Reservoir characteristics of the Bass Islands dolomite in Otsego County, Michigan: Results for a saline reservoir CO_2 sequestration demonstration

William B. Harrison III, G. Michael Grammer, and David A. Barnes

ABSTRACT

As part of a phase II plan to understand, test, and evaluate the CO_2 sequestration potential for deep saline reservoirs in Michigan, a demonstration test well was completed in late 2006 in Otsego County, northern lower Michigan. The well was drilled to 3630 ft (1006 m) and open-hole logged. Selected conventional cores totaling 180 ft (55 m) were taken in the saline reservoir (Bass Islands Formation), the immediately overlying confining unit (Bois Blanc Formation), and the overlying seal (Amherstberg Formation). Additionally, 24 sidewall cores were taken in several uphole formations. The whole core was sampled every foot by drilling 2-in. (5-cm)-long and 1-in. (2.5-cm)-diameter test plugs for porosity and permeability (P&P) analyses. Seventy-four horizontal plugs, 12 vertical plugs, 6 whole cores, and 17 sidewall core plugs were sent to Core Laboratories for routine P&P analyses. Fifteen blue-dyed, epoxy-impregnated thin sections were made from selected P&P plugs. The whole core was slabbed for examination and description of lithology, sedimentary structures, and facies characteristics. This Upper Silurian and Lower–Middle Devonian stratigraphic section was carefully examined for lithology and facies characteristics that relate to reservoir and seal properties pertinent to CO_2 sequestration. The overlying primary seal (Amherstberg Formation) is a low-porosity, low-permeability limestone that is highly fossiliferous and densely cemented with calcite and chalcedony. This unit is the ultimate vertical barrier to the vertical migration of fluids. The immediately overlying confining unit (Bois Blanc Formation) is a very cherty limestone and dolostone with moderate porosity and low permeability. Some fluids may move into this unit, but very low permeability will severely restrict the vertical flow. Thin sections show abundant microporosity. The

DOI:10.1306/eg.05080909011

AUTHORS

William B. Harrison III ~ *Department of Geosciences, Western Michigan University, Kalamazoo, Michigan, 49008; harrison@wmich.edu*

William Harrison is a Professor Emeritus and curator at the Michigan Geological Repository for Research and Education (MGRRE), part of the Department of Geosciences at Western Michigan University. He received his Ph.D. from the University of Cincinnati in 1974. He joined the faculty at Western Michigan University in 1973 and founded MGRRE in 1982. His research interests are stratigraphy, subsurface, and petroleum geology of the Michigan Basin.

G. Michael Grammer ~ *Department of Geosciences, Western Michigan University, Kalamazoo, Michigan, 49008*

Michael Grammer is an associate professor and research scientist at the Michigan Geological Repository for Research and Education (MGRRE), part of the Department of Geosciences at Western Michigan University. He received his Ph.D. from the University of Miami in 1991. He joined the faculty at Western Michigan University in 2002. His research interests are in carbonate sedimentology and sequence stratigraphy.

David A. Barnes ~ *Department of Geosciences, Western Michigan University, Kalamazoo, Michigan, 49008*

David Barnes is a professor and research scientist at the Michigan Geological Repository for Research and Education (MGRRE), part of the Department of Geosciences at Western Michigan University. He received his Ph.D. from the University of California, Santa Barbara, in 1982. He joined the faculty at Western Michigan University in 1986. His research interests are in clastic sedimentology and diagenesis and geological carbon sequestration.

ACKNOWLEDGEMENTS

The authors thank Kristen Carter, Paul Daniels, and Eric Venteris for their thoughtful reviews of this manuscript. We also thank our colleagues at the Midwest Regional Carbon Sequestration Partnership and Battelle Memorial for intellectual and financial support during this project.

Stephen Kelley provided yeoman service in slabbing core and drilling core plugs for porosity and permeability analyses. Thanks to Linda Harrison for the high-resolution core photographs. Robert G. Mannes and Allen Modroo at Core Energy, LLC have provided timely discussions about the geology in and around the St. Charlton #4-30 well. The Michigan Geological Repository for Research and Education has provided research space and facilities for the study of the samples and data.

target saline reservoir interval (Bass Islands Formation) is a variably porous and permeable dolostone composed of several tidal flat cyclic packages. The Bass Islands Formation has a gross thickness of 70 ft (21 m) with a reservoir interval composed of more than 40 ft (12 m) of greater than 10% porosity and permeability zones exceeding 500 md. Average porosity over the entire Bass Islands is 12.5%. Average permeability is 22.4 md. The CO_2 injection tests, using the Bass Islands section, were completed during February and March 2008. Analysis of the Bass Islands Formation in northern Michigan indicated excellent reservoir quality for injection and storage of CO_2 and high-quality sealing units to prevent vertical migration. Monitoring well data conducted during and after the injection test validates preinjection reservoir simulation modeling performed at Battelle Pacific Northwest Labs using well data and rock observations from this study.

INTRODUCTION

As part of a phase II geological study and pilot CO_2 injection test program, the Bass Islands Formation in northern lower Michigan was evaluated as a possible candidate for geological carbon sequestration. The Bass Islands Formation has long been recognized in Michigan as a widespread, brine-filled carbonate unit that caps the Silurian stratigraphic section (Lilienthal, 1978). It is overlain, and truncated in places, by the major interregional unconformity at the Tippecanoe-Kaskaskia sequence boundary (Sloss, 1963). Although the Bass Islands Formation is mostly known from the subsurface in Michigan, scattered outcrops of the Raisin River Dolomite member are observed in southeastern Michigan and the St. Ignace Dolomite member near the Straits of Mackinac in northern lower Michigan and Michigan's upper peninsula. Most of the data about the Bass Islands Formation have been derived from well data acquired by the drilling of oil and gas wells throughout the Michigan Basin. Most wells have wireline logs that record various lithologic and fluid properties, although it is a common practice for drillers to set casing a few feet into an anhydritic bed in the Bass Islands Formation. Many of the logs, therefore, only comprise gamma-ray and cased-hole neutron porosity logs. A few open-hole wireline logs through the Bass Islands Formation exist, and they are the most useful in estimating reservoir properties (Barnes et al., in press). A few wells have collected sets of drill cuttings, so the lithology interpreted from logs can be confirmed. Although wireline logs and drill cuttings can provide general lithologic and porosity properties, rock core samples can provide additional critical data for reservoir evaluation. Facies characteristics and rock permeability are only satisfactorily determined from core samples. Very few core samples from the Bass Islands Formation throughout the Michigan Basin exist; however, Gardner (1974) reported core from a part of the Bass Islands Formation in two wells: the Sun-Bradley #4, Newaygo County, Sec. 11-T12N-R13W and the Sun-Mancelona #1, Antrim County, Sec. 36-T29N-R5W.

