UNIVERSITY OF ALBERTA

3-DIMENSIONAL MODELING OF THE STRATAL ARCHITECTURE OF THE McMURRAY FORMATION, NORTHEASTERN ALBERTA: SYNCRUDE NORTH MINE

by

Robert William Grover ©

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Abstract

The Lower Cretaceous McMurray Formation of northeastern Alberta, Canada, is host to one of the richest hydrocarbon reserves on Earth. A dataset from the McMurray Formation, consisting of 2107 closely-spaced vertical well-bores, is used to generate a three-dimensional visualization of nine facies and respective stratal archtiecture of Syncrude's North Mine Area. Geostatistical analysis was used to define correlation ranges for the highly variable stratigraphy. The correlation ranges were subsequently applied to the modeling process to create a detailed sedimentologic and stratigraphic model from high-density well-bore data (commonly less than 100m spacing). The derived model provides an opportunity to assess the depositional system of the McMurray Formation. In the study area, the stratal architecture of the McMurray deposits is interpreted to represent a tide-dominated delta.

Acknowledgements

This current work could not have been completed without the dataset acquired from Syncrude Canada Ltd and the financial support provided by Nexen Inc.. Schlumberger Information Systems, Petrel Division, was integral to this study in providing the software, technical support and necessary training needed to model the data in three dimensions.

Over the course of my thesis, I have bounced back and forth between three different cities: Fredericton, Calgary, and Edmonton. In Fredericton, at the University of New Brunswick the faculty and staff provided a close knit community of people that always made you feel welcome and at home in the work place.

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To William and Hendrika Grover,

my loving parents

Preface

The human race that treads upon Earth presently requires petroleum and petroleum products to function as a civilization. *Homo sapiens* are heavily dependant upon the exploration, exploitation and recovery of fossil fuels to live on a daily basis. Where must the supply for this demand come from? Canada, and specifically, Alberta, holds one of the greatest accumulations of hydrocarbons in the world within it's subsurface to provide a portion of this demand. As the world's human population increases the demand for the current societal fuel is every increasing at an exponential rate; therefore, we, as a race, must procure a proficient method of delineating the occurrence of the remaining resource to feed the consumer.

The Athabasca Oil Sands contains a double-fold wealth, rich in geological complexity and rich in resource, but this complexity yields a great hindrance to the individual trying to recover the resource. As a result, exploitation of oil sand deposits has fueled the evolution of recovery technology. Will we, *the superior race*, be able to find the key to unlock this colossal store? If so, how long will the supply last? Will we do it with respect for the delicate balance of the planet? Will the fall of the Petroleum Age coincide with the demise or rise of *homo sapien's* existence?

Table of Contents

List of Tables

List of Figures

Appendices

Chapter 1 – Introduction to The McMurray Formation

Introductory Remarks

The McMurray Formation of northeastern Alberta, Canada (Fig. 1.1), is host to one of the largest hydrocarbon accumulations on Earth. The McMurray Formation (Fig. 1.2) and overlying Wabiskaw Member of the Clearwater Formation contain approximately 148.5 x 10^9 m^3 (934.5 billion barrels) of bitumen in the Athabasca Oils Sands Area and about 24 x 10^9 m^3 (152 billion barrels) occur in the surface mineable area (Alberta Energy and Utilities Board, 1996). This lower-Cretaceous siliciclastic deposit has never been buried to significant depths; therefore, the quality of the resource closely reflects the distribution of sedimentary facies, as diagenesis has been minimal. Although McMurray strata have suffered only minor alteration, the heterolithic complexity of the deposit necessitates an understanding of the sand- and mud-body characteristics and their geometry. Accordingly, intense sedimentologic and stratigraphic research has been conducted on these strata (Carrigy, 1959; Mossop, 1980; Pemberton et al., 1982; Flach and Mossop, 1985; Mossop and Flach, 1983; Flach, 1984; Cuddy and Muwais, 1987; Mattison, 1987; Fox, 1988; Ranger 1994; Bechtel, 1996; Ranger and Pemberton 1992, 1997; Wightman and Pemberton, 1997). The aforementioned studies have focused on the mesocopic and macroscopic complexity of the McMurray Formation with 2-dimensional (outcrop and core) data; however, crude 3-Dimensional (3-D) models have been inferred from these core and borehole data sets. Building on previous research, this study aims to develop a detailed 3-D sedimentologic and stratigraphic model from high-density well-bore data collected by Syncrude Canada Ltd. (Syncrude) from the North Mine (Fig. 1.1C and 1.3), north of Fort McMurray, Alberta. This research differs from previous work in that the facies modeling will be used to generate a detailed 3-dimensional stratigraphic framework for the local strata. Conversely, the study is similar to previous work in that: (1) the data points are closely spaced (commonly less than 100m spacing); and (2)

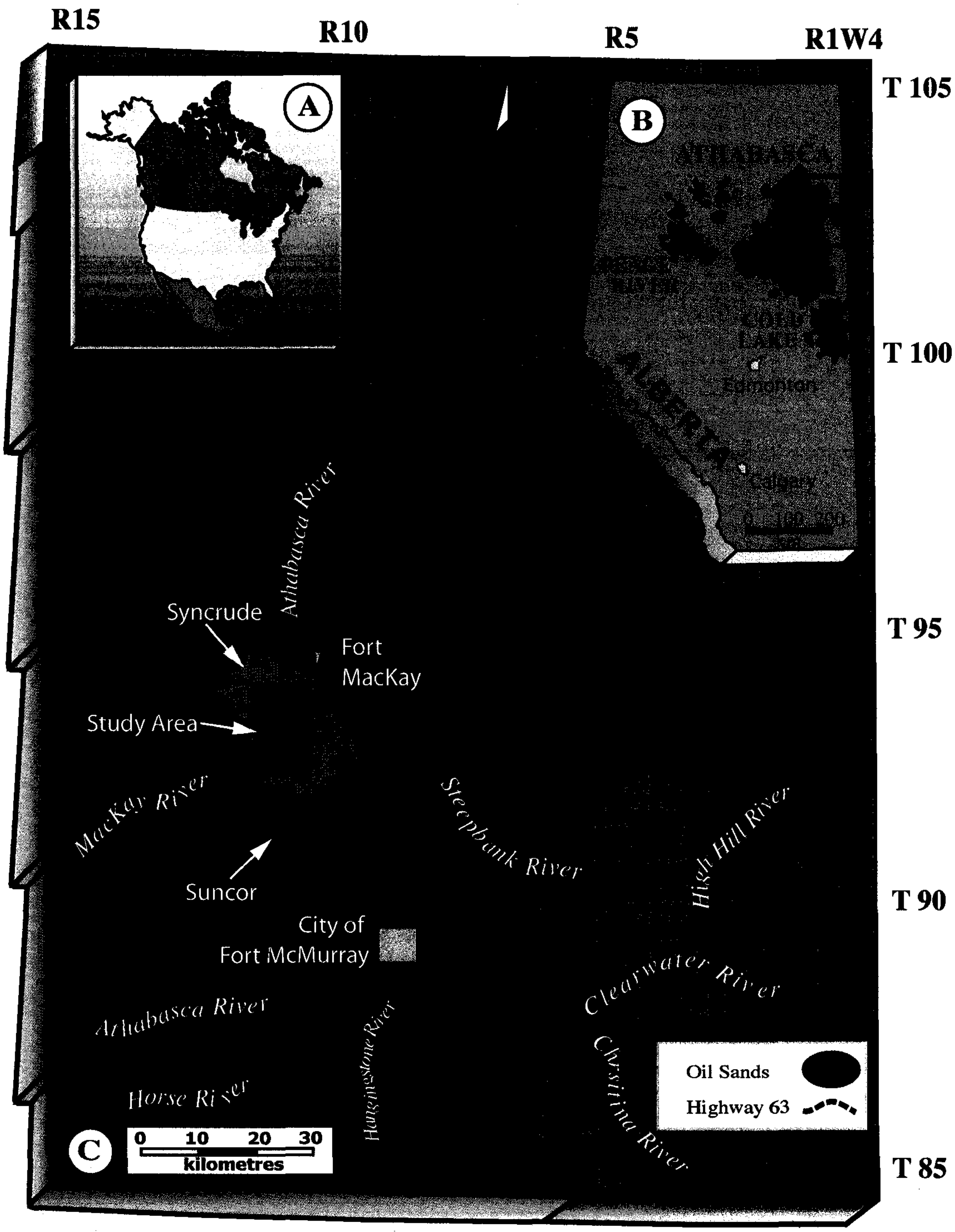

Figure 1.1. Location of Study Area (A) Map of North America with the province of Alberta, Canada in red. (B) Aerial distribution of oil sands deposits within Alberta. (C) Aerial distribution of the Athabasca Oil Sands within the vicinity of study area (modified from Wightman and Pemberton, 1997).

various types of data have been collected for each borehole including dip-meter (attitude of bedding planes), depth-demarcated facies, and digitally archived core photography. An academic study utilizing a similar dataset and methods is unprecedented.

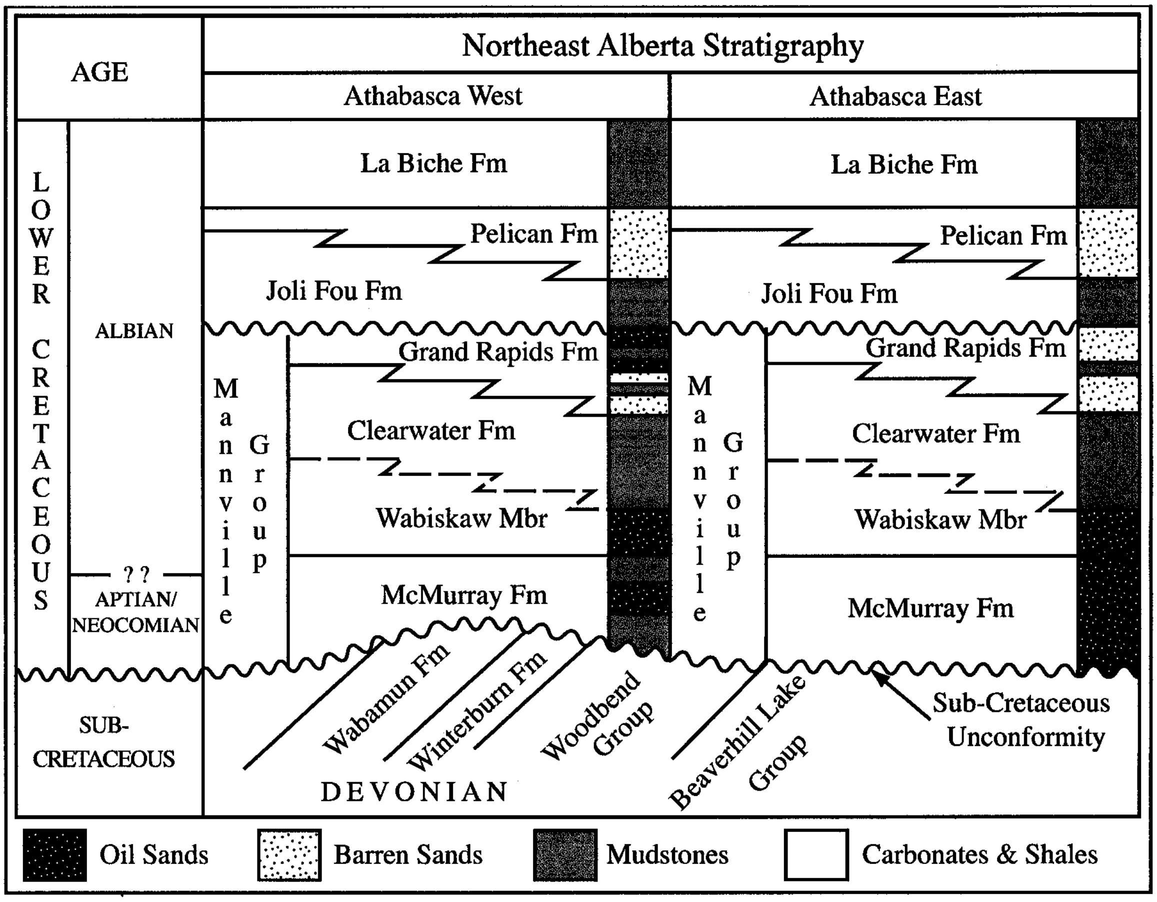

Figure 1.2. Regional Stratigraphy of the Athabasca Oil Sands Deposit of Northeastern Alberta (Modified after Wightman and Pemberton, 1997).

Study Area and Data Set

The study area (Fig. 1.1C and 1.3) is located approximately 45 kilometres north of Fort McMurray, Alberta, within Syncrude's North Mine. Syncrude's North Mine is approximately 150 km^2 and spans Township 92-, 93-, and 94 - Range 11W4 and 12W4. The study is located within the surface mineable portion of the Athabasca Oil Sands Deposit. Due to computer hardware and modeling constraints, the North Mine Lease was divided into two separate areas (north and south areas) based on well density (Fig. 1.3B). Comparatively, the south area holds a higher well-density (1567 well-bores) than the north area (540 well-bores). Hereafter each area will be referred to accordingly when deemed significant.

The dataset, generated between 1957 and 2002 consists of 2107 closely spaced

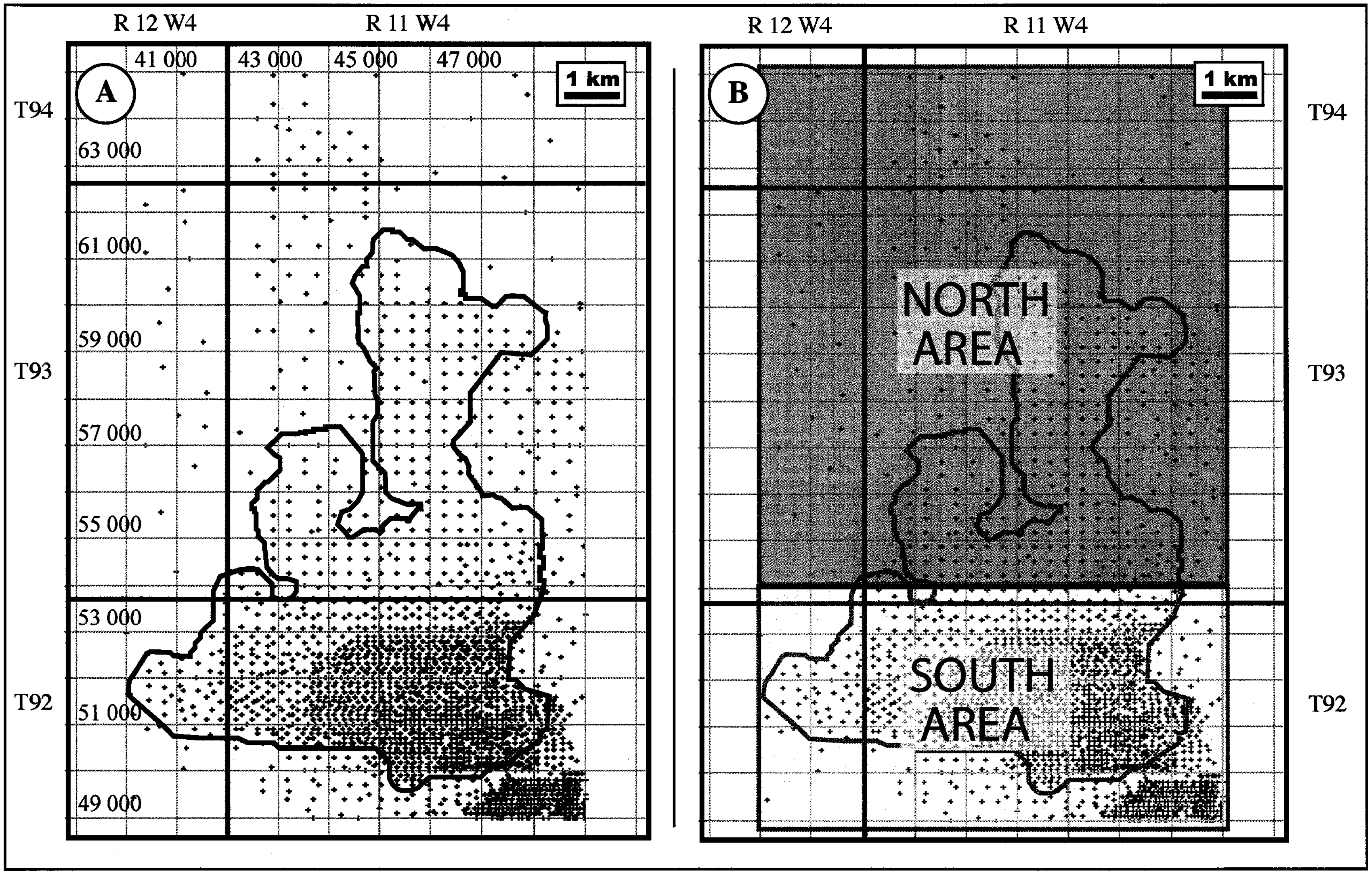

Figure 1.3. Location of the Local Study Area and Syncrude's North Mine Well Density. (A) A total of 2107 well-bores populate the area. Each black cross-hair indicates one well-bore. The grey grid sytem is a 1 km X 1 km grid used by Syncrude. The red line encompasses the surface mineable portion of Syncrude's North Mine reserves. (B) Division of Lease based on well density. North Area = Low Density (540 well bores) versus South Area = High Density (1567). (Image Courtesy of Syncrude Canada Ltd. 2002).

vertical well bores, with the majority of data being collected following 1980. The dataset is composed of two components: (1) depth-demarcated facies data for each well bore; and, (2) digitally achieved core photos (517 well bores).

Regional Stratigraphy and Geologic Framework

The McMurray Formation represents the basal formation in the lower Cretaceous Mannville Group (Fig. 1.2) and lies directly atop the regionally extensive sub-Cretaceous unconformity developed on Paleozoic carbonates. The McMurray Formation represents the initial response to a relative rise of the Boreal Sea to the north (Flach, 1984). The relative rise in sea level and subsequent sedimentation were related to a second major episode within the Columbian Orogeny. However, the overall transgression during this time has been grossly over generalized (Ranger and Pemberton, 1997). Consideration must be given to the minor fluctuations, incremental transgressions and regressions, within the overall transgression. The key control on initial sedimentation within the McMurray was the topography of the unconformity. Collectively, dissolution of the Elk Point Group evaporites and sporadic karsting of the Beaverhill Lake Group shaped an expansive environment for deposition of the McMurray sediments known as the McMurray subbasin. This depositional center was constrained by the Precambrian Shield to the east and by carbonates of the Grosmont Formation to the west. The main portion of the McMurray was deposited in a northwesterly trending paleovalley (Wightman et al., 1989).

The ages of the McMurray Formation deposits have received much debate. Burden (1984) and Selby and Creaser (2005) provide useful end-member constraints for age determination of the deposit. Burden (1984) using palynomorph biostratigraphy appointed an age of Late Valanginian (Hauterivian) and Early Barremian to initial McMurray sedimentation. Subsequent and final deposition of the McMurray sediments were allocated to the late Barremian, Aptian, and earliest Albian ages. Selby and Creasar

(2005) indirectly established that McMurray deposition ceased prior to the Early Albian. Using Renium-Osmium dating Selby and Creaser (2005) dated the oil in the McMurray sediments at 112 Ma ± 5 Ma. Therefore, deposition of the McMurray Formation is restricted to the *very* Early Albian.

Informally, the McMurray Formation has been divided into a lower, middle and upper member (Carrigy, 1959). A general description of each member as provided by Wightman and Pemberton (1997) is presented below; therefore, this should not be taken as a detailed account of the depositional history of the McMurray Formation. Extensive literature exists on the specific sedimentologic, stratigraphic, and ichnologic characteristics of each member and the reader is referred to the cited references of Table 1.1 and 1.2. The lowest portion contains continental sediments deposited within the poorly organized drainage system that existed atop the carbonates (Flach, 1984). The overlying, middle and upper members were deposited by a major, northward-flowing drainage system represented by sediments that accumulated in fresh- to brackish-water environments. The degree of marine influence generally increases stratigraphically upwards and to the north. Almost all of the carbonate topographic highs were completely submerged when deposition of the upper member was initiated, but a relative drop in sea level initiated another incision of valleys into the upper member. This final incision was followed by a southward transgression of the Boreal Sea, resulting in deposition of the marine Wabiskaw Member of the Clearwater Formation (Jeletzky, 1971). The Wabiskaw Member is lithologically recognized by the first appearance of visible glauconite (Bagdan, 2005).

Current models for the McMurray Formation are the result of extensive outcrop and core studies. However, most researchers agree that the existing esturaine depositional model is not helpful in providing a predictive model for the respective strata. This is contrary to the existence of an accepted regional architectural framework. Although all of the previous works represent invaluable contributions, they also demonstrate that the

Temporal Evolution of Notable Works Pertaining to the McMurray Formation

Author(s)/Pub. Date	Notable Accomplishment
Carrigy (1959)	Informally divided the McMurray Formation into Lower, Middle, and Upper Members and this basic stratigraphy has not evolved since
	Defined the main sedimentological features of the McMurray Formation *Members*
Carrigy (1971)	Interpreted large inclined bedsets exposed at Steepbank to be delta foresets
Carrigy (1973)	Interpreted much of the McMurray Formation of northern Athabasca Deposit a deltaic system
Nelson and Glaister (1978)	Recognized regional correlatable radioactive (gamma ray) shales and reinforced the three-fold division
	Produced a detailed sedimentologic delatic model
Flach and Mossop (1978)	Interpreted inclined heterolithic stratification (originally epsilon cross-strata (Allen, 1963) as point bars within deeply incised channels)
Stewart and McCallum (1978)	Proposed that much of the deposit may have been deposited under estuarine conditions after many years of subsurface and outcrop work (Stewart, 1963, 1981)
	Suggested that the McMurray consists of a lower fluvial *Member* , a thick middle estuarine *Member* , and a upper marine *Member* ; all of which are mappable on a regional stratgraphic scale
Mossop (1980a); Flach and Mossop (1985)	Identified a limited success in extrapolating outcrop observations into the subsurface
Pemberton et al. (1982)	Utilized ichnology to provide evidence of marine brackish conditions during McMurray time
Flach (1984)	Produced palynological evidence indicating fresh water conditions with rare brackish water influence for the Lower member
Flach and Mossop (1985)	Identified the best reservoirs of the Athabasca Deposit are deep, sand-filled, incised channels
Beynon & Pemberton (1992); Ranger & Pemberton (1992)	Enhanced ichnological evidence of the McMurray suggested the Middle *Member* was deposited under estuarine conditions with the deposits being dominated by ichnofossils from the *Skolithos* and *Cruziana* ichnofacies; while the Lower member ichnological assemblage is low in abundance and diversity
Wightman and Pemberton (1997)	Revised and reinterpreted measured cross sections along the Steepbank, MacKay and High Hill Rivers to produced a detailed sedimentological and ichnological account for each member
Ranger and Pemberton (1997)	Produced a detailed stratigraphic framework for the southern Athabasca Deposit using a minimum of four parasequences
	First to identify shoreface strata incised by a incised valley complex
Ranger and Gingras (2003)	Reinterpreted the McMurray Formation to represent sedimentation accumulation within a tide-dominated delta

Table 1.1. Temporal evolution of published literature pertaining to the McMurray Formation.

Unpublished Works Pertaining to the McMurray Formation Geology	
Author	**Title of Thesis**
Mellon, G. B. (1955)	Age and origin of the McMurray Formation
Flach, P. D. (1977)	A lithofacies analysis of the McMurray Formation, lower Steepbank River, Alberta
James, D. P. (1977)	The sedimentology of the McMurray Formation, East Athabasca
Burden, E. T. (1984)	Lower Cretaceous terrestrial palynomorph biostratigraphy of the McMurray Formation, northeastern Alberta
Cowart, J. H. (1983)	Ichnology and depositional environments of the Athabasca Oil Sands, Steepbank River area (McMurray Formation)
Wanklyn, R. P. (1985)	Stratigraphy and depositional environments of the Ostracode Member of the McMurray Formation (Lower Cretaceous; late Aptian-early Albian) in west-central Alberta
Fox, A. J. (1988)	The Lower Cretaceous McMurray Formation in the subsurface of Syncrude Oil Sands Lease 17, Athabasca oil sands, northern Alberta - a physical sedimentological study in an area of exception drill core control
Mattison, B. W. (1987)	Ichnology, paleotology, and depositional history of the Lower Cretaceous McMurray Formation, Athabasca oil sands area, northeastern Alberta
Ranger, M. J. (1994)	A basin study of the southern Athabasca oil sands deposit
Yuill, C. N. (1995)	Sedimentology, stratigraphy, and ichnology of the McMurray Formation, northeastern Alberta
Bechtel, D. J. (1996)	The stratigrphic succession and paleoenvironmental interpretation of the McMurray Formation, O.S.L.O. area, northeastern Alberta
Harris, C. R. E. (2003)	Aspects of the sedimentology,ichnology, stratigraphy and reservoir character of the McMurray Formation, northeastern Alberta
Riddell, J. H. T. (1993)	Stratigraphy, structure, sedimentology, and natural gas potential of the Lower Cretaceous Mannville Group in the Leismer area, northeastern Alberta
Crerar, E. E. (2003)	Sedimentology and stratigraphic evolution of a tidally-influenced marginal-marine complex; the Lower Cretaceous McMurray Formation, Athabasca Oil Sands Deposit, northeastern Alberta
Lettley, C. D., (2004)	Elements of a Genetic Framework for Inclined Heterolithic Strata of the McMurray Formation, Northeastern Alberta
Bagdan, C. (2005)	Stratigraphy, Sedimentology and Ichnology of the McMurray Formation; Northeastern Alberta, Canada.

Table 1.2. Temporal evolution of unpublished graduate thesis pertaining to the McMurray Formation.

existing basic marginal-marine model, as applied to the McMurray Formation, has not evolved significantly since Pemberton et al.'s (1982) seminal 'estuary' model. The intent of this study is to provide a 3-D high-resolution stratigraphic architectural model for the North Mine Lease that can be applied to the entire Athabasca Oil Sands deposit.

McMurray subbasin Paleotopography

The sub-Cretaceous unconformity of the Western Canadian Sedimentary Basin is an indurated surface and can be considered as the basement surface for the Early Cretaceous deposits. This surface is largely responsible for the distribution of facies in the McMurray Formation (Ranger and Pemberton, 1997). Accordingly, the distribution of ore-grade reservoir and non-reservoir rock is heavily influenced by the topographic relief of the unconformity.

Ranger (1994) stated that the sub-Cretaceous unconformity can be mapped more accurately by mapping the thickness of a suitable interval the base of which lay directly on the unconformity surface. If it is assumed that some overlying stratigraphic marker approximated a regionally *flat* surface (relative to paleo-sea level), then an isopach map of the respective interval between the upper surface and the unconformity forms a mold of the unconformity surface. Therefore, areas of thick accumulation represent topographic lows and areas of thin accumulation indicate highs on the unconformity (Fig. 1.4). Hereafter, the top of McMurray Formation is used as a datum to model the unconformity and all stratigraphic interpretations discussed within this study because it is the flattest surface available from the dataset.

During the early Cretaceous three main drainage systems deposited sediment on the sub-Cretaceous erosional surface of Northern Alberta (Ranger, 1994). The Peace River subbasin occupies the subsurface of western Alberta while the Red Earth Ridge and Grosmont High centralized deposition of the Wabasca subbasin in north central region of Alberta (Fig. 1.4). East of the Grosmont High and west of the Canadian Shield

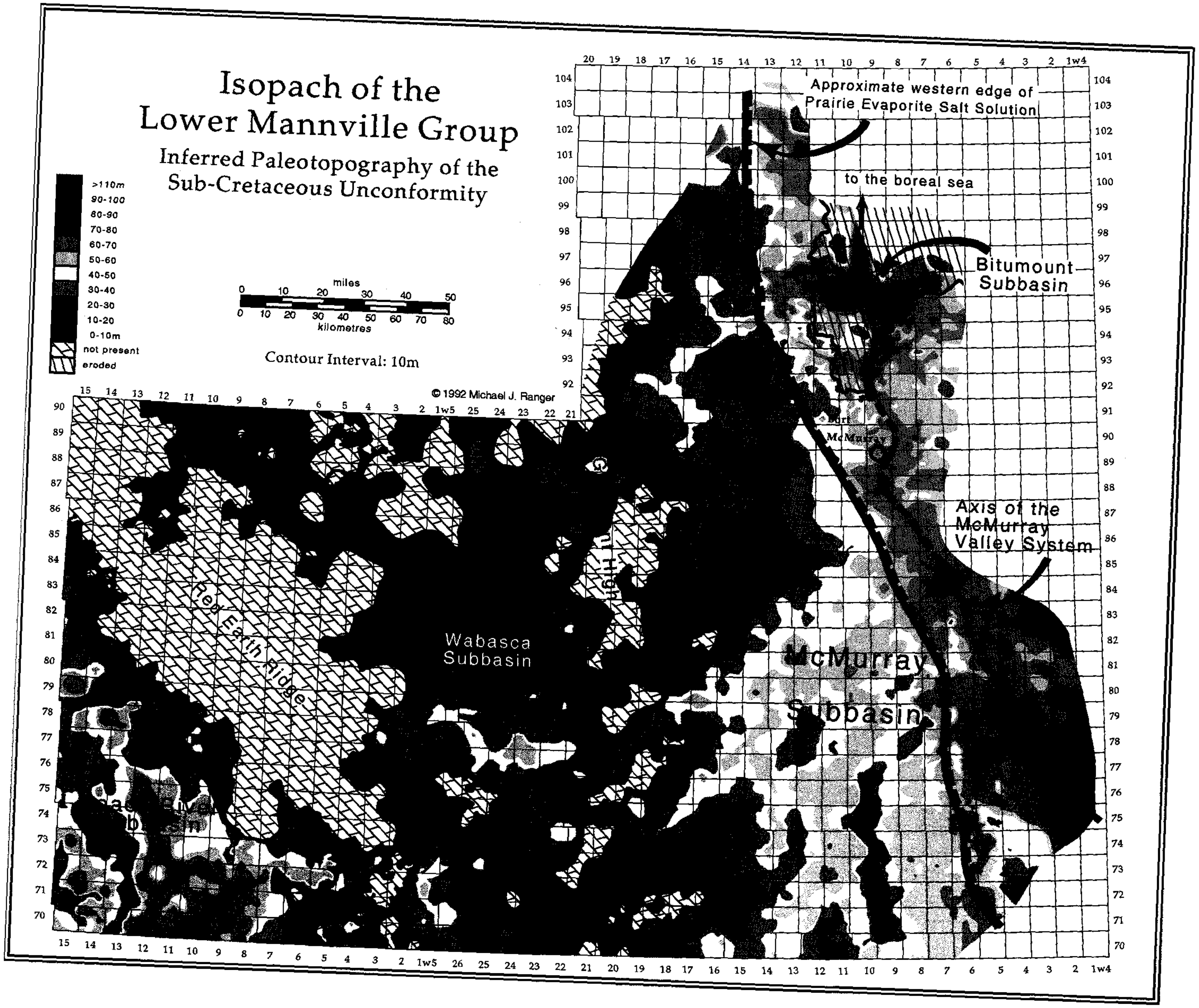

Figure 1.4. Inferred Paleotopography of the sub-Cretaceous unconformity. Courtesy of Michael J. Ranger.

the McMurray Formation was confined to deposition within the McMurray subbasin. The McMurray Formation was subsequently eroded or was not deposited over the crest of the Grosmont High. Small positive elements of the resistant Grosmont Formation exist below the McMurray succession and if present causes the deposit to be very thin or non-existent. The topographic highs of Figure 1.4 would have been interfluves, drainage divides, and headlands during the deposition of the McMurray Formation or islands during early marine transgressions. These headlands trend in a northeast direction on the east side of the Grosmont High; therefore, deposition is forced into northeast flowing tributaries. These tributaries have been mapped across to the eastern edge of the McMurray subbasin and they drain into the main trunk of the valley complex (Ranger and Gingras, 2003). The western limit of the main valley system is coincident with underlying dissolution of middle Prairie Evaporite, and in part by the collapse of lower Devonian Cold Lake and Lotsberg formations. This dissolution formed paleotopographic lows responsible for the McMurray Valley Complex and responsible for subsidence within the McMurray and Wabiskaw subbasins before, during and after accumulation of the lower Mannville succession. Dissolution and karsting of these carbonates is ongoing (Gingras and Ranger, 2003).

Geologic Setting of Study Area

With respect to the study area, Syncrude's North Mine is situated within the trunk of the McMurray subbasin (Fig. 1.4); therefore, the McMurray strata are relatively thick in this locale. Within the study area, the McMurray Formation is characterized by a range in thickness from 35 – 75m (Fig. 1.5; 1.6A). Trends observed within the study area are as follows: (1) the thickest strata (55-75m) are characterized by approximately linear (slightly sinuous) features 1 – 2 km wide oriented in a southeast-northwest direction. These trends are thick in the east and gradually thin toward the northwest limit of the area. (2) Thickness of the formational sediments decreases proportionally (55-35m) away from the abovementioned linear features. (3) Solitary, circular elements are dispersed

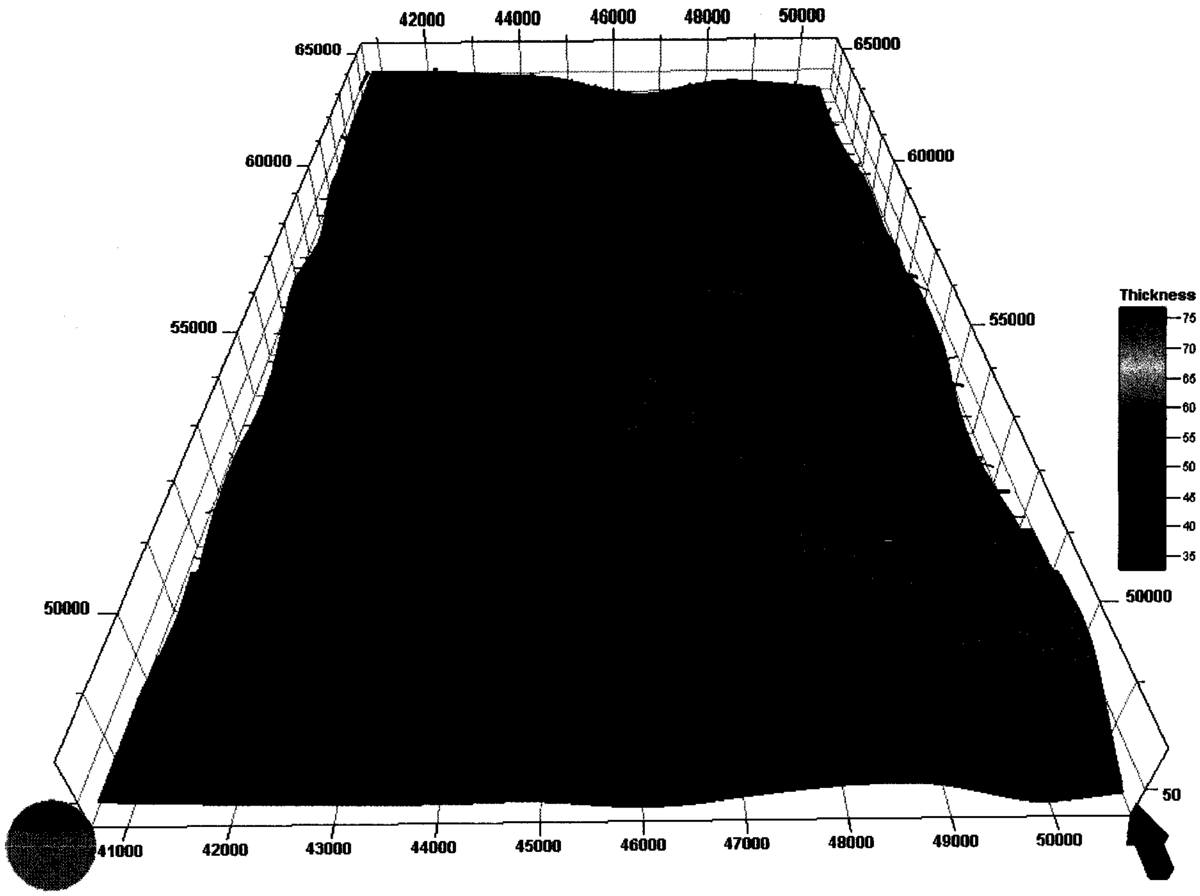

Figure 1.5. 3-D Surface Rendering of the McMurray Formation Isopach within the study area. Thicknes in metres.

throughout the area although these features generally occur proximal to the thickest strata. Respectively, the thick strata are representative of topographic lows of the sub-Cretaceous unconformity. Early Cretaceous sediments would have initially occupied these areas while subsequent sedimentation would have infilled the remaining area.

Presently, the generalized structural relief of the sub-Cretaceous unconformity (Fig.1.6B and 1.7) is characterized by a main trunk or structural low (190 m - 230 m) trending from the southeast to northwest. This main topographic low is flanked by two terraces at two different elevations. The first terrace flanks the main trunk, to the southwest and northeast, and is characterised by elevations ranging from 230 m - 260 m. The second terrace flanks the first terrace with elevations ranging from 260 m to a maximum of 285 m.

