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

DEEP SUBSURFACE AQUIFERS 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 June, 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 – Deep Subsurface Aquifer 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, any associate or affiliate of PTAC.
- The evaluation was prepared based on information available in the public domain.

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 deep subsurface 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".

In Year 1 of the study, completed June 2013, six deep saline aquifers with substantial regional extent were mapped and characterized. 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 Belloy Formation aquifer;
- Regional mapping and characterization of the Basal Belly River aquifer;
- An additional level of detailed mapping for selected areas of the Montney and Bluesky/Glauconitic regional aquifers;
- Additional work to quantify productive potential of all deep saline aquifers.

A stratigraphic database supporting this work is presented in Appendix 1, and core analysis data in Appendix 2. Even with this additional work, however, it is clear that there are areas where deep saline aquifers do not offer sufficient water source potential to support unconventional oil and gas development. Much of PRCL's effort in Year 2 therefore was focused on mapping and characterization of the Paskapoo Formation non-saline aquifer, which is summarized in the accompanying Year 2 report on shallow non-saline aquifers.

With the completion of regional deep saline aquifer characterization, future projects can build upon this work to characterize the most prospective aquifers in specific unconventional development project areas.

REGIONAL SUBSURFACE HYDROGEOLOGY OF THE WCSB

For completeness, most of this section is reproduced from the Year 1 report.

Regional hydrogeology of the Western Canada Sedimentary Basin (WCSB) is a complex product of various mechanisms including sedimentation/stratigraphic patterns, tectonic compression, compaction, erosional rebound, topography, and buoyancy. Based on the huge amount of information available from shallow water wells and deep petroleum boreholes, numerous local reports have been published, and several regional syntheses have been completed – e.g., Hitchon *et al.* (1990), Bachu and Underschultz (1995), Bachu (1999), and Anfort *et al*. (2001). Regional hydrogeology controls water movements and the accumulation of hydrocarbons in the basin, and so is important in understanding aquifers that can serve as water sources and disposal zones supporting unconventional reservoir development.

Bachu (1999) identified two basin-scale flow systems in the undeformed part of the WCSB, one located north of the Peace River Arch and the other in southern and central parts of the basin, including the current study area. Hydrostratigraphic units, consisting of major regional aquifers separated by aquitards (where fluid flow is much restricted) and aquicludes (within which fluids cannot flow) are defined primarily by porosity/permeability characteristics of their constituent sedimentary rocks (Fig. 1). Formation water flow is driven by topography in local to regional and basin-scale systems, from areas of recharge at high elevations to areas of discharge at low elevations.

In southern and central Alberta, meteoric water recharge occurs in the south where Devonian through Cretaceous aquifers crop out at high elevations in Montana (Bachu, 1999). Water flows northward and discharges at outcrops of the Grosmont Formation along the Peace River. In Cretaceous and Tertiary aquifers to the west and south, however, there is a significant component of southwestward flow, driven by underpressuring in the thick interbedded shale-dominated aquitards as they rebound in response to recent erosion (Bachu, 1999; Fig. 2, 3). Local flow systems in shallower aquifers occur throughout the basin, controlled largely by surface topography. Large-scale cross-formational flow occurs only where older aquifers subcrop beneath the sub-Cretaceous unconformity. More local cross-formational flow may occur where "pipes" such as major reef buildups allow communication between regional aquifers (Bachu, 1999).

Mesozoic clastic reservoirs host regional aquifers with conventional hydrocarbon traps through much of the basin, but to the west and downdip pass to the Deep Basin regime (Masters, 1979) (Fig. 4). Key attributes of the Deep Basin include:

- Regionally pervasive hydrocarbons, primarily gas in the WCSB, although oil occurs locally. Water occurs for the most part in irreducibly bound form associated with matrix clays and small pore spaces;

- Highly-cemented, relatively low-permeability sandstones;

- Abnormal reservoir pressures – most reservoirs are underpressured, with overpressuring limited to deeper, more remote areas;

- Reservoir “sweet spots”, featuring relatively high porosities and permeabilities associated with particular stratigraphic trends (such as conglomeratic shorelines), are common but areally limited.

Each of the Mesozoic regional aquifers reviewed in this study exhibits a westerly Deep Basin regime, and thus is prospective for water sourcing and disposal only to the east. The boundary between the Deep Basin and regional aquifer regime is unique to each aquifer, and indeed is controlled to some extent by regional stratigraphic / reservoir quality variations within aquifer units. Looking specifically at the Basal Belly River aquifer studied in Year 2, we have attempted to identify test and production data for the relatively continuous basal sandstone unit only, and have excluded tests from isolated channel sandstones higher in the section, in an effort to focus on delineating the Deep Basin in the Basal Belly River only.

WORK PLAN

PRCL's workplan for regional characterization of the Belloy and Basal Belly River aquifers, as well as more limited analysis of Montney and Bluesky units, was built upon the methodology used in Year 1. Key features include:

- A limited number of wells were selected for regional mapping, focusing on those wells having high-quality well logs, cores and sample cuttings, and appropriate test data. Regional mapping employs 1-4 wells per township in general, although there are areas where denser well control for the Basal Belly River was requested by the project Steering Committee. Stratigraphic data are presented in Appendix 1.

    - Although we have selected for wells with good test data, our searches were not exhaustive, and we have not captured all test data to support regional mapping. Followup studies to focus on high-potential areas will require additional data gathering.

- Net porous reservoir maps were constructed using formation-appropriate cutoff values.

    - Net clean sands were picked using a gamma cutoff approximately 50% of the way between pure shale and clean sandstone lines in each well.

    - Porosity cutoffs were established considering both fluid flow and core analysis data. We reviewed logs on wells that flowed appreciable fluid on DST to get an approximate idea of what porosity is associated. We compared these porosity values with porosity-permeability crossplots from core analysis data (Appendix 2) to ensure that reasonable permeability levels were being represented.

- DST data were derived from Hydrofax but stratigraphic assignments were made by PRCL. We did not systematically review Hydrofax data or interpretations, although we did review individual tests where anomalies were apparent, and where raster DST charts were available. DST data are presented in Appendix 3.

    - Interpretation of formation permeabilities from DST is semi-quantitative, following the style of PRCL regional studies, as follows:

  - EX – Excellent (>50 mD)
  - HI – High (20-50 mD)
  - RH – Relatively High (10-20 mD)
  - AV – Average (2-10 mD)
  - RL – Relatively low (0.1-2 mD)
  - LO – Low (0.01-0.1 mD)
  - VL/VN – Very Low / Virtually Nil (<0.01 mD)

- Water chemistry was characterized by screening analysis data to ensure only formation water samples are considered, and mapping total salinity values on a regional basis. Water analyses are presented in Appendix 4.

  - Project participants indicated that they are looking for reliable listing of formation water chemistries; consideration of potential water compatibility issues is not required.