In November 2006, an important core was collected as part of the Midwest Regional Carbon Sequestration Partnership phase II research program. This particular site was chosen because it coincided with an ongoing CO_2 enhanced oil recovery (EOR) project owned by Core Energy, LLC. This EOR project takes high-purity CO_2 separated from produced Devonian Antrim Shale gas at nearby gas processing plants, compresses it to approximately 1100 psi (77 kg/cm), and pumps it along an 11-mi (18-km)-long pipeline to a series of Silurian Niagaran Pinnacle reefs (Grammer et al., in press). This research project and injection experiment was able to take advantage of the existing infrastructure of the EOR activity and acquire core and logs from the Bass Islands Formation during drilling of a new well for EOR operations. The Core Energy-State Charlton #4-30 well, API permit number 21-137-57916-0000 (Figure 1), was drilled in Otsego County of northern lower Michigan as an additional EOR operation well in a Niagaran reef oil field. The well was initially drilled and logged to a depth of 3630 ft (1006 m), then deepened to the Silurian Niagaran reef zone for future use in the ongoing EOR activities. The shallower part of this well is currently being used as a field demonstration well to sequester anthropogenic CO_2 in the Bass Islands Formation, a deep saline reservoir. In early 2008, slightly more than 10,000 tons of CO_2 was injected into the Bass Islands Formation. Additional injections of up to 50,000 tons CO_2 are being completed during the spring and summer of 2009.

This study was undertaken to delineate site-specific lithologic and reservoir properties for the Bass Islands in the area of the test well, and to use the detailed core-to-log correlations to extrapolate reservoir characteristics and CO_2 storage capacity estimates to nearby areas of the Michigan Basin using wireline-log data along with very limited core and sample data. Applying a sequence stratigraphic approach further provides vertical and lateral predictability in the reservoir.

Regional Setting

The Michigan Basin is a cratonic basin located on the southern margin of the Canadian shield and centered on the lower peninsula of Michigan. The basin has more than 16,000 ft (4877m) of Paleozoic sediments in the center and thins dramatically toward the margins. It also occupies parts of eastern Wisconsin; southwestern Ontario, Canada; northwestern Ohio; northeastern Illinois; and northern Indiana and covers more than 100,000 mi^2 (160,000 km^2) (Catacosinos et al., 1991). There have been more than 58,000 wells (Figure 1) drilled for oil and gas exploration and development since the 1920s. Cumulative production from all formations exceeds 1.25 billion bbl of oil and 6.5 tcf of natural gas. Although more than one-third of the wells drilled in Michigan have produced hydrocarbons, many others have encountered porous and permeable subsurface formations that contain only brine with salinity values up to 400,000 ppm (40%). These saline reservoirs are considered target reservoirs for CO_2 sequestration. The Bass Islands Formation, a saline reservoir with no historic hydrocarbon production, is such a potential reservoir in the Michigan Basin.

The Bass Islands Formation in northeastern Otsego County is a porous and permeable dolostone produced by the diagenetic alteration of Late Silurian shallow-water carbonate sedimentary rocks. Much of the alteration is caused by the diagenetic processes associated with the Late Silurian–Early Devonian exposure related to the sequence-bounding sub-Kaskaskia interregional unconformity (Sloss, 1963). The unconformity is overlain by the Bois Blanc Formation in this study area but may be overlain by other formations in other parts of the Michigan Basin (Figure 2). The reservoir properties of the Bass Islands Formation are primarily controlled by the original depositional texture and fabric, which is overprinted by early and late diagenesis.

Regional mapping and examination of wireline logs from wells in other counties in northern and central Michigan show thicknesses of the Bass Islands reservoir of up to 90 ft (27 m) (Figure 3). A large area in the northern half of Michigan's lower peninsula has a gross reservoir thickness of greater than 50 ft (15 m). Figure 3 also shows the area of a minimum burial depth of 2600 ft (788 m) required to maintain CO_2 in its supercritical phase. A slightly more conservative estimate of 2600 ft (788 m) was chosen for mapping purposes instead of the typical 2500 ft (762 m) (U.S. Department of Energy, 2007, p. 12). Lateral correlation using wireline logs shows that the Bass Islands reservoir interval can be identified in surrounding counties to the St. Charlton #4-30 well in Otsego County (Figure 4).

RESULTS AND DISCUSSION

Bass Islands Formation Lithology and Facies

The Bass Islands Formation has its type area in outcrops on the Bass Islands near the north-central Ohio coastline

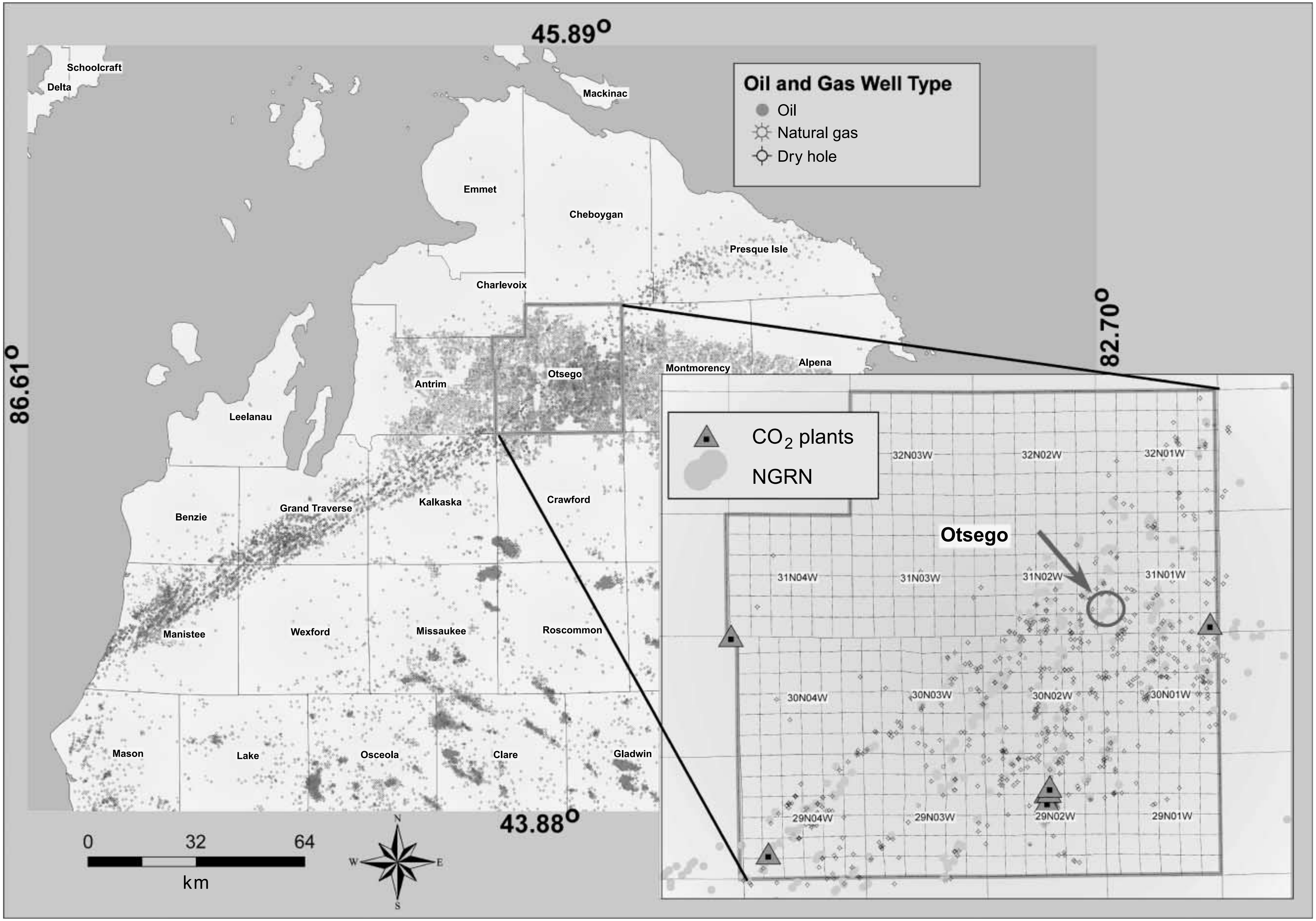

Figure 1. Location map of the Core Energy-State Charlton #4-30 well in northern lower Michigan. The map shows oil, gas, and dry wells with the inset showing Otsego County, Michigan. Southwest–northeast-trending oil and gas wells in Manistee to Presque Isle counties are mainly in the northern Niagaran (Silurian) reef trend. The east–west swath of gas wells in Antrim to Alpena counties are predominantly Devonian Antrim Shale gas wells. NGRN = Silurian Niagaran pinnacle reef oil and gas fields.

