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"Integrated Geologic-Engineering Model for Reef and Carbonate Shoal Reservoirs Associated with Paleohighs: Upper Jurassic Smackover Formation, Northeastern Gulf of Mexico"

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ABSTRACT

The University of Alabama in cooperation with Texas A&M University, McGill University, Longleaf Energy Group, Strago Petroleum Corporation, and Paramount Petroleum Company are undertaking an integrated, interdisciplinary geoscientific and engineering research project. The project is designed to characterize and model reservoir architecture, pore systems and rock-fluid interactions at the pore to field scale in Upper Jurassic Smackover reef and carbonate shoal reservoirs associated with varying degrees of relief on pre-Mesozoic basement paleohighs in the northeastern Gulf of Mexico. The project effort includes the prediction of fluid flow in carbonate reservoirs through reservoir simulation modeling which utilizes geologic reservoir characterization and modeling and the prediction of carbonate reservoir architecture, heterogeneity and quality through seismic imaging.

The primary objective of the project is to increase the profitability, producibility and efficiency of recovery of oil from existing and undiscovered Upper Jurassic fields characterized by reef and carbonate shoals associated with pre-Mesozoic basement paleohighs.

The principal research effort for Year 1 of the project has been reservoir description and characterization. This effort has included four tasks: 1) geoscientific reservoir characterization, 2) the study of rock-fluid interactions, 3) petrophysical and engineering characterization and 4) data integration. This work was scheduled for completion in Year 1.

Overall, the project work is on schedule. Geoscientific reservoir characterization is essentially completed. The architecture, porosity types and heterogeneity of the reef and shoal reservoirs at Appleton and Vocation Fields have been characterized using geological and geophysical data. The study of rock-fluid interactions has been initiated. Observations regarding the diagenetic processes influencing pore system development and heterogeneity in these reef and shoal reservoirs have been made. Petrophysical and engineering property characterization is progressing. Data on reservoir production rate and pressure history at Appleton and Vocation Fields have been tabulated, and porosity data from core analysis has been correlated with porosity as observed from well log response. Data integration is on schedule, in that, the geological, geophysical, petrophysical and

engineering data collected to date for Appleton and Vocation Fields have been compiled into a fieldwide digital database for reservoir characterization, modeling and simulation for the reef and carbonate shoal reservoirs for each of these fields.

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INTRODUCTION

The University of Alabama in cooperation with Texas A&M University, McGill University, Longleaf Energy Group, Strago Petroleum Corporation, and Paramount Petroleum Company is undertaking an integrated, interdisciplinary geoscientific and engineering research project. The project is designed to characterize and model reservoir architecture, pore systems and rock-fluid interactions at the pore to field scale in Upper Jurassic Smackover reef and carbonate shoal reservoirs associated with varying degrees of relief on pre-Mesozoic basement paleohighs in the northeastern Gulf of Mexico. The project effort includes the prediction of fluid flow in carbonate reservoirs through reservoir simulation modeling that utilizes geologic reservoir characterization and modeling and the prediction of carbonate reservoir architecture, heterogeneity and quality through seismic imaging.

The Upper Jurassic Smackover Formation (Figure 1) is one of the most productive hydrocarbon reservoirs in the northeastern Gulf of Mexico. Production from Smackover carbonates totals 1 billion barrels of oil and 4 trillion cubic feet of natural gas. The production is from three plays: 1) basement ridge play, 2) regional peripheral fault play, and 3) salt anticline play (Figure 2). Unfortunately, much of the oil in the Smackover fields in these plays remains unrecovered because of a poor understanding of the rock and fluid characteristics that affects our understanding of reservoir architecture, heterogeneity, quality, fluid flow and producibility. This scenario is compounded because of inadequate techniques for reservoir detection and the characterization of rock-fluid interactions, as well as imperfect models for fluid flow prediction. This poor understanding is particularly illustrated for the case with Smackover fields in the basement ridge play (Figure 3) where independent producers dominate the development and management of these fields. These producers do not have the financial resources and/or staff expertise to substantially improve the understanding of the geoscientific and engineering factors affecting the producibility of Smackover carbonate reservoirs, which makes research and application of new technologies for reef-shoal reservoirs all that more important and urgent. The research results from studying the fields identified for this project will be of direct benefit to these producers.

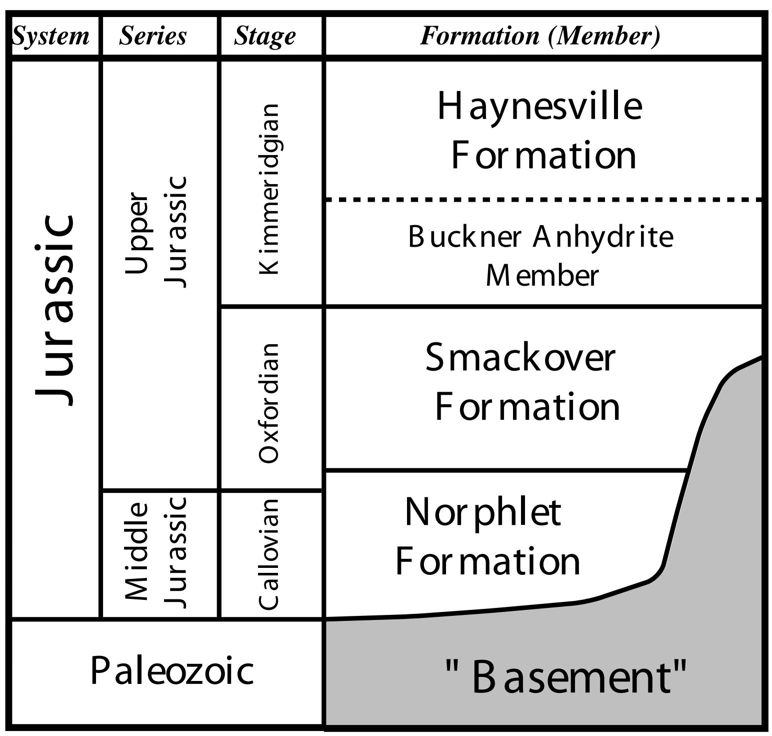


Figure 1. Jurassic stratigraphy in the study area.

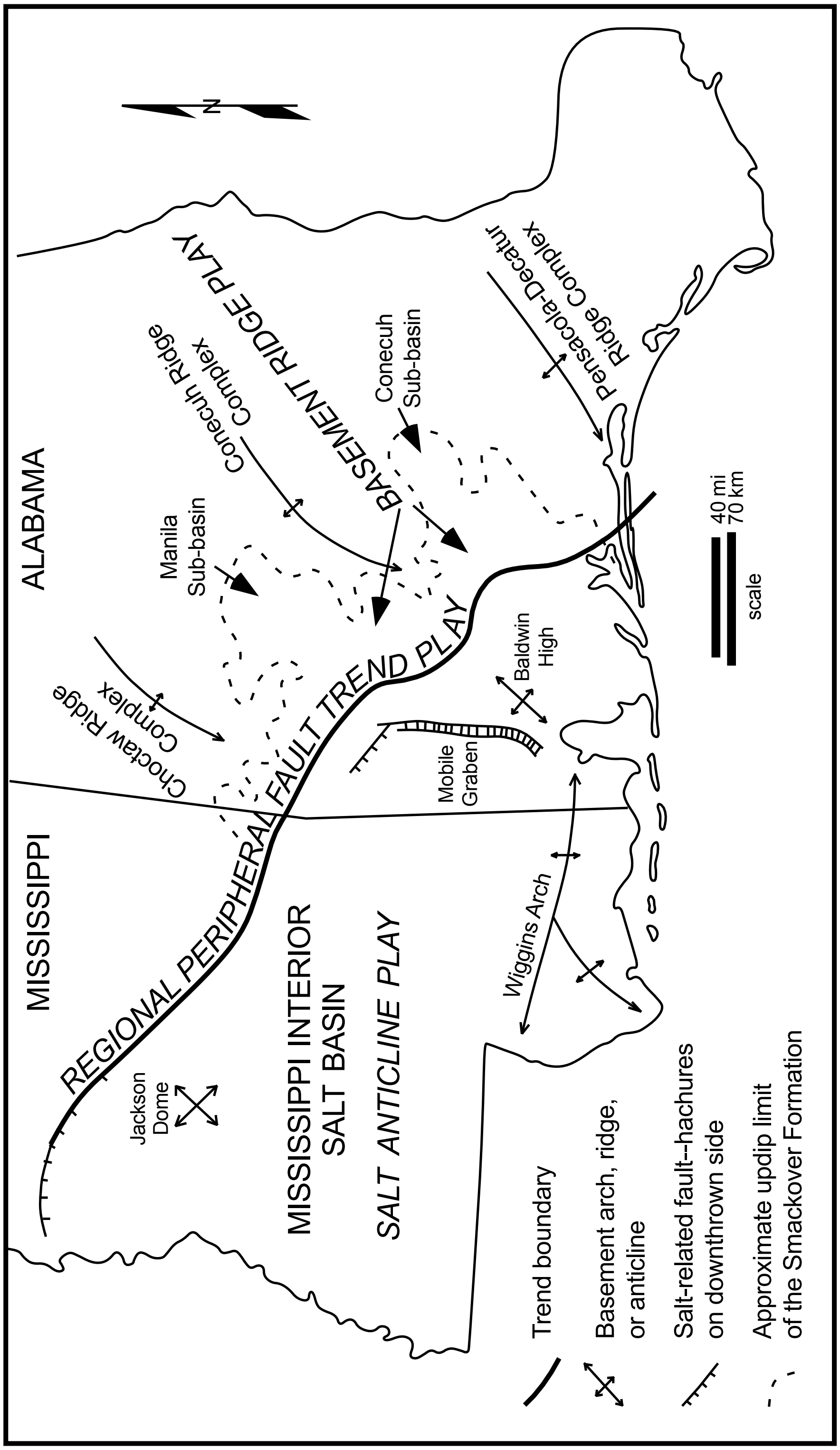


Figure 2. Major petroleum trends in study area.

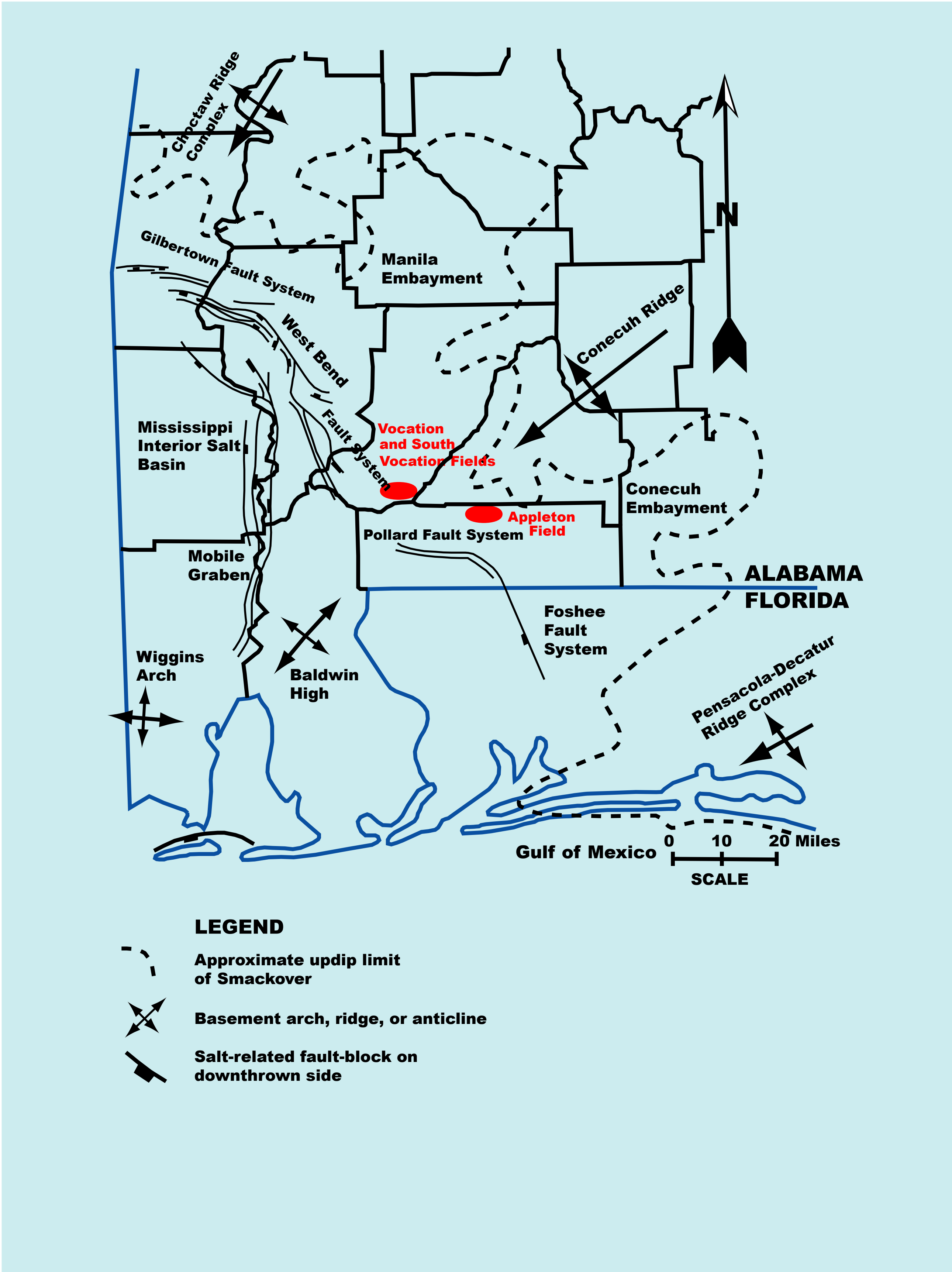


Figure 3. Location of Appleton and Vocation / South Vocation Fields.

This interdisciplinary project is a 3-year effort to characterize, model and simulate fluid flow in carbonate reservoirs and consists of 3 phases and 11 tasks. Phase 1 (1 year) of the project involves geoscientific reservoir characterization, rock-fluid interactions, petrophysical and engineering property characterization, and data integration. Phase 2 (1.5 years) includes geologic modeling and reservoir simulation. Phase 3 (0.5 year) involves building the geologic-engineering model, testing the geologic-engineering model, and applying the geologic-engineering model.

The principal goal of this project is to assist independent producers in increasing oil producibility from reef and shoal reservoirs associated with pre-Mesozoic paleotopographic features through an interdisciplinary geoscientific and engineering characterization and modeling of carbonate reservoir architecture, heterogeneity, quality and fluid flow from the pore to field scale.

The objectives of the project are as follows:

1. Evaluate the geological, geophysical, petrophysical and engineering properties of reef-shoal reservoirs and their associated fluids, in particular, the Appleton (Figure 4) and Vocation Fields (Figure 5).
2. Construct a digital database of integrated geoscience and engineering data taken from reef-shoal carbonate reservoirs associated with basement paleohighs.
3. Develop a geologic-engineering model(s) for improving reservoir detection, reservoir characterization, flow-space imaging, flow simulation, and performance prediction for reef-shoal carbonate reservoirs based on a systematic study of Appleton and Vocation Fields.
4. Validate and apply the geologic-engineering model(s) on a prospective Smackover reservoir through an iterative interdisciplinary approach, where adjustments of properties and concepts will be made to improve the model(s).

This project has direct and significant economic benefits because the Smackover is a prolific hydrocarbon reservoir in the northeastern Gulf of Mexico. Smackover reefs represent an underdeveloped reservoir, and the basement ridge play in which these reefs are associated represents an underexplored play, Initial estimations indicate the original oil resource target

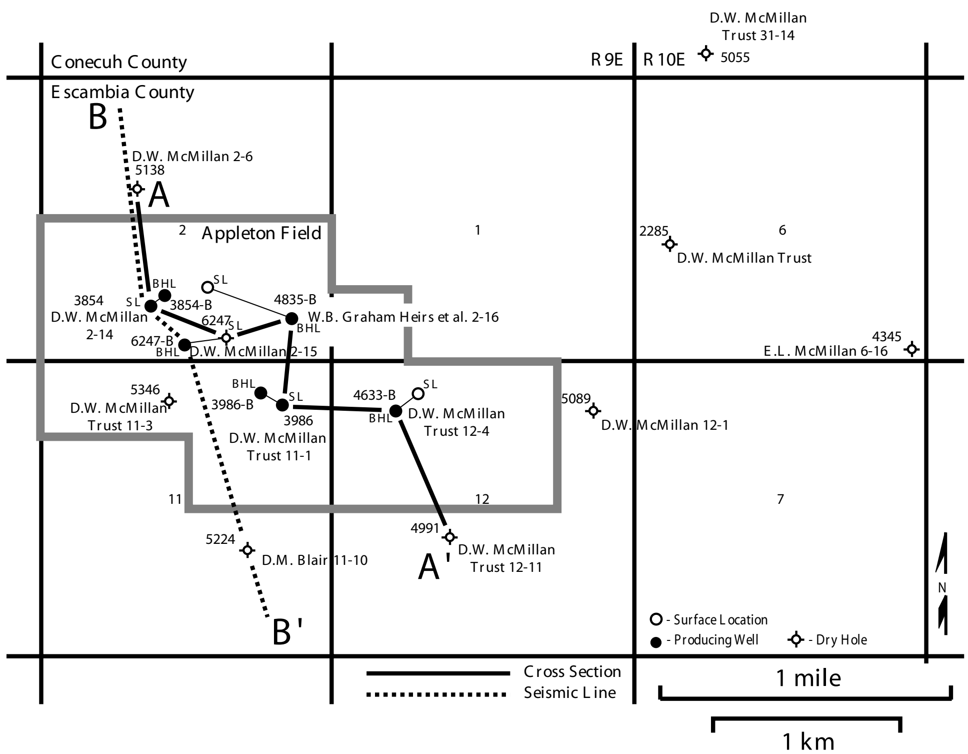
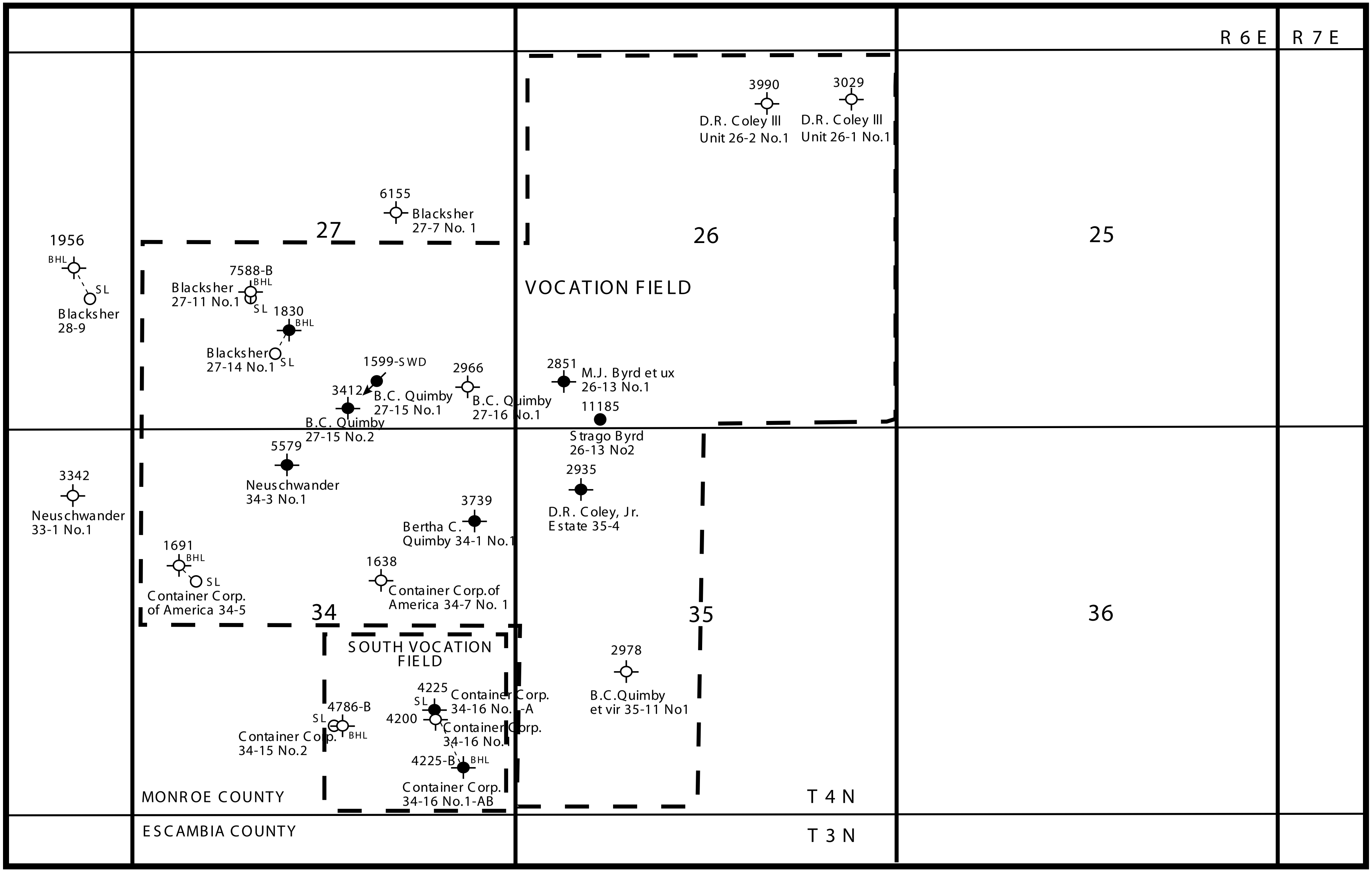


Figure 4. Appleton Field Unit area.



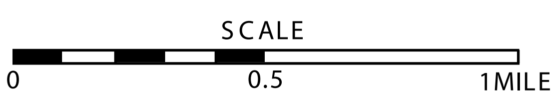


Figure 5. Vocation Field area.

available in this play from the 40 fields that have been discovered and developed approximates at least 160 million barrels. Any newly discovered fields are expected to have an average of 4 million barrels of oil. The combined estimated reserves of the Smackover fields (Appleton and Vocation Fields) proposed for study in this project total 9 million barrels of oil. Successful completion of the project should lead to increased oil producibility from Appleton and Vocation Fields and from Smackover reservoirs in general. Production of these domestic resources will serve to reduce U.S. dependence on foreign oil supplies.

Completion of the project will contribute significantly to the understanding of: the geologic factors controlling reef and shoal development on paleohighs, carbonate reservoir architecture and heterogeneity at the pore to field scale, generalized rock-fluid interactions and alterations in carbonate reservoirs, the geological and geophysical attributes important to geologic modeling of reef-shoal carbonate reservoirs, the critical factors affecting fluid flow in carbonate reservoirs, particularly with regard to reservoir simulation and the analysis of well performance, the elements important to the development of a carbonate geologic-engineering model, and the geological, geophysical, and/or petrophysical properties important to improved carbonate reservoir detection, characterization, imaging and flow prediction.

EXECUTIVE SUMMARY

The University of Alabama in cooperation with Texas A&M University, McGill University, Longleaf Energy Group, Strago Petroleum Corporation, and Paramount Petroleum Company are undertaking an integrated, interdisciplinary geoscientific and engineering research project. The project is designed to characterize and model reservoir architecture, pore systems and rock-fluid interactions at the pore to field scale in Upper Jurassic Smackover reef and carbonate shoal reservoirs associated with varying degrees of relief on pre-Mesozoic basement paleohighs in the northeastern Gulf of Mexico. The project effort includes the prediction of fluid flow in carbonate reservoirs through reservoir simulation modeling which utilizes geologic reservoir characterization and modeling and the prediction of carbonate reservoir architecture, heterogeneity and quality through seismic imaging.

The primary objective of the project is to increase the profitability, producibility and efficiency of recovery of oil from existing and undiscovered Upper Jurassic fields characterized by reef and carbonate shoals associated with pre-Mesozoic basement paleohighs.

The principal research effort for Year 1 of the project has been reservoir description and characterization. This effort has included four tasks: 1) geoscientific reservoir characterization, 2) the study of rock-fluid interactions, 3) petrophysical and engineering characterization and 4) data integration. This work was scheduled for completion in Year 1.

Geoscientific reservoir characterization is essentially completed. The architecture, porosity types and heterogeneity of the reef and shoal reservoirs at Appleton and Vocation Fields have been characterized using geological and geophysical data. All available whole cores (11) from Appleton Field have been described and thin sections (379) from these cores have been studied. Depositional facies were determined from the core descriptions. The thin sections studied represent the depositional facies identified. The core data and well log signatures have been integrated and calibrated on graphic logs. For Appleton Field, the well log, core, and seismic data have been entered into a digital database and structural maps on top of the basement, reef, and Smackover/Buckner have been constructed. An isopach map of the Smackover interval has been prepared, and thickness maps of the sabkha facies, tidal flat facies, shoal complex, tidal flat/shoal complex, and reef complex have been prepared. Maps have been constructed using the 3-D seismic data that Longleaf contributed to the project to illustrate the structural configuration of the basement surface, the reef surface, and Buckner/Smackover surface. Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project.

All available whole cores (11) from Vocation Field have been described and thin sections (237) from the cores have been studied. Depositional facies were determined from the core descriptions. From this work, an additional 73 thin sections are being prepared to provide accurate representation of the lithofacies identified. The core data and well log signatures have been integrated and calibrated on the graphic logs. The well log and core data from Vocation Field have been entered into a digital database and structural and isopach maps are being constructed using these data. The graphic logs are being used in preparing cross sections across Vocation Field. The core and well log data are being integrated with the 3-D seismic data that Strago contributed to the project. Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project.

The study of rock-fluid interactions has been initiated. Thin sections (379) are being studied from 11 cores from Appleton Field to determine the impact of cementation, compaction, dolomitization, dissolution and neomorphism has had on the reef and shoal reservoirs in this field. Thin sections (237) are being studied from 11 cores from Vocation Field to determine the paragenetic sequence for the reservoir lithologies in this field. An additional 73 thin sections are being prepared from the shoal and reef lithofacies in Vocation Field to identify the diagenetic processes that played a significant role in the development of the pore systems in the reservoirs at Vocation Field.

Petrophysical and engineering property characterization is progressing. Petrophysical and engineering property data are being gathered and tabulated. The production history for Appleton Field and the production history for Vocation and South Vocation Fields have been obtained and graphed. Water and oil saturation data for core analyses for Appleton Field have been tabulated. Porosity versus permeability cross plots for wells in the fields have been prepared, and porosities from core analyses have been calibrated with porosities determined from well log studies.

Data integration is on schedule, in that, geological, geophysical and engineering data collected to date for Appleton and Vocation Fields have been compiled into a fieldwide digital database for reservoir characterization, modeling and simulation for the reef and carbonate shoal reservoirs for each of these fields.

EXPERIMENTAL

The principal research effort for Year 1 of the project is reservoir description and characterization. This effort includes four tasks: 1) geoscientific reservoir characterization, 2) the study of rock-fluid interactions, 3) petrophysical and engineering characterization, and 4) data integration (Table 1).

Table 1. Milestone Chart.

Tasks	Project Year/Quarter 2000		2001				2002				2003	
	3	4	1	2	3	4	1	2	3	4	1	2
Reservoir Characterization (Phase 1)												
Task 1—Geoscientific Reservoir Characterization	xxxxxx		xxx									
Task 2—Rock-Fluid Interactions	xxxxxx		xxx									
Task 3—Petrophysical Engineering Characterization	xxxxxx		xxx									
Task 4—Data Integration				xxx								
3-D Modeling (Phase 2)												
Task 5					xxxxxx							
Task 6—3-D Reser							xxxxxx					
Task 7—Geolo									xxxxxx			
Testing and Applying Model (Phase 3)												
Task 8—Testing Geologic-Engineering Model											xxxxxx	
Task 9—Applying Geolo											xxxxxx	
Technological Transfer												
Task 10—Workshops							xx					xx
Technical Reports												
Task 11—Quarterly, Topical and Annual Reports		x	x	x	x	x	x	x	x	x	x	x

Work Accomplished in Year 1

Reservoir Description and Characterization (Phase 1)

Task 1—Geoscientific Reservoir Characterization.--This task will characterize reservoir architecture, pore systems and heterogeneity based on geological and geophysical properties. This work will be done for all well logs, cores, seismic data and other data for Vocation Field and will be done for Appleton Field by integrating the new data obtained from drilling the sidetrack well in Appleton Field and the data available from five additional cores and 3-D seismic in the field area. The first phase of the task includes core descriptions, including lithologies, sedimentary structures, lithofacies, depositional environments, systems tracts, and depositional sequences. Graphic logs constructed from the core studies will depict the information described above. Core samples will be selected for petrographic, XRD, SEM, and microprobe analyses. The graphic logs will be compared to available core analysis and well log data. The core features and core analyses will be calibrated to the well log patterns. A numerical code system will be established so that these data can be entered into the digital database for comparison with the core analysis data and well log measurements and used in the reservoir modeling. The next phase is the link between core and well log analysis and reservoir modeling. It involves the preparation of stratigraphic and structural cross sections to illustrate structural growth, lithofacies and reservoir geometry, and depositional systems tract distribution. Maps will be prepared to illustrate lithofacies distribution, stratigraphic and reservoir interval thickness (isolith and isopach maps), and stratal structural configurations. These cross sections and maps, in association with the core descriptions, will be utilized to make sequence stratigraphic, environment of deposition, and structural interpretations. Standard industry software, such as StratWorks and Z-Map, will be used in the preparation of the cross sections and subsurface maps. The third phase will encompass the interpreting of seismic data and performing stratigraphic and structural analyses. Seismic interpretations will be guided by the generation of synthetic seismograms resulting from the tying of well log and seismic data and by the comparison of seismic transects with geologic cross sections. Seismic forward modeling and attribute-based characterization will be performed. Structure and isopach maps constructed from well logs will be refined utilizing the seismic data. The seismic imaging of the structure and stratigraphy, forward modeling and attribute characterization will be accomplished utilizing standard industry software, such as 2d/3d PAK, Earthwave and SeisWorks. The next phase includes identification and quantification of carbonate mineralogy and textures (grain, matrix and cement types), pore topology and geometry, and percent of porosity and is performed to support and enhance the visual core descriptions. These petrographic, XRD, SEM and microprobe analyses will confirm and quantify the observations made in the core descriptions. This analysis provides the opportunity to study reservoir architecture and heterogeneity at the microscopic scale. The fifth phase involves study of pore systems in the reservoir, including pore types and throats through SEM analysis. This phase will examine pore shape and geometry and the nature and distribution of pore throats to determine the features of the pore systems that are affecting reservoir producibility.

Appleton Field. All available whole cores (11) from Appleton Field have been described and thin sections (379) from these cores have been studied. Graphic logs were constructed describing each of the cores (Figures 6 through 16). Depositional facies were determined from the core descriptions. The thin sections represent the depositional facies identified. The core data and well log signatures have been integrated and calibrated on these graphic logs.

For Appleton Field (Figure 4), the well log and core data have been entered into a digital database and structural maps on top of the basement (Figure 17), reef (Figure 18), and Smackover/Buckner (Figure 19) have been constructed. An isopach map of the Smackover interval has been prepared (Figure 20), and thickness maps of the sabkha facies (Figure 21), tidal flat facies (Figure 22), shoal complex (Figure 23), tidal flat/shoal complex (Figure 24) and reef complex (Figure 25) facies have been constructed. A cross section (Figure 26) illustrating the thickness and facies changes across Appleton Field has been prepared.

