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Hydraulic properties of the Paskapoo Formation in west-central Alberta

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Abstract

In an effort to better understand the hydraulic properties of the Paskapoo Formation, hydraulic conductivity and porosity were evaluated for a region in west-central Alberta. Whereas previous studies have focused mainly on sandstone units in the lower portion of the Paskapoo Formation, in southern and central parts of the province, this study focuses on the middle to upper portions. Hydraulic conductivity values were determined by air-permeametry for seven drill cores from the area between Hinton and Fox Creek, Alberta. Thin section petrology and porosity analyses using photomicrographs were also conducted for three of the seven drill cores. Results confirm previous findings that the Paskapoo Formation has heterogeneous hydraulic properties, with horizontal hydraulic conductivity values ranging from 10^{-10} to 10^{-5} m/s (determined by air-permeametry) and porosity values ranging from 0.02 to 15.3%. The first measurements for the upper sandstone units are provided (1.1×10^{-9} to 2.6×10^{-5} m/s and 0.08 to 15.3%) and numerous measurements of the middle siltstone/mudstone unit (1.1×10^{-10} to 4.9×10^{-8} m/s and 0.02 to 1.8%) for the north-western portion of the Paskapoo Formation. Qualitative petrologic analysis suggests that the degree of cementation, rather than grain size, is the dominant control on the hydraulic properties of this portion of the formation. This study determined primary hydraulic properties for both the highly conductive units often considered as aquifers and the low conductivity units considered as aquitards or confining layers. When combined with previous findings, this study helps expand the understanding of the Paskapoo Formation and provides critical data for assessing groundwater resources.

Keywords: groundwater, Paskapoo, hydraulic conductivity, hydraulic properties, permeability

Introduction

The Paskapoo Formation (Fm.) contains what is perhaps the most important aquifer system in the Canadian Prairies (Grasby et al. 2014) from which shallow groundwater could potentially be sourced for multiple uses in west-central Alberta. The Paskapoo Fm. covers approximately 65 000 km² of Alberta (Fig. 1) and is host to over 64 000 water wells (Grasby et al. 2008). Although vital to Albertans as the most prolific groundwater source in the province, very little is known about the Paskapoo Fm. in terms of the sustainability and extent of its groundwater resources. The relatively shallow nature of this formation allows for high levels of interaction between surface and groundwater (Schwartz and Gallup 1978), such that extraction from one source can impact the other (Hayashi and Farrow 2014). A better understanding of the hydraulic properties of the formation is an essential first step in evaluating the potential impacts of increased water usage in the region, and for quantifying the interactions between surface and groundwater.

Previous hydrogeological investigations of the Paskapoo Fm. have been largely focused on the prairie landscapes located in the central and southern parts of the province (Grasby et al. 2008; Riddell et al. 2009; Burns et al. 2010), leaving the forested region surrounding west-central Alberta relatively under-studied. This region has experienced a significant increase in water use since 2012 because of exploration and development of shale-gas plays in the Duvernay Fm. (Foundry Spatial 2014; Alessi et al. 2017), primarily near the Town of Fox Creek, Alberta. Shale-gas plays of the Duvernay Fm. in this region require on the order of 30 000 m³ of water per well to successfully complete fracturing operations (PRCL 2014). Due to restrictions on surface water permits in Alberta (AER Bulletin 2015-25), groundwater is an increasingly important alternative water source for hydraulic fracturing in the region, and the greatest

potential for shallow groundwater availability is the Paskapoo Fm. (Fig. 2). The shale-gas plays in the Duvernay Fm. near Fox Creek also coincide with headwaters of many tributaries that drain into the Peace and Athabasca rivers, and these tributaries rely on baseflow sourced from the Paskapoo Fm. (Smerdon et al. 2016). To understand the cumulative effects of increased development on the shallow groundwater supplies in this region and potential influence on baseflow to local rivers, consideration must be given to the complete hydrologic system, beginning with an investigation into the hydraulic properties of the Paskapoo Fm.

The objective of this study is to characterize some of the hydraulic properties of the Paskapoo Fm. in west-central Alberta using air-permeameter testing and thin section petrology of core samples to estimate the hydraulic conductivity and porosity ranges, respectively. Whereas previous studies were focused on the hydraulic properties of the lower part of the Paskapoo Fm., this study provides the first measurements for the middle and upper parts of the formation. The findings are compared with previous hydraulic characterization results that used similar methodology and contribute to a more comprehensive characterization of the Paskapoo Fm. in Alberta. Such data are critical for parameterizing quantitative hydrologic models that may ultimately assist in better assessing Paskapoo Fm. groundwater resources and quantifying interaction with surface water.

Geological Setting

Paskapoo Formation

The Paskapoo Fm. is a Paleogene fluvial deposit dominated by siltstone and mudstone and interbedded with high permeability coarse-grained channel sands (Grasby et al. 2008). It covers much of southwestern Alberta (Fig. 1) and represents the uppermost bedrock unit over its

area of occurrence (Hamblin 2004; Chen et al. 2007; Prior et al. 2013). The Paskapoo Fm. was deposited unconformably over the Upper Cretaceous/Paleocene Scollard Formation (Jerzykiewicz 1997; Burns et al. 2010) as high-energy alluvial fan and floodplain deposits sourced from the eroding Rocky Mountains to the west (Hamblin 2004). Its deposition into the subsiding foreland basin and subsequent erosion formed an asymmetric clastic wedge with a present-day maximum thickness of up to 850 m in the Foothills of the Canadian Rocky Mountains, pinching out to a few tens of metres towards the plains (Hamblin 2004).