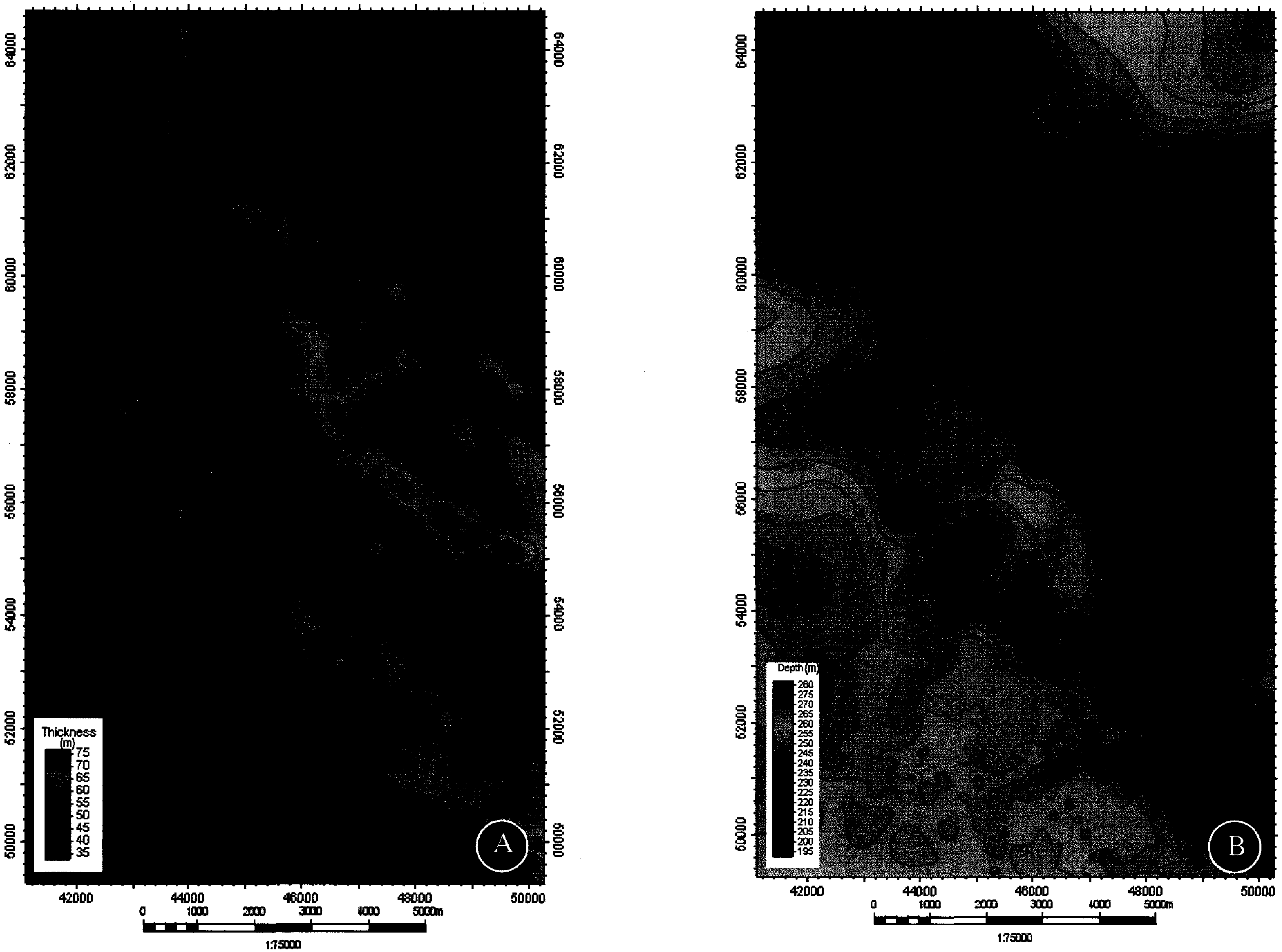

Figure 1.6. (A) 2-D Representation of the McMurray Formation Isopach. (B) 2-D Representation of the sub-Cretacesous unconformity structural elevation.

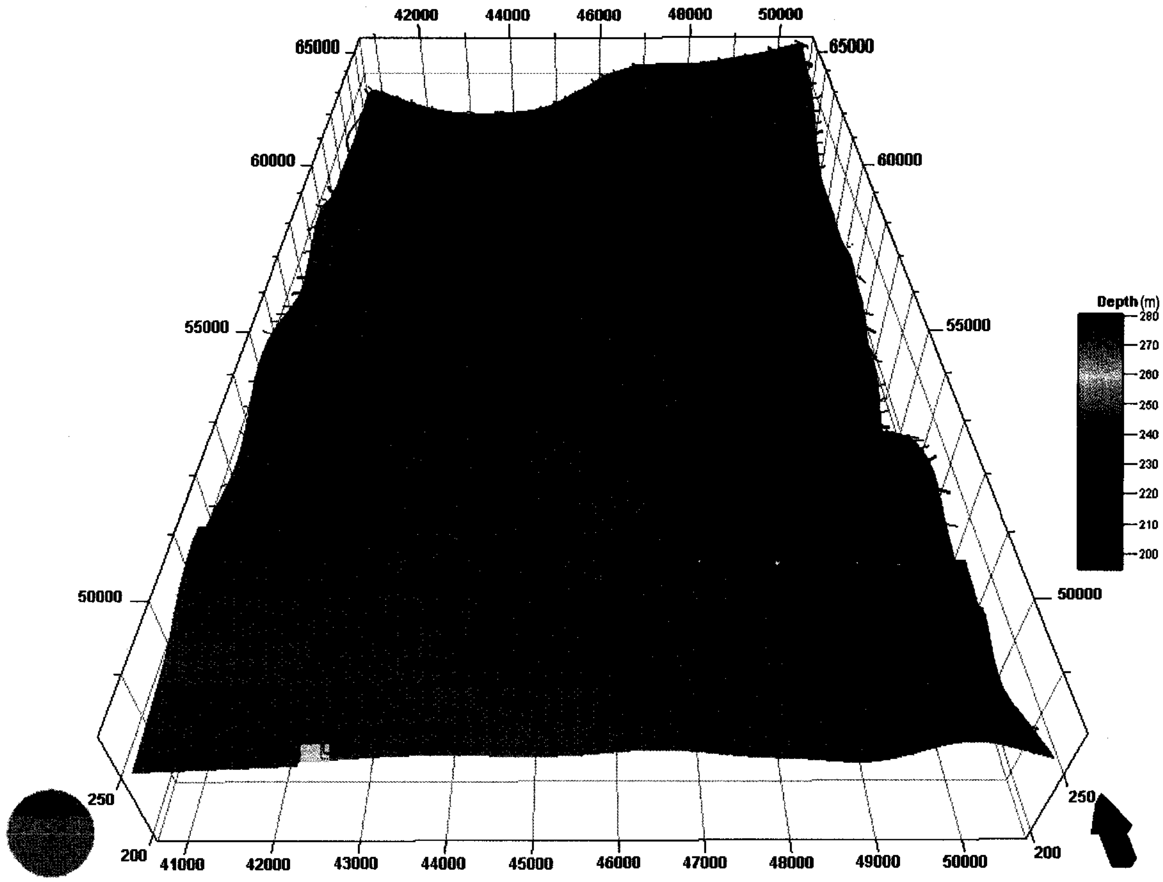

Figure 1.7. 3-D Surface Rendering of the sub-Cretacesous unconformity structural elevation.

Scope of Thesis

The intent of this thesis is to outline a research rationale, methodology, and a 3-D stratigraphic and sedimentologic framework for the McMurray Formation within Syncrude's North Mine. Specifically, the study strives to establish an architectural framework based on facies, thus providing a predictive model that can be applied elsewhere in the McMurray Formation. The data used to create maps, cross-sections and 3-D models are used to answer the following questions:

1) What subsurface mapping techniques are the most effective for the evaluation of the facies geometry, especially those that apply to reservoir units?

2) What is the genetic relationship between reservoir (sand) and non-reservoir (mud) facies? Does that relationship improve the ability of subsurface mapping to predict the location and geometry of the gross units?

3) How does the paleogeographic evolution of the system change throughout the deposition of the McMurray Formation?

Three main phases constitute the entirety of the project: (1) The first phases consists of extracting relevant data from the immense digital archive and synthesizing the data into a useable from; (2) the second phase consists of analysis of the synthesized dataset and development of efficient methods for modeling the geology of the McMurray Formation; and (3) mapping the procured sedimentologic and stratigraphic packages in three dimensions constitutes the final phase. The last two aforementioned phases occupies the bulk of the proceeding chapters. It should be noted that due to nature of Syncrude's data, such as core and facies descriptions, are electronically archived as depth-demarcated numbered facies; therefore, a detailed sedimentologic or ichnologic investigation shall not be revisited due to the shear volume of core data. More importantly, the focus of the research is to establish facies centered on the sedimentary and spatial relationships of the 3-dimensional nature of the depositional packages within the McMurray Formation.

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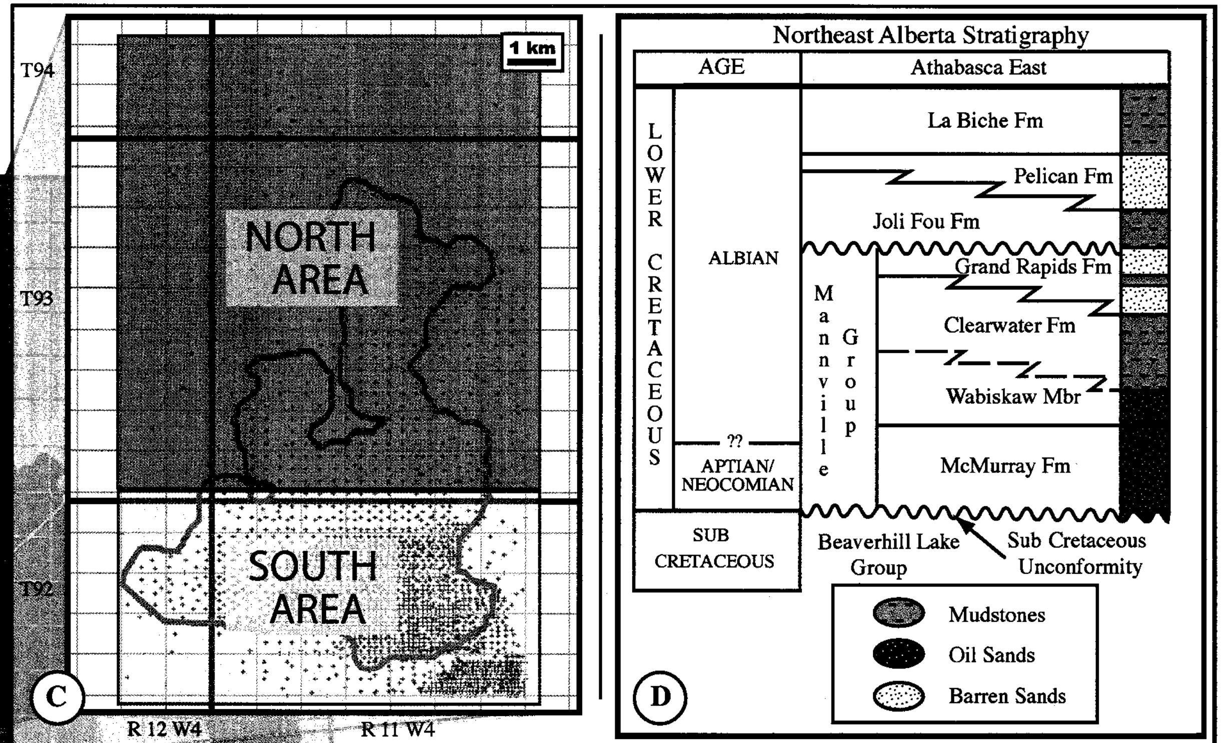
Chapter 2 – Establishing Correlation Ranges within a Facies Framework: A Collaborative Effort to Model the McMurray Formation of northeastern, Alberta

Introductory Remarks

The geologic complexity of the Athbasca Oil Sands Deposit, of northeastern Alberta, Canada (Fig. 2.1A and B) has enticed geologists and petroleum geologists since the late 1800's. Research on the complex deposit has gained exponential momentum within the last 25 years as the quest for a predictable architectural model at the local scale persists. Mossop (1980) was the initial investigator to identify a limited success in extrapolating outcrop observations of McMurray strata into the subsurface. A limited success of a different nature inhibits the understanding of the McMurray Formation within the subsurface. This obstacle, is correlation of lithologically similar units (facies) over short distances (commonly less than 200 m). Presently, this factor is one of the greatest obstructions impeding the progress of research pertaining to the lower Cretaceous deposit. An understanding of the distribution of depositional environments within the McMurray Formation is crucial for development of 3-D stratigraphic models. A detailed methodology for establishing this distribution is presented within this study.

Approximately 15% of the recoverable resource (152 billion barrels (Alberta Energy and Utilities Board, 1996)) within the Athabasca Oil Sands is surface mineable whereas the remaining reservoir is beyond the present limit of surficial exploitation. Three large surface excavations, Syncrude Canada Ltd. (Syncrude), Suncor Energy, and Shell Canada Ltd. (Fig. 2.1B), are currently in operation while several other companies have recently initiated mining of the ore. With the depletion of mineable stores, the energy sector is turning to in situ technologies. This recovery style requires high-resolution 3-D models for efficient exploitation.

The scientific intent of this paper explores the details and rationale of the methods developed and employed to enhance the 3-D sedimentologic, stratigraphic



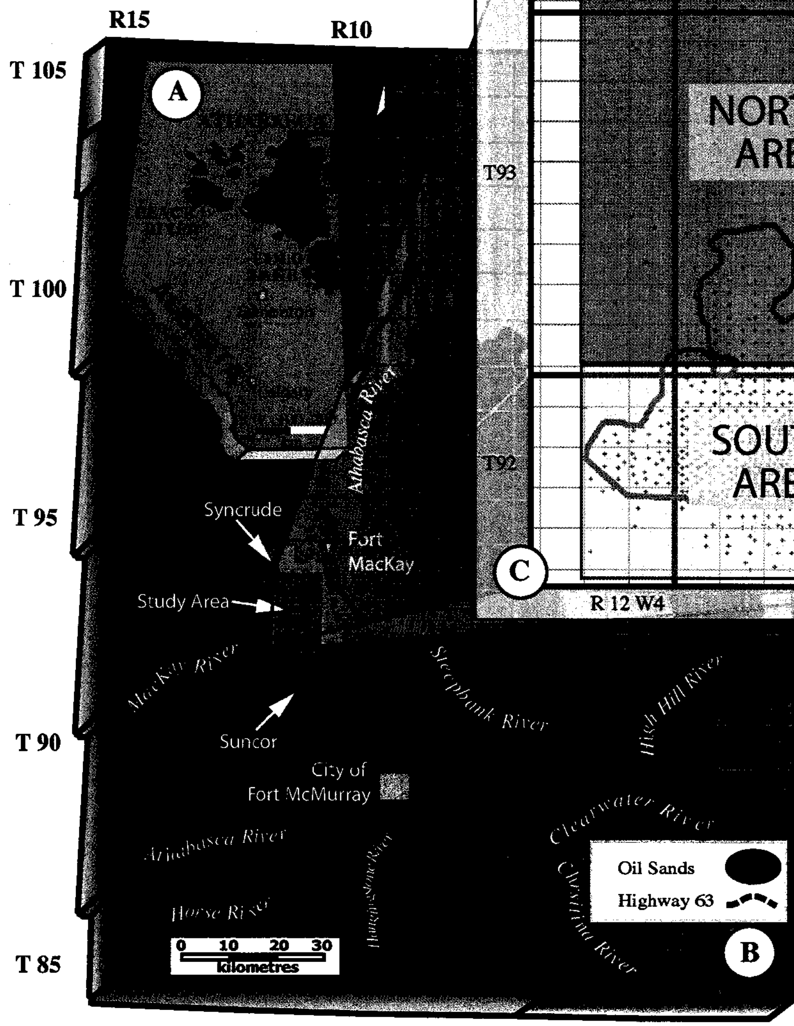


Figure 2.1. (A) Areal Distribution of the Athabasca Oil Sands within Alberta, Canada (modified from after Wightman and Pemberton, 1997). (B) Areal Distribution of the oil sands deposit in the regional vicinity of the study area (modified from after Wightman and Pemberton, 1997). (C) Syncrude's North Mine. Each well is represented by a small cross-hair. The yellow line indicates the surface mineable reserves. The study area is divided into two separate areas based on average well-density per square kilometre (modified from Syncrude Canada Ltd., 2002). (D) Stratigraphy of northeast Alberta (modified from after Wightman and Pemberton, 1997).

and paleogeographic understanding of the McMurray Formation within the Athabasca Oil Sands. In particular, the use of 3-D variography applied to a facies framework will be accessed. This method strives to analyze the existing data to establish correlation ranges of the nine facies with respect to varying well-densities. Petrel™ Workflow Tools (Petrel), 3-D modeling software, acquired from Schlumberger Canada was used extensively throughout the study.

Study Area and Dataset

The study area is located approximately 45 kilometres north of Fort McMurray, Alberta, within Syncrude's North Mine (Fig. 2.1B and C). For the purpose of this study, the North Mine Lease was divided into two separate areas (north and south areas) based on well density. Comparatively, the south area holds a higher well-density (1567 well-bores) than the north area (540 well-bores). The geologic setting and regional stratigraphy of the study area are discussed at length in Chapter 1; therefore, the reader is referred to the relevant preceding material.

Although acquisition of the primary data was conducted by Syncrude Canada Ltd., a short account of how the data was collected will be examined. Acquisition of well-bore data was conducted mainly by Syncrude with drilling of each well-bore consisting of the following: (1) recovery of core from present-day surface, through the McMurray Formation (Fig. 2.1D), to approximately 10 metres into the underlying Waterways Formation (Beaverhill Lake Group); and, (2) geophysical wireline logging consisting of the typical log suite (gamma ray, neutron density, bulk density, spontaneous potential, resistivity, and dip-meter logs) for the bulk of the wells within the study area. Subsequent to core recovery, numerous geologists logged the significant sedimentary features of the core and categorized each lithologic unit using Syncrude's Lithofacies Chart (Appendix A) by depth-demarcation. A lithologic unit must be greater than 0.3 m to be logged as an individual facies. Thirty centimetres was deemed the vertical constraint on a stratigraphically significant lithofacies for local- and regional-modeling. Fifty-four McMurray Formation facies were applied to the core. Laboratory analysis consisted of particle-size distribution analysis and modal proportions of mass-bitumen, mass-water and mineral content. Of the 2107 well bores, 517 cores were photographed and digitally archived. It should be noted that due to the immensity of the dataset the scope of the current study focuses on the use of the depth-demarcated facies and core photo database of the McMurray Formation.

Methods

Before delving into the 3-D modeling method used in this study, clarification of the term facies as the term is used in the context of this paper is necessary. A depositional facies is a body of rock with specific characteristics that formed under certain conditions of sedimentation, reflecting a particular process, set of conditions, or environment (Middleton, 1973). A lithofacies (facies) is one for which the primary consideration is given to the physical and chemical characteristics of the rock; therefore, it may be defined based on color, bedding, mineralogy, texture, fossils, ichnofossils, and sedimentary structures (Reading and Levell, 1996). For the purpose of this study, a facies framework is used.

As stated above, the heterolithic nature of the McMurray strata necessitates a more evolved approach to model the 3-D stratal-architecture. The modeling technique of this study has been developed to advance the sedimentologic and stratigraphic understanding of the complex deposit. This technique uses a facies framework and variography in a collaborative effort to refine the current geologic models of the McMurray Formation. Variography, generation of variograms, strives to establish correlation ranges for each of the respective facies in the x, y, and z directions; therefore, a highly detailed architectural framework of the deposit is available for interpretation. The lateral and vertical extent of the facies is not well established within the current literature. This study will also test the ability to correlate the facies within the McMurray deposit based on differing spacing of the existing well-bores; hence the division of the south from the north area.

Spatial Framework

Before interpolation of core data can occur, the 3-D spatial framework of the model must be defined. The horizontal resolution of the framework is based on the spatial density of the data. A high-density of vertical well bores will consequently yield a high-resolution grid in the horizontal direction. Formation tops provide the primary vertical zone boundaries and define the lowest degree of vertical resolution for the 3-D grid (Fig. 2.2). Secondary vertical zoning (Fig. 2.2) of the strata is typically based on gross depositional environments (Badiozamani et al., 1992). Correlation and interpolation of potentially related units across a zone boundary will not occur, therefore, it is important to visually inspect the *raw* data before the zones are defined. The highest degree of vertical resolution, tertiary vertical zoning (Fig. 2.2), divides the geological zones into fine-scaled layers that can capture the pertinent spatial relationships of the data being modeled. The number of layers in each geologic zone is defined by the desired resolution. For example, if the maximum thickness of a zone equals 60 m and the desired resolution equals 0.5 m the resultant number of layers will total 120 layers. Cell height or the number of layers is typically based on the resolution of the data being modeled and a restriction on the minimum cell thickness of 0.5 m is imposed. Therefore, the number of layers is dependant upon the thickness of the zone of interest (Fig. 2.4). Definition of a high-resolution 3-D spatial framework, both horizontally and vertically, permits a viable grid system for interpolation of the data.

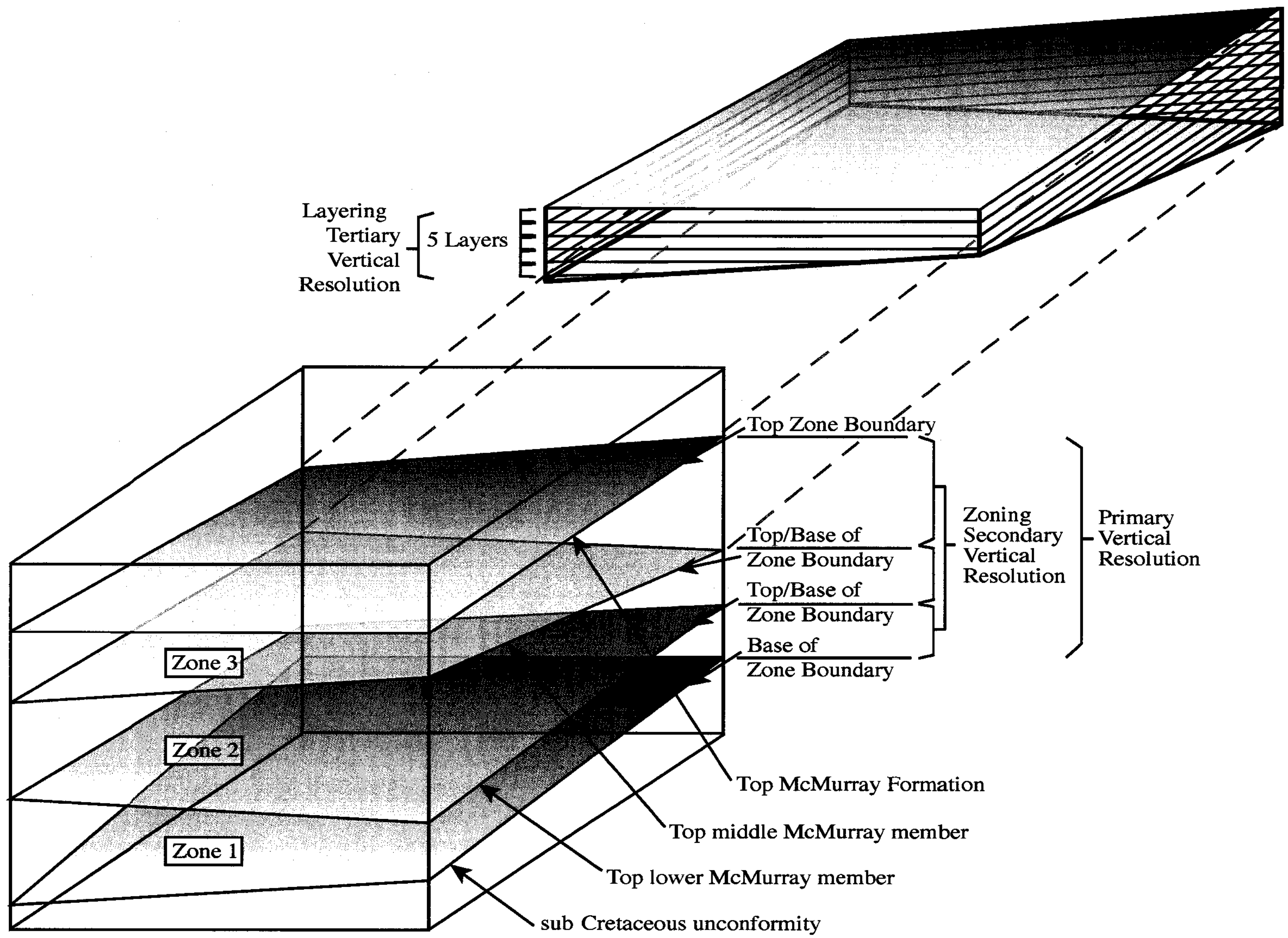


Figure 2.2. Spatial Framework. 3-Dimensional schematic illustrating the primary, secondary, and tertiary vertical resolution of the model block.

Geostatistics of Modeling

Another important feature of the modeling practices imposed on the dataset is the use of geostatistics. Not only is a comprehensive understanding of the geology required, but a thorough understanding of the geostatistical modeling methods available within a software package must also be acquired. Two different methods were considered for the current study – deterministic and stochastic modeling. Stochastic modeling parametizes the geological media by its statistical properties; this is in contrast to deterministic modeling whereby the characteristics of an available parameter(s) define the exact spatial distribution of the questioned parameter within the final product (Davis, 1986) - what you see is what you *map*. These two modeling methods are end-members within the realm of modeling. For the purpose of this study, both methods will be used to model the strata of Syncrude's North Mine. Geostatistical analysis of the data is used to define the correlation ranges of the facies. The directional trends are typically characterized by the regional sediment transport direction. Then, the indicator method of kriging is used to populate the spatial framework of the 3-D grid based on the predetermined statistics. Herein, a brief account of kriging and the statistical methods imposed on the data will be provided. The reader is referred to Davis (1986) for a detailed description of the kriging method.

Kriging is an estimation method of interpolation named after D. G. Krige who developed the technique in an attempt to more accurately predict ore reserves (Davis, 1986). This method is based on the assumption that the parameter being interpolated can be treated as a regionalized variable. A regionalized variable is intermediate between a truly random variable and a completely deterministic variable in that it varies in a continuous manner from one location to the next; therefore, points that are near each other have a certain degree of spatial correlation, but points that are widely separated tend to be statistically independent (Davis, 1986). Kriging is a set of linear regression routines that minimize estimation variance from a predefined covariance model. As mentioned above, regionalized variables have continuity from point to point, but the changes in the variable are so complex that they cannot be described by any tractable deterministic function. The regionalized variable for the current paper is defined as the spatial distribution of the facies. The size, shape, orientation, and spatial arrangement of samples (the boreholes and respective core) constitute the support of the regionalized variable. Thus, the study area was divided into two separate areas based on well-density as the well-spacing is markedly different in the north as compared to the southern portion of the study area (Fig. 2.1C). Accordingly, the distribution of the facies will have different characteristics and correlation ranges. *Therefore, well-bore locations within each area, but outside the normal well density area will have a low correlation confidence.*

The most important dependent of the kriging method is that of the defined variogram, which expresses the spatial variability of the facies. The spatial variability of each facies within the *raw* data is defined by a sample variogram. This variogram, generated within the in-house software, samples the major (y-axis), minor (x-axis) and vertical (z-axis) data set of facies for statistical correlation ranges. Upon detection of an anisotropy, directional trends (azimuth and dip) of the principal axes must be defined. Regional sediment-transport direction most accurately defines the directional trends. If anisotropy is not detected, the respective facies is deemed isotropic.

Specifically, a variogram is defined by the, sill, nugget, range and variogram type (Fig. 2.3). Results for the variograms herein are discussed in a proceeding section, but it is necessary to provide the reader with the basic definitions of the abovementioned terms pertaining to the understanding of a variogram. With respect to the sample variogram, point pairs are calculated according to specified search parameters, and the resultant variogram graphically represents the separation distance (x-axis) and the variance (y-axis). At each separation distance, a single point is generated representing the average of the square of total number of point pairs. The nugget indicates the point at which the variogram intersects the y-axis or the variance where the separation distance is zero.

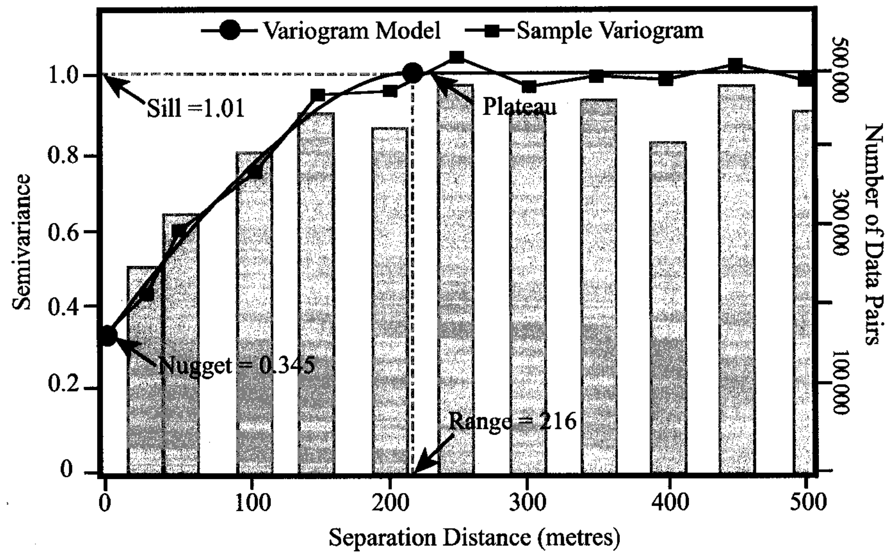


Figure 2.3. Typical variogram showing the relationship between the variance and the separation distance. Note the position of the sill and correlation range. The histogram represents the number of calculated data pairs at each separation distance.

This describes the short-scale variation in the data. The second part to the variogram is the sill, which is the variance where the separation distance is greater than the range and describes the variation between two unrelated samples. The point at which the variogram reaches the plateau (the range) is the separation distance (along the x-axis) where there is no longer any change in the degree of correlation related between pairs of data values. The range is used to define the correlation range of the facies in all three directions (x, y, z). The spatial distribution for each facies is thusly defined.

Generation of a variogram (Fig. 2.3) yields two plots: (1) a sample variogram calculated from the raw data using a direction and separation distance; and, (2) a variogram model which uses a continuous mathematical expression to describe the sample variogram. The variogram model is a linear regression, or line of best fit, to the sample variogram. Two different variogram models are available, spherical and exponential, to fit the sample data (Fig. 2.4) within Petrel.

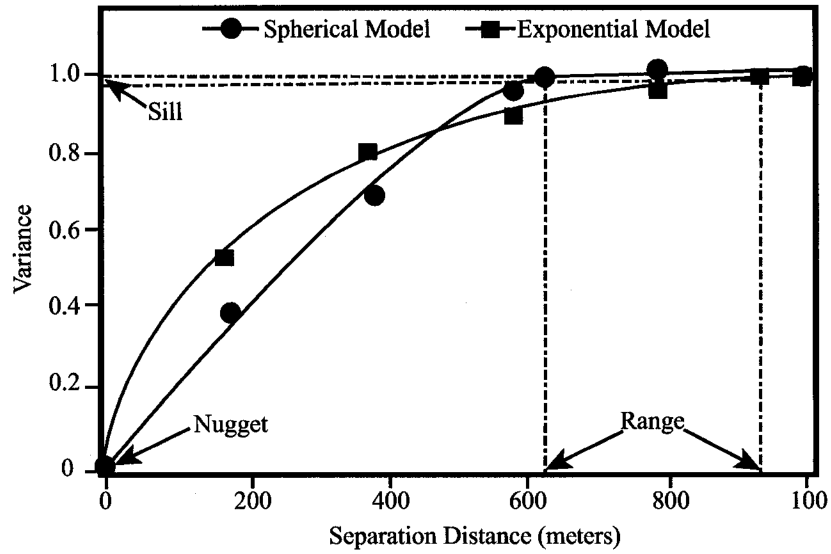


Figure 2.4. Spherical versus exponential variogram models. The exponential model reaches the sill asymptopically and the range is defined at a separation distance = 0.95c (c = sill - nugget). The spherical model produces a linear behavior at short separation distances and reaches the sill at the effective range. The variance of the exponential model is lower than the spherical model for all distances less than the range.

Application of the Modeling Method

Data Synthesis and Scope of Modeling

Upon receiving the dataset, the *raw* data from Syncrude's North Mine was synthesized into a usable form via custom Visual Basic code (Phase 1). This process eliminated redundancies within the data and allowed for quality control of the data. *Raw*, synthesized data (Well Collars, Formation Tops, and facies data) was then imported into Petrel whereby the Syncrude's Lithofacies were converted to the facies used in this study (Table 2.1). A detailed description and interpretation of each facies is presented within the proceeding chapter. The database of core photos complemented the development of the facies. Subsequent to Phase 1, variograms were generated for each facies (Phase 2) and then the variographic results were used to model the respective facies. Thus, providing a model ready for interpretation to gain an understanding of the stratigraphic framework within the McMurray Formation (Phase 3). The results of this model will occupy the bulk of the proceeding paper.

Facies used for 3-D Modeling	
Facies	Facies Descriptor
Facies 1	Small- to Medium-scale Massive to Cross-stratified Sand (lower member)
Facies 2	Large-scale Massive to Cross-stratified Sand (middle member)
Facies 3	Inclined Interbedded to Interlaminated Sand and Mud (>50% Sand)
Facies 4	Inclined Interbedded to Interlaminated Sand and Mud (>50% Mud)
Facies 5	Grey Mud to mudstone with Coal
Facies 6	Flat-lying Interbedded to Interlaminated Sand and Mud
Facies 7	Massive to Cross-stratifed Sand with Shells
Facies 8	Wavy Interbedded to Interlaminated Sand and Dark Grey Mud
Facies 9	Large-scale Massive to Cross-stratified Sand (upper member)

Table 2.1. Facies used in the modeling process for the north and south area.

Spatial Framework

As previously mentioned, the McMurray Formation is heterolithic, and the continuity of facies is very difficult to predict with widely-spaced data control. Data control for this study is very high in the south area and comparatively low in the north area. Respectively, the average well-spacing distance is 89 m (ranging from 25 - 2600 m) and 350 m (ranging from 75 - 2700 m). The interpolation process is heavily influenced by well-spacing within the laterally discontinuous McMurray deposits. Thus, the interpolation process within the models produces attractive results for the south model and less reliable results for the north area.

The top of the McMurray Formation and the sub-Cretaceous unconformity define the vertical extent of the model block (primary zoning) (Fig. 2.5). The top of the McMurray Formation is used as a datum and is generally observed at an elevation of 284 m. With secondary vertical zoning, the McMurray Formation is divided into three zones (Fig. 2.5). Each zone grossly represents the three informal members of the McMurray Formation (lower, middle, upper members). The final element of the vertical resolution is a function of the desired resolution of the 3-D grid and due to computational time a 0.5 m resolution was deemed appropriate.

Each model area is defined by cells that populate the model block and the horizontal resolution is strongly influenced by well-spacing. The following cell

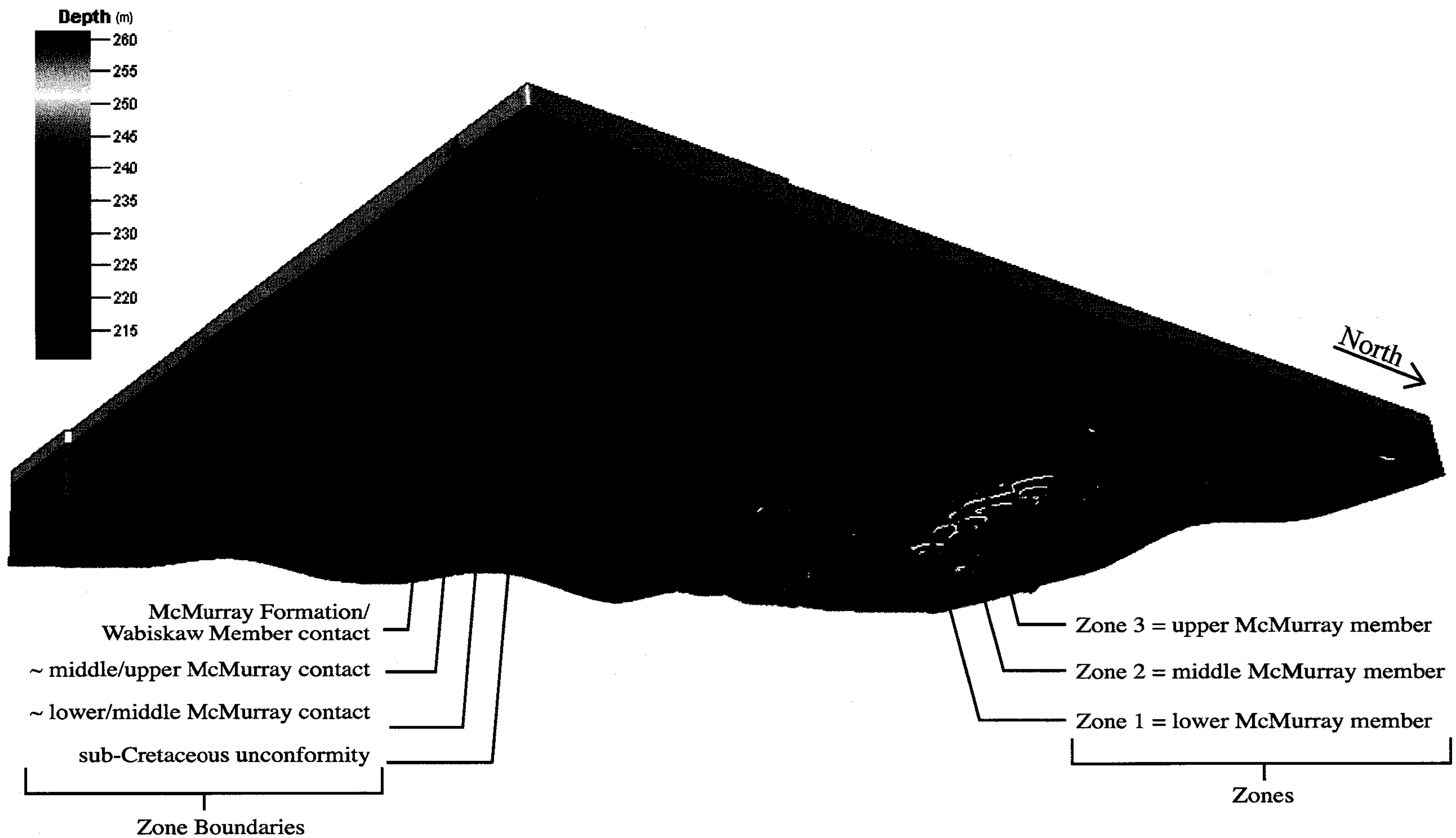


Figure 2.5. Primary and Secondary Vertical Zonation for the entire study area. View is from below the sub-Cretaceous unconformity. Block dimension = 16 km (length x 9 km (width).

parameters are considered average dimensions for each 3-D block. The south area is characterized by a 50 m X 50 m X 0.5 m (length X width X height) grid and cell dimensions for the north area are 75 m X 75 m X 0.5 m. Using three geologic zones, a high number of layers within these zones and superior well-control allow for the development of a reliable high-resolution model for the lower Mannville deposit in the south area. Comparatively, lack of well-control in the north area delivers a less reliable model.