Water production and disposal / injection data were analyzed in a separate section for all deep saline aquifer units (Appendix 5, 6). Our goal is to better quantify potential volumes and rates for water production and injection that could be expected from each of the major regional aquifers.

BELLOY FORMATION (Permian)

Regional Geology

The Belloy Formation is a fairly thin but laterally continuous and extensive sheet of porous sandstones and dolostones which can be mapped throughout the northern part of the study area (Naqvi, 1972; Barclay *et al.*, 1997; Fig. 5). Oil and gas are produced from a number of structural closures formed by drape over deeper reefs or basement structures, and from stratigraphic traps in erosional outliers near subcrop edges. Throughout much of the study area, however, the formation is water-bearing and presents substantial aquifer potential. To the north, the Belloy section thickens into the Dawson Creek Graben Complex, and becomes more stratigraphically intricate (Barclay *et al*., 1990).

Mixed carbonate-clastic lithologies, and complex mineralization arising from deposition in a restricted shelfal setting make detailed reservoir characterization difficult (Naqvi, 1972). In addition, upper Belloy strata may be leached in association with erosion at the overlying post-Permian unconformity.

Project Area Mapping and Reservoir Characterization

Belloy strata range up to more than 60 metres thick in the northwestern third of the study area; they reach a subcrop edge to the southeast, beneath the sub-Triassic unconformity (Fig. 6). There is one substantial and several smaller erosional outliers to the southeast. Cross-sections A-A' and B-B' illustrate continuity and dominantly clean lithologies of the Belloy; note the subcrop edge and southeasterly outlier on cross-section A-A' (Fig. 7, 8). The upper contact is picked at a hot gamma spike marking the unconformity beneath the Montney Formation (or the Nordegg to the east). The basal contact is less definitive – it was picked at the top of a tighter carbonate section interpreted to be the Debolt Formation – which is also marked by a hot gamma spike in most cases. At the scale of our regional cross-sections, no clear facies, lithological, or porosity patterns are evident.

Applying a 60API unit gamma cutoff, net clean Belloy reservoir values are little reduced from total isopach values, reaching in excess of 50m (Fig. 9). Application of a 15% sandstone density log cutoff reduces the prospective aquifer section to about 20m or less, primarily in the northeastern corner of the study area (Fig. 10). Deeper burial depths and greater burial diagenesis substantially reduce porosity values to the southwest. Core analysis data (Appendix 2; Figure 11) suggest the 15% porosity cutoff corresponds to a permeability value of about 10 mD; note, however, the large scatter at lower porosity values, reflecting variable reservoir lithologies in the Belloy. This suggests that some sections of the Belloy, particularly where carbonate-rich, might have significant permeability below the 15% map cutoff.

Figure 12, the Belloy Depth to Formation map, shows the shallowest burial depths to top Belloy to be under 1100m in the northeast, increasing steadily southwestward to >4500m at the front of the Foothills. Most substantial porous Belloy reservoir sections are at 2500m or less.

Oil and gas production data from the Belloy were compiled and plotted for wells reviewed in the study (Appendix 7, Fig. 13). Substantial oil pools at Virginia Hills and Sakwatamau are contained in stratigraphic pinchouts in the large southeastern outlier. Gas pools to the northwest occur in geographically-restricted structures, part of the Belloy/Peace River structural Eagle Play of Barclay *et al*. (1997). Examples of gas occurrences are highlighted on the regional cross-sections, although the structural traps cannot be illustrated at this scale (Fig. 7, 8).

Belloy Hydrogeology

Drillstem tests reviewed for the project are posted on Figure 14. 97 valid DSTs were identified altogether; 70 of these had useable pressures and could be plotted on a Pressure/Elevation graph (Fig. 15) (Appendix 3). Based on valid formation water salinities, a water gradient of 0.477 psi/ft (10.8 kPa/m) was applied.

Two water systems are defined on the P/E graph, and their geographic boundaries are outlined on the DST map (Fig. 14). The Regional water system covers most of the aquifer fairway, while the Northeastern water system covers a relatively small area, and is offset only slightly on the P/E graph. The division between the two systems can be traced into the Belloy southeastern outlier (Fig. 14). Three tests show significantly higher pressures than the regional gradients; these map in the middle of the Regional water system, and we do not currently have an explanation for them.

On the potentiometric surface map (Fig. 16), values are contoured using a 50 m contour interval, and each water system is contoured separately. Overall, we observe very low gradients, but potential flow is directed generally southwest to northeast.

We identified 43 valid Belloy formation water analyses, with salinities ranging from 61,494 to 169,135 mg/L TDS (Appendix 4). Values are posted and hand contoured separately within each water system (Fig. 17). Salinity values generally range between 140,000 and 160,000 mg/L through the middle of the map area, with somewhat lower values being found toward the fringes. On a Piper plot, Belloy formation waters exhibit a strong sodium chloride chemistry (Fig. 18).

Summary and Conclusions

The Belloy aquifer is geographically well defined. Reservoir quality is locally very good, although mixed carbonate/clastic lithologies cast some uncertainty on reservoir quality mapping. The Belloy grades to poorer-quality rock to the southwest. Key issues that must be addressed in considering the Belloy as a water source or disposal zone:

- It is relatively deep for a source aquifer (and, as noted below, it is not commonly used to source water).
- Oil and gas production is confined primarily to discrete and mappable structural and stratigraphic traps, and so do not pose risks to aquifer capabilities in a regional view.
- Belloy formation waters are fairly saline, measuring >100,000 mg/l TDS in most areas. Using this water as a source to support drilling and completions operations may impose an economic burden on unconventional projects.

MONTNEY FORMATION (Lower Triassic)

Montney strata accumulated on a broad continental ramp on the western flank of the North American craton, as the product of fluvial and aeolian transport of silts and fine sands from the easterly landmass (Gibson and Edwards, 1990; Davies *et al.*, 1997). Davies *et al.* (1997) interpreted a sequence stratigraphic framework, documenting stacked, prograding highstand parasequences, interrupted by a medial transgressive event separating a lower Montney member from the upper member (Fig. 19). Shoreface to subtidal facies in the east grade westward to basinal facies, which are cut by turbidite deposits associated with lowstand events.

The Montney consists of sand-rich shoreline deposits along its eastern flank, which subcrop beneath younger Triassic through Cretaceous strata. Petrographically, the Montney is a complex unit – detrital components include substantial amounts of feldspar and detrital dolomite, with common authigenic pyrite, dolomite, and locally anhydrite (Davies *et al.*, 1997). Matrix and authigenic clays are rare. It is therefore difficult to characterize Montney reservoir quality on well logs, particularly on a regional basis where mineralogic variations are accentuated by grain size and sorting trends in various facies.

