Biogenically enhanced permeability: A petrographic analysis of Macaronichnus segregatus *in the Lower Cretaceous Bluesky Formation, Alberta, Canada*

John B. Gordon, S. George Pemberton, Murray K. Gingras, and Kurt O. Konhauser

ABSTRACT

A detailed petrographic analysis was conducted on several core samples from the Cretaceous-aged Bluesky Formation in the La Glace area in Alberta, Canada. Within the gas-producing zone of these upper shoreface sediments, a fine- to mid-medium-grained chert-rich litharenite is intensely bioturbated with *Macaronichnus segregatus*. Petrographic analysis showed that the burrow mantle is generally lined with dark-colored, iron-rich (mainly chert, shale clasts, and organic grains) fragments, whereas the burrow fill contained mainly quartz and light-colored chert fragments. The reason for the dark-colored grain segregation of the tracemaker is unclear, but in the Bluesky Formation presented in this study, grain segregation has improved the reservoir quality by effectively resorting compaction- and cement-resistant chert and quartz into the burrow fill. Primary reservoir quality can be preserved in the presence of chert as pore-occluding quartz overgrowths do not form on chert fragments as they do on monocrystalline quartz, thus leaving open, well-connected primary pores and hence elevated permeability. Chert fragments are resistant to the effects of mechanical compaction and are not easily squeezed into adjacent pore spaces as are ductile rock fragments. Further research is needed

Manuscript received October 12, 2009; provisional acceptance December 4, 2009; revised manuscript received January 15, 2010; final acceptance April 6, 2010.
DOI:10.1306/04061009169

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ACKNOWLEDGEMENTS

The authors thank Richard Evoy from Suncor Energy Inc. for offering the use of the petrographic equipment and the Scanning Electron Microscope. Jason Lavigne from Talisman Energy graciously donated the use of the 100/06-24-076-07W6/00 slabbed core. Jussi Hovikoski from the University of Alberta is thanked for offering his time for the instruction on the minipermeameter and core handling. Bradley Connatty from Suncor Energy Inc. is thanked for the last minute graphics help. Funding for this research was generously provided by the Natural Sciences and Engineering Research Council Operating Grants to M. K. Gingras, S. G. Pemberton, and K. Konhauser and an equipment grant to M. K. Gingras. The Alberta Science Research Authority is also thanked for a generous equipment grant made to K. Konhauser and S. G. Pemberton. The authors acknowledge the Canada Research Chairs program for their support. This manuscript greatly benefited from the expert reviews of Ed Clifton, David E. Eby, Howard J. White, Hugh Balkwill, and two anonymous reviewers. The AAPG Editor thanks the following reviewers for their work on this article: David E. Eby, Howard J. White, and an anonymous reviewer.

EDITOR'S NOTE

Color versions of Figures 1–15 may be seen in the online version of this article.

to test the chemical constituents of the grains that modern tracemakers ingest. This may lead to a better understanding of why sands burrowed with *Macaronichnus* and similar burrowed sediment can have elevated reservoir quality.

INTRODUCTION

Petrography can be a useful technique in assessing reservoir quality in sediments; it presents informative views of mineralogical controls affecting reservoir quality but is commonly overlooked because of the reliance on wireline log analysis and other large-scale reservoir evaluation methods such as numerical modeling. Petrography potentially provides a window into small-scale burrow-associated heterogeneities that influence the flow characteristics of hydrocarbon reservoir rocks. The Lower Cretaceous (Albian to Aptian) Bluesky Formation in the La Glace area of western Alberta, Canada, represents a high-energy, upper shoreface succession that provides an excellent case study for the utility of petrographic analysis pertaining to biogenically enhanced reservoir quality because (1) the Bluesky Formation is a significant gas-bearing reservoir in the area, (2) locally good core control is observed, and (3) burrow-associated enhanced permeability is evident. The La Glace field is located approximately 50 km (31 mi) northwest of Grande Prairie, Alberta, Canada (Figure 1).

The focus of this article is to present the results of petrographic techniques (thin-section and scanning electron microscopy), along with conventional core analysis and minipermeametry data, in an attempt to explain the elevated permeability and associated reservoir quality of the intensely bioturbated *Macaronichnus segregatus* zone of these upper shoreface sandstones that lies within the gas producing zone. Six cores were described in detail from the Bluesky Formation in the La Glace field, but to avoid repetition, only one (100/06-24-074-07W6/00) is presented below and discussed herein.

Biogenic alterations of reservoir flow and storage include a local increase of porosity and permeability. These can be due to the reorganization of the sediment fabric associated with animal burrowing or result from heterogeneous cement distribution influenced by the bioturbate texture. Biogenic enhancement of reservoir character may be especially important for play development in unconventional, thinly bedded, silty to muddy, low-permeability reservoirs that have been recently exploited in the United States and, in particular, western Canada where high-reserve and high-deliverability plays are nearing an end.

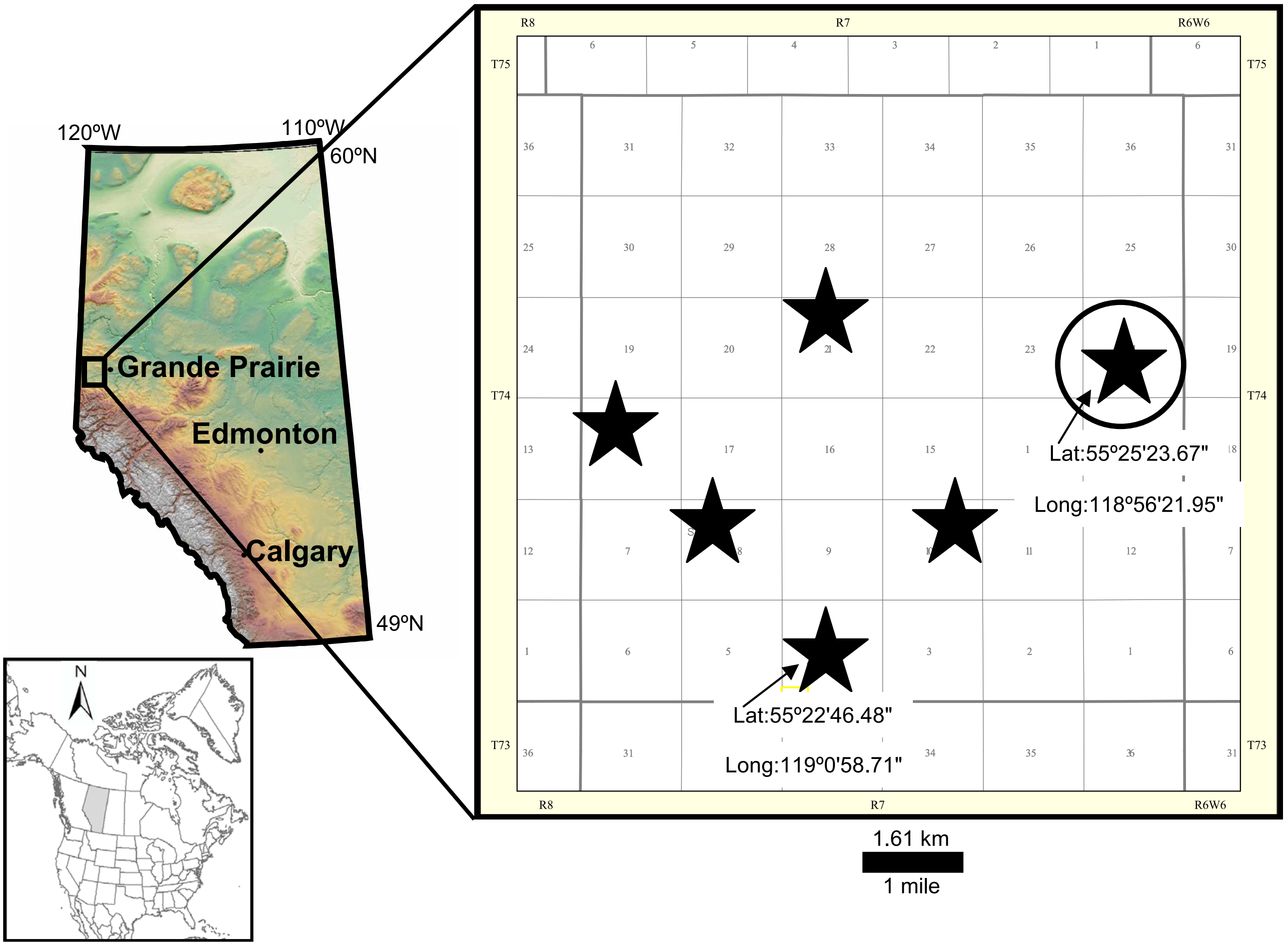

Figure 1. Study area map. The box indicates the La Glace area. Stars indicate cored wells viewed. The circle shows the location of 06-24-074-07W6 that was described in detail for this study.

