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INTEGRATED ASSESSMENT OF WATER RESOURCES FOR UNCONVENTIONAL OIL AND GAS PLAYS, WEST-CENTRAL ALBERTA

AQUIFERS IN SHALLOW BEDROCK AND SURFICIAL SEDIMENTS

Final (Year 2) Report

prepared for:

Petroleum Technology Alliance of Canada (PTAC)

July, 2014

Petrel Robertson Consulting Ltd.

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CERTIFICATE OF QUALIFICATION

BRAD J.R. HAYES, Ph.D., P.Geol.

I, Brad J.R. Hayes, Professional Geologist at Petrel Robertson Consulting Ltd., Suite 500, 736 – Eighth Avenue SW, Calgary, Alberta, Canada and author of a report dated July, 2014, do hereby certify that:

I am a professional geologist employed by Petrel Robertson Consulting Ltd., which Company did undertake a study entitled *Integrated Assessment of Water Resources for Unconventional Oil and Gas Plays, West-Central Alberta – Aquifers in Shallow Bedrock and Surficial Sediments Final (Year 2) Report* for the Petroleum Technology Alliance of Canada (PTAC).

- I attended the University of Toronto, and that I graduated with a Bachelor of Science (Honours) Degree, Geology Specialist Program (1978), and obtained a Doctor of Philosophy Geology (1982) from the University of Alberta (Edmonton, Alberta); that I am a member of APEGA; that I have in excess of 30 years experience including geological studies relating to both Canadian and international oil and gas properties.

- I have not, directly or indirectly, received an interest, and I do not expect to receive an interest, direct or indirect, from any associate or affiliate of PTAC.

- The evaluation was prepared based on information available in the public domain.

PROFESSIONAL GEOLOGIST DR. BRAD J. HAYES ALBERTA

Brad J.R. Hayes, Ph.D., P.Geol. (Alberta)

INTRODUCTION

Petrel Robertson Consulting Ltd. (PRCL), as part of the Integrated Water Resources team, undertook systematic regional characterization of shallow subsurface non-saline aquifers across Montney / Duvernay unconventional exploration fairways for the project “Integrated Assessment of Water Resources for Unconventional Oil and Gas Plays, West-Central Alberta”.

Shallow non-saline aquifers in surficial sediments and shallow bedrock represent an important potential water source for unconventional oil and gas projects in west-central Alberta. However, they are also important to other stakeholders such as domestic and agricultural users. Consequently, a great deal of work has been undertaken in recent years to better understand these aquifers and their contained waters. Our work presents a regional synthesis of data and interpretations concerning shallow non-saline aquifers, as a basis for more local, project-based assessment of water source potential.

In Year 1 of the study, completed June 2013, we compiled and summarized existing work on shallow bedrock aquifers (Basal Belly River and Paskapoo formations), and shallow aquifers in surficial sediments. Project participants reviewed Year 1 results and subsequently agreed upon the following tasks to be completed in Year 2:

- Regional mapping and characterization of the Paskapoo Formation;
- Regional mapping and characterization of the Basal Belly River Formation;
    - This work has been moved to the accompanying deep saline aquifers report, as it is recognized that Basal Belly River aquifers are relatively deeply buried and contain saline waters over much of the project area;
- Closer work with Alberta Geological Survey personnel to make more complete use of relevant data and methodologies they have developed for shallow aquifer characterization.

This report documents completion of these tasks, and is supported by data filed in several Appendices.

SHALLOW BEDROCK AQUIFERS

A considerable amount of geological and hydrogeological work has been completed on shallow bedrock aquifers in Alberta, much by the Energy Resources Conservation Board / Alberta Geological Survey and the Geological Survey of Canada. While some projects have been academically-oriented stratigraphic studies, much of the work in recent years has been focused on resource assessment and characterization, particularly coal-bed methane (CBM) and water resources.

Bedrock subcropping beneath Quaternary cover in west-central Alberta is Late Cretaceous to Tertiary in age (Fig. 1). Most of this section is non-marine in origin, and contains varying proportions of sandstones derived from coarse clastics shed from the western orogen, and deposited in fluvial settings within thick fine-grained floodplain packages. It is thus difficult to identify continuous trends that might offer regional aquifer potential. Bachu and Michael (2002) addressed the following aquifer units (from oldest to youngest [Fig. 2-4]):

- Basal Belly River
- Upper Belly River
- Edmonton-Upper Wapiti
- Scollard-Paskapoo

Of these, only the Basal Belly River and the basal Paskapoo part of the Scollard-Paskapoo succession offer sufficient sandstone quality and continuity to merit consideration in our assessment of aquifer potential to support unconventional resource development. Generally low net sandstone / gross thickness ratios and thin sandstone bodies make other units such as the Horseshoe Canyon Formation poor water source candidates, although recent work has identified more prospective parts of the section (*e.g.*, Eberth and Braman, 2012). However, the Project Steering Committee specifically rejected undertaking further work on the Scollard, as they felt aquifer continuity would be inadequate, and the risk of gas production (in association with Ardley coals) too great.

As noted above, in Year 2 the Basal Belly River is being addressed in the deep saline aquifers report. This report on shallow bedrock aquifers focuses on the Paskapoo Formation.

DATA SOURCES

Characterization of shallow bedrock aquifers is supported by information from three primary sources: outcrop mapping and shallow test holes, shallow water wells (domestic and agricultural), and deep petroleum boreholes.

Data Gaps

Significant data gaps become evident when undertaking a comprehensive regional characterization of shallow aquifers (Fig. 5). These include:

- Poor outcrop control, particularly as strata are relatively flat-lying in the Project Area. Most of the Upper Cretaceous and Tertiary shallow bedrock units are relatively poorly consolidated and therefore weather recessively. As a result, we are limited to exposures in stream and river valleys. Even here, only resistant channel sandstones are well exposed in most cases – this is clearly evident in the Paskapoo Formation in the Calgary area.

- Shallow water wells penetrate only tens to perhaps 150 metres below ground, as they are drilled only until a good groundwater source reveals itself. Data collected are limited primarily to driller's lithologs, which are basic observations distinguishing unconsolidated sediments from bedrock, and when in bedrock, sandstone from shale. Alberta Geological Survey has developed a methodology to make systematic use of this information, as reviewed below.

  Some shallow water wells do have limited geophysical logs available, but most of these have not been scanned and fully integrated with the well reports. At our last correspondence with the regulator, we were told that if one knows that a specific well has geophysical logs, one can supply the well ID to the regulator, who will look to make those logs available.

- Deep petroleum boreholes are drilled in segments. The uphole portion is generally drilled quickly to the designated Base of Groundwater Protection (BGWP) or deeper, and surface casing is set without logging samples or running open hole wireline logs. Thus, we obtain little information regarding surficial sediments and shallow non-saline bedrock aquifers. Limited information may be available from observations while drilling (driller's logs), but as for shallow water wells, this is usually very generalized. As well, this information is usually buried in driller's reports, and has not been systematically curated for public access

Petroleum Borehole Data

Petroleum borehole wireline logs are the primary tool used to characterize the Paskapoo Formation. Sandstone density curves and induction/resistivity logs, acquired below base of surface casing, are the preferred dataset, but other logs were used where the preferred curves were not available. To provide good stratigraphic coverage over the very large study area, up to four petroleum boreholes were selected per township. There are a total of 1825 wells with wireline log data in our Paskapoo stratigraphic database (Appendix 1).