High-Prospectivity Aquifer

Year 1 project work identified a high-prospectivity aquifer region along the northeastern flank of the study area (Twp 67-75, Rge 17-26W5), defined by an abundance of DSTs showing good to excellent permeabilities and formation water recoveries (Fig. 20). Net porous sandstone mapping of the entire Montney showed substantial thicknesses of high-quality reservoir in this area, but did not accurately reflect local variations arising from variably stacked shoreline sandstone reservoirs.

A porosity-permeability cross-plot from Montney core analyses in the high-prospectivity area provides further evidence of very good reservoir quality (Fig. 21). As we noted in Year 1 for the entire Montney fairway, a scattering of high-permeability, relatively low-porosity points are from dolomitic siltstones of the “Montney coquina”.

For Year 2, PRCL proposed to undertake more detailed mapping of individual sandstone reservoir bodies in the high-prospectivity area. West-east Cross-section A-A’ demonstrates westward thickening of the Montney from near the eastern subcrop edge, beneath the sub-Jurassic unconformity (Fig. 22), at depths of 1400 to 1700 metres. In the east, we see a single well-developed reservoir sandstone. Moving westward along the section, additional sandstones on the order of 10-20m thick are evident, and in some locations, two or three of these units are stacked. We have correlated them tentatively as offlapping shoreline sands, in the fashion suggested by Davies *et al*. (1997) (Fig. 19).

Refinement of the Montney DST database to include only wells in the high-prospectivity area confirmed abundant formation water recoveries, with salinities ranging from 97,400 to 176,900 mg/L TDS (Appendix 3, 4).

After consideration of Cross-section A-A’ and the refined DST data, the project Steering Committee elected not to undertake further work on characterizing Montney aquifer source and disposal potential.

Summary and Conclusions

Limited Year 2 work confirmed the presence of very good reservoir quality in stacked shoreline sandstones in the eastern “high-prospectivity” area of the Montney. Additional work was proposed to better define aquifer potential, but was not undertaken because:

- The prospective area lies generally northeast (updip) of fairways prospective for unconventional reservoir development;
- High formation water salinities make the Montney relatively unattractive as a water source.

BLUESKY / GLAUCONITIC (Lower Cretaceous)

The Bluesky / Glauconitic interval encompasses a wide variety of reservoir sandstone bodies associated with mid-Mannville transgression and subsequent regression of the Boreal Sea across the WCSB. Gas, oil, and heavy oil are produced in the western part of the basin from conventional quality reservoirs (Fig. 23). East of the Red Earth and Keg River Highlands, equivalent strata host large heavy oil and bitumen reserves.

Because the Bluesky / Glauconitic is so variable, Year 1 study focused upon identifying broad areas and stratigraphic trends where water-bearing reservoir development is sufficient to offer significant water source and disposal zone potential. Additional work was undertaken in Year 2 to better characterize aquifer potential in three areas that appeared particularly prospective from Year 1 work:

- Pembina Barrier (Twp 49-57, Rge 1-10W5)
- Sturgeon Lake (Twp 66-72, Rge 18-26W5)
- Meekwap (Twp 64-67, Rge 12-17W5)

Pembina Barrier Complex

The Pembina Barrier complex (also termed the Drayton Valley complex by Rosenthal, 1988) was deposited along a lowstand shoreline, subsequent to progradation and deposition of the Hoadley Barrier in the south (Fig. 24) (Rosenthal, 1988). Pembina / Drayton Valley reservoirs produce relatively little gas in the Deep Basin, and have not been adequately characterized in the literature. These sandstones contain substantial feldspathic and volcaniclastic grains, and thus exhibit poorer reservoir potential in areas of relatively deep burial. A detailed log study using 582 unique wells was completed.

Strike- and dip-oriented cross-sections show a fairly uniform sandier- and coarsening-upward succession across the Pembina Barrier, thinning abruptly on the northwestern and southeastern margins (Fig. 25, 26). Depth to top Bluesky ranges from 1200 to 1600 metres. A net clean sandstone isopach map (60 API unit cutoff on the gamma log) shows 8-12 metres of sandstone through much of the area (Fig. 27). Scattered thicker sand values to the southeast are more likely linked to the Hoadley Barrier complex and/or isolated valley fills. Applying a 12% sandstone porosity cutoff, we see that almost the entire clean sand section is porous in the heart of the barrier complex, but porosities diminish off the barrier axis to the northwest and southeast (Fig. 28). Porosity values and net porous sandstone thickness also decrease downdip to the southwest, toward the Deep Basin.

Core analysis data from 30 wells in the Pembina Barrier show a strong linear porosity-permeability relationship (Appendix 2, Fig. 29). We interpret this as indicative of a fairly uniform, high-quality sandstone reservoir, with abundant rock showing >10 mD permeability.

Hydrogeology

Eighty-four valid DSTs were identified for this study; 65 of these had useable pressures and could be plotted on a Pressure/Elevation graph (Fig. 30, 31) (Appendix 3). Based on valid formation water salinities, a water gradient of 0.453 psi/ft (10.2 kPa/m) was applied.

Bluesky tests plot fairly closely along the regional water gradient. A number of the deeper tests deviate significantly from the gradient, and are interpreted to lie in the downdip Deep Basin area (Fig. 30, 31). The Deep Basin updip limit line has been updated to reflect locations of these tests. A few wells deviating from the regional gradient at shallower levels appear to have experienced pressure drawdown from nearby gas-producing wells.

Most DSTs along the depositional axis of the Pembina Barrier, where porous sandstones are thick, exhibit good to excellent permeabilities (Fig. 30). Lower permeability values are more common to the far northwest and southeast, where sands are thinner.

We identified 21 valid Bluesky water analyses, with salinities ranging from 22,000 to 80,000 mg/L TDS, with an average of 58,287 mg/L (Appendix 4). Values are posted and hand contoured, and generally appear to be most saline along the depositional axis of the Pembina Barrier (Fig. 32). Bluesky formation waters exhibit a strong sodium chloride chemistry.

Sturgeon Lake

Year 1 mapping identified a multi-township area around Sturgeon Lake with substantial reservoir thicknesses and continuity in the Bluesky Formation. We undertook a scoping review, which showed what appears on logs to be an incised valley / shoreface complex, forming a relatively isolated high-quality sandstone reservoir body at 1400 to 1600 metres depth (Fig. 33). The regional Bluesky in the area consists of relatively thin, stacked shoreface sandstones with poor reservoir development (see 7-29-69-20W5, Fig. 30). While no additional geological work was undertaken, on logs this complex compares closely to the estuarine valley / shoreface complex in the Edson area documented by Hardy (1989).