The core and well log data have been integrated with the 3-D seismic data for Appleton Field that Longleaf contributed to the project. A typical seismic profile for the field illustrating the reef reservoir is shown in Figure 27. A structural configuration of the basement surface, the reef

MADDEN 9-15 #1
PERMIT # 10084B
KB: 263.2'

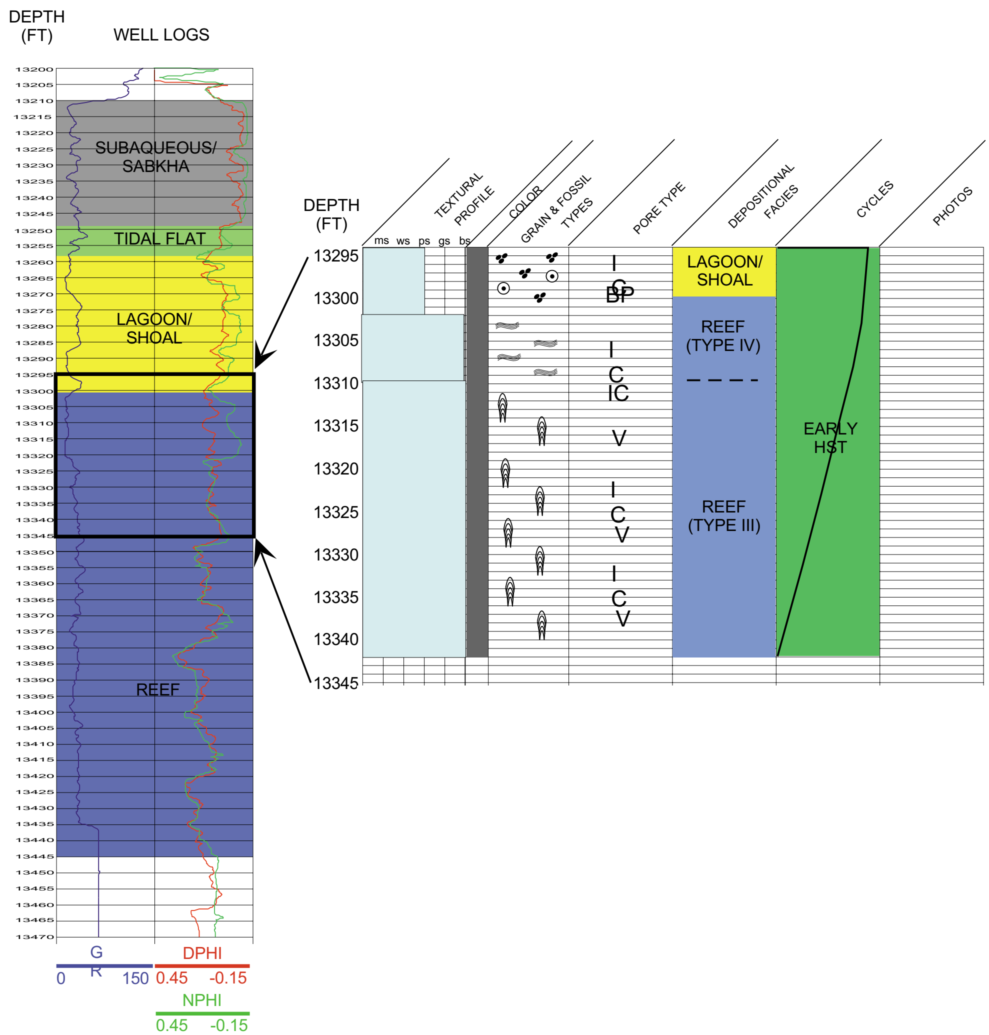


Figure 6. Graphic log for well Permit # 10084B
by W.C. Parcell

MCMILLAN 3-9 #1
PERMIT # 11030-B
KB: 237'

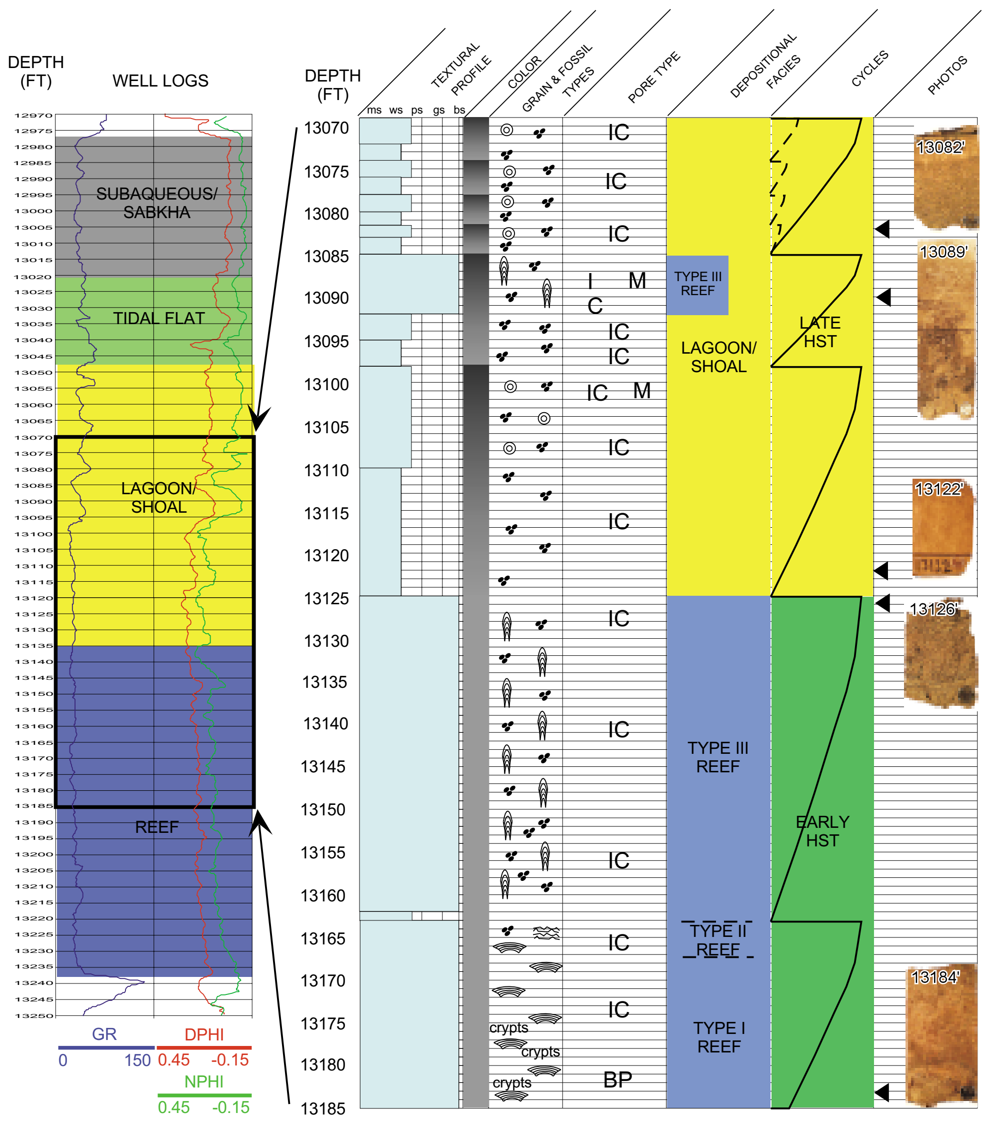


Figure 7. Graphic log for well Permit # 11030B
by W.C Parcell

HOOPER MATHEWS UNIT 4-8 #1
PERMIT # 2377
KB: 202.9'

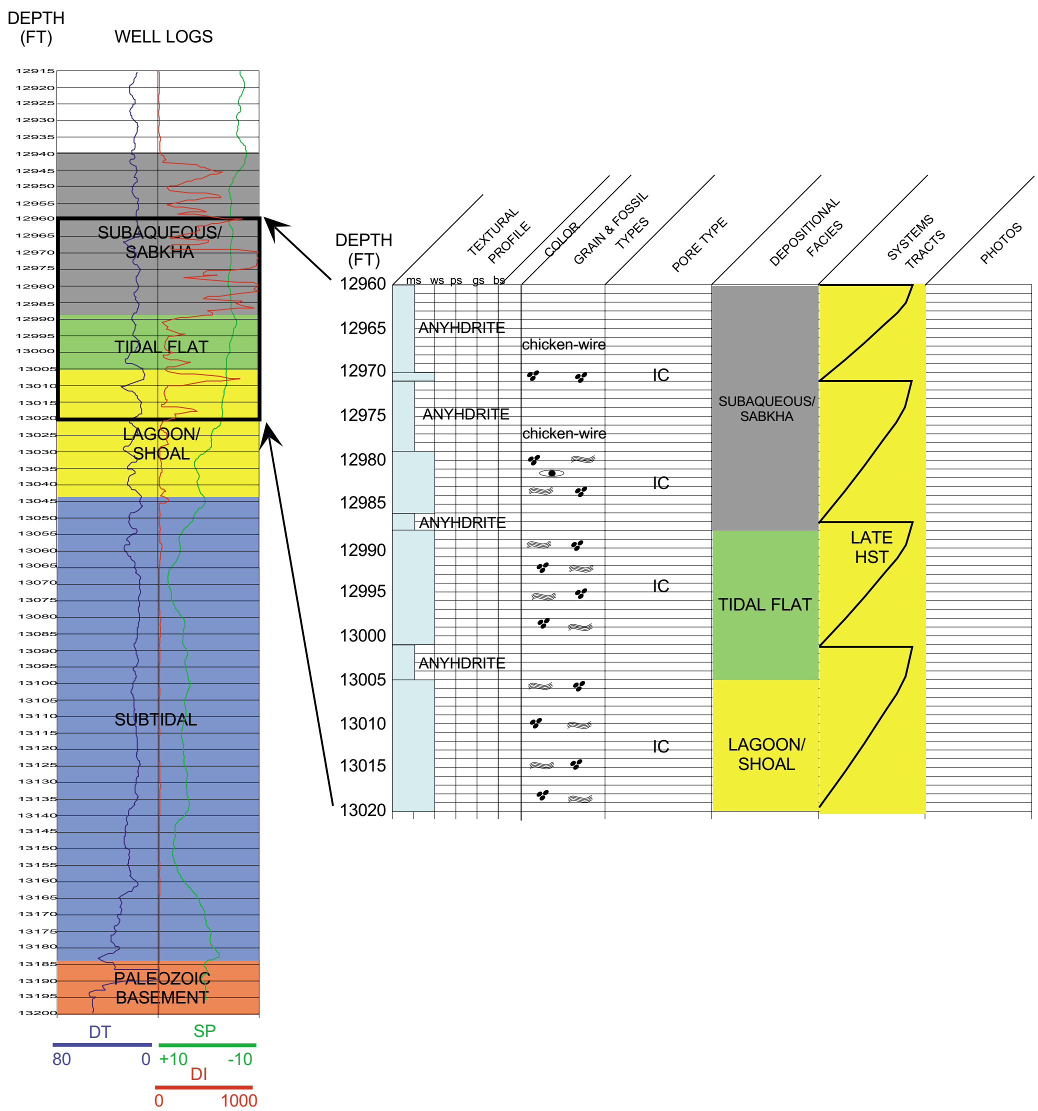


Figure 8. Graphic log for well Permit # 2377
by W.C. Parcell

#4 D.W. McMILLAN 2-14
Permit # 3854
KB: 242 ft

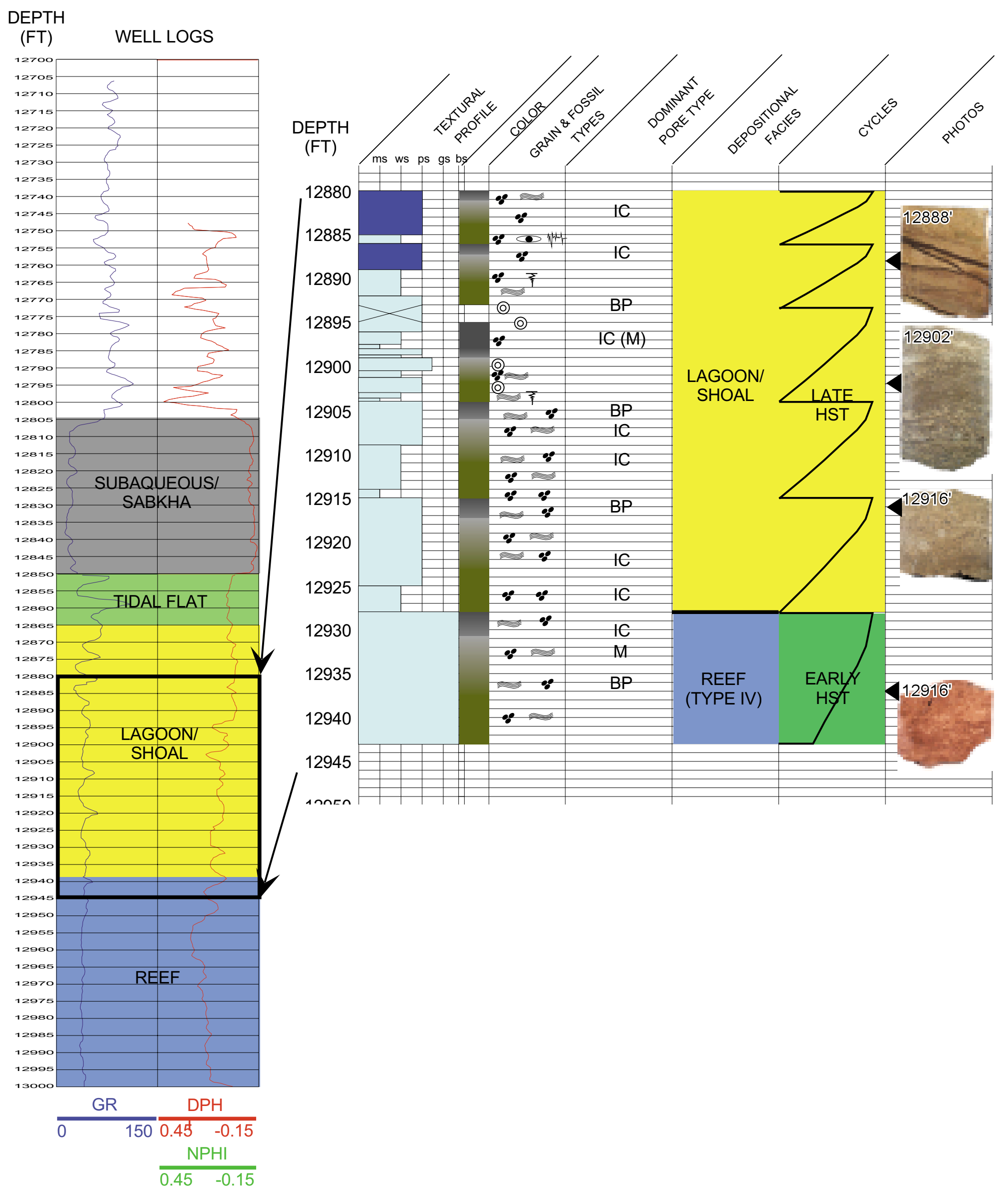


Figure 9. Graphic log for well Permit # 3854
by W.C. Parcell

#2 D.W. McMILLAN 1-1
Permit # 3986
KB: 254'

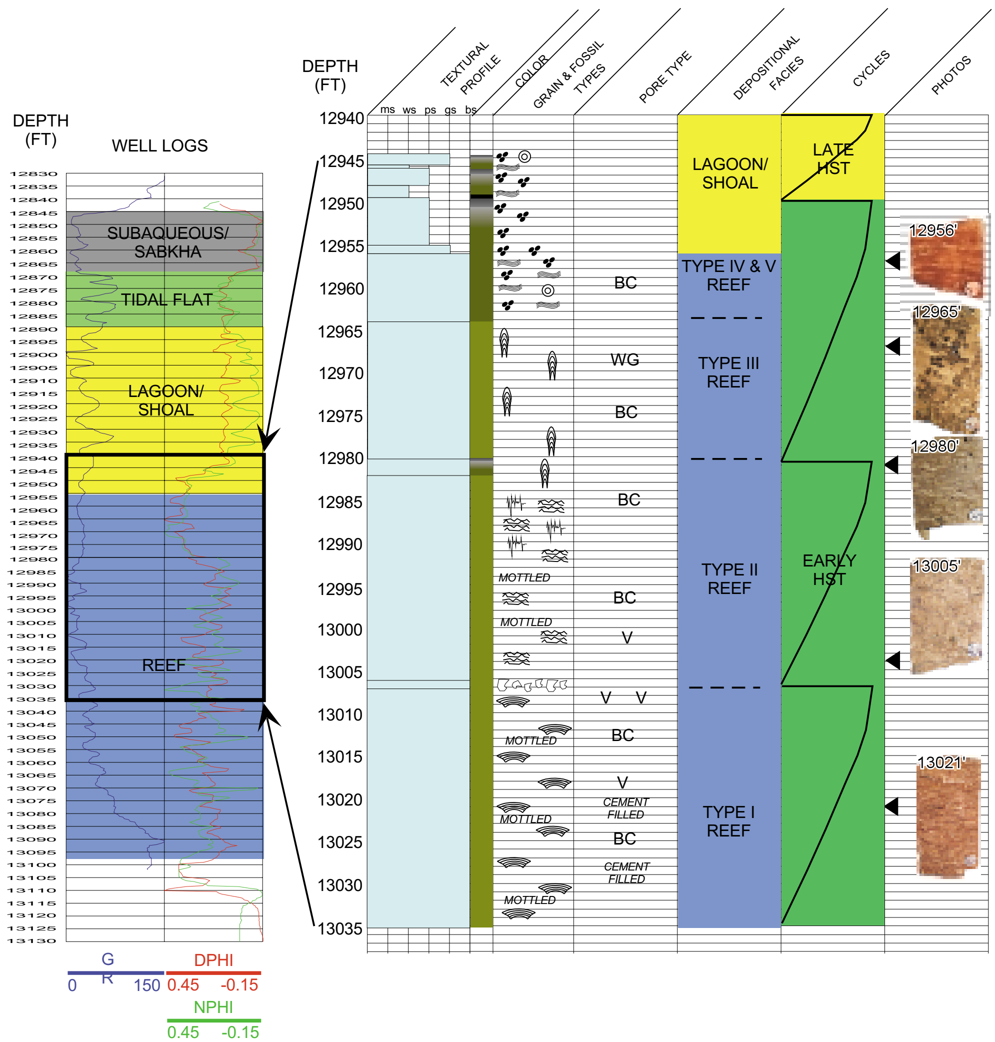


Figure 10. Graphic log for well Permit # 3986
by W.C. Parcell

D.W. McMILLAN 12-4
Permit # 4633-B
KB: 268'

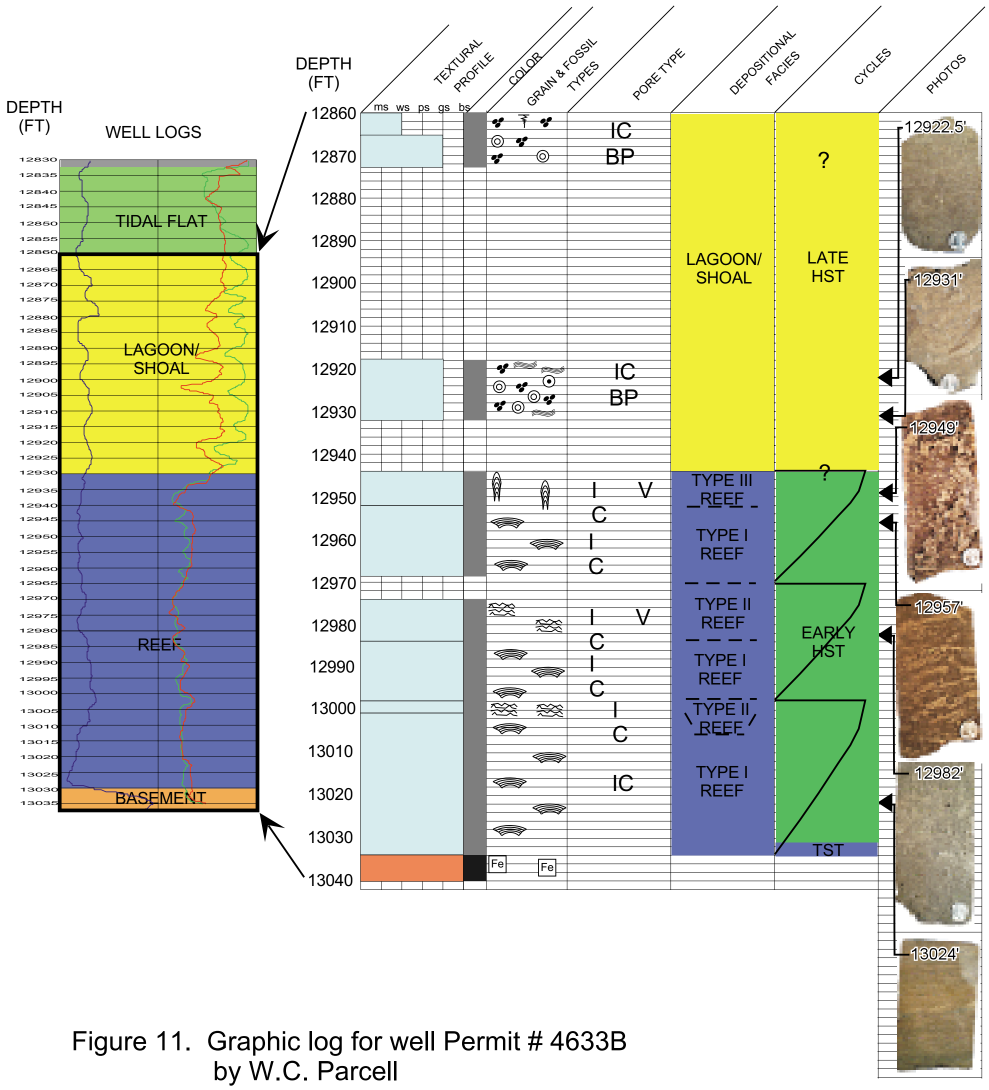


Figure 11. Graphic log for well Permit # 4633B
by W.C. Parcell

#1 W.B. GRAHAM HEIRS 2-16
PERMIT # 4835-B
KB: 244'

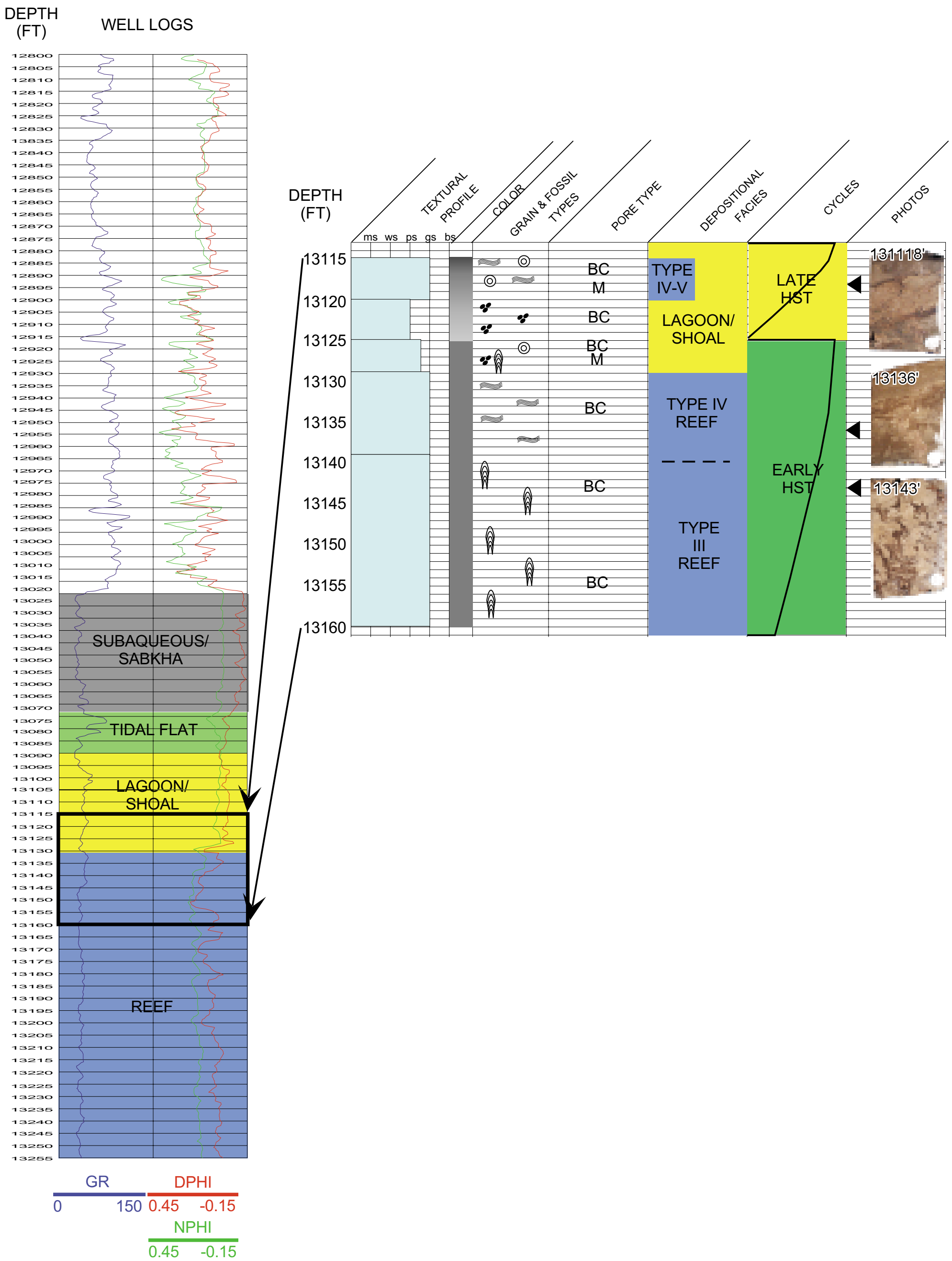


Figure 12. Graphic log for well Permit # 4835B
by W.C. Parcell

#4 D.W. McMILLAN 12-11
PERMIT # 4991
KB: 247'

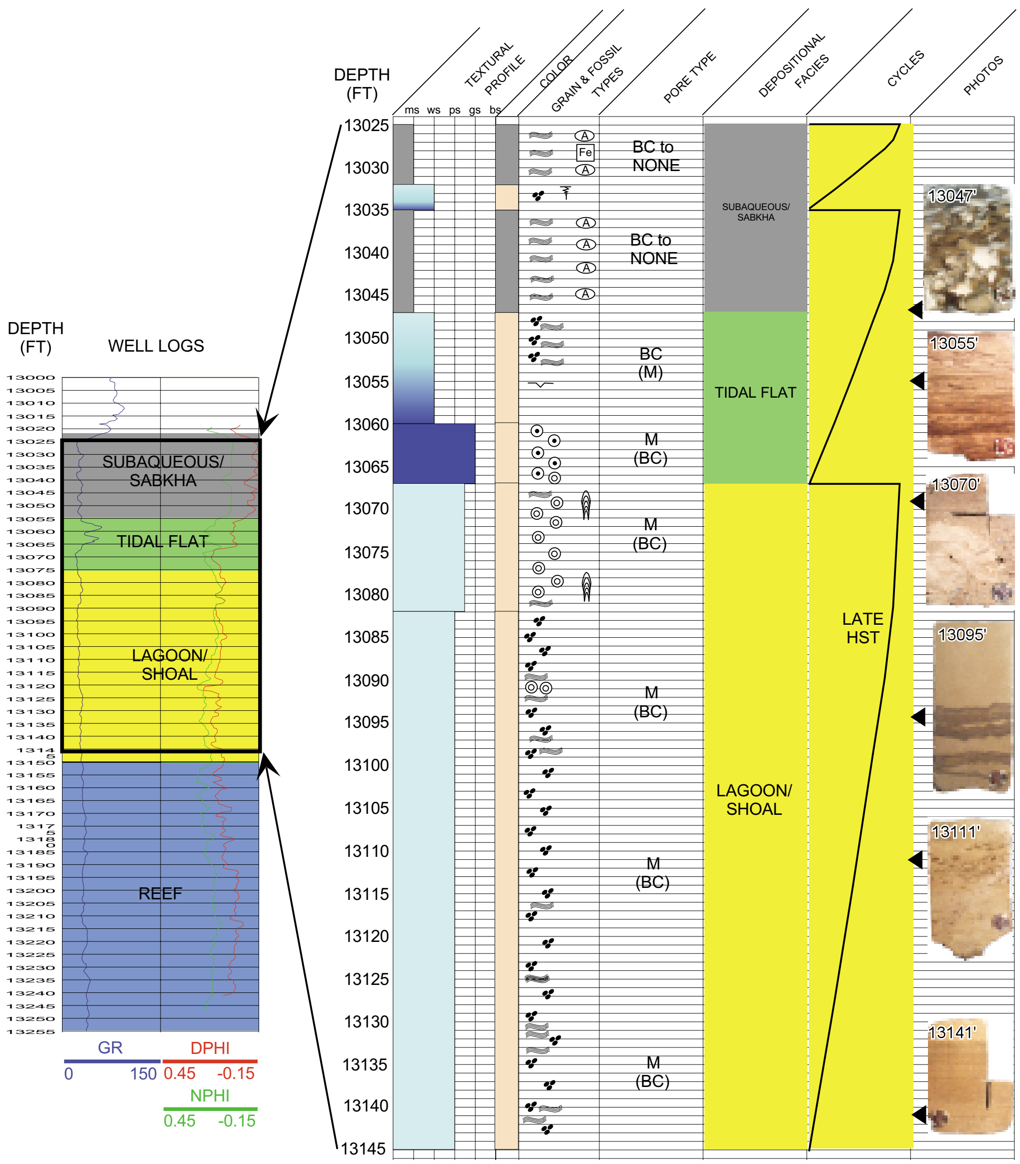


Figure 13. Graphic log for well Permit # 4991
by W.C. Parcell

D.W. McMILLAN 12-1
PERMIT # 5089
KB: 256'

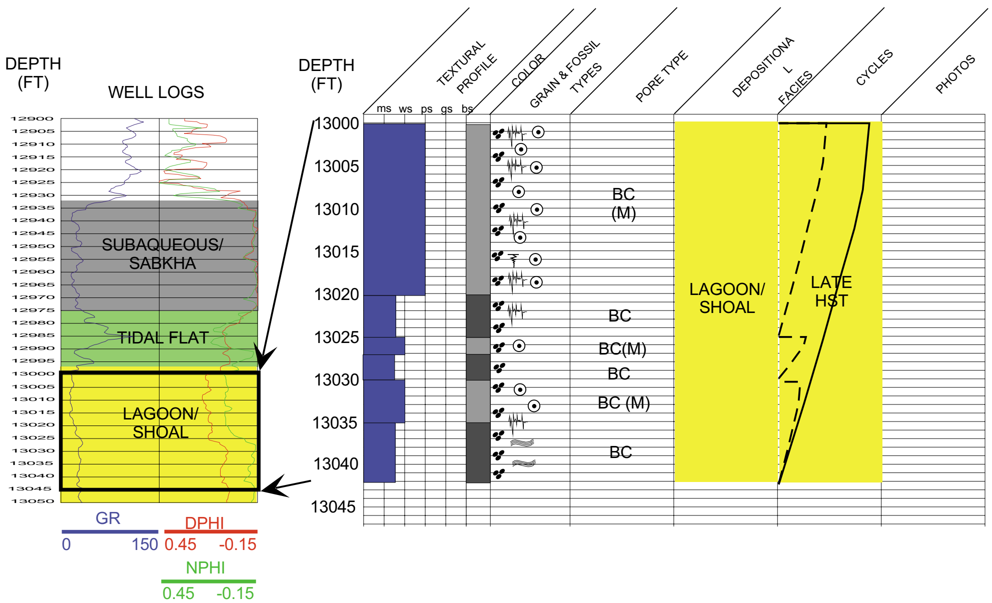


Figure 14. Graphic log for well Permit # 5089
by W.C. Parcell

D.W. McMILLAN 2-6 #1
Permit # 5138
KB: 245'

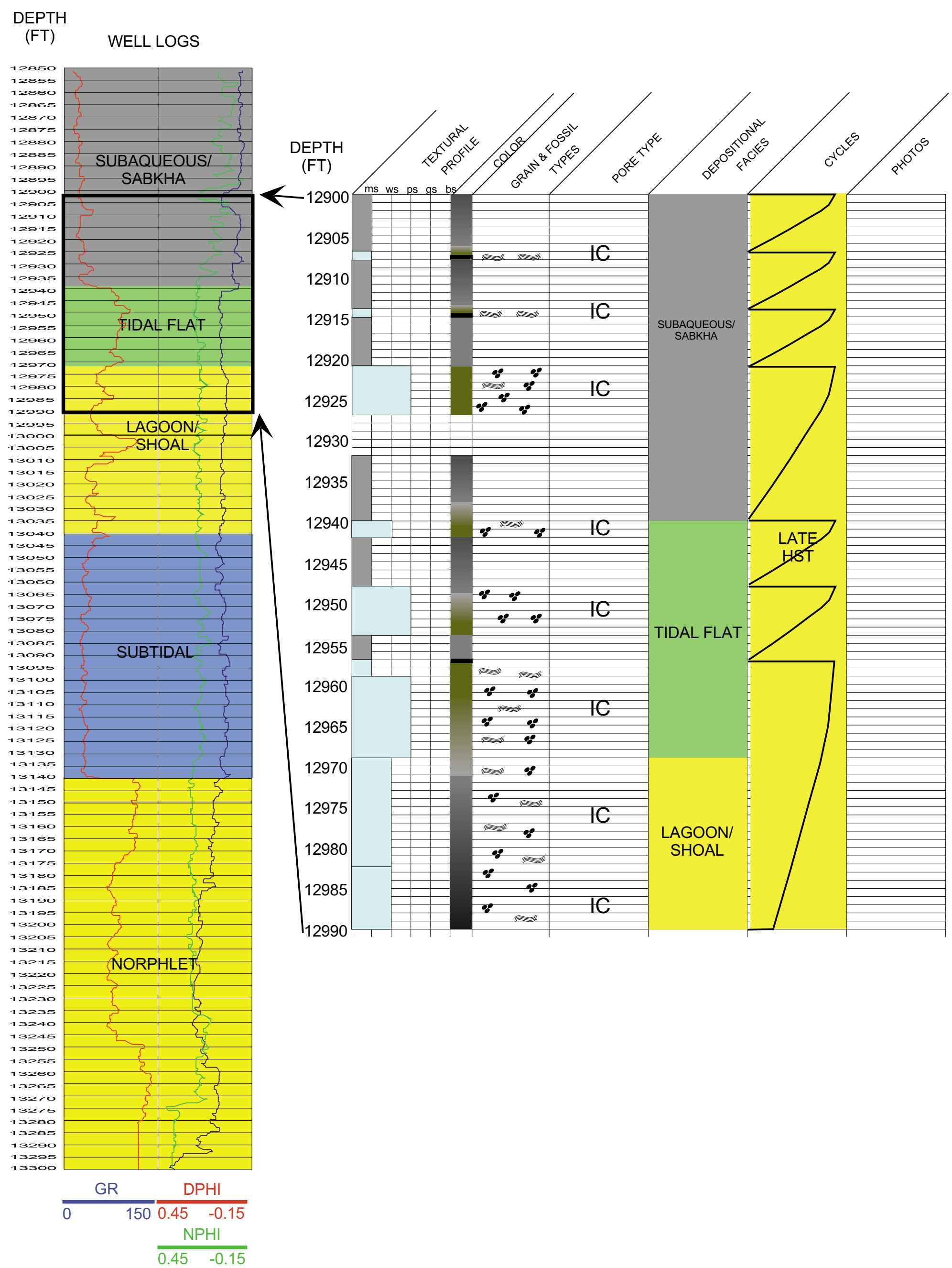


Figure 15. Graphic log for well Permit # 5138
by W.C. Parcell

LUVETA GRAMBLING 9-13 #1
PERMIT # 6663B
KB: 300'