The Paskapoo Fm. has been divided into three members by Demchuk and Hills (1991): the Haynes, Lacombe and Dalehurst members. The lowermost Haynes Member is dominated by the thick, massive, coarse-grained sandstones that are characteristic of the Paskapoo Fm. (Demchuk and Hills 1991), although a recent study suggests that this basal sandstone unit is restricted to the southern portion of the formation (Quarero et al. 2015). The Lacombe member consists of interbedded siltstone, mudstone, shale and coal with minor fine- to medium-grained sandstones (Demchuk and Hills 1991) and is thought to directly overlay the Scollard Formation in the north where the Haynes Member is absent (Quarero et al. 2015). It is rarely exposed in outcrop due its recessive nature, despite being the dominant component of the Paskapoo Fm. (Grasby et al. 2008). The overlying Dalehurst Member is present only in the foothills of Alberta and displays interbedded sandstone, siltstone, mudstone and shale with at least five thick (1.3 m to 6.1 m) coal seams (Demchuk and Hills 1991).

Sandstone in the Paskapoo Fm. occurs as isolated, high-permeability channels that interconnect locally to form semi-continuous sandstone horizons (Grasby et al. 2008; Atkinson and Glombick 2015). Outcrops of the Paskapoo Fm. are often biased towards these massive, cliff-forming channel sandstones, leading early interpretations to suggest a sandstone-dominated

system (Grasby et al. 2008; Lyster and Andriashek 2012). Further division of the Paskapoo Fm. has been made based on the occurrence of sandstones, resulting in three informal hydrostratigraphic units suggested by Lyster and Andriashek (2012): the Haynes and Sunchild aquifers and the Lacombe aquitard. The Haynes aquifer and Lacombe aquitard units correlate to the Haynes and Lacombe Members, respectively, as proposed by Demchuk and Hills (1991). The Sunchild aquifer is suggested to be correlative to the Dalehurst Member and is characterized by permeable sandstone bodies that display variable interconnectivity due to incision by present-day streams (Lyster and Andriashek 2012). Throughout the formation, sandstones are typically classified as litharenites and generally dominated by chert and quartz grains that range from coarse to very fine, sub- to well-rounded and poorly to well-sorted (Farvolden 1961). Carbonate and other cements are present to varying degrees resulting in a range of competencies from friable to very well-consolidated (Farvolden 1961).

Previous Studies

The Paskapoo Fm. has been the subject of several hydrogeological investigations that predominantly focus on regions of central and southern Alberta. Grasby et al. (2007) conducted air-permeameter testing and thin-section petrology on six drill cores of the Paskapoo Fm. from the Red Deer and Calgary region (Fig. 1). A bimodal permeability distribution was obtained, with a mean value of $2.8 \times 10^{-11} \text{ m}^2$ (corresponding to a hydraulic conductivity of $2.7 \times 10^{-4} \text{ m/s}$) from 159 measurements (Fig. 3). High permeability values were interpreted as representing either coarse-grained basal sandstones or sandstones from weathered zone where surface weathering processes can locally enhance near-surface permeability (Grasby et al. 2007). Low permeability values were interpreted as representing fine-grained sandstones or mudstones. Helium porosity analysis was also conducted, with results ranging from 4.2% to 32.5% and a

mean of 19.2% for sandstones (Grasby et al. 2007). No relationship between porosity and depth of measurement was observed. Additionally, petrologic analysis of 56 thin sections was completed. Sandstones were classified as litharenites based on Folk's classification (Folk 1968) and three types of porosity were identified (intergranular porosity, secondary porosity and microporosity) (Grasby et al. 2007). Most sandstone was found to be massive and grain-supported, with several pore-filling phases including authigenic clays (chlorite, kaolinite), calcite cement and pyrite (Grasby et al. 2007).

In 2008, the Alberta Geological Survey conducted 172 air-permeameter tests on ten drill cores from the Edmonton-Calgary Corridor as part of a larger groundwater mapping project for the region (Riddell et al. 2009) (Fig. 1). Measurements were focused primarily on sandstones, and a mean hydraulic conductivity of 5.3×10^{-6} m/s was obtained for samples of the Paskapoo Fm. (Fig. 3). Low-permeability lithologies such as siltstone and mudstone were found to have little variability in hydraulic conductivity (from 1.0×10^{-9} to 9.5×10^{-9} m/s) whereas sandstone intervals showed a range of conductivities spanning several orders of magnitude (from 4.5×10^{-9} to 4.9×10^{-5} m/s). Such large variation in sandstone conductivity was attributed to grain size distribution and degree of cementation (Riddell et al. 2009).

Burns et al. (2010) investigated the effect of paleo-fluvial architecture on the hydrogeological properties of the Paskapoo Fm. in the Calgary region. Two drill cores were subject to air-permeameter measurements, resulting in a bimodal distribution of both permeability and hydraulic conductivity values. High and low values were interpreted as reflecting either channel sands or overbank flood deposits, respectively. Burns et al. (2010) found that channel sands were up to three orders of magnitude more permeable than overbank

deposits, with a mean hydraulic conductivity of 1.0×10^{-3} m/s for channel sands and a mean of 1.0×10^{-6} m/s for overbank deposits.

In a 2014 report prepared for the Petroleum Technology Alliance of Canada (PTAC), Petrel Robertson Consulting Ltd. (PRCL 2014) conducted an assessment of water resources for unconventional petroleum plays in west-central Alberta. The assessment includes a summary of permeability and porosity data and pore-throat analysis for nine cores from within the Paskapoo Fm. (Fig. 1), two of which were also subjected to thin section petrology. The mean permeability and porosity values were determined to be 3.4×10^{-13} m² (corresponding to an average hydraulic conductivity of 3.8×10^{-6} m/s; Fig. 3) and 23.2%, respectively. Thin section analysis found the majority of samples to be poorly sorted litharenites with significant proportions of both sedimentary and volcanic rock fragments. Pore-filling processes observed include authigenic clays derived from the dissolution of feldspars and/or volcanic fragments; patchy calcite cement was observed to a much lesser extent and only in one borehole.

