that were possibly separated from each other by narrow gaps for periods of time. Slice 227 does not show any features or contrast because the average gamma ray amplitude of the reef and non-reef (Salina) lithologies is equal; using pseudo-wells would eliminate this lack of contrast. The top slice (446) shows the island or supratidal stage of reef growth.

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

The Chester 18 Field is located in the northern reef trend (Figure 2), covers an area of about 600 acres, and was discovered in 1971 (Figure 9). The field has produced over 13.5 million barrels of oil (MMBO) and 11 billion cubic feet (BCF) of gas from 20 wells from a depth of 5900 ft. Water flooding 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 gamma ray curve 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 gamma ray amplitude slicing (Figure 9). No detailed stratigraphic analysis like the work of Gill has been completed for the Chester 18 Field and core was taken in only one of the vertical wells. 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 curve for these wells in the proper spatial (vertical) position relative to the reef base (null values were used to populate amplitude values over these intervals for gridding).

Figure 10 shows gamma ray slice 214 (214 feet above the base or estimated base of the reef). The gamma ray curve on the left shows the position of the slice relative to the base and top of the reef. In this example, the reef outline was not used to constrain the gridding algorithm, therefore, anomalies (contouring spool ups) are evident around the periphery of the map in no data areas. Slice 214 shows two carbonate depositional centers that are even more evident when the full animation is viewed in color. Production engineering data from the operator that was released as part of the application for the waterflood project also suggested the Chester 18 Field was composed of two reservoir compartments.

4.0 CONCLUSION

Contract negotiations for the supply of CO2 that will be injected into the Charlton 6 reef are nearing completion. These contract negotiations have taken longer than anticipated. The time necessary for acquisition of the CO2 supply for future injection and sequestration projects must be taken into consideration when determining the time frame for future DOE contract awards.

Initial log curve amplitude slicing of the gamma ray curves for the Belle River Mills and Chester 18 ‘type-reef’ reservoirs has been completed. Results indicate significant heterogeneity exists in large Niagaran reefs that must be considered in the placement of injection and production wells.

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6.0 FIGURES

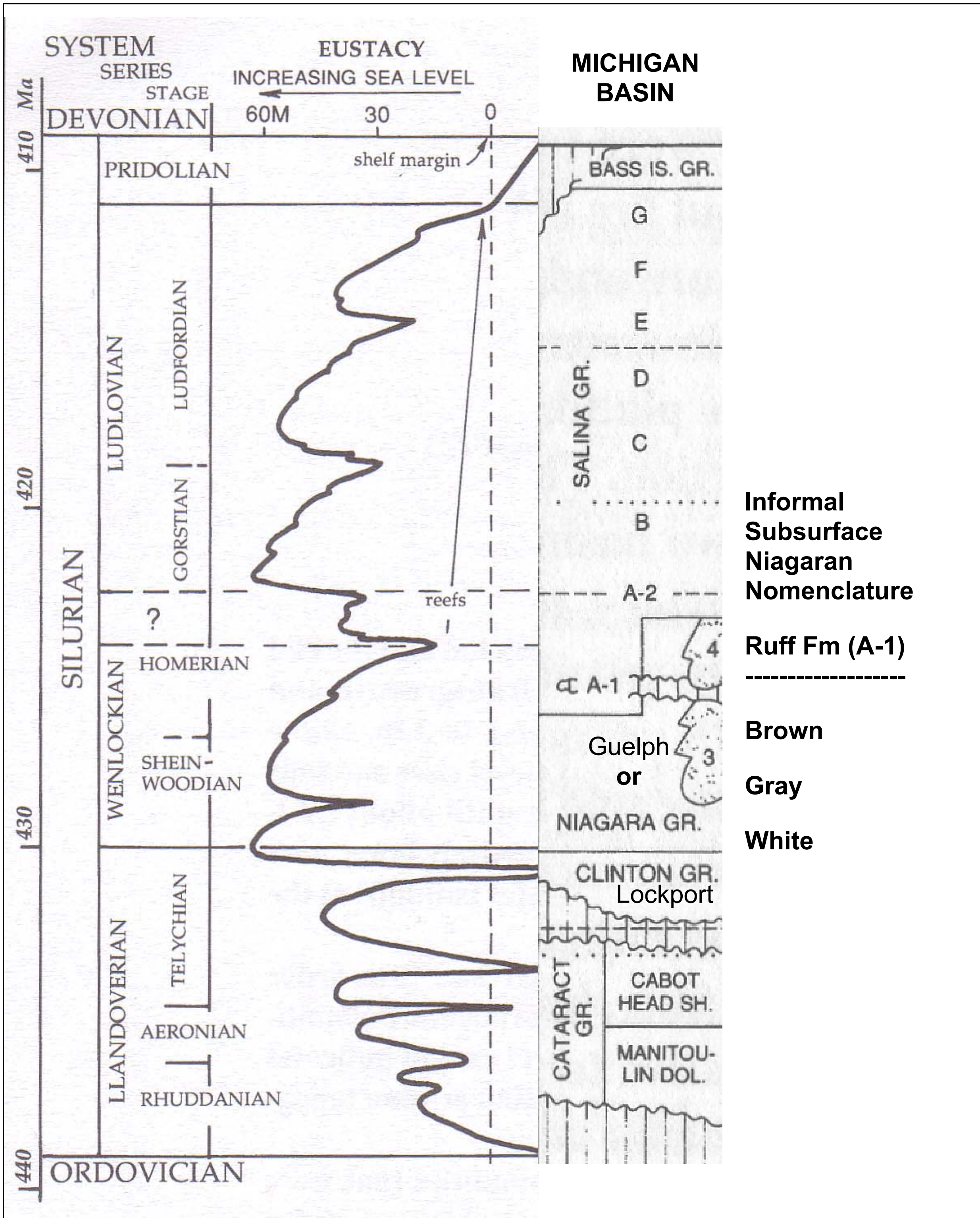

Figure 1. Stratigraphy of Silurian rocks in Michigan Basin together with sea level curve (modified from Shaver, 1996 and Ross and Ross, 1996).

