GEOLOGIC CROSS-SECTIONS OF THE SPOKANE RIVER FROM COEUR D'ALENE TO THE IDAHO/ WASHINGTON STATELINE: TOWARDS A DETALED HYDROGEOLOGIC FRAMEWORK ALONG THE SOUTHERN MARGIN OF THE SPOKANE VALLEY-RATHDRUM PRAIRIE

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Acknowledgments

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1.0 Summary

The Spokane Valley-Rathdrum Prairie (SVRP) aquifer is primarily viewed and modeled as an unconfined valley aquifer comprised of Quaternary sediments. Geophysical, geologic, and hydrologic work on the SVRP aquifer recently led to a developed regional geology and calibrated, alternative hydrological models (Kahle and Bartolino, 2007; Hsieh et al., 2007; Kahle et al., 2005), however significant questions remain, specifically in the southern Rathdrum Prairie region, where along with other surface water bodies (i.e., Fernan Lake and Coeur d'Alene Lake), the Spokane River has been identified as a major contributor of groundwater to the SVRP aquifer.

This report shows the geology along the Spokane River from the Idaho-Washington State line to Lake Coeur d'Alene using eighteen primary north-south, four to five mile long interpretive cross-sections and associated strip maps. These cross-sections detail about fifteen miles of the southern SVRP aquifer margin, and show a selection from about one thousand available driller's well logs from over 60 Public Land Survey (PLS) sections. The driller's logs were balanced with published surficial and geologic maps showing the exact or estimated locations of wells, their lithology, stratigraphy, and other data of geological and hydrological interest.

The geologic cross-sections represent working hypotheses of directly measured and locally projected data that can be used as a guide to the geohydrologic framework from Fernan Lake (east of Coeur d'Alene) to the head of the Spokane River and Blackwell Island (~3 miles east to west in Coeur d'Alene area), and from the Blackwell Island/Marina Yacht Club area along the Spokane River to the Idaho/Washington State line in the west (~11 miles). Analyses of geologic cross-sections allowed for the definition of six zones in the study area that share similar geologic and hydrogeologic features. These zones include four segments along the Spokane River and two areas near Coeur d'Alene Lake that share gross lithology, depth of unsaturated and saturated Quaternary sediments, presence or absence, and depth to Miocene basalts and associated tight Latah Formation sediments, and estimated depth to crystalline basement (the latter being highly speculative with greater distance away from the

range fronts, although finding some control and corroboration with previous geophysical studies).

The base of the SVRP aquifer becomes highly speculative with regard to which geologic system forms the actual base of the unconfined aquifer as one moves northward away from shallow marginal areas below the Spokane River along a bounding range front, and from a subsurface basement saddle below the northern margin of Lake Coeur d'Alene. Quaternary SVRP aquifer sediments in the study taper from about 1000 ft to a feather edge of perched sediments along the range fronts. Complex cut and fill geometries comprised of sands and gravels form the majority of the known upper SVRP aquifer (upper ~350 ft), although fine-grained silt and clay occur both as mixtures within the matrix of these sediments and as distinct interbedded units, especially at depth. Miocene sandy clays, and less common sorted sands and gravels occur in the Latah Formation, which together with Columbia River Basalts discontinuously underlie Quaternary sediments. Differentiation between the Quaternary and Miocene sedimentary units in driller's well logs is important as it marks one of the SVRP aquifer limits; this can be a very clear to more obscure boundary the deeper and more basin-ward the wells are. Both the Miocene and Quaternary depositional systems show strong lateral buttress contacts within paleovalley systems (i.e., are laterally discontinuous and occur over irregular unconformities). Furthermore, it is also unknown whether there is porosity and permeability partitioning within the mid and upper levels of the SVRP aquifer or if even a locally confined, aquifer occurs directly below it (although this remains outside of the reach of the more shallow wells used in this project).

This study provides working hydrogeologic correlations along the southern margin of the SVRP aquifer, such that we can now: 1) more easily visualize and evaluate partly spatially referenced data within interpretive geologic cross-sections that both consolidate, summarize, and push the limits of known data, 2) cross-check and evaluate lithology and hydrological data from drillers well logs with geologic maps and other data sets, and 3) decide what are the next steps towards refining surface and subsurface water quantity, quality and flow questions within the study area.

This project locally develops an established regional geohistory (summarized in Kahle et al., 2005 and Kahle and Bartolino, 2007) and initiates some primitive steps towards defining a sequence stratigraphic framework for Quaternary valley fill sediments. The cross-sections show areas within these sediments where clays maybe associated with glacial lake deposits, where calcareous/or clay cementation occurs indicative of changing water tables or later physical clay infilling of sand and gravel matrixes near the Spokane River. A working knowledge of these factors together with a better sense of the genetic stratigraphy would provide a better understanding of compartmentalization of aquifer porosity and permeability[1]. Ultimately, the data and cross-sections in this study provide: 1) localized hydrogeological reviews of the Spokane River and Coeur d'Alene Lake area; 2) a surficial relative stratigraphy developed after the field work and surficial mapping of Breckenridge and Othberg (1998a; 1999b); 3) a very tentative deeper stratigraphy based on depth, general sediment type, and probable relative age (i.e., using basic geologic principles, regional analogues, and a sort of "sequential catastrophist" uniformitarianism, required when thinking about the unusual Missoula flood geohistory), and; 4) a generalized subsurface map summarizing some of the geological phenomena observed. Any further sedimentological efforts would require more field work, more review of Missoula flood-like catastrophic analogues, and primarily more detailed and better controlled well data.

2.0 Problems and Project Objectives

Kahle et al. (2005) and Kahle and Bartolino (2007) recently provided a large-scale geologic history, hydrogeologic framework, and water budget components for the entire Spokane Valley-Rathdrum Prairie (SVRP) aquifer and surrounding highlands. Using previously published geologic maps, well logs, and hydrological studies, their work synthesized the hydrogeology, which was concurrently developed into a ground water flow model by Hsieh et al. (2007). Recharge estimates to the aquifer (primarily during low-flow late summer conditions) included some seepage from Lake Coeur d'Alene and Lake Fernan, and significant recharge from the Spokane River. This study was developed in an effort to better

[1] Note: While fine-grained sediments associated with late stage catastrophic Missoula flood events or possibly intra-flood lacustrine conditions are observed/suspected in the study area, such fine gained sediments are confirmed to have resulted in a confined aquifer below the upper SVRP aquifer in the Hillyard trough, near Spokane (Kahle and Bartolino, 2007).

characterize local geology, potential pathways of recharge, and to address a few of the many SVRP aquifer data needs mentioned in Kahle et al. (2005). These include: 1) Determination of the conditions (saturated or unsaturated) beneath the lakes (i.e., Lake Coeur d'Alene); 2) Characterization of the cross-sectional area and hydrostratigraphy of the aquifer at key locations; 3) Better definition of cross-sectional area connecting lakes to the aquifer and better characterization of the hydraulic properties of sediments and ground-water flow paths across this interface; 4) Detailed deep drilling to identify the presence or absence of fine-grained layers, their thickness, and the true depth to the bottom of the aquifer.