Data Analysis and Results

A total of 2107 wells, 1567 wells in the south and 540 wells in the north area, were used in the analysis of the data to generate the variograms and resultant correlation ranges for each facies. Variograms were produced for each facies within the individual areas.

Specifically, the resultant variograms for each facies have one of three generalized forms: 1.) a *parabolic* form (Fig. 2.6A), indicating continuity of the facies distribution over a specific distance (range); 2.) a *nugget* effect (Fig. 2.6B), or apparent failure of the semivariogram to go through the origin, indicating that the distribution of the facies is highly variable over the sampling interval; and 3.) a *horizontal effect* (Fig. 2.6C) indicating no spatial correlation for the distribution of the facies. For each facies, the searches conducted were initiated to establish the nugget effect. The rationale for establishing the nugget effect is presented within the discussion. All variograms acquired through the data analysis process, for both the north and south facies, are presented in

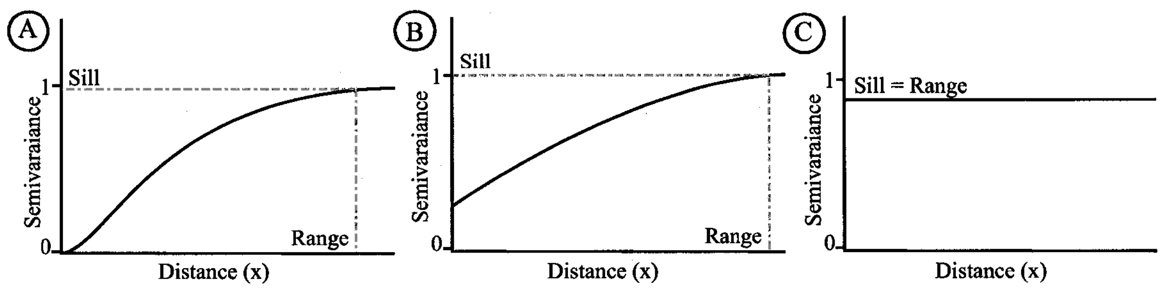


Figure 2.6. Three different forms of the resultant varigrams (A) Parabolic form. (B) Nugget effect. (C) Horizontal effect (modified after Davis, 1986)

Appendix B. With respect to fitting the sample variogram to the variogram model the exponential type was observed to best fit the majority of the sample data.

The search parameters used to generate the variograms are highly variable and only the final realizations are presented within Appendix C. Countless realizations were conducted to attain the final correlation lengths for each direction. For this reason they will not be discussed at length. The major axis orientation, 350°, is defined as the regional sediment-transport direction and the minor axis is oriented perpendicular to the major axis at 260°. Originally, the same search parameters for development of the variograms in south were applied to the north area but all resultant variograms produced a horizontal effect (Fig. 2.6C) indicating no correlation over the specified distances. Thus, the search parameters were expanded to achieve a parabolic or nugget form.

The variogram results defining the correlation range(s) for the nine facies are displayed in Table 2.2. The length (major axis) to width (minor axis) ratio for all the facies ranges from 1.3:1 to 1:1 (average 1.1:1) for the south area and ranges from 2:1 to 1:1 (average 1.42:1) for the north area. The correlation ranges were subsequently applied to the respective facies within the indicator kriging process, thereby influencing the inferred spatial distribution of each depositional environment.

Discussion

The current modeling technique uses a collaborative effort to model the stratigraphy of the McMurray Formation by using a facies framework and variography to define the correlation ranges of the respective facies. The modeling process is a simple three-fold process: (1) definition of the facies; (2) data analysis and variogram development; and (3) application of the results by modeling the data analysis by indicator kriging. This systematic technique permits the development of a more objective model. Upon completion of the discrete modeling process, the geologist can subjectively observe and interpret the model to gain a greater understanding of the McMurray's 3-Dimensional stratal-architecture.

Variogram Results and Correlation Ranges Applied to Synthesized Facies Data						
South Area						
Facies	Axis	Orientation (degrees)	Nugget	Range Distance (metres)	Model Type	Major:Minor Ratio
1	Vertical	0	0.129	7.69	Exponential	1.1:1
	Major	350	0.525	493	Exponential	
	Minor	260	0.526	464	Exponential	
2	Vertical	0	0.246	9.38	Exponential	1.6:1
	Major	350	0.683	263	Exponential	
	Minor	260	0.443	169	Exponential	
3	Vertical	0	0.0604	4.46	Exponential	1.3:1
	Major	350	0.591	451	Exponential	
	Minor	260	0.668	342	Exponential	
4	Vertical	350	0.274	6.56	Exponential	1.1:1
	Major	350	0.574	444	Exponential	
	Minor	260	0.584	394	Exponential	
5	Vertical	0	0.149	8.99	Exponential	1.0:1.0
	Major	350	0.447	423	Exponential	
	Minor	260	0.493	410	Exponential	
6	Vertical	350	0.0137	6.31	Exponential	1.1:1
	Major	350	0.446	174	Exponential	
	Minor	260	0.138	192	Exponential	
7	Vertical	0	0.129	7	Exponential	1.0:1.0
	Major	350	0.517	123	Exponential	
	Minor	260	0.182	115	Exponential	
8	Vertical	350	0.145	6.74	Spherical	1.0:1
	Major	350	0.356	242	Spherical	
	Minor	260	0.304	224	Spherical	
9	Vertical	350	0	3.68	Exponential	1.2:1
	Major	350	0.636	340	Exponential	
	Minor	260	0.777	289	Exponential	
North Area						
Facies	Axis	Orientation (degrees)	Nugget	Range Distance (metres)	Model Type	Major:Minor Ratio
1	Vertical	0	0.264	11.7	Exponential	1.1:1
	Major	350	0.458	217	Exponential	
	Minor	260	0.195	206	Exponential	
2	Vertical	0	0.0177	10.2	Exponential	1.7:1
	Major	350	0.188	224	Exponential	
	Minor	260	0.0576	133	Exponential	
3	Vertical	350	0.23	16.6	Exponential	1:1.25
	Major	350	0.332	146	Exponential	
	Minor	350	0.336	182	Exponential	
4	Vertical	350	0.239	16.8	Exponential	1.6:1
	Major	350	0.129	202	Exponential	
	Minor	260	0.222	326	Exponential	
5	Vertical	0	0.0867	16.7	Exponential	1.2:1
	Major	350	0.206	215	Exponential	
	Minor	260	0	176	Exponential	
6	Vertical	0	0.191	5.1	Exponential	1:1
	Major	350	0.443	169	Exponential	
	Minor	260	0.475	167	Exponential	
7	Vertical	0	0.00445	8.43	Exponential	1:1
	Major	350	0	141	Exponential	
	Minor	260	0	135	Exponential	
8	Vertical	350	0.0154	8.47	Spherical	1:1.2
	Major	350	0.176	181	Spherical	
	Minor	260	0.156	218	Spherical	
9	Vertical	350	0.339	9.47	Exponential	1:2
	Major	350	0	152	Exponential	
	Minor	260	0	311	Exponential	

Table 2.2. Variogram results and Correlation Ranges for the modeled facies for the south and north area.

Spatial Framework

The *finite* stratigraphic elements of the McMurray Formation are resolvable at a local scale with a high-resolution dataset and a rational approach. The vertical and horizontal resolution of the model is defined by the resolution of the available data. Resolution of the spatial framework drastically affects the final architectural model; therefore, the desired resolution of the modeled parameter(s) and desired quality (i.e resolution) of the product must be carefully considered.

The location of each zone boundary is yet another crucial factor for proper modeling of the heterolithic McMurray Formation. For the purpose of this study, the stratigraphic position of each boundary is a crucial element in refining the geologic understanding of the McMurray Formation.

Variography

With extremely complex geology, it is imperative to statistically analyze the available data. Although tedious, variogram development for each facies is necessary to provide reliable constraints on the regionalized variable (i.e. the spatial distribution of each facies). Effectiveness and form of the applied variogram must be scruntinized as the confidence of correlated facies decreases proportionally away from areas outside the range of average well-spacing.

The spatial distributions of the successions within the McMurray Formation are highly variable; therefore, the nugget effect form is necessary to allow for variability in the modeling process. If the parabolic form is generated, the resultant correlation range is less than the average well-spacing; therefore, the modeling process fails to correlate the facies. Conversely, generation of the nugget effect form and application of the resultant ranges produces an attractive model with substantially greater compartmentalization of the facies, rendering a detailed model for interpretation.

The most important factor effecting the variogram results and respective correlation ranges is that of well-spacing. The length to width ratios are heavily influenced by the well-spacing. A nearly isotropic relationship, 1.1:1 (towards 350°), is present in the south area and an anisotropic ratio is present in the north (1.4:1 (towards 260°). The difference of these ratios is most likely due to the difference in well-spacing. With respect to correlation ranges, the south area attained greater correlation ranges because the short well-spacing distance provides a sufficient sampling grid to determine the continuity of the highly variable successions within the McMurray deposits. In contrast, the north area variogram analysis delivered shorter correlation ranges resulting from the inability of the sampling grid to attain a sufficient value for the continuity of the facies. Therefore, the model derived from the data of the north model fails to provide an adequate model for interpretation. The south area provides a viable model ready for interpretation. For this reason, the bulk of chapter 3 will be centered on the model attained from the south area.

Conclusion

An understanding of the complex distribution of depositional environments within the McMurray Formation is crucial for development of high-resolution 3-D stratigraphic models. The modeling technique used in this study, using facies in conjunction with variography, is undoubtedly invaluable and applicable to similar deposits of heterolithic complexity within the subsurface. Generation of variograms produces correlation ranges for each facies within two different areas with respect to well-spacing. To correlate and model the lower Cretaceous deposit of northeastern Alberta a well-spacing ranging from 50-100 m is required to model the stratal-architecture at a facies level. The north area of Syncrude's North Mine requires an increase in well-spacing if a stratigraphic model is to be derived.

As the petroleum industry moves toward in-situ exploitation of the Athabasca Oil Sands within the McMurray Formation the application of variography within modeling processes will render desirable results and consequently efficient production of the resource. The results of the modeling process will be examined and discussed in Chapter 3.

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Chapter 3 – 3-Dimensional Stratal Architecture of the McMurray Formation, northeastern Alberta: Syncrude's North Mine

Introductory Remarks

The depth-demarcated facies data from 2107 closely-spaced wells from Syncrude's North Mine (Fig. 3.1A and 3.1B) provides an excellent opportunity to develop a 3-D depositional model of the McMurray Formation (Fig. 3.1D) over a large area (9 km x 16 km). Upon synthesis of the dataset, variogram analysis and application of the results (from Chapter 2), a high-resolution 3-D model from the south area (Fig. 3.1C) can be constructed for interpretation. The south area comprises the highest density data - 1567 well-bores. The variogram results applied to the lower well-density north area deliver an unreliable model that is useful to illustrate the data-density required to erect a 3-D model.

Intense sedimentologic and stratigraphic investigations have been conducted on the McMurray Formation (Carrigy, 1959, 1971; Flach, 1977; James, 1979; Mossop, 1980; Pemberton et al., 1982; Cowart, 1983; Mossop and Flach, 1983; Flach, 1984; Cuddy and Muwais, 1989; Fox, 1988; Ranger and Pemberton, 1992, 1997; Wightman and Pemberton, 1993, 1997; Yuill, 1995; Bechtel, 1996; Hein and Cotterill, 2000; Crerar, 2003; Harris, 2003; Lettley, 2004; Bagdan, 2005). The physical sedimentary structures are widely accepted within the literature, but the environmental interpretations and resulting stratigraphic models are naturally somewhat divergent. Although invaluable, present models allude to sediment accumulation within a fossil estuary and provide an interpretation of the McMurray Formation strata that is difficult to apply to core and outcrop. This paper proposes that the respective strata are more effectively explained by the establishment of a tidally-influenced delta. There are few documented ancient examples of tide-dominated deltas. Most examples occur in large outcrops in rift basins (Nio and Yang, 1991; Mellere and Steel, 1996), or in broad embayments (Willis et al., 1999; Willis and Gabel, 2001; Bhattacharya and Willis, 2001). This study differs from

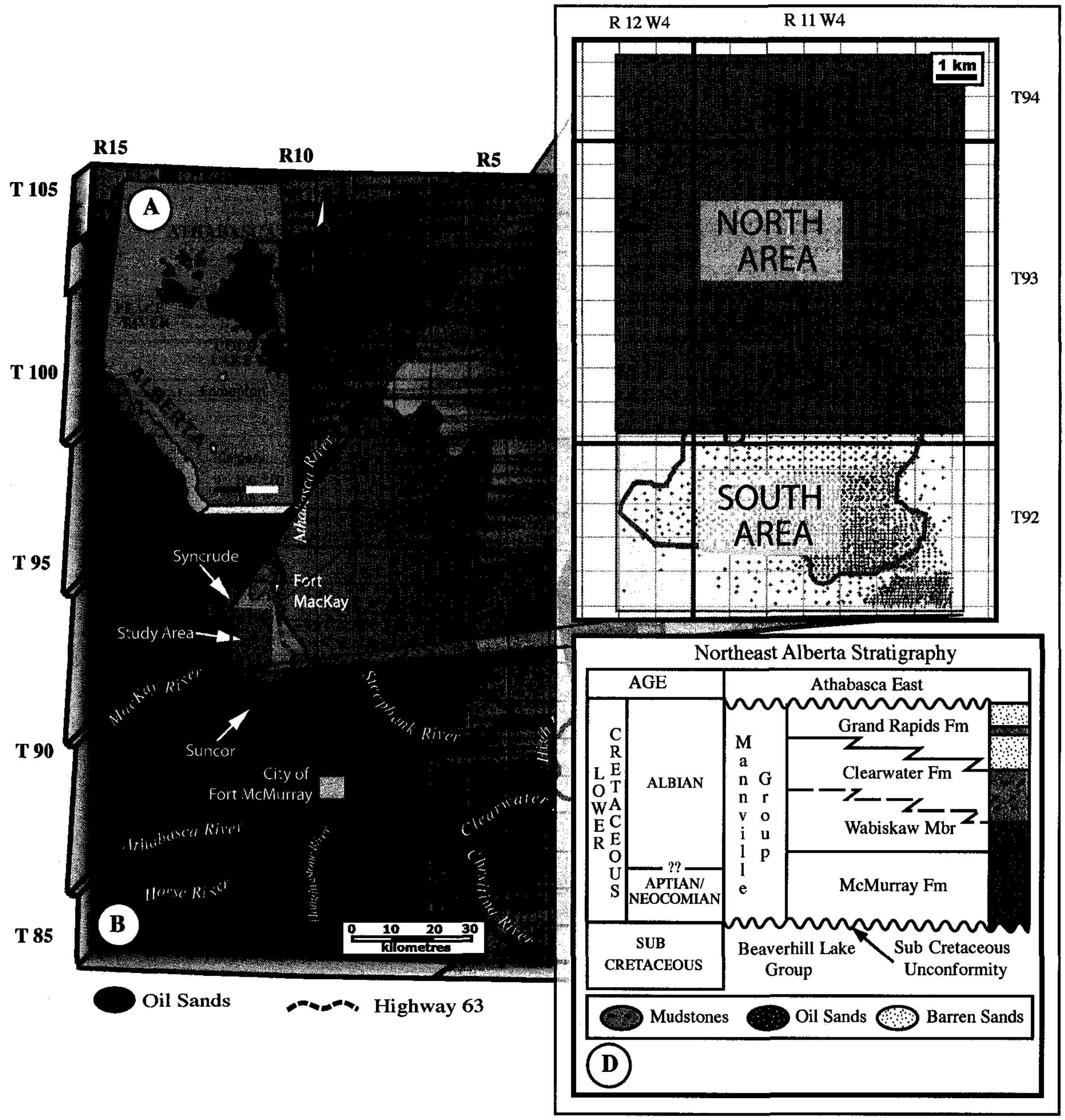


Figure 3.1. (A) Areal Distribution of the Athabasca Oil Sands within Alberta, Canada (modified from after Wightman and Pemberton, 1997). (B) Areal Distribution of the oil sands deposit in the regional vicinity of the study area (modified from after Wightman and Pemberton, 1997). (C) Syncrude's North Mine. Each well is represented by a small cross-hair. The yellow line indicates the surface mineable reserves. The study area is divided into two separate areas based on average well-density per square kilometre (modified from Syncrude Canada Ltd., 2002). (D) Stratigraphy of northeast Alberta (modified from after Wightman and Pemberton, 1997).

these previous works in that the depositional system is interpreted from a subsurface dataset.

It is the objective of this paper to briefly discuss the sedimentology and build a firm understanding of the respective strata from a 3-D high-resolution model. Another aspect of the current work is to examine the overall transgression within the Western Interior Seaway responsible for deposition of the Lower Cretaceous McMurray sediments. This transgression is grossly over generalized; and, therefore, affects interpretation of the succession (Ranger and Pemberton, 1997). Consideration is given to the minor fluctuations, incremental transgressions and regressions, within the overall transgression. These fluctuations are inferred from the stratigraphic positioning of nine facies within the study area.

Presentation of Facies

It should be noted, that numerous geologists from 1957 to 2003 recorded the lithology, sedimentary texture and structures of the respective wells and assigned a lithofacies code (Appendix A) for each facies. As previously stated, the sedimentologic characteristics of the McMurray Formation have been studied extensive. The framework of the descriptions herein is based on Syncrude's Lithofacies Chart (Appendix A) and previous work (Flach, 1977; Mattison, 1987; Fox, 1988; Pemberton et al., 1982, Bechtel, 1996; Wightman and Pemberton, 1993, 1997; Ranger and Pemberton, 1997; Crerar, 2003; Lettley, 2004). The descriptions are complemented by core photos provided by Syncrude Canada Ltd. (Syncrude). Each core has been slabbed and v-notched for laboratory analysis. The average dimension of each core photo is 75 cm x 6.9 cm (length x width). Due to this vast knowledge base, only a brief account of the sedimentologic characteristics of the McMurray Formation is presented herein (Table 3.1). The descriptions are complemented by core photos provided by Syncrude. Within the study area, nine facies were identified in the dataset from the McMurray Formation (F1 through F9; Table 3.1). The sedimentologic investigation noted the lithology, grain-size, sedimentary structures, thickness of beds and bedsets, degree of bioturbation and ichnological assemblages.

Descriptions of Facies within the 3-D Model of the McMurray Formation								
Facies	Facies Description	Lithologic Proportions	Grain Size	Physical Sedimentary Structures	Thickness	Degree of Bioturbation	Ichnology	Figure
1	Massive to cross-stratified sand	90-100% sand : <10% mud	fine- to coarse-grained sand with dispersed pebbles/granule sand	sand: small-to medium scale planar tabular or trough cross-stratification; less common massive	<5-25m bedsets; cm-dm-scale beds of sand with mud laminae	rare bioturbation limited to mud	small *Cylindrichnus,Planolites,* rooting/rootlets (Bechtel, 1996; Crerar, 2003)	Fig. 3.2
				mud: massive to planar laminated				
1a	Mud intraclast breccia	0-100% Sand	matrix: fine- to coarse-grained sand	sand matrix: typically massive	1 cm to 4 m	Matrix: absent	*Cylindrichnus* and *Planolites* (Bechtel, 1996; Crerar, 2003)	Fig. 3.3
			angular clasts: ranging in size from mm- to m-scale	mud clasts: interlaminated sand and mud to massive mud		Clast: absent to moderate		
2	Massive to cross-stratified sand	90 - 100% Sand: < 10% Mud	Medium- to coarse-grained sand with mud drapes and/or clasts	Large-scale massive to planar tabular & trough-cross stratified sand with planar & wavy laminations; grain-stripping (rhythmic bedding); flaser & lenticular bedding	50 cm - 12 m bedsets; dm- to m-scale beds	rare bioturbation	Robust *Conichnus, Planolites, Skolithos and Cylindrichnus* (Gingras and Ranger, in press)	Fig. 3.4
3	Sand-dominated Inclined Heterolithic Stratification (SIHS)	90-50% sand : 10-50% mud/ silt	fine-grained sand with mud/silt	Inclined (5-15 degrees) interlaminated to interbedded sand and mud/silt	10 - 30 m	generally within mud component: varies from absent to abundant	*Cylindrichnus, Planolites, Gyrolithes, Teichichnus, Skolithos, Paleophycus, Arenicolites;* rare occurrences of *Chondrites, Rosselia, Ophiomorpha, Asterosoma, Thalassinoides* and fugichnia (Bechtel, 1996; Crerar, 2003; Lettley, 2004)	Fig. 3.5
				sand: planar tabular, trough, low angle planar and ripple cross-stratification	cm- to dm-scale			
				mud/silt: massive to interlaminated sand and mud (planar parallel, wavy and lenticular bedding and laminations)	cm- to dm-scale			
4	Mud-dominated Inclined Heterolithic Stratification (MIHS)	90-50% mud/ silt : 10-50% sand	mud/silt with very fine to fine-grained sand	Inclined (8-12 degrees) interlaminated to interbedded mud/silt and sand	5 - 20 m	generally within mud component: varies from absent to abundant	*Gyrolithes, Teichichnus, Planolites, Paleophycus, Skolithos, Teichichnus, Arenicolites, Cylindrichnus;* rare ocurrences of *Thalassinoides and Rosselia* (Bechtel, 1996; Crerar, 2003; Lettley, 2004)	Fig. 3.6
				sand: small-scale cross-stratifaction	cm- to mm-scale			
				mud: laminated mud to interlaminated sand and mud; synaresis cracks	mm- to dm-scale			

Table 3.1. Description of Facies within the 3-D Model of the McMurray Formation.

....continued....

Table 3.1 continued....								
5	Grey mud to mudstone with coal	90-100% Mud : < 10% Sand/ Silt; 100% Coal	mud or mudstone with dispersed silt, very fine- to coarse-grained sand and rare pebbles; coal	Massive to laminated mud and fissile mudstone with coalified rootlets and roots; slickensides; rare lenticular sand and/ or silt	<5- 20 m	generally absent to moderate;	rare to moderate rooting and/or rootleting; rare occurrences of *Gyrolithes, Cylindrichnus, Planolites,* and *Paleophycus* (Bechtel, 1996; Crerar, 2003)	Fig. 3.7
				coal with coalified roots and rootlets	10-40 cm thick			
6	Interbedded to interlaminated sand and mud	25-75% Sand; 25-75% Mud	very fine- to fine-grained sand and mud	Horizontal interbedded to interlaminated sand and mud	<1-10m	moderate to abundant	Mottled bioturbate texture including *Planolites, Teichichnus, Cylindrichnus, Paleophycus, Rosselia, Skolithos, Lockeia, small Arenicolites, Conichnus, Ophiomorpha,* fugichnia, *and Terebellina* (Bechtel, 1996; Crerar, 2003)	Fig. 3.8
				sand: ripple cross-lamination or obliterated	cm- to dm-scale			
				mud: interlaiminated sand and mud or obliterated	mm- to cm scale			
7	Massive to cross stratifed sand with shells	95-100% Sand	fine- to medium-grained sand	Small to medium-scale massive to planar tabular to trough-cross stratified sand with abundant shells	cm- to dm-scale	rare	Robust *Teichichnus Asterosoma, Thalassinoides,* and *Berguria* (Mattison, 1987)	Fig. 3.9
8	Horizontally Interbedded dark grey mud and sand	10-90% sand: 10 - 90% mud	very fine to fine-grained sand with mud/silt	Low-angle to horizontal laminated sand with wavy mud interbeds/interlaminae; mud beds may be continuous or discontrinuous due to abundant bioturbation	<5-20m	rare to uncommonly abundant	Robust *Teichichnus, Planolites, Thalassiniodes, Lockeia, and Astersoma; small Planolites, Palaeophcus, Skolithos, and Lockeia* (Bechtel, 1996)	Fig. 3.10
9	Upper massive to cross-stratified sand	90-100% Sand	very fine- to medium- grained sand	Flat to low-angle planar cross-stratified sand with rare wavy dark grey mud interlaminations	50 cm -5m	rare to moderate	Robust *Teichichnus, Thalasinnoides, Paleophycus, Astersoma,* and *Skolithos* (Mattison, 1987)	Fig. 3.11

Table 3.1 continued. Description of Facies within the 3-D Model of the McMurray Formation.

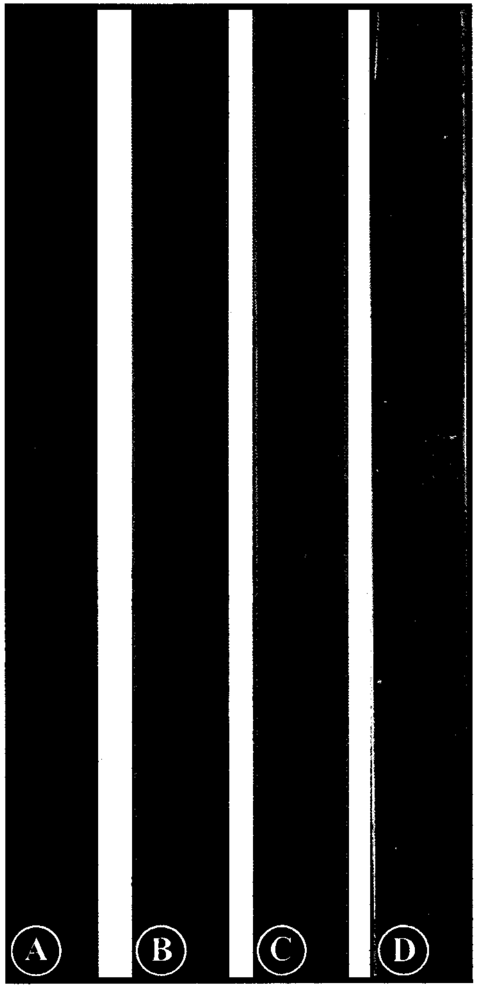


Figure 3.2. Facies 1- Massive to cross-stratified sand (lower McMurray member). (A) Massive sand. (B) Planar tabular cross-stratified sand. (C) Trough-cross-stratified sand. (D) Coarse-grained massive sand with planar-tabular cross-stratified sand.

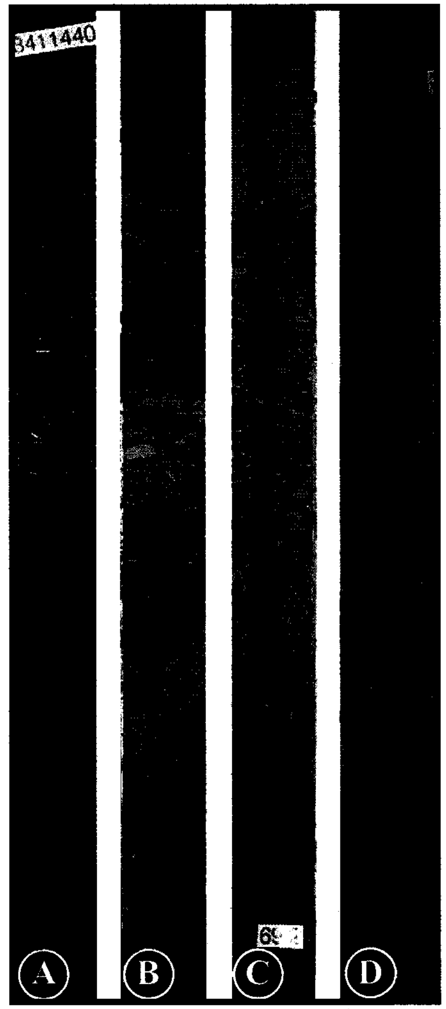


Figure 3.3. Subfacies 1a - Mud-intraclast breccia. (A) - (D) Clast size varies from mm-scale (A) to cm-scale (B) & (C) to dm-scale (D).

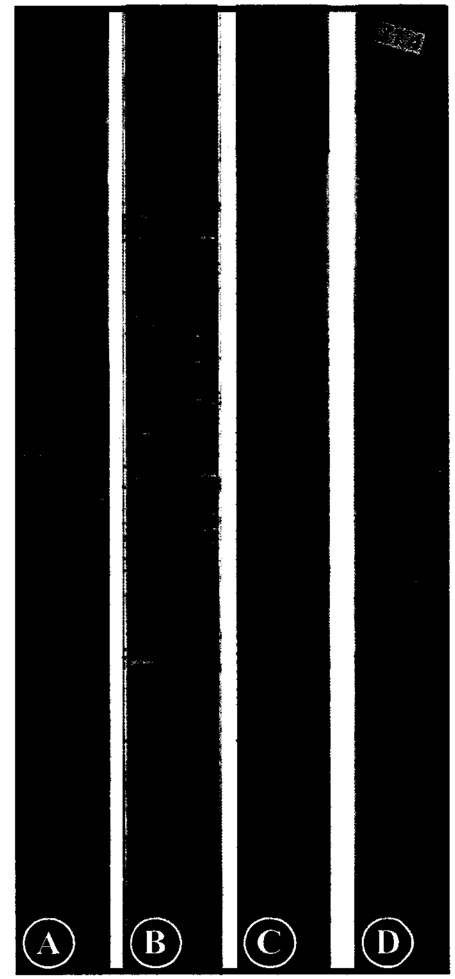


Figure 3.4. Facies 2 - Massive to cross-stratified sand (middle McMurray member). (A) Planar tabular cross-stratified sand with mud drapes. (B) Flaser and lenticular bedding. (C) Trough-cross-stratified sand with grain-stripping. (D) Massive sand.

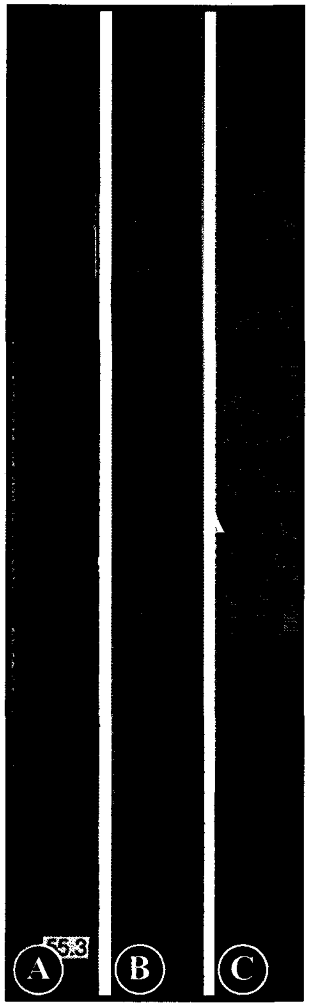


Figure 3.5. Facies 3 - Sand-dominated Inclined Heterolithic Stratification. (A) Interbedded sand and mud with dm-scale sand beds. (B) Interbedded to interlaminated sand and mud. (C) Interbedded to interlaminated sand and mud with moderate bioturbation.

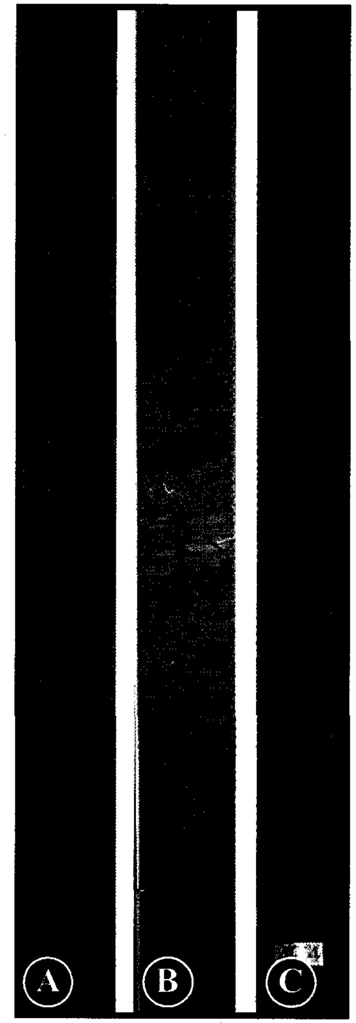


Figure 3.6. Facies 4 - Mud-dominated Inclined Heterolithic Stratification. (A) Interlaminated to Interbedded sand and mud. (B) Interlaminated sand and mud with moderate bioturbation. (C) Interlaminated sand and mud.

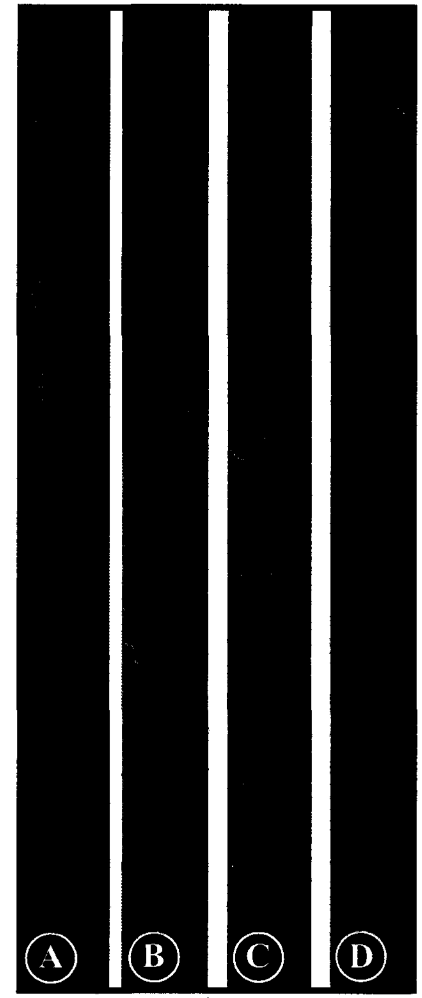


Figure 3.7. Facies 5 - Grey mud to mudstone with coal. (A) Massive light grey with rootlets. (B) medium grey mud with silt/sand laminations and lenses. (C) Light grey mud with coal. (D) Interbedded coal and dark grey mud.

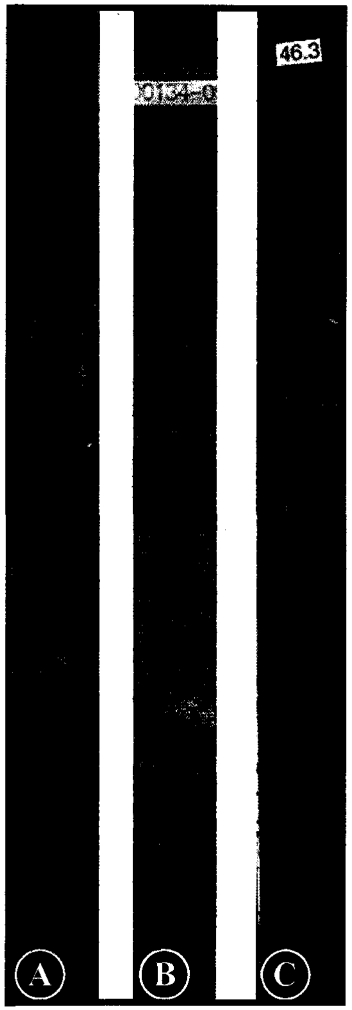


Figure 3.8. Facies 6 - Horizontally Interbedded to Interlaminated sand and mud (A) Interbedded to interlaminated sand and mud with dm-scale sand beds (common bioturbation). (B) Interbedded to interlaminated sand and mud with dm-scale sand beds (moderate bioturbation). (C) Interlaminated sand and mud (common to abundant bioturbation)

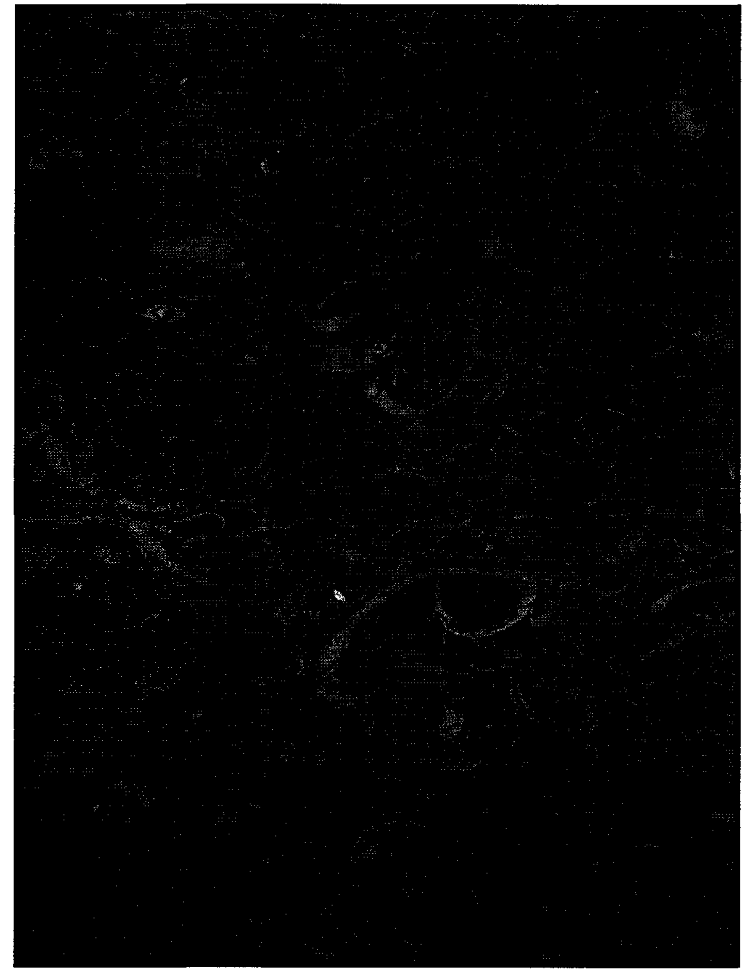


Figure 3.9. Facies 7 - Massive to cross-stratified sand with shells. (A) Limey mud with shells (gastrodpods and disarticulate and articulate bivalves). Picture acquired from core as database contained no photos of this facies. Well within study area (I.D. unknown). Width of core photo = 69 centimetres.