Core analysis data from 22 wells shows high-quality sandstone reservoir, comparable to or even slightly better than at the Pembina Barrier (Appendix 2, Fig. 34). Logs show thick continuous sections of high-quality sandstone, most of which appear clearly wet (Fig. 33). Hydrocarbon trapping potential appears limited largely to relatively thin, isolated sandstone successions at the top of the Bluesky, which may be enhanced by structural drape over Leduc reefs in the area (e.g., 14-17-69-24W5, Fig. 33).

Meekwap / Virginia Hills

Year 1 mapping identified another multi-township area with substantial reservoir thicknesses and continuity in the Bluesky Formation, this one in the Meekwap / Virginia Hills area, at depths of 1600 to 1800 metres. Our scoping review revealed a Bluesky section 25-35m thick, which appears to consist of stacked shoreface sandstone successions, becoming more mud-rich (more distal?) to the west and east (Fig. 35). Compared to the Pembina Barrier and Sturgeon Lake sandstone bodies, the Bluesky at Meekwap appears less well-defined stratigraphically, and shows substantial continuous sections of clean porous sandstone in relatively few wells (e.g., 7-13-65-17W5, Fig. 35).

Core analysis data from 14 wells suggests Meekwap sandstones are of comparable quality to those at Pembina and Sturgeon Lake (Appendix 2, Fig. 36). However, if there are more shale interbeds at Meekwap, as suggested by well logs, tabulated K_{max} values may not reflect poorer vertical permeabilities. Aquifer quality may thus be poorer overall, despite comparable core analysis data. Log signatures suggest the Bluesky is regionally wet, although isolated stratigraphic / structural traps may exist, as described above.

Summary and Conclusions

Bluesky sandstones in the Pembina Barrier complex present highly attractive aquifer potential, spanning a 40-township area (and likely extending further northeastward from the eastern boundary of the project study area). Reservoir quality and continuity are very good; core and drillstem test data both indicate very good permeabilities and potential fluid flow rates. While waters are quite saline, they are within the limits specified by several Project partners.

At Sturgeon Lake, comparable reservoir quality and greater aquifer thicknesses are evident in the heart of an estuarine valley / shoreface complex. Additional mapping work is required to better define this aquifer, although it appears to be more areally-limited than the Pembina Barrier. While hydrogeological work was not undertaken, the Sturgeon Lake sand body appears regionally wet, with hydrocarbon occurrences in isolated thin sandstones at the top of the unit.

At Meekwap / Virginia Hills, the regional Bluesky thick is less clearly defined, and lacks the continuous clean and porous sandstone sections characterizing the Pembina and Sturgeon Lake sand bodies. While the Bluesky is regionally wet at Meekwap, interbedded tighter facies may limit vertical and lateral reservoir continuities.

BASAL BELLY RIVER

Regional Geology

The term “Basal Belly River” refers to basal thick sandstone units of the Upper Cretaceous Belly River Group clastic wedge in the subsurface of the Alberta and adjacent Saskatchewan Plains. Regional subsurface correlations show that the Basal Belly River can be divided into a series of at least seven stacked, composite, primarily regressive cycles (Hamblin and Abrahamson, 1996; Hamblin and Lee, 1997).

Figure 37 is a stratigraphic cartoon illustrating this composite section, and demonstrating that the “Basal Belly River” sandstone section is progressively younger to the east, as the result of regional progradation. Hamblin and Abrahamson (1996) produced clean sandstone isopach maps of each cycle, thus delimiting their eastern updip margins. Power and Walker (1996) undertook a similar exercise, although their allostratigraphic subdivision of the Basal Belly River differs in detail. Current work includes studies at Simon Fraser University by James MacEachern and students, refining ichnological and sedimentological interpretations of Basal Belly River strata.

The Basal Belly River was not selected for study in Year 1 because of widespread oil and gas occurrences and a known Deep Basin regime that, in our opinion, rendered it non-prospective over large areas. However, given the limitations established for many of the deeper subsurface aquifer targets in Year 1, we have re-examined these assumptions regarding the Basal Belly River in Year 2.

Mapping in the PTAC Study Area

Continuity of shoreline and associated channelized sandstones in the various Basal Belly River depositional cycles suggests that we can map regional aquifer trends with sufficient reservoir volumes to present attractive water source targets. The Basal Belly River lies at sufficient depth to be considered a deep saline aquifer beneath much of the project area, but it lies at shallow depths towards the margins of the project area, and reaches outcrop to the north.

Figure 38 illustrates the challenges in regional mapping of aquifer sandstones in the Basal Belly River. While Power and Walker (1996) have interpreted correlations of individual allomembers, the best-quality water-bearing sandstones occur at different stratigraphic levels from well to well. In order to map these sands, we have selected the best-developed shoreline sandstone in each Basal Belly River section, but have also included well-developed shoreline and channel sandstones, more than five metres thick, in adjacent allomembers lying within 10 metres of the primary unit – as illustrated in Fig. 38. While this makes identification of the map unit somewhat subjective in some wells, it allows us to capture the best reservoir units at a regional scale. Where more local mapping is undertaken, each allomember will need to be considered separately.

Regional cross-sections illustrate correlation of the Basal Belly River and associated sands throughout the study area (Fig. 39, 40, 41; see lines of section on Fig. 42). Basal Belly River tops were picked in 1111 wells (Appendix 1). On all maps, three focus areas specified by members of the Project Steering Committee are outlined in blue – at Ansell (Twp 48-54, Rge 17-21W5), Willesden Green (Twp 46-51, Rge 5-11W5), and Pembina (Twp 40-45, Rge 5-9W5).

Figure 42 maps net clean sandstone, using a 60 API unit gamma cut-off, and exhibits two, roughly orthogonal, thick trends. One trend running northwest-southeast is produced by relatively continuous shoreface / deltaic sandstones within each allomember / cycle. These are best displayed just northeast of the study area, but are overprinted by southwest-northeast thicks within the study area proper. This second set of thick clean sandstones represent continuous channelized complexes, originating in westerly source areas and feeding the primary shoreface / deltaic trends. While our regional mapping illustrates these general trends, much denser well control would be required on a local basis to satisfactorily map potential aquifer sandstones.

Figure 43, a porosity/permeability cross-plot from core analysis data (Appendix 2), shows that 15% porosity equates to permeabilities of greater than 1 mD – although the spread of values is quite wide, reflecting a variety of grain sizes and rock quality in different depositional settings. Members of the Steering Committee confirmed that 15% is an appropriate porosity cutoff to distinguish Basal Belly River sandstones that are likely to flow water at significant rates.

A net porous sandstone map for the Basal Belly River was produced by applying the 15% porosity cutoff to the net clean sandstone values (Fig. 44). It demonstrates that porous Basal Belly River sandstones are restricted largely to the northeastern part of the study area, and that porosities of <15% predominate to the southwest. Note that there is very little net porous sandstone in the Ansell and Pembina focus areas, while most of the Willesden Green block has at least some porous sandstone.