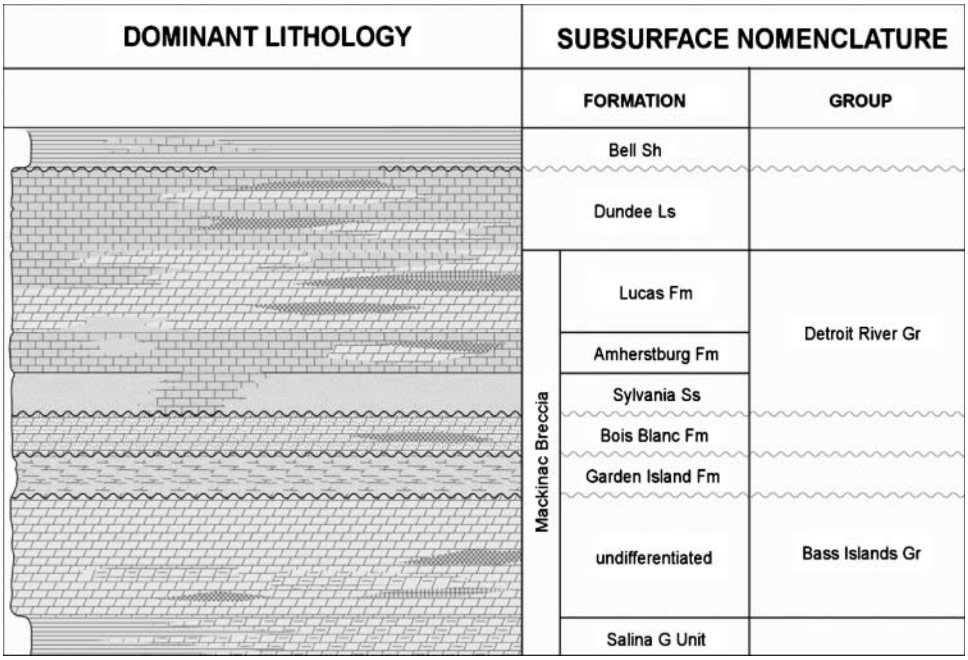

Figure 2. Part of the generalized Michigan stratigraphic column showing Upper Silurian and Lower–Middle Devonian strata. The Silurian-Devonian boundary is placed at the top of the Bass Islands. The Mackinac Breccia, Garden Island Formation, and Sylvania Sandstone are not present in Otsego County.

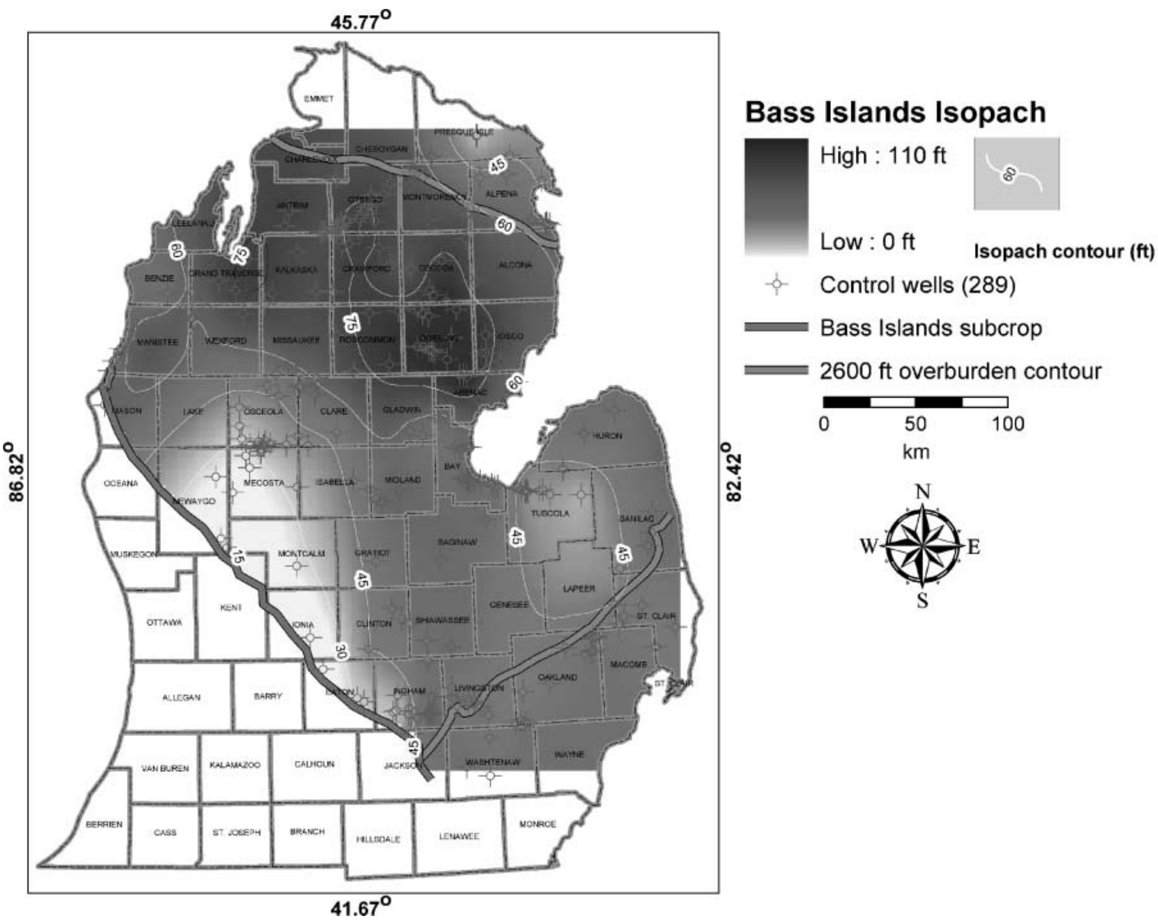

Figure 3. Isopach map of Bass Islands Dolomite in northern and central Michigan. The 2600-ft (788-m) structural contour line marks the minimum depth for maintaining supercritical-phase CO_2 in the subsurface. Gridding and contouring were done using ordinary kriging and a spherical variogram model. The root-mean-square error was 13.6 ft (4.1 m).