Since December 2006, ERCB / AER has required operators to run at least one wireline log from base of surface casing to surface. This is generally a cased-hole gamma log, which can provide limited information on lithologies and stratigraphic relationships, although not on reservoir quality or fluids. Quartero *et al*. (2014b) outlined procedures for normalizing cased-hole gamma log data from digital log curves in the Paskapoo. Such curves have been used in more local mapping / modeling projects undertaken by AGS, but were not used for the regional maps generated by Lyster and Andriashek (2012), and were not used in this study. However, mapping success with this methodology has been demonstrated by Quartero *et al*. (2014a), and it should be considered to support detailed mapping in more local operations project areas.

The Paskapoo is not a petroleum exploration and coring target, but partial cored sections have been acquired from wells targeting Scollard / Ardley coals for CBM and shallow gas sand development. A search for Paskapoo cores in the geoSCOUT™ database yielded 28 hits; a number of these showed only very short recoveries in the Paskapoo, and/or no core recovery. Several cores were reviewed at the AER Core Research Centre; a graphic core log and montage from a partial section of the basal sandstone at 12-19-43-3W5 is presented in Appendix 2. Ten cores had core analysis data, which was used in our reservoir quality and petrophysical evaluations (Appendix 2).

Wellbore cuttings are collected from most wells, and provide direct lithological sampling of formations penetrated. Cuttings description lithologs from wellsite geology reports are available in the geoSCOUT raster log image database – although only from a limited number of wells, as sampling generally is not required across the Paskapoo. A systematic search for available cuttings descriptions through the Paskapoo, followed by detailed screening for appropriate stratigraphic coverage, yielded 74 logs with some useful information (these are noted in Appendix 1).

Shallow Water Well Data

Lyster and Andriashek (2012) mapped sandiness in shallow Paskapoo strata from lithologs generated by water well drillers, following methodologies outlined by Slattery *et al*. (2011). Relative sandstone abundances were calculated in 25m-thick slices paralleling the ground surface, down to 150m depth (Fig. 5). Lyster and Andriashek (2012) examined approximately 33,500 water well lithologs, and generated about 48,160 data points.

We reviewed these procedures with AGS staff to gain a better understanding of the methodology. While assumptions and approximations must be made, it appears that the procedures reasonably capture the proportion of sandstone in each 25m-thick slice of the Paskapoo, and support regional map grids generated by Lyster and Andriashek (2012). However, no assessment of sandstone reservoir quality can be made; this method is strictly a sandstone vs. not-sandstone determination.

Given the volume of data and time taken to calculate sandiness values, we concluded that we could not undertake additional work that would substantially augment the AGS work, particularly in the time allotted to the Project. However, the AGS shallow water well methodology should be considered to support detailed mapping in more local operations project areas.

Geophysical wireline well logs, typically resistivity curves, are available in digital (.las) format for selected water wells throughout Alberta (AESRD, 2014). These were not investigated for this report, as short resistivity curves are unlikely to have significant value in regional mapping. Locally, however, some of these curves may be useful.

Other Data Sources

Locally, high-quality information is available from research boreholes drilled by Alberta Geological Survey, from coal and mineral exploration boreholes, and from outcrop sections. Some of these data points are outside the study area but are close enough to provide useful information. Graphic core / outcrop section logs and core photos are included in Appendix 1. Specific sources include:

- Demchuk and Hills (1991);
- ERCB / AGS Open File 2009-17 (Riddell *et al*.);
- GSC Open File 5535 (Hamblin 2007a);
- GSC Open File 5537 (Hamblin 2007c);
- GSC Open File 6504 (Hamblin 2010);
- Kennecott minerals report (Ball, 1997) (14 closely-spaced wells in the area).

Wellbore geophysical logs (usually very restricted – often only a resistivity or gamma log) have been run in many of the stratigraphic test holes and mineral exploration wells. Alberta Geological Survey has just released Report DIG 2014-003, which contains a number of water well .las files (AESRD, 2014).

PASKAPOO FORMATION

Regional Geology

The Paskapoo and equivalent Porcupine Hills formations represent a vast eastward-thinning wedge of nonmarine sediments deposited into the Western Canada Sedimentary Basin from the rising Cordillera (Hamblin, 2004). During latest Cretaceous time, the broad interior seaway that had occupied the basin during much of the Late Cretaceous withdrew, and renewed high-energy sedimentation occurred as the Laramide Orogeny re-activated Cordilleran deformation. Alluvial fan and floodplain environments dominated; Hamblin (2004) interpreted the sediment package as a third-order sequence, analogous to the classic molasse facies associated with the Alps. As Laramide deformation waned in the Eocene, the supply of detritus was greatly reduced, and isostatic uplift created an erosional unconformity and peneplain, at or near the present-day land surface.

Paskapoo strata crop out or lie beneath Quaternary glacial sediments over southern and central portions of the study area (Fig. 1, 6). Preserved thicknesses have been measured at 750 metres in the Calgary area, and up to 1500 metres in the equivalent Porcupine Hills on the Oldman River in southern Alberta (Hamblin, 2004). The Paskapoo lies disconformably on the Scollard Formation, the uppermost formation of the Edmonton Group, and is the youngest formation preserved in the WCSB (Fig. 2-4).

Demchuk and Hills (1991) made the first systematic regional interpretation of Paskapoo internal stratigraphy, defining three members: the basal Haynes, middle Lacombe and upper Dalehurst. They designated two Alberta Research Council coal exploration boreholes as reference sections for the Haynes and Lacombe members, clearly illustrating typical lithologies and log expressions (Core logs 4-6-39-24W4, 2-13-40-26W4, Appendix 2). The Haynes is characterized in outcrop by cliff-forming, stacked, thick medium- to coarse-grained sandstone beds sharply overlying the fine-grained upper Scollard Formation. Sandstones are characterized by sharp bases with conglomeratic lags, trough crossbedding and root and plant fragments. Lesser interbeds of grey or greenish fine-grained clastics are common. The overlying Lacombe Member comprises interbedded grey to green siltstone, mudstone, thin argillaceous coals and minor fine-grained sandstones. It is recessive in outcrop, although sandstone-dominated channel fills are prominent, particularly in valley cut sections. The uppermost Dalehurst member is found only in the Hinton area, where it consists of interbedded fine-grained sandstones, grey mudstones and at least five thick coal seams.

While alternative views of Paskapoo stratigraphy exist (*e.g.*, Jerzykiewicz (1997)) and magnetostratigraphic and biostratigraphic work continues, the Demchuk and Hills stratigraphic scheme is useful in subsurface characterization, and has been referenced in subsequent studies.

Lyster and Andriashek (2012) modeled sandstone distribution within the Paskapoo Formation, and related sedimentation patterns to the interplay of clastic sediment supply and rate of growth of accommodation space in the basin (Fig. 7). Of particular importance to this study, their model demonstrates that basal Haynes Member strata accumulated by amalgamation of multi-storey coarse-grained channel deposits in a broad depression atop the Scollard Formation, as growth in accommodation space was limited prior to a major episode of deformation. As active tectonism caused accommodation space to grow more rapidly, Lacombe Member sandstones accumulated in isolated high-sinuosity channels encased in much larger volumes of fine-grained floodplain sediments. A capping Sunchild aquifer unit, roughly equivalent to the Dalehurst Member, was mapped by Lyster and Andriashek (2012), and was interpreted as the product of another episode of reduced tectonism and slow growth of accommodation space.