STUDY AREA AND GEOLOGICAL SETTING

The study area is located in township 074 and range 07 west of the sixth meridian in western Alberta, Canada (Figure 1). Within the La Glace field, the Bluesky Formation produces from four pools with initial established reserves of 1502 × 10^6 m^3 (53,043 ft^3) (Walsh, 1999).

The Cretaceous (Aptian to Albian) Bullhead Group of the Western Canada sedimentary basin was deposited during a major episode of subsidence and sedimentation. The strata comprise mainly clastic rocks derived from older strata as a result of a long period of uplift, exposure, and erosion (Mossop and Shetsen, 1994). The lower Albian sediments were deposited during a regional southward transgression of the Moosebar Sea and are stratigraphically complex and widely distributed (Brekke, 1995).

Figure 2 shows a stratigraphic chart with the northwest plains terminology used in this study. The lower Albian Bluesky Formation of the Fort St. John Group is overlain conformably by the shales of the Wilrich Member and underlain by the sandstones, shales, and coals of the Gething Formation. It correlates with the Glauconitic Sandstone of the Mannville Group of central Alberta, Canada, and with the Wabiskaw Member of the Clearwater Formation of northern Alberta, Canada. The reservoir strata of the Bluesky Formation at La Glace were interpreted by O'Connell (1997) as representing fluvial to estuarine deposits that overlie a lowstand unconformity, which in turn is overlain by highstand shoreface deposits.

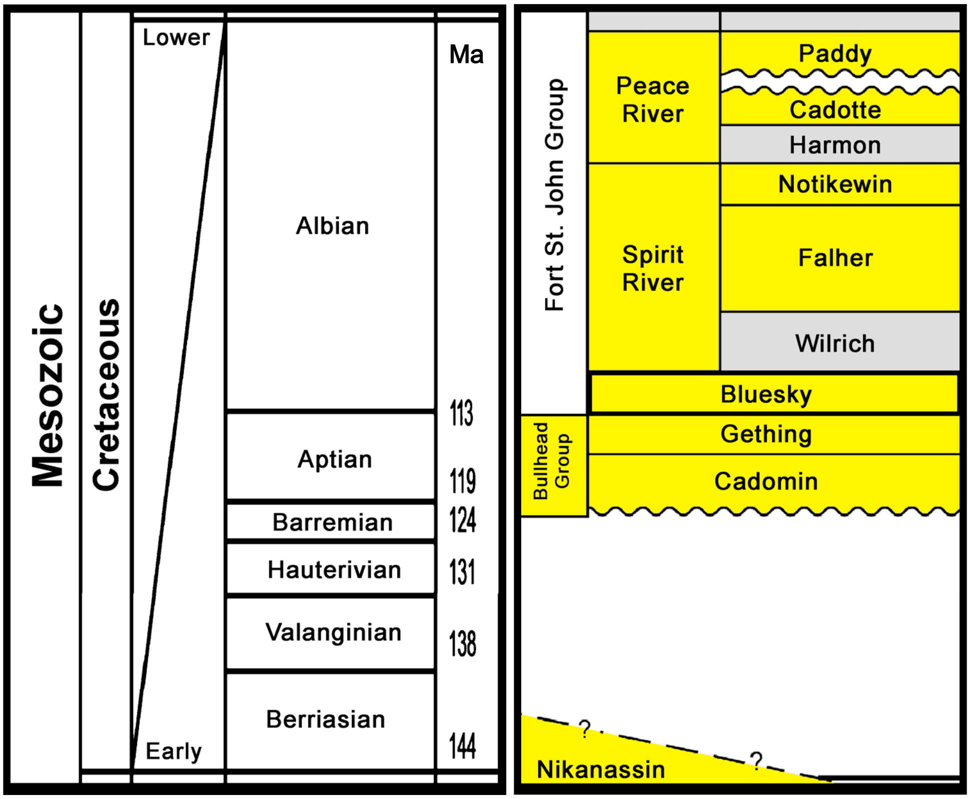

Figure 2. Geological time scale showing the stratigraphic nomenclature for the La Glace area. The Bluesky Formation is highlighted by a black box. Dark gray indicates shales and light gray (yellow in color version) indicates sandstones.

PREVIOUS WORK ON *MACARONICHNUS SEGREGATUS*

Clifton and Thompson (1978) first described *M. segregatus* as a deposit-feeding behavior of polychaete worms as they search for food in modern, high-energy, well-oxygenated, near-shore sediments. They observed that these polychaetes ingest light-colored minerals such as quartz and feldspar while avoiding dark-colored mafic minerals, leaving the burrow fill lighter in color than the host sediment. Saunders (1989) recognized three distinct forms of *Macaronichnus* in the Upper Cretaceous Horseshoe Canyon Formation in Alberta, Canada, differentiated on the basis of foraging pathway configurations: (1) *Macaronichnus simplicatus*, characterized by random interpenetrating burrows; (2) *M. segregatus*, also characterized by random burrows but showing an avoidance of interpenetration structures; and (3) *Macaronichnus spiralis*, characterized by distinct planispiral configurations. Pemberton et al., (2001) described the presence of *M. segregatus* to be a diagnostic of the foreshore and upper shoreface depositional environment. Pemberton and Gingras (2005) demonstrated that permeability enhancement and vertical transmissivity can be enhanced in relatively low permeable sediments by bioturbation and the subsequent filling of burrows with contrasting sediment from overlying deposits. Pemberton and Gingras (2005) concluded that the grain segregation and passive sorting of *M. segregatus* have led to elevated reservoir quality.

METHODOLOGY

Six Bluesky Formation cores were examined for this study in township 074, range 07W6 in the La Glace field (Figure 1). All six cores showed elevated permeability within the *Macaronichnus* burrowed zone, but only one well (Talisman La Glace 100/06-24-074-07W6) was studied in petrographic detail forming the central part of this article. Figure 3 shows a schematic display of the core. Three hundred and twenty-eight spot-permeability measurements were taken along the core's length at