Primary objectives included identification and locations and depth characteristics for zones where the subsurface is dominated by: 1) Relatively fine-grained Quaternary sediments (fine sand, silt and clay); 2) Medium-grained Quaternary sediments (medium to coarse sand); 3) Coarse-grained Quaternary sediments (gravel and boulders); 4) Miocene sediments of the Latah Formation (clay, sandy clay, sand, and minor gravel, and 5) Miocene volcanics of the Columbia River Basalt Group (CRBG) that may include irregular saprolites, and which together with interbedded Latah Formation are not considered part of the SVRP aquifer. Finally, to build on and cross-examine the large scaled cross-sections of Kahle and Bartolino (2007), we worked to identify the crystalline basement of the SVRP paleovalley floor, comprised of metamorphic, meta-sedimentary, and igneous rocks of Proterozoic, Mesozoic and Eocene age. These rocks may include irregularly preserved, clay-bearing, deeply altered regolith associated with pre-Miocene relief and subearial exposure and form a part sediment/part rock hydrologic unit typically not considered in other works, below what are generally considered highly porous and permeable Quaternary SVRP aquifer sediments.

Many of these key SVRP aquifer defining elements have been previously investigated using geophysics. Seismic and gravity surveys (Adema 1999, Sprenke, 2005; Oldow and Sprenke, 2006; Mark Nell, 2008, in prep.) have been especially useful, although inaccuracies may result with inaccurate rock densities. There is virtually no deep well data as one moves away from the uplands of the SVRP margin (except for some very private water wells drilled deep into highland areas outside of the SVRP aquifer). Even after 50 years of intermittent geophysical study, with few well that penetrate valley fill down to the basement, the deep subsurface geology of many parts of the SVRP aquifer remains somewhat conjectural. This study develops a geological framework using traditional cross-section techniques and estimated extrapolations that were then compared with existing geophysics (e.g., Adema, 1999; Oldow and Sprenke, 2006), and can be tested or ground-truthed by subsequent geophysics and/or drilling. Each cross-section includes a graphic synthesis of multiple lines of evidence that also must hang on decisions made in preceding cross-sections; ergo, the methodology of cross-section construction is critical, arduous and tenuous. Each cross-section will help investigators to better understand and predict local elements of the SVRP aquifer such as local depth of unsaturated and saturated sediments and potential vertical and horizontal connectivity. Thus the primary goal is a product that is both a synopsis of hydrogeological data along a specific interval, a comparison with geophysical transects where possible, and testable local interpretations.

3.0 Study Area Location

The margin of the SVRP aquifer, from the Coeur d'Alene Mountains and Fernan and Coeur d'Alene lakes in the east through Post Falls to the Idaho-Washington Stateline in the west is the focus of this report (Figs. 1 and 2). Mountains border the southern and eastern margins of the study area (e.g., Blossom Mountain, Blackwell Hill, Potlatch Hill and Best Mountain, Figs. 3 and 4, Plate 2) and the central Rathdrum Prairie bounds the northern limit of the study area (probably the deepest part of the SVRP aquifer; Oldow and Sprenke, 2006). The study area was extended in the west to reach the northern margin of the Rathdrum Prairie, where mountains extend down from the Mount Spokane area, and where valley constriction occurs (i.e., beginning of the Spokane Valley). The study area and cross-sections locations are shown with increasing details and topographic detail in Figs. 1, 2, 3 and 4 and Plate 2.

4.0 Hydrogeology and geomorphology in the study area

The SVRP aquifer is primarily viewed as an unconfined valley aquifer. The Spokane River from near Coeur d'Alene Lake to Flora Road in the Spokane Valley (~6 miles west of the Idaho/Washington State line) was identified as one of two loosing reaches in the region, where recharge into the SVRP aquifer from stream flow loss was estimated at 606 ft^3/sec (Kahle and Bartolino, 2007). Of the total annual estimated inflow to the aquifer from all sources (1,471ft^3/s) the latter represents a significant percentage. Also, the nine major adjoining lakes around the margins of the SVRP aquifer, Fernan and Coeur d'Alene lakes were estimated to contribute 13 and 37 ft^3/sec respectively. The study area contains this loosing reach of the Spokane River, but it is unknown which segments are hydrogeologically similar and which might discharge more or less water to the SVRP aquifer (especially during high flow conditions).

The pre-Miocene, Miocene, and Quaternary geologic history and hydrogeologic units of the region has been reviewed at great length by Kahle and Bartolino (2005; 2007; and authors therein). We do not see a need here to repeat this detailed geological background other to than to accentuate some specific points of interest with regard to Quaternary geology and Holocene geomorphology that pertain specifically to the Quaternary sediments in the study area after Box and Wallace (2002). These include:

- The SVRP valley, generally devoid of surface drainage because of the permeable character of these glacial outburst flood deposits, preserves bedforms developed during the repeated late Pleistocene catastrophic glacial outburst floods.

- These bedforms include the primary deepest channel (thalweg), interconnected secondary channels, intrachannel bars, channel margin bars, eddy bars, and erosional bedforms.

- The present surface features on the Rathdrum Prairie developed during the last one or few outburst floods between 13,000 and 11,000 years ago.

- The outburst flood deposits in the thalweg consist of 3-5 m (10-16 foot) thick layers of cobble to boulder gravel with foreset layering inclined downstream. Large-boulder lag horizons (1-3 m diameter boulders) occur at the base of some of the layers.

- The Spokane River outflow from Lake Coeur d'Alene follows a secondary outburst flood channel until it intersects the primary thalweg channel west of the Idaho-Washington state line. (see Box and Wallace, Figure, 3)

- The Spokane River flows out of the northern end of Lake Coeur d'Alene. The flow rate of the Spokane River out of the lake is controlled by a bedrock-incised reach of the river at Post Falls, Idaho.

- The Spokane River significantly interchanges water with the groundwater of the Spokane Aquifer. During low-flow periods, stream flow can triple between Post Falls and downtown Spokane due to inflow of groundwater to the river.