Alberta Geological Survey work on the Paskapoo, culminating in Lyster and Andriashek (2012), forms a solid basis for more detailed investigation. We include the following key maps and sections to summarize the AGS work:

- Regional cross-section illustrating Paskapoo stratigraphy and log expression (Fig. 8).
- Regional isopach maps of basal Haynes Member, medial Lacombe Member, and upper Sunchild / Dalehurst Member, generated from map grids supplied with the Lyster and Andriashek (2012) report (Fig. 9-11).

Note that recent regional work on the Paskapoo by AGS, including Lyster and Andriashek (2012), and work in progress on smaller regions, uses the approach of mapping the Paskapoo in slices of uniform or systematically-varying thickness, in order to subdivide the formation in the absence of reliable stratigraphic markers. This is certainly a valid approach for this type of work, and could be undertaken for more local studies as well.

Detailed Mapping

Stratigraphic Picks

PRCL built a grid of seven regional cross-sections to support stratigraphic picks across the entire PTAC study area (Fig. 1) (Cross-sections A-A’ to G-G’). The top of the Battle Formation, a distinctive bentonitic mudstone interval at the base of the Scollard Formation, was used as a stratigraphic datum where it could be picked. Coal-rich intervals in the Scollard Formation were highlighted and correlated; these are best developed in central and eastern areas. In general, stratigraphic picks become more difficult westward as the overall section thickens and markers become less distinct. Approaching the Foothills, thrust faults generate structural repeats that are very difficult to identify in the uppermost Cretaceous and Tertiary section. Figure 1 highlights stratigraphic control points taken from the literature, which were tied to cross-sections and used to assist in stratigraphic picks throughout (sources include Dawson *et al*., 1994; Jerzykiewicz, 1997; Langenberg *et al*., 2007; and Parks and Andriashek, 2009).

Top of Battle Formation, base of Paskapoo, and top of basal Paskapoo sandstone were picked where they occurred on borehole logs, and tops are catalogued in a stratigraphic database (Appendix 1).

- Top of Battle is easily picked on logs in the east, but loses character westward (Langenberg *et al*., 2007).

- Base of Paskapoo was picked as per convention at the first substantial sandstone above Scollard / Ardley coals (where they are evident), checked against the stratigraphic control points posted on Figure 1. While it is a substantial unconformity, stratigraphy above and below is not easily distinguished where Ardley coals are not well developed (as at western end of regional cross-sections), and so there is considerable uncertainty locally in picking base Paskapoo. Core control was insufficient, and wellsite sample descriptions inadequate to support the pick systematically. Outcrop and shallow borehole core descriptions provide general support, but cannot be tied to petroleum borehole logs with confidence. The basal Paskapoo unconformity is well illustrated in numerous core logs in Appendix 2 (note in particular core log and core photographs at 12-12-46-28W4, and montage for core at 12-19-43-3W5).

  In some areas (*e.g*., eastern wells on Cross-section B-B'), locally-persistent channel sandstones in the upper Scollard are difficult to distinguish from the basal Paskapoo. Tracing coal seam stratigraphy in the Scollard supports distinguishing these sands in most cases, but it is possible that we have included some upper Scollard channel sands in the basal Paskapoo in some places. Regardless of their stratigraphic assignment, upper Scollard sands may be viable aquifers locally. There are good examples at Ansell (Twp 51-52, Rge 20-21W5) and Pine Creek (Twp 55-56, Rge18W5).

- Top of basal Paskapoo sandstone was picked to best distinguish the sand-rich basal part of the Paskapoo from overlying mudstone-dominated intervals. While best efforts were made to be stratigraphically consistent, we were biased toward including as much sandstone as possible in the basal sandstone unit. In isolated cases, a relatively large amount of non-sandstone rock was included to maintain stratigraphic consistency with nearby wells (compare wells 5-2-47-17W5 and 6-7-47-15W5 in western part of Cross-section C-C').

  While our basal Paskapoo sandstone is similar to the Haynes Member (as illustrated in the picks by Parks and Andriashek (2009) in Fig. 8), our picks are somewhat more variable, and more likely to include high-quality sandstones higher in the section. We chose not to use the term Haynes Member, as we felt it could not be linked to the outcrop type section with sufficient confidence.

There are places where the basal Paskapoo sandstone is very thin or absent – in these cases, base Paskapoo and top basal sandstone picks have been made at a stratigraphic level to conform with offsetting wells, even if there is no well-developed sandstone present (*e.g*., 1-19-48-7W5, Cross-section C-C').

Net clean sandstone, net porous sandstone, and average porosity values were picked and databased for the basal Paskapoo sandstone, where supported by adequate log quality. These are discussed further below under Reservoir Characterization.

- Thick stacked sandstones were noted toward the top of the Paskapoo in several wells on the western flank of the study area, particularly where surface casing was set relatively shallow (*e.g*., 02/15-26-60-25W5, 02/15-22-61-24W5), but there are too few control points to confidently define and map an upper sandstone (Sunchild / Dalehurst) member. Very thick upper Paskapoo sandstones were also noted in core in the Kennecott exploration area (Twp 57-24W5) (Appendix 2, Kennecott NC 44-1 core).

  Net porous sandstone units greater than 10m thick were tabulated in the upper Paskapoo section, above the top basal Paskapoo sandstone up to the top of the logged section at base of surface casing (generally equivalent to the medial Paskapoo Lacombe Member in outcrop terminology). The net / gross ratio of the upper Paskapoo section was mapped, as discussed below.

Map Results

A structure map on the base Paskapoo shows the highest structural elevation (>1000m) in the northeasternmost corner of its range in Twp 67-12W5, dipping southwesterly towards the Foothills to a minimum structural elevation of <400m (Fig. 12). More variable structural elevations in the far west reflect structural deformation in the outer Foothills. Note the lack of control points and contours in the far northwest, where few picks could be made with confidence.

Depth to the top of the basal Paskapoo sandstone ranges from 350 to 500 metres through much of the study area, ranging to more than 700m in the outer Foothills (Fig. 13). Contours are based on well data only, and so surface topography is not well represented in some areas. For example, several wells drilled within the Athabasca River valley (*e.g*., Twp 56-22W5) exhibit relatively small depth to top basal sand values compared to offsetting wells, but there are not sufficient wells along the valley course to demonstrate this relationship everywhere.

Isopach / total thickness of the basal Paskapoo sandstone shows pronounced SSW-NNE thicks, ranging from >200m thick in the Foothills to 75-100m in the east (Fig. 14).

This map has been hand-contoured to maximize continuity of the sands, which we have interpreted as profound channelized fairways, distributing sediment from western highlands eastward into the foreland basin. While there are very few zero thickness values, broad areas in the northeast feature less than 25m basal Paskapoo sandstone thickness. Note that thicknesses in some wells are minimum values, where the base of Paskapoo is picked on well logs, but the top of the basal Paskapoo sandstone lies above the base of surface casing.

Reservoir Characterization

Petrography

Sandstone composition and reservoir quality in a thick, regionally-extensive unit like the Paskapoo shows considerable variation. While a systematic, wide-ranging petrographic study has not been completed, we have summarized descriptions from a variety of sources, and supplemented them with petrographic work done for this study.

Hamblin (2004) summarized petrographic descriptions from several legacy studies, some of which suggested two petrogenetically distinct source areas: a southern system derived from Paleozoic thrust slices in the southern Cordillera, and a northern system derived from more volcanic sources in the central Cordillera. As a result, Paskapoo (and equivalent Porcupine Hills Formation in the south) exhibit different compositions:

- Central Foothills: 32% sedimentary rock fragments, 36% volcanic rock fragments, 31% metamorphic rock fragments, and <1% plutonic rock fragments (with 42% quartz and chert overall).

