2014-04-28

Gamma ray normalization and Regional Fluvial Architecture: The Paleocene Paskapoo Formation, Alberta

Quartero, Erik

UNIVERSITY OF CALGARY

Gamma ray normalization and Regional Fluvial Architecture: The Paleocene Paskapoo Formation, Alberta

By

Erik Quartero

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTERS OF SCIENCE

GRADUATE PROGRAM IN GEOLOGY AND GEOPHYSICS

CALGARY, ALBERTA

APRIL, 2014

Abstract

The Paskapoo formation is composed of several hundred meters of heterogeneous fluvial strata that were deposited in the subsiding foreland basin of the Canadian Cordillera. The Alberta government require the gamma ray log from petroleum wells to be collected through this formation. The first step in utilizing this new data is to correct for the suppressive effect that surface casing has on the natural gamma ray response. A simple and efficient method was used to normalize the gamma ray data collected through surface casing. The method adjusts the cased gamma ray values so that the maximum and minimum of the distribution are equal to those of non-cased values. Net-to-gross maps and stratigraphic cross-sections identify a megafan/DFS in the north and variation in the fluvial stratigraphy across the study area. Tectonic activity is interpreted as the primary control on fluvial stratigraphy, controlling the variable ratio of sediment flux to accommodation creation.

Preface

Chapter 2

Quartero, E. M., Bechtel, D., Leier, A.L., and Bentley, L. R, 2014. Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta. Canadian Journal of Earth Science, vol 51, pp. 327-340

Chapter 3

Quartero, E. M., Leier, A.L., Bentley, L. R., and Glombick, P., 2014, Basin-scale stratigraphic architecture and Paleocene distributary fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada. In preparation for submission to Sedimentary Geology

Acknowledgments

I would like to thank the Alberta Geological survey and the Alberta Energy Regulator for their continued support and partnership with this project, in particular; David Bechtel for developing the methodology and work flow demonstrated in Chapter 2, and for his guidance in the manuscripts drafting process; Paul Glombick for his help and guidance with the work flow and methods used in Chapter 3; Laurence Andriashek and Dan Palombi for their efforts in maintaining a good working partnership between the AGS and University of Calgary.

I would also like to thank my supervisors Larry Bentley and Andrew Leier, for their patient support and guidance during my graduate studies. I would also like to Thank Stephen Hubbard and Per Pedersen for their open door and advice, and Philip Sokol for being a motivated and helpful field assistant.

I would like to acknowledge IHS (Information Holding Systems) for providing software licence to the University of Calgary and to Kris Canivet for being extremely helpful and available for any questions regarding data acquisition, and the IHS software.

I would like to express my thanks to my family and close friends for their support and encouragement, and to Anna for her love and care over that past three years.

TABLE OF CONTENTS

Abstract…………………………………………………………………………………...ii

Preface………………………………………………………………………………………iii

Acknowledgments……………………………………………………………………..…iv

Table of Contents……………………………………………………………………….....v

CHAPTER ONE: Introduction…………………………………………………………………1

CHAPTER TWO: Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta……………………………………………………...19

CHAPTER THREE: Basin-scale stratigraphic architecture and Paleocene distributary fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada……………………………………52

CHAPTER FOUR: Conclusions…………………………………………………………………95

CHAPTER ONE: Introduction

The Paskapoo Formation is Alberta's most important aquifer with some 64 000 water wells, one third of all water wells in Alberta (as of 2006), completed within this formation (Grasby et al. 2008). The Paskapoo covers a regional extent of 65 000 km^2. The majority of water wells in the Paskapoo Formation are situated in the Red Deer-Calgary corridor (Grasby et al. 2008). The province of Alberta has seen the highest rate in population growth for the past several years with 2.37 % growth in 2012. This has been a continuing trend since 2007 with inflow of interprovincial migrants (Quarterly Population Report 2012). The high annual population growth and a hold on licenses for surface water extraction are placing a greater demand on groundwater resources (Grasby et al. 2008). This stress on ground water systems is exacerbated by new water intensive oil and gas drilling and production operations. Current regional modeling techniques rely on data from water well records and petroleum well logs of the lower Paskapoo Formation, below the surface casing (Grasby et al. 2008; Lyster and Andriashek 2012). What is needed is a greater understanding of the subsurface geology and heterogeneity of the Paskapoo Formation to better inform these hydrogeologic models. Water well records contain qualitative reports of lithology during drilling. The water well driller does not take regular interval samples but rather records major changes in lithology (Lyster and Andriashek 2012). Quality of water well logs is heavily dependent on the driller's observations, ability, and familiarity with the geologic setting. The natural gamma ray response collected from oil and gas wells record a high resolution response of the naturally emitting gamma radiation of the subsurface strata (Rider and Kennedy 2011). The gamma ray response is correlated with grain size and clay content, in clastic sediments. Low gamma ray values is associated with coarser grained sandstones and coals, and higher API readings are associated with fine-grained muds and shales (Rider and Kennedy 2011). The gamma ray not only tracks approximate grain size/clay but alongside additional logging tools can provide lithological and facies information. As of December 1, 2006, the Government of Alberta mandated that wire-line log readings (e.g., natural gamma-ray) must be collected to surface. This mandate has resulted in a flood of new near-surface geophysical well log data that have the potential to improve our understanding of the poorly mapped near-surface stratigraphy of the WCSB. Motivation for this well-logging requirement came from growing public concern over the future of shallow aquifers which are under stress from both a growing population and oil and gas activities (Hamblin 2004; Lyster and Andriashek 2012; EUB 2006). The near surface gamma ray log however is run through the surface cased interval. Surface casing is steel casing that is cemented in place for wellbore stability, improved mud circulation, and to protect aquifers from oil and gas related contaminates. The surface casing suppresses the natural gamma ray response, generating a gamma curve that is not suitable for conventional correlations. Chapter two demonstrates a method for gamma-ray normalization of the cased zone, so that the curve is then suitable for correlative efforts. The workflow is described in detail and normalized logs are used to generate generic stratigraphic section of the near surface Paskapoo Formation. The normalized gamma ray response may improve regional models that previously relied on qualitative water well records. The new data also provides a unique look at a quantitative three dimensional data set to characterizing the regional fluvial stratigraphy. Characterizing the three dimensional distribution of aquifers is a first-order requirement for assessing and predicting groundwater resources (Burns et al. 2010). This is particularly important for the heterogenic Paskapoo Formation, which is composed of complex arrangement of fluvial sandstone bodies encased in finer grained mudstone and siltstone (Demchuk and Hills 1991; Lyster and Andriashek 2012). The objective of the thesis is to present a viable method for the normalization of the natural gamma ray response run through the surface casing interval. The normalization methodology is presented with applications to the Paleocene Paskapoo Formation. However it is the goal of the thesis to present a methodology with potential applications to cased gamma-ray well log data in many areas. The resultant normalized curve would then suitable for conventional correlative efforts. To demonstrate the utility of the normalized curve, net-to-gross maps and stratigraphic sections are used to analyse the Paskapoo's fluvial architecture. This is in attempt to provide an improved regional fluvial model for the northern portion of the Paskapoo Formation.

Background

Foreland basin

The Cordilleran foreland basin is one of the most intensely studied basins in the world (Mclean and Jerzykiewicz 1977; Leckie and Smith 1992; Price 1994; Hamblin 2004). It was formed in response to crustal loading resulting from folding and thrusting during the Cordilleran Orogeny. This involved both accretion of terranes and east-verging thrusting of early Paleozoic-Mesozoic strata. This foreland basin stage is thought to have occurred from the Late Jurassic to early Eocene, near the end of which time the Paskapoo Formation was deposited (Price 1994). The late stage basin fill of the Paskapoo Formation is believed to have occurred during early to late Paleocene (Demchuk and Hills 1991). The foreland basin strata deposited during the Late Jurassic to Paleocene is thought to have a provenance associated with the igneous rocks of the Omineca Crystalline belt and sedimentary rocks of the Rocky mountain belt (Mack and Jerzykiewicz 1988). It is likely that there was thrusting occurring during the early Paleocene along the eastern margin of the orogeny. Sediments of the Late Jurassic to Paleocene were deposited in shallow marine and non-marine settings, and by Paleocene time the marginal seaway of the foreland basin had regressed. The Paskapoo's deposition in the foreland basin is believed to be entirely non-marine (Mack and Jerzykiewicz 1988, Leckie and Smith 1992). Climate during this time is thought to be variable between the southern and central portions of the basin (Jerzykiewicz and Sweet 1987). Lack of coal and diversity in palynological assemblages indicate a semi-arid climate to the southern portion of the foreland basin. A more humid environment is consistent with the coals and palynomorphs in the central/northern portion of the basin. This trend was found to be consistent throughout all the Upper Cretaceous and Paleocene strata of the Western Canadian Foreland Basin (WCFB) (Jerzykiewicz and Sweet 1987).

Paskapoo Formation

The Paskapoo Formation is a 0-800m thick heterogeneous fluvial unit that forms an asymmetric wedge in the WCSB (Beaumont 1981; Cant and Stockmal 1989; Demchuk and Hills 1991; Leckie and Smith 1992; Price 1994; Jerzykiewicz 1997; Lyster and Andriashek 2012). The formation was deposited in response to Cenozoic uplift and transport of sediment into the subsiding foreland basin, and covers an approximate area of 65,000km^2 (Mclean and Jerzykiewicz 1977; Beaumont 1981; Cant and Stockmal 1989; Leckie and Smith 1992; Price 1994; Hamblin 2004; Grasby et al. 2008). The formation is commonly delineated into three members; the Haynes, Lacombe, and Dalehurst members (Fig. 1). The basal Haynes Member has a maximum thickness of 100 m near the deformational edge of the basin, and averages approximately 50 m in thickness throughout the basin (Demchuk and hills 1991; Lyster and Andriashek 2012). This member is characterized by its amalgamated massive coarse-grained sandstones and stacked multi-story fluvial channel deposits (Demchuk and Hills 1991;

Jerzykiewicz 1997; Hamblin 2004). Palynology of the Haynes member indicated that it is Paleocene in age (Fox 1990, Lerbekmo 1990, Demchuk and Hills 1991).

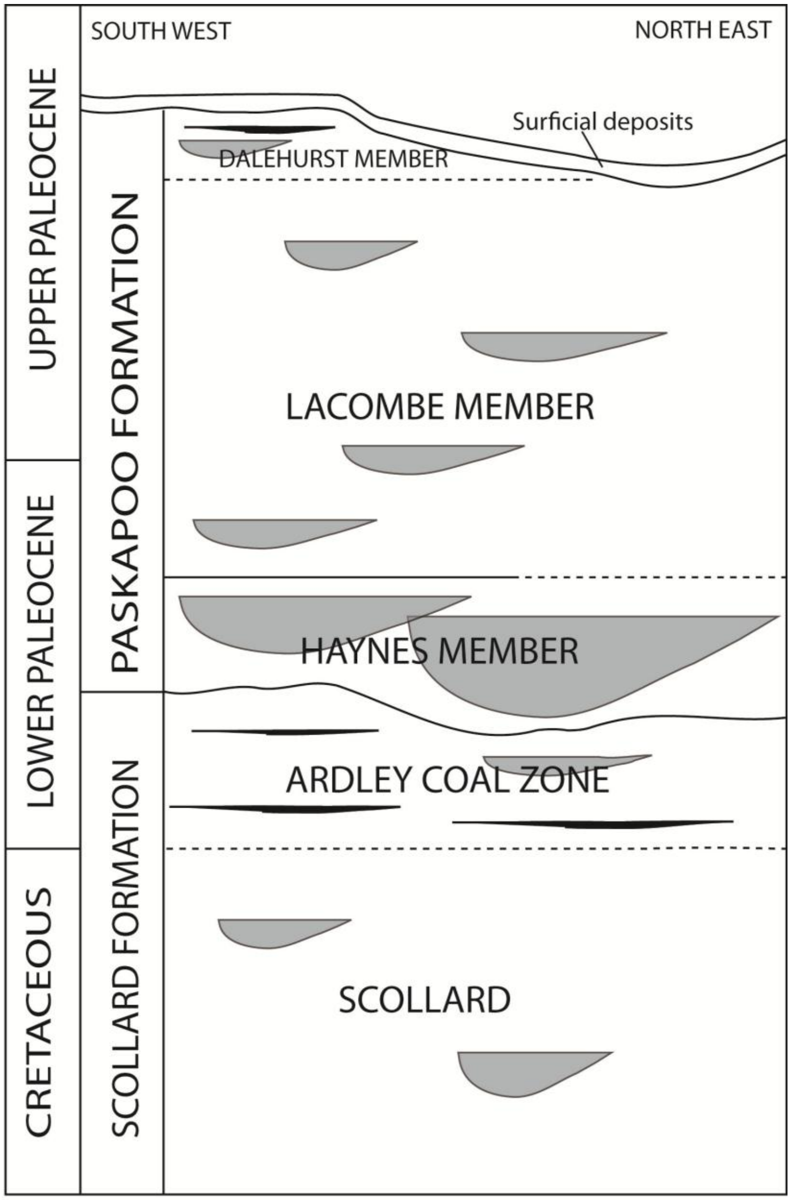


Fig. 1: Stratigraphic column as described by Demchuk and Hills 1991. The basal boundary between the Ardley coal zone and the Haynes is poorly understood. The majority of the section is comprised of fine silts and muds, with isolated and stacked channel sequences. Coal is found within the Ardley coal zone and the upper portion of the Dalehurst member. Section proposed by both Demchuk and Hills, 1991, and Lyster and Andriashek, 2012

The classical definition for the base of the Haynes Member, and by extension the Paskapoo Formation, is the first prominent sandstone above the uppermost significant coal seam within the underlying Ardley coal zone of the Scollard Formation (Gibson 1977; Demchuk and Hills 1991; Dawson et al 1994). This surface is interpreted to be an unconformable erosional contact with an estimated hiatus of 1-2 million years (m.y) (Lerbekmo et al. 1992, 2008).

The Lacombe Member comprises the majority of the Paskapoo Formation and is characterized by heterogeneous siltstone and mudstone beds with isolated, fine-grained sandstone channel deposits (Demchuk and Hills 1991; Lyster and Andriashek 2012). The Lacombe Member has a maximum thickness of roughly 500 m at the deformational edge of the basin and tapers out away from the mountain front. The siltstones, mudstones, and shales have few sedimentary structures but contain abundant plant fragments and pedogenic structures (Demchuk and Hills 1991; Dawson et al 2008; Lyster and Andriashek, 2012). The isolated sandstone bodies are very-fine to medium grained (Demchuk and Hills, 1991). Based on vertebrate paleontology and palynology, the Lacombe Member is interpreted as late Paleocene in age (Krause 1978; Demchuk 1990; Fox 1990).

The uppermost unit is commonly referred to as the Dalehurst Member and consists of fine-grained sandstone beds interbedded with siltstone mudstone, shale, and coals (Demchuk and Hills 1991). This unit is classified from reference core taken near the town of Hinton, and its regional extent is limited. The Dalehurst Member extent is unknown and is assumed to be restricted and confined to the northern portion of the study area near Hinton. The Dalehurst is distinctive from the Lacombe with thick economic coals and coarser grained sand (Demchuk and Hills 1991).The coal seams indicate a minimum burial depth and exhumation of approximately 2 km of overburden from erosion (Demchuk and Hills 1991; Hamblin 2004). The Dalehurst contains many of the same palynological assemblages as the Lacombe member, although certain missing palynomorphs of the lower Paleocene may indicate that the Dalehurst is marginally younger then the upper Lacombe (Demchuk 1990, Demchuk and Hills, 1991).

Gamma Ray Logs

Conventional normalization work flows are done to correct for tool bias which may be the result of discrepancies in the calibration of the gamma ray tool. During conventional gamma ray normalization maximum and minimum percentile constants are either derived from a type well log, or average values from across a study area (Shier 2004). The advantage of conventional normalization is that the constants are derived from a horizon or section of log that is also being normalized, i.e. the values are known to be representative of the formation or horizon. The methodology used for normalizing the cased zone is unique in that the constants are derived from what is considered analogous strata below surface casing. The gamma ray normalization relies on a simple normalization equation (equation 1). The terms $\overline{\mathrm{UP95}}$ and $\overline{\mathrm{UP2}}$ are derived from the zone that lies directly below surface casing, and represent the 95th and 2nd percentile of API values of the uncased zone. The uncased zone extends from the base of the surface casing to the base of the Ardley coal zone. The normalization equation results in a shift to higher overall API values and the variance of the distribution is increased. This results in the distribution of the cased zone to have approximately the same spread in the API values as that from the uncased zone.

$$\text{Normalized Value} = \overline{\mathrm{UP2}} + \text{Cased Value} - \mathrm{CP2} * \frac{\overline{\mathrm{UP95}} - \overline{\mathrm{UP2}}}{\mathrm{CP95} - \mathrm{CP2}} \qquad \text{Eq. [1]}$$

The Gamma ray curve is heavily relied upon for conventional correlative efforts when looking at the subsurface geology. Many previous studies supplement gamma ray with other geophysical well log data and reference core (Shier 2004; Cluff and Cluff, 2004; Medina and Rupp, 2012). The normalized gamma ray curve is suitable for regional correlative efforts, but with only the normalized gamma ray, detailed correlative efforts are limited.

The normalized gamma ray represents a regional three dimensional data set for the fluvial architecture of the Paskapoo Formation. While detailed elements of fluvial channels cannot be derived from gamma ray alone, the data may be used to analyze sediment distribution and stratigraphic architecture at a regional basin-scale. Conventional reconstructions rely upon extrapolating observations from small-scale studies of outcrop and core or on qualitative water well record (Demchuk and Hills, 1991; Grasby et al 2008;Lyster and Andriashek 2012).The methods used in chapter 3 include the generation of stratigraphic sections, for correlating large regional features, and net-to-gross sand maps (sand thickness divided by an interval thickness). These tools greatly improve the understanding of the regional character of the Paskapoo Formation.

Previous Studies

Characterization and descriptions of the Paskapoo took off in the 1990's (Demchuk and Hills 1991; Jerzykiewicz 1997; Hamblin 2004; Grasby et al. 2008; Lyster and Andriashek 2012). Previous to Demchuk and Hills, mentions of the Paskapoo were limited and described in the broader context of the upper Cretaceous and Tertiary strata of the foreland basin (Gibson 1977; Mclean and Jerzykiewicz 1977, Jerzykiewicz 1985; Jerzykiewicz and Sweet 1987). Demchuk and Hills (1991) designate the stratigraphy of the Paskapoo into three distinct members based on two reference core sections. The sections display regional sequences of the Paskapoo and are accompanied with well log data (Gamma ray and resistivity), the reference section display the interpreted core logs alongside the gamma ray curve. Thee principle members are identified and there gamma ray character can be observed. The Haynes Member being massive amalgamated sandstone is identifiable by characteristically low API values as the first prominent sand above that last predominant coal. This is also the definition of the base of the Paskapoo previously identified by Gibson (1977). The Lacombe Member is characterized by highly heterogeneous fluvial sands and overbank muds which correspond to higher API values with thin sections of low sand API response from the curve. The Dalehurst Member is the uppermost member and is characterized by fine sands and coals. The Dalehurst Member is regionally discontinuous and rarely seen away from Hinton where the coals are the focus of mining operations. These cores and corresponding well log responses give us the confidence to accurately correlate the regional distribution of the Haynes and Lacombe members, as well as infer the sand fraction volume based on the gamma ray log response.

Past regional construction of the Paskapoo Formation (Grasby et al., 2008; Lyster and Andriashek, 2012) have been built by integrating water well log data and available oil and gas geophysical well log information, principally gamma ray logs. The gamma ray logs are restricted to the zone below surface casing, only covering the lower portion of the Paskapoo Formation. The water well and petroleum well logs were used to assess the sand faction/net sand content of the Paskapoo Formation. The petroleum well logs are more accurate in determining sand volume and its variation, but the log has not been collected through the surfaced cased interval prior to 2006. The normalized logs data set can more accurately assess the variation and distribution of the sand content, identifying large surfaces associated with the members classified in Demchuk and Hills (1991), and possible areas of high sand content not previously identified in literature. This data set may provide us with a better regional characterization of the Paskapoo aquifer system. The focus of the following chapters is to demonstrate the methods for normalization and the capability of the data.

Organization of the Thesis

In Chapter Two the focus of the manuscript is the methodology involved in normalizing the shallow subsurface gamma ray logs as to allow for conventional gamma ray correlation. This chapter is essentially the manuscript: *Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta*, which was accepted for publication on January 23rd 2014 by the Canadian journal of Earth Science, with co-authors David Bechtel, Andrew Leier and Laurence Bentley. The original concept and workflow was developed by David Bechtel at the Alberta Geological Survey. The data used became available after the EUB mandated in 2006 that natural gamma ray response was to be collected to surface through the surface casing. 572 well logs were used; the wells were divided into two zones for the normalization procedure. The cased zone was defined as the section of strata that extends from the base of surface casing to surface, and the uncased zone, extending from the base of the Ardley coal zone to the base of surface casing. Since the surface casing typically covers the upper most 150m - 500m, the uncased zone consists of the lower Paskapoo and Ardley coal zone. The 2nd and 95th percentile averages of the API values of individual wells were calculated for the uncased zone. These constants were then used in the normalization of the cased zone. The principal assumption of the work flow is that the constants derived from the uncased zone are representative of the above cased zone. This assumption was determined to reasonable given the previous lithological information collected on the both the Paskapoo and Scollard formations. The cased logs are then clipped at the base of surface casing and attached to the normalized gamma ray log to generate a continuous gamma ray curve that extends to surface. The interface between the normalized cased section and the uncased section is also reviewed for consistency. The normalized curve creates a seamless log response that extends to surface and is comparable to open-hole logged gamma ray. The normalized log can now be used to generate regional stratigraphic sections and sand maps. The goal of the normalized curve and manuscript in chapter two is to provide an improved subsurface data set for the near surface aquifers in the Paskapoo Formation. My contributions to this collaborative work began with compiling the data necessary for the normalization. The normalization procedure is a reproduction of the workflow developed by David Bechtel at the AGS. My work included implementing the workflow, performing tests of the interface between normalized gamma and the open-hole, comparing normalized curve to open-hole logged offsets, using the method to produce example geologic interpretations within the Paskapoo Formation and drafting of the manuscript, and submission for publication.

Chapter Three entitled *Basin-scale stratigraphic architecture and Paleocene distributary fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada*, contains a paper in preparation for submission to *Sedimentary Geology* journal with coauthors Andrew Leier, Laurence Bentley, and Paul Glombick. The chapter utilizes a new normalized data set to generate stratigraphic cross-sections and net-to-gross sand fraction maps. The study area in this chapter benefits from significantly greater well control in the north portion of the basin, thanks to supplementary data provided by IHS (Information Holding Systems). Large-scale net-to-gross maps were generated for the north and central portion of the Paskapoo Formation. However, structural variation in the base of the Paskapoo along the NW – SE direction and poor well control in the central basin makes large area net-to-gross slice maps problematic. The lack of internal time surfaces make net-to gross sand mapping more difficult. Net-to-gross maps in the northern portion of the basin use thick horizons that are reliant on the base and top pick for the Paskapoo. Stratigraphic strike and cross sections are generated and interpreted for the study area. The Ardley base coal is used as a regional datum, and the layers used for the net-to-gross slice maps are shown on the stratigraphic cross-sections and schematic figures. Ardley base pick is chosen on neutron porosity and density logs (Fig. 2). Each layer of the stratigraphic cross-section is populated with conceptual channel fill, informed by the calculated net-to-gross. The stratigraphic cross-sections and net-to-gross maps are used to interpret the stratigraphy and regional fluvial architecture. A non-marine fluvial model was interpreted based on the observations from the stratigraphic sections and sand maps, and is consistent with previously proposed models for the Paskapoo Formation. My contribution to this paper included the generation of net-to-gross sand maps, with multiple iterations using variable layer thicknesses, the generation of stratigraphic cross-sections to best capture the interpreted features of the net-to-gross sand maps and contributions to the interpretation of the results. I prepared the initial manuscript and preparation for publication.

Chapter four contains a synthesis of the results from both Chapter two and three, with the main conclusions and interpretations, as well as recommendations for future research and work.

