Geostatistical Determination of Sand-Body Geometry in the Paskapoo Formation

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Summary

The Paskapoo Formation (Fm.) in western Alberta is a major source of non-saline groundwater. The internal architecture of the Paskapoo Fm. is composed of successive beds of sandstone and mudstone, with sandstone contained as lateral and downstream accretionary elements and splay deposits of variable thickness within non-marine channel complexes. This work examines gamma-ray log data from the oil and gas industry to determine the vertical extents of the sand bodies for the purpose of geomodeling and groundwater modeling. The vertical variogram and higher-order statistics (runs) of the log data are used for the determination. Sand bodies up to 3 m thick with a typical thickness of 1-2 m are interpreted as splay sands and make up as much as 25% of the sand volume in the Paskapoo Fm. Thicker sand bodies up to a maximum of 20-25 m are interpreted as single-story channels. The thickest sand bodies, often 50 m thick or greater, are interpreted as multi-story channels.

Introduction

The Alberta Geological Survey (AGS) maps and quantitatively inventories the nonsaline and saline groundwater resources in Alberta. Though there is really only a single groundwater resource in Alberta with gradations of salinity, the AGS program structures its activities based on relative groundwater salinity to ensure a strong linkage between AGS outcomes to Alberta's policy and regulatory framework for groundwater. Understanding the architecture of the Paskapoo Formation (Fm.) helps achieve AGS goals.

The Paskapoo Fm. in western Alberta is a significant bedrock aquifer system. The Paskapoo Fm. covers approximately 10% of Alberta and forms a wedge from 0 m thick in the east to over 800 m thick along the edge of the Rocky Mountains (Dawson et al, 1994; Demchuk and Hills, 1991; Jerzykiewicz, 1997, Grasby et al, 2008). The Paskapoo Fm. consists of sandstone and mudstone beds in succession with sandstone being contained within thick channel-fill sequences and thinner splay deposits.

Previous studies have stated that within channels the thickness of sandstone beds exceeds 15 m with successions greater than 60 m (Dawson et al, 1994), or have individual stories 3-12 m thick with successions up to 50 m thick (Grasby et al, 2008). According to Grasby et al (2008) splay deposits are generally less than 3 m thick and typically no more than 1 m in thickness. The purpose of this paper is to quantify the thickness of the sand bodies in the Paskapoo Fm. to aid in modeling for a groundwater inventory program.

Method

Sandstone bodies in the Paskapoo Fm. were identified using gamma-ray logs from the oil and gas industry. Only data from non-cased intervals from wells drilled through the Paskapoo Fm. east of the deformed belt were used. If multiple gamma-ray logs were available for a given well, the log with the maximum number of recordings was used. This amounts to 2803 logs. All of the logs are vertical or near-vertical for the intervals in the Paskapoo Fm. Intervals with gamma values less than 75 API were interpreted as sand and those over 75 API as shale. Refer to Parks and Andriashek, 2009 for the justification of this cutoff.

The thicknesses of sand bodies in the Paskapoo Fm. were inferred from the data using the vertical variogram (Hong and Deutsch, 2009) and the distribution of sand thickness intersected by the logs, also called the distribution of *runs* (Boisvert, 2007, Boisvert et al, 2007). The vertical variogram is a second-order statistic calculated using the equation:

$$\gamma(h) = 0.5 \cdot E\{Z(u) - Z(u+h)\}$$

In this work, the variable Z is the sandiness of an interval in a log and the lag vector h is vertical. Ideally the variable would be an indicator with all values equal to either 0 or 1 (that is, shale or sand), but because of the large number of data and the different sampling intervals in the logs the sandiness was averaged over 1 m increments to calculate the variogram. Even with the discretization, over 70% of the data were either 0 or 1.

The distribution of runs for a string of numbers is a count of the length of consecutive occurrences of a given value. In this case, consecutive occurrences of gamma-ray values less than 75 API form a run of sand. The cumulative distribution of runs can be expressed as:

$$f_L = P(R \leq L)$$

where f_L is the frequency of runs less than or equal to length L and R is the length of a random run from the distribution. The distribution of runs can be used to assess the thickness of splays, individual channels, and multi-story channels. Each individual run is an apparent thickness, as the probability of intersecting the thickest part of a channel is relatively small.

