Buried Bedrock Channels in the Athabasca Oil Sands Region Conceptual Understanding and Implications to Water Supply

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Abstract

Quaternary and Tertiary Period buried bedrock channels are present throughout the Athabasca Oil Sands region. Geologic mapping of these channels has been completed by the Alberta Geologic Survey and various oil sand operators within the region. These channels can incise into the top of the Cretaceous bedrock surface greater than 150 m and can vary in width from less than 500 m to greater than 30 km. Channel length can vary from less than 10 km to greater than 200 km. This hydrogeological case study incorporates Quaternary, Tertiary and Cretaceous geological, hydraulic head and groundwater chemistry mapping. The depth of channel incision and subcropping Cretaceous units strongly influence the hydraulic head distribution within the channel sediments as well as the underlying Grand Rapids Formation. The distribution of total dissolved solids concentrations within the Grand Rapids Formation also appears to be influenced by the presence of the channels where overlying aquitards of the Colorado Group have been eroded. The presence of these buried bedrock channels have important implications to water supply in terms of deliverability and source water chemistry.

Introduction

Buried bedrock channels are prominent geological and hydrogeologic features in the Athabasca Oil Sands region. The geometry of these buried bedrock channels is highly variable and is largely due to the geologic setting in which they were formed. Typically, two general types of channels are observed in the study area. Channels that were formed by the catastrophic release of subglacial meltwater are typically narrow and deeply incising (Andriashek, 2003). Channels that were formed by pre-glacial river systems are generally wider, with observed widths up to 30 km. The local and regional hydrogeological regime is influenced by the presence of these buried bedrock channels where the aquitards of the Colorado Group have been eroded. This case study highlights the influence that buried bedrock channels have on the distribution of total dissolved solids (TDS) concentrations and hydraulic head in the Grand Rapids and the implications of these influences on identifying and securing a saline water source for the Devon ARL Corporation Jackfish and Jackfish 2 Projects (the Projects). This work was collaboratively completed by Matrix Solutions Inc. and Devon ARL Corporation in support of the application for approval of the Jackfish 2 Project (Devon, 2006).

Study Area

The Projects are located approximately 100 km northeast of Lac La Biche and approximately 150 km south Fort McMurray and are flanked by the Stony Mountain Uplands to the northwest, the May Hills to the west and the Mostoos Hills Uplands to the south (Figure 1).

The limits of the local study area (LSA) are Townships 74 to 76 and Ranges 5 to 8 west of the 4th Meridian. The LSA is found within the Winefred Lake and Christina Lake watersheds. The main tributaries to Christina Lake are Birch Creek and Sunday Creek.

The regional study area (RSA) was defined primarily on the basis of interpreted regional geology and groundwater flow patterns. The extent of the RSA is defined by the following:

- North – The Clearwater River, extending from the Saskatchewan border to the Confluence of the Athabasca River and the eastward flowing section of the Athabasca River to the confluence of the Clearwater River;
- East – The Saskatchewan border extending from the centre of Township 69 to the Clearwater River;
- South – The centre of Township 69 extending from the Saskatchewan border to the Athabasca River; and
- West – The northerly flowing portion of the Athabasca River, extending from the centre of Township 69 to Township 87.