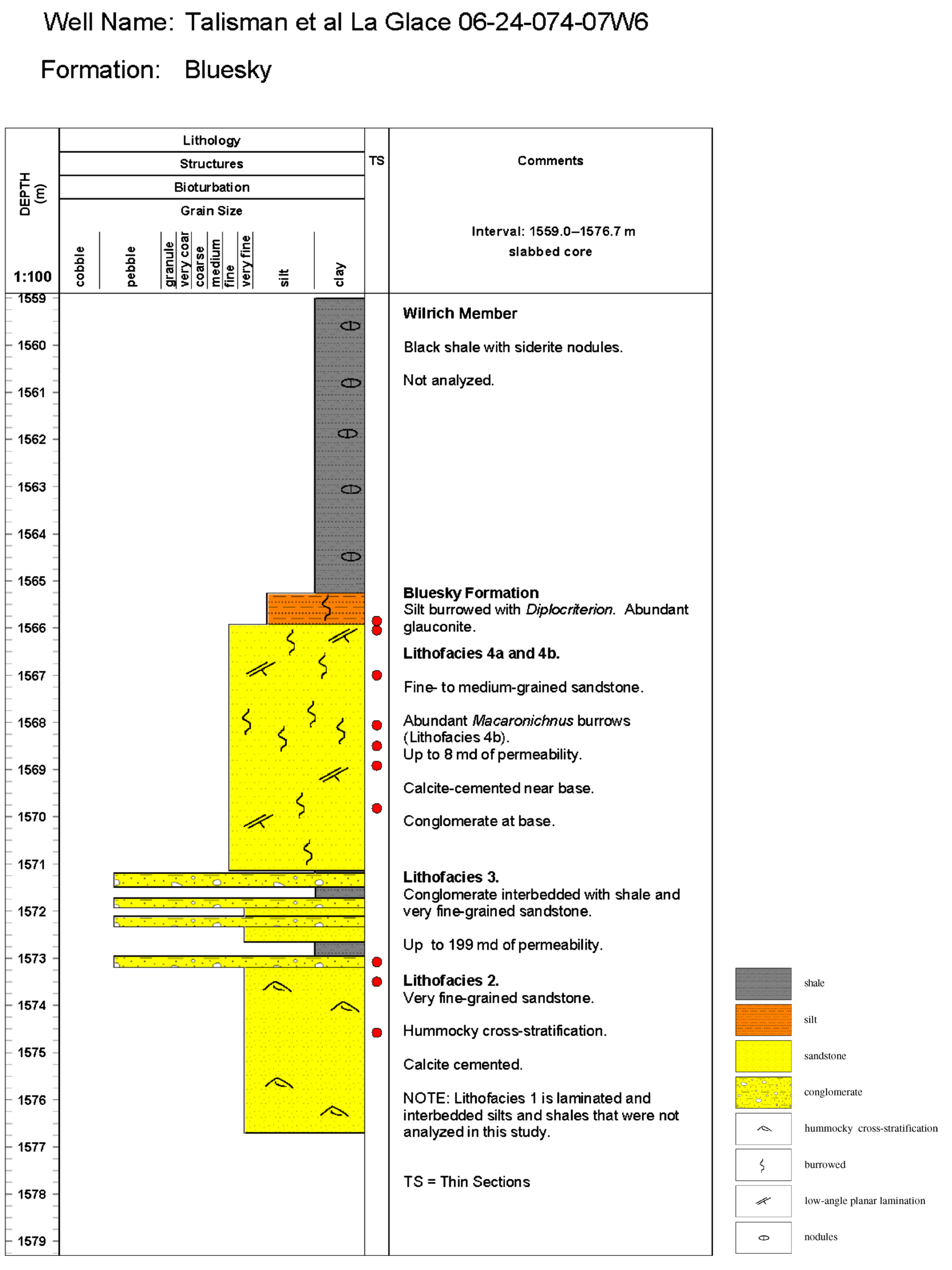

Figure 3. Core description for 100/06-24-074-07W6/00.

Table 1. Thin-Section Point-Count and Grain-Size Data

Depth	Texture				Framework Grains (%)					
Meters (m)*	Mean Framework Grain Size (Phi)	Wentworth Classification**	Sorting (Standard Deviation of Phi)	Sorting†	Monocrystalline Quartz	Polycrystalline Quartz	Feldspar	Light-Colored Chert	Dark-Colored Chert	Sedimentary Rock Fragments
Lithofacies 4a: Fine to Medium-Grained Low-Angle Cross-Stratified Sandstone										
SP 2 1565.85	1.94	LM	0.59	MS	23.0	4.0	0.5	18.5	20.0	15.0
SP 3 1566.05	1.93	LM	0.53	MWS	22.5	9.5	0.5	19.0	19.5	9.5
SP 8 1567.00	2.16	UF	0.41	WS	23.5	10.0	3.5	14.5	6.0	18.5
SP 13 1568.22	2.11	UF	0.48	WS	20.5	6.0	0.0	12.5	12.5	2.5
SP 16 1568.92	1.77	LM	0.44	WS	20.5	9.5	0.0	14.5	10.0	16.5
SP 20 1569.82	2.36	UF	0.36	WS	19.0	9.0	0.0	15.5	11.0	28.0
Lithofacies 4b: Fine to Medium-Grained Intensely Bioturbated Sandstone										
SP 10 1567.5	1.57	MM	0.37	WS	17.0	10.0	0.0	20.0	22.5	7.0
Lithofacies 3: Pebbly Sandstone to Localized Matrix-Supported Conglomerate										
SP 28 1572.45	1.51	MM	0.66	MWS	10.5	4.0	0.0	36.5	18.0	4.0
Lithofacies 2: Fine-Grained, Low-Angle Cross-Stratified, Carbonate-Cemented Sandstone										
SP 29 1572.82	2.24	UF	0.39	WS	20.0	5.0	0.0	10.0	8.0	17.0
SP 31 1574.58	2.75	MF	0.32	WS	19.0	6.0	0.0	10.0	6.0	30.0

*SP = small plug.
**LM = lower medium; UF = upper fine; MM = mid-medium; MF = mid-fine.
†MS = moderately sorted; MWS = moderately well sorted; WS = well sorted.

approximately 2-cm (0.7-in.) intervals using a miniprobe permeameter to obtain data on permeability heterogeneity. A 7 × 12 measurement spot-permeability grid was preformed using 84 spot-permeability measurements over an area of core within the intensely bioturbated zone spaced approximately 1 cm (0.3 in.) apart. These data were mapped in an attempt to show the bioturbation behavior of *M. segregatus*. Routine porosity and permeability core analyses were performed on 32 one-inch (2.5 cm) core plugs. Ten representative samples from the 1-in. (2.5-cm) core plugs were chosen for standard format thin sections. Before preparation, the samples were impregnated with a blue-dyed epoxy resin to identify porosity and to preserve pore-filling material. The samples were stained with Alizarin Red S to differentiate calcite and dolomite, and with potassium ferricyanide to identify ferroan calcite and ferroan dolomite.

A detailed petrographic analysis was performed from the thin sections, including no less than 100-point long-axis grain-size measurements and a 200-point count per sample mineral inventory of framework and authigenic mineral phases (Table 1). The 95% confidence limit on the point-count data for 200 counts is less than ±7%. This is considered an acceptable error for the purpose of this study, which is to show general mineralogical trends that may have an influence on reservoir quality.

Scanning electron microscopy and x-ray dispersive analysis were used to further refine mineral chemistry. Simple image analysis was used on an overview scan of a thin section representing *Macaronichnus* to segregate light and dark minerals into only two colors (black and white respectively) to better illustrate the unique behavior of *Macaronichnus*.

LITHOFACIES, PETROGRAPHY, AND RESERVOIR QUALITY

The Bluesky Formation at La Glace can be divided into five distinct lithofacies based on lithology, sedimentary structures, ichnofossil assemblages, petrographic analysis, and reservoir quality. Figure 4

			Authigenic Minerals (%)				Matrix	Reservoir		
Volcanic Rock Fragments	Metamorphic Rock Fragments	Glauconite + Altered Glauconite	Silica Cement	Ferroan Carbonate Cement	Kaolinite	Pyrite	Pseudomatrix	Core Analysis Porosity (%)	Core Analysis Permeability (md)	Thin-Section Point-Count Porosity (%)
0.5	2.5	trace	3.5	0.5	5.5	0.0	0.0	11.90	1.39	6.5
1.5	2.5	trace	3.5	0.0	6.5	1.0	0.0	14.00	2.36	4.5
2.5	2.0	trace	5.0	0.0	3.0	1.0	10.0	10.00	0.22	1.5
10.0	2.0	trace	1.0	28.0	3.5	1.0	0.0	5.40	0.01	0.5
3.5	4.5	trace	2.5	5.5	4.0	2.5	0.0	11.10	1.68	6.5
2.5	2.0	trace	2.0	5.0	0.0	3.0	0.0	8.50	0.21	3.0
2.5	2.0	trace	3.5	0.0	5.0	1.0	0.0	13.10	8.43	9.5
1.5	1.5	trace	1.0	5.5	5.5	0.5	0.0	14.00	199.00	11.5
2.0	2.5	trace	1.0	28.0	5.0	0.5	0.0	4.20	0.01	1.0
2.5	3.0	trace	2.5	9.0	5.0	1.0	0.0	11.30	0.57	6.0

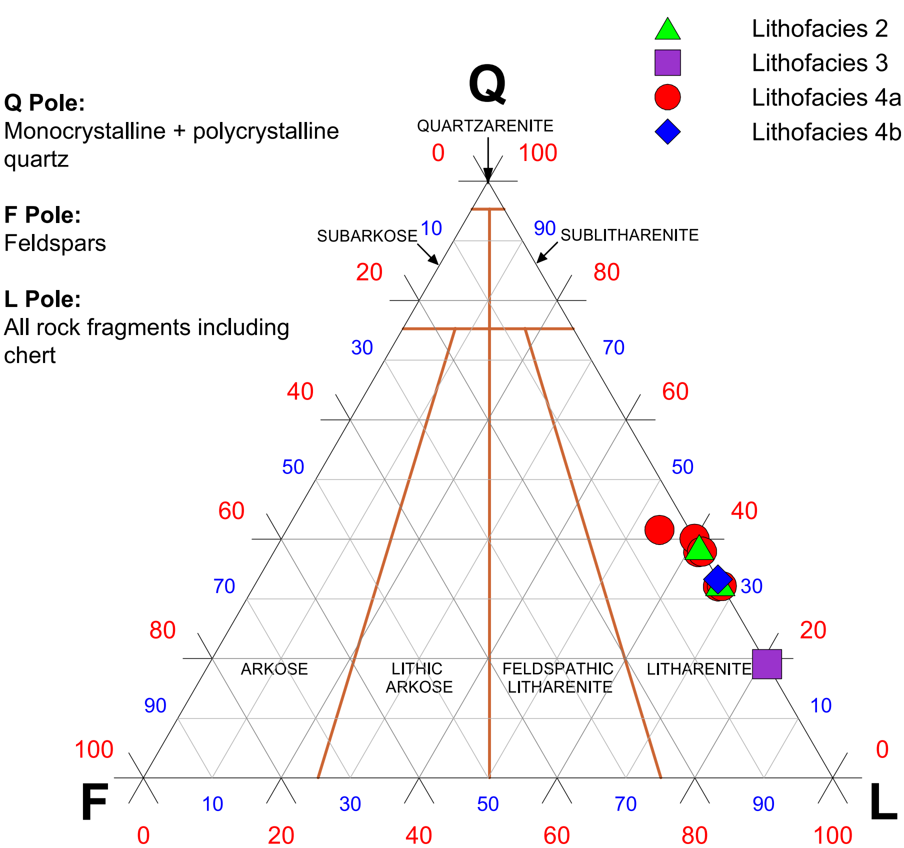

Figure 4. Folk (2002) ternary plot showing petrographic data.

