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Paskapoo Groundwater Study, Part II: Sandstone thickness and porosity estimations using well log data for the aquifer system in the Tertiary Paskapoo Formation, Alberta

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2007

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Available from
Geological Survey of Canada (Calgary)
3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

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2007: Paskapoo Groundwater Study, Part II: Sandstone thickness and porosity estimations using well log data for the aquifer system in the Tertiary Paskapoo Formation, Alberta, Geological Survey of Canada, Open File 5445, 14 p.

Open files are products that have not gone through the GSC formal publication process.

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Abstract

Although the Tertiary Paskapoo aquifer system is the most important groundwater supply in Alberta and has been under increasing development pressure since 1970's, little public information is available with respect to the regional aquifer characteristics and the sustainable groundwater yield of the system. To study the groundwater storage capacity and its spatial variation, digital borehole geophysical logs, such as the gamma-ray (GR) and sonic (DT) logs, collected by the oil industry for the identification and characterization of petroleum reservoirs, were used to estimate sand content and aquifer porosity of the system in this study. A total of 220 oil industry wells, covering a large portion of the system mostly in south Alberta, were selected. This open file report provides a regional overview of the study and presents some of the aquifer parameters within the Paskapoo aquifer system.

Introduction

The Paskapoo Formation of southern Alberta is an extensive Tertiary fluvial/alluvial complex covering over 10,000 km^2 (Fig. 1). Approximately 107,000 water wells (roughly one third of wells in Alberta) are located within the Paskapoo outcrop belt and an estimated 96% of these penetrate bedrock. This makes the Paskapoo aquifer system the most important groundwater supply in the Canadian Prairies. Increased agricultural use, due to severe drought in the past a few years, and rapid suburban development of agricultural lands, have resulted in a sharp increase in the number of new water wells completed in the Paskapoo Formation (Fig. 2). Although groundwater in the aquifer system of the Paskapoo Formation is under increasing development pressure, there is little information with respect to the sustainable groundwater yield and regional distribution of groundwater supply within the aquifer system.

A sustainable groundwater development plan for the Paskapoo Formation requires a better understanding of spatial characteristics of water availability. This in turn requires knowledge of the stratigraphic architecture of the aquifer system. Typically this information is difficult to obtain without extensive drilling programs to provide core samples for a quantitative study. Given the large areal extent of the Paskapoo, there are surprisingly few public domain cores available to conduct such an assessment. Only seven continuous cores and about 10 partial cores are available for this type of study.

An alternative to examining physical cores is the quantitative interpretation of geophysical well log data collected by petroleum industry drilling. In the past 100 years, the search for and production of oil and gas has resulted in more than 450,000 wells in the Western Canada Sedimentary Basin. The petroleum industry routinely uses gamma-ray (GR) and sonic logs to estimate sand content and evaluate the petroleum reservoir. In addition, resistivity logs allow the distinguishing of water from gas/oil in porous sedimentary rocks. Petroleum reservoirs and groundwater aquifers are essentially identical: both are porous media, providing storage capacity and allowing a specific type of fluid to flow in the media. Thus these petroleum industry logs can be used to assess sand volume, calculate porosity and evaluate water content in an aquifer system, providing crucial information for assessing groundwater storage capacity and its spatial variation in an area of interest. While such logs are seldom run as part of water drilling programs, there are abundant logs available from oil and gas wells, which drill through the Paksapoo to deeper targets in Alberta.

The objective of this project is to evaluate our ability to employ available data from petroleum industry well logs as the first step toward an assessment of groundwater availability in southern Alberta, with specific focus on the spatial characteristics of the thickness and porosity of the Paskapoo Formation aquifer system. For this study we have selected and obtained digital data for 208 oil and gas wells on a grid spacing between Calgary and Red Deer (Fig. 3, Table 1). The logs from individual wells were used to estimate total sandstone thickness and average porosity. The resulting data allowed mapping of the spatial variability of these parameters within the Paskapoo Formation in the Calgary to Red Deer corridor. This open file report provides a review of work completed and the first regional overview of some of the aquifer parameters within the Paskapoo Formation.

Paskapoo Formation

The Paskapoo Formation represents an eastward-thinning wedge of nonmarine sediment deposited in the Western Canada Sedimentary Basin. In the Plains, the strata are near-horizontal, dipping westward at $<1^{\circ}$ as a homoclinal wedge into the core of the Alberta Syncline. Relatively few outcrops, cores or geophysical logs are available for study, and those that do exist are widely scattered stratigraphically and geographically.