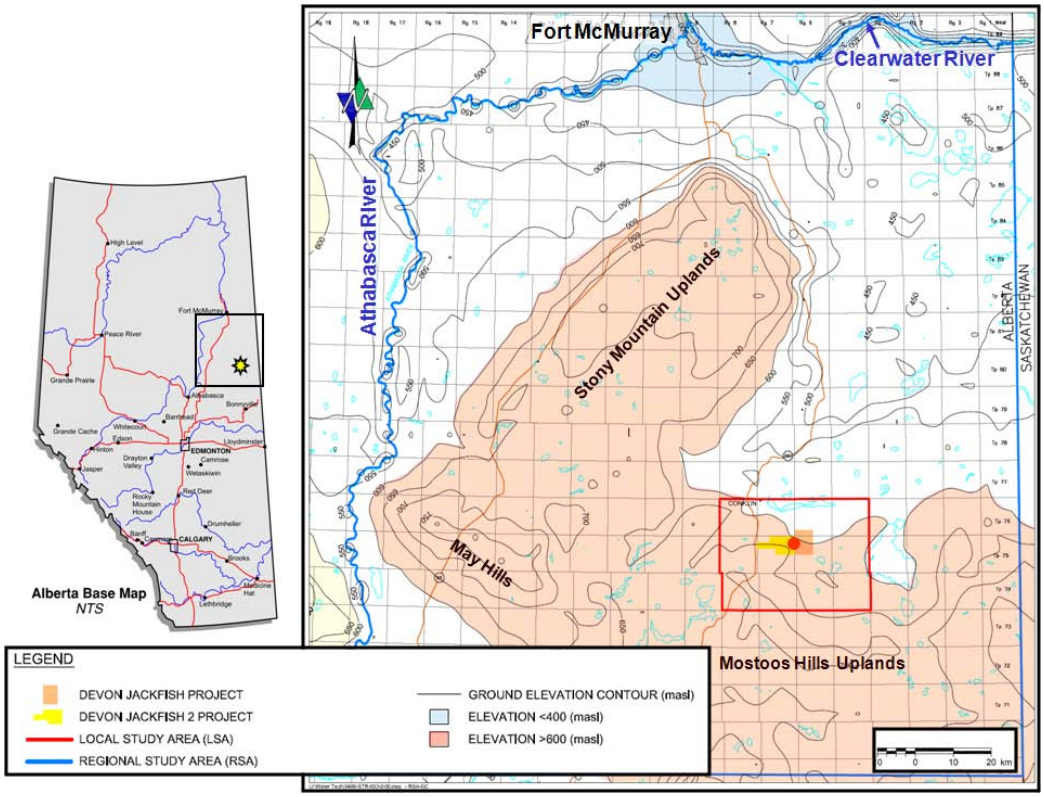

Figure 1: Local and Regional Study Area.

Methodology

Geologic Mapping

Detailed geologic mapping in the LSA included a review of 870 wire line well logs. Additional geologic mapping was conducted within the RSA and included a review of approximately 200 wire line well logs in order to extend selected hydrostratigraphic surfaces throughout the RSA. The LSA and RSA mapping was complimented with publicly available maps such as those prepared by Andriashek (2003).

Hydraulic Head Mapping

Hydraulic head mapping was completed for the RSA using topography, geologic subcrop and outcrop locations and several types of data sets including:

- on-site water level measurements;
- published hydraulic heads from Environmental Impact Assessments (EIAs) completed for neighboring projects;
- published hydraulic heads from regional hydrogeologic studies; and
- drill stem test (DST) data from the Alberta Energy and Resources Conservation Board (ERCB) database.

Additional data source background, the quality assurance/quality control process employed in screening the data and a tabular summary of the water level and pressure data is reported by Devon (2006).

Groundwater Chemistry Characterization

Characterization of groundwater quality in the LSA was completed by complimenting water analyses data collected by Devon with publicly available data such as:

- published groundwater quality results from EIAs completed for neighboring projects;
- published groundwater quality results from regional hydrogeologic studies; and
- representative drill stem test (DST) formation water analyses from the ERCB database.

The quality assurance/quality control process employed in screening the DST water analyses data and a tabular summary of the water analyses results is reported by Devon (2006).