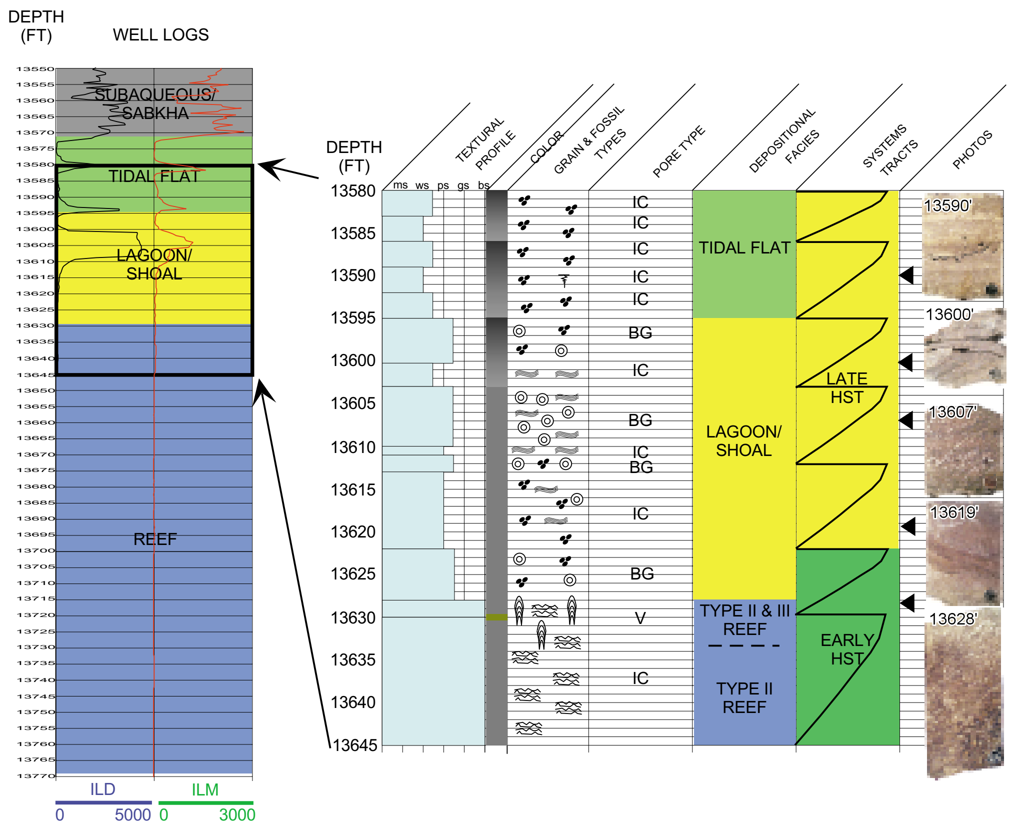


Figure 16. Graphic log for well Permit # 6663B by W.C. Parcell

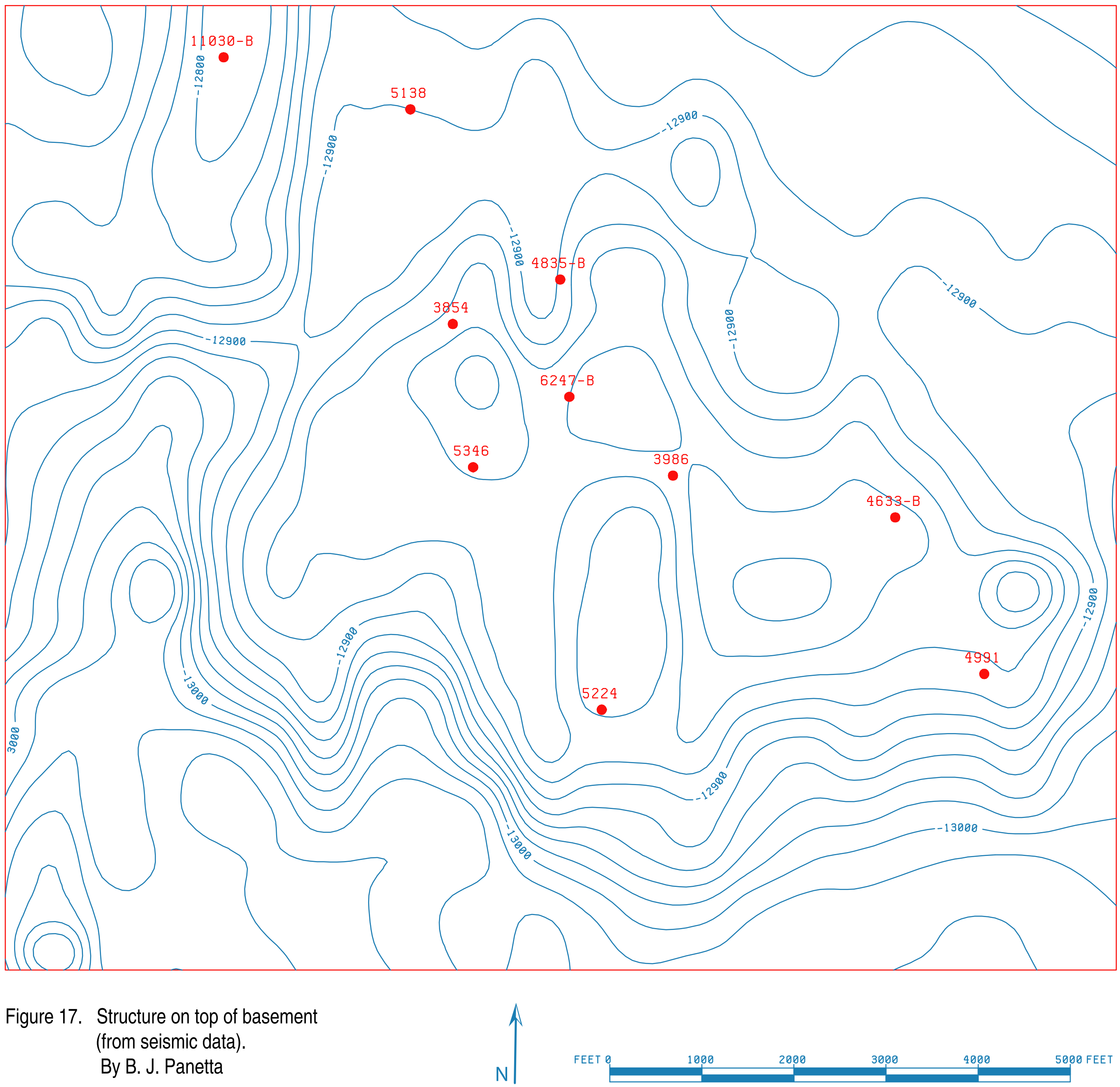


Figure 17. Structure on top of basement (from seismic data).
By B. J. Panetta

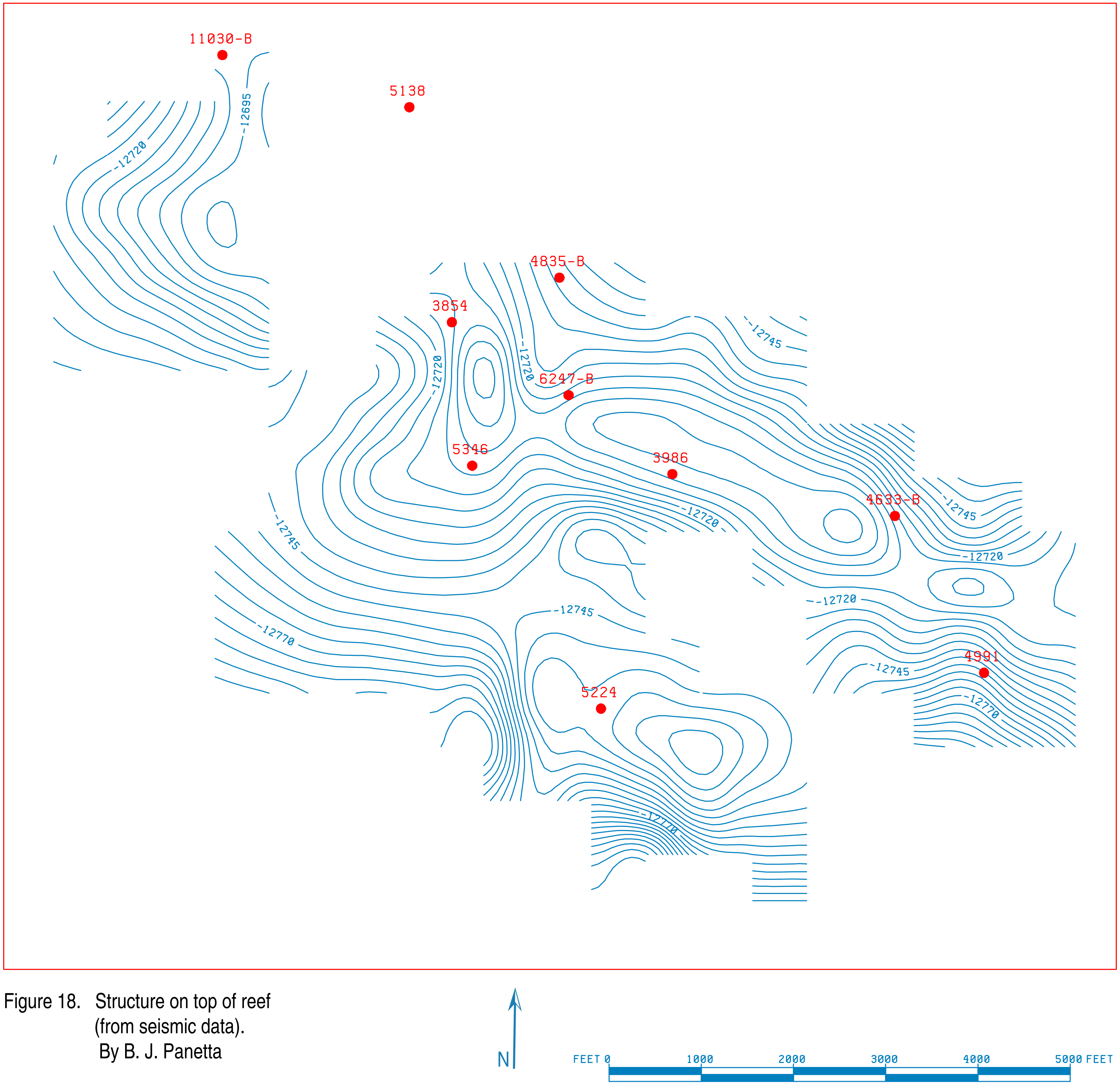


Figure 18. Structure on top of reef (from seismic data). By B. J. Panetta

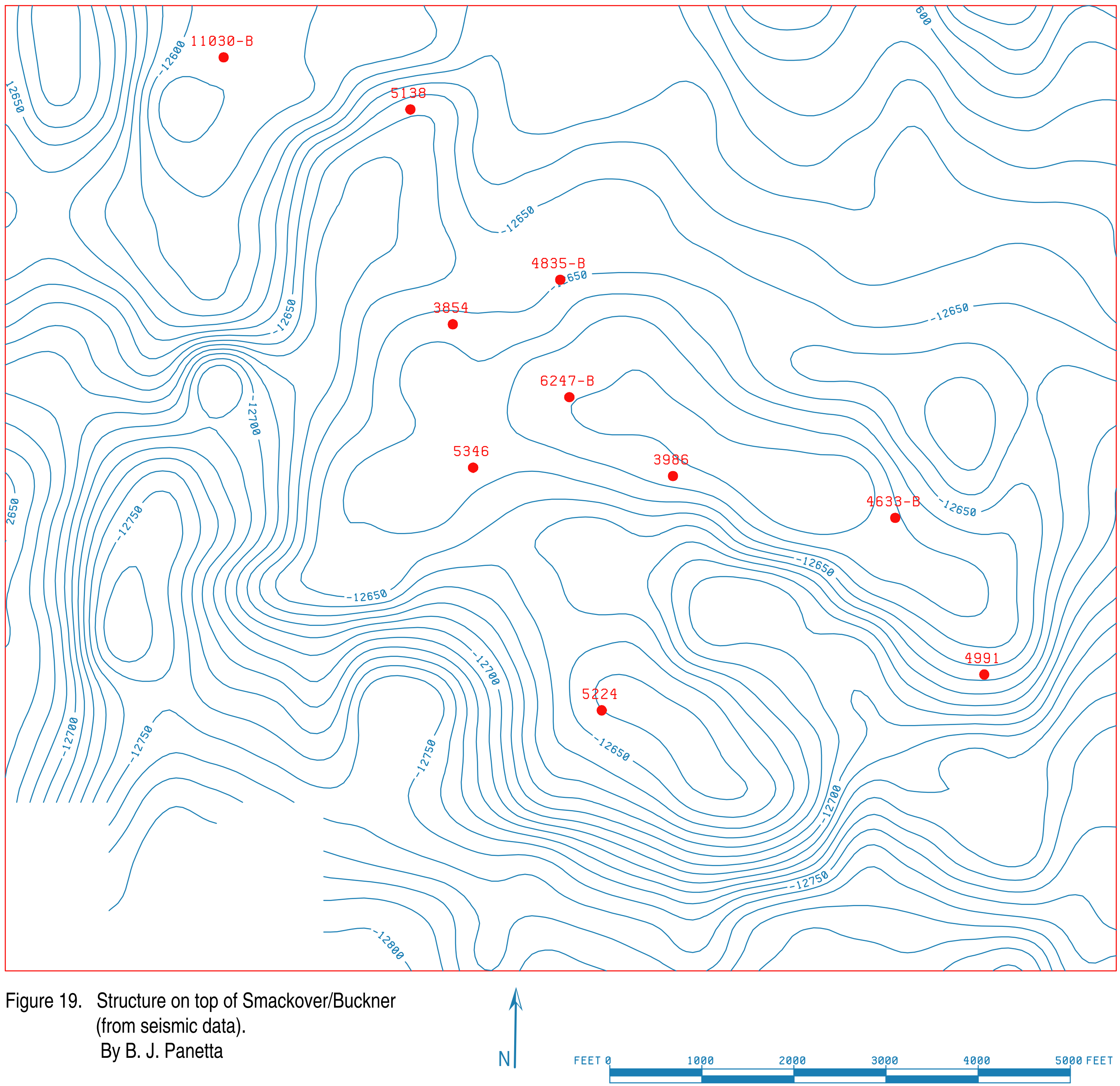


Figure 19. Structure on top of Smackover/Buckner (from seismic data).
By B. J. Panetta

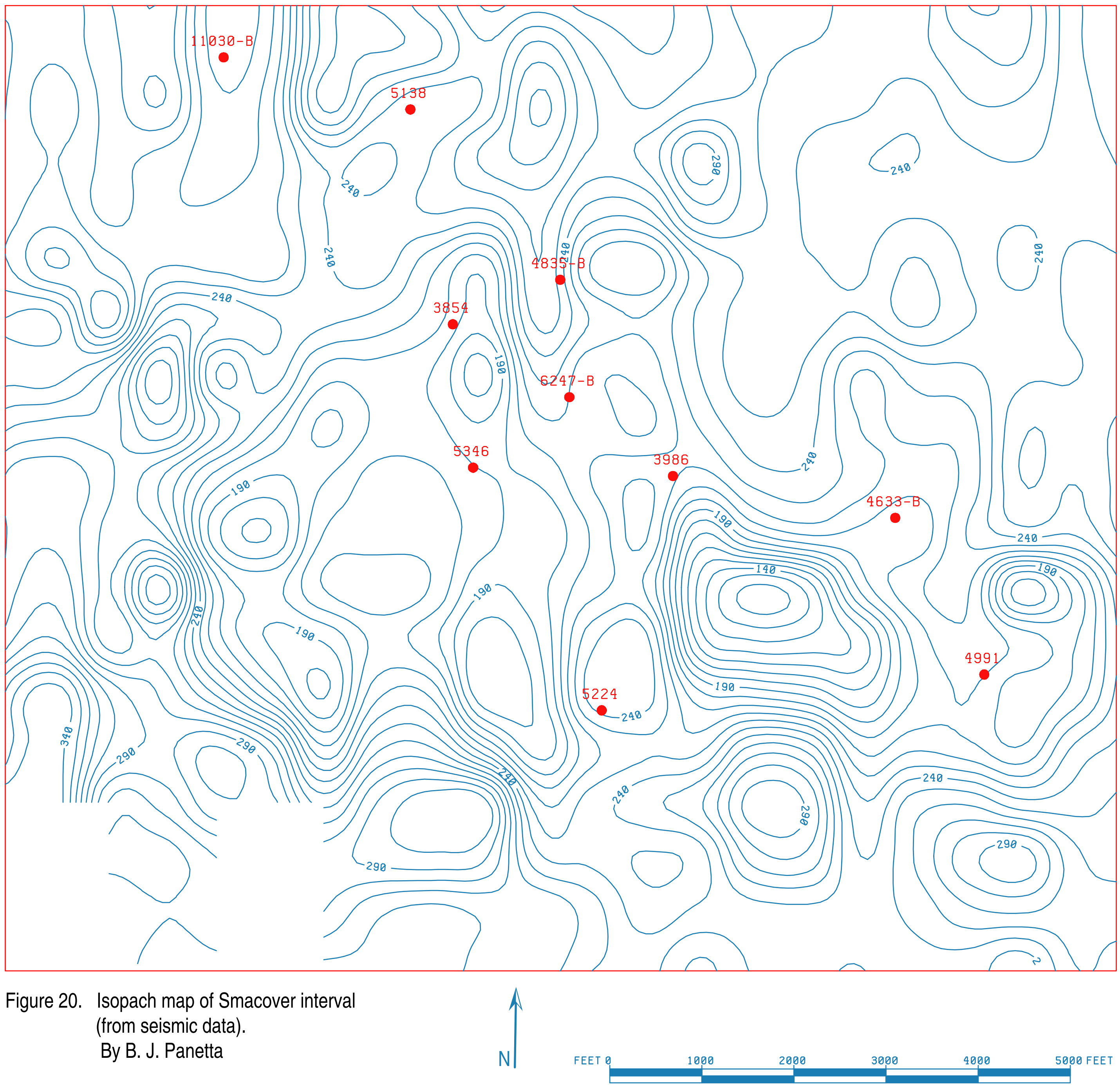


Figure 20. Isopach map of Smacover interval (from seismic data).
By B. J. Panetta

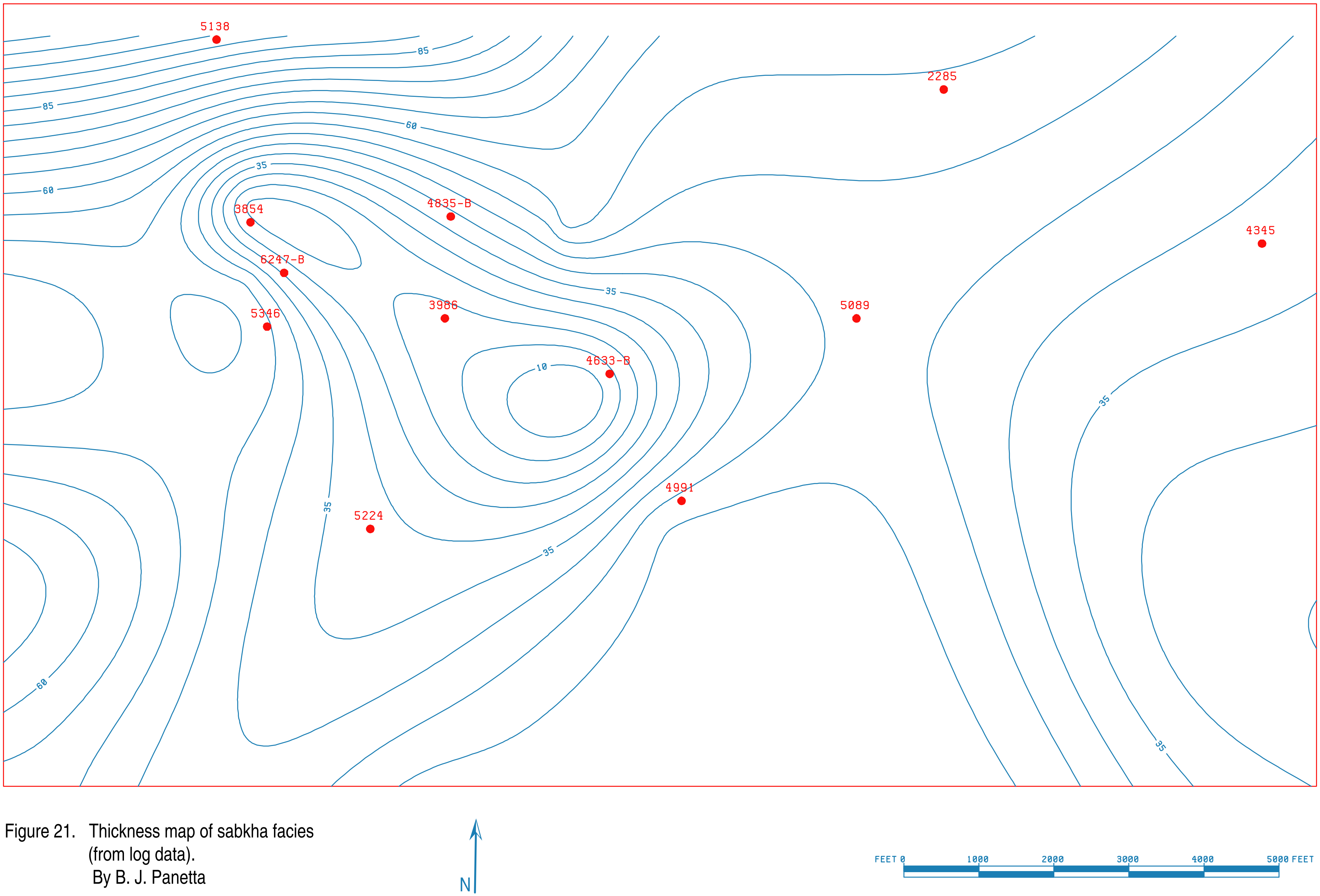


Figure 21. Thickness map of sabkha facies (from log data).
By B. J. Panetta

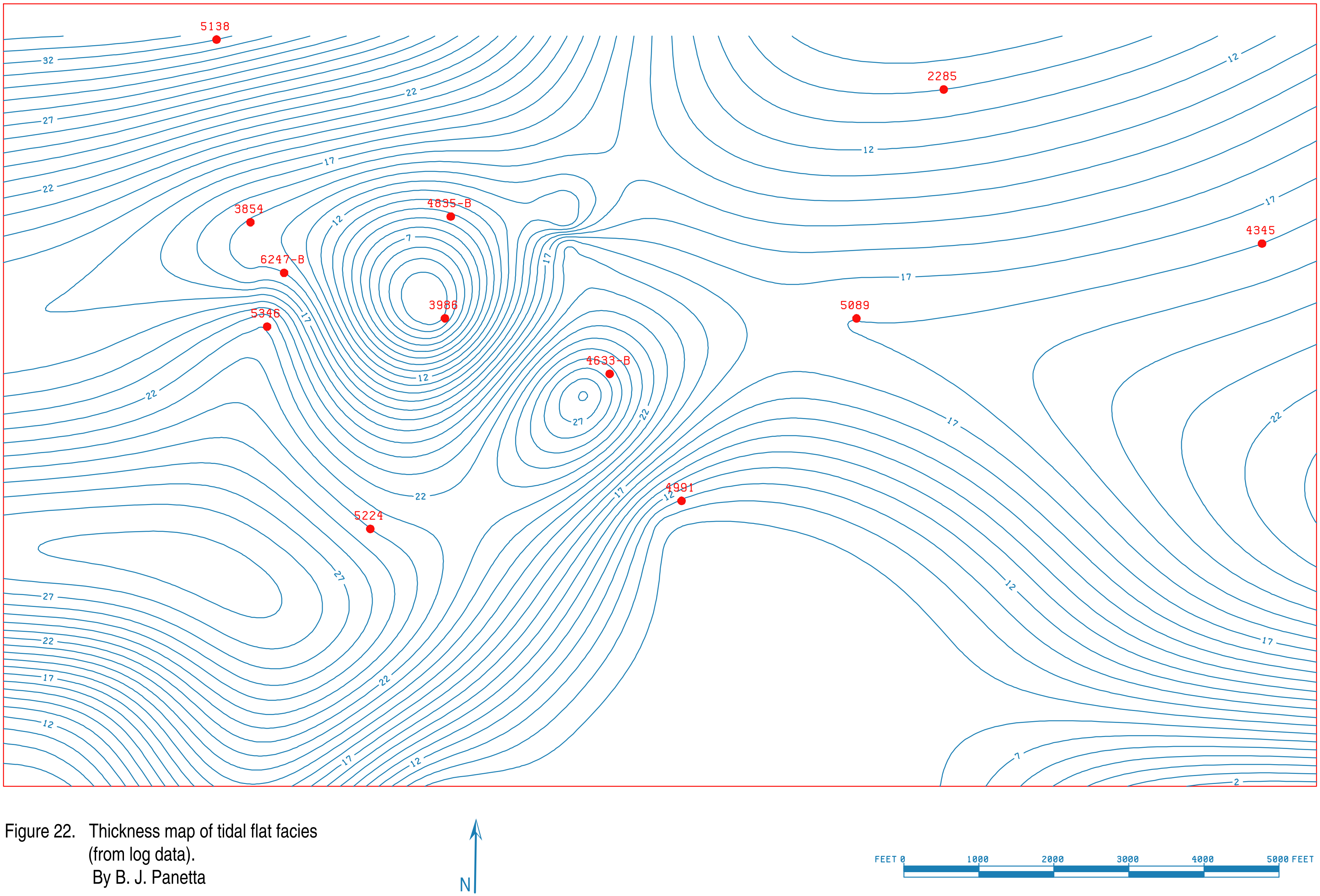


Figure 22. Thickness map of tidal flat facies (from log data).
By B. J. Panetta

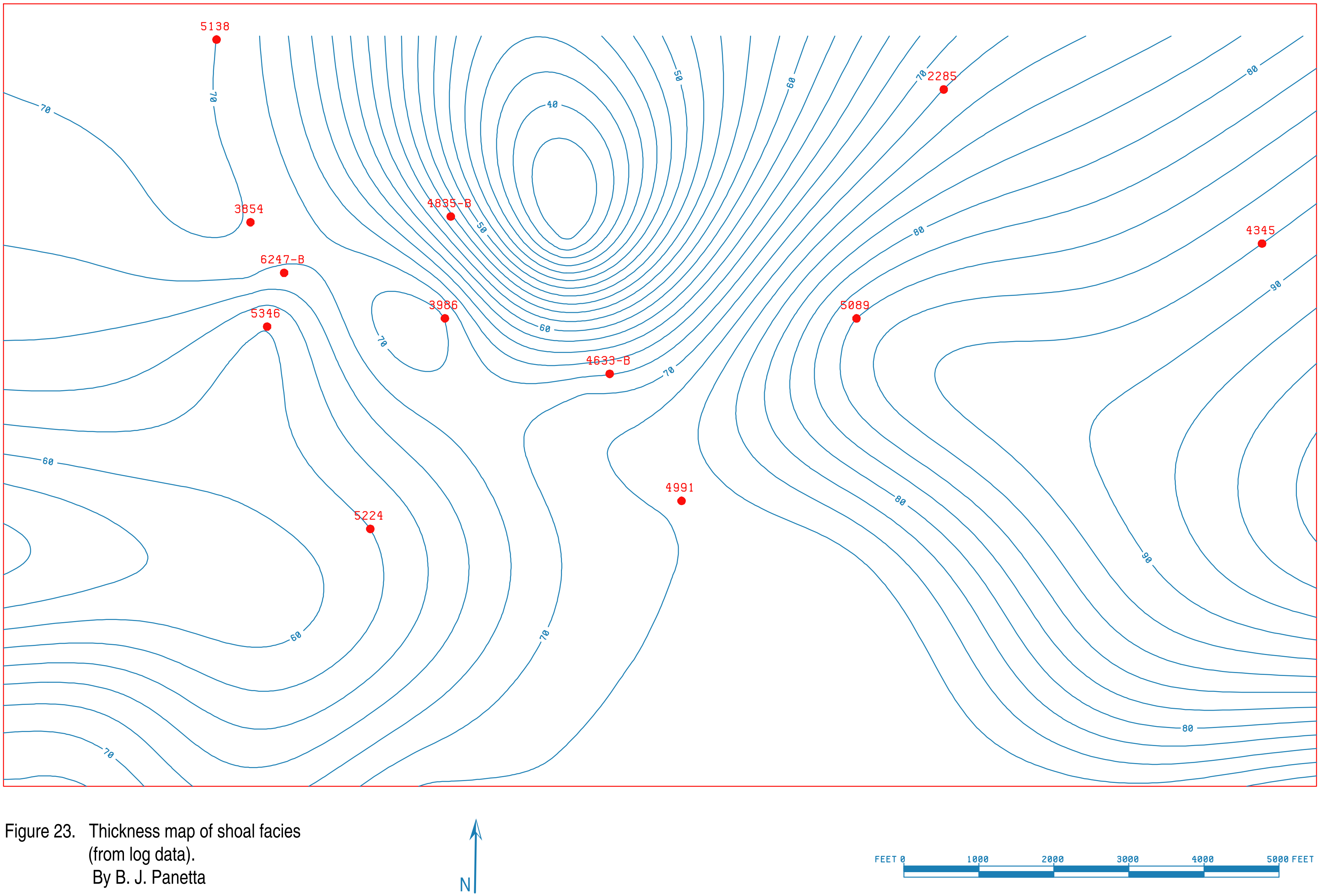


Figure 23. Thickness map of shoal facies (from log data).
By B. J. Panetta

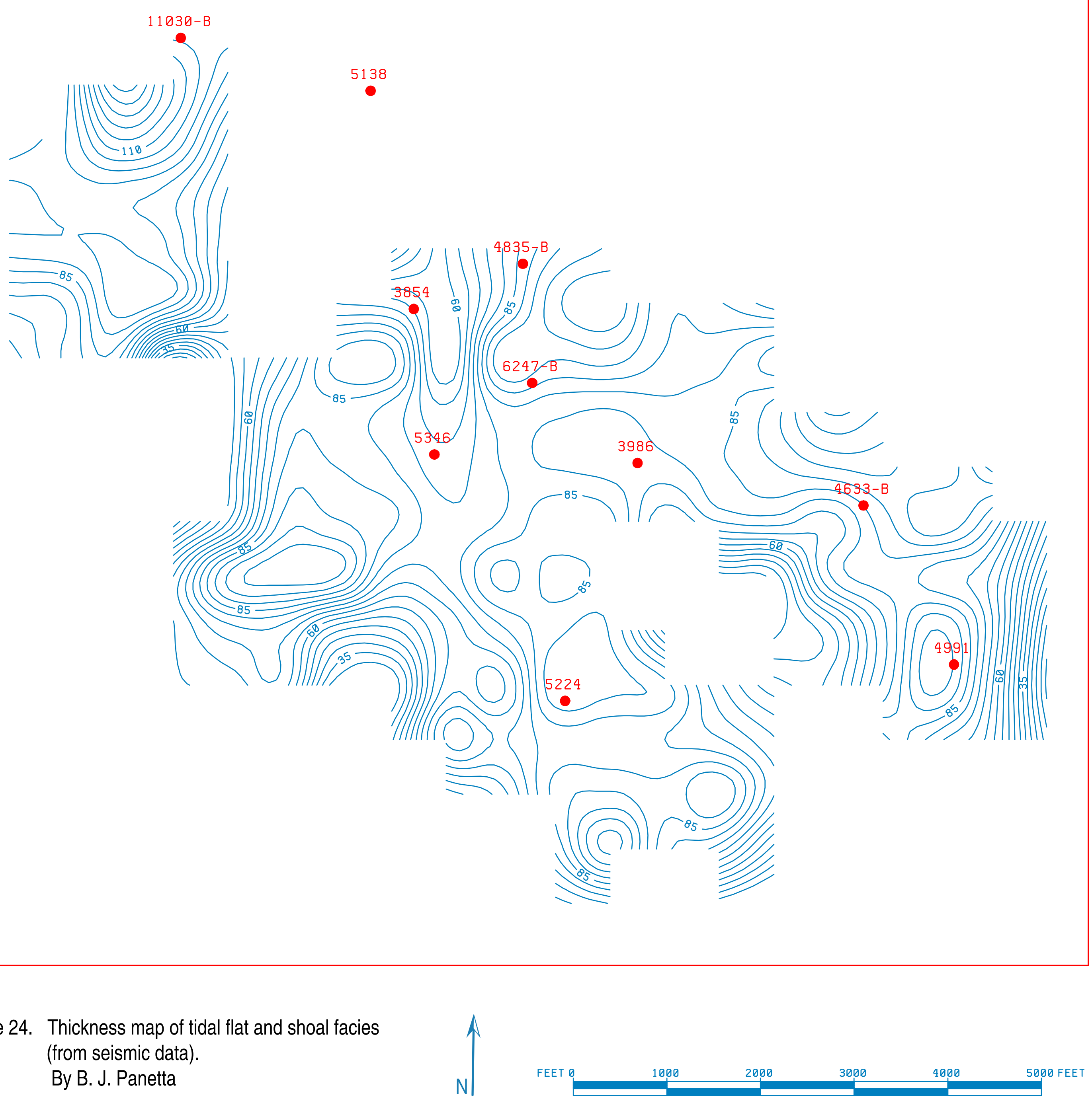


Figure 24. Thickness map of tidal flat and shoal facies (from seismic data).
By B. J. Panetta

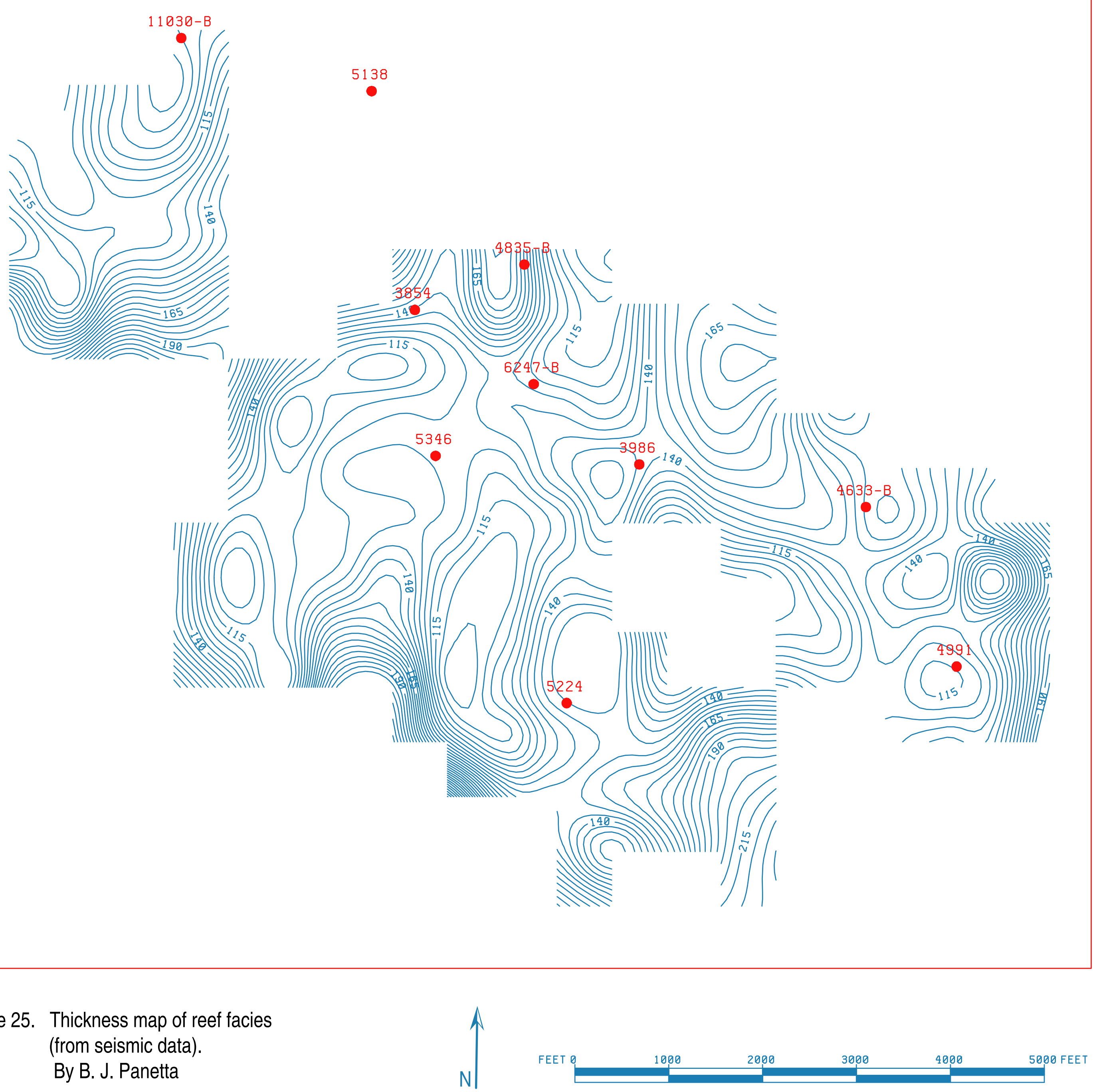


Figure 25. Thickness map of reef facies
(from seismic data).
By B. J. Panetta

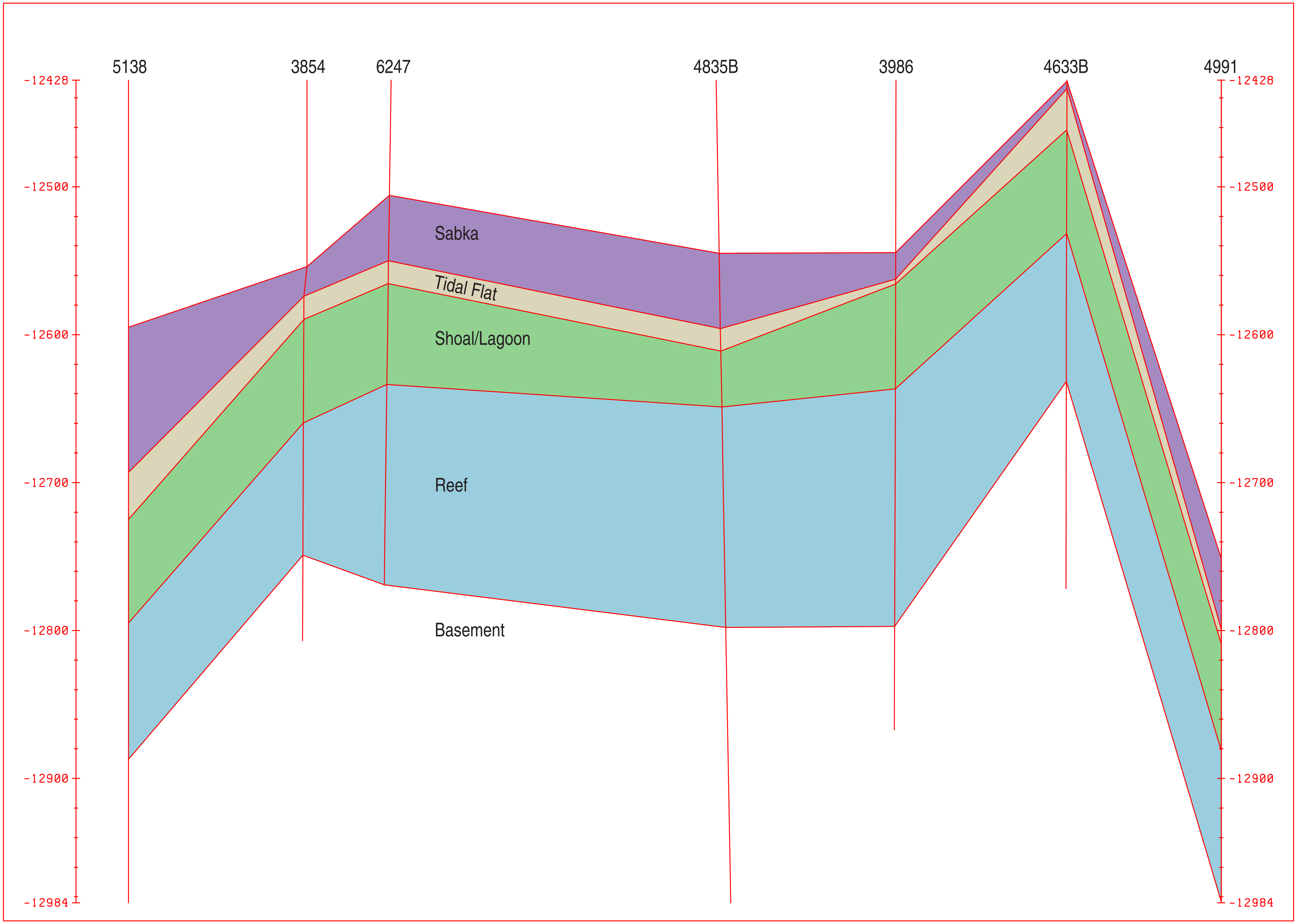


Figure 26. Cross section A - A'.
By B. J. Panetta.