Figure 45, the Basal Belly River Depth to Formation map, shows the Basal Belly River to subcrop beneath Quaternary sediments north of Twp 70-71, and to reach depths of up to 2100m at the front of the Foothills. Most substantial porous Basal Belly River reservoir sections are at 1500m or less.

Regional Hydrogeology

Our Year 1 report reviewed regional work by Bachu and Michael (2002), which is reproduced in part here:

> Bachu and Michael (2002) reviewed 442 water analyses and 1137 DSTs from the Basal Belly River, 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 1000 mg/l close to erosional boundaries, up to >15,000 mg/l where more deeply buried. Severe underpressuring in the west corresponds to the occurrence of the Deep Basin, which was not mapped specifically by Bachu and Michael (2002). However, they did note that hydraulic head contours are generally oriented along depositional and structural strike, and appear to align with boundaries of the component regressive cycles.

PRCL Year 2 Hydrogeology Work

To verify the applicability of Bachu and Michael's work to the current study, to ensure stratigraphic consistency with PRCL tops, and to investigate the presence of a Basal Belly River Deep Basin, we undertook a regional hydrogeological analysis based upon our own datasets.

Two hundred and twenty-one Basal Belly River DSTs from 202 wells were reviewed, and 35 valid water chemistry analyses were mapped (Appendix 3, 4). Drillstem tests are mapped on Figure 46; 171 have usable pressures and were plotted on a Pressure/Elevation plot on Figure 47. DSTs fit well onto the calculated water gradient, and suggest that four separate pressure systems can be defined. Figure 46 shows systems 3 and 4 comprise relatively few wells and are confined to the extreme northwestern and southeastern corners of the study area. Systems 1 and 2 cover most of the area; note that only three DSTs define a questionable northern portion of System 2.

An anomalously-pressured Deep Basin area has been outlined to the southwest, based upon the distribution of numerous underpressured tests (falling to the left of the water gradients in Fig. 47) and fewer overpressured tests (falling to the right of the water gradients). The Deep Basin outline is highly simplified, but serves to outline an area where one would not expect to find continuous aquifers. Oil and gas production from the Basal Belly River is focused in the southeast, some in the Deep Basin and some in more conventional traps in regional water systems 1, 2, and 3 (Fig. 48). Note (as discussed in the following section), that existing water disposal wells are widely scattered, but that existing water source wells lie updip of the Deep Basin, and in areas with substantial net porous sandstone thicknesses.

A potentiometric surface map, made from calculated values based on DST data and water gradient, was hand-contoured by water system (Fig. 49). Gradients are low overall, although steeper gradients in the southeast may indicate some influence from production drawdown. In general, values are higher to the northwest, near outcrop recharge.

Water chemistry (TDS values [Appendix 4]) are plotted and hand contoured, again observing water system boundaries, on Figure 50. Values range from 2615 to 17431 mg/L, and average 8561 mg/L. In general agreement with the Bachu and

Michael (2002) work, we see fresher (lower TDS) values northwestward toward outcrop, and higher values in excess of 15,000 mg/L in the south, near the Deep Basin edge. However, the only two water analyses in regional water system 3 show fresh water (<4000 mg/L). Thus, although we see better aquifer quality in more updip areas, low salinities may complicate efforts to access these waters. On a Piper plot, we see a predominantly sodium chloride water chemistry, but some tests trend toward a sodium bicarbonate chemistry (Fig. 51).

WATER PRODUCTION AND INJECTION POTENTIAL

A major objective of Year 2 study is to better quantify the capacity of deep saline aquifers to produce water, and to accept injected waters.

Our initial approach was to consider reservoir modeling work, whereby one would model fluid flow through an aquifer body with defined characteristics to one or more wellbores. The goal of such an exercise would be to develop drilling plans for a particular aquifer to support projected project water needs over a certain development period. Reviewing the necessary input parameters, however, made apparent that useful models could not be developed in an abstract "regional" fashion because of the large number of assumptions and simplifications required.

Instead, we have examined actual water production and injection data for various formations and groups of formations, as measures of aquifer potential; these data are presented in Appendix 5 and 6. Both water production and injection are dictated to some extent by external factors – water demand in the first case, and volumes available for injection in the second – and so these data are not perfect representations of aquifer capacity. We note, for example, that existing high-capacity water source wells are clustered in the north, where they provide water to support Triassic (and older) oil pool production, and at West Pembina / Brazeau, where Devonian waters are injected for pressure support into small Nisku oil pools.

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. Three examples:

- A Bluesky water source well discussed below (3-17-65-15W5/02) was re-entered several years after the initial completion and re-completed in the Basal Belly River. Although most of the cumulative volume was produced early from the Bluesky, it is unclear what proportion of the water was produced from which formation after the recompletion. However, this well is classified as a Bluesky water source well only.

- A database search showed 9-27-47-14W5 to be a Basal Belly River water source well, with cumulative production of 662.2 e^3m^3 water since October, 1999. Careful review of well data revealed, however, that water was actually being injected into the Basal Belly River (64.0 e^3m^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.

- Some oil and gas producers are converted to water source wells at the end of their producing lives. We have found cases, as for the Montney well discussed below, where water volumes co-produced with oil and gas, prior to conversion, are reported as water source well volumes – but in fact, no water has been produced after the well status was changed.

We recommend that completion and production / injection histories be checked carefully, on a well-by-well basis, when undertaking analysis of water production and injection histories in local study areas.

WATER SOURCE WELLS

A geoSCOUT™ search for water source wells yielded 625 results for all formations over the entire study area. Several have been screened out because of low cumulative production volumes, or because they produce from stratigraphic units not addressed in our review. Seven deep saline stratigraphic units were assessed, ranging from Paleozoic to Basal Belly River; these are listed on separate worksheets in Appendix 5, and address a total of 121 water source wells.

Paleozoic

Twenty-one wells have produced water from Paleozoic formations – 18 from the Devonian, 2 from the Mississippian, and 1 from the Belloy (Appendix 5, Fig. 52). Most of these have come on production since 2005, and most are suspended, having produced less than five years. Many have been drilled to provide water for injection/pressure support into nearby Devonian oil reservoirs – particularly for Nisku producers in the West Pembina / Brazeau area, where 14 of the 21 wells are located.

The single Belloy water source well was drilled in the middle of intensive horizontal Montney development at Ante Creek, and may have served a very specific need relating to that development. The well maintained a fairly steady production rate of 127 m^3/day throughout its productive life of just under a year.

We have not analyzed Paleozoic stratigraphy or water well production in detail, as the waters are highly saline and the aquifers generally deep. Such saline waters are unlikely to be suitable for use in drilling and frac fluids under most circumstances. That being said, a number of wells have produced more than a million cubic metres of water, and clearly are capable of long-term production at rates of hundreds to >1000 m^3/day (Appendix 5, Paleozoic top producers folder).