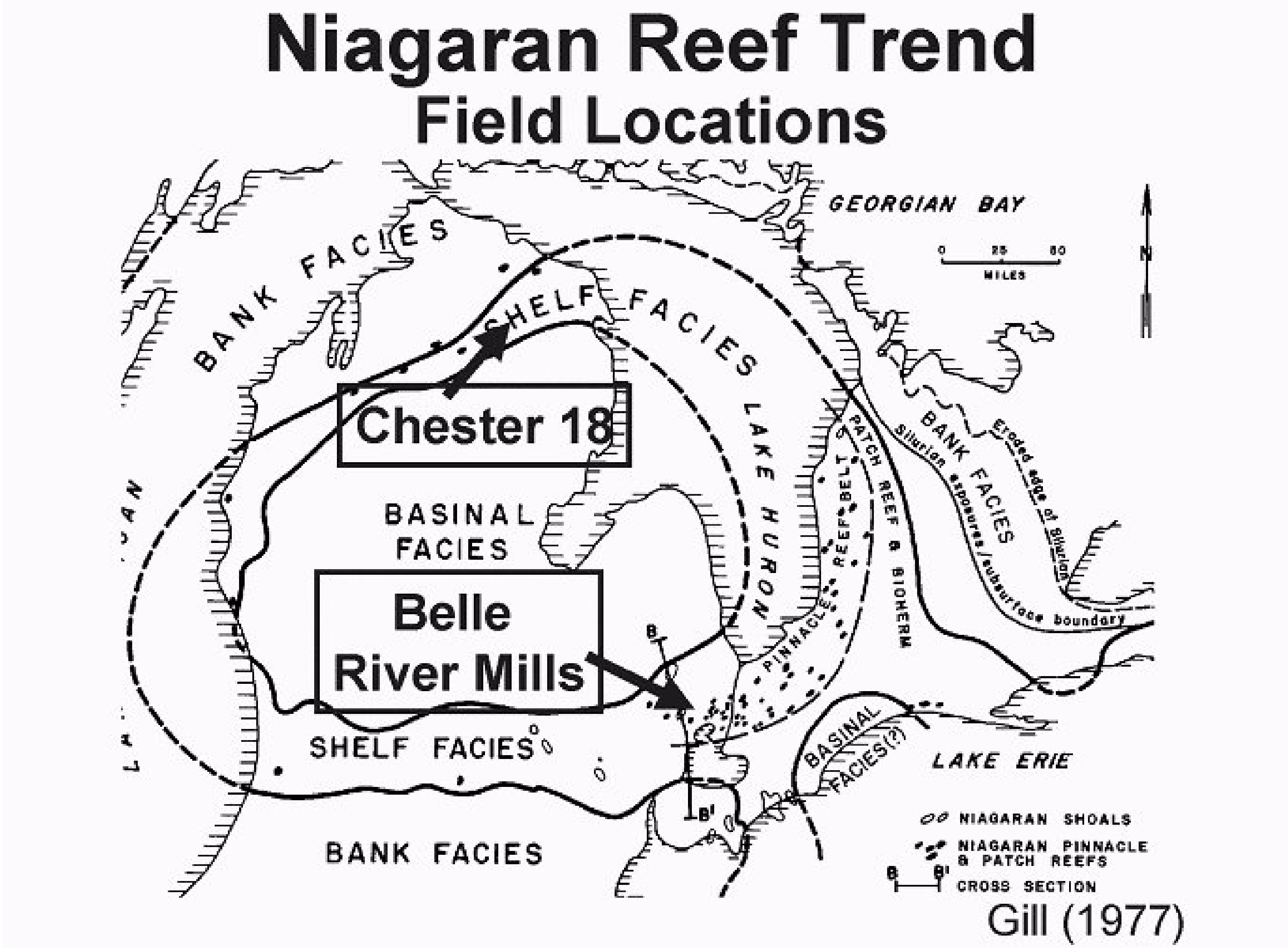

Figure 2. Map of Niagaran rocks in the Michigan basin showing three depositional areas and location of Belle River and Chester 18 Fields.

