In Search of Cordilleran Point Sources to the Southern McMurray Sub-Basin

by

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Abstract

In east-central Alberta, isopach thicknesses of the McMurray Formation, measured from the overlying Wabiskaw Marker datum, show that paleotopographic relief on the sub-Cretaceous Unconformity including three paleovalleys carved into the Grosmont-Wainwright Highlands. The paleovalleys are named herein as: Grouse, Quail, and Ptarmigan. Mineralogical analysis of McMurray Formation sandstones in each of the paleovalleys resolves subtle but recognisable vertical and spatial variations in composition. Feldspar contents decrease and lithic contents increase with stratigraphic depth.

Based on petrographic analyses, the McMurray Formation sandstones are sourced dominantly from a continental-scale drainage across the craton, with secondary input from the west and from the Canadian Shield in the east. Potential paleo-tributaries bisect the highland, suggesting that the highland did not prevent sediment from the Edmonton Valley from entering the Ptarmigan and Quail paleovalleys. The sediment delivered from the Edmonton Valley constitutes approximately 46% of the sediment supplied to the McMurray channel system.

Dedication

This thesis project is dedicated to Almighty God; and also to my wife Temitope, and my children Bimola and Bimade Adewale-Basiru.

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Chapter 1.

Introduction

1.1. Introduction

The McMurray Sub-Basin contains the largest proven reserves of oil sands in the world, with about 168 billion barrels of recoverable oil (Fig. 1.1; Oil and Gas Journal, AER 2013). The majority of these reserves are within the Lower Cretaceous (Aptian) McMurray Formation. These sedimentary strata are interpreted, in general, as the deposits of a major fluvial system that was slowly drowned, and which stepped landward during multiple transgressive-regressive cycles of the Boreal Sea (Gingras et al., 2003; Blum et al., 2013; Benyon et al., 2014). The stratigraphic fill of the basin mainly comprises fluvial deposits in the lower McMurray Formation, estuarine channel deposits in the middle McMurray, marginal-marine bay deposits in the upper McMurray, and fully-marine deposits in the Wabiskaw Member of the Clearwater Formation (Stewart and MacCallum, 1978; Keith et al., 1988, Hein, 2006; Gingras et al., 2003; Broughton, 2013).

The McMurray Sub-Basin was adjacent to an active orogenic belt in the west; however, a series of paleotopographic highs that bordered the basin to the south and west in central Alberta may have prevented sediments from the west (i.e., the Cordillera) reaching the basin (Fig. 1; Leckie and Smith, 1992; Ranger and Pemberton, 1997). In fact, petrographic and detrital zircon studies propose that much of the sand in the McMurray Formation may been derived from the Canadian Shield (Carrigy, 1959; Potocki and Hutcheon, 1992; Hein et al., 2012), the southwest USA, or potentially as far away as the southeastern USA (Benyon et al., 2013, 1014). Leckie and Seif El-Dein (2009) determined the Canadian Shield to be a major sediment source, by using paleogeographic reconstructions of the sub-Cretaceous Unconformity (SCU) to map the regional drainage area. However, the most recent paleogeographic reconstruction (Christopher, 2003;

Benyon et al., 2014) of the basin proposes that McMurray Formation sandstones were derived from a continental-scale south-to-north paleo-drainage network with its headwaters in the southwestern USA, similar in scale to the modern-day Mississippi drainage system (Mossop and Flach, 1983; Benyon et al., 2013, 2014; Blum and Pecha, 2013).

A host of other factors may have also impacted the mineralogy of the McMurray Formation sandstones deposited in the paleovalleys carved into the Grosmont-Wainwright Highland, and these include paleoclimate and the types of depositional environments. At the time of deposition, Alberta's climate was hot and humid (Bayliss and Levinson, 1976; Potocki and Hutcheon, 1992), implying that hydrolysis, dissolution, and oxidation of minerals were prevalent, resulting in the chemical and physical disintegration of unstable mineral compositions (Potocki and Hutcheon, 1992).

Depositional environments can significantly impact the mineralogy as well, as some minerals and rock fragments are more stable in some depositional settings than others (Bayliss and Levinson, 1976; Potocki and Hutcheon, 1992) For this reason, the proportion of stable to unstable mineral grains in lower, middle and upper McMurray Formation should significantly differ because they were deposited in different depositional settings. In particular, focus is made on the detrital quartz, feldspar, detrital lithic fragments and mica flakes.

It is pertinent to establish the reliability of using the top of the Wabiskaw Member (Wabiskaw Marker) as a regional correlatable surface to map the Wabiskaw-McMurray interval in the study area. If the top of the Wabiskaw Member is consistently picked across the study area, the isopach of the Wabiskaw Member can be used to delineate the top of the McMurray Formation, as the top of the McMurray Formation is defined as the base of the marine shale at the base of the Wabiskaw Member of the Clearwater Formation (Hein et al., 2012; Broughton, 2013).

This study involves a mineralogical assessment by point-counting thin sections, and isopach and net-sand mapping of the Lower Cretaceous McMurray Formation in central Alberta to address the following objectives:

1) Determine the suitability of the top of the Wabiskaw Member (Wabiskaw Marker) as a regionally correlatable surface across the southern McMurray Sub-Basin.

2) Ascertain whether the Grosmont-Wainwright Highlands prevented Cordilleran sediments from reaching the McMurray Sub-Basin from the south and southwest. This objective will be accomplished through isopach and net sand mapping of the McMurray and Wabiskaw-McMurray intervals.

3) Quantify the percentage of possible Cordilleran sediments that reached the McMurray Sub-Basin from the Edmonton Valley through Grosmont-Wainwright Highlands. This objective will be achieved by calculating the proportion of Ellerslie Formation sandstones that would have to be mixed with Dina Formation sandstones to produce the mineralogical composition observed in paleovalleys carved into the Wainwright-Grosmont Highland in the study area.

4) Show whether there are any variations in mineralogical composition of the McMurray Formation among paleovalleys that adjoin the southern McMurray Sub-Basin. This objective will be achieved by classifying sandstones and also plot sample depths from the top of the McMurray Formation against average percentage feldspar or lithic fragments in McMurray Formation sandstones in paleovalleys.
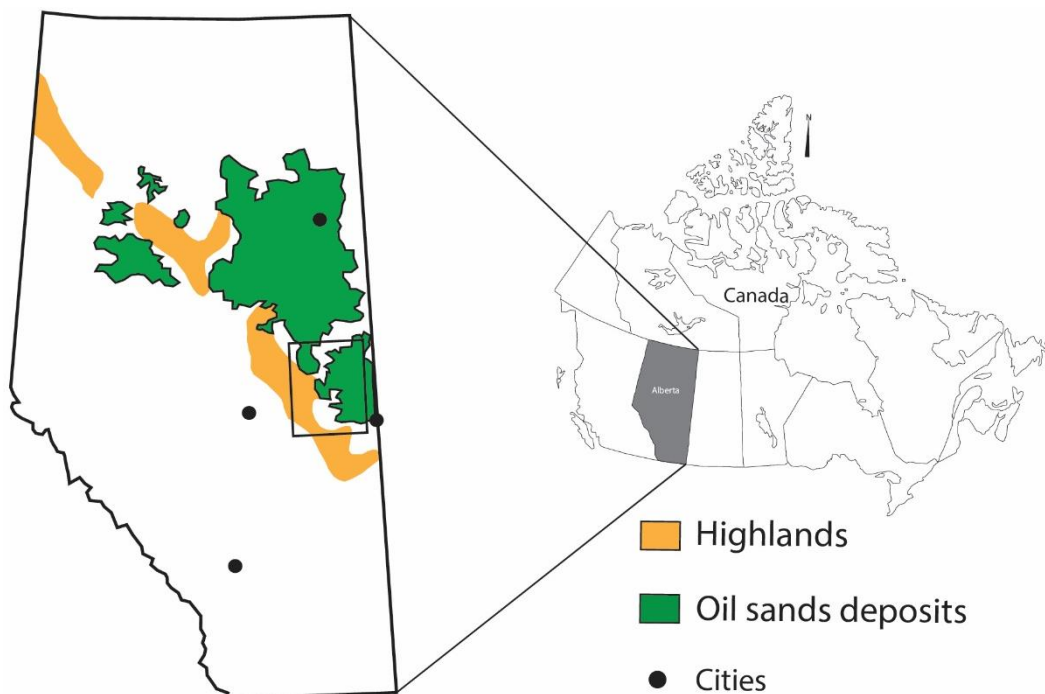
Figure 1.1. **Map of oil sands deposits and paleotopographic highs that serve as drainage divide between the Assiniboine Valley / McMurray Sub-Basin and in Edmonton Valley in Alberta, showing the position of study area (black box).**

1.2. McMurray Stratigraphy

The Lower Cretaceous (Aptian) McMurray Formation unconformably overlies westerly dipping Paleozoic carbonates, and is overlain by the Wabiskaw Member of the Clearwater Formation (Fig. 1.2; Nelson and Glaister, 1978; Flach and Mossop, 1985; Wightman and Pemberton, 1997; Hein and Cotterill, 2000; Hein et al., 2006; Hein et al., 2012). The major contact between the McMurray Formation and the Devonian carbonates is an angular unconformity called the sub-Cretaceous Unconformity (SCU). Within the Athabasca oil sands region, the SCU represents a period of non-deposition and erosion that spans from the Devonian to the Early Cretaceous (Flach, 1984; Smith, 1994; Keith, et al., 1988; Broughton, 2013), a period approximately 274 Ma. The contact that separates the Wabiskaw Member from the underlying McMurray Formation is sharp and erosive (Fig. 1.2), and is interpreted as a transgressive ravinement surface cut during the incursion of the Boreal Sea (Hein and Cotterill, 2000; Hein et al., 2012). The stratigraphic interval from the top of the Wabiskaw Member to the SCU is described as a transgressive system tract (Keith et al., 1988; Wightman et al., 1995).

The McMurray Formation is informally subdivided into lower, middle and upper members (Carrigy, 1959). Carrigy (1959) based his stratigraphic subdivision on lithological criteria that he established from outcrops in the Athabasca and Clearwater areas. Stewart and MacCallum (1978) built on Carrigy's work, and defined the lower McMurray as fluvial, the middle McMurray as estuarine, and the upper McMurray as marginal marine. Flach and Mossop (1985) and Keith et al. (2009) argued that the subdivision of the McMurray Formation into lower, middle and upper units only applies to the McMurray Formation in the northern McMurray Sub-Basin. Subsequent studies by Burden (1984), Wightman and Pemberton (1997) and Hein and Cotterill (2000) hypothesized that mineralogy and fossil content cannot be used to separate the middle McMurray from the upper McMurray. In fact, using facies and biostratigraphic analysis, Burden (1984) and Hein and Cotterill (2000) postulated that middle and upper McMurray cannot be differentiated and that they should be considered as one entity. The McMurray Formation is stratigraphically equivalent to both the Ellerslie Formation in the Edmonton Valley (west of the study area) and the Dina Formation in the Lloydminster area (east of the study area), while the Glauconitic Sandstone and Cummings Formation are coeval with Wabiskaw Member of

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the Clearwater Formation (Fig. 1.2; Kramers, 1974; Flach, 1984; Ranger, 1984; Keith et al., 1988). It is important to show that the Dina, Ellerslie and McMurray formations are stratigraphically equivalent because sandstones that comprise these formations are compared, and also because the feldspar and lithic composition of Dina and Ellerslie formations sandstones are used to quantify the percentage of sediment that reached McMurray Sub-Basin from the Edmonton Valley.
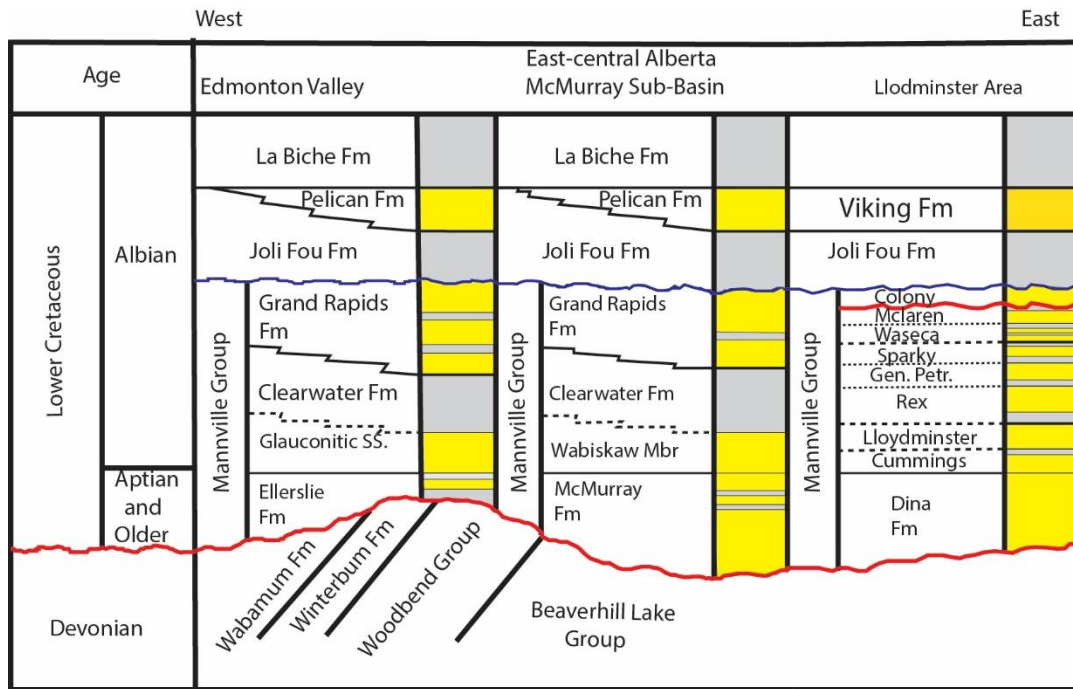
Figure 1.2. **Stratigraphic Chart of Devonian and Lower Cretaceous strata in the east-central Alberta (modified from Kramers, 1974). Grey colour = mudstone. Yellow colour = sandstones / semi-consolidated sands (oil sands / barren sands). Red wiggle line = unconformity. Blue wiggle line = transgressive surface of marine erosion.**

1.3. Paleogeography of the McMurray Sub-Basin

The paleo-topography of the sub-Cretaceous Unconformity during the Late Jurassic to Early Cretaceous controlled drainage patterns, and hence deposition of lower and middle McMurray-aged sediments (Hein and Cotterill, 2000; Keith et al., 1988; Leckie and Self El-Dein, 2009; Broughton, 2013). Paleo-topography of the SCU had been mapped historically using the isopach values from the following stratigraphic intervals: 1) top of the Base Fish Scale Marker to the SCU (Williams, 1963); 2) top of the Mannville

Group to the SCU (Ranger et al., 1994); and 3) top of the Wabiskaw Member, Clearwater Formation, to the SCU (Flach, 1984; Keith et al., 1988). Each of these approaches presupposes that the overlying marker is essentially flat and near to horizontal so that all thickness variations are largely due to relief on the SCU. The topography of the SCU is a dominant control on the south-north depositional strike of the basin (Flach and Mossop, 1985; Wightman and Pemberton, 1997; Ranger et al., 1994; Hein and Cotterill, 2000). Flach and Mossop, (1985) argue that the SCU is karstic, and deposition is largely controlled by the depth of karsting. The Main Valley tracks the salt scarp left behind by dissolution of the Prairie Evaporite of the Elk Point Group (Flach and Mossop, 1985; Wightman et al., 1995; Hein and Cotterill, 2000; Broughton, 2013). Preceding and throughout the Early Cretaceous, the north-to-south-trending main valley was occupied by fluvial to estuarine drainage systems that enhanced karst development in the underlying Devonian carbonates, and this impacted deposition patterns within the McMurray Sub-Basin (Flach and Mossop, 1985; Broughton, 2013).

The SCU comprises a series of northwesterly trending paleotopographic ridges and valleys across the Western Canada Sedimentary Basin (Fig. 1.3; Ranger et al., 1994; Smith, 1994; Hein et al., 2012; Mei et al., 2015). Major topographic features (Fig. 3) include: 1) the Pembina Highlands and Fox Creek Escarpment, which form a drainage divide between Spirit River Valley and Edmonton Valley; 2) the Keg River, Red Earth, Grosmont-Wainwright, Kindersley, and Medicine Swift Current Highlands on the eastern side of the Edmonton Valley and flanking western side of the McMurray Sub-Basin; 3) the Edmonton Valley that forms the central drainage on the SCU; and 4) the McMurray-Assiniboine Valley that lies to the east of the Wainwright High – Grosmont Ridge. Deposition of the Lower Cretaceous McMurray Formation and coeval strata coincides with the initial drowning and burial of the large ridges on the SCU during the Aptian of Lower Cretaceous (Fig. 1.3; Smith, 1994). During the Albian, widespread transgression of the Boreal Sea is recorded by deposition of glauconitic shallow-marine sands of the Wabiskaw Member of the Clearwater Formation (Fig. 1.2; Wightman et al., 1995; Strobl et al., 1997; Hein et al., 2012). As relative sea level continued to rise, open-marine shales of Clearwater Formation were deposited.
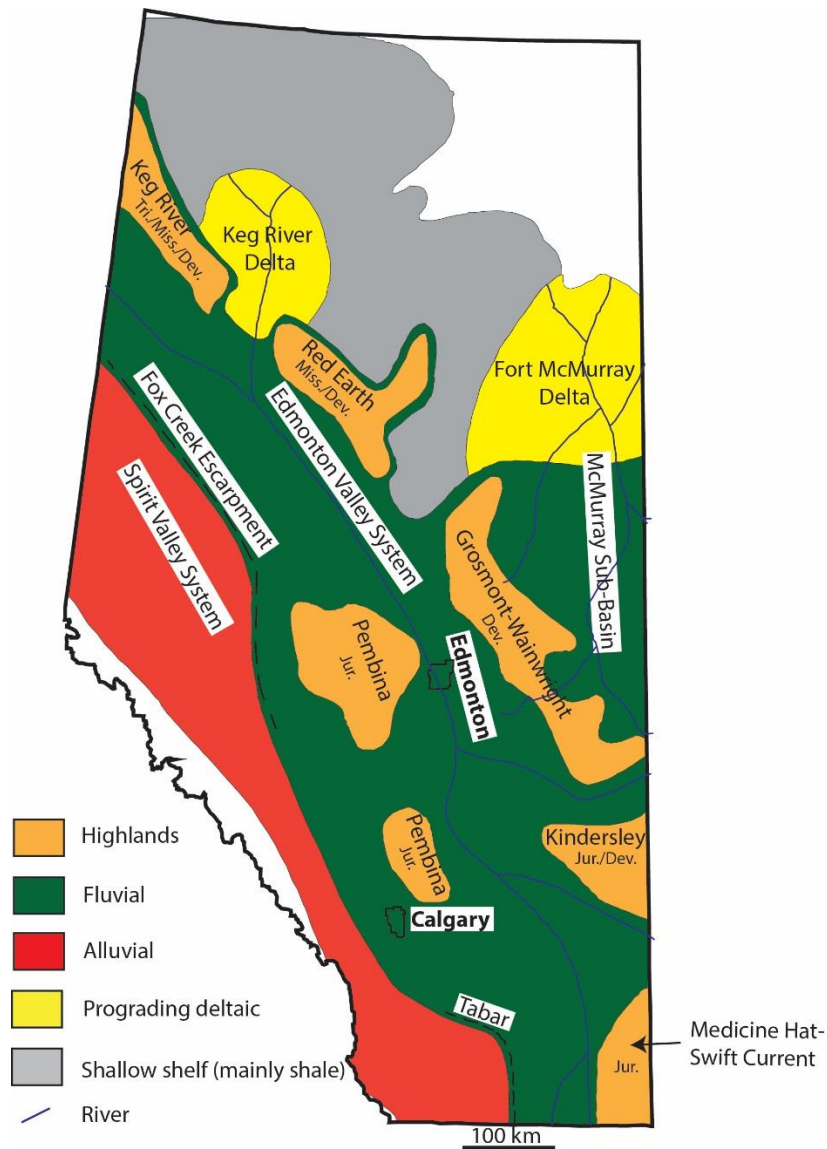
Figure 1.3. **Paleogeographic map of Alberta during deposition of the Lower Cretaceous McMurray Formation and coeval strata (modified from Smith, 1994). The map shows paleo-topographic lows and highs, and the ages of strata forming high area - Devonian (Dev.), Mississippian (Miss.), Triassic (Tri.) and Jurassic (Jur.).**

1.4. Mineralogy

The sources of sediments into the McMurray Sub-Basin and mineralogical variation within the Lower Cretaceous McMurray Formation have been debated extensively in the literature (e.g., Carrigy, 1963; Baylis and Levinson, 1976; Mossop and

Flach, 1983; Potocki and Hutcheon, 1992; Hein et al., 2012). Carrigy (1963) completed the first petrographic study on the McMurray Formation and analyzed samples from seven cores within Township 81 – 91 and Ranges 9 – 17W4. He reported that, on average, 99% of framework grains are detrital quartz. Detrital feldspar grains, where present, rarely exceeds 10%, and lithic fragments, comprising mainly chert, may be high as 9% in individual samples. Interestingly, Carrigy (1963) included detrital quartzite grains as part of the detrital quartz component rather than as metamorphic lithic fragments, and concluded that McMurray Formation sediments were derived from the Canadian Shield. In 1976, Bayliss and Levinson published a petrographic study of the McMurray Formation in the Athabasca area, and concluded that sand grains comprised 41–97% detrital quartz, 0–16% detrital feldspar, 0–8% detrital mica (dominantly muscovite), and with only sporadic occurrences of lithic fragments. Bayliss and Levinson (1976) pointed out that detrital feldspar mainly orthoclase increases in abundance upward through Lower Mannville strata, and that the mineralogy of the Lower Cretaceous Mannville Group depended on the source-area geology. Potocki and Hutcheon (1992) argued that the presence of feldspar and mica in McMurray sandstones indicates that they are derived from weathering of crystalline rock of the Canadian Shield. They explained further that the high textural maturity of the sandstones, which consist of chert and heavy mineral assemblages, suggests that they are recycled Precambrian sandstones, Paleozoic carbonates, and clastics that had formed an apron on the Canadian Shield. Bayliss and Levinson (1976) analyzed sandstones of the Dina Formation (Fig. 1.2; McMurray Formation equivalent) in the Lloydminster area and demonstrated that these sandstones consist of 80–100% quartz, 0–19% feldspar, 0–1% lithic fragments.

Williams (1963) completed a mineralogical study on the Ellerslie sandstone (Fig. 1.2; time equivalent to the McMurray Formation) in the Edmonton Valley, and found that the mineralogy of sand grains was more diverse and of discrete composition compared to those of the McMurray Formation. Williams reported that Ellerslie Sandstones in the Edmonton Valley consisted of 73–98% detrital quartz, 2–21% lithic fragments, 0–6% detrital feldspar (mainly orthoclase). Williams (1963) described Ellerslie sandstones as texturally mature and demonstrated that the abundance of rock fragments and detrital feldspar increased upward through the formation. In contrast to Carrigy (1963), Williams

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(1963) included both detrital quartzite grains and chert grains as lithic fragments and concluded that Ellerslie Formation sediments were sourced from the Cordillera.

Besides the Ellerslie Formation, other formations that are more obviously derived from the thrust belt include the Belly River (basal), Cadomin, Blairmore, Cardium, Spirit River, Dunvegan Kootenay formations (Tater, 1964; Blatt et al., 1972; Iwuagwu and Lerbekmo, 1982; Potocki and Hutcheon, 1992). Blatt et al. (1972) showed that compositionally, Cardium, Cadomin and Spirit River formations sandstones consist almost entirely of chert and they classified these sandstones as chert-arenites. The mineralogical analysis done on Belly River sandstones by Iwuagwu and Lerbekmo (1982) showed that the sandstones consist of 61–75% lithic fragments (mainly chert), 24–26% quartz (mainly monocrystalline quartz), and 1–13% altered feldspar (both orthoclase and plagioclase with plagioclase being the dominant) Iwuagwu and Lerbekmo (1982) classified Belly River sandstones as compositionally mature litherarenites.

Sandstones that are interpreted as being derived from the thrust belt differ greatly in their mineralogical compositions from McMurray Formation sandstones (Tater, 1964; Blatt et al., 1972; Bayliss and Levinson, 1976; Iwuagwu and Lerberkmo, 1982; Potocki and Hutcheon, 1992; Hein et al., 2012). Sandstones derived from the thrust belt in the west consist nearly entirely of sedimentary lithic fragments, which are mainly chert. They are poor in quartz and feldspar. Potocki and Hutcheon (1992) classified sandstones derived from the thrust belt as sublitharenites and litharenites, and they demonstrated that all of these sandstones plot on recycle orogeny quadrant of Dickinson and Suczeck (1979) and Dickinson et al. (1983) QmFLt ternary diagram.

Despite the fact that sandstones of the McMurray Formation are time equivalent with sandstones of the Ellerslie and the Dina formations, the three units differ in composition. Dina Formation sandstones are compositionally similar to the McMurray Formation except for having higher feldspar and micas content. Ellerslie Formation sandstones are distinct from both the McMurray and Dina formations, because they contain a higher percentage of lithic fragments. Hein et al. (2012) proposed that sediments derived from the Cordillera are less mature, and correspond to lithic arenites dominated by microcrystalline and megacrystalline chert, and volcanic grains. Conversely, sands

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derived from the Canadian Shield and the southwest USA are characterized by compositionally mature quartz arenite (Hein et al., 2012).

Recently, both Appalachian and southwestern USA sources have been proposed for parts of the McMurray Formation based on detrital zircon analysis (e.g., Benyon et al., 2013, 2014; Blum and Pecha, 2013). The southwestern USA source hypothesis argues that McMurray Formation sediments were deposited by a southeast-to-northwest fluvial system that flowed to the northwest (e.g., Benyon et al., 2014; Blum and Pecha, 2013). Detrital zircon analysis suggests that sediments were dominantly sourced from the Appalachian Mountains, but that tributaries entered the river from both the southwest USA and the Canadian Shield (e.g., Benyon et al., 2013, 2014; Blum and Pecha, 2013). Benyon et al. (2014) also pointed out that there are vertical variations in the sediment composition within the McMurray Formation, reflecting provenance changes during the deposition of the interval.