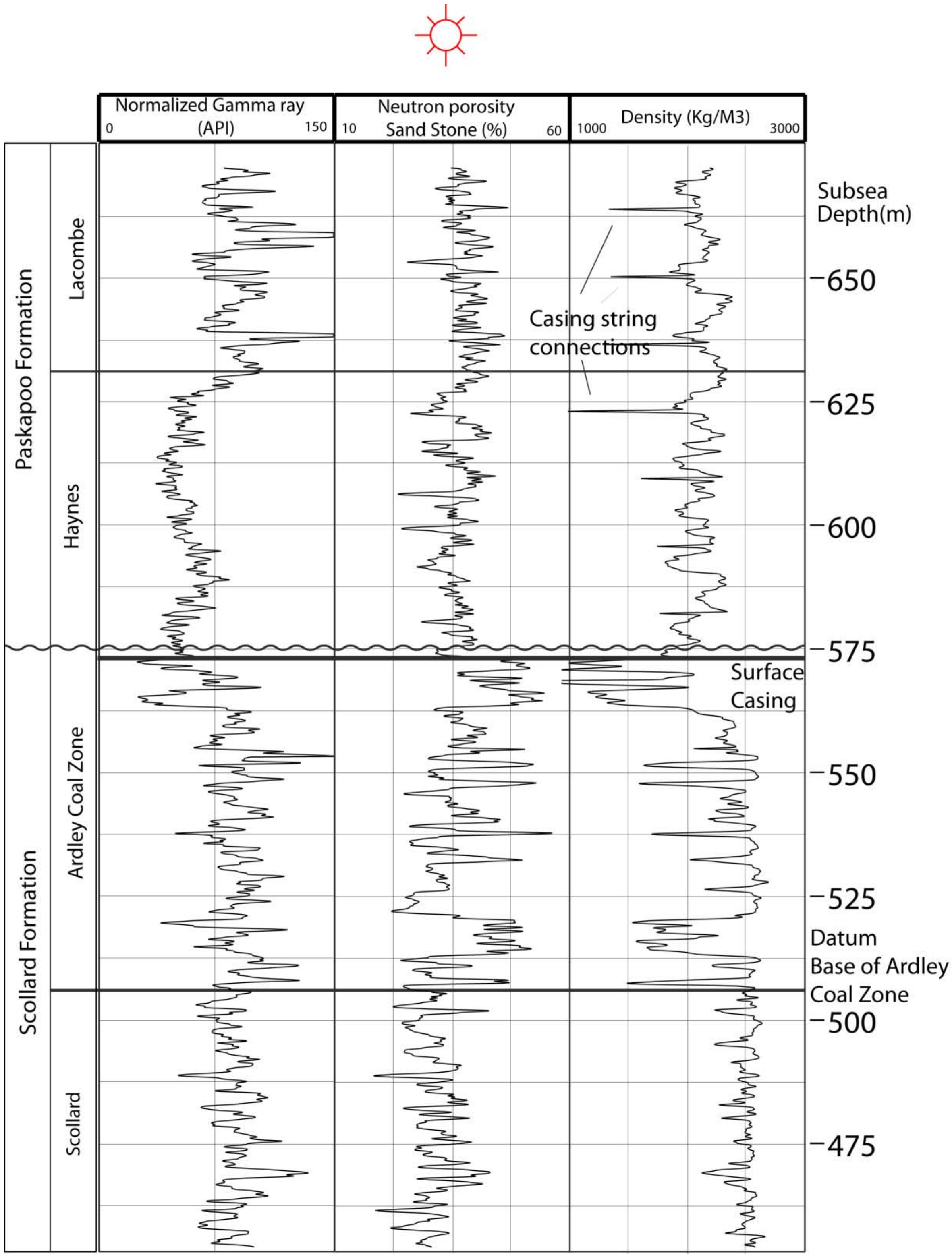


Fig.2: Sample logs for the base Ardley coal zone pick. Thick coals are seen as low density anomalies with corresponding high neutron porosity sandstone response. Base Paskapoo is shown with the chevron line. (UWI: 100-10-25-051-09W5/00)

References

Beaumont, C. 1981. Foreland Basins, Geophysical Journal of the Royal Astronomical Society, 65(2), pp. 291-329

Burns E. R., Bentley, L.R., Hayashi, M., Grasby, S.E., Hamblin, A.P., Smith, D.G., and Wozniak, P. R. J. 2010. Hydrogeological implications of Paleo-fluvial architecture for the Paskapoo Formation, SW Alberta, Canada: a stochastic analysis, Hydrology Journal, Vol 18, pp.1375-1390

Cant, J. D, Stockmal, G.S. 1989. The Alberta foreland basin: relationship between stratigraphy and Cordilleran terrane-accretion events, Canadian Journal of Earth Science, 26(10), 1964-1975

Cluff, S. G., and Cluff, M. R., 2004. Petrophysics of the Lance Sandstone Reservoirs in Jonah Field, Sublette County, Wyoming. Jonah field: case study of tight gas fluvial reservoir, Rocky Mountain Association of Geologists (2004), Chapter 12. pp.215-241

Dawson, F. M., Evans, C. G., Marsh, R., and Richardson, R, 1994, Uppermost Cretaceous and Tertiary strata of the Western Canada sedimentary basin. Geological atlas of the Western Canadian Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, 387-406.

Demcuk, T. D, 1990, Palynostratigraphic zonation of Paleocene strata in the central and south-central Alberta Plains, Canadian Journal of Earth Science, Vol.27 pp. 1263-1269

Demchuk, T.D, and Hills, L. V. 1991, A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members, Bulletin of Canadian Petroleum Geology, Vol 39, No. 3, pp. 270-282

EUB directive 043, 2006, Well Logging Requirements – Surface casing Interval, Energy Research Conservation Board, ERCB/AGS

Fox, R.C, 1990, Pronothodectes Gaoi N. SP. From the late Paleocene of Alberta, Canada, and the early evolution of the Plesiadapidae (Mammalia, Primates). Journal of Paleontology, 64(4), pp. 637-647

Gibson, D. W, 1977, Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River valley, Alberta. Energy, Mines and Resources Canada pp. 41

Grasby, S.E., Zhuoheng, C., Hamblin, A. P., Wozniak, P. R. J., and Sweet, A. R. 2008, Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta, Canadian Journal of Earth Science. Vol. 45, pp. 1501-1516

Hamblin, A.P, 2004, Paskapoo-Porcupine Hills Formations in Western Alberta: Synthesis of Regional Geology and Resource Potential, Geological Survey of Canada, Open File 4679

Jerzykiewicz, T. 1985, Tectonically deformed pebbles in the Brazeau and Paskapoo formations, central Alberta Foothills, Canada, Sedimentary Geology, 42(3), pp. 159-180

Jerzykiewicz, T. 1997, Stratigraphic framework of the uppermost Cretaceous to Paleocene strata of the Alberta Basin. Ottawa (Ont.)

Krause, D. W., 1978, Paleocene Primates from western Canada, Canadian Journal of Earth Science, 15, pp. 1250-1271

Leckie, D. A, and Smith, D. G. 1992, Regional Setting, Evolution, and depositional Cycles of the Western Canada Foreland Basin, American Association of Petroleum geologists, Memoir 55, pp. 9-46

Lerbekmo, J. F., Demchuk, T. D., Evans, M. E., and Hoye, G. S. 1992, Magnetostratigraphy and Biostratigraphy of the Continental Paleocene of the Red Deer Valley, Alberta, Canada, Bulletin of Canadian Petroleum Geology, 40 (1), pp. 24-35

Lerbekmo, J. F., and Sweet, A. R. 2008, Magnetobiostratigraphy of the continental Paleocene upper Coalspur and Paskapoo formations near Hinton, Alberta, Bulletin of Canadian Petroleum Geology, Vol. 56, p. 118-146

Lyster, S., Andriashek, L. 2012, Geostatistical Rendering of the Architecture of Hydrostratigraphic Units within the Paskapoo Formation, Alberta. Energy Research Conservation Board, ERCB/AGS Bulletin 66.

Mack, G. H., and Jerzykiewicz, T., 1989, Provenance of post-Wapiabi sandstones and its implications for Campanian to Paleocene tectonic history of the southern Canadian Cordillera, Canadian Journal of Earth science, 26(4), pp. 665-676

Mclean, J. R., Jerzykiewicz, T.1977, Cyclicity Tectonics and Coal: Some aspects of Fluvial Sedimentology in the Brazeau-Paskapoo Formations, Coal Valley Area, Alberta, Canada, Canadian Society of Petroleum Geologists. Memoir (5)

Medina, C. R., and Rupp, J. A. 2012 Reservoir characterization and lithostratigraphic division of the Mount Simon Sandstone (Cambrian):implications for estimations of geologic sequestration storage capacity. Environmental Geosciences, Vol 19(1), pp. 1-15

Price, R. A, 1994, Cordilleran Tectonics and the Evolution of the Western Canada Sedimentary Basin, Geological Atlas of the Western Canada Sedimentary Basin, 13-24.

Quarterly Population Report, 2012, first quarter, Alberta treasury board and finance, Economics, Demography and public Finance, Statistics Canada.

Rider, M., Kennedy, M. 2011, The Geological Interpretation of well logs, 3rd edition, Rider and French consulting Limited, pp. 1-4, pp. 117-146

Shier, D.E. 2004, Well Log Normalization: Methods and Guidelines, Petrophysics, 45(3), pp.268-280

CHAPTER 2

Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta

[1]Quartero, E. M., [2]Bechtel, D., [3]Leier, A.L., [1]Bentley, L. R.
emquarte@ucalgary.ca, David.Bechtel@aer.ca, aleier@geol.sc.edu, lbentley@ucalgary.ca
[1]Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4
[2]Alberta Geological Survey, Alberta Energy Regulator, Edmonton, AB T6B 2X3
[3]Department of Earth and Ocean Sciences, University of South Carolina, Columbia, 29208

Abstract

Understanding aquifer architecture is critical for managing groundwater resources in western Canada. Recent regulations have yielded abundant new gamma-ray well log data from the principal aquifer in Alberta, the Paleocene Paskapoo Formation. A major obstacle to utilizing this data is the fact that gamma-ray measurements in the shallow subsurface are made through surface casing, which suppresses gamma-ray readings and effectively prohibit stratigraphic characterization. Here we describe and demonstrate a relatively simple and efficient method for normalizing gamma-ray data from stratigraphic horizons that are behind surface casing and apply this method to the Paskapoo Formation in west-central Alberta. The gamma-ray normalization procedure adjusts the cased gamma-ray values so that a high and a low percentile value of the resulting gamma-ray statistical distribution are equal to those of the non-cased values. The effectiveness of this procedure is demonstrated by comparing the normalized gamma-ray values from cased intervals to those from nearby wells without casing. Good matches between these wells, as well as the transition between normalized curves at the base of cased zones and the gamma-ray curves at the uppermost portion of uncased zones, suggest this methodology is effective for studying the Paskapoo Formation. The normalized curve allows cased and uncased intervals to be correlated, enabling improved stratigraphic characterization and mapping of fluvial sand bodies behind surface casing. This new data provides the framework for better characterization of aquifer dimensions and the derivation of stratigraphic parameters used to constrain hydrogeological models and enhance groundwater recovery.

Introduction

The Western Canadian Sedimentary Basin (WCSB) of Alberta, Canada (Fig. 1) is one of the most intensely explored regions in North America, with thousands of new wells being drilled in this region every year. As of December 1, 2006, the Government of Alberta mandated that wire-line log readings (e.g., natural gamma-ray) must be collected to surface. This mandate has resulted in a flood of new near-surface geophysical well log data that has the potential to advance the understanding of the poorly mapped near-surface stratigraphy of the WCSB. Motivation for this well-logging requirement came from growing public concern over the future of shallow aquifers which are under stress from both a growing population and oil and gas activities (Hamblin 2004; Lyster and Andriashek 2012; EUB 2006). The Paleocene Paskapoo Formation (Fig. 1), in particular, has been a source of concern in Alberta. The fluvial sandstones in this formation are one of Alberta's most important sources of groundwater (Demchuk and Hills 1991; Grasby et al. 2008; Lyster and Andriashek 2012).

Some 64 000 water wells, one third of all water wells in Alberta (as of 2006), are completed within this formation (Grasby et al. 2008). The majority of water wells in the Paskapoo Formation are concentrated in and around the Red Deer-Calgary corridor (Grasby et al. 2008), where high annual population growth, and a hold on licenses for surface water extraction are placing a greater demand on groundwater resources (Grasby et al. 2008). Techniques associated with the development of unconventional resources have further stressed groundwater supplies in Alberta. Methods such as hydraulic fracturing ("fracking") of oil and gas fields simultaneously require a significant amount of water and have the potential to contaminate shallow aquifers (Osborn et al. 2011).

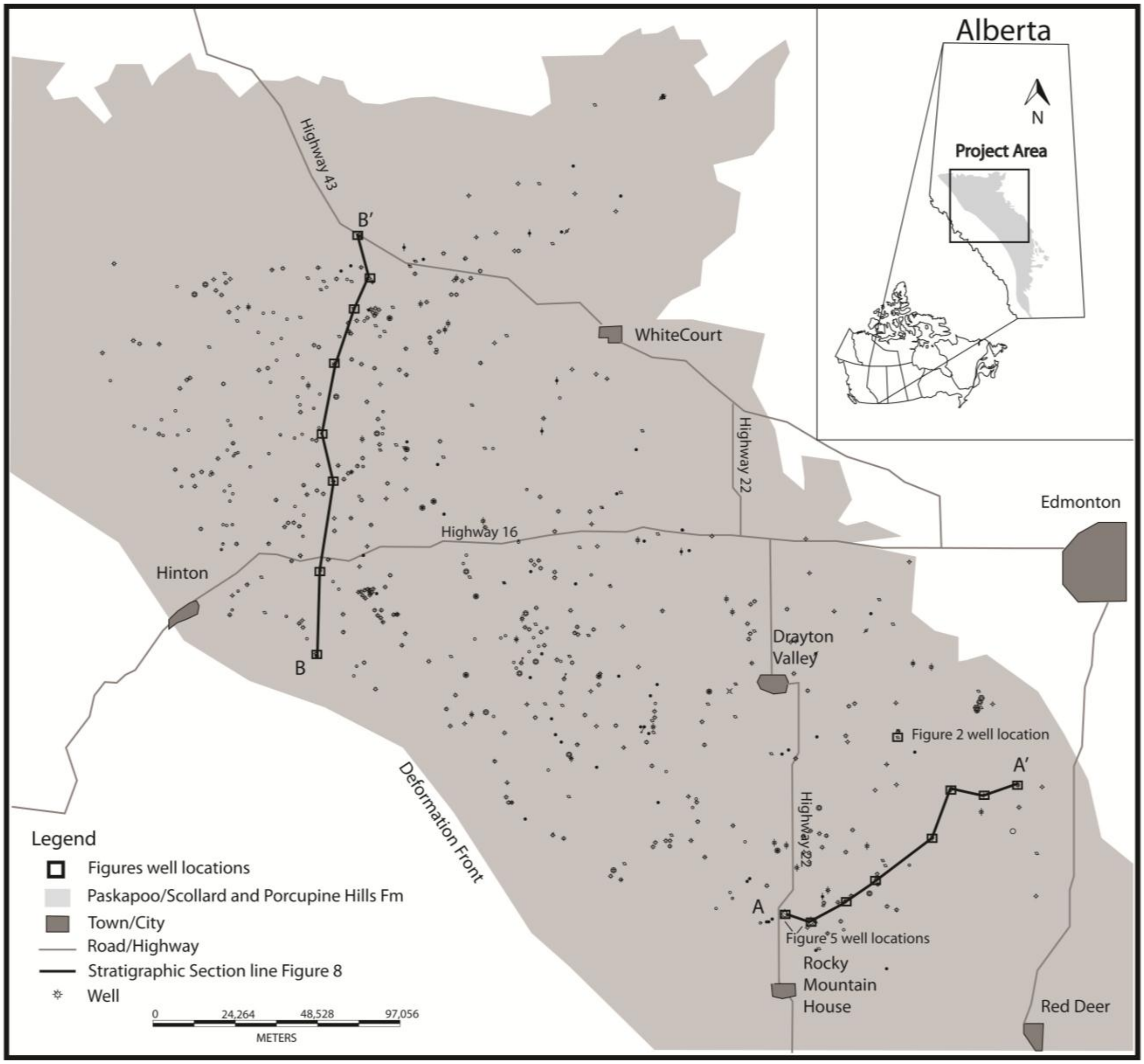


Fig. 1: Map of project area. The extent of the Paleocene Paskapoo/Scollard Formation is shown in gray. The well locations of 572 used in this study are shown as pluses. Map displays stratigraphic-section locations of both the south and north cross-sections shown in figures 8A and B, respectively. Well locations used in Figure 8 are outlined with red squares as is the well locations for Figures 2 and 5.

Characterizing the three dimensional distribution of aquifers is a first-order requirement for assessing and predicting groundwater resources (Burns et al. 2010). This is particularly important for the Paskapoo Formation, which is composed of complex arrangement of fluvial sandstone bodies encased in finer grained mudstone and siltstone (Demchuk and Hills 1991; Lyster and Andriashek 2012). In most subsurface studies, the natural gamma ray response of the formation is a robust method for distinguishing between sandstone channel remnants and mudstone. Whereas the recent regulations have yielded significant amounts of raw data on the Paskapoo Formation, thus far, much of it has remained unused because the data are obtained through surface casing. The surface casing in the wells, which separate the near surface strata from the well-log tools, suppresses the gamma ray response from the formation and reduces the amplitude and variance of the data (Fig. 2 and 6). This suppressed curve is distorted, making stratigraphic correlations between cased and uncased zones nearly impossible (Fig. 2). However, data from these intervals should still be useful, as gamma rays are capable of penetrating several inches of steel casing (Rider and Kennedy 2011). What is needed is a relatively simple and straightforward methodology that can be used to correct for the effects that the casing has on the natural gamma ray responses.

In this paper, we describe and demonstrate a normalization methodology that allows for the correlation of gamma ray readings from intervals behind surface casing and uncased intervals. This methodology increases the value of the newly collected data gathered from surface-cased zones in Alberta and lays the groundwork for much needed characterization and mapping of the near-surface stratigraphy. The establishment of a normalization technique for characterizing near surface aquifers will lead to improved groundwater models and water resource management practices in western Canada.

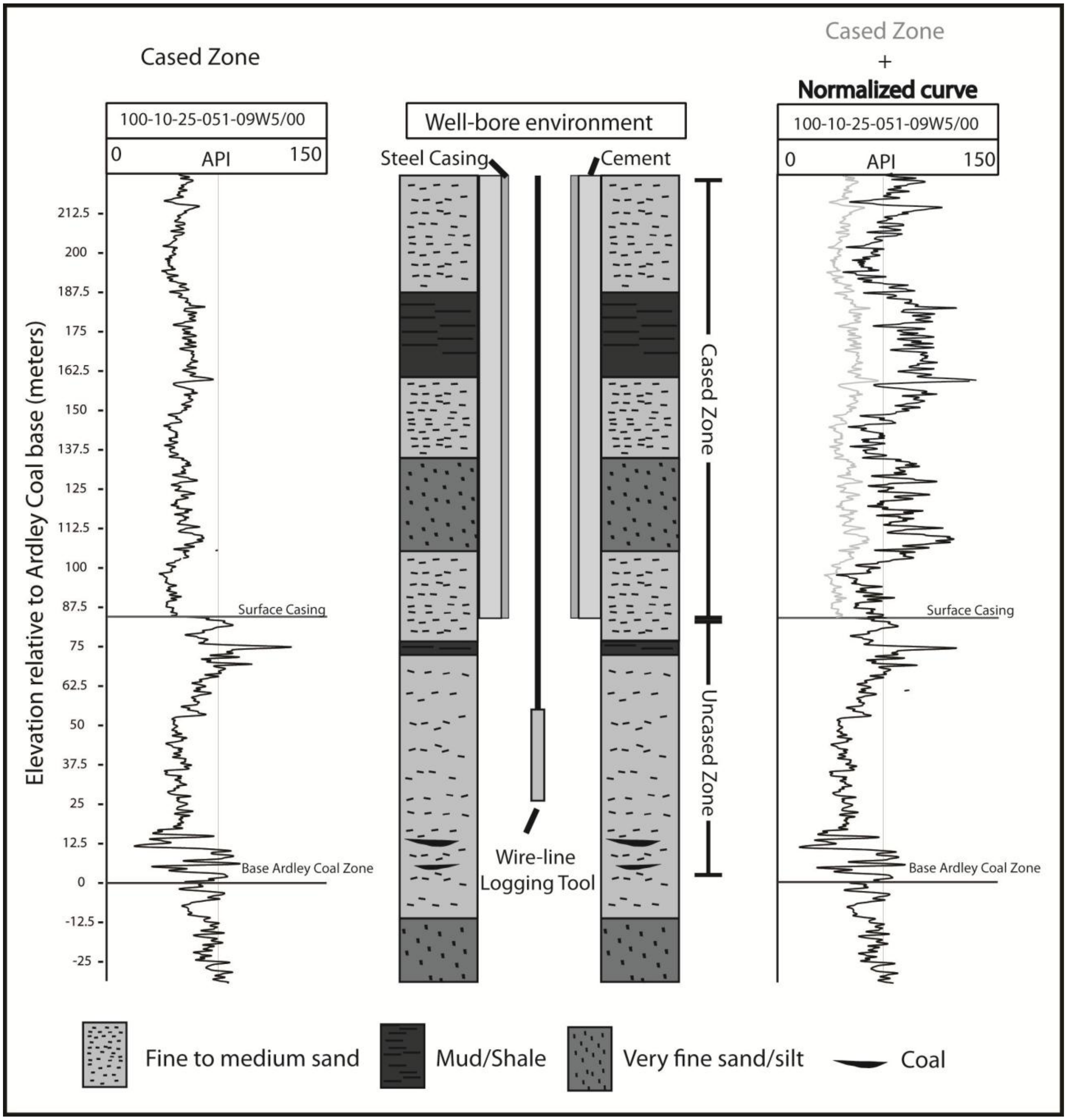


Fig. 2: Schematic diagram of cased section of borehole, and its effect on the neutral gamma-ray log. Line down gamma-ray log represents the 75 API cut-off used as a sand/shale discriminator. Bore-hole diagram includes a basic geological interpretation. Well location visible in Figure 1

Study area

Foreland Basin

The tectonic setting and depositional history of Mesozoic-Cenozoic strata in Alberta are described at length in many publications (e.g., Leckie and Smith 1992; Price 1994); therefore, we focus only on those aspects relevant to this study. The Paleocene-aged Paskapoo Formation was deposited in the Alberta Foreland Basin of western Canada (Demchuk and Hills 1991; Leckie and Smith 1992; Jerzykiewicz 1997). The westward-thickening foreland basin formed in response to crustal loading associated with thrusting in the adjacent Cordilleran fold-thrust belt (Beaumont 1981; Cant and Stockmal 1989; Price 1994). The Paskapoo Formation was deposited during the final stages of the Cordilleran orogeny (Mclean and Jerzykiewicz 1977; Hamblin 2004). Although exposed at the surface in many places in Alberta today, thick economic coals near Hinton indicate the formation was once buried by up to 2 km of strata, which have subsequently been removed (Demchuk and Hills 1991; Hamblin 2004). Today, a thin veneer of glacial deposits overlies the Paskapoo Formation across the majority of Alberta (Demchuk and Hills 1991).

Paskapoo Formation

The Paskapoo Formation is a heterogeneous fluvial unit with a maximum thickness near 800 m at the deformational edge of the Canadian Cordillera (Fig. 1; Jerzykiewicz 1997; Lyster and Andriashek 2012). This unit forms an asymmetric wedge of clastic strata that generally thins to the northeast, away from the deformed belt, and covers an estimated 65 000 km^2 (Grasby et al. 2008). The Paskapoo Formation contains a succession of both isolated and stacked fluvial channels with varying percentages of overbank mudstone and isolated coals (Demchuk and Hills 1990; Jerzykiewicz 1997; Hamblin 2004) The sediments were deposited between middle to late

Paleocene, making it the youngest preserved foreland basin strata throughout much of the region (Mclean and Jerzykiewicz 1977; Demchuk and Hills 1990; Grasby et al. 2008).

The Paskapoo Formation is commonly divided into three members, which are, from oldest to youngest, the sand-dominated Haynes Member, the mud-dominated Lacombe Member, and the uppermost Dalehurst Member (Fig. 3; Demchuk and Hills 1991; Grasby et al. 2008). The basal Haynes Member consists of amalgamated, medium-grained sandstone units representing stacked, multi-story fluvial channel deposits (Demchuk and Hills 1991; Jerzykiewicz 1997; Hamblin 2004). The Haynes Member is 100 m thick near the westernmost edge of the basin, and averages approximately 50 m throughout the basin (Lyster and Andriashek 2012). The base of the Haynes Member, and by extension the Paskapoo Formation, is commonly defined as the first prominent sandstone above the uppermost major coal within the underlying Scollard Formation (Demchuk and Hills 1991; Gibson 1977). This surface is an unconformable erosional contact with an estimated hiatus of 1-2 million years (m.y) (Lerbekmo et al. 1992).