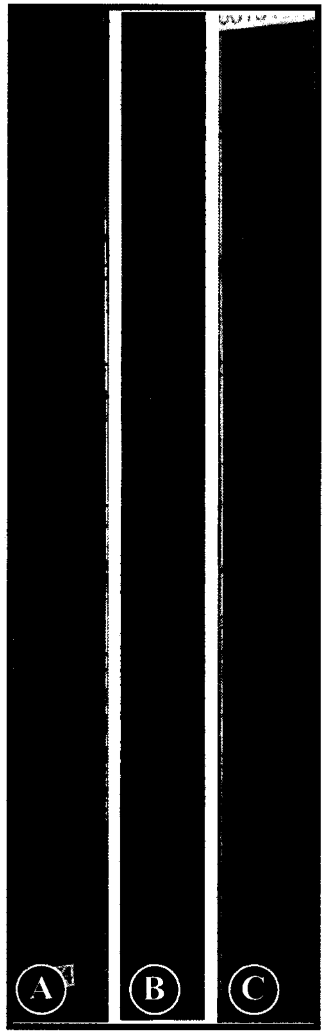


Figure 3.10. Facies 8 - Interbedded dark grey mud and sand. (A) - (C) Wavy interlaminated mud with low-angle to horizontally laminated sand. Mud content increases from (A) to (C).

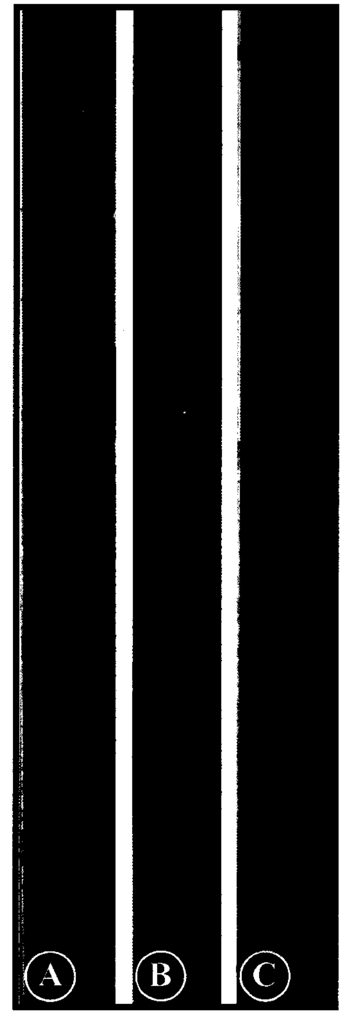


Figure 3.11. Upper massive to cross-stratified sand. (A) Planar tabular cross-stratified sand. (B) Massive sand. (C) Mud intraclast breccia with dark grey mud intraclasts.

Conversely, a detailed interpretation for each facies will be provided as the environmental interpretation of the facies drastically affects the resultant stratigraphic model. Much debate is centered upon the environmental interpretations of the lower and middle members; thus, the interpretations are presented in their informal member context.

Interpretation of Facies

Facies 1 (F1) – Massive to cross-stratifed sand

LOWER MCMURRAY MEMBER

Facies 1 is only preserved within the lower McMurray member; F1 lies directly atop the sub-Cretaceous unconformity (atop). The basal and top contact of F1 is characteristically sharp. F1 is typically < 5 m thick. This facies is characterized by fine- to coarse-grained sand with small- to medium-scale cross-stratification (planar tabular and trough cross-stratification) and is interpreted to represent migration of two-dimensional and three-dimensional subaqueous dunes in a channelized regime (Harms and Fahnestock, 1965; Reinick and Singh, 1980). Facies 1 medium- to coarse-grained massive sand interbeds, with dispersed pebbles, suggest rapid deposition dominantly from suspension during floods (McCabe, 1977) or liquefaction and flow of in-channel bars and bank collapse (Jones and Rust, 1983; Rust and Jones, 1987). These massive sands are typically characterized by coarse-grained sediment and poor sorting suggesting proximity to source and minimal reworking of sediment. Absent to rare bioturbation (small trace fossils) within F1 is interpreted to represent instability of substrate due to advancing 2-D and 3-D dunes. The ichnia are comprised of a brackish-water assemblage (Pemberton et al., 1982). Conversely, rooting in F1 suggests decrease in flow conditions. In summary, the lower McMurray F1 is interpreted to represent deposition within a meandering-fluvial dominated environment with subordinate marine influence.

Facies 1a (F1a) – Mud intraclast breccia

LOWER MCMURRAY MEMBER

The mud intraclast breccia subfacies within the lower McMurray member is deposited in association with F1. The angular nature of the intraclasts is indicative of proximity to source (Ranger and Gingras, 2003). The size of the intraclasts is likely proportional to distance from the source. Intraformational clasts are commonly associated with erosional surfaces related to channel migration when overbank floodplain sediments are eroded (Reading, 1996). The clasts within the lower member are typically composed of massive mud and lack bioturbation. Accordingly, the intraclasts of the lower member are interpreted to represent clasts sourced from overbank deposits of F4.

MIDDLE MCMURRAY MEMBER

The mud intraclast breccia subfacies within the middle member differs from the lower member as the intraclasts are commonly composed of interlaminated sand and mud and are characterized by rare to moderate bioturbation. It is hypothesized that these intraclasts originate from tidal currents vacuuming pieces of sediment off the top of inclined heterolithic strata (F2 and F3). Thus, the intraclasts of the middle member are interpreted to represent clasts sourced from laterally accreting point-bars.

Facies 2 (F2) – Large-scale Trough and Planar Tabular Cross-stratified Sand

MIDDLE MCMURRAY MEMBER

Facies 2 is only preserved within the middle McMurray member (Zone 2). The sedimentologic characteristics and respective interpretation for F2 within the middle McMurray member differs from the lower member F1 sand facies. Facies 2 is characterized by large-scale cross-stratified sands (planar tabular and trough cross-stratification), rhythmic bedding and grain stripping and is interpreted to represent migration of two-dimensional and three-dimensional subaqueous dunes (Harms and Fahnestock, 1965; Reinick and Singh, 1980) The scale of stratification within F2 suggests abundant sediment supply, rapid deposition, and flow depths of several metres. Additionally, the rhythmic bedded and grain stripping is interpreted to represent deposition in a tidally-influenced environment. Bioturbation within F2 differs greatly from the lower member. The presence of rare but robust trace fossils (*Skolithos, Cylindrichnus and Conichnus)* and the scale of cross-strata suggests deposition in deep channels proximal to an open marine system. In summary, F2 is interpreted to represent sediment accumulation within longitudinal subtidal channel bars in the distal portion of the depostional system (Fig. 3.12) (Gingras et al., 2003; Ranger and Gingras, 2003). This interpretation is contrary to several current models and will be reinforced within the discussion.

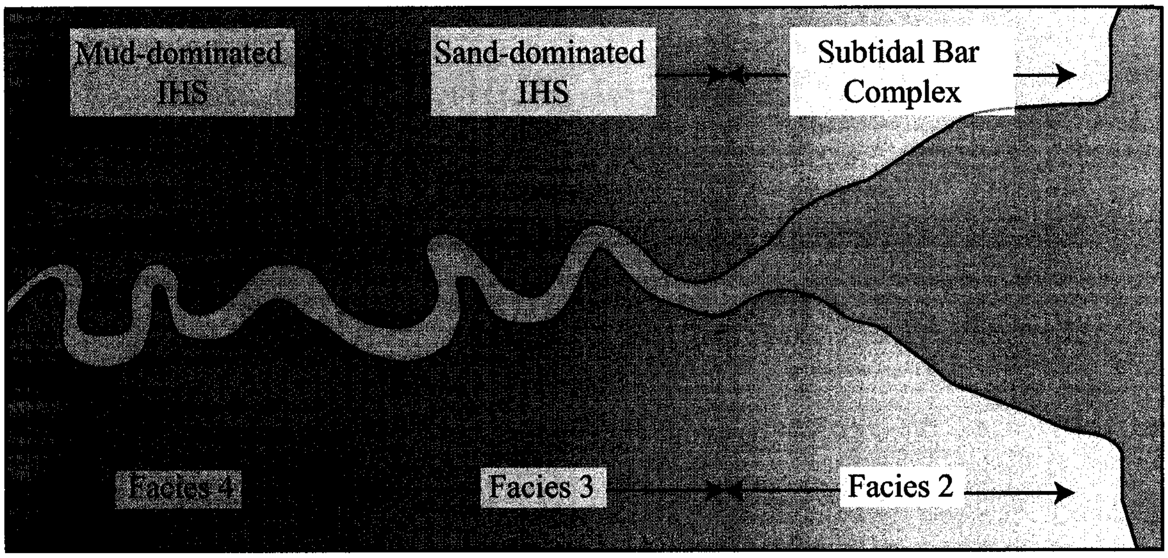


Figure 3.12. Planview schematic representation of the lateral distribution of Facies 2, 3, and 4 with respect to the landward to seaward location of facies within the depositional system.

Inclined Heterolithic Stratification

Prior to delving into the sedimentologic interpretations pertaining to inclined heterolithic stratification (IHS) (*sensu* Thomas et al., 1987), a brief account of this type of stratification will be discussed. Inclined heterolithic stratification, within the McMurray Formation, is typically composed of interlaminated to interbedded sand and mud in varying proportions exhibiting dips of 2 – 25 degrees. Stewart and MacCallum (1978) were the primary investigators to suggest deposition of IHS within estuarine channels to explain IHS in the McMurray Formation (then known as epsilon cross-stratification (Allen, 1963)). However, it was Pemberton et al.'s (1982) seminal work, using ichnologic criteria, that really established the presently accepted estuarine point-bar interpretation using ichnologic criteria. Typically, IHS represent lateral accretion of tidally-influenced point-bars of meandering estuarine channels (Smith, 1987; Thomas et al., 1987; Smith, 1988; Ainsworth and Walker, 1994; Wightman and Pemberton, 1997; Gingras et al., 2002; Lettley, 2004). The two-fold lithologic contrast results from seasonally variable hydraulic energy and sediment supply. It is well established within the current literature that within marginal-marine settings IHS represents reallocation of the turbidity maximum (Allen et al., 1980; Dyer, 1986; Uncles and Stephens, 1993; Ranger and Pemberton, 1997; Ciffroy et al., 2003; Gingras et al., 2002; Lettley, 2004). This shifting is due to fluctuations in discharge from the fluvial end of the system and tidal forces from the marine end of the system. For a detailed account of IHS the reader is referred the references within the abovementioned text.

Within the following intepretations of the McMurray IHS deposits an informal nomenclature is used to differentiate lower from middle member IHS. Lower McMurray member IHS facies are followed by the letter L. Middle McMurray member IHS facies are followed by the letter M.

Facies 3 (F3)– Sand-dominated Inclined Heterolithic Stratification

LOWER MCMURRAY MEMBER

The lower McMurray member F3 (F3L) is typically preserved atop F1 or F5. The basal and upper contact of F3L is sharp. Facies 4-lower generally lies atop F3L. Facies 3-lower is dominated by inclined (0-15 degrees) fine-grained sand interlaminated to interbedded with mud and represent IHS. The sand portion of F3L IHS couplet is characterized by small- to medium-scale planar tabular, trough, low-angle planar, and ripple cross-stratification. The mud portion of the couplet is typically massive and only rarely interlaminated in the lower member. Facies 3-lower is generally thinner than F3M. This lower preservation potential can be attributed to truncation due to erosion and subsequent deposition of overlying deposits.

Bioturbation within F3L ranges from absent to moderate. Where present, the F3L assemblage (*Skolithos*, *Cylindrichnus*, *Planolites*) is similar to F1 where both assemblages are characterized by small trace fossils. The ichnia within F3 comprise a brackish-water assemblage (Pemberton et al., 1982; Bechtel, et al., 1994; Yuill, 1995). This comparative abundance alludes to a more seaward deposition for F3L as compared to F1, but still within the proximal part of the marginal-marine depostional system. F3L is interpreted to represent lateral accretion of tidally-influenced point-bars of estuarine channels within the middle portion of the depositonal system (Fig. 3.12).

MIDDLE MCMURRAY MEMBER

The middle McMurray member F3 (F3M) is typically preserved atop F2. The basal and upper contact of F3M is typically sharp. Facies 3-middle is generally thicker than F3L suggesting that the preservation potential of facies increases upwards within the McMurray Formation. Facies 3-middle is interpreted in a similar manner as F3L. F3M represent IHS; and, are thusly interpreted to be tidal channel deposits. The sand portion of the F3M IHS couplet is characterized by sedimentary structures similar to F3L. One distinction in F3M is the presence of flaser bedding suggesting tidal engeries are more pronounced than with F3L. The mud portion of the couplet is also different and commonly characterized by interlaminated sand and mud with small-scale planar parallel, wavy and lenticular bedding and laminations. As compared to F2, the smaller scale of the physical sedimentary structures would imply a slightly landward depositional locale for F3M. As compared to F3L, the existence of flaser, wavy and lenticular bedding and the interlaminated character of the mud beds in F3M would imply a greater tidal influence for F3M.

Bioturbation within F3M ranges from absent to abundant with trace fossils typically smaller than trace fossils preserved within F2. The ichnologic assemblage of F3M is more diverse than the assemblage preserved in F2. The traces within F3 comprise a typical brackish-water assemblage (Pemberton et al., 1982; Bechtel, et al., 1994; Yuill, 1995). This comparative diversity alludes to a more landward depositional locale for F3M as compared to F2. With respect to the IHS deposits of the lower and middle members, the greater diversity of ichnogenera in F3M, as compared to F3L, would suggest a low energy input from the fluvial end of the system (Fig. 3.12). Therefore, it is interpreted that fluvial discharge is minimal during deposition of F3M and comparatively greater during deposition of F3L. Comparatively, trace fossils in F3M are characteristically smaller than F2 ichnogenera. This reinforces the idea of a more proximal deposition for F3M as compared to F2. In summary, F3 is interpreted to represent laterally accretion of tidally-influenced estuarine channels within the middle portion of the depositional system.

Facies 4 (F4) – Mud-dominated Inclined Heterolithic Stratification (MIHS)

The comparison and subsequent interpretation between the lower and middle member MIHS is consistant with the interpretations provided for the lower and middle member SIHS. Accordingly, only a comparison between F3 and F4 will be assessed.

The contact between F4 and F3 is always sharp and F4 is preserved consistently atop F3. It is contended herein that this contact is a significant stratigraphic marker. Facies 4 is similar to F3, because it represents lateral accretion deposits in estuarine channels, but differs from F3 in that it is characterized by a > 50% mud content. The high mud content is interpreted to result from a more proximal position within the depositional system (Fig. 3.12). The lateral relationship between MIHS and SIHS is best explained by examining compartmentalization of sediments within the modern estuarine environments. For example, in the Bay of Fundy and Williapa Bay, mud is typically confined to the landward parts of those systems.

The trace assemblage for both F3 and F4 are similar. However, Facies 4 is typified by ichnogenera smaller than trace fossils preserved in F3. This distinction suggests a salinity difference between the depositional environments of F3 and F4. This is exemplified by the existence of monospecific assemblages of both *Teichichnus* and *Gyrolithes* in F4 (Bechtel, 1996; Crerar, 2003; Lettley 2004). Benyon and Pemberton (1992) interpreted the presence of *Gyrolithes* to reflect the organism's attempt to escape salinity fluctuations at the sediment-water interface. Therefore, the F4 assemblage character suggests a higher degree of salinity stress. Facies 4 is interpreted to represent a more landward depositional environment than F3 (Fig. 3.12).

Facies 5 (F5) – Dark Grey Mud to Grey Mudstone with Coal

F5 is only preserved within the lower McMurray member. Stratigraphically, F5 is typically positioned within the topographic lows of the sub-Cretaceous unconformity and at the top of the lower member deposits. Facies 5 is closely associated with F1. The contact between F1 and F5 is always sharp.

Thick mud and mudstone suggest sediment accumulation occurred under low-energy conditions. F5 is preserved in <5-20 m thick beds. The dark grey color of these muds can be attributed to a high organic content and proximity to a terrestrial environment. Becthel (1996) and Crerar (2003) documented the preservation of abundant carbonaceous debris, pyrite nodules, and siderite nodules in F5 and suggested these characteristics indicate soil formation in a floodbasin environment. Alluvial palaeosols are characterized as such (Besly and Fielding, 1989) and reflect relatively continuous sedimentation (Reading, 1996). The massive to laminated character of the preserved mud lack well-defined horizons or soil profiles and thus suggests deposition in an alluvial environment (Kraus and Aslan, 1993). Coal interbeds are common and are interpreted to represent deposition in a swamp environment proximal to mud deposition. The intercalated character of the coal and mud/mudstone indicate fluctuating energy conditions in the floodbasin. Rare sand and silt lenses suggest sporadic high-energy conditions and most likely indicate flood-stage discharge. Conversely, rooting and slickensides are interpreted to represent low-energy conditions indicating periodic subaerial exposure (Reading, 1996). Rare bioturbation characterized by *Cylindrichnus, Gyrolithes, Planolites and Palaeophycus* (brackish-water assemblage (Pemberton et al., 1982) suggests episodic salinity fluctuations and local influx of marine water into the system. In summation, F5 is interpreted to represent deposition within a swampy coastal floodbasin prior to and during the development of the meandering-fluvial system.

Facies 6 (F6) – Horizontally Interbedded to Interlaminated Sand and Mud

Facies 6 is preserved in the upper most portion of the middle McMurray member. Facies 6 typically overlies F3 or F4 and F8 typically lies atop F6. Facies 6 occupies the topographically high areas within middle McMurray member of the study area.

Facies 6 is distinguished from F3 and F4 by the horizontal character of the interbeds and/ or interlaminations. Facies 6 is also characterized by alternating sand and mud couplets that are generally regularly-spaced; this suggests an alternating flux of energy. The inferred cyclicity, as compared to modern coastal environments (Allen, 1991; Dalrymple et al. 1991), is characteristic of tidal energies. The sand portion of the couplet being deposited during bedload deposition (during flood and ebb stages) and mud being deposited out of suspension during low energy conditions (during transition from flood to ebb stages or vice versa). The trace fossil assemblage alludes to a highly-stressed environment. Although the biodiversity is high, the ichnogenera are generally the smallest of all traces preserved within the McMurray deposits. It could also be assessed that F6 contains the highest degree of bioturbation. In modern environments, tidal flat deposits are typically marked by abundant bioturbation (Reinick and Singh, 1980; Gingras et al., 1999). Accordingly, F6 is interpreted to correspond to deposition within a tidal flat environment.

Facies 7 (F7) – Massive Sand with Shell Lag

Facies 7 is only preserved at the top of the middle McMurray member. The basal contact is always sharp and F8 always overlies F7; therefore, within the aerial extent of the facies, the basal contact of F7 demarcates the upper limit of middle McMurray sediment accumulation. The thickness of F7 ranges from <50cm to several metres. Facies 7 is characterized by medium- to coarse-grained, massive to cross-stratified sand with a distinct shell deposit. Mattison (1987) identified these shells as a gastropod assemblage consisting of mixed fresh, brackish, and marine affinities. The ichnogenera of F7 is inidicative of a brackish-water assemblage influenced greatly by marine conditions. Thus, F7 most likely was mostly deposited under high-energy flow conditions. Facies 7 is a localized sinuous deposit trending in a north-northeast to south-southwest direction, which suggests channelized depositon. In summary, the bedding character, spatial trend, rare, but robust bioturbation and fresh to marine gastropod assemblage suggests deposition of F7 in an estuarine channel in the most distal part of the depositional system. F7 is possibly a transgressive lag deposit.

Facies 8 (F8) - Wavy interbedded sand and dark grey mud

Facies 8 is only preserved within the upper McMurray member and is distinct due to the blue-grey color of the mud. In the study area, F8 always demarcates the contact between the middle and upper member. The thickness of F8 varies from <5 – 20 m. Facies 8 is characterized by very fine- to fine-grained low angle- to horizontal-laminated sand with wavy to lenticular bedding of continuous to discontinuous mud interbeds/interlaminations. Becthel (1996) suggests that the low angle- to horizontal laminated sand represent hummocky cross-stratification, swaley cross-stratification, and quasi-planar laminations. It is well established within the literature (Leckie and Walker, 1982) that these sedimentary structures generally indicate deposition in a high-energy oscillatory regime (i.e. wave reworking). The bioturbation within F8 varies from absent to abundant and is indicative of increasingly marine conditions with a minimal brackish-water influence. Where bioturbation is present, F8 is characterized by robust ichnogenera representing colonization of the substrate following storm reworking (Bechtel, 1996). Accordingly, F8 is interpreted to represent accumulation within a shoreface environment of a shallow marine shoreline.

Facies 9 (F9) – Upper McMurray Cross-stratified Sand

Facies 9 is only preserved in the middle to upper most portion of the upper McMurray member. Facies 9 is always preserved within F8. Facies 9 is characterized by fine- to medium-grained sand with flat to low angle planar cross-stratification. Bioturbation is rare to moderate and characterized by a comparatively marine assemblage with a brackish-water influence. The spatial configuration of F9 (discussed later) is characterized by linear features trending north-northwest to south-southeast. Thus, F9 is interpreted to represent deposition of shoals within a shallow marine shoreline (Gingras et al., 2003). F8 and F9 are the most distal or seaward deposits within the McMurray Formation.

Results

3-Dimensional Characteristics of Modeled Facies

Due to high-density well control, it is possible to map individual facies within the model block. The modeled facies are presented as slices, in respective x- (east-west), y- (north-south), z-directions (horizontal) (Fig. 3.13 - 3.23), and provide sufficient data necesssary to develop an understanding of the stratigraphic succession within the McMurray Formation. The model zone boundaries, as mentioned in Chapter 2, are approximately located at the boundaries for the lower, middle, and upper member contacts. However, the results are compartilized into Zone 1, 2, and 3 and are taken to represent the abovementioned members respectively. Syncrude's Lithofacies Chart (Appendix A) was used to define the facies within each zone. Table 3.2 contains the facies that were used to erect the three zones.

Facies used to Define Zone Boundaries		
Zone	Facies within Zone	Facies Descriptor
Zone 1	Facies 1	Massive to Cross-stratified Sand with mud intraclast breccia
	Facies 3	Sand-dominated Inclined Heterolithic Stratification
	Facies 4	Mud-dominated Inclined Heterolithic Stratification
	Facies 5	Grey Mud to Mudstone with Coal
Zones 2	Facies 2	Large-scale Massive to Cross-stratified Sand
	Facies 3	Sand-dominated Inclined Heterolithic Stratification
	Facies 4	Mud-dominated Inclined Heterolithic Stratification
	Facies 6	Horizontally interlaminated to interbedded sand and mud
Zone 3	Facies 7	Massive to Cross-stratified Sand with shells
	Facies 8	Interbedded dark grey mud and sand
	Facies 9	Upper Massive to Cross-stratified sand

Table 3.2. Facies used to define the three zones within the model block. The three zones grossly represent the lower, middle, and upper McMurray members.

The following results define characteristics of the modeled facies within the lower, middle and upper McMurray members. Model analysis concentrated on characteristics such as position, shape, and relationships of the facies within the respective zones. Thus, the modeled facies provide the context for a stratigraphic interpretation of the McMurray deposits.

SOUTH MODEL

ZONE 1 – LOWER MCMURRAY MEMBER

The base of the Zone 1 is always demarcated by the sub-Cretaceous unconformity. The facies within the lower member (i.e. Zone 1) occupy the topographically low areas of the unconformity and consequently have a limited lateral extent (Fig. 3.13; 3.14; 3.18-

3.23). Facies 5 typically lies directly atop the sub-Cretaceous unconformity. Facies 1 overlay F5 and is preserved as discontinuous sinuous bodies following the topographic lows. Two different trends are observed - east-west and north-south trending. Laterally, F1 is most frequently associated with F5 and less frequently with F4 (MIHS) and F3 (SIHS). Facies 5, the most common facies of Zone 1, characteristically blankets the sub-Cretaceous low-lying areas and is the thickest unit. With respect to inclined heterolithic deposits, F3 and F4 form arcuate lobes of limited vertical and horizontal extent. Sand-dominated inclined heterolithic stratification (F3) occurs lower in the succession than F4. Mud-dominated inclined heterolithic stratification (F4) is the most commonly occurring IHS deposit. Facies 4 deposits are always immediately atop F3. The top of Zone 1 is marked by F4 or F5. An idealized vertical succession for Zone 1 is characterized by F5 at the base, followed by F1, F3, and F4 at the top. Facies 5 marks the top of Zone 1 where F4 is not present.

ZONE 2 – MIDDLE MCMURRAY MEMBER

Zone 2 is populated by four facies: Facies 2, 3, 4, and 6. Facies 2 demarcates the base of the zone (Fig. 3.14). The contact between F2 and Zone 1 facies is highly variable and is characterized by an undulatory surface. Facies 2 dominates Zone 2 and blankets it isopachously at two different intervals. The first interval marks the base of the zone and the second interval is located in the middle portion. Facies 3 and F4 interfinger F2 in the lower portion of the middle zone and F3 dominates the upper portion of the zone; F3 and F4 typically have a limited lateral and vertical extent. In the lower section of Zone 2, both facies seldomly form connected volumes. However, sinuous units are observed in the upper portion (Fig. 3.15; 3.16). Facies 3 (SIHS) occurs most frequently in the northern half of the area whereas F4 (MIHS) is the most common facies in the southern half of the study area (Fig. 3.15; 3.16; 3.18-3.23). In the lower part of Zone 2, F3 is generally observed below F4 (Fig. 3.18-3.23). Facies 6, Horizontally interbedded to interlaminated sand and mud, is the last facies in the vertical succession, and is laterally extensive (Fig. 3.16). Facies 6 covers the highest topographic areas in sheet-like manner. Facies 6 commonly denotes the top of the Zone 2. Two separate vertical successions characterize Zone 2. Firstly, in the lower part of Zone 2, F2, marks the base, followed by F3 and F4 intercalated within F2. Secondly, in the upper section of the respective zone, F2 marks the base, followed by F3 and capped by F6.

ZONE 3 – UPPER MCMURRAY MEMBER

Zone 3 is populated by three facies: F7, F8, and F9. Facies 7, is localized, and generally observed at the base of Zone 3. F7 is typically the lowest topographic facies of Zone 3 and forms an approximately north northeast-south southwest trending sinuous body throughout the study area (Fig. 3.16; 3.18-3.22). In the middle portion of Zone 3, F7 is observed as isolated bodies within F8. However, F8 typically overlies F7. Facies 8 occupies the bulk of Zone 3 and F8 blankets Zone 3 isopachously. Facies 8 most commonly demarcates the contact between Zone 2 and Zone 3. Facies 9 is encompassed by F8 and is present as north-west to south-east trending lath-shaped units. All facies within Zone 3 are easily mapped.

In summary, an idealized vertical succession for Zone 3 is: F7 at the base followed by F8 with intercalations of F9. The top of Zone 3 marks the contact between the McMurray Formation and overlying Wabiskaw Member (Clearwater Formation). The contact between Zone 2 and Zone 3 has minimal relief over the area of the model block.

NORTH MODEL

In the north area of the sudy location, the correlation ranges failed to correlate the facies in the horizontal direction (Fig. 3.24) and over-correlated the facies in the vertical direction (Fig. 3.24; 3.25); therefore, the results obtained from the north area do not provide a viable model for interpretation and will not be discussed further.

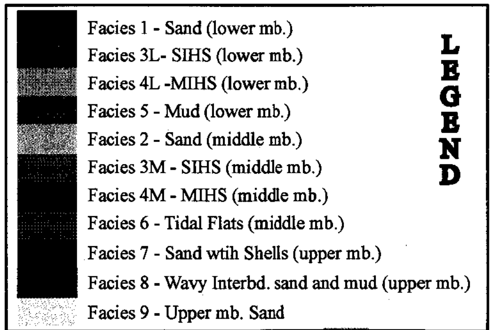


Figure 3.13. South Model. Horizontal slice at the base of the lower McMurray member. Each of the following slices from the model contains a small rectangular prism in the lower left corner noting the area the respective slice is taken from within the 3-D model block for the south area. Each facies is represented by the colors noted n the legend. The blue surface in the western half of the slice is the sub-Creteceous unconformity. Each of the following represents the entire south area for the respective direction.

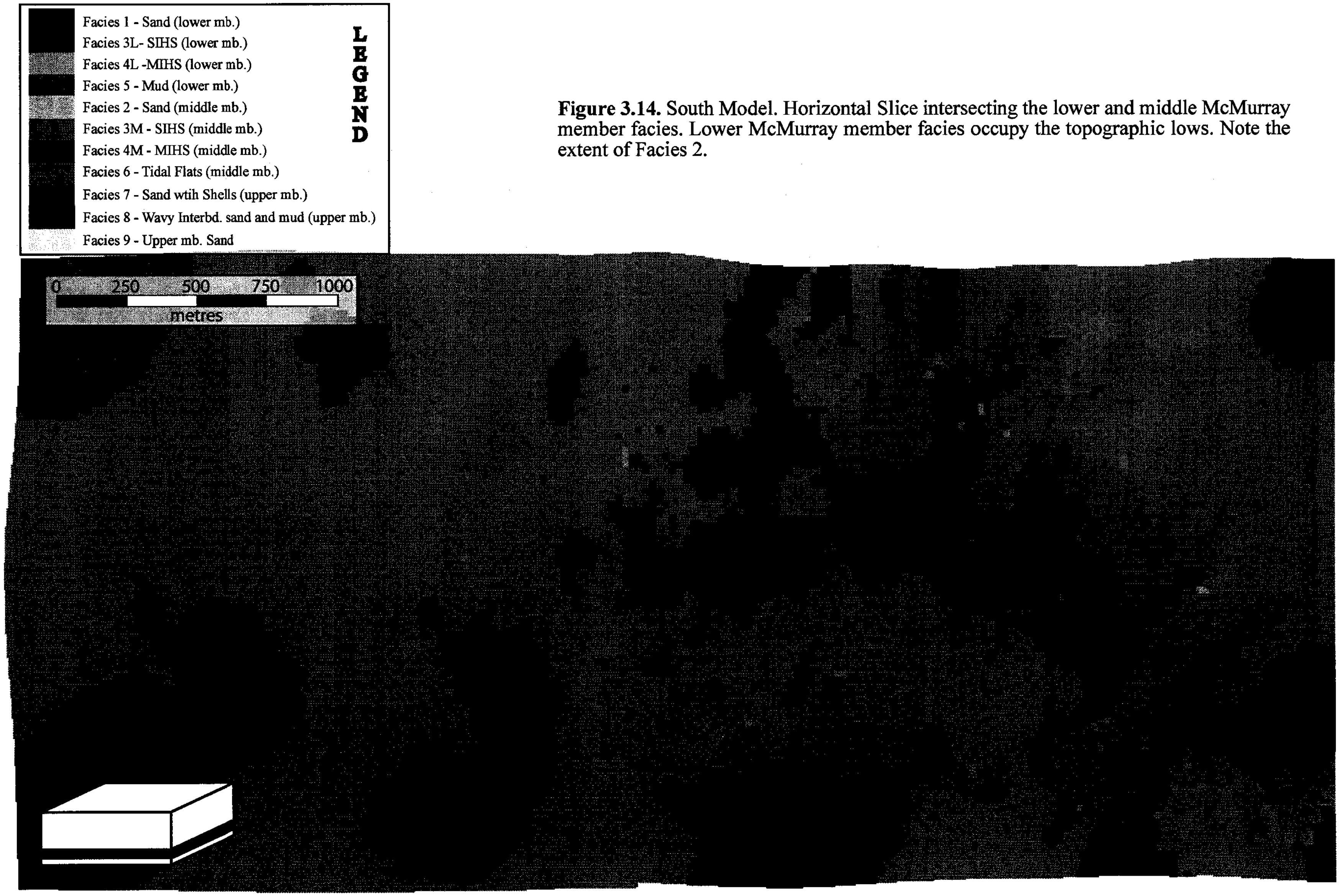


Figure 3.14. South Model. Horizontal Slice intersecting the lower and middle McMurray member facies. Lower McMurray member facies occupy the topographic lows. Note the extent of Facies 2.

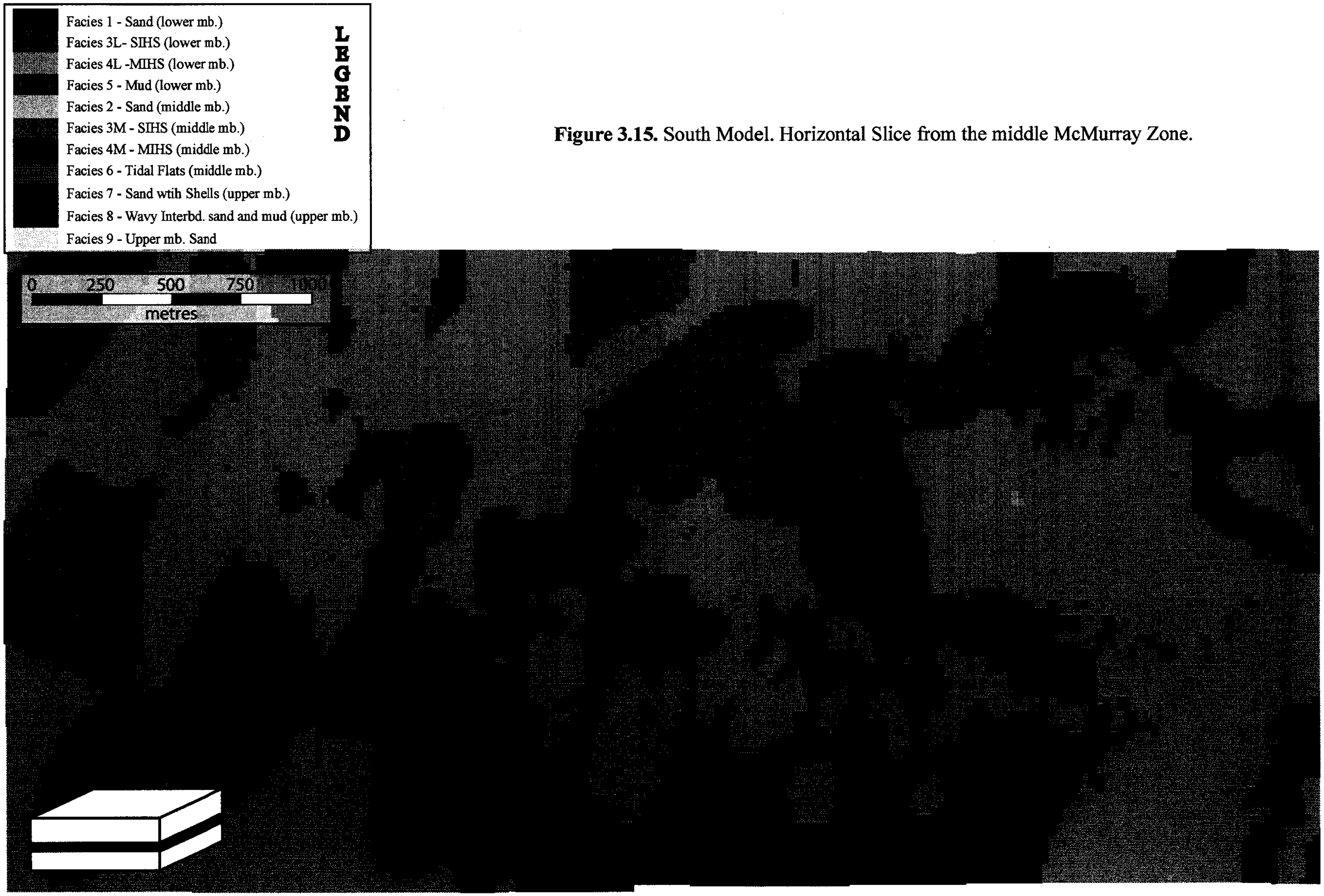


Figure 3.15. South Model. Horizontal Slice from the middle McMurray Zone.