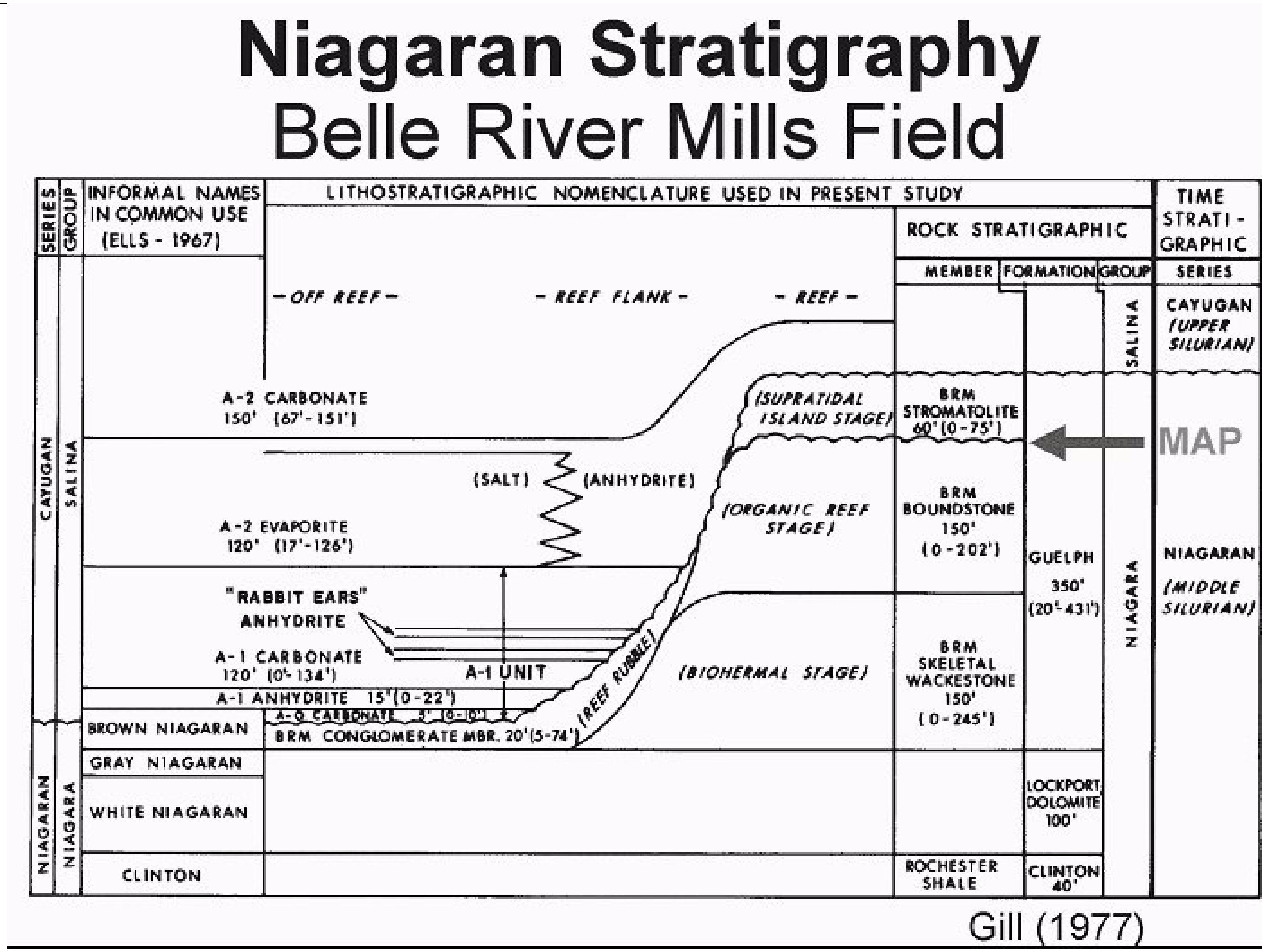

Figure 3. Stratigraphic column showing the detailed stratigraphy of the Belle River Mills Field and surrounding area.