The overlying Lacombe Member comprises the majority of the Paskapoo Formation and is characterized by extensive siltstone and mudstone beds with isolated, fine-grained sandstone channel deposits (Demchuk and Hills 1991; Lyster and Andriashek 2012). The Lacombe Member has a maximum thickness of 500 m in the westernmost portion of the basin, but thins to 50 m at its eastern margin. Based on vertebrate paleontology and palynology, the Lacombe Member is interpreted as late Paleocene in age (Fox 1990; Demchuk 1990).

The Dalehurst Member, as proposed by Demchuk and Hills (1991), consists of fine-grained sandstone beds interbedded with siltstone, mudstone, shale, and coal. The Dalehurst Member is characterized by economic coals seams and is discontinuous in the northern portion of the study area near Hinton (Fig. 1), and is not preserved south of this region (Demchuk and

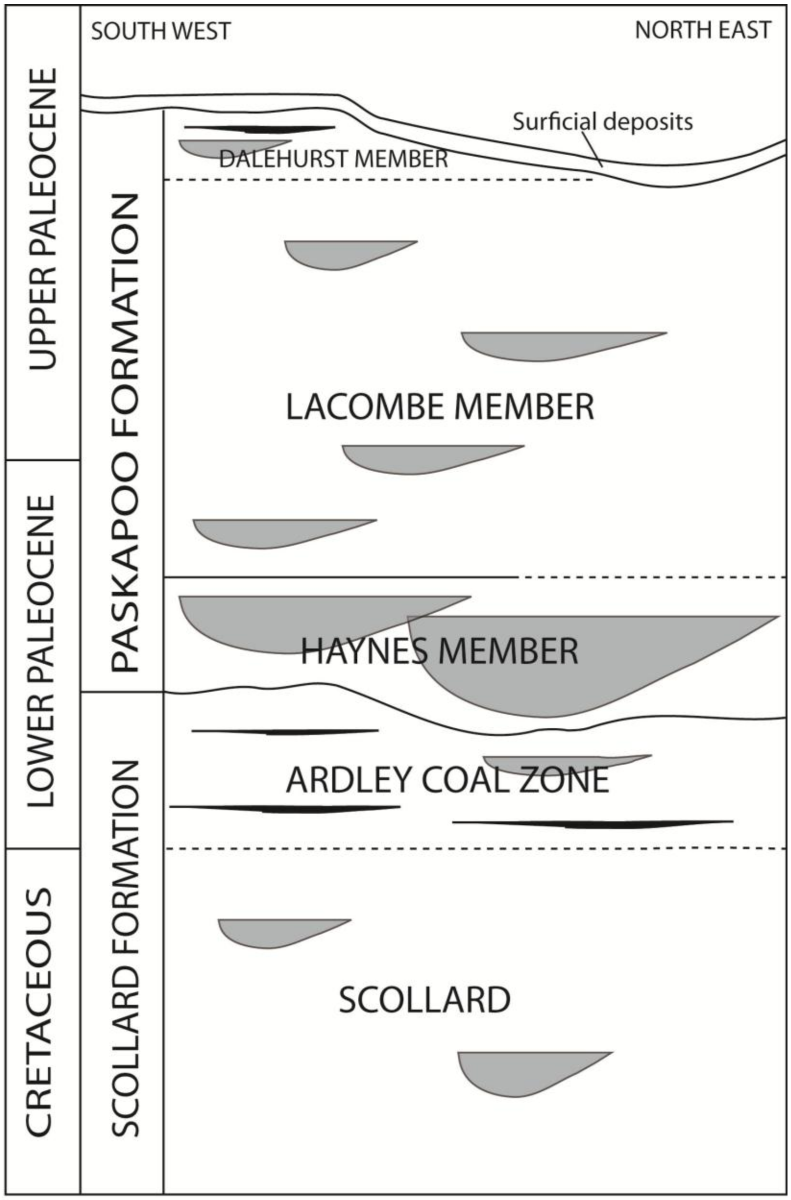


Fig. 3: Stratigraphic column as described by Demchuk and Hills 1991. The basal boundary between the Ardley coal zone and the Haynes is poorly understood. The majority of the section is comprised of fine silts and muds, with isolated and stacked channel sequences. Coal is found within the Ardley coal zone and the upper portion of the Dalehurst member. Section proposed by both Demchuk and Hills, 1991, and Lyster and Andriashek, 2012

Hills 1991). Uppermost strata of the Lacombe Member in the Red Deer area may be laterally equivalent to the Dalehurst Member (Demchuk and Hills 1991).

Scollard Formation

The Scollard Formation underlies the Paskapoo Formation and is discussed here because the lithologies and gamma-ray values of the upper portion of the Scollard Formation are used in the normalization process, and a key datum is located within the Scollard Formation. The Scollard is a fluvial succession of interbedded sandstone, siltstone, and mudstone with regionally correlative coal beds; most notably, the Ardley Coal Zone (Fig. 3) (Gibson 1977; Lerbekmo and Sweet 2008). The base of the Ardley Coal Zone is used as a regional correlation marker for the normalization process and regional cross-sections. The basal coal seam represents the Cretaceous-Tertiary boundary as determined by palynology and U-Pb dating (Langenberg et al. 2007), representing an effective datum and time horizon. Coals of the Ardley zone are thick and laterally extensive, and developed in marshy environments in very low gradient fluvial systems (Langenberg et al. 2007). Highly radioactive bentonite beds also exist within the Ardley coal zone, as result of volcanic ash falls, and must also be considered during normalization procedures (Kalkreuth and Langenberg 2002).

Data

In this study, we utilize gamma-ray logs from more than 500 wells drilled in west-central Alberta since the introduction of new provincial regulations in 2006 (EUB 2006). The wells are logged through the Paskapoo Formation and contain the natural gamma-ray response throughout the surface casing interval. The natural gamma-ray response in wells is commonly used to determine the lithology and stratigraphy of the subsurface. Natural gamma-ray response is the measure of the naturally occurring radioactive elements found within the Earth’s crust which, in the case of sedimentary rocks, are typically uranium, thorium and potassium. Gamma rays have the ability to penetrate several inches of steel casing; a necessary feature of the spectrometer, for the sodium iodide crystal (typically 2 cm in diameter and 5 cm long) is housed in a steel tube several meters long, along with other wire-line logging tools (Rider and Kennedy 2011). Measurements are reported and range from 0-150 API units (American Petroleum Institute), where higher values indicate greater gamma-ray responses, which are typically associated with uranium, thorium and potassium found in clay minerals. On average, the standard shale is recorded at 100 API, and ~75-85 API is typically used to distinguish between shale (>75-85) and sandstone (<75-85). Gamma-ray measuring tools commonly measure at an interval of ~12 cm (5 inches).

Surface casing typically consists of large-diameter steel tubing cemented into a newly drilled surface section of borehole. Casing significantly adds to wellbore stability and improves drilling mud circulation, as well as protecting near-surface aquifers from oil and gas infiltration. The steel surface casing also suppresses the gamma ray tool's ability to detect the naturally emanating radioactivity from the formation. This in turn, lowers the overall API values measured by the gamma ray tool.

Methodology

Background

Gamma-ray normalization is a procedure commonly done when a particular well tool displays a bias. Gamma-ray tools are not calibrated to the same standards; therefore it is common to normalize curves prior to doing volumetrics or correlation work (Shier 2004). The work flow involves taking the statistical average high and low values from a type well within the zone of interest, or averaged wells, and normalizing each well across the project area (Shier 2004). The method utilizes the values derived from the subsurface stratigraphic zone and re-applies those values to the biased data of other wells in the zone of interest (Shier 2004). The methodology presented here differs in that it utilizes values derived from an analogous stratigraphic zone and then applies these to the zone of interest, the cased interval of the well bore.

Data gathering

The software utilized in this study is the Petra™ suite available from IHS (Information Handling Systems) as well as the academic licence to the well log files. However, a variety of commercially available software and licences contains the capacity for this work-flow. The data available through the academic data licence used in this study from IHS is limited compared to commercial data licences. Here, we focus on gamma-ray well data collected from the northern portion of the Scollard and Paskapoo Formations since the implementation of provincial regulations in 2006 (EUB 2006). Within these constraints, approximately 572 wells met the criteria and comprise a project area of some 33 000 km^2 (Fig. 1). Data were imported using IHS Data Manager, and manually imported into Petra™. Data quality is safeguarded by the software and requires little visual inspection by the user. If the API digits for an interval are not recorded or continuous through the interval, the software records the interval as a null value and continues to the next well. The data consists of 274 logs with continuous logs in the uncased zone with 298 nulls, and for cased zone 386 good logs with 186 nulls (Fig. 4). A significant portion of the wells are rejected due to the poor quality of well data, however many wells with coverage over the uncased interval, but not the cased can be used in the normalization equation (Eq. 1).

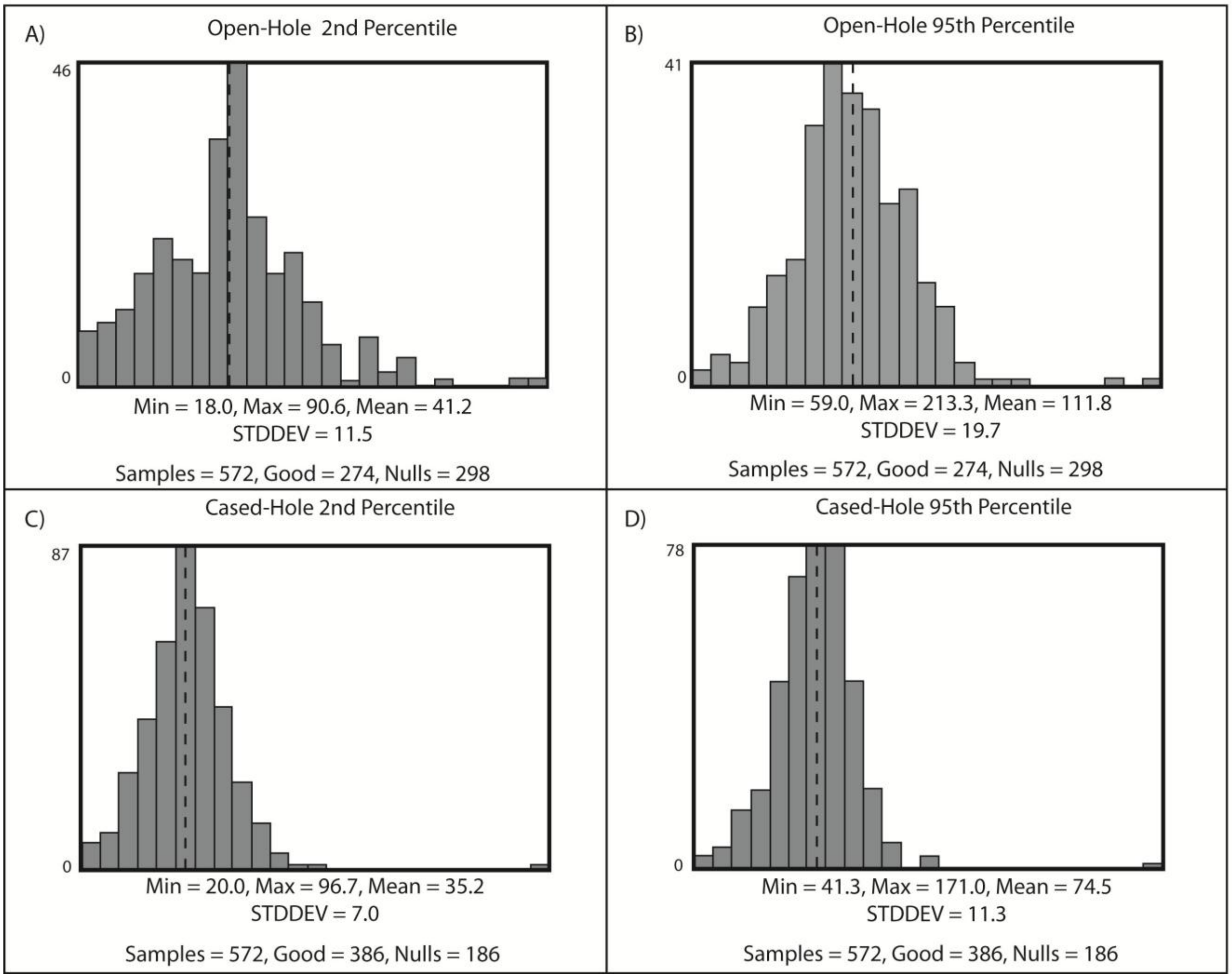


Fig. 4: Distribution of P2 and P95 API values of both the defined cased and uncased zones. The average values calculated from the uncased zone are used as constants in the normalization equation (Equation 1). The values from the cased zone are labelled in Figure 6, indicating expected "cased" spread of API values. *a*) The open-hole 2nd percentile distribution for all wells.

Normalization workflow

Defining cased and uncased zones

The normalization process for the cased interval begins with the definition of two distinct subsurface zones: 1) the cased zone; and 2) the uncased zone. The cased zone extends from 20 meters below Kelly Bushing to the base of surface casing (Fig. 2). This zone must be defined within the software by assigning the top and bottom boundaries to the zone. These include the surface elevation as an upper boundary and the bottom of the surface casing, either provided by well report data (e.g., from GeoScout™), or imported manually and reassigned to represent a "pseudo-formation top," which is simply the bottom of surface casing. Once the cased zone is defined, the API statistical values from this zone are calculated using Petra™ software.

An uncased zone is defined and the API statistical values from this region area used to "correct" for the effects of casing in the cased zone. Whereas the cased zone is easily defined (Fig. 2), definition of the uncased zone requires interpretation. Because the uncased interval is used to "correct" for the surface casing in the cased zone, it is important that the lithologies in the uncased zone are comparable to those in the cased zone. The bottom boundary of the uncased zone cannot extend past what is considered to be analogous strata. In the example we present here, the basal marker for the uncased zone is set at the base of the Ardley coal zone. The Ardley coal zone is used because it is a widespread and easily identifiable regional stratigraphic marker and is also an approximate time horizon (Langenberg et al. 2007; Lerbekmo and Sweet 2008). In this study, it is important to note that the surface casing point varies from 150 meters measured depth (MD, meters below Kelly Bushing) to 700 meters MD in the project area and that the uncased zone cannot be defined in the instance where the surface casing point extends below the base of the Ardley coal zone. In the instance where surface casing is set well above the base of the Ardley coal zone, the uncased zone may contain strata of the lower Paskapoo Formation, which is appropriate for the normalization process.

Statistics from the zones

With the cased and uncased zones defined, statistical values of gamma-ray readings are calculated. Instead of using a type well, all of the gamma-ray data from the uncased zone is combined. Histograms of a lower bound percentile and an upper bound percentile for each data set are then created (Fig. 4). The objective is to translate and scale the cased data so that the transformed histogram of the API data matches the uncased histogram of the API data. For the uncased zone, a low and high API value are chosen for the normalization equation (Eq. 1). The high-value is chosen as the 95th percentile (P95) and the low-value is chosen as the 2nd percentile (P2). The mean and variance of the distribution of P95 and P2 values are measures of the amplitude and variance of the zones. It is important to account for lithology when defining high and low values (Shier, 2004). The Ardley coal zone contains laterally extensive coals up to 3 m thick that do not exist in the overlying Paskapoo Formation, except in the Obed-Marsh coal zone in the northern part of the project area (Demchuk and Hills 1991). These coals are effective markers, as their anomalously low gamma ray values and can readily be identified from gamma-ray log. Similarly the Ardley coal zone contains bentonitic sandstones, which produce anomalously high gamma-ray values (Kalkreuth and Langenberg 2002) that are not present in the Paskapoo Formation. The extreme values that are present in the Ardley coal zone but not in the Paskapoo Formation adversely bias the resultant normalization parameters. Using the P2 and P95 values mitigates the effects of the extreme values caused by the presence of the Ardley coal zone.

Normalization

The normalization process is based on the following equation:

$$\text{Normalized Value} = \overline{\text{UP2}} + \text{Cased Value} - \text{CP2} * \frac{\overline{\text{UP95}} - \overline{\text{UP2}}}{\text{CP95} - \text{CP2}} \qquad \text{Eq. [1]}$$

where $\overline{\text{UP2}}$ is the average P2 of all of the wells' uncased zones; $\overline{\text{UP95}}$ is the average P95 of all of the wells' uncased zones ; CP2 = P2 of the cased zone for the individual well under consideration ; CP95 = P95 of the cased zone for the individual well under consideration ; and the Cased Value is equal to the cased API value for the individual well under consideration to be normalized. The P2 and P95 uncased API values are 41 And 112, and for the cased section 35 and 75 (Fig. 4). The values for the cased zone are not treated as constants as the CP2 and CP95 are derived from individual wells. This means that the equation is unique to each well as the CP2 and CP95 Cased zone values are derived from within the well's Cased zone. Histograms in Figure 4 define the range of P2 and P95 values found in this study in the cased zone. The normalization process is a translation since $\overline{UP2}$ is greater than CP2, as well as scaling so that the spread and amplitude of the normalized histogram is similar to the histogram of the uncased data (Fig. 5 and 6). Once the algorithm is run by the software, a series of new gamma-ray curves are produced, which we term "normalized curves" (Fig. 2). The normalization algorithm only corrects the defined cased zone, generating a new curve that only exists from surface to casing point. Once created, the normalized curve must be clipped at the base of surface casing and merged with the original gamma-ray curve of the uncased zone. The simple addition of the two zones can be done with most commercially available geologic software. The work flow for the statistical generation of the values found in Equation 1 is demonstrated in a flow diagram, illustrating the parallel operations for the two zones in Figure 7.

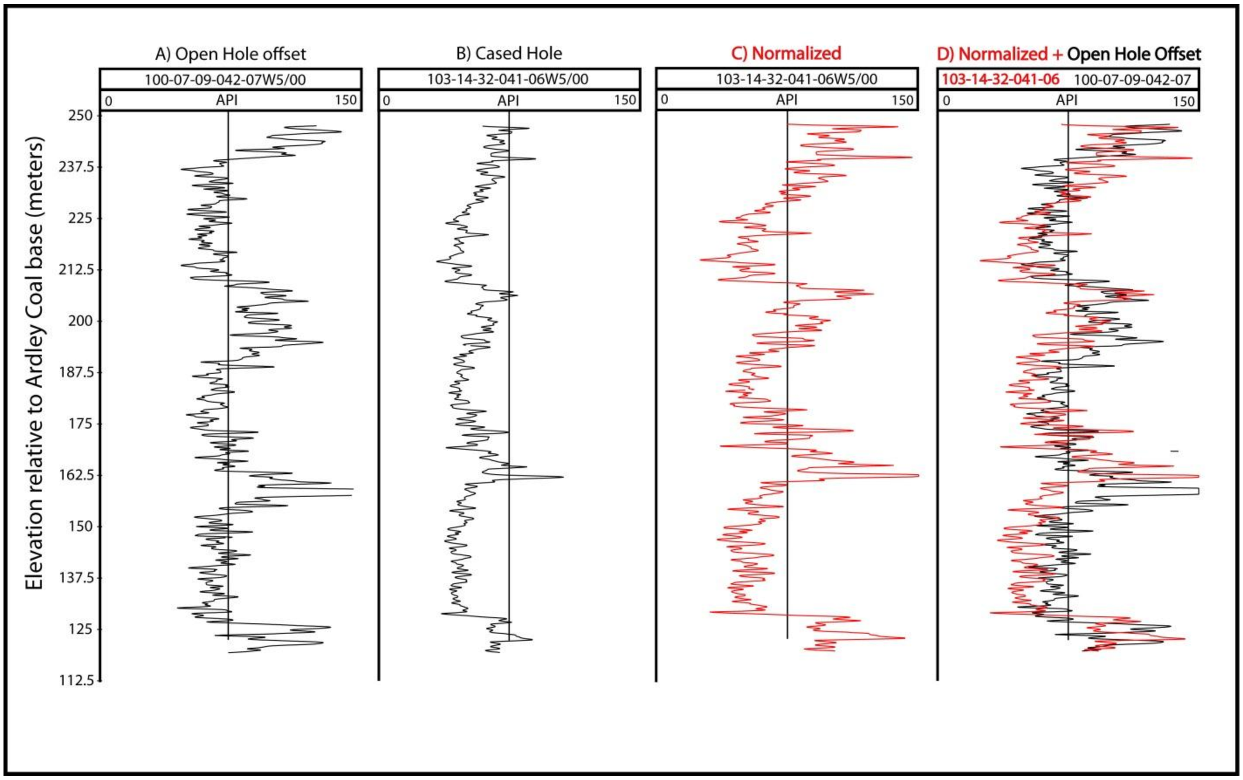


Fig. 5: Example of uncased, cased and normalized gamma ray logs. Raw gamma-ray through the Haynes Member, taken from the same stratigraphic interval in the two wells 8 km apart(the two westernmost wells in section AA' of Figure 1).. *a*) Haynes Member logged in an open-hole. *b*) Haynes Member logged through surface casing. *c*) Normalized cased section, gamma ray log shown in red. *d*) Normalized (red) gamma ray log offset is superimposed on uncased gamma ray log (black). 75 API sand shale line is drawn in for reference.

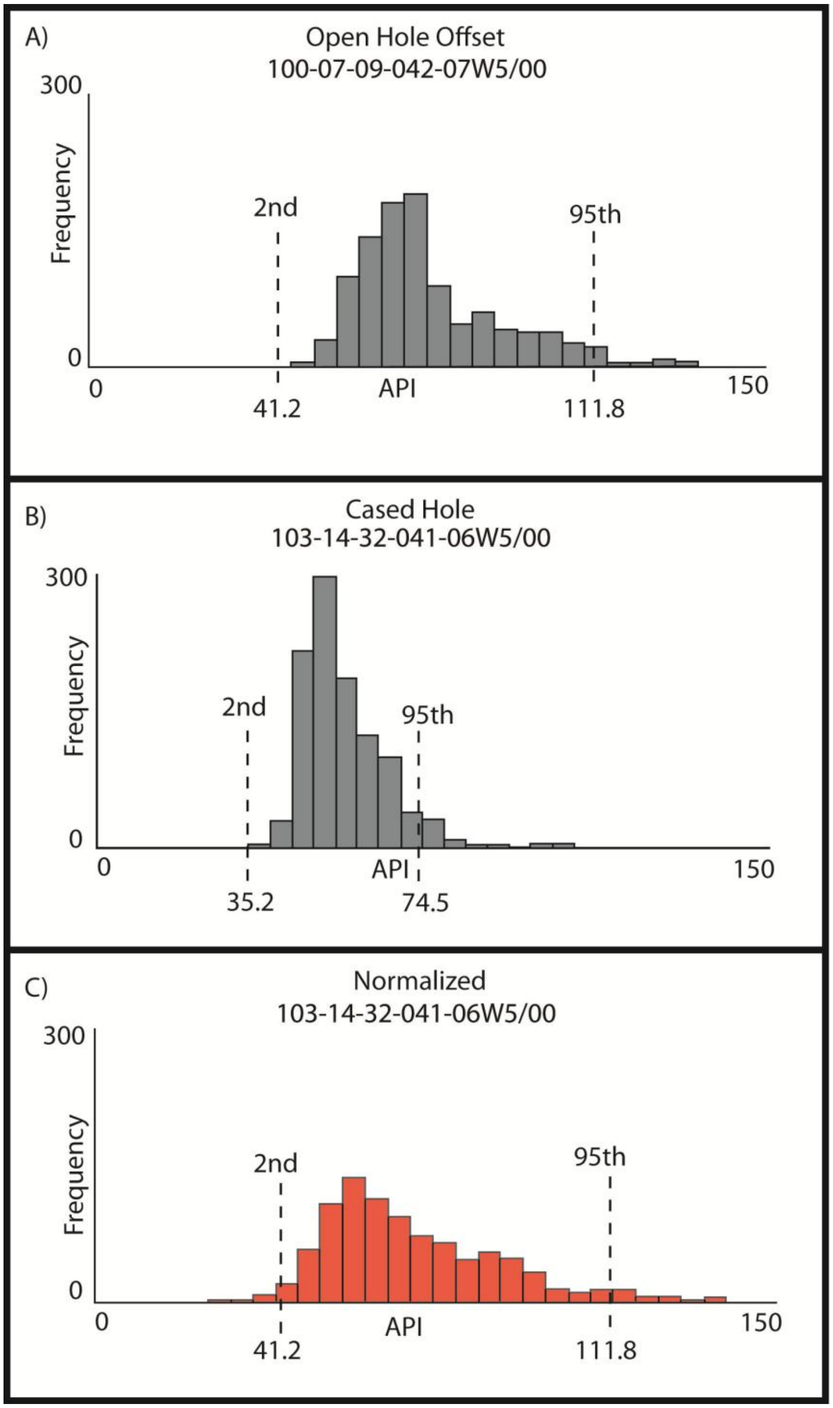


Fig. 6: Distribution of API values from Figure 5. *a*) open-hole offset portion of the Haynes Member from Figure *5a*. *b*) Cased-hole portion of the Haynes Member from Figure *5b*. *c*) Normalized portion from Figure *5c*. average 2nd and 95th percentile values are indicated by the dashed lines.