Geology and Hydrostratigraphy

Precambrian crystalline basement below the LSA occurs approximately 450 m below sea level (mbsl) (Bachu *et al.*, 1993). Unconformably overlying the Precambrian basement in the LSA is Devonian and Cretaceous bedrock. The Devonian and Cretaceous sediments are separated by the Pre-Cretaceous Unconformity. Devonian bedrock includes the Elk Point Group and Beaverhill Lake Group. The overlying Cretaceous sediments include the Mannville Group (McMurray, Clearwater and Grand Rapids Formations) and the Colorado Group (Joli Fou, Viking and La Biche Formations). Unconformably overlying the Cretaceous sediments is unconsolidated Tertiary and Quaternary deposits of the

Empress, Terrace, Bronson Lake, Muriel Lake, Bonnyville, Ethel Lake, Marie Creek, Sand River and Grand Centre Formations. In general, the Devonian and Cretaceous bedrock Formations across the LSA dip to the southwest. Figure 2 illustrates the Cretaceous to Quaternary stratigraphy and hydrostratigraphy. Five key features are highlighted in Figure 2 that will be discussed in more detail: 1) the coarsening upwards Grand Rapids 'C' unit (or Lower Grand Rapids Aquifer) of the Manville Group, 2) the Joli Fou Formation (Aquitard) of the Colorado Group, 3) the La Biche Formation (Aquitard) of the Colorado Group, 4) the top of bedrock surface and 5) the Empress Formation (or Channel Sand Aquifer) that occurs within buried bedrock channels of which locally can erode through the aquitards of the Colorado Group into the Grand Rapids 'C' unit (Figure 3).