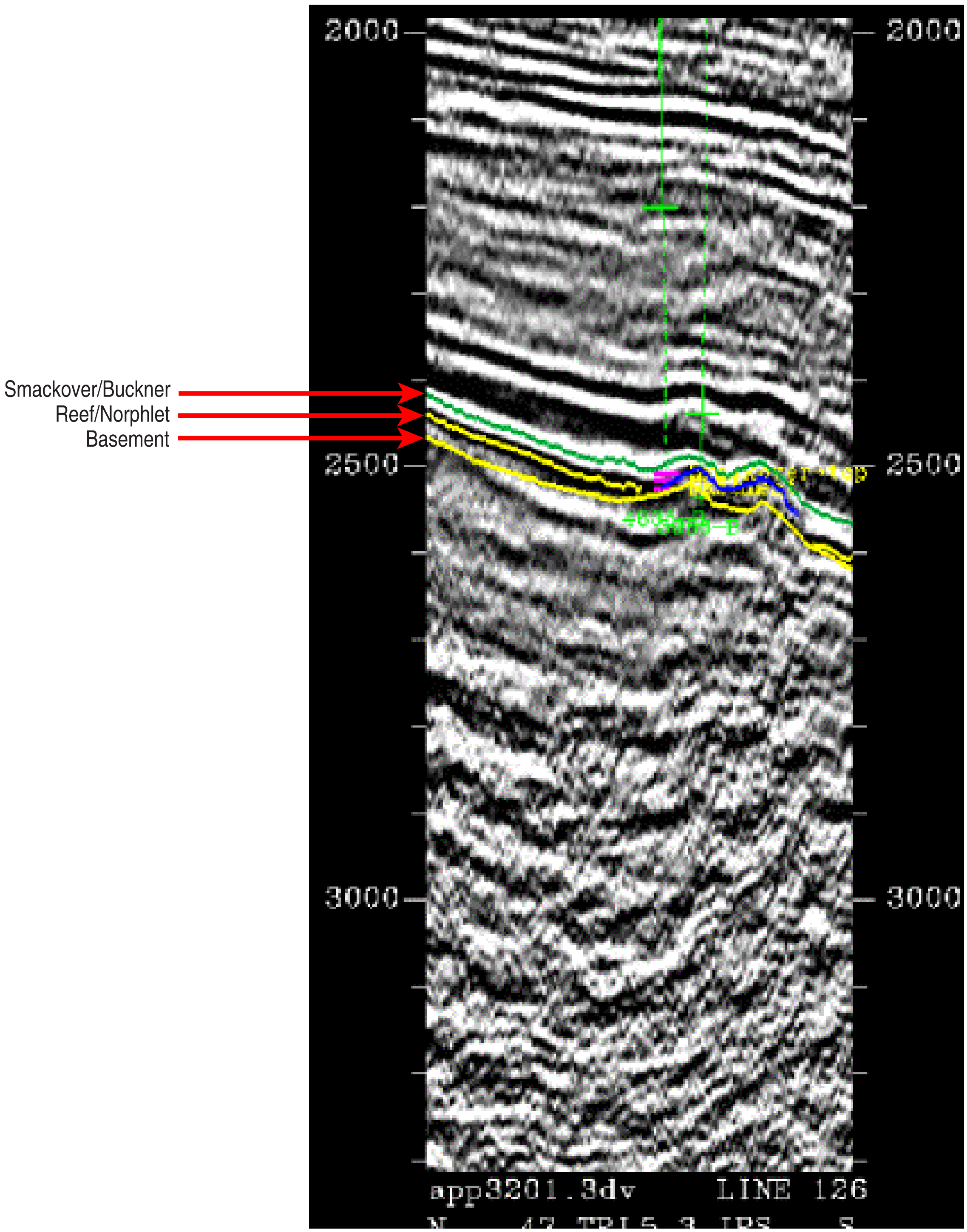


Figure 27. Seismic Profile.

surface, and Buckner/Smackover surface are illustrated in Figures 28 through 30. Cross sections (Figures 31 and 32) illustrating the reservoir facies based on well data and on seismic data have been prepared.

Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project. Tables 2 and 3 provide a tabulation of the initial work in these two areas of research.

Vocation Field. All available whole cores (11) from Vocation Field have been described and thin sections (237) from the cores have been studied. Graphic logs were constructed describing each of the cores (Figures 33 through 43). Depositional facies were determined from the core descriptions. From this work, an additional 73 thin sections are being prepared to provide accurate representation of the lithofacies identified. The core data and well log signatures have been integrated and calibrated on the graphic logs.

The well log and core data from Vocation Field have been entered into a digital database and structural and isopach maps are being constructed using these data. Graphic logs have been constructed for each of the cores. The core data and well log signatures are integrated and calibrated on these graphic logs. The graphic logs are being used in preparing cross sections across Vocation Field.

The core and well log data are being integrated with the 3-D seismic data that Strago contributed to the project.

Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project. Table 4 provides a tabulation of the initial work in these areas of research.

Task 2—Rock-Fluid Interactions.--This task is a continuation of the study of reservoir architecture and heterogeneity at the microscopic scale. While macroscopic and mesoscopic heterogeneities are largely a result of structural and depositional processes, microscopic heterogeneities are often a product of diagenetic modification of the pore system. Macroscopic and mesoscopic heterogeneities influence producibility by compartmentalizing the reservoir and providing barriers to large-scale fluid flow. Microscopic heterogeneities, on the other hand, influence producibility by controlling the overall rate of fluid flow through the reservoir. This task

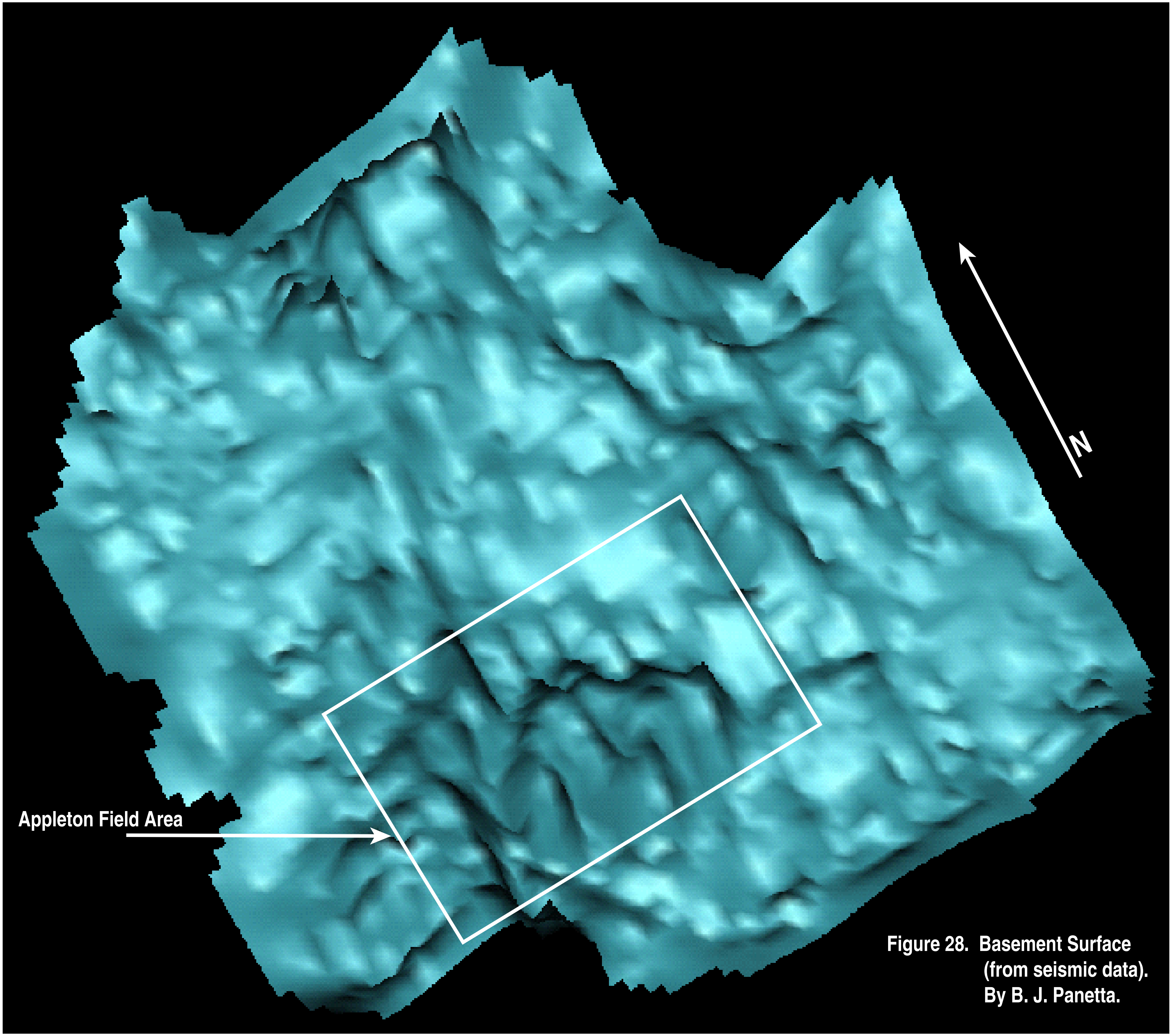


Figure 28. Basement Surface (from seismic data). By B. J. Panetta.

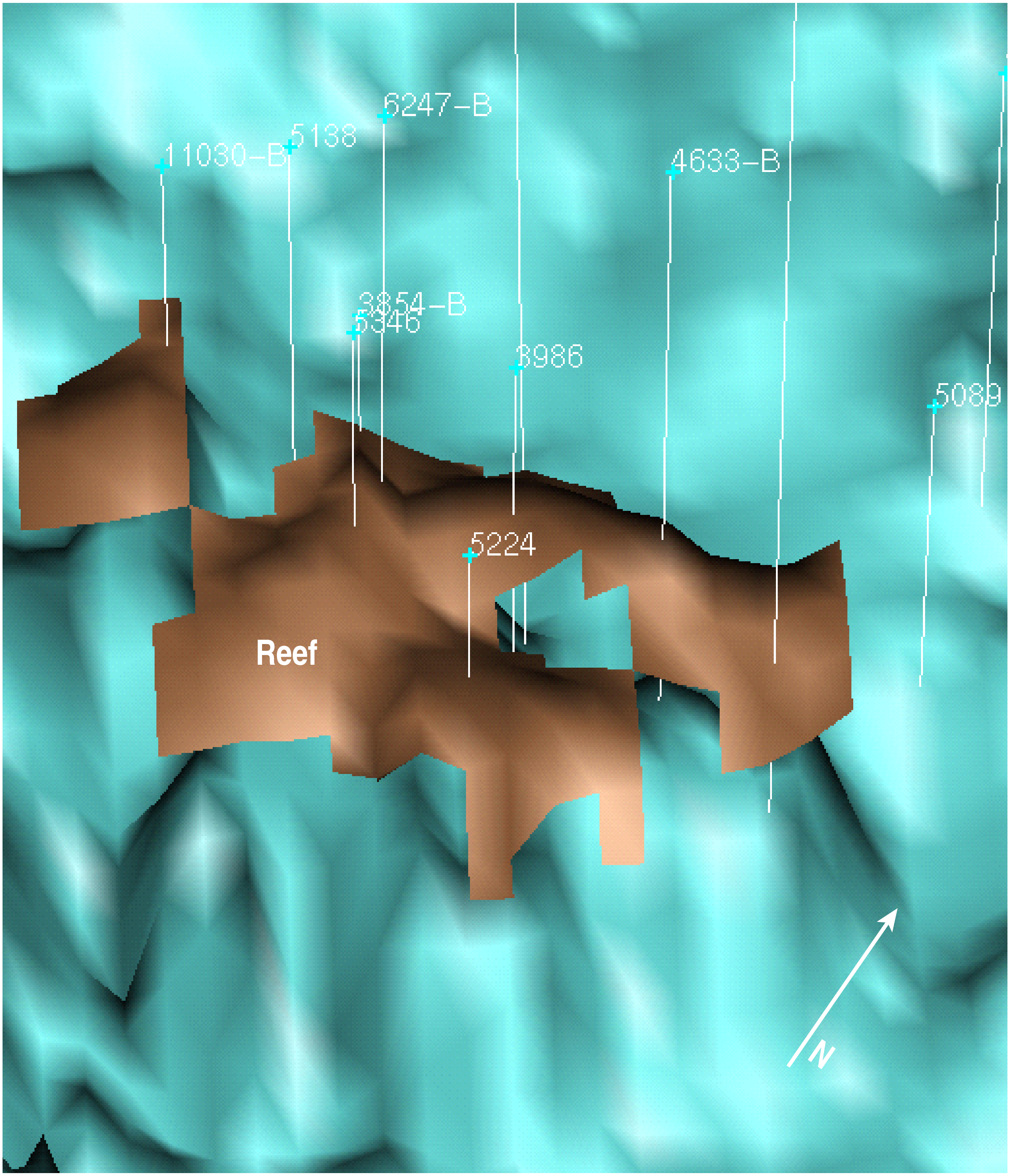


Figure 29. Reef Surface
(from seismic data).
By B. J. Panetta.

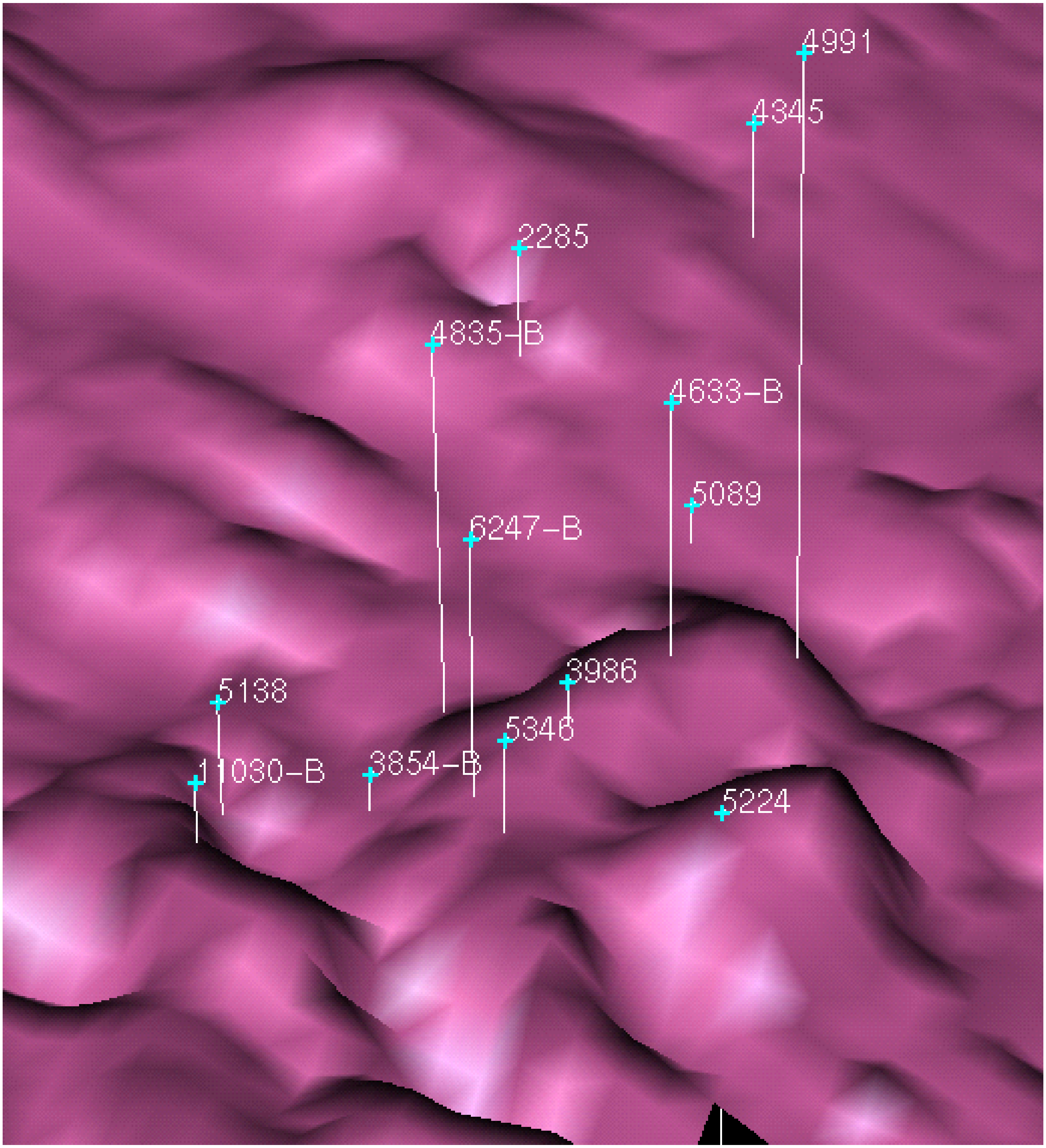


Figure 30. Buckner/Smackover surface
(from seismic data).
By B. J. Panetta.

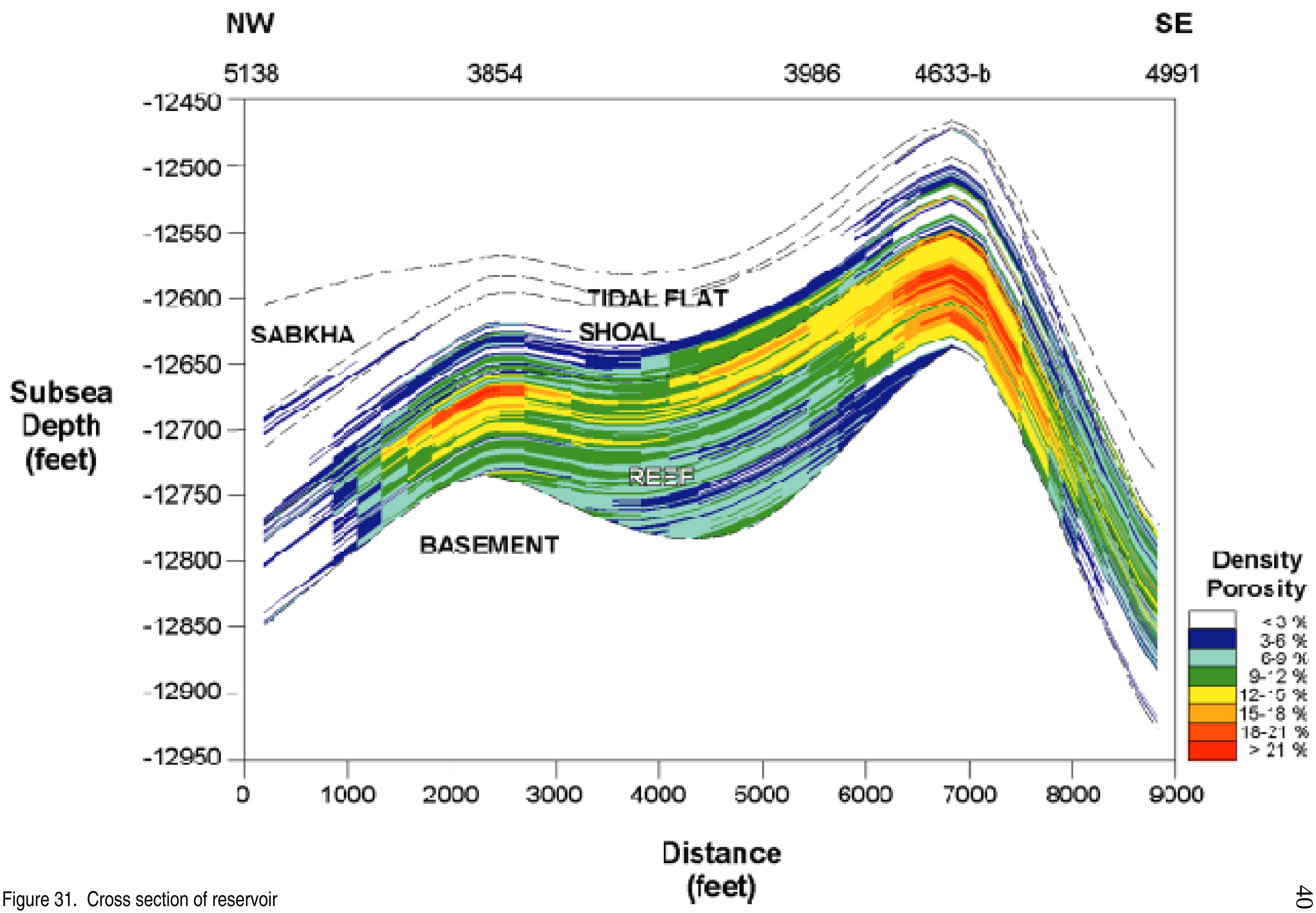


Figure 31. Cross section of reservoir facies (from well logs). By B. J. Panetta.

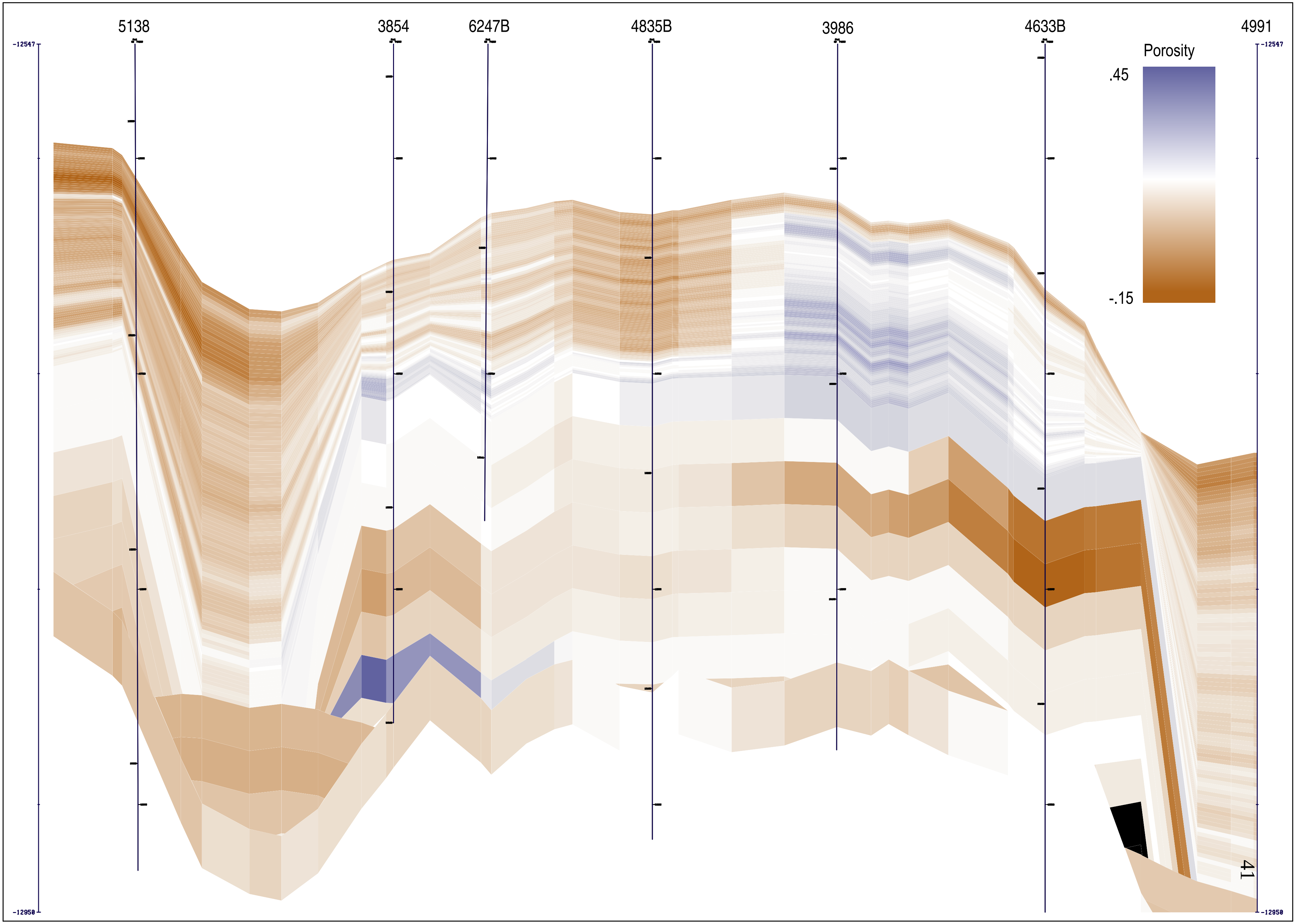


Figure 32. Cross section of reservoir facies (from seismic data). By B. J. Panetta.

Table 2. Characteristics of Smackover Lithofacies in the Appleton Field Area.

Lithofacies	Lithology	Allochems	Pore Types	Porosity	Permeability
Carbonate mudstone	Dolostone and anhydritic dolostone	None	Intercrystalline	Low (1.2 to 2.5%)	Low (0.01 md)
Peloidal wackestone	Dolostone to calcareous dolostone	Peloids, ooids, intraclasts	Intercrystalline, moldic	Low to moderate (2.6 to 12.4%)	Low (0.01 to 0.11 md)
Peloidal packstone	Dolomitic limestone	Peloids, ooids, oncoids, intraclasts	Interparticulate, moldic, intercrystalline	Low to moderate (1.1 to 12.4%)	Low to moderate (0.01 to 0.51 md)
Peloidal/oncoidal packstone	Dolostone to calcareous dolostone	Peloids, oncoids, intraclasts	Interparticulate	Low (1.2 to 6.1%)	Low (0.01 md)
Peloidal/oolitic packstone	Dolostone	Peloids, ooids, skeletal grains, intraclasts	Moldic, intercrystalline, interparticulate	Low (1.3 to 4.5%)	Low (0.01 md)
Peloidal grainstone	Calcareous dolostone	Peloids, oncoids, algal grains, intraclasts	Interparticulate, fenestral, moldic, interparticulate, vuggy	Low to high (1.0 to 19.9%)	Low to high (0.01 to 722 md)
Oncoidal grainstone	Calcareous dolostone to dolostone	Oncoids, peloids, intraclasts	Interparticulate, intraparticulate, fenestral	Low to moderate (1.4 to 11.9%)	Low to high (0.01 to 8.27 md)
Oolitic grainstone	Dolostone to limestone	Ooids, peloids, oncoids, intraclasts	Interparticulate, moldic, intercrystalline	Moderate to high (8.3 to 20.7%)	Moderate to high (3.09 to 406 md)
Oncoidal/peloidal/ oolitic grainstone	Dolostone to calcareous dolostone	Oncoids, peloids, ooids, algal grains	Interparticulate, moldic, vuggy	Low to high (1.9 to 19%)	Low to high (0.01 to 219 md)
Algal grainstone	Dolomitic limestone to calcareous dolostone	Algal grains, oncoids, peloids, ooids	Interparticulate, moldic, vuggy, fenestral, intercrystalline	Low to high (1.7 to 23.1%)	Low to high (0.01 to 63 md)
Microbial boundstone (bafflestone)	Dolostone	Algae, intraclasts, oncoids, peloids	Shelter, vuggy, interparticulate, intercrystalline	High (11.0 to 29.0%)	High (8.13 to 4106 md)
Microbial bindstone	Dolostone	Algae, peloids, ooids	Shelter, vuggy, fenestral, moldic, interparticulate	High (11.9 to 20.7%)	High (11 to 1545 md)
Algal laminite	Dolostone to dolomitic limestone	Algae, peloids, oncoids, intraclasts	Interparticulate, intercrystalline	Low (1.1 to 7.0%)	Low (0.01 md)
Anhydrite	Anhydrite	None	None	Low (1.0%)	Low (0.01 md)

Table 3. Smackover Genetic Depositional Systems at Appleton Field.

Genetic Depositional System	Depositional Environment	Lithofacies
Sabkha	Sabkha	Anhydrite
Tidal flat	Tidal flat	Algal laminite, carbonate mudstone
Shoal	Shoal crest, shoal flank, lagoon	Algal grainstone, oncoidal/peloidal/oolitic grainstone, oolitic grainstone, oncoidal grainstone, peloidal grainstone, peloidal/oolitic packstone, peloidal/oncoidal packstone, peloidal packstone, peloidal wackestone
Reef	Reef crest, reef flank, subtidal	Microbial boundstone (bafflestone), microbial bindstone, carbonate mudstone

Well Permit No. 11185
STRAGO-BYRD 26-13 #2

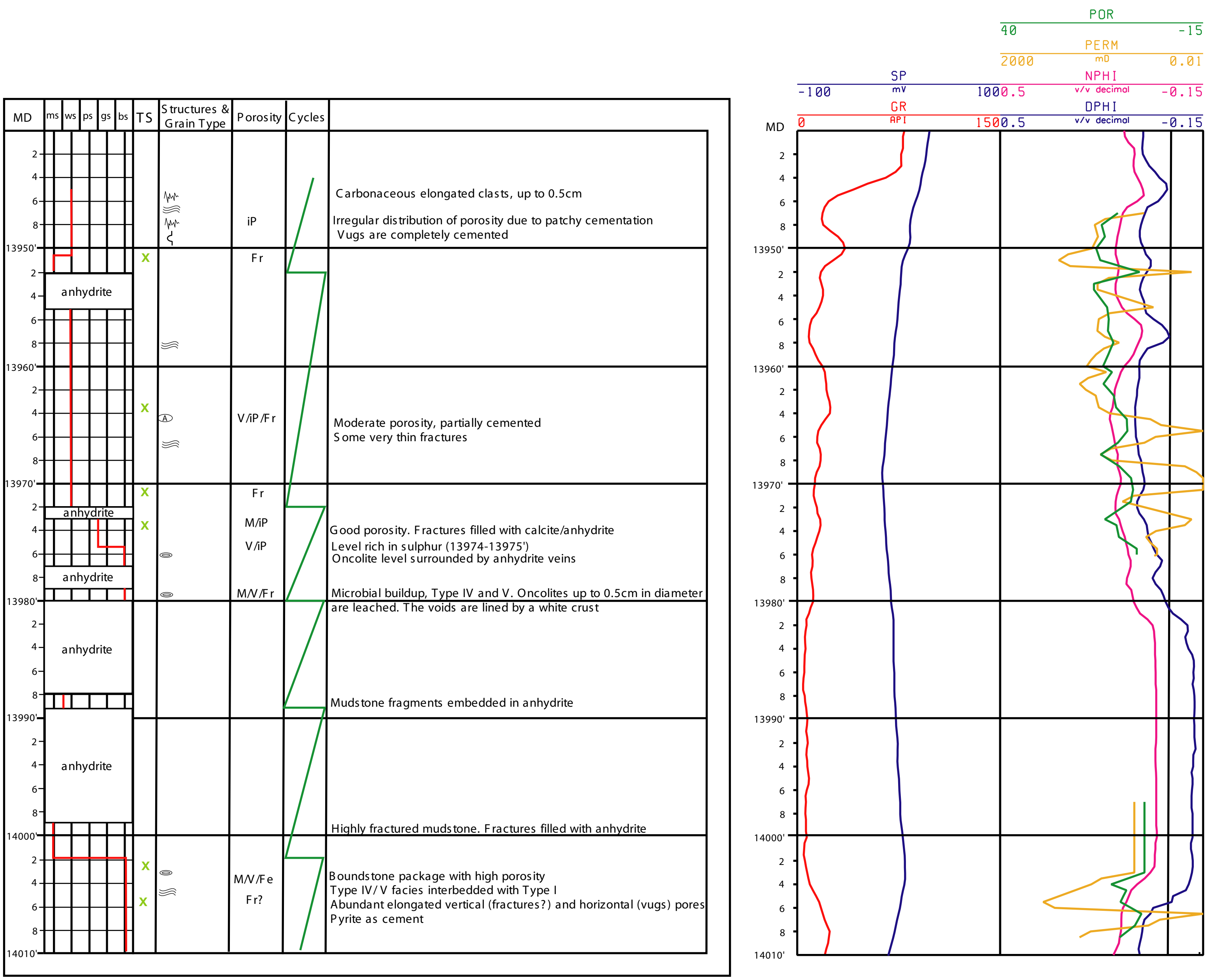


Figure 33. Graphic log for well Permit # 11185.
By J. C. Llinas.

Well Permit No. 1599
B.C. QUIMBY 27-15 #1

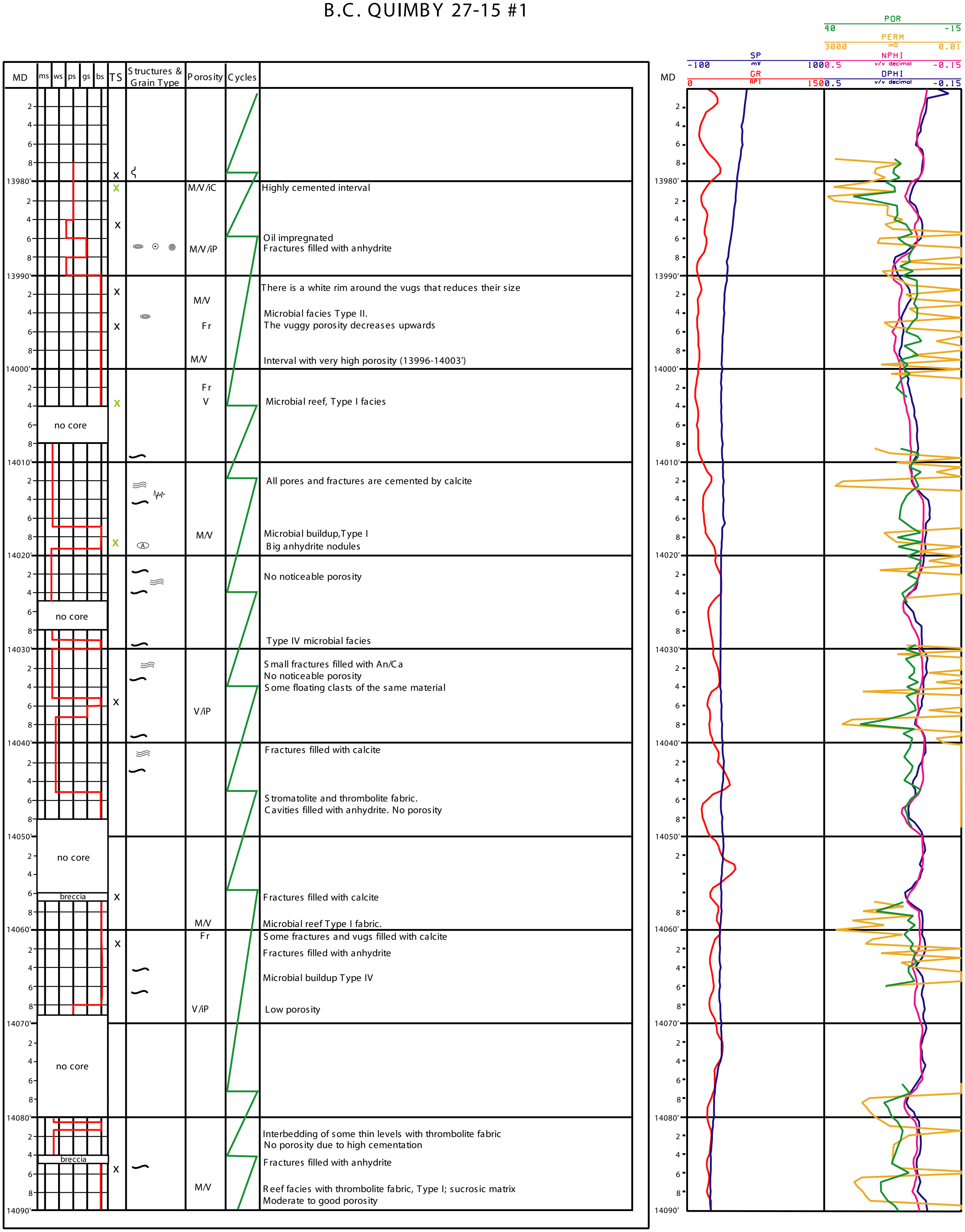


Figure 34. Graphic log for well Permit # 1599.
By J. C. Llinas.