5.0 Methodology

Balanced hydrogeological cross-sections created together with topographic and geologic strip maps were developed for the purpose of local synopsis. The cross-sections in this work represent weighed syntheses of geomorphologic and geological maps compiled together with carefully reviewed, exactly to approximately located driller's well logs to provide elevation-controlled, partly ground-truthed, and best-fit interpretations of the subsurface. These visual summations help to test and refine previous work, and were used in conjunction with geophysical studies (i.e., parts of profiles produced by Adema, 1999 are noted with the cross-sections) and regional geologic cross-sections developed by (Kahle and Bartolino, 2007; their plate 2). [2]

Eighteen primary north-south, 4 to 5 mile long interpretive cross-sections were integrated with strip maps so investigators can directly follow the complications of well projection onto 2-dimensional space. East to west, these detail about 15 miles of the southern SVRP aquifer margin, and show the locations of driller's well logs included in each section (Figs. 2, 3, and 4 and Plate 2). General method of projection of well data into lines of section is shown in Figure 5. These cross-sections together with strip maps are generally about 24 inches long by 20 inches wide (horizontal scale is 1 inch = 1056 ft, or 5 inches = one mile) and were drawn with x8.5 vertical exaggeration (vertical scale is 1 inch = 125 ft). Two additional cross-sections (A-A' and B-B') were developed to dissect Blackwell Island near Coeur d'Alene; these summarize shallow wells (e.g., wells at the Marina Yacht Club), provide estimations of the deep subsurface, and add context to hydrological work near the head of the Spokane River (see Robin Nimmer's report). These cross-sections were drawn with x42 vertical exaggeration; B-B' is 48" tall x 22" wide, A-A' is 17" tall x 11" wide. All cross-sections were drawn in Canvas, and converted to Adobe PFDs.

[2] Note initial projections to crystalline basement were made using available well data and slope of nearby highlands; these estimates were later compared with, and in some cases adjusted to earlier geophysical estimates to hard rock basement at specific well sites. Previous estimates to basement [sediment/rock transition] are clearly labeled within associated cross-sections.

5.1 Cross-section Construction

Geologic Maps and Driller's Logs

Cross-sections were primarily constructed using surficial geologic maps of the Post Falls and Coeur d'Alene 71/2 minute Quadrangles of Breckenridge and Othberg (2004; 1999; 1998). Where bedrock geology (other than basalt) was undifferentiated in these maps (symbolized by their map unit "S"), the smaller-scaled geologic map of Lewis et al. (2002) provided updated interpretations and differentiated geologic units. 1097 or more well logs from 57+Public Land Survey (PLS) sections were reviewed from primarily the following Townships and Ranges 51N 05W, 50N 05W, 51N 04W, 50N 04W, and sections either side of these (Fig. 2). USGS located well logs are shown in Figures 3 and 4, Plates 1 and 2, and on maps associated with each cross-section. Well logs were organized, sorted, rejected, and accepted; in some areas very few well logs were available (e.g., cross-section 30 near Coeur d'Alene), whereas in others (e.g., cross-section 17, near Harbor Island) a large number of potentially representative sections were available and had to be creatively adapted to a two dimensional cross-section. In some cases this required clearly showing the well log to occur in front of or behind the line of projection by a significant distance (e.g., by ~1/2 mile), although this was mostly avoided. Most data points were simply projected into the line of section following the method outlined in Figure 5. Note that initially we placed only those wells used in the cross-section on the associated strip maps, although in some sections additional wells locations were placed on the maps. The number of well logs in each PLS section is indicated as a small number placed directly next to the section numbers on all the strip maps.

Overall topographic relief and surficial geology was held true to the exact section line, although there are some departures from this for the purpose of showing the greatest amount of pertinent data and due to slight spatial inaccuracies. We maintain that such inconsistencies are ultimately inconsequential to final interpretations, and that potential errors have been minimized.

Prone to both accuracies, mistake, and mis-location, ambiguous interpretation and surprises in general, driller's logs were selected for those reaching deeper intervals, those of quality lithological data, those that appeared to be accurately located or had a well address, and those that correlated more consistently with nearby wells and outcrop data. In many cases well logs were ignored based on their unlikely geology or in some cases obvious mis-location.[3] Those well logs that were USGS located (complete with latitude and longitude and land surface altitude, using the NAD 83, North American Datum or 1983 and NAVD88 North American Vertical Datum of 1988; see Kahle and Bartolino, Table 3) are shown on the strip maps accompanying each cross-section as red circles (see also Plate 2 for their locations). Those well logs that were not located received estimated locations (typically a PLS Quarter/Quarter Section as shown by blue circles), although sometimes it was possible to match more closely where a well occurred (e.g., using building locations in rural areas found via Google Earth Satellite information). In some cases almost exact locations using a PLS Quarter/ Quarter/Quarter section, or by searching for a well address. Mapquest, Google Earth, National Geographic Topo and topographic quadrangle contour lines were used to verify driller's locations and to estimate elevation.

Complete with geographic location on the strip maps, all well logs in the cross-sections appear labeled with 1) surface elevation, 2) name of the owner, 3) driller's name, 4) year drilling was complete, 5) maximum depth reached, and 6) PLS Section location. Along with a well's lithology information is included a) saturated sediments (indicated in blue), b) static water level (indicated with a blue line), and 3) gallons per minute (written next to the latter). In the case of USGS located wells (highlighted in red text), their corresponding name is included (found also Kahle and Bartolino, 2007; Table 3), together with their latitude, longitude, and exact elevation.

Most wells conformed well enough to the selected topographic line of section, however all wells were hung from their determined elevations (so they often appear above or below the topographic surface). Although the cross-sections should be viewed as a geologic guide with limitations, we are confident that the many overlaid human processes involved in the construction of these cross-sections actually work to produce a reasonable hydrogeologic picture (i.e., assumptions stacked upon assumptions work [barring new data] !). Although a number of physical data point locations may turn out to be incorrect, if the well logs were of

[3] We especially applaud the well logging and details provided by the driller Zinkgraf.

great interest (yet contained mediocre location data), in many cases we placed them onto the cross-section anyway. Finally we attempted to hang all the well logs exactly, or to within 5 ft to 15 ft of their actual elevation. Thus, each cross-section carries a wealth of referenced and usable information.

Order of Construction

Cross-sections were constructed starting with cross-section number 22 near Coeur d'Alene, which bisects Blackwell Hill. Grader initially spent some time familiarizing himself with the Spokane River, local topography and outcrops on Blackwell Hill. Ideally more time would have been spent on active drilling sites or doing more field work, but this was not possible due to the significant time involved building this cross-section data base. Cross-section construction continued towards cross-section number 34 (where Interstate 90 exits east of Coeur d'Alene) and towards cross-section number 11, close to Post Falls (where the Spokane River begins to partially flow directly over crystalline basement). Cross-section construction later continued towards the western most part of the study area (sections 9 through 1, Fig. 2), where cross–sections were extended a mile or two to cross most or all of the Rathdrum Prairie where the valley narrows near to the Idaho/Washington state line. The order of construction is important because what was learned at each cross-section was partly reapplied, adapted, and adjusted to the neighboring sections to accommodate and show changes in the geology, and to conform to new basement projections. The basement projections of neighboring cross-sections are shown in most cases as light grey dashed lines.

Once all cross-sections had been created, we worked methodically back from cross-section number 1 in the west towards cross-section number 34, checking total depths of well logs, reinterpreting/adjusting estimated depth and geometry of SVRP sediments, and placing gross lithology types and depositional environment types (see larger italic text within cross-sections). A number of human generated errors were corrected by this editing process.