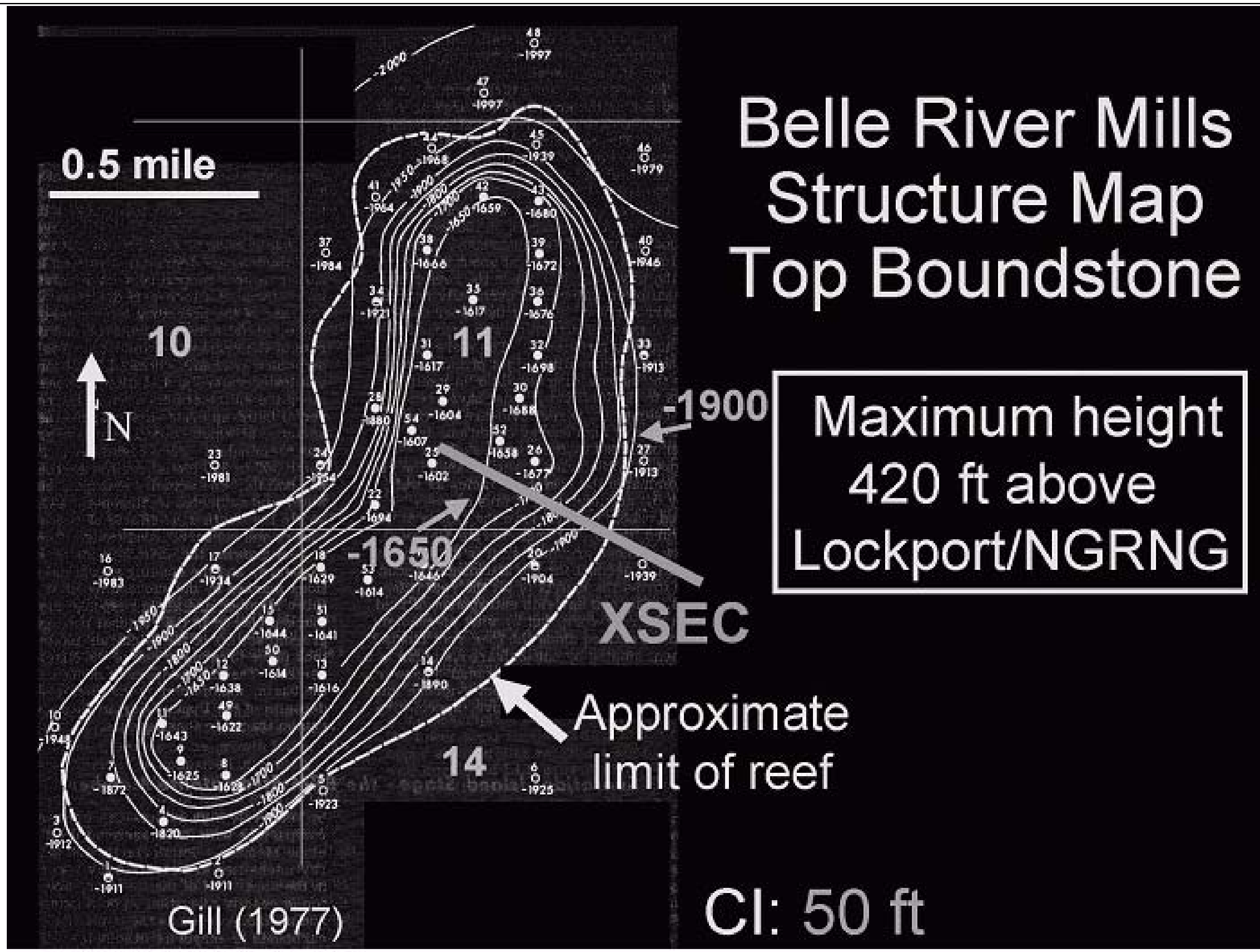

Figure 4. Structure map of the Belle River Mills Field on the top of the boundstone (refer to Figure 3).