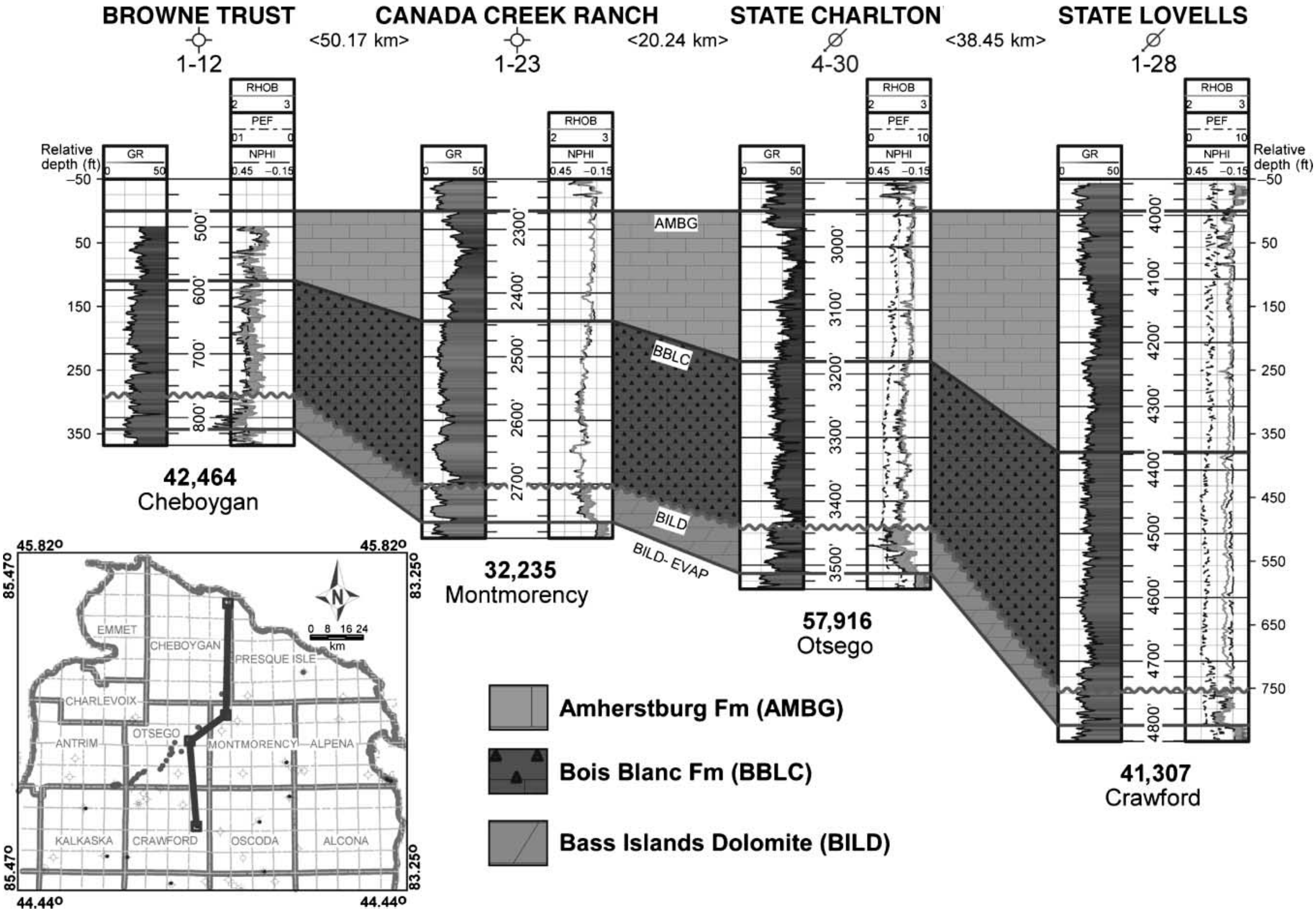

Figure 4. North–south wireline-log cross section showing the Bass Islands Formation (BILD) reservoir interval and the overlying confining unit Bois Blanc Formation (BBLC) and the major seal unit Amherstberg Formation (AMBG). Well number 57916 is the Core Energy-St. Charlton #4-30 well. GR = gamma ray; RHOB = bulk density; NPHI = neutron porosity; PEF = photoelectric factor; BILD-EVAP = Bass Islands evaporate.

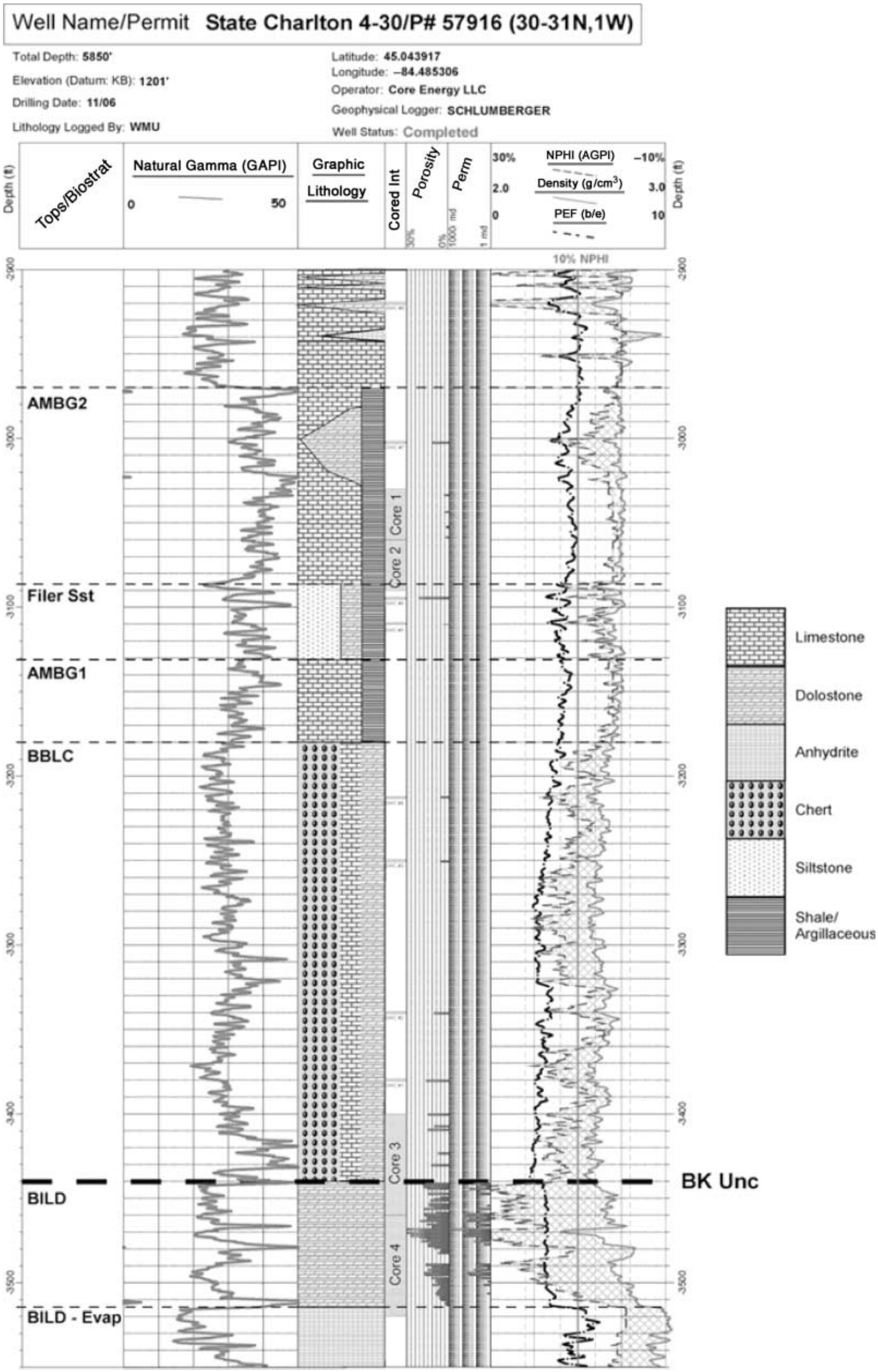

Figure 5. Well logs and core data from the lower part of the Core Energy-St. Charlton #4-30 well, section 30, T31N-R1W, Otsego County, Michigan. BK = base of the Kaskaskia megasequence and position of unconformity on top of the Bass Islands Formation; BILD = Bass Islands Formation; BBLC = Bois Blanc Formation; AMBG = Amherstberg Formation. The core interval reported in this study is the lower half of core 3 and all of core 4. NPHI = neutron porosity; PEF = photoelectric factor.

