ABSTRACT

Reservoir Assessment of Late Devonian Kakisa Formation, Northeastern British Columbia, Canada

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The Late Devonian Kakisa Formation of northeastern British Columbia, Canada is a high energy, aggradational, discontinuous carbonate bank complex that is composed of three distinct allocycles designated the “Upper”, “Middle”, and “Lower” Kakisa. The study region includes a 5500 square mile area across which the Kakisa was evaluated in regards to the nature and distribution of facies and their relationship to reservoir quality and its spatial distribution. Data integrated into the study include detailed core descriptions for seven wells, and well logs from 116 wells correlated within a grid of 37 cross sections. Gamma ray logs are particularly useful in characterizing petrofacies that are interpreted to have accumulated within low energy, “off-bank” (relatively higher gamma ray activity and lower reservoir quality) and high energy, “on-bank” (relatively lower gamma ray activity and higher reservoir quality) marine settings. The potentially gas-charged reservoir is only associated with “on-bank” stromatoporoid reef complexes observed within the Upper and Middle Kakisa. Reservoir bodies are

isolated within the eastern portion of the study area, and coincide with north-trending, high-energy "on-bank" deposits.

Reservoir Assessment of Late Devonian Kakisa Formation, Northeastern British Columbia

by

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A Thesis

Approved by the Department of Geology

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER ONE

Introduction

Introduction and Objectives

The Kakisa Formation is a Late Frasnian carbonate bank complex that accumulated as an aggradational succession within the Western Canadian Sedimentary Basin (WCSB) (Geldsetzer, 1993). Of the 51.9 trillion cubic feet (tcf) of in-place gas reserves that are estimated to occur within the British Columbia portion of the WCSB, the Kakisa Formation is estimated to account for 0.088 tcf of the in-place total (Adams, 2006). Few published studies have been completed on the Kakisa Formation. This study will help fill this gap by providing insight to the nature of the depositional components and the stratal architecture of the Kakisa.

The objectives of this study are to 1) gain an understanding of the depositional and stratigraphic controls on reservoir quality, and 2) develop a means by which these controls may be predicted petrophysically, and subsequently, spatially.

Geologic Setting

The Kakisa Formation is of Devonian (Latest Frasnian) age (Figure 1) (Belyea and McLaren, 1962; McLean, 1982) and is 57 m thick in the type section located in the southwestern portion of the Northwest Territories, south of the Mackenzie River. At the type section, the Kakisa Formation has an average thickness of 30 m (Hills et al., 1981). This study evaluates a 14,175 km^2 area in northeastern British Columbia adjacent to the British Columbia – Alberta border. Within the study area the Kakisa conformably overlies the Red Knife Formation and is disconformably overlain by the Trout River

Formation (Figure 2). The Kakisa Formation was deposited on the Great Slave Shelf which was bound on the east by the Canadian Shield, to the south by the submerged Tathlina High (Belyea, 1971) (Figure 3).

Data and Methodology

Seven core from wells within the study area were described in detail at the Charlie Lake Core Research Facility located in Fort St. John, British Columbia. Observations documented during core description include facies, Dunham's (1963) textural classification, grain type(s) and relative abundance, pore type and relative abundance, cement type, fracture density, and sedimentary structures. Photographs were taken of diagnostic facies attributes and/or conspicuous features in each core. Facies, facies association, fracture density and textural class were digitized and merged with core analysis porosity and permeability data within Microsoft Excel.

The Kakisa Formation was correlated across the study area using logs from 116 wells within a grid of 37 cross sections (Figure 4). Two regional cross sections were created by combining and calibrating detailed core descriptions with well logs (Kelly_Jones3_regional_cross_section.pdf). Cross sections A-A' and B-B' were used to develop the petrophysical guidelines by which facies could be interpreted in wells lacking core control. Stratigraphic correlations were completed using Halliburton Geographix® Xsection™ software. Stratigraphic tops correlated within Geographix were exported into Microsoft Excel and Surfer® for computer mapping. Computer-generated maps from Surfer were exported into ACD Canvas® where they were hand-refined.

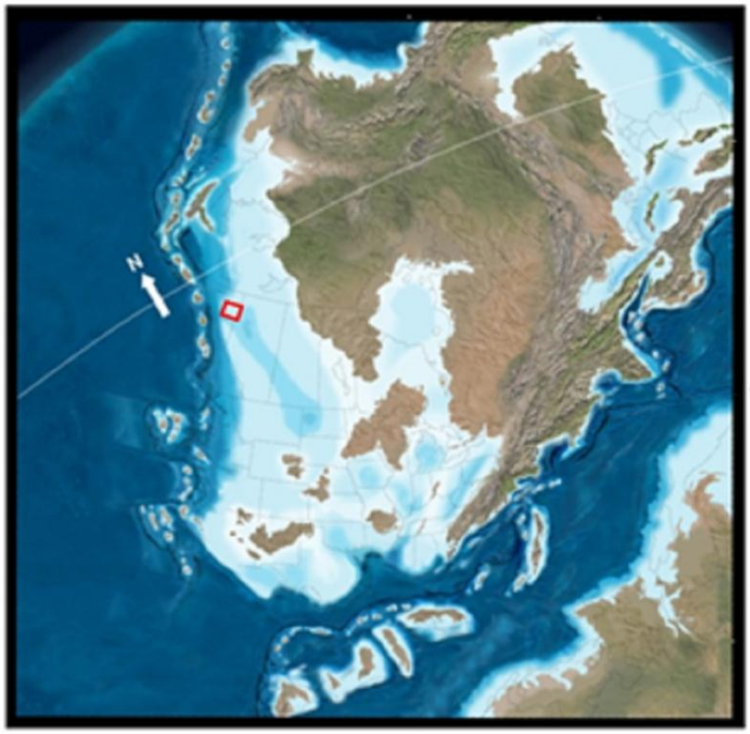

Figure 1**.** Paleogeography of North America during Late Devonian (modified from Blakey, 2010). The small red box highlights the study area and white line demarcates the location of the contemporaneous paleoequator (360Ma).

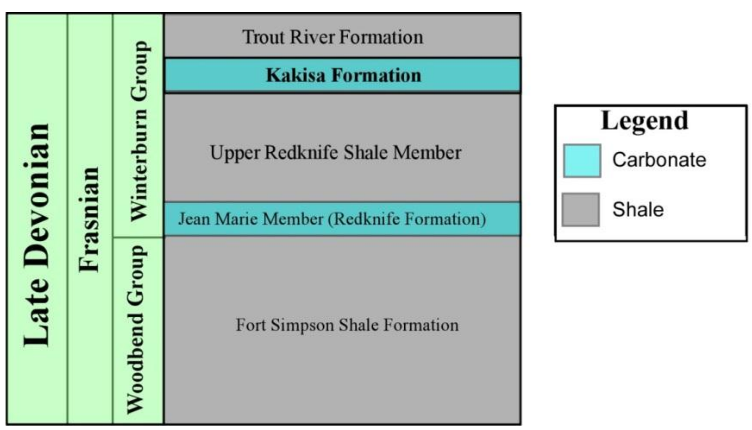

Figure 2. Late Devonian (Frasnian) stratigraphy of northeastern British Columbia. Modified from Switzer (1994).