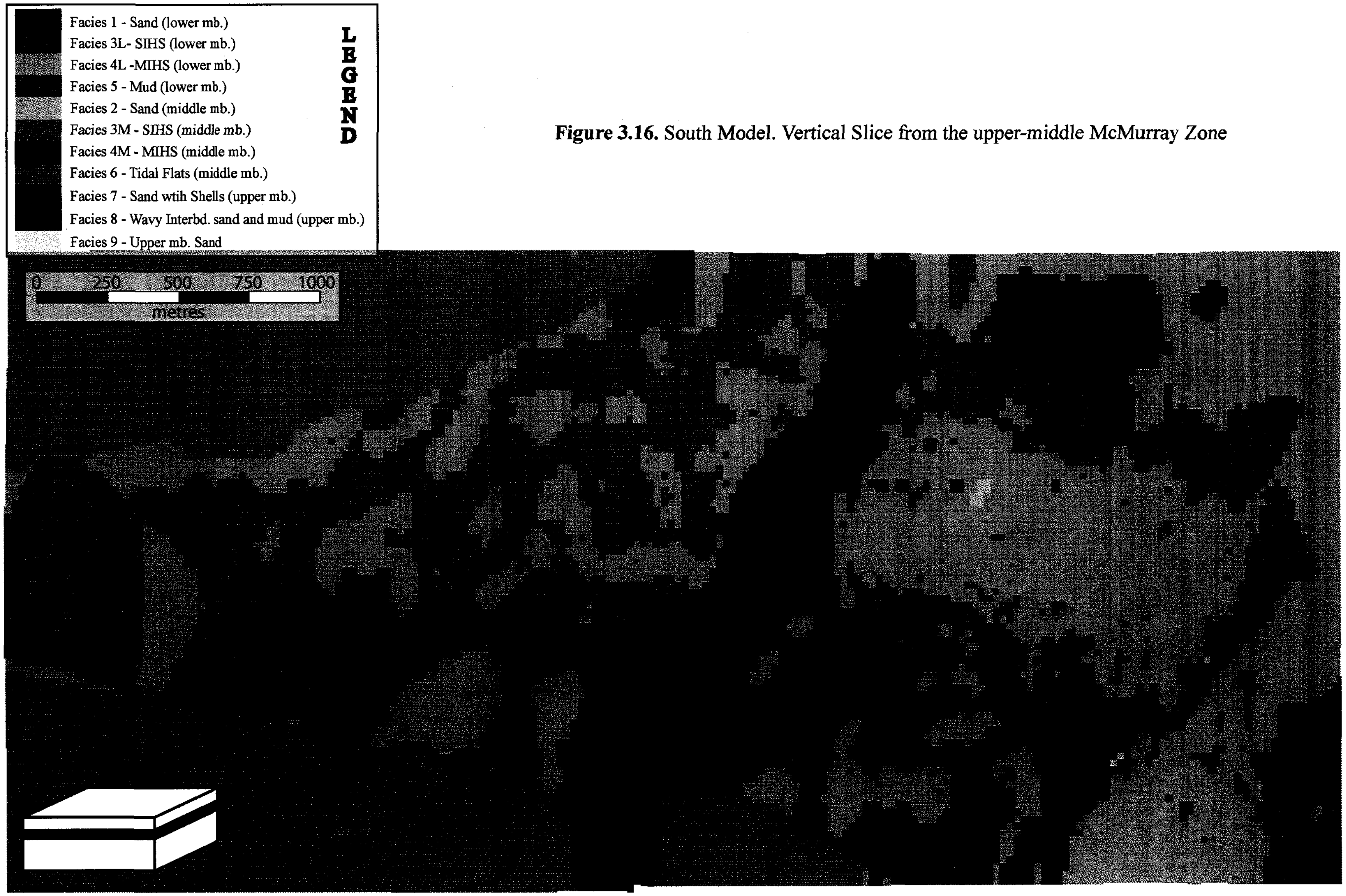


Figure 3.16. South Model. Vertical Slice from the upper-middle McMurray Zone

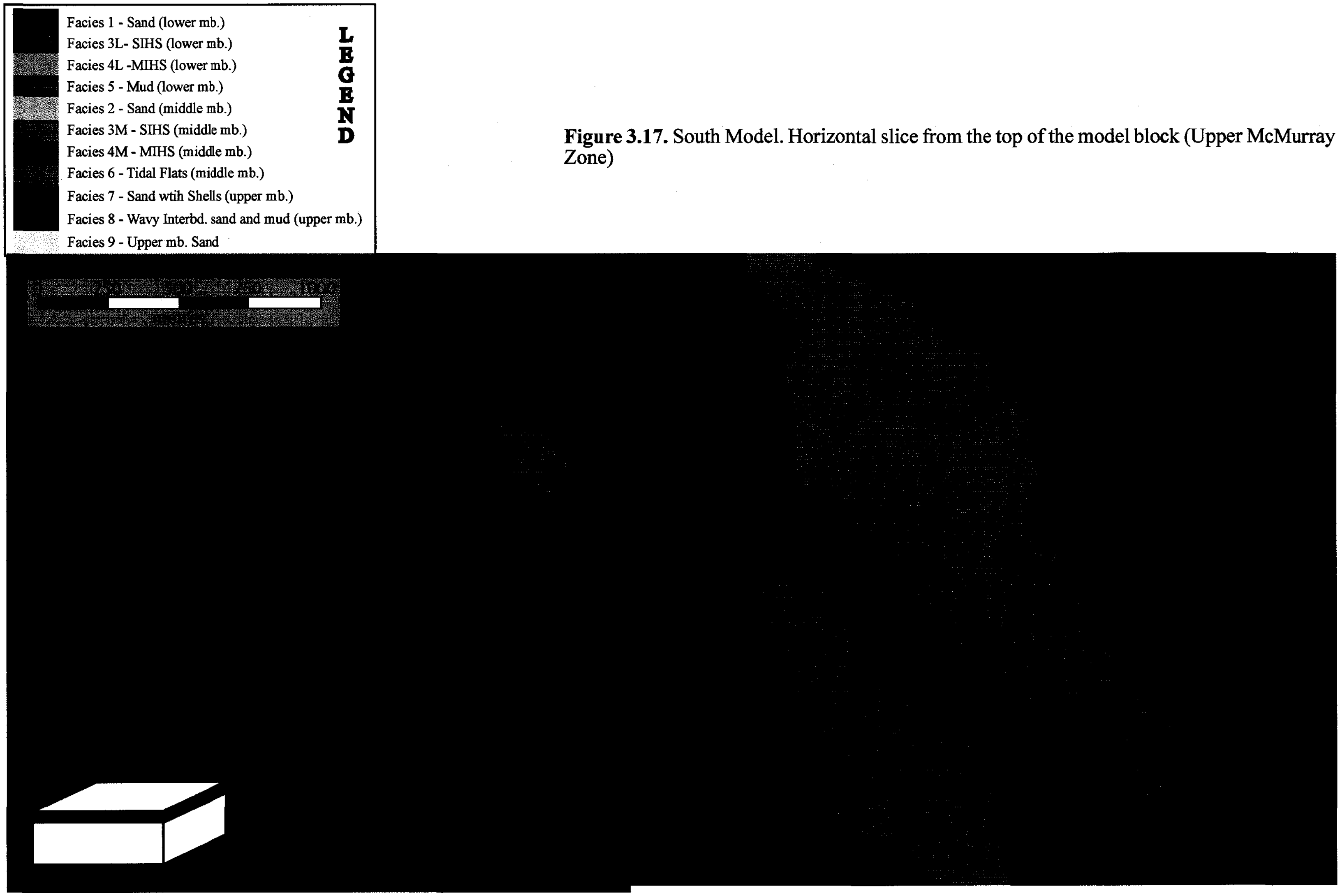


Figure 3.17. South Model. Horizontal slice from the top of the model block (Upper McMurray Zone)

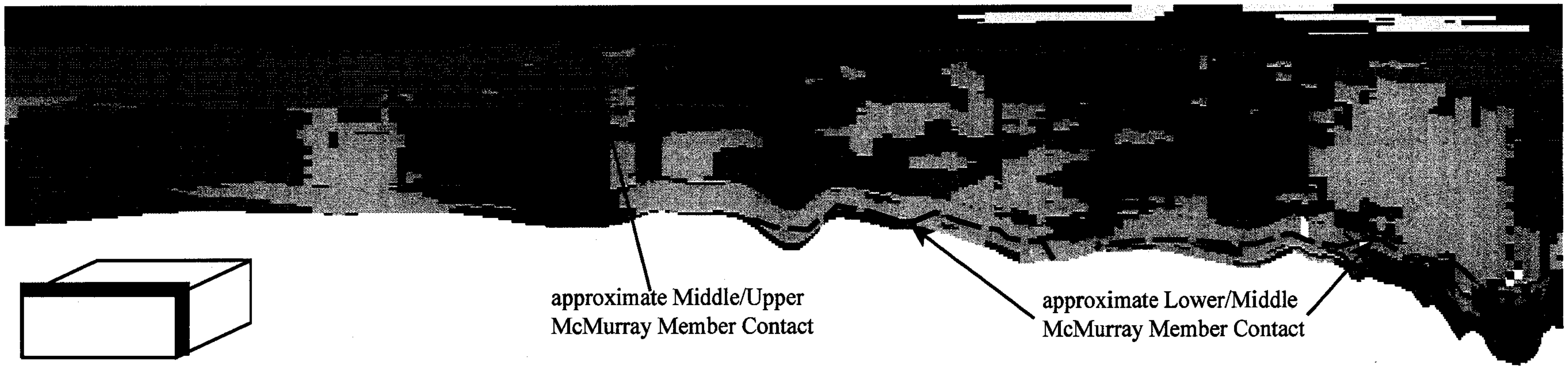
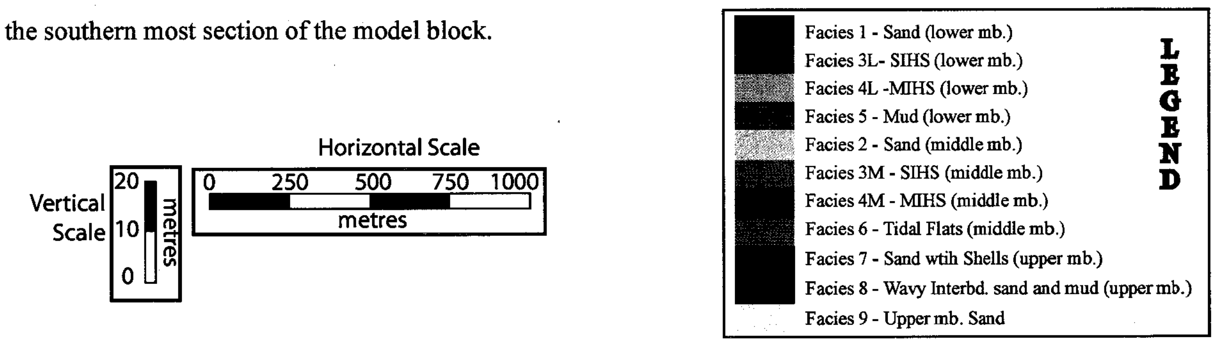


Figure 3.18. South Model East-west slice from the southern most section of the model block.



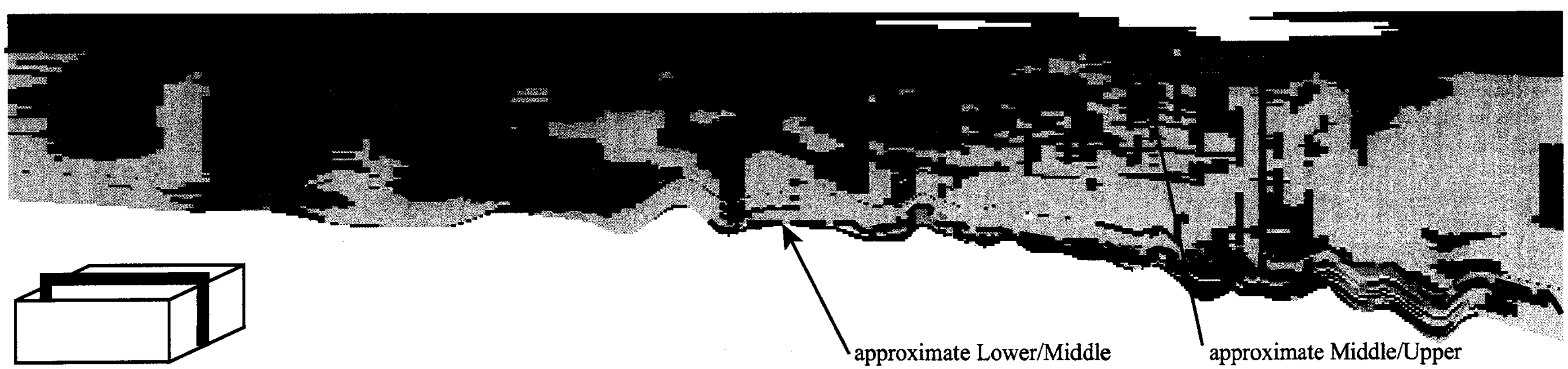
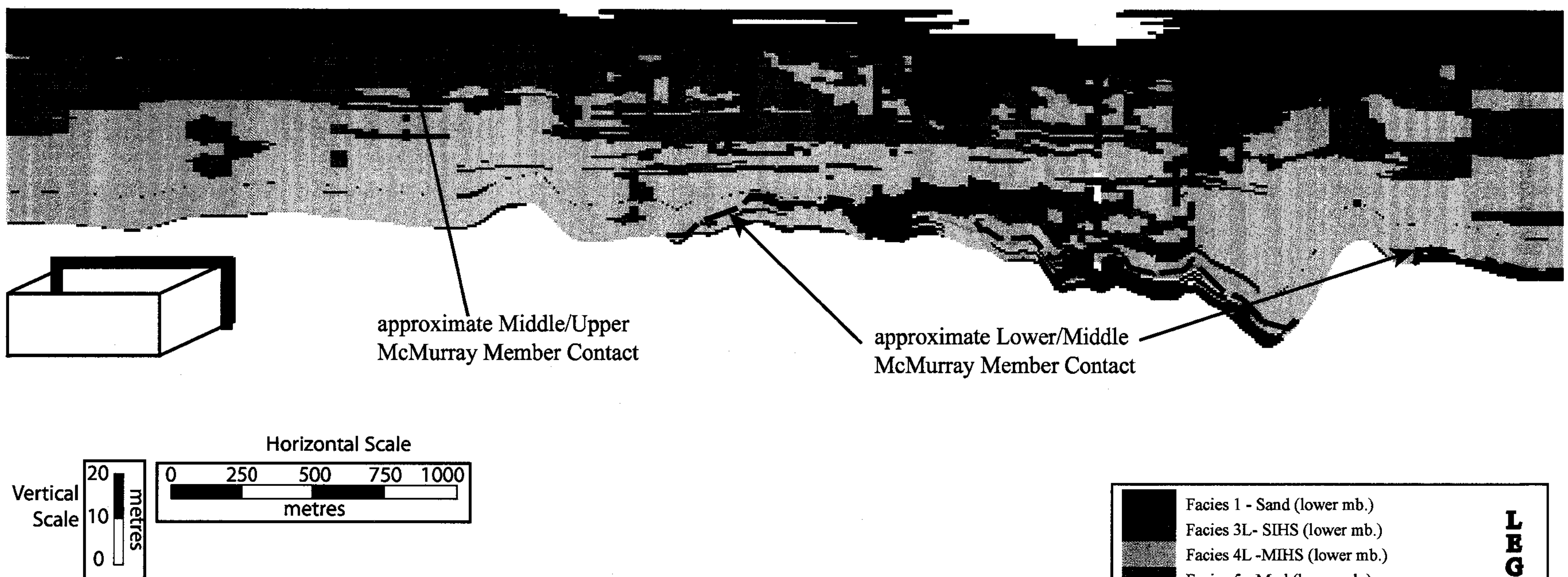


Figure 3.19. South Model. East-west slice from the middle section of the model block.



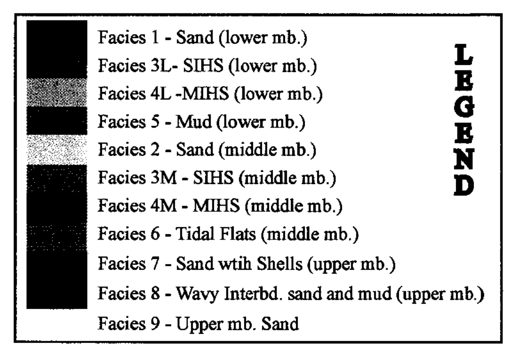


Figure 3.20. North Model. East-west slice from the northern section of the model block.

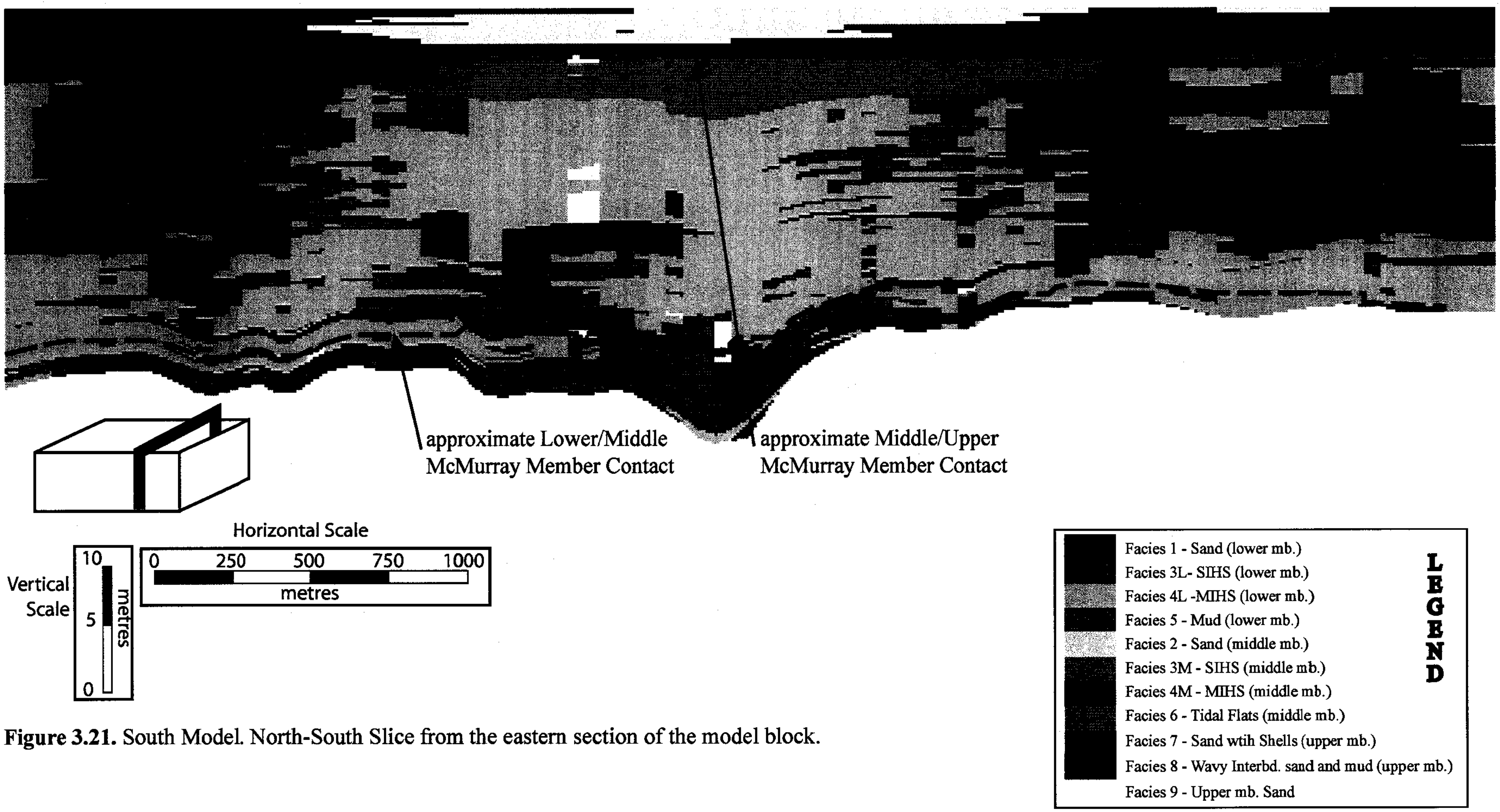
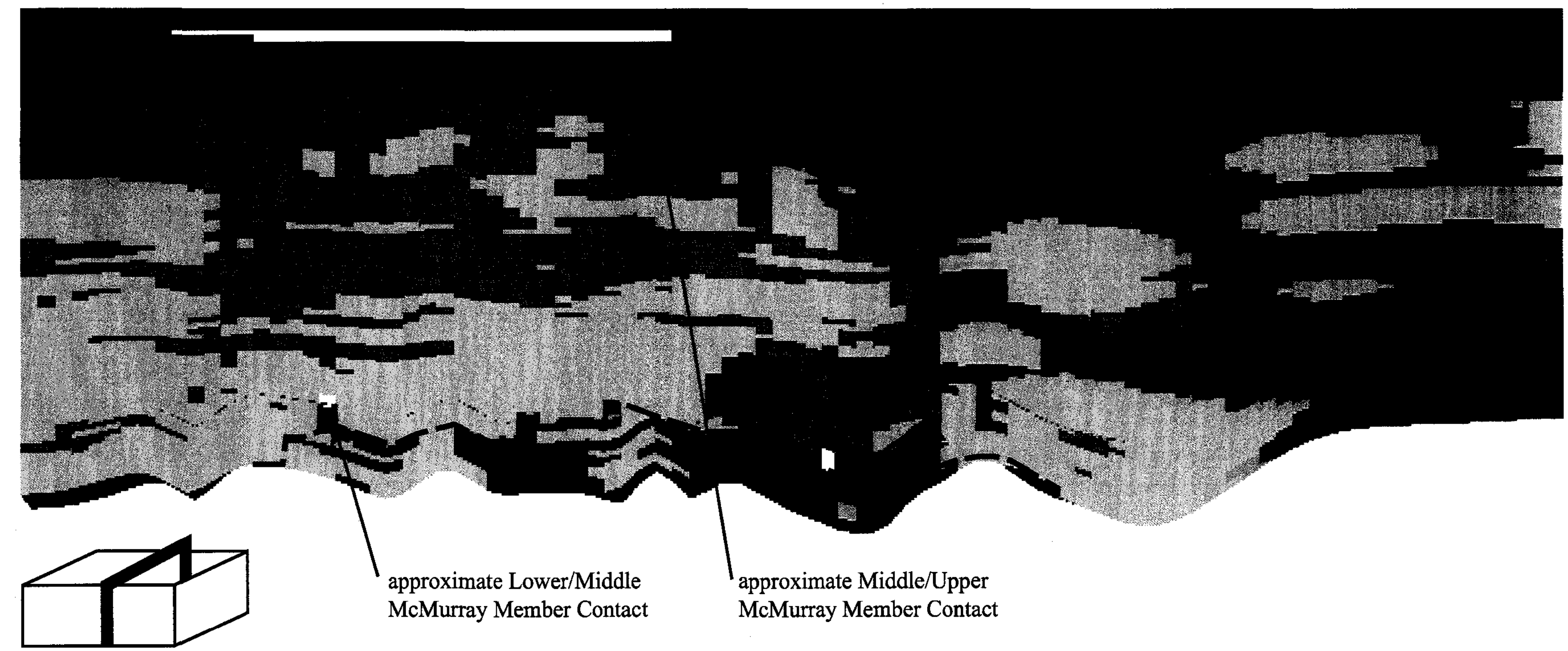
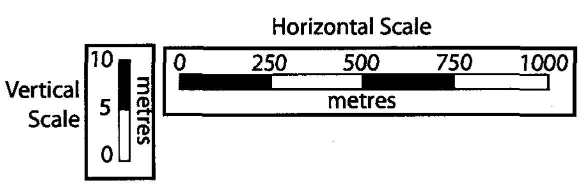


Figure 3.21. South Model. North-South Slice from the eastern section of the model block.





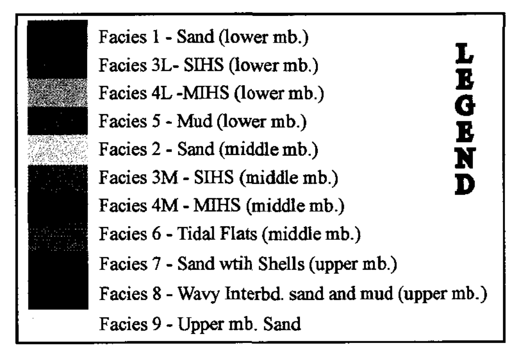


Figure 3.22. South Model. North-South Slice from the middle section of the model block.

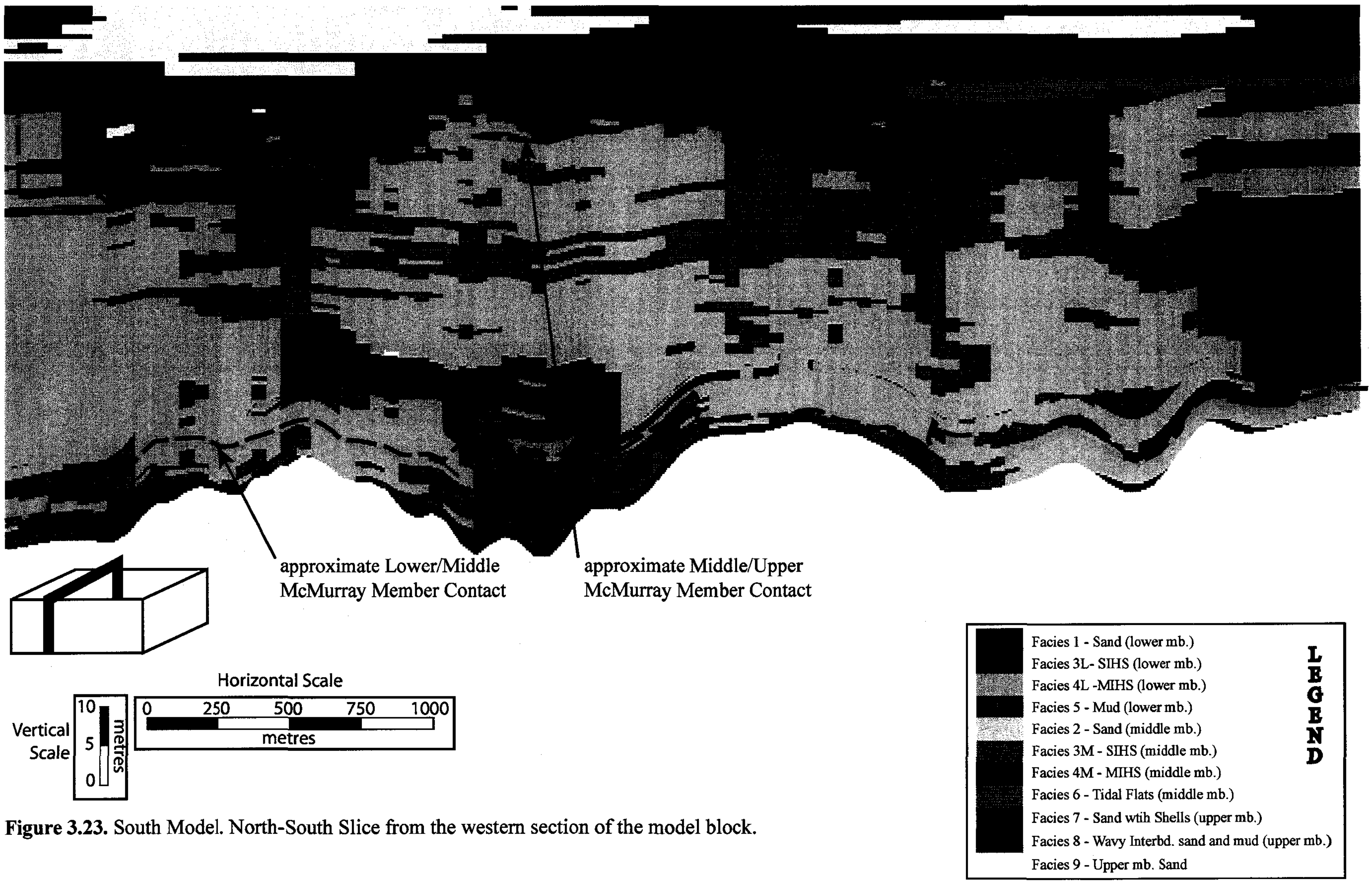


Figure 3.23. South Model. North-South Slice from the western section of the model block.

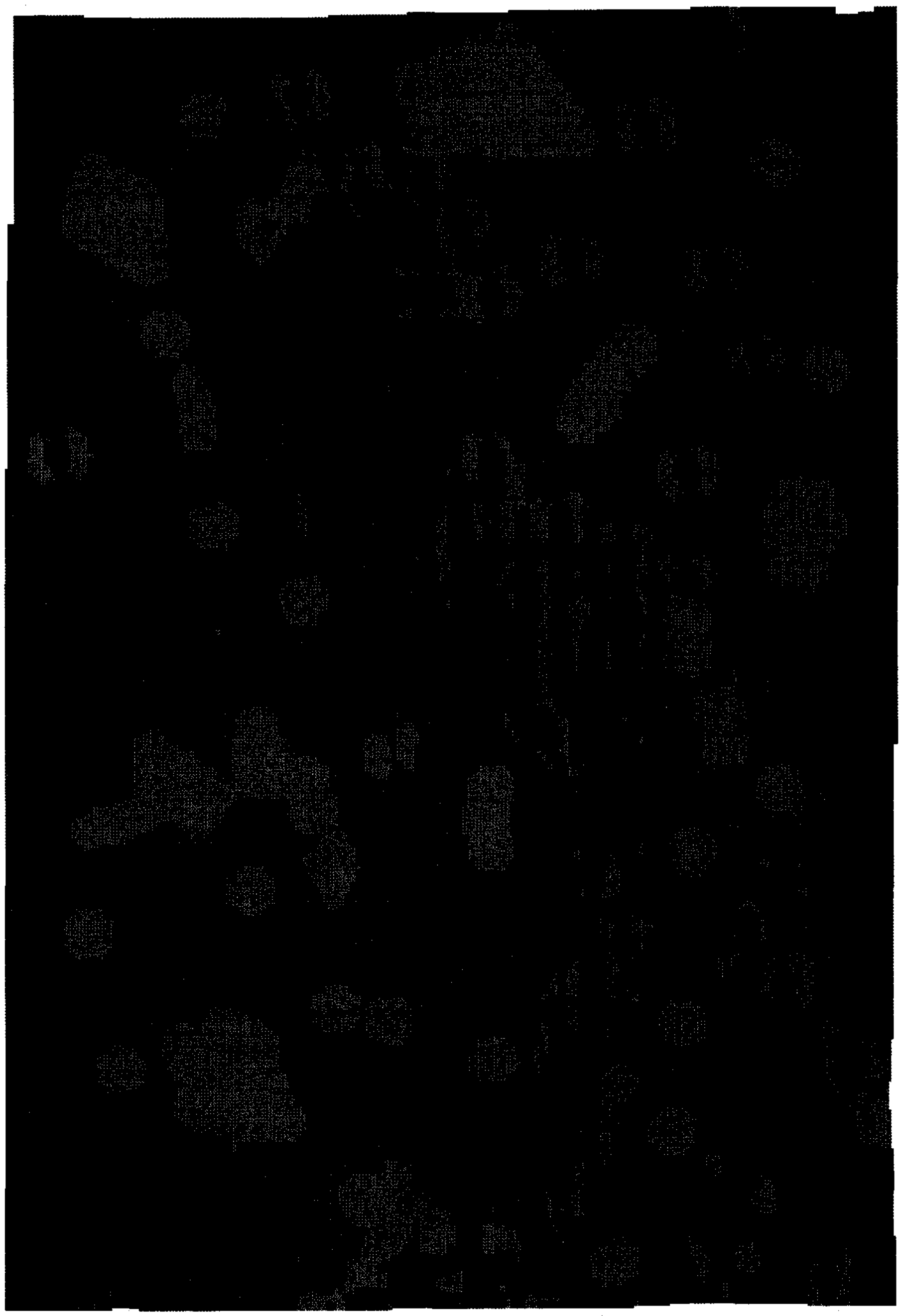


Figure 3.24. North model. Horiszontal slice taken from the upper portion of the middle McMurray illustating the failure of the ranges to correlate facies.

Facies 1 - Sand (lower mb.)	L
Facies 3L- SIHS (lower mb.)	E
Facies 4L -MIHS (lower mb.)	G
Facies 5 - Mud (lower mb.)	E
Facies 2 - Sand (middle mb.)	N
Facies 3M - SIHS (middle mb.)	D
Facies 4M - MIHS (middle mb.)	
Facies 6 - Tidal Flats (middle mb.)	
Facies 7 - Sand wtih Shells (upper mb.)	
Facies 8 - Wavy Interbd. sand and mud (upper mb.)	
Facies 9 - Upper mb. Sand	

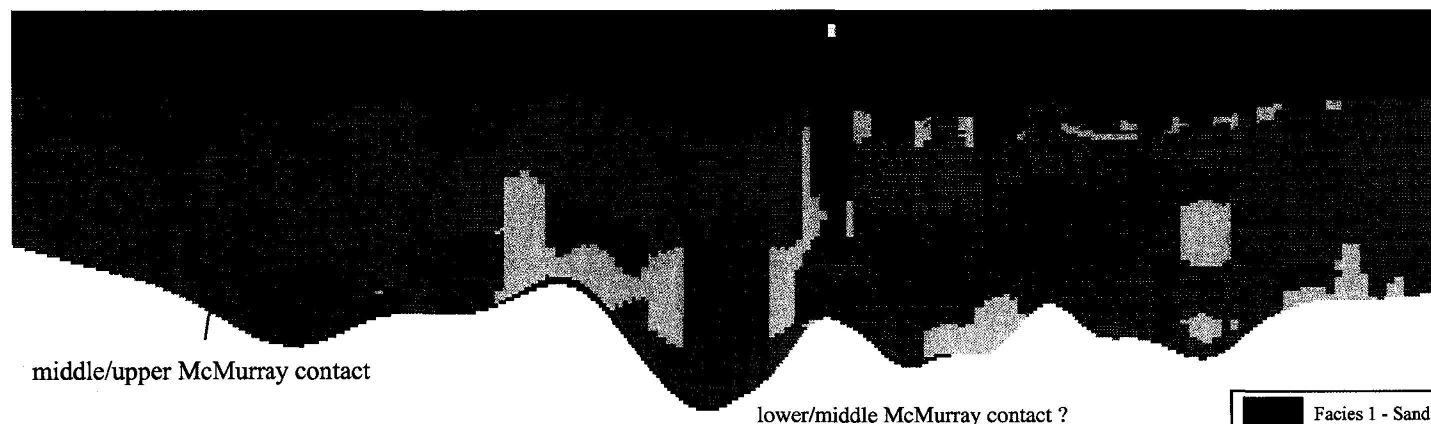


Figure 3.25. North Model. East-west section.

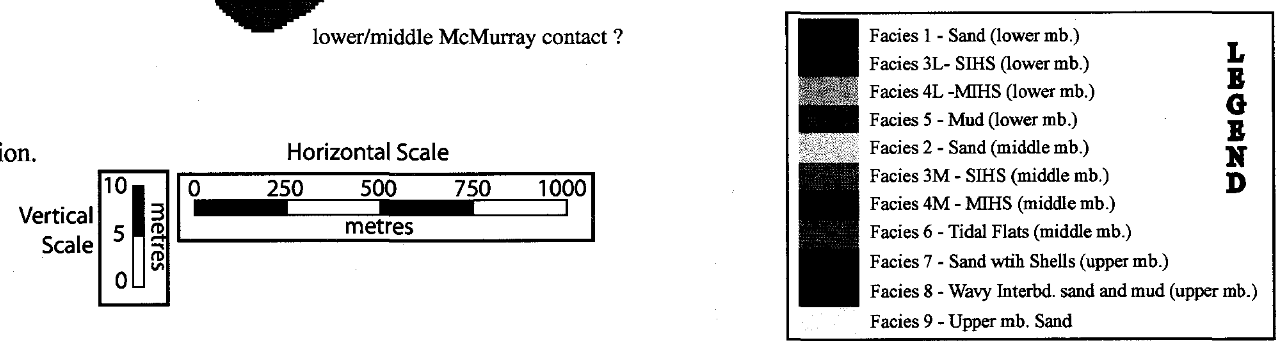


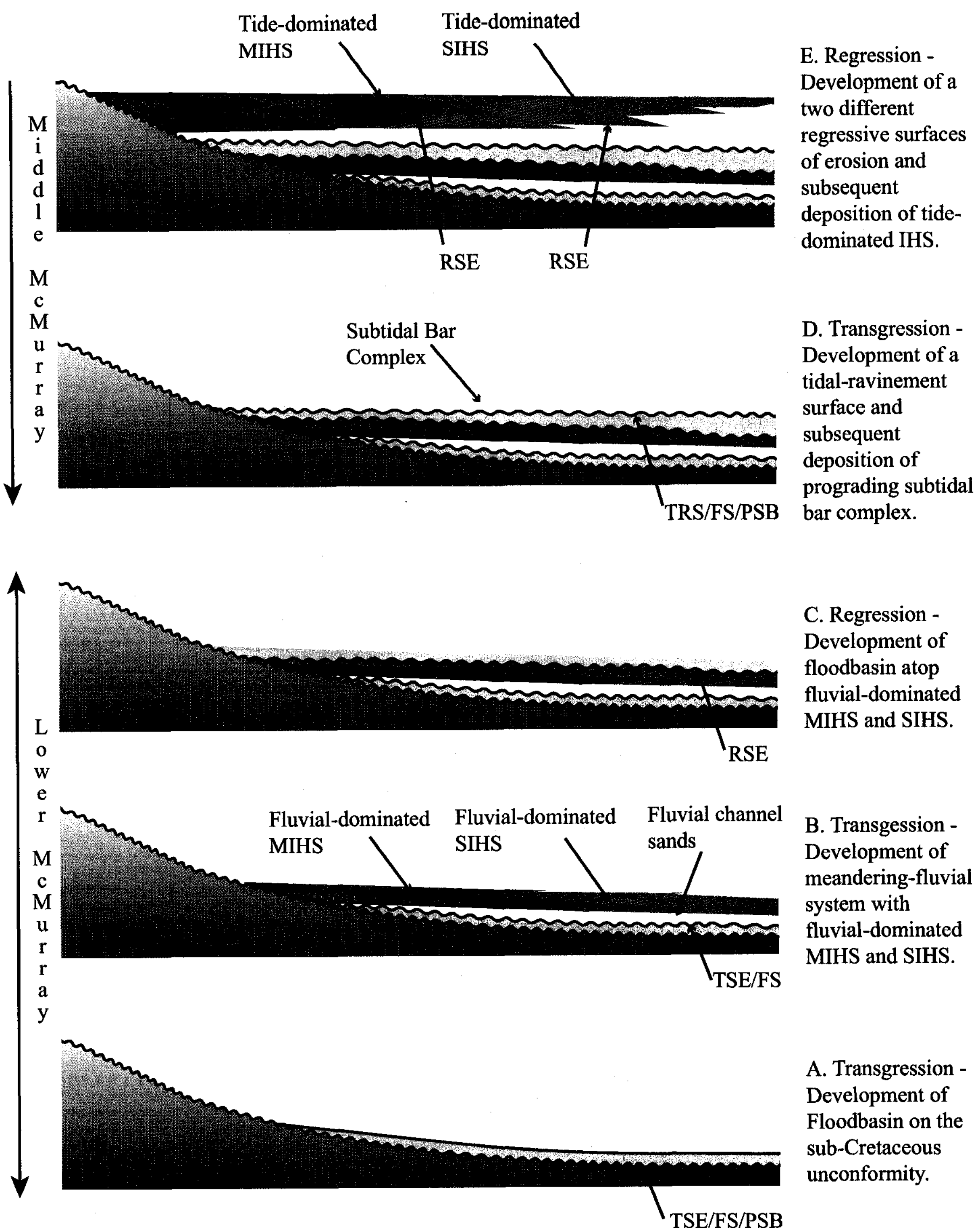
Figure 3.26. North Model. North-south section.