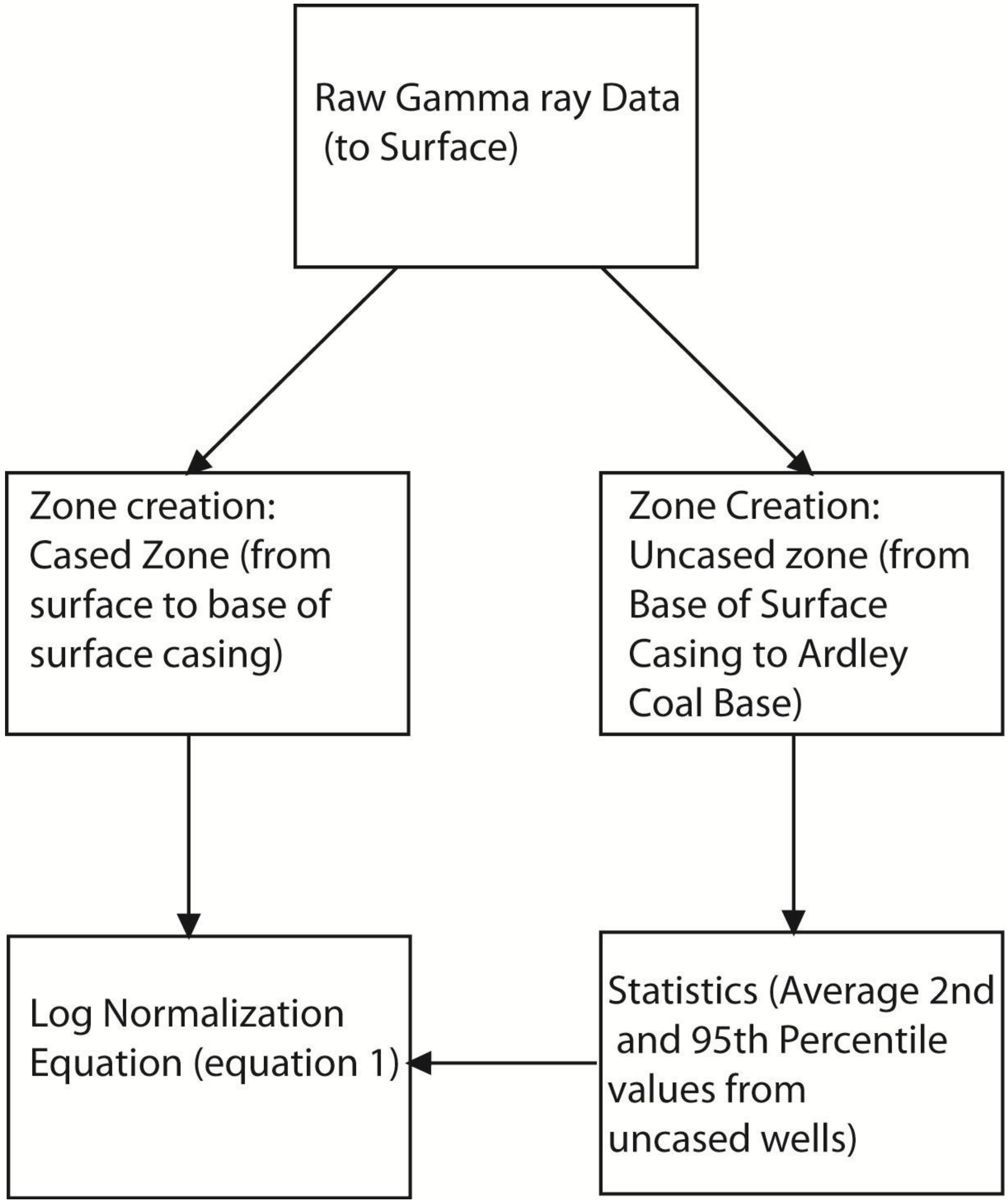


Fig. 7: Flow diagram of the work flow for the statistical evaluation of the project area. The two zones contribute to Equation 1.

Conditions and assumptions

The principal assumption of this methodology is that the lithologies and gamma-ray values of the uncased zone are representative of those in the cased zone. Specifically, that the P95 and P2 values are consistent between the two zones. Representative API values of mudstone/shale of the uncased zone should be equivalent to the API values of the same lithologies in the cased zone, and similarly with minimum sandstone API values. This assumption pertains to the entire study area. We acknowledge that lithologies across a basin are not necessarily consistent and lateral regional and local variation may be present. For our study area, there is ample evidence in the sedimentary analysis of these formations to indicate these assumptions are reasonable (Demchuk and Hills 1991; Jerzykiewicz 1997; Lyster and Andriashek 2012). In addition, it is assumed that gamma-ray tool calibration variations and its distribution are unbiased. The relatively high number of wells used in this study (572; and increasing) means a few poorly calibrated gamma-ray tools will have minimal impact on the normalization. The surface casing point at the base of the cased zone is reported by the well operators and its depth pre-determined by oil and gas engineers. An inaccurate report of the true base of the casing could result in incorrect lithology identification. For example, an interpretation of sandstone bed (low gamma-ray API value) in the instance where casing is reported at a depth above the actual depth.

The effectiveness of the normalization technique can be tested by comparing average differences between 20 m sections of the gamma logs. The mean of the API value for each of three 20 m zones is computed. One section is last 20 m directly above the bottom of the surface casing. The other two sections are from 0 to 20 m and 20 to 40 m below the bottom of the surface casing. The difference between the mean values of the cased section and the section immediately below the cased section and the difference between the mean values of the two uncased sections is computed. If the normalization procedure is effective, the distribution of the differences between the cased and uncased means should be similar to the distribution of the two uncased sections. The distributions of the differences are seen in Figure 8. The difference between the "raw" cased zone and the uncased zone directly below casing has a mean of -25.41 API, demonstrating that the mean API in the cased section before normalization is significantly lower than the API values in the adjacent uncased section (Fig. 8*a*). Figure 8*b* shows the distribution of differences between the means of two adjacent uncased and non-normalized 20 m sections. The mean of the difference distribution is 0.13 API with a standard deviation of 14.4 API. Figure 8*c* shows the distribution of the differences between the means of the 20 m normalized sections and the adjacent 20 m open hole sections. The mean is much closer to zero with a value of -1.46 API, than the -25 API average difference before normalization (Fig. 8). A mean close to zero indicates a lack of significant bias in the process. The distribution has a greater standard deviation than the distribution of the differences of the two open hole sections, indicating a level of uncertainty in the normalization results.

Apart from this test wells are visually checked for any apparent artefacts or data gaps; wells with partial curves and missing log information are not used in cross-sections and characterization work. Any variations in cement and casing material are assumed to be corrected by the large sample population, in the calculation of the P95 and P2 constants, and the casing material is assumed to be relatively consistent along the depth of the well. This is a reasonable assumption, as industry standards and practices are fairly consistent and regulated. Effects of intermediate casing are also minimal due to the high sample number, but care must be taken with interpretations in areas with intermediate casing, as individual wells will still exhibit its effect

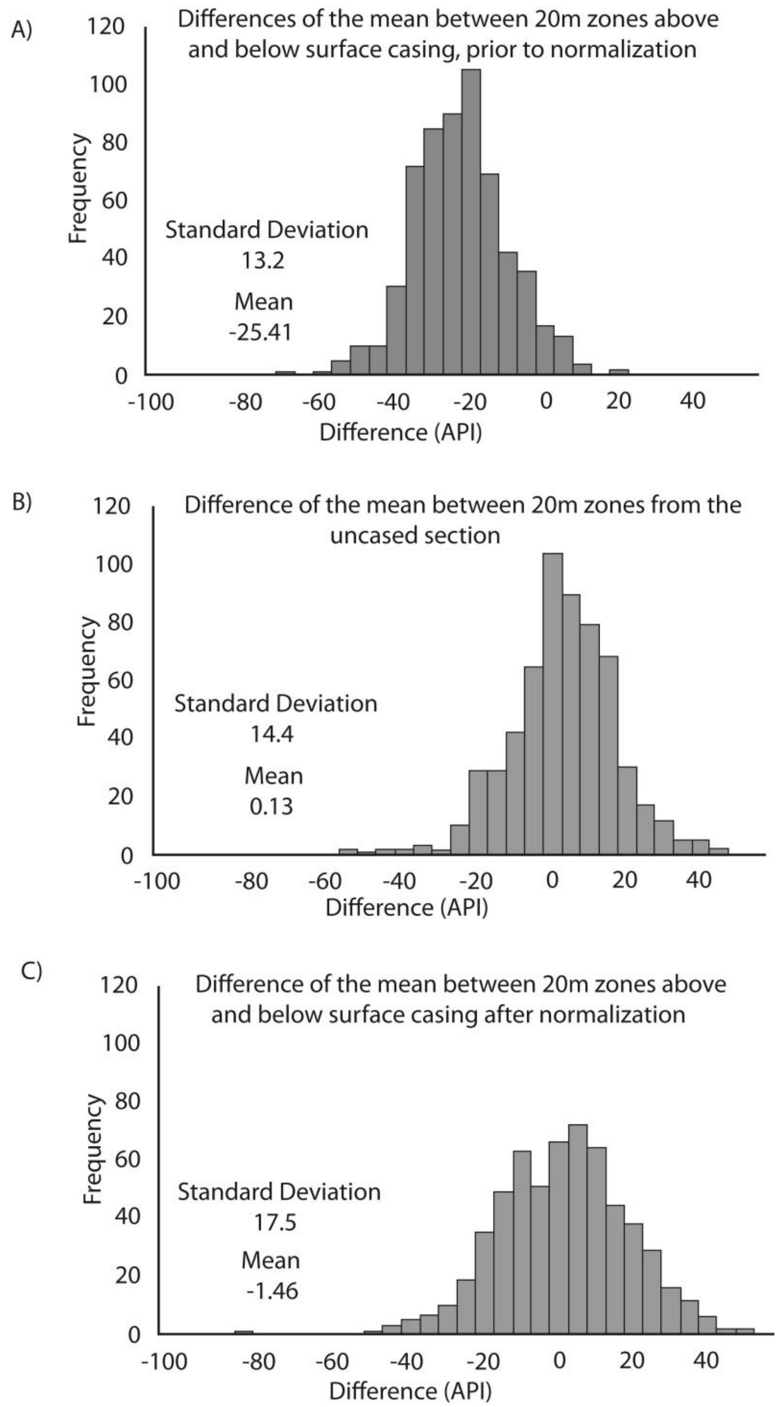


Fig. 8: Histograms of the differences of the mean between two 20m thick zones, one located above casing, and two zones (0-20m and 20-40m) below casing. *a*) Histogram of the differences of the mean between a 20m cased zone above surface casing, prior to normalization, and a 20m uncased zone directly below. *b*) Histogram of the differences of the mean between two 20m zones both located in the uncased section of the borehole. *c*) Differences of the mean histogram of the surface casing interface after normalization.

after the normalization. The effects of glacial till are minimal to negligible as this thin veneer of sand and gravel is normalized with the fluvial units behind casing. Values from cased zone are suppressed and varying lithology does not contribute as significantly to the normalization equation, areas with thick drift may skew the distribution shape of a histogram; however the min and max values of the cased zone will not be significantly altered.

Results and evaluation

Normalization yields gamma-ray values that are much more consistent with expected values (Fig. 2), The normalized curves have similar patterns of alternating high and low values to the cased-zone curve (Fig. 2). The values of the normalized curve are shifted to higher API values, and the variance of the values has increased (Fig. *6c*). These results are demonstrated by the well in Figure 2 and 5. Figure 2 consists of a 250 m section from base of the Ardley coal zone to the middle Lacombe Member. The majority of the cased portion consists of the Lacombe Member. This stratigraphic unit is characterized by interbedded siltstone, mudstone, and relatively thin (<10 m) sandstone beds (Demchuk and Hills 1991). The cased zone prior to normalization has gamma-ray values less than 75 API, which is the value commonly used to demarcate sandstone (<75 API) from mudstone (>75 API). This "apparent" sandstone lithology, based on the pre-normalized curve, is inconsistent with the Lacombe Member of the Paskapoo Formation (Demchuk and Hills 1991). In contrast, following the normalization procedure, the gamma-ray values are much more consistent with the heterolithic nature of the Lacombe Member, including sandstone units within mudstone. Figure 6 illustrates the overall effect of the normalization procedure. The shift in individual values is on the order of 20 to 50 API and the variance of the values has increased.

The normalization procedure has produced good matches at the transition from normalized to uncased values in the transformed logs (Fig. 2). Major discrepancies between the values near the base of the normalized curve and the top of the uncased zone would indicate that the normalization procedure was ineffective or the depth of casing was misreported.

Another test of the effectiveness of the normalization process is to compare an interval from a well behind casing to the same interval in a nearby well logged through mud (Fig. 5). Figure 5 displays two wells, one cased and one uncased, that record gamma-ray logs from the sandstone-dominated Haynes Member of the Paskapoo Formation (Demchuk and Hills 1991). The Haynes Member in Figure *5a* is from an uncased interval, whereas the Haynes Member in well Figure *5b* is behind surface casing. The general stratigraphic correlation between the two wells is well defined based on the position of the underlying Ardley coal zone. Figure 5 displays the consistency of the profiles over the same interval between the uncased zone curve (black) and the normalized curve (red). Prior to normalization, correlation of features between the two wells is speculative given the difference in amplitudes (Fig. 5). However, after the normalization, prominent features in the two wells can be correlated with relative ease (Fig. *5d*). Histograms in Figure 6 show the distribution of the curves from Figure 5. The spread of the uncased and cased values illustrates the transformative effect of the methodology. The similarity between normalized log and the uncased log can be seen in Figure *6a* and *c*. Similar results have been obtained at other locations throughout the study area.

Not all wells respond well to the transformation. An area of particular concern is those wells that contain intermediate casing. Intermediate casing, located below the surface casing, has a similar suppressing effect on gamma-ray values. In Alberta, these wells are typically located close to the deformation front and commonly target deep oil and gas horizons. Deep oil and gas targets require multiple casing strings to safely drill to depth. Care must be taken with deep wells to recognize intermediate casing nearer the deformation front of the Rocky Mountains.

Applications

We demonstrate the effectiveness of this normalization procedure by constructing stratigraphic cross-sections in the Paskapoo Formation across the Alberta foreland basin using a combination of uncased and normalized cased gamma ray log sections (Fig. 9). The stratigraphic-sections utilize the underlying Ardley coal zone as a stratigraphic datum (picked on porosity and resistivity logs not presented) and focus on thick (>20 m) stratigraphic packages dominated by sandstone.

The A-A' stratigraphic section (Fig. *9a*) is located in the southern portion of the study area (Fig. 1) and spans roughly 80 km, trending southwest to northeast. It illustrates how the basal Haynes Member can be correlated across the basin using both normalized and raw gamma ray curves. The A-A' section is consistent with the traditional interpretation of the Haynes Member as a thick stacked channel-fill succession progressively thinning to the northeast, away from the deformation front (Demchuk and Hills 1991). The base of Paskapoo Formation is here identified as the first predominant sand above the last predominant coal of the Ardley coal zone (Demchuk and Hills 1991; Gibson 1977). This surface is also interpreted as an unconformity formed over 1-2 my (Lerbekmo et al. 1992). The Haynes Member is thick and laterally continuous and it incises into the underlying Scollard Formation. The B-B' stratigraphic section (Fig. *9b*) trends south to north 120 km across the northwest portion of the study area (Fig. 1), a portion of the Paskapoo that has not been previously described in the literature. The logs indicate a sandstone-rich area to the northwest that is located in the upper portion of the Paskapoo Formation. The increase of channels and sandstone

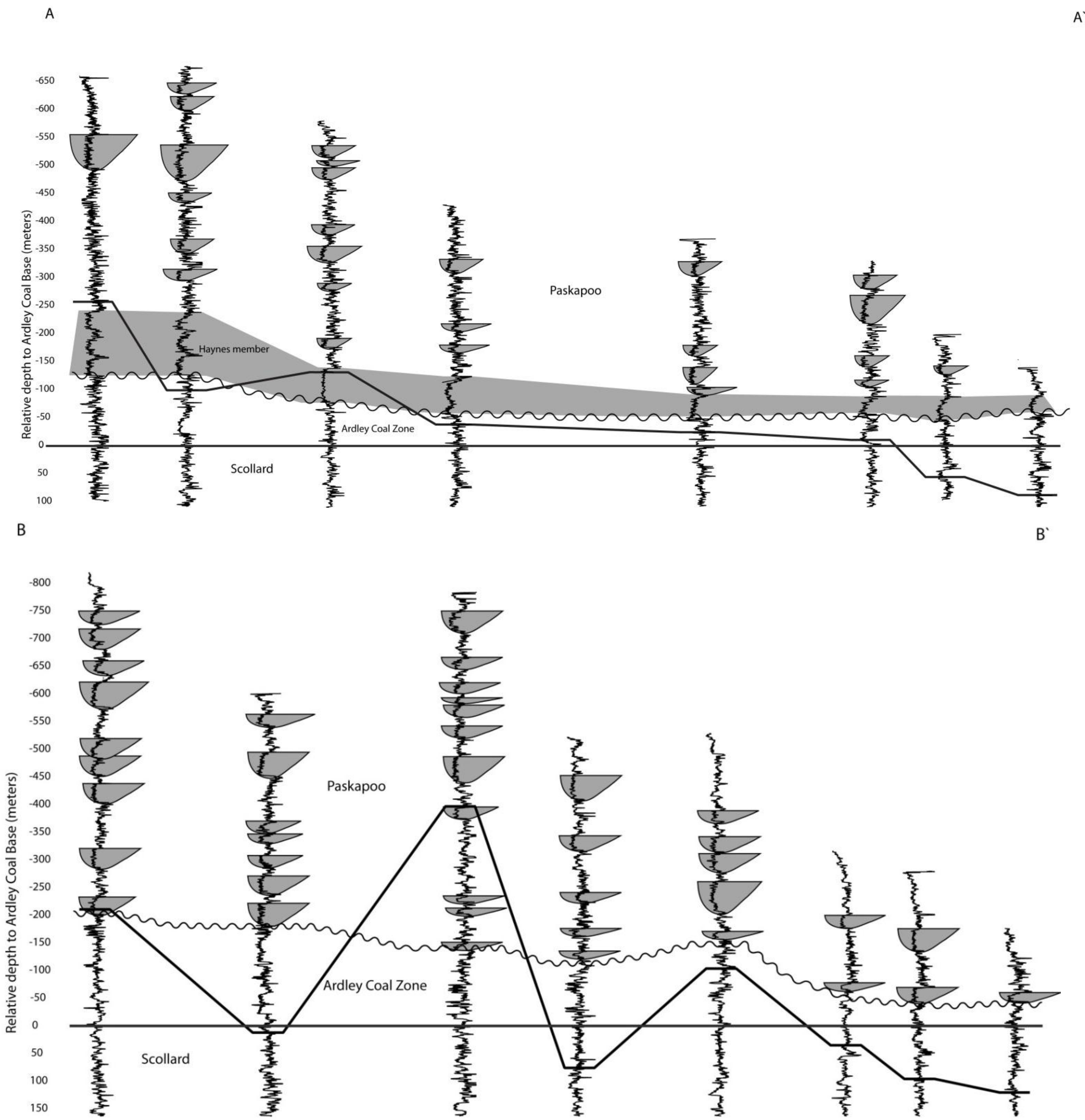


Fig. 9: Stratigraphic sections of uncased and normalized gamma-ray logs. Datum is set to the base of the Ardley coal zone. Thick line shows the bottom of surface casing. A 1-2 my unconformity is interpreted for the base of the Paskapoo (Lerbekmo et al. 1992) and shown as a chevron line. Sandstone bodies are highlighted in grey. Most sand bodies greater than 10 meters thickness likely represent multistory channel fill successions. *a*) A-A' spans 80 km of the project area, *b*) B-B' stratigraphic-section trends south to north and is 120 km in length.

packages in the northwest portion of the area demonstrates changes in fluvial regimes within the Paskapoo Formation. A thick laterally continuous sandstone-dominated basal Haynes Member is not obvious in the northern stratigraphic section

These and future stratigraphic and structural cross-sections can be utilized to better understand groundwater resources and to improve reconstructions of fluvial deposition in the Alberta foreland basin during the Paleocene. Creation of a normalized continuous log curve permits alternate mapping techniques in fluvial successions, such as slice-mapping. The bimodal lithological nature of the Paskapoo Formation (i.e. clean channel fill or mud) is amenable to this technique, whereas more classical lithostratigraphic analysis based on correlation may not be as effective.

Conclusion

We have described and demonstrated a normalization methodology for the suite of new gamma-ray data made available since December of 2006, in the WCSB. The methodology makes use of established normalization equations and statistical values derived from uncased zones in "analogous" strata. It utilizes the current understanding of fluvial strata and basic geologic assumptions to generate normalized curves suitable for geological interpretation. Here we have established a work flow for the use of gamma ray as a correlative tool in the "cased zone". The data in our example consisted of 572 wells, with gamma-ray curves either from the cased or uncased zone. The principal assumption is that the gamma-ray lower and upper bound values of the uncased zone (Scollard and Ardley coal zone and lower Paskapoo) are the same as those of the cased zone. The methodology makes use of proximal strata directly below surface casing, but any available data on strata considered analogous may be utilized regardless of proximity. The use of P2 and P95 values helps mitigate the negative effects of coal and bentonite, lithologies with extremely low and high API values, respectively. The range of normalized gamma-ray values produced in this example is consistent with the expected range of values. The character/shape of the normalized cased curves are similar to those of the open-hole logged curves, creating a continuous log to surface. The resultant curves are suitable for discriminating between sand bodies and fine grained silty sands and muds. The normalization equation specifically relies on the P2 and P95 values being consistent between the uncased and cased zones. Varying sandiness and general heterogeneity will be retained after normalization, as the histogram of API values may take any shape, skew left, skew right, bi-modal, as long as the P2 and P95 values are similar. The normalization merely increases the spread and the overall values, and does not alter its distributional character (Fig. 6). The histograms of the differences of the mean observed in Figure 8 provide quantitative support for our principal assumption. The normalization procedure is effective, as the mean of Figure 8*c* (-1.5) is much closer to the mean of 8*b* (0.13) than the mean of 8*a* (-25.4). Future applications for the normalized curves include the construction of conventional dip/strike sections, as well as sand slice maps and potential mapping of channel belts. The new logged to surface gamma-ray data combined with the normalization technique will lead to a better understanding of the Paskapoo Fm. and contribute to improved depositional models and understanding of the groundwater resources in the region

References

Beaumont, C. 1981. Foreland Basins, Geophysical Journal of the Royal Astronomical Society, 65(2), pp. 291-329

Burbank, D.W. 1992. Causes of recent Himalayan uplift deduced from depositional patterns in the Ganges basin, letters to Nature, Vol, 357, pp. 680-683

Burns E. R., Bentley, L.R., Hayashi, M., Grasby, S.E., Hamblin, A.P., Smith, D.G., and Wozniak, P. R. J. 2010. Hydrogeological implications of Paleo-fluvial architecture for the Paskapoo Formation, SW Alberta, Canada: a stochastic analysis, Hydrology Journal, Vol 18, pp.1375-1390

Cant, J. D,and Stockmal, G.S. 1989. The Alberta foreland basin: relationship between stratigraphy and Cordilleran terrane-accretion events, Canadian Journal of Earth Science, 26(10), 1964-1975

Dawson, F. M., Evans, C. G., Marsh, R., and Richardson, R, 1994, Uppermost Cretaceous and Tertiary strata of the Western Canada sedimentary basin. Geological atlas of the Western Canadian Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, 387-406.