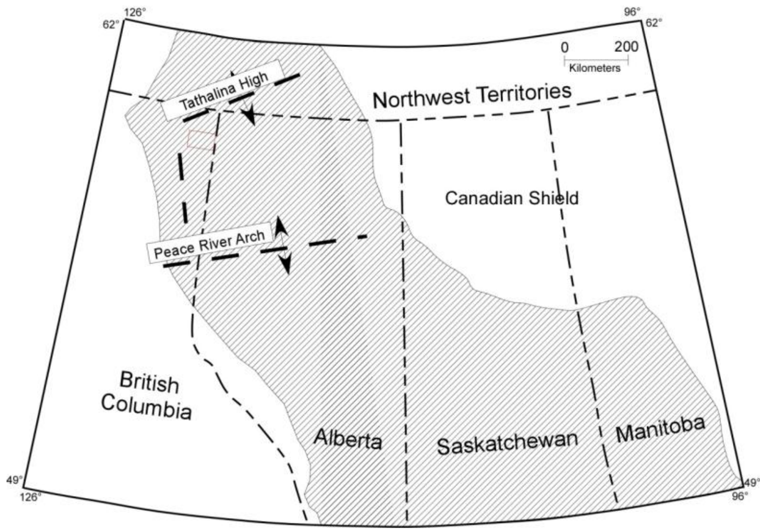

Figure 3. Major structural features during Kakisa deposition. Modified from Switzer et al. (1994)

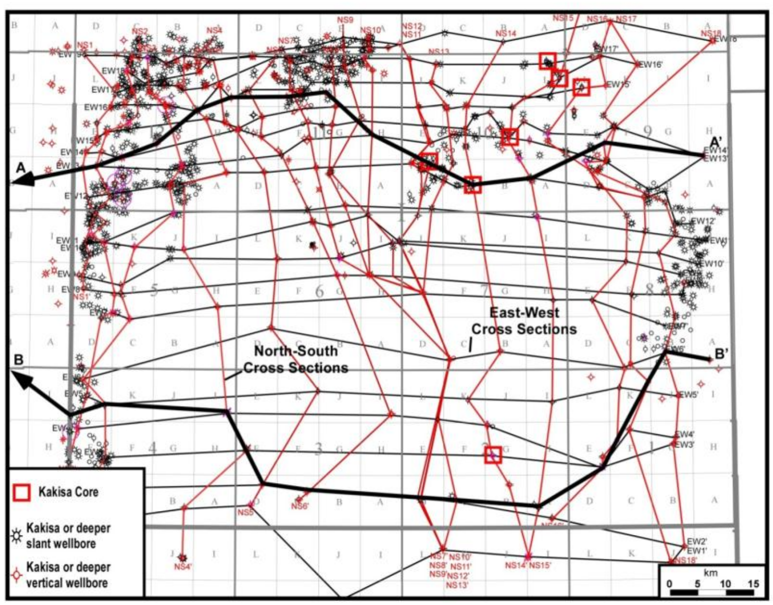

Figure 4. Basemap of study area. Red boxes highlight the location of wells that include Kakisa core. Red well symbols indicate vertical wellbores that penetrate the Kakisa. Black well symbols indicate slant wellbores that penetrate the Kakisa. The heavy black lines labeled A-A' and B-B' are regional cross sections where core-calibrated petrofacies are correlated in detail across the study area (Plate 1). Thinner black lines trending E-W and red lines trending N-S are cross sections where only Kakisa stratigraphic tops are correlated.

CHAPTER TWO

Facies Framework

Facies Model

Eight facies are recognized within the Kakisa and are distinguished on the basis of variations in texture and grain type (Table 1).

Facies 1- Argillaceous Crinkly Laminated Mudstone (ACLM)

Facies 1 is a black to brown mudstone or wackestone with abundant crinkly and/or horizontal lamina (Figure 5A). Mudcracks are present but are relatively uncommon. Carbonate allochems are uncommon, but when present include undifferentiated skeletal grains, gastropods, and intraclasts (Figure 5B). Facies 1 is interpreted to have accumulated within a tidal flat environment.

Facies 2 – Ooid Grainstone (OG)

Facies 2 is a planar laminated ooid grainstone (Figure 5C, 5D). Ooids suggest sediment accumulation within a relatively high-energy shoreface to foreshore environment.

Facies 3 – Restricted Skeletal Packstone (RSP)

Facies 3 is is an oncoid packstone (Figure 5E, 5G) Accessory grains include rugose corals, gastropods, platy, bulbous and cylindrial stromatoporoids, bivalves, and tabulate corals. Facies 3 is generally massive in appearance; however, *Thalassinoides* burrows (Figure 5F) are occasionally differentiated. The inferred depositional environment is interpreted as a shallow, somewhat restricted subtidal environment below

Table 1. Kakisa facies and their diagnostic features.

Facies	Environment of Deposition	Dominant Textures	Diagnostic Grains	Accessory Grains	Sedimentary Structures	Select Photos
Argillaceous crinkly laminated mudstone (ACLM) 1	Tidal Flat	Wackestone	None	Undifferentiated skeletal grains, gastropods, intraclasts	Crinkly and mechanical lamina, mudcracks	Figures 5A, 5B
Ooid grainstone (OG) 2	Shorefact to beach	Grainstone	Ooids	None	Millimeter-scale horizontal lamina	Figures 5C, 5D
Restricted skeletal packstone (RSP) 3	Shallow subtidal	Packstone	Oncoids	Undifferentiated skeletal grains, gastropods, intraclasts	*Thalassinoides*	Figures 5E, 5F, 5G
Massive encrusting stromatoporoid boundstone (MESB) 4	Reef crest	Fraimstone, bindstone	Massive encrusing stromatoporoids	Rugose corals, bulbous, platy, cylendrical stromatoporieds, gastropods, bivalves	Geopetal fabric within primary pore space	Figures 6A, 6B, 6C, 6D, 6F, 6G
Platy stromatoporoid boundstone (PSB) 5	Middle slope	Bindstone	Platy Stromatoporoids	Rugose corals, bulbous, platy, cylendrical stromatoporieds, gastropods, bivalves	Geopetal fabric within primary pore space	Figures 6H, 6I
Diverse skeletal wackestone to packstone (DSW) 6	Lower slope	Wackestone to packstone	Tabulate and rugose corals, oncoids	Brachiopods, massive encrusting stromatoporoids	None	Figures 7A, 7B
Diverse skeletal shale (DSS) 7	Basinal	Wackestone	Tabulate corals, intraclasts, undiff. Skeletal grains	None	Millimeter-scale horizontal lamina	Figure 7C

fairweather wave base. Restricted marine conditions are suggested by the abundance of oncoids.