In an accompanying investigation to the present study, Hughes et al. (2017) conducted pumping test analyses from publically available records for 50 water wells in the northernmost portion of the Paskapoo Fm. The resultant mean hydraulic conductivity of 2.4×10^{-4} m/s was interpreted as being representative predominantly of sandstone from only the uppermost 80 m and potentially biased towards higher producing units suitable for water supply wells.

Methods

Study Area

The region of interest is the northern portion of the Paskapoo Fm., located approximately 260 km northwest of Edmonton (Fig. 1). The study area is in the vicinity of shale-gas

development from the Duvernay Fm., southwest of the Town of Fox Creek, Alberta (Fig. 2). Surficial Neogene-Quaternary deposits of diamict, glacial lake sediments and gravel are present throughout the study area with thickness varying from 0 to 50 m (MacCormack et al. 2015). The area is forested and outcrops of Paskapoo Fm. are scarce except along major rivers and road cuts, making subsurface data invaluable when characterizing properties at a regional scale. The Paskapoo Fm. ranges in thickness from zero to more than 400 m in the study area.

Air-permeameter testing

Seven drill cores were tested using an air-permeameter (Temco MP-401) at the Mineral Core Research Facility in Edmonton (Hughes et al. 2017). The drill cores were collected in 1997 for mineralogical exploration by Kennecott Canada Exploration Inc. and are 47.6 mm diameter (NQ size). Since their collection 20 years ago, the drill cores have been stored in unsealed cardboard core boxes and thus were sufficiently dry for air-permeameter testing at the time of this study. Each core was subject to between 12 and 38 spot measurements using a three-millimeter diameter probe placed perpendicular to the core axis to obtain horizontal permeability (Hurst and Goggin 1995). Sampling intervals and locations were chosen such that a range of depths and lithologies were represented; intervals that were found to be poorly consolidated, or displayed extensive fracturing, were excluded. A total of 161 permeability measurements were made (in mD) at relatively regular depth intervals along each core. Resultant permeability data were used to obtain hydraulic conductivities according to:

$$(1) \quad K = \frac{k\rho g}{\mu}$$

where, K = hydraulic conductivity of sample (m/s); k = permeability of sample (m^2); ρ = density of water (assumed to be 999.9 kg/m^3); g = gravitational constant (9.81 m/s^2); μ = dynamic

viscosity of water ($8.9 \times 10^{-4} \text{ kg/m}\cdot\text{s}$). All measurements are available in Table S1 and as part of the summary digital tabular data by Smerdon et al. (2017).

Porosity analysis

A subset of three drill cores was chosen for porosity analysis (NC44-1, NC19-1, MT28-1; Fig. 2) based on observed variation in lithology (i.e. significant representation of sandstone, siltstone and mudstone) and corresponding variation in permeability. These drill cores intersect the Sunchild aquifer and Lacombe aquitard mapped by Lyster and Andriashek (2012). For each drill core, thin-section samples were collected from the same depths that had been tested using the air-permeameter. A total of 25 samples were selected for thin section preparation (10 samples from NC44-1, 8 samples from NC19-1 and 7 samples from MT28-1) and were impregnated with a blue epoxy resin resulting in infill of the pores. Each of the 25 thin sections was photographed through a petrographic microscope 25 times in a gridded pattern to ensure representative properties were captured. The photomicrographs were then analysed using the Adobe Photoshop Quantification (PSQ) method as described by Zhang et al. (2014) to determine the average porosity of each thin section photograph. Using the *Colour Range* tool in the *Select* menu of Adobe Photoshop, a range of blue pixels was selected such that all occurrences of visible blue epoxy resin were included. The percentage of blue pixels (i.e. porosity) was then calculated for each image using:

$$(2) \quad (\text{number of blue pixels} / \text{total number of pixels}) \cdot 100\% = \text{porosity}$$

Grove and Jerram (2011) compare the blue pixel method of estimating porosity to manual point counting and helium porosimetry measurements. They find that the computer calculated blue pixel areas are an excellent estimate of both the point counting and porosimetry measurements.

These authors further test the blue pixel method by having 10 operators estimate blue pixel areas, and all operators calculated similar porosities.

Thin Section analysis

Qualitative analysis of thin sections was conducted using a petrographic microscope to determine the general structure, texture, and composition of each thin section. Preference was given to properties that are deemed to affect fluid flow such as grain size, sorting, roundness, type/amount of interstitial material, and pore type. Pore types are based on the three categories of porosity identified by Grasby et al. (2007): intergranular pores (occur between framework grains where there is a lack of interstitial material), secondary pores (occur as a result of leaching of feldspars or other grains) and micropores (less than a few microns in size, typically associated with kaolinite cements). Framework grains were identified and relative abundances were recorded.

Results

Air-permeameter test results show a broad range in hydraulic conductivities for the study area, from 1.1×10^{-10} to 2.6×10^{-5} m/s, with a slight bimodal distribution about a mean of 4.2×10^{-7} m/s (Table 1; Fig. 3). A mean hydraulic conductivity of 7.6×10^{-7} m/s was obtained for sandstone intervals, whereas the mean for mudstone, siltstone and shale is 3.2×10^{-9} m/s (Table 1; Fig. 4a). Permeability values range from 9.9×10^{-18} m² to 2.4×10^{-12} m², with a mean permeability of 3.8×10^{-14} m² (Table 1). No visible trend is apparent between hydraulic conductivity and depth (Fig. 4b). When considering data from an individual core, measurements commonly show an observable transition from high to low conductivity that corresponds to the hydraulic properties of different units within the Paskapoo Fm. (Fig. 5).