1.5. Study Area

The study area is located in east-central Alberta from Township 50 – R5W4 (southeast corner) to Township 70 – R17W4 (northwest corner; Fig. 1.4), and includes 273 townships (approximately 27,300 km2). There are 7228 wells in the study area that penetrate the Mannville Group and have well log (LAS and Raster) files. In the study area, the Wainwright Highland-Grosmont Ridge trend, Edmonton Valley and McMurray Sub-Basin are intercepted (Figs. 1.3 and 4a; Ranger et al., 1994; Smith, 1994; Hein et al., 2012). The study area lies in the southern McMurray Sub-Basin and is sub-divided into three northeast-trending paleovalleys named: the Ptarmigan, Quail, and Grouse paleovalleys (Fig. 1.4b-c). These valleys are an offshoot from Grosmont-Wainwright Highlands (Fig 1.4c).
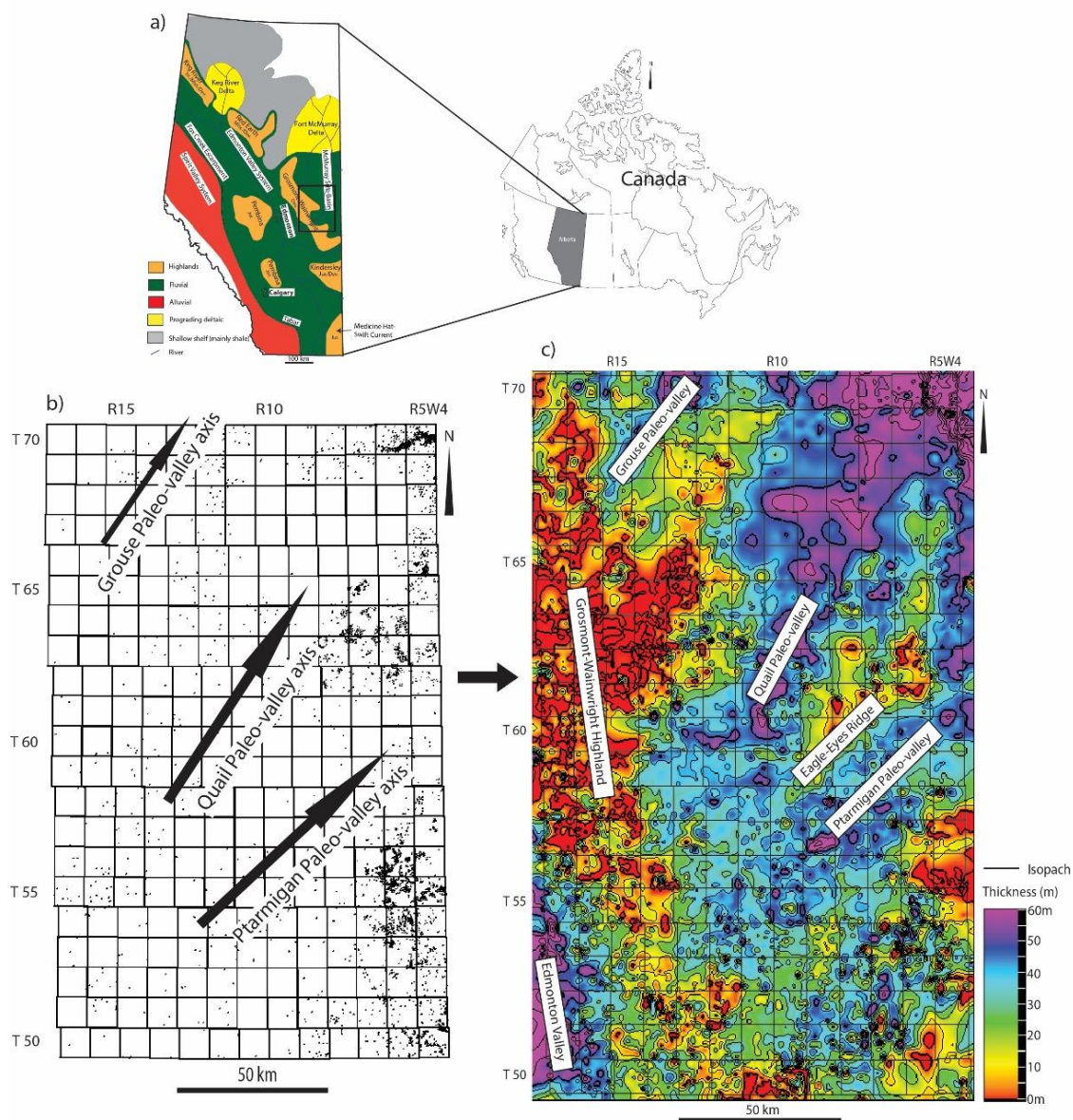
Figure 1.4. **Map of the study area a) Map of Canada and Alberta's paleogeography map (after Smith, 1994) showing the position of the study area. b) Index map of the study area. The black dots represent individual wellbores with digital well-log Files (LAS and Raster; map from Geoscout); black arrows show axes of the three valleys. c) Isopach map of the southern McMurray Sub-Basin for the McMurray Formation (based on 7228 wells), which is equal to the paleo-topography or paleo-drainage pattern on the top of the Sub-Cretaceous Unconformity (SCU); the bright red-orange-yellow colours represent the topographic highs whereas the cool purple-blue-green colours represent the topographic lows. The map shows sub-division of the southern McMurray Sub-Basin into three paleovalleys: Ptarmigan, Quail and Grouse Paleovalleys.**

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1.6. Research Methodology

This project involves two distinct phases, each with different research methodologies: isopach and net-sand mapping, and thin-section analysis.

1.6.1. *Isopach and Net-Sand Mapping*

For isopach mapping, a maximum of 2 well logs per section were selected, and logs were chosen based on their geographic distribution, quality, and availability of gamma ray, photoelectric (Pe), resistivity, and sandstone neutron/density porosity tracks. Stratigraphic surfaces were picked and correlated using Geoscout. The top of the Wabiskaw Member as well as the base and top of the McMurray Formation were picked in all 7228 LAS and Raster files. The base of the McMurray Formation is selected at the sandstone to carbonate contact (marking the SCU), which is easily identifiable on neutron-density well-logs by a sharp deflection to the right (lower porosity; Figs. 1.5 and 1.6) with depth. In the absence of sandstone neutron-density curves, the base of the McMurray Formation is identified by an increase (downwards) in the Pe reading from 2-3 to 5, and a higher resistivity on the deep resistivity curve (Fig. 1.7). The top of the McMurray Formation and top of the Wabiskaw Member are more difficult to pick on well-logs, and they change character across the study area. However, the top of the Clearwater Formation is easier to identify, and the Clearwater isopach was used to help delineate the top of the Wabiskaw Member (Figs. 1.5 – 1.7). The Wabiskaw-McMurray Isopach is obtained by measuring the thickness from the top of the Wabiskaw Member to the SCU, and the McMurray Isopach is taken from the top of the McMurray Formation to the SCU (Figs. 1.5 – 1.7).

Net sand is measured on gamma ray logs, and is the cumulative length of the gamma ray log when readings are less than 60 API, and where neutron-density well-logs do not sharply deflected to the left (Fig. 1.8, indicating coal). The values obtained from the Wabiskaw-McMurray isopach, McMurray isopach and McMurray net sands from Geoscout were contoured using Petrel.
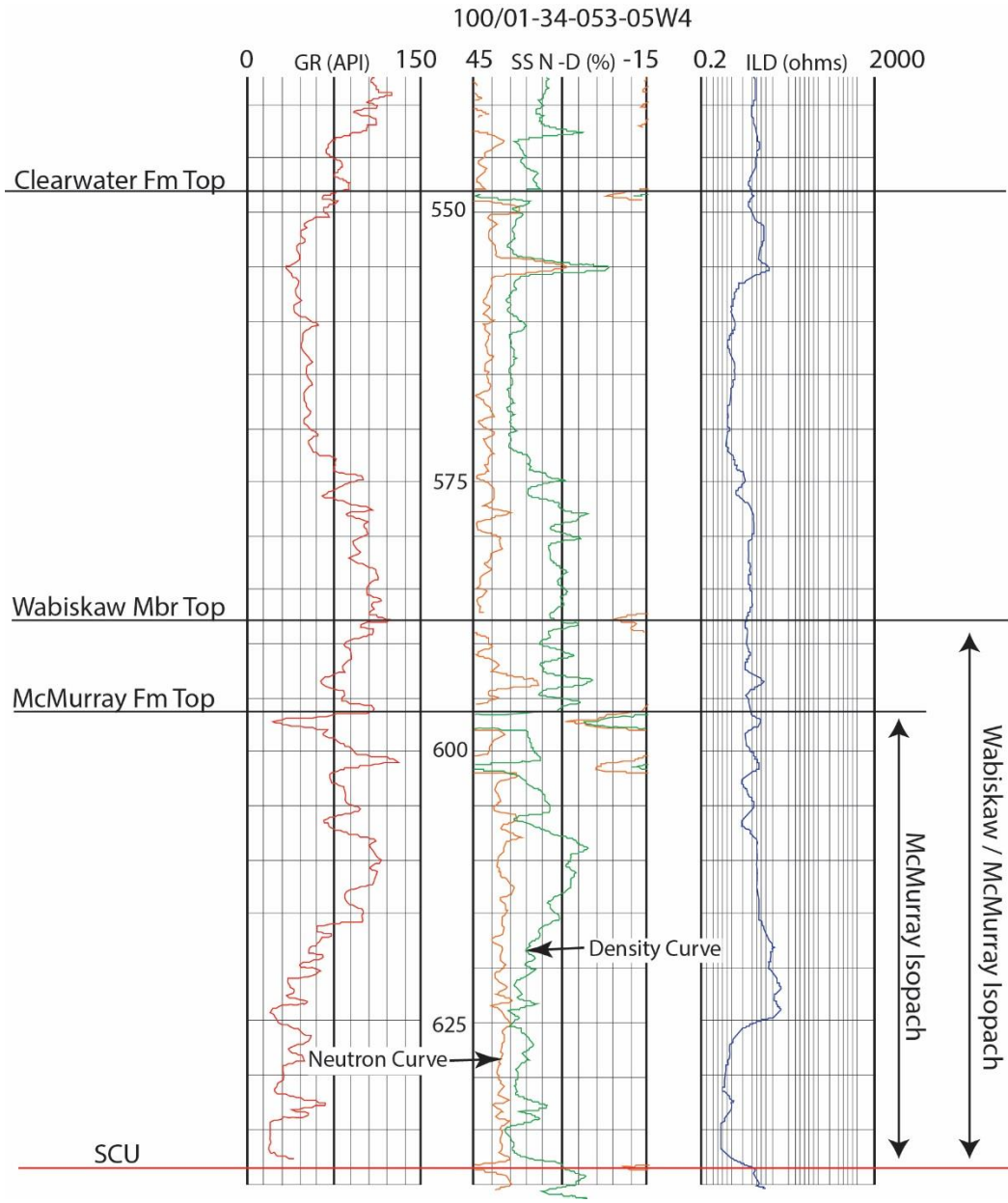
Figure 1.5. **Representative well-log, showing the picks for the top of the Wabiskaw Member and McMurray Formation between Townships 50 to 55 and Range 5 to 8W4. The SCU is picked on the change in the neutron-density reading, and the intervals used to calculate the Wabiskaw-McMurray and McMurray isopachs are shown on the right. Gamma-ray curve (GR), sandstone neutron-density (SS N-D), and deep resistivity (ILD).**
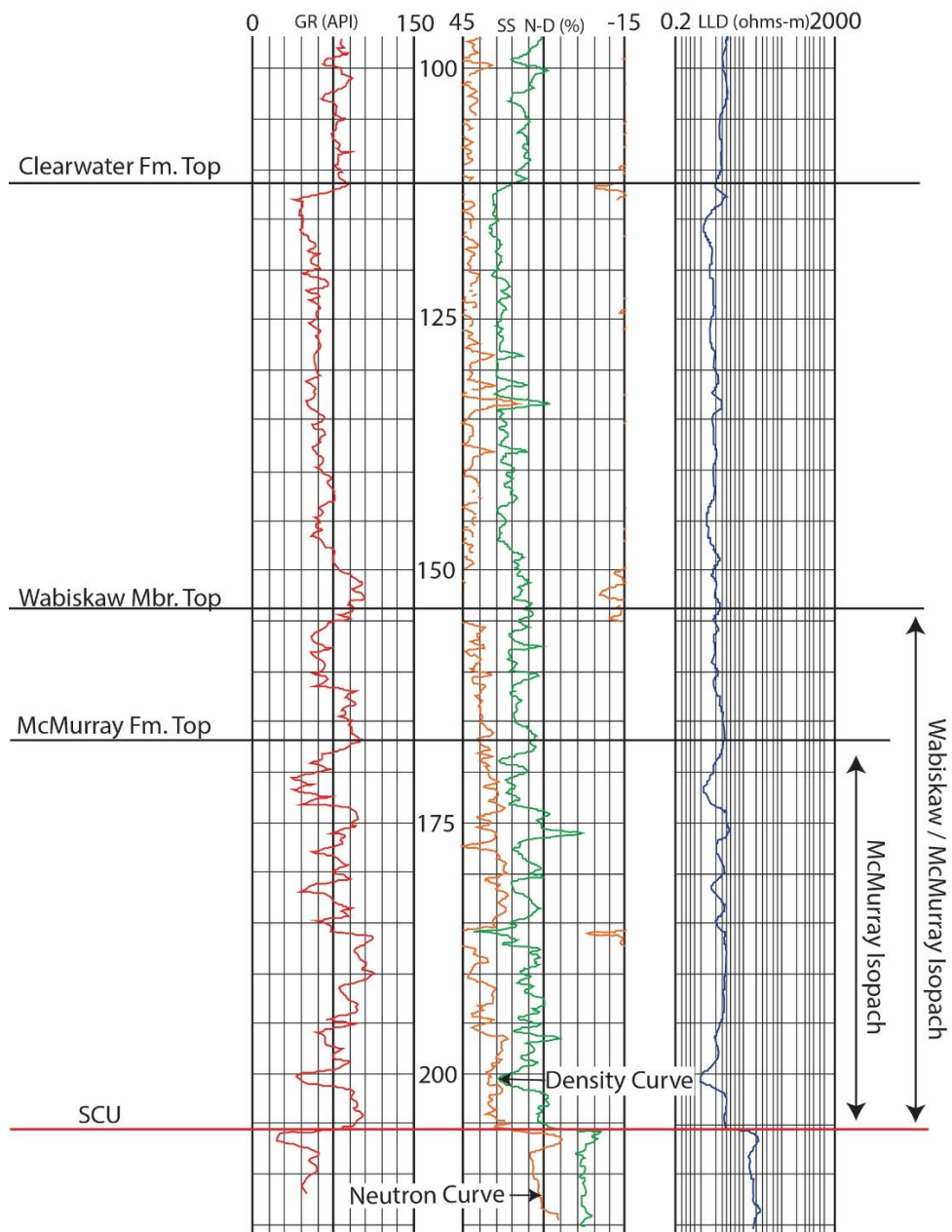
Figure 1.6.   **Characteristic well-logs, showing the picks for the top of the Wabiskaw Member and McMurray Formation between Townships 56 to 70 and Ranges 5 to 10W4. The SCU is picked on the change in the neutron-density reading and the intervals used to calculate Wabiskaw-McMurray and McMurray isopachs are shown on the right. Gamma-ray curve (GR), sandstone neutron-density scale (SS N-D), and deep resistivity (ILD).**
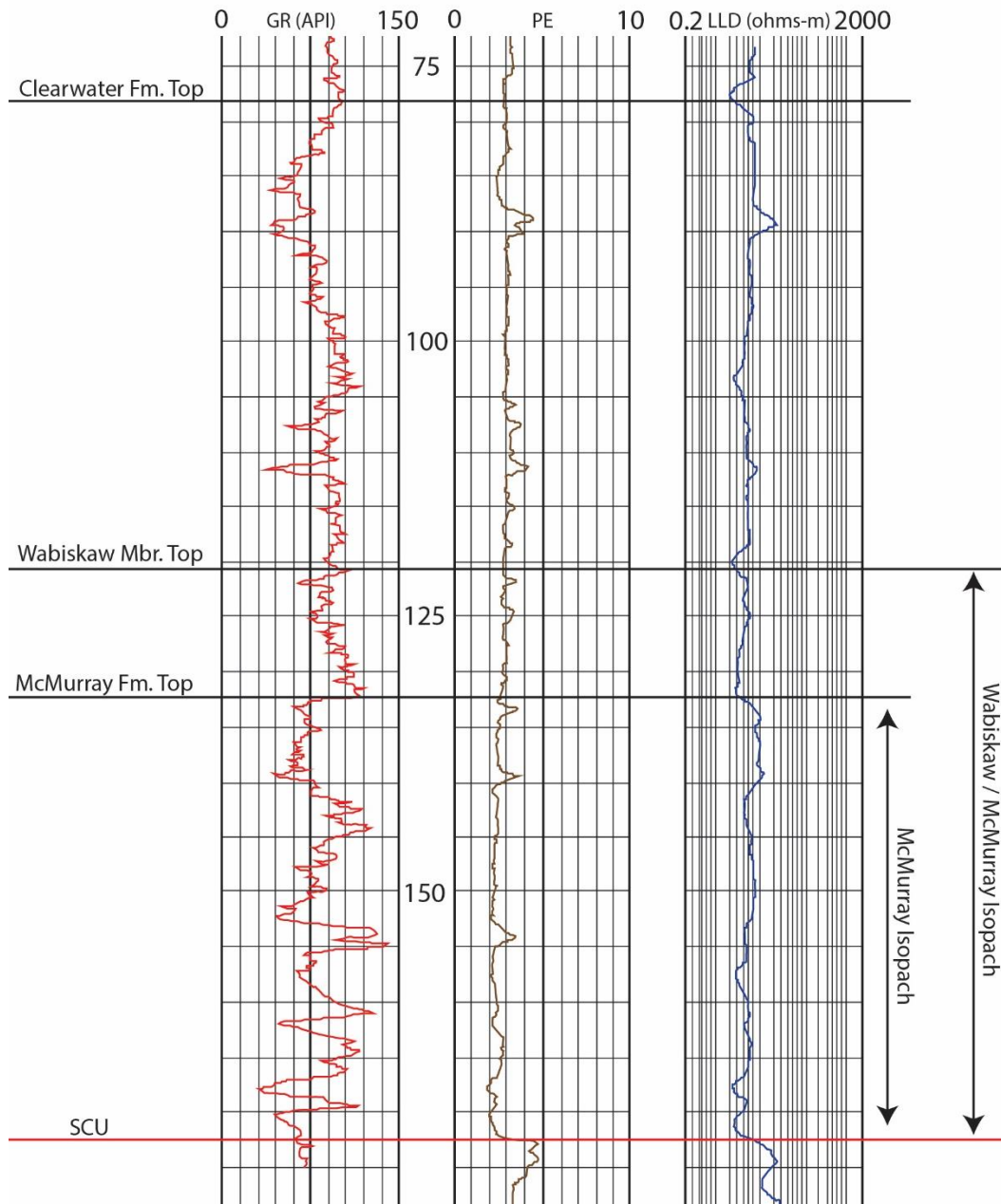
Figure 1.7. Representative well-log, showing the top of the Wabiskaw Member and McMurray Formation between Townships 56 to 70 and Range 5 to 10W4. The SCU is picked on the change in Pe reading, and the intervals used to calculate the Wabiskaw-McMurray and McMurray isopachs are shown on the right. Gamma-ray curve (GR), photoelectric (PE), and deep resistivity (ILD).

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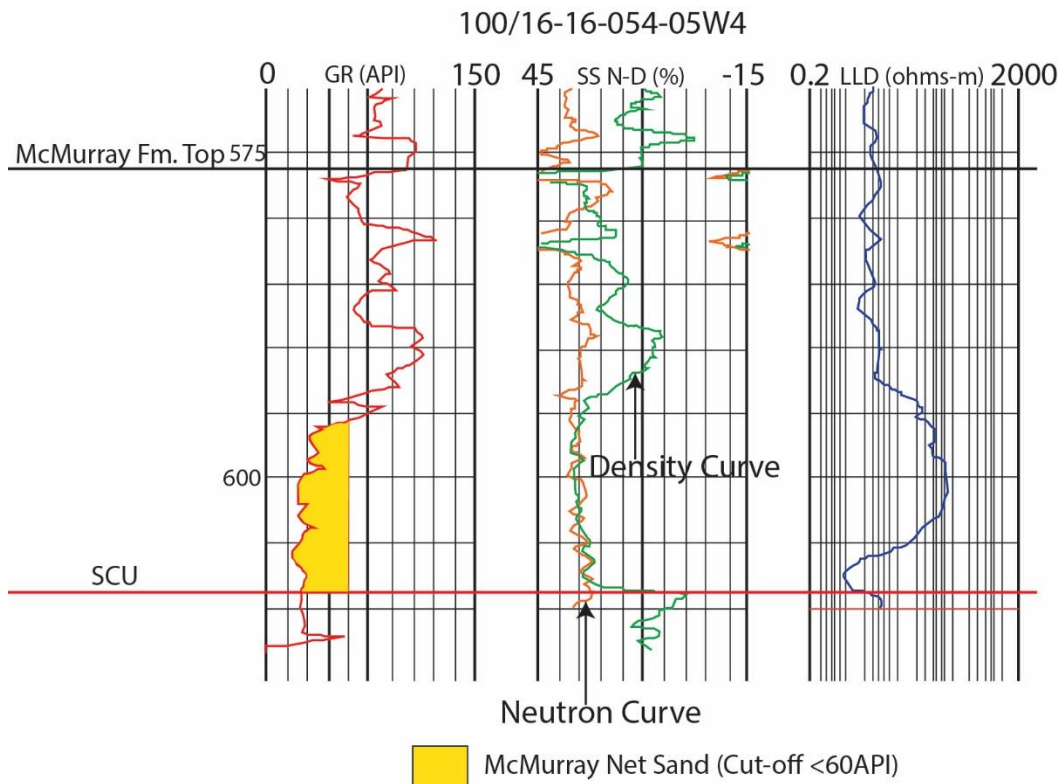
Figure 1.8. **The yellow colour on the gamma-ray curve represents McMurray net-sand, and a gamma ray cut-off of less than 60 API is used to define clean sandstones. Gamma-ray curve (GR), sandstone neutron-density scale (SS N-D), and deep resistivity (ILD).**

1.6.2. Section Analysis

A total of 30 cores (Fig. 1.9) that penetrated through the McMurray Formation from Township 50 (T50) to T70 and Range 5 (R5) to R17 west of the 4th Meridian, were logged, and their sedimentological, and ichnological characteristics were recorded with Applecore (courtesy of Mike Ranger). From 26 of these cores, 55 McMurray sandstones samples were taken from the upper McMurray and upper part of the middle McMurray Formation, though some samples occur only a few meters above the sub-Cretaceous Unconformity (SCU). Thin sections were made at Core Laboratory in Calgary. Petrographic analyses were undertaken on all 55 thin sections by point-counting the grains. An average of 508 grains was counted per thin section. Point counting was performed using maximum possible grid spacing (i.e., 0.5 mm spacing; Ingersoll, 1978), and data are presented and discussed in Chapter Three.

The mineralogical components identified in thin sections are: 1) detrital quartz (very fine to coarse grain) - monocrystalline and polycrystalline quartz; 2) detrital feldspar (very fine to coarse grain) - microcline, orthoclase, and albite; 3) lithic fragments (very fine to coarse grain) – chert (microcrystalline, megacrystalline and cryptocrystalline), sandstone, siltstone, carbonate, and quartzite; 4) detrital mica - muscovite and biotite; 5) authigenic minerals – chlorite and glauconite; and 6) heavy minerals which are difficult to differentiate in thin section. Microsoft Excel was used to tabulate and statistically analyze the mineralogical data. Analysis techniques includes: 1) calculating the percentage of each mineralogical sub-component (e.g., monocrystalline quartz, chert, microcline, muscovite) as a portion of the whole rock; and, 2) determining the total percentage of quartz, feldspar and lithic fragments in the sample. Micas and heavy minerals are not included in mineralogicial classification because determination of Quartz-Feldspar-Lithic (QFL) components is based on bulk mineralogy that exclude mica and heavy minerals.