Facies 4 – Massive Encrusting Stromatoporoid Boundstone (MESB)

Facies 4 is dominated by an intergrown framework of massive encrusting stromatoporoids (Figure 6A, 6B). Common accessory grains include rugose coral, cylindrical stromatoporoids (Figure 6D). Geopetal structures are common (Figure 6E). The environment of deposition is interpreted to be a high-energy reef crest. Facies 4 is the most common observed within the Kakisa (70% of all core observations). Growth framework pores are commonly cemented by coarsely-crystalline sparry calcite; however, open macropores are observed (Figure 6C).

Facies 5 – Platy Stromatoporoid Boundstone (PSB)

Facies 5 and facies 4 commonly co-occur within a gradational vertical succession with facies 5 transitioning into facies 4. Facies 5 is similarly a framestone; however, stromotoporoids are notably thinner (cm-thick or less) (Figure 6H). Accessory grains include rugose corals, *Thamnopora*, brachiopods, and crinoids (Figure 6I). As with facies 4, geopetal structures are common. Facies 5 is interpreted to have accumulated within a high energy, middle slope environment.

Facies 6 – Diverse Skeletal Wackestone to Packstone (DSW)

Facies 6 is a wackestone to packestone with common tabulate and rugose corals, and crinoid fragments (Figure 7A, 7B). Accessory grains include brachiopods and stromatoporoids. No mechanical or biological sedimentary structures were observed within Facies 6. The inferred depositional environment is lower slope.

Facies 7 – Diverse Skeletal Shale (DSS)

Facies 7 is a dark, millimeter-laminated wackestone (Figure 7C). Allochems include tabulate corals, intraclasts, and undifferentiated skeletal grains. Facies 7 accumulated within a basinal marine setting.

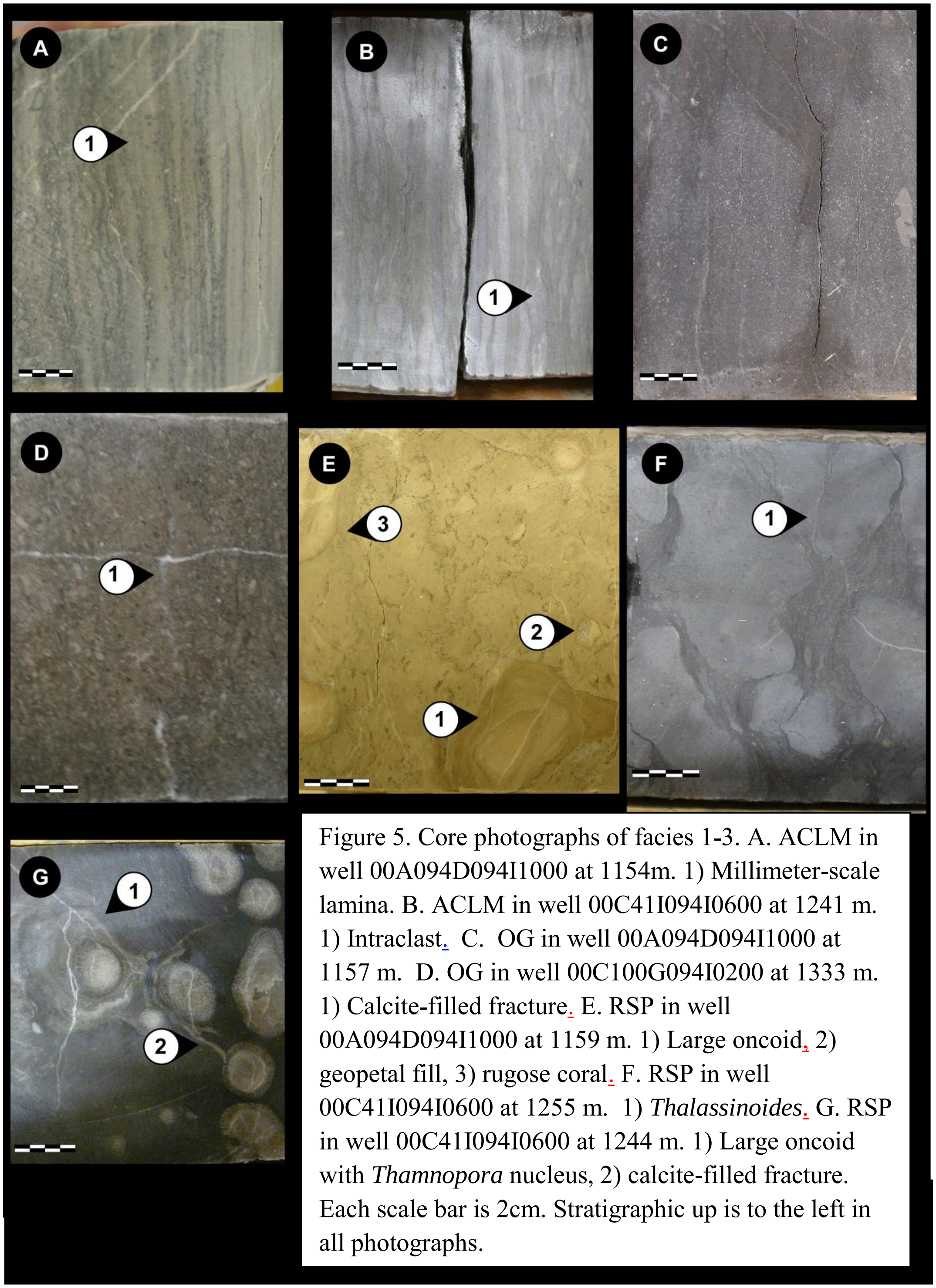

Figure 5. Core photographs of facies 1-3. A. ACLM in well 00A094D094I1000 at 1154m. 1) Millimeter-scale lamina. B. ACLM in well 00C41I094I0600 at 1241 m. 1) Intraclast. C. OG in well 00A094D094I1000 at 1157 m. D. OG in well 00C100G094I0200 at 1333 m. 1) Calcite-filled fracture. E. RSP in well 00A094D094I1000 at 1159 m. 1) Large oncoid, 2) geopetal fill, 3) rugose coral. F. RSP in well 00C41I094I0600 at 1255 m. 1) *Thalassinoides*. G. RSP in well 00C41I094I0600 at 1244 m. 1) Large oncoid with *Thamnopora* nucleus, 2) calcite-filled fracture. Each scale bar is 2cm. Stratigraphic up is to the left in all photographs.

Figure 6. Core photographs of facies 4-5. A. MESB in well 00A45G094I1000 at 1053 m. 1) Massive encrusting stromatoporoid, 2) geopetal-fill within a bivalve, B. MESB in well 00A45G094I1000 at 1058 m. 1) Macropore within growth framework that is otherwise pervasively cemented with coarsely crystalline sparry calcite, 2) rugose coral. C. MESB in well 00B53C094I1000 at 1120 m. 1) Massive encrusting stromatoporoid, 2) macropore within calcite cemented growth framework intergranular volume. D. MESB in well 00C41I094I0600 at 1261 m. 1) *Thamnopora,* 2) large encrusting stromatoporoid, 3) platy stromatoporoid. E. MESB in well 00C41I094I0600 at 1258 m. 1) Geopetal-fill within a bivalve, 2) rugose coral, F. MESB in well 00C52I094I1000 at 976 m. 1) Massive encrusting stromatoporoid. G. MESB in well 00C85I094I1000 at 992 m. 1) Macropore surrounded by calcite cement within stromatoporoid growth framework, 2) Stromatoporoid H. PSB in well 00A45G094I1000 at 1062 m. 1) Skeletal fragment, 2) platy stromatoporoid, 3) *Thamnopora*, 4) bivalve . I . PSB in well 00B53C094I1000 at 1123 m. 1) Platy stromatoporoid, 2) *Thamnopora*. Each scale bare is 2cm. Stratigraphic up is to the left in all photographs.