The purpose of creating traditional cross-sections allows for synthesis and insight into the hydrogeological space of the aquifer, although the result is not always unique or reproducible. A trade off was made in favor of making hand drawn cross-sections over imputing data into excel files and using 3D imaging software. Although the latter may have been less time consuming and would have resulted in a shareable dataset, the information derived may ultimately have required the same kinds of qualitative projections employed using the traditional method.

Deep SVRP aquifer boundary

Of great interest is the deeper SVRP aquifer boundary, although there is simply a lack of data at depth especially as on moves north of the Spokane River / upland margin. Some of the deeper, main lithological breaks are either not reached or if they are reached at depths typically over 200-300 ft, their transitions are either ambiguous or potentially confused by three very different (temporal and physical) units that bear clay. In some wells lithology breaks are fairly clear (e.g., "basalt," "granite," or "quartzite"), only in some cases it is not clear whether a well ends in crystalline granitic basement, or a basalt layer, or simply within a very large meter to house sized boulder. On the other hand, in some cross-sections true basement versus a final boulder at T.D. (total depth or refusal) can be easily differentiated based on comparison to nearby well logs. Driller's logs that penetrated into the basement and convincingly encountered and identified specific rock types (e.g., shale, schist or gneiss) further helped to inform basement geometry under the SVRP aquifer and bedrock composition of nearby highlands.

Water Saturated vs. Unsaturated Sediment Level method

Water levels and approximate saturated/unsaturated sediments shown in all the cross-sections are derived from simulated water levels shown in Hsieh et al. (2007; Figure 42). In the western cross-sections of the study area this is shown as a fairly flat surface across the entire Rathdrum Prairie subsurface (e.g., at 1983 ft in cross-section number 3). Gradual elevation increases in this surface occur towards the eastern end of the study area. In cross-sections near Coeur d'Alene this surface tilts more sharply from higher elevations in the south to lower elevations in the northern limits of the cross-sections. Overall, this gross, east to west sloping surface fits individual well logs showing saturated sediments (see indicated blue fill on the bottom right of each well), although there appear to be some significant local departures from the regional trend (of potential hydrologic interest). The chosen aquifer water levels in each cross-section is a dashed dark blue line labeled with one or more elevation points (in blue). For comparison between cross-sections of physical relief, river surface, and subsurface water a constant datum (a dashed pink line at 2125 ft) is shown in each cross-section (corresponding to average water level in Lake Coeur d'Alene). Also a blue line is drawn in each cross-sections at 2600 ft marking the highest inundation of Missoula Flood waters.

6.0 Observations

Cross-section interpretation and working differentiation of five stratiform Quaternary intervals – Q1 through Q5.

Basically there are three rock or sediment groups encountered in the subsurface: Ancient crystalline basement comprised of Proterozoic metamorphic rocks and Cretaceous and Eocene intrusive rocks (overlain by decomposed regolith which at many locations may be missing), Miocene Columbia River Basalt Group and associated Latah Formation sediments, and Quaternary Sediments (the primary SVRP aquifer). These units and the explanation to the cross-sections are shown in Appendix 1. Other surficial units ranging into the Holocene are also included in the cross-sections, however most of the valley fill aquifer sediments is dominated by catastrophic Pleistocene Missoula flood sediments that are in total about 1000 ft thick in the deeper part of the study area and thin to a feather edge along much of the southern range front. In general, the aquifer ~100 to 300 ft below the Rathdrum surface is known for its very coarse-grained texture (Kahle and Bartolino, 2007), and several large producing municipal wells are shown along with small private water wells on the cross-sections.

Most of the well logs in the study area encountered sandy gravel or gravelly sand, with occasional boulders and generally higher components of clay and silt with depth and towards the Rathdrum Prairie valley sides. Towards the center of the Rathdrum Valley in the study area, Pleistocene sediments thin from about 700 ft near the Idaho/Washington Stateline, where the valley is horizontally and laterally constricted, and increase to about 1000 ft between Post Falls and Coeur d'Alene, especially north and east of Ross Point (Figure 4). In the Coeur d'Alene area they measure 600 ft thinning to about 200 ft near the head of the

Spokane River.[4] Throughout the study area sediments thin to a feather edge over basement or contact basement in a steeped buttressed manner along the southern range front. Based on abundant well evidence, quaternary sediments in the eastern part of the study are thought to overlie a ragged, erosional unconformity with Miocene Rocks. It is not known if they occur in the deep subsurface to the north, but we suspect if they did they were deeply excavated there (see also maps of Sprenke 2006; Oldow and Sprenke, 2006; and cross sections/figures herein).

Due to the cut and fill nature of these periglacial mega-flood and waning stage catastrophic fluvial and in part lacustrine quaternary sediments, sharp lateral facies changes are expected and observed in the cross-sections (suggesting possible variations in porosity). As rather coarse sands and gravels dominate the upper part of the Quaternary stratigraphy, we suggest that water encountering these fine-grained layers (e.g. clays and hard pan of 1 to 10 ft) would be easily bypassed following vertical and horizontal conduits of abundant coarse-grained facies. However, along most of the Spokane River, areas of "cementation" and fine-grained silt and clay fractions are consistently reported in nearby well logs, in otherwise fairly coarse sands and gravels suggesting degrees of matrix clogging in sediments proximal to the river.

Below we outline how the shallow, intermediate and deep Quaternary aquifer sediments were interpreted. Quaternary glacial flood and less well understood deeper valley fill sediments were divided into a working scheme of five approximately stratiform intervals that young-upward (from Q1 through Q5; Appendix 1).

[4] Possibly some of the basal parts of this thickness include Oligocene sediments and/or Miocene sediments without associated basalt flows at depth. We suggest this because the original SVRP paleovalley was a structural basin that would have accommodated both coarse and fine sediments, before being excavated by the Missoula Floods. Such sediments might be difficult to distinguish from Pleistocene sediments using geophysical techniques.

Working Differentiation of Five Stratiform Quaternary Intervals

Intervals Q0, Q1 and Q2: Intervals Q1 and Q2 represent about 450 ft of basal to intermediate lower Pleistocene valley fill sediments occurring between the projected base of the paleovalley (about 1400 ft in the study area to about 1800 ft or 1900 ft). These intervals are based on little data. On some cross-sections an interval "Q0" is shown below Q1/Q2, indicative of an area in the subsurface where it is not clear whether it represents: 1) Quaternary sedimentary fill, 2) Miocene sediments and possible Basalts (especially widespread in the Coeur d'Alene area), or 3) a hybrid lithology comprised of crystalline basement seen in many well logs along the SVRP margin that is essentially a decomposed, altered sediment composed of thick clays bearing altered rock fragments. The latter unit, where it occurs in well logs is shown in green and given the label Ts/YXgn/Kog (e.g., cross-section number 17). This interval represents a supra bedrock paleosol unconformity representative of Paleogene exposure that, where preserved, may be up to 200 ft thick, the density of which may not have been considered in previous geophysical studies.