The lateral extents of the sand bodies are much more difficult to determine from the data because of the relatively wide spacing. Width to thickness ratios have been determined for a number of cases (Gibling, 2006), but finding an exact analogue is difficult and imprecise. Horizontal variograms can be used to match a conceptual model of geology to real data but by varying the channel width, sinuosity, and structure (sinusoidal, meandering, etc.) it is possible to produce a number of conceptual geological models with the same variogram (Lyster, 2009). Outcrop mapping can produce runs in the horizontal direction but this data source is limited and prone to weathering bias towards massive sandstone units. Horizontal sand body dimensions are not considered in this work and will be investigated in the future.

Results

Figure 1 shows the vertical variogram of the 1 m sandiness data. The range of the variogram is about 25 m; this represents the maximum extents of the largest geobodies represented by the random variable. For this work, those bodies are the sandstone channels. The thin splay sand is represented by the nugget effect and steeper slope of the variogram near the origin; the vertical extents of the splays are so small relative to the channels (<3 m) that the structure is difficult to discern from the variogram

Figure 2 shows the distribution of runs for the Paskapoo Fm. data. The points represent the probability of a run being within a certain 1 m increment, while the line represents the cumulative probability of runs being less than a given thickness. Both distributions are weighted by thickness, i.e. a single 10 m sand body has the same weight as ten 1 m bodies.

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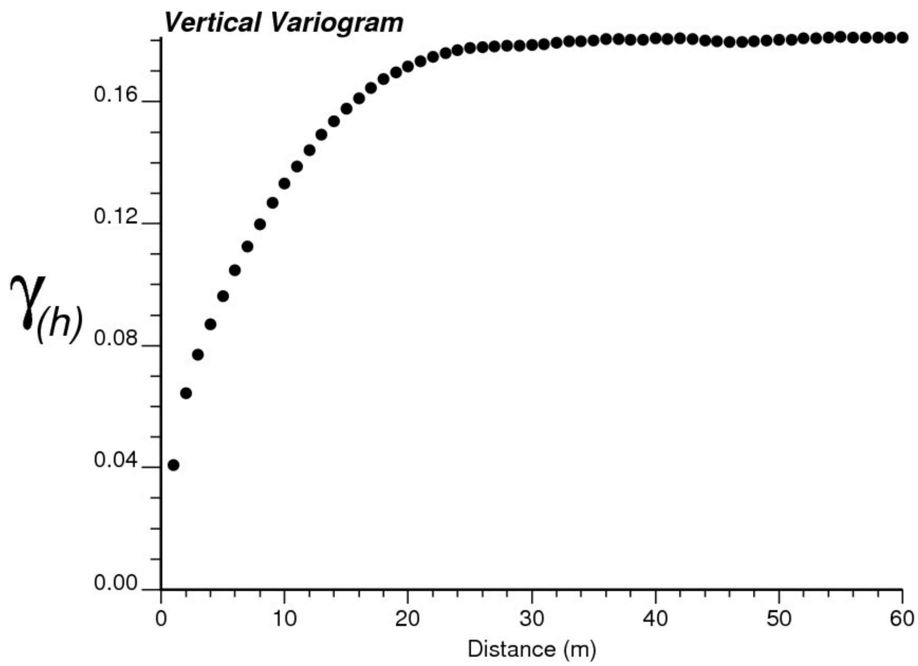

Figure 1: Vertical variogram of the sandiness in the Paskapoo Fm.