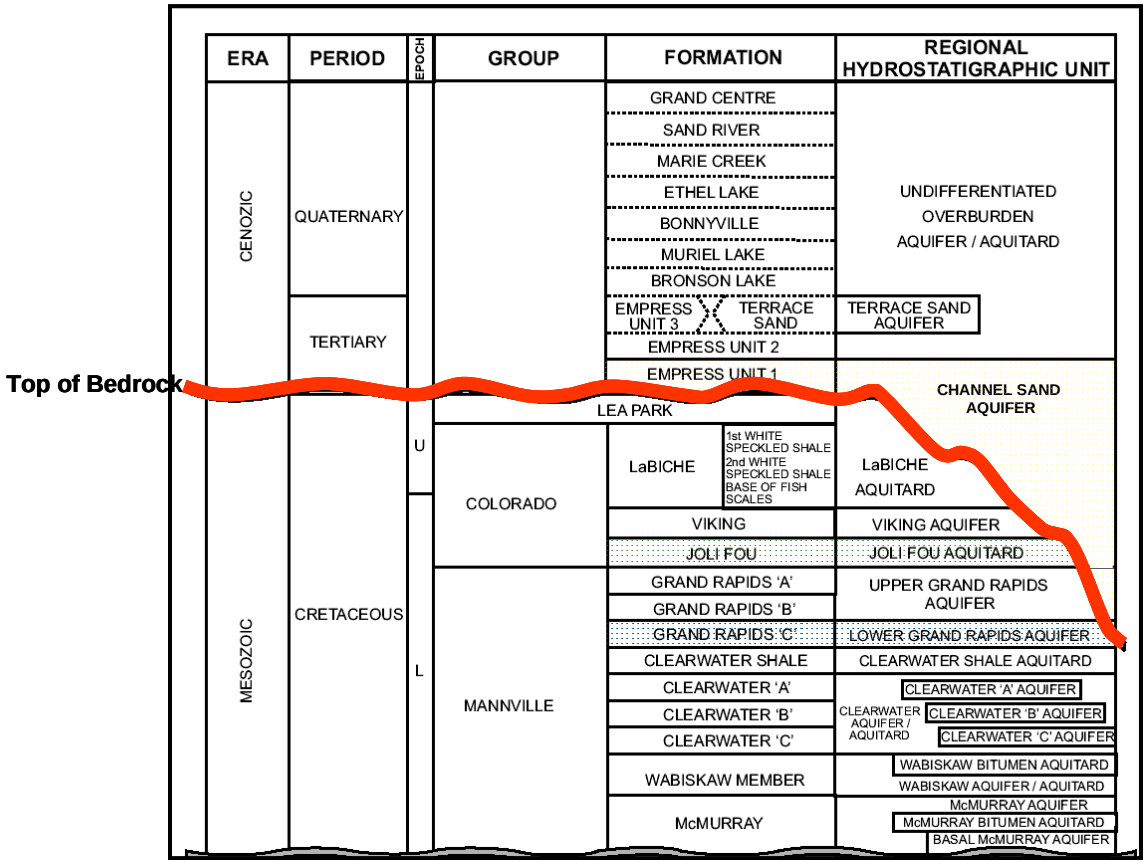

Figure 2: Stratigraphic and hydrostratigraphic column highlighting the coarsening upwards Grand Rapids 'C' unit (or Lower Grand Rapids Aquifer) of the Manville Group, the Joli Fou and La Biche Formations (Aquitards) of the Colorado Group, the top of bedrock surface and the Empress Formation (or Channel Sand Aquifer).

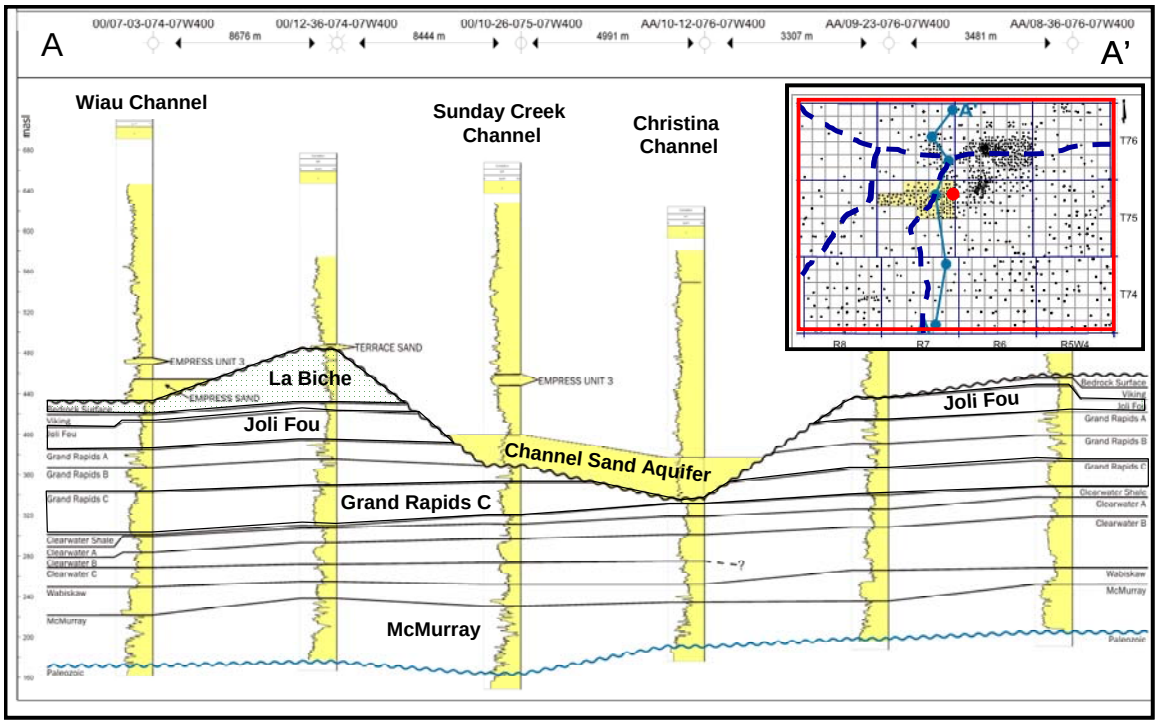

Figure 3: West to east cross section highlighting the depth of incision of the Sunday Creek and Christina channels through the La Biche and Joli Fou formations into the Grand Rapids 'C' unit (Lower Grand Rapids Aquifer).

Geologic Features

Andriashek (2003) mapped three buried bedrock channels within the LSA, the Wiau Channel, Christina Channel and Kirby Channel. With additional well control and by incorporating 2-D and 3-D seismic data, Devon (2006) mapped an additional buried bedrock channel to the east of the Kirby Channel that was interpreted to connect the Christina and Wiau Channels. This channel is referred to as the Sunday Creek Channel. The LSA is located in the Wiau Lowlands bedrock physiographic region. Within the LSA, the bedrock lowland elevation ranges from less than 320 m above sea level (masl) in the Christina and Sunday Creek channels, to greater than 480 masl on the Wiau-Christina Interfluve Bench (Figure 4).