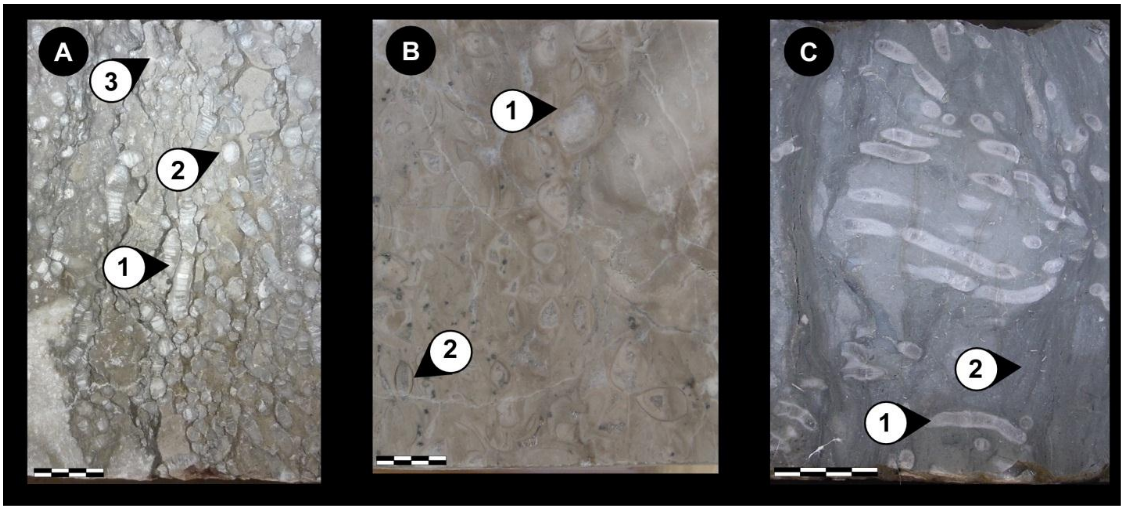

Figure 7. Core photographs of facies 6-7 A. DSW in well 00A45G094I1000 at 1063 m. 1) Crinoid ossicles, 2) rugose coral, 3) *Thamnopora*. B. DSW in well 00A094D094I1000 at 1178 m. 1) Bivalve filled with calcite cement, 2) geopetal-fill. C. DSS in well 00A094D094I1000 at 1186 m. 1) *Thamnopora*, 2) dark muddy matrix. Each scale bar is 2 cm. Stratigraphic up is to the left in all photographs.

Facies Associations

Facies within the Kakisa are grouped into facies associations on the basis of petrophysical (natural gamma radiation) attributes. Two distinct gamma ray "classes" are observed within the Kakisa. The "on-bank" class is characterized by a relatively consistent, low gamma ray response suggestive of relatively pure carbonate free of clay minerals. Such conditions are more likely associated with high-energy reefal environments, i.e., facies 4 and 5. The "off-bank" class is characterized by an erratic, i.e., serrated, gamma ray response suggestive of higher and more irregular clay content (Figure 8) (Table 2). Such features are more likely associated with either lower-energy subtidal and/or intertidal environments, i.e., facies 1, 2, 3, 6, and 7.

A large portion (70%) of the observed core consists of the "on-bank" facies association. The "off-bank" association was only encountered in a single cored well. To distinguish "on-bank" versus "off-bank" petrofacies, the gamma ray response within the underlying Late Devonian Jean Marie Formation was used as the gamma radiation baseline (minima) for comparison. Kakisa intervals with gamma radiation comparable to the Jean Marie are classified as "on-bank", and intervals with gamma radiation in excess of that observed in the Jean Marie are classified as "off-bank".

Table 2. Facies associations of the Kakisa Formation as defined by natural gamma radiation.

Facies Associations	Depositional Environment	Associated Facies	Petrophysical Characteristics
On-Bank	High-Energy (reefal)	4,5	Reduced gamma ray activity
Off-Bank	Low Energy (subtidal and intertidal)	1,2,3,6,7	Elevated gamma ray activity

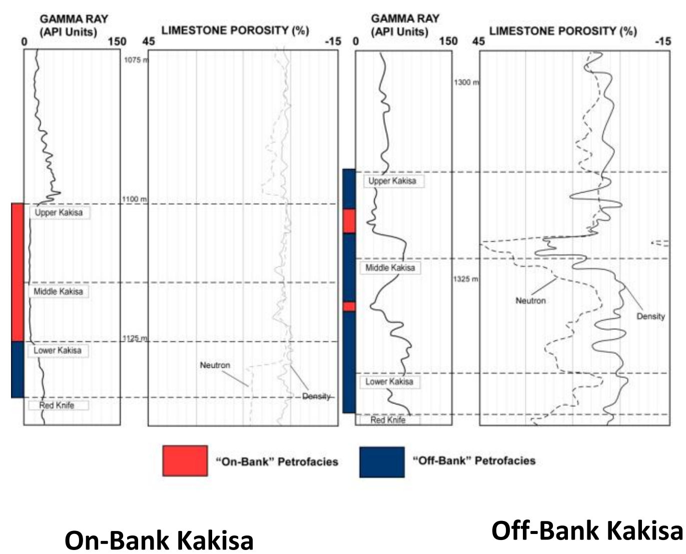

Figure 8. Wirleline logs representative of "on-bank" and "off-bank" petrofacies. The bar chart to the immediate left of each well log depicts the interpreted distribution of petrofacies.

Controls on Reservoir Quality

Reservoir potential within the Kakisa is facies dependent. Large interconnected macropores and the highest fracture density are most common within Facies 4 (MESB) and to a lesser extent Facies 5 (PSB) (Figures 6B, 6C, 6G). There are an average of 19 fractures per meter within the "on-bank" facies association, whereas the "off-bank" facies association averages 4 fractures per meter (Figure 9). Growth framework porosity within the "on-bank" facies association accounts for most pore volume within core. "Off-bank" facies are more mud-rich, and generally lack macropores. Consequently, "on-bank" porosity averages 2.4% with median permeability of 0.5 md, and "off-bank" porosity averages 1.9% with a median permeability of 0.01 md (Figure 10). A higher percentage of more grain rich, and therefore, higher reservoir quality facies (facies 4 and 5) occur in the “on-bank” facies association (Figure 11).