Well Permit No. 1599 (cont.)
B.C. QUIMBY 27-15 #1

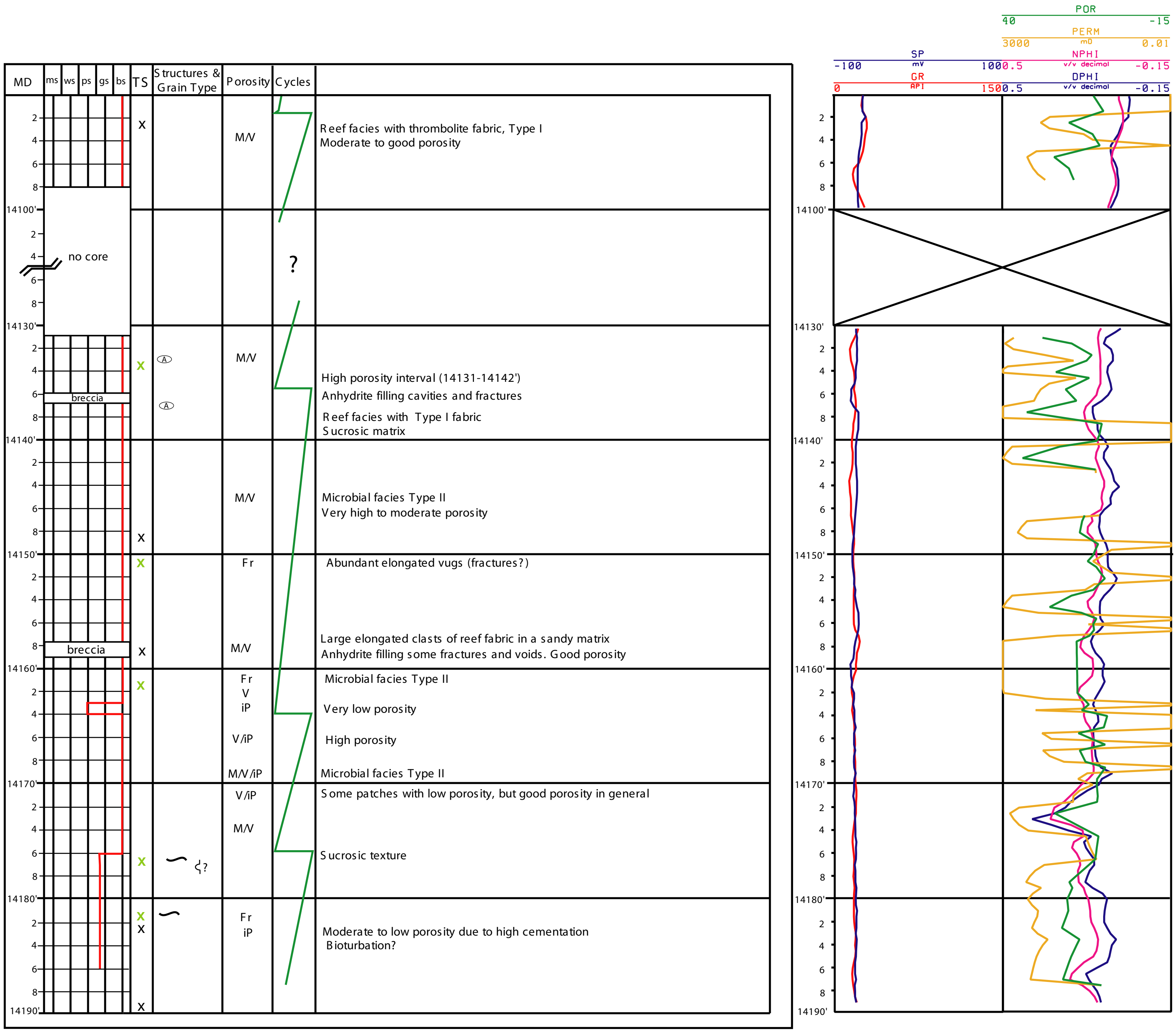


Figure 34 (continued). Graphic log for well Permit # 1599.
By J. C. Llinas.

Well Permit No. 1691

CONTAINER CORP. OF AMERICA 34-5 #1

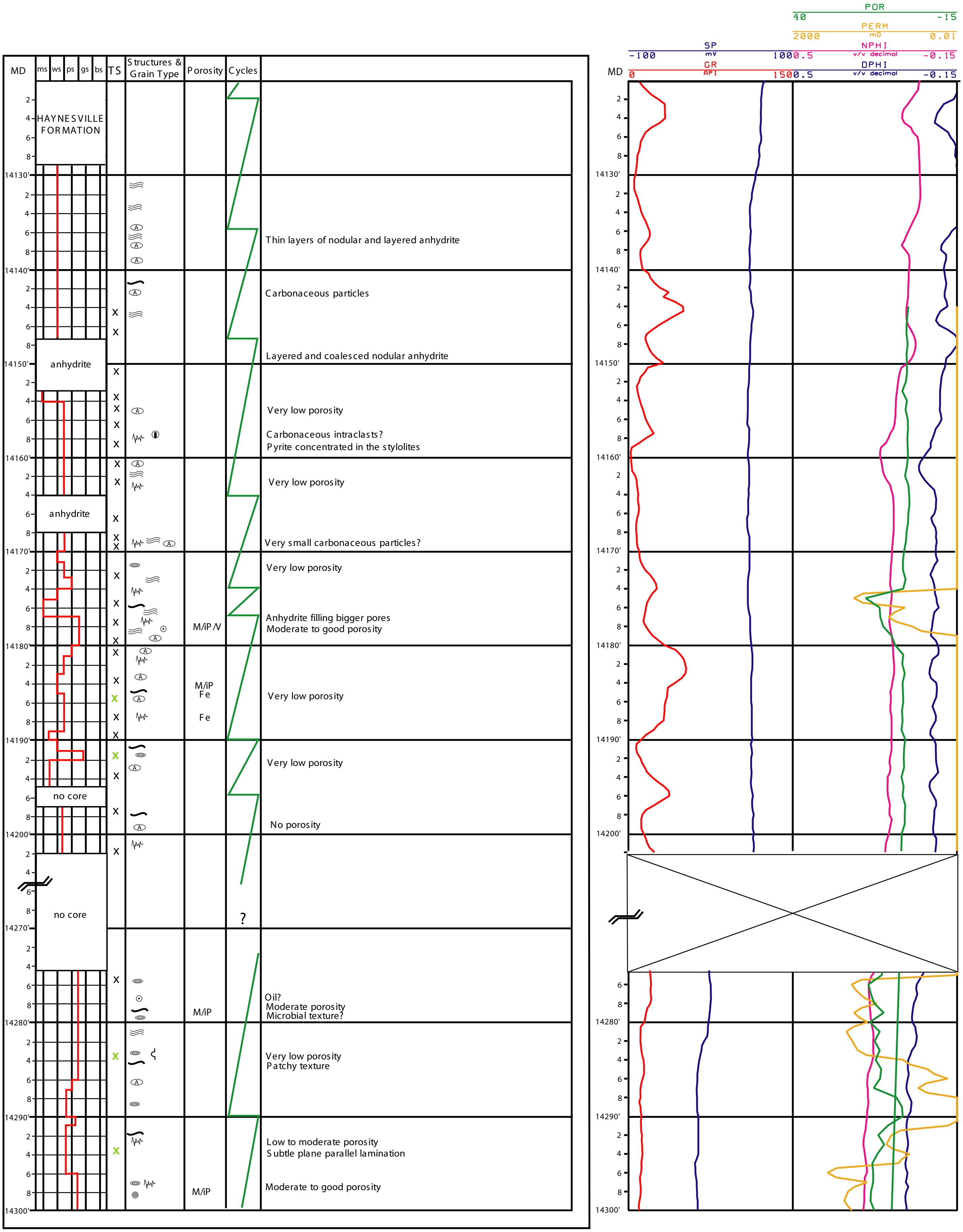


Figure 35. Graphic log for well Permit # 1691.
By J. C. Llinas.

Well Permit No. 1691(cont.)

CONTAINER CORP. OF AMERICA 34-5 #1

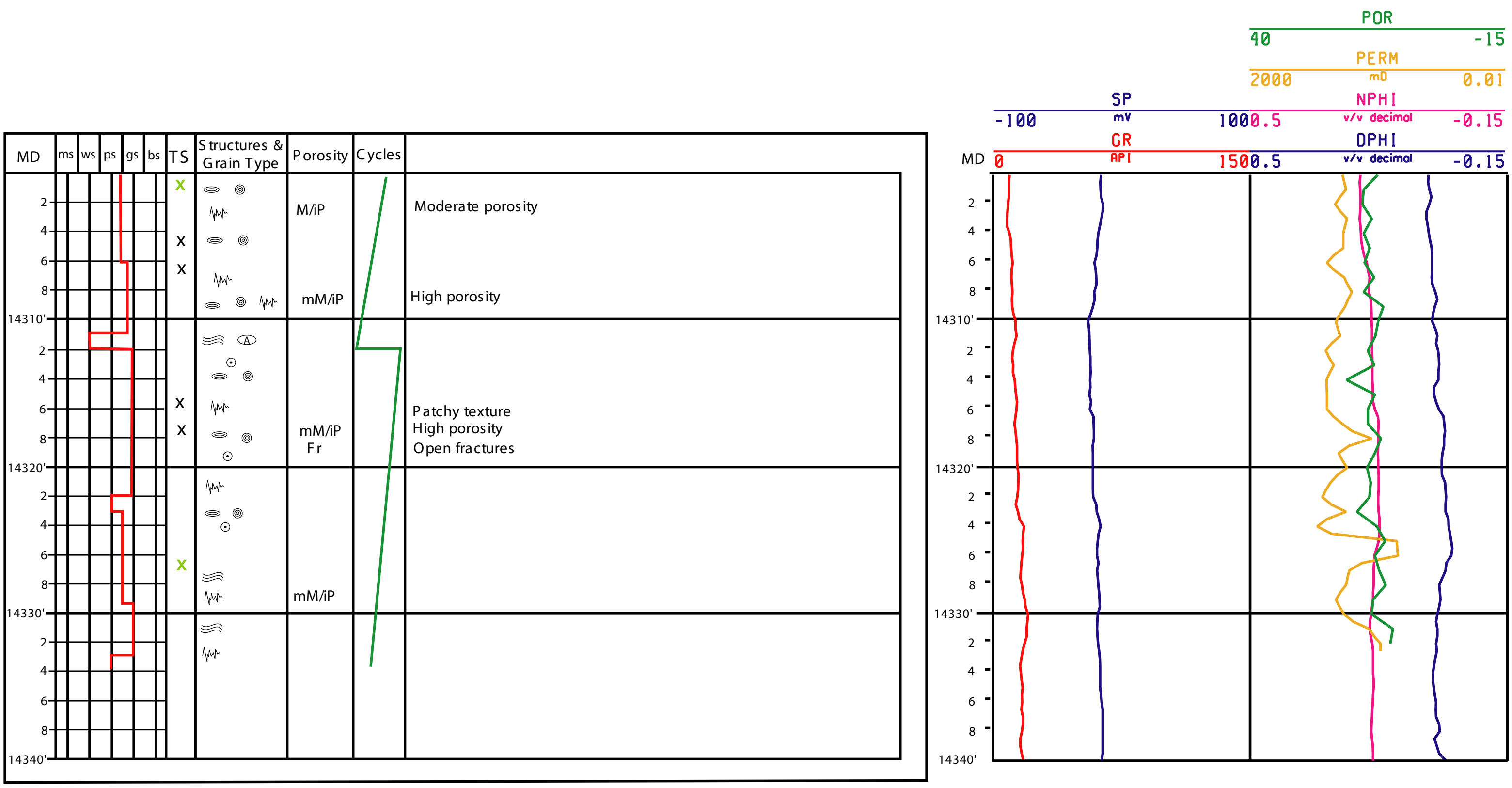


Figure 35 (continued). Graphic log for well Permit # 1691B.
By J. C. Llinas.

Well Permit No. 2851

M.J. BYRD ET UX 26-13 #1

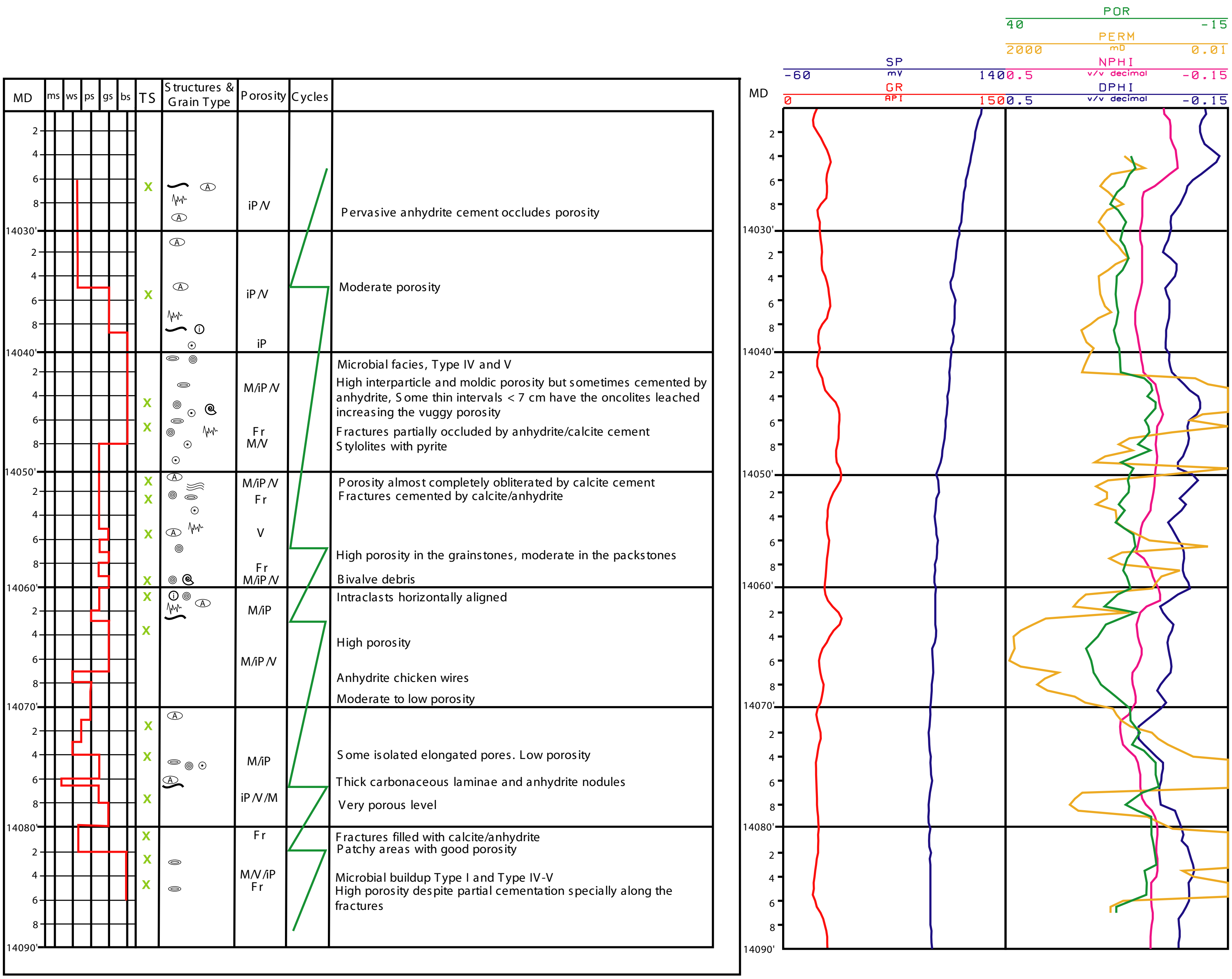


Figure 36. Graphic log for well Permit # 2851.
By J. C. Llinas.

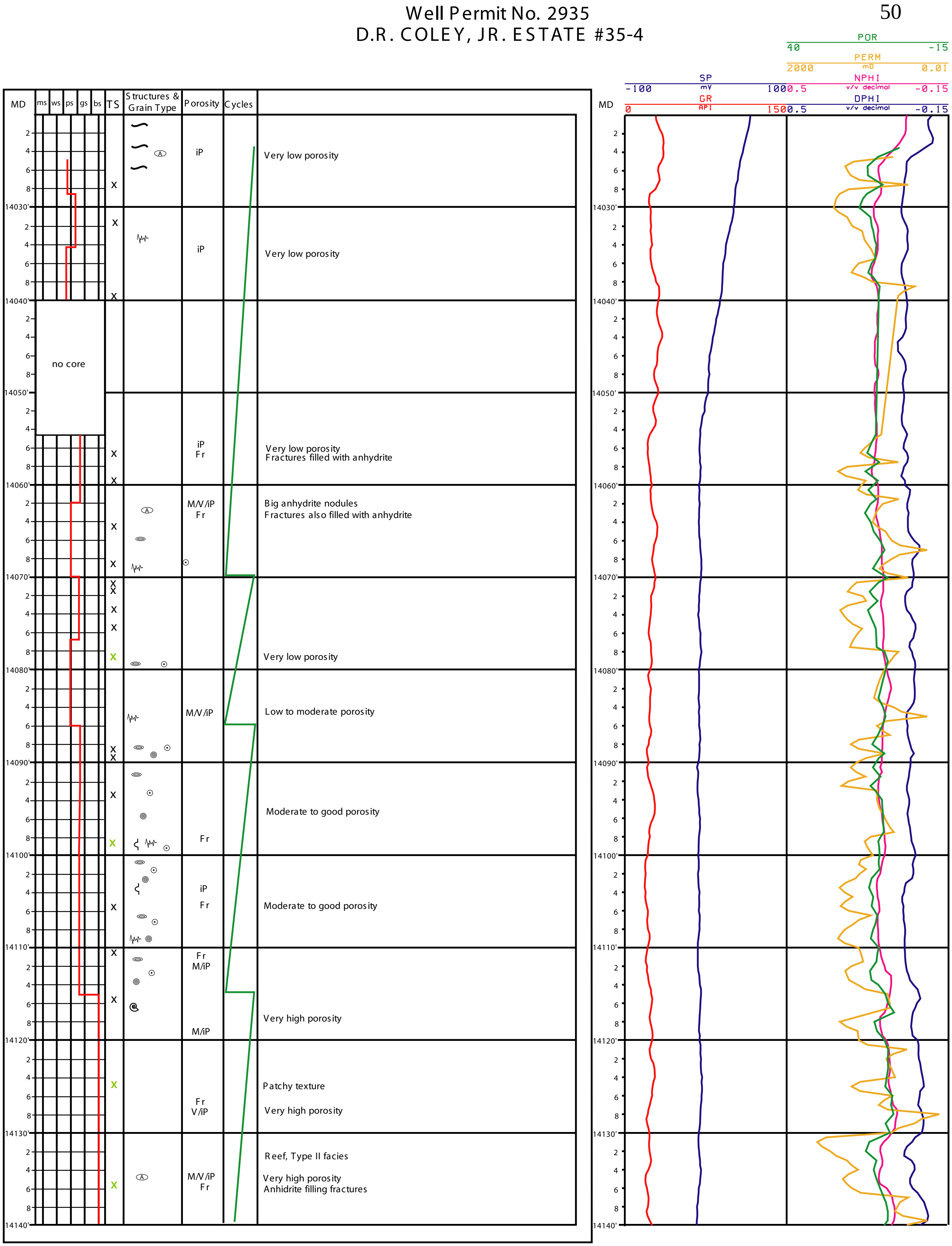


Figure 37. Graphic log for well Permit # 2935.
By J. C. Llinas.

Well Permit No. 2935 (cont.)
D.R. COLEY, JR. ESTATE #35-4

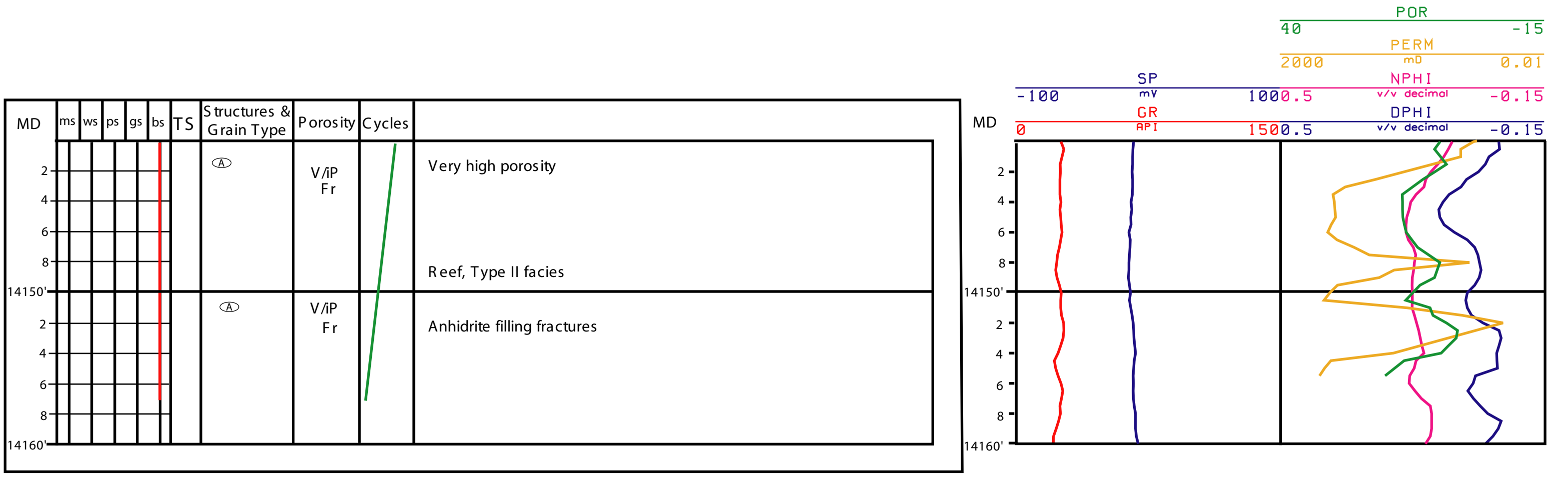


Figure 37 (continued). Graphic log for well Permit # 2935.
By J. C. Llinas.

Well Permit No. 2966
B.C. QUIMBY 27-16 #1

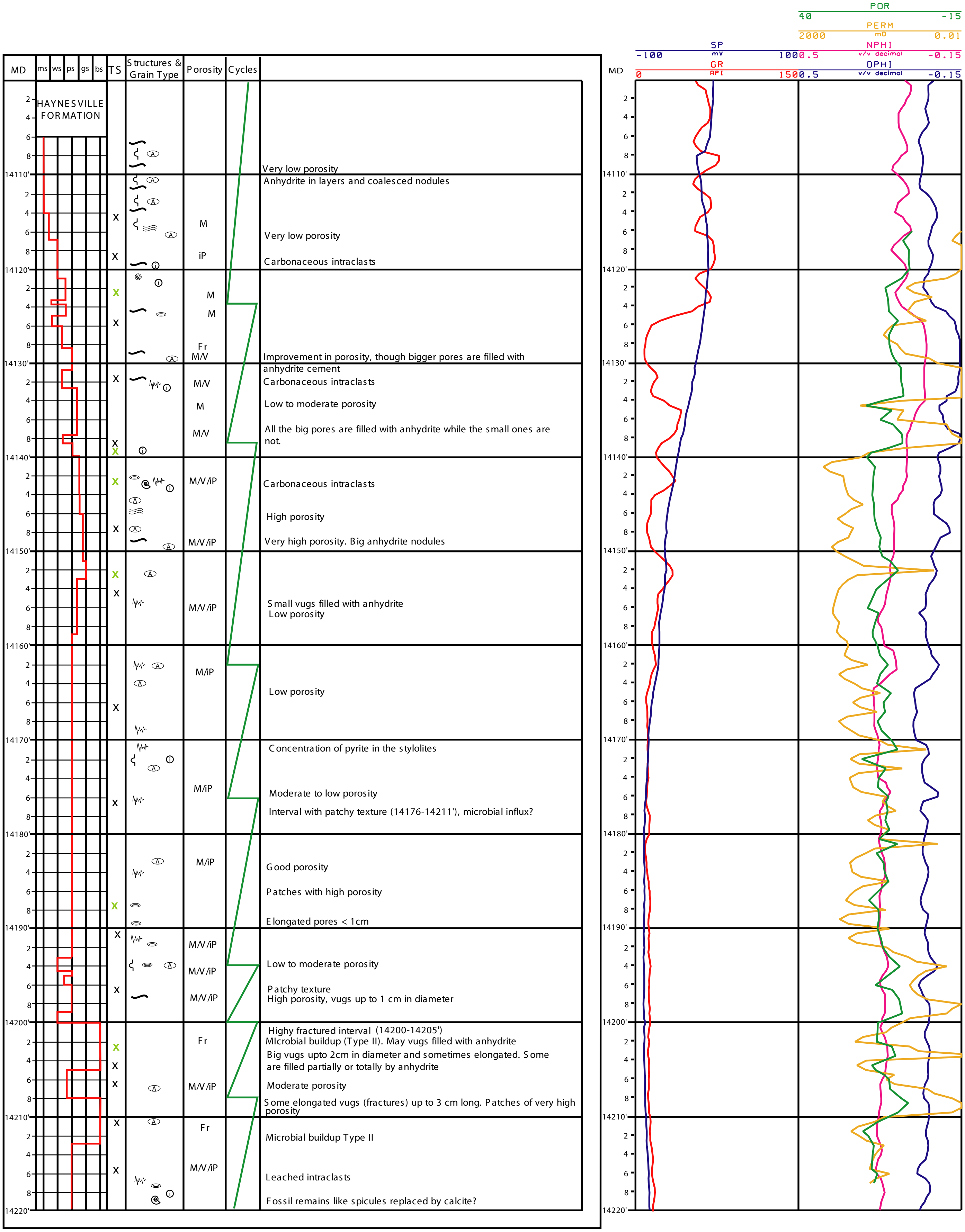


Figure 38. Graphic log for well Permit # 2966.
By J. C. Llinas.

Well Permit No. 2966 (cont.)
B.C. QUIMBY 27-16 #1

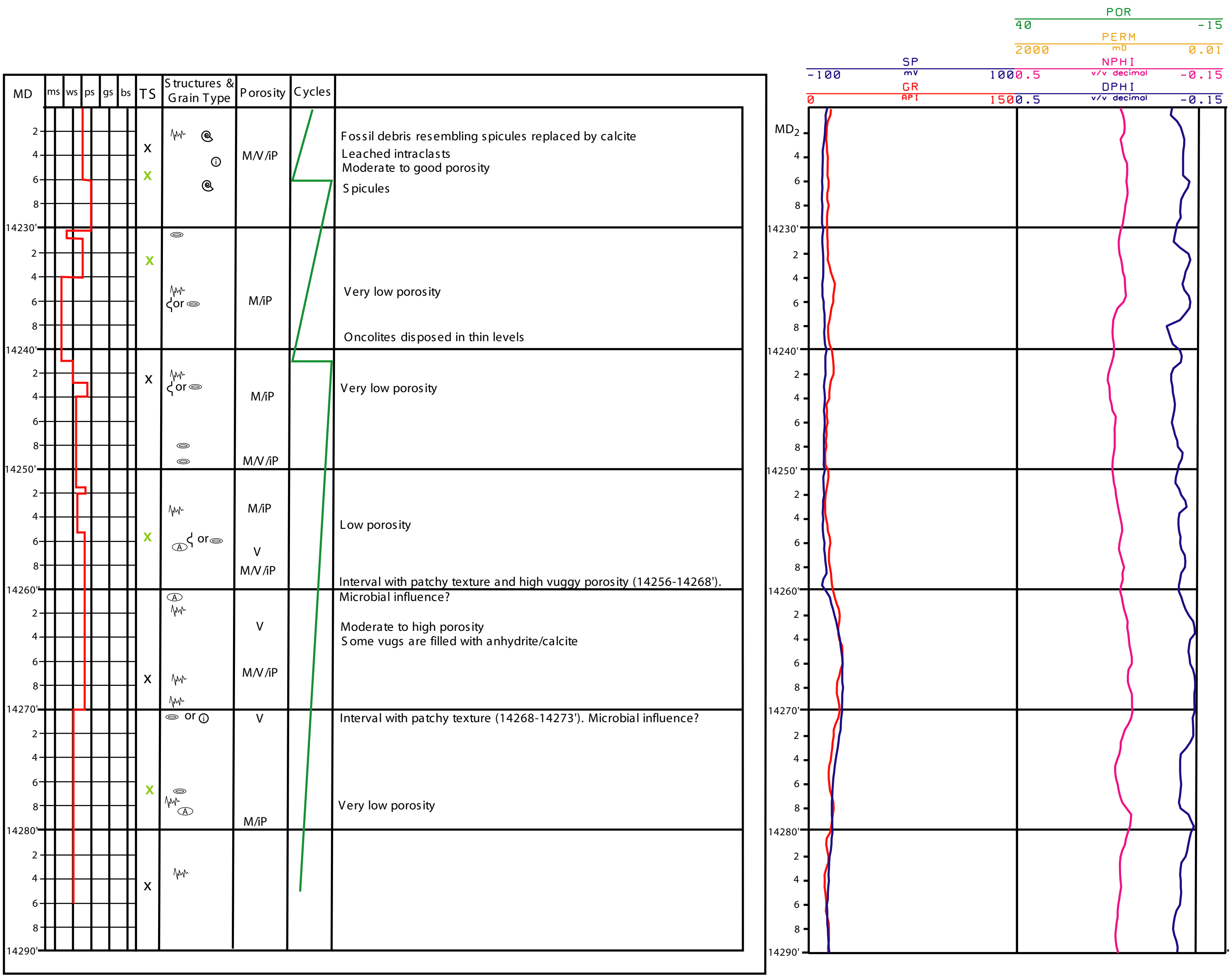


Figure 38 (continued). Graphic log for well Permit # 2966.
By J. C. Llinas.

Well Permit No. 3412
B.C. QUIMBY 27-15 #2

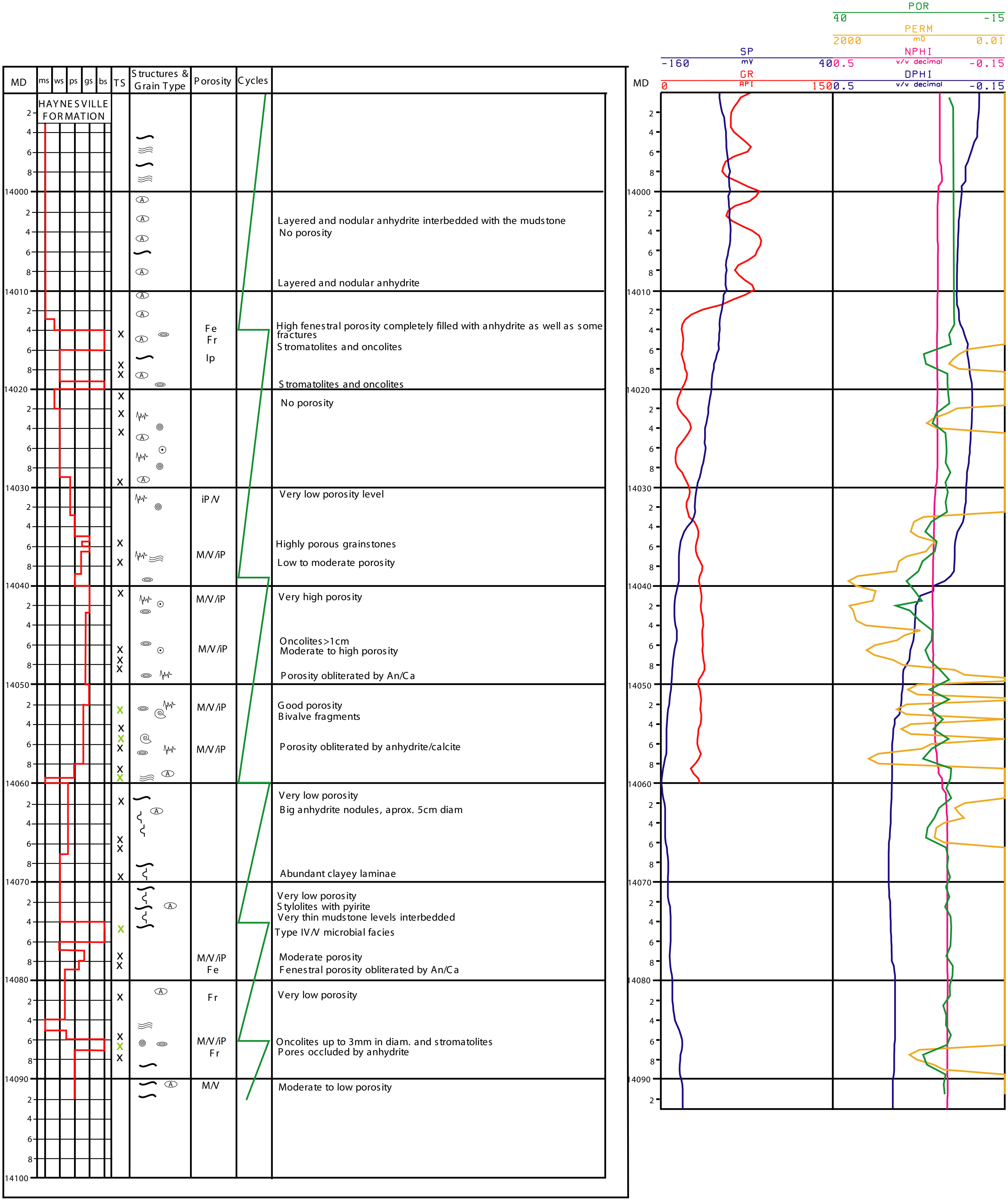


Figure 39. Graphic log for well Permit # 3412. By J. C. Llinas.

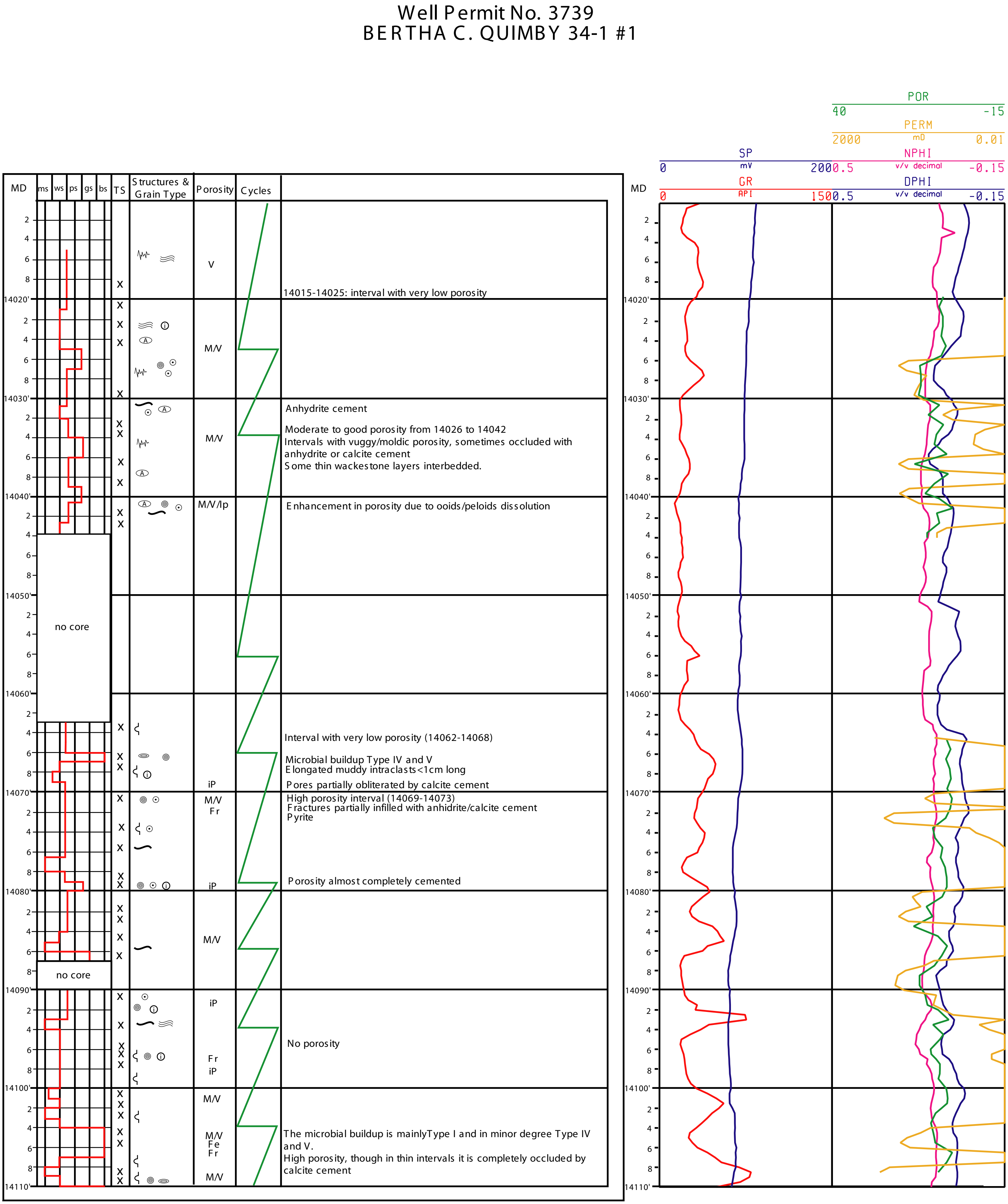
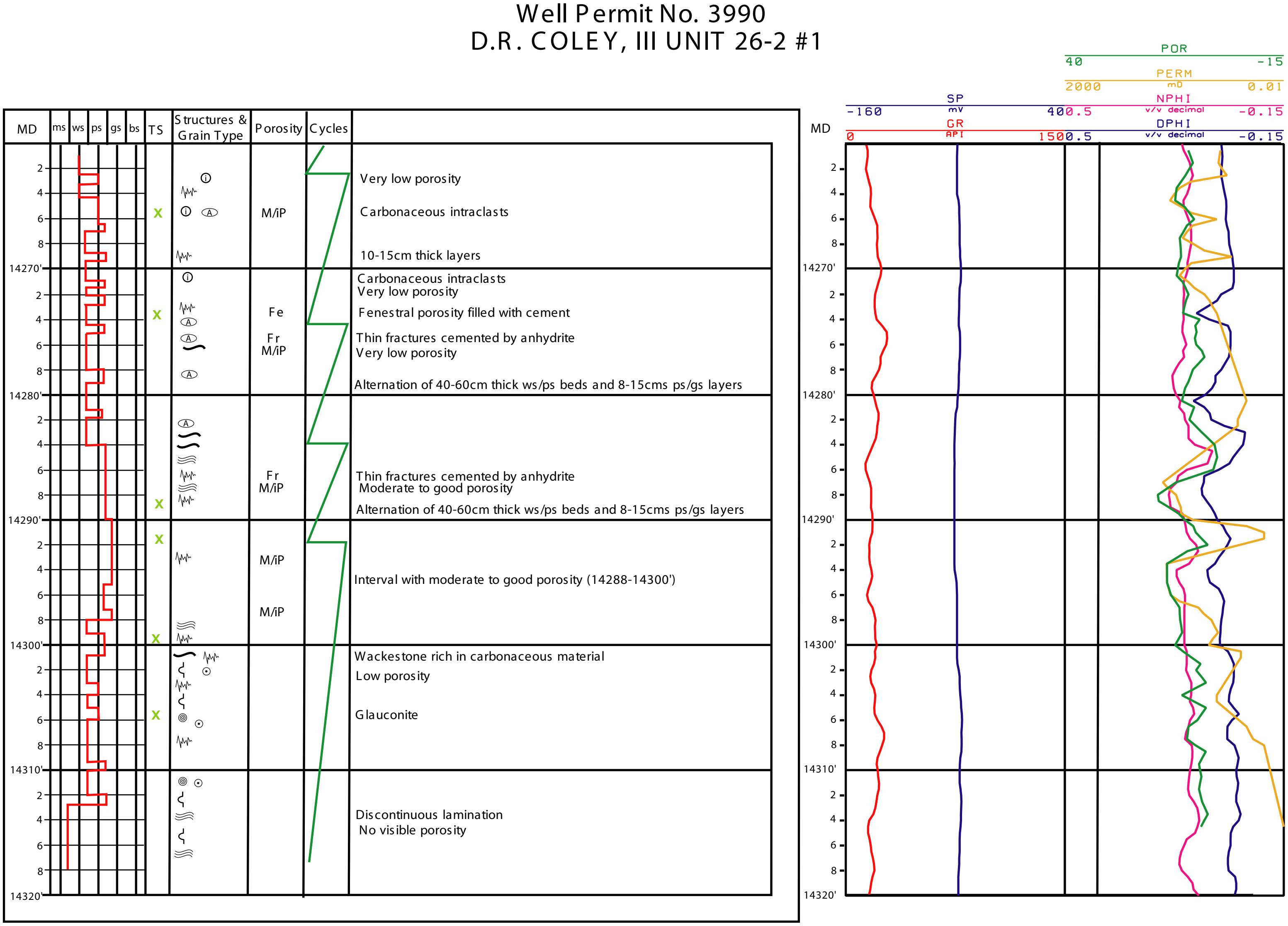


Figure 40. Graphic log for well Permit # 3739. By J. C. Llinas.