Demcuk, T. D, 1990, Palynostratigraphic zonation of Paleocene strata in the central and south-central Alberta Plains, Canadian Journal of Earth Science, Vol.27 pp. 1263-1269

Demchuk, T.D, and Hills, L. V. 1991, A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members, Bulletin of Canadian Petroleum Geology, Vol 39, No. 3, pp. 270-282

Demchuk, T.D, Nelson-Glatiotis, D. A. 1993, The Identification and significance of Kaolinite-rich, volcanic ash horizons (tonsteins) in the Ardley coal zone, Wabamun, Alberta, Canada, Bulletin of Canadian Petroleum Geology, Vol.41, pp.464-469

EUB directive 043, 2006, Well Logging Requirements – Surface casing Interval, Energy Research Conservation Board, ERCB/AGS

Fox, R.C, 1990, Pronothodectes Gaoi N. SP. From the late Paleocene of Alberta, Canada, and the early evolution of the Plesiadapidae (Mammalia, Primates). Journal of Paleontology, 64(4), pp. 637-647

Gibson, D. W, 1977, Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River valley, Alberta. Energy, Mines and Resources Canada pp. 41

Grasby, S.E., Zhuoheng, C., Hamblin, A. P., Wozniak, P. R. J., and Sweet, A. R. 2008, Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta, Canadian Journal of Earth Science. Vol. 45, pp. 1501-1516

Hamblin A. P, 1997, Regional distribution and dispersal of the dinosaur Park Formation, Belly River Group, Surface and subsurface of southern Alberta, Bulletin of Canadian Petroleum Geology, Vol. 45, pp. 377-399

Hamblin, A.P, 2004, Paskapoo-Porcupine Hills Formations in Western Alberta: Synthesis of Regional Geology and Resource Potential, Geological Survey of Canada, Open File 4679

Jerzykiewicz, T. 1997, Stratigraphic framework of the uppermost Cretaceous to Paleocene strata of the Alberta Basin. Ottawa (Ont.)

Kalkreuth, W., and Langenberg, C. W. 2002, Petrography of Ardley Coals, Alberta-Implications for Coalbed Methane Potential, EUB/AGS special report 55

Langenberg, C., Berhane, W. H., Sweet, A. R., Marchioni, D., and Heaman, L. M. 2007, Regional Correlations of the Ardley Coal Zone, Alberta, EUB/AGS Earth Science Report, 05(21)

Leckie, D. A, and Smith, D. G. 1992, Regional Setting, Evolution, and depositional Cycles of the Western Canada Foreland Basin, American Association of Petroleum Geologists, Memoir 55, pp. 9-46

Lerbekmo, J. F., Demchuk, T. D., Evans, M. E., and Hoye, G. S. 1992, Magnetostratigraphy and Biostratigraphy of the Continental Paleocene of the Red Deer Valley, Alberta, Canada, Bulletin of Canadian Petroleum Geology, 40 (1), pp. 24-35

Lerbekmo, J. F., and Sweet, A. R. 2008, Magnetobiostratigraphy of the continental Paleocene upper Coalspur and Paskapoo formations near Hinton, Alberta, Bulletin of Canadian Petroleum Geology, Vol. 56, p. 118-146

Lyster, S., Andriashek, L. 2012, Geostatistical Rendering of the Architecture of Hydrostratigraphic Units within the Paskapoo Formation, Alberta. Energy Research Conservation Board, ERCB/AGS Bulletin 66.

Mclean, J. R., Jerzykiewicz, T.1977, Cyclicity Tectonics and Coal: Some aspects of Fluvial Sedimentology in the Brazeau-Paskapoo Formations, Coal Valley Area, Alberta, Canada, Canadian Society of Petroleum Geologists. Memoir (5)

Osborn, S. G, Vengosh, A., Warner, N. R., and Jackson, R. B. 2011, Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proceedings of the National Academy of Sciences, Vol, 108, no. 20

Price, R. A, 1994, Cordilleran Tectonics and the Evolution of the Western Canada Sedimentary Basin, Geological Atlas of the Western Canada Sedimentary Basin, 13-24.

Rider, M., Kennedy, M. 2011, The Geological Interpretation of well logs, 3rd edition, Rider and French consulting Limited, pp. 1-4, pp. 117-146

Shier, D.E, 2004, Well Log Normalization: Methods and Guidelines, Petrophysics, Vol, 45.3, pp.268-280

CHAPTER 3

Basin-scale stratigraphic architecture and Paleocene distributary fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada

[1]Quartero, E. M., [2]Leier, A.L., [1]Bentley, L. R. [3]Glombick, P.
emquarte@ucalgary.ca, aleier@ucalgary.ca, lbentley@ucalgary.ca
[1]Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4
[2]Department of Earth and Ocean Sciences, University of South Carolina, Columbia, 29208
[3]Alberta Geological Survey, Alberta Energy Regulator, Edmonton, AB T6B 2X3

ABSTRACT

The Paleocene Paskapoo Formation is composed of several hundred meters of fluvial strata that were deposited in an actively subsiding retro-arc foreland basin adjacent to the southeast Canadian Cordillera during the latest stages of oogenesis. Here, we utilize newly available subsurface data from down-hole gamma-ray geophysical well logs to reconstruct the large-scale fluvial architecture and depositional history of the northern part of the Paskapoo Formation. Paleocene fluvial strata in this region contain several important characteristics, including varying degrees of channel sandstone amalgamation, regionally-varying stratigraphic architecture, and an interpreted paleo-distributary fluvial system that emanated from the adjacent fold-and-thrust belt. In the southern portion of the study area, the base of the formation consists of amalgamated fluvial channel sandstone bodies, which become less prominent to the north. The middle interval of the Paskapoo Formation is characterized by abundant mudstone and isolated channel sandstone bodies and is relatively consistent throughout the study area. The upper portion of Paskapoo Formation is dominated by expansive sandstone- located in the northern part of the basin. This sandstone is present adjacent to the fold-thrust belt and fans out into the basin in two distinct lobes, covering an area of over 4,000 km^2. Based on the geometry, we interpret this feature to be a distributive fluvial system, or fluvial megafan. The correspondence between the location of this feature and the modern-day Athabasca River outlet suggests this area of the fold-thrust belt may be the site of a long-lived fluvial outlet. The variable degree of sandstone amalgamation in the Paskapoo Formation suggests two different modes in the relative ratio of accommodation to sediment supply. Periods of rapid subsidence, likely associated with thrust emplacement in the adjacent fold thrust belt, resulted in mudstone dominated successions with isolated sandstone bodies, whereas tectonically inactive periods

associated with less subsidence resulted in amalgamated sandstone units. The principal stratigraphic features reconstructed from the data in this area can be used to better understand and predict fluvial stratigraphy within other foreland basins.

1. INTRODUCTION

Fluvial systems that emanate from fold-and-thrust belts typically represent the principal mechanism for transporting clastic sediment from mountains to the adjacent foreland basin. Foreland basin deposits resulting from this process can be highly complicated, both in the vertical succession of strata, and laterally, along depositional strike (i.e., parallel to mountain front). Stratigraphic trends in non-marine foreland basins are strongly influenced by subsidence rates (e.g., Heller, 1988; Shuster and Steidtmann, 1988; Jordan and Flemings, 1989; Bridge, 1993; Paola, 2000), but can also be impacted by other factors such as the location of fluvial outlets (e.g., Gupta, 1997; DeCelles and Cavazza, 1999, Weissmann et al., 2010). For ancient foreland basin successions, isolated outcrop-based studies are an excellent source of detail about paleo-river systems, but because of their localized nature, they are not always well-suited for characterizing regional fluvial stratigraphy. Modern foreland basins contain a number of large-scale depositional features and sedimentary trends, many of which may be unrecognized in ancient successions owing to the fact that regional data sets are often required (e.g., DeCelles and Cavazza, 1999; Shukla et al., 2001; Weismann et al., 2010). Ideally, a three-dimensional reconstruction of fluvial stratigraphy in a foreland basin is based on a regional, three-dimensional dataset; however, data of this nature are not common.

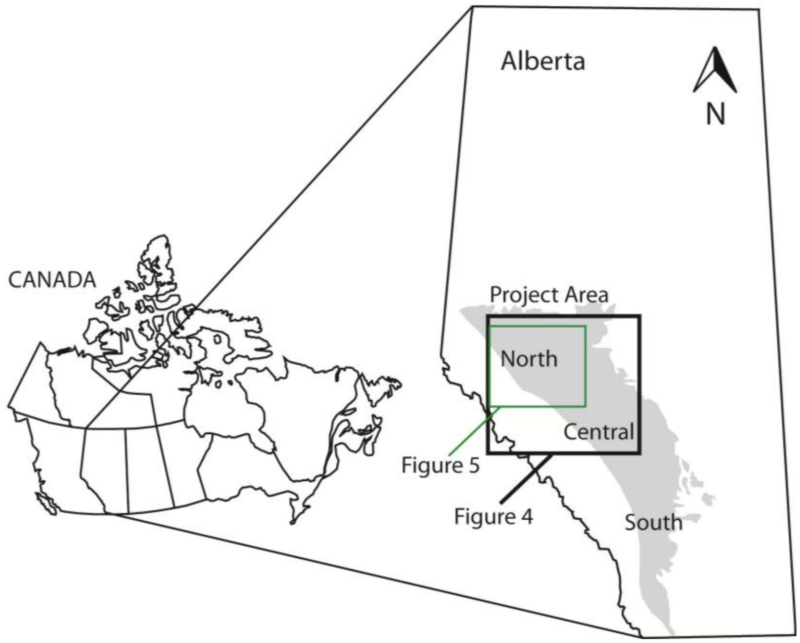


Fig 1: Map of project area. The extent of the Paleocene Paskapoo and Scollard formations is shown in gray. Basin is subdivided into northern, central, and southern areas. Zero edge of formation is based on Dawson et al, 1994, (Fig. 24.1). Figure 4 and 5 map boundaries are displayed.

The Alberta foreland Basin formed east of the Canadian Cordillera (Fig. 1; Bally et al., 1966; Cant and Stockmal, 1989; Price, 1994; Miall, 2008) and contains data from thousands of down-hole geophysical well logs from oil and gas wells. As of 2006, regulations from the Energy Utilities Board (EUB), now the Alberta Energy Regulator (AER), require that all oil and gas wells drilled in Alberta log the natural gamma-ray response to the ground surface, which as a result, has produced an influx of new data on the near-surface stratigraphy (<500 m below surface). The majority of this stratigraphy belongs to the Paskapoo Formation, a Paleocene-age fluvial unit deposited in the Alberta foreland basin concomitant with folding and thrusting in the Canadian Cordillera fold-thrust belt (Fig. 2). The Paskapoo Formation has long been known to contain a complex stratigraphic architecture of fluvial sandstones and mudstones, although the regional stratigraphic models vary (Demchuk and Hills, 1991; Hamblin, 2004; Grasby et al., 2008; Lyster and Andriashek, 2012). Characterizing the regional-scale distribution of fluvial sandstone packages within the Paskapoo Formation has become more important recently owing to the fact these units are the primary aquifers for much of the region (Lyster and Andriashek, 2012). Because of the data's areal coverage, the stratigraphic architecture of this succession can be used as an analogue for other non-marine foreland basins where data are less abundant.

Here, we utilize well-log gamma-ray data from more than 1000 recently drilled wells from the northern and central portion of the Alberta foreland basin in order to characterize and interpret the basin-scale fluvial stratigraphy of the Paleocene Paskapoo Formation (Fig. 1). Sandstone-to-mudstone ratio maps (hereafter referred to as net-to-gross) from the study area reveal several first-order features. These include a feature interpreted as a large, distributary fluvial fan in the northern portion of the basin, and significant along depositional-strike variations in the amount and amalgamation of fluvial channel sandstone bodies. A mudstone-dominated succession in the middle of the Paskapoo Formation, which has been recognized previously in core, reference sections, and outcrop, is pervasive throughout the region and likely correlates to a period of active thrusting in the adjacent fold-and-thrust belt (e.g., Heller et al., 1988; Demchuk and Hills, 1991). Overall, the data set presented here provides a new look at some of the youngest preserved fluvial stratigraphy of the Alberta foreland basin across an area >35,000 km^2.

2. REGIONAL GEOLOGY

2.1 Foreland Basin

Accretion of terranes in the southwest Canadian Cordillera produced a crustal load of over-thickened lithosphere on the western margin of the North America, and resulted in the formation of the Alberta foreland Basin (Fig. 1; Bally et al., 1966; Price, 1994; Miall, 2008). Subsidence in the foreland basin initiated during Late Jurassic and continued until the early Eocene (Price, 1994). The foreland basin was infilled largely by clastic sediment derived from the adjacent fold-and-thrust thrust belt (Bally et al., 1966; Leckie and Smith, 1992). This sediment was deposited in non-marine and marine environments, as a relatively shallow continental seaway occupied the region for part of its history (Leckie and Smith, 1992; Miall 2008). By Paleocene time, the continental seaway had receded and deposition in the basin was dominated by non-marine fluvial environments, which today comprise the Paskapoo Formation (Mack and Jerzykiewicz, 1988; Leckie and Smith, 1992). Subsidence in the Alberta foreland basin ceased by early Eocene time as contraction in the adjacent fold-thrust belt came to an end (Price 1994).

2.2 Stratigraphy

2.2.1 Paskapoo Formation

The near-surface stratigraphy in west-central Alberta is composed primarily of the Paleocene Paskapoo Formation. This unit is 0-800 m in thickness, composed of heterogeneous fluvial strata, and covers an area over 65,000 km^2 (Fig. 1; Grasby et al., 2008). It is thickest at the edge of the deformed belt, and is thought to be the product of Cenozoic synorogenic and post-orogenic deposition in the basin (Beaumont, 1981; Cant and Stockmal, 1989; Demchuk and

Hills, 1991; Leckie and Smith, 1992; Price, 1994; Jerzykiewicz, 1997). The Paskapoo Formation is middle to late Paleocene in age and represents the youngest preserved strata of the foreland basin (Demchuk and Hills, 1991; Lerbekmo et al., 1992; Lerbekmo and Sweet, 2008).

The Paskapoo Formation unconformably overlies the Scollard Formation (Fig. 2), an interbedded succession of fluvial sandstone, siltstone, and mudstone; with localized coal seams present (Gibson, 1977; Dawson et al., 1994; Lerbekmo and Sweet., 2008). Within the uppermost portion of the Scollard Formation is the Ardley coal zone, a regionally correlatable interval composed of several coal seams. This coal zone is correlatable over large distances and is commonly used as a stratigraphic datum in the region (Langenberg et al., 2007). The base of the Paskapoo Formation is defined as the base of the first prominent sandstone situated above the uppermost coal seam in the underlying Scollard Formation (Gibson, 1977; Demchuk and Hills, 1991; Dawson et al., 1994). This surface is understood to be an unconformable erosional contact representing an estimated hiatus of 1-2 million years (Lerbekmo et al., 1992, 2008). However, the definition of the base of the Paskapoo Formation is an operational definition and, in some locations, it may not coincide with the unconformity associated with the top of the underlying Scollard (Gibson, 1977). The uppermost boundary of the Paskapoo Formation is represented by an erosional contact with Pleistocene glacial deposits or the modern-day surface topography (Demchuk and Hills, 1991; Lyster and Andriashek, 2012).

The Paskapoo Formation is divided into three members, which from oldest to youngest consist of the sandstone-dominated Haynes Member, the mudstone-dominated Lacombe Member, and the uppermost Dalehurst Member (Fig. 2; Demchuk and Hills, 1991). The basal Haynes Member averages 50 m thick and is composed of coarse-grained amalgamated fluvial channel deposits (Demchuk and Hills, 1991; Jerzykiewicz, 1997; Hamblin, 2004). The Haynes Member is Middle Paleocene in age (Fox, 1990; Demchuk and Hills, 1991).

The overlying Lacombe Member (Fig. 2) comprises the majority of the Paskapoo Formation and is characterized by extensive siltstone and mudstone beds with isolated, very fine to medium grained, sandstone channel deposits (Demchuk and Hills, 1991; Lyster and Andriashek, 2012). The Lacombe Member has a maximum thickness of roughly 500 m along the western margin of the basin, and thins towards the northeast. The siltstones and shales contain abundant plant fragments and pedogenic structures (Demchuk and Hills, 1991; Dawson et al., 1994). Based on vertebrate paleontology and palynology, the Lacombe Member is interpreted as late Paleocene in age (Krause, 1978; Demchuk, 1990; Fox, 1990).

The Dalehurst Member is the uppermost unit, and consists of fine-grained sandstone beds interbedded with siltstone, mudstone, and coal (Demchuk and Hills, 1991). In outcrop, the Dalehurst Member is regionally restricted, present only in the northern portion of the study area (Fig. 1 and 2) near the town of Hinton. The Dalehurst Member is distinguished from the Lacombe Member by its coarser grained sandstones and thick economic coals (Demchuk and Hills, 1991). The Dalehurst Member is late Paleocene in age, slightly younger than the underlying Lacombe Member (Demchuk and Hills, 1991).

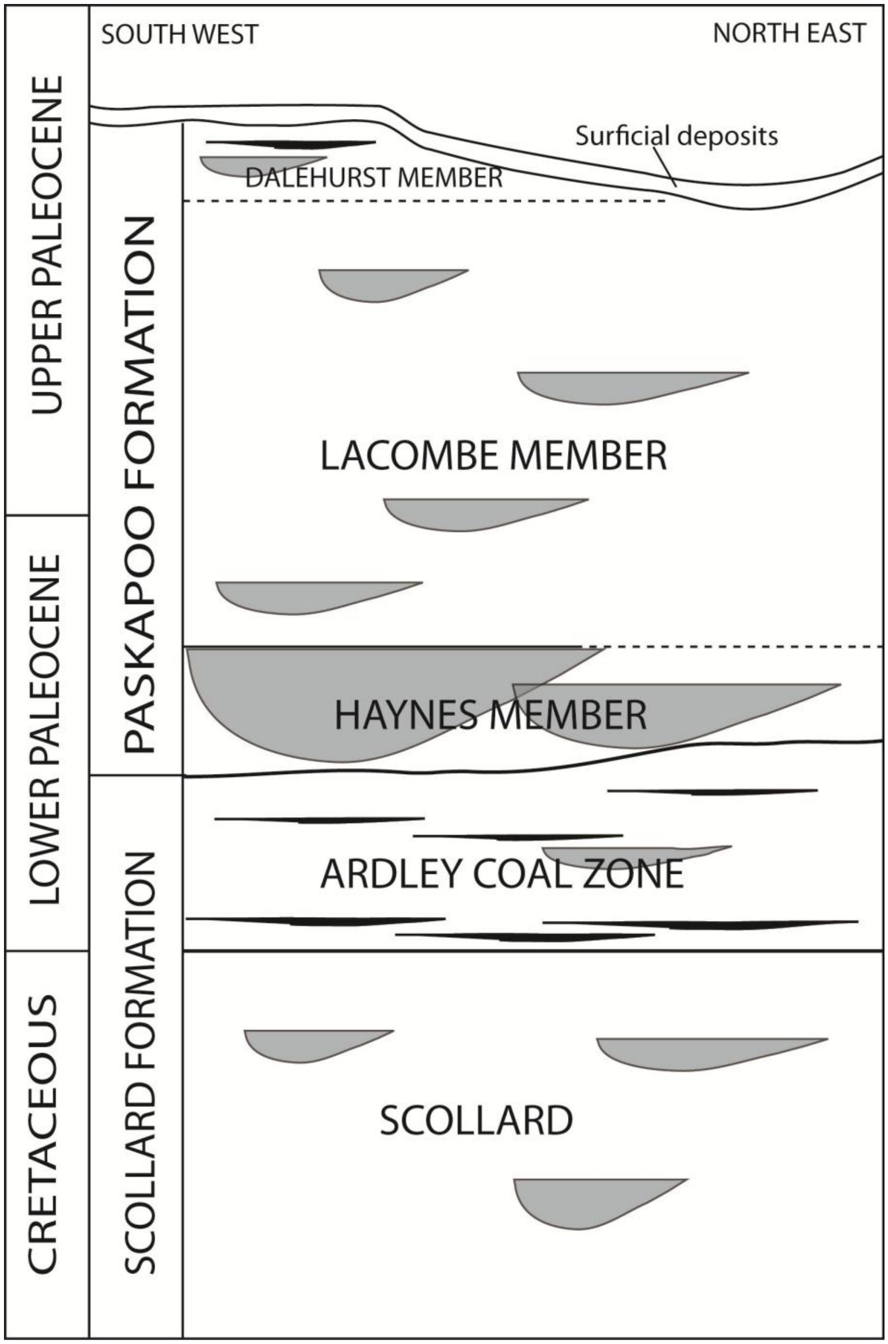


Fig 2: Stratigraphic column of the fluvial dominated late Cretaceous through Paleocene strata of the Alberta basin (from Demchuk and Hills, 1991; Lyster and Andriashek, 2012). The majority of the section is comprised of fine siltstone and mudstone, with isolated and stacked channel sandstone sequences (shown in grey). Coal seams are present within the Ardley coal zone and the upper portion of the Dalehurst Member.

3. WELL-DATA

We used 1002 wells from the Alberta foreland basin to map, characterize, and interpret the fluvial strata of the Paskapoo Formation. The wells were chosen because they post-date the 2006 regulation that requires all well operators to collect the natural gamma-ray response all the way to the surface (EUB 2006). Wells drilled prior to this time usually only contained data located below surface casing which at best captures the lower portion of the formation (e.g., Demchuk and Hills, 1991; Grasby et al., 2008). Well-data are publically available in the province of Alberta and digital files of the gamma-ray logs from individual wells were loaded into IHS Petra® software. The total regional coverage encompasses an area of approximately 35,000 km^2 (Fig. 4). In all of the wells, the gamma-ray log coverage extends from 20 m below the Kelly bushing (KB) to the base of the Ardley coal zone in the underlying Scollard Formation. Well data are present throughout most of the study area, although the distribution of our data is concentrated in the northern portion of the basin (Fig. 4).

3.1 Lithology

The discrimination between sandstone and mudstone lithologies within the Paskapoo Formation was made using the gamma-ray values of the well-logs. We used a gamma ray value cut-off of 75 API to determine sandstone (<75 API) and mudstone-siltstone (>75 API), which is commonly employed for Alberta and much of North America (e.g., Cluff and Cluff, 2004; Andriashek and Lyster, 2012; Medina and Rupp, 2012). Varying the cut-off value did not significantly alter our results, and the presence of K-feldspar in the sandstones is not an issue for the Paskapoo Formation (Demchuk and Hills, 1991; Rider and Kennedy, 2011). Because of the shallow nature of the strata, portions of the well-logs had gamma-ray readings measured through the surface casing interval, which suppresses the natural gamma-ray response. To correct for this, we used a statistical normalization procedure with constants derived from analogous strata in uncased portions of the Paskapoo Formation and Scollard Formation (Quartero et al, 2014). Normalized logs displayed excellent correlation with uncased zones; a detailed description of the process can be found in Quartero et al. (2014).

3.2 Datum

We used the base of the Ardley coal zone as a regional datum. The Ardley coal zone is easily recognizable on density logs, and occurs throughout the basin (Langenberg et al., 2007). Moreover, palynology and U-Pb dating indicate the basal coal seam of the Ardley coal zone represents the Cretaceous-Paleocene boundary (Langenberg et al., 2007; Lerbekmo and Sweet 2008), making this zone a useful stratigraphic datum with chronostratigraphic significance.

4. MAP RECONSTRUCTIONS

4.1 Methodology

We generated two net-to-gross maps that cover a vast area of the north and central portion of the Alberta Basin with well-log data (Fig. 1, 3 and 4), and four semi-regional maps that cover the northern portion of the map area (Fig. 3 and 5), where data-density is highest. The net-to-gross maps represent the net sandstone thickness as a ratio of the gross interval thickness (based on a <75 API cut-off; see explanation above) divided by the measured thickness of specific stratigraphic intervals.

Net-to-gross maps derived from the entire thickness of the Paskapoo Formation are ineffective at revealing detail about depositional architecture, net-to-gross ratios are over too great of a thickness, as multiple distinct depositional zones are averaged over the entire formation thickness. To examine detailed variations in net-to-gross values within particular intervals of the formation, we subdivided the succession into distinct layers, and examined the net-to-gross variations within these zones (Fig. 3). Subdividing the Paskapoo Formation is complicated, as: 1) the formation lacks any regionally mappable internal chronostratigraphic or lithostratigraphic markers, 2) the formation thickens from east to west, and 3) it is present at varying elevations throughout the basin. Figure 3 depicts the scheme used to generate the different sets of exploratory net-to-gross sand maps.