Porosity values range from 0.02% to 15.3% with an average of 4.8% (Table 1). Summary porosity results for each drill core can be found in Table 2. Sandstone units display values that span virtually the entire range of results, from 0.08% to 15.3%, with an average of about 5.84% (Fig. 6a). No significant trend is observed between porosity and depth (Fig. 7a); however, a linear relationship exists between PSQ porosity and log of hydraulic conductivity values that were obtained using air permeametry (Fig. 7b).

Qualitative analysis of thin sections produced a wide range of observations (Table 2), most of which are consistent with previous investigations (Hamblin 2004; Grasby et al. 2008; Chen et al. 2007; Riddell et al. 2009; PRCL 2014). Thin-section samples generally show massive structure, though a few fine-grained samples display lamination defined by micas or organics. Both grain-supported and matrix-supported textures are observed and framework grains consist of quartz, feldspar and rock fragments (e.g. chert, detrital carbonate, and sedimentary, metamorphic and volcanic fragments). Sandstone is classified as litharenite based on Folk's classification (1968) and ranges from very fine- to very coarse-grained, very well to poorly sorted, and very well to poorly cemented; grains typically range from angular to sub-rounded. Interstitial material includes various types of carbonate cement (e.g. poikilotopic, blocky, drusy) and/or authigenic clay minerals (predominantly kaolinite) and is present to varied degree in all samples. Evidence of compaction is observed, but only in softer grains such as mica and shale clasts. Feldspathic grains commonly display sericite alteration and/or significant dissolution along crystal twinning planes resulting in secondary porosity. Microporosity is typically associated with the occurrence of interstitial authigenic kaolinite, although it also occurs as a result of dissolution of feldspar grains and/or volcanic fragments. Accessory minerals include

micas (muscovite, biotite), zircon, and glauconite. Sample micrographs for a coarse- and a fine-grained sandstone are shown in Figure 6*b* and 6*c*.

Discussion

The results from this study indicate that the petrologic composition of the Paskapoo Fm. located in west-central Alberta is heterogeneous, with hydraulic conductivity values that differ by several orders of magnitude, a wide range of porosity values and large variations in physical properties. These observations are consistent with previous studies of the Paskapoo Fm. from central and southern Alberta, although the focus of this study lies further north as well as stratigraphically higher in the formation.

Hydraulic properties

The previous work of Grasby et al. (2008), Riddell et al. (2009) and PRCL (2014) characterized the basal sandstone portion of the Paskapoo Fm. (i.e. Haynes aquifer). In comparison, this study spans the other hydrostratigraphic units identified in the Paskapoo Fm., sampling both the Sunchild aquifer and the Lacombe aquitard. Given that hydraulic conductivity was determined by the same air-permeametry technique, collectively these data represent each of the hydrostratigraphic units conceptualized for the Paskapoo Fm. When all measurements are combined (Fig. 8*a*), the mean hydraulic conductivity is found to be 1.8×10^{-4} m/s with a standard deviation of 6.8×10^{-4} m/s for the Haynes aquifer, and 9.8×10^{-7} m/s with a standard deviation of 3.6×10^{-6} m/s for the Sunchild aquifer (Fig. 8*b*). Although Hughes et al. (2017) reported a mean hydraulic conductivity of 2.4×10^{-4} m/s for the Sunchild aquifer (which is within one order of magnitude of mean estimates for the Haynes aquifer from the studies listed above), it is not conducive to compare pumping test and air-permeameter data due to differences in scale of

measurement. The air-permeameter analyzes a very small volume of rock (approximately 1cm^3) that is virtually homogeneous whereas data obtained from in situ testing will be representative of several m^3 of rock surrounding the tested interval, including fractures and other heterogeneities that might alter permeability. Typically, values obtained in situ (i.e. from pumping tests) are higher than those determined in laboratory settings (Ingebritsen et al. 2006) due to inclusion of larger-scale heterogeneity (e.g. fractures) and bias towards testing more permeable zones suitable for water supply. Thus, we would expect pumping test analysis of the Haynes aquifer to produce hydraulic conductivities at least an order of magnitude higher than those obtained by Hughes et al. (2017) for the Sunchild aquifer. As such, these findings may indicate that sandstones in the Haynes aquifer could be at least an order of magnitude more conductive than those in the Sunchild aquifer (Fig. 8b), if not more. The data also indicate that cm-scale hydraulic conductivity is centred on a single order of magnitude for mudstone, siltstone, and shale of the Lacombe aquitard (Fig. 4a).

A wide range of porosity values was also found in this study, particularly among sandstone samples. Figure 6a shows that sandstone samples classified as medium-to-coarse grained can have a similar porosity value as a fine-grained sandstone, especially where porosity is less than 10%. The majority of porosity and hydraulic conductivity values agree with the relationship identified in Figure 7b (R^2 of 0.84). There are two samples that have hydraulic conductivity values higher than expected based on the trend, which could be a result of the inability of the PSQ method to detect micro-pores in very fine-grained samples, or the inability of a 2D image to properly capture a fracture system that would be captured by air-permeameter measurements.