The majority of the LSA overlies the Wiau-Christina Interfluve Bench. The bench is present from west to east across Townships 74 and 75 through Ranges 7, 6, 5 and 4. Sedimentary deposits on the bedrock terrace are glacial in origin.

The Wiau Channel is a prominent regionally extensive bedrock feature and occurs at the southern edge of the LSA. Within the RSA, the Wiau Channel incises into the Cretaceous bedrock surface and extends in a west-northwest to east-southeast direction from the Alberta-Saskatchewan border to the Athabasca River valley. As mapped by Andriashek (2003) it is greater than 30 km wide in some areas. The Wiau Channel is interpreted to be formed by a preglacial river system that flowed eastward from the Rocky Mountains (Andriashek, 2003).

The Kirby Channel trends in a north-northeast to south-southwest direction between the Christina and Wiau channels in Townships 74 to 76 Range 8 W4M. It is uncertain whether the Kirby Channel was formed by glacial melt water or a preglacial fluvial system that connected the Wiau and Christina channels (Andriashek, 2003). Along the northern portion of its thalweg, the Kirby channel incises through La Biche, Viking and Joli Fou Formations (Figure 5).

The Christina Channel occurs in the northern portion of the LSA and trends east-west (Figure 4). Within the RSA, the Christina Channel was mapped by Andriashek (2003) to extend from east of the Alberta/Saskatchewan border to the Wiau Channel. The Christina Channel is interpreted to be of preglacial fluvial origin, however, over deepening and reworking of the Channel deposits by sub-glacial melt water may have occurred in some areas (Andriashek, 2003). Along its thalweg, the Christina Channel incises through the La Biche, Viking and Joli Fou formations (Figure 5). At the confluence of the Sunday Creek and Christina channels, the Grand Rapids A and B units have been completely eroded and the Grand Rapids C unit subcrops below sand and gravel of the channel (Figure 5).

The Sunday Creek Channel trends in a north to south direction between the Christina and Wiau channels in Townships 74 to 76, Range 7 W4M. The orientation, location and extent of the Sunday Creek Channel were largely based on seismic data (both 2-D and 3-D) that was then confirmed with additional wells recently drilled through this feature. The Sunday Creek Channel is narrow (less than 2 km wide) and down cuts into the Cretaceous bedrock approximately 150 m (Figure 6). Along the northern portion of its thalweg, the Sunday Creek Channel erodes through the La Biche, Viking, Joli Fou and Grand Rapids A formations (Figure 5). In Section 22, Township 75, Range 7W4M, the Sunday Creek Channel erodes through the Grand Rapids B where channel sand and gravel are in contact with the Grand Rapids C unit (Figure 5 and 6). Because of the narrow and deeply incising nature of the Sunday Creek Channel, it is interpreted to have been formed by glacial melt water.