The quartz (Qm, Q), Feldspar (F), and lithic (Lt, L) components are plotted using the Folk (1974) sandstone classification scheme. Chert, quartzite and polycrystalline quartz are counted as lithic fragments and not as quartz in QmFLt ternary diagrams. Monocrystalline and polycrystalline quartz, quartzite and chert are counted as part of the quartz component in QFL ternary diagrams and both ternary diagrams are used to classify the sandstones and also for determining provenance. Quartzites are differentiated from polycrystalline quartz by looking at their crystals, polycrystalline quartz consist of crystals that have straight boundaries while quartzite crystals have elongated boundaries. To facilitate easy identification of feldspars that have broken along their cleavage plane, feldspars were stained yellow with sodium colbaltrinitrite.
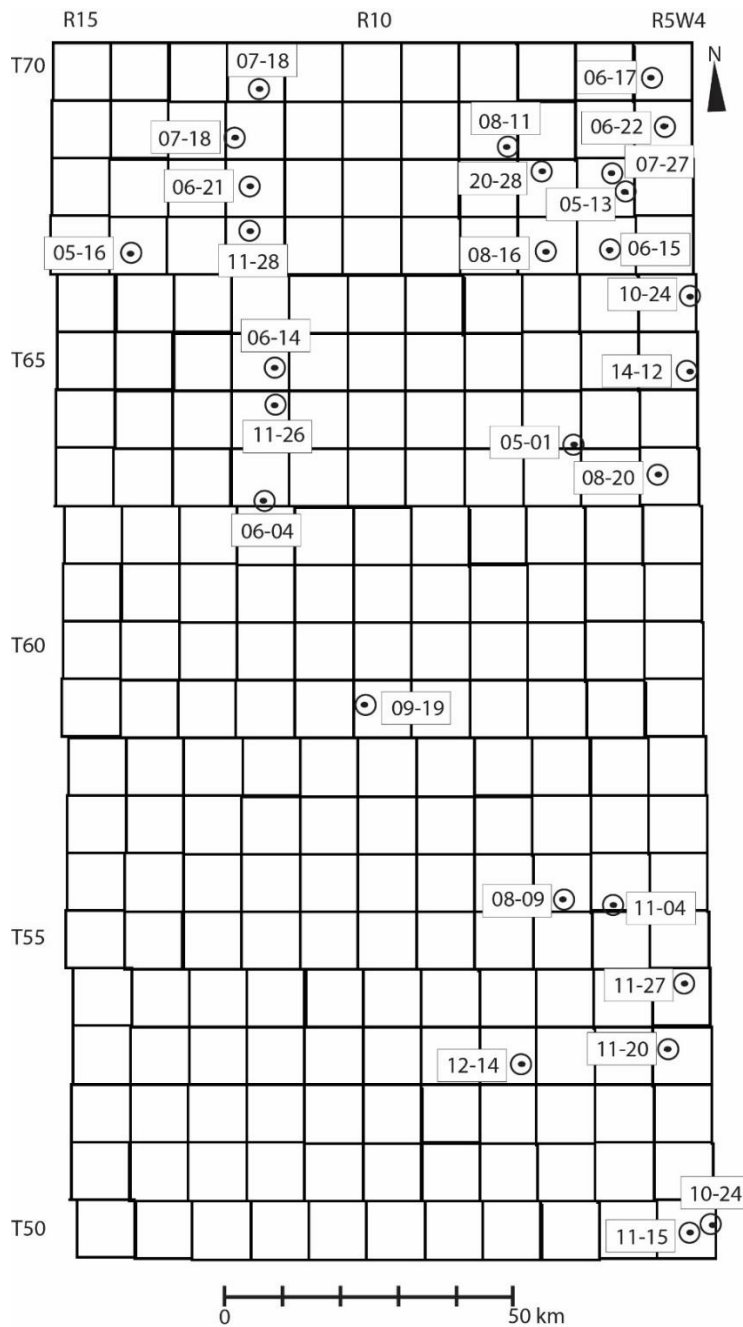
Figure 1.9. Core locations in the study area. Cores were selected based on availability and distribution in the study area.

1.7. Thesis Organization

Chapter 2 focuses on the Wabiskaw Member marker and variations in the well log character of this interval. This evaluation was undertaken because the placement of the

top of the Wabiskaw Member of the Clearwater Formation controls the isopach mapping of the Wabisaw and McMurray intervals, and is crucial, therefore, for the study of the McMurray Formation.

Chapter 3 centers on petrographic analysis and paleogeographic reconstructions of the study area. These studies are essential because they not only help to ascertain if the Grosmont-Wainwright Highlands prevented Cordilleran sediment from reaching the McMurray Sub-Basin from the south and southwest, but also to quantify the percentages of Cordilleran sediments that reached the McMurray Sub-Basin.

Finally, Chapter 4 concentrates on discussion of the study and the final conclusion.
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Chapter 2.

The Wabiskaw Marker

2.1. Introduction

Chapter 2 focuses on the suitability of employing the top of the Wabiskaw Member (Wabiskaw Marker) as a regionally correlatable surface and on describing variations in the well log character of the Wabiskaw interval. This assessment is undertaken because the placement of the Wabiskaw Marker controls isopach mapping of the Wabiskaw and McMurray intervals (Figs. 2.1 and 2.2), and hence, is crucial for the study of the McMurray Formation. If the top of the Wabiskaw Member is consistently picked across the study area, the Wabiskaw isopach can be used to help delineate the top of the McMurray Formation where the log pick is not apparent. The resulting McMurray Formation isopach map will therefore more accurately reflect the paleo-topography of the sub-Cretaceous Unconformity (SCU), and this enables accurate reconstruction of the paleogeography of the southern McMurray Sub-Basin (study area) at the inception of McMurray Formation deposition.
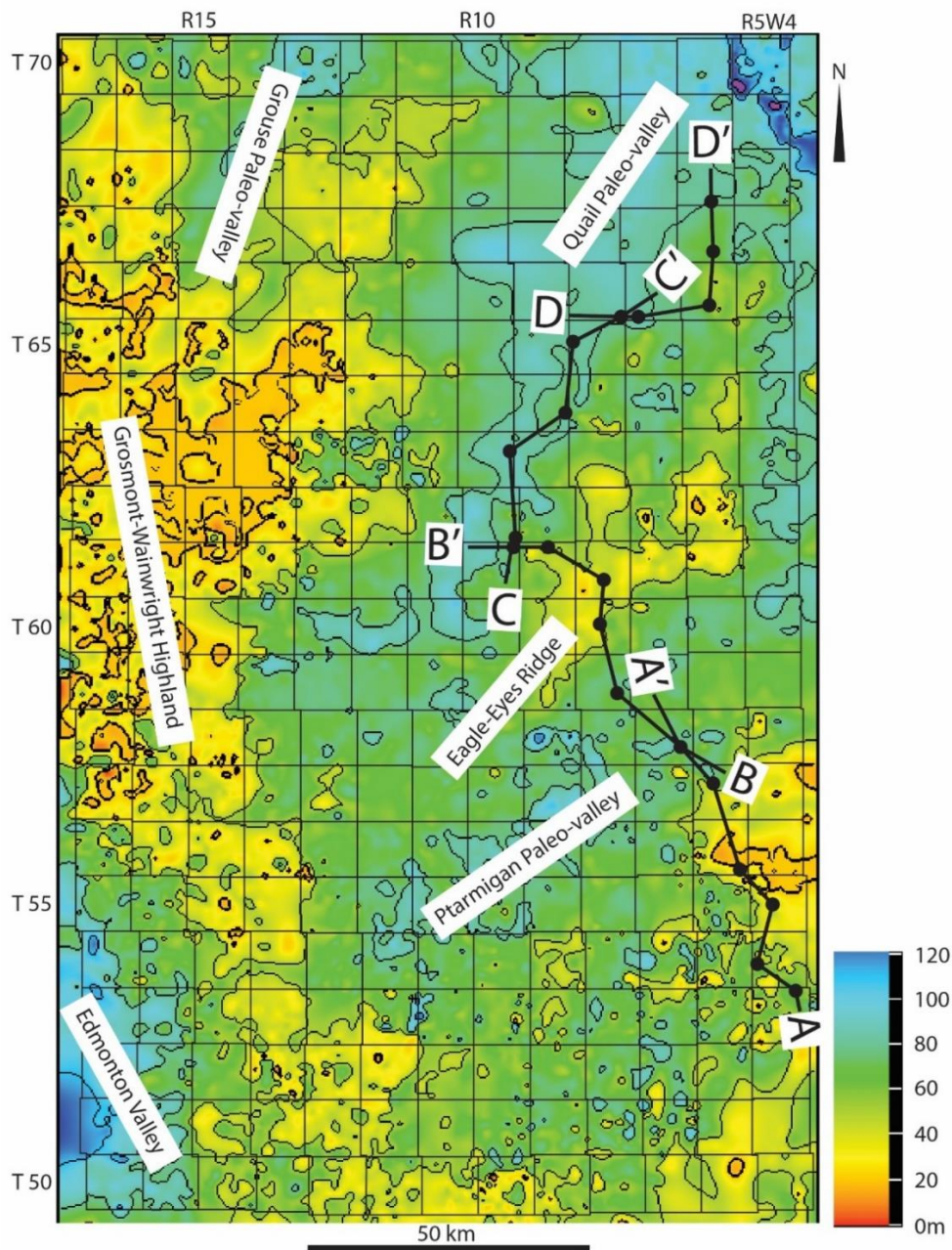
Figure 2.1. **Isopach map of Wabiskaw-McMurray interval (based on 7228 wells) showing the position of regional cross-sections A–A' through to D–D' (Figs. 2.3–2.6) in the southern McMurray Sub-Basin. The map presupposes the upper surface is horizontal and that all thickness variations reflect paleotopographic relief on the SCU. The cool green-blue-purple colours represent paleotopographic lows, whereas the bright yellow-orange-red colours represent paleotopographic highs on the sub-Cretaceous Unconformity (SCU). The map shows sub-division of the southern McMurray Sub-Basin into the Ptarmigan, Quail, and Grouse paleovalleys.**

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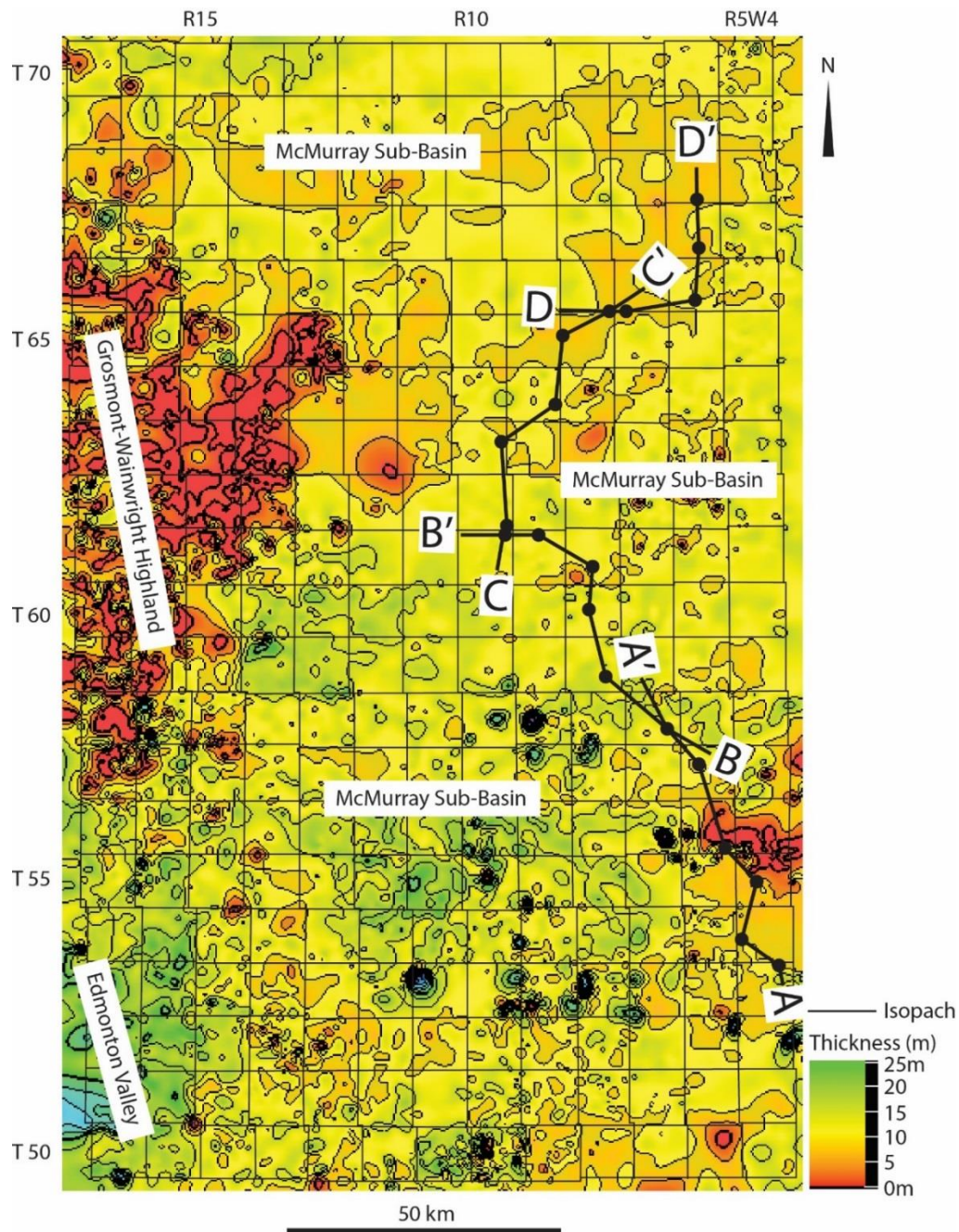
Figure 2.2. **Wabiskaw isopach map with the position of regional cross-sections A–A' through to D–D' (Figs. 2.3–2.6) shown. The bright red colour represents isopach thin values, interpreted to reflect paleo-topographic highs on the sub-Cretaceous Unconformity (SCU), wherein both the Wabiskaw Member and all of the McMurray Formation strata are missing. The map shows that the Edmonton Valley and southern McMurray Sub-Basin were largely connected as single seaway during deposition of the Wabiskaw Member.**

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2.2. Suitability of the Wabiskaw Top as a Key Marker Surface in the Study Area

The stratigraphic interval that includes the Wabiskaw Member and McMurray Formation is regarded as a transgressive system tract (TST; cf. Wightman et al., 1995). The log character of the TST and its upper surface change markedly across the study area. The surface that separates the McMurray Formation from the overlying Wabiskaw Member is sharp and erosive, and is interpreted as a transgressive ravinement surface cut during incursion of the Boreal Sea (Hein and Cotterill, 2000; Hein et al., 2012). The top of the Wabiskaw Member is a flooding surface and is referred to as the Wabiskaw Marker. The top of the Wabiskaw Member of Clearwater Formation (Wabiskaw Marker) separates the Wabiskaw-McMurray interval from the overlying marine shale of the Clearwater Formation (Keith et al., 1988; Wightman et al., 1995; Hein and Cotterill, 2000; Hein; 2006).

Previous studies define the top of the Wabiskaw Member of the Clearwater Formation in well-logs as the top of the first coarsening-upward cycle at the base of Clearwater Formation (Flach, 1984; McPhee, 1994; Rangers et al., 1994; Keith et al., 1988; Hein et al., 2001; Hein et al., 2012; Broughton, 2013). For this reason, the Clearwater Formation isopach can be used to assist in delineating the top of the Wabiskaw Member in wells where the pick is not obvious, as it can be picked on the top of the first coarsening-upward cycle at the base of the Clearwater Formation (Figs. 2.3–2.6). The Wabiskaw Marker is easily picked using gamma ray and deep resistivity logs, because it corresponds to a high gamma-ray value and low resistivity value that is regionally correlatable (Flach, 1984; Keith et al., 1988). The base of the marine shale at the base of the Wabsikaw Member is chosen as the top of the McMurray Formation (Figs. 2.3–2.6; Hein et al., 2012; Broughton, 2013). The top of the McMurray Formation top is recognizable on well-logs everywhere in the study area, except from Townships (T) 50–55. From Township 50–55, the top of McMurray Formation is picked at the top of a regionally mappable coal (Fig. 2.3) that appears to be stratigraphically equivalent to the base of the marine shale at the base of the Wabiskaw Member.

The gamma-ray well-log profile of the Wabiskaw Member from T56–T70 and Ranges (R) 5–17W4 displays a decrease in radioactive values upwards (i.e. coarsens or sands upward); however, from T50–T55 and R5–R12W4, the well-log profile is blocky (60 or 75 API) and underlain by regionally correlatable coal (e.g., Figs. 2.3–2.6).

Figure 2.3. Stratigraphic cross-section A–A', showing picked tops for the Clearwater Formation, Wabiskaw Member, McMurray Formation and sub-Cretaceous Unconformity from Townships 53–58 and Ranges 5–7W4. The black line = top of the Clearwater Formation (datum); blue line = top of the Wabiskaw Member; purple line = top of the McMurray Formation, and red line = top of the sub-Cretaceous Unconformity. The position of cross-section A–A' is shown on Figures 2.1 and 2.2.

Figure 2.4. Stratigraphic cross-section B–B', showing picked tops for the Clearwater Formation, Wabiskaw Member, McMurray Formation and sub-Cretaceous Unconformity from Townships 58–61 and Ranges 7–10W4. The black line = top of Clearwater Formation (datum); blue line = top of the Wabiskaw Member; purple line = top of the McMurray Formation, and red line = top of the sub-Cretaceous Unconformity. The position of cross-section B–B' is shown on figures 2.1 and 2.2.

Figure 2.5. Stratigraphic cross-section C–C', showing picked tops for the Clearwater Formation (datum), Wabiskaw Member, McMurray Formation and sub-Cretaceous Unconformity from Townships 61–66 and Ranges 8–10W4. The black line = top of Clearwater Formation (datum); blue line = top of the Wabiskaw Member; purple line = top of the McMurray Formation, and red line = top of the sub-Cretaceous Unconformity. The position of cross-section C–C' is shown on figures 2.1 and 2.2.

Figure 2.6. Stratigraphic cross-section D–D', showing picked tops for the Clearwater Formation (datum), Wabiskaw Member, McMurray Formation and sub-Cretaceous Unconformity from Townships 66–68 and Ranges 6–8W4. The black line = top of Clearwater Formation (datum); blue line = the top of the Wabiskaw Member; purple line = top of the McMurray Formation, and red line = top of the sub-Cretaceous Unconformity. The position of cross-section D–D' is shown on figures 2.1 and 2.2.

Stewart and McCallum (1978), Keith et al. (1988), Hein (2006) and Broughton (2013) described deposits of the Wabiskaw Member as fully-marine in origin. Additionally, Wightman et al. (1997) defined the Wabiskaw Member as a coarsening-upward succession that was deposited by punctuated progradation of the shoreline during overall southward transgression of the Boreal Sea. Ranger et al. (1988) and Wightman et al. (1997) show that the Wabiskaw Member (Wabiskaw A, B, and C intervals) consists of well-developed marine shoreline deposits that thin and pinch out towards the north. Based on the data presented in these previous studies, this study interprets the Wabiskaw Marker as a marine flooding surface on the top of the transgressive system tract (TST) Wabiskaw-McMurray interval (Ranger et al., 1994; Wightman et al., 1997; Hein, 2006) and the Wabiskaw Member is the first coarsening-upward cycle at the base of Clearwater Formation (Flach, 1984; McPhee, 1994; Ranger et al., 1994; Keith et al., 1988; Hein et al., 2001; Hein et al., 2012; Broughton, 2013). Consequently, the Wabiskaw Marker is the surface on the top of the first coarsening upward cycle at the base of the Clearwater Formation. The Wabiskaw Marker is used for studying the McMurray interval because it corresponds to a high gamma-ray value and low resistivity value and hence, is easy to pick on gamma-ray and resistivity well-logs (e.g., Figs. 1.5; 2.3–2.6).

2.3. Paleogeographic Reconstruction of the Study Area

The sub-Cretaceous Unconformity (SCU) throughout the Western Canada Sedimentary Basin is defined by a series of northwesterly trending paleotopographic highlands and paleovalleys (Fig. 2.7; Jackson, 1984; Ranger et al., 1994; Smith, 1994; Hein et al., 2012; Mei et al., 2015). Principal topographic features include: 1) the Fox Creek Escarpment and Pembina Highlands that formed a ridgeline between the Edmonton Valley and Spirit River Valleys; 2) the Wainwright, Grosmont, Red Earth, Kindersley, Keg River and Medicine Hat-Swift Current Highlands that form a drainage divide between the Edmonton Valley in the west and McMurray Sub-Basin in the east; and 3) McMurray Sub-Basin – Assiniboine Valley that lies to the east of the Grosmont–Wainwright Ridge. Of these paleotopographic features, only the Wainwright-Grosmont Highlands, Edmonton Valley, and Assiniboine – McMurray Sub-Basin are intercepted in the study area (Fig. 2.7).

Prior to the deposition of the Lower Cretaceous McMurray Formation, three large paleovalleys were carved into the Wainwright Highland in the study area. These are named, herein, as the Grouse, Quail and Ptarmigan paleovalleys (Fig. 2.8). The Eagle-Eyes Ridge is also named, and forms a drainage divide between the Ptarmigan and Quail paleovalleys (Fig 2.8). The valleys range from 25–60 m deep, and are 4–9 km wide in the south-southwest and 8–18 km wide in the northeast (Fig. 2.8). The depth of the paleovalleys increases from less than 25 m in the southwest to deeper than 60 m in the northeast.

During deposition of the Lower Cretaceous McMurray Formation (Fig. 2.2), the Ptarmigan, Quail, and Grouse paleovalleys were filled with sediment, and the Grosmont-Wainwright Highland was partially covered. The filling of these valleys is stratigraphically equivalent to the Upper McMurray and upper part of Middle McMurray Formation. The timing of drainage from the west (Edmonton Valley) entering into the southern McMurray Sub-Basin coincides with the beginning of the deposition of the upper part of the Middle McMurray. As the Clearwater Sea flooded across the Western Canada Sedimentary Basin (WCSB) and the paleovalleys filled, the Wabiskaw Member of Clearwater Formation received higher percentages of Cordilleran sediments than the McMurray Formation (Ranger and Pemberton, 1997; Wightman et al., 1997; Hein and Conterill, 2006; Blum and Pecha, 2012; Benyon et al., 2014). In fact, at the onset of deposition of the Wabiskaw Member, the southern portion of the southern McMurray Sub-Basin was already fully connected to the Boreal Sea in the Edmonton Valley (Fig. 2.2).
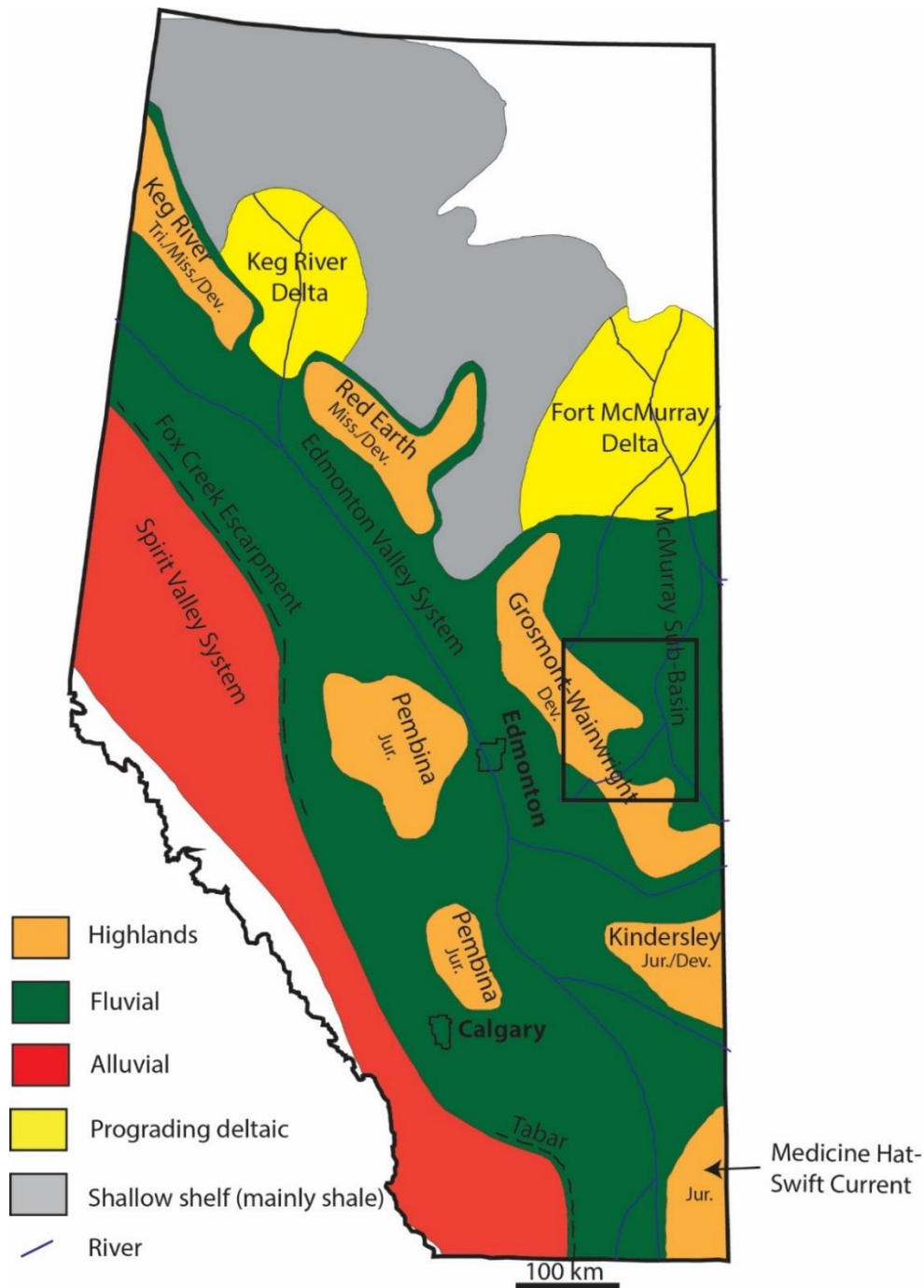
Figure 2.7.   **Paleogeographic map of Alberta at the time of deposition of the Lower Cretaceous McMurray Formation and age-equivalent strata (modified from Smith, 1994). The map shows paleo-topographic lows and highs, and the ages of strata that form the highs.- Abbreviations: Devonian (Dev.), Mississippian (Miss.), Triassic (Tri.), and Jurassic (Jur.). The inset rectangle is the outline of the study area which encompasses part of the Edmonton Valley, the Wainwright-Grosmont Highlands, and the McMurray Sub-Basin.**

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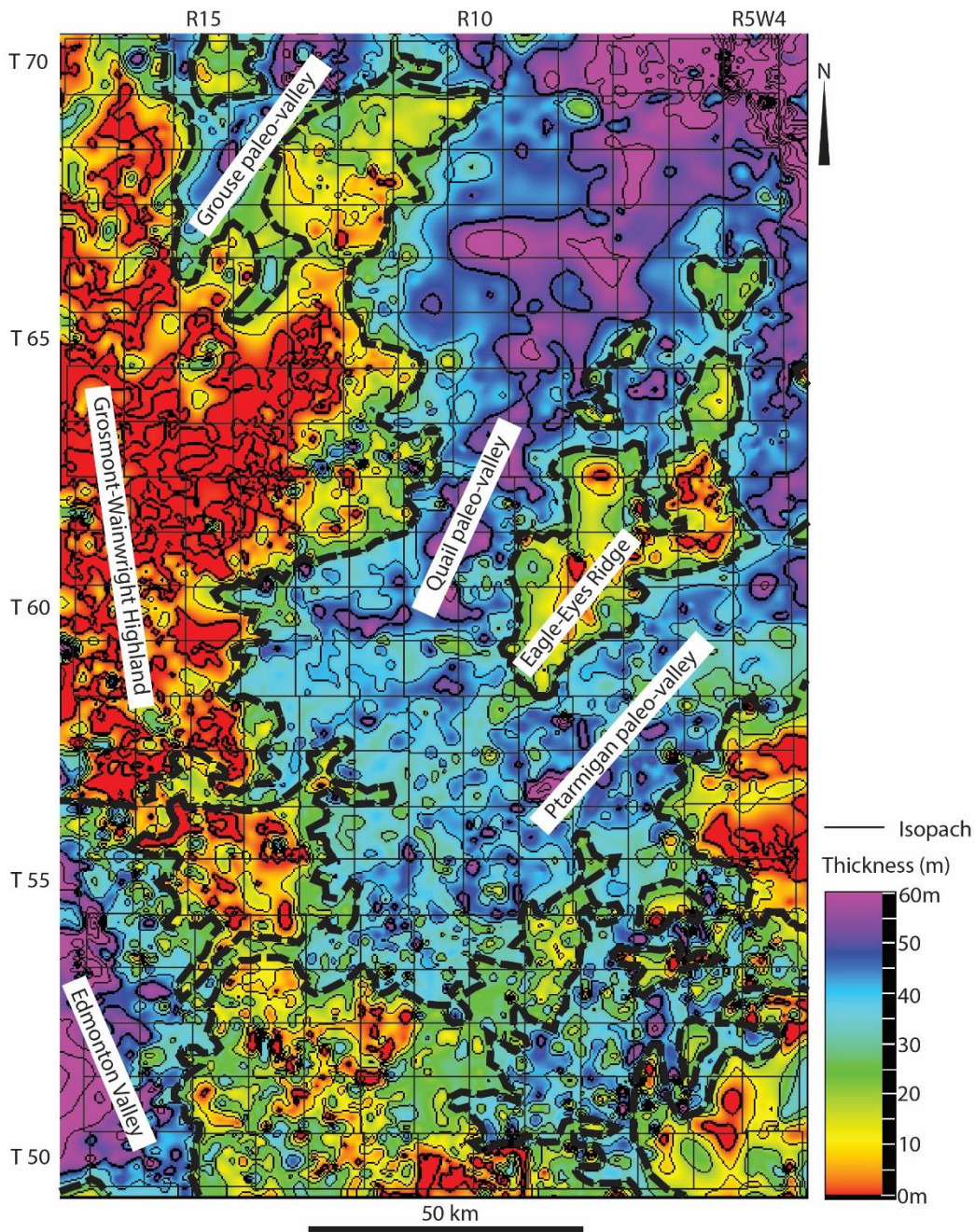
Figure 2.8. **Isopach map of the McMurray Formation and time-equivalent strata.**
-The map of possible channel conduits superimposed on the paleo-
topography of the sub-Cretaceous Unconformity. The bright red-
orange-yellow colours represent the paleotopographic highs on the
sub-Cretaceous Unconformity, whereas the cool green-blue-purple
colours represent paleotopographic lows. Thick, white lines
delineate possible paleo-channels across the top of paleo-
topographic highs that would have connected the McMurray Sub-
Basin to the Edmonton Valley.