Intervals Q1 and Q2 are shown as light gray occurring above crystalline basement or Miocene basalts and deposits that survived the erosional power of Missoula Flood events. They are a "gray area." Q1/Q2 are very poorly understood, associated with massive boulders, sand and gravel and are probably saturated. An attempt to differentiate Q1 and Q2 is shown differentiated in cross-section 22. These intervals are typically shown as a single unit Q1/Q2, but two or many more syn- or post-flood, valley-filling depositional events are implied. Q2 shows some evidence for fine-grained sediments, suggesting lower energy depositional regimes (e.g., base of cross-section B-B', cross-sections 25, 26, 28). Fine-grained layers also occur higher in the stratigraphic succession in Q3, and any intervals of 1 or more feet are indicated in the cross-sections, typically accentuated for visual observation by their a color (i.e., a clay symbol with brown, blue, or gray color). As observed Kahle and Bartolino (2007), there are intervals of significant clay thickness, but for the most part they are discontinuous (and fairly easily distinguished from the Latah Formation). As these authors describe, alternating beds of Pleistocene lake and flood deposits occur at considerable depth (400-600 ft) throughout much of the SVRP valley and we agree with their analysis why: multiple episodes of fine-grained sediment deposition followed by subsequent scour and deposition of coarse-grained material (whether subaqueously in a glacial lake or subearially during a post glacial lake mega flood).

Intervals Q3 and Q4: Intervals Q3 and Q4 represent about 250 ft of intermediate valley fill (i.e., middle Pleistocene sediments comprised primarily of sand and gravel) occurring between 1800 ft and 2000 ft or 2100 ft. Intervals Q3 and Q4 (or the general composite interval Q3/Q4) extends from the bottom of known mostly unsaturated surficial units (Q5, upper Q4) to the top of Q2. Q4 generally is very similar to the overlying coarser sands and gravels of Q5. Q3 in most cross-sections is a continuation of the same coarser facies deeper into the subsurface, although there is evidence of finer-grained units including thick, medium to fine sand bodies, silt and clay in the Coeur d'Alene area (see cross-sections #22, 24, 26 and 28 for an attempt to differentiate these intervals and facies therein). Whereas the upper Q4 interval remains mostly unsaturated, interval Q3 is typically entirely saturated.

The color scheme for interval Q3/Q4 is at first confusing but is explained here: Q4 is a light blue unit that fades to white and light gray directly above a dashed dark blue line that shows the approximate vadose to saturated sediment transition (approximate water table). Below this line, what is mainly interval Q3, sediments are given a turquoise color that fades to gray approximately near the transition to Interval Q1/Q2. Plenty of well log evidence shows that sediments at below this depth are indeed also saturated.

Interval Q5: Interval Q5 represents about 250 ft (or much, much less) of upper Pleistocene sediments associated with sediments and later flood processes mapped on the surface. They range from about 2100 ft elevation to about 2400 ft, where they occur at the top of Ross Point, an isolated relict bar facies that was later cut away by successive upper Pleistocene erosional events).[5] The upper 5 to 100+ ft of sediments on the Rathdrum Prairie were correlated according to their mapped distribution and suggested thickness (see Breckenridge and Othberg, 1998; 1999). In many cases their thickness was extended to ~150 ft below the Rathdrum Prairie. Q5 sediments are shown in light greens (representing younger, overlying

[5] Note: that Ross Point comes to within 200 feet of the maximum flood inundation level (2600' ft), yet is the oldest Q5 sediment (i.e. earliest recognized flood deposit in the area) with presumably relatively deep roots and composed of primarily fine sand and gravel (?). Given the intersection of a number of curious feature near to Ross Point, I can't help thinking that this interesting geomorphological feature isn't there because of some basement caused hydraulic underneath or near it (see Figure 6).

channel fill and fan sediments), blues and progressively darker blues (for generally older proximal and distal Quaternary sediments).

Interval Q5 is comprised primarily of sand and gravel sediments that are further divided into named units Q5a through Q5f, thus a sequence of relative ages is implicit. This nomenclature is designed to help the reader get away from the plethora of named units to instead focus the relatively younger age of each Quaternary unit (graphically expressed in all the cross-sections of Appendix 1). Q5 sediments are named following their area of initial identification and mapping (i.e., for example "Qdg" = Gravel of Dalton Gardens = proximal high energy deposits in the Coeur d'Alene area = Q5e, occurring spatially/temporally above/after Q5d and below/before Q5f; see "correlation of map units" in Breckenridge and Othberg, 1998; 1999).

For the most part, the cross-sections remain approximately true to the colors chosen in the surficial maps following Breckenridge and Othberg, (1998; 1999; see Appendix 1). In some cases the darker blue color representing relatively older units does not work, for example distal deposits perched along valley sides and tributaries, which are correlative or directly time-equivalent to other Q5 units (e.g., Qgrv, Qsrv, and Qspv, which can be seen to shallowly mantle bedrock along the southern and western margins of the study area in cross-sections 1 through 17). Most of these kinds of valley margin deposits are understood to have formed in eddy bar flood environments (see descriptions in Appendix 1). Other marginal "perched distal deposits" include gravels further west in the Coeur d'Alene Quadrangle (e.g., see Qgc on Blackwell Hill in Cross section 22), which may occur high above the Rathdrum Prairie. These tend to be a coarser, are given a lighter green color indicating a younger relative age, although their origin and timing is probably older. These "undivided gravels" also occur on the Rathdrum Prairie as late, "lower flow regime channelway deposits cut into older high energy channels and bar features." As "undivided gravels" partly suggests, there is probably no genetic correlation between the units on top of Blackwell Hills and those occupying abandoned, waning stage Missoula flood pathways on the Prairie below, other than the fact that they both occupy channelways. Only in this case these channelways are separated by ~300 ft of elevation!

Thicknesses attributed to all of the Q5 sediments were suggested by Breckenridge and Othberg (1998; 1999), although caution should be exercised due to the poorly understood and complex cut and fill nature of all these Quaternary sand and gravel units (pers. comm., Roy Breckenridge, 2008). Their extent into the subsurface is estimated on the cross-sections, in many cases extending quite deeply below the surface. Contacts with underlying, virtually identical facies in the top of Interval Q4, were chosen based on significant, possible genetic lithological breaks. In most cases these contacts must be considered as simply convenient and over simplified: lithological breaks (e.g., changes in gravel grain size) - the main information derived from well logs – do not necessarily represent actual genetic and time-controlled contacts. On the other hand, significant changes at depth from sand and gravel dominated facies to silt and clay, or fine sand dominated facies (e.g., as within intervals Q2 and Q3 in the Coeur d'Alene area) suggests potential occurrence of different depositional regimes, and switches from flood, or post-flood fluvial environments to lacustrine environments associated with the establishment of proglacial lakes such as Glacial Lake Columbia.