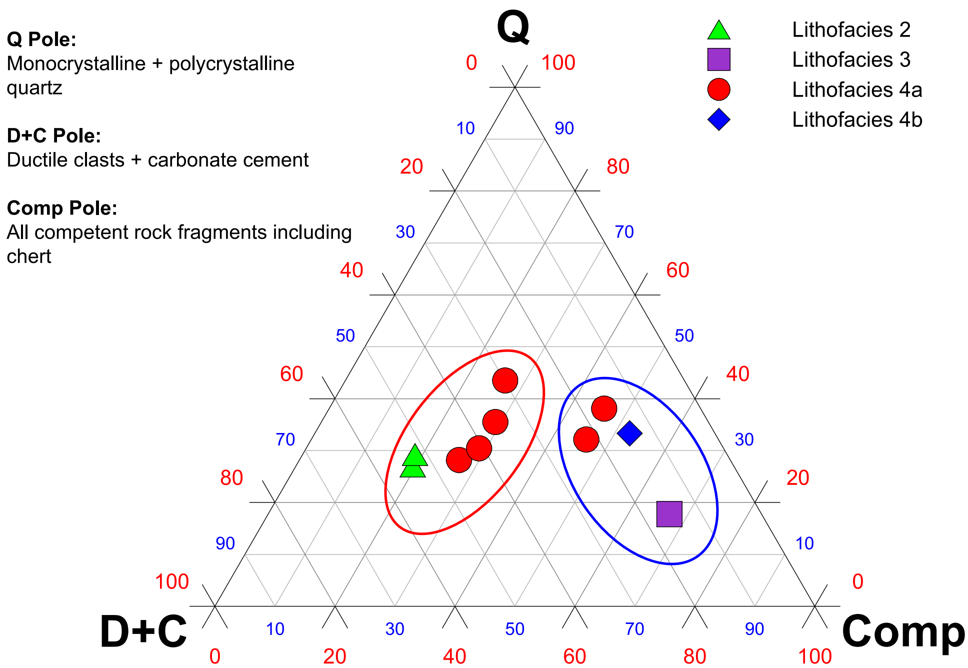

Figure 5. Modified ternary plot with quartz (Q), competent clasts (Comp), and ductile and carbonate cement (D + C) as end members. This plot shows the distinction between reservoir (circle on the right) and nonreservoir rocks (circle on the left). A 1-md cutoff was used in this study to define reservoir versus nonreservoir rock.

shows all point-count data plotted on a Folk (2002) ternary diagram. Petrographically, all samples taken from the 06-24-074-07W6 core are chert-rich litharenites and chert-pebble conglomerate. Figure 5 is a modified ternary diagram showing a distinction between lithofacies with best reservoir quality and poorest reservoir quality. Poor reservoir quality for this study was determined to be lees than 1 md of permeability. The rocks with the best reservoir quality have the highest chert content, whereas the rocks with the poorest reservoir quality have the highest ductile rock fragment content and carbonate cement.

Note that a wide disparity between core analysis porosity and thin-section point-count porosity exists. This is due to microporosity in pore-occluding kaolinite and microporous sedimentary rock fragments. This type of porosity (up to 6% in some samples) may be considered ineffective. Therefore, thin-section point-count porosity can be considered a good proxy for effective porosity.

Lithofacies 1: Interbedded Sand and Shale

This facies exhibits 1–3-cm (0.3–1.1-in.) organic-rich shale interbedded with coarser gained sandstones (Figure 6). This lithofacies was not analyzed petrographically.

Lithofacies 2: Fine-Grained, Low-Angle Cross-Stratified, Carbonate-Cemented Sandstone

Lithofacies 2 (Figure 7A) consists of light gray, fine-grained sandstones with low-angle cross-stratification, interpreted to be hummocky cross-stratification, and internal scour surfaces. Trace fossils are rare and generally absent, but where present, they are representative of the *Skolithos* ichnofacies. Carbonate cement is pervasive throughout. This lithofacies is interpreted as high-energy storm deposits.

Petrographically, this lithofacies is a well-sorted, subangular to subrounded, mid- to upper fine-grained litharenite (Figure 7B). The framework minerals are dominated by monocrystalline quartz (20% average) and chert (10% average light colored and 7% average dark colored). Sedimentary rock fragments (24% average) are mainly detrital carbonate fragments and minor illitic shale clasts. Polycrystalline quartz (6% average), volcanic rock fragments (2% average), and metamorphic rock fragments (3% average) make up the remainder of the detrital clasts. The authigenic minerals are dominated by ferroan carbonate cement (19% average). Silica cement (2% average) occurs as syntaxial overgrowths on monocrystalline quartz grains, kaolinite (5% average) is

Figure 6. Lithofacies 1: Interbedded sand and shale. This facies exhibits 1–3-cm-thick (0.3–1.1-in.) organic-rich shale interbedded with coarser gained sandstones and was not analyzed petrographically (scale is 10 cm [4 in.] long).

likely the result of feldspar degradation, and pyrite (1% average) is also present.

Reservoir quality of the lithofacies is poor because of pervasive ferroan carbonate cement (Figure 7B). Core porosities range from 4 to 11%, but poor pore connectivity is evident from poor permeability values of 0.01 and 0.57 md. Spot permeametry measurements show localized permeability up to 1 md.

Lithofacies 3: Pebbly Sandstone to Localized Matrix-Supported Conglomerate

Lithofacies 3 (Figure 8A) consists of dark gray, upper fine- to mid-medium-grained chert-rich sandstone and chert pebble matrix-supported conglomerate. These beds are generally thin (10–20 cm [4–8 in.]) and are separated by fining-upward sands and shales.

Petrographically, lithofacies 3 is a moderately well-sorted, but locally poorly sorted, dominantly mid-medium-grained, pebbly litharenite to localized matrix-supported chert-pebble conglomerate (Figure 8B). Chert (37% average light colored and 18% average dark colored) dominates the framework grains. Monocrystalline quartz (11% average) is also present. Polycrystalline quartz (4% average), sedimentary rock fragments (4% average), volcanic rock fragments (2% average), and metamorphic rock fragments (2% average) make up the remainder of the detrital clasts. The authigenic minerals include ferroan carbonate cement (6% average), silica cement (1% average), kaolinite (6% average), and pyrite (1% average).

Reservoir quality of this lithofacies is excellent (Figure 8B). Core porosity is 14% and permeability is 199 md. However, this zone was not the primary target of oil and gas companies because it is, in general, very thin and may be water wet.

Lithofacies 4a: Fine- to Medium-Grained Low-Angle Cross-Stratified Sandstone

Lithofacies 4a (Figure 9A) includes dark gray, upper fine-grained, chert-rich sandstones that are in sharp contact with the overlying glauconitic sands and sideritic shales of the Wilrich Member. Low-angle cross-stratification is abundant. Rare small-scale trough cross-beds occur at the top of this unit. Rare internal scour structures are also present. Thin organic-rich shales lie near the base. Carbonate cement is present but pervasive near the base. Localized *Macaronichnus* burrows are present, suggesting deposition in a shallow, high-energy shoreface environment.