Stratigraphic Interpretations

The following presents stratigraphic interpretations for the informal members (lower, middle, and upper) of the McMurray strata. Much debate is focused on the depositional environments of middle McMurray member; therefore, interpretations pertaining to the respective member occupy the bulk of the proceeding section.

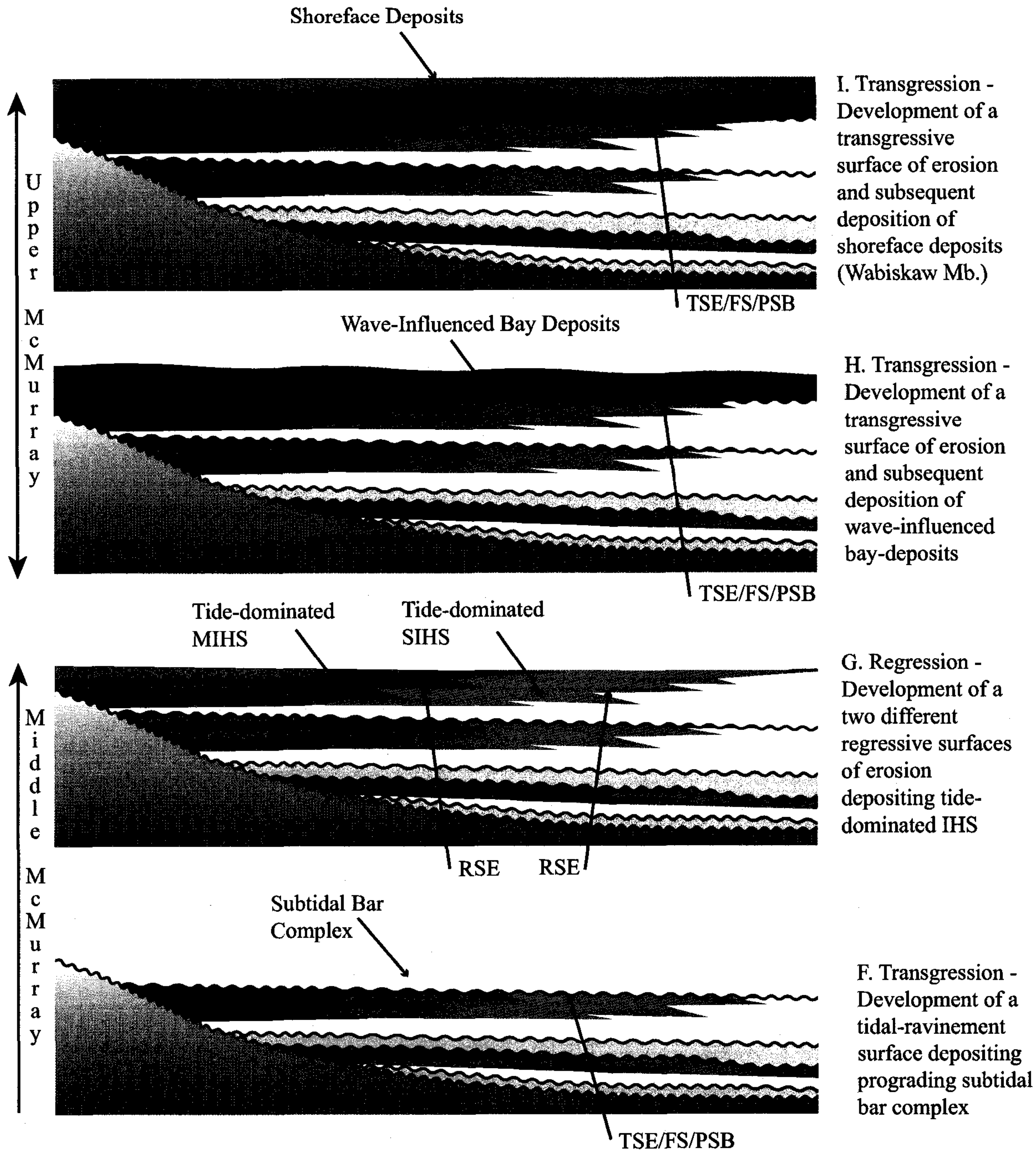
Lower McMurray Member

The lower McMurray member is characterized by four facies: F1, F3, F4, and F5. All four of which are closed related to each other. The occurrence of (F5) on the sub-Cretaceous unconformity suggests development of a floodplain within a landward part of depositional system during the initial stage of transgression of the Western Interior Seaway (Fig. 3.27A). These deposits are preserved throughout the vertical succession in the lower McMurray. Facies 1, the massive to cross-stratified sand with associated point-bar deposits of F3, and F4, indicates development of a fluvial-dominated system with minimal marine influence. The massive to cross-stratified sands suggest deposition during flood-stage and normal discharge respectively. All of these deposits are constrained within the paleo-topographic lows and therefore have a limited extent due to low accommodation space. This low accommodation space contributes to cannibalization and amalgamation of preexisting deposits because the meandering system would avulse frequently within the confines of the paleo-valley. As stated above, IHS typically represent lateral accretion of tidally-influenced point-bars of meandering estuarine channels. Thus, the IHS deposits of the lower McMurray member indicate tidal influence and influx of marine energy within the fluvial-dominated environment. Sand-dominated IHS typically sits stratigraphically below mud-dominated IHS. This suggests that the meandering system was initially dominated by sand and as the system matured the mud-dominated IHS retrogrades overtop the SIHS. Accordingly, the deposition of channel sand and IHS on top of the basal F5 is indicative of incremental transgressive event



TSE: Trangressive Surface of Erosion
TRS: Tidal Ravinement Surface
FS: Flooding Surface
PSB: Parasequence Boundary
RSE: Regression Surface of Erosion

Fgure 3.28. Stratigraphic evolution of the McMurray Formation within the North Mine study area (modified from Ranger and Gingras, 2003).



Fgure 3.28. Continued. Stratigraphic evolution of the McMurray Formation within the North Mine study area (modified from Ranger and Gingras, 2003).

(Fig. 3.27B). The top of the lower member is most commonly marked by the presence of F5, therefore this would suggest that a minor regression was responsible for progradation of floodplain mud overtop the channel sands and IHS deposits (Fig. 3.27C).

The brackish-water trace fossil assemblage throughout all deposits within the lower member suggests presence of brackish-water, but the influx of marine water was minimal as bioturbation is characteristically rare. However, the rhythmicity within IHS deposits suggests that tidal forces were substantial and thereby, produced inclined heterolithic strata. In summary, the entire deposition system of the lower member (Fig. 3.28) can be attributed to deposition within the most landward portion of the McMurray system in the study area. The end of lower McMurray deposition, paleo-topographic highs of the Devonian were most likely covered by a thin veneer of the sediments of the lower McMurray member.

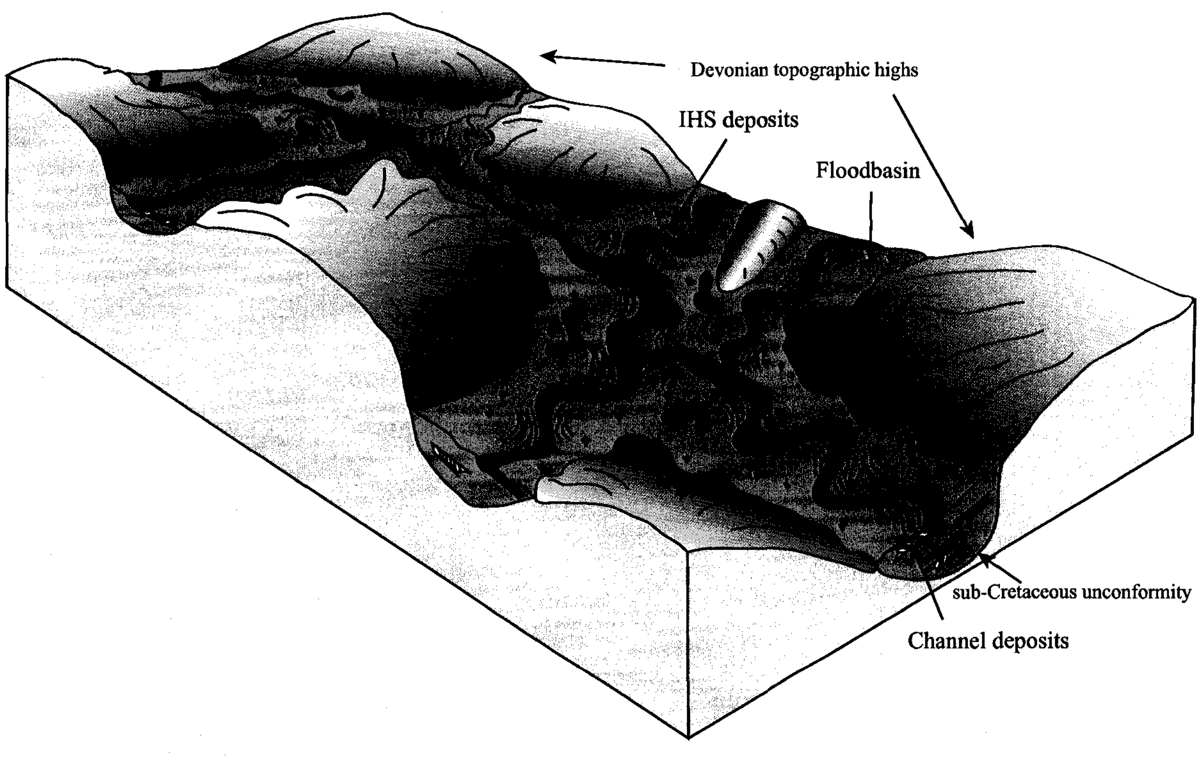


Figure 3.28. 3-D schematic representation of the lower McMurray depositional system.

Middle McMurray Member

The middle McMurray member is characterized by four facies: F2, F3, F4, and F6. The basal contact for the middle member sediments is most commonly marked by the large-scale cross-stratified dune sands of F2. Stratigraphically, F2 is preserved directly atop positive elements of the paleotopography of the sub-Cretaceous unconformity. F2 erodes the lower member sediments in the topographic lows. Thus, this contact is interpreted to represent a tidal ravinement surface (TRS) and incremental stage of transgression (Fig. 3.27D). Facies 2 is preserved in a sheet-like geometry; this suggests the sand-dominated facies represents amalgamation of broad channels and subtidal bars in the distal portion of the paleovalley (Fig. 3.29). Accretion, liquefaction, and avalanching of sediment down the lee side of the dune are the proposed mechanisms responsible for the deposition of sediment within F2. Thusly, producing the variable cross-stratified to massive character of F2. The paucity of trace fossils in F2 cannot be ignored but is attributed to rapid sedimentation. The presence of robust ichnogenera indicates proximity to marine conditions with a strong brackish-water influence.

Facies 2 in the lower portion of the middle member is most commonly overlain by stacked SIHS to MIHS successions. This horizontal stacking is interpreted to represent progradation of laterally-accreting estuarine channels overtop the F2 sands (Fig. 3.29) (Gingras et al., 2003; Ranger and Gingras 2003; Gingras and Ranger, 2005). This contact is interpreted to represent a regressive surface of erosion (RSE) (Fig. 3.27E) (Gingras et al., 2003; Ranger and Gingras 2003; Gingras and Ranger, 2005). Bioturbation within the IHS successions is generally comprised of similar ichnologic assemblages, but the size of individual trace fossils is noticeably different. Comparatively, the ichnia within MIHS are characteristically smaller than ichnia of SIHS. This suggests that the trace makers within the MIHS were more stressed than the organisms within SIHS. Fluvial input was most likely negligible pushing the turbidity maximum into the proximal system (Lettley, 2004). Salinity stress is the probably cause for the diminutive character of the ichnologic assemblage. Accordingly, MIHS is attributed to deposition with the proximal system and SIHS to the medial depostional system (Fig. 3.29) (Ranger and Gingras 2003; Gingras et al., 2003, Gingras and Ranger 2005; Lettley, 2004).

The lower sets of IHS were indirectly influenced by the topographic lows of the sub-Cretaceous unconformity as they typically occupy the areas directly above the low-lying areas of this surface. In the upper portion of the middle member, IHS deposits have a greater vertical thickness as the influence of the unconformity decreases upwards throughout the McMurray Formation.

The succession within the lower part of the middle McMurray member is similar to the upper part of the middle McMurray member. The base of this succession is marked by transgressive surface of erosion (Fig. 3.27F). Similarly, following the transgression deposition of prograding subtidal bar complexes occurs (Fig. 3.27F). This is followed by an incremental regression and deposition of another set of prograding IHS deposits atop the sub-tidal bar complex. (Fig. 3.27G).

Deposition of F6, tidal flat deposits, is predisposed to the effects of the paleotopgraphy because F6 is preferentially preserved in the areas above topographically high areas of the unconformity. Facies 6 is only preserved at the top of the middle member. In modern environments, tidal flats commonly flank the edges of the inner to middle portions of the tidally-influenced system. Therefore, the tidal flat succession is attributed to deposition within the landward to medial portions of system. The top of F6 commonly marks the top of the middle member.

Historical depositional models of the McMurray Formation attribute deposition of the cross-stratified sand and overlying IHS sediment to a single, deep meandering channel (Mossop and Flach, 1983). Cross-stratified sand deposition would have taken place at the base of the channel, while IHS was deposited on a contemporaneous point-bar. The current work provides substantial evidence contrary to the single channel model. The sheet-like geometry of F2 deposits suggests the massive to cross-stratifed sands were deposited within multiple channels and associated subtidal bar complexes. Although macrotidal, large-scale sand bar complexes in the Cobequid Bay (Dalrymple et al., 1990), provided a contextual modern analogue for the outer estuarine channel and bar deposits of the middle McMurray Formation. The sand-bar complexes in the Cobequid Bay are similarly characterized by large-scale massive to cross-stratified sand and rare bioturbation. Secondly, the intercalated character and the patchy distribution of the IHS also suggest that many different channels accreted laterally within the confines of the paleo-valley system.

The lower part of the Cretaceous Sego Sandstone Member in east-central Utah provides an ancient example of tide-dominated deltaic sands (Willis and Gabel, 2001) comparable to the deposits of middle McMurray member. Large-scale cross-stratified sands are interpreted to represent prograding tidal bar complexes (Willis and Gabel, 2001). These deposits are similar to the middle McMurray member F2. The Sego Sandstone is similarly characterized by large-scale cross-stratified sand with internal dips up to 15 degrees. The Sego sandstone, like the McMurray F2, is interfingered with sand-dominated inclined heterolithic stratification. Similarly, bioturbation in the Sego member is characterized by rare, but robust ichnogenera. Therefore, the Sego Sandstone Member is potentially analogous to the deposits of middle McMurray member.

During deposition of middle McMurray member, fluvial energies were most likely low delivering only mud and silt to the system. Conversely, due to the abundance of tidal signatures within the McMurray Formation tidal energies were mostly likely high. Thus, it can be suggested that sand was largely supplied by tidal forces. Although a detailed sedimentologic study was not the primary concern of this study, previous work (Mattison, 1987; Fox, 1988; Yuill, 1995; Becthel, 1996, Crerar, 2003) characterized the grain-size of sand as follows: (1) F2, the most seaward deposit, is typically composed of fine to coarse-grained sand; (2) F3 is comprise of fine-grained sand; and (3) the most landward deposit, F4, is composed of very-fine grained sand (Fig. 3.29). This grain-size profile illustrates an increase in grain-size from the landward to the seaward deposits within the McMurray depositional system. It also reinforces the interpretations of the energetic mechanisms responsible for sediment accumulation.

In summary, the deposits of the middle member (Fig. 3.29) can be ascribed to a depositional continuum within the marginal-marine system: (1) F2, is deposited in the most seward part of the depositional system; (2) F3 (SIHS) and F6 are deposited in the middle portion of the continuum; and (3) accumulation of sediment for F4 (MIHS) and F6 (tidal flats) took place in the most landward part of the depositional system.

Upper McMurray Member

The basal contact of the upper member is locally marked by F7 and regionally by F8. This contact represents a trangressive surface of erosion (Fig.3.27H). F7 erodes sediments of the middle McMurray member as it cuts through F6 in the middle of the study area. F8 is interpreted to represent deposition with wave-influenced bay (Fig. 3.29) and the localized north-northwest trending sand ridges are interpreted to present deposition of shoals within the bay. Sharply overlying F8 and F9 is the Wabiskaw member of the Clearwater Formation. This contact is the final transgressive surface whereby deposition moves to a fully-open marine system (Fig. 3.27I).

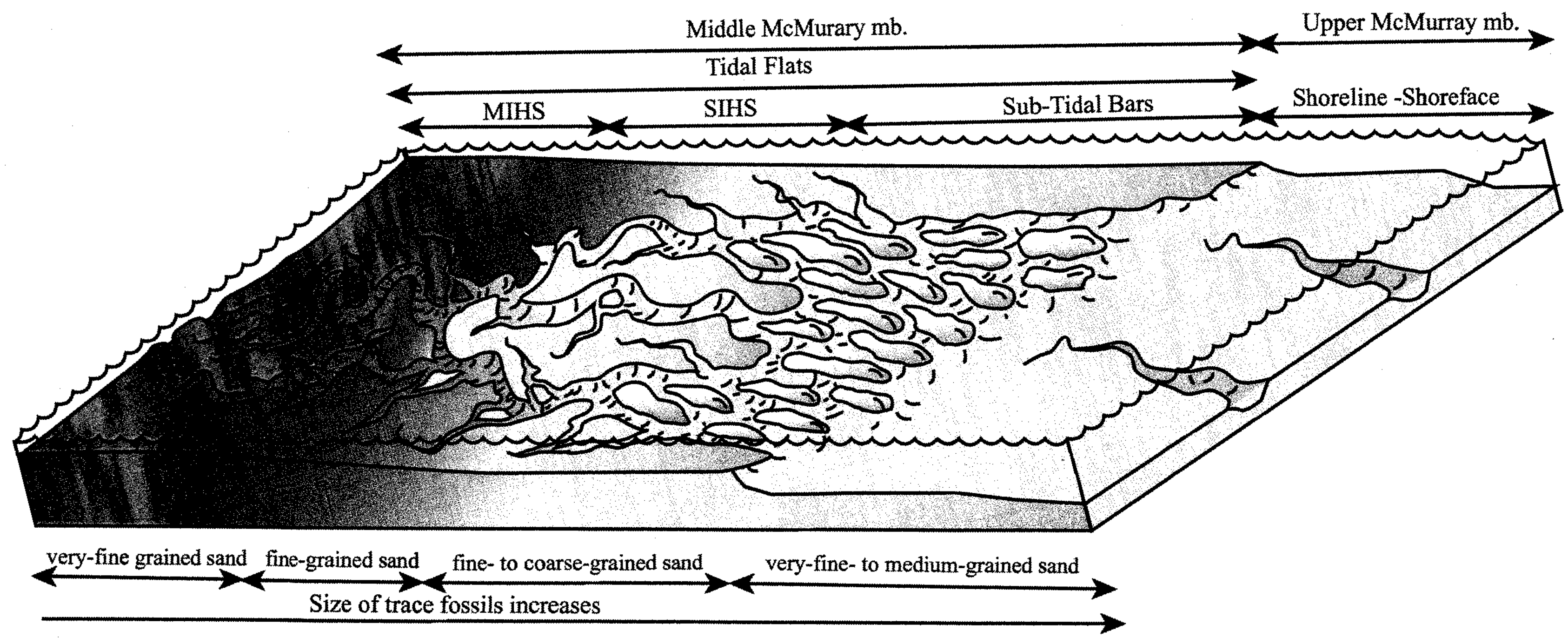


Figure 3.29. 3-D Schematic representation of the middle and upper McMurray member depositional systems.

Discussion

The McMurray Formation in the south area of the North Mine represents deposition during an extended period of transgression with intermittent regressions and trangressions. The stratigraphic framework is highly variable and predictable at a local scale. Current depositional models ascribe sediment accumulation to an estuarine paleo-valley fill (Mattison, 1987; Fox, 1988; Yuill, 1995; Bechtel, 1996; Strobl et al., 1997; Ranger and Pemberton, 1997). This study differs from previous work in that the marginal-marine system is interpreted to represent accumulation and progradation of sediments within a tide-dominated delta. Several studies (Ranger and Gingras, 2003; Gingras et al., 2003; Gingras and Ranger, 2005), from outcrop and core, have provided work consistent with the following interpretations. These invaluable works provided a local scale stratigraphic model for the McMurray Formation that is potentially applicable at a regional scale.

The lower McMurray deposits preserve a low-stand meandering-fluvial system laterally constrained within narrow margins of paleo-valley. Floodplain mud dominates the initial sediment accumulation followed by a minor transgression resulting in the incision of a meandering-fluvial system within a proximal environment. The last stage of sediment accumulation is marked by a minor regression resulting in the development of a floodplain.

Commonly, the lower member succession is sharply overlain by outer estuarine channel-fills and associated subtidal bar deposits (F2). This contact represents a tidal ravinement surface (TRS) whereby the entire depositional system is shifted landward. As a result, the outer estuarine channel deposits incise and prograde overtop the lower member sedimentary succession. These deposits cannibalize the upper deposits of lower member; and, consequently, the outer estuarine channel deposits lie on top of point-bar deposits of the lower member. This destructive force is the probable cause for development of abundant breccia deposits throughout the McMurray Formation.

Cannibalization of preexisting sediment is frequent with in the areas related to the topographically low areas of the sub-Cretaceous unconformity. Ranger and Pemberton (1997) suggest that McMurray Formation lowstand facies are preferentially preserved in relation to paleo-topographic lows and even though the effect of the unconformity decreases upwards throughout the McMurray Formation, it is observed that present channel trends corresponds to negative elements of the paleo-valley. Within the study area, the lower portion of the middle member is characterized by intercalated SIHS and MIHS. These sedimentary units are most commonly preserved in areas that correspond to lows of the paleo-valley; thus, this potentially exemplifies the effect of the indurated sub-Cretaceous surface. Furthermore, the subdued effect of the paleo-valley is observed in the upper portion of the middle member as the IHS deposits are characterized by continuous vertical successions of SIHS, rather than intercalated SIHS and MIHS. This subdued effect would also allow for an increase in lateral accommodation space because the depositional system would not be confined to the narrow paleo-valley margins.

In the upper portion of the middle McMurray Formation, sediments are characterized by a similar succession as compared to the lower portion. The base of the upper-middle member unit is interpreted to represent a transgressive surface of erosion whereby the entire depositional system is shifted landward again. Subsequent to relocation of the system, outer estuarine channel deposits prograde overtop the lower-middle member IHS deposits. In the upper portion, IHS deposits are deposited atop the outer estuarine channel sediments. The contact between the I.H.S deposits and underlying subtidal bars represents a regressive surface of erosion resulting in a basinward shift of sediments. The McMurray Formation accumulated in a valley-tributary topography characterized by a low gradient; therefore, minor sea level fluctuations would have caused large-scale basinward or landward shifts in the distribution of sedimentary environments (Ranger and Pemberton, 1992). With respect to the middle McMurray member deposits, the large-scale relocation of the sedimentary environments is interpreted to exemplify minor sea-level fluctuations. Breccia deposits are less commonly preserved in the upper portion of the middle member. This suggests the entire system is more stable as the effect of the paleo-topography is subdued. For example, the tidal flats (F6) are extensively preserved at the top of the middle member. Tidal flats were most likely deposited throughout the depostional history of the middle McMurray member but were subsequently cannibalized by laterally-accreting point-bars and channel avulsions within the lower-middle member.

There are two significant surfaces in the upper member. Firstly, the base of the upper McMurray member is locally marked by a massive to cross-stratified channel sand with abundant shell fragments (F8). This contact is the first transgressive surface of erosion. Previous work (Mattison, 1987; Fox, 1988; Fox and Pemberton, 1989) attributed this facies to the middle member, but the current author suggests categorizing F7 within the upper member because it is also encompassed by sediments of F8 in the middle portion of the upper McMurray member. The presence of tidal channels suggests a minor transgressive event whereby outer estuarine channels were deposited overtop middle member sediments. Sand bars typically associated with these channels did not develop as the second and larger event took place shortly after the minor transgression. Within the study area, the second and more significant surface is marked by the deposition of wave-influenced bay deposits. This sharp contact is interpreted to represent a transgressive surface of erosion and corresponds to a landward shift of the depositional system. Deposition the wave-influence bay deposits is interpreted to represent the last major change in depositional dynamics within the McMurray Formation prior to the basin-wide transgression responsible for deposition of the Wabiskaw Member.

The modern Colorado River Delta, California, (Fig. 3.30; 3.31) provides a useful modern analogue for the McMurray Formation. Although, the current basinal system is anthropogenically modified, the sediment distribution and energetic mechanisms provide a contextural framework potentially applicable to lateral distribution of facies of the

McMurray Formation. Presently, fluvial discharge is low delivering only mud and silt to the system while tidal mechanisms deliver mainly sand-size particles. This coastal zone is tide-dominated with limited wave fetch (Meldhal, 1995). The most landward deposits are characterized by a tidally-influenced channel system potentially analogous to the middle McMurray member facies (F2, F3, F4, and F6). Incursion of marine waters would be substantial enough to develop inclined heterolithic stratified sediment. These deposits are potentially analogous to the IHS deposits (F3 and F4) of the McMurray Formation. Tidal flats flank the system on the east and west sides. Moving basinward, deposits are characterized by large subtidal channels and sand bars possibly analogous to the distal estuarine channels and bar deposits (F2) of the middle McMurray member.

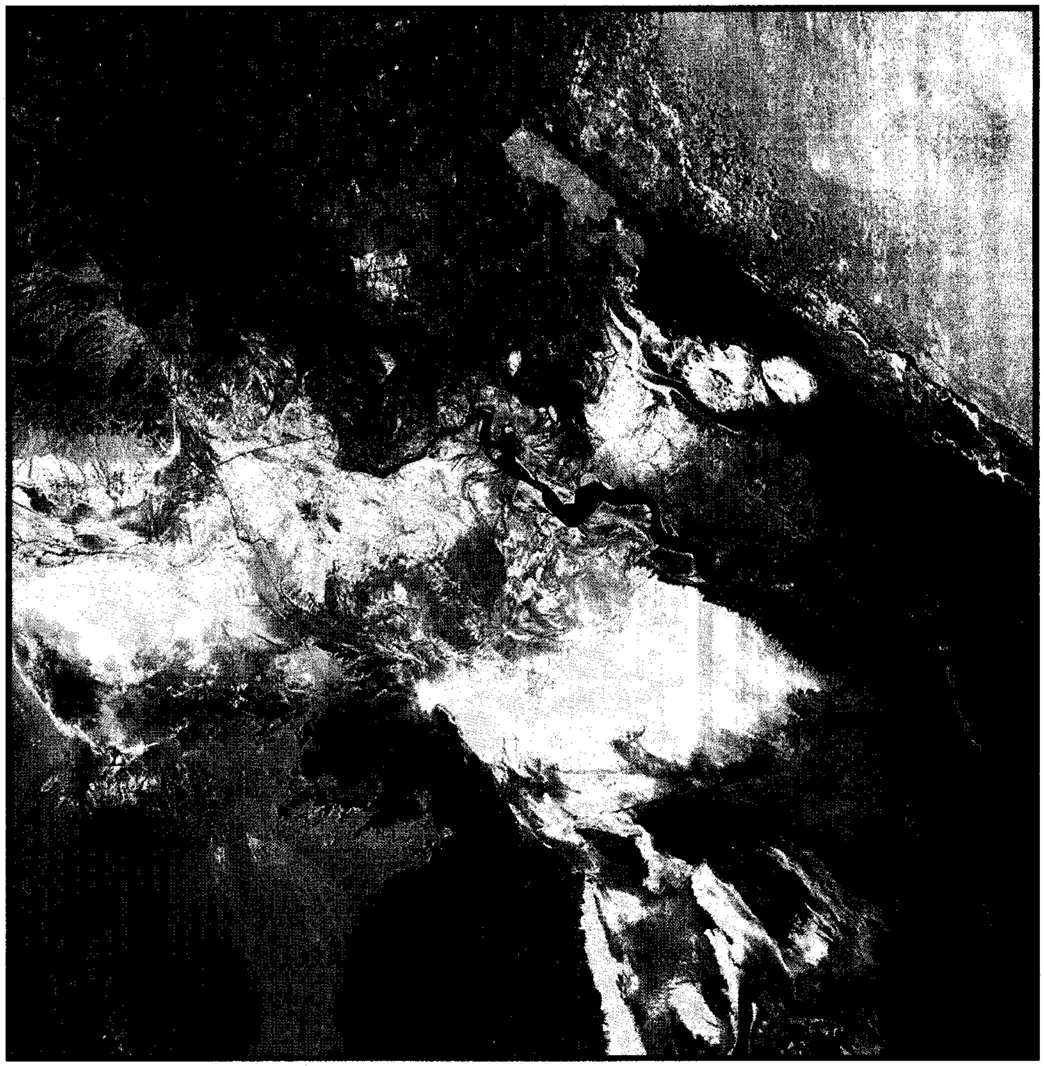


Figure 3.30. Colorado Tide-dominated Delta. Gulf of California, Mexico (taken from www.visibleearth.na sa.gov).

Figure 3.31. The Colorado River Delta from space. Deposition of the tide-dominated delta is confined to a narrow valley similar to interpretations of the McMurray paleovalley (courtesy of www.visibleearth.nasa.gov).

In summary, the McMurray Formation deposits within the south area of Syncrude's North Mine can be attributed to deposition within four parasequences (Fig 3.27). The first parasequence is demarcated by the sub-Cretaceous unconformity, which is the initial flooding surface. Lower McMurray member deposits characterize the first parasequence that preserves a floodbasin to meadering-fluvial dominated depositional system. The second and third parasequences, within the middle member, are demarcated by a tidal ravinement surface or transgressive surface of erosion respectively. In general, subtidal bars prograde overtop the underlying parasequence deposits followed by the progradation of laterally accreted estuarine channels. The final parasequence is demarcated by a transgression surface of erosion at the base and is characterized by wave-influenced bay deposits. This parasequence represents the final stage of deposition within McMurray Formation prior to the final transgression and subsequent deposition of the Wabiskaw Member (Clearwater Formation).

Conclusion

Nine facies were identified in the subsurface well-bore dataset within Syncrude's North Mine and subsequent modeled in three dimensions. The highest density dataset, from the south area, delivered an attractive model for interpretation of the McMurray stratigraphy. The lower well-density north area illustrates that well-density must be closely spaced (50-100 m) to erect a reliable 3-D model for the highly variable deposits of the McMurray Formation.

In general, the McMurray strata can be attributed to a depositional continuum within the marginal-marine system from: (1) fluvially-dominated sediments in the lower member; (2) tidally-influenced deltaic deposits in the middle member; and (3) wave-influenced bay deposits in the upper McMurray member. This continuum can be attributed to an overall transgression during the Lower Cretaceous, but incremental transgressions and regressions result in relocation of the depositional system within the respective members. Consideration of these minor relative sea level fluctuations is necessary because these fluctuations probably cause large-scale shifts in the distribution of sedimentary environments within the inferred low-gradient McMurray depositional system (Pemberton and Ranger, 1997).

Although, contrary to the current fossil estuary model, the derived high-resolution 3-D model suggests that the McMurray Formation is more effectively explained by the progradation of sediment within a tidally-influenced delta. This local model is potentially applicable to core and outcrop at a regional scale.

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Chapter 4 – Conclusion

The dataset, consisting of 1567 well-bores in the south area of the study, acquired from Syncrude Canada Ltd. provides the necessary data resolution required to develop a high resolution 3-D model for the McMurray Formation. Variography, in conjunction with nine facies, derived from Syncrude's Lithofacies Chart produced correlation ranges for the respective facies. This geostatistical analysis provides the framework to develop a model to understand the relationship of the facies within lower, middle, and upper McMurray members. This data analysis technique is applicable to bitumen saturated McMurray strata in other areas of the Athabasca Oil Sands deposits. This technique is applicable to other economically viable subsurface deposits characterized by internal heterogeneities. Within this study, it is demonstrated that well-density must be less than 100 m to produce a model for reliable interpretation; therefore, the density of data and variability of respective strata must be considered.

Current accepted models for the McMurray succession attribute sediment accumulation to a depositional continuum from fluvial-dominated to a marine-influenced bay deposits within a fossil estuary. The model of this study is consistent with the previously stated continuum, but differs with respect to environment responsible for deposition of the McMurray strata. The intermediary interpretation of these two end-members is more effectively explained by progradation of sediment within a tidally-influenced environment. Specifically, this study attributes accumulation of sediment within a marginal-marine system in a tidally-influenced delta. Consideration of minor relative sea level changes within the inferred low-gradient system provides the necessary mechanism to develop an understanding of the complex McMuray strata. Thus, the interpreted stratal-architecture of the McMurray Formation within the south area of the North Mine, provides a predictive framework for the distribution of facies potentially applicable to other core and outcroppings of the McMurray Formation.

With the depletion of surface mineable oil sand deposits, the energy sector is initiating in situ exploitation. Within this study, the geostatistical techniques applied to the dataset and the subsequent high-resolution stratigraphic framework potentially delivers both a modeling technique and a predictive stratal-architecture necessary for efficient exploitation of the heterolithic McMurray Formation.

Appendix A

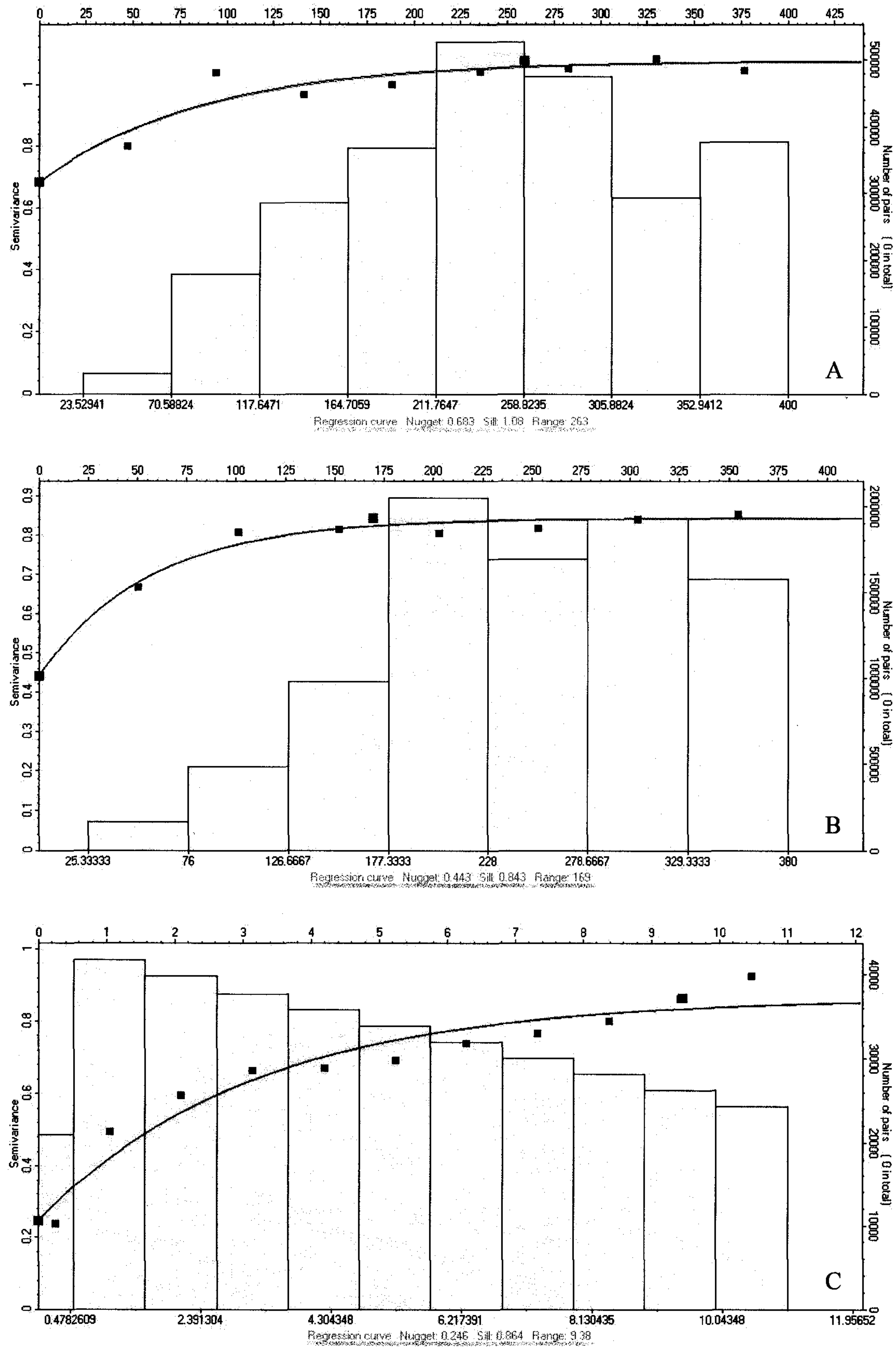
Syncrude's Sedimentary Lithofacies Chart (Modified from Syncrude Canada Ltd., 1997).