Overall, Interval Q5 has few fine-grained interbeds compared to deeper intervals, although sediments in Q4/Q5 that occur closer to the Spokane River, including gravels seem to contain higher percentages of fine-grained material. It should be noted that the Holocene Spokane River appears to have cut out late Q5 flood sediments having cut down further into the stratigraphic succession below the dams at Post Falls (leaving also more terraces below the dams than above; Box and Wallace, 2002). Where the Spokane River actually contacts the Q4/Q5 SVRP aquifer sediments below the dams (where not running over perched sediments over very shallow basement, or over basement itself), the water table tends to be much closer to the river (e.g., the water table in cross-section 19 along Blackwell Hill is about 80 ft or more versus in cross-section 3, near Skalan Creek, where the water table is 40 ft or less below the river). Note also that unusual elevated water levels occur in the University of Idaho research monitoring well (USGS well 51N 05W 7 DABC1), along with associated fairly clean, coarse sediments nearby (see cross-section 3, yet note also the presence of clay, only near to the river). We believe this area was also pointed to by Caldwell and Bowers, (2003) as an area of elevated water tables and potential point of recharge to the SVRP aquifer.

Hydrogeological River Segments and Areas within the Study Area

Plate 1 shows the study area divided into six hydrogeologically similar areas which are described below. This includes four segments along the Spokane River (Segments A through D) and two general areas showing similar features in the Coeur d'Alene area (Area E and Area F). Expanded observations and discussion for each cross-section can be found in Appendix 3 and should be referred to as a guide when reviewing specific cross-sections.

Segment A (cross-sections 1): Between the Ross Point and Harbor Island area and the Idaho/Washington state line (about 7.5 miles east to west), the Spokane River runs over six major basement promontories and five shallow embayments containing SVRP aquifer sediments. The last promontory to promontory embayment feature, about one and a half miles wide, corresponds to Segment A. This is the last geomorphologic embayment feature before the Spokane River breaks out completely into and over the Spokane Valley / Rathdrum Prairie. Here fairly coarse SVRP sand and gravel aquifer deposits reach a thickness of 200 ft below the river (see cross-section 1, below for further discussion).

Segment B (cross-sections 3, 5, 7, 9 and 11) is about ~5 miles long and corresponds to where the Spokane River cut down over and into crystalline basement, potentially also following relict channels scoured by Lake Missoula Floods across north-south oriented bedrock spurs. As there is evidence for thick accumulations of decomposed bedrock in other parts of the study area, it is easy to see how cataclysmic day to week long processes may have started what the later established Spokane River accomplished – the cutting down into hard crystalline intrusive and metamorphic rocks instead of going around bedrock promontories and excavating Quaternary sands and gravels.

Crystalline bedrock along Segment B was strongly, hydraulically cleaned by Missoula flood erosive events, before being mantled by sands, gravels, and some finer-grained "distal" deposits during waning flood stages. For comparison, areas for example in Segment C and D, where Miocene rocks are preserved, show significant decomposed crystalline rocks below them. These rock/sediment (essentially paleosols) in Segment B appear to have been removed from unprotected areas that received the full force of Missoula flood events. For Segment B we suggest that Miocene basalts and sediments do not occur because 1) Crystalline basement is relatively shallow, 2) they were not originally deposited here in large quantity, and, 3) if they were extant, they have effectively been completely removed.[6] In this part of the Rathdrum Prairie valley and along the range front margins there is virtually no sign of basalt, except for a thick accumulation found deep in the subsurface on the northern side of the valley, and probably preserved there due to a basement promontory (see cross-section 3 and Plate 1). This distribution is interesting as Miocene basalts outcrop again west of the study area, and the upper Grande Ronde and Priest Rapids basalts occur all around the Coeur d'Alene area (Plate 1).

Segment B is characterized by the Spokane River intermittently riding above basement promontories, relatively thin SVRP aquifer sediments in embayments superposed over relatively shallow basement, and directly above some marginal intervals where steep basement drop-off occurs directly below the river (e.g., see cross-section 7). Whereas opportunities exit for river recharge of aquifer sediments below the river appear to include more fine-grained interbeds or matrix components, and contrast coarser, possibly cleaner surficial sediments in the center of the valley.

Segment C (cross-sections 13 and 15): This short segment, approximately one and half miles long, occurs along the river opposite Ross Point (Plate 1). Here the Spokane River occurs against relatively steep basement drop offs above fairly shallow crystalline basement and SVRP aquifer sediments. This segment is transitional between Segment B and D, and is associated with local geologic/geomorphologic features (Harbor Island and Ross Point), as well as a fault (termed the Harbor Island Fault for the purposes of this study). All these features considered together suggest the possibility of a real geological discontinuity here. This is supported by significant changes in subsurface geology within the next cross-sections to the east (i.e., cross-sections 17, 19, 22, and 24 of Segment D). Also associated with this fault is a general transition from younger intrusive rocks (Kog) to older metamorphic rocks (mostly gneiss of the Priest River Metamorphic core complex – unit YXgn).

[6] Note that in cross-section 11 an anomaly of two wells show thick decomposed bedrock overlain by Miocene sediments and basalt.

The NNE trending Harbor Island normal fault crosses the Spokane River at river mile 106, just west of Harbor Island. Immediately east of the fault, a remnant of uppermost Grande Ronde basalt is exposed next to the river. Moving away from the river to the north, the sediment/crystalline basement is relatively shallow compared to cross-sections in Segment D further east, where also significant deposits of Miocene basalts and sediments were accommodated (either by pre-Miocene relief or by active Miocene fault control). The Miocene rocks in Segment D also survived erosional later plucking forces of the Pleistocene Missoula floods. Thus in Segment C, basalt does not occur in the subsurface (i.e., in wells reaching over 300 ft to below 1900 ft elevation), whereas subsurface basalt flows and Latah Formation are common in this interval across the rest of Segment D (except intriguingly cross-section 19).

The Harbor Island fault is shown as a normal fault – Segment B and C are on the up-thrown hanging wall and Segment D is on the down-thrown foot wall. No such movement is specified in Breckenridge and Othberg (1998), nor is such an apparently subordinate fault shown on the smaller scale geologic map of Lewis et al. (2002). Although it is most likely of Eocene age and more likely a splay or antithetic to the main Purcell Trench Fault structure further east (Plate 1; see also Miller et al., 1999), well evidence discussed in more detail below under cross-sections 13, 15 and 17 suggests that the structure is real and coincident with, if not genetically associated with some post-Eocene lithology distributions[7].

Segment D (Sections 17, 19, 22, and 24): This 3+ mile long segment parallels a fairly straight east-west portion of the Spokane River that follows Blackwell Hill, an undulating highland area that experienced harsh Missoula flood currents creating irregular slopes and scallops manifested partly in ponds on its summit. Landslide deposits occurring there are interpreted as Late Pleistocene/Holocene (Breckenridge and Othberg, 1999). Blackwell Hill consists largely of Latah Formation sediments preserved between Grande Ronde basalts below and a Priest Rapids basalt cap. Basalt outcrops terminate at, or just past the Harbor Island fault on the western end of this river segment, near to Harbor Island (Plate 1).