2.4. Conclusions

This assessment confirms that the top of the of the Wabiskaw Member (Wabiskaw Marker) is a suitable datum for mapping the Wabiskaw-McMurray interval on well-logs, because the surface is a regionally mappable flooding surface that can be correlated throughout the entire study area (Figs. 2.1, 2.3 – 2.6). This is consistent with the finding of previous studies (e.g., Flach, 1984; McPhee, 1994; Rangers et al., 1994; Keith et al., 1988; Hein et al., 2001; Hein et al., 2012; Broughton, 2013). These studies also show that the Wabiskaw Marker can be mapped further north of the study area. Given the flat-lying character of the marker, isopach mapping of the Wabiskaw-McMurray interval clearly defines the paleotopography on the top of sub-Cretaceous Unconformity at the initiation of McMurray Formation deposition.

The reconstruction of the paleogeography of the southern McMurray Sub-Basin shows that there are three paleovalleys carved into the Wainwright-Grosmont Highlands. These are named, herein, as the Grouse, Quail, and Ptarmigan paleovalleys (Fig. 2.8). The isopach map of the McMurray Formation and time-equivalent strata (Fig 2.8) also illustrates that there may have been paleo-channels that cut east–west across the paleo-topographic highs to the west of the McMurray Sub-Basin, and may have served as conduits for the sourcing of sediments from the west during the time of the McMurray deposition.

Deposition of the Lower Cretaceous McMurray Formation coincides with the drowning and burial of all three paleovalleys. At the end of deposition of the McMurray Formation, the Ptarmigan, Quail, and Grouse paleovalleys were filled; however, the Wainwright-Grosmont Highland was only partially covered with sediments. Consequently, there are gaps in the regional correlatability of the Wabiskaw Marker in position overlying these highlands (Fig. 2.2).

2.5. References

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Chapter 3.

Identifying Cordilleran Point Sources

3.1. Introduction

In Chapter 3, I present and compare petrographic and statistical analyses of bulk mineralogical data for McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys of the southern McMurray Sub-Basin, AB (Table 3.1; Fig. 3.1). These data are then compared with published mineralogical data from the McMurray Formation in the Athabasca area, the Dina Formation in Saskatchewan and east-central Alberta, and the Ellerslie Formation in the Edmonton Valley (Carrigy, 1959; William, 1963; Bayliss and Levinson, 1976; Potocki and Hutcheon, 1992; Hein et al., 2012). Mineralogical compositions are compared between paleovalleys to determine whether there are any variations in the McMurray sandstones in Ptarmigan, Quail, and Grouse paleovalleys. Finally, using mineralogical data coupled with isopach and net-sand maps, a discussion is presented as to whether Cordilleran-supplied sediments reached the southern McMurray Sub-Basin from the west, southwest, and/or south. The list of all samples and results of their petrographic analyses are shown in Appendix A.

Table 3.1. UWI of cores and depths from which sandstones samples were collected for thin sections in the Ptarmigan, Quail, and Grouse paleovalleys.

Paleovalleys	UWI	Depth (m)
Ptarmigan	08-20-063-05W4	453.50
	08-20-063-05W4	458.40
	11-15-050-04W4	654.90
	11-15-050-05W4	667.60
	08-09-056-07W4	568.50
	08-09-056-07W4	578
	08-09-056-07W4	585.90
	10-24-066-05W4	512.70
	10-24-066-05W4	515.80
	10-24-066-05W4	522.50
	10-24-050-05W4	666.60
	10-24-050-05W4	672.10
	08-20-063-05W4	461.80
	11-04-056-06W4	577.50
	11-04-056-06W4	596.30
	14-12-065-05W4	508.30
	12-20-053-05W4	625.10
	12-20-053-05W4	630.30
	12-20-053-05W4	634
	11-27-054-05W4	598.30
	11-27-054-05W4	601.30
Quail	08-11-069-08W4	443
	08-11-069-08W4	448
	08-11-069-08W4	451.40
	13-30-068-08W4	566.40
	13-30-068-08W4	583.30
	10-28-068-07W4	505.10
	10-28-068-07W4	512.10
	07-27-068-06W4	530.40
	07-27-068-06W4	541.10
	08-16-067-07W4	502.30

Paleovalleys	UWI	Depth (m)
	08-16-067-07W4	506.60
	05-01-064-07W4	484.10
	05-01-064-07W4	503.50
	05-13-068-06W4	528.80
	05-13-068-06W4	535.10
	06-17-070-05W4	491.10
	06-17-070-05W4	529
	06-17-070-05W4	532.40
	06-04-063-12W4	547
	06-04-063-12W4	557.40
	11-28-067-12W4	477
	06-22-069-05W4	511
	06-22-069-05W4	518.80
	11-26-064-12W4	518
	11-26-064-12W4	523.20
Grouse	06-10-070-12W4	449
	06-10-070-12W4	464.20
	06-10-070-12W4	460.80
	05-16-067-14W4	462
	05-16-067-14W4	473.10
	07-18-069-12W4	452.50
	07-18-069-12W4	461.30
	06-21-068-12W4	456.50
	06-21-068-12W4	468.50
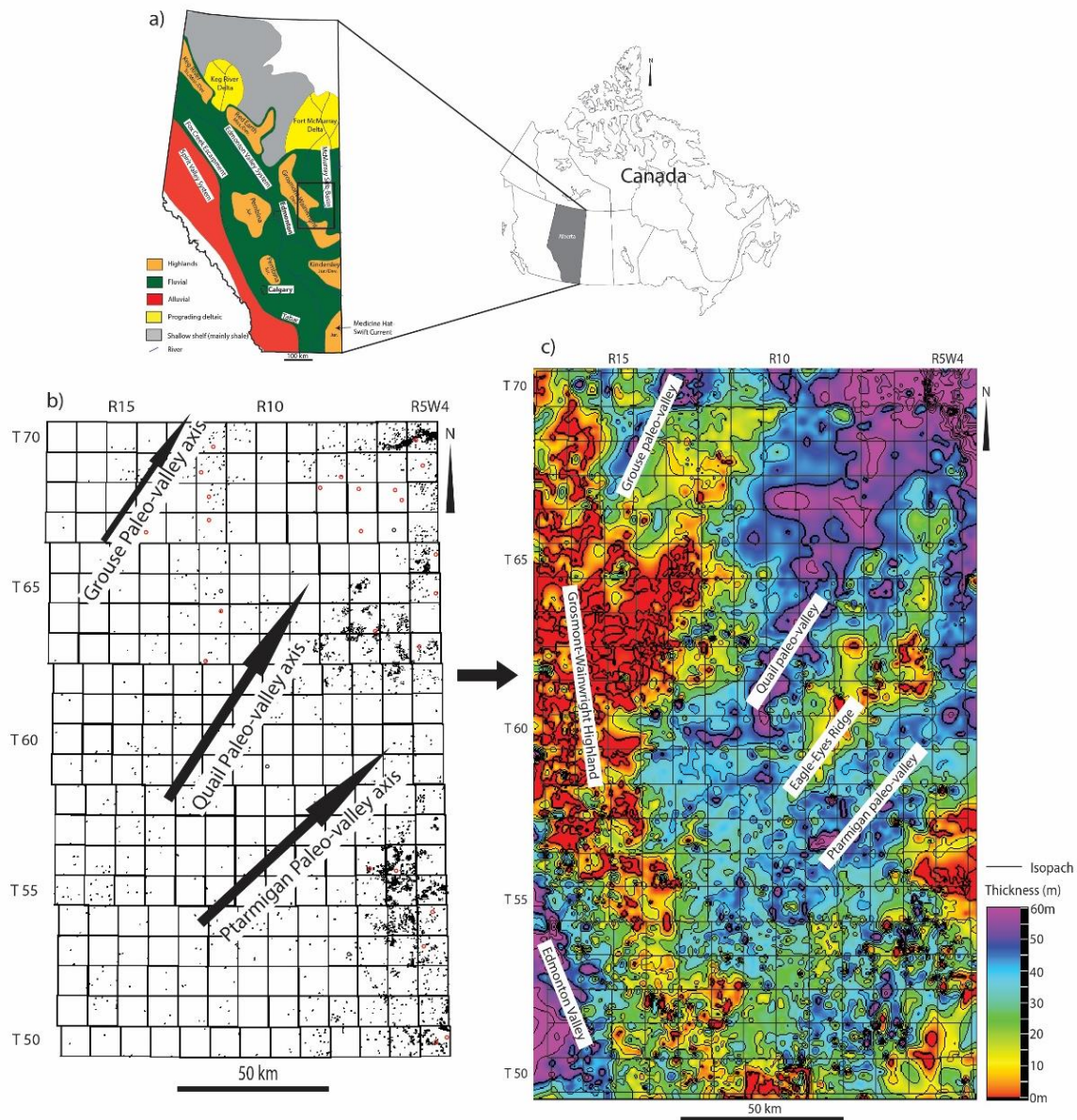
Figure 3.1.　**a) Map of Canada and Alberta paleogeography (after Smith, 1994), showing the position of study area (black box). b) Map of study area. The black dots represent individual wellbores with digital well-log files, whereas red circles represent cored wells from which thin sections were taken. c) Isopach map of the McMurray Formation across the southern McMurray Sub-Basin (based on 7228 wells). Red-orange-yellow colours represent paleotopographic highs on the sub-Cretaceous Unconformity, and green-blue-purple colours represent paleotopographic lows. The study area includes three paleovalleys, herein named the Ptarmigan, Quail, and Grouse. The Eagle-Eyes Ridge is likewise defined in this study. The Grosmont-Wainwright High was named by Smith (1994).**

3.2. Bulk Mineralogy of McMurray Formation Sandstones in Ptarmigan, Quail, and Grouse Paleovalleys

The mineralogy of McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys includes monocrystalline (Fig. 3.2a) and polycrystalline quartz (Fig. 3.2b), microcline (Fig. 3.2c) and orthoclase potassium feldspar (Fig. 3.2d), albite plagioclase feldspar (Fig. 3.2e), microcrystalline chert (Fig. 3.2g), megacrystalline chert (Fig. 3.2g), cryptocrystalline chert (Fig. 3.2h), quartzite lithic fragments (Fig. 3.3a), sandstone lithic fragments (Fig. 3.3b), siltstone lithic fragments (Fig. 3.3c), and carbonate lithic fragments (Fig. 3.3d-e).

The minor mineralogical constituents of McMurray sandtones in the Ptarmigan, Quail, and Grouse paleovalleys include glauconite (Fig. 3.3d), micas including muscovite (Fig. 3.3f) and biotite (Fig. 3.3g), chlorite (Fig. 3.3g), and heavy minerals (Fig. 3.3h).

Determination of Quartz-Feldspar-Lithic (QFL) components is based on bulk mineralogy excluding mica and heavy minerals, because these components are generally not included in QFL and QmFLt ternary diagrams (Dickinson and Suczeck, 1979; Dickinson et al., 1983). Also, carbonate grains are included as part of the lithic component when plotting on QFL and QmFLt diagrams, and Dickinson and Suczeck (1979) and Dickinson et al. (1983) did not do this. However, the inclusion of carbonate grains has limited impact on the results of this study because it constitutes < 2% of total lithic fragments. The QFL are normalised before they are plot on QFL and QmFLt ternary diagrams. Micas and heavy minerals are analysed separately in this study because they can give important information regarding source area (Carrigy, 1963; Bayliss and Levinson, 1976; Potocki and Hutcheon, 1992). Lt in QmFLt ternary diagram means total lithic fragments that includes all quartzose excluding monocrystalline quartz and other lithic fragments found in the sandstone.
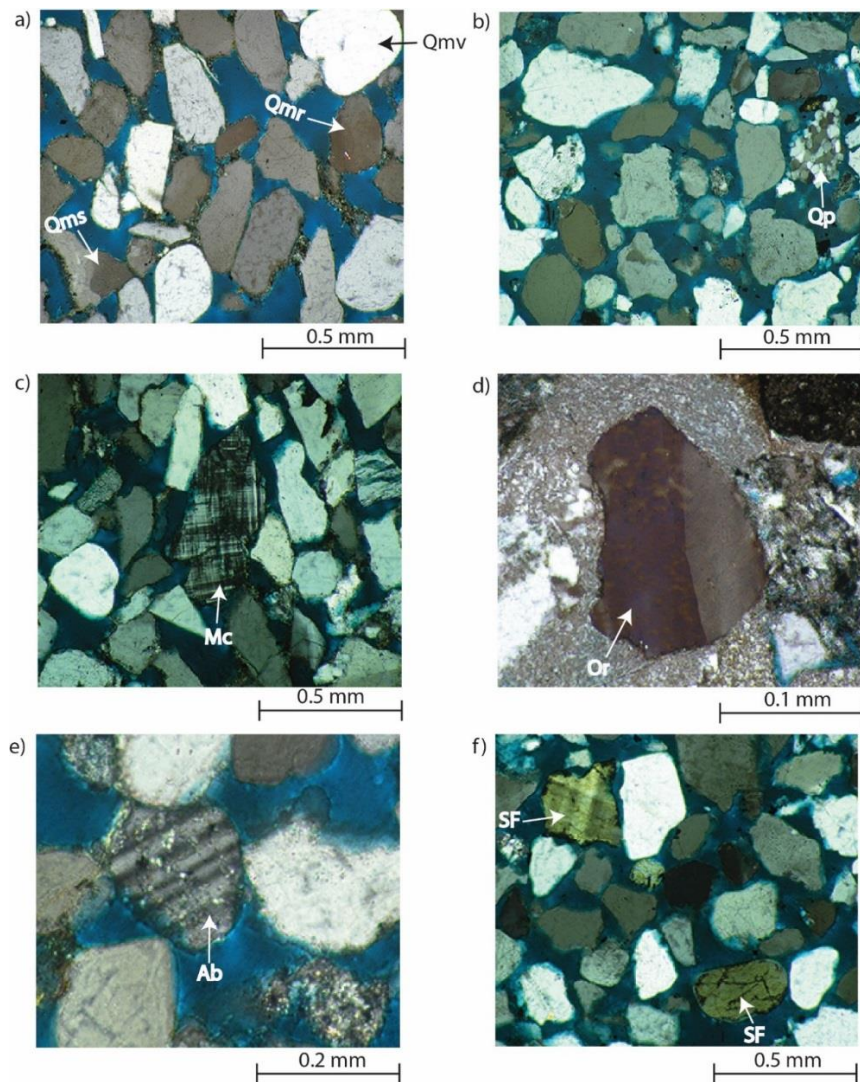
Figure 3.2. Principal mineralogical constituents of McMurray sandstones in Ptarmigan, Quail, and Grouse paleovalleys: a – b) detrital quartz, and c – f) detrital feldspar. All images are in cross-polarized light (XPL). Blue in all photos is the epoxy stain and indicates pore space. a) 99% of image consists of monocrystalline quartz. Qms is strained quartz. Qmr is monocrystalline quartz with a needle-like, high birefringence inclusion (rutile or sillimanite). Qmv is monocrystalline quartz with vacuole (black dot). b) A single grain of detrital polycrystalline quartz (Qp) that is surrounded by monocrystalline quartz. Qp crystals show straight boundaries. c) Monocrystalline quartz surrounding a single grain of unaltered microcline (Mc) with tartan twinning. d) Unaltered orthoclase (Or) with Carlsbad twinning that is surrounded by microcrystalline chert cement. e) Monocrystalline quartz with a single grain of albite (Ab) that is slightly altered. f) Two grains of stained feldspar (SF) with monocrystalline quartz. SF are detrital orthoclase grains that have broken along their twin planes.

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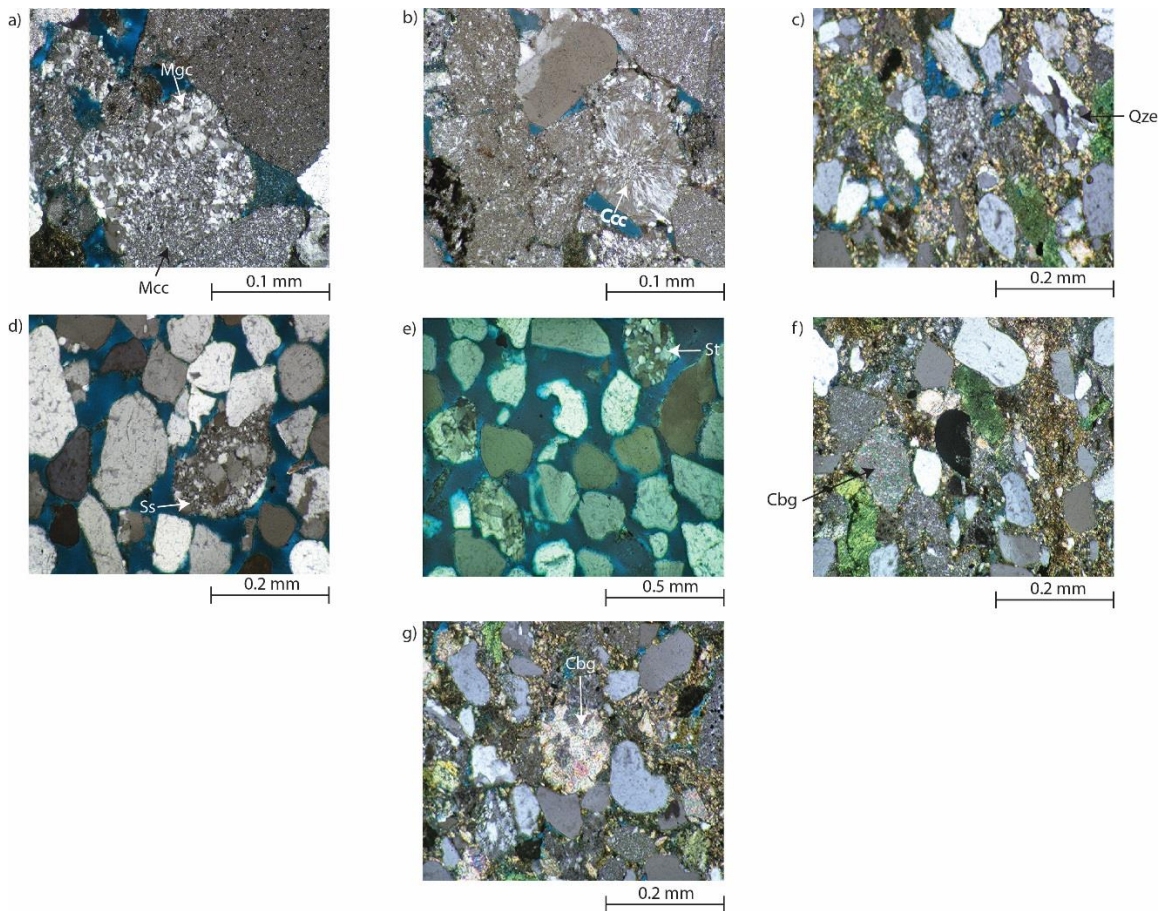
Figure 3.3. **Major mineralogical constituents of McMurray sandstones in Ptarmigan, Quail, and Grouse paleovalleys: a – g) lithic fragments. All images are in cross-polarized light (XPL). Blue in all photos is the epoxy stain and indicates pore space. a) Microcrystalline chert (Mcc) and megacrystalline chert (Mgc). b) Cryptocrystalline chert (Ccc, chalcedony) with microcrystalline chert. c) A single grain of quartzite grains (Qze) with microcrystalline chert, monocrystalline quartz, and glauconite. d) A sandstone grain (Ss) that consists of monocrystalline quartz and grains of monocrystalline and fractured quartz. e) Monocrystalline and fractured quartz with a single grain of siltstone (St) consisting of monocrystalline quartz and orthoclase feldspar. g) Carbonate lithic grain (Cbg) with monocrystalline quartz and authigenic glauconite. f) Carbonate lithic grain (Cbg) with authigenic glauconite and monocrystalline quartz.**
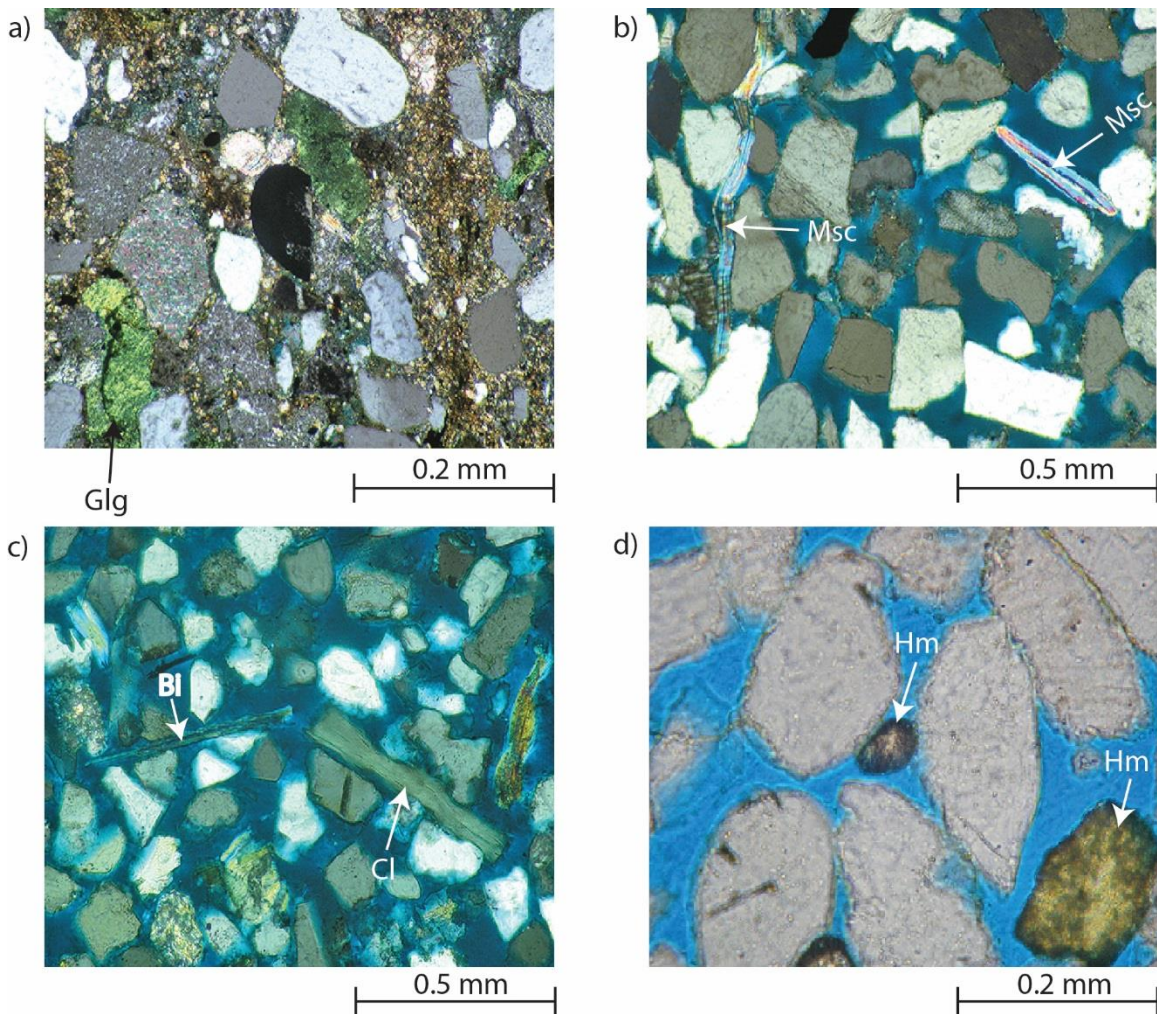
Figure 3.4.   Minor mineralogical constituents of McMurray sandstones in Ptarmigan, Quail, and Grouse paleovalleys: a) authigenic minerals, b – c) mica, and d) heavy minerals. All images are in cross-polarized light (XPL) except for heavy minerals images that are in plane-polarized light (PPL). Blue in all photos is epoxy stain and indicated pore space. a) glauconite (Glg) with monocrystalline quartz and carbonate lithic grain. b) Monocrystalline quartz with muscovite fragment (Msc) showing parallel extinction in cross-polarized light. c) Biotite fragment (Bl) showing inclined extinction in cross-polarized light, and a chlorite grain (Cl). d) Heavy minerals (Hm) are high relief grains in plane-polarized light (white arrows).