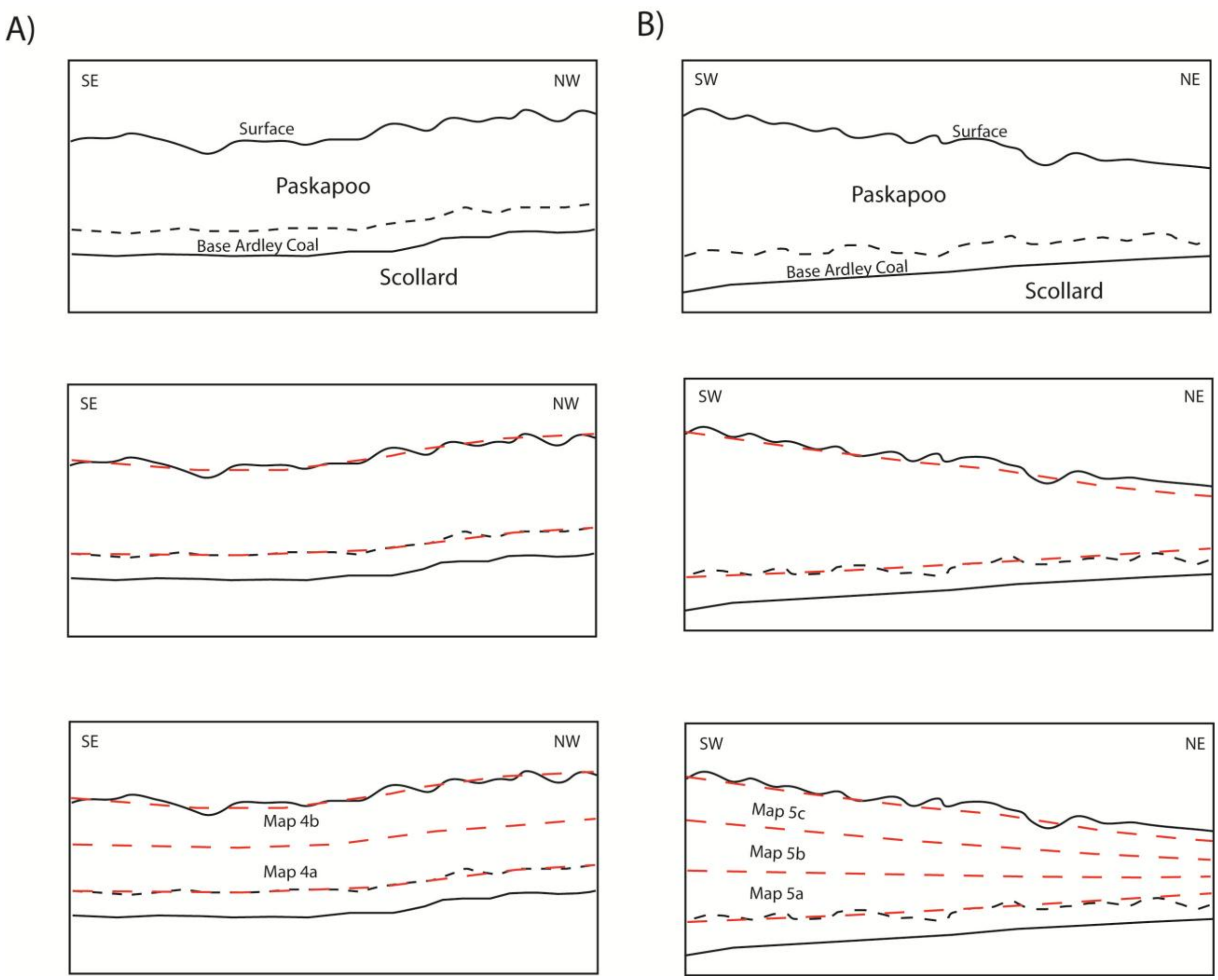


Fig 3: A) Schematic diagram of the layers for maps in Figure 4, in strike section view. Map division shown by red dashed line, interval set at half the formation thickness, relative to the generalized surface estimates of the upper and lower formation boundaries. B) Schematic work flow for the generation of layers used in Figure 5, in cross section view. Smoothed surfaces first estimated for the unconformable base and top of the formation, to generate lower middle and upper layers for Figure 5.

For the regional net-to-gross maps (Fig. 4), the Paskapoo Formation was divided in two (Fig. 3a). The formation thickens considerably to the west, but lacks any correlative internal horizons, which makes dividing the formation into distinct stratigraphic intervals problematic. In attempt to objectively overcome this we divided the formation thickness in each well. This started with the generation of smoothed generalized top and base picks for the formation, established by selecting a top and base pick from a small number of wells across the study area, and generating a gridded surface is superimposed on the remaining wells. The use of generalized upper and lower bounds is crucial for the generation of the net-to-gross layers, in order to mitigate the effects of erosional topography on the formation's division. As previously mentioned the formation was first divided in two, creating an upper and lower Paskapoo (Figs. 3a and 4). Potentially any number of divisions of the formation can be used to correlate between wells to yield stratigraphic horizons that thicken toward the front of the fold-thrust belt and thin proportionally toward the eastern zero-edge of the formation (Fig. 3b). The net-to-gross maps that focus on the northern portion of the basin, where the data density is higher (Fig. 5), use same base and top of the formation delineated for regional mapping (Fig. 4). However, here the strata are divided into three intervals instead of two. Three proportionally thick sections correspond to the mapped lower, middle and upper intervals (Fig. 3b, 7 and 8). Although not perfect, this method replicates the general stratigraphic trend of deposits in a foreland basin and is repeatable. These divisions do not correspond to true time-stratigraphic horizons, and as a result some individual depositional features may be sampled in more than one net-to-gross interval. With this methodology the incidence of depositional features sampled across multiple net-to-gross intervals will positively correlate with a greater number of intra-formational divisions, thus we used a lower number of such divisions. Our interpretations are relatively conservative because the formation was divided into three relatively thick intervals. Moreover, the fact that the same first-order features and trends are present in the larger-scale maps and the semi-regional maps (cf. Fig. 4b and 5c) provides confidence that these features are real and not a function of the methodology. However, it should be noted that where wells are located in low topography, and hence below the smoothed upper boundary of the Paskapoo Formation, the net-to gross value is calculated with missing log coverage resulting in a lower overall net-to-gross. This affects roughly 5% of the wells and the majority seem to be concentrated around the Athabasca river valley (i.e., cross hatched areas of Figs. 4b and 5c). No distinct low net-to gross values are observed trending along the modern river systems, and therefore this factor does not alter our interpretations.

4.2 Results

4.2.1 Regional maps

The net-to-gross maps from the entire study area are divided into a lower and upper interval (Fig. 4a and 4b, respectively). Within the lower interval of the Paskapoo Formation (Fig. 4a), the areas of higher net-to-gross tend to be located along the western (proximal) portion of the foreland basin, near the fold-thrust belt, although some zones of slightly higher net-to-gross are present in the northeast (distal) margin of the basin. No distinct linear features are evident in the lower portion of the Paskapoo Formation (e.g., channel belts) however this may be a function of the coarse divisions used to generate this map. Isolated lobate high net-to-gross, features are present in the southwestern portion of the study area.

One large-scale trend present in the lowermost portion of the Paskapoo Formation is a general decrease in net-to-gross values from south to north (Fig. 4a). The areas with the lowest net-to-gross values (~<0.2) are located almost exclusively in the northern portion of the study area. The Paskapoo Formation is at a slightly higher elevation in the northern portion of the study area; however, the net-to-gross values are based on ratios of sandstone to overall thicknesses (not absolute values of sandstone), so this cannot be used to explain why the net-to-gross values are lower in the north. This along-strike variation in the relative amount of sandstone within the Paskapoo Formation is supported by regional stratigraphic-strike cross-sections (Fig. 6).

The net-to-gross map of the upper interval differs from the lower interval (Fig. 4b). Areas of higher net-to-gross values are distributed more evenly across the basin. However, the overall trends should be viewed cautiously given that well coverage in the southern portion of the basin is limited. The most prominent feature in the upper interval is the zone with high net-to-gross values in the northern portion of the basin (Fig. 4b). In this area there is two north-trending features with high net-to-gross values (>0.6), one almost parallel to the strike of the fold-thrust belt.

A)

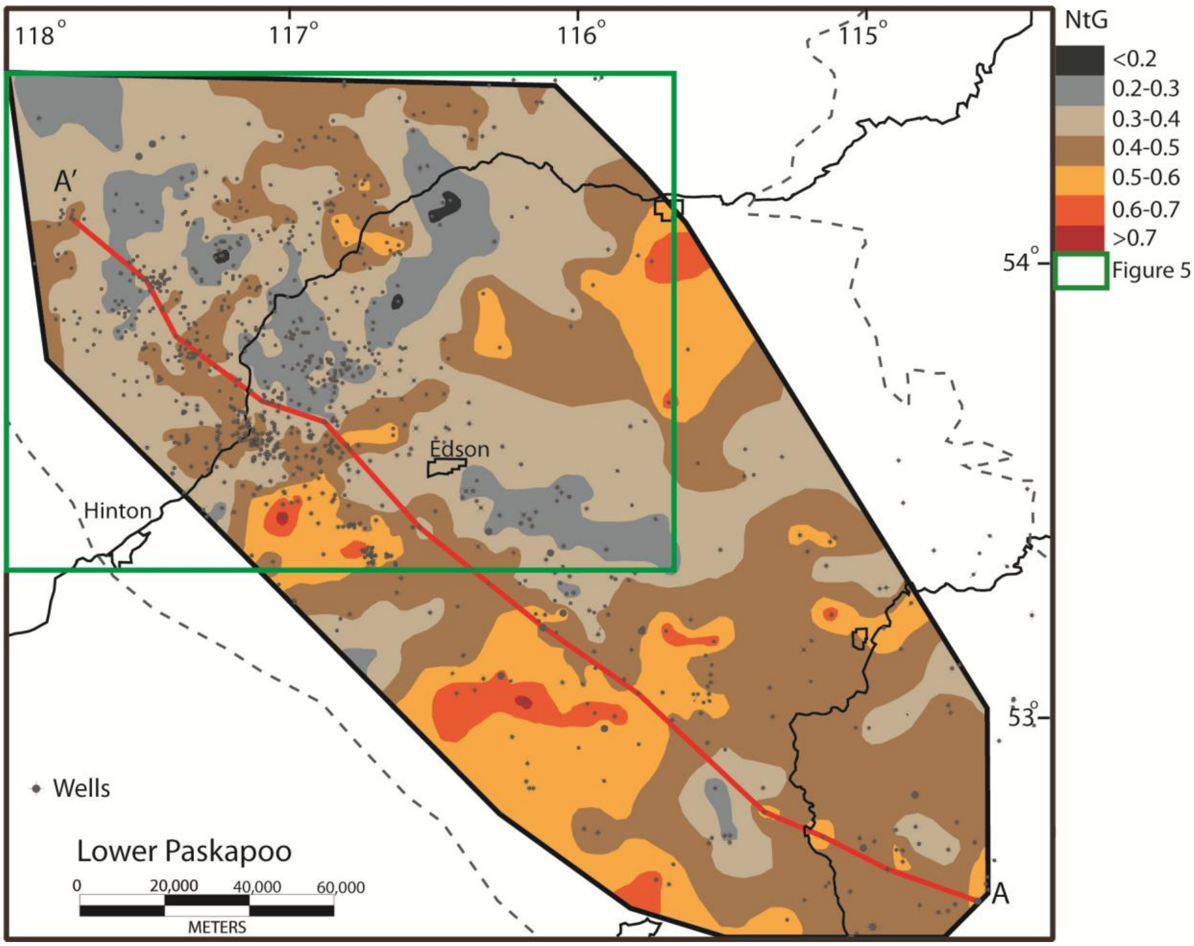


Fig 4: Maps of the regional study area. Well locations are plotted as point symbols. The map was constructed from 1002 wells with normalized logs. The net-to-gross maps divided into upper and lower layers of the Paskapoo Formation. (see Fig. 6 for The zone tops. Note the location of the stratigraphic strike cross-section line indicated in red (A-A'). Paskapoo Formation boundaries (deformational edge to the SW) marked by dashed line, and the Athabasca and North Saskatchewan Rivers with thin black lines. Map is contained within polygon where data are available. Hatched area indicates missing erosion windows through the upper section. Location of semi-regional net-to-gross maps outlined in green (Fig. 5). A) Lower Paskapoo, predominantly mudstone with higher net-to-gross rations in the central portion of the basin.

B)

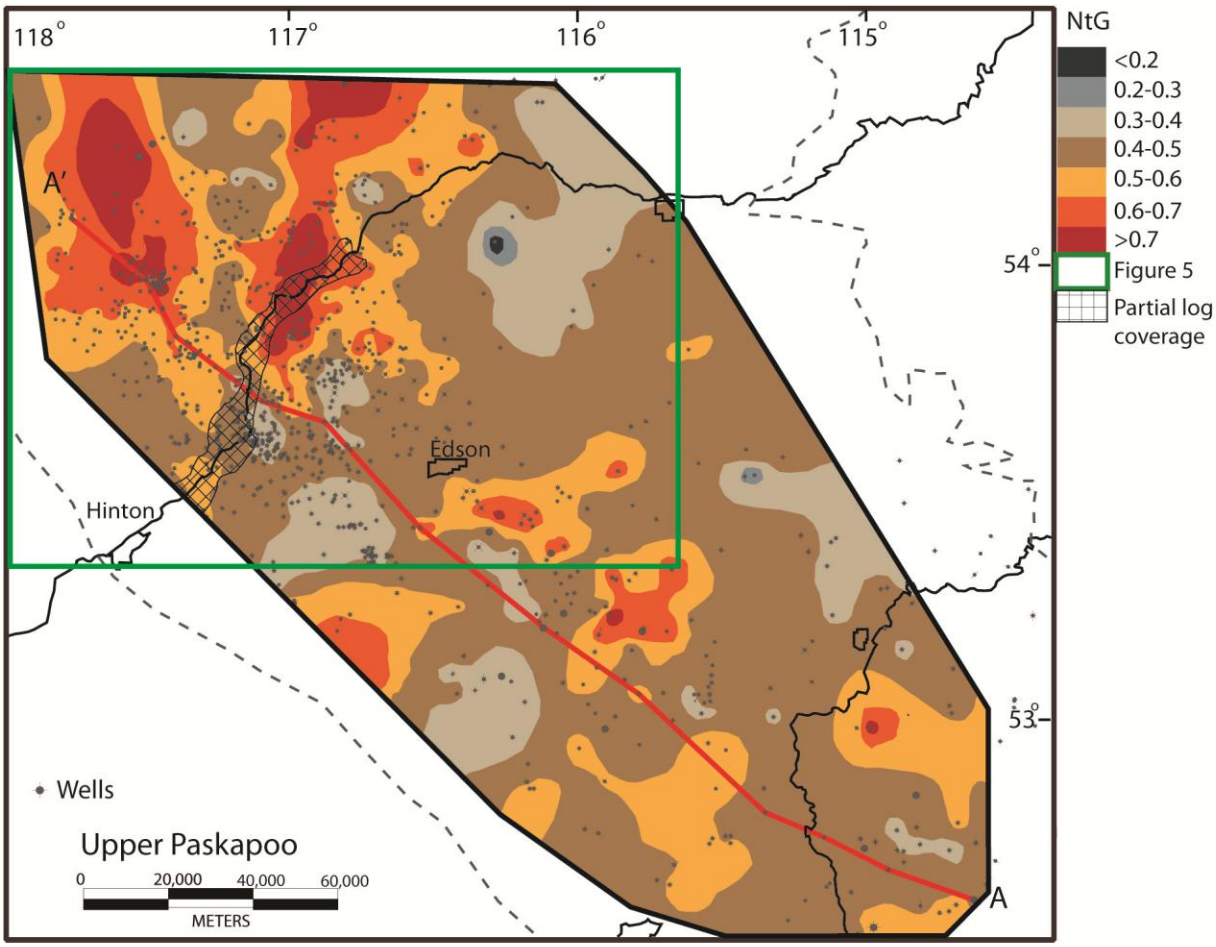


Fig 4. B) Upper Paskapoo with marginally higher net-to-gross ratios over a larger area in the southeast, and a high net-to-gross ratio feature in the northwest.

4.2.2 Semi-Regional maps: Northern Area

We focused detailed analysis on the northern portion of the study area because of the greater well-density. In this area, we divided the Paskapoo Formation into three intervals: a lower, middle and upper (Figs. 3 and 5). In this portion of the study area, the lower third of the Paskapoo Formation is characterized by relatively low net-to-gross values, with the exception of the area between the towns of Hinton and Edson, Alberta (Fig. 5a). The relative lack of sandstone in this area is consistent with the net-to-gross map constructed for the lower half of the Paskapoo Formation across the entire study region (Fig. 4a), and cross-section C-C' (Fig. 8). The middle and upper third of the Paskapoo Formation are characterized by the presence of high (> 0.7) net-to-gross zones, the same features as those in Figure 4b. The middle third interval contains an areal extensive and wide high net-to-gross zone that trends to the north (Fig. 5b). The uppermost interval within the Paskapoo Formation is dominated by two distinct lobate sandstone units with high net-to-gross values over 0.70 (Fig. 5c). This high net-to-gross feature covers an area of 4,000-5,000 km^2. Of the two high net-to-gross zones in this interval, one trends to the north, whereas the other is located proximal to the fold-thrust belt in the west and trends to the northwest. These features appear to intersect and abut against the fold-thrust belt near the town of Hinton, Alberta (Fig. 4c), and widen toward the north-northwest.

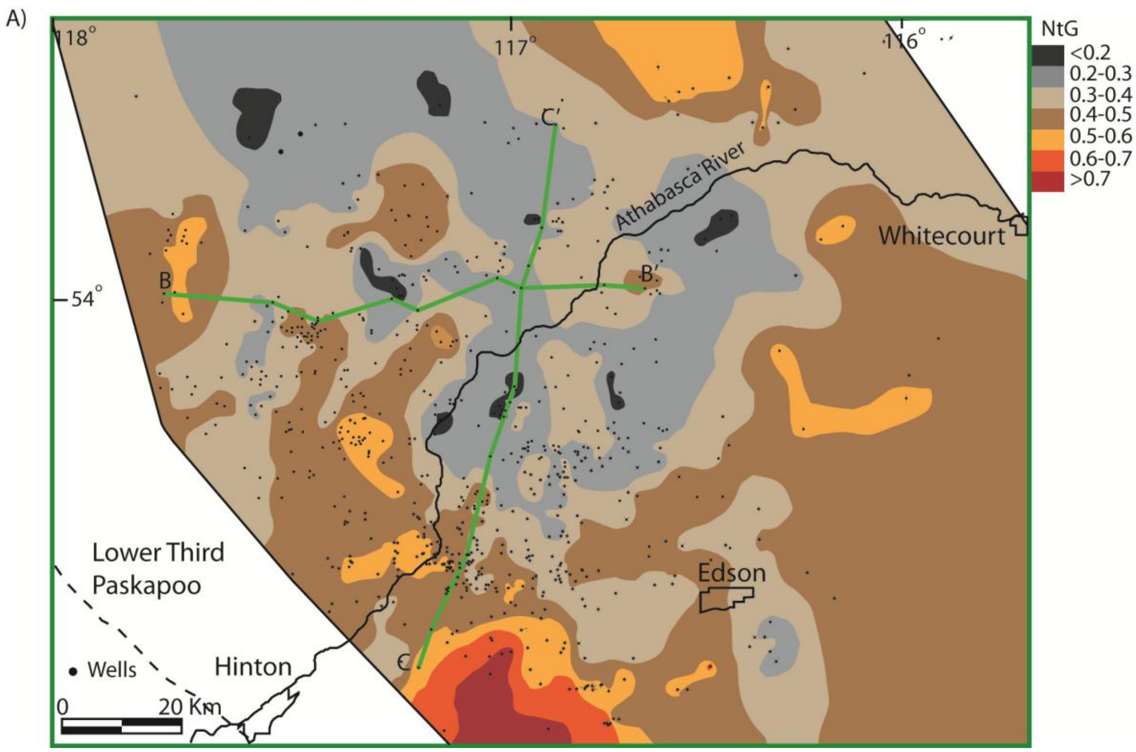
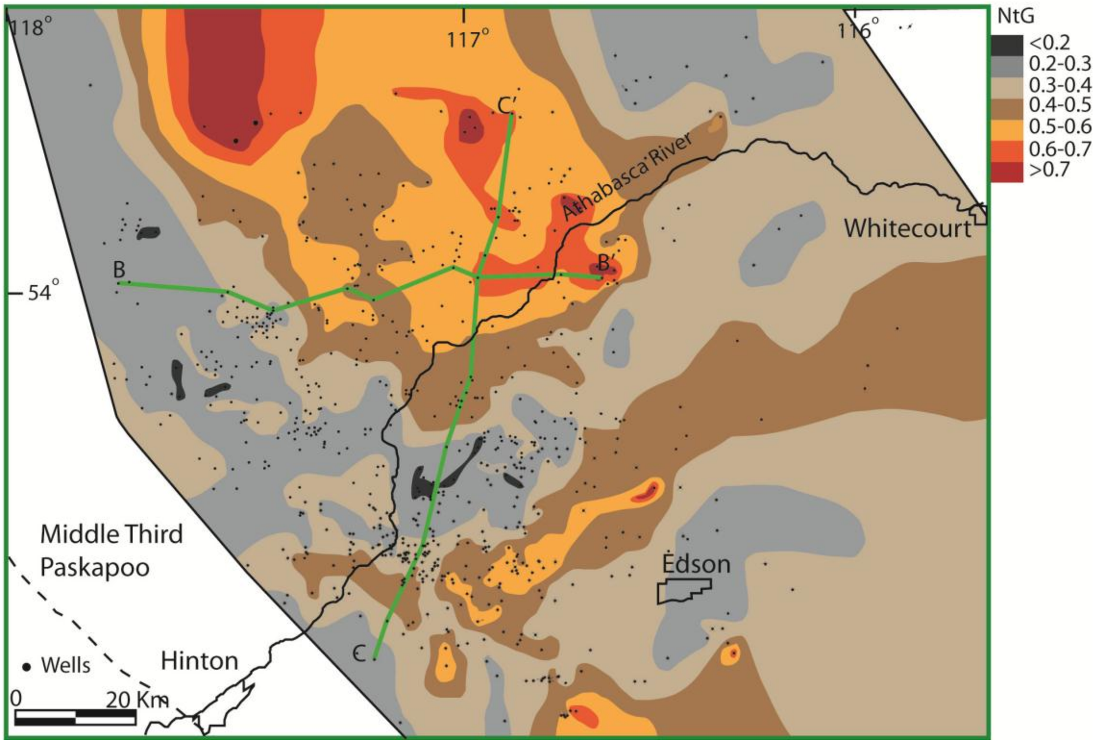


Fig 5: Three net-to-gross maps of the northern portion of the study area. Stratigraphic section lines B-B' and C-C' seen in green. Hatched area indicates an erosional window in the upper section. A) Lower third Paskapoo Formation, Low net-to-gross over the majority of the area, higher net-to-gross area in the south.