The Paskapoo Formation is often given the misnomer ‘sandstone’. In reality the formation is a mudstone dominated unit with a series of sand-filled channels which can form isolated aquifer units. The characteristic channel sandstone beds range up to 15 m, but are typically 5-10 m thick. Sand-filled channels are lenticular and can pinch out laterally over short distances (100-150 m or more). The small amount of measured paleocurrent data suggests a general northeastward trend (e.g. Jerzykiewicz and Labonte, 1991), which might suggest that aquifer units within the Paskapoo have greater continuity, on average, along that orientation.

The fluvial sandstones of the Paskapoo are interbedded with light grey to greenish or brownish, sandy siltstone and mudstone (Williams and Dyer, 1930; Allan and Sanderson, 1945). These fine grained facies form intervals several to several tens of metres thick between the major sandstone horizons (Jerzykiewicz, 1997) and likely act as effective aquitards, except where connected through fracture systems.

Data Source

Data available for this study include about 600 log curves from 208 oil industry exploratory wells and data from five cored stratigraphic test wells (Fig. 3). In order to ease data handling and analyses three well logs: gamma ray (GR), sonic (DT) and induction resistivity log (ILD) were digitized for each of the 208 industry wells. For wells where no sonic log was acquired, a density log was used instead. Table 1 provides details of the wells used in this study.

Core data and paper copies of logs from five cored wells are also available. Porosity measurements were made from the cores for sandstone intervals. Fifty-six thin sections were prepared from the cores. Table 2 provides information on the cored wells.

The use of oil industry well data for groundwater aquifer studies has the advantage of allowing aquifer property estimation directly, using digital geophysical logs and the extensive areal coverage in the Western Canada Sedimentary Basin (WCSB). However, because the target intervals in oil and gas exploration are typically deeper than groundwater aquifers, it is common that the shallowest 200 – 500 meters do not have any well log data. Still, given the overall dip of the Paskapoo Formation we are able to use petroleum well data to characterize deeper portions of the Paskapoo, which form aquifer units in shallower exposures further east.

Methods

Core Porosity measurements

Porosity was measured on 57 sandstone samples selected from Paskapoo cores. Samples were trimmed to reduce dead volume in the matrix cup then dried in a gravity oven. Once dry, samples were analysed for porosity by Boyle's Law technique using helium as the gaseous medium. The porosity measurements are listed in Table 2.

Shale volume and aquifer thickness determination

Because shale is more radioactive than sandstone or carbonates, GR logs can be used to estimate the volume of shale content in porous sedimentary rocks. In this study, we use gamma ray index (I_{GR}) to approximate the shale volume (V_{sh}) (Rowan, et al., 2003). The formula for I_{GR} is written as (Asquith and Gibson, 1982):

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} GR_{\min}} \qquad (1)$$

where Gr_{log} is the gamma ray log readings, GR_{min}: minimum gamma-ray (from clean sandstone) and GR_{max}: maximum gamma ray reading (from pure shale interval).

Once Vsh is estimated, sandstone can be defined by the amount of shale content, say <50%, and sandstone thickness is the sum of all individual sandstone intervals in the Paskapoo Formation or within a given sedimentary rock succession.

Porosity calculations

Sonic and gamma ray logs were used for the estimation of aquifer porosity throughout the study region. Rajga-Clemencean et al. (1988) proposed a method of acoustic formation factor for more accurate porosity estimation from sonic transmit time data. The formula for the sonic porosity ϕ estimation can be written as:

$$\Phi = 1 - (\frac{T_{ma}}{T})^{1/x} \qquad (2)$$

where T_{ma} is the matrix sonic transmit time, T is the sonic log readings, and x is an exponent specific to the matrix lithology.

To estimate T_{ma}, the following equation is used:

$$T_{ma} = V_{sh} * T_{sh} + (1 - V_{sh}) T_{ss} \qquad (3)$$

where T_{sh} is the sonic transmit time for shale matrix and T_{ss} is the transmit time for sand matrix.

For wells where no sonic log is available, a density log is used to estimate the aquifer porosity (ϕ_{den}). The estimation formula has the following form:

$$\Phi_{den} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad (4)$$

where ρ_b is the density log readings, ρ_{ma} represents matrix density, and ρ_f is the density of pore fluid of the aquifer.

No comparison was made between sonic log derived porosity and the density log derived porosity in this stage of the study.

Results

Well log interpretation of the base of Paskapoo Formation

The criteria used to define the basal boundary of the Paskapoo Formation is still controversial. In this study, the basal boundary follows the definition used by Jerzykiewicz (1997) and Hamblin's (2004) synthesis of the Paskapoo Formation. The base of the Paskapoo Formation in the northern part of the study region is placed at the base of the first prominent sandstone unit above a major coal seam of the Coalspur Coal Zone (Jerzykiewicz, 1997). In southern Alberta (township 30 and south), the Paskapoo Formation equivalents (i.e., Porcupine Hills and Ravenscrag formations) consist of mudstone interbedded with sandstone layers. The southern formations are shalier and thinner and lack coal seams. It is difficult to determine the base and to correlate the base with other wells using log curves.