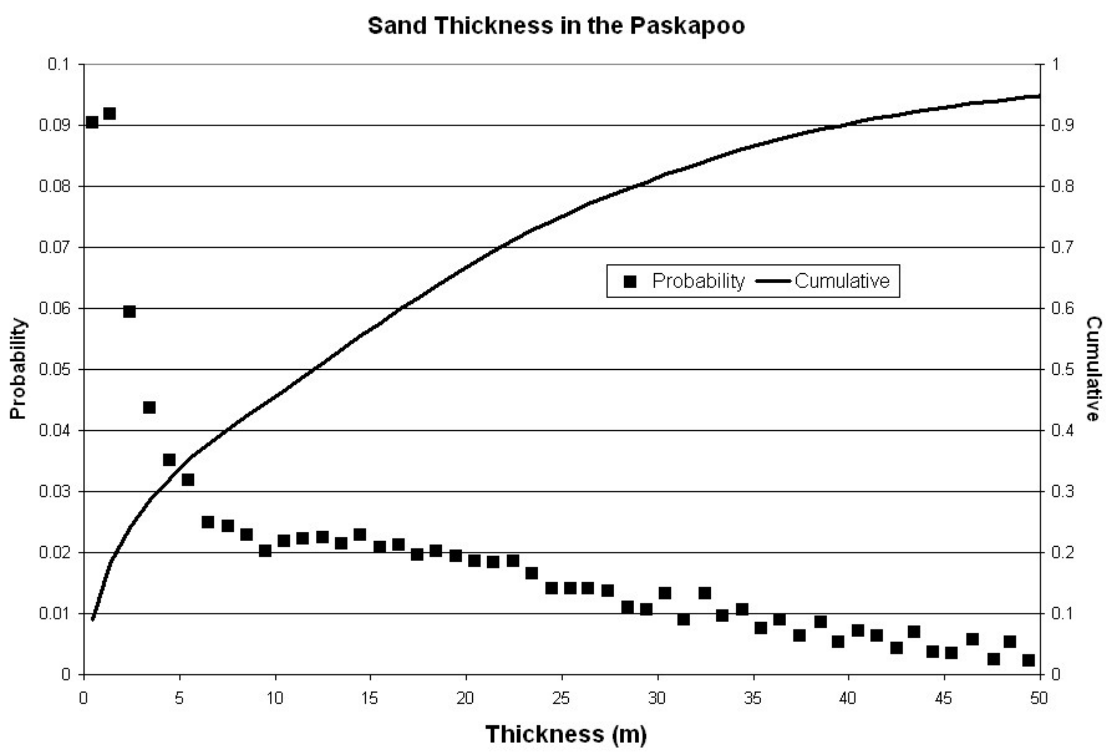

Figure 2: Probability distribution and cumulative distribution of sand layers in the Paskapoo Fm.

The spike in the probability distribution at 0-2 m thickness represents the majority of the splay sand bodies. The dropoff in probability up to 5 m shows the transition from splays to the margins of channels and the long plateau from 5 m to over 20 m shows the intersections of the logs with the nearly-thickest parts of the channels. The dropoff above about 23 m shows the decreasing probability of encountering thicker sand bodies as the only sandstone beds thicker than 20-25 m are multi-story channels. There is a long tail on the probability distribution caused by a number of sand runs that are thicker than 50 m and are clearly multi-story channel features. Fourteen runs of greater than 100 m were encountered in the data.

Looking at the cumulative distribution, if the maximum thickness of the splay sand bodies is 3 m then about 25% of the sand in the Paskapoo Fm. is contained in this type of structure. The cumulative distribution up to 23 m is about 0.7, so 45% of the sand is contained in the single-story channels. The remaining 30% of the sand volume is made up of multi-story channels, some of which are in excess of 100 m. About 5% of the sandstone in the Paskapoo Fm. is contained in multi-story channel complexes thicker than 50 m.

Conclusions

On the basis of gamma-ray-log analysis, sand bodies less than 3 m thick (typically 1-2 m) are interpreted as splay sands and make up as much as 25% of the sandstone volume in the Paskapoo Fm. Sand bodies up to 20-25 m thick are interpreted as single-story channels and make up about 45% of the sandstone volume. Thicker sand bodies, interpreted as multi-story channels, are relatively infrequent but because of their great thickness account for around 30% of the sandstone. Multi-story channels greater than 50 m thick make up 5% of the sand volume and there are some structures that are over 100 m thick.

Future work will include building conceptual models of geology and comparing the structure of the models (variograms, runs, etc) with the structure inferred from the gamma-ray log data. The conceptual models will be created by object- or process-based simulation methods. The horizontal extents and geometries of the sand bodies may be determined by this methodology, and verified by comparisons to outcrop and analogues.

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