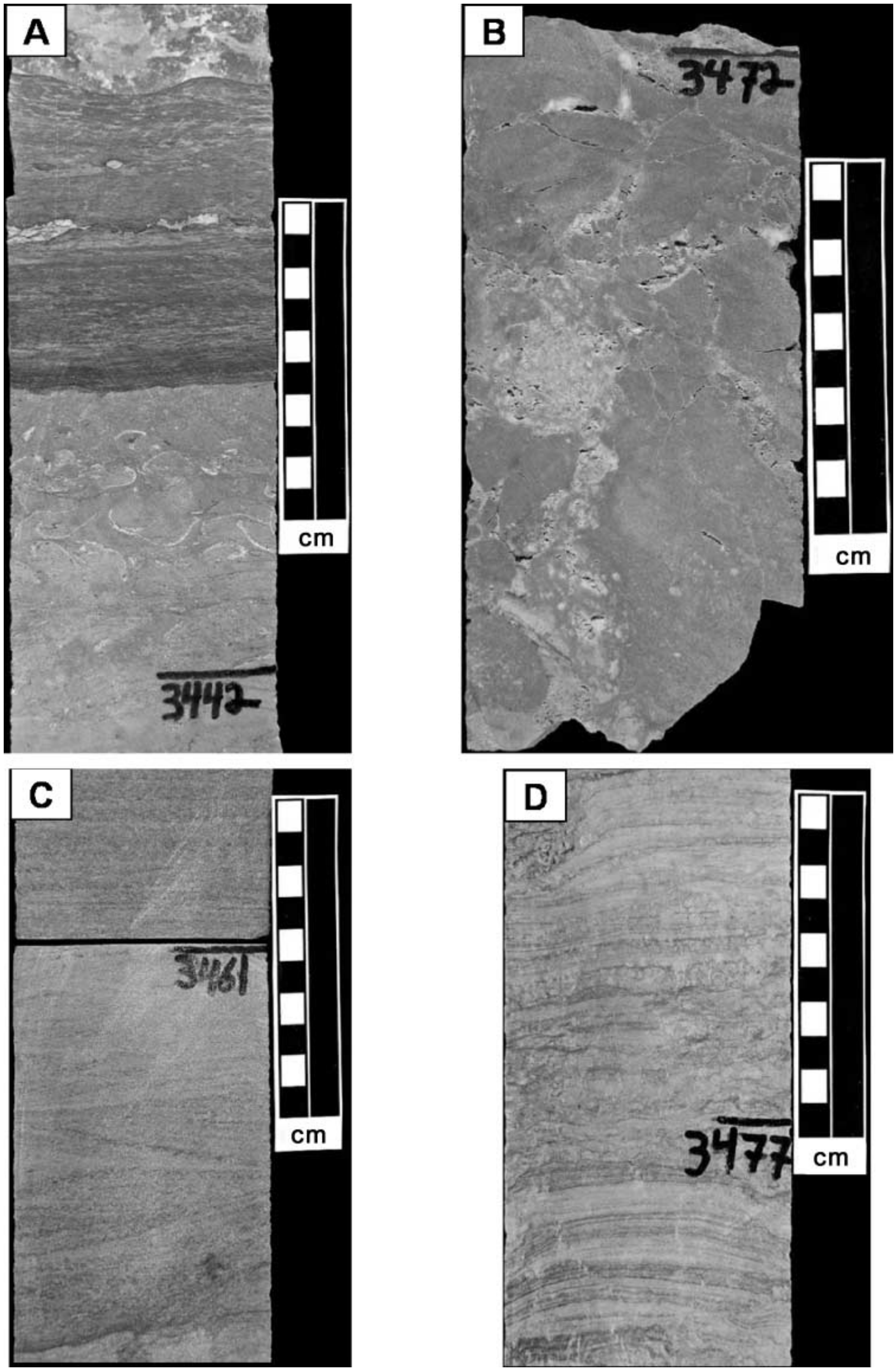

Figure 6. (A) Core photograph (3442 ft [1049 m]) showing the boundary between the Tippecanoe and Kaskaskia megasequences of Sloss (1963) with shell lag followed by condensed interval and a chert-rich zone near the top of the core. (B) Core photograph (3472 ft [1058 m]) showing brecciation and solution pipes related to karst developed during subaerial exposure. (C) Core photograph (3461 ft [1055 m]) showing well-developed cross-bedding in peloidal grainstone associated with high-energy carbonate sand shoals. (D) Core photograph (3477 ft [1060 m]) of laminated cyanobacterial mats associated with tidal flat deposits. Photos are by Linda Harrison.

of Lake Erie (Lane et al., 1909). Sparling (1970) extensively described the Bass Islands lithofacies as a series of shallow-water carbonate deposits that have been dolomitized and diagenetically altered by processes associated with the Tippecanoe-Kaskaskia sequence-bounding unconformity. Dissolution of primary grains and larger-scale dissolution and formation of solution collapse breccias are characteristics of the Bass Islands in the outcrop area. Although wireline-log correlations show that the Bass Islands in the Michigan Basin subsurface continues this dolomitic lithology, they cannot help to determine the facies and fabric characteristics seen in outcrop.