Petrographically, this lithofacies is a moderately well to well sorted, upper fine- to lower medium-grained, subangular to subrounded litharenite (Figure 9B, C). Chert (16% average light colored and 13% average dark colored) and monocrystalline quartz (11% average) dominate the framework

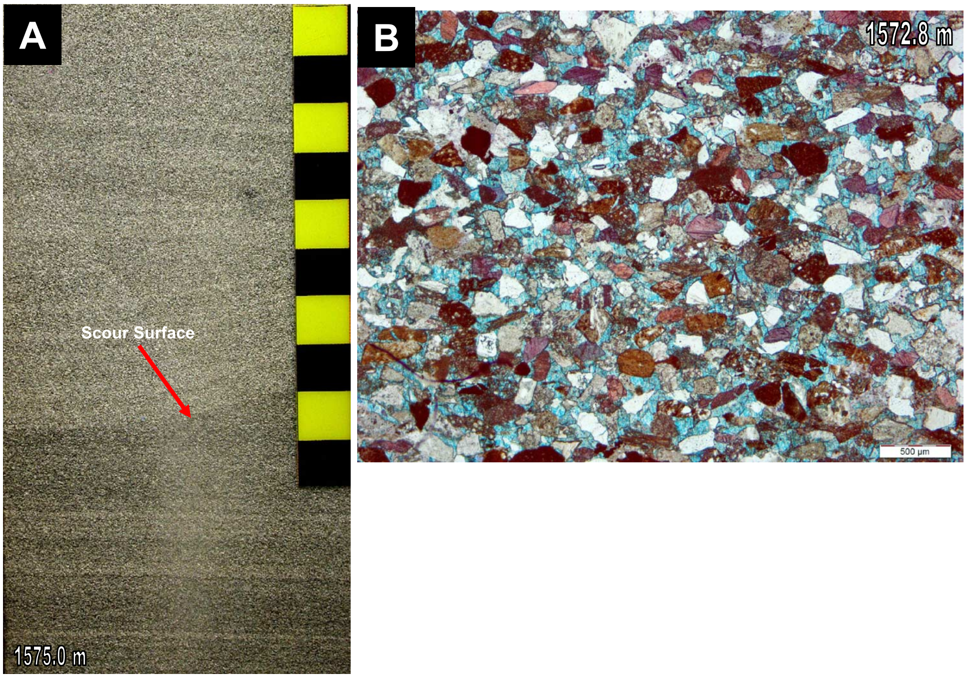

Figure 7. Lithofacies 2: fine-grained, low-angle cross-stratified, carbonate-cemented sandstone. (A) Light gray, fine-grained sandstones with hummocky cross-stratification, and internal scour surfaces. Carbonate cement is pervasive throughout (scale is 10 cm [4 in.] long). (B) Well-sorted, subangular to subrounded, mid- to upper fine-grained litharenite. Some porosity is still preserved, but pervasive ferroan carbonate cement fills almost all porosity.

grains. Sedimentary rock fragments (15% average), polycrystalline quartz (8% average), volcanic rock fragments (3% average), metamorphic rock fragments (3% average), and plagioclase feldspar (1% average) represent the remainder of the detrital clasts. One sample at 1567.0 m (5141 ft) contains 10% pseudomatrix resulting from the mechanical compaction of illitic and micaceous shale clasts into adjacent pore space. The authigenic minerals include localized ferroan carbonate cement (11% average), silica cement (3% average), kaolinite (5% average), and pyrite (1% average).

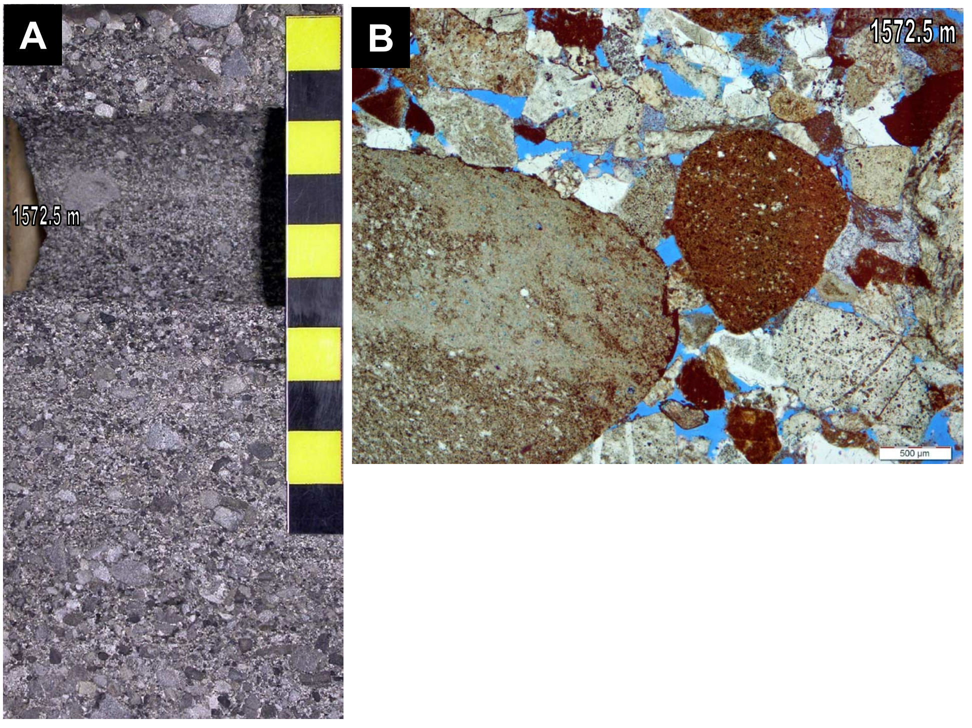

Figure 8. Lithofacies 3: pebbly sandstone to localized matrix-supported conglomerate. (A) Dark gray, upper fine- to mid-medium-grained chert-rich sandstone and chert-pebble matrix-supported conglomerate. These beds are generally thin (10–20 cm [4–9 in.]) and are separated by fining-upward sands and shales (scale is 10 cm [4 in.] long). (B) Moderately well sorted, but locally poorly sorted, dominantly mid-medium-grained, pebbly litharenite to localized matrix-supported chert-pebble conglomerate. Porosity preservation is excellent.

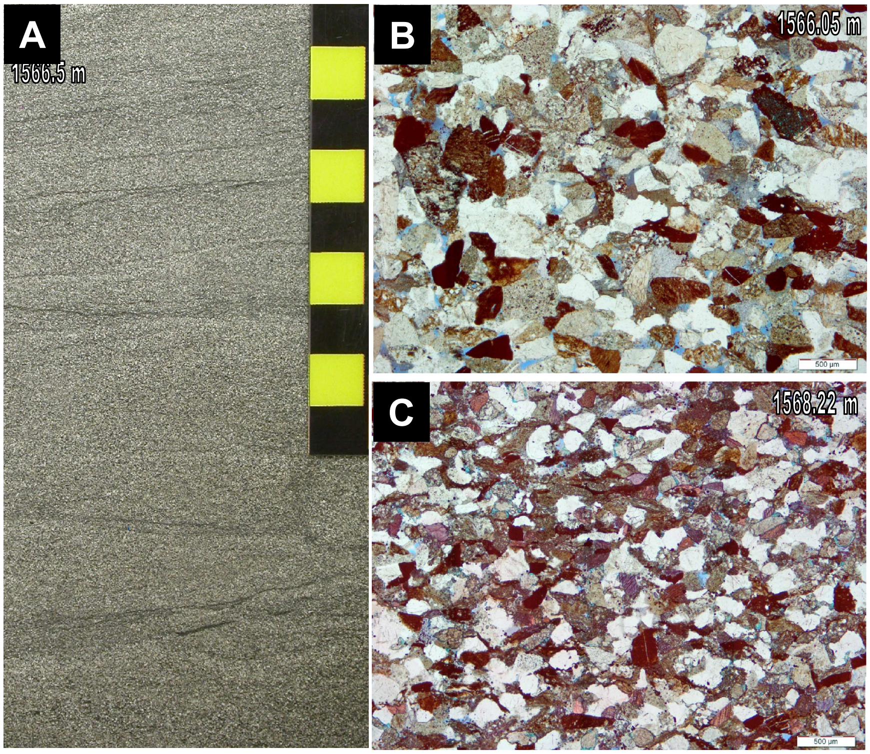

Figure 9. Lithofacies 4a: fine-grained low-angle cross-stratified sandstone. (A) Dark gray, upper fine-grained, chert-rich sandstones with low-angle cross-stratification. Rare small-scale trough cross-beds occur at the top of this unit. Rare internal scour structures are also present. Carbonate cement is present but pervasive near the base. Minor *Macaronichnus* burrows are present (scale is 9 cm [3 in.] long). (B) Moderately well sorted to well-sorted, upper fine- to lower medium-grained, subangular to subrounded litharenite. (C) Finer grained than above and carbonate cemented (this sample was taken near the base of the unit).