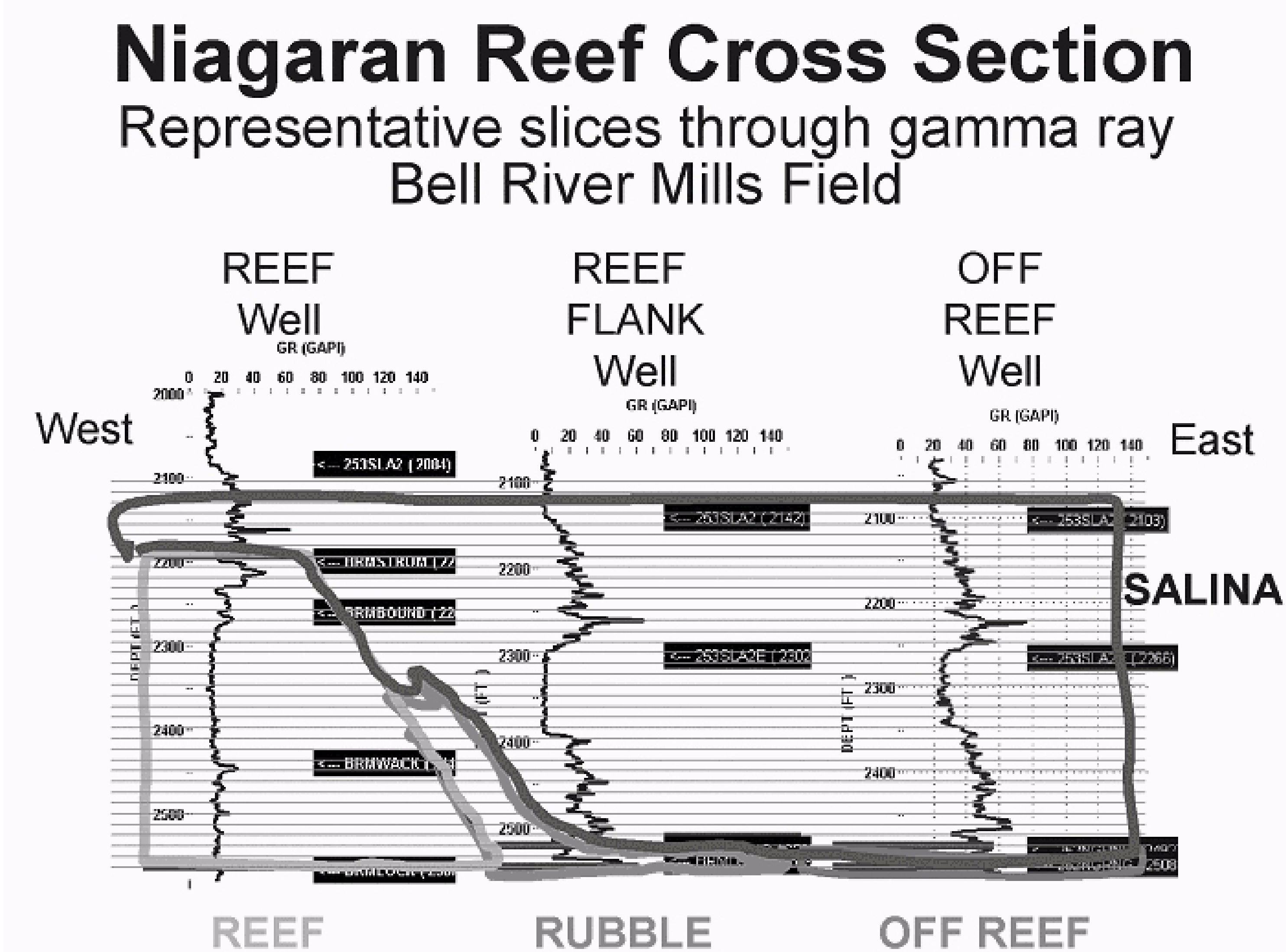

Figure 5. Gamma ray curve cross section from reef to non-reef for the Belle River Mills Field (location shown on Figure 4). Representative log curve slices are flattened using the base of the reef and slice horizontally from reef to non-reef.

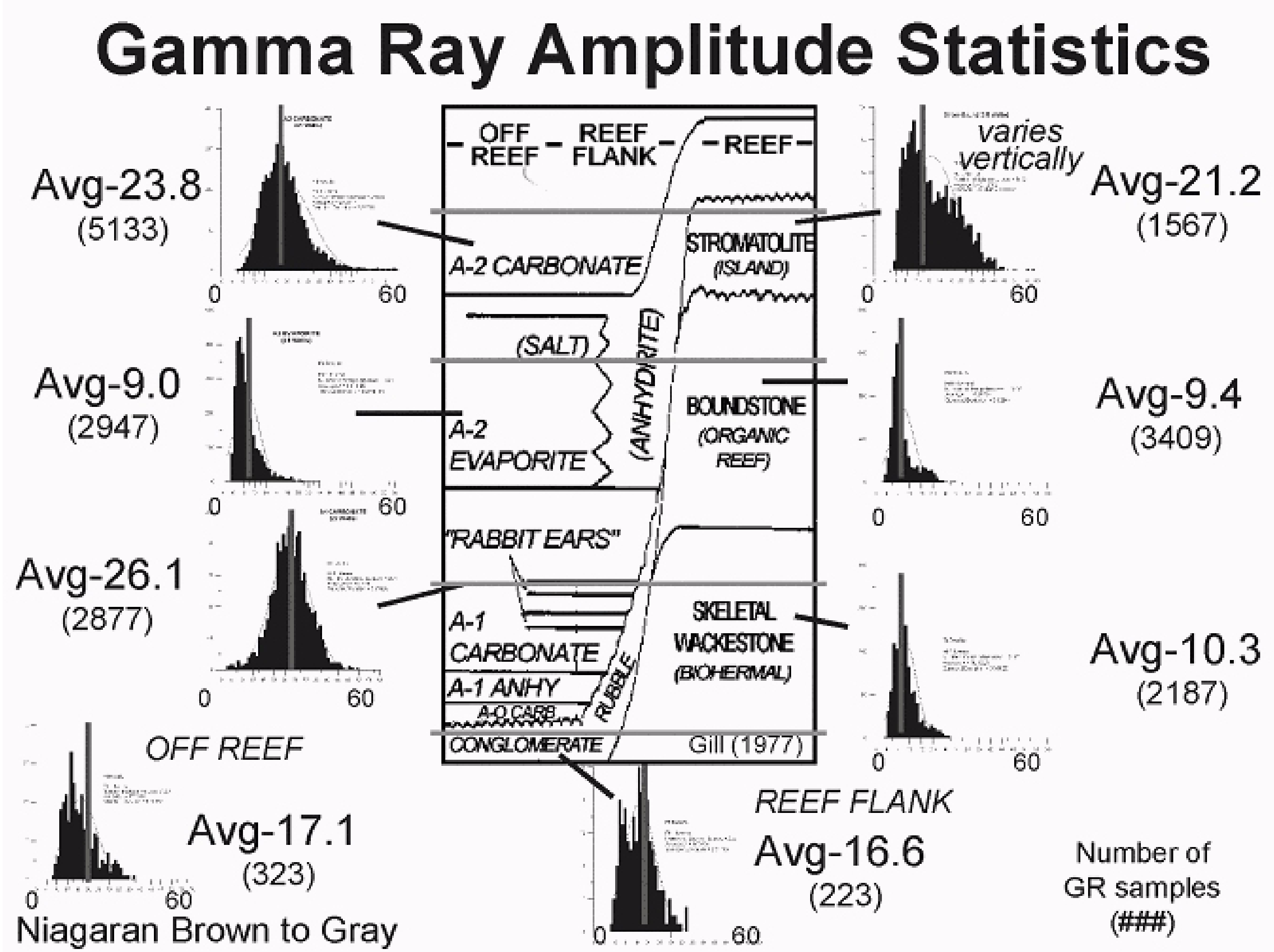

Figure 6. Gamma ray curve amplitude ranges and statistics for reef and non-reef facies based upon correlations of Gill (1977). The variation in average amplitude between the reef and non-reef (Salina lithologies) allows this variation of the log curve slicing technique that can be used to show trends in the normalized gamma ray amplitudes.