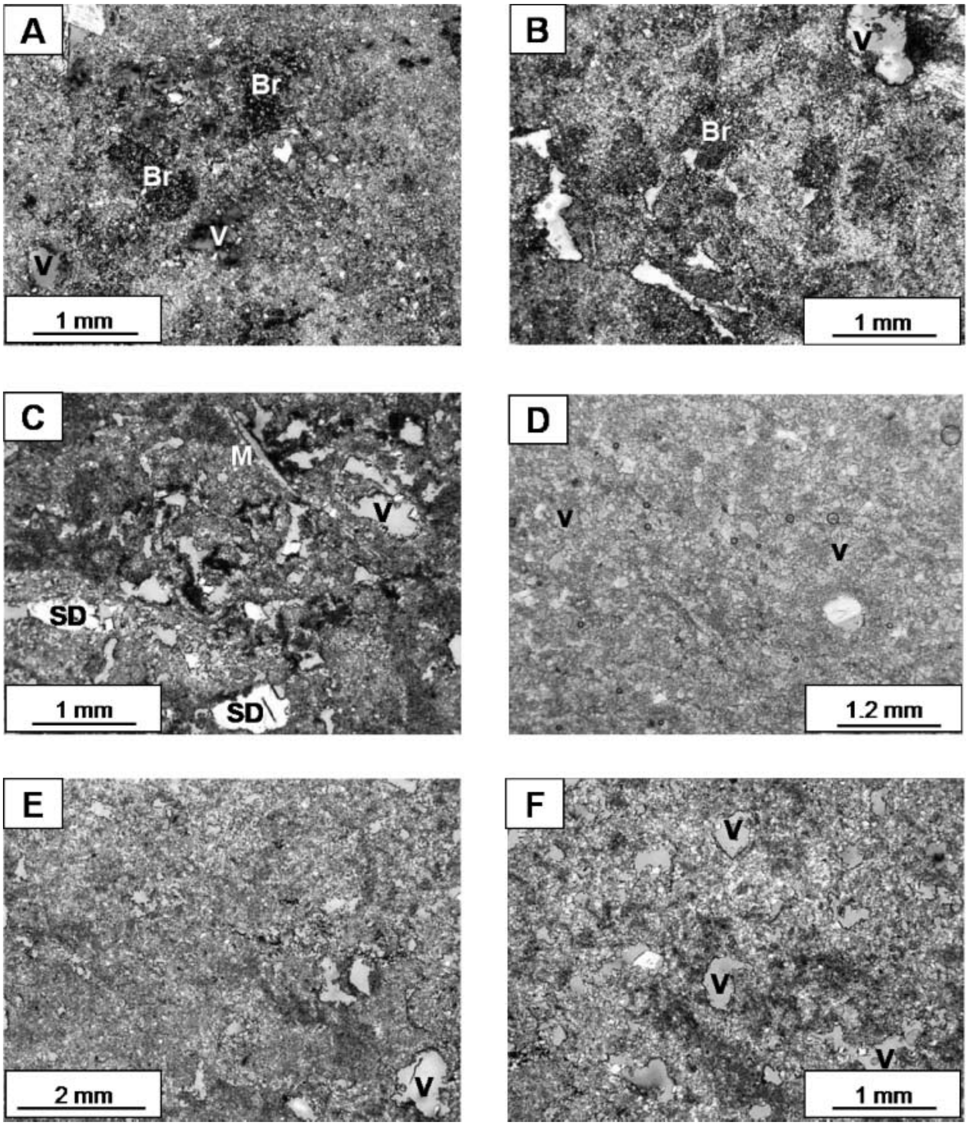

Figure 7. Thin-section photomicrographs (plane light) of reservoir intervals. (A) Brecciated (Br), finely crystalline dolomite related to karst developed in response to subaerial exposure (3469 ft [1057 m]). Well-developed solution-enhanced vugs (V) and intercrystalline porosity. The measured porosity and permeability (Klinkenberg) in this zone are >31% and >290 md, respectively. (B) Brecciated (Br), finely crystalline dolomite related to karst developed in response to subaerial exposure (3472.2 ft [1058.3 m]). Well-developed solution-enhanced vugs (V) and intercrystalline porosity. The measured porosity and permeability (Klinkenberg) in this zone are >26% and 90 md, respectively. (C) Dolomitized, burrowed, peloidal, skeletal wackestone. Pore types include fossil molds (M), solution-enhanced vugs (V), and intercrystalline pores. Late saddle dolomite (SD) partially occludes local vugs (3466 ft [1056 m]). (D) Dolomitized, peloidal packstone to grainstone. Well-developed solution-enhanced vugs (V), small molds, and intercrystalline porosity (3461 ft [1055 m]). (E) Dolomitized, bioturbated, peloidal wackestone-packstone. Well-developed solution-enhanced vugs (V), small molds, and intercrystalline porosity (3495 ft [1065 m]). (F) Higher-magnification photograph of sample E showing well-developed solution-enhanced vugs (V), small molds, and intercrystalline porosity.

Limited core observations (Gardner, 1974) do suggest shallow-water deposits and diagenetic alteration, including brecciation.

Acquisition of a new core from the Core Energy-St. Charlton #4-30 well provides an opportunity to carefully evaluate the reservoir properties of this formation. The well penetrated at least 188 ft (57 m) of Bass Islands Formation and cored 78 ft (24 m) of the uppermost Bass Islands, along with 42 ft (13 m) of the overlying Bois Blanc Formation (Figure 5). This is the most complete

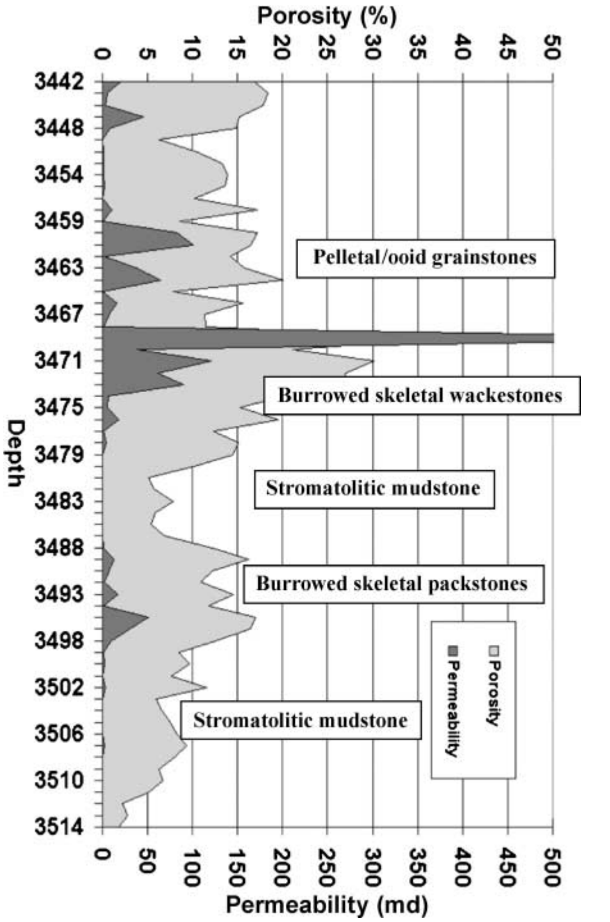

Figure 8. Porosity and permeability from core-plug analyses of the Core Energy-St. Charlton #4-30 well. Generalized facies types are indicated throughout the cored section.

subsurface core sample known for the Bass Islands Formation in Michigan. The Tippecanoe-Kaskaskia sequence-bounding unconformity is apparent in the core at 3442.4 ft (1049.3 m) (Figure 6A). Immediately overlying the unconformity is a bed of brachiopod shells and an abundance of siliceous replacement of the original carbonate. The Bass Islands lithology immediately underlying the unconformity is a dolomitized, bioturbated, skeletal wackestone. This package can be subdivided into several meter-scale, shallowing-upward cycles of stacked facies. The cycles begin with a shallow subtidal, burrowed and bioturbated, skeletal and peloidal wackestone to packstone (Figure 6B). These subtidal facies shallow upward into higher-energy cross-bedded and laminated peloidal grainstones (Figure 6C). The grainstones are capped by laminated and crenulated cyanobacterial mat mudstones that represent high intertidal or supratidal environments with subaerial exposure and represent the top of the shallowing-upward cycle (Figure 6D).

Reservoir Properties

Although the reservoir properties of shallow-water carbonate deposits in the Bass Islands of Michigan are greatly influenced by dissolution and diagenesis, strong fabric characteristics, which are inherited from their original depositional facies character, influence reservoir properties. This carbonate reservoir has some preserved primary porosity, as well as abundant secondary porosity. Dissolution has produced significant secondary pores (Figures 6B; 7A, B). Fossil grains are most vulnerable because dissolution processes have selectively removed grains instead of the finer, micritic matrix (Figure 7C, E, F). In addition to moldic porosity, abundant intercrystalline porosity resulting from dolomitization is observed. In the grainstones, abundant intergranular porosity and significant permeability are observed. Much of the porosity in the grainstones is primary, intergranular porosity, although some pores have been modified into vugs by dissolution. Figure 7D shows a thin section of the cross-bedded grainstone seen in Figure 7C at 3461 ft (1055 m).