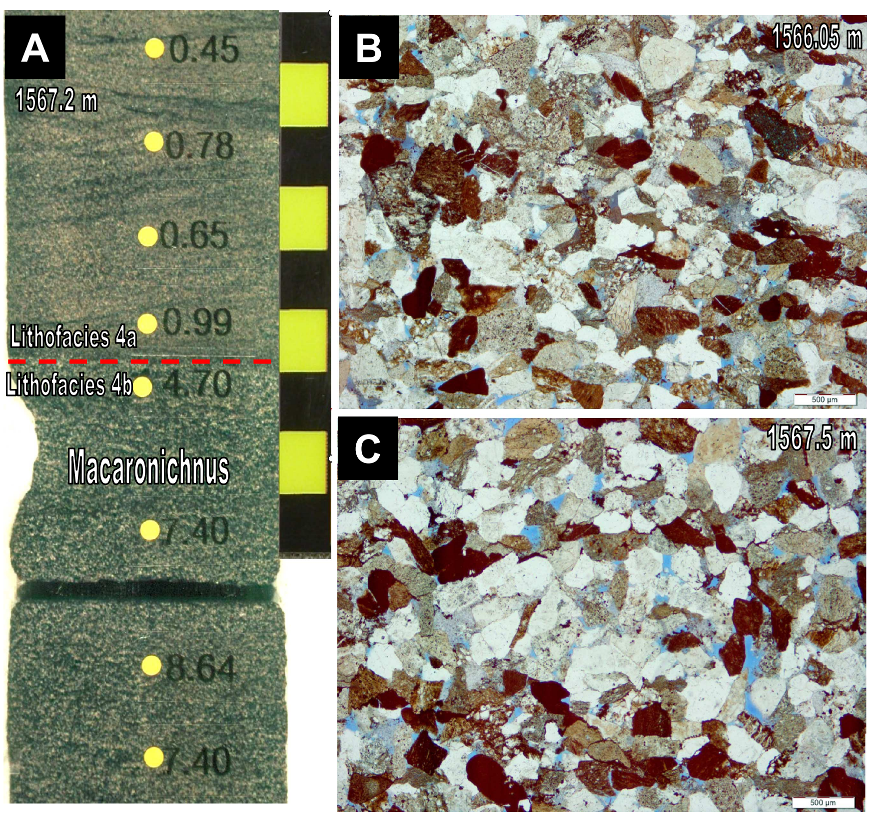

Figure 10. Lithofacies 4b: fine- to mid-medium-grained intensely bioturbated sandstone. (A) Sharp contact between lithofacies 4a and 4b, which is completely burrowed with *Macaronichnus*. Note the elevated profile permeability measurements across the contact (scale is 9 cm [3 in.] long and permeability is in millidarcies). Permeability increases by an order of magnitude across the contact. (B) This photomicrograph shows chaotic sorting of light- and dark-colored grains. (C) This photomicrograph shows a *Macaronichnus* burrow with dark grains forming the halo and light-colored quartz and chert as the burrow filling.

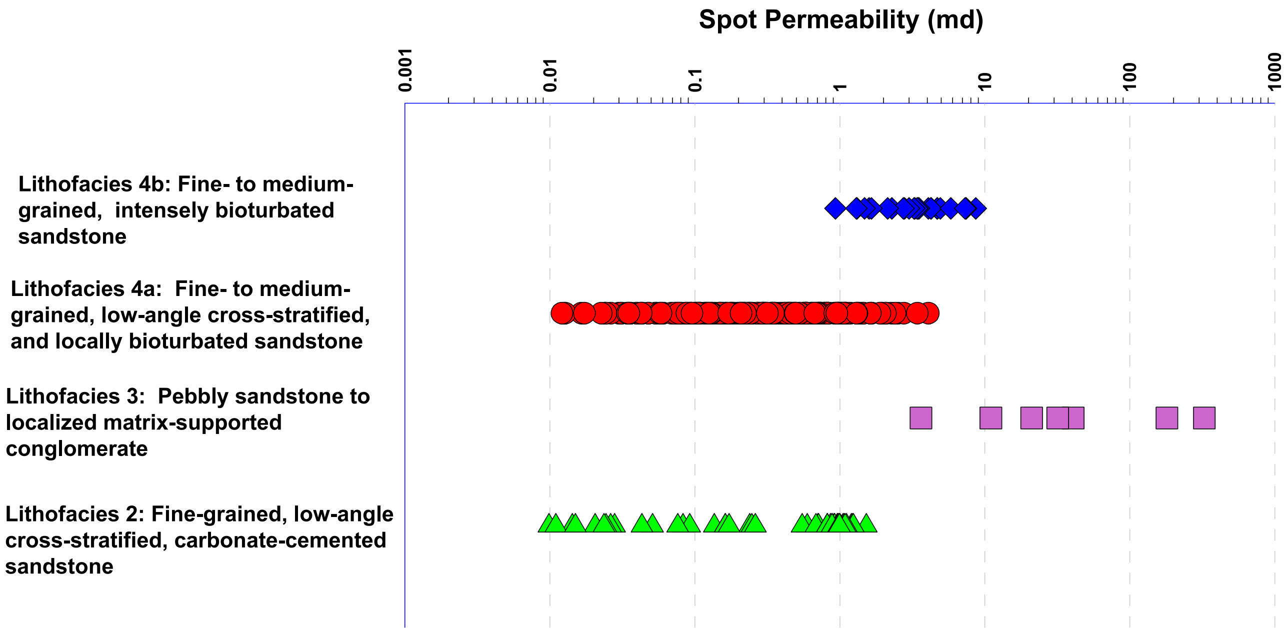

Figure 11. Spot-permeability measurements by lithofacies. These data show that very little permeability variation in the *Macaronichnus* burrowed facies exists. The permeability in this lithofacies ranges from 1 to 10 md. A greater range of permeability in lithofacies 4a is observed. Although some permeability measurements are above 1 md in lithofacies 4a, most permeability measurements fall well below. Lithofacies 3 shows the best permeability but is not a reservoir target as mentioned. Some permeability measurements are up to 1 md in lithofacies 2, but these data points are highly localized and poorly developed within the lithofacies.

Reservoir quality is marginal (Figure 9B, C). The average porosity is 10%, and permeabilities range from 0.01 to 2.36 md. Average point-count porosity from the thin sections is 4%. This suggests that approximately half of the measured core analysis porosity is caused by microporosity attributed to microporous kaolinite and partially leached unstable clasts. Localized pervasive ferroan carbonate cement completely occludes porosity and associated reservoir quality. This lithofacies is considered the reservoir facies.

Lithofacies 4b: Fine- to Mid-Medium-Grained Intensely Bioturbated Sandstone

Lithofacies 4b is approximately 1 m in thickness and lies within lithofacies 4a (Figure 10). This lithofacies is similar to and is in sharp contact with lithofacies 4a; however, the entire zone is intensely burrowed with *M. segregatus* defined by tabular, nonbranching burrows that have a distinct dark-colored grain halo that is lithologically different from the light-colored burrow fill and surrounding matrix. Burrows are approximately 1–2 mm (0.03–0.07 in.) in diameter. The unit appears homogenized and all bedding features have been obliterated by burrowing activities except for rare, poorly defined, low-angle laminations. Although lithologically and texturally similar to lithofacies 4a, lithofacies 4b (Figure 10B) has a higher chert content, lower monocrystalline quartz content, and is dominantly mid-medium grained. However, pervasive biogenic reworking of this sand is evident. The grains are not randomly distributed as in lithofacies 4a and a halo of dark-colored grains consisting of chert, shale clasts, and organic matter surround the light-colored burrow fill consisting of monocrystalline quartz, chert, and minor feldspar (Figure 10C).

Reservoir quality of this lithofacies is elevated with a core porosity value of 13% and a permeability of 8.43 md. Lithofacies 4a and 4b are consistently perforated on wireline logs and are the main target of oil and gas companies in the Bluesky Formation at La Glace. The permeability enhancement of lithofacies 4b is scrutinized below.