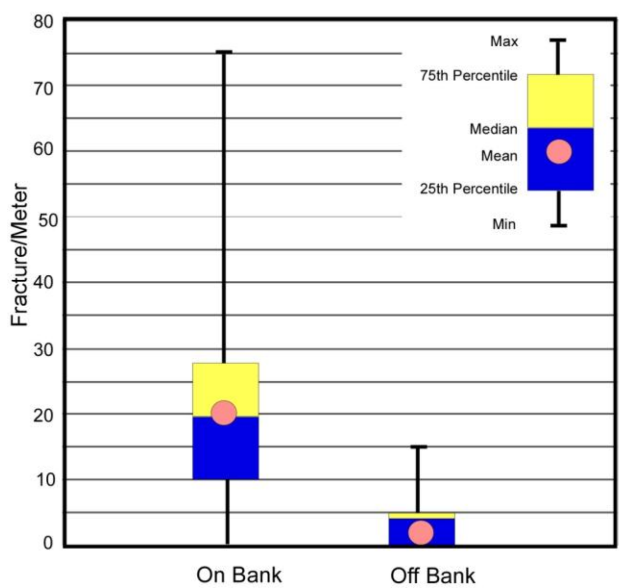

Figure 9. Box and whisker plot of facies association versus fracture density.

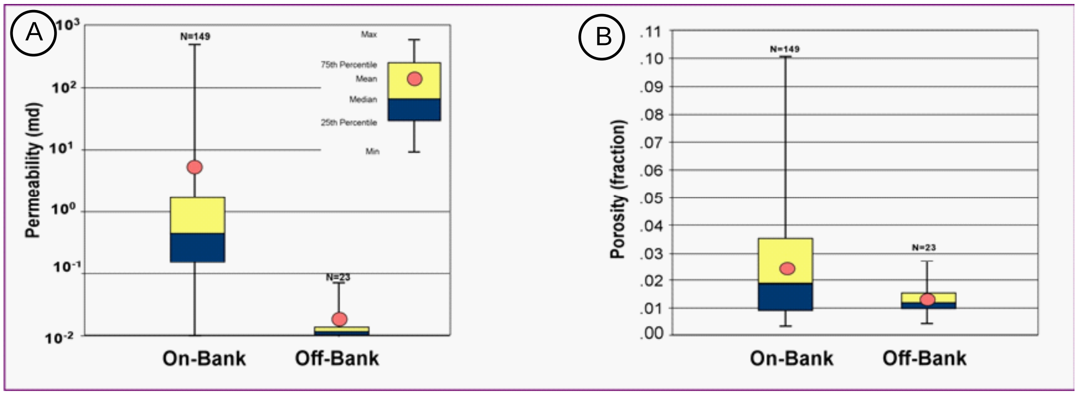

Figure 10. Box and whisker plots of facies association versus permeability A), and porosity B).

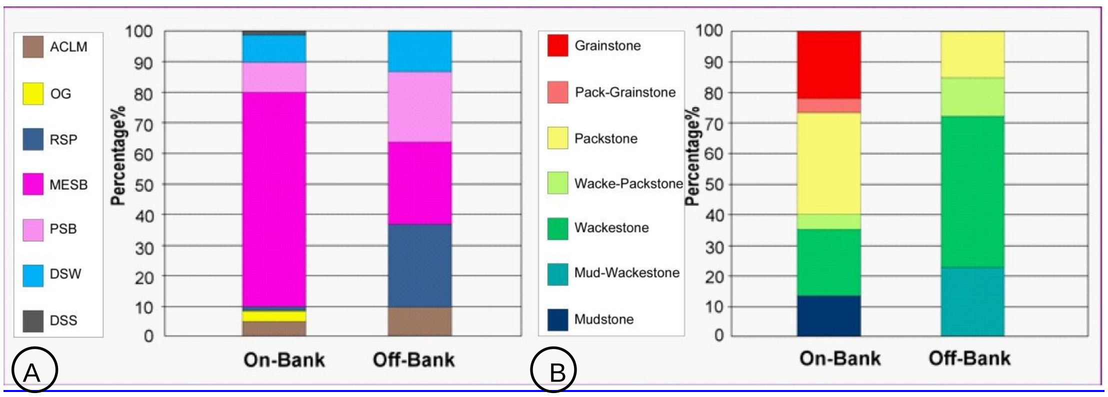

Figure 11. Stacked bar charts of A) facies proportions within "on-bank" and "off-bank" facies association,and B) textural proportions within "on-bank" versus "off-bank" facies association.

Reservoir quality within the Kakisa is also dependent on the presence or absence of calcite cement. Calcite cement occurs pervasively throughout facies 5 and occludes large macropores associated with growth framework porosity (Figure 6B, 6C, 6G). The occurrence of calcite cement complicates the predictability of reservoir quality rock as it preferentially occludes pore space within potentially the best reservoir quality facies.

CHAPTER FOUR

Stratigraphic Framework

The Kakisa Formation was deposited as three shallowing-upward depositional cycles, designated the "Lower", "Middle" and "Upper". The "Lower", "Middle" and "Upper" Kakisa cycles are conspicuous on well logs and readily differentiated into "on-bank" and "off-bank" petrofacies (Figure 8) (Plate 1). In general, cycle boundaries are distinguished by an abrupt contact of more highly radioactive "off-bank" deposits above less radioactive "on-bank" deposits (Figure 8). In some instances, however, facies (and hence petrofacies) amalgamation obscures the placement of cycle boundaries (Figure 8). The Lower, Middle and Upper Kakisa and their associated petrofacies have been correlated across the study area as highlighted on the two regional cross sections (Plate 1).

CHAPTER FIVE

Regional Reservoir Quality Distributions

Introduction

Two main controls on reservoir quality are observed within the Kakisa: the presence or absence of the "on-bank" facies association and the associated occurrence of coarsely crystalline calcite cement.

Lower Kakisa

The Lower Kakisa consists exclusively of non-reservoir, "off-bank" petrofacies. As a result, no maps were generated for this interval.

Middle Kakisa

"On-bank" Isopach Thickness

The Middle Kakisa is observed to include two north-south trending "on-bank" carbonate buildups: a large, primary buildup in the eastern portion of the study area where the thickness reaches 20+ meters, and a smaller, similarly thick, less laterally continuous buildup along the western edge of the study area (Figure 12).