Conventional core porosity and permeability (P&P) have been measured from 2-in. (5-cm)-long by 1-in. (2.5-cm)-diameter sample plugs drilled from whole core collected in the Core Energy-St. Charlton #4-30 well. Seventy-four horizontal plugs, 12 vertical plugs, 6 whole cores, and 17 sidewall core plugs were sent to Core Laboratories for routine P&P analyses. Sixty-six horizontal plugs were collected in the Bass Islands reservoir interval. Different facies show substantially different reservoir properties (Figure 8). Intergranular porosity in the grainstone facies is representative of primary porosity that forms useful porosity zones in the Bass Islands in this well. Good porosity also exists as the result of selective dissolution of some carbonate grains producing moldic porosity. This facies is further enhanced by karst dissolution and brecciation to become the best P&P in the entire formation. These facies are relatively thin beds stacked in a series of shallowing-upward packages that follow a predictable stratigraphic framework. This framework can provide a better understanding of the vertical and lateral distribution of the porous reservoir facies.

Stratigraphic Framework

The Bass Islands interval exhibits 5-m (16-ft)-scale cycles nested within two high-frequency sequences (HFS, approximately 10 m [33 ft]) (Figure 9). Sequence and cycle boundaries were determined from core analysis

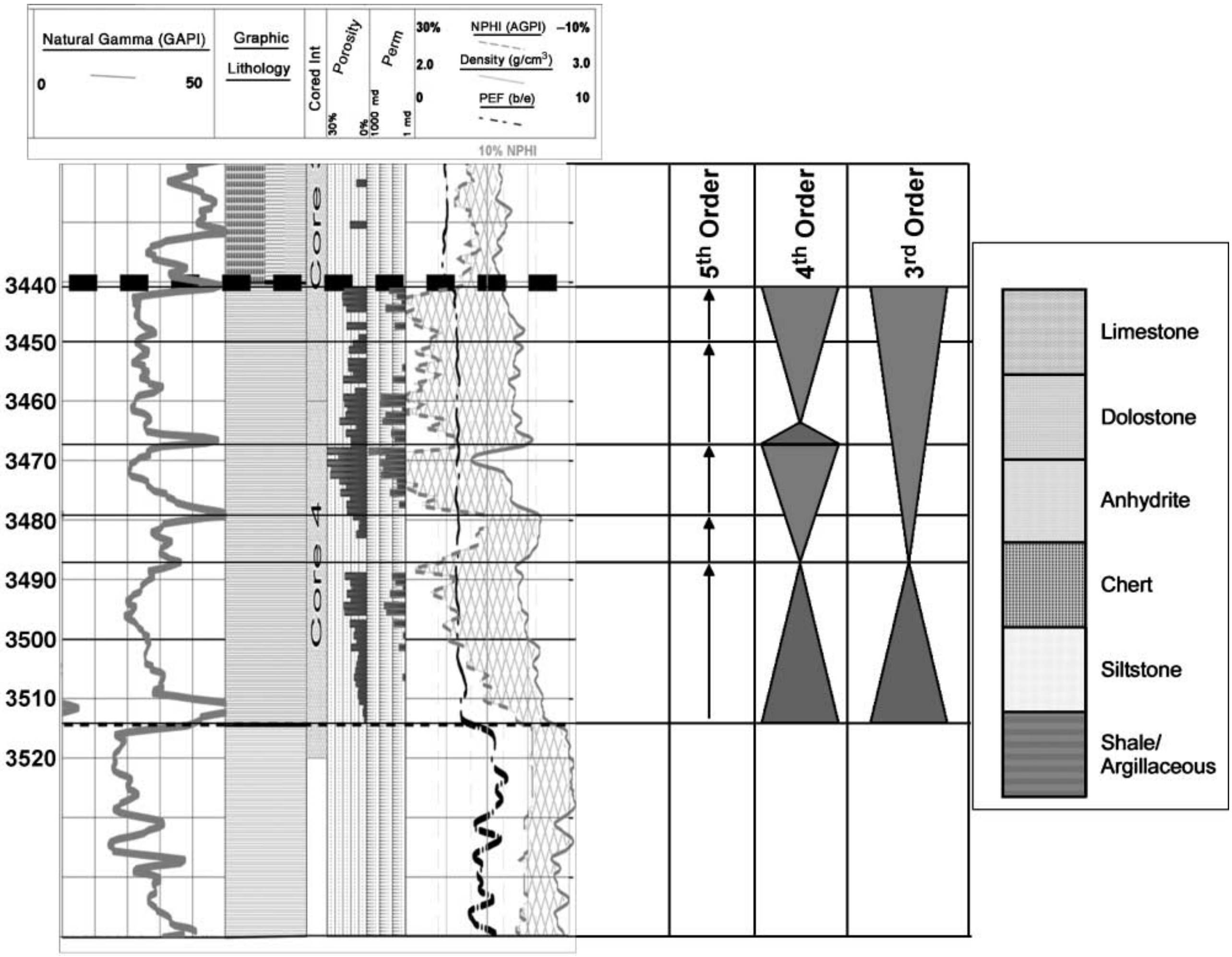

Figure 9. Stratigraphic hierarchy observed in the Bass Islands interval. High-frequency sequences (HFS) along with higher-frequency cycles correlate well to the stratigraphic position of the best reservoir intervals, and many of the HFS and cycle boundaries are manifested by higher gamma-ray log values. Regressive hemicycles of both the HFS and higher-frequency cycles correlate to the best development of reservoir throughout much of the cored interval. NPHI = neutron porosity; PEF = photoelectric factor.

and were specifically based on evidence for subaerial exposure caused by a fall in relative sea level, the presence of flooding surfaces indicating a transgressive event, or vertical successions of facies indicating an overall flooding event followed by a shallowing of facies indicating a relative fall in sea level. Subaerial exposure horizons are marked by brecciation (collapse breccia), solution pipes, and local development of terra rosa, all of which are common diagnostic indicators of exposure (e.g., Esteban and Klappa, 1983). The highest frequency packages are the cycles, which are a maximum of approximately 24 ft (7.3 m) thick and have an average thickness of 14 ft (4.3 m). The HFS range from 28 to 44 ft (8.5 to 13.4 m) thick, and the Bass Islands interval is approximately 72 ft thick (22 m).