- Southern Foothills: 81% sedimentary rock fragments, 6% volcanic rock fragments, 12% metamorphic rock fragments, and <1% plutonic rock fragments (with 76% quartz and chert overall).

The northerly, volcanic-rich suite would be more subject to diagenetic alteration, and development of carbonate cements and interstitial clays.

Chen *et al*. (2007a) examined 56 thin section samples of Paskapoo sandstones from five shallow stratigraphic boreholes in or flanking the southeastern part of the current study area. They summarized petrography as follows:

> "Grain size ranges from very fine to coarse (with most between very fine and fine). 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). Alteration and dissolution of rock fragments and feldspare 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. Calcite cement occludes intergranular pore space.
>
> Intergranular porosity is the major pore type. The other types include secondary porosity (as a result of feldspar dissolution) and microporosity (associated with authigenic kaolinite, leached chert and clay matrix)."

PRCL sampled the Paskapoo in three petroleum borehole cores (two samples from the basal Paskapoo, and one from an upper Paskapoo sandstone), from the basal Paskapoo at 12-12-46-28W4 (described by Riddell *et al*., 2009), and from the upper Paskapoo sandstones in the mineral exploration borehole at 9-17-57-24W5. Thin section petrography is described and illustrated in Appendix 3. All samples are litharenites, showing poor sorting and significant components of sedimentary and volcanic rock fragments and feldspars. Significant grain dissolution was observed, but altered clays are confined largely to the relic grain boundaries. Despite the lithic composition, poor sorting, and presence of clays, very good reservoir quality was observed and confirmed with core analysis data. Shallow burial depths and limited burial compaction appears to be responsible, along with general lack of authigenic cementation. Patchy calcite cement at 12-19-43-3W5 suggests localized reservoir degradation, which is discussed further below.

Raster image wellsite sample logs were inspected for 74 petroleum wells penetrating the Paskapoo (Appendix 1). These were found to have limited value in characterizing Paskapoo petrography because:

- Many descriptions were cursory, particularly in deeper wells where the primary objective was far below the Paskapoo. Many of these descriptions were likely generated by junior and/or non-geological staff;

- Sample quality is often poor when drilling quickly through shallow strata;

- Paskapoo samples were recovered largely as unconsolidated sand grains in many sections. Generally, this should signify poorly-cemented, high-quality reservoir – but many descriptions did not reflect this. Instead, they focused on consolidated chips, which likely represent poorer-quality cemented streaks. We noted several examples where wellbore logs show very good porosity, but sample descriptions indicate poor porosity.

In some of the better-quality sample descriptions, substantial grain size variations were logged, and conglomerates were identified locally.

Quantitative Petrophysical Analysis

Core analysis data were collated from Paskapoo cores in nine petroleum boreholes, sampling both basal and upper sandstones (Appendix 3). A cross-plot of maximum permeability vs porosity shows low permeability values below 15% porosity, and then a sharp rise to good permeabilities above 24% porosity (Fig. 15).

Average pore throat sizes can be calculated using a relationship called the Winland equation; these are shown as coloured curves on Fig. 15. These illustrate that porosities below about 14% are associated primarily with fine-grained rocks, which feature tortuous pore throats and relatively ineffective microporosity in altered grains. High permeability values are associated with much larger pore throat sizes, indicating that most high-quality rock in the Paskapoo is in coarser-grained sandstones.

Other observations from core analysis data:

- Tightly-clustered grain densities, with an average value around 2678.5 kg/m^3, indicate Paskapoo sands are fairly uniform in mineral composition – although considerably denser than pure silica sand. Within the sample set, there is not much grain density variation with depth (Appendix 3, grain density plots);

- Within the sample sets, porosity and permeability do not vary systematically by depth.

Building on core analysis data, quantitative petrophysical analysis was undertaken for two wells – a basal Paskapoo sand in 12-19-43-3W5 and an upper Paskapoo sand in 02/6-23-47-9W5 (Appendix 3). Core analysis values for grain density, porosity and permeability are plotted. Note that both analyses show very good matches between core-measured values for porosity versus calculated effective porosity, and somewhat more variable matches between core-measured permeability and permeability values calculated from porosity-permeability relationships (by well and aggregated).

Note also in well 12-19 that tight streaks in the upper part of the core show as being carbonate-rich, likely indicating the presence of carbonate cements. Petrographic analysis at 12-19, discussed above, showed patchy calcite cements. Carbonate-cemented streaks are common in many thicker basal Paskapoo sandstones (see regional cross-sections), suggesting that vertical permeabilities in some sections may be impaired. The lateral extent of such carbonate-cemented beds is unknown, but it is our experience that they commonly occur as discontinuous nodules along particular stratigraphic horizons, and do not form continuous barriers to fluid flow.

We conclude that quantitative petrophysical analysis calibrated to core data can accurately represent reservoir quality in the Paskapoo.

Reservoir Quality Mapping

Figure 16 depicts net clean porous sandstone thickness within the basal Paskapoo sandstone unit, using the following cutoffs (note that thickness posted for some wells is a minimum value, as the top of the basal Paskapoo sandstone lies above the base of surface casing):

- 75 API units on the gamma log for clean sandstone. This relatively high value was chosen to reflect the variable lithic composition of the sandstones;

- 15% porosity on the sandstone density porosity curve, reflecting the porosity-permeability relationship observed in core.

Applying these cutoffs further highlights reservoir quality variations in the basal Paskapoo across the study area. While the major east-west channelized thicks can still be picked out, they are less distinct in the north, and better developed toward the south. Net porous sandstone thicknesses are generally low in the west, and many of the thickest basal Paskapoo sandstone sections show little or no net clean porous sandstone. Log data are thus indicating a general porosity reduction westward, likely as a result of increased burial compaction. Figure 17, mapping average porosity values for the basal Paskapoo sandstone estimated from logs, supports this interpretation.

Net clean porous sandstones greater than five metres thick were tabulated for each well in the section between the top of the basal sandstone and the base of surface casing (Fig. 18). This map shows a high degree of variability, because it is controlled not only by the net/gross ratio within the Paskapoo itself, but by the thickness of section logged within individual wellbores (a function of both Paskapoo thickness and the depth to which surface casing was set). It does show fairly large areas where there is essentially no sandstone above the basal sandstone pick. Along the western flank of the map, however, there are considerable areas with net/gross ratios >0.4. These correspond fairly well with the Sunchild isopach map generated by Lyster and Andriashek (2012) (Fig. 11). In these areas, where porosity is relatively low in basal Paskapoo sandstones, there may be substantial aquifer targets higher in the Paskapoo, but still hundreds of metres below ground level.

Hydrogeology

Regional Background

Grasby *et al*. (2008) estimated that about 64,000 water wells (roughly one-third of water wells completed in Alberta up to August 2006) are located in the Paskapoo outcrop belt, and that the Paskapoo is the most significant supply of groundwater in the Canadian Prairies.

Bachu and Michael (2002) reviewed 705 water analyses and 21 DSTs from the Scollard and Paskapoo formations (which make up the Scollard-Paskapoo bedrock aquifer), using data collected from petroleum boreholes and shallow Alberta Research Council wells, but not from shallow water wells (in which bedrock stratigraphy is generally not interpreted). They found salinities to range from about 100 to 3000 mg/l, but to be less than 1000 mg/l over most of the area (Fig. 19). Comparable results were mapped in the Edmonton-Calgary Corridor by Barker *et al*. (2011). Huff *et al*. (2012) collected water samples from the Paskapoo and overlying glacial drift aquifers and interpreted variations in geochemistry in terms of mineral dissolution and precipitation overprints on meteoric water signatures. Lemay (2003) tabulated a variety of geochemical analyses of formation waters from the Paskapoo-Scollard through Belly River aquifers.