Note: The core is coated by drilling mud, therefore the descriptions are not very reliable. Thin sections must be done to confirm and improve them.

Figure 41. Graphic log for well Permit # 3990.
By J. C. Llinas.

Well Permit No. 5779
NEUSCHWANDER 34-3 #1

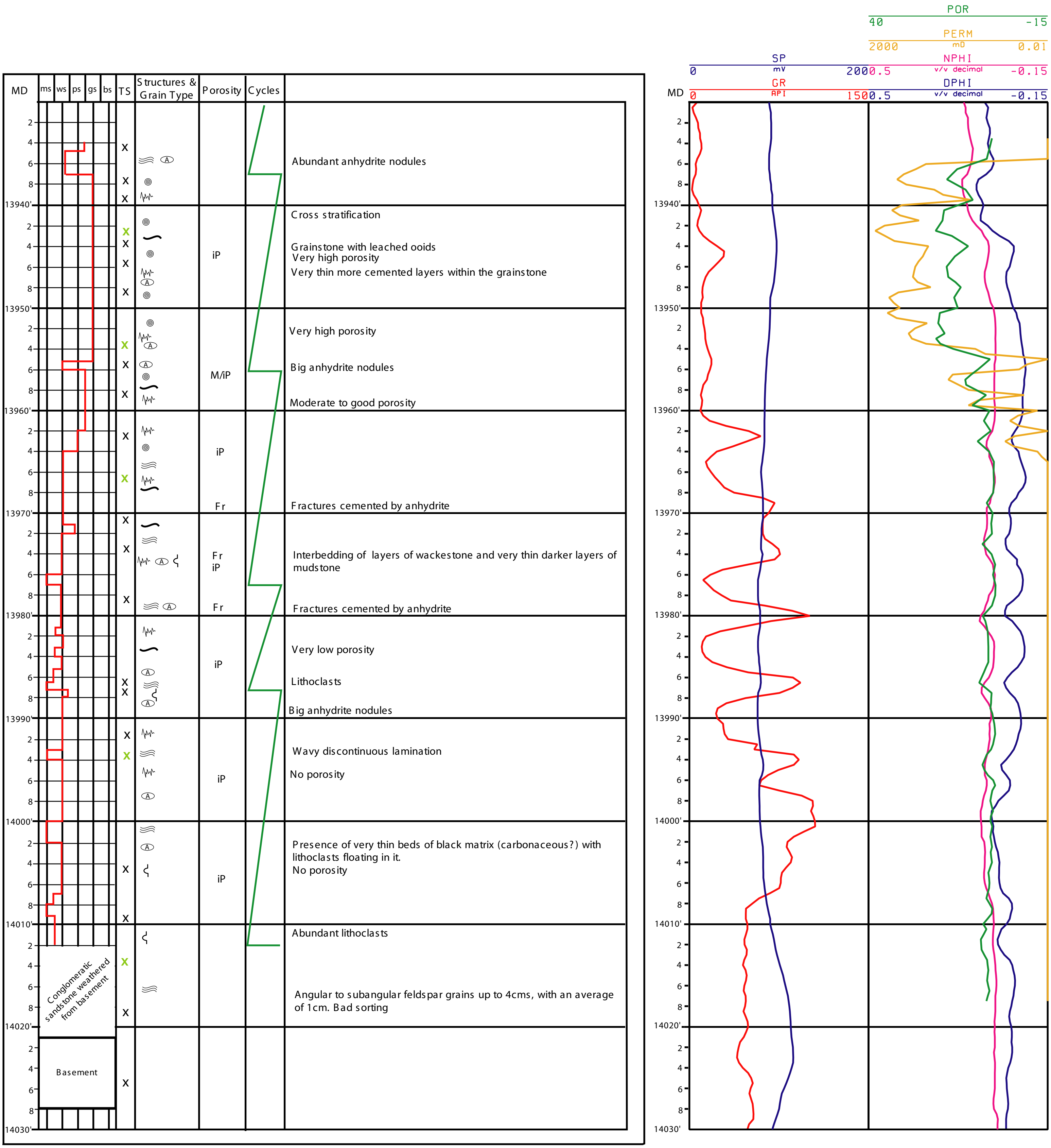


Figure 42. Graphic log for well Permit # 5779. By J. C. Llinas.

Well Permit No. 7588B
BLACKSHER 27-11 #1

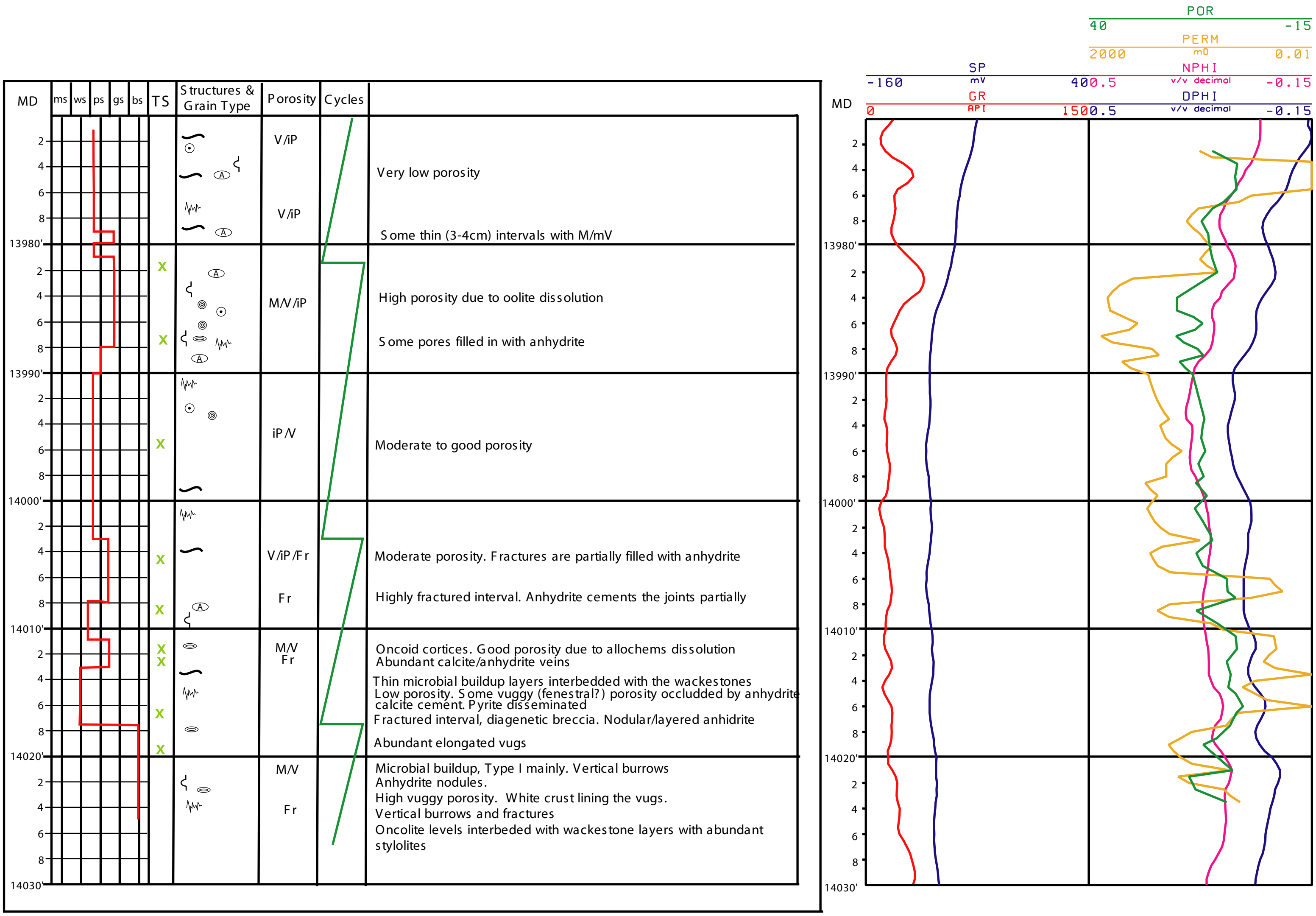


Figure 43. Graphic log for well Permit # 7588B.
By J. C. Llinas.

Table 4. Characterization of Smackover Lithofacies in the Vocation Field Area.

Lithofacies	**Lithology**	**Allochems**	**Pore Types**	**Porosity (percent)**	**Permeability (md)**
ooid-dominated, grain-supported (grainstone/packstone)	dolostone, limestone	ooids, oncoids, peloids	moldic, interparticulate, intercrystalline	high (1.5-28.3)	high (0-2,230)
ooid-dominated, matrix-supported (wackestone)	dolostone	ooids, oncoids, peloids	moldic	moderate (1.2-14.0)	moderate (0-8)
oncoid-dominated grain-supported (grainstone/packestone)	dolostone	oncoids, peloids, ooids, intraclasts	interparticulate, moldic, vuggy	high (1.6-20.1)	high (0-1,635)
oncoid-dominated matrix-supported (wackestone)	dolostone	oncoids, peloids	vuggy, moldic	low (2.5-8.3)	low (0-0.39)
peloid-dominated grain-supported (grainstone/packestone)	dolostone, limestone	peloids, oncoids, ooids	interparticulate, intercrystalline, vuggy	high (0.8-25.6)	high (0-587)
peloid-dominated matrix-supported (wackestone)	dolostone, anhydritic dolostone	peloids, oncoids	intercrystalline	moderate (1.0-18.2)	moderate (0-39)
mudstone	dolostone, limestone	none	fracture	low (1.2 to 8.8)	low (<0.01)
algal stromatolite (boundstone)	dolostone	algae, peloids, oncoids	fracture, vuggy, fenestral	low (1.1-8.8)	moderate (0-16)
algal boundstone	dolostone	algae, peloids, oncoids	vuggy, fracture, breccia, moldic	high (3.0-33.6)	high (0-2,998)

will involve an expansion of previous general studies of diagenesis within the Smackover and will identify those diagenetic processes that have influenced reef and shoal carbonates in paleohigh reservoirs using Appleton and Vocation Fields as models. This work will document the impact of cementation, compaction, dolomitization, dissolution and neomorphism on reef and shoal reservoirs. A detailed paragenetic sequence will be constructed for reservoir lithologies in each field to document the diagenetic history of these lithologies and to determine the timing of each individual diagenetic event. Attention will be focused on spatial variation in diagenesis within each field and also in variations in diagenesis between fields. The influence of paleohigh relief on diagenesis will be identified. This work will incorporate petrographic, XRD, SEM, and microprobe analyses to characterize, on a microscopic scale, the nature of the pore system in the Appleton and Vocation reservoirs. This task will focus on the evolution of the pore systems through time and on the identification of those diagenetic processes that played a significant role in the development of the existing pore systems. The ultimate goal of the task is to provide a basis for characterization of porosity and permeability with the reef and shoal reservoirs.

Thin sections (379) are being studied from 11 cores from Appleton Field to determine the impact of cementation, compaction, dolomitization, dissolution and neomorphism has had on the reef and shoal reservoirs in this field. Thin sections (237) are being studied from 11 cores from Vocation Field to determine the paragenetic sequence for the reservoir lithologies in this field. An additional 73 thin sections are being prepared from the shoal and reef lithofacies in Vocation Field to identify the diagenetic processes that played a significant role in the development of the pore systems in the reservoirs at Vocation Field.

Task 3—Petrophysical and Engineering Property Characterization.--This task will focus on the characterization of the reservoir rock, fluid, and volumetric properties of the reservoirs at Appleton and Vocation Fields. These properties can be obtained from petrophysical and engineering data. This task will assess the character of the reservoir fluids, as well as quantify the petrophysical properties of the reservoir rock. In addition, considerable effort will be devoted to the rock-fluid behavior (i.e., capillary pressure and relative permeability). The production rate and pressure histories will be cataloged and analyzed for the purpose of estimating reservoir properties such as permeability, well completion efficiency (skin factor), average reservoir pressure, as well as in-place and movable fluid volumes. A major goal is to assess current reservoir pressure conditions and develop a simplified reservoir model. New pressure and tracer survey data will be obtained to assess communication within the reservoir at Appleton and Vocation Fields, including among and within the various pay zones in the Smackover. This work will serve as a guide for the reservoir simulation modeling. Petrophysical and engineering data are fundamental to reservoir characterization. Petrophysical data are often considered static (non-time dependent) measurements, while engineering data are considered dynamic (time-dependent). Reservoir characterization is the coupling or integration of these two classes of data. The data are analyzed to identify fluid flow units (reservoir-scale flow sequences), barriers to flow, and reservoir compartments. Petrophysical data are essential for defining the quality of the reservoir, and engineering data (performance data) are crucial for assessing the producibility of the reservoir. Coupling these concepts, via reservoir simulation or via simplified analytical models, allows for the interpretation and prediction of reservoir performance under a variety of conditions. The first phase of the task involves the review, cataloging, and analysis of available core measurements and well log data. This information will be used to classify porosity, permeability, oil and water saturations, grain density, hydrocarbon show, and rock type for each foot of core. Core data will be correlated to the well log responses, and porosity-permeability relationships will be established for each lithofacies evident in the available data. The next phase involves the measurement of basic relative permeability and capillary pressure relations for the reservoir from existing cores. These data will be compiled and analyzed and then used for reservoir simulation and waterflood/enhanced oil recovery calculations. The third phase focuses on the collection and cataloging of fluid property (PVT) data. In particular, basic (black oil) fluid property data are available, where these analyses include standard measurements of gas-oil-ratio (GOR), oil gravity, viscosity, and fluid composition. The objective of the fluid property characterization work is to develop relations for the analysis of well performance data and for reservoir simulation. The final phase will be to develop a performance-based reservoir characterization of Appleton and Vocation Fields. This phase will focus exclusively on the analysis and interpretation of well performance data as a mechanism to predict recoverable fluids and reservoir properties. This analysis will focus on the production data, but any other well performance data will also be considered, in particular, pressure transient test data and well completion/stimulation data will also be analyzed and integrated into the reservoir description. Historical pressure data will be compared to new pressure and tracer survey data for wells obtained as part of this work. The material balance decline type curve analysis will be emphasized for the analysis of the data.

Petrophysical and engineering property data are being gathered and tabulated. The production history for Appleton Field and the production history for Vocation and South Vocation Fields have been obtained and graphed (Figures 44 and 45). Water and oil saturation data for core analyses for Appleton Field have been plotted on Figures 46 through 50. Porosity versus permeability cross plots for wells in the fields have been prepared (Figures 51 through 54). Porosities from core analyses have been calibrated with porosities determined from well log studies (Figures 33 through 43 and Figures 55 through 58).

Task 4—Data Integration.--This task will integrate the geological, geophysical, petrophysical and engineering data into a comprehensive digital database for reservoir characterization, modeling and simulation. Separate databases will be constructed for Appleton and Vocation Fields. This task serves as a critical effort to the project because the construction of a digital database is an essential tool for the integration of large volumes of data. This task also serves as a means to begin the process of synthesizing concepts. The task will involve entering geologic data and merging these data with geophysical imaging information. Individual well logs will serve as the standard from which the data are entered and compared. The data will be entered at 1-foot intervals. All well logs in the fields will be utilized. The researchers will resolve any apparent inconsistencies among data sets through an iterative approach. This task also will involve entering petrophysical data, rock and fluid property data, production data, including oil, gas and water production, and well completion data, including perforated intervals, completion parameters, well

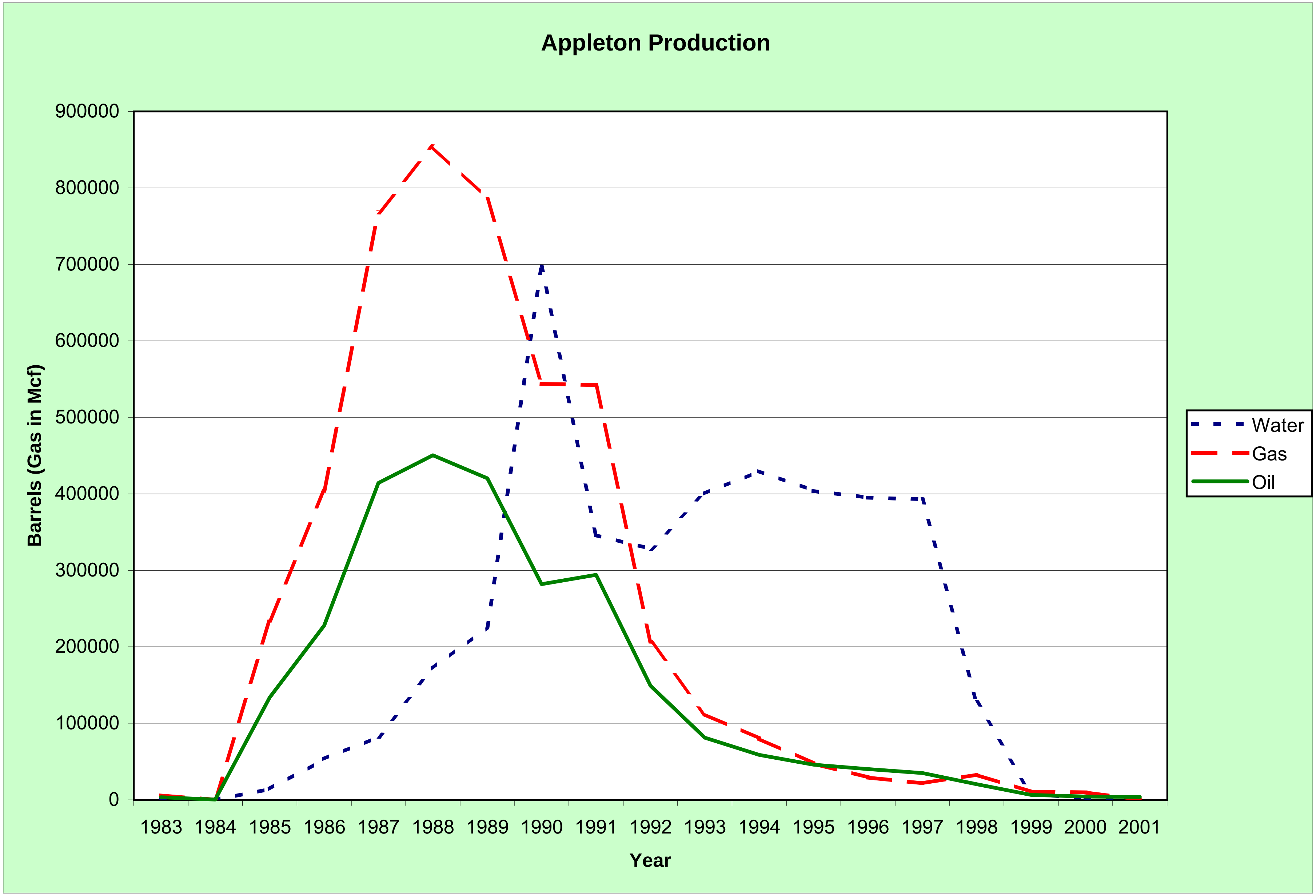


Figure 44. Production history for Appleton Field.
By B. J. Panetta.

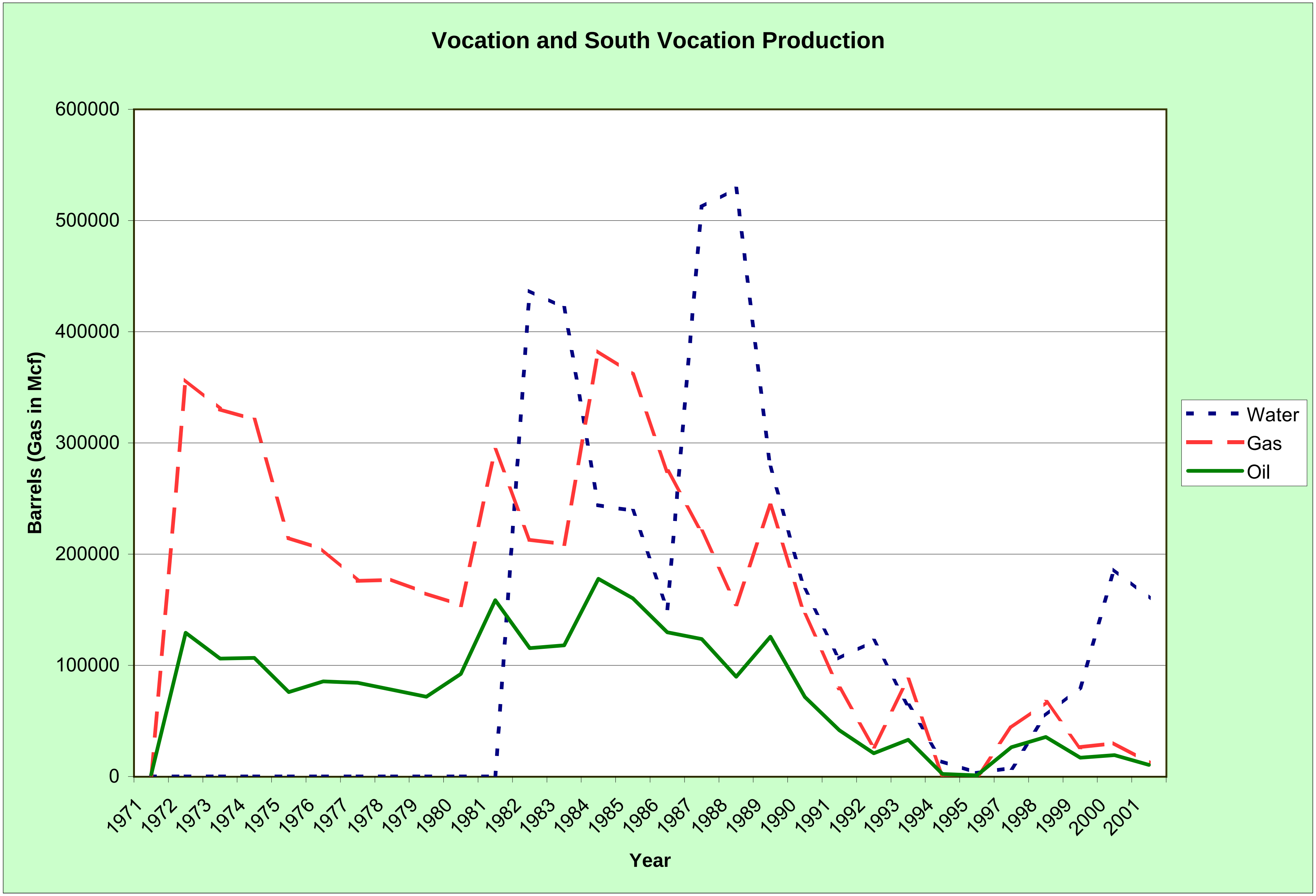


Figure 45. Production history for Vocation and South Vocation Fields.
By B. J. Panetta.

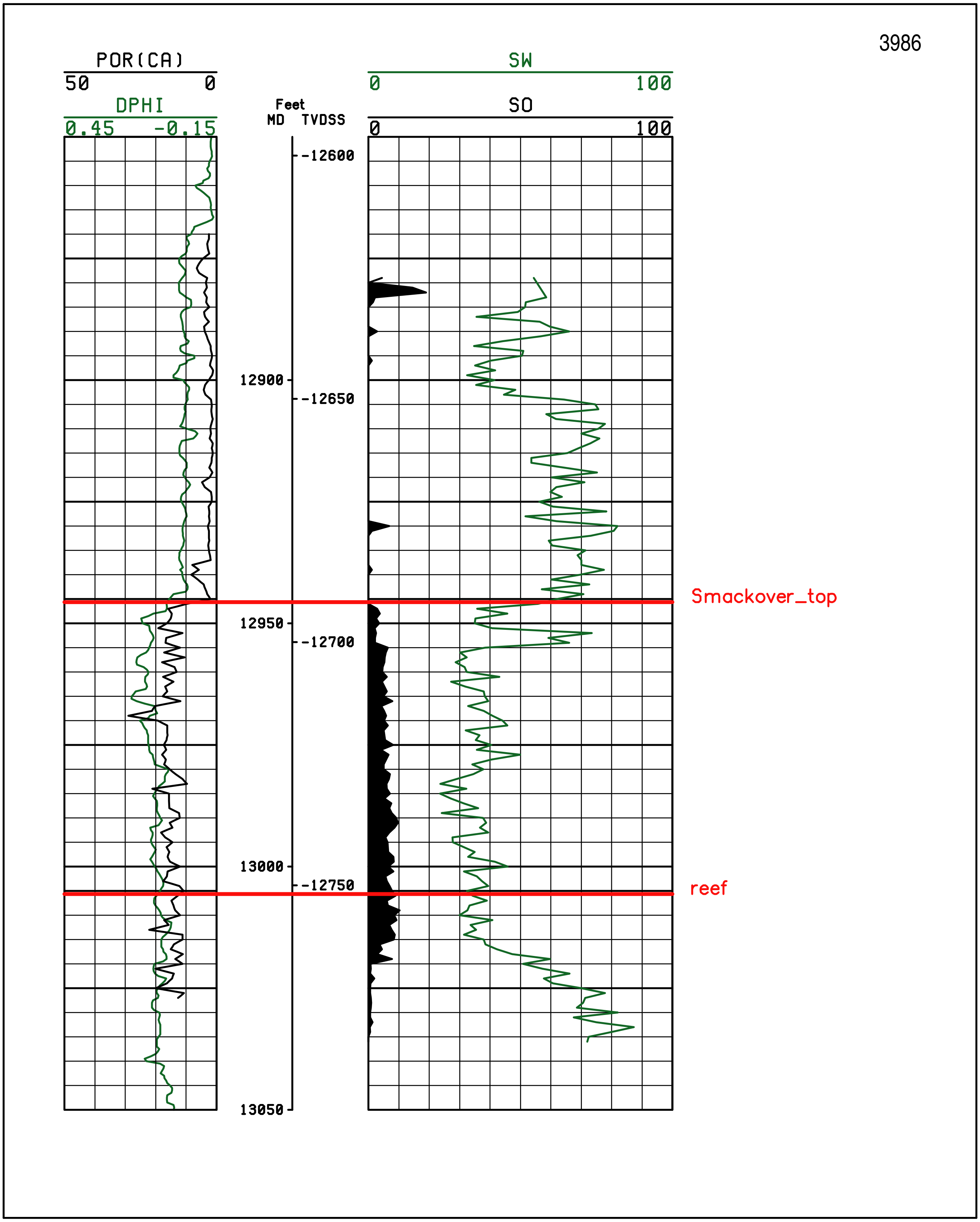


Figure 46. Vertical plot of water saturation and oil saturation data for well permit # 3986.
By Brian Panetta.

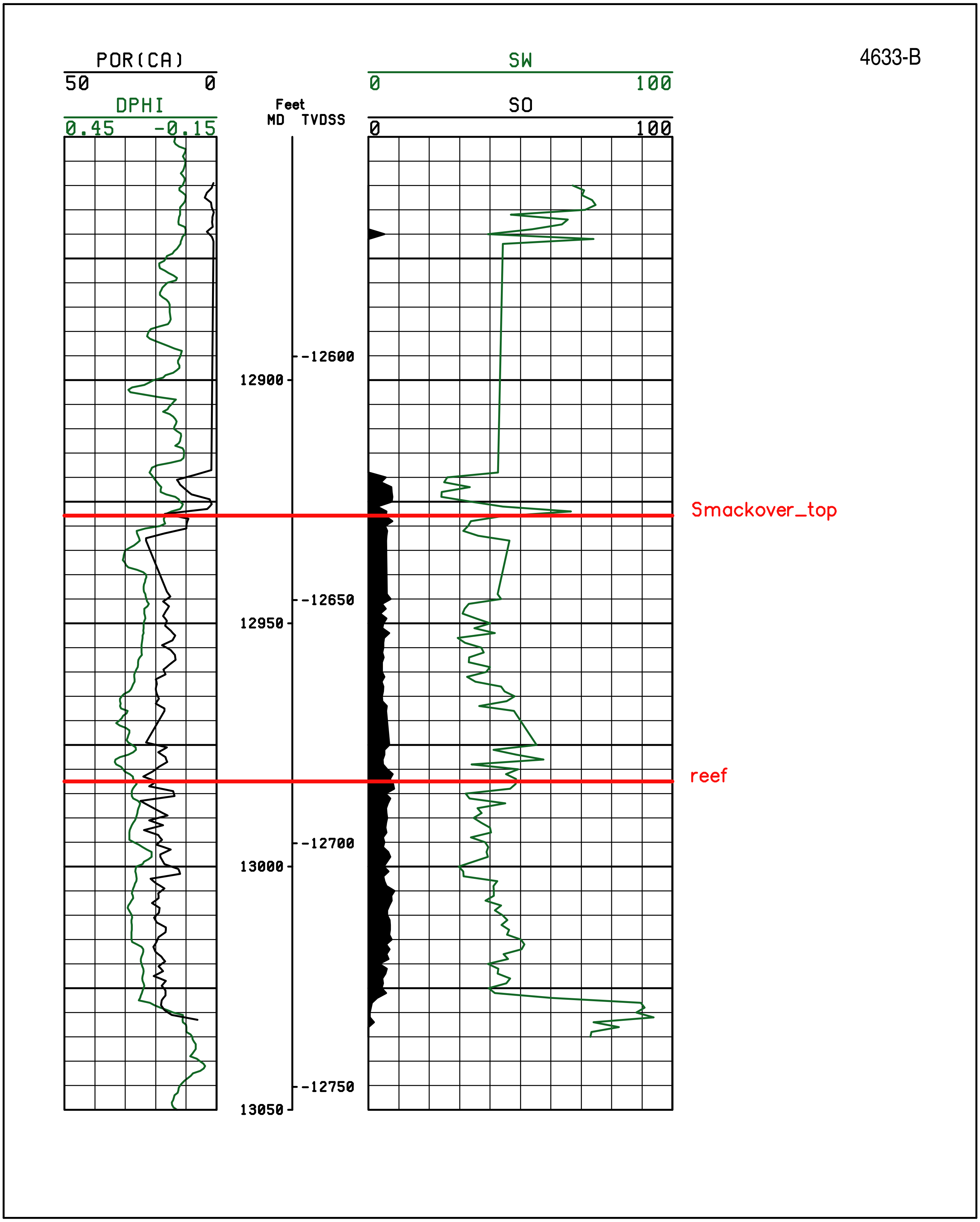


Figure 47. Vertical plot of water saturation and oil saturation data for well permit # 4633-B. By Brian Panetta.

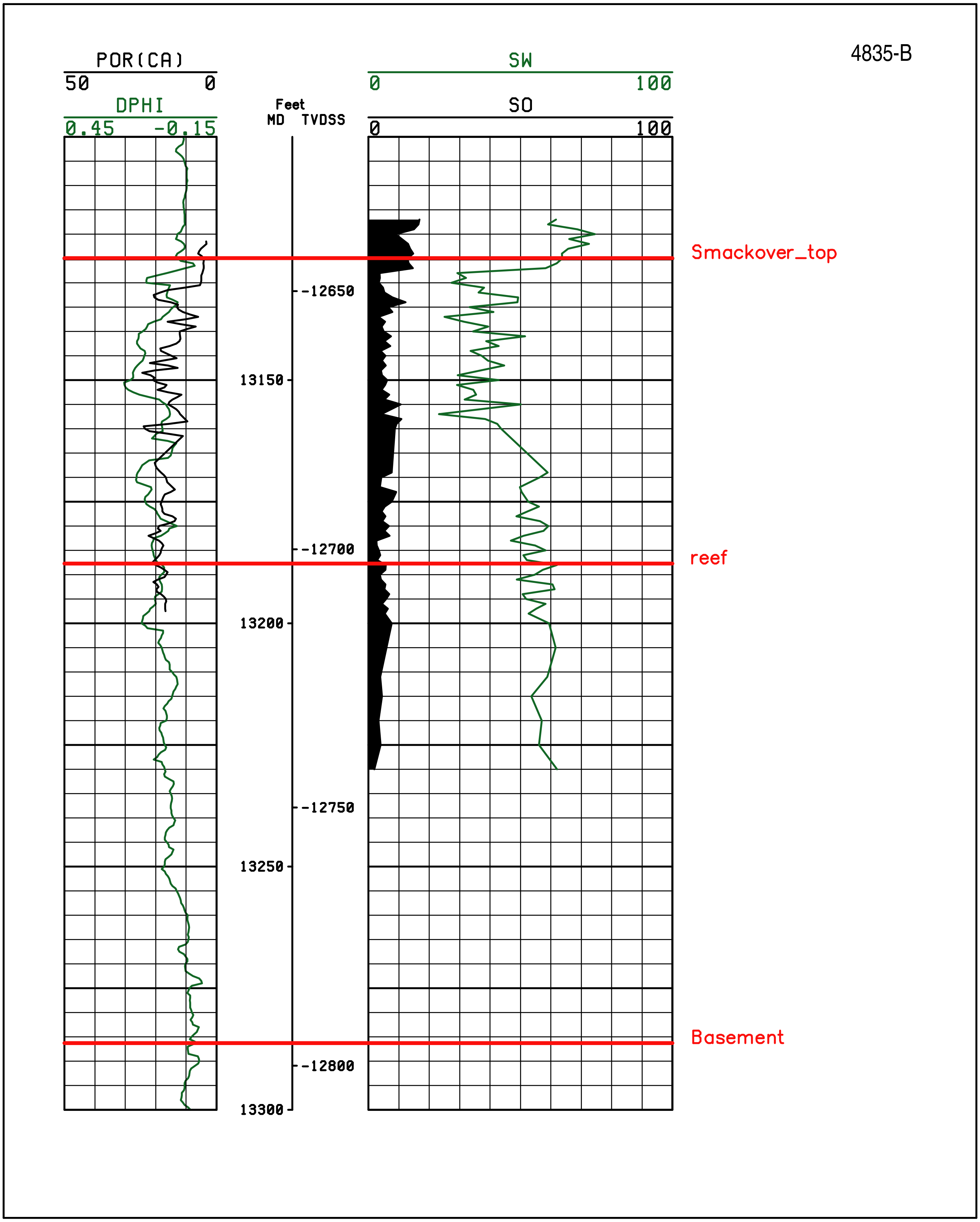


Figure 48. Vertical plot of water saturation and oil saturation data for well permit # 4835-B.
By Brian Panetta.