3.2.1.   *Quartz*

Approximately 99% of detrital quartz grains in the McMurray sandstones are monocrystalline in character. Quartz grains range from very angular to well-rounded.

Medium to coarse grains (0.25 to 1 mm diameter) tend to be better rounded than are the fine to very fine grains (0.0625 to 0.25 mm diameter; Fig. 3.2a–b). Approximately 30% of the monocrystalline quartz grains show slight to very strong undulatory extinction (Fig. 3.2a). The percentage of quartz in samples (as a proportion of the total grain population) varies with depth from the top of the McMurray Formation as well as between the different paleovalleys, although these differences are commonly subtle.

In the Ptarmigan paleovalley, quartz comprises 80–95.5% (average 91.0%, n = 9) in samples from the upper 15 m of the McMurray Formation (Table 3.2). From 15 to 30 m below the top of the McMurray Formation, quartz percentages range from 83.5–96.3% (average 91.2%, n = 10), and for samples greater than 30 m below the top of the McMurray Formation, the quartz component ranges from 85.3–92.9% (average 89.1%, n = 2).

In the Quail paleovalley, samples within the upper 15 m of the McMurray Formation, contain between 76.3 and 94.3% quartz (average 89.5%, n = 9; Table 3.2). Samples from 15 to 30 m below the top of the McMurray Formation, show quartz components ranging from 74.3–91.6% (average 86.5%, n = 9), and samples taken from depths greater than 30 m from the top of the McMurray Formation, display quartz components varying from 49.7–94.6% (average 82.9%, n = 7).

In the Grouse paleovalley, the quartz component ranges from 76.2–92.2% (average 85.7%, n = 4; Table 3.2) for samples within the upper 15 m of the McMurray Formation. For samples taken 15–30 m below the top of the McMurray Formation, the quartz component ranges from 88.8–94.2% (average 91.6%, n = 5). No data are available for samples 30 m below the top of the McMurray Formation in Grouse paleovalley.

Table 3.2. Range and average percentage and roundness of quartz (Qm and Qp) grains in McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys. Depth (m) refers to the sampling interval below the top of the McMurray Formation. N = number of samples.

Paleovalley	Depth (m)	N	Quartz			
			Range (%)	Average (%)	Degree of Roundness	Average Grain Size (mm)
Ptarmigan	0–15	9	80.0–95.5	91.0	Subrounded–well-rounded	Fine upper (0.20)
	15–30	10	83.5–96.3	91.3	Subangular–well-rounded	Fine lower (0.18)
	>30	2	85.3–92.9	89.1	Subangular–well-rounded	Medium lower (0.28)
Quail	0–15	9	76.3–94.3	89.5	Angular–well-rounded	Very fine upper (0.12)
	15–30	9	74.3–91.6	86.1	Very angular–well-rounded	Fine lower (0.14)
	>30	7	49.7–94.6	82.9	Subangular–well-rounded	Fine upper (0.21)
Grouse	0–15	4	76.2–92.2	85.7	Angular–subangular	Fine lower (0.12)
	15–30	5	88.8–94.2	91.6	Subangular–well-rounded	Fine lower (0.15)
	>30	0	N/A	N/A	N/A	N/A

3.2.2. Feldspar

The detrital feldspar component of all samples consists of approximately 87% orthoclase, 10% albite, and 3% microcline. The roundness of feldspar grains ranges from angular to subrounded, and the degree of roundness is not dependent upon grain size (Fig. 3.2c–f). Under both plane- and cross-polarized light, detrital feldspar grains appear relatively unaltered (Fig. 3.2c–d), except for a few grains of subrounded to rounded albite that have undergone some sericitization (Fig. 3.2e). As a proportion of the total grain population, the percentage of detrital feldspar varies vertically with depth, and between paleovalleys; however, the variations are quite subtle.

In the Ptarmigan paleovalley, samples from the upper 15 m of the McMurray Formation (Table 3.3) contain 3.3–11.3% feldspar (average 6.4%, n = 9). From 15 to 30

m below the top of the McMurray Formation, the detrital feldspar percentage ranges from 1.9–9.8% (average 5.9%, n = 10), and for samples greater than 30 m below the top of the McMurray Formation (Table 3.3), the feldspar component ranges from 3.7–4.5% (average 4.1%, n = 2).

In the Quail paleovalley, samples from the upper 15 m of the McMurray Formation show feldspar ranging from 3.6–14.1% (average 6.4%, n = 9; Table 3.3). For samples taken from 15–30 m below the top of the McMurray Formation, the feldspar component ranges from 4.2–14.1% (average 7.7%, n = 9). For samples taken from greater than 30 m below the top of the McMurray Formation, the feldspar component ranges from 2.6–8.9% (average 5.5%, n = 7).

In the Grouse paleovalley, samples from the upper 15 m of the McMurray Formation show feldspar ranging from 2.3–16.3% grains (average 7.5%, n = 4; Table 3.3). Samples from 15–30 m below the top of the McMurray Formation have feldspar constituting 3.3–6.8% of the grains (average 5.3%, n = 5). There are no samples taken from greater than 30 m from the top of the McMurray Formation in the Grouse paleovalleys.

Table 3.3. The range and average percentage and roundness of feldspar grains in McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys. Depth (m) is the sample interval below the top of the McMurray Formation. N = number of samples.

Paleovalley	Depth (m)	N	Feldspar			
			Range (%)	Average (%)	Degree of Roundness	Average grain size (mm)
Ptarmigan	0–15	9	3.3–11.3	5.6	Subangular–rounded	Fine lower (0.15)
	15–30	10	1.9–9.8	5.9	Angular–rounded	Fine lower (0.18)
	>30	2	3.7–4.5	4.1	Angular–rounded	Fine lower (0.16)
Quail	0–15	9	3.6–14.1	6.4	Subangular–subrounded	Fine upper (0.22)
	15–30	9	4.2–14.1	7.7	Very angular–subrounded	Fine lower (0.15)
	>30	7	2.6–8.9	5.5	Angular–subrounded	Fine upper (0.23)
Grouse	0–15	4	2.3–16.3	7.5	Very angular–subrounded	Fine upper (0.22)
	15–30	5	2.3–16.3	5.3	Angular–subrounded	Fine lower (0.14)
	>30	0	N/A	N/A	N/A	N/A

3.2.3. Lithic Fragments

Lithic fragments include , microcrystalline chert (Fig. 3.3a), megacrystalline chert (Fig. 3.3a), cryptocrystalline chert (Fig. 3.3b) quartzite (Fig. 3.c3), sandstone (Fig. 3.3d), siltstone (Fig. 3.3e), and carbonate (Fig. 3.3f-g). Chert accounts for about 90% of the lithic components of McMurray Formation sandstones. Microcrystalline chert makes up approximately 70% whereas megacrystalline chert constitutes approximately 20% (Table 3.4). Of the remaining 10% of lithic grains, detrital sandstones and siltstones make up about 84% of grains, carbonate grains are approximately 11% (1% of total sample), and the rest is quartzite. Lithic fragments are angular to well-rounded: chert grains are subrounded to well rounded; detrital sandstones / siltstones are angular to rounded; and, carbonate grains are angular to rounded. In the Ptarmigan, Quail, and Grouse paleovalleys lithic fragments differ in their composition, and percentages of lithic fragments varies with depth in all paleovalleys.

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In the Ptarmigan paleovalley, lithic fragments range from 0.0–2.1% (average 0.9%, n = 9; Table 3.4) for samples in the upper 15 m of the McMurray Formation. From 15 to 30 m below the top of the McMurray Formation, the percentage of lithic fragments ranges from 0.1–4.9% (average 1.5%, n = 10). For samples greater than 30 m below the top of the McMurray Formation, lithic fragments constitute 0.6–5.6% (average 3.5%, n = 2) of the grains.

In the Quail paleovalley, lithic fragments constitute 0.2–1% (average 0.4%, n = 9) for samples in the upper 15 m of the McMurray Formation (Table 3.4). Samples from 15–30 m below the top of the McMurray Formation show lithic fragments ranging from 0.0–2.1% (average 1.0%, n = 9). For samples greater than 30 m below the top of the McMurray Formation, lithic fragments range from 0.1–36.5% (average 9.4%, n = 7; Table 3.4).

In the Grouse paleovalley, lithic fragments range from 0.5–1.7% (average 0.9%, n = 4), for samples in the upper 15 m of the McMurray Formation (Table 3.4). For samples taken from 15–30 m below the top of the McMurray Formation, lithic fragments constitute 0.1–1.0% (average 0.8%, n = 5; Table 3.4). There are no samples taken from greater than 30 m from the top of the McMurray Formation in Grouse paleovalley.

Table 3.4. **The range and average percentage and roundness of lithic fragments in McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys. Depth (m) is the sampled interval below the top of the McMurray Formation. N = number of samples.**

Paleovalley	Depth (m)	N	Lithic Fragments			
			Range (%)	Average (%)	Degree of Roundness	Average grain size (mm)
Ptarmigan	0–15	9	0.0–2.1	0.9	Subrounded–rounded	Fine upper (0.24)
	15–30	10	0.1–4.9	1.0	Subangular–well-rounded	Fine lower (0.18)
	>30	2	0.6–5.6	3.5	Subangular–well-rounded	Medium lower (0.30)
Quail	0–15	9	0.2–1.0	0.4	Subrounded–well-rounded	Fine lower (0.18)
	15–30	9	0.2–2.1	1.0	Subangular–subrounded	Fine lower (0.17)

	>30	7	0.1–36.5	9.4	Angular–subrounded	Medium lower (0.26)
Grouse	0–15	4	0.5–1.7	0.8	Angular–rounded	Fine lower (0.18)
	15–30	5	0.1–10	0.9	Subrounded–rounded	Fine lower (0.20)
	>30	0	N/A	N/A	N/A	N/A

3.2.4. *Micas and Heavy Minerals*

Detrital mica flakes identified in McMurray Formation sandstones within the Ptarmigan, Quail, and Grouse paleovalleys include muscovite (Fig. 3.4b) and biotite (Fig. 3.4c), . Of these detrital mica flakes, muscovite is the most abundant and accounts for about 80% of all lithic mineral grains. In McMurray Formation sandstones of the Ptarmigan paleovalley, detrital mica range from 0–6% (average 1%, n = 21). In the Quail paleovalley, the detrital micas range from 0–12% (average 2%, n = 25), and in the Grouse paleovalley, detrital mica constitute 0–6% of all grains (average 3%, n = 9).

Heavy minerals are undifferentiated, due to difficulty in differentiating between the different minerals using petrographic microscope on these small grains. Nonetheless, heavy minerals (Fig. 3.3h) constitute a minor component of McMurray Formation sandstones in the three paleovalleys. In the Ptarmigan paleovalley, heavy minerals range from 0–3% (average 1%, n = 21). In the Quail paleovalley, McMurray Formation sandstones contain 0–6% (average 1%, n = 25) heavy minerals. In the Grouse paleovalley, heavy minerals also range from 0–6% (average 1%, n = 9).

3.3. Mineralogical Variation between Paleovalleys

McMurray Formation sandstones in the study area (Ptarmigan, Quail and Grouse paleovalleys) exhibit subtle but recognizable vertical and spatial variations in the composition of their principal grains (quartz, feldspar, lithic fragments; Tables 3.1 – 3.3; Fig. 3.5). William (1963) demonstrated that detrital feldspar (mostly orthoclase) and lithics (predominantly chert) increase in abundance upward through the Ellerslie Formation, which is a stratigraphic equivalent to the McMurray Formation. Further north, Benyon et

al. (2014) collected samples from the lower, middle and upper McMurray Formation. They identified vertical variations in sediment composition based on detrital zircon signatures within the McMurray Formation, and they attributed those changes to changing sediment sources during the deposition of various units of the McMurray Formation. McMurray sandstones samples used in this study are taken from strata that are equivalent to the upper McMurray and upper part of the middle McMurray Formation, even though some samples occur only a few meters above the sub-Cretaceous Unconformity (SCU).

Comparison of mean composition of the principal components (QFL) of McMurray Formation sandstones in the three paleovalleys (Table 3.5) reveals a number of important trends. Sandstones in the Ptarmigan paleovalley contain the lowest percentage of unstable grains and the highest percentage of quartz (detrital quartz) and lithic quartz grains (quartzite and chert). By contrast, McMurray sandstones in the Quail paleovalley contain the highest percentage of unstable constituents (e.g., feldspar, sandstones/siltstones, and carbonates). The feldspar component decreases with increasing depth throughout the McMurray Formation (Fig. 3.5a). The lithic percentages in the Ptarmigan and Quail paleovalleys correspondingly increase in abundance with increasing depth (Fig. 3.5b), whereas the percentage of lithics in the Grouse paleovalley subtly decreases with increasing depth (Fig. 3.5b). Increases in the abundance of feldspar with decreasing depth shows that feldspar might have been contributed from another source other than the Canadian Shield, and possibly from the Edmonton Valley. This is because the presence of subrounded to rounded altered feldspar indicates transportation of feldspar from a distance source. Also, feldspar in Ellerslie sandstones increases in abundant upward through the Ellerslie Formation (Williams, 1963). Increases in the lithic component with increasing depth suggests that carbonate rock that comprises the Wainwright-Grosmont Highland likely contributed locally to the lithic component in McMurray sandstones in all three paleovalleys. Based on the percentage of the average principal components, McMurray sandstones in the Ptarmigan and Grouse paleovalleys are classified as subarkoses to quartz arenites, whereas the McMurray Formation sandstones in the Quail paleovalley transition upwards from sublitharenites to subarkoses (Table 3.5).

Table 3.5. Comparison of average composition percentage of the principal minerals of McMurray Formation sandstones in the Ptarmigan, Quail and Grouse paleovalleys. Depth (m) is the sampled interval below the top of the McMurray Formation.

Paleovalley	Depth (m)	Number of Samples	% Quartz (Normalized)	% Feldspar (Normalized)	% Lithics (Normalized)
Ptarmigan	0–15	9	91.0 (93.3)	5.6 (5.7)	0.9 (1.0)
	15–30	10	91.3 (93.0)	5.9 (6.0)	1.0 (1.0)
	>30	2	89.1 (92.1)	4.1 (4.2)	3.5 (3.7)
Quail	0–15	9	89.5 (92.9)	6.4 (6.6)	0.4 (0.5)
	15–30	9	86.1 (90.8)	7.7 (8.1)	1.0 (1.1)
	>30	7	82.9 (84.8)	5.5 (5.6)	9.4 (9.6)
Grouse	0–15	4	85.7 (91.2)	7.5 (8.0)	0.8 (0.9)
	15–30	5	91.6 (93.5)	5.3 (5.4)	0.9 (1.1)
	>30	0	N/A	N/A	N/A
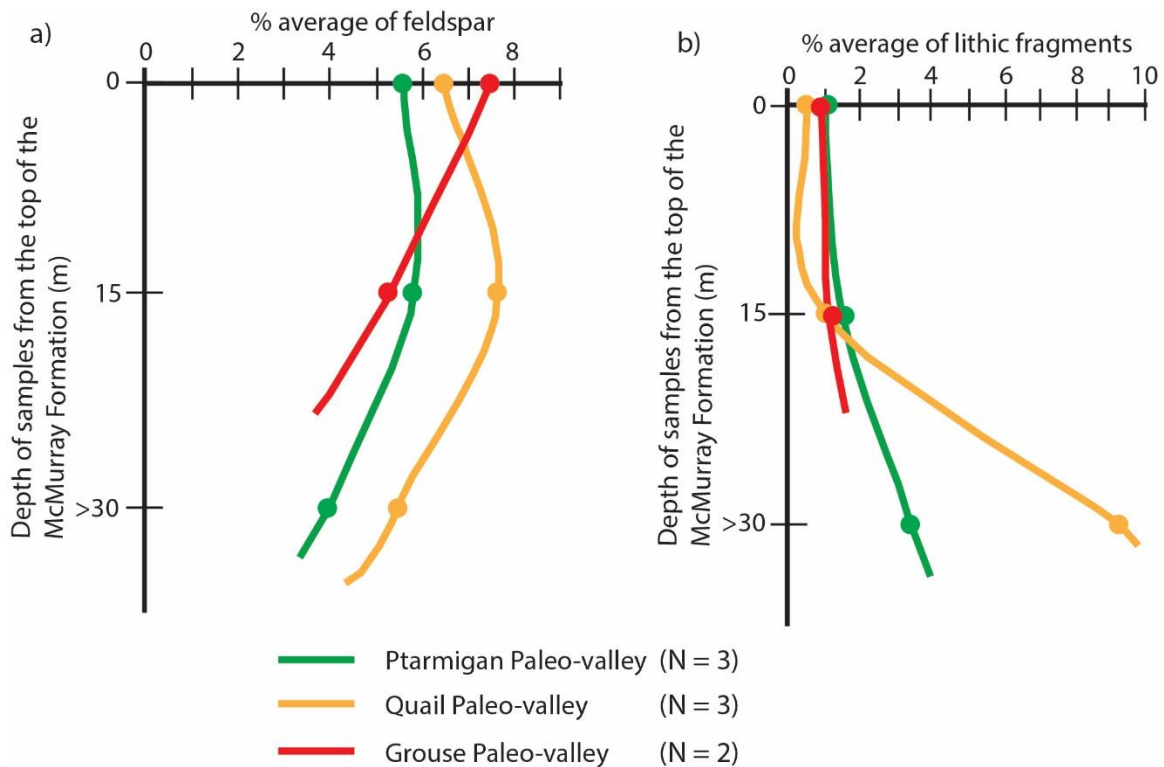
Figure 3.5. **Comparison of vertical variation in mineralogy between the three paleovalleys. a) Vertical variation in the average percentage of feldspar in the Ptarmigan (n = 24), Quail (n = 25), and Grouse (n = 9) paleovalleys. b) Vertical variation in the mean percentage of lithic fragments in the Ptarmigan (n = 24), Quail (n = 25), and Grouse (n = 9) paleovalleys. Note the decrease in feldspar and increase in lithic fragments with the depth of samples below the top of the McMurray Formation for all three valleys.**

Comparison of McMurray sandstones in the Ptarmigan, Quail, and Grouse paleovalleys with previously reported mineralogical data from the Ellerslie and Dina formations, and sandstones proposed to have been derived from thrust belt (e.g., Belly River (basal) is crucial, because the Ellerslie and Dina comprise sandstones derived from the south, southwest and west (Ellerslie Formation, Edmonton Valley), southeast (Dina Formation, Saskatchewan) and the thrust belt in the west (Belly River; Table 3.6). Bayliss and Levinson (1976), Nelson and Glaister (1978) and Hein et al. (2012) determined that McMurray Formation sandstones in the Athabasca area (directly to the north of the study area) are quartz arenites to subarkoses. Petrographic analysis of time-equivalent Dina Formation sandstones in Saskatchewan (east of the study area) also recognized the bulk composition to correspond to subarkoses and quartz arenites (Bayliss and Levinson,

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1976). Williams (1963) and Hopkins (1981) conducted a petrographic study on the age-equivalent Ellerslie Formation in the Edmonton Valley (west and southwest of the study area), and classified the sandstones as compositionally mature and supermature sublitharenites, litharenites, and quartz arenites that contain to about 6% feldspar.

McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys are plotted on both QFL and QmFLt ternary diagrams. The key difference between these two plots is that chert and quartzite can be included in the Quartz component in a QFL diagram, but are included in the lithic component in a QmFLt diagram (Dickinson and Suczeck, 1979; Dickinson et al., 1983). Regardless of the plot type, sandstones of the McMurray Formation in this study have similar mineralogical compositions to those of both the Dina Formation and Ellerslie Formation (Table 3.6). McMurray Formation sandstones within the Ptarmigan paleovalley plot within subarkose, sublitharenite and quartz arenites fields on the QmFLt ternary plot (n = 21; Fig. 3.6a), and in subarkose and quartz arenite fields on a QFL ternary plot (n = 21; Fig. 3.6b). In the Quail paleovalley, McMurray Formation sandstones plot as quartz arenites, subarkoses to litharenites on QmFLt ternary plots (n = 25; Fig. 3.7a) as well as on QFL ternary plots (Fig 3.7b). In the Grouse paleovalley, McMurray Formation sandstones plot as subarkoses and quartz arenites on QmFLt and QFL ternary plots (n = 9; Fig. 3.8a and b). The sandstones in the three paleovalleys are compositionally mature, and include supermature subarkoses, sublitharenites, litharenites, and quartz arenites .

Table 3.6. Comparison of mineralogical data from McMurray Formation sandstones in this study, with those of previously published examples from the McMurray Formation in the Athabasca area (north of the study area), time-equivalent Dina Formation in the Lloydminster area (east), and Ellerslie Sandstone in the Edmonton Valley (west and southwest). William (1963), Bayliss and Levinson (1976), Nelson and Glaister (1978) and Hopkins (1981) included chert, argillite and quartzite as part of the lithic fragments (QmFLt diagram), while Hein et al. (2012) included chert and quartzite in the quartz component (QFL diagram). Both are used herein for comparison. Note all previous mineralogical data are normalized to 100%.

Formation (Area/Valley)	Quartz (%)	Feldspar (%)	Lithic Fragments (%)	Authors
McMurray Fm. (Athabasca)	90–92	5–7	2–4	Hein et al. (2012)
McMurray Fm. (Athabasca)	90–95	2–7	2–4	Nelson and Glaister (1978)
Dina Fm. (Lloydminster)	80–100	0–19	0–1	Bayliss and Levinson (1976)
McMurray Fm. (Athabasca)	86–100	0–14	Trace	Bayliss and Levinson (1976)
Belly River (basal) Pembina	24–26	1–13	61–75	Iwuagwu and Lerbekmo (1982)
Ellerslie Sandstone (Edmonton Valley)	73–98	0–6	2.2–21	Williams (1963)
Ellerslie Sandstones (Medicine River)	91–99	Trace	1–9	Hopkins (1981)
Ellerslie Sandstones (Niton field)	86.9–99.1	0.4–0.8	0.4–12.3	Potocki (Unpublished)
McMurray Fm. (Ptarmigan)	80–97	2–11	1–6	Present Study
McMurray Fm. (Quail)	49–94	3–14	0–37	Present Study
McMurray (Grouse)	76–94	2–16	0–2	Present Study

Figure 3.6. The relative proportion of the three major mineral constituents of McMurray sandstones in the Ptarmigan paleovalley (n = 21). a) QmFLt ternary plot and b) QFL ternary plot. Red dots represents samples from the upper 15 m of the McMurray Formation (n = 9). Green circles are samples taken from 15 – 30 m below the top of the McMurray Formation (n = 10). Yellow circles are samples from greater than 30 m below the top of the McMurray Formation (n = 2).