As the definition for saline water in Alberta is >4000 mg/l, all Paskapoo waters are considered to be non-saline, meaning that there are considerable regulatory requirements in accessing these waters for industry use.

Within the limitations of the scanty DST data, Bachu and Michael (2002) showed hydraulic head values of >1000m adjacent to the Foothills, decreasing to about 700m in the northeast. While generally indicating southwest-northeast flow from high-elevation recharge areas, it was thought that locally the hydraulic head values should more closely resemble the local water table. Grasby *et al*. (2008) agreed that with this conclusion, and concluded that local recharge is important in most areas.

Parks and Andriashek (2009) showed that basal Paskapoo channels can incise through upper Scollard mudstones, and place the Haynes Member in contact with the underlying Ardley coal zone (shown schematically in Fig. 8). They concluded that strong local hydraulic connectivity between the Ardley coals and Paskapoo can occur, resulting in formation pressures and hydraulic heads in the Ardley being similar to those of the Paskapoo. Biogenic gas from the Ardley can be introduced into the Paskapoo aquifer, which must be regarded as a risk to formation water continuity and quality in the context of this Project (see Paskapoo Gas Production, below).

Local Hydrogeological Studies

Several local hydrogeological studies have been published, highlighting characteristics of groundwater production from the Paskapoo – all from very shallow depths typical of water source wells. Two examples reviewed below have focused on isolated channels and associated splay sands in the medial, mud-dominated Lacombe Member.

Farvolden (1961) studied groundwater resources of the Paskapoo in the Pembina Field area, where in the early 1960’s, 600 million gallons (2.3×10^6 m^3) of water were withdrawn each year to supply 60% of water injected to support Cardium oil production. Most Paskapoo water was obtained from porous and permeable sandstones, although some production from fractured calcareous sandstones and siltstones. Water wells were generally drilled to between 150 to 300 feet and encountered interbedded sandstones and shales that in most cases could not be correlated from one borehole to the next – which would be expected where most wells reach total depth in the low net/gross Lacombe Member. Based on 138 wells, Farvolden mapped areas of poor (0 to 300 gallons/day/foot), good (300 to 1000 gpd/ft) and very good (1000-3000 gpd/ft) apparent transmissibility as calculated from production test data. Wells in the "very good" area generally feature thick, massive sandstones, and most were found to be capable of producing more than 50 gal/min (325 m^3/d).

Farvolden concluded that on a regional basis, meteoric recharge was sufficient to ensure that the Paskapoo aquifer was not being significantly depleted by water well production. He recommended that a network of observation wells should be extended as new areas were drilled, in order to monitor depletion and recharge regionally and on a local basis.

Tokarsky (1971) reported on the shallow (surface to approximately 1000 feet) hydrogeology of the Rocky Mountain House area. Paskapoo strata form the bedrock across most of this area, with the exception of the southwestern corner of the area, where thrust faulting brings older strata to surface in the Rocky Mountains and inner Foothills. Thousands of shallow water source wells have been drilled, with most completed in bedrock. Tokarsky concluded that most of the area underlain by the Paskapoo is capable of producing water at 100 to 500 l/min, while peak yields of 500 to 2500 l/min may be possible in the best wells. Where good sandstones are lacking in the Paskapoo, however, yields of less than 25 l/min are expected. All these rates are based on relatively short pump and bail tests, and may not be indicative of long-term sustained yields.

Chen *et al.* (2007b) analyzed single-well pump tests to estimate transmissivity of the Paskapoo in 1309 shallow water wells, most located in the southeastern corner of the present study area and southward. Data contours are very intricate, suggesting high lateral variability of transmissivity values. Better spatial continuities trending NE-SW suggest that both dominant sandstone channel trends and regional fracturing support enhanced transmissivity along that trend.

At present, hydrogeological modeling work (MODFLOW) is being undertaken in the shallow Paskapoo at University of Alberta (Dr. Daniel Alessi), with the goal of researching regional to local impacts of withdrawing groundwater on surface water bodies and shallow aquifers.

Deep Paskapoo Hydrogeology

In Year 2 study work, we focused on characterizing hydrogeology of "deep" basal Paskapoo sandstones – those that lie 100 metres or more below surface. The intention is to focus on potential aquifers in the basal Paskapoo that lie below total depth of most domestic / agricultural water wells, and which can be related to the basal Paskapoo sandstone mapping undertaken in this study.

Drillstem tests analyzed for the project are posted on Figure 20, and are listed in Appendix 4. Twenty-two valid DSTs from 20 wells were identified as testing the basal Paskapoo (highlighted in red), while 28 DSTs from 24 wells tested the Scollard Formation. Nineteen Paskapoo and 15 Scollard DSTs had useable pressures and could be plotted on a Pressure/Elevation graph (Fig. 21). Based on valid formation water salinities, a water gradient of 0.435 psi/ft (9.84 kpa/m) was applied.

Scollard DSTs are scattered across the P/E graph, and do not appear to align into any regional water systems. Paskapoo tests define two water systems, termed the Paskapoo Regional and Pembina water systems. Pembina water system wells cluster in a small area on the northwestern flank of Pembina oilfield, generally in wells with relatively thin basal sands (Fig.20). Note on the P/E graph that the Pembina water system gradient intersects the Pembina River (plotted with zero pressure head and using elevations from Google Earth) – suggesting a pressure connection between the river and the pressure system.

One well, 11-28-44-11W5, appears to be underpressured relative to the regional water systems, but because the 60m test interval spans several sand bodies, we are reluctant to assign it to its own pressure system.

On the potentiometric surface map (Fig. 22), values are contoured using a 50m contour interval, and each water system is contoured separately. Note that both petroleum borehole data and water well data are used for this map. Overall, we observe weak southwest to northeast flow potential; lower values in the Pembina water system may reflect interaction with the river, as discussed above. Grasby *et al*. (2008) suggested that there is no regional flow within the Paskapoo, but instead that local recharge dominates – but his dataset was dominated by shallow tests.

We identified 10 valid basal Paskapoo water analyses from petroleum borehole data, with salinities ranging from 1567 to 2627 mg/L TDS, for an average value of 2038 mg/L (Appendix 5; Fig. 23). All are therefore technically fresh waters, although non-potable, and generally more saline than indicated regionally by Bachu and Michael (2002) (Fig. 19). Values from the basal Paskapoo in shallow water wells near the subcrop edge are generally lower, with many <1000 mg/L. On a Piper plot, Paskapoo formation waters exhibit a sodium bicarbonate chemistry, with some trending toward sodium chloride (Fig. 24).

Paskapoo Water Source Wells

Existing water source wells producing from the Paskapoo were reviewed to determine performance measured to date. We have searched the petroleum well database only, where accurate production statistics are available. As noted previously, there are thousands of shallow water source wells taking water from the Paskapoo. There is, of course, no water disposal into the Paskapoo, as it is too shallow and contained waters are non-saline.

A cautionary note – routine queries of public databases sometimes do not accurately capture or depict the full range of operations that take place in some wellbores. For example, a database search showed 9-27-47-14W5 to be a Basal Belly River water source well, with cumulative production of 662.2e^{3}m^3 water since October 1999. Careful review of well data revealed, however, that water was actually being injected into the Basal Belly River (64.0e^{3}m^3 since April 1996), as pressure support for nearby oil production. An upper zone (listed as Quaternary, but probably the upper Paskapoo) was perfed in 1998, and is actually the interval from which water is being sourced.