The mean sandstone porosity values obtained by Grasby et al. (2007) are much higher than those determined in this study (19.2% vs. 5.8%, respectively). The mean porosity (23.2%) obtained by PRCL (2014) was also higher, and while most measurements from the PRCL (2014) data set do not include specific lithologic descriptions we can assume that the majority are representative of sandstone. Although helium porosity measurements, such as those collected by Grasby et al. (2007), produce values slightly higher than those obtained using the PSQ method (Zhang et al. 2014), such a large difference in mean values cannot be attributed to measurement technique alone. Consequently, this study suggests that sandstone units in the upper Sunchild aquifer of the Paskapoo Fm. have significantly lower porosity and hydraulic conductivity than the sandstone units in the lower Haynes aquifer.

Geographic and lithologic variation

Any explanation regarding differences in hydraulic properties of major sandstone units of the Paskapoo Fm. (i.e. Sunchild and Haynes aquifers) must also recognize the stratigraphic difference observed across the geographic extent of the formation. The younger sandstone unit (i.e. Sunchild aquifer) is more prevalent in the northern portion of the formation, where the older sandstone unit (i.e. Haynes aquifer) is generally more prevalent in the southern portion (Fig. 1). Differences in the hydraulic conductivity – the fundamental property of fluid flow – are related to porosity, which in this case is hypothesized to be governed by cementation rather than grain size. Qualitative thin section analyses begin to provide some explanation for the disparity between hydraulic properties of the sandstone units of the Paskapoo Fm. (i.e. Sunchild and Haynes aquifers). As depicted in Figure 6, although samples might be similar in grain size, a wide range in porosity values can arise due to the amount of cementation and other pore-filling processes. The net effect is that a sandstone sample may have similar hydraulic properties to a

siltstone sample if interstitial pores are filled with authigenic clays rather than being held together with carbonate cement. No pattern was observed to suggest a relationship between type of interstitial material and porosity (Table 2). Similarly, no significant relationship exists between composition of framework grains and porosity.

The potential role of authigenic clay in controlling hydraulic properties may be partially explained by geographic and stratigraphic variation in volcanic fragment content. Mack and Jerzykiewicz (1989) suggest a higher percentage of volcanic fragments is present in the Paskapoo Fm. in the central Foothills area (100 km southeast of the area where drill cores were collected for the present study) compared to the southern Foothills area. The lower porosity values obtained in this study for the younger sandstone units may be a result of more volcanic fragments, which would be more susceptible to dissolution and alteration, and in turn create more authigenic clays that would reduce pore volume. Widespread distribution and deposition of volcanic fragments could have been aided by the sedimentary structure, which is hypothesized to either be a distributed fluvial system or more individual channel belt (Quartero et al. 2015), the end result being that the younger sandstone units have a high percentage of interstitial pores filled with authigenic clays, and relatively low porosity.

Conversely, Hamblin (2004) indicated that the southern part of the Paskapoo Fm. (and its equivalent Porcupine Hills Fm. in southern Alberta) has fewer volcanic fragments and more clastic carbonate grains. For the older sandstone units, authigenic carbonate cement could be derived from detrital carbonate. To more completely differentiate the hydraulic properties of each of these hydrostratigraphic units, and in-turn better understand the architecture of the Paskapoo Fm., a combination of high-resolution mapping with well data, helium porosimetry

measurements, and more quantitative examination of thin sections would establish the percentage of clast composition, and better define the pore-filling processes.

Implications for future studies

The findings of this study help expand the understanding of the Paskapoo Fm. as an important groundwater resource. Assessing the effects of increasing water demand in a region with high surface-groundwater interaction is often achieved using a groundwater model. Characterizing the hydraulic properties of key hydrostratigraphic units, both the highly conductive units often used as aquifers and the low conductivity confining units, is crucial to support model development and accurately quantify water fluxes. Hydraulic properties can be determined from various laboratory (e.g. air-permeametry) and in situ (e.g. pumping tests) experiments resulting in measurements that often represent a specific spatial scale (Rovey and Cherkauer 1995). As previously mentioned, values obtained in situ are higher than those determined in laboratory settings (Ingebritsen et al. 2006) due to inclusion of larger-scale heterogeneity (e.g. fractures) and bias towards testing more permeable zones suitable for water supply. Additionally, the pumping test analyses of existing water wells in the study area (Hughes et al. 2017) can be difficult to analyze with confidence due to variability in well construction and knowing the conditions under which the data were collected (i.e. quality of water well records). By contrast, values obtained from laboratory testing, albeit at a small spatial scale, establish a larger statistical population that represents a wide range of lithology and produce relatively reliable data about small scale heterogeneity, which can be useful when developing models to assess groundwater resources within the region. For the Paskapoo Fm., the same air-permeametry technique has been used in different regions by several researchers. As such, the results obtained from this study can be combined with previous research findings to facilitate

future groundwater assessments and potential modelling of the groundwater resources in this region.

Summary

The extreme range in hydraulic properties of the Paskapoo Fm. previously found in the southern part of the formation is also found in the north; however, different stratigraphic horizons within the formation are exposed in the two regions. This study found that the hydraulic conductivity of upper sandstone units in the Paskapoo Fm. may be at least an order of magnitude lower, and possibly more, than those described for lower/basal sandstone units described in previous studies. Porosity values determined for the upper sandstone units are also significantly lower than those determined for lower units, although overall composition of framework grains and pore-filling material were found to be relatively consistent with results from previous investigations. The wide range in both porosity and conductivity values found in both upper and lower sandstone units suggest that lithology alone is not a sufficient indicator of potential hydrogeological properties in the Paskapoo Fm. Instead, the degree of cementation and amounts of pore-filling phases such as authigenic clays are the dominant controlling factor.