Syncrude's Lithofacies Chart - McMurray Formation (1997)

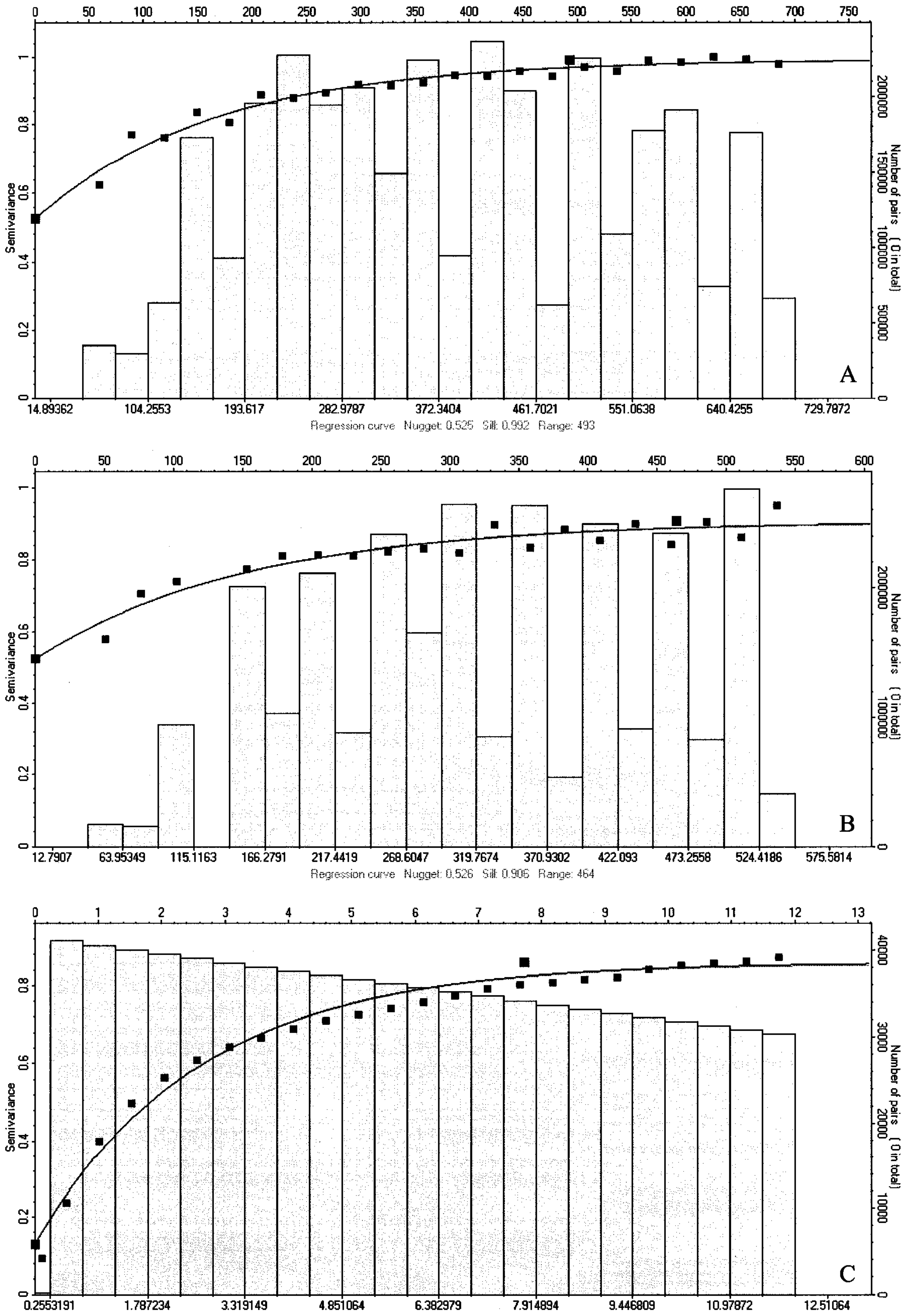
Fm./ Mb.	DESCRIPTIVE LITHOLOGY, SEDIMENTARY TEXTURES & STRUCTURES	LITHO CODE
McMurray Formation/upper member	Breccia	27
	Medium to coarse grained sand with abundant shell material and occasional carbonaceous fragments. Clay 10 - 35% in laminae and thin interbeds.	[illegible]
	Fine to medium grained, well sorted sand with low angle cross bedding. May be massive, homogeneous, and contain scattered carbonaceous debris.	26
	Medium to coarse grained sand with even parallel laminae and high to low angle cross bedding. Can be massive and homogenous. Clay less than 10%.	18
	Well bedded sand/silt with occasional thin (mm to cm scale) interbeds of dark grey to black clay. Clay 10 - 35%.	95
	Lithologically similar to lithotype 95 but with discontinuous bedding and high bioturbation.	[illegible]
	Well bedded sandy/silty clay and clayey sand/silt. Thin (mm to cm scale) interbeds of dark grey to black clay. Clay 35 -	96
	Lithologically similar to lithotype 96 but with discontinuous bedding and high bioturbation.	16
	Well bedded dark grey to black clay with thin (mm scale) interbeds of sand/silt. Sand/silt 10 -35%.	19
	Lithologically similar to lithotype 19 but with discontinuous bedding and high bioturbation.	17
	Dark grey to black clay, commonly massive and plastic. Sand/silt less than 10% in lenticular beds and burrow fills.	14
	Carbonaceous dark grey to black clay. Generally fissile.	69
	Coal in beds thicker than 30 cm.	68
McMurray Formation/middle member	Coal beds thicker than 30 cm.	67
	Carbonaceous muds or clay/mud with carbonaceous laminae and/or thin coal beds.	[illegible]
	Lithologically similar to lithotype 50 but with root casts and minor bioturbation.	51
	Massive clay with less than 10% sand/silt.	[illegible]
	Clay/mud with very thin beds (mm scale) or laminae of sand. Sand/silt 10 - 35%.	21
	Lithologically similar to lithotype 21 but with high bioturbation.	22
	Interbedded (mm to cm scale) sand/silt and mud/clay. Sand beds homogenous or with ripple cross laminae. Bedding types include, even, flaser, lenticular and wavy parallel and non-parallel beds. Sand/silt 35 - 50%.	12
	Lithologically similar to lithotype 12 but with high bioturbation. Indistinct bedding.	13
	Interbedded (cm scale) sand/silt and mud/clay. Sand beds are homogenous or with small scale cross- bedding or can display the same features described for lithotype 7. Clay/mud and/or carbonaceous material 35 - 50%.	10
	Lithologically similar to lithotype 10 but with high bioturbation of the clay/mud interbeds.	9
	Fine to very fine grained, thick(dm scale) sand beds with thin (cm to mm scale) clay interbeds. Sand beds are massive and/or cross-bedded. May contain carbonaceous laminae, mud flasers, clay clasts, current ripples and parallel (horizontal) laminations. Clay and/or carbonaceous material 10 - 35%.	7
	Lithologically similar to lithotype 7 but with high bioturbation of the clay/mud interbeds.	8
	Fine to very fine grained, very thick (dm scale) sand beds, with or without clay/mud interbeds. Sand beds contain the same features described for lithotype 7. Clay/carbonaceous material < 10%.	11
	Chaotic mixture of clay/mud clasts in a homogenous sand matrix. Clay greater than 35%.	6
	Medium to coarse grained sand, pebbly sand with mud/clay drapes and/or clasts of estuarine origin. Occasional carbonaceous debris or laminae. Massive or cross bedded sand.	25
McMurray Formation/lower member	Conglomerate	78
	Coarse to very coarse sands and pebble/granule sands. Massive or cross bedded. May contain carbonaceous debris.	[illegible]
	Fine to medium grained sand, massive or cross bedded. May contain pebbles or granules and carbonaceous debris.	41
	Interbedded sand/silt and clay. Clay 15 - 30%.	[illegible]
	Lithologically similar to lithotype 74 but with high bioturbation of the clay/mud interbeds.	72
	Interbedded sand/silt and clay. Clay 30 - 50%.	[illegible]
	Lithologically similar to lithotype 76 but with high bioturbation of the clay/mud interbeds.	79
	Clayey sand/silt. Clay 15 - 30% dispersed throughout.	[illegible]
	Clayey sand/silt. Clay 30 - 50% dispersed throughout.	71
	Interbedded sand/silt and clay. Clay 50 - 70%.	[illegible]
	Lithologically similar to lithotype 87 but with high bioturbation of the clay/mud interbeds.	89
	Sandy/silty clay, sand/silt 30 - 50% dispersed throughout. May contain carbonaceous debris.	[illegible]
	Interbedded (mm to cm scale) sand/silt and mud/clay. Sand beds homogenous or with ripple cross laminae. Clay 70 -	83
	Lithologically similar to lithotype 83 but with high bioturbation. Indistinct bedding.	[illegible]
	Sandy/silty clay, sand/silt 15 - 30% dispersed throughout. May contain carbonaceous debris.	3
	Sand/silt and clay with chaotic bedding. May contain thin carbonaceous beds or debris.	[illegible]
	Pebbly clay.	75
	Coal in beds thicker than 30cm.	[illegible]
	Clay with abundant thin carbonaceous beds or debris. Commonly dark grey to black.	61
	Clay with occasional thin carbonaceous beds or debris and rootlets. Light colored or grey. Can be lightly burrowed, massive or laminated. Sand/silt 0 - 15%.	[illegible]
	Medium grey clay, can be massive, but more commonly containing less than 10% sand/silt in lenticular beds and laminae. Little or no carbonaceous material.	84
	Massive, high plastic and/or waxy clay. Commonly slickensided.	[illegible]
	Breccia.	66

Appendix B

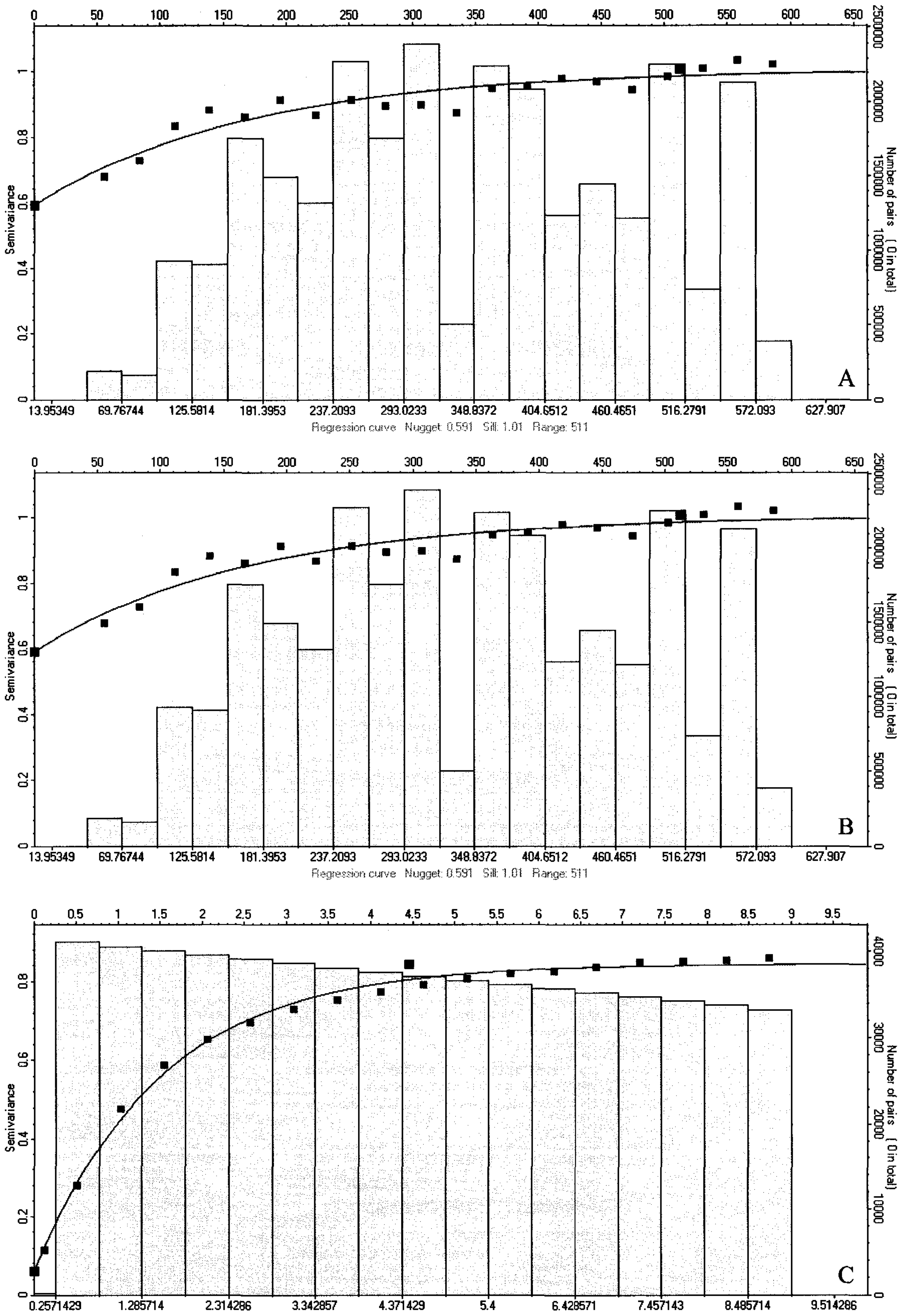
Variogram Results for the South and North Area



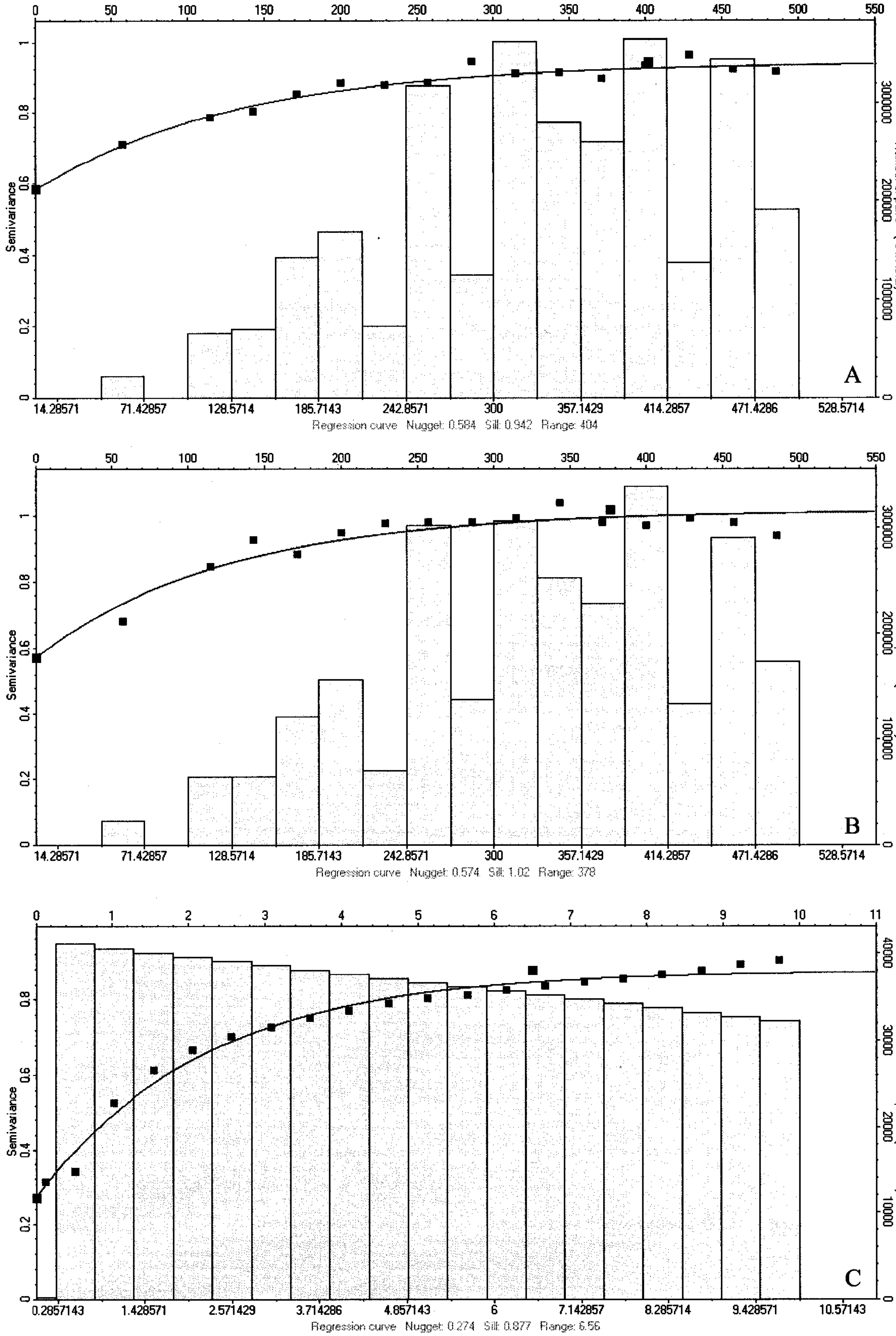
Facies 1 - South Variograms. (A) Major range, (B) Minor range, and (C) Vertical range



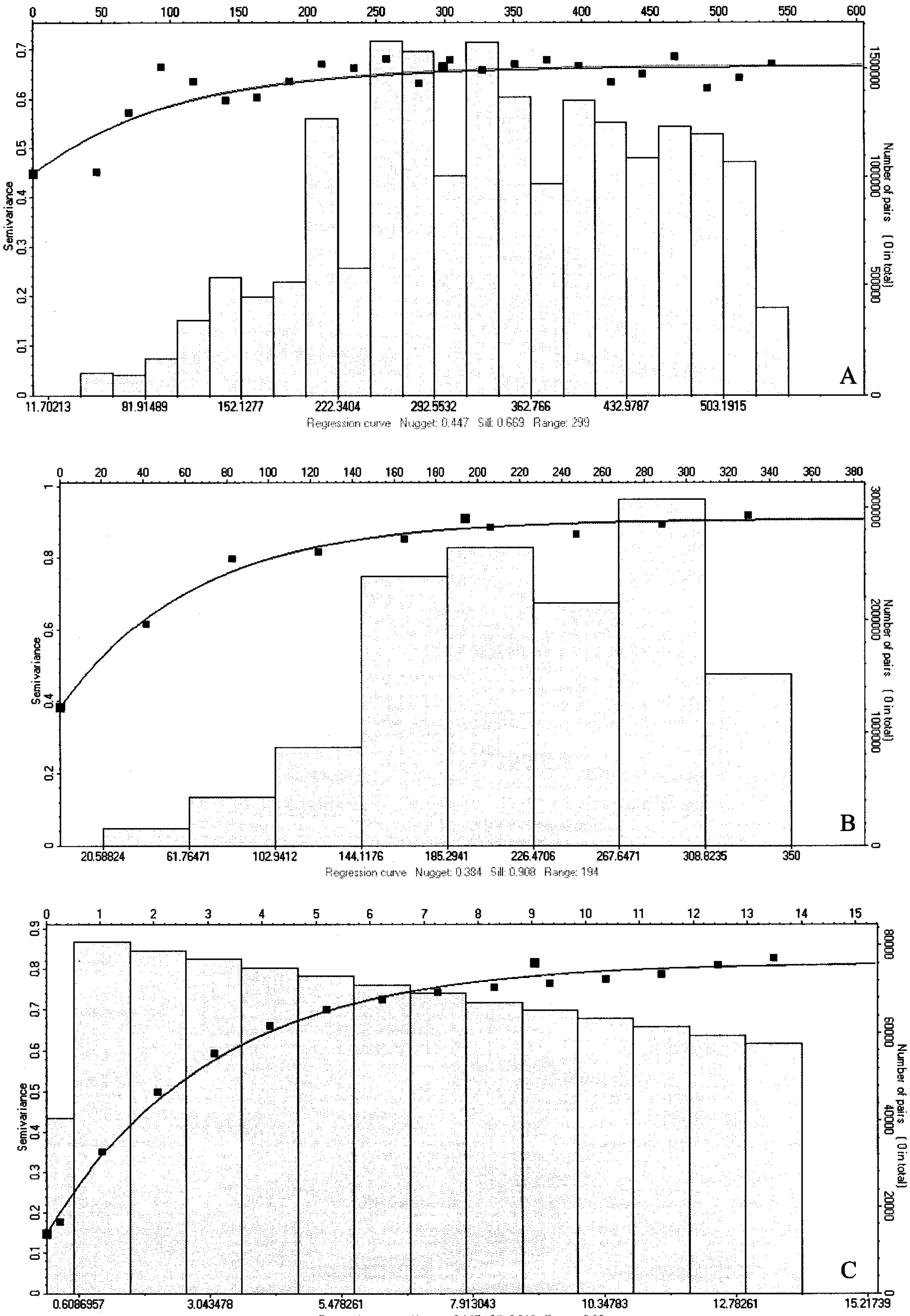
Facies 2 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



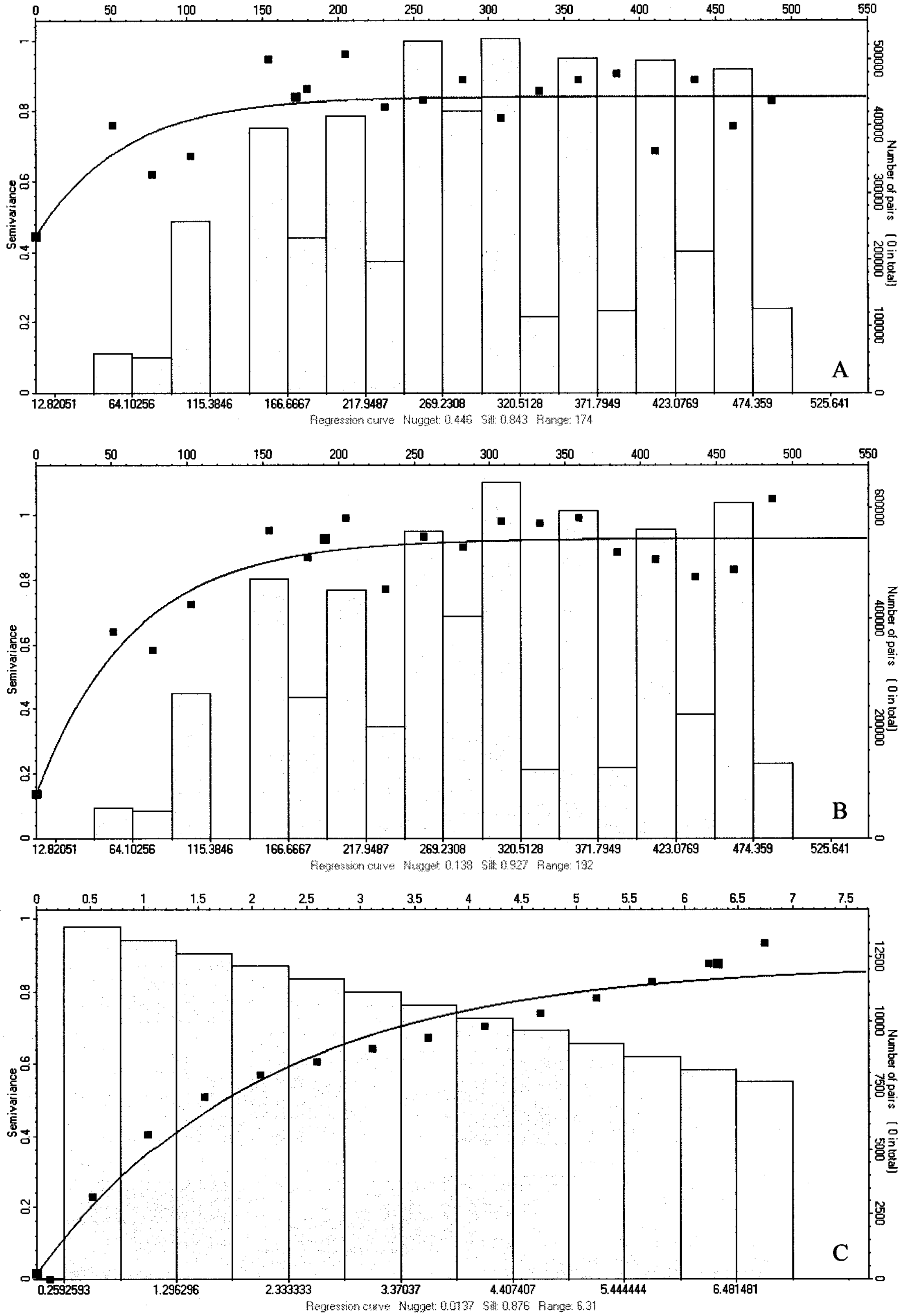
Facies 3 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



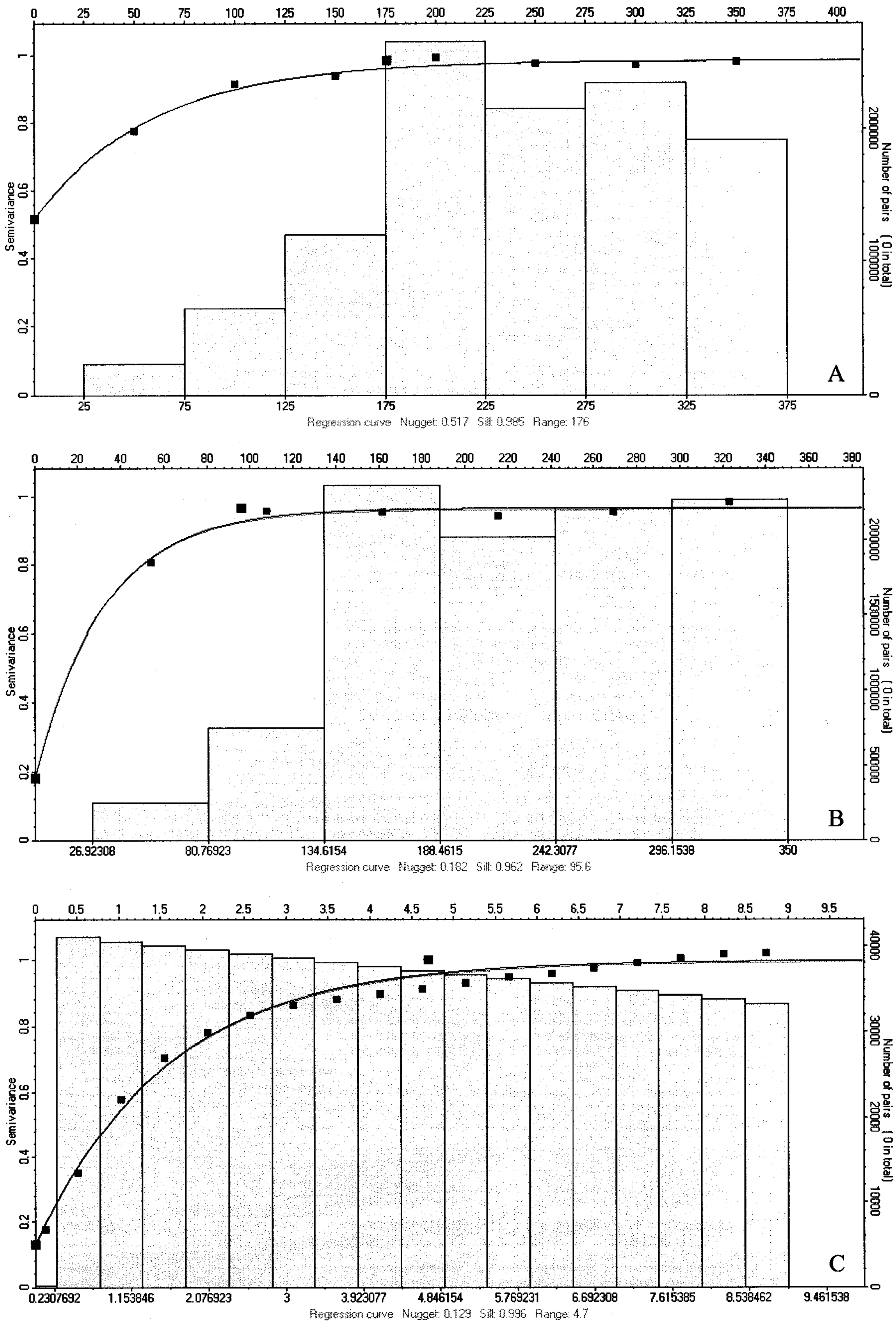
Facies 4 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



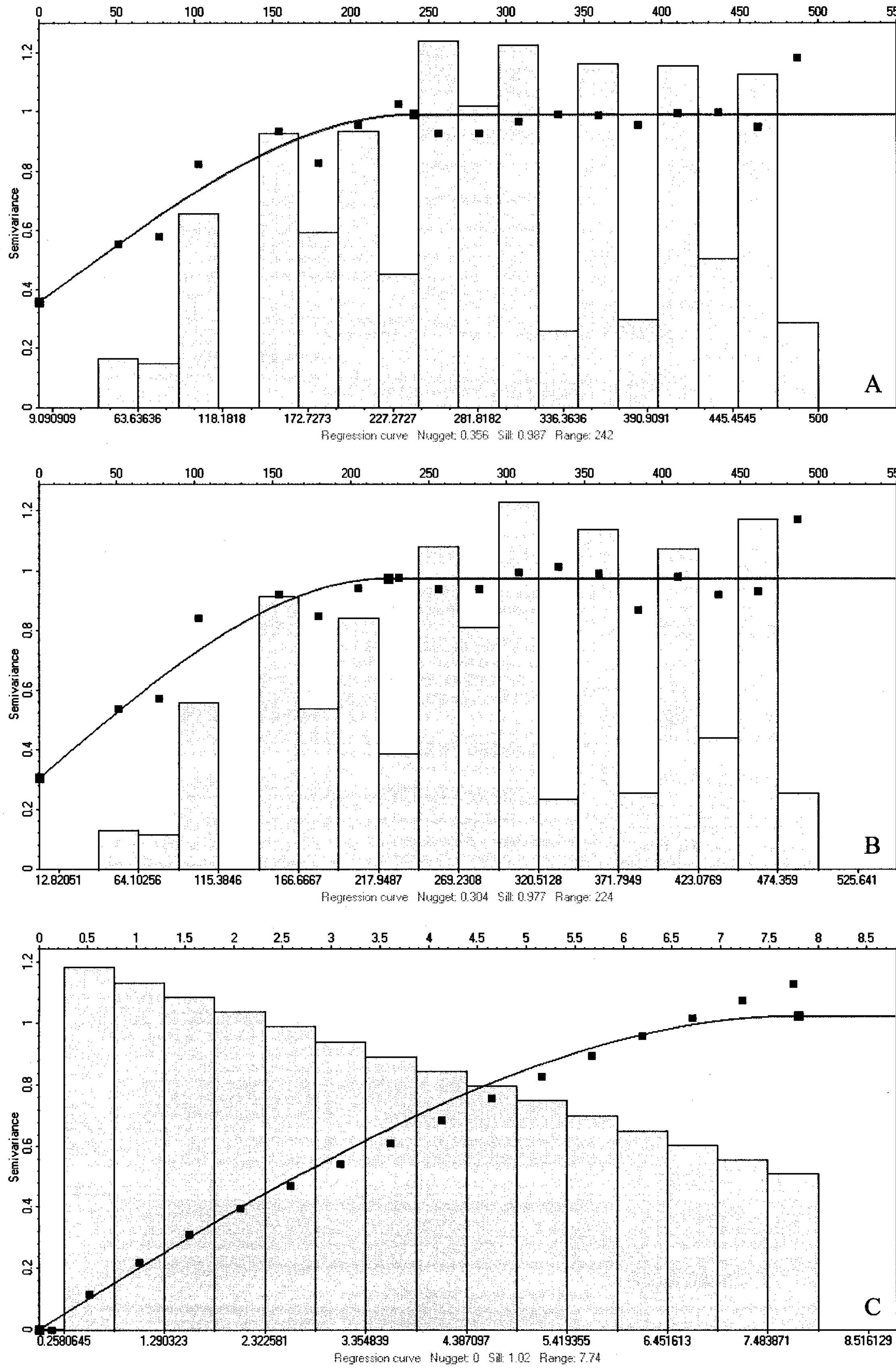
Facies 5 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



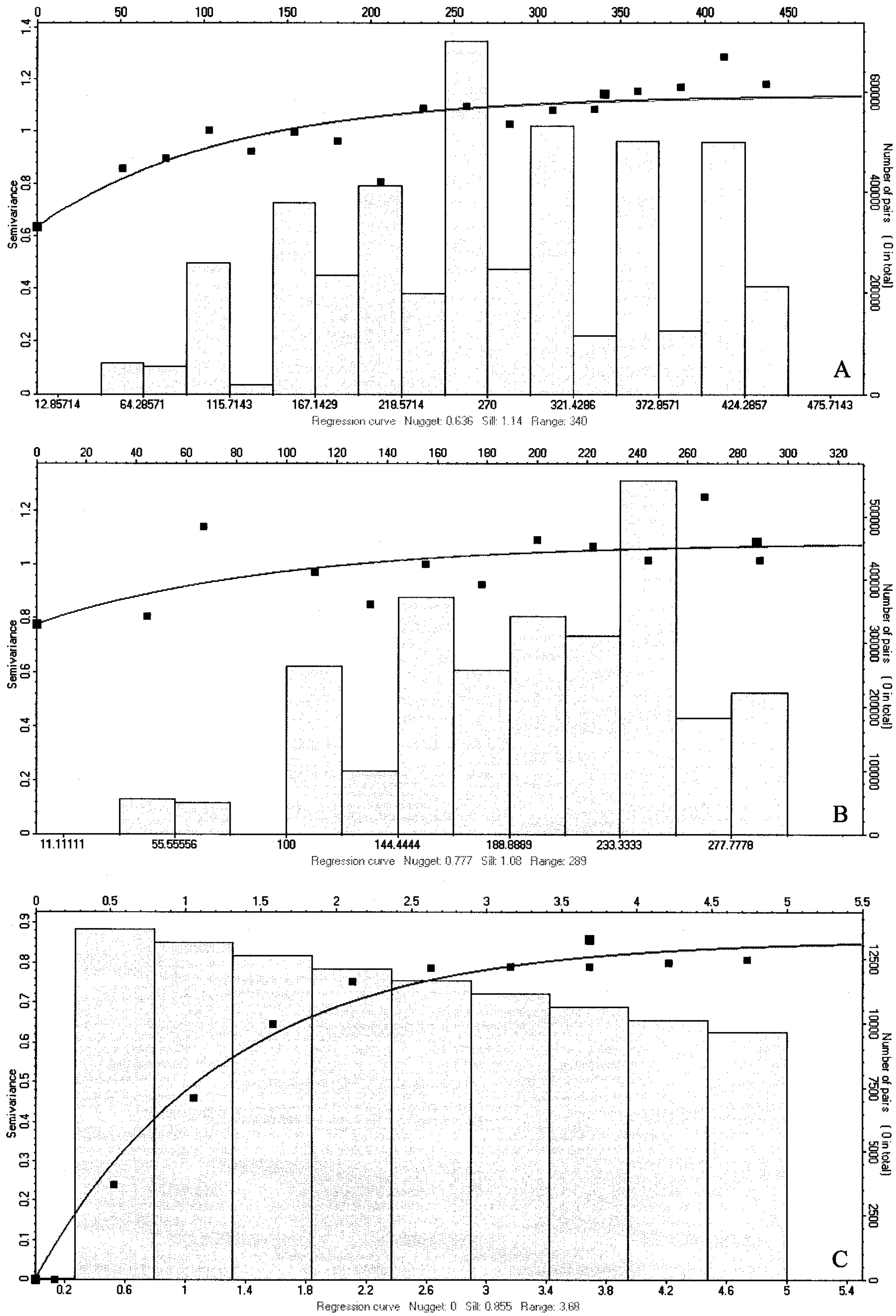
Facies 6 - South Variograms. (A) Major range, (B) Minor range, and (C) Vertical Range



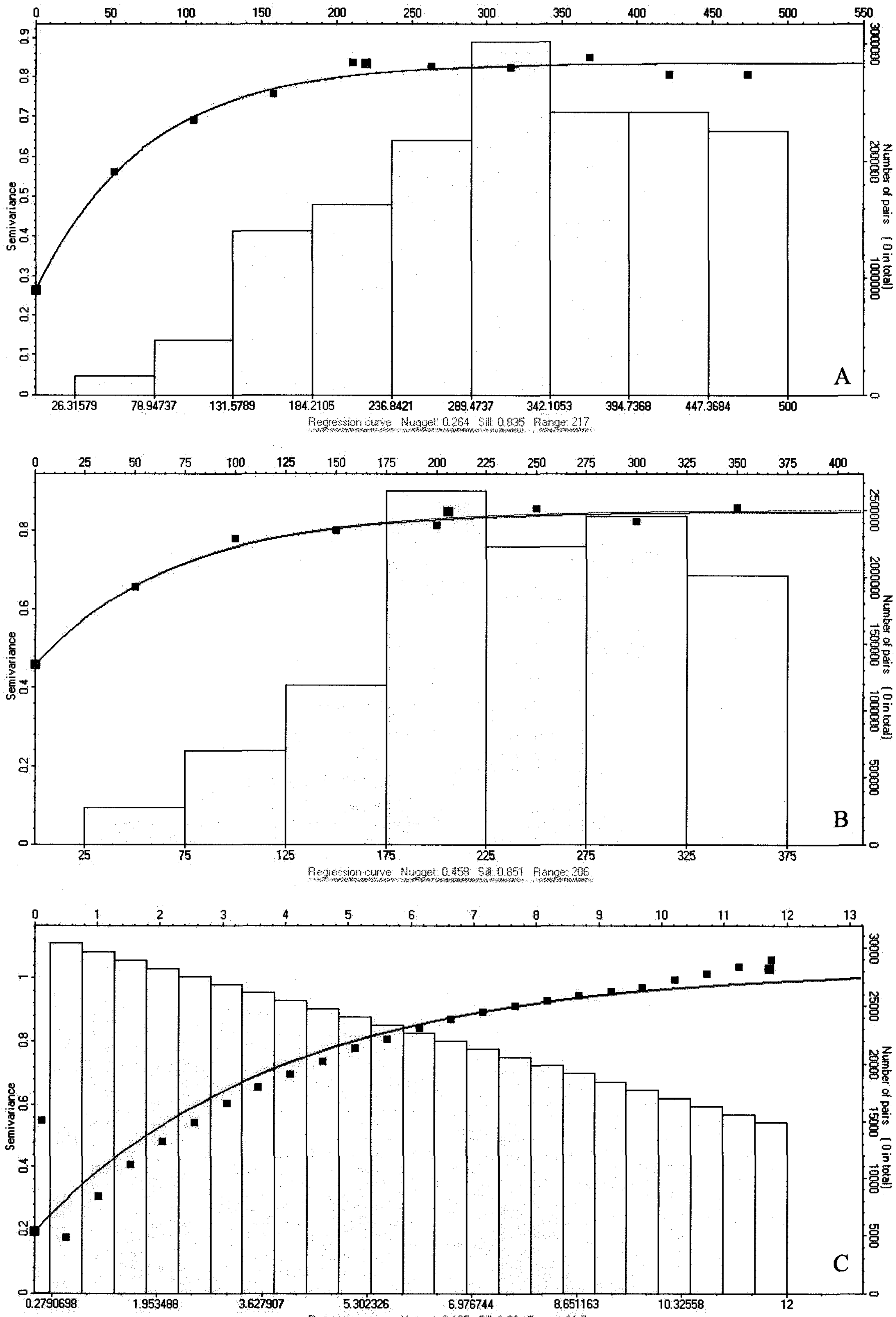
Facies 7 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