Paskapoo water source wells are subdivided into three categories – those producing from the basal Paskapoo sandstone (Basal), those from near the surface (<100m deep) (Shallow), and those from intervals in between (Other) (Appendix 6). Most of the 220 Shallow and 73 Other wells were put on stream in the 1960's and 1970's in support of waterflooding at Pembina and surrounding fields. While a number produced for substantial lengths of times and did substantial volumes (>10^{6}m^3), few are active today. As discussed above, Farvolden (1961) concluded that the best shallow wells in the Pembina area were excellent producers, capable of >300 m^3/day with local recharge from meteoric waters.

There are only 15 Basal Paskapoo water source wells (Appendix 6). Most were drilled in the 1960's and 1970's, and only two are active today. Cumulative water production values are relatively modest, with the top four wells having produced 0.43-1.40x10^{6}m^3, although three of these are situated in adjacent LSD's in section 30-40-3W5 where net porous sandstones map at 50-75m thick (Fig. 16) (unfortunately, daily production data are not available for any of these wells, as illustrated by the production curves in Appendix 6).

We conclude that the Paskapoo has very substantial water source capacity, demonstrated primarily by the large and sustained production in many closely-spaced wells in the general Pembina area. Basal Paskapoo sandstones lying deeper than 100m below the surface have been accessed in only a few locations, where they have been produced at relatively modest rates. This history appears to be controlled primarily by the current regulatory regime, restricting access to non-saline waters. The performance of the three basal Paskapoo water producers in section 30-40-3W5 (about 2 million m^3 water produced from 3 LSD's from 1966 to 1977) demonstrates excellent production performance from thick basal Paskapoo sandstones.

Paskapoo Gas Production

Hamblin and Lee (1997) discussed a conceptual gas play in the Paskapoo based on charge from the Ardley coals, but stated that no discoveries have been made in the play. Parks and Andriashek (2009), however, documented the presence of Paskapoo gas production from wells in the Rocky Mountain House – Drayton Valley area. They linked gas occurrence in the Paskapoo to two key factors:

- Basal Paskapoo sandstones sitting on or only a short distance above Ardley coal seams (Fig. 25).

- High net /gross ratio in the lower part of the Paskapoo, overlain by lower net / gross section, thus allowing gas to percolate up through the lower Paskapoo, and to be trapped near the top of the basal sand section.

A geoSCOUT search revealed 83 Paskapoo gas wells in the study area (Appendix 7). The best cumulative production is 68.9 e^6m^3 (2.43 BCF) over 12 years, while 11 wells have produced >0.5 BCF (14.2 e^6m^3). A number of wells were perfed over several intervals, including sandstones and shales in the Scollard Formation, so not all this production can be attributed to the Paskapoo. Figure 26 illustrates a clear example of gas production from the basal Paskapoo sandstone – note three metres of crossover on the neutron-density log at the top of the sand, and also that the basal Paskapoo sandstone is resting directly on a Scollard / Ardley coal seam.

While gas in basal Paskapoo sandstones is relatively rare and generally confined to small stratigraphic traps in isolated wells, care must be taken when evaluating potential water source wells to ensure that viable gas resources are not ignored.

DISCUSSION – WATER NEEDS FOR UNCONVENTIONAL PLAYS

The Alberta Energy Regulator is currently proposing a play-based regulatory framework for unconventional oil and gas development, which will encourage collective industry management of water resources. Water management goals of the proposed Play-Based Regulations include:

- Reduce use of surface water and nonsaline groundwater;
- Increase water reuse;
- Protect surface water and nonsaline groundwater;
- Protect the aquatic environment.

Use of saline water from deep aquifers is therefore being encouraged, and these aquifers should be considered first in play-based water planning. However, our mapping of deep saline aquifers has demonstrated that they cannot collectively provide the necessary water source volumes in all areas (see Deep Saline Aquifer Year 2 Report). As well, deeper non-saline sources, where present, are preferred to shallower non-saline alternatives.

AER has designated an area of the Duvernay play fairway in the Fox Creek area as the first pilot project for Play-Based Regulation (http://www.aer.ca/about-aer/media-centre/news-releases/news-release-2014-07-02). We have overlain the Fox Creek PBR Pilot Area on our Paskapoo net porous sandstone map (Fig. 30). We have also analyzed two other important development areas:

- **Rycroft-Gordondale** – Characterized by intensive horizontal multi-frac development of various Triassic reservoir targets, including Montney, Doig, and Charlie Lake;

- **Pembina** – Emerging area for systematic waterflooding of established and new Cardium oil production. Also has potential for horizontal multi-frac development of Duvernay and Cretaceous targets.

Below, we review water source potential from the Paskapoo for each of these areas, with reference to our regional mapping work. These development areas are also addressed in our Deep Saline Aquifers report.

Water Source Needs

Source water volumes for unconventional plays vary greatly, based on specific reservoir characteristics, completion methodology, and pace of development. Although there has been experimentation with oil- and gas-based fracs, most wells in unconventional reservoirs in the WCSB are completed with water-based fluids, and some with relatively large slickwater fracs. Many figures are available, but here are some typical ones that have come to our attention:

- Cardium: 1500-4000 m^3/well;
- Wilrich: 1000-5000 m^3/well;
- Montney: 12,500-37,000 m^3/well;
- Duvernay: 20,000-30,000 m^3/well.

Water demand to support waterflooding is relatively low on a per-well basis (tens of m^3/day per well), but there are hundreds of water injectors now, particularly in the Cardium and Basal Belly River. In the Pembina / Willesden Green area, operators plan to drill infill injectors in existing waterflood areas, as well as to expand injector well counts and injection volumes as the fringe / halo areas are developed. In both areas, horizontal producers will be converted to water injectors, eventually to attain a ratio of approximately one water injector for each oil producer.

Members of the Project Steering Committee have expressed the desire to establish water source wells with capacities exceeding 1000 m^3/day/well for long time periods, in order to minimize the number of wells required to support major development projects. While this sort of capacity may exist in the best deep saline aquifers, the shallower units containing less saline waters generally top out at 200-600 m^3/day over the long term. These lower volumes may represent desirable and attainable targets for plays like the Cardium, where fracture completions and waterfloods require lesser water volumes than the deeper, tighter plays.

Fox Creek PBR Pilot Area

While development of the Duvernay Formation shales is the primary driver in the Fox Creek PBR Pilot area, unconventional potential exists in other reservoirs, including the Montney and Wilrich / lower Falher. Assuming full-scale development of the Duvernay proceeds, water source requirements in the area could be on the order of 50,000 m^3/d or greater for a number of years. The area is very large, however, and it is reasonable to assume that even with a play-based plan for water, there will be several centres of activity.

Observations regarding source potential from the Paskapoo:

- Basal Paskapoo sandstones exist at depths of greater than 100m beneath about 60% of the area. Substantial channelized thicks occur in west-central and southeastern areas, and present excellent source potential;
- Regional degradation of reservoir quality is a concern to the southwest;
- Thick upper Paskapoo (Sunchild / Dalehurst) sandstones are present in the far southwest, and may represent additional aquifer potential;
- Thick sandstone channels in the upper Scollard Formation may provide substantial water sources locally, although reservoir quality and lateral extent are questionable;
- North of the Paskapoo subcrop edge, shallow aquifer potential is limited to relatively isolated channel sands in the uppermost Cretaceous section;
- Proximity to major river valleys such as the Athabasca must be considered when developing plans to access Paskapoo aquifers.