Montney

Only one Montney water source well was listed in our database search of the study area, at 10-13-62-21W5 (Kaybob South). Closer examination shows that the listed water volume was produced during the 1963-1992 time period, when the well was producing oil and gas – and that there has been no water produced since the well status was changed to water source well. In terms of production performance, this well is really no different than many other Montney producers at Kaybob South that have watered out.

We conclude that there are no dedicated Montney water source wells in the study area upon which we can build an analysis.

Cadomin

Six water source wells have produced from the Cadomin; only two are currently classified as active (Appendix 5). Five are located along the updip edge of the Cadomin aquifer, where Cadomin sandstones exhibit their best thicknesses and reservoir quality (Fig. 53). Four of these are in the Kleskun-Puskwaskau area, where we believe they are supplying water for injection/pressure support into local oil pools.

The two best Cadomin source wells have produced more than half a million cubic metres of water at rates of several hundred cubic metres per day (Fig. 54; Appendix 5, Cadomin top producers folder). While the other four wells have produced less than 0.25 e^6m^3, they were all on stream for relatively short periods of time (<1 to 3 years).

We conclude that there is substantial water source potential from thick sections of the Cadomin in updip positions, particularly near the edge of the Fox Creek Escarpment.

Bluesky

Only three water source wells were found to have produced from the Bluesky (Appendix 5). Two of these produced relatively small volumes over periods of 1-1.5 years, while only one (3-17-65-15W5/02) is a substantial, longer-term water source well (Appendix 5, Bluesky top producers folder). It is interesting to note that 3-17 features a very regional Bluesky shoreface section, with only four metres of net porous sandstone. While the Basal Belly River was also perfed in 2011, most of the water did indeed come from the Bluesky, at rates of >100 m^3/d for the first four years, before declining to about 30 m^3/d in 2012.

The performance of the 3-17 well indicates that relatively thin but continuous Bluesky shoreface sandstones may have considerable water source potential over large areas. We expect that the thicker, continuous sands mapped in the Pembina Barrier and Sturgeon Lake and Meekwap / Virginia Hills features would exhibit significantly better performance if accessed by water source wells.

Cadotte

The Cadotte is an important source aquifer in the northern part of the study area – our search revealed 44 water source wells, including two in the Paddy Member and three in the equivalent Viking Formation in the Thorsby area in the south (Appendix 5). Figure 55 shows that all of the Cadotte / Paddy water source wells lie in the high-prospectivity aquifer area of the Cadotte, where burial depths are shallow (<1400m) and waters are moderately saline (20,000-24,000 mg/L TDS) (see maps and data in Year 1 report). It appears that many of these wells are supplying water to support production in numerous nearby Triassic oil pools.

Six Cadotte / Paddy wells have produced more than $10^6 m^3$ water, all over nine or more years, at rates of hundreds of m^3/day (or more – most early day rate data are missing) (Fig. 56; Appendix 5, Cadotte top producers folder). Many of the wells with lower cumulative volumes were on production for shorter periods of time, indicating widespread potential for day rates >100m^3/d. We would expect this magnitude of productive potential throughout the Cadotte high-prospectivity aquifer area (Fig. 55).

Cardium

The Cardium is also an important source aquifer in the northern part of the study area, with 40 water source wells (Appendix 5). Figure 57 shows that all of the Cardium water source wells lie in the updip high-prospectivity aquifer area, where burial depths are shallow (<600m) and waters are right around the saline / non-saline boundary of 4000 mg/L TDS (see maps and data in Year 1 report). It appears that, like the Cadotte, many of these wells are supplying water to support production in the numerous nearby Triassic oil pools.

Six Cardium wells have produced more than $10^6 m^3$ water, all over eight or more years (Fig. 58; Appendix 5, Cardium top producers folder). Compared to the Cadotte, peak sustained rates appear to be lower (generally around 200 m^3/day), but wells are generally onstream for longer periods – a number of current producers were put on stream in the 80's and 90's. The fact that the two top water producers from the Cardium (14-2 and 16-2-73-8W6) are about 1 km apart indicates that large volumes can potentially be withdrawn from closely-spaced wells. We would expect this magnitude of productive potential throughout the Cardium high-prospectivity aquifer area (Fig. 54).

Basal Belly River

Only ten Basal Belly River water source wells were confirmed – five abandoned or suspended, and five currently active (Appendix 5) (Fig. 48). The four in Twp 46-47 have produced relatively small volumes and are immediately adjacent to substantial oil production, the two in 49-7W5 have come on stream only in late 2013, while the two in Twp 65 have produced the most substantial volumes (Fig. 59).

The top producer, at 11-30-65-22W5/02, was completed across three stacked Basal Belly River sandstones at depths of 700-750m. The next most productive well, at 1F1/16-16-65-23W5, was perfed in the Basal Belly River, in a channel sand about 40m above, and in an upper zone that does not appear to be a sandstone (possibly fractured?). Production plots show these wells producing at tens to 100-200 m^3/d over substantial time periods (Appendix 5, Basal Belly River top producers folder).

Quantifying Belly River water source potential is more difficult than for most other regional aquifers, as the basal sandstone itself does not show potential comparable to high-prospectivity trends in units such as the Cadomin, Cadotte and Cardium. Uphole channels sands are perfed along with the basal unit in some wells. It is clear that substantial water production is possible from even moderately thick sands at relatively shallow depths in central to northeastern areas. Note, however, that water source potential appears to be absent in the Pembina focus area, and limited in Ansell and Willesden Green.

Within the overall study area, porous Basal Belly River sandstone trends have not been systematically exploited to date.

WATER DISPOSAL WELLS

A geoSCOUT search for water disposal and injection wells yielded 4334 results for all formations over the entire study area. A small number were screened out because of low cumulative production volumes, or because they produce from areally-limited aquifer formations. The remaining wells have been broken out into 10 stratigraphic units, ranging from Devonian to Basal Belly River, and are listed in separate worksheets in the Water Disposal Spreadsheet in Appendix 6. As there is no disposal in shallow aquifers, the uppermost Cretaceous, Tertiary and Quaternary aquifers were not included in this analysis.

A second screening step was undertaken to distinguish true water disposal wells from wells into which water is injected to support adjacent oil production. For each formation, all disposal and injection wells were plotted on a map, along with producing wells from the same formation. All wells lying immediately on the flanks of pools producing from the same stratigraphic unit were judged to be providing pressure support, and are called "Injection" wells in the PRCL Well Status column. Wells away from producing pools were judged to be true disposal wells, and are called "Disposal".

We screened out injection / production support wells because production management considerations strongly influence injected volumes. True disposal wells, drilled away from existing production, are still subject to available disposal volumes; however, we assume that these wells are run as close to maximum capacity as much as possible, and hence give a truer indication of injection capacity. While some of the assignments may be questioned, we feel this procedure is a good approximation on a regional basis.