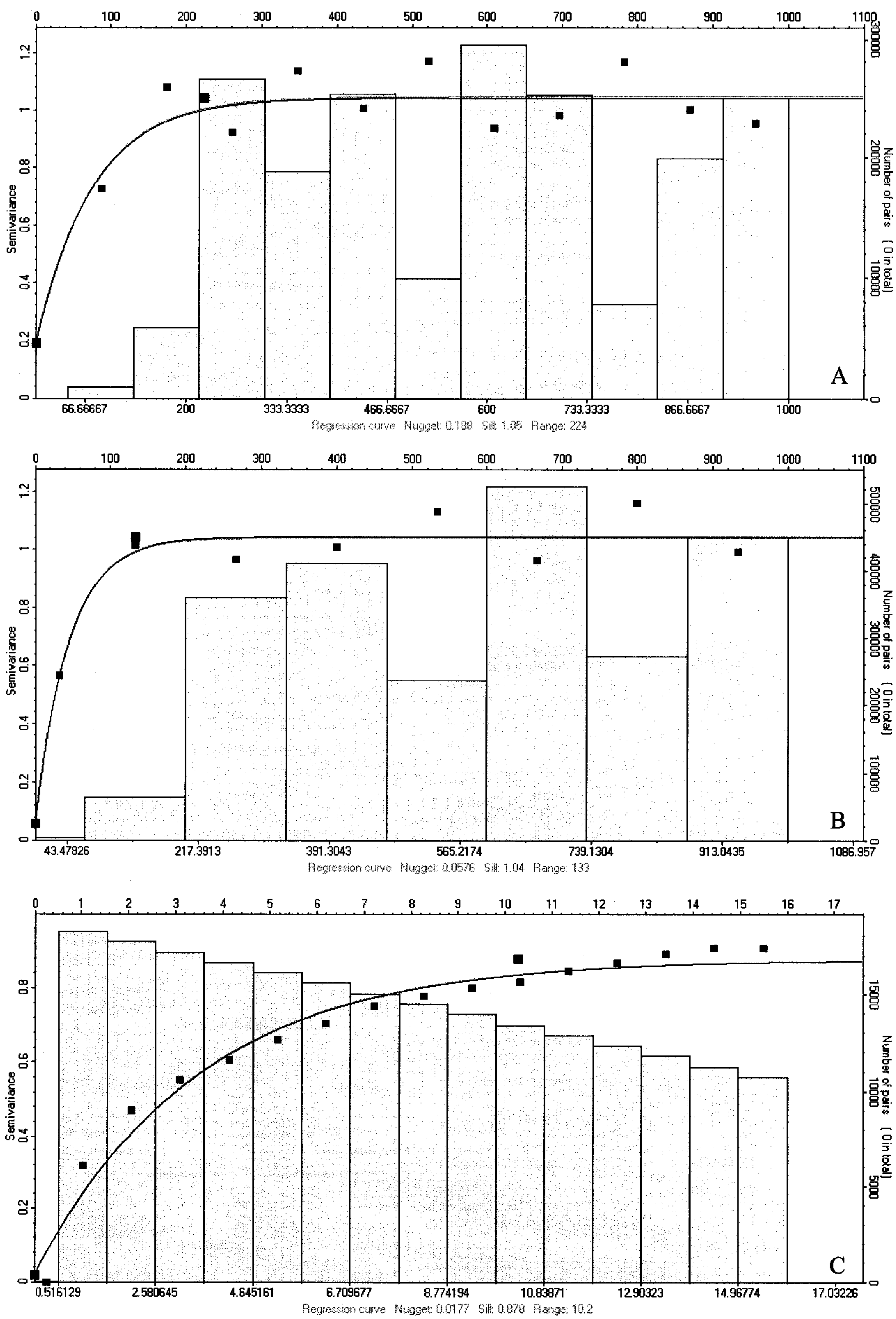
Facies 8 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



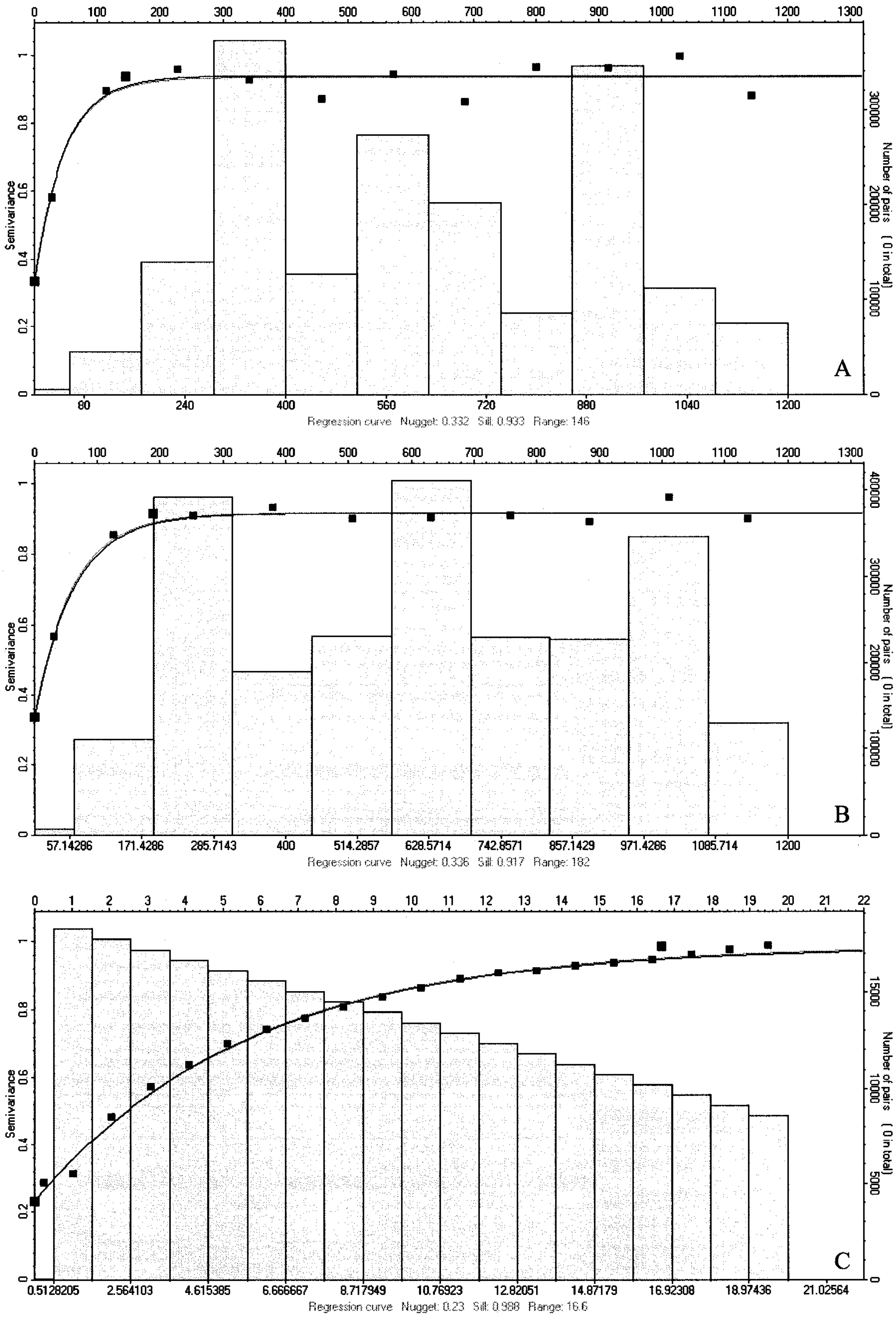
Facies 9 - South Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



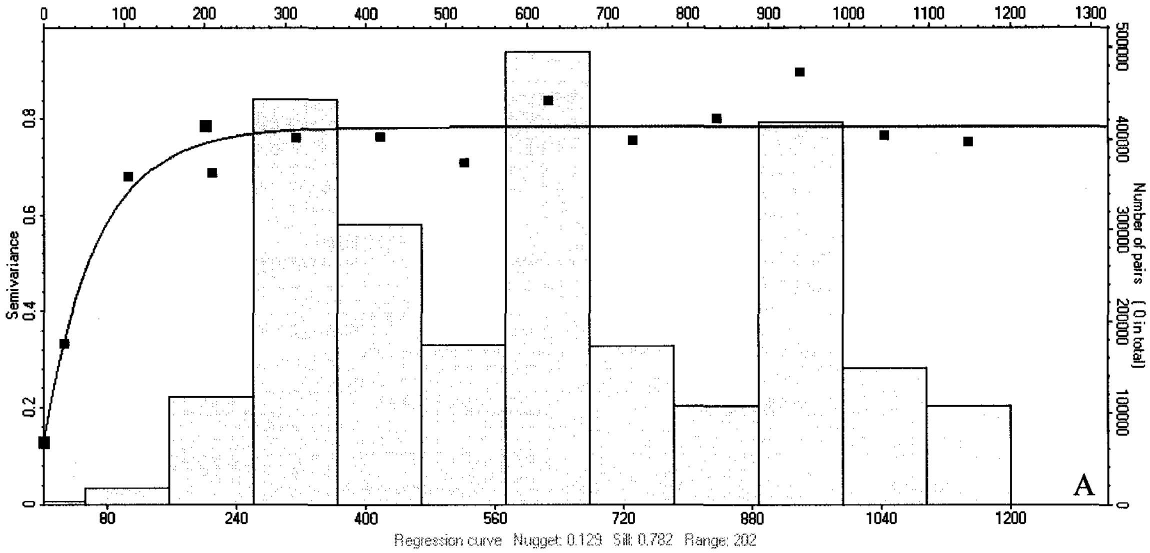
Facies 1 - North Variograms. (A) Major range, (B) Minor range, and (C) Vertical Range

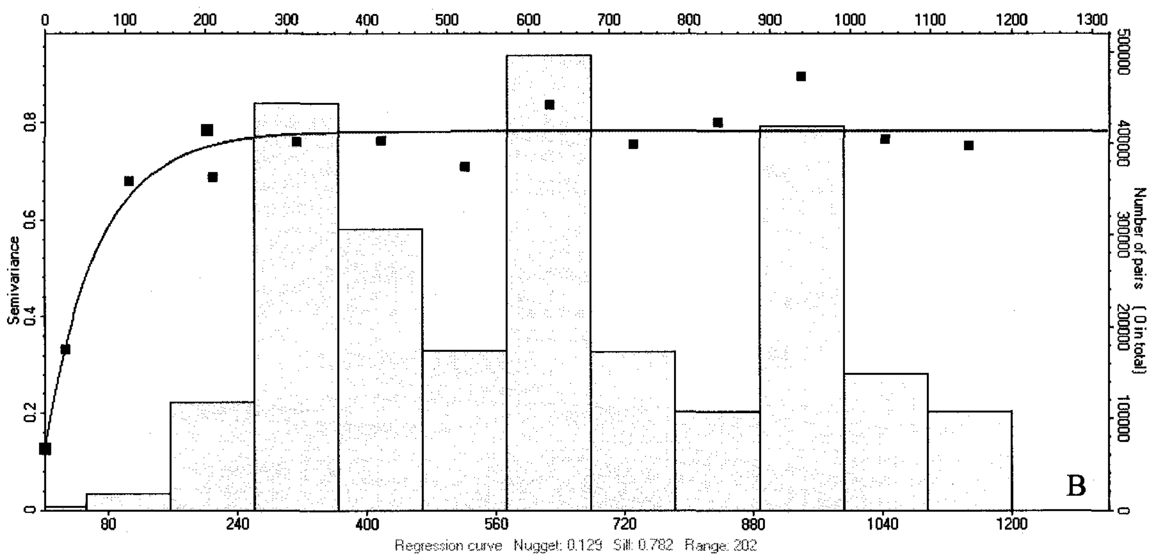


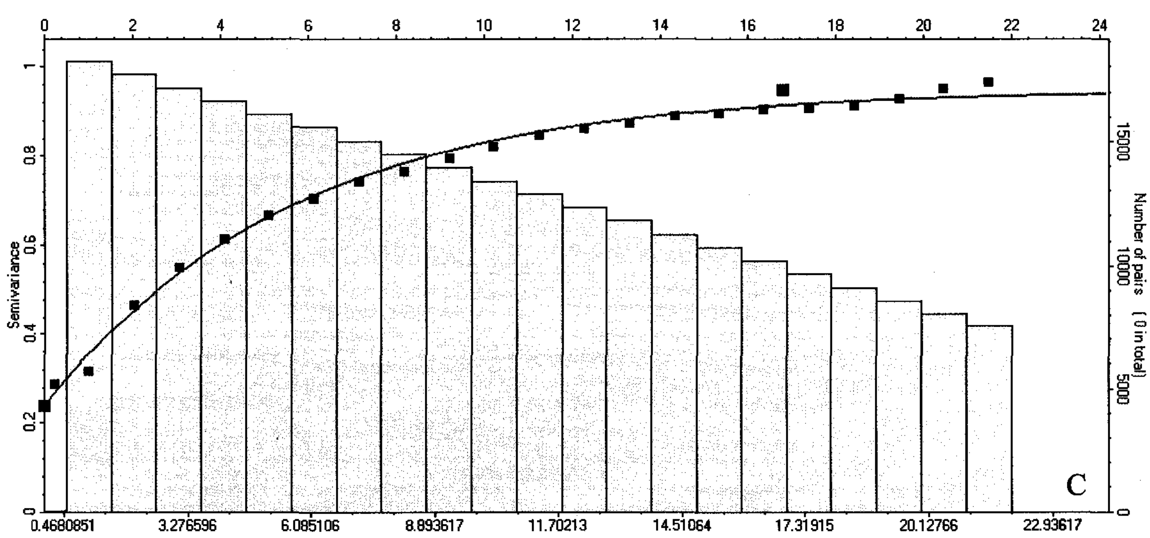
Facies 2 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



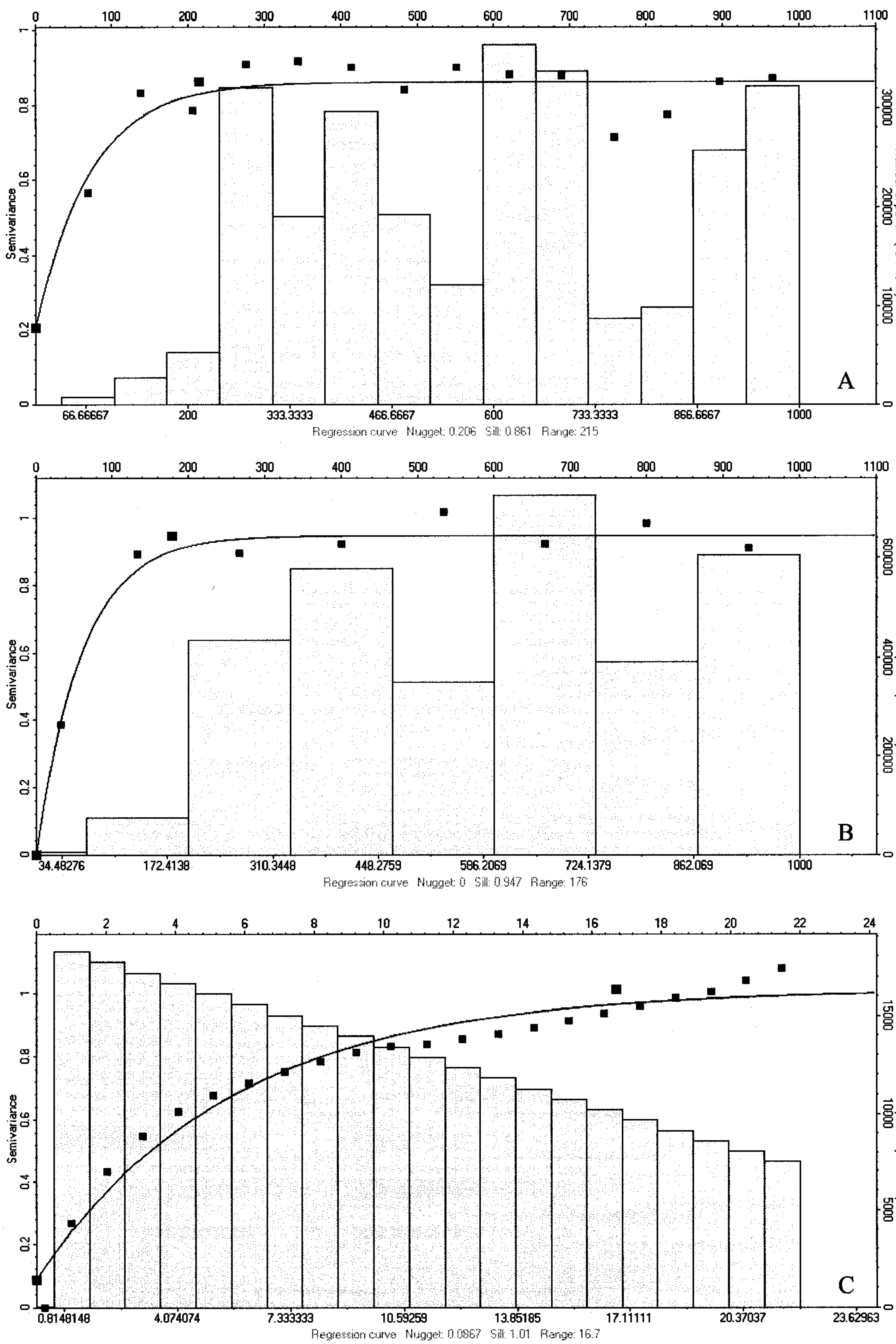
Facies 3 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



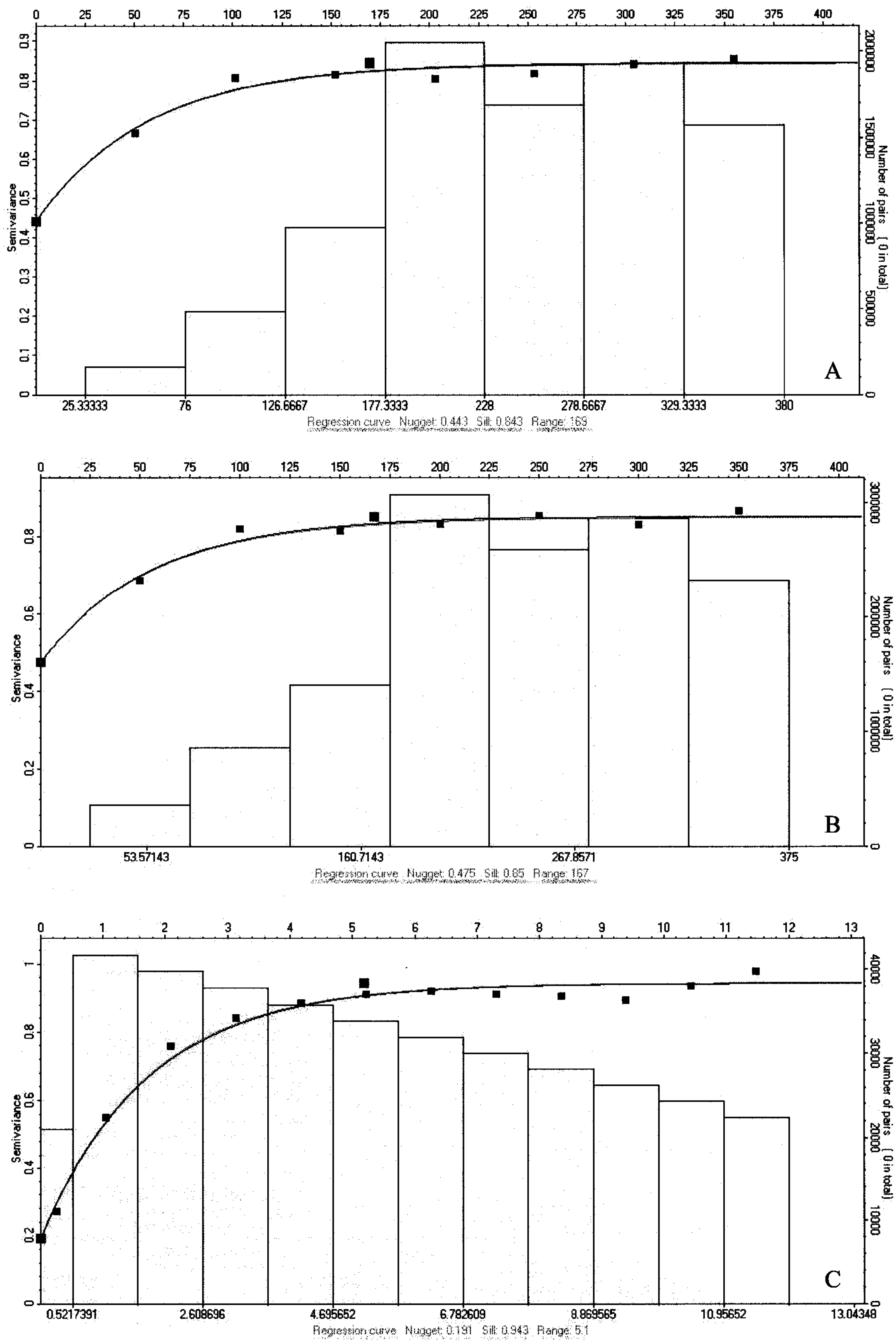




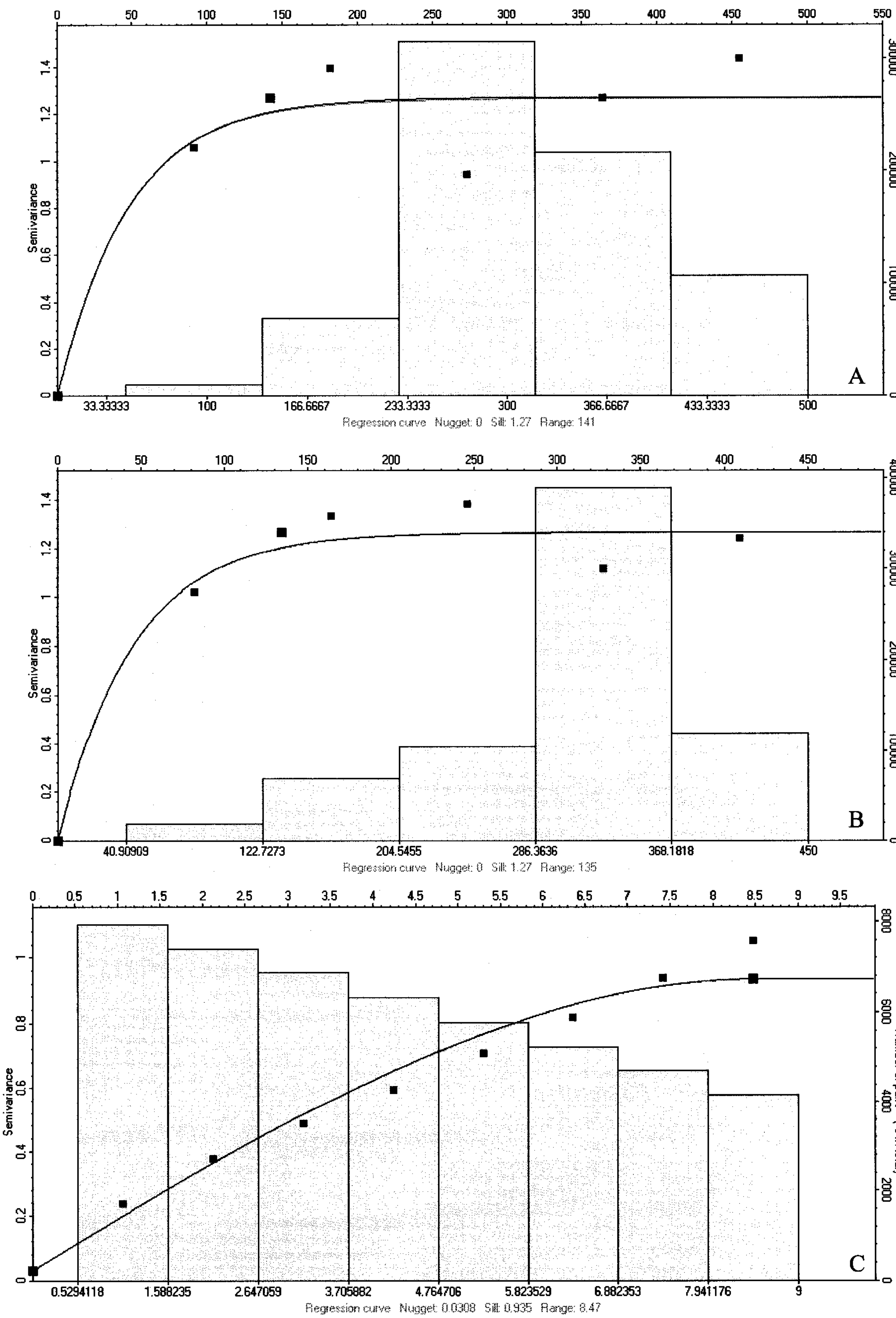
Facies 4 - North Variograms. (A) Major range, (B) Minor range, and (C) Vertical Range



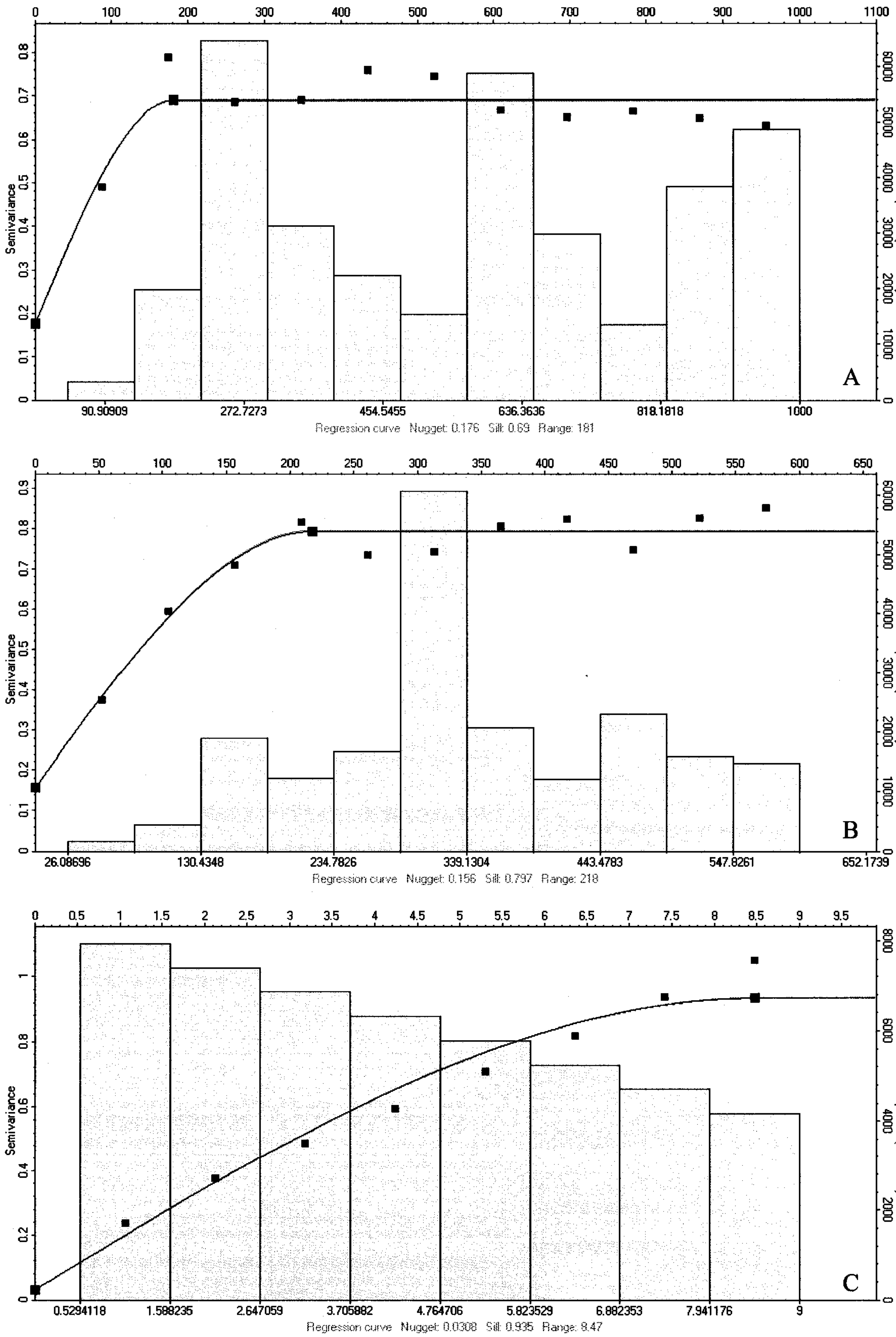
Facies 5 - North Variograms. (A) Major range, (B) Minor range, and (C) Vertical range



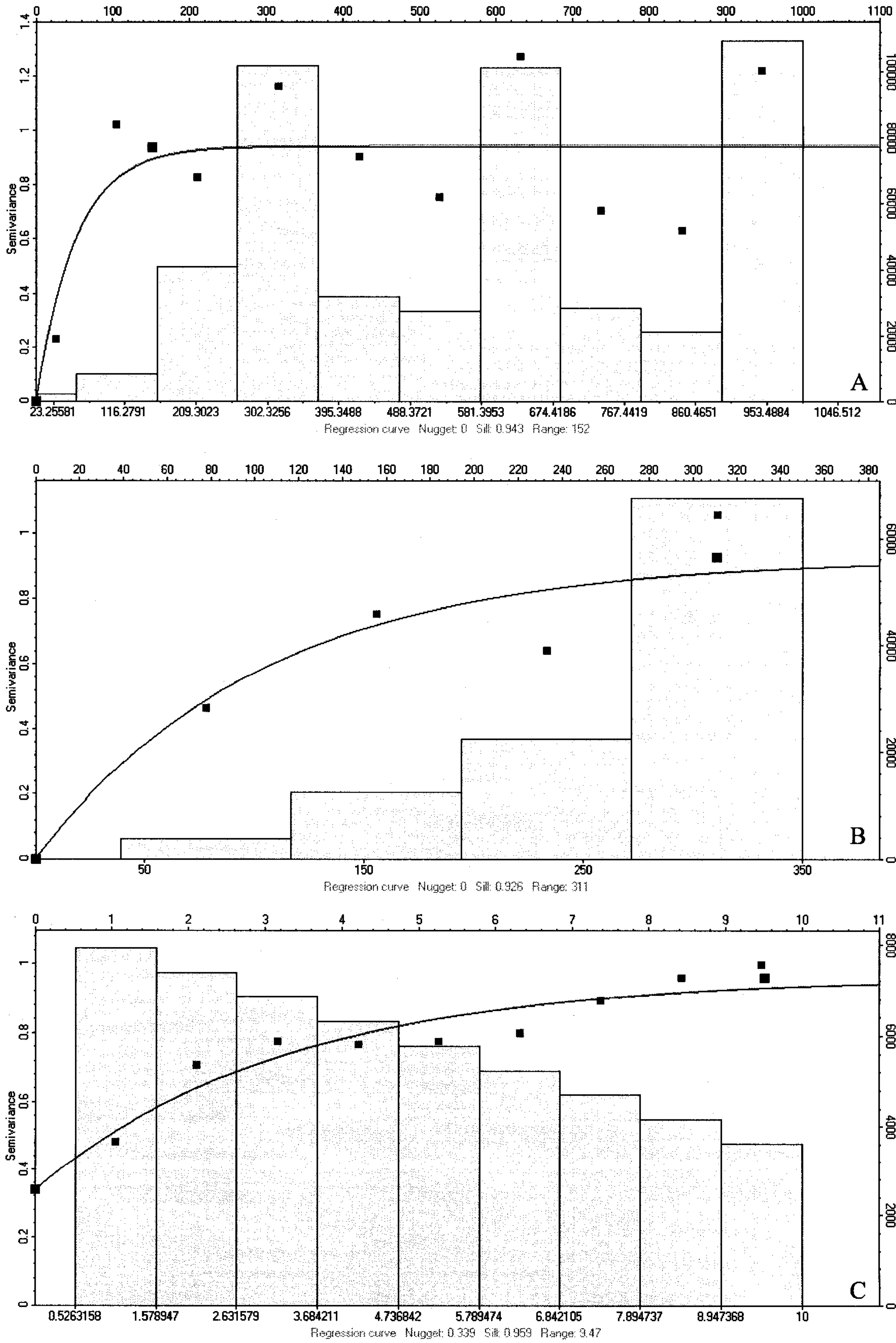
Facies 6 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical range



Facies 7 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



Facies 8 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range



Facies 9 - North Variograms. (A) Major range, (B) Minor Range, and (C) Vertical Range

Appendix C - Search Parameters for the Development from Variogram Analysis for the North and South Area

Search Parameters for Variogram Development for South Area									
Facies	Range	Orientation	Bandwidth	Thickness	Search Radius	Tolerance Angle	Lag Tolerance	Number of Lags	Lag Distance
1	vt	0	50		11	70	50	11	1
	mj	350	200	15	400	50	50	8	50
	mn	260	200	15	380	50	50	7	54.2
2	vt	350	50		12	70	50	24	0.5
	mj	350	200	15	700	50	50	24	29.8
	mn	260	200	15	550	50	50	22	25.6
3	vt	350	200		600	50	50	22	27.9
	mj	350	200	10	600	50	50	22	27.9
	mn	350	200	10	10	70	50	20	0.5
4	vt	350	200		10	70	50	20	0.5
	mj	350	300	15	500	50	50	18	28.6
	mn	260	300	15	500	50	50	18	28.6
5	vt	0	50		14	70	50	14	1
	mj	350	250	10	550	50	50	24	23.4
	mn	260	250	10	350	50	50	8	43.8
6	vt	350	50		7	70	50	14	0.5
	mj	350	200	15	500	50	50	20	25.6
	mn	260	200	18	500	50	50	20	25.6
7	vt	0	50		9	70	50	18	0.5
	mj	350	200	10	375	50	50	8	50
	mn	260	170	10	350	50	50	7	53.8
8	vt	350	50		8	70	50	16	0.5
	mj	350	200	15	500	50	50	20	25.6
	mn	260	200	15	500	50	50	20	25.6
9	vt	350	50		5	70	50	10	0.5
	mj	350	200	15	450	50	50	18	25.7
	mn	260	200	15	300	50	51	14	22.2

Search Parameters for Variogram Development North Area									
Facies	Range	Orientation	Bandwidth	Thickness	Search Radius	Tolerance Angle	Lag Tolerance	Number of Lags	Lag Distance
1	vt	0	50		12	70	50	24	0.5
	mj	350	200	15	500	50	50	9	55.5
	mn	260	200	15	375	50	50	7	53.5
2	vt	0	50		9	70	50	9	1.1
	mj	350	200	10	1000	50	50	12	87
	mn	260	200	10	600	50	50	12	52.2
3	vt	0	50		22	70	50	22	1
	mj	350	350	22	1000	50	50	15	69
	mn	260	350	22	1000	50	50	8	133.3
4	vt	0	50		18	70	50	18	1
	mj	350	300	18	500	50	50	6	90.9
	mn	260	300	18	450	50	50	6	81.8
5	vt	350	200		22	70	50	22	1
	mj	350	300	22	1200	50	50	12	104.3
	mn	260	350	22	1200	50	50	12	104.3
6	vt	0	50		12	70	50	12	1
	mj	350	250	15	380	50	50	7	54.3
	mn	260	300	15	375	50	50	7	53.6
7	vt	350	50		20	70	50	20	1
	mj	350	200	20	1200	50	50	11	114.3
	mn	260	200	10	1200	50	50	10	126.3
8	vt	350	50		10	70	50	10	1.1
	mj	350	200	10	1000	50	50	10	105.3
	mn	260	200	20	350	50	51	5	77.8
9	vt	350	50		10	70	50	10	1.1
	mj	350	200	15	500	50	50	20	25.6
	mn	260	200	18	500	50	50	20	25.6

Appendix D

Computer Harware and Model Block Properties

Computer Hardware
Processor: Dual-core at 2.8GHz with 2x2MB L2 cache or single-core 64-bit Intel® processors
Memory: 1 Gigabyte dual-channel DDR2 400MHz SDRAM memory
Graphics Card Memory: 512 MB

Model Block
Petrel Workflow Tools 2005
Approximate Number of Cells for North Area = 1 764 000
Average cell dimensions for North Area = 75 m x 75 m x 0.5 m (length x width x thickness)
Approximate Number of Cells for South Area = 1 985 000
Average cell dimensions for South Area = 75 m x 75 m x 0.5 m (length x width x thickness)
Average Run Time Per Realization: 37 hours