While we lack local performance data for basal Paskapoo aquifers, it appears likely that they could provide substantial water volumes from wells drilled along the mapped thicks. This potential complements deep saline aquifer potential quite well, which is better developed in the northwestern part of the area.

Rycroft-Gordondale

As noted above, the Rycroft-Gordondale area is characterized by intensive horizontal multi-frac development of various Triassic reservoir targets, including Montney, Doig, and Charlie Lake. While water needs for individual wells are likely smaller than at Fox Creek, there are many reservoirs and development projects in the general area. At peak development, we might be looking at water source needs on the order of 10,000 m^3/d over sustained periods.

There is no Paskapoo source potential in this area, as the formation has been eroded completely. Bedrock in the area consists of Upper Cretaceous marine shales and the Basal Belly River at the southern edge. Deep saline aquifers thus offer the primary subsurface water source potential for this project area.

Pembina

As discussed above, Pembina is an emerging area for systematic waterflooding of established and new Cardium oil production. New horizontal wells are being drilled to develop the Cardium, particularly in fringe/halo areas. On a more restricted scale, horizontal multi-frac development of relatively areally-restricted Jurassic and Cretaceous Deep Basin targets is also taking place. While horizontal multi-frac development of the Duvernay is still in the appraisal stages, potential exists in the future for large water needs associated with this play.

We don't have any reasonable estimate for present or future water requirements in the area, but the need for tens of thousands of cubic metres per day is certainly foreseeable.

Observations regarding Paskapoo aquifer potential:

- Basal Paskapoo sandstones, including substantial channelized thicks, are mapped throughout the area at depths of >100m, except in the far northeast;
- Existing water source well performance supports potential for substantial and sustained production from the basal Paskapoo;
- Gas zones exist in many basal Paskapoo sections in the area, and must be considered when assessing water source potential.

Should unconventional development proceed to its apparent potential in this area, shallow aquifers must play a role, as deep saline aquifer potential appears to be inadequate (see Deep Saline Aquifer report).

AQUIFERS IN SURFICIAL SEDIMENTS

In our Year 1 report, we described data and reports relevant to evaluation of aquifers in shallow unconsolidated sediments. These include:

- AGS Map 601 (Fenton *et al*., 2012) – provincial compilation map of surficial materials;
- Alberta Sand and Gravel Deposits with Aggregate Potential (Edwards and Budney, 2009);
- Natural Suitability of Geological Settings for Waste Management (Andriashek and Waters, 2005);
- Compilation of Alberta Groundwater Information from Existing Maps and Data Sources (Lemay and Guha, 2009);
- Regional hydrogeological reports with local cross-sections;
- Comprehensive water well database (accessed through gwinfo@gov.ab.ca);
- Bedrock topography of Alberta, Canada; ERCB/AGS Map 550 (Atkinson and Lyster, 2010).

Some of this material is included as map layers within our NOLA framework.

Additional work on shallow unconsolidated aquifers was planned during Year 2. To initiate this process, we consulted with researchers at Alberta Geological Survey and University of Alberta, where a number of projects are being conducted.

Palombi (2014) outlined groundwater initiatives currently underway at the Alberta Geological Survey. Their work focuses on three regional project areas which are very important to future industrial, agricultural and domestic water use in the province (Fig. 27):

- Edmonton – Calgary Corridor;
- Beaver River Basin (oil sands);
- South Saskatchewan River Basin (work is targeted to assist with a groundwater management framework under the Landuse Framework of AESRD).

Three phases of the program are planned in each project area:

- Characterize the natural system (groundwater atlas);
- Understand dynamics of groundwater system under development (numerical modeling);
- Develop decision support tools for resource management, regulation, and policy development.

The work being undertaken on these projects highlights the level of detail and intricacy necessary to quantitatively assess surface / groundwater interactions, and communication between shallow surficial sediments and bedrock aquifers (Fig. 28). This point is well illustrated by AGS' current sub-basin scale modeling project in the Sylvan Lake area, which addresses shallow unconsolidated aquifers and bedrock of the Paskapoo and Wapiti formations (Fig. 29).

Hydrogeological modeling work (MODFLOW) is also being undertaken at University of Alberta by Dr. Daniel Alessi, addressing the shallow Paskapoo Formation and surficial sediments. A primary goal is to research regional to local impacts of withdrawing groundwater from the Paskapoo on shallow aquifers.

The level of detail required to undertake this modeling work demonstrates that attempting to model or quantify interactions between bedrock, shallow unconsolidated aquifers and surface waters is a task not to be undertaken at the regional scale of the current project. We simply do not have the necessary level of mapping detail for either unconsolidated aquifers or shallow bedrock. Instead, we will need to build from the scale and methodology of both the U of A and AGS model exercises to adequately understand aquifer behaviours in local unconventional development areas.

SUMMARY AND CONCLUSIONS

The Paskapoo Formation is a huge, shallow non-saline aquifer found beneath much of the Montney / Duvernay play fairway area. Basal Paskapoo sandstones occur almost everywhere, and channelized thicks with >25m net porous sandstone are highly mappable. Limited test and production data show that these sandstones are highly permeable, and are capable of producing large water volumes at substantial daily rates.

Most water production from the Paskapoo to date has been from tens of thousands of shallow water wells, predominantly from middle to upper Paskapoo (Lacombe Member through Dalehurst / Sunchild Member) sandstones and fractured mudstones. In the Pembina area, hundreds of shallow to moderate-depth Paskapoo wells drilled in the 1960's and 1970's provided water to support waterfloods in the Cardium and other oilfield formations. Only 15 of these wells drilled deeper and produced from basal Paskapoo (Haynes Member) sandstones. More recently, there have been very few Paskapoo water source wells drilled to support oil industry activity, as the regulator discourages such use of non-saline waters.

Regional mapping in the accompanying Deep Saline Aquifer report demonstrates that source water (and disposal zones) to support unconventional gas and oil development can be supplied by deep saline aquifers in some areas, particularly in the northern Montney / Duvernay fairway. In other areas, particularly in the south, saline aquifers offer limited potential, whereas the Paskapoo hosts large non-saline water volumes at moderate depths – substantially deeper than most domestic / agricultural water source wells.

Under the evolving Play-Based Regulatory regime being developed by the Alberta Energy Regulator, operators are asked to prioritize use of saline waters, and to minimize use of non-saline waters from shallow aquifers and surface water bodies. Our work demonstrates that while this is possible in certain areas, elsewhere producers will need to look to non-saline sources to meet their needs. We propose that basal Paskapoo sandstones, where buried to depths of >100m (below most domestic and agricultural water wells), offer substantial volumes of technically non-saline (but nonpotable) waters that are not being accessed by other users, and meet the Regulator's preference for using deeper non-saline aquifers over shallower non-saline alternatives.

REFERENCES

Alberta Environment and Sustainable Resource Development, 2014. Geophysical wireline well logs from Alberta Environment and Sustainable Resource Development water well drill hole data holdings in log ASCII Standard (LAS) format. http://www.ags.gov.ab.ca/publications/abstracts/DIG_2014_0002.html

Andriashek, L.D., and E.J. Waters. 2005. Natural Suitability of Geological Setting for Waste Management, Alberta, Canada. Energy Resources Conservation Board, ERCB/AGS Map 330.