[7] Note that although the Purcell Trench Fault is a mostly covered low angle(?) detachment fault associated with the uplift of the Eocene Priest River Metamorphic Core complex west of the fault, the Harbor Island fault that crosses Segment C is more likely a high angle normal fault with steep dip slip.

About one mile north of the river basement in Segment D falls off from about 1750 ft in cross-section 24, deepening towards 1600 ft in cross section 17 before shallowing again in Segment C. Overall, the crystalline basement is fairly consistent, whereas overlying Miocene rocks appear to come and go, reducing or increasing the actual volume of SVRP sediments under or near to the Spokane River. In cross-section 19, Miocene rocks are missing, apparently having been intensely excavated ahead of the range front there. This is illustrated in Plate 1 and finds corroboration in gravity data (Oldow and Sprenke, 2006; Mark Knell, 2007, pers. comm.; Figure 6).[8]

Area E (cross-sections 25, 26, and 28) equates to the head of the Spokane River and its first mile where it swings around Blackwell Island and the Marine Yacht Club (an area composed of Late Pleistocene gravels, Holocene alluvium, and manmade fill and about one and a half miles of the Coeur d'Alene Lake front between Highway 95 and Tubbs Hill (see also cross-sections 25 A-A', B-B'). Although there is less concentrated data in this area (compared to the eastern part of Segment D), well logs over all suggest a highly eroded, relict Miocene paleorelief occurring above a fairly shallow crystalline basement. The latter is comprised primarily of Cretaceous gneiss, which at Tubbs Hill is a very fresh, hard, highly foliated and folded rock. Tubbs Hill is thought to occur within the footwall of the Purcell Trench detachment fault, whose fault trace can seen in Plate 1, and cross-sections 32 and 34.

A subsurface saddle or paleovalley tributary to the main SVRP paleovalley occurs between Tubbs Hill and Blackwell Hill (here termed "Coeur d'Alene Channel;" Plate 1). Like the SVRP basin in general, the subsurface here carries a clear geological overprint, whose details must be extrapolated from nearby data. The Coeur d'Alene Channel was first cut by pre-Miocene rivers that initially cut out crystalline bedrock (this is stylistically shown in cross-section B-B' to have occurred at a contact between more easily eroded metamorphic rocks and gneiss – as vaguely supported in the small-scaled geologic map of Lewis et al., 2002). This particular feature is obviously highly speculative, but the main point is that a main subsurface channel connects the Coeur d'Alene Lake basin with the SVRP basin at this location. In comparison, a relatively high basement connects Potlatch Hill to the east with Tubbs Hill forming a significant sill and barrier between the Lake Coeur d'Alene and SVRP

[8] Note cross-section correlations were made initially independently of later added geophysical data.

aquifer sediments along this part of the Coeur d'Alene area (see strip map in cross-section 34 and Plate 1).

After the Miocene basalt and lacustrine depositional system was superimposed over this paleorelief (essentially over a fairly short period in the mid-Miocene; Reidel and Hooper, 1989; Martin et al., 2005) a long period of regional fluvial incision reoccurred in the Coeur d'Alene channel area. At this time Late Miocene and Pliocene fluvial incision also cut back through the Miocene deposits in the drainage system now occupied by Fernan Lake following the same sequence of events (see Area F below).

The area in question below the present day position of the head of the Spokane River, the area north of Tubbs Hill, and the gneissic outcrops forming a clear basement sill leading to the east (i.e. Area E and F; Plate 1) were an area of constriction during powerful early Missoula flood events. Primary and secondary channels and probably large scale potholes (similar to the Scabland features in central Washington) were cut into Miocene rocks, as the Pliocene paleorelief was radically impacted and reshaped during the Pleistocene. The Fernan Channel (Plate 1; discussed below), where it opens to the north to the rest of the main SVRP paleovalley was probably deepened, with basalt and Latah Formation finding protection in the lee of topographic features such as Best Hill, and probably southeast of Tubbs Hill (see cross-sections 32 and 34).[9]

Apparently, at least according to calculations implied and carried across cross-sections 25, 26, 28, 30, 32, and 34, the Fernan Channel (or pothole) before it was filled by Quaternary deposits during waning flood stages was deepened to approximately ~1630 ft, whereas the Coeur d'Alene channel, a resistant narrows was only deepened to somewhere in between 1700 and 1800 ft. Our calculations and cross–sections are of course tentative, yet augment and support similar estimates made by Kahle and Bartolino (2007; Plate 2 profile I-I' and G-G'). Consider City of Coeur d'Alene well #671 (50N 4W 14 AA1) positioned closer to the Coeur d'Alene channel, compared to City of Coeur d'Alene well #672 (50N 04W 13 DAA1) in cross-sections 26, 28, 30 and 32. Admittedly, many parts of these cross-sections are highly

[9] Interpretation in here, and associated cross-sections can be compared with gravity data shown in Figure 6; it could be the Coeur d'Alene Channel discussed here was originally more or a paleosaddle, a divide in the ancient drainage system.

interpretive, yet they are ultimately testable with a refined local geophysical approach (if indeed, these areas become of significant concern in the future). [10]

The interpretation provided in cross-section B-B' provides reasonable speculation highlighting the known regional geological history. We feel that this basement silled area (paleohigh) provided a sort of venturi effect during Missoula floods across Area E and the Coeur d'Alene channel below. More of a scalloped hole in the form called "Fernan Channel" occurred north of Tubbs Hills; at least 3 or perhaps many more(?) later events of variable intensity are interpreted to have filled this hole (paleolow), partly with sediments deposited in a large flood eddy (see the Q2 through Q5 stratigraphy of City of Coeur d'Alene well #672, cross section 32). It is possible that the Coeur d'Alene channel is significantly deeper than the Fernan Channel, and includes perhaps deep, pre-Miocene V shaped cut gorge – but we have not emphasized this in cross-section B-B" nor is this suggested in the gravity data of Figure 6.

South of the Coeur d'Alene channel within the southern part of the study area (and probably within the channel) giant ripple bed forms and cross-bedding are observed in a seismic section between Tubbs Hill and North Cape (see profile A - A' presented in Breckenridge and Othberg, 1999). These gravel features occur below the lake bottom showing long chord spacing (¼ mile?); a southern current direction can be deduced from internal cross-bedding. Although we are unsure of the mega ripple heights, these flood bed forms appear to be very large in scale (they are drawn at ~30 ft, somewhat larger than maximum mean heights – 22 ft – for giant ripples suggested by Baker, 1973). These intriguing features possibly associated with accelerating and decelerating flood flow down stream of the constriction between Blackwell Hill and Tubbs Hill (i.e., Coeur d'Alene channel) are stylistically added to otherwise rather data-poor cross-sections 25, 26 and 28. We have however attempted to stay true to regional geology.[11]

Area F (cross-sections 30, 32 and 34) equates to the area bound to the south by Tubbs Hill and to the east by foothill of the Coeur d'Alene Mountains composed of folded Proterozoic

[10] Note that a low area in the gravity data is indicated in the Area F in Figure 6.
[11] Note that there are further questions with regard to these mega ripples as discussed in more detail under Area E, below.

metasediments and overlain by thick Latah Formation and Columbia River Basalts. In the valley between and in front of Best Hill and Potlatch Hill, limited Pleistocene sands and gravels occur, having dammed up and created Lake Fernan. An erosional post-Miocene and Missoula erosional feature filled with sand and gravel occurs in the subsurface and is referred to as the "Fernan Channel." It is a deep feature that predictably tapers towards the lake, although there is little well control. If the SVRP aquifer is fed by Fernan lake, it occurs through this feature. This area is partly covered in the discussion above.