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Tables

Table 1. Summary statistics from air-permeameter and digital Photoshop Quantification (PSQ) porosity analyses. All permeameter and porosity measurements are available in a supplementary table (Table S1) and as part of the digital tabular data by Smerdon et al. (2017).

Permeability; k (m^2)	Min	Max	Mean	Std. Deviation	n
All data	9.9×10^{-18}	2.4×10^{-12}	3.8×10^{-14}	2.1×10^{-13}	161
Sandstone	9.8×10^{-17}	2.4×10^{-12}	6.9×10^{-14}	2.8×10^{-13}	89
Mudstone, siltstone, shale	9.9×10^{-18}	4.5×10^{-15}	2.9×10^{-16}	5.6×10^{-16}	72
Hydraulic conductivity; K (m/s)	Min	Max	Mean	Std. Deviation	n
All data	1.1×10^{-10}	2.6×10^{-5}	4.2×10^{-7}	2.4×10^{-6}	161
Sandstone	1.1×10^{-9}	2.6×10^{-5}	7.6×10^{-7}	3.1×10^{-6}	89
Mudstone, siltstone, shale	1.1×10^{-10}	4.9×10^{-9}	3.2×10^{-9}	6.1×10^{-9}	72
Porosity; n (%)	Min	Max	Mean	Std. Deviation	n
All data	0.01	15.3	4.8	4.6	25

Table 2: Summary of qualitative thin section analyses.

Borehole	Depth (m)	Rock Type	Sorting	Porosity (%)	Pore Types	Cement
NC44-1	16.5	Sltst	Good	0.2	Ig	micro-crystalline Cal
NC44-1	31.1	m-c Sst	Mod	8.2	Ig, Sp	mod; Kln
NC44-1	39.6	c Sst	Mod	15.3	Ig, Sp	poor; Kln
NC44-1	52.1	m-c Sst	Mod	8.6	Ig, Sp	mod; Kln
NC44-1	59.9	c Sst	Poor	14.6	Ig, Mp	rare; Kln
NC44-1	76.9	Mdst	Good	1.8	Frac	good; Kln
NC44-1	87.6	m-c Sst	Mod	10.2	Ig, Sp	poor; Kln, minor Cal
NC44-1	104.7	f Sst	Good	5.3	Ig, Sp	very good; Kln
NC44-1	119.2	f-m Sst	Mod	7.3	Ig Sp	mod; Kln
NC44-1	131.9	c Sst	Poor	8.5	Ig, Sp	mod; Kln, minor Cal mod; Cal (poikilotopic, drusy), minor Kln good; Cal (poikilotopic, drusy), Kln
NC19-1	33.9	m Sst	Mod	6.4	Ig, some Sp	
NC19-1	61.2	m Sst	Mod	4.9	Ig, Sp, some Mp	
NC19-1	84.5	m Sst	Mod	0.9	Ig, Sp, some Mp	good; Cal (drusy, blocky), minor Kln
NC19-1	90.3	c Sst	Very poor	11.3	Ig, some Sp, Mp	rare; Kln
NC19-1	114.8	Sltst	Very good	1.0	Ig, Frac	good; Kln, Cal very good; Cal (drusy), rare Kln
NC19-1	131	f Sst	Good	0.3	Rare; Sp	
NC19-1	176.7	f Sst	Good	4.5	Ig, some Sp	good; Kln, rare Cal
NC19-1	184	Sltst	Very good	0.01	Rare; Frac	good; Kln; rare Cal
MT28-1	27.1	vf Sst	Good	0.5	Rare; Ig	good; Kln, rare Cal
MT28-1	42.7	Sltst	Very good	0.4	Frac	very good; Kln, minor Cal (drusy)
MT28-1	56.7	f Sst	Good	2.6	Ig	very good; Cal (drusy), minor Kln
MT28-1	72.7	vf Sst	Very good	0.1	None	very good; Kln, Cal (drusy)
MT28-1	85.7	f-m Sst	Good	1.9	Ig, some Sp	good; Cal (poikilotopic), Kln
MT28-1	97.3	vf Sst	Very good	1.0	Ig; rare Sp, some Mp	
MT28-1	112.2	f-m Sst	Mod	4.4	Ig, Sp	good; Kln
						good; Kln, minor Cal

Note: Sltst = siltstone, Sst = sandstone, Mdst = mudstone; vf = very fine, f = fine, m = medium, c = coarse, vc = very coarse; Ig = intergranular, Sp = secondary porosity, Mp = Microporosity; Cal = calcite, Kln = kaolinite

Figure Captions

Figure 1. Extent of the Paskapoo Fm. shown with the Sunchild and Haynes aquifers as proposed by Lyster and Andriashek (2012). Locations of air permeameter measurements from this and previous studies with symbols colour-coded to match Figure 3. The location of the Paskapoo Fm. within the Province of Alberta shown on the inset.

Figure 2. Location of cores examined in this study in proximity to the Sunchild Aquifer.

Figure 3. Summary of hydraulic conductivity values for the Paskapoo Fm. Colour coded to match the location symbols in Figure 1.

Figure 4. Summary of hydraulic conductivity values obtained from air-permeameter testing. *a)* Distribution of hydraulic conductivity values for lithological groups. *b)* Distribution of hydraulic conductivity values compared with sample depth.

Figure 5. Portion of strip log for drillcore NC05-1 (location shown on Figure 2) with hydraulic conductivity measurements.

Figure 6. *a)* Porosity measurements for sandstone categorized by grain size with bar shading to match data points in Figure 7. Photomicrographs *b)* and *c)* correspond to two medium-grained samples with low and high porosity measurements (indicated by B and C on *a)*), respectively, and emphasize the variation in cementation among samples.