The Paskapoo-Porcupine Hills formations are divided into informal lower and upper members (Jerzykiewicz, 1997). The lower member is characterized by thick, medium to coarse grained sandstone beds sharply overlying the fine grained upper Scollard Formation. The upper member is characterized by interbeded siltstone, mudstone, minor fine grained sandstone, and thin coal seams that are limited to northern and central Alberta Plains (Jerzykiewicz, 1997). In this study, an effort was made to separate these two members. However, only the lower sandy interval was examined due to data limitation and time constraints.

The base of Paskapoo Formation was interpreted from well logs based on the GR and resistivity responses of the first prominent sandstone unit above the major coal seam of the Coalspur Coal Zone. To produce a consistent result, several cross-sections were constructed to form a framework of the basal boundary correlation, and other wells were then tied to one of the closest cross-sections. The interpreted depths of the base Paskapoo Formation are listed in Table 1.

Figure 4 and 5 show two cross-sections, one NE-SW and the other NW-SE, respectively, showing the well log responses and interpreted basal boundary for the

Paskapoo Formation (see Fig. 3 for locations of the cross section). Figure 6 contours the depth to the basal boundary of the Paskapoo Formation from KB (representing an approximate thickness of the Paskapoo Formation because of the KB height and the thickness of the surface Quaternary material). In general the Paskapoo is a westward thickening sedimentary wedge with a maximum thickness of about 1100 meters.

Assuming an effective aquifer is sandstone with Vsh <50%, the net aquifer thickness is the sum of all individual sandstone intervals in the formation which meets this criterion. Figure 7 is a map showing the spatial variation in estimated net sandstone thickness (Vsh < 50%) within the Paskapoo Formation. Figure 8 shows the net-sand/formation thickness ratio.

Well log derived porosity was calculated either from sonic logs or density logs for all depth intervals in wells where data are available. An average value was calculated for all the sandstone porosities. Figure 9 shows the average porosity of the sandstone intervals in the Paskapoo Formation. It should be made clear though that most geophysical logs lack data from surface to a few tens or to a few hundreds of metres. This means that if lithology is significantly different in this depth range, the maps derived from available log data may not represent the real spatial variation of the shallow aquifer properties in the Paskapooo Formation, where most water wells will be located.

To avoid the above mentioned data availability problem and to reveal the spatial characteristics of the aquifer properties, an attempt has been made to map the aquifer system in the Paskapoo lower member. Figures 10 to 12 are histograms, cumulative probability distribution curves and contour maps of the sandstone thickness and average sandstone porosity in the lower member of the Paskapoo Formation.

It is more practical to consider the sandstones in the near surface portion of the formation as the potential groundwater supply. In this approach, the net sandstone thickness and average sandstone porosity of the sedimentary rocks in the uppermost 800 meter interval were estimated. The spatial variations of the sandstone thickness and average porosity are displayed in various maps (Fig. 13b and 14b). Histograms and cumulative probability distribution curves for the same variables are plotted in Figs.13a, and 14a.

Core sample porosity study

Fig. 15 is a depth and porosity relationship plot for the porosity measurements from core samples. There is a general trend of reduced porosity with increasing depth. However, porosity at the same depth shows a great range of variation perhaps due to differences in lithology and diagenesis. Figure 16 is a histogram of the core sample porosity for all five cored water wells. The average core porosity is 19.2% with a standard deviation of 7.3%.

Thin Section petrography study

Thin section petrography was conducted on fifty-six (56) Paskapoo samples from five (5) wells; Airdrie, Lacombe, Wizard Lake, Balzac and Haynes, to determine their mineralogical, textural, diagenetic and reservoir characteristics. Work was focused on pore systems and processes affecting the porosity evolution.

The 56 Paskapoo samples include 53 sandstones and 3 siltstones/mudstones. Most Paskapoo sandstones are massive, with occasional shale/siltstone laminate and burrows. Grain size ranges from very fine to coarse (with most between very fine and fine). Most samples demonstrate fining upward vertical trends. Framework grains are well to poorly sorted, and fabric is grain-supported. Sandstones are classified as litharenites. Major framework grains include quartz, chert and rock fragments (volcanic, metamorphic and sedimentary rock fragments). Alteration and dissolution of rock fragments and feldspar commonly generate abundant microporosity and secondary porosity.

The most common diagenetic phases include authigenic chlorite, kaolinite, calcite and pyrite. Chlorite and kaolinite occur as grain coatings, pore lining and pore filling phases, significantly reducing the permeability of these sandstones. Calcite cement occludes intergranular pore spaces. Mechanical compaction is reflected by grain contact patterns (varying from point-contact, concave-convex-contact, deformation of ductile grains and pseudo matrix).