Atkinson, N., and S. Lyster, 2010. Bedrock topography of Alberta, Canada. Energy Resources Conservation Board, ERCB/AGS Map 550.

Bachu, S. and K. Michael, 2002. Hydrogeology and stress regime of the Upper Cretaceous-Tertiary coal-bearing strata in Alberta. Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-04.

Bachu, S., 1999. Flow systems in the Alberta Basin: patterns, types, and driving mechanisms. Bulletin of Canadian Petroleum Geology, v. 47, #4, p. 455-474.

Ball, S., 1997. Kennecott Canada Exploration Inc., New Claymore exploration block geological, geophysical, geochemical and drilling report. Assessment report submitted to Alberta Energy.

Barker, A.A, Riddell, J.T.F., Slattery, S.R., Andriashek, L.D., Moktan, H., Wallace, S., Lyster, S., Jean, G., Huff, G.F., Stewart, S.A. and Lemay, T.G., 2011. Edmonton-Calgary Corridor groundwater atlas; Energy Resources Conservation Board, ERCB/AGS Information Series 140, 90 p.

Chen, Z., S.E. Grasby, T. Hamblin and S. Xiu, 2007a. 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.

Chen, Z., S.E. Grasby, and P.R.J. Wozniak, 2007b. Paskapoo groundwater study, Part VI: aquifer transmissivity estimation and a preliminary data analysis of the Paskapoo Formation, Alberta. Geological Survey of Canada Open File 5444.

Dawson, F.M., C. Evans, R. Marsh, and B. Richardson, 1994. Uppermost Cretaceous and Tertiary strata of the Western Canada Sedimentary Basin. In: Geological Atlas of the Western Canada Sedimentary Basin, edited by G.D. Mossop and I. Shetsen. Calgary, Canadian Society of Petroleum Geologists / Alberta Research Council.

Demchuk, T.D. and L.V. Hills, 1991. A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members. Bulletin of Canadian Petroleum Geology, v. 39, p. 270-282.

Eberth, D.A. and D.R. Braman, 2012. A revised stratigraphy and depositional history for the Horseshoe Canyon Formation (Upper Cretaceous), southern Alberta Plains. Canadian Journal of Earth Sciences, v. 49, p. 1053-1086.

Edwards, W.A.D., and H.D. Budney. 2009. Alberta Sand and Gravel Deposits with Aggregate Potential. Energy Resources Conservation Board, ERCB/AGS Digital Data 2004-0034.

Farvolden, R.N. 1961. Groundwater resources Pembina area, Alberta. Research Council of Alberta Preliminary Report 61-4.

Fenton, M.M., E.J. Waters, S.M. Pawley, N. Atkinson, D.J. Utting and K. McKay, 2012. Surficial Geology of Alberta. Alberta Geological Survey Map 601.

Fulton, R.J., 1995. Materials of Canada. Geological Survey of Canada, "A" Series Map 1880A.

Grasby, S.E., Z. Chan, A.P. Hamblin, P.R.J. Wozniak, and A.R. Sweet, 2008. Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta. Canadian Journal of Earth Sciences, v. 45, p. 1502-1516.

Hamblin, A.P., 2004. Paskapoo-Porcupine Hills formations in western Alberta: synthesis of regional geology and resource potential. Geological Survey of Canada Open File 4679.

Hamblin, A.P., 2007a. Paskapoo groundwater study Part IV: detailed outcrop measured sections of the Paskapoo Formation in the Red Deer region, Alberta. Geological Survey of Canada Open File 5535.

Hamblin, A.P., 2007b. Paskapoo groundwater study Part V: detailed outcrop measured sections of the Scollard, Porcupine Hills and Paskapoo Formations in the Calgary region, Alberta. Geological Survey of Canada Open File 5536.

Hamblin, A.P., 2007c. Paskapoo groundwater study Part III: detailed core measured sections of the Paskapoo Formation in central Alberta. Geological Survey of Canada Open File 5537.

Hamblin, A.P., 2010. Paskapoo groundwater study Part VIII: detailed core measured sections of the Paskapoo Formation in two cores at Sylvan Lake, Alberta. Geological Survey of Canada Open File 6504.

Hamblin, A.P., and P.J. Lee, 1997. Upper Cretaceous, Post-Colorado Group gas resources of the Western Canada Sedimentary Basin, Interior Plains. Geological Survey of Canada Bulletin 518.

Huff, G.F., L. Woods, H. Moktan and G. Jean, 2012. Geochemistry of groundwater and springwater in the Paskapoo Formation and overlying glacial drift, south-central Alberta. Energy Resources Conservation Board / Alberta Geological Survey Open File Report 2012-05.

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

Langenberg, C.W., H. Berhane, A.R. Sweet, D. Marchioni, and L.M. Heaman, 2007. Regional correlations of the Ardley Coal Zone, Alberta. EUB / AGS Earth Sciences Report 2007-05.

Lemay, T., 2003. Chemical and physical hydrogeology of coal, mixed coal-sandstone and sandstone aquifers from coal-bearing formations in the Alberta Plains region, Alberta. EUB/AGS Earth Sciences Report 2003-04.

Lemay, T.G., and S. Guha, 2009. Compilation of Alberta Groundwater Information from Existing Maps and Data Sources. Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-02. pp. 43.

Lyster, S., and L. Andriashek, 2010. Insights into the Internal Architecture of the Paskapoo Formation. Extended Abstract, GeoCanada 2010 conference.

Lyster, S. and L.D. Andriashek, 2012. Geostatistical rendering of the architecture of hydrostratigraphic units within the Paskapoo Formation, central Alberta. Energy Resources Conservation Board / Alberta Geological Survey Bulletin 66.

Palombi, D., 2014. Review of AGS groundwater initiatives. Presentation to Integrated Assessment of Water Resources Project Steering Committee, February 27 2014.

Parks, K. and L. Adriashek, 2009. Preliminary investigation of potential, natural hydraulic pathways between the Scollard and Paskapoo formations in Alberta: implications for coalbed methane production. Energy Resources Conservation Board / Alberta Geological Survey Open File Report 2009-16.

Prior, G.J., B. Hathaway, P.M. Glombick, D.I. Pana, C.J. Banks, D.C. Hay, C.L. Schneider, M. Grobe, R. Elgr, and J.A. Weiss, 2013. Bedrock geology of Alberta. Alberta Energy Regulator, AER/AGS Map 600, 1:1,000,000.

Quartero, E.M., L.R. Bentley, and A. Leier, 2014a. Basin-scale stratigraphic architecture and Paleocene distributary fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada. Geoconvention 2014: Focus.

Quartero, E.M., D. Bechtel, A.L. Leier, and L.B. Bentley, 2014b. Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo Formation, Alberta. Canadian Journal of Earth Sciences, v. 51, p. 452-465.

Riddell, J.T.F., L.D. Andriashek, G. Jean, and S.R. Slattery, 2009. Preliminary results of sediment and bedrock coring in the Edmonton-Calgary corridor, central Alberta. Energy Resources Conservation Board / Alberta Geological Survey Open File Report 2009-17.

Slattery, S.R., A.A. Barker, L.D. Andriashek, G. Jean, S.A. Stewart, H. Moklan, and T.G. Lemay, 2011. Bedrock topography and sediment thickness mapping in the Edmonton-Calgary Corridor, central Alberta: an overview of protocols and methodologies. ERCB / AGS Open File Report 2010-12.

Tokarsky, O., 1971. Hydrogeology of the Rocky Mountain House area, Alberta. Research Council of Alberta Report 71-3.