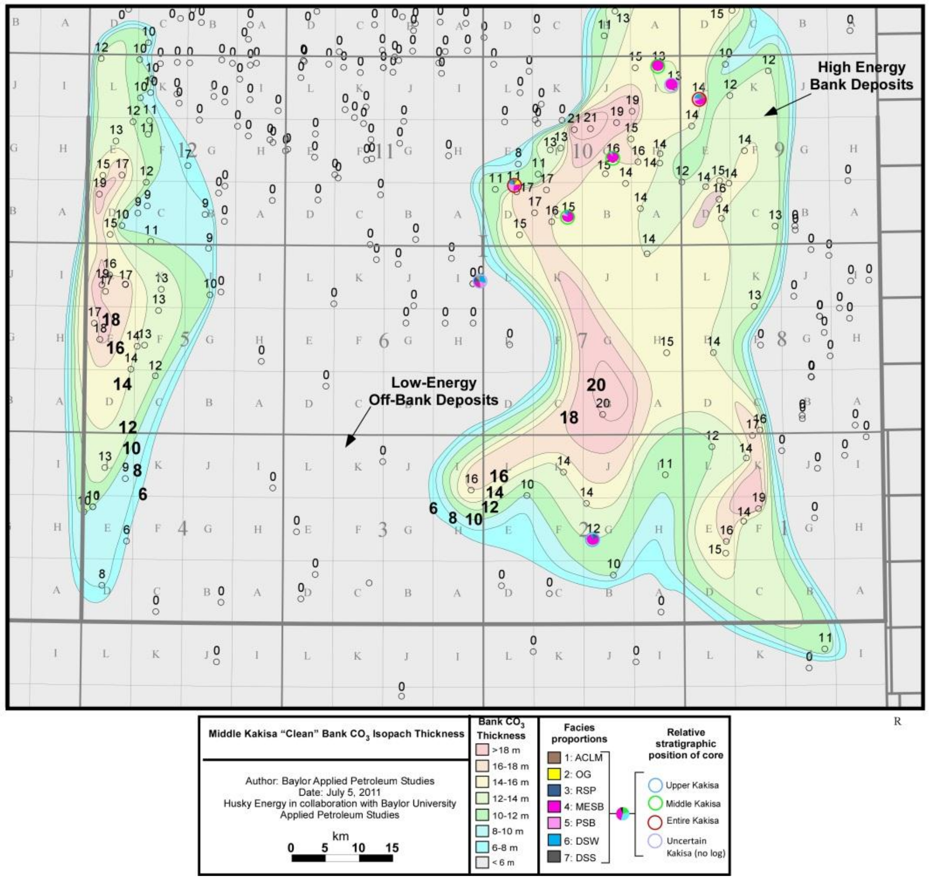

Figure 12. Middle Kakisa "on-bank" isopach thickness map. Mapped values reflect the total thickness of relatively "low" gamma radiation intervals. "Low" Kakisa gamma radiation is defined as similar to that observed within the uderlying Jean Marie Formation. Core-observed facies proportions and the stratigraphic position of core are also provided (see the legend, above).

Gross Porosity

Density porosity was analyzed over the study area by compiling the total gross thickness of wireline log interval where density porosity calibrated to limestone matrix exceeds 3%. The gross porosity thickness values from all wells within the study area were contoured using the "on-bank" isopach map as a contouring template (Figure 13).

Note that trends of gross porosity thickness do not correlate well with the Middle Kakisa isopach map (Figure 12).

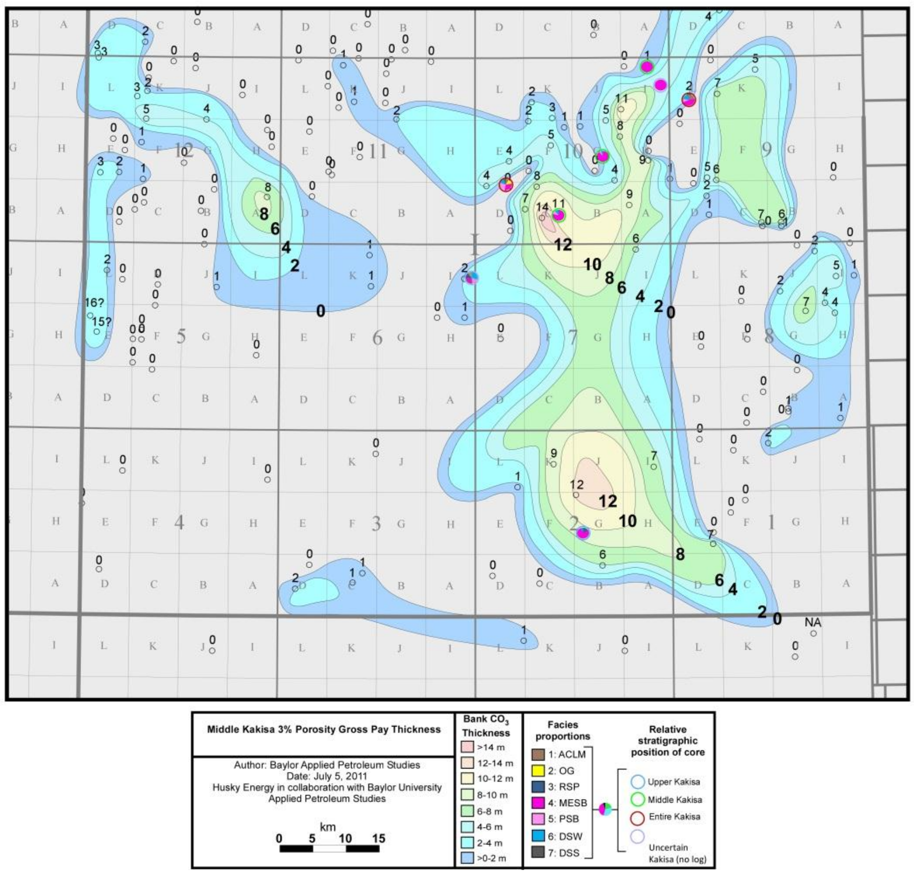

Figure 13. Middle Kakisa >3% density porosity gross pay isopach map. Core-observed facies proportions and the stratigraphic position of core are also provided (see the legend, above).

Pore-Volume

Pore-meter thickness was calculated as follows for gas-saturated reservoir intervals: (gross density porosity thickness > 3%)*(median density porosity >3%). Gas-saturation was identified on wireline log intervals where density porosity exceeds neutron porosity, i.e., for logs calibrated to limestone matrix. The Middle Kakisa pore-meter map (Figure 14) corresponds closely with the on-bank carbonate isopach map (Figure 13).