Quail Paleo-valley
McMurray Sandstones (n = 25)

Samples from the upper 15 m
of the McMurray Formation
(n = 9)

Samples from 15 to 30 m below
the top of the McMurray Formation
(n = 9)

Samples > 30 m below the top of
the McMurray Formation (n = 7)

Qm = Monocrystalline quartz
Q = Monocrystalline and polycrystalline quartz, and chert
F = Orthoclase, microcline, and albite
Lt = Microcryatalline and megacrystalline chert, carbonate, sandstone/siltstone,
and polycrystalline quartz
L = Sandstone/siltstone and carbonate
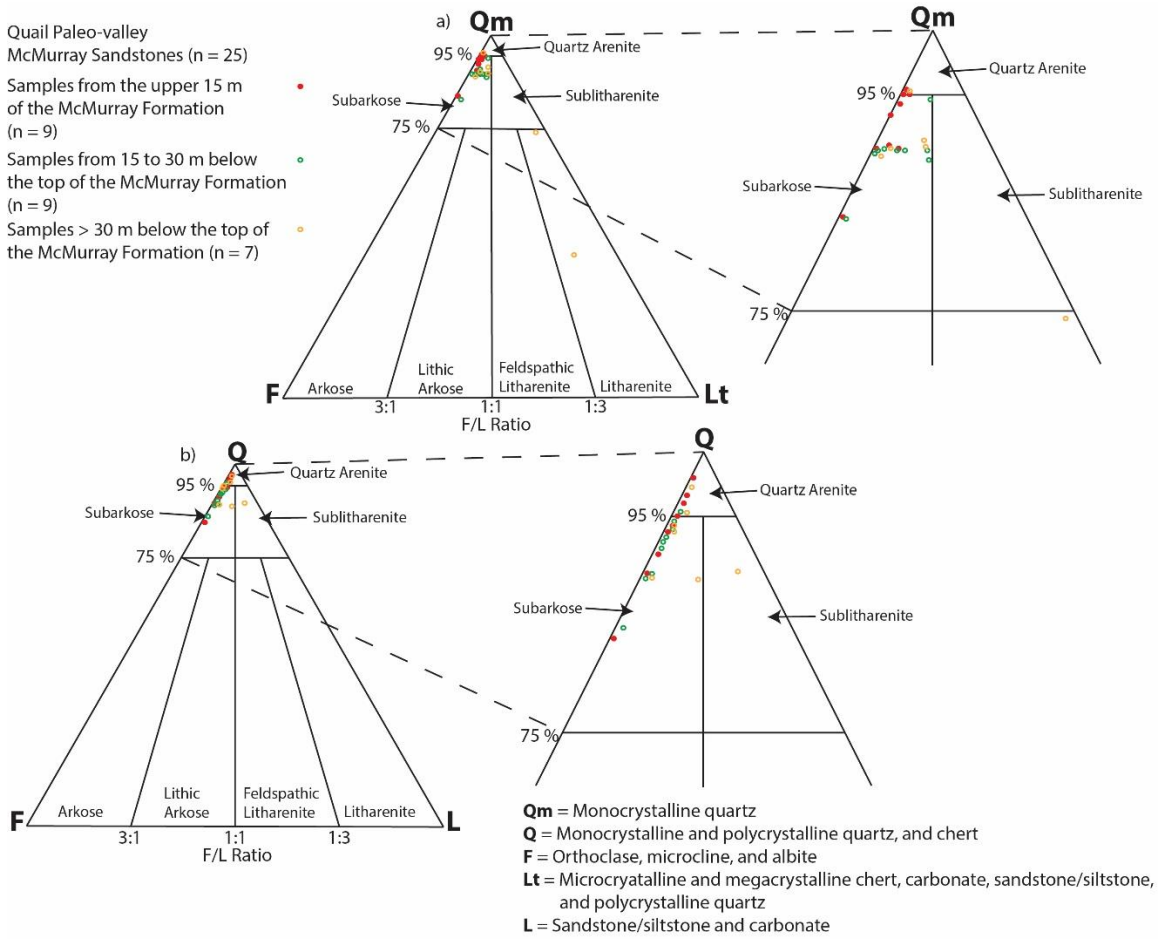
Figure 3.7. **The relative proportion of the three major mineral constituents of McMurray Formation sandstones in the Quail paleovalley (n = 25). a) QmFLt ternary plot and b) QFL ternary plot. Red dots are samples within the upper 15 m of the McMurray Formation (n = 9). Green circles represent samples from 15 to 30 m below the top of the McMurray Formation (n = 9). Yellow circles record compositions of samples collected greater than 30 m below the top of the McMurray Formation (n = 7).**

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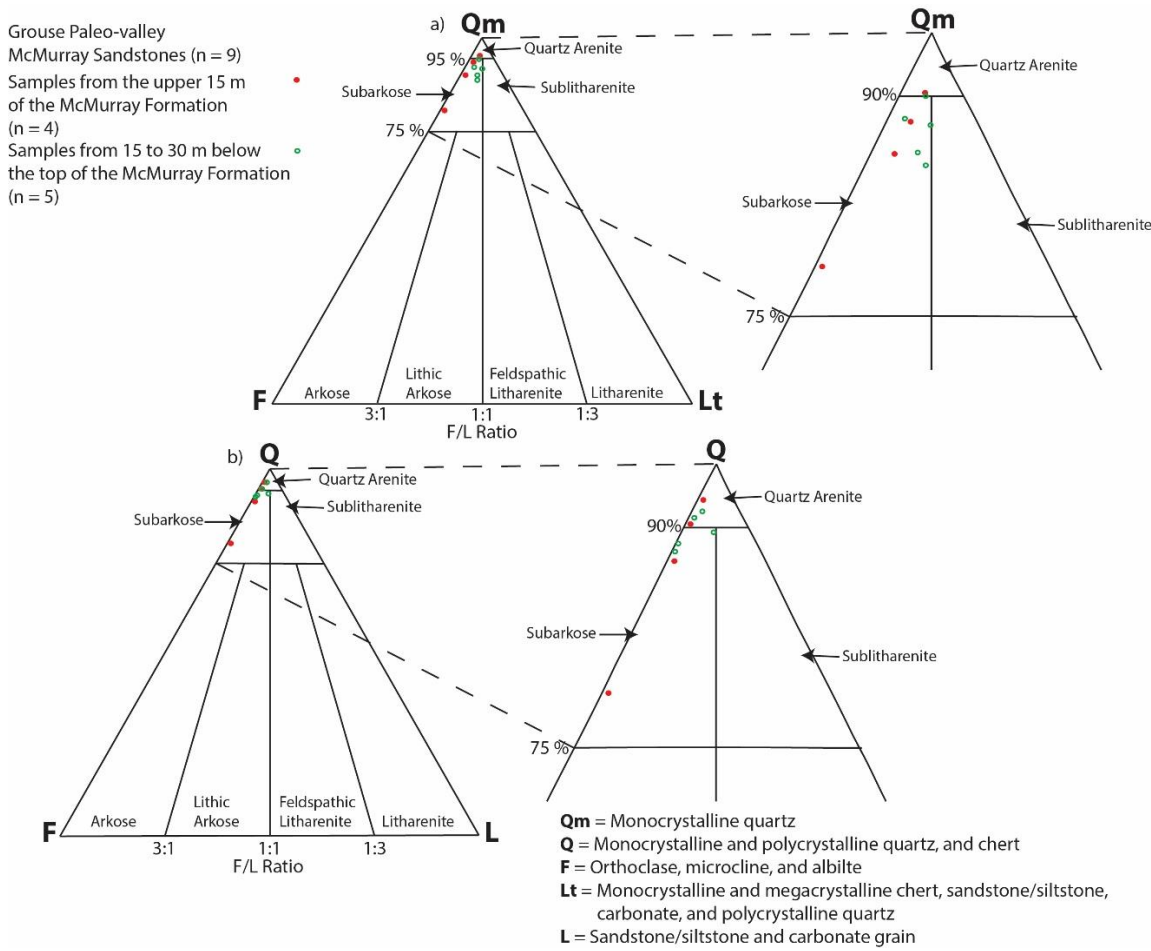
Figure 3.8. The relative proportion of the three major mineral constituents of McMurray Formation sandstones within the Grouse paleovalley (n = 9). a) QmFLt ternary plot and b) QFL ternary plot. Red dots denote sample within the upper 15 m of the McMurray Formation (n = 4). Green circles are samples from 15 – 30 m below the top of the McMurray Formation (n = 5). There are no samples taken from greater than 30 m below the top of the McMurray Formation.

Another significant difference in sandstone composition between the three paleovalleys is the mineralogy of their lithic constituents (Table 3.7). These differences can be attributed to materials available in the source area. In the Ptarmigan paleovalley, the lithic fraction of McMurray sandstones consists of chert, sandstones/siltstones, and quartzite (Table 3.7). The lithics in McMurray Formation sandstones from the Quail and Grouse paleovalleys comprises chert, sandstone/siltstone, and carbonate (Table 3.7). Detailed analysis of the lithic fraction shows that in the Ptarmigan paleovalley, percentages of chert increases with increasing in depth, while percentages of

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sandstone/siltstone and quartzite decrease with increasing in depth (Table 3.7). In the Quail paleovalley, samples from 0–15 m depth have the highest percentage of chert, while samples from 15–30 m have the highest percentage of sandstone/siltstone fragments. Samples from >30 m have the highest percentage of carbonate grains (Table 3.7). The percentage of chert in the lithics of the Grouse paleovalley is low compared to that of sands in the Ptarmigan and Quail paleovalleys (Table 3.7). However, in the Grouse paleovalley, the percentage of chert in the lithic component decreases with increasing depth, while the percentage of sandstone/siltstone and carbonate increases with increasing depth. The carbonate grains in sandstones in the Quail and Grouse paleovalleys may have been sourced locally when highlands were exposed. This is because carbonate grains are mechanically unstable and cannot withstand rigorous transport (Schwab, 1986).

Carrigy (1953), William (1963), Bayliss and Levinson (1976), and Potocki and Hutcheon (1992) all argued that chert within McMurray sandstones are sourced from chert nodules within the Paleozoic carbonates of the Western Canada Sedimentary Basin. They further state that detrital sandstone/siltstone and carbonate are probably sourced from recycled Paleozoic carbonates and clastics that formed the apron on the Canadian Shield or / and recycled from other sedimentary rock in the west. Alternatively, detrital sandstone/siltstone may reflect increased supply of grains derived from erosion of siliciclastic strata on the Grosmont-Wainwright Highlands.

Table 3.7. Percentages of lithic fragment compositions as a percentage of all lithics (normalized to 100%) from the McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys. Depth (m) corresponds to sampling intervals below the top of the McMurray Formation. Mic chert = microcrystalline chert. Meg chert = megacrystalline chert. SS/St = sandstones/siltstones. Qze = quartzite. Carb = detrital carbonates.

Paleo- valley	Depth (m)	Mic Chert (%)	Mega Chert (%)	Total Chert (%)	SS/St (%)	Qze (%)	Carb (%)
Ptarmigan	0–15	59.5	23.8	83.3	11.9	4.8	0.0
	15–30	77.7	8.8	86.5	12.8	0.7	0.0
	>30	60	31.4	91.4	8.6	0.0	0.0
Quail	0–15	78.4	13.5	91.9	8.1	0.0	0.0
	15–30	64.4	17.8	82.2	15.6	0.0	2.2
	>30	59.2	25.4	84.6	7.6	0.0	7.8
Grouse	0–15	60.0	20.0	80.0	20.0	0.0	0.0
	15–30	50.0	21.4	71.4	23.8	0.0	4.8
	>30	N/A	N/A	N/A	N/A	N/A	N/A

3.4. Sources Area for McMurray Sandstones in All the Three Paleovalleys

3.4.1. Source area based on whole rock composition

Dickinson and Suczeck (1979) and Dickinson et al. (1983) produced ternary plots (Dickinson plots) of sediment provenance based on the work of Ingersoll (1978), Dickinson et al. (1981), Cavazza (1989), Schwab (1986), Potocki and Hutcheon (1992) and others. In the Dickinson plots, sediment compositions are plotted on QmFLt and QFL diagrams, and the area of plots is divided into quadrants based on likely sediment provenance. The dominant quadrants include the continental block, recycled orogen, and magmatic arc (Figs. 3.9–3.11).

Ingersoll (1978), Dickinson et al. (1983), Cavazza (1989), and Schwab (1986) demonstrated that sediment sources (provenance) within the continental block quadrant (yellow-orange quadrant in Figs. 3.9–3.11) is the Precambrian Shield and continental platforms. Dickinson et al. (1983) hypothesized that sediments sourced from continental

blocks are quartzofeldspathic and lithic (stable and unstable) poor, but they also point out that anomalous volumes of sedimentary lithic fragments can occur locally due to recycling of strata overlying basement. Sediments that constitute the recycled orogen quadrant (green quadrant in Figs. 3.9–3.11) include grains sourced from mainly sedimentary strata, with minor contributions from volcanic rocks and few metamorphic rocks exposed to erosion through uplift of fold belts and thrust sheets. Dickinson and Suczeck (1979) and Dickinson et al. (1983) showed that sandstones from recycled orogenic sources typically have low feldspar contents, because first cycle igneous rock is not their major source. However, Dickinson et al. (1983) and Schwab (1986) suggest that quartzose grains (chert and quartzite) in recycled orogenic sandstones are not derived from recycled cratonic sources, but instead are attributed to metamorphosed sandstone sources within fold belts and thrust sheets. They go one to also indicate that most chert is sourced from uplifted oceanic terranes, and sepcifically from nodules in the associated carbonate successions.

Based on Dickinson and Suczeck (1979) and Dickinson et al. (1983) model, Potocki and Hutcheon (1992) demonstrate that lithic sandstones of Western Canada Sedimentary Basin that are proposed to be sourced from the thrust belt in the west (e.g., Belly River (basal), Cardium sandstones, Spirit River Formation, Cadomin, Blairmore, Ellerslie) plot in the recycle orogenic quadrant of QmFLt ternary diagrams because these sandstones contain higher proportion of lithic (chert) grains. They conclude that these sandstones are recycled orogeny sandstones.

Sediments classified to have been derived from within Magmatic Arc (blue quadrant in Figs. 3.9–3.11), are largely sourced from volcanic rocks and granitic plutons (Dickinson and Suczeck, 1979; Dickinson et al., 1981). Sediments from the Magmatic Arc are rich in feldspars, mainly albite and anorthite, and as well as lithic fragments, including volcanic, granitic, and metamorphic grains. Consequently, sandstones derived from a magmatic arc source area should be either feldspatholithic or lithofeldspathic.

In the Ptarmigan, Quail, and Grouse paleovalleys, sandstone compositions (Table 3.4) are overlain on Dickinson plots to determine possible source terrains for the sediments (Figs 3.9–3.11). For the Ptarmigan paleovalley, McMurray Formation sandstones plot as being derived mainly from craton interior, with minor sediment volumes

derived from recycled quartzose material (Fig. 3.9). In the Quail paleovalley, McMurray Formation sandstones also appear to be dominated by materials from the craton interior, but recycled quartzose materials is more prevalent (Fig. 3.10). For McMurray sandstones in the Grouse palleo-valley, the provenance for sandstones is mainly craton interior with potential minor transitional continental material (Fig. 3.11). Based on these plots of whole rock composition, it is not possible to discern the source of McMurray Formation sediments as sandstones in the Ptarmigan and Quail paleovalleys could be derived from the Canadian Shield, erosion of sedimentary strata in the Cordillera, or from across the North American continent. In the Grouse paleovalley, the major sediment source appears to be erosion of the craton; either the Canadian Shield or some other cratonic material.
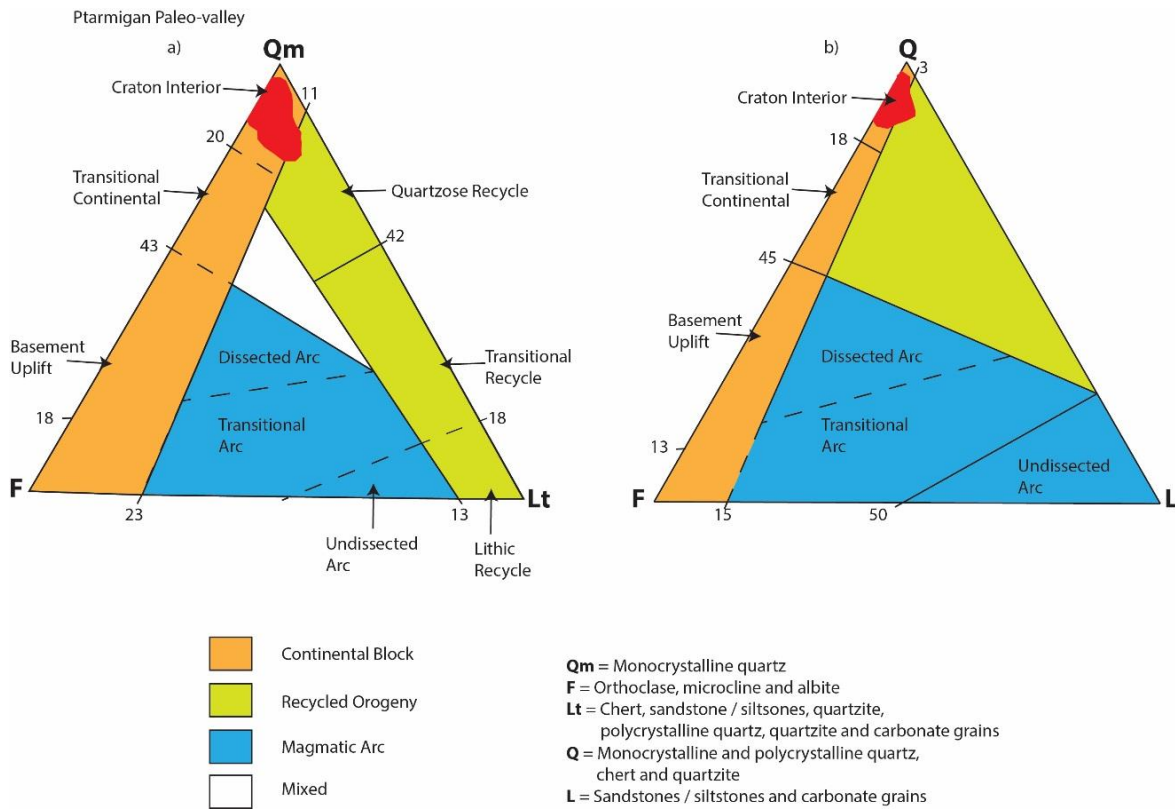
Figure 3.9. **Dickinson and Suczeck (1979) QmFLt (a) and QFL (b) ternary diagrams showing provenance of McMurray sandstones in the Ptarmigan paleovalley. McMurray Formation sandstones in the Ptarmigan paleovalley plot as being derived from craton interior with minor sediments volumes from recycled quartzose.**
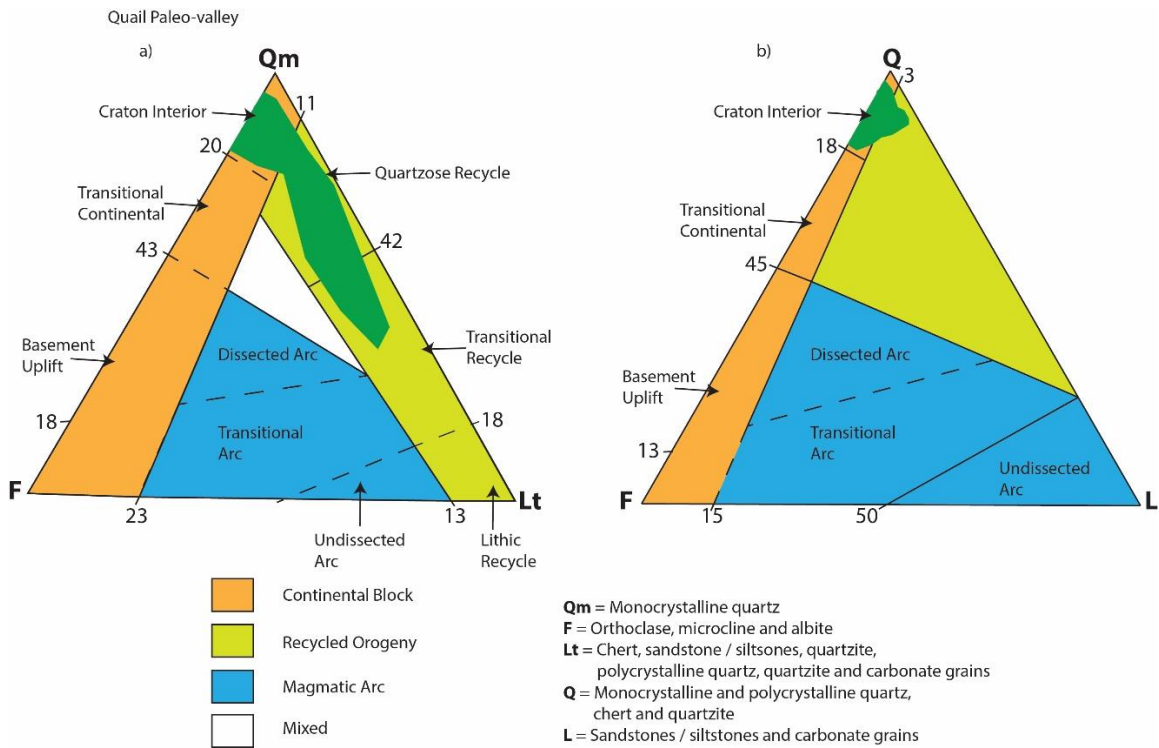
Figure 3.10. **Dickinson and Suczeck (1979) QmFLt (a) and QFL (b) ternary diagrams showing provenance of McMurray sandstones in the Quail paleovalley. In the Quail paleovalley, McMurray Formation sandstones appear to be dominated by materials from the craton interior, but recycled quartzose materials are more prevalent.**
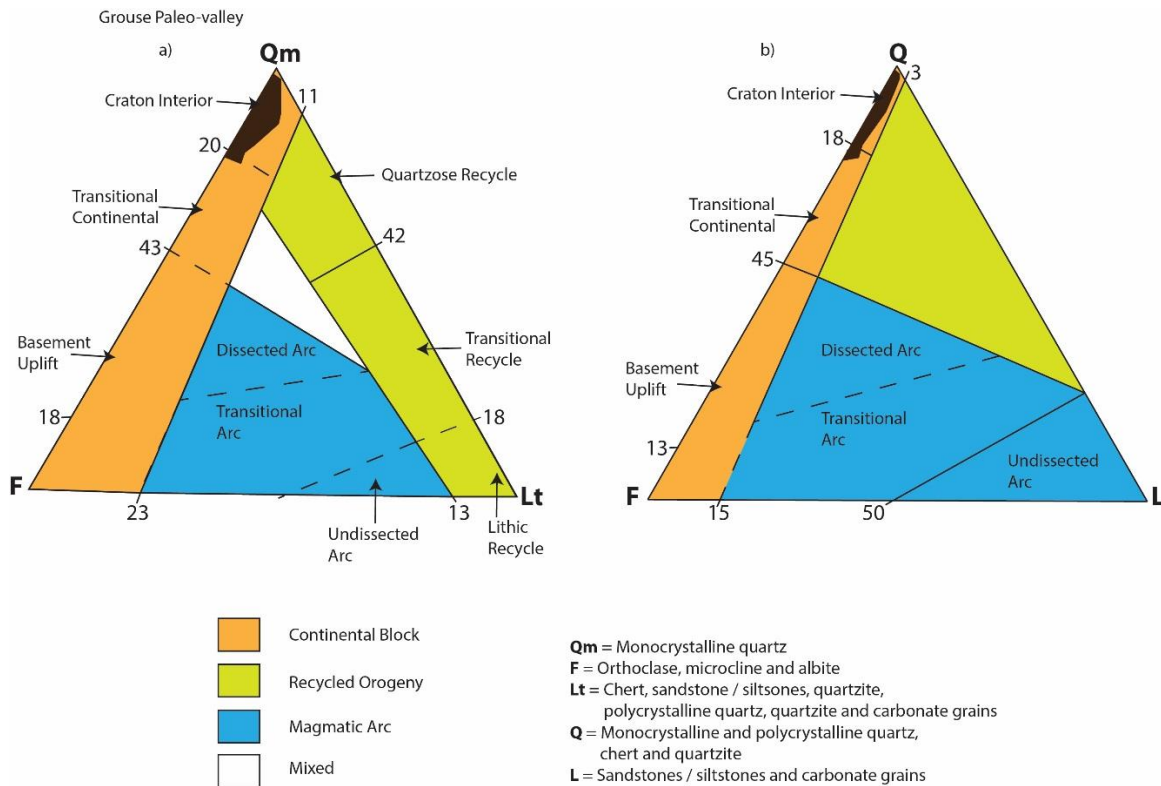
Figure 3.11. **Dickinson and Suczeck (1979) QmFLt (a) and QFL (b) ternary diagrams showing provenance of McMurray sandstones in Grouse paleovalley. The provenance for McMurray sandstones in the Grouse paleovalley is mainly from the craton interior with potential minor transitional continental materials.**

3.4.2. *Source area based on feldspar composition*

Using Potassium -feldspar (K) – Albite (Al) – Anorthite (An) ternary diagrams, feldspar in McMurray sandstones within the Ptarmigan (Fig. 3.12a–c), Quail (3.13a–c), and Grouse (3.14a–c) paleovalleys plot mainly between potassium (alkali) feldspar and albite (sodic feldspar). Dickinson et al. (1983) and Cavazza (1989) hypothesize that the erosion and transport of phaneritic granitoid and gneissic rocks are major sources of Potassium (alkali) feldspar and Albite (sodic feldspar) in sandstones. The fact that about 90% of feldspar grains in all the 3 paleovalleys are mostly unaltered, and are predominantly very angular to subrounded with no correlation between roundness and grain size, suggests that these feldspar were first cycle and were derived from a source that was in close proximity to the southern McMurray Sub-Basin. The closest source is the Canadian Shield (Bayliss and Levinson, 1976; Potocki and Hutcheon, 1992; Quinney et

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al., 2013; Benyon et al., 2014). This is consistent with the work of Bayliss and Levinson (1976), who showed that Dina Formation sandstones east of the study area contain considerable amounts of feldspar, mainly Potassium (alkali) feldspar and minor albite, and that these sandstones are positioned close to the Canadian Shield. However, other source smay exist for altered feldspar which is about 10% of the feldspar population in the Ptarmigan, Quail and Grouse paleovalleys. These feldspar are second cycle because some of the grains are subrounded to rounded and hence their alteration was likely pre-depositional. The source of second cycle feldspar may have been the west, probably the Cordillera, because sandstones sourced from the Cordillera (e.g., Ellerslie, Belly River and Upper Mannville formation sandstones) contain plagioclase feldspar grains that are mostly altered (Williams, 1963; Iwuagwu and Lerbekmo, 1982; Potocki and Hutcheon, 1992). Consequently, the source of the second cycle, mainly subrounded to rounded altered plagioclase feldspar may be the west.