B)



C)

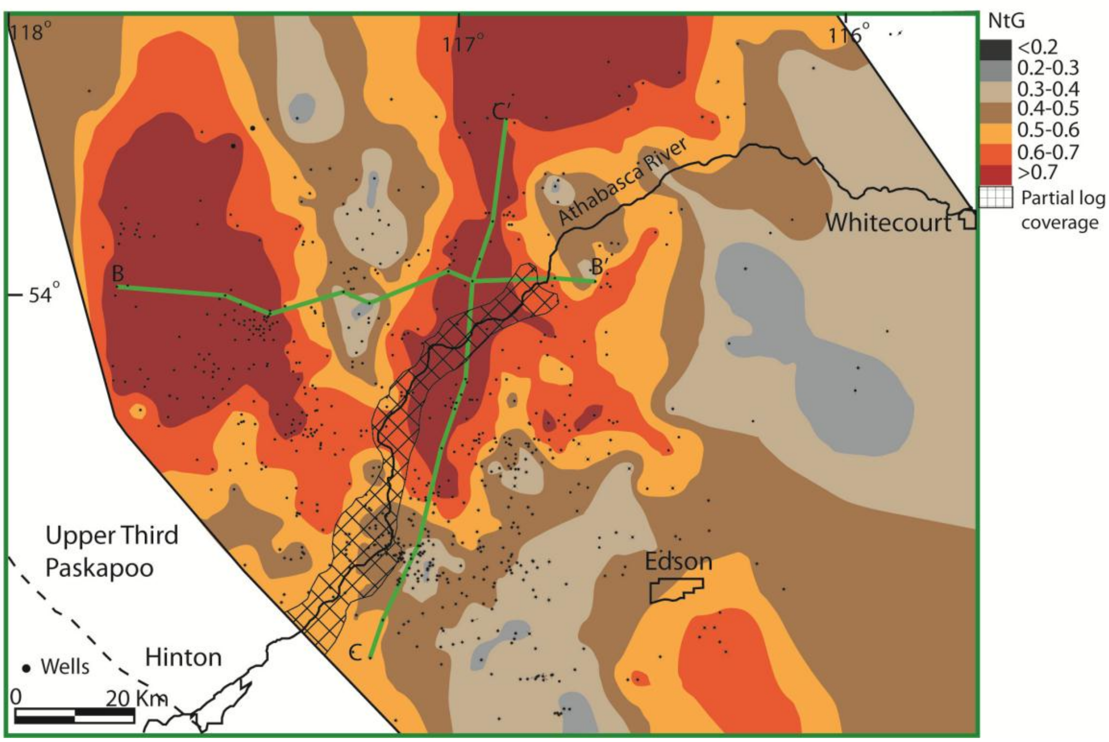


Fig. 5 B) Middle third layer of the formation, with northern trending high net-to-gross area apparent. C) Upper third layer of the formation, relatively high net-to-gross feature covering 4000 – 5000 km^2.

5. STRATIGRAPHIC CROSS-SECTIONS

5.1 Methodology

To further explore the results of the net-to-gross maps, we constructed three stratigraphic cross-sections. A 280-km regional cross-sectionwas constructed approximately parallel to the axis of the basin, along depositional strike (Fig. 6). Two additional stratigraphic cross-sections were constructed in the northern portion of the study area parallel and perpendicular to the basin axis (Fig. 7 and 8). These sections were constructed to further examine the high net-to-gross feature observed in the northern portion of the Paskapoo Formation (Fig. 7 and 8). The base of the Ardley coal zone was used as the datum for all stratigraphic-sections, and API values <75 were interpreted as sandstone. Stratigraphic intervals with high net-to-gross sandstone ratios are interpreted. Highlighted in grey, are the interpreted boundaries of the high net-to-gross feature in the upper section and sandstone at the base of the Paskapoo Formation. The apparent degree of amalgamation and channelization is unknown. However, fluvial architecture models predict channel sandstone superposition is near certainty in areas with net-to-gross values >0.75 (Bridge and Mackey, 1993; Bridge and Tye, 2000). Based on this, areas with ≥0.75 net-to-gross values likely are related to the amalgamated channel sandstone. The upper high net-to-gross feature is conservatively interpreted, and likely does not have the sharp boundaries depicted, but a more diffuse transition from high to low net-to-gross values.

5.2 Results

The regional southeast-northwest trending stratigraphic strike-section through the Paskapoo Formation illustrates many of the features observed in the net-to-gross maps (Fig. 6). The lower Paskapoo Formation in the central and southern of the western margin of the study area is sandstone-rich (Fig. 4a) and most likely corresponds to the Haynes Member, and a sandier lower Lacombe (Demchuk and Hills, 1991). Thick sandstone sequences become less abundant to the northwest, in the lower Paskapoo. As well, a thick basal sandstone that definitively correlates with Haynes member is not observed. Stratigraphic strike sections interpret a Haynes member across the basin (Fig. 6), but this interpretation may be an artifact of the classical definition for the base of the Paskapoo Formation (Fig. 4a and 6) being the first major sandstone sequence above the Ardley coal zone.

The semi-regional stratigraphic cross-sections (Fig. 7 and 8) highlight the high net-to-gross features observed in the maps (Figs. 4b and 5c). The high-net-to-gross features in the northern portion of the study area are present in the stratigraphic cross-sections as thick zones with <75 API values (Fig. 7 and 8). In the upper interval of the Paskapoo Formation the wells contain abundant sandstone (<75 API) packages that commonly range between 100-175m in thickness. The net-to-gross map in Figure 5c depicts two distinct zones with high net-to-gross values, one near the fold-thrust belt in the west and another that trends toward the north. The two high net-to-gross areas are separated by a zone with relatively low values. This feature is evident in the upper interval of the stratigraphic cross-section B-B' (Fig. 7). The high net-to-gross features are interpreted as multistory channels or channel belts. The sandstone-rich portions in the upper interval likely correlate to a succession of sandstones near the westernmost edge of the basin (Fig. 8b), although some of these deposits were omitted from the net-to-gross maps because they are stratigraphically above the generalized top used for mapping of the Paskapoo Formation.

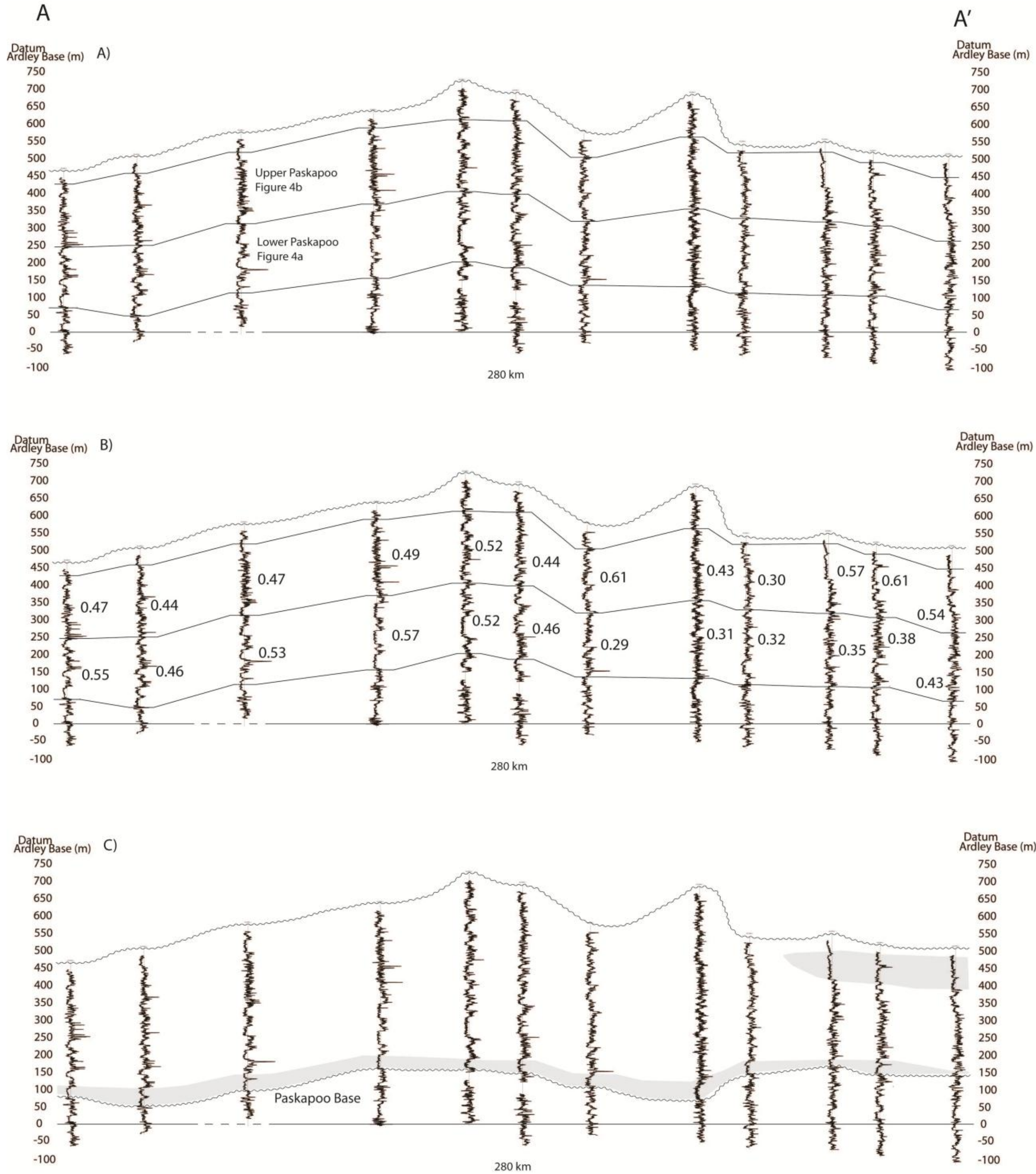


Fig 6: Stratigraphic strike-section A- A'(Ardley base coal datum) wells with normalized gamma-ray logs. Section location can be seen on Figure 4. A) Twelve wells showing the net-to-gross zone divisions for figure 4. B) Net-to-gross values of the twelve wells and layers of maps in Figure 4 are shown. C) Highlighted in grey, interpreted boundaries of high net-to-gross zone in the upper section, as well as the basal sand.

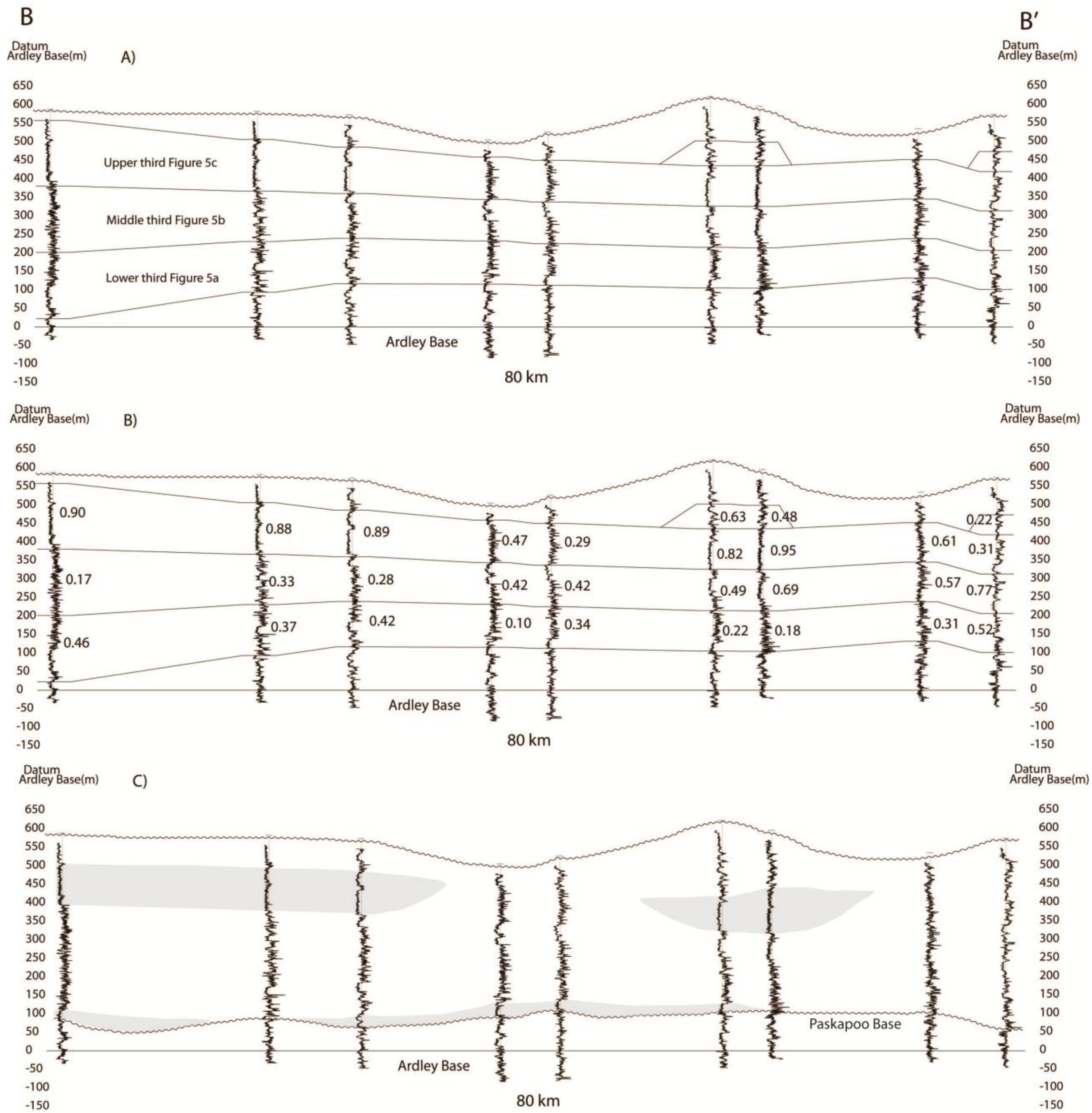


Fig 7: Stratigraphic cross-section B-B' (Ardley base coal datum) A) Nine well cross section with zone division used for net–to-gross maps in Figure 5. B) Layers from Figure 5 are populated with net-to-gross values of the nine wells. Where ~50 m of additional gamma-ray curve extends above the smoothed surface, net-to-gross is calculated. Section location can be seen on Figure 5. C) Interpreted base Paskapoo and high net-to-gross feature. Highlighted in grey are two distinct lobes of elevated sand fraction that are seen in Figure 5. Lower gray shading indicates the basal sand of the Paskapoo Formation where it exists.

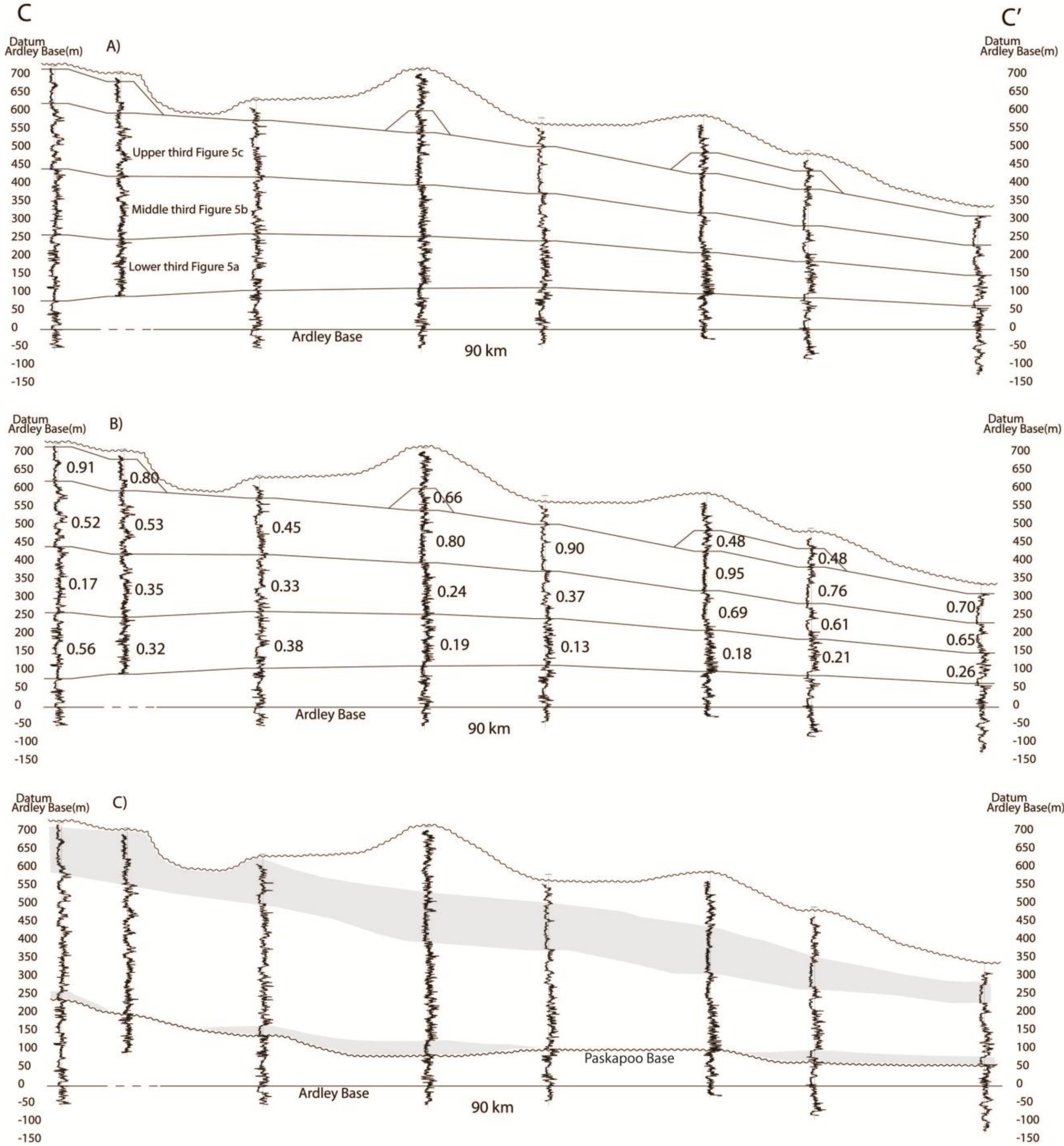


Fig 8: Stratigraphic cross-section C-C' (Ardley base coal datum) constructed from eight wells spanning 90 km. A) layers from maps in Figure 5. B) Calculated net-to-gross values for the eight wells, where ~50 m of additional gamma-ray curve extends above the smoothed surface. C) Interpreted base Paskapoo Formation and gray shading representing upper high net-to-gross feature. Lower gray shading indicates basal sandstone where it exists.

6. INTERPRETATION AND DISCUSSION

6.1 Foreland Basin Fluvial Stratigraphy

The Paskapoo Formation has been subdivided, based on lithostratigraphy, into three members: the Haynes, Lacombe, and Dalehurst members (Demchuk and Hills, 1991). These divisions are based on three reference cores taken from different locations from the central portion of the foreland basin. Well data and core was limited to the section below surface casing and a coal exploration core hole located near Hinton (Demchuk and Hills, 1991). The overall stratigraphy outlined by Demchuk and Hills (1991) is consistent with our observations from the gamma-ray response. However, some variation in the spatial extent and distribution of the members is evident in this new data set.

The lowermost interval considered in this study (Figs. 4 and 6) corresponds to the Haynes Member and lower Lacombe Member. The proportion of sandstone in this lowermost interval diminishes in the northern portion of the basin. The Haynes Member is difficult to trace north of the town of Hinton (Figs. 7 and 8). This is consistent with findings from Lyster and Andriashek (2012), who observed that the Haynes Member is more robust in southern and central Alberta. The along depositional-strike variability in the Haynes Member and lower Lacombe Member indicates the stratigraphic framework for one portion of the basin, namely the south and central portion, may not be appropriate for other parts of the basin such as those in the north.

The Haynes Member has been interpreted to overlie an erosional surface that, at least in some locations, incised into the underlying Scollard and Ardley coal zone. This surface is thought to represent a 1-2 million year hiatus (Lerbekmo, 2007). The base of the Paskapoo Formation is structurally shallower in the northern margin of the foreland basin (Fig. 6). Here, a thick basal sandstones are intermittent and the base of the Paskapoo Formation is interpreted by an absence of coals from the underlying Ardley coal zone (Figs. 6, 7 and 8; Lyster and Andriashek, 2012). Consequently, the thick package of sandstone typically associated with the Haynes Member does not exist in the northern part of the basin. For the most part, the proximal portion of the basin contains higher net-to-gross values and is also thicker, consistent with more rapid syn-depositional subsidence and a greater relative influx of sand-sized sediment, which is consistent with general foreland basin models (DeCelles and Giles, 1996). Care must be taken with interpretations of the regional maps produced (Fig. 4) as a significant decrease in well control to the south makes detailed interpretations tenuous.

A zone of overall relatively low net-to-gross values, interpreted to reflect an abundance of mudstone and siltstone, is present in the middle of the formation throughout most of the study area. This zone may correspond with the Lacombe Member to the south (Demchuk and Hills, 1991). As previously mentioned, where the Haynes Member is absent, the Lacombe Member, and by extension, the base of the Paskapoo Formation, is inferred from the termination of coal seams in the underlying Ardley coal zone (Figs. 7 and 8). The potential juxtaposition of the Lacombe Member directly above the Scollard Formation poses issues for the typical method of identifying the base of the Paskapoo Formation and a revised methodology may be necessary to distinguish subsurface units in this area. Additional core data may be required to identify the base of the Paskapoo Formation where the Haynes Member is absent or poorly developed.

The high net-to-gross feature present in the northwest portion of the study area overlying the Lacombe Member is interpreted to belong to the Dalehurst Member, which was originally described from coal exploration core hole taken near Hinton, by Demchuk and Hills (1991). Demchuk and Hills (1991) described a new member at the near surface that is characterized by thick economic coals and fine-grained sandstone that are mostly absent from the underlying

Lacombe Member. Palynological investigations suggested that the Dalehurst Member may be slightly younger in age than the upper Lacombe Member. Although Demchuk and Hills (1991) did not identify extensive amalgamated sandstones, this significant change in lithology at this stratigraphic location in the Paskapoo Formation is consistent with a distinct stratigraphic member (e.g., Fig. 7 and 8).

6.2 Distributary Fluvial System

The high net-to-gross feature present in the upper interval of the uppermost Paskapoo Formation in the study area (Fig. 5c) covers an area of 4,000-5,000 km^2. It is distributed over narrow zone adjacent to the fold-and-thrust belt near the town of Hinton, and becomes wider to the north and northeast. In addition, the western terminus of this feature coincides with outcrops of the High Divide Ridge Conglomerate, a localized unit of conglomerate beds within the Paskapoo Formation (Fig. 9a; Jerzykiewicz, 1985). The dimensions of the feature, the geometry of the high-percentage sandstone areas, the association with coarse-grained deposits, and the relationship to a fold-thrust belt are all consistent with a distributary fluvial system or fluvial megafan (e.g., Singh et al, 1993; Sinha and Friend, 1994; Gupta, 1997; DeCelles and Cavazza 1999; Horton and DeCelles, 2001; Leier et al, 2005; Weismann et al, 2010). Distributary fluvial systems and fluvial megafans are large fluvial features (~>2000 km^2) that emanate from an outlet in the fold-thrust belt, and deposit a large fan-shaped body of sediment in the adjacent foreland basin (DeCelles and Cavazza, 1999). The grain size of sediment in fluvial megafans reduces outward from the outlet (e.g., DeCelles and Cavazza, 1999). These features are relatively common in modern non-marine foreland basins, occurring, for example, in the Himalayan and Andean foreland basins (e.g., Singh et al., 1993; Sinha and Friend, 1994; Horton and DeCelles, 2001). Although such features have been recognized in ancient stratigraphic successions, they are likely under-recognized in the sedimentary record (DeCelles and Cavazza, 1999; Weismann et al., 2010).

We interpret the high net-to-gross feature near the town of Hinton Alberta as a Paleocene fluvial megafan. A modern analog is the Parapeti River megafan in the Chaco plain of Bolivia (Fig. 9b; Horton and DeCelles, 2001). This megafan is active today off the eastern slope of the Andes and covers an area over 5,800 km^2 (Horton and DeCelles, 2001). Other fans in the Chaco plain cover an area comparable to the sand feature in the Paskapoo, such as the Grande and Pilcomayo megafans, 12,600 km^2 and 22,000 km^2 respectively. Our data set does not allow us to determine channel dimensions and other channel parameters; however, the recognition of a Paleocene megafan allows the use of analogous features from modern fluvial megafans such as the Parapeti megafan in Bolivia and the Kosi River megafan in the Himalaya to better understanding potential reservoir or aquifer characteristics.

The location of the high net-to-gross feature and the High Divide Ridge Conglomerates corresponds with the outlet of the modern day Athabasca River. Although this is a possible coincidence, this may also indicate this area is a long-lived fluvial outlet. The location of modern day fluvial megafans is governed by the position of major drainage outlets (Lawton et al., 1994, Gupta, 1997, Jones, 2004). Lawton et al. (1994) argue that the locations of transverse structural zones controlled the position and establishment of long-lived drainage outlets that connected the hinterland drainage to the foreland basin (e.g., Gupta, 1997; Vincent and Elliot, 1997; Jones, 1999 and 2004). Once established these outlets may remain active for a period of time that exceeds the length of the orogen (Lawton et al., 1994). Furthermore, Isopach mapping of the underlying Battle Formation (Hathway, 2011) reveals the location of fluvial paleo-valleys, where the Battle Formation has been removed through incision by the Scollard Formation. A deep incised paleo-Athabasca paleovalley system trends from the southwest to the northeast between Edson and Whitecourt (Hathway, 2011). This paleovalley system supports the hypothesis for a long lived drainage network associated with the Athabasca river system. More detailed work, including further analysis of underlying strata, and exhumation histories in the adjacent fold-thrust belt may provide a way to further test this hypothesis.