7.0 Discussion

Although there are no obvious discoveries in this study, a visual hydrogeological subsurface database in the form of localized testable cross-sections are developed together with a concept summary map that gives a limit of the Miocene depositional system in the study area (see Plate 1; Figure 6). We feel that the gravity derived depth-to-basement maps of Oldow and Sprenke (2006) and M. Nell (pers. comm., 2008; Figure 6) show a clear view of a central Paleogene lake basin, and some good working correlations with cross-section data in the Coeur d'Alene area. These maps together with the cross-sections in Appendix 2 have helped to refine the sediment/rock contacts at depth and help to identify the thickness of the SVRP aquifer and where it is underlain by Miocene basalts and sediments, or by crystalline basement. Two stacked and cross-cutting Miocene and Quaternary depositional systems occur above an intermittently decomposed or relatively freshly scoured crystalline basement. The differential geometry of these incised depositional systems, the potential for geological artifacts associated with Cenozoic Faults (i.e., Harbor Island Fault), and the effects of Quaternary Missoula flood excavation are clear in the well data along the Spokane River (e.g., cross-sections of Segments B, C and D, Plate 1).

The study area is divided into four segments along the Spokane River, and two areas near Coeur d'Alene Lake that show geological and hydrological similarities. These have been outlined and illustrated over the following basic hydrogeologic areas (see Plate 1):

1) A fairly deep SVRP aquifer embayment below the Spokane River (Segment A);

2) Numerous thin embayments of short distance and promontories of basement that contain the Spokane River (most of Segment B);

3) Steep drops to basement where the river follows bedrock on one side and rides directly over the SVRP aquifer sediments on the other (parts of Segment B and transitional Segment C;

4) Areas where the river rides over relatively thin aquifer sediment above significant relict Miocene deposits (most of Segment D, and probably much of the northern part of Area E, and subordinate areas where these Miocene rocks have been removed. For example as seen in cross-section 19 and in the Coeur d'Alene channel, where the Spokane River or Coeur d'Alene Lake occur above relatively coarse SVRP aquifer sediments; and finally,

6) An area where SVRP sediments appear to be strongly limited by both crystalline basement relief and relict Miocene rocks in the subsurface (Area F and the Fernan Channel).

Whereas the surface water in the study area permanently or seasonally discharges into the SVRP aquifer, some of the defined segments along the Spokane River and Area E (including the head of the Spokane River and part of Coeur d'Alene Lake) may leak more than others. Originally we hoped to provide more insight into the nature of the sediments lying adjacent to Lake Coeur d'Alene and the Spokane River's course in the study area. While we do supply key, accessible well logs in geological context, and comment in general on associated stratigraphy, sediment grain size, distribution, and stacking pattern, it was not possible at this time to develop a clear predictive sedimentological facies model to further shed light on porosity and permeability.

The complexity of the timing, magnitude and associated depositional processes of Missoula Flood processes in alternatively subearial and subaqueous environments (i.e., Missoula floods cutting and filling across the SVRP valley or debouching into sometimes present Glacial Lake Columbia) is basically beyond the resolution of the data. The data set – about 1000 driller's well logs – is however highly useful, yet ultimately often too shallow and without specific detail. Overall the well logs used in this study work well within the scale of the cross-sections developed.

We can emphasize exactly what Hsieh et al. (2007) quoted from Kahle and Bartolino (2007): “the aquifer generally has a greater percentage of finer material near the margins of the valley and becomes more coarse and bouldery near the center throughout the Rathdrum Prairie and Spokane Valley.” This was precisely the gross depositional pattern deduced from reviewing all the wells in the vicinity of the Spokane River.

Five essentially depth and relative age related Quaternary intervals – Intervals Q1 through Q5 – were developed to show some details and degrees of similarity. This stratigraphic succession appears to coarsen-upward. Usually this would indicate higher energy depositional conditions through time, but that is not necessarily the case in the unique setting of the Missoula Floods. We suggest that initial powerful lower Pleistocene floods cut a deep paleotopography into the Miocene depositional system that had filled much of the SVRP valley floor. Mostly unknown, but coarse gravel, giant boulder, and clay-bearing deposits of interval Q1/Q2 are associated with these floods and post-flood environments.

Later floods debauched into glacial lakes, (e.g. Glacial Lake Columbia, a lake crated by the Okanogan lobe of the cordilleran Ice Sheet; Atwater, 1986) resulting in coarse ‘slack water’ turbidite successions that include some large boulders and coarse gravel, through sand-sized sediments and varved clay deposits.[12] These deposits potentially fit some of the stratigraphic patterns in Q2 or Q3. Later, relatively less powerful, yet still cataclysmic floods channelized and reworked some of these materials, resulting in some fining-upward gravel-dominated, almost fluvial looking deposits (and giant ripple trains) in Q4 and Q5. These occur within the central parts of the Rathdrum Prairie on the edge of the study area (see northern part of cross section 17) and they also occur in the subsurface of Area E in the Coeur d’Alene channel. Interval Q4, the sediments below the surficial units of Q5 is really very similar to the later, reflecting similar stacked depositional environments (high energy, poorly sorted, coalescing gravelly fans, bars, extensive sheets, cross cut primary and secondary channelways, etc.).

[12] Note: no varved Quaternary clays were reported in the driller’s logs, but they are known in the Spokane area.

In conclusion, there are certain places along some stretches of the Spokane River in the study area where recharge to the aquifer might be especially likely. There are probably some areas within the present rather coarse grid of cross-sectional resolution where cleaner sediments and an elevated water table might suggest potential recharge areas to the greater SVRP aquifer. Our sense is that much of the river should slowly leak into the vadose zone (e.g., along Segment D and in Area E), although this may not be the case due to clogged or cemented pore space, especially anywhere above the Post Falls dams. Some areas down stream of these dams, where the river runs a more natural course may show stronger recharge to the aquifer (e.g., Segment A and specific parts of Segment B).

Further surficial field work, search for analogues, and detailed logging of wells (together with split spoon samples or a coring rig) would provide a better sense of the actual sedimentology and stratigraphy, in order to compare with the geologic framework here provided. We hope that the cross-sections of Appendix 2 and descriptions in Appendix 3 will be of use to interested geologists, hydrologists, drillers and land owners.

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