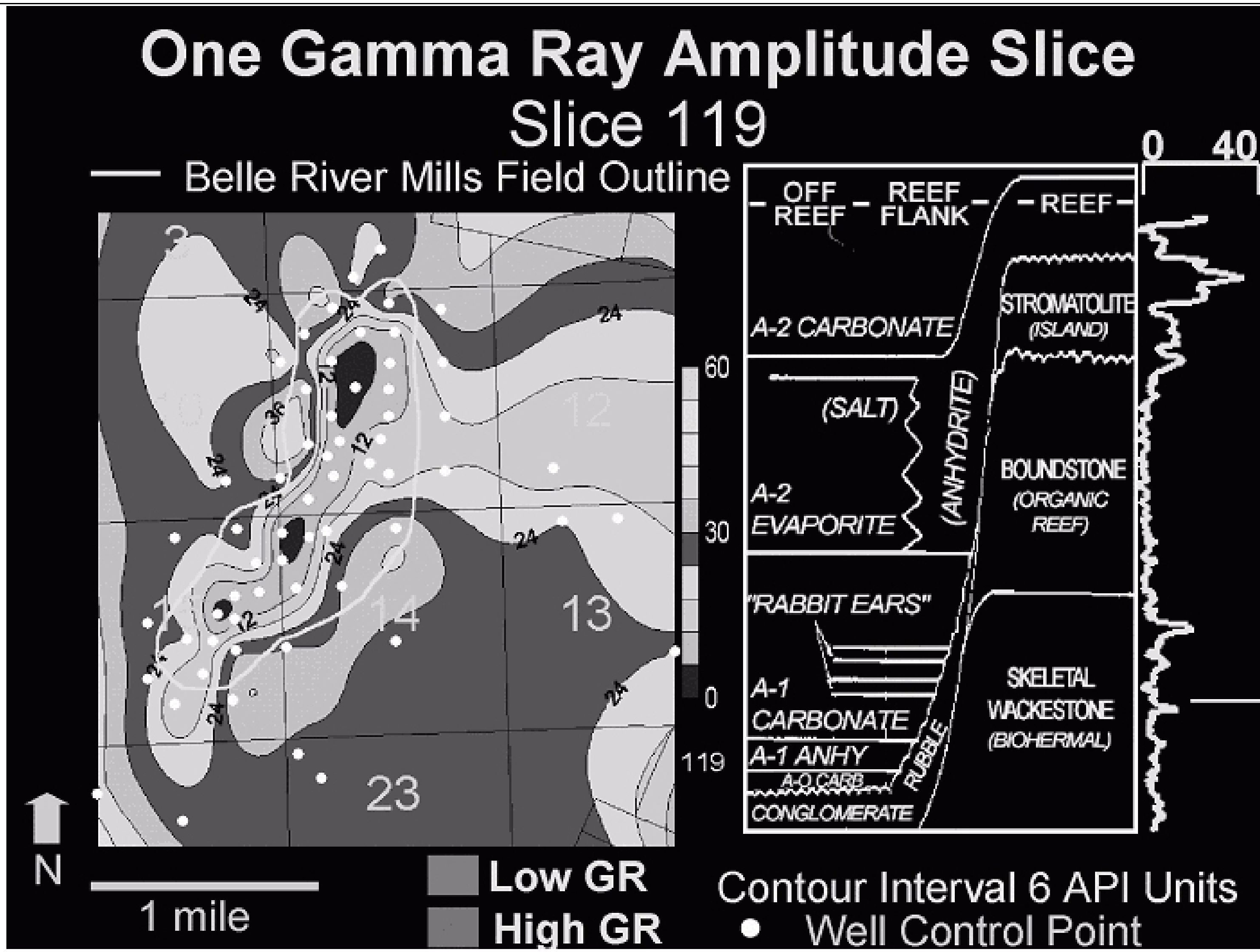

Figure 7. One gamma ray amplitude slice through Belle River (119 feet from reef base) displaying trends in the amplitude of the gamma ray curve.