In the Water Disposal spreadsheet (Appendix 6), true disposal wells are listed first on each worksheet. Injection / production support wells are also listed, but are not addressed in our discussion of disposal wells below. Oil and gas production volumes are also listed, to highlight wells which have been converted from production to water injection.

Devonian

Large water volumes are injected into many Devonian units, ranging from basal Gilwood sandstones to uppermost Wabamun platform carbonates. Most of these wells have been interpreted as water injector / pressure support, but we have judged 30 to be true disposal wells. Most of these are still active, and many have been on injection for long periods (up to 40 years). Nine have accepted more than $10^6 m^3$ water, and one Nisku well has taken $27.8x10^6 m^3$.

The longevity of many Devonian disposal wells and the high volumes accepted demonstrate excellent potential for significant disposal in various basal sands, reefs, and carbonate platforms throughout the study area.

MIssissippian

Much like the Devonian, large water volumes have been injected into Mississippian aquifers, ranging from Banff through Debolt platform carbonates. Twenty-eight of the 109 wells on the list are interpreted to be true disposal wells, many have been on stream for long periods of time, and eight have accepted more than $10^6 m^3$ water. The top Mississippian disposal well has seen $28.4x10^6 m^3$ injected over 44 years.

As for the Devonian, the longevity and high injection volumes for many Mississippian disposal wells demonstrate excellent potential for high-volume disposal in well-mapped carbonate platforms throughout the study area.

Belloy

Thirteen wells have injected large volumes of water into the Belloy at Virginia Hills and Sakwatamau. Most were converted from producers, and ten have injected more than $10^6 m^3$. Eleven other wells were judged to be true water disposal wells. Although injected volumes are smaller, there is still considerable capacity at these locations, with up to $2.11x10^6 m^3$ injected. Note in particular that 6-2-78-7W6 accepted almost $700x10^3 m^3$ in less than six years.

Figure 13 shows distribution of Belloy water disposal wells; note that all but one occur in the northeast, where net porous reservoir is thicker and more continuous (Fig. 10).

Belloy disposal potential is more limited geographically and in terms of reservoir capacity and (likely) rates compared to Mississippian and Devonian aquifers, but may offer substantial capacity in areas where the older units do not exist.

Montney

Only three of 218 Triassic wells identified were interpreted to be water disposal wells. The remainder are injectors, many converted from producers, on the flanks of long-established conventional pools like Kaybob South. A few newer wells appear to be providing pressure support for horizontal developments.

There are two Montney water disposal wells in Twp 56-22W5; water has been injected into well-developed Montney "coquina" sections, which exhibit good reservoir quality and aquifer capacity locally. These are not sufficient to give us a good measure of Montney aquifer capacity distribution, although there is clearly abundant high-quality aquifer around existing Montney oil pools such as Kaybob South (Twp 62-20W5). Interestingly, there are no disposal wells into Montney shoreline sandstone wells in the northeast – which may be attributed at least in part to little need for water disposal in this area.

Jurassic

The Jurassic worksheet in Appendix 6 encompasses a number of reservoir units, none of which were mapped as regional aquifers for this project. Most of the 105 wells listed are converted oil and gas producers providing pressure support. Modest disposal capacity is indicated in the five disposal wells with reported injection volumes, but these have not been reviewed for correct stratigraphy or mappability.

Where water disposal has taken place in Jurassic reservoirs, we can conclude that capacity is more limited and compartmentalized than for many of the older regional aquifers.

Cadomin

There are six water disposal wells in the Cadomin and no water injectors / pressure support wells, as the Cadomin produces gas almost exclusively, and largely in the Deep Basin. As we noted for Cadomin water source wells, the disposal wells are located in thick Cadomin sections along the updip edge near the Fox Creek Escarpment, where the formation is thickest and most consistently developed (Fig. 53). Water disposal capacity of at least 300-400 m^3/d is indicated in 10-10-79-10W6 and 8-32-71-26W5/03.

Bluesky / Glauconitic / Gething

There are numerous water injector / pressure support wells on the flanks of oil pools in the southern part of the study area, but only six wells appear to be true disposal wells. Their widespread distribution and widely-varying active service times make it difficult to draw any conclusions about the suitability of the Bluesky as a disposal zone, although clearly there is at least modest capacity in a number of areas.

Cadotte / Paddy / Viking

All injector / pressure support wells in this tabulation are associated with Viking oil pools in the southern part of the study area. While there are 18 disposal wells in the Cadotte and Paddy, most have accepted only modest water volumes, and only one more than $10^6 m^3$ (Fig. 55). Most of these are in the northeastern high-prospectivity aquifer area close to the more prolific water source wells. We interpret the greater water source volumes to indicate that there is more need in these areas for water source supply as opposed to disposal capacity, and that the water source volumes are likely more indicative of aquifer capacity.

Cardium

Only two out of more than 2000 wells on the Cardium list are interpreted to be water disposal wells; the rest supply pressure support to various Cardium oil pools, primarily in the Pembina / Brazeau area. Note that the two disposal wells are relatively far southwest in the regional aquifer, out of the high-prospectivity aquifer zone (Fig. 57). Further northeast, the Cardium becomes so shallow, with the potential for artesian flow in some areas (noted in Year 1 report), that disposal of large saline water volume could be risky.

Basal Belly River

Of 282 Basal Belly River water wells, only 14 were interpreted as disposal wells; the remainder provide pressure support for oil pools in the Pembina / Brazeau area. Disposal wells are widely scattered, and feature relatively modest injection volumes (Fig. 48). Note that several are located in the Deep Basin, and in areas where little or no net clean porous sandstone has been mapped.

These observations are consistent with those for water source wells – Belly River aquifer potential is less continuous and of generally poorer quality than Cadomin and Cadotte – but may be found over broader areas.

DISCUSSION – WATER NEEDS FOR UNCONVENTIONAL PLAYS

With the rollout of the Play-Based Regulatory framework by the Alberta Energy Regulator, water needs in unconventional play development areas will need to be addressed collectively across broad play fairway areas. The water management goals of the PBR are:

- 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.

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). As an example of the application of our deep saline aquifer mapping to AER's Play-Based Regulation approach, we have outlined the Fox Creek PBR Pilot Area on our composite regional aquifer summary map (Fig. 60). 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. This is the same area outline as the Pembina focus area in the Belly River assessment.

Below, we review water source and disposal potential in deep saline aquifers for each of these areas, with reference to our regional mapping work. These development areas will also be addressed in our Shallow Aquifers report.

WATER SOURCE AND DISPOSAL 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.