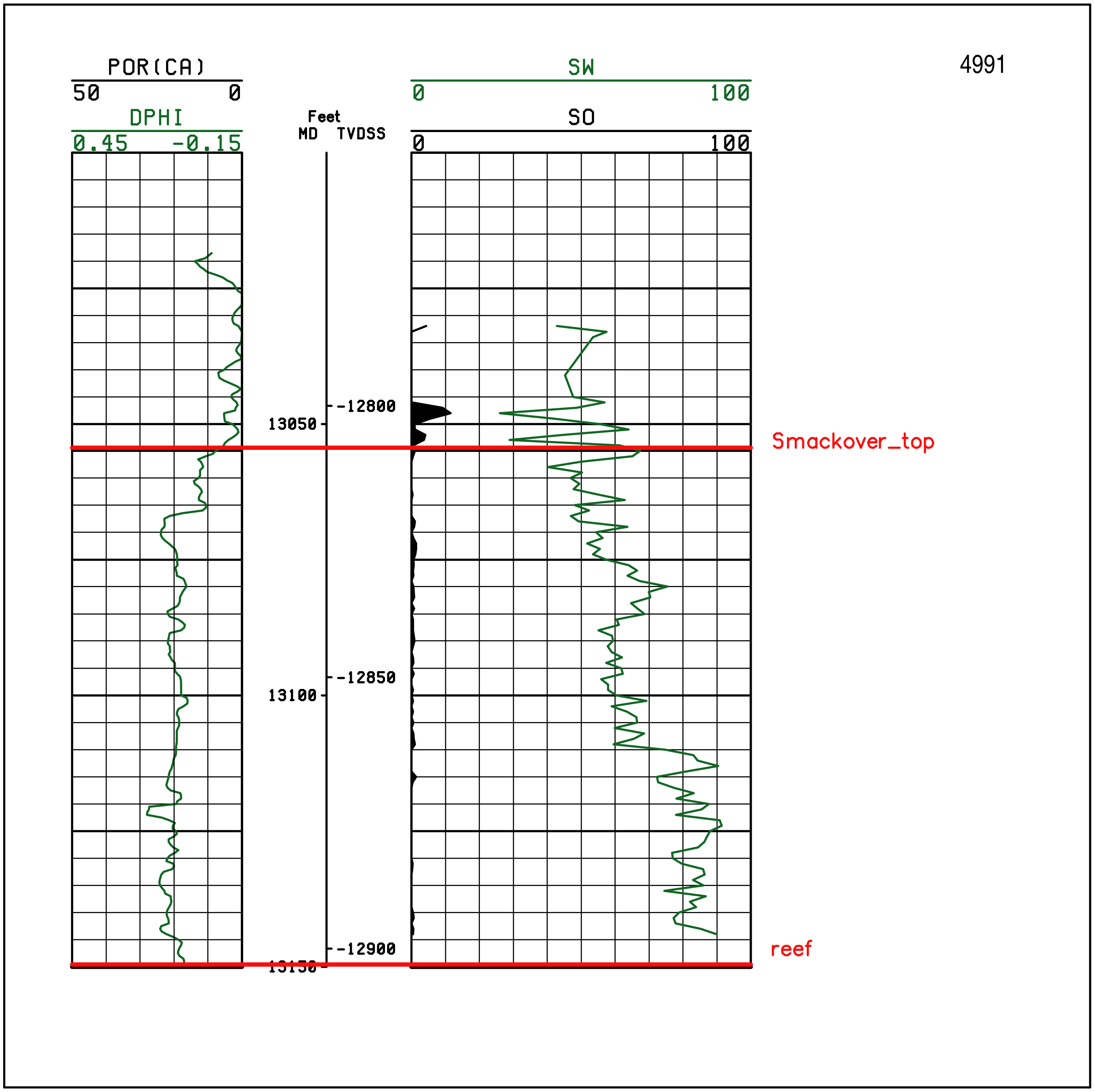


Figure 49. Vertical plot of water saturation and oil saturation data for well permit # 4991.
By Brian Panetta.

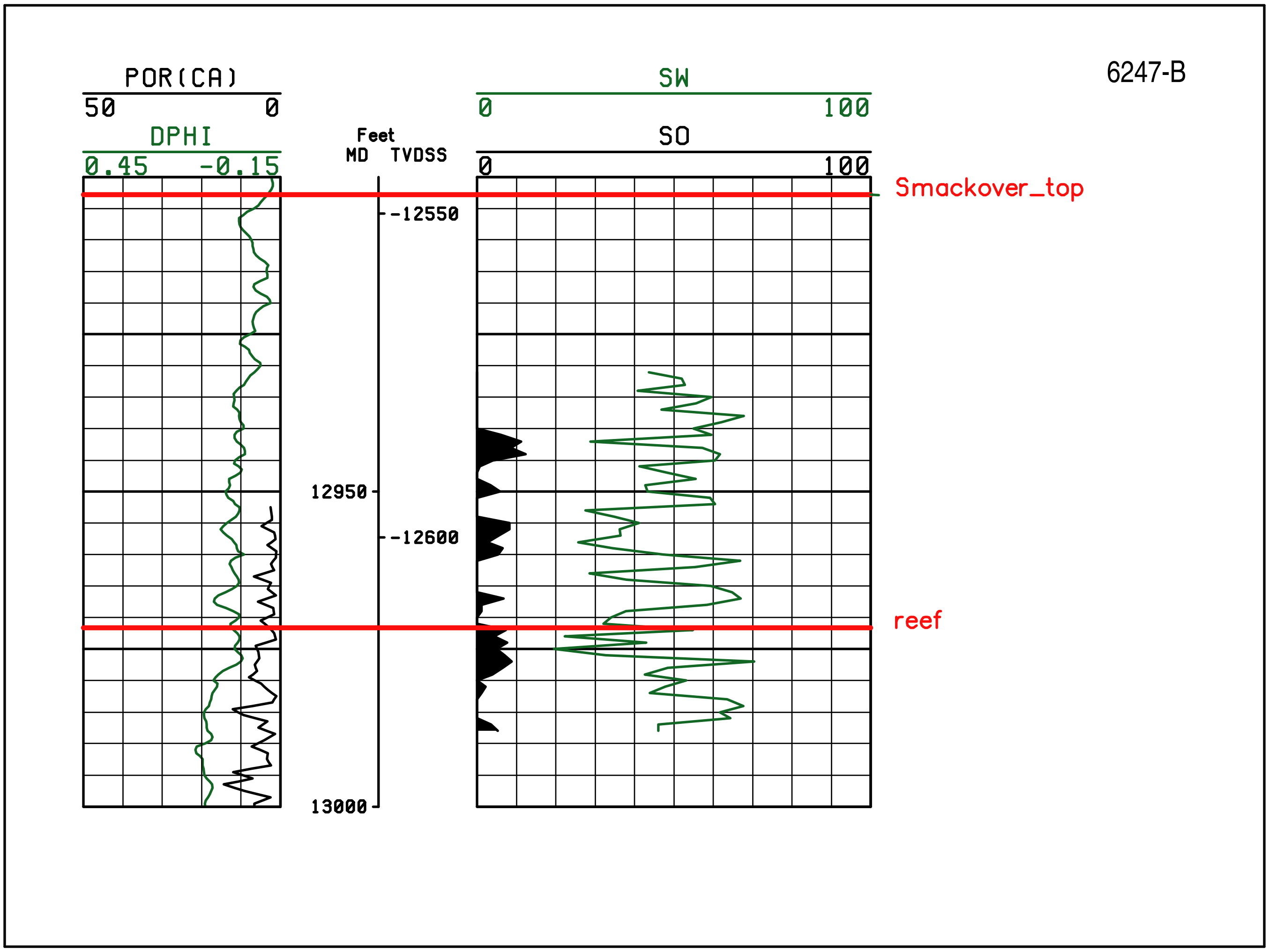


Figure 50. Vertical plot of water saturation and oil saturation data for well permit # 6247-B.
By Brian Panetta.

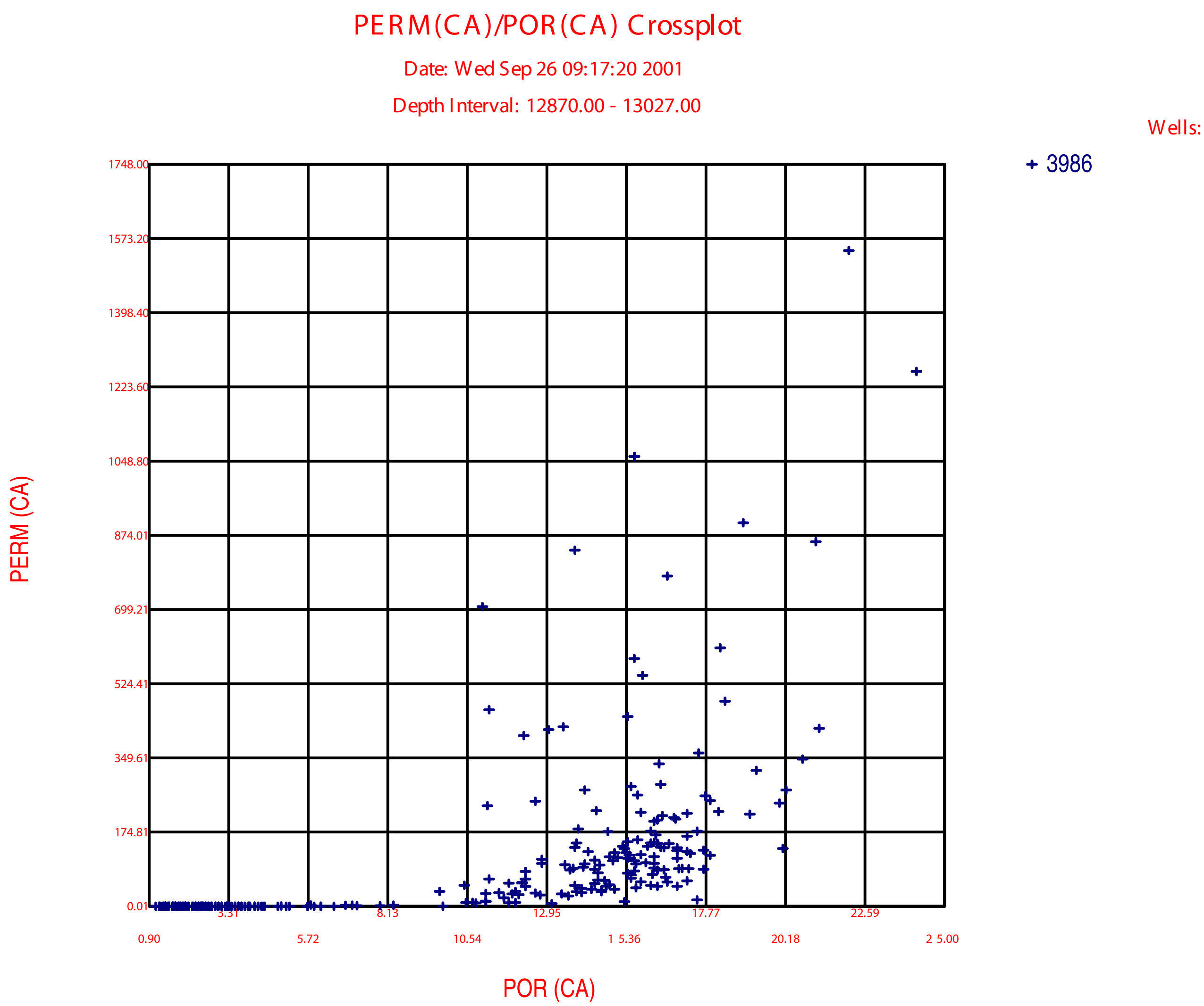


Figure 51. Cross plots of porosity versus permeability for well permit # 3986.
By Brian Panetta.

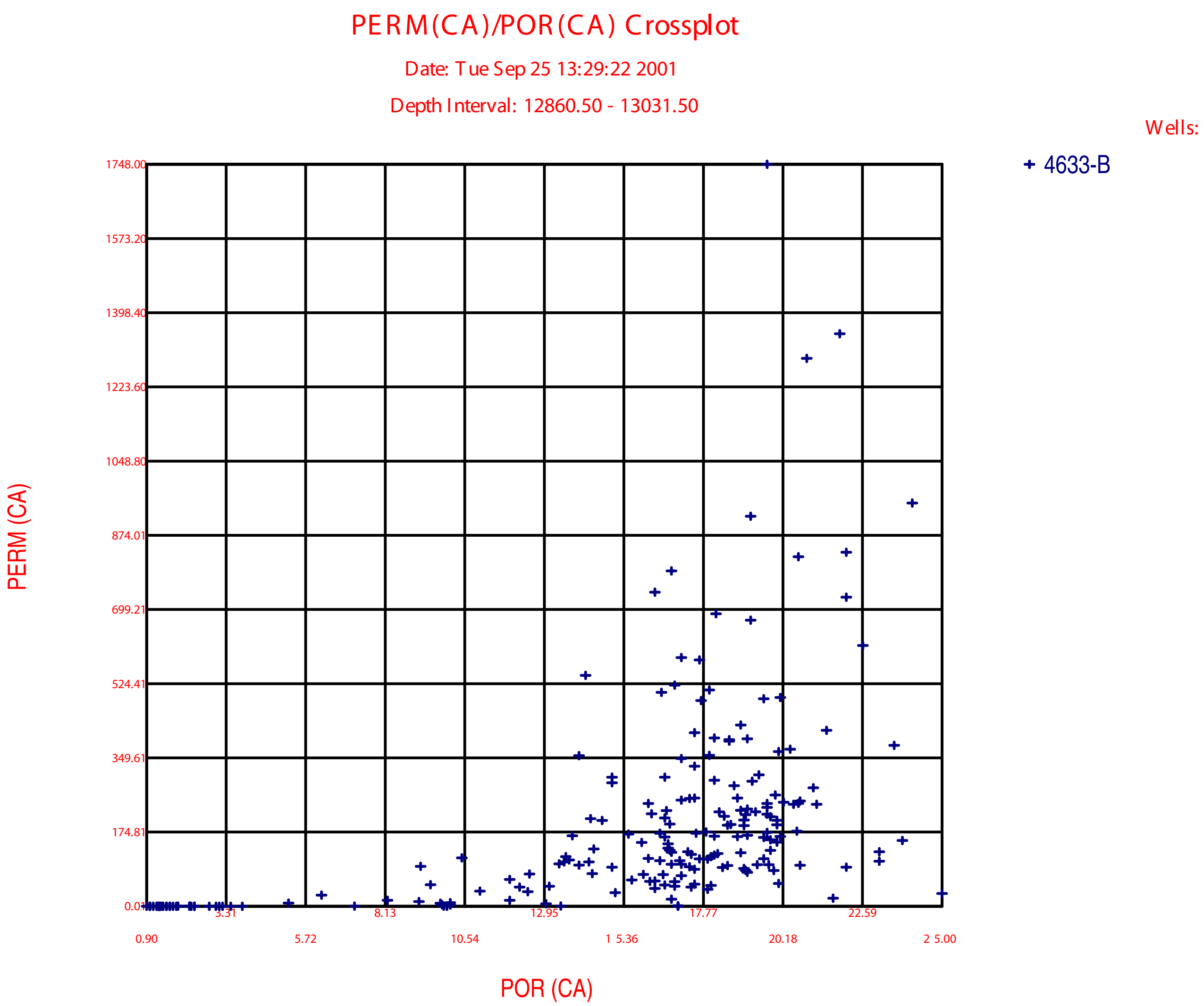


Figure 52. Cross plots of porosity versus permeability for well permit # 4633-B.
By Brian Panetta.

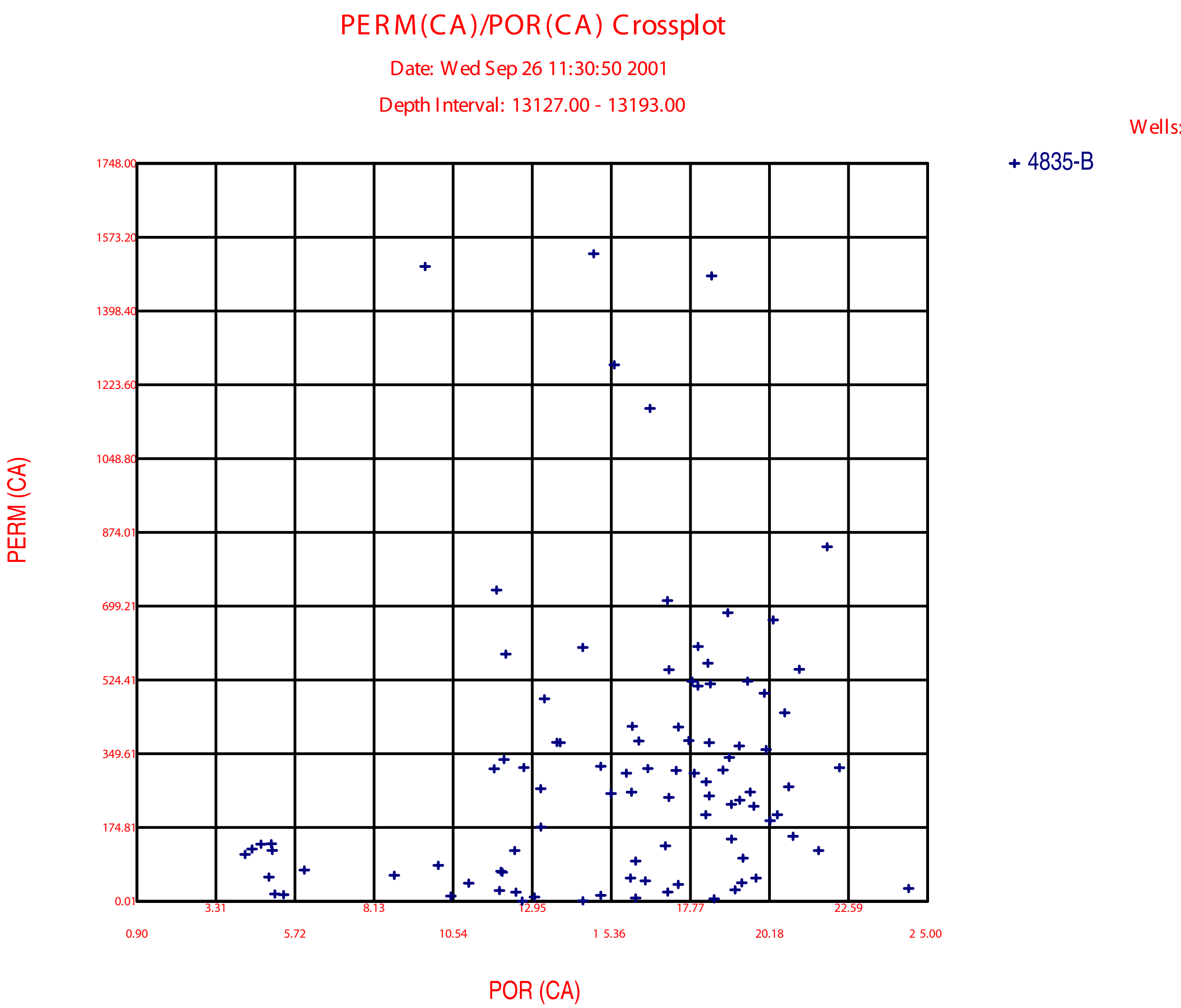


Figure 53. Cross plots of porosity versus permeability for well permit # 4835-B.
By Brian Panetta.

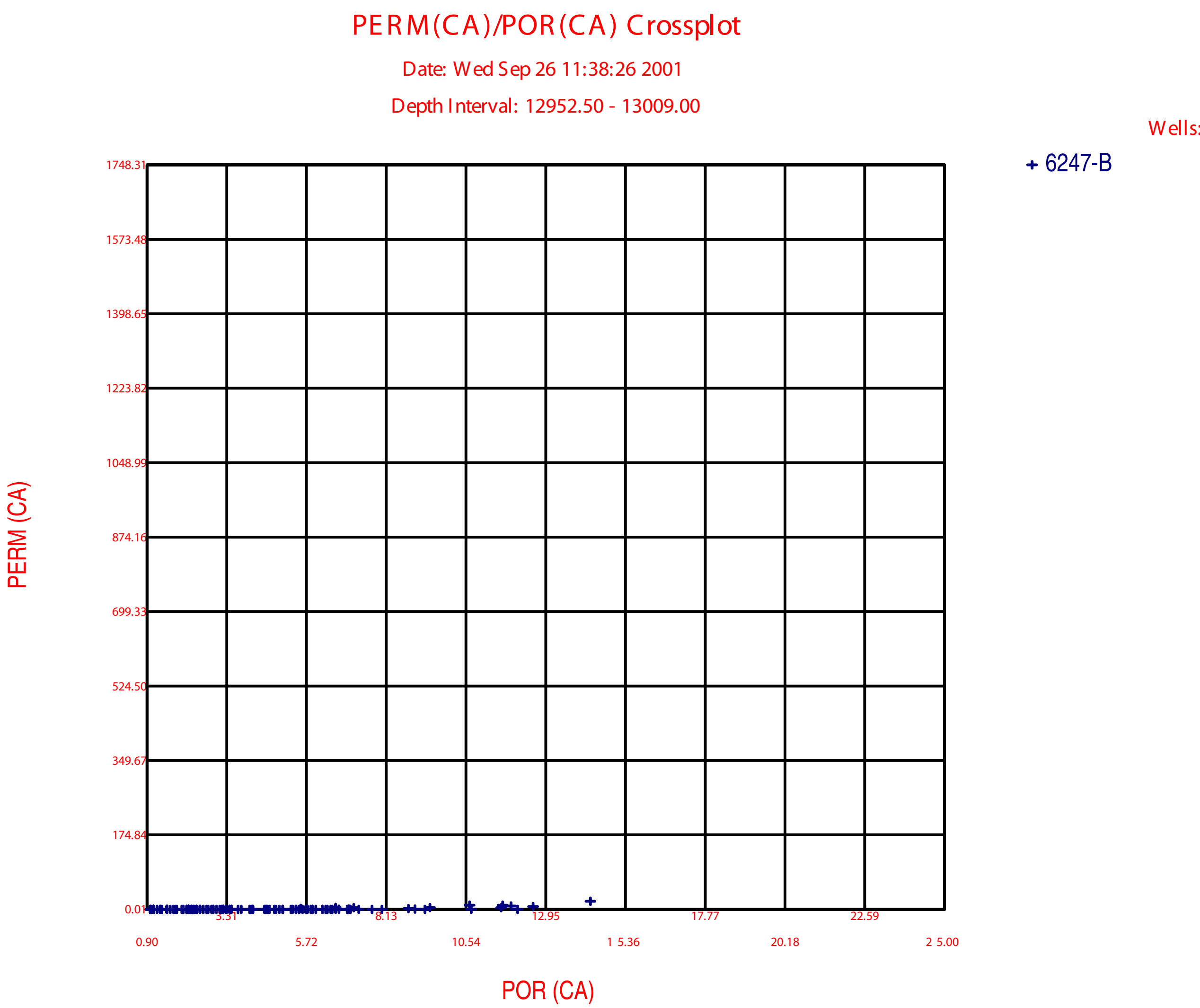


Figure 54. Cross plots of porosity versus permeability for well permit # 6247-B.
By Brian Panetta.

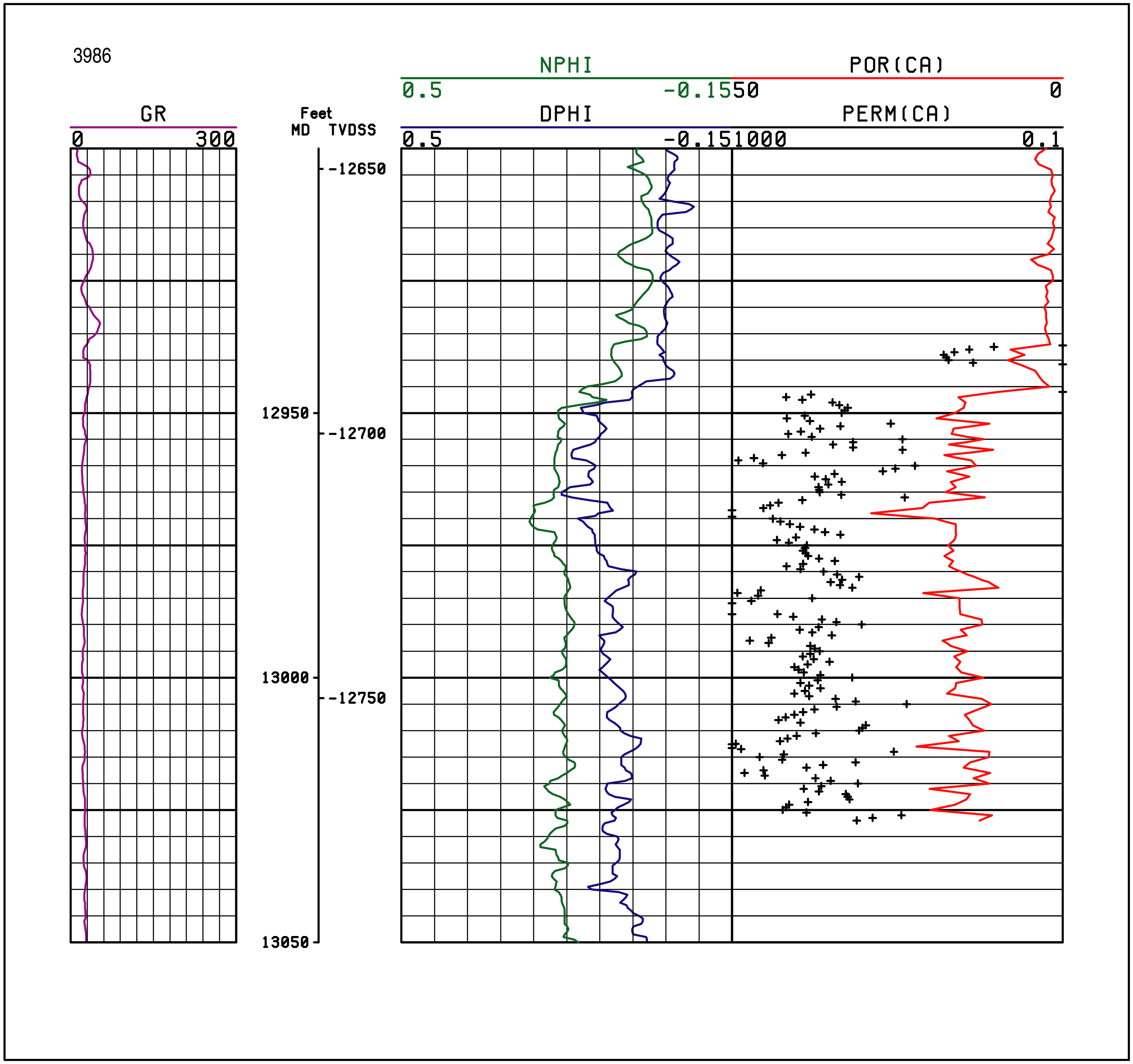


Figure 55. Porosity calibrated plot for well permit # 3986.

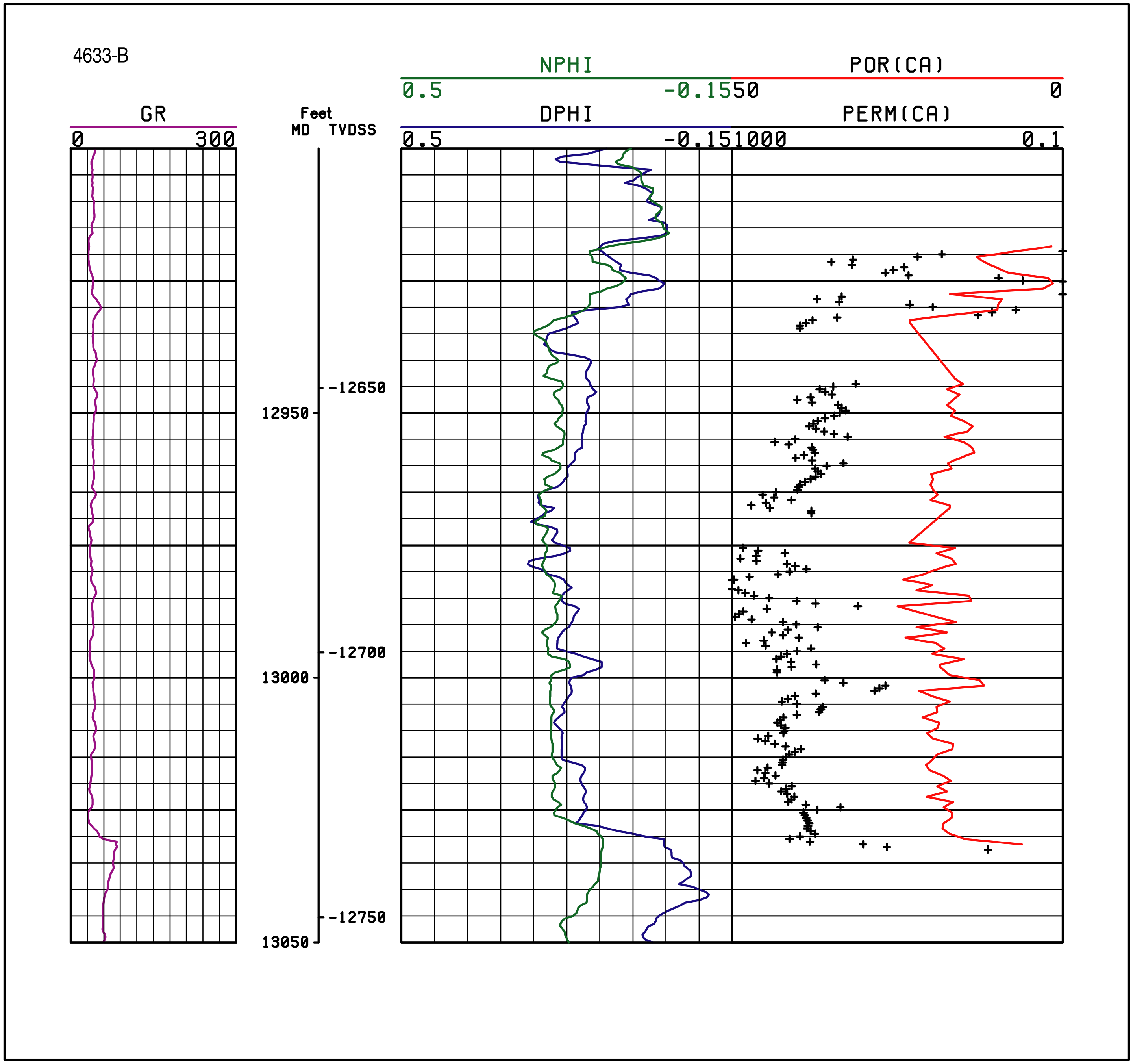


Figure 56. Porosity calibrated plot for well permit # 4633-B.

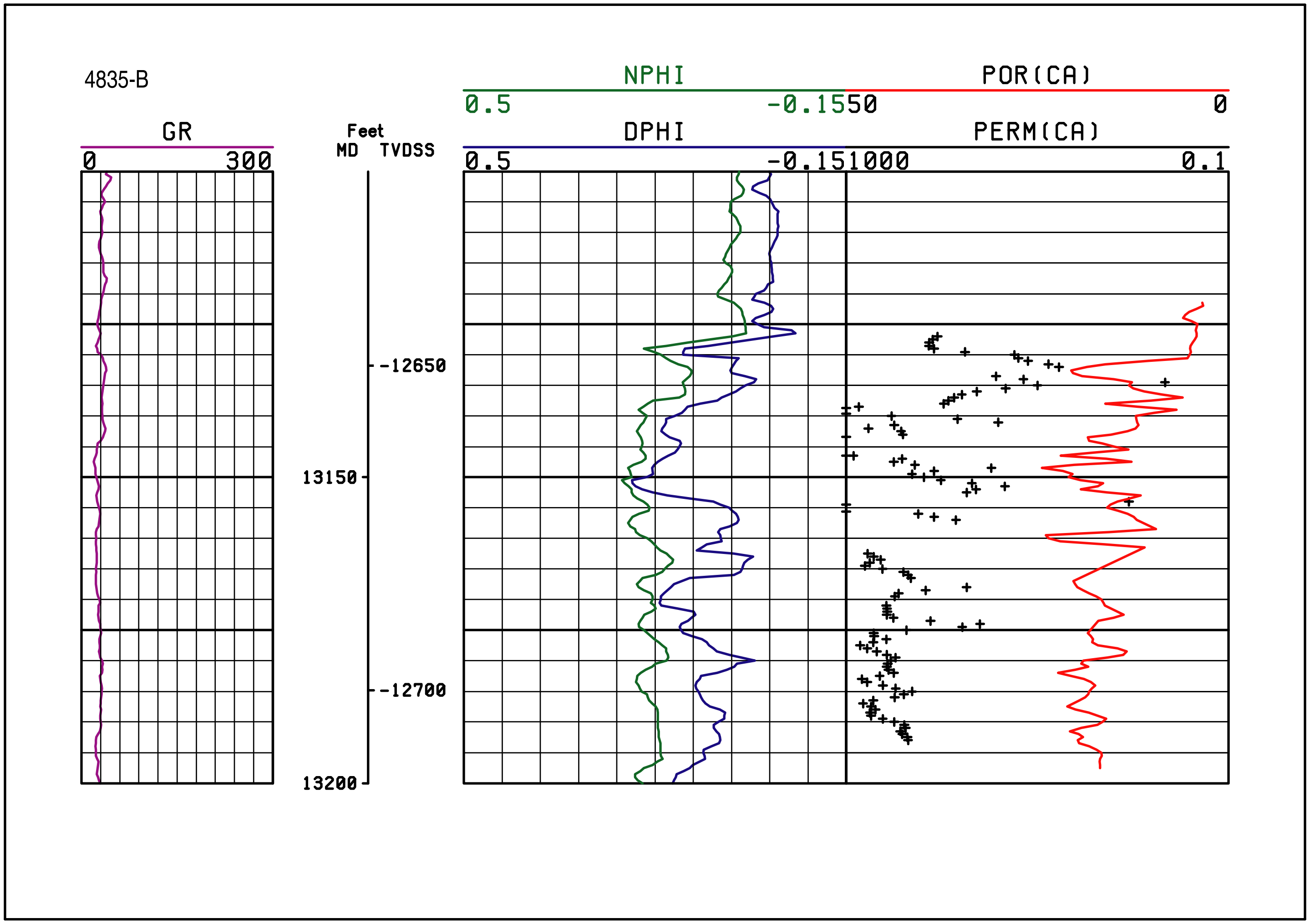


Figure 57. Porosity calibrated plot for well permit # 4835-B.