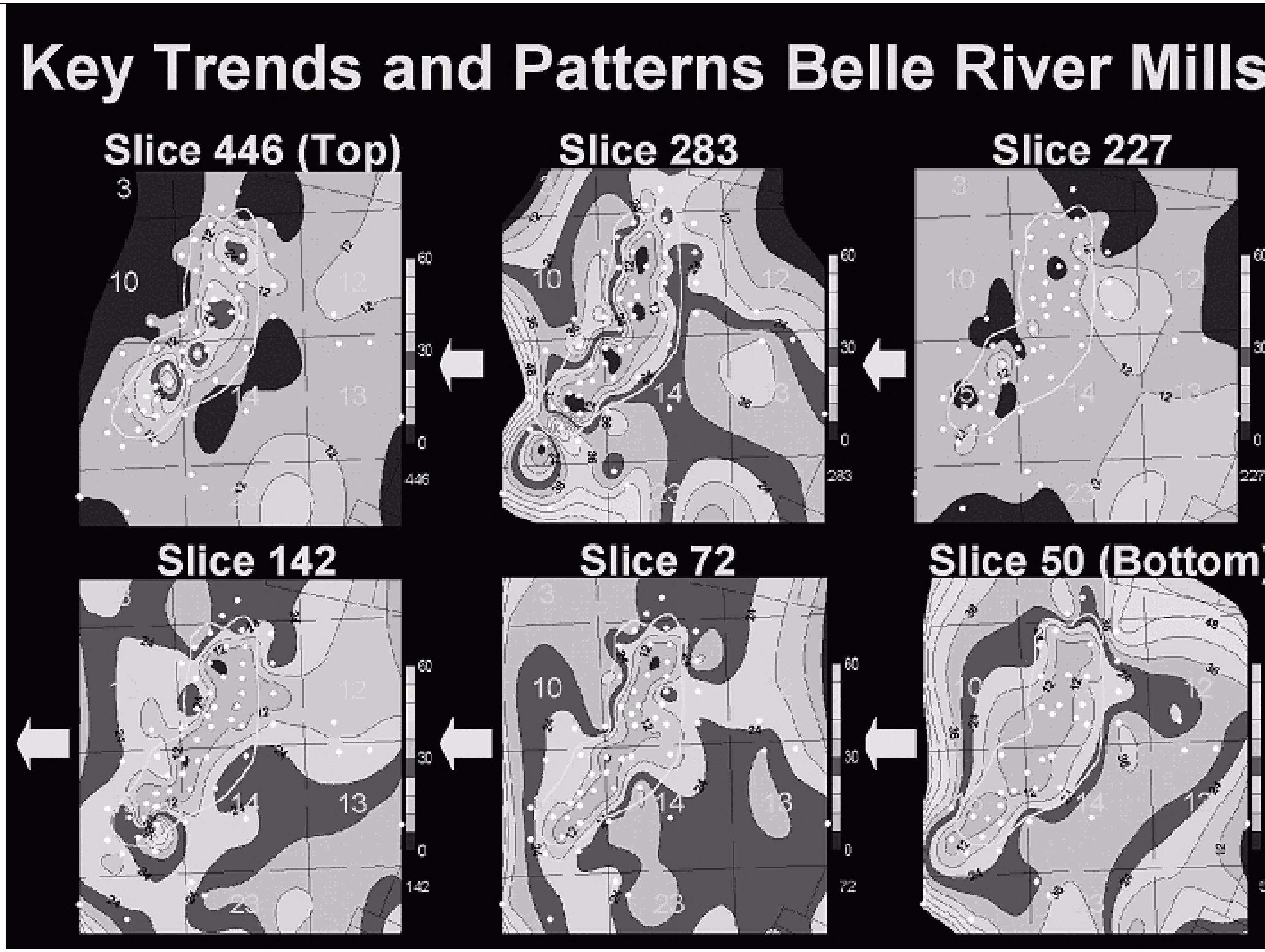

Figure 8. Slice maps of the gamma ray amplitude showing trends and patterns in six slices from the reef to non-reef.