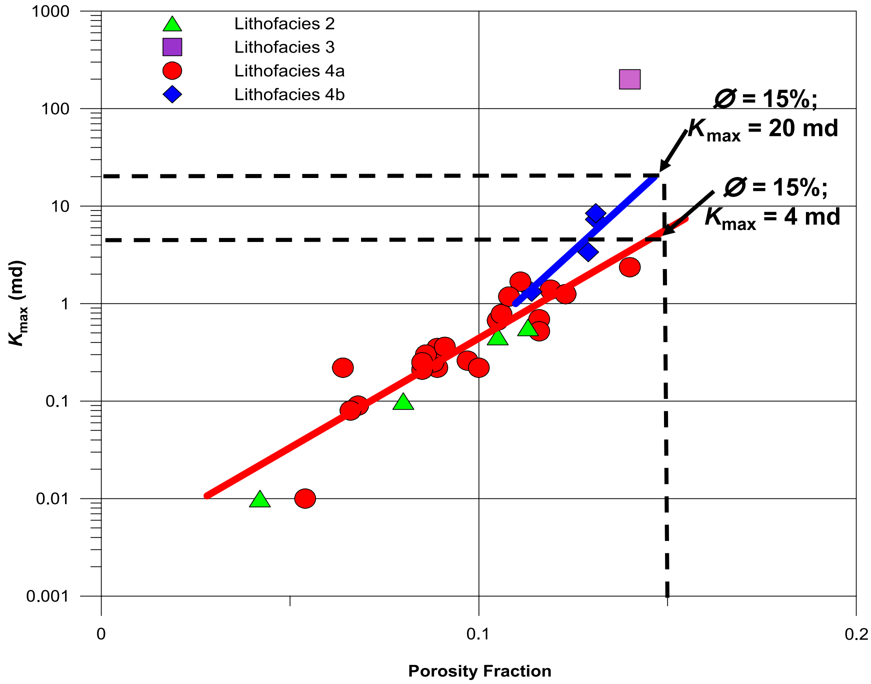

Figure 12. Maximum permeability versus porosity plot of measured core analysis data. These data show that the *Macaronichnus*-burrowed lithofacies 4b lies on a different trend from lithofacies 4a. These data extrapolated to 15% porosity would yield permeabilities of approximately 4 md for lithofacies 4a and approximately 20 md for lithofacies 4b.

MACARONICHNUS SEGREGATUS AND ENHANCED PERMEABILITY

Figure 11 shows spot-permeability measurements by lithofacies. These data show that very little permeability variation in the *Macaronichnus* burrowed facies exists. The permeability in this lithofacies ranges from 1 to 10 md. A greater range of permeability in lithofacies 4a is observed. Although some permeability measurements are above 1 md in lithofacies 4a, most permeability measurements fall well below. Lithofacies 3 shows the best permeability but is not a reservoir target as mentioned above. Some permeability measurements are up to 1 md in lithofacies 2, but these data points are highly localized and poorly developed within the lithofacies.

Figure 12 shows a maximum permeability versus porosity plot of measured core analysis data. These data show that the *Macaronichnus* burrowed lithofacies 4b lies on a different trend from lithofacies 4a. These data extrapolated to 15% porosity would yield permeabilities of approximately 4 md for lithofacies 4a and approximately 20 md for lithofacies 4b.

Spot-permeability measurements across a part of the intensely *Macaronichnus* burrowed zone were preformed in a 7 × 12 measurement grid pattern (Figure 13A). A graphical representation, or permeability map, of this spot permeametry data is shown in Figure 13B. This map indicates that *M. segregatus* burrows have effectively homogenized the permeability of this zone. Permeability is increased toward the base of the sample.

Figure 14A shows an overview scan of a large-format thin section taken over the *Macaronichnus* burrowed zone (lithofacies 4b). Figure 14B is the same field of view, but with dark-colored rock fragments shown in black only. Light-colored fragments remain white showing the burrow fill. This image clearly shows that the *M. segregatus* burrows are visually defined by a halo of dark-colored rock fragments. The burrows can be seen in cross section and longitudinally and are oriented horizontally to subhorizontally.

This behavior has been reported by other workers (e.g., Clifton and Thompson, 1978; Pemberton et al., 2001; Gingras et al., 2002, 2007). Dafoe et al. (2008) recently showed that the modern polychaete, *Euzonus mucronata*, preferentially ingests felsic grains over mafic grains, and en-masse feeding in felsic-rich deposits provides a mechanism for ancient *M. segregatus*. Pemberton et al. (2001) suggested that the same modern polychaete *E. mucronata* ingests

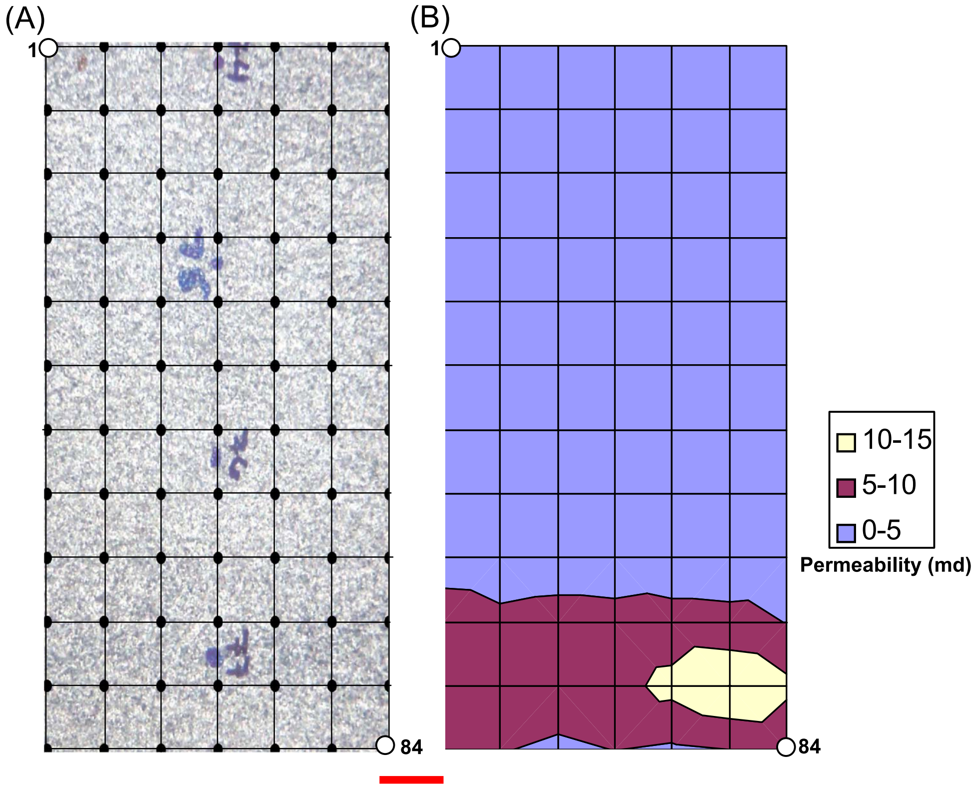

Figure 13. (A) Spot-permeability measurements across a part of the slabbed core in the intensely *Macaronichnus* burrowed zone in a 7 × 12 (points 1 and 84 are marked for reference) measurement grid pattern. (B) A graphical representation or permeability map of this spot permeametry data. This map indicates that *Macaronichnus segregatus* burrows have effectively homogenized the permeability of this zone. Permeability is increased toward the base of the sample. Numbers on the core in photo A are from whole-core minipermeametry measurements. Scale bar is 1 cm (0.3 in.).

sand in search for an epigranular bacterial food source and excretes the ingested sand that backfills the burrow structure. Clifton and Thompson (1978) originally described *M. segregatus* and found the modern polychaete O*phelia limicina* to exhibit identical behavior. In all of these examples, the polychaetes burrow structure contains light-colored grains as the fill and dark-colored grains as a burrow mantle.

In the Bluesky Formation, the presence of *Macaronichnus* burrows in the chert-rich sediment of lithofacies 4b is apparently the key to reservoir

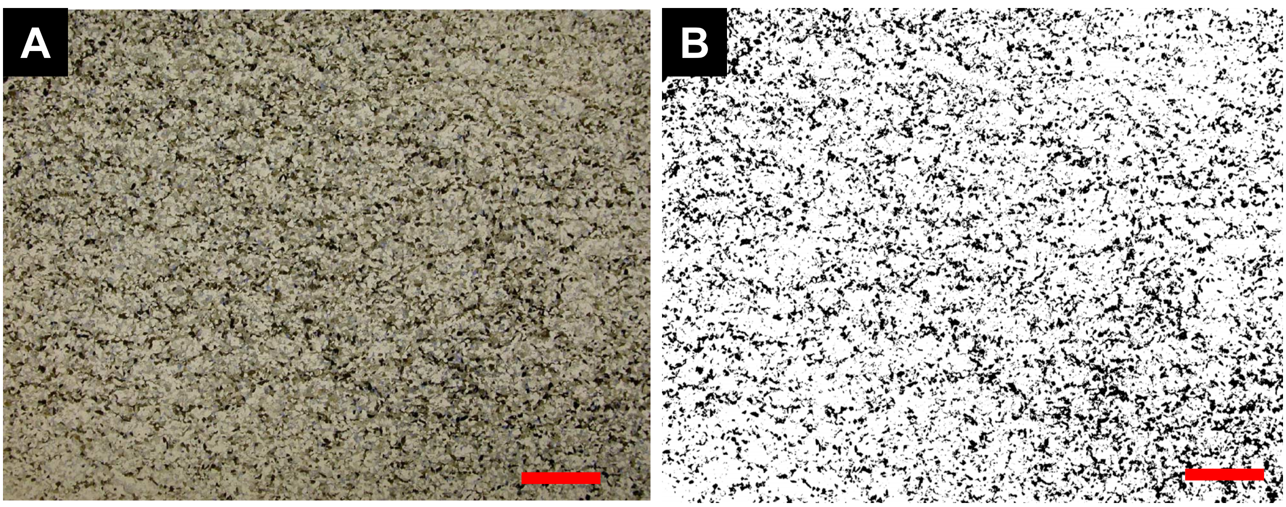

Figure 14. (A) Overview photo of *Macaronichnus*-burrowed sand of lithofacies 4b. (B) The same field of view showing image-enhanced burrow structures. The burrow halo is outlined in black, and the white area is the burrow fill (scale bar = 0.5 cm [0.1 in.]). Image B was obtained using simple image analysis.