Water disposal volumes are generally much smaller than water sourcing needs, as flowback volumes from fracture completions are only a fraction of injected volumes. As well, companies are motivated to maximize recycling of flowback waters when engaging in a systematic development program. Finally, where water is required to support systematic waterflooding, less net water disposal should be required, as produced waters are in many cases recycled.

Members of the Project Steering Committee have expressed the desire to establish water source and disposal 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 disposal zone 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 deep saline aquifer potential:

- The northwestern third of the area shows both source and disposal potential in the Cardium, Cadotte, and Cadomin – but in the southeastern corners of their ranges, and downdip from the higher-quality mapped aquifer potential.

- High-quality Montney and Pekisko aquifers are found on the northern and eastern margins of the area, respectively, and may represent considerable disposal potential. High salinities detract from their value as source aquifers.

- High-quality Bluesky source potential at Sturgeon Lake and Meekwap are also on the margins of the area

  - Note, however, that the 3-17-65-15W5 high-volume Bluesky water producer (about 100 m^3/d for four years) is in the northeastern corner of the area.

- Basal Belly River sandstones are well developed on the northern and eastern sides of the Pilot Area. Shallow depths and good water source production history in two existing water source wells suggest good source potential over several townships. However, the Belly River appears to be too tight to offer substantial potential in the southwestern third of the area.

- There are a number of high-capacity Mississippian and Devonian water disposal wells in the area; regional mapping suggests abundant potential for more in relatively deep carbonate reefs and platforms.

Should unconventional development proceed to its apparent potential in this area, deep saline aquifers are unlikely to be adequate to provide sufficient source water, meaning that shallow aquifers and surface waters will need to play a role. Disposal capacity is abundant, although operators may need to move to deep Mississippian and Devonian aquifers.

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.

Observations regarding deep saline aquifer potential:

- High-capacity water source potential is available in the Cardium, Cadotte and Cadomin. These aquifers are at shallow to moderate depths, and contain waters with low to moderate salinities. The Bluesky also offers source potential, although it has not been quantified to the same extent.

- High-capacity water disposal potential is available in the Cadomin and Belloy.

It is conceivable that the source water needs in this area could be met completely by as few as about 15-20 wells into Cretaceous aquifers.

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 deep saline aquifer potential:

- Water source potential from deep saline aquifers is limited. The Pekisko may yield substantial flows, particularly along the updip subcrop edge, but it is relatively deep and highly saline. The Basal Belly River has definite aquifer potential in central and northeastern areas, but water source well performance in this area has been very limited compared to the volumes potentially required.

- High-capacity water disposal is available in the Pekisko and deeper in the Mississippian. While major Devonian reefs of Swan Hills and Leduc age are not developed in the area, there is disposal capacity as well in younger Devonian carbonates (Nisku and Wabamun).

Should unconventional development proceed to its apparent potential in this area, deep saline aquifers will not be adequate to provide sufficient source water, meaning that shallow aquifers and surface waters must play a role. Disposal capacity is abundant, but in relatively deep aquifers.

CONCLUSIONS AND RECOMMENDATIONS – DEEP SUBSURFACE AQUIFERS

Year 2 study of deep saline aquifers allows us to augment our Regional Aquifer Summary Map, showing areas with the best potential for systematic development of water source and disposal wells or projects (Fig. 60). The map shows the most prospective fairways for each of the eight regional aquifer units, and is colour-coded to highlight the shallowest prospective aquifer in each area.

Updated notes to accompany this map are:

- *Pekisko*: The Pekisko aquifer fairway is large and well-defined, but reservoir quality can vary abruptly over short distances as the result of complex depositional and diagenetic controls. Relatively high salinities, some potential for H_2S, and deep burial depths detract from its quality as a potential water source, but it may serve well as a disposal zone. Water disposal statistics indicate excellent disposal characteristics in Mississippian platformal carbonates, including the Pekisko.

- *Belloy*: The Belloy aquifer fairway is large and stratigraphically well-defined, but reservoir quality mapping is relatively uncertain, as mixed carbonate-clastic reservoirs are difficult to evaluate. Relatively high salinities and deep burial depths detract from its quality as a potential water source, which explains why only one Belloy water source well was located.

  Mapping shows that the Belloy is overlain by shallower aquifer fairways (Montney through Cardium) over almost its entire range, and unfortunately, therefore, it does not enlarge the geographic coverage of regional deep saline aquifers within the study area.

  The Belloy does have good qualities as a disposal zone, and may be particularly valuable in the north, where Cretaceous units are shallow.

- *Montney*: The outline of the Montney high-prospectivity aquifer remains unchanged from Year 1; Year 2 work illustrates the multi-cyclic nature of stacked shoreline sandstones in the area. Substantial burial depths and saline formation waters detract from the Montney's potential value as a water source and, not surprisingly, we found no valid examples of Montney water source wells.

  There are likely a number of townships on the northeastern flank of the study area where there are few viable shallower alternatives, leaving the Montney as perhaps the most attractive deep saline aquifer for disposal purposes, and possibly for water sourcing.

- *Cadomin*: The Cadomin aquifer is well defined by depositional and Deep Basin edges. Burial depths and salinities are higher than desirable for a water source zone, and it appears that other units such as the Cadotte and Cardium would be alternative and possibly better choices in most areas. However, we do note that relatively thick and high-quality Cadomin sands along the northeastern depositional flank are viable water source and disposal wells supporting production of deeper oil zones.

- *Bluesky / Glauconitic*: This is a highly heterogeneous interval, and has not been characterized to the same extent as units like the Cadotte, Cardium, and Cadomin. Sub-regional aquifer bodies like the Pembina Barrier and the estuarine / shoreface features at Sturgeon Lake and Virginia Hills offer local high-quality source and disposal potential. Substantial water production was measured from one relatively thin Bluesky shoreface section, indicating potential upside even in areas without mapped thicks.

- *Cadotte*: The Cadotte low- and high-prospectivity aquifer areas are tightly defined by regional mapping, although they can be refined with additional well and test control. Moderate burial depths and formation water salinities make the Cadotte a high-priority water source target in a relatively limited area, as demonstrated by the numerous existing water source wells. It is, however, generally too shallow to serve as an effective disposal zone.

- *Cardium*: The Cardium low- and high-prospectivity aquifer areas are tightly defined by regional mapping, although they can be refined with additional well and test control. Shallow burial depths and formation water salinities make the Cardium a high-priority target in a relatively limited area, as demonstrated by the numerous existing water source wells. It is, however, generally too shallow to serve as an effective disposal zone.

- *Basal Belly River*: Basal Belly River shoreline and channel sandstones exhibit good water source potential along the eastern margin of the study area. They can be mapped much further south (into the Devonian West Shale Basin) than other Cretaceous aquifers. Moving westward, however, porosity/permeability and source well performance degrade rapidly. While the Basal Belly River serves locally as a water disposal zone in deeper parts of the basin, its potential is limited.

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