3.4.3. *Source area based on lithic composition*

Analysis of lithic constituents: sandstone/mudrock (SS/Sh) – carbonate (C) – chert (Ch) provides some interesting results. Lithic rock fragments in McMurray Formation sandstones in the Ptarmigan paleovalley plot between sandstone/mudrock and chert in all depth intervals (Fig. 3.12d–f). In the Quail paleovalley, samples in the upper 15 m of the McMurray Formation plot between sandstone/mudrock and chert, while samples from 15–30 m and >30 m from the top of the McMurray Formation plot among sandstone/mudrock, carbonate and chert (Fig. 3.13d–f). In the Grouse paleovalley, lithics in samples from the upper 15 m of the McMurray Formation comprise mainly sandstone/mudrock and chert with the majority being chert (3.14d). Lithics in samples from15–30 m below the top of the McMurray Formation in the Grouse paleovalley plot between sandstone/mudrock, carbonate and chert (Fig 3.14e). In contrast, William (1963) and Hopkins (1981) show that lithic rock fragments in Ellerslie Formation sandstones are mainly chert, and they hypothesized that the source of the chert is primarily from chert nodules that were eroded out of the highlands to the west (i.e. the Cordillera). Also, other sandstones from formations more obviously derived from the thrust belt (west of study area) such as those that comprise the Belly River, Spirit River, Cardium, Cadomin formations contain significant percentages of lithic (chert) fragments (Blatt et al., 1972; Hopkins, 1981;

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Iwuagwu and Lerbekmo, 1982; Potocki, 1992). Chert in these sandstones (Belly River, Spirit River, Cardium, Cadomin) are hypothesised to have been derived from chert nodules within uplifted carbonate strata in the thrust belt (Blatt et al., 1972; Hopkins, 1981; Iwuagwu and Lerbekmo, 1982; Potocki, 1992). However, it is possible that some chert was derived locally from the uplifted carbonates in the Growmont-Wainwright Highland. This possibility is supported by the fact that chert grains increase in abundance with depth in the Ptarmigan paleovalley. As well, carbonate grains in the Quail and Grouse paleovalleys are derived locally from Grosmont-Wainwright Highland because they increase in abundant with depth in the Quail and Grouse paleovalleys (Table 3.7).

3.4.4. Summary of Sediment Source based on Composition

Based on evaluation of lithic and feldspar compositions, the logical conclusion is that McMurray sandstones in the three paleovalleys were sourced from recycling of uplifted sedimentary rock in the west (cf. Ingersoll et al., 1987, Potocki and Hutcheon, 1992) with contributions of sediments, including detrital feldspar, from the Canadian Shield in the east and west. However, the overwhelming dominance of monocrystalline quartz grains, which are medium to coarse grained (0.25 to 1 mm diameter) and are better rounded than fine to very fine grains (0.0625 to 0.25 mm diameter) indicates a long transport distance of detrital quartz grains. This indicates that the craton is the major source of sediment, and this could include a continental-scale drainage that has been suggested by others (e.g., Bayliss and Levinson, 1976; Christopher, 1980 and 1997; Potocki and Hutcheon, 1992; Blum and Pecha, 2013; Benyon et al., 2014). The uncertainty in the likely source of sediments suggests multiple sediment inputs into the paleovalley.
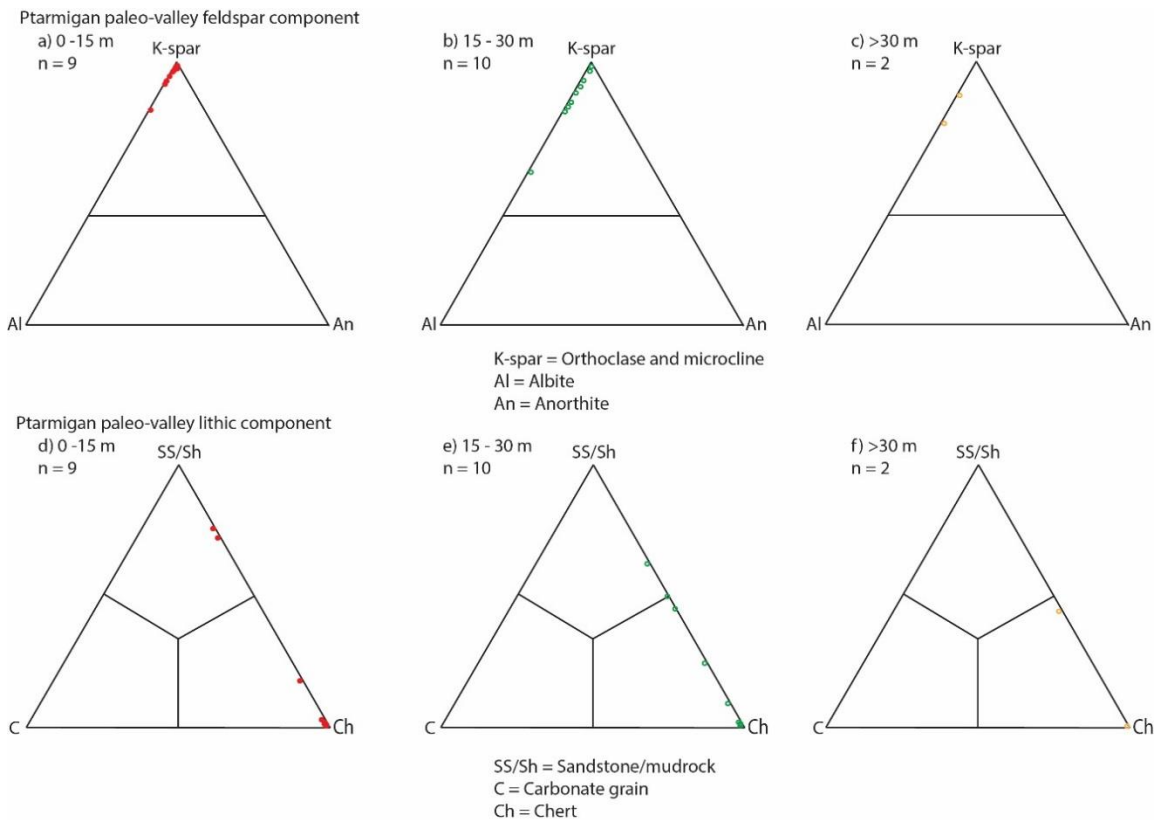
Figure 3.12. Relative proportion of feldspar and lithics in McMurray sandstones of the Ptarmigan paleovalley. The feldspar and lithic components presented in Appendix A are normalized to 100% in this figure. a – c) K-spar –Al –An ternary diagram. d – f) SS/Sh – C – Ch lithics ternary diagram. a) Samples within the upper 15 m of the McMurray Formation (n = 9). b) Samples taken from 15–30 m below the top of the McMurray Formation (n = 10). c) Samples from greater than 30 m from the top of the McMurray Formation (n = 2). d) Samples within the upper 15 m of the McMurray Formation (n = 9). e) Samples taken from 15–30 m below the top of the McMurray Formation (n = 10). f) Samples from the greater than 30 m from the top of the McMurray Formation (n = 2).

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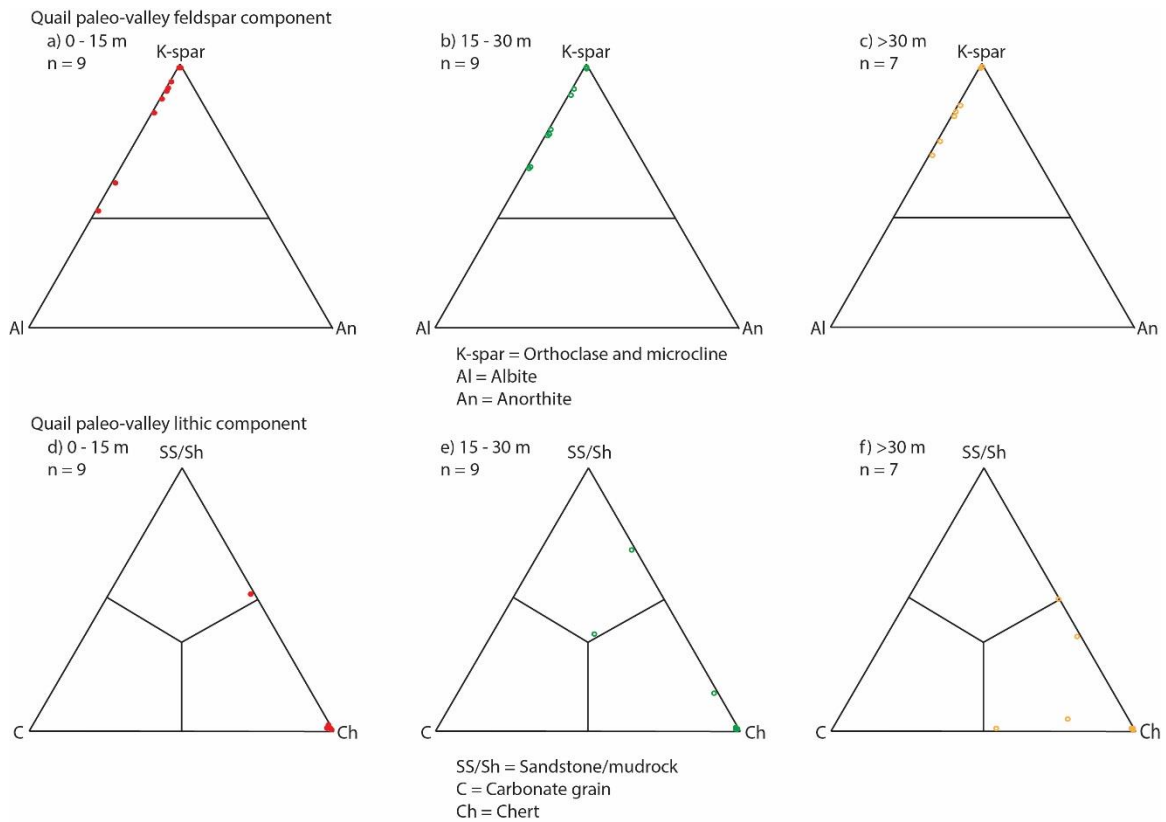
Figure 3.13. **Relative proportion of feldspar and lithics in McMurray sandstones of the Quail paleovalley. The feldspar and lithic components presented in Appendix A are normalized to 100% in this figure. a – c) K-spar – Al – An ternary diagram. d – f) SS/Sh – C – Ch lithics ternary diagram. a) Samples within the upper 15 m of the McMurray Formation (n = 9). b) Samples taken from 15–30 m below the top of the McMurray Formation (n = 9). c) Samples from the greater than 30 m from the top of the McMurray Formation (n = 9). d) Samples within the upper 15 m of the McMurray Formation (n = 9). e) Samples taken from 15–30 m below the top of the McMurray Formation (n = 9). f) Samples from the greater than 30 m from the top of the McMurray Formation (n = 7).**
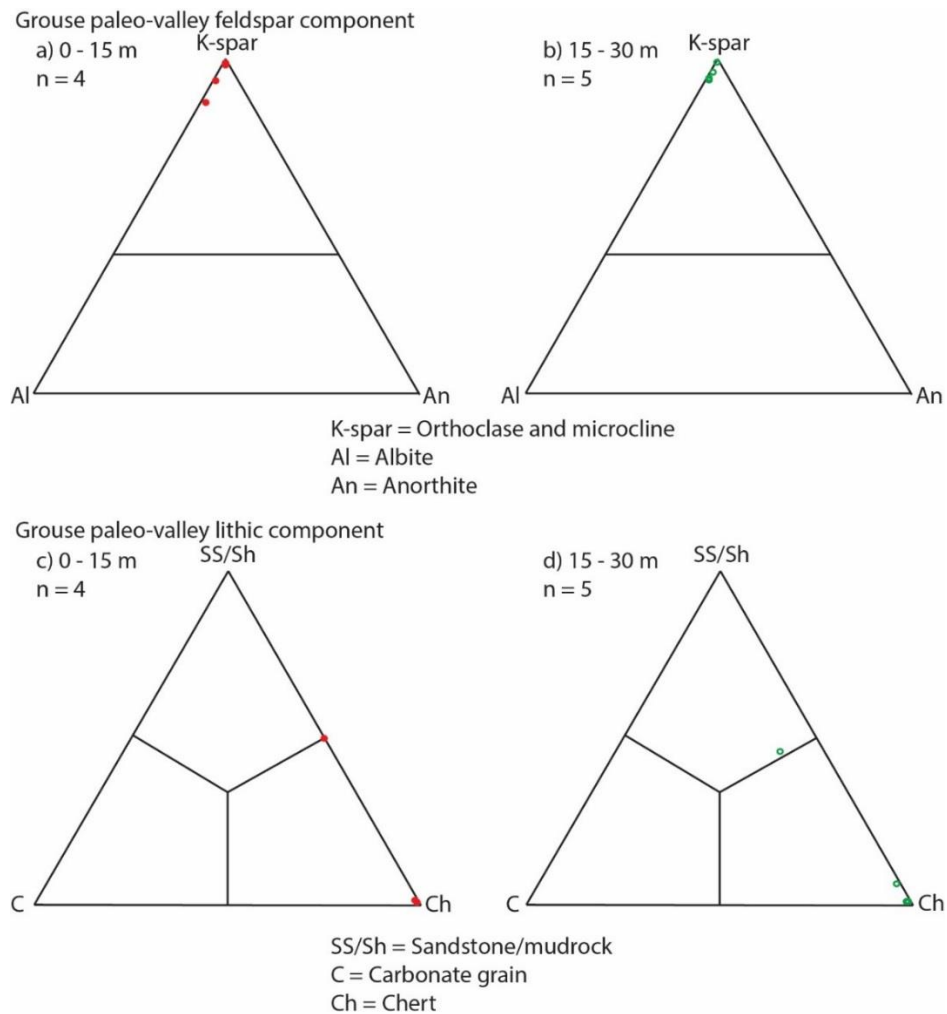
Figure 3.14. **The relative proportion of feldspar and lithics in McMurray sandstones of the Grouse paleovalley. The feldspar and lithic components presented in Appendix A are normalized to 100% in this figure. a – b) K-spar – Al – An feldspar ternary diagram. c – d) SS/Sh – C – Ch lithics ternary diagram. a) Samples within the upper 15 m of the McMurray Formation (n = 4). b) Samples taken from 15–30 m below the top of the McMurray Formation (n = 5). c) Samples within the upper 15 m of the McMurray Formation (n = 4). d) Samples taken from 15–30 m below the top of the McMurray Formation (n = 5).**

3.5. Quantification of Sediment Delivery to the Ptarmigan and Quail paleovalleys from the Edmonton Valley

As demonstrated above, the vast majority of sediments in the Ptarmigan, Quail, and Grouse paleovalleys appear to have been sourced from the Craton, and this has

previously been hypothesized to be either the SW USA or via a continental-scale drainage (Christopher, 1980 and 1997; Hein et al., 2012; Blum and Pecha, 2013; Benyon et al., 2014). However, the subtle variations in the mineralogy of McMurray Formation sandstones in the various paleovalleys suggest that other sources existed as well. One such aspect is the presence of well-preserved feldspars that probably originated from the Canadian Shield and were not transported a long distance. Also, subrounded to well-rounded, altered 2nd cycle plagioclase feldspar and the abundance of lithic (chert) fragments that probably were derived from the west (Edmonton Valley). To the south and west, the McMurray Sub-Basin is bordered by the Grosmont-Wainwright Ridge, which also served as a drainage divide between the McMurray Sub-Basin / Assiniboine Valley and the Edmonton Valley (Jackson, 1984; Ranger et al., 1994; Smith, 1994; Mei et al., 2015). During the filling of the McMurray Sub-Basin, it has been proposed that the Grosmont-Wainwright Ridge may have prevented Cordilleran sediments from reaching the basin (Leckie and Smith, 1992; Ranger and Pemberton, 1997).

In Figure 3.15, potential paleo-tributary directions are superimposed on the isopach map of the McMurray Formation across the southern McMurray Sub-Basin. The positions of these tributaries are based on paleo-topographic lows that cross-cut the Grosmont-Wainwright Ridge and connect the Edmonton Valley with the Ptarmigan and Quail paleovalleys. The position of these valleys is further supported through net-sand mapping of the McMurray interval (Fig. 3.16), wherein thicker sands are positioned throughout the valleys, including in the conduits identified in Figure 3.15. These conduits range from 25 to 40 m deep, and are approximately 4 – 9 km wide (Fig. 3.15). The occurrence of these conduits suggests that the Ptarmigan and Quail paleovalleys could have received sediments from the south, southwest and west (i.e., Edmonton Valley) during their filling phase, and this may explain their higher concentration of lithics relative to McMurray sandstones situated further to the north (e.g. Carrigy, 1963; Nelson and Glaister, 1976; Hein et al., 2012).
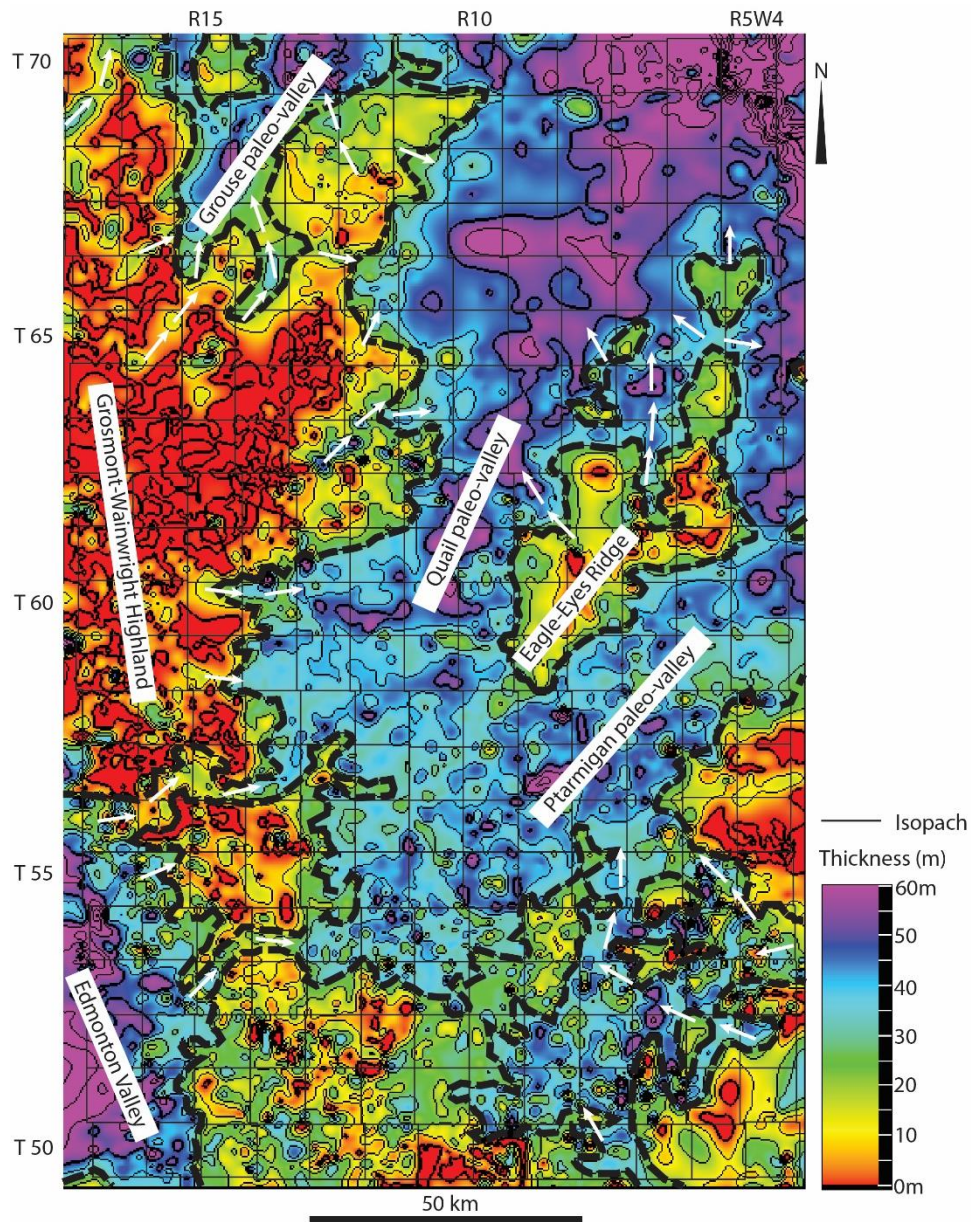
Figure 3.15. **Paleo-tributary locations superimposed on an isopach map of the McMurray Formation. White arrows show possible sediment transport directions into and within the southern McMurray Sub-Basin from the southwest, south, west and southeast. Thick, dark blue lines are outlines of paleo-channels that bisect the southern portion of the Grosmont-Wainwright Highlands and may have served as conduits for sediments into the Ptarmigan, Quail, and Grouse paleovalleys. Note, Ptarmigan, and Quail paleovalleys received drainage from the Edmonton Valley in the west and the Saskatchewan area in the east. The Grouse paleovalley appears to have only received sediments from the east and from drainage off the Wainwright-Grosmont Highland.**
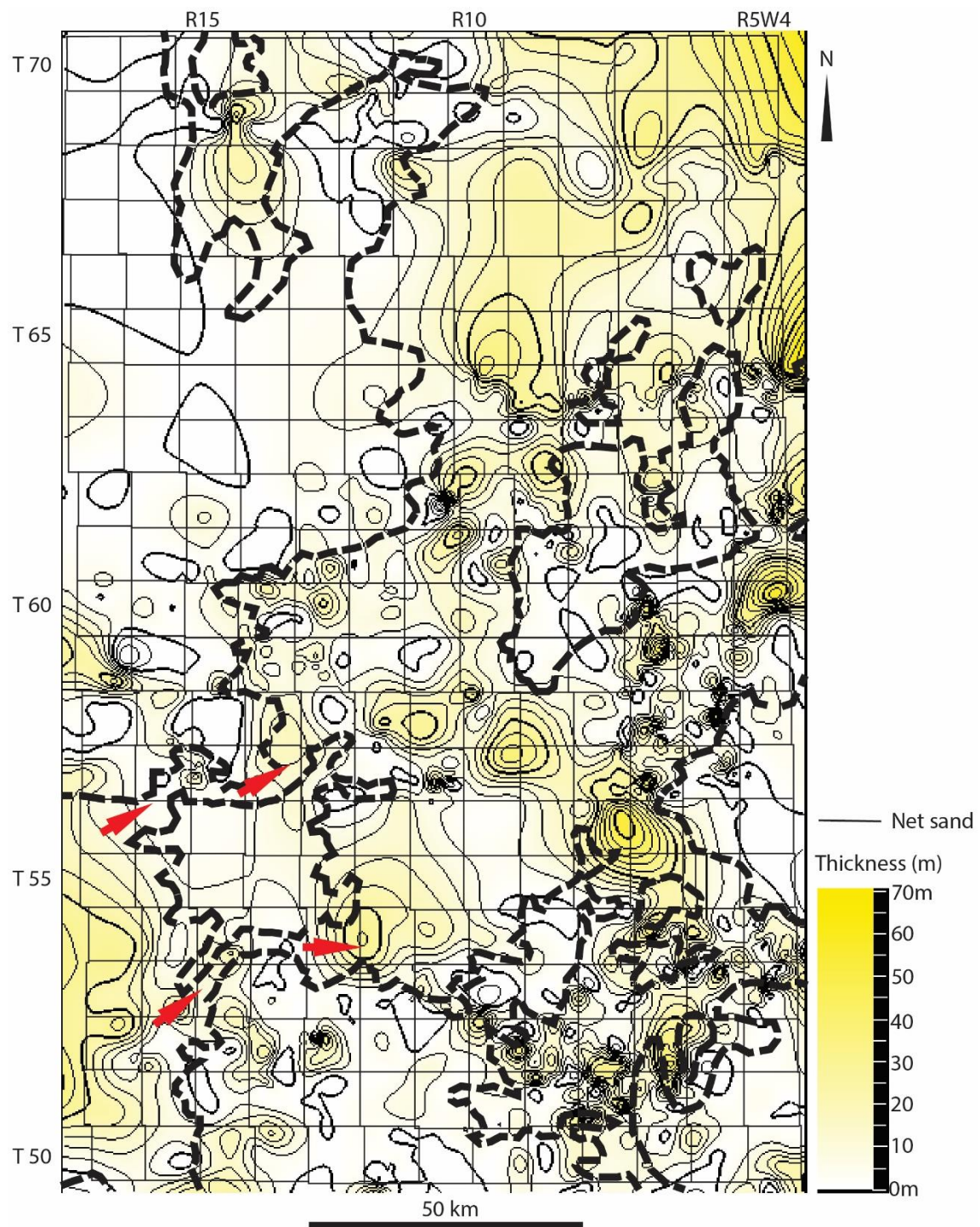
Figure 3.16.   Net-sand map showing the relationship between the southern McMurray Sub-Basin and the Edmonton Valley. Red arrows show the likely point sources for Cordilleran sediments delivered through the Edmonton Valley into the southern McMurray Sub-Basin.

Quantification of sediment delivered into the Ptarmigan and Quail paleovalleys has been accomplished by calculating the proportion of Ellerslie Formation sandstone composition that would have to be mixed with Dina Formation sandstone composition from the east to have produced the mineralogical compositions obseverd in the McMurray Formation sandstones in the Ptarmigan and Quail paleovalleys. This is done because the paleotopography map of the southern McMurray Sub-Basin shows that the upper 30 m of the McMurray Formation in the Ptarmigan and Quail paleovalleys likely received sediment from the west via the Edmonton Valley, and from the east from the proposed continental-scale drainage (Figs. 3.15 and 3.16). As well, the bulk compositions of McMurray sandstones in the Ptarmigan and Quail paleovalleys suggest that sediment was sourced from the continental block, with lesser contributions of recycled orogenic materials (Figs. 3.9 and 3.10). Quantification of sediment source was not done for McMurray Formation sandstones in the Grouse paleovalleys because there is no clear connection between this paleovalley and the west (Figs. 3.15 and 3.16).

To quantify sediment contributions to the Ptarmigan and Quail paleovalleys, only feldspar and lithic components were used because their percentages constitute the major difference between the Dina and Ellerslie sandstones (William, 1963; Bayliss and Levinson, 1976; Hopkins, 1981). Ellerslie Formation sandstones do not contain significant percentages of feldspar but do have higher percentages of lithics which are mainly chert (William, 1963; Hopkins, 1981). Conversely, Dina Formation sandstones contain lower percentage of lithics but have significant percentages of feldspar which are dominantly orthoclase.