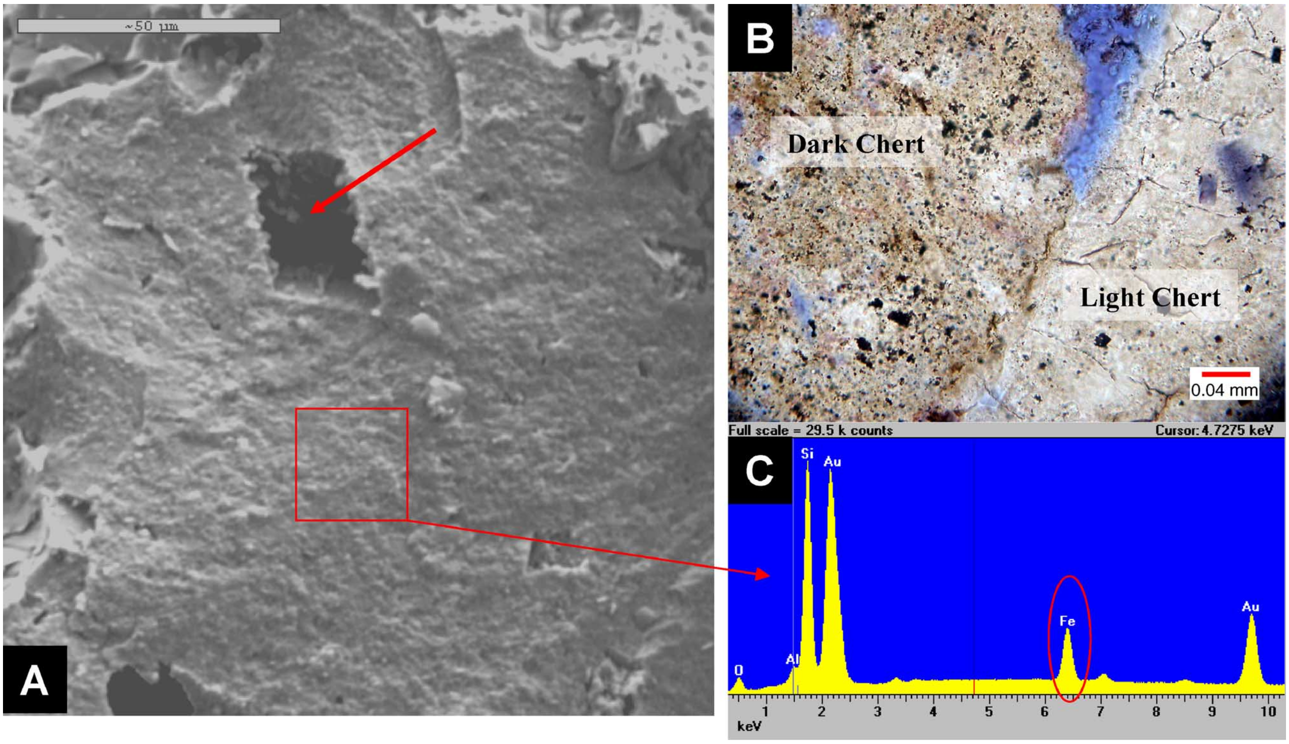

Figure 15. (A) Scanning electron photomicrograph of a dark-colored chert grain. Note the leached dolomite rhomb (arrow). The box indicates the energy-dispersive x-ray analysis (EDX) scanned area. (B) Similar dark chert in thin section. (C) The EDX analysis showing iron peak.

preservation. Chert, like quartz, resists the effects of mechanical compaction, thereby preserving primary porosity, much better than ductile detrital grains (i.e., shale clasts), which under the stress of depositional overburden can be squeezed into adjacent pore space; a process that severely reduces reservoir quality. Moreover, pore-occluding authigenic syntaxial quartz overgrowths that form on monocrystalline quartz grains do not form on chert grains because of the microcrystalline structure of chert. Alternatively, euhedral quartz microcrystals can form on chert fragments and can cause porosity reduction, but this rarely results in complete porosity occlusion. Using simulated quartz cementation models, Landers et al. (2008) showed that quartz cementation rates are significantly slower for polycrystalline quartz and chert. Larese and Hall (2003) noted that chert-rich sandstones may have better reservoir quality than similar intervals with greater amounts of monocrystalline quartz.

The dark-colored detritus forming the burrow mantle includes chert, shale clasts, and organic-rich grains. Energy-dispersive x-ray analysis showed the dark-colored chert in the Bluesky Formation to have high iron content (Figure 15). The elevated iron content may be attributed to the presence of authigenic pyrite and/or hematite that formed in the parent sediment. In-situ secondary iron precipitation localized to the burrow mantle can be ruled out as the dark iron-rich fragments appear in the nonbioturbated sand, indicating that the iron-rich grains were transported.

The result of grain segregation into the burrow fills is that zones with a chert-rich lithology are resorted locally. The ancient burrowers of the Bluesky Formation have conveniently rearranged the sediment locally, leaving light-colored compaction and cement-resistant chert and quartz as the burrow fill while discarding dark-colored compactable clasts (shale and organic grains) to the burrow mantle setting up permeability conduits within this sediment. The dark-colored chert fragments behave similarly as the light-colored chert fragments but are in general part of the burrow mantle. In some burrows where quartz grains alone make up the burrow fill, syntaxial quartz overgrowths have formed and primary porosity is correspondingly reduced. This indicates that if the Bluesky detritus of lithofacies 4b had a higher quartz to chert ratio or if quartz and chert were evenly distributed, the reservoir quality would be severely reduced due to silica cementation of the primary porosity.

CONCLUSION

The Lower Cretaceous Bluesky Formation in the La Glace area in western Alberta, Canada, is an upper shoreface deposit comprising fine- to medium-grained lithic sandstones with thin conglomeratic lag deposits and fine-grained carbonate-cemented storm beds. Within the lithic reservoir sand is a medium-grained litharenite interval heavily bioturbated with *M. segregatus*. This bioturbated zone is indicative of high-energy shoreface deposits, showing a more elevated preserved permeability than in the surrounding sediment.

Petrographic techniques have aided in understanding the effects *M. segregatus* has on reservoir quality in these upper shoreface sediments. The use of thin sections and scanning electron microscopy has led to the interpretation that the tracemaker of *M. segregatus* avoided iron-rich detrital fragments while exploiting the sediment for food. This grain avoidance led to a resorting of the sand that shed the dark-colored rock fragments to outline the burrow, whereas light-colored competent grains were ingested and became the burrow fill. The light-colored burrow fill contains a high chert to quartz ratio. Primary reservoir quality can be preserved in the presence of chert as pore-occluding quartz overgrowths do not form on chert fragments as they do on monocrystalline quartz, thus leaving open, well-connected primary pores and hence elevated permeability. Chert fragments are resistant to the effects of mechanical compaction and are not easily squeezed into adjacent pore space as are ductile rock fragments.

Detailed petrographic examination of microfabrics is essential to assessing reservoir quality in burrowed hydrocarbon-bearing sediments, leading to a better understanding of the depositional environments that contain *Macaronichnus* and similar burrowed sediment. Also important is the recognition that hydrocarbon production from bioturbated rock is generally more complex than production from laminated media. This is because flow paths through burrow-related flow conduits are comparatively tortuous. Further complicating geological and reservoir models, these tortuous, heterogeneous media present notable complications for reservoir development. Burrows may provide flow conduits that interact extensively with the surrounding matrix as shown in this study; their tortuous nature implies that dead ends and cutoffs may be common. An understanding of how burrow-associated heterogeneities control fluid flow within sedimentary units is necessary if production from bioturbated reservoirs is to be optimized.

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