Intergranular porosity is the major pore type in the Paskapoo sandstones. The other types of porosity include secondary porosity (as a result of feldspar dissolution) and microporosity (associated with authigenic kaolinite, leached chert and clay matrix). Evolution of the pore system appears to be controlled by the following factors: mechanical alteration/dissolution of rock fragments, compaction, authigenic chlorite, kaolinite and calcite. Details of the petrographic study can be found in Grasby et al. (2006).

Summary

1) The Paskapoo Formation represents an eastward-thinning sedimentary wedge that includes alluvial and fluvial floodplain deposits with a maximum thickness of about 1100 meters.
2) Two sandy units separated by a shaly interval exist in the Paskapoo Formation (the informal lower and upper members), representing two potential aquifer systems. In general, the upper sandy unit could be eroded in the eastern part of the region and along the foothills; whereas the lower sandy unit may be too deep as potential aquifer in the west along the foothills region. The potential regional aquifer in the east could be dominated by the lower Paskapoo sandy unit, and in the west, it could be dominated by the upper Paskapoo sandy unit. In the area between, we may find both sandy units.
3) The stratigraphic correlation based on physical responses of the GR and resistivity logs, shows that the interpreted sand body may have a better spatial continuity in a NW-SE direction. The sand thicknesses in the formation may vary significantly in a short distance, particularly along the NE-SW direction.
4) Based on thin section study, the grain size of the sandstones ranges from very fine to coarse (with most sizes between very fine and fine). Intergranular porosity is the major pore type in the Paskapoo sandstones. Other types of porosity include secondary porosity and microporosity.

5) Chlorite and kaolinite occur as grain coatings, pore lining and pore filling phases, therefore significantly reducing permeability of these sandstones.
6) The interpreted Paskapoo Formation shows thick sands in the northwest part of the study region. However the formation net sand/gross thickness ratio does not display the same pattern.
7) The calculated average porosity from different sandstone intervals (Figures 9, 12, 14) exhibits a similar spatial pattern. The eastern part of the map area has the highest average log-derived porosity.
8) The sandy unit in the lower member of the formation shows a larger sandstone thickness in the northern part of the region, in the south, the same unit becomes more shaly and thinner.
9) The stratigraphic interpretation of the base of Paskapoo Formation is based on well log response, which reflects primarily lithological changes in the stratigraphic succession. The log correlation could be problematic in the south (township 30 and south) where no distinctive log responses exists to define the base of Paskapoo Formation. While we have tried to tie each well with others in cross-sections, it is difficult to always tie each well to all neighboring wells. Miscorrelation may occur where wells are not tied with others. This result is preliminary and may need more work to refine the basal boundary. The log correlations could be problematic in the south (township 30 and south) where there are no distinctive log responses to define the base Paskapoo Formation, as well as in the northwest where thrust faults have interrupted the continuity of the Paskapoo Formation.

Conclusions

1) For most of the available well logs from oil industry, there are no data for the shallowest depth interval ranging from a few tens to a few hundred meters. The estimated aquifer thickness and porosity could be biased and may not represent the near surface intervals of the aquifer. Data from groundwater wells may provide crucial information for estimating the aquifer properties for the shallow intervals. It is recommended that groundwater well data be collected and aquifer

property estimations be conducted for the shallow parts of the region. That being said, the data presented here does provide the most reasonable characterization of the range and variability of sand abundance and porosity which can be used for developing groundwater models.

2) Stratigraphic correlation of the basal boundary of the Paskapoo Formation using well log data needs calibration with results of biostratigraphic studies. Refinement of the boundary using more control points and ties with cross-sections are needed.
3) It appears that aquifers in the Paskapoo Formation are not continuous sand sheets with constant reservoir quality extending over large regions, but rather aquifer systems consisting of isolated fluvial channels and other types of sand bodies with limited spatial continuity. To define practical aquifer units and their spatial variation, more detailed work is needed.
4) Fractures appear to be an essential control for the connections among the "isolated sandstone aquifer units". A better understanding of the characteristics and occurrence of the fracture system is essential.
5) No calibration of the log-derived porosity with core sample porosity was made due to time and data constraints. It is necessary to calibrate the log-derived porosity with core porosity to improve the quality of sandstone porosity estimation.
6) In the south and northwest, where stratigraphic correlation using log data appears to be difficult, a refinement of the stratigraphic correlation is strongly recommended to ensure a correct correlation of the base boundary of the Paskapoo Formation.

Acknowledgements

Critical review by Dr. J. Dixon, Geological Survey of Canada (GSC), Calgary, improved the quality of this open file report. Mr. P. Wozniak, GSC, Calgary, provided help with some of the graphics in the report.

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