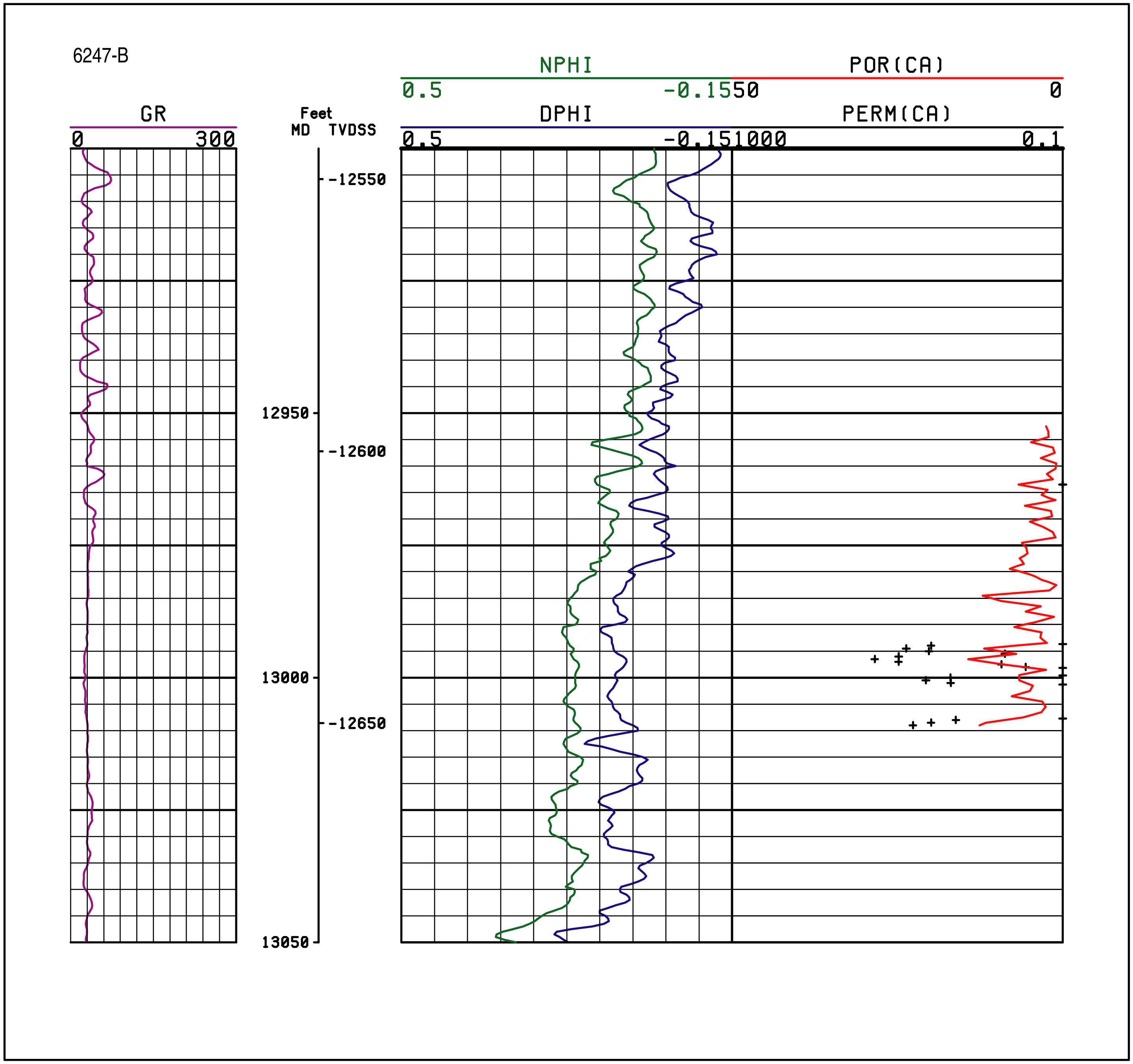


Figure 58. Porosity calibrated plot for well permit # 6247-B.

stimulation information, etc. A validation effort will be conducted to resolve any apparent inconsistencies among data sets through an iterative approach.

All geoscientific and petrophysical data generated to date from this study have been entered and integrated into digital databases for Appleton and Vocation Fields for reservoir characterization, modeling and simulation.

Work Planned for Year 2

Reservoir Description and Characterization (Phase 1)

Task 2—Rock-Fluid Interactions.--Work on this task will continue into Year 2 (Table 5).

Task 3—Petrophysical and Engineering Property Characterization.--Work on this task will continue into Year 2.

Task 4—Data Integration.--Data resulting from Tasks 2 and 3 will be integrated into the digital databases for Appleton and Vocation Fields during Year 2 of the project.

3-D Modeling (Phase 2)

Task 5—3-D Geologic Model.--This task involves using the integrated database which includes the information from the reservoir characterization tasks to build a 3-D stratigraphic and structural model(s) for Appleton and Vocation Fields. For Appleton Field, the existing, but independently completed, geological and geophysical studies will be integrated and used in combination with the new information from the drilling and producing of the sidetrack well in the field and from the study of the additional five cores and additional 3-D seismic data from the field area to revise, as needed, the current Appleton geologic model. The Appleton reef-shoal paleohigh (low-relief) model will be applied to Vocation Field (high-relief paleohigh). The application of the Appleton model to Vocation Field could result in the Appleton model being reasonable for modeling the Vocation reservoir or could result in the need to modify the Appleton model to honor the characteristics of the Vocation reservoir and structure. The result, therefore, could be a single geologic model for reef-shoal reservoirs associated with basement paleohighs of varying degrees of relief or two geologic models—one for reef-shoal reservoirs associated with low-relief paleohighs and one for reef-shoal reservoirs associated with high-relief paleohighs. This task also provides the

Table 5. Milestone Chart—Year 2.

Tasks	S	O	N	D	J	F	M	A	M	J	J	A
Reservoir Characterization												
Task 2—Rock Fluid Interactions	■	■	■	■	■	■						
Task 3—Petrophysical & Engineering Characterization	■	■	■	■	■	■						
Task 4—Data Integration	■	■	■	■	■	■						
3-D Modeling												
Task 5—3-D Geologic Modeling	■	■	■	■	■	■						
Task 6—3-D Reservoir Simulation Model							■	■	■	■	■	■
Technology Transfer												
Task 10—Workshop											■	■
Technical Report												
Annual Report											■	■

■ Work Planned
xxxxx Work Accomplished

framework for the reservoir simulation modeling in these fields. Geologic modeling sets the stage for reservoir simulation and for the recognition of flow units, barriers to flow and flow patterns in the respective fields. Sequence stratigraphy in association with structural interpretation will form the framework for the model(s). The model(s) will incorporate data and interpretations from sequence stratigraphic, depositional history and structural studies, core and well log analysis, petrographic and diagenetic studies, and pore system and petrophysical analysis. The model(s) will also incorporate the geologic observations and interpretations made from studying stratigraphic and spatial lithofacies relationships observed in Late Jurassic microbial reefs in outcrops. The purpose of the 3-D geologic model(s) is to provide an interpretation for the interwell distribution of systems tracts, lithofacies, and reservoir-grade rock. This work is designed to improve well-to-well predictability with regard to reservoir parameters, such as lithofacies, diagenetic rock-fluid alterations, pore types and systems, and heterogeneity. The geologic model(s) and integrated database become effective tools for cost-effective reservoir management for making decisions regarding operations in these fields. Accepted industry software, such as Stratamodel and GeoSec, will be used to build the 3-D geologic model(s). GeoSec software will be used in the 3-D structural interpretation and Stratamodel software will be used to construct the geologic model(s).

Task 6—3-D Reservoir Simulation Model.--This task focuses on the construction, implementation and validation of a numerical simulation model(s) for Appleton and Vocation Fields that is based on the 3-D geologic model(s), petrophysical properties, fluid (PVT) properties, rock-fluid properties, and the results of the well performance analysis. The geologic model(s) will be coupled with the results of the well performance analysis to determine flow units, as well as reservoir-scale barriers to flow. Reservoir simulation will be performed separately for cases of the Appleton and Vocation Fields to determine if a single simulation model can represent these reef-shoal reservoirs. However, because these reservoirs are associated with basement paleohighs of varying degrees of relief, two simulation models may be required—one for reef-shoal reservoirs associated with low-relief paleohighs (Appleton) and one for reef-shoal reservoirs associated with high-relief paleohighs (Vocation). The purpose of this work is to validate the reservoir model with history-matching, then build forecasts that consider the following scenarios: 1) base case (continue field management as is); 2) optimization of production practices (optimal well completions, including stimulation); 3) active reservoir management (new replacement and development wells); and 4) initiation of new recovery methodologies (targeted infill drilling program and/or possible enhanced oil recovery scenarios). The purposes of reservoir simulation are to forecast expected reservoir performance, to forecast ultimate recovery, and to evaluate different production development scenarios. We will use reservoir simulation to validate the reef-shoal reservoir model, then extend the model to predict performance for a variety of scenarios (as listed above). Our ultimate goals in using reservoir simulation are to establish the viability of a simulation model for a particular reservoir, then make optimal performance predictions. Probably the most important aspect of the simulation work will be the setup phase. The Smackover is well known as a geologically complex system, and our ability to develop a representative numerical model for both the Appleton and Vocation Fields is linked not only to the engineering data, but also to the geological, petrophysical, and geophysical data. We expect to gain considerable understanding regarding carbonate reservoir architecture and heterogeneity, especially with regard to large-scale fluid flow from our reservoir simulation work.

This task requires a setup phase which will be performed in conjunction with the creation and validation of the integrated reservoir description. However, this work has more specific goals than simply building the reservoir simulation model; considerable effort will go into the validation of the petrophysical, fluid (PVT), and rock-fluid properties in order to establish a benchmark case, as well as bounds (uncertainty ranges) on these data. In addition, well performance data will be thoroughly reviewed for accuracy and appropriateness.

The history matching phase in this task will involve refining and adjusting data similar to previous tasks, but in this work our sole focus will be to establish the most representative numerical model for both the Appleton and Vocation Fields. Adjustments will undoubtedly be made to all data types, but as a means to ensure appropriateness, these adjustments will be made in consultation and collaboration with the geoscientists on the technical team. Our goal is to obtain a reasonable match of the model and the field data, and to scale-up the small-scale information (core, logs, etc.) in order to yield a representative reservoir simulation model. We will use a black oil formulation for this work.

RESULTS AND DISCUSSION

The Project Management Team and Project Technical Team are working closely together on this project. This close coordination has resulted in a fully integrated research approach, and the project has benefited greatly from this approach.

Geoscientific Reservoir Characterization

Geoscientific reservoir characterization is essentially completed. The architecture, porosity types and heterogeneity of the reef and shoal reservoirs at Appleton Field and Vocation Fields have been characterized using geological and geophysical data.

The architecture and heterogeneities of reservoirs that are a product of a shallow marine carbonate setting are very complex and a challenge technically to predict. Carbonate systems are greatly influenced by biological and chemical processes in addition to physical processes of deposition and compaction. Carbonate sedimentation rates are primarily a result of the productivity of marine organisms in subtidal environments. In particular, reef-forming organisms are a crucial component to the carbonate system because of their ability to modify the surrounding environments. Reef growth is dependent upon many environmental factors, but one crucial factor is sea-floor relief (paleotopography). In addition, the development of a reef structure contributes to depositional topography. Further, the susceptibility of carbonates to alteration by early to late diagenetic processes dramatically impacts reservoir heterogeneity. Reservoir characterization and the quantification of heterogeneity, therefore, becomes a major task because of the physiochemical and biological origins of carbonates and because of the masking of the depositional rock fabric and reservoir architecture due to dissolution, dolomitization, and cementation. Further, the detection, imaging, and prediction of carbonate reservoir heterogeneity and producibility is difficult because of an incomplete understanding of the lithologic characteristics and fluid-rock dynamics that affect log response and geophysical attributes.

Appleton Field

Based on the description of cores (8) and thin sections (379), 14 lithofacies had been identified previously in the Smackover/Buckner at Appleton Field (Table 2). Analysis of the vertical and lateral distributions of these lithofacies indicates that these lithofacies were deposited in one or more of eight depositional environments: 1) subtidal, 2) reef flank, 3) reef crest, 4) shoal flank, 5) shoal crest, 6) lagoon, 7) tidal flat, and 8) sabkha in a transition from a catch-up carbonate system to a keep-up carbonate system. These paleoenvironments have been assigned to four Smackover/Buckner genetic depositional systems for three-dimensional stratigraphic modeling (Table 3). Each of these systems has been interpreted as being time-equivalent from that work, two principal reservoir facies, reef and shoal were identified at Appleton Field.

In Year 1 of this project, we have studied the subfacies of the reef and shoal facies. Based on the description of 11 cores (Figures 6 through 16) and 379 thin sections, three subfacies have been recognized in the reef facies. These subfacies include thrombolitic layered, reticulate and dendroid. Each represents a different and distinct microbial growth form which has inherent properties that affect reservoir architecture, pore systems, and heterogeneity. The layered growth form is characterized by a reservoir architecture that is characterized by lateral continuity and high vertical heterogeneity. The reticulate form has a reservoir architecture that is characterized by vertical continuity and moderate lateral heterogeneity. The dendroid form has a reservoir architecture that is characterized by vertical and lateral continuity and low heterogeneity. The pore systems in each of these reservoir fabrics consist of shelter and enlarged pore types. The enlargement of these primary pores is due to dissolution and dolomitization resulting in a vuggy appearing pore system. Three subfacies have been recognized in the shoal facies. These subfacies are the lagoon/subtidal, shoal flank, and shoal crest. The lagoon/subtidal subfacies has a mud-supported architecture and therefore is not considered a reservoir. The shoal flank has a grain-supported architecture but has considerable carbonate mud associated with it, and therefore, has low to moderate reservoir capacity. The shoal crest has a grain-supported architecture with minimal carbonate mud, and therefore, has the highest reservoir capacity of the shoal subfacies. The pore systems of the shoal flank and shoal crest reservoir facies consist of intergranular and enlarged pore types. The enlargement of the primary pores is due to dissolution and dolomitization. Heterogeneity in the shoal reservoir is high due to the rapid lateral and vertical changes in this depositional environment. Graphic logs were constructed for each of the cores. The core data and well log signatures are integrated and calibrated on these graphic logs (Figures 6 through 16).

Appleton Field (Figure 4) was discovered in 1983 with the drilling of the D.W. McMillan 2-14 well (permit #3854). The discovery well was drilled off the crest of a composite paleotopographic structure, based on 2-D seismic and well data (Figure 59). The well penetrated Paleozoic basement rock at a depth of 12,786 feet. The petroleum trap at Appleton was interpreted to be a simple anticline associated with a northwest-southeast trending basement paleohigh. After further drilling in the field, the Appleton structure was interpreted as an anticline consisting of two local paleohighs. The D.W. McMillan 2-15 well (permit #6247) was drilled in 1991. The drilling of this well resulted in the structural interpretation being revised to consist of three local paleohighs. In 1995, 3-D seismic reflection data were obtained for the Appleton Field area. The interpretation of these data indicated three local highs with the western paleohigh being separated into a western and a central feature.

Based on the structural maps that we have prepared for the Appleton Field, we have concluded that the Appleton structure is a low-relief, northwest-southeast trending ridge comprised of local paleohighs. This interpretation is based on the construction of structure maps on top of the basement (Figure 17), on top of the reef (Figure 18), and on top of the Smackover/Buckner (Figure 19) from 3-D seismic data. Also, maps of the basement surface (Figure 28), of the reef surface (Figure 29) and of Smackover/Buckner surface (Figure 30) support this interpretation.

The Smackover reservoir at Appleton Field has been influenced by antecedent paleotopography. The Smackover thickness ranges from 177 feet in the McMillan 2-14 well (permit #3854) to 228 feet in the McMillan Trust 11-1 well (permit #3986) in the field. As observed from the cross sections based on well log data (Figures 26 and 31) and on seismic data (Figure 32) and on the seismic profile (Figure 27), the sabkha facies thins over the composite

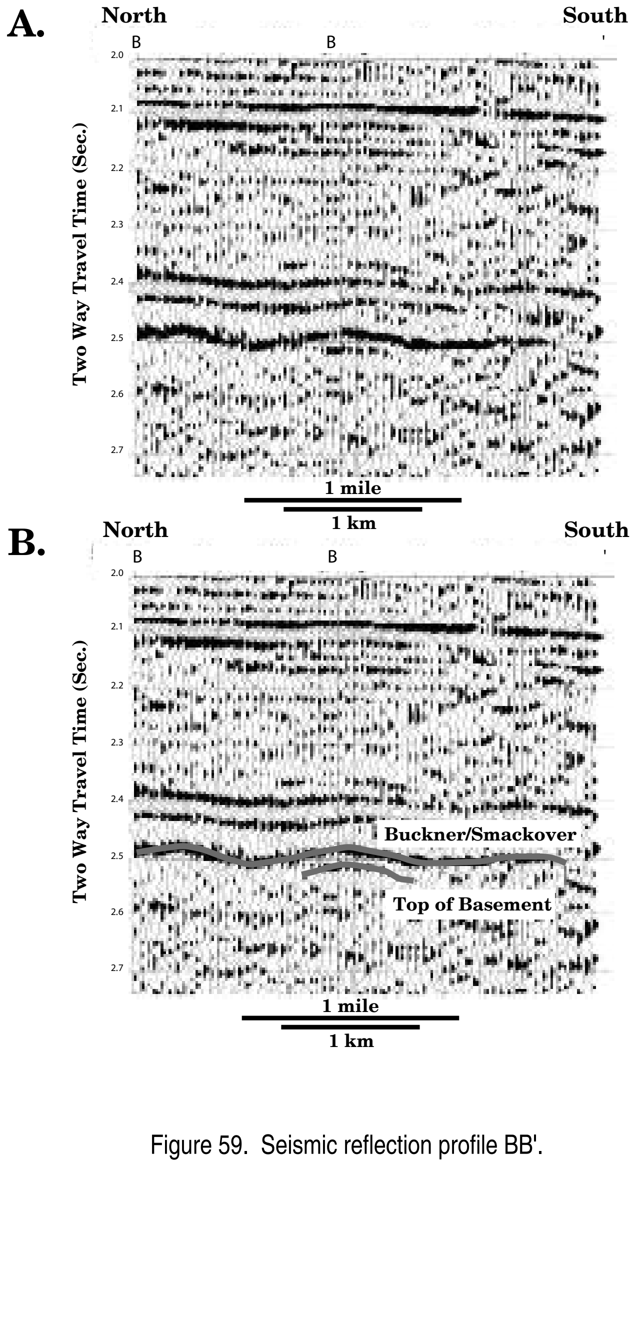


Figure 59. Seismic reflection profile BB'.

paleohigh, while the reservoir lithofacies are thicker on the paleohigh. Thickness maps of the sabkha facies (Figure 21), tidal flat facies (Figure 22), shoal complex (Figure 23), tidal flat/shoal complex (Figure 24), and reef complex (Figure 25) facies illustrate the changes in these lithofacies in the Appleton Field.

Vocation Field

Based on the description of cores (7) and thin sections (237), 9 lithofacies had been identified previously in the Smackover at Vocation Field (Figure 5). These lithofacies (Table 3) include: ooid-dominated, grain-supported; ooid-dominated, matrix-supported; oncoid-dominated, grain-supported; oncoid-dominated, matrix-supported; peloid-dominated, grain-supported; peloid-dominated, matrix-supported; mudstone; algal stromatolite; and algal boundstone. Analysis of the vertical and lateral distributions of these lithofacies indicates that these lithofacies were deposited in one or more of six depositional environments: 1) subtidal, 2) reef, 3) shoal flank, 4) shoal crest/beach, 5) lagoon and 6) intertidal. These paleoenvironments have been assigned to four Smackover/Buckner genetic depositional systems for three-dimensional stratigraphic modeling. Each of these systems has been interpreted as being time-equivalent. From that work, two principal reservoir facies, reef and shoal, were identified at Vocation Field.

In Year 1 of this project, we have studied the subfacies of the reef and shoal facies. Based on the description of 11 cores (Figures 33 through 43) and thin sections, two subfacies have been recognized in the reef facies. These subfacies include thrombolitic layered and reticulate. As with the reef subfacies at Appleton Field, each represents a different and distinct microbial growth form. The reservoir architecture, pore system, and heterogeneity for these subfacies are like those for the same reef subfacies at Appleton Field. Three subfacies have been recognized in the shoal facies. These subfacies are the lagoon, shoal flank and shoal crest. These shoal subfacies have a reservoir architecture, pore system and heterogeneity similar to those for the shoal reservoir at Appleton Field.

Vocation Field (Figure 5) was discovered in 1971 with the drilling of the B.C. Quimby 27-15 (permit #1599) well. The discovery well was drilled near the crest of a paleotopographic structure based on 2-D seismic and well log data. The well penetrated Paleozoic basement rock at a depth of 14,209 feet. The petroleum trap at Vocation was interpreted to be an anticline associated with a basement paleohigh.

Based on structural maps that we have prepared for the Vocation Field, we concluded that the Vocation Field structure is a high-relief composite paleotopographic ridge. There may be as many as eight local paleohighs associated with this paleohigh which are separated by basement troughs or faults. The Smackover thins and, in some cases, is absent, over these features.

Rock-Fluid Interactions

The study of rock-fluid interactions have been initiated. Observation regarding the diagenetic processes influencing pore system development and heterogeneity in these reef and shoal reservoirs have been made.

Based on initial petrographic studies, reservoir-grade porosity in the Smackover at Appleton field occurs in microbial boundstones in the reef interval and in oolitic, oncoidal, and peloidal grainstones and packstones in the upper Smackover. Porosity in the boundstones is a mixture of primary shelter porosity overprinted by secondary intercrystalline and vuggy porosity produced by dolomitization and dissolution that is pervasive throughout the field. Porosity in the grainstones and packstones is a mixture of primary interparticle and secondary grain moldic porosity overprinted by secondary dolomite intercrystalline porosity.

Based on core analysis data, there is a distinct difference in reservoir quality between the grainstone/packstone and boundstone reservoir intervals. Although the difference in reservoir quality between these lithofacies is principally the result of depositional fabric, diagenesis acts to enhance or impair the reservoir quality of these lithofacies. Porosity in the grainstone/packstone reservoir interval in the McMillan 2-14 well (permit #3854) ranges from 9.7 to 21.5% and averages 14.8%. Permeability ranges from 1.1 to 618 md, having a geometric mean of 63.5 md (Figure 60A). Porosity in the reef boundstone reservoir interval in the McMillan Trust 12-14 well (permit #4633-B) ranges from 11.9 to 25.0% and averages 18.1%. Permeability ranges from 14 to 1748 md, having a geometric mean of 252 md (Figure 60B).

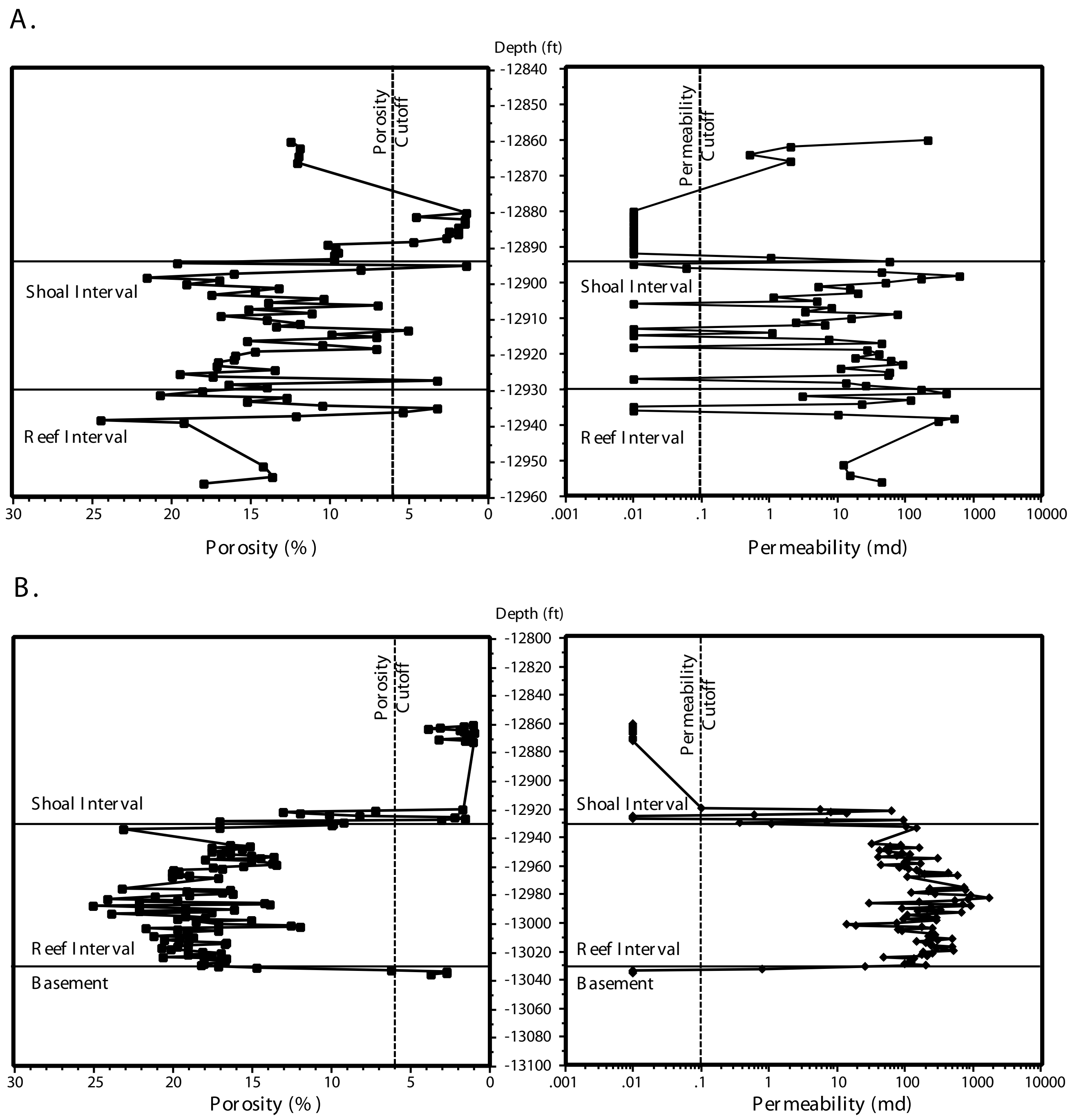


Figure 60. Porosity vs. depth and permeability vs. depth plots for (A) well permit # 3854 and (B) well permit # 4633-B.

The higher producibility for the reef lithofacies is attributed to the higher permeability of this lithofacies and to the nature of the pore system (pore-throat size distribution) rather than the amount of porosity. Pore-throat size distribution is one of the important factors determining permeability, because the smallest pore throats in cross-sectional areas are the bottlenecks that determine the rate at which fluids pass through a rock.

Although both the reef and shoal lithofacies accumulated in diverse environments to produce mesoscopic-scale heterogeneity, dolomitization and dissolution acted to reduce the microscopic-scale heterogeneity in these carbonate rocks. The grainstones/packstones accumulated in shoal environments and were later subjected to dolomitization and vadose dissolution. The resulting moldic pore system, which includes primary interparticulate and secondary grain moldic and dolomite intercrystalline porosities, is characterized by multisize pores that are poorly connected by narrow pore throats. Pore size is dependent on the size of the carbonate grain that was leached.

The boundstones accumulated in a reef environment and were later subjected to pervasive dolomitization and nonfabric-selective, burial dissolution. The intercrystalline pore system, which includes primary shelter and secondary dolomite intercrystalline and vuggy pores, is characterized by moderate-size pores having uniform pore throats. The size of the pores is dependent upon the original shelter pores, the dolomite crystal size, and the effects of late-stage dissolution. The reef reservoir and its shelter and intercrystalline pore system, therefore, has higher producibility potential compared to the shoal reservoir and its moldic pore system.

As confirmed from well-log analysis and well production history, hydrocarbon production in Appleton field has occurred primarily from the boundstones of the Smackover reef interval, with secondary contributions from the shoal grainstones and packstones of the upper Smackover. Total reservoir thickness in the producing wells ranges from 20 ft (6 m) in the McMillan Trust 11-1 well (permit #3986) to 82 ft (25 m) in the McMillan Trust 12-4 well (permit #4633-B). With the exception of the McMillan 2-14 well (permit #3854), where production has been primarily from grainstones and packstones of the upper Smackover, the majority of the productive reservoir occurs in boundstones.

The higher production from the reef interval is attributed to the better reservoir quality of the boundstones and to the better continuity and connectivity of these carbonates. Whereas, the grainstone/packstone interval is discontinuous, both vertically and laterally, the boundstone interval appears to possess excellent vertical and lateral continuity.

In addition, although the microbial reef reservoir interval is more productive than the shoal reservoir interval at Appleton Field, the dendroidal thrombolites have higher reservoir quality than the layered thrombolites (Figure 61). Dendroidal thrombolites have a reservoir architecture characterized by high lateral and vertical pore interconnectivity and permeability, while layered thrombolites have good lateral but poorer vertical pore interconnectivity and permeability. Both thrombolite architectures are characterized by pore systems comprised of shelter and enlarged pores.

Petrophysical and Engineering Property Characterization

Initial results from work related to this task show that Appleton (Figure 44) and Vocation and South Vocation Fields (Figure 45) have experienced a substantial decline in oil production since their initial discoveries. To date, petrophysical characterization of the reservoir properties has consisted of tabulating water and oil saturations (Figures 46 through 50), preparing porosity versus permeability cross plots for wells in the fields (Figures 51 through 54) and calibrating porosities resulting from core analyses to those observed from well logs (Figures 55 through 58). These graphs and data are in agreement with the geoscientific characterization results in that the reef reservoirs consistently have higher reservoir quality than the shoal reservoirs.

Data Integration

All geoscientific and petrophysical data generated to date from this study have been entered and integrated into digital databases for Appleton and Vocation Fields for reservoir characterization, modeling and simulation.

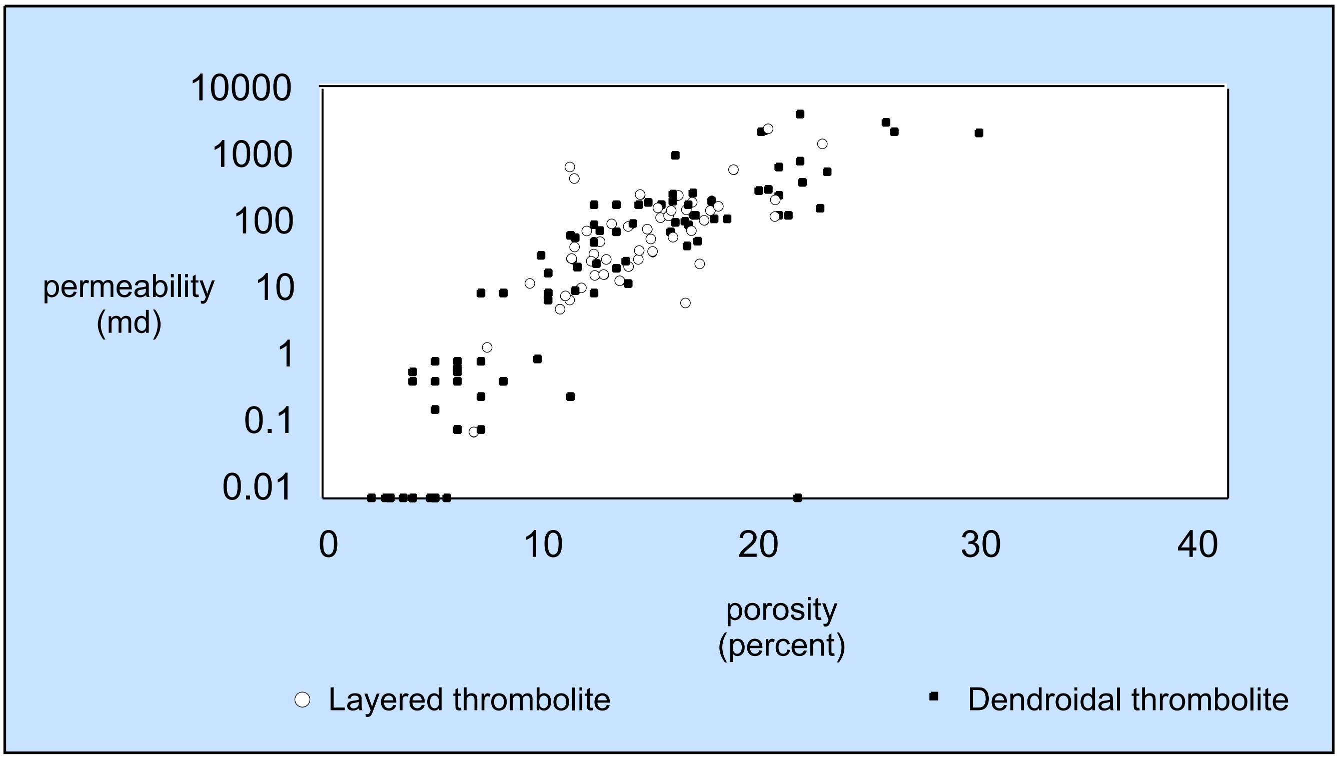


Figure 61. Reservoir quality of thrombolitic facies.

CONCLUSIONS

The University of Alabama in cooperation with Texas A&M University, McGill University, Longleaf Energy Group, Strago Petroleum Corporation, and Paramount Petroleum Company are undertaking an integrated, interdisciplinary geoscientific and engineering research project. The project is designed to characterize and model reservoir architecture, pore systems and rock-fluid interactions at the pore to field scale in Upper Jurassic Smackover reef and carbonate shoal reservoirs associated with varying degrees of relief on pre-Mesozoic basement paleohighs in the northeastern Gulf of Mexico. The project effort includes the prediction of fluid flow in carbonate reservoirs through reservoir simulation modeling which utilizes geologic reservoir characterization and modeling and the prediction of carbonate reservoir architecture, heterogeneity and quality through seismic imaging.

The primary objective of the project is to increase the profitability, producibility and efficiency of recovery of oil from existing and undiscovered Upper Jurassic fields characterized by reef and carbonate shoals associated with pre-Mesozoic basement paleohighs.

The principal research effort for Year 1 of the project has been reservoir description and characterization. This effort has included four tasks: 1) geoscientific reservoir characterization, 2) the study of rock-fluid interactions, 3) petrophysical and engineering characterization and 4) data integration. This work was scheduled for completion in Year 1.

Geoscientific reservoir characterization is essentially completed. The architecture, porosity types and heterogeneity of the reef and shoal reservoirs at Appleton and Vocation Fields have been characterized using geological and geophysical data. All available whole cores (11) from Appleton Field have been described and thin sections (379) from these cores have been studied. Depositional facies were determined from the core descriptions. The thin sections studied represent the depositional facies identified. The core data and well log signatures have been integrated and calibrated on graphic logs. For Appleton Field, the well log, core, and seismic data have been entered into a digital database and structural maps on top of the basement, reef, and

Smackover/Buckner have been constructed. An isopach map of the Smackover interval has been prepared, and thickness maps of the sabkha facies, tidal flat facies, shoal complex, tidal flat/shoal complex, and reef complex have been prepared. Maps have been constructed using the 3-D seismic data that Longleaf contributed to the project to illustrate the structural configuration of the basement surface, the reef surface, and Buckner/Smackover surface. Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project.

All available whole cores (11) from Vocation Field have been described and thin sections (237) from the cores have been studied. Depositional facies were determined from the core descriptions. From this work, an additional 73 thin sections are being prepared to provide accurate representation of the lithofacies identified. The core data and well log signatures have been integrated and calibrated on the graphic logs. The well log and core data from Vocation Field have been entered into a digital database and structural and isopach maps are being constructed using these data. The graphic logs are being used in preparing cross sections across Vocation Field. The core and well log data are being integrated with the 3-D seismic data that Strago contributed to the project. Petrographic analysis and pore system studies have been initiated and will continue into Year 2 of the project.

The study of rock-fluid interactions has been initiated. Thin sections (379) are being studied from 11 cores from Appleton Field to determine the impact of cementation, compaction, dolomitization, dissolution and neomorphism has had on the reef and shoal reservoirs in this field. Thin sections (237) are being studied from 11 cores from Vocation Field to determine the paragenetic sequence for the reservoir lithologies in this field. An additional 73 thin sections are being prepared from the shoal and reef lithofacies in Vocation Field to identify the diagenetic processes that played a significant role in the development of the pore systems in the reservoirs at Vocation Field.

Petrophysical and engineering property characterization is progressing. Petrophysical and engineering property data are being gathered and tabulated. The production history for Appleton Field and the production history for Vocation and South Vocation Fields have been obtained and graphed. Water and oil saturation data for core analyses for Appleton Field have been tabulated. Porosity versus permeability cross plots for wells in the fields have been prepared, and porosities from core analyses have been calibrated with porosities determined from well log studies.

Data integration is on schedule, in that, geological, geophysical and engineering data collected to date for Appleton and Vocation Fields have been compiled into a fieldwide digital database for reservoir characterization, modeling and simulation for the reef and carbonate shoal reservoirs for each of these fields.

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