Quantification of the percentage of sediments delivered into the Ptarmigan and Quail paleovalleys from the west is done in two stages. 1) I calculate the proportion of sediments from the Edmonton Valley in the west (Ellerslie Formation sandstone) that must be mixed with sediments from the east (Dina Formation sandstone) to produce the resulting McMurray Formation sandstone compositions. This is done by using simple linear equations based on differences in the proportion of feldspars and lithics in the Dina and Elerslie sandstones, and the average and range of percentages of lithics and feldspars McMurray Formation sandstones in the Ptarmigan and Quail paleovalleys [Eq. 1 and Eq. 2]. Equation 1 uses the range and average percentage of feldspar in Ellerslie

sandstone, Dina sandstones, and McMurray sandstones in the Ptarmigan or Quail paleovalleys. Whereas Equation 2 uses the range and average percentage lithics Ellerslie Formation sandstones, Dina Formation sandstones, and McMurray Formation sandstones in the Ptarmigan or Quail paleovalleys. The proportion of sediment from west (Edmonton Valley) that must be mixed with sediment from the east (both Canadian Shield and continental-scale drainage) to produce the composition of McMurray sandstones in either the Ptarmigan or Quail paleovalley is always equal to one. 2) The proportion of sediments delivered into either the Ptarmigan or Quail paleovalleys from the west and east, respectively, is calculated by dividing the proportion of sediment from west or east by the sum of the proportion of sediment from west and east and then multiplying it by 100 [Eq. 3 and Eq. 4].

$$F_S = (F_W)x + (F_E)y \qquad\qquad\qquad\qquad [Eq.\ 1]$$

$$L_S = (L_W)x + (L_E)y \qquad\qquad\qquad\qquad [Eq.\ 2]$$

Where:

F_S = average or percentage range of feldspar in McMurray sandstones in paleovalleys,

F_W = average or percentages range of feldspar in Ellerslie Fm (from the west),

F_E = average or percentage range of feldspar in Dina Fm (from the east),

L_S = average or percentage range of lithics in McMurray sandstones in paleo-valleys,

L_W = average or percentage range of lithics in Ellerslie Fm (from the west),

L_E = average or percentage range of lithics in Dina Fm (from the east),

x = the proportion of sediment received from the south, southwest and west (Cordilleran materials), and

y = the proportion of sediment received from southeast (main truck valley).

Both x and y are absolute values, and x + y = 1

Based on the above equation,

$$M = \left(\frac{x}{x+y}\right) X \ 100 \qquad \text{[Eq. 3]}$$

$$N = \left(\frac{y}{x+y}\right) X \ 100 \qquad \text{[Eq. 4]}$$

Where:

M = percentage of sediment received from the south, southwest and west (i.e., Cordilleran materials).

N = percentage of sediment received from the southeast (i.e., continental-scale drainage).

Table 3.8 shows the average and range of feldspar and lithics percentages from the Dina Formation (Bayliss and Levinson, 1976), Ellerslie Formation (Potocki, unpulished data), and McMurray sandstones in the Ptarmigan and Quail paleovalleys. Mineralogical data provided in William (1963) and Hopkins (1981) are not used in calculation of sediment sources because the studies only provide the range percentages of the principal minerals and not average values. Quantification of sediment transported into the Ptarmigan and Quail paleovalleys was calculated using average percentages presented in Table 3.8. From these data, sediment source contributions are determined.

Calculation of sediment source based on average feldspar percentages shows that the Quail paleovalley received 38% of its sediments from the west and 62% from the east, whereas the Ptarmigan paleovalley received 34% of its sediments from the west and 66% from the east (Table 3.9). Calculation of sediment source based on average lithics

percentages shows that the Quail paleovalley received 86% from the west and 14% from the east, while the Ptarmigan paleovalley received 37% of its sediments from the west and 63% from the east (Table 3.9).

Table 3.8. **Average- and range of percentages of feldspar and lithics constituent used to determine the percentages of sediment received from the Edmonton Valley (Cordilleran sediments) and from the Assiniboine Valley (proposed continental-scale drainage). Data are derived from Bayliss and Levinson (1976) and Potocki (unpublished data).**

Paleovalley /Formation	Dina Formation (Bayliss and Levinson)	Ellerslie Sandstone (Potocki)	Ptarmigan McMurray sandstone	Quail McMurray sandstone
% Range of Feldspar	0 – 19	0.4 – 0.8	2 – 11	3 14
% Range of Lithics	0 – 1	0.4 – 12.3	1 – 6	0 – 39
% Average of Feldspar	3	0.6	5.6	6.6
% Average of Lithics	0.1	3.6	1.4	3.1

Table 3.9. **Calculated percentages of sediments delivered into the Ptarmigan and Quail paleovalleys from the Edmonton Valley to the south-southwest (Cordilleran materials) and percentages of sediment derived from the Assiniboine Valley to the southeast and east (proposed continental-scale drainage).**

Paleovalley	Values	Percentages (%) of sediments from Edmonton Valley (Cordillera)		Percentages (%) of sediments from Saskatchewan (continental-scale drainage)	
		Feldspar	Lithics	Feldspar	Lithics
Ptarmigan	Average	34	37	66	63
	Minimum	56	62.5	44	37.5
	Maximum	44	43	56	57
Quail	Average	38	86	62	14
	Minimum	62.5	-	37.5	-
	Maximum	28	59	72	41

There is remarkable consistency in the calculated percentages of sediment sources for both feldspar and lithics. Based on this, it is hypothesized that the upper 30 m

of both the Ptarmigan and Quail paleovalleys received approximately 46% of its sediments from the west (Edmonton Valley, Cordilleran source) and 54% from the east (Assiniboine, continental-scale drainage). The bulk of sediments in the Ptarmigan, Quail, and Grouse paleovalleys are derived from the craton across the North America probably through the proposed continental-scale drainage. It is possible that these sediments were transported into the paleovalleys via either tidal processes from the northeast or valley flooding during high-flow stage in the main river system and its tributaries. Westerly-derived sediments reached the Ptarmigan and Quail paleovalleys at a relatively late stage of their filling history by small- to medium-scale rivers that flowed through paleo-channels that bisected the Grosmont-Wainwright Highland. The paleo-channels connected the upper 30 m of the Ptarmigan and Quail paleovalleys with the Edmonton Valley (Fig. 3.15).This hypothesis is supported by the increase in abundance of feldspar with decreasing depth potentially indicating a greater abundance of easterly-derived sediments during the early filling stages of all 3 paleovalleys (Fig. 3.5). Note that there is variation in these data, and it is possible that the Quail paleovalley received more sediment from the Edmonton Valley than Ptarmigan paleovalley.

3.6. Conclusions

Isopach and net-sand mapping of the McMurray Formation coupled with a mineralogical analysis of sandstones in paleovalleys in the study area was undertaken to investigate whether there was a Cordilleran source of sediment to the southern McMurray Sub-Basin. The following conclusions are reached:

1. There are three paleovalleys carved into the Grosmont–Wainwright Highland in the study area. These are named herein as the Grouse, Quail, and Ptarmigan paleovalleys. Their fill is stratigraphically equivalent to the upper part of the Middle McMurray and lower part of the Upper McMurray (Figs. 3.15).

2. There are subtle, yet detectable vertical and spatial variations in the bulk mineralogy (quartz, feldspar, and lithic fragments) of sandstones in the upper 30 m of all three paleovalleys. The feldspar component decreases and lithic component increases in abundance with depth. Moreover, the decrease in abundance of feldspars with increasing depth may correspond to the period when easterly-derived feldspar reached the paleovalleys, although, altered feldspar may have a different source other than the east (Fig. 3.5). McMurray sandstones

in the upper 30 m of the southern McMurray Sub-Basin can be classified as compositionally mature subarkoses, sublitharenites, litharenites, and quartz arenites (Figs. 3.6–3.8).

3. Mineralogical composition of McMurray sandstones in the upper 30 m of the Ptarmigan, Quail, and Grouse paleovalleys shows that the majority of sediment was derived from the craton, and possibly from the continental drainage hypothesized to exist in the Assiniboine paleovalley (Figs. 3.9–3.11; Christopher, 1980 and 1997; Benyon et al., 2014). That said, the percentage of feldspar suggests sediment in all the three paleovalleys was also derived from the Canadian Shield in the east, and the percentage lithics indicate that all three paleovalleys received sediment from the recycling of uplifted sedimentary rock in the west (Cordilleran materials).

4. The Wainwright–Grosmont Highlands did not prevent sediments from entering the southern McMurray Sub-Basin, because within the study area, a series of channels bisect the highland and provide conduits for the sediment to enter the Assiniboine Valley from the Edmonton Valley (Figs. 3.15 and 3.16). Quantification of sediment delivered into the Ptarmigan and Quail paleovalleys indicates that both the Ptarmigan and Quail paleovalleys likely received 46% of their sediments from the west, although it is possible that the Quail paleovalley received more sediment than the Ptarmigan paleovalley from the Edmonton Valley (Table 3.9).

3.7. References

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Chapter 4.

Conclusions

The McMurray Sub-Basin holds the largest proven reserves of oil sands in the world, with the bulk of these reserves occurring the McMurray Formation (Oil and Gas Journal, AER 2013). During filling, the McMurray Sub-Basin was adjacent to an active orogenic belt in the west, which potentially served a sediment source. It is generally believed, however, that a relatively continuous paleotopographic high that bordered the basin to the west and south (Grosmont-Wainwright Highland) prevented westerly derived sediment from reaching the sub-basin. To test the validity of this assumption, this research project attempted to answer the questions "Is there point sources from the west-southwest to the McMurray Sub-Basin through the Grosmont-Wainwright Highland? If yes, how much sediment might have been sourced from the west?" In this study, mineralogical data coupled with isopach and net-sand mapping were used to gain insight as to whether westerly-supplied sediments reached the southern McMurray Sub-Basin from the west, southwest, and/or south. Mineralogical compositions were compared between paleovalleys to determine whether there is any variation in the composition of McMurray Formation sandstones present in the Ptarmigan, Quail, and Grouse paleovalleys.

Below, conclusions are provided as answers to the study objectives outlined in Chapter One. Possible avenues for future work that can test and build on the findings of this work are also suggested.

4.1. Objectives and Conclusions

1.   **Objective 1:** *Determine the suitability of the top of the Wabiskaw Member (Wabiskaw Marker) as a regionally correlatable surface across the southern McMurray Sub-Basin.*

In Chapter 2, I correlated and mapped the Wabiskaw Marker across the study area (Figs. 2.3–2.6). Through that assessment, it was confirmed that the top of the Wabiskaw

Member (Wabiskaw Marker) is a suitable datum for mapping the Wabsikaw-McMurray interval. The Wabiskaw Marker is a regionally mappable flooding surface, and can be correlated throughout the entire study area and even further north. Mapping of the isopach thickness of the Wabiskaw interval shows that it thickens slightly into the Ptarmigan and Quail paleovalleys, and thins to almost 0 m over the top of the Grosmont-Wainwright Highland (Fig. 2.2). The Wabiskaw Member also changes character around townships T50–T55, with the unit being coal-bearing to the south.

Isopach mapping of the Wabiskaw-McMurray interval using the Wabiskaw Marker as a datum clearly delineates the paleotopography on the top of the sub-Cretaceous Unconformity (SCU) at the beginning of McMurray Formation deposition. Variations in the McMurray isopach values show paleo-topographic lows corresponding to thick packages of the McMurray, and paleotopographic highs reflected by thin packages of the McMurray.

2.   **Objective 2:** *Ascertain whether the Grosmont-Wainwright Highlands prevented Cordilleran sediments from reaching the McMurray Sub-Basin from the south and southwest.*

Based on mineralogical compositions of McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalleys coupled with the reconstruction of the paleogeography of the study area (see chapter 3), this study concludes that the Wainwright–Grosmont Highland did not prevent Cordilleran sediment from entering the southern McMurray Sub-Basin. Evaluation of quartz, feldspar and lithic compositions does indicate that that McMurray sandstones in the three paleovalleys are sourced overwhelmingly from the craton, and this sediment was likely derived through a continental-scale drainage (Bayliss and Levinson, 1976; Christopher, 1980 and 1997; Potocki and Hutcheon, 1992; Blum and Pecha, 2013; Benyon et al., 2014). However, analysis of lithic and feldspar contents suggest that sediment was also sourced from the recycling of uplifted sedimentary strata lying in the west (Ingersoll et al., 1987) and from the Canadian Shield in the east (detrital feldspar). More importantly, the reconstruction of the paleogeography of SCU shows a series of channels that bisect the Wainwright-Grosmont Highland and could have served as conduits for Cordillera-derived sediments entering the McMurray Sub-Basin from the Edmonton Valley.

3.   **Objective 3**: *Quantify the percentage of Cordilleran sediments that reached the McMurray Sub-Basin from the Edmonton Valley through the Grosmont-Wainwright Highlands.*

Quantification of sediment transported into the Ptarmigan and Quail paleovalleys (see chapter 3) indicates that both the Ptarmigan and Quail paleovalleys received approximately 46% of their sediments from the Cordillera. It is possible, however, that the Ptarmigan paleovalley received less sediment than Quail paleovalley. Based on this study, the Grouse paleovalley received 0% of Cordilleran sediments.

4.   **Objective 4:** *Show whether there are any variations in mineralogical composition of the McMurray Formation among paleovalleys that adjoin the southern McMurray Sub-Basin.*

McMurray sandstones in the southern McMurray Sub-Basin (Ptarmigan, Quail, and Grouse paleovalleys) (see chapter 3) exhibit subtle but detectable vertical and spatial variations in the composition of quartz, feldspar, and lithic fragments within the upper 30 m of the paleovalley. The feldspar component decreases with increasing depth. Conversely, the lithics increase with increasing in depth. McMurray sandstones in the southern McMurray Sub-Basin are classified as subarkoses, sublitharenites, litharenites, and quartz arenites; however, McMurray sandstones in all three paleovalleys are mature and are rich in chert.

4.2. Future Work

In conjunction with mineralogical analyses and paleogeographic reconstructions achieved in this study, other avenues of study would help advance the findings of this work and add further insight into the hypothesis presented herein that Cordilleran sediments were delivered to the McMurray Sub-Basin through the Ptarmigan and Quail paleovalleys. One suggested study is to undertake a mineralogical analysis of chert grains using grain mounts. This would help to discriminate different varieties of chert present in the sandstones, which will enable direct linkage of chert to its source (Schwab, 1986; Ingersoll et al., 1987). For example, DeCelles and Gutschick (1983) did analysis on wood-grained

chert of the Western Interior Seaway in the United States, which is a nodular chert that has internal light- and dark- coloured layers and were able to show that the chert can be correlated to Mississippian Lodgepole, Deseret, and Great Blue Limestones and hence is of Mississippian age. If a similar study was undertaken on chert in McMurray Formation sandstones, it should be possible to determine if the source of the chert were supplied from carbonates of Paleozoic age. As chert can preserve fossil materials, it might also possible to determine wether they were supplied from Devonian or Mississippian strata, and perhaps identify the specific source areas and stratigraphic intervals that supplied the compositions.

In conjunction with detrital chert analysis, detrital zircon U-Pb ages dating can be employed to derived the age of detrital zircons in McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalley. This method has been employed to suggest that the vast majority of McMurray Formation sandstones north of study area are sourced from the southeast USA and delivered via continental drainage (Benyon et al., 2014). By doing a similar study in the three paleovalleys in this study, it might be possible to establish whether the Ptarmigan, Quail, and Grouse paleovalleys show the necessary values in their spectrum of detrital zircon ages supporting influx of Cordilleran sediment.

Another important analysis that could shed light on the provenance of McMurray Formation sandstones in the Ptarmigan, Quail, and Grouse paleovalley is a heavy mineral analysis using grain mount. This is useful because heavy minerals are sensitive indicators of source-area (Morton and Hallsworth, 1994, 1999). This method employs the specific mineralogical and isotopic characteristics of heavy minerals would allow to indicate what particular stratigraphic units exposed in the Cordillera supplied them to the McMurray (Nechaev and Isphording, 1993; Morton and Hallsworth, 1999). That is, heavy mineral analysis could be used to fingerprint the specific source units and prove unequivocally that westerly-derived sediments find their way into the southern McMurray Sub-Basin.

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Appendix A

Mineralogy Table

This table shows the result of mineralogical analysis performed on 55 thin section samples taken from 26 of the cores. An average of 508 grains were counted per thin section and point counting was performed using maximum possible grid spacing (i.e., 0.5 mm spacing). Chert and quartzite are counted as lithic fragments and not as detrital quartz. The result show herein consists of bulk mineralogy of McMurray Formation sandstones before quartz-feldspar-lithic are normalised prior plotting them on QmFLt and QFL ternary diagrams.

Name		Quartz (%)		Feldspar (%)			Lithic Fragments (%)						Others (%)				
UWI	Depth (m)	Qm	Qp	Mc	Or	Ab	Mcc	Mgc	Ccc	Ss/St	Qze	Cbg	Msc	Bl	Cl	Hm	Glg
08-20-063-05W4	453.50	93.76	0.75	0	3.22	0.64	0.51	0.13	0	0.09	0.36	0	0.09	0	0	0.45	0
08-20-063-05W4	458.40	80	0	0	11.25	0	0	0	0	0	0	0	4.61	1.02	0	3.12	0
11-15-050-04W4	654.90	87.80	3.83	0	4.88	0	0.7	0	0	0	0	0	1.05	0	0	1.73	0
11-15-050-05W4	667.60	83.24	2.78	0.40	5.18	1.20	0.75	0.45	0	0.40	0	0	1.80	0.93	0.07	2.80	0
08-09-056-07W4	568.50	91.71	2.34	0	3.87	0	1.1	0	0	0	0	0	0.14	0	0	0.83	0
08-09-056-07W4	578	90.14	2.27	0	4.7	0.75	0.91	0	0	0	0	0	0.16	0	0	1.06	0
08-09-056-07W4	585.90	88.50	1.07	0.27	7.77	0	1.07	0	0	0	0	0	0.93	0	0	0.40	0
10-24-066-05W4	512.70	94.55	0.96	0	3.05	0.24	0.33	0	0	0.64	0	0	0.16	0	0	0.07	0
10-24-066-05W4	515.80	91.35	0.92	0.50	4.90	0.67	0.50	0	0	0.5	0.16	0	0.33	0	0	0.17	0
10-24-066-05W4	522.50	92	2.73	0.67	3.4	0.45	0.3	0	0	0.3	0	0	0	0	0	0.15	0
10-24-050-05W4	666.60	93.32	0.53	0.31	4.29	0.15	0.3	0.12	0	0.31	0	0	0.15	0	0	0.77	0
10-24-050-05W4	672.10	92.66	0.37	0.15	4.44	0.23	0.90	0	0	0.16	0	0	0.31	0	0	0.77	0
08-20-063-05W4	461.80	92.12	0.18	0	4.74	0.49	0.6	0.4	0.09	0	0	0	0.50	0.37	0	0.49	0
11-04-056-06W4	577.50	76.51	8.30	0	7.62	0.34	0.4	1.5	0.17	0	0	0	1.10	0.50	0.12	2.99	0.44
11-04-056-06W4	596.30	84.97	0.28	0	3.89	0.56	3.85	1.5	0.2	0	0	0	1.70	0	0.28	2.28	0
14-12-065-05W4	508.30	93.40	0.70	0	3.6	0.2	0.5	0	0	0	0	0	0.7	0	0	0.9	0
12-20-053-05W4	625.10	82.46	1.05	1.05	7.02	1.75	1.9	1.76	1.26	0	0	0	0.35	0	0	1.4	0
12-20-053-05W4	630.30	88.48	5.63	0	3.48	0.53	0.53	0	0	0	0	0	0	0	0	1.33	0
12-20-053-05W4	634	91.76	1.15	0	3.13	0.56	0	0.85	0	0.56	0	0	0.44	0.12	0	1.42	0
11-27-054-05W4	598.30	95.9	0.35	0	1.75	0.12	0.82	0	0	0.57	0	0	0.07	0	0	0.21	0
11-27-054-05W4	601.30	87.75	0.68	0	6.8	2.03	1.20	0.17	0	0	0	0	0.32	0.22	0.14	0.68	0
08-11-069-08W4	443	91.26	0.38	0.25	3.8	0.38	1.02	0	0	0	0	0	0.75	0	0	2.16	0
08-11-069-08W4	448	87.78	0	0	5.56	0	0	0	0	0	0	0	1.52	0	0.7	4.44	0

Name		Quartz (%)		Feldspar (%)			Lithic Fragments (%)						Others (%)				
UWI	Depth (m)	Qm	Qp	Mc	Or	Ab	Mcc	Mgc	Ccc	Ss/St	Qze	Cbg	Msc	Bl	Cl	Hm	Glg
08-11-069-08W4	451.40	74.34	0	0	6.81	1.74	0	0	0	0	0	0	8.04	1.82	2.18	5.24	0
13-30-068-08W4	566.40	94.3	0	0.1	3.1	0.4	0.2	0	0	0.3	0	0	0.8	0	0	0.7	0
13-30-068-08W4	583.30	89.5	2.1	0	6.8	0.4	0.4	0	0	0	0	0	0.22	0	0.18	0.4	0
10-28-068-07W4	505.10	90.90	1.11	0	5.13	0.66	0.21	0	0	0	0	0	0.66	0	0	1.32	0
10-28-068-07W4	512.10	79.50	0	0	14.14	0	0.35	0	0	0	0	0	3.15	1.10	0	1.77	0
07-27-068-06W4	530.40	76.28	0	0	14.13	0	0	0	0	0	0	0	3.95	0	0	5.65	0
07-27-068-06W4	541.10	90.78	0.48	0.27	3.93	0	0.83	0	0	0	0	0	1.52	0.99	0	0.83	0
08-16-067-07W4	502.30	93.20	0.14	0	3.26	0.74	0.44	0	0	0	0	0	1.93	0	0	0.29	0
08-16-067-07W4	506.60	93.68	0	0.12	3.2	0.36	0.48	0	0	0	0	0	0.95	0	0	1.2	0
05-01-064-07W4	484.10	88.36	1.04	0	4.57	3.53	0.99	0.04	0	0	0	0	0.83	0	0	0.63	0
05-01-064-07W4	503.50	90.55	0.63	0.31	4.42	1.26	0.88	0.38	0	0	0	0	0.31	0	0	1.26	0
05-13-068-06W4	528.80	86.71	0	0	8.19	0.36	0	0	0	0	0	0	2.37	1.12	0.88	0.36	0
05-13-068-06W4	535.10	85.13	1.27	0	5.04	0.76	1.51	0	0	0.51	0	0	3.02	0	0	2.26	0
06-17-070-05W4	491.10	89.36	1.78	0	5.96	0.60	0.96	0	0	0.60	0	0.24	0.13	0	0	0.37	0
06-17-070-05W4	529	94.94	0.72	0.82	1.28	0.47	0.23	0	0	0	0	0	1.3	0	0	0.24	0
06-17-070-05W4	532.40	91.80	1.43	0	3.55	0.67	0.78	0	0	0.22	0	0	0.88	0.12	0	0.55	0
06-04-063-12W4	547	80.83	0	0	8.37	1.2	0	0	0	0	0	0	4.50	1.59	0.50	2.99	0
06-04-063-12W4	557.40	42.56	7.14	0	5.95	2.09	25.63	7.32	3.66	0.60	0	1.65	2.38	0	0	0.90	0.14
11-28-067-12W4	477	88.38	0.31	0	5.51	1.53	1.7	0.43	0	0.31	0	0	0.22	0	0.19	0.41	0
06-22-069-05W4	511	89.28	2.15	0.53	3.90	1.20	0.93	0.14	0	0	0	0	0.87	0.2	0	0.67	0
06-22-069-05W4	518.80	87.68	0.18	0.37	8.33	0.18	0.56	0.16	0	0.72	0	0	1.27	0	0	0.55	0
11-26-064-12W4	518	70.48	3.43	0	2.40	0.34	9.61	3.69	1.48	1.71	0	4.98	0.88	0.15	0	0.69	0.16
11-26-064-12W4	523.20	87.60	0.8	0	6.4	0	1.2	0	0	0	0	0	3.2	0	0	0.8	0

Name		Quartz (%)		Feldspar (%)			Lithic Fragments (%)						Others (%)				
UWI	Depth (m)	Qm	Qp	Mc	Or	Ab	Mcc	Mgc	Ccc	Ss/St	Qze	Cbg	Msc	BI	CI	Hm	Glg
06-10-070-12W4	449	89.69	0	0	4.3	0.29	0.81	0.90	0	0	0	0	3.20	0.53	0	0.29	0
06-10-070-12W4	464.20	94.24	0	0.32	2.85	0.15	0.63	0	0	0.88	0	0.23	0.46	0	0	0.23	0
06-10-070-12W4	460.80	89.90	0.28	2.17	4.33	0	0.55	0	0	0	0	0	0.67	0.44	0.26	1.37	0
05-16-067-14W4	462	84.42	0.33	0.60	5.37	0.67	0.33	0.25	0.09	0.57	0	0.10	5.06	1.10	0.17	0.98	0
05-16-067-14W4	473.10	86.13	2.70	0.2	6	0.63	0.83	0.2	0	0	0	0	1.45	0	0	1.88	0
07-18-069-12W4	461.30	76.15	0	0	16.33	0	0	0	0	0	0	0	2.31	1.22	0.78	3.21	0
06-21-068-12W4	456.50	91.69	0.46	0	2.31	0	0.46	0	0	0	0	0	2.20	1.03	0	1.38	0
06-21-068-12W4	468.50	92.62	0.67	0.49	3.62	0.49	0.82	0	0	0.07	0	0	0.65	0	0	0.49	0

Qm = Monocrystalline quartz
Qp = Polycrystalline quartz
Mc = Microcline
Or = Orthoclase
Ab = Albite
Mcc = Microcrystalline chert
Mgc = Megacrystalline chert
Ccc = Cryptocrystalline chert (chalcedony)
Ss/St = Sandstone/siltstone
Qze = Quartzite
Cbg = Carbonate
Msc = Muscovite
BI = Biotite
CI = Chlorite
Hm = Heavy minerals
Glg = Glauconite