Reservoir Intervals

The best reservoir units in the Core Energy-St. Charlton #4-30 core are present in two different intervals. The first is related to solution, brecciation, and recrystallization of limestones caused by subaerial exposure where well-developed interparticle, intercrystalline, and solution-enhanced vugs contribute to the creation of high porosities and permeabilities. The second unit is related to inner platform (midramp) bioturbated facies where the burrow galleries have been preferentially dolomitized with coarser crystalline sucrosic dolomite. Figure 10 illustrates how these types of facies, commonly referred to as tubular tempestites, may be in excellent communication because of the nature of the three-dimensional burrow galleries

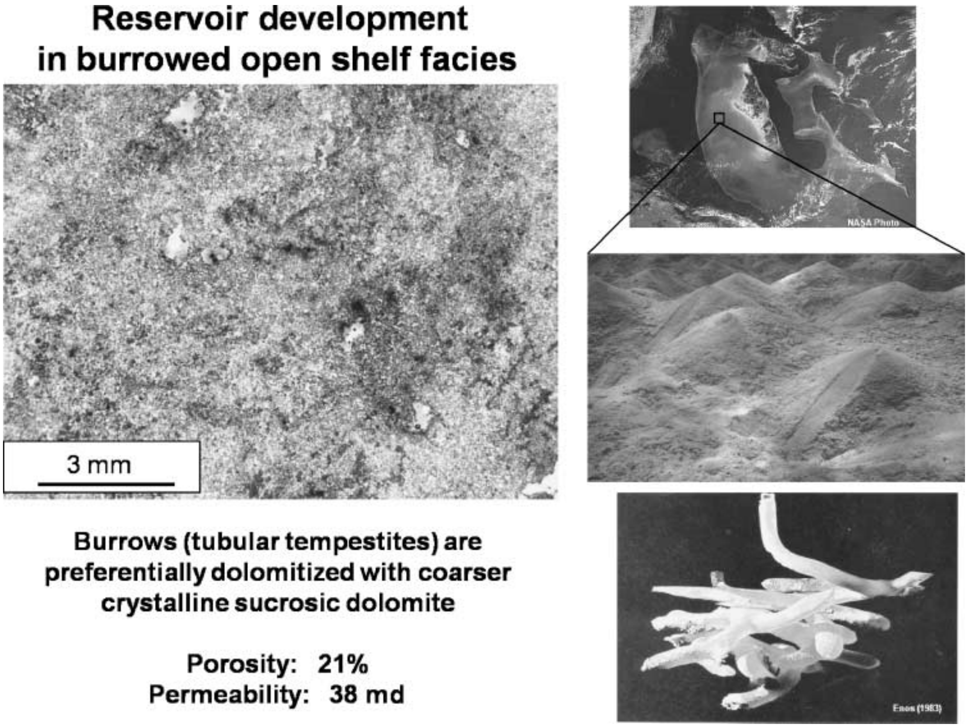

Figure 10. Some of the best reservoirs in the Bass Islands exists in the thoroughly bioturbated inner platform facies. Burrows are of the *Thalassinoides* ichnofacies, which is similar to the three-dimensional galleries formed today by burrowing shrimp (e.g., *Callianassa*). Photograph of the Great Bahama Bank with the location of heavily bioturbated inner platform facies. In many modern environments, these facies may extend for thousands of square kilometers. Note the high density of burrows and three-dimensional distribution of an individual burrow gallery preserved in epoxy, both of which illustrate the potential for such facies to be laterally and vertically connected in three dimensions, commonly leading to excellent reservoir potential. The plastic cast photograph of the ghost shrimp *Callianassa* burrow gallery is courtesy of E. A. Shinn.

and the density of burrows commonly found in similar types of environments.

Reservoir development also correlates well with the stratigraphic framework (Figure 9). Sequence and cycle boundaries were identified by the presence of subaerial exposure horizons as indicated by karstic brecciation and solution, flooding surface, and facies stacking patterns. As mentioned above, a well-constrained hierarchy exists within the Bass Islands interval whereby the higher-frequency cycles exist within two medium-scale HFS. From a reservoir standpoint, the HFS and most of the higher-frequency cycles constrain the development of the best reservoir intervals. Regressive hemicycles of both the HFS and higher-frequency cycles correlate to the best development of the reservoir throughout much of the cored interval. Many of the HFS and cycle boundaries are manifested by higher gamma-ray log values and can be identified in wells without core data. We believe that the correlation of depositional facies observed in core to stratigraphic packages and wireline-log signatures is a powerful tool to help interpret the geologic properties of the Bass Islands interval in other areas throughout Michigan where only wireline logs are available.

CONCLUSIONS

The Bass Islands Formation can be mapped throughout much of northern and central lower Michigan where it is an important saline reservoir target for CO_2 sequestration with more than 40 ft (12 m) of greater than 10% porosity and permeabilities exceeding 500 md. Average porosity in the Bass Islands cored interval in the Core Energy-St. Charlton #4-30 test well is 12.5% and average permeability is 22.4 md.

The Bass Islands in the area of the Core Energy-St. Charlton #4-30 well is composed of a series of shallow-water and tidal flat carbonate facies that are stacked in a predictable shallowing-upward pattern. The Bass Islands Formation seen in this core can be subdivided into two HFS and five higher-frequency cycles. Stratigraphic analysis helps predict vertical and lateral facies patterns and contributes to the evaluation of regional reservoir properties. The best reservoir quality occurs in the subtidal, burrowed packstones that have some dissolution of grains and develop moldic porosity. This facies is also enhanced further by karst dissolution and brecciation related to the Tippecanoe-Kaskaskia sequence-bounding unconformity at the top of the Bass Islands Formation.

Additional porosity can be found in carbonate grainstone facies that preserve some primary intergranular porosity. The shallowest tidal flat or stromatolitic facies show minimal P&P and are likely to be internal baffles or barriers to fluid flow through the formation. In addition, correlation of wireline logs shows that the Bass Islands cyclic porosity seen in the St. Charlton #4-30 well is present throughout the northern part of lower Michigan.

REFERENCES CITED

Barnes, D. A., W. B. Harrison III, and A. Wahr, in press, Assessment of regional geological carbon sequestration potential in Upper Silurian to Middle Devonian strata of the Michigan Basin, *in* M. Grobe, J. C. Pashin, and R. L. Dodge, eds., Carbon dioxide sequestration in geologic media—State of the science: AAPG Studies in Geology 59.

Catacosinos, P. A., P. A. Daniels Jr., and W. B. Harrison III, 1991, Structure, stratigraphy, and petroleum geology of the Michigan Basin, *in* M. W. Leighton, D. R. Kolata, D. F. Oltz, and J. J. Eidel, eds., Interior cratonic basins: AAPG Memoir 51, p. 561–602.

Esteban, M., and C. F. Klappa, 1983, Subaerial exposure environment, *in* P. A. Scholle, D. G. Bebout, and C. H. Moore, eds., Carbonate depositional environments: AAPG Memoir 33, p. 1–95.

Gardner, W. C., 1974, Middle Devonian stratigraphy and depositional environments in the Michigan Basin: Michigan Basin Geological Society Special Paper 1, 138 p.

Grammer, G. M., D. A. Barnes, W. B. Harrison III, and A. E. Sandomierski, in press, Practical synergies for increasing domestic oil production and geological sequestration of anthropogenic CO_2: An example from the Michigan Basin, *in* M. Grobe, J. C. Pashin, and R. L. Dodge, eds., Carbon dioxide sequestration in geologic media—State of the science: AAPG Studies in Geology 59.

Lane, A. C., C. S. Prosser, W. H. Sherzer, and A. W. Grabau, 1909, Nomenclature and subdivision of the Upper Silurian strata of Michigan, Ohio and western New York: Geological Society of America Bulletin, v. 19, p. 553–556.

Lilienthal, R. T., 1978, Stratigraphic cross-sections of the Michigan Basin: Department of Natural Resources, Geological Survey Division, Report of Investigation No. 19, 36 p.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 75, p. 93–113, doi:10.1130/0016-7606(1963)74[93:SITCIO]2.0.CO;2.

Sparling, D. R., 1970, The Bass Islands Formation in its type region: The Ohio Journal of Science, v. 70, no. 1, p. 1–33.

U.S. Department of Energy, 2007, Carbon sequestration atlas of the United States and Canada: Pittsburgh, Pennsylvania, National Energy Technology Laboratory, 86 p.