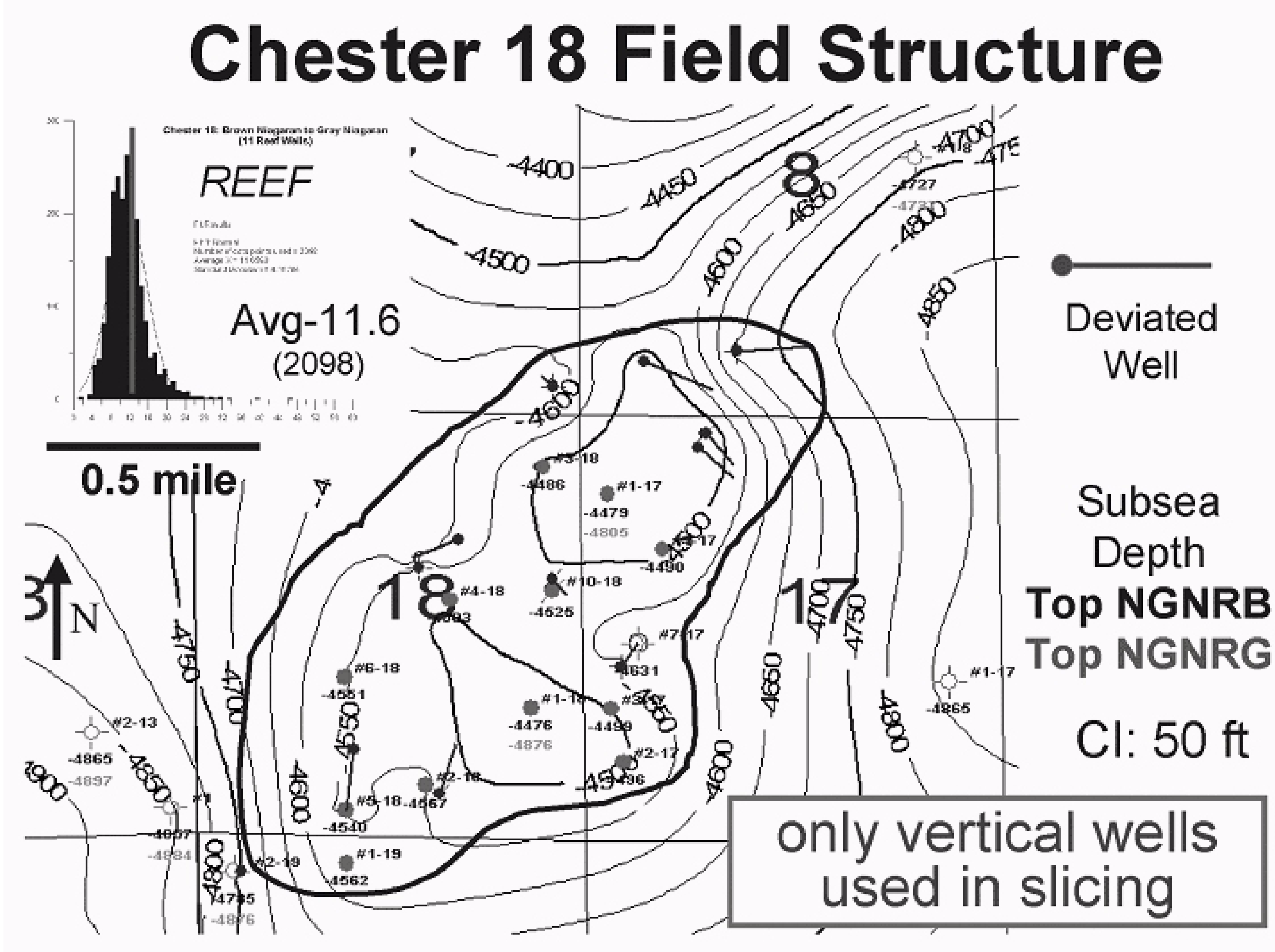

Figure 9. Structure map on the top of the Brown Niagaran (reservoir) for the Chester 18 Field.

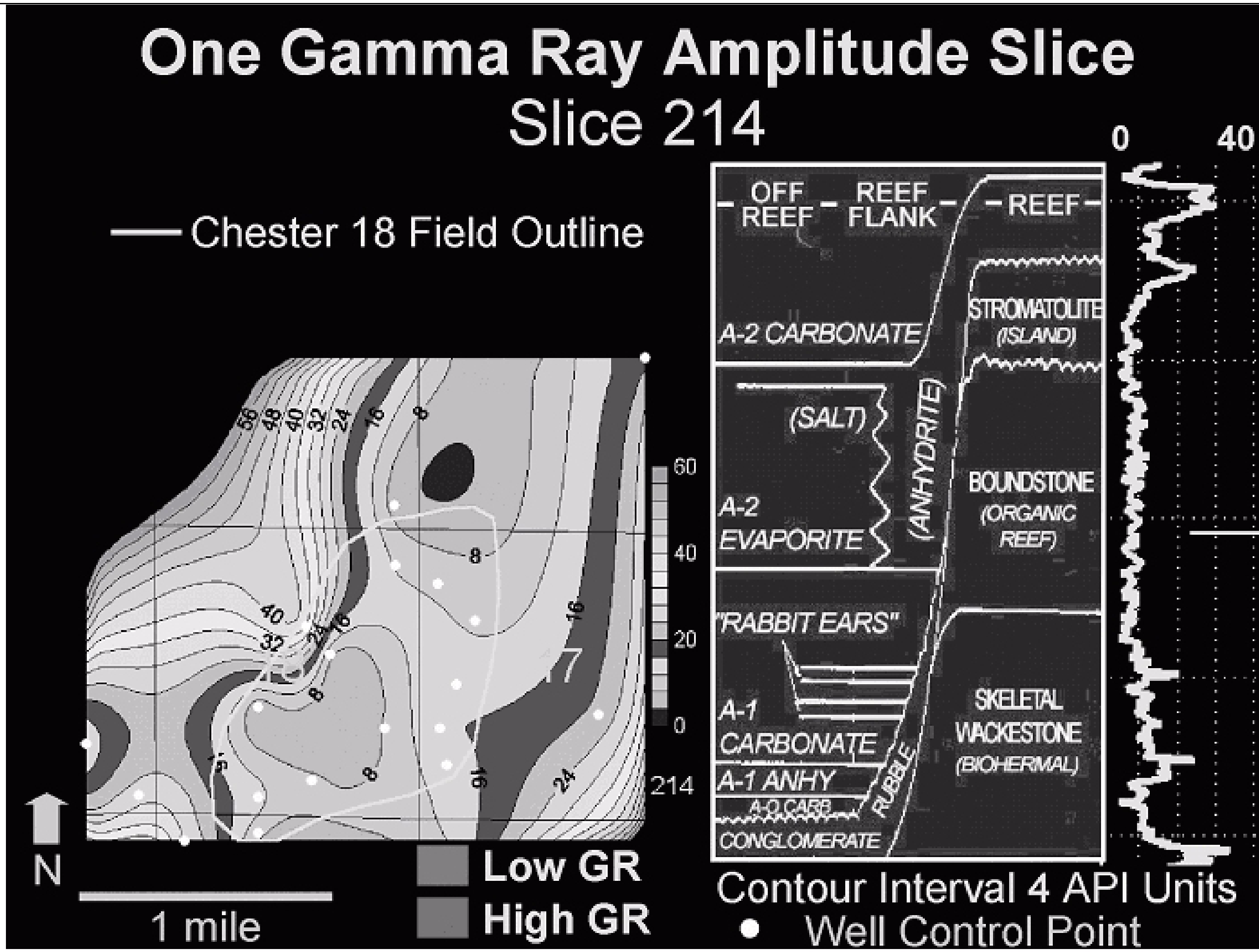

Figure 10. One gamma ray amplitude slice through Chester 18 Field (214 feet from reef base) displaying trends in the amplitude of the gamma ray curve.