Figure 7. *a)* Adobe Photoshop Quantification (PSQ) porosity measurements with depth. *b)* Hydraulic conductivity data obtained using air-permeametry plotted against PSQ porosity data.

Figure 8. (a) Summary of hydraulic conductivity values for sandstone samples tested by Grasby et al. (2007), Riddell et al. (2009), PRCL (2014) and this study. Results have been grouped into upper and lower sandstone portions of the Paskapoo Fm., which would correspond to the Sunchild and Haynes aquifers proposed by Lyster and Andriashek (2012). (b) Summary statistics for the major hydrostratigraphic units of the Paskapoo Fm. from all available measurements.

Draft

Figure 1. Extent of the Paskapoo Fm. shown with the Sunchild and Haynes aquifers as proposed by Lyster and Andriashek (2012). Locations of air permeameter measurements from this and previous studies with symbols colour-coded to match Figure 3. The location of the Paskapoo Fm. within the Province of Alberta shown on the inset.

279x361mm (300 x 300 DPI)

Figure 2. Location of cores examined in this study in proximity to the Sunchild Aquifer.

139x103mm (300 x 300 DPI)

Figure 3. Summary of hydraulic conductivity values for the Paskapoo Fm. Colour coded to match the location symbols in Figure 1.

80x43mm (300 x 300 DPI)

Figure 4. Summary of hydraulic conductivity values obtained from air-permeameter testing. a) Distribution of hydraulic conductivity values for lithological groups. b) Distribution of hydraulic conductivity values compared with sample depth.

151x273mm (300 x 300 DPI)

Figure 5. Portion of strip log for drillcore NC05-1 (location shown on Figure 2) with hydraulic conductivity measurements.

192x568mm (300 x 300 DPI)

Figure 6. a) Porosity measurements for sandstone categorized by grain size with bar shading to match data points in Figure 7. Photomicrographs b) and c) correspond to two medium-grained samples with low and high porosity measurements (indicated by B and C on a)), respectively, and emphasize the variation in cementation among samples.

168x382mm (300 x 300 DPI)

Figure 7. a) Adobe Photoshop Quantification (PSQ) porosity measurements with depth. b) Hydraulic conductivity data obtained using air-permeametry plotted against PSQ porosity data.

143x258mm (300 x 300 DPI)

Figure 8. (a) Summary of hydraulic conductivity values for sandstone samples tested by Grasby et al. (2007), Riddell et al. (2009), PRCL (2014) and this study. Results have been grouped into upper and lower sandstone portions of the Paskapoo Fm., which would correspond to the Sunchild and Haynes aquifers proposed by Lyster and Andriashek (2012). (b) Summary statistics for the major hydrostratigraphic units of the Paskapoo Fm. from all available measurements.

127x207mm (300 x 300 DPI)

NC05-1	NC05-1	NC05-1	NC19-1	NC19-1	NC19-1	NC19-1	NC20-1	NC20-1	NC20-1
Depth (m)	Permeability	Hydraulic Conductivity	Depth (m)	Permeability	Hydraulic Conductivity	Porosity (-)	Depth (m)	Permeability	Hydraulic Conductivity
31.7	9.7E-15	1.1E-07	25.3	5.5E-16	6.0E-09	-	10.9	1.4E-16	1.6E-09
37.1	1.7E-15	1.8E-08	33.9	1.7E-14	1.8E-07	0.064	16.3	1.5E-16	1.6E-09
42.4	3.4E-16	3.8E-09	45.0	1.5E-14	1.7E-07	-	21.0	8.7E-16	9.6E-09
49.4	2.9E-15	3.2E-08	53.8	1.5E-16	1.7E-09	-	24.6	1.7E-15	1.9E-08
53.7	3.8E-16	4.2E-09	61.2	3.7E-15	4.1E-08	0.049	29.5	8.0E-16	8.8E-09
61.0	7.5E-16	8.3E-09	71.6	5.3E-16	5.8E-09	-	32.2	1.7E-16	1.9E-09
67.6	4.2E-16	4.7E-09	84.5	2.4E-16	2.7E-09	0.009	41.0	7.4E-14	8.1E-07
72.9	2.0E-14	2.3E-07	90.3	2.4E-12	2.6E-05	0.113	47.5	2.5E-14	2.8E-07
80.2	4.8E-14	5.3E-07	99.5	6.6E-15	7.3E-08	-	53.1	2.2E-16	2.4E-09
87.6	5.0E-15	5.5E-08	105.7	2.8E-15	3.1E-08	-	61.8	1.2E-15	1.3E-08
97.4	1.3E-16	1.4E-09	114.8	2.8E-16	3.1E-09	-	69.1	1.6E-16	1.8E-09
101.5	1.3E-14	1.4E-07	123.0	6.3E-15	7.0E-08	-	77.8	1.9E-16	2.0E-09
105.5	1.2E-14	1.4E-07	131.0	9.8E-17	1.1E-09	0.003	81.8	2.3E-16	2.6E-09
110.9	8.6E-15	9.5E-08	146.1	5.1E-16	5.6E-09	-	87.1	2.4E-16	2.7E-09
115.0	1.9E-14	2.0E-07	154.0	1.1E-16	1.2E-09	-	100.9	1.8E-16	1.9E-09
119.4	2.0E-16	2.2E-09	163.9	2.2E-16	2.4E-09	-	105.9	4.0E-16	4.5E-09
122.4	3.5E-15	3.8E-08	176.7	9.3E-15	1.0E-07	0.045	112.0	1.7E-16	1.8E-09
128.6	1.0E-13	1.1E-06	184.0	7.8E-17	8.6E-10	-	119.5	1.9E-16	2.0E-09
136.1	4.0E-14	4.4E-07					126.3	1.1E-16	1.2E-09
143.5	2.2E-16	2.4E-09					132.6	1.5E-16	1.6E-09
149.0	5.2E-16	5.8E-09					139.0	2.0E-16	2.3E-09
150.5	1.5E-16	1.7E-09					142.9	1.3E-16	1.4E-09
156.2	2.4E-16	2.6E-09					150.0	1.0E-16	1.1E-09
157.4	1.3E-16	1.4E-09					157.3	1.5E-16	1.6E-09
160.8	2.5E-16	2.8E-09					164.0	1.2E-16	1.3E-09
163.9	1.1E-16	1.3E-09					167.8	1.2E-16	1.3E-09
168.0	1.1E-16	1.3E-09					173.7	2.8E-16	3.1E-09
172.9	1.2E-16	1.3E-09					177.3	1.2E-16	1.4E-09
175.5	1.9E-16	2.1E-09					181.8	1.3E-16	1.4E-09
180.5	2.4E-16	2.6E-09							
188.0	1.9E-16	2.1E-09							
192.1	1.3E-16	1.4E-09							
195.5	2.3E-16	2.6E-09							
199.2	2.4E-16	2.7E-09							
203.2	4.1E-16	4.5E-09							
209.5	1.9E-14	2.1E-07							
215.7	1.5E-14	1.7E-07							
220.6	9.8E-15	1.1E-07							