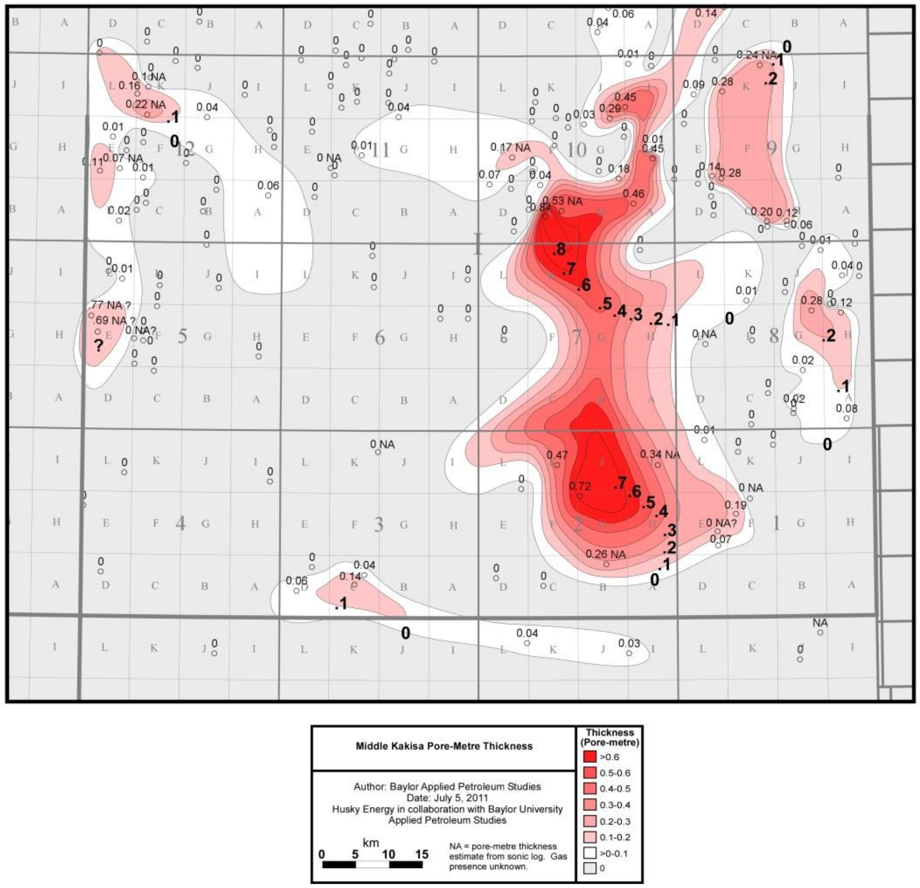

Figure 14. Middle Kakisa pore-meter isopach map.

Upper Kakisa

"On-Bank" Isopach Thickness

The Upper Kakisa consists of a large north-south trending, arcuate-shaped "on-bank" carbonate buildup within the eastern portion of the study area. This buildup reaches a maximum thickness of at least 16+ meters within its southern portion (Figure 15).

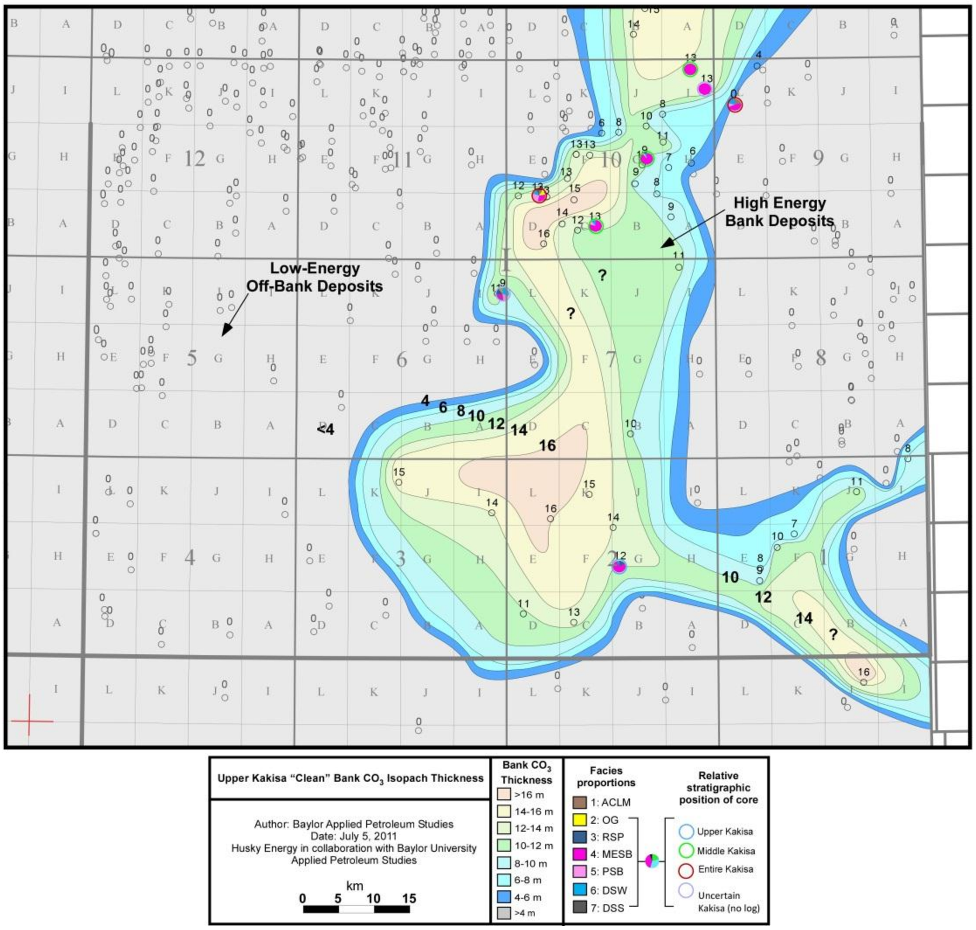

Figure 15. Upper Kakisa "on-bank" isopach thickness map. Estimates reflect the total thickness of relatively "low" gamma radiation. "Low" Kakisa gamma radiation is defined as similar to that observed within the underlying Jean Marie Formation. Core-observed facies proportions and the stratigraphic position of core are also provided.

Gross Porosity

A >3% gross porosity thickness map was generated for the Upper Kakisa per the guidelines described for the Middle Kakisa (see the preceding Middle Kakisa "Gross Porosity" section). Note the relatively close correspondence between the arcuate-shaped trend of isopach thickness within the eastern portion of the study area (Figure 15) and gross porosity thickness (Figure 16).