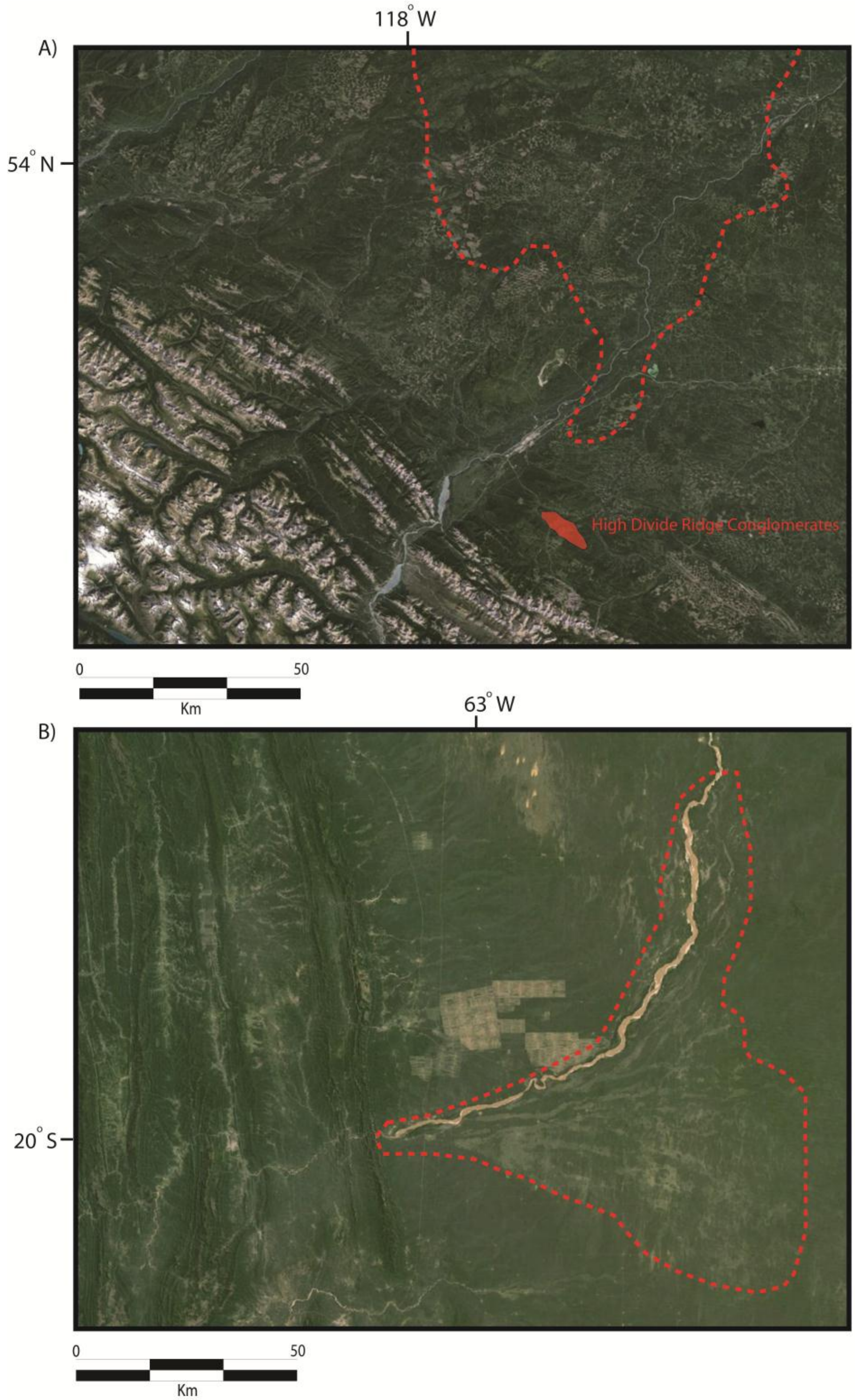


Fig 9: Proposed modern analog for the high net-to-gross area seen in Fig. 5c, the Parapeti megafan, southern Bolivia. A) Satellite photo of part of the Paskapoo Formation study area showing the approximate trace of the proposed fluvial megafan remnant observed in Figure 5c. And location of the High divide ridge conglomerates (Jerzykiewicz, 1985). Source: "Hinton" 53° 38'36.38" N 117° 17' 28.89" W Google Earth April 9, 2013. February 15, 2014 B) Satellite photo of the Parapeti Megafan, with approximate trace of abandoned or ephemeral megafan channels, from Horton and DeCelles (2001). Source: "Chaco Plain" 19° 54' 14.55" S 62° 56'58.55" W Google Earth April 9, 2013. February 15, 2014

6.3 Vertical Variations in Fluvial Stratigraphy

The large-scale stratigraphy of fluvial deposits in a subsiding basin is generally considered to be a function of two factors: sediment flux and accommodation. The absolute contribution of each to controlling the stratigraphic record is hard to determine, therefore a general relative ratio is typically used (e.g., Shuster and Steidtmann, 1987; Martinsen et al., 1999). In general, periods with low accommodation and subsidence are characterized by amalgamated channel sandstones and continuous sandstone units, whereas periods of high accommodation and subsidence are related to more abundant fine-grained material and less amalgamated channel sandstones (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Shuster and Steidtmann 1987; Heller et al., 1988; Jordan and Flemings, 1989; Bridge and Mackey, 1993). Consistent with this trend, the Haynes Member at the base of the Paskapoo Formation represents a period of relatively low subsidence relative to sediment influx, whereas the fine-grained Lacombe Member records a period of relatively higher subsidence with greater accommodation creation (e.g., Lyster and Andriashek, 2012). Accommodation can be created by several factors, most notably tectonic-driven subsidence and rises in base-level or sea-level (e.g., Currie 1997, Legarreta and Uliana, 1998; Blum and Tornqvist, 2000). By the time of deposition of the Paleocene Paskapoo, the Cordilleran Foreland Basin was completely non-marine (Leckie and Jerzykiewicz, 1989; Leckie and Smith, 1992). Thus, we infer that accommodation during deposition of the Paskapoo Formation was largely controlled by tectonic processes, namely, rapid subsidence resulting from thrust sheet emplacement and lesser subsidence during times of tectonic inactivity (e.g., Heller et al., 1988; Lyster and Andriashek, 2012). Following Lyster and Andriashek's (2012) interpretation, we interpret the Haynes Member to represent a period of relative inactivity in the adjacent thrusts, resulting in decreased subsidence and more amalgamated channels, and the mudstone-dominated Lacombe Member is interpreted to be associated with greater subsidence, synchronous with thrust emplacement. Similarly, the high net-to-gross feature to the north is interpreted as the result of high relative ratio of sediment flux to accommodation creation.

7. SUMMARY AND CONCLUSIONS

The Paskapoo Formation represents the most important aquifer in Alberta (Grasby et al., 2008). This is due to its near-surface proximity and lithology. The Paskapoo has been characterized using water well logs, core, and out crop, but lacks a regional subsurface description of its fluvial architecture and distribution. Tectonic activity is interpreted as the primary control on vertical variation in fluvial stratigraphy, controlling the relative ratio of sediment flux to accommodation creation. Whereas the position of long lived fluvial outlets emanating from the fold-thrust belt, impose a greater control on the lateral variation in fluvial stratigraphy.

The newly available data set of gamma ray logs has created a new opportunity to evaluate regional scale stratigraphy. In order to be useful, gamma-ray logs collected through surface casing must be normalized. The curves are then suitable for the production of net-to-gross maps. These maps, supplemented by stratigraphic cross-sections, are useful in identifying areas dominated by high or low net-to-gross values. Primary observations of the maps and stratigraphic sections include: (1) The lower interval associated with the Haynes Member and/or lower Lacombe shows a south-to-north decrease in sandiness. In the lower interval high sand fraction is most prominent adjacent to the deformation front and does not extend to the northern portion of the basin. (2) A 4,000 to 5,000 km^2 high net-to-gross feature exists in the upper part of the northern study area. This feature is highly interconnected and appears consistent with what has been described in literature as a DFS/megafan. (3) The exit point from the fold-and-thrust belt of the present-day Athabasca River is located in the vicinity of the apparent point source of the proposed DFS/megafan remnant. It is hypothesized that a paleo-Athabasca River is the source of the DFS. The hypothesis of the proposed DFS remnant is based mainly on geometric observations and comparison with modern analogues. Further study should be done on its internal structure and facies distributions to test whether they are consistent with a DFS and if so, to constrain channel dimensions and sinuosity.

References

Allen, J.R.L., 1978. Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion controlled alluvial suites. Sedimentary Geology, n 21.2, pp. 129-147.

Bally, A. W., Gordy, P. L., and Stewart, G. A., 1966. Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains, Bulletin of Canadian Petroleum Geology, vol. 14, pp. 337-381.

Beaumont, C. 1981. Foreland Basins, Geophysical Journal of the Royal Astronomical Society, 65(2), pp. 291-329.

Blum, M.D., and Tornqvist, T.E., 2000, Fluvial response to climate and sea-level change: a review and look forward: Sedimentology, vol. 47, pp. 2-48.

Bridge, J. S., and Leeder, M. R., 1979. A simulation model of alluvial stratigraphy. Sedimentology, vol.26, pp. 617-644.

Bridge, J.S., 1993, Description and interpretation of fluvial deposits; a critical perspective, Sedimentology, vol. 40, pp. 801-810.

Bridge, J. S., and S. D. Mackey. 1993 A theoretical study of fluvial sandstone body dimensions. The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues, pp. 213-236.

Bridge, J. S., and Tye, R. S., 2000, Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores, AAPG bulletin, vol. 84, pp. 1205-1228.

Cant, J. D, Stockmal, G.S. 1989. The Alberta foreland basin: relationship between stratigraphy and Cordilleran terrane-accretion events, Canadian Journal of Earth Science, 26(10), 1964-1975.

Cluff, S. G., and Cluff, M. R., 2004. Petrophysics of the Lance Sandstone Reservoirs in Jonah Field, Sublette County, Wyoming. Jonah field: case study of tight gas fluvial reservoir, Rocky Mountain Association of Geologists (2004), Chapter 12. pp. 215-241.

Currie, B. S. 1997 Sequence stratigraphy of nonmarine Jurassic-Cretaceous rocks, central Cordilleran foreland-basin system, GSA bulletin, vol. 109, pp. 1206-1222.

Dawson, F. M., Evans, C. G., Marsh, R., and Richardson, R, 1994, Uppermost Cretaceous and Tertiary strata of the Western Canada sedimentary basin. Geological atlas of the Western Canadian Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council, 387-406.

DeCelles, P. G., and Cavazza, W. 1999, A comparison of fluvial megafans in the Cordilleran (Upper Cretaceous) and modern Himalayan foreland basin systems Geological Society of America Bulletin, 111(9), pp. 1315-1334.

DeCelles, P.G., and Giles, K.A., 1996, Foreland basins systems. Basin Research. n8.2, pp. 105-123

Demchuk, T. D, 1990, Palynostratigraphic zonation of Paleocene strata in the central and south-central Alberta Plains, Canadian journal of Earth Science, Vol.27 pp. 1263-1269.

Demchuk, T.D, and Hills, L. V. 1991, A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members, Bulletin of Canadian Petroleum Geology, Vol. 39, No. 3, pp. 270-282.

EUB directive 043, 2006, Well Logging Requirements – Surface casing Interval, Energy Research Conservation Board, ERCB/AGS.

Fox, R.C, 1990, Pronothodectes Gaoi N. SP. From the late Paleocene of Alberta, Canada, and the early evolution of the Plesiadapidae (Mammalia, Primates). Journal of Paleontology, 64(4), pp. 637-647.

Flemings, P. B., and Jordan, T. E. 1989, A synthetic stratigraphic model of foreland basin development, Journal of Geophysical Research: Solid Earth, 94(B4), pp. 3851-3866.

Gibling, M. R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record; a literature compilation and classification, Journal of Sedimentary Research, vol. 75, pp. 731-770.

Gibson, D. W, 1977, Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River valley, Alberta. Energy, Mines and Resources Canada pp. 41.

Grasby, S.E., Zhuoheng, C., Hamblin, A. P., Wozniak, P. R. J., and Sweet, A. R. 2008, Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta, Canadian Journal of Earth Science. Vol. 45, pp. 1501-1516.

Gupta, S., 1997, Himalayan drainage patterns and the origin of fluvial megafans in the Ganges foreland basin, Geology, 25(1), pp. 11-14.

Hamblin A. P, 1997, Regional distribution and dispersal of the dinosaur Park Formation, Belly River Group, Surface and subsurface of southern Alberta, Bulletin of Canadian Petroleum Geology, Vol. 45, pp. 377-399.

Hamblin, A.P, 2004, Paskapoo-Porcupine Hills Formations in Western Alberta: Synthesis of Regional Geology and Resource Potential, Geological Survey of Canada, Open File 4679, pp. 1-29

Hathway, B., 2011, Late Maastrichtian paleovalleys systems in west-central Alberta: Mapping the Battle Formation in the subsurface, Bulletin of Canadian Petroleum Geology, vol. 59, pp. 195-206

Heller, P. L., Angevine, C.L., Winslow, N. S., and Paola, C., 1988, Two phase stratigraphic model of foreland-basin sequences. Geology, 16(6), pp. 501-504.

Horton, B. K., and DeCelles, P. G., 2001, Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold thrust belts, Basin Research, 13, pp. 43-63.

Ingersoll, R. V., 1988, Tectonics of sedimentary basins, Geologic Society of America Bulletin, 100(11), pp. 1704-1719.

Jerzykiewicz, T., 1985, Tectonically deformed pebbles in the Brazeau and Paskapoo formations, Central Alberta, Foothills, Canada: Sedimentary Geology, v. 42, p. 159-180.

Jerzykiewicz, T. 1997, Stratigraphic framework of the uppermost Cretaceous to Paleocene strata of the Alberta Basin, Geologic Survey of Canada, Bulletin 510,pp. 121

Jones, J. J., Frostick, L. E., and Astin, T. R., 1999. Climatic and tectonic controls on fluvial incision and aggradation in the Spanish Pyrenees. Journal of the Geological society, London, vol. 156, pp. 761-769.

Jones, J. J., 2004. Tectonic controls on drainage evolution and development of terminal alluvial fans, southern Pyrenees, Spain. Terra Nova 16.3, pp. 121-127.

Koss, J. E., Ethridge, F. G., and Schumm, S. A., 1994. An experimental study of the effects of base-level change on fluvial, coastal plain and shelf systems. Journal of Sedimentary Research, vol. B64, pp. 90-98.

Krause, D. W., 1978, Paleocene Primates from western Canada, Canadian Journal of Earth Science, 15, pp. 1250-1271.

Langenberg, C., Berhane, W. H., Sweet, A. R., Marchioni, D., and Heaman, L. M. 2007, Regional Correlations of the Ardley Coal Zone, Alberta, EUB/AGS Earth Science Report, 05(21).

Larue, D. L, and Hovadik, J., 2006, Connectivity of channelized reservoirs: a modeling approach. Petroleum Geoscience, vol. 12, pp. 291-308.

Lawton, T. F., Boyer, S. E., and Schmitt. J. G. 1994. Influence of inherited taper on structural variability and conglomerate distribution, Cordilleran fold and thrust belt, western United States. Geology, vol. 22, pp. 339-342.

Leckie, D. A, and Smith, D. G. 1992, Regional Setting, Evolution, and depositional Cycles of the Western Canada Foreland Basin, American Association of Petroleum geologists, Memoir 55, pp. 9-46.

Leeder, M.R., 1978. A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness. In: A.D. Miall (Editor), Fluvial Sedimentology. Canadian Society of Petroleum Geology., Memoir. 5, pp.587 596.

Legarreta, L., and Uliana, M. A. 1998, Anatomy of Hinterland depositional sequences: upper cretaceous fluvial strata, Neuquen Basin, West-Central Argentina, SPEM, society for Sedimentary Geology, No.59 pp. 83-92.

Leier, A. L., DeCelles, P. G., and Pelletier, J. D., 2005, Mountains, Monsoons, and megafans, Geological society of America, 33(4), pp. 289-292.

Lerbekmo, J. F., Demchuk, T. D., Evans, M. E., and Hoye, G. S. 1992, Magnetostratigraphy and Biostratigraphy of the Continental Paleocene of the Red Deer Valley, Alberta, Canada, Bulletin of Canadian Petroleum Geology, 40 (1), pp. 24-35.

Lerbekmo, J. F., and Sweet, A. R. 2008, Magnetobiostratigraphy of the continental Paleocene upper Coalspur and Paskapoo formations near Hinton, Alberta, Bulletin of Canadian Petroleum Geology, Vol. 56, p. 118-146.

Lyster, S., Andriashek, L. 2012, Geostatistical Rendering of the Architecture of Hydrostratigraphic Units within the Paskapoo Formation, Alberta. Energy Research Conservation Board, ERCB/AGS Bulletin 66.

Mack, G. H., and Jerzykiewicz, T., 1989, Provenance of post-Wapiabi sandstones and its implications for Campanian to Paleocene tectonic history of the southern Canadian Cordillera, Canadian Journal of Earth Science, 26(4), pp. 665-676.

Martinsen, O. J., Ryseth, A., Hellard-Hansen, W., Flesche, H., Torkildsen, G., and Idil, S. (1999). Stratigraphic base level and fluvial architecture: Ericson Sandstone (Campanian), Rock Springs Uplift, SW Wyoming, USA. Sedimentology, vol 46(2), pp. 235-263.

Medina, C. R., and Rupp, J. A. 2012, Reservoir characterization and lithostratigraphic division of the Mount Simon Sandstone (Cambrian): implications for estimations of geologic sequestration storage capacity. Environmental Geosciences, Vol. 19(1), pp. 1-15.

Miall, A. D., 2008, The Sedimentary Basins of the United States and Canada. Sedimentary basins of the world., vol. 5.

Price, R. A, 1994, Cordilleran Tectonics and the Evolution of the Western Canada Sedimentary Basin, Geological Atlas of the Western Canada Sedimentary Basin, 13-24.

Paola, C., 2000, Quantitative models of sedimentary basin filling, Sedimentology, vol. 47, pp. 121-178.

Quartero, E. M., Bechtel, D., Leier, A.L., and Bentley, L. R, 2014, Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta. Canadian Journal of Earth Science, vol 51, pp. 327-340

Rider, M., Kennedy, M. 2011, The Geological Interpretation of well logs, 3rd edition, Rider and French consulting Limited, pp. 1-4, pp. 117-146.

Shuster, M. W., and Steidtmann, J. R., 1987, Fluvial-sandstone architecture and thrust-induced subsidence, northern Green River basin, Wyoming, SEPM recent developments in luvial Sedimentology, SP, 39, pp.279-285.

Shuster, M. W., and Steidtmann, J. R., 1988, Tectonic and sedimentary evolution of the northern Green River basin, western Wyoming, Geological society of American memoirs, vol. 171, pp. 515-530.

Singh, H., Parkash, B., and Gohain, K., 1993, Facies analysis of the Kosi megafan, Sedimentary Geology, vol. 85, pp. 87-113.

Sinha, R., and Friend, P, F., 1994, River systems and sediment flux, Indo-Gangetic plains, Northern Bihar, India, Sedimentology, vol. 41, pp. 825-845.Tucker, G. E., and Slingerland, R., 1996. Predicting sediment flux from fold and thrust belts, Basin Research, 8(3), pp. 329-349.

Vincent, S. J., and Elliot, T. 1997. Long-lived transfer-zone paleovalleys in mountain belts: an example from the tertiary of the Spanish Pyrenees. Journal of Sedimentary Research, vol. 67(2), pp. 303-310.

Weissmann, G. S., Hartley, A.J., Nichols, G. J., Olson, M. Buehler, H., and Banteah, R. 2010. Fluvial form in modern continental sedimentary basins: Distributive fluvial systems. Geological Society of America, vol. 38(1), pp. 39-42.

CHAPTER FOUR: Conclusions

Chapter 2 describes and demonstrated a normalization methodology for a suite of new near surface gamma-ray data. This data was made available by the EUB mandate to log the surface casing interval. The methodology makes use of a commonly used normalization equation and statistical values derived from what is considered analogous strata of the uncased zone. An understanding of fluvial strata and basic geologic assumptions are required to generate normalized curves suitable for geological interpretation. The principal assumption is that the max and min percentile gamma-ray values of the uncased zone (Scollard and Ardley coal zone and lower Paskapoo Formation) is representative of the max and min percentile values of the cased zone. The use of the 2nd percentile (P2) and 95th percentile (P95) values helps mitigate the negative effects of variable lithology. The range of gamma-ray values produced by the underlying uncased zone is consistent with the expected range of values for the cased zone. The character and shape of the normalized cased curves is similar to the distribution of those from an open-hole curve, creating a seemingly continuous log to surface.

The interface between the normalized curves at the base of surface casing with the uncased curve is continuous and no longer an identifiable pick on the gamma ray log. This smooth continuation of the normalized log into the uncased zone is quantified by measuring the average difference between API values in zones directly above and below surface casing, and comparing them to the difference between zones form within the uncased zone. The average difference between zones above and below casing was found to be -1.46, down from -25.41 prior to normalization, and much closer to the difference in the uncased zones which had an average difference of 0.13. The produced gamma ray curves are suitable for discriminating between fluvial sand bodies and fine grained silt and muds. Varying percentage of sandiness and general heterogeneity will be retained after normalization, as the histogram of API values may take any shape, skew left, skew right, bi-modal, as long as the minimum and maximum values are similar. This is essential for net-to-gross mapping and log interpretation.

In Chapter 3 the curves were used to produce net-to-gross sand maps, as well as stratigraphic cross-sections. These sections were generated and populated with the net-to-gross sand fraction, and interpretive channel fill. This requires the calculated net-to-gross, and a conceptual infilling of channels based on sand fraction and the apparent sandstone succession thickness from the logs. The channel caricatures are meant to highlight the sand distribution and an approximate boundary, and are not meant to present any information on channel belt dimensions. The net-to-gross maps and stratigraphic sections support the tectonic model proposed by Heller et al. (1988), and for the Paskapoo, Lyster and Andriashek (2012). With the Paskapoo Formation likely represents two sequences of tectonic processes, quiescence; resulting in low accommodation high sand amalgamation of the Haynes Member, followed by emplacement and subsidence resulting in wide spread accommodation and deposition of the muddy heterogeneous Lacombe Member.

Primary observations of the maps and stratigraphic sections include (1) variable fluvial architecture along the foreland basin's long axis (NW to SE) including north to south variation in sandiness, and a discontinuous Haynes Member, as the Haynes in restricted to the central and southern portion of the basin adjacent to the deformation front, and does not extend to the North. (2) The high net-to-gross interpreted megafan feature to the north. This feature covers an estimated area of 4000 km^2. It likely consists of highly interconnected sandstone channels and is consistent with what has been described in literature as a DFS/megafan. (3) The overlap of the present day Athabasca River with the apparent point source of the high net to gross feature, indicating a possible location for a long-lived fluvial outlet.

Recommendations for future research

The collection of the gamma ray log through the surface cased interval is a continuing practice for oil and gas drillers in Alberta. This ever-growing data set becomes larger every year. The data obtained for this study was through an academic licence agreement with IHS. The academic licence agreement only grants access to data that is the sole property of IHS, as a large portion of new data is held and obtained with partner companies. With an improved academic or commercial licence and unfettered access to it, the data set would greatly improve in size and quality. Generating normalized curves for regional modeling can be easily done. The study area consists of the north and central portions of the basin, with the high density data located in the north. The net-to-gross sand maps in the central portion of the basin are based on widely spaced and relatively sparse data. The regional sand distribution and fluvial architecture cannot be confidently captured in all areas with this data. With high density quality data for the entire Paskapoo, regional reconstructions would subsequently improve.

The interpretations of the high net-to-gross feature can be further tested by obtaining core data. Logged core sections through the observed high net-to-gross area, with either gamma ray from nearby wells or collected by hand held spectrometer may reveal crucial facies information. Small bed–scale observations can be extrapolated to provide constraints on channel dimensions and test the hypothesis of a DFS megafan. Other crucial information may include a paleo-flow and provenance analysis. As mentioned before the Dalehurst Member is slightly younger than the Lacombe and further palynological analysis of the interpreted megafan may be able to formally classify the feature into the Dalehurst or Lacombe member.