NC44-1	NC44-1	NC44-1	NC44-1	NC45-1	NC45-1	NC45-1	MT19-1	MT19-1	MT19-1
Depth (m)	Permeability	Hydraulic Conductivity	Porosity (%)	Depth (m)	Permeability	Hydraulic Conductivity	Depth (m)	Permeability	Hydraulic Conductivity
16.5	1.4E-16	1.6E-09	-	16.9	6.2E-15	6.8E-08	19.2	8.2E-16	9.0E-09
23.3	1.5E-16	1.6E-09	-	28.9	9.3E-14	1.0E-06	22.3	2.7E-16	3.0E-09
26.4	7.2E-14	8.0E-07	-	40.2	1.1E-15	1.3E-08	26.6	1.2E-14	1.3E-07
31.1	7.2E-14	7.9E-07	0.082	52.1	4.3E-16	4.7E-09	30.1	1.8E-14	1.9E-07
33.7	4.1E-13	4.5E-06	-	63.7	3.0E-14	3.3E-07	34.8	1.2E-16	1.3E-09
39.6	2.6E-13	2.9E-06	0.153	74.6	1.0E-13	1.1E-06	38.9	1.5E-16	1.6E-09
45.3	1.0E-15	1.1E-08	-	86.6	3.6E-14	4.0E-07	44.8	9.9E-18	1.1E-10
52.1	4.4E-14	4.9E-07	0.086	97.2	7.5E-13	8.2E-06	51.2	2.0E-17	2.2E-10
57.2	6.9E-14	7.6E-07	-	109.2	5.3E-16	5.8E-09	55.8	8.9E-17	9.8E-10
59.9	9.9E-13	1.1E-05	0.146	118.4	5.8E-14	6.4E-07	58.9	1.6E-16	1.8E-09
63.2	3.9E-16	4.3E-09	-	128.3	9.2E-17	1.0E-09	63.8	2.9E-16	3.2E-09
68.1	1.3E-15	1.5E-08	-	138.7	1.1E-15	1.2E-08	66.4	1.5E-16	1.7E-09
72.2	1.4E-16	1.5E-09	-				74.3	2.1E-16	2.4E-09
76.9	4.7E-16	5.1E-09	-				79.4	1.1E-16	1.2E-09
79.1	2.3E-16	2.6E-09	-				83.0	9.4E-17	1.0E-09
82.3	1.5E-16	1.7E-09	-				96.6	1.0E-16	1.1E-09
87.6	2.5E-14	2.8E-07	0.102				102.3	1.2E-16	1.3E-09
96.5	8.9E-14	9.8E-07	-				110.1	1.0E-16	1.1E-09
100.9	1.1E-14	1.2E-07	-				119.0	1.2E-16	1.3E-09
104.7	9.4E-15	1.0E-07	0.053				125.6	1.6E-16	1.8E-09
111.8	2.8E-14	3.0E-07	-				130.7	1.3E-16	1.5E-09
							135.7	4.5E-15	4.9E-08
							143.8	1.0E-16	1.1E-09
							145.8	4.1E-16	4.6E-09
							150.8	1.4E-16	1.6E-09
							155.1	3.2E-16	3.6E-09
							159.0	1.9E-16	2.1E-09
							163.2	1.4E-14	1.5E-07
							166.0	8.1E-17	9.0E-10

MT28-1	MT28-1	MT28-1	MT28-1
Depth (m)	Permeabili	Hydraulic (	Porosity (-)
21.2	1.6E-16	1.8E-09	-
27.1	6.1E-15	6.7E-08	0.005
37.6	1.3E-16	1.4E-09	-
42.7	5.0E-16	5.5E-09	-
48.2	1.1E-15	1.2E-08	-
56.7	1.7E-16	1.8E-09	0.026
72.7	1.1E-16	1.2E-09	0.001
83.1	3.4E-15	3.7E-08	-
85.7	2.9E-16	3.2E-09	0.019
88.5	1.0E-16	1.1E-09	-
92.7	4.2E-16	4.6E-09	-
97.3	4.0E-16	4.4E-09	0.010
110.8	1.1E-15	1.2E-08	-
112.2	7.0E-15	7.7E-08	0.044

Draft