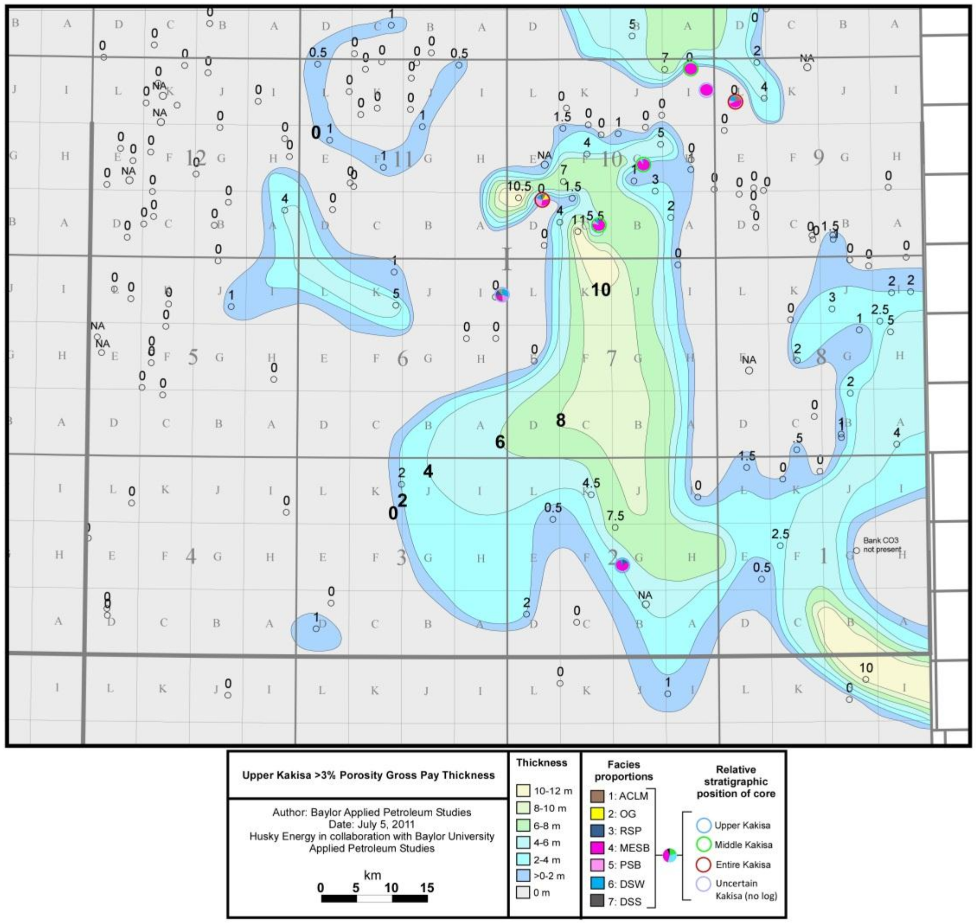

Figure 16. Upper Kakisa >3% density porosity gross pay isopach map. Core-observed facies proportions and the stratigraphic position of core are also provided.

Pore-Volume

A pore-meter map was generated for the Upper Kakisa per the guidelines described for the Middle Kakisa (see the preceding Middle Kakisa "Pore-Volume" section). The Upper Kakisa pore-meter map (Figure 17) also corresponds closely with the on-bank carbonate isopach map (Figure 16).

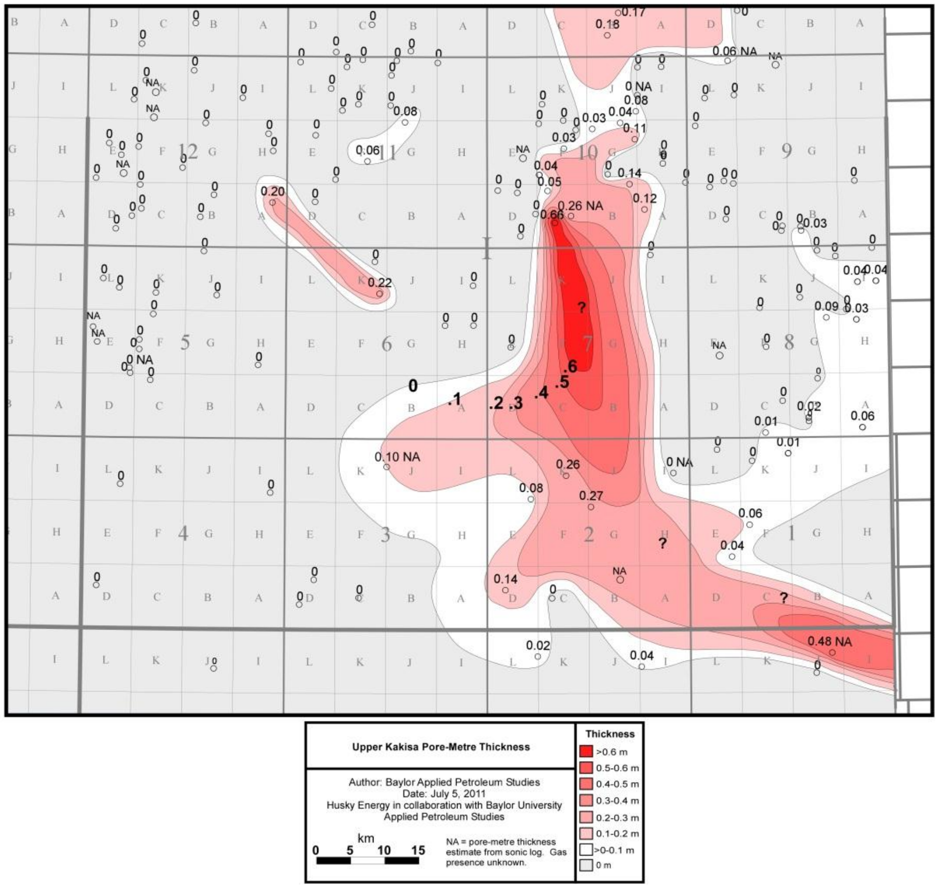

Figure 17. Upper Kakisa pore-meter isopach map.

Discussion

Within both the Upper and Middle Kakisa, a large fairway of "on-bank", potentially gas-saturated high reservoir quality rock is present (Figures 14, 17). Although the Middle Kakisa fairway is slightly offset to the east of the Middle Kakisa fairway (compare Figures 14 and 17), both fairways coincide with high-energy reefal deposits of the "on-bank" facies association (i.e., facies 4, 5)(Figures 12 and 15).

Within the Middle Kakisa, the thickest occurrence of gas-saturated reservoir occurs within the central portion of the largest, north-south trending fairway within the eastern portion of the study area (Figure 14). The pore-volume reaches a maximum observed value of 0.84 in this area, and is as high as 0.72 within the southern portion of the fairway (Figure 14). The Upper Kakisa is not as extensive as that of the Middle Kakisa, nor are pore-volume maxima as high (Figure 17). Maximum pore-volume reaches 0.66 within the central portion of the Upper Kakisa fairway (Figure 17).

CHAPTER SIX

Conclusions

1. The Late Frasnian Kakisa Formation is composed of 7 depositional facies that accumulated as a carbonate bank complex across the study area. Depositional environments include basinal, slope and reef crest, subtidal and intertidal.
2. Facies are organized into two facies associations. Facies 4 and 5 are grouped into the on-bank facies association, characterized by a high-energy, reefal depositional environments. Facies 1, 2, 3, 6, and 7 are combined into the off-bank facies association which correlates to a low-energy, subtidal to intertidal depositional environment.
3. The highest potential reservoir quality is associated with facies 4 (massive encrusting stromatoporoid boundstone, MESB) and facies 5 (platy stromatoporoid boundstone PSB) of the "on-bank" facies association. Both porosity and permeability are higher within the on-bank facies association which has permeability approximately two orders of magnitude higher than the “off-bank” facies association.
4. The Kakisa is divided into three shallowing-upward depositional cycles designated the "Lower", "Middle" and "Upper”, and are distinguished by gamma ray wireline logs. Variations in natural gamma radiation allow the discrimination of "on-bank" and "off-bank" petrofacies .
5. Within the Lower Kakisa, only non-reservoir “off-bank” facies association are observed.

6. Within the Middle Kakisa there are two areas of reservoir-prone “on-bank” buildups. A large fairway occurs within the eastern portion of the study area, as well as a less extensive buildup in the western portion. Gas saturation is associated only with the broad eastern fairway.

7. Within the Upper Kakisa, one large fairway of “on-bank” facies was identified within the eastern portion of the study area, and almost directly coincides with the location of the Middle Kakisa “on-bank” fairway. The Upper Kakisa fairway is less extensive and of lower pore-meter thickness.

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