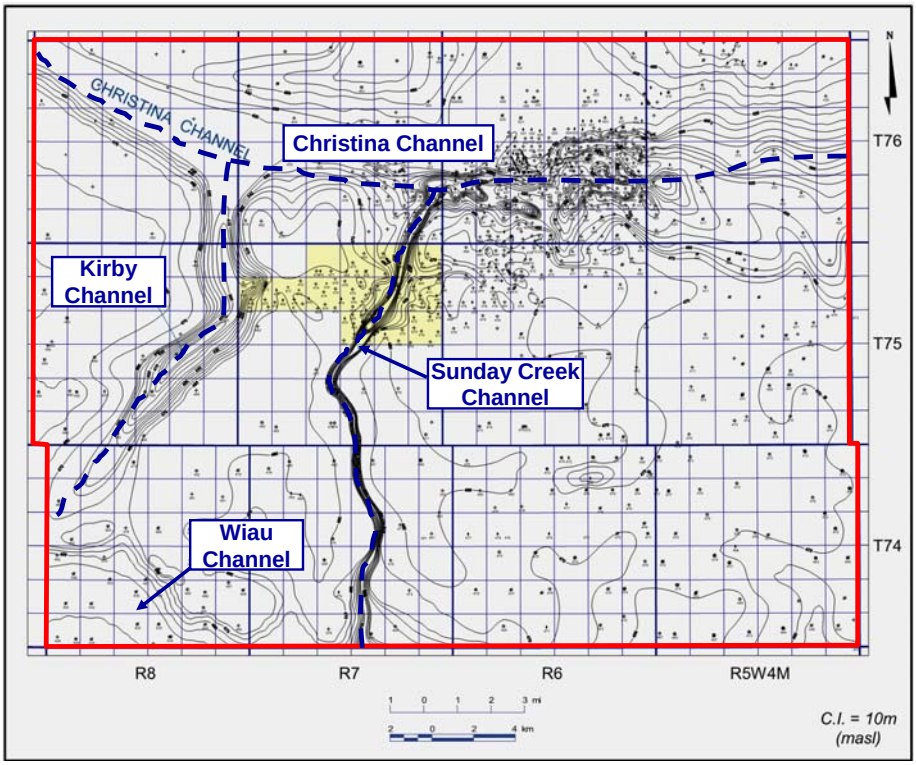

Figure 4: LSA Bedrock topography. The thalwegs of the Christina, Kirby and Sunday creek channels are highlighted in blue.

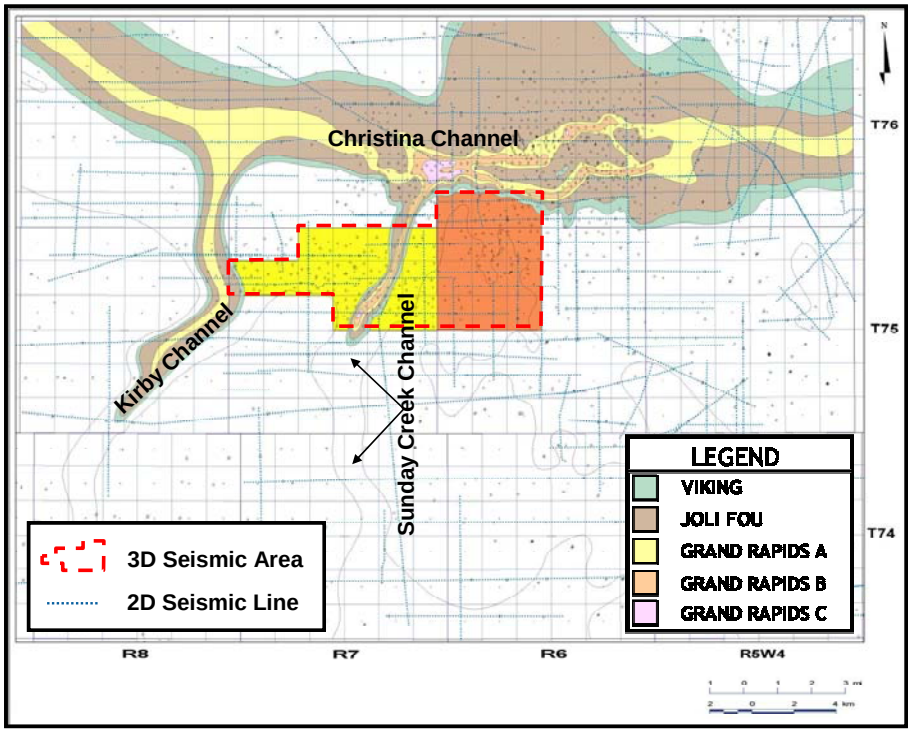

Figure 5: Subcropping Cretaceous Formations. In the thalwegs of the Kirby, Christina and Sunday Creek channels, aquitards of the La Biche and Joli Fou formations are eroded and the Grand Rapids units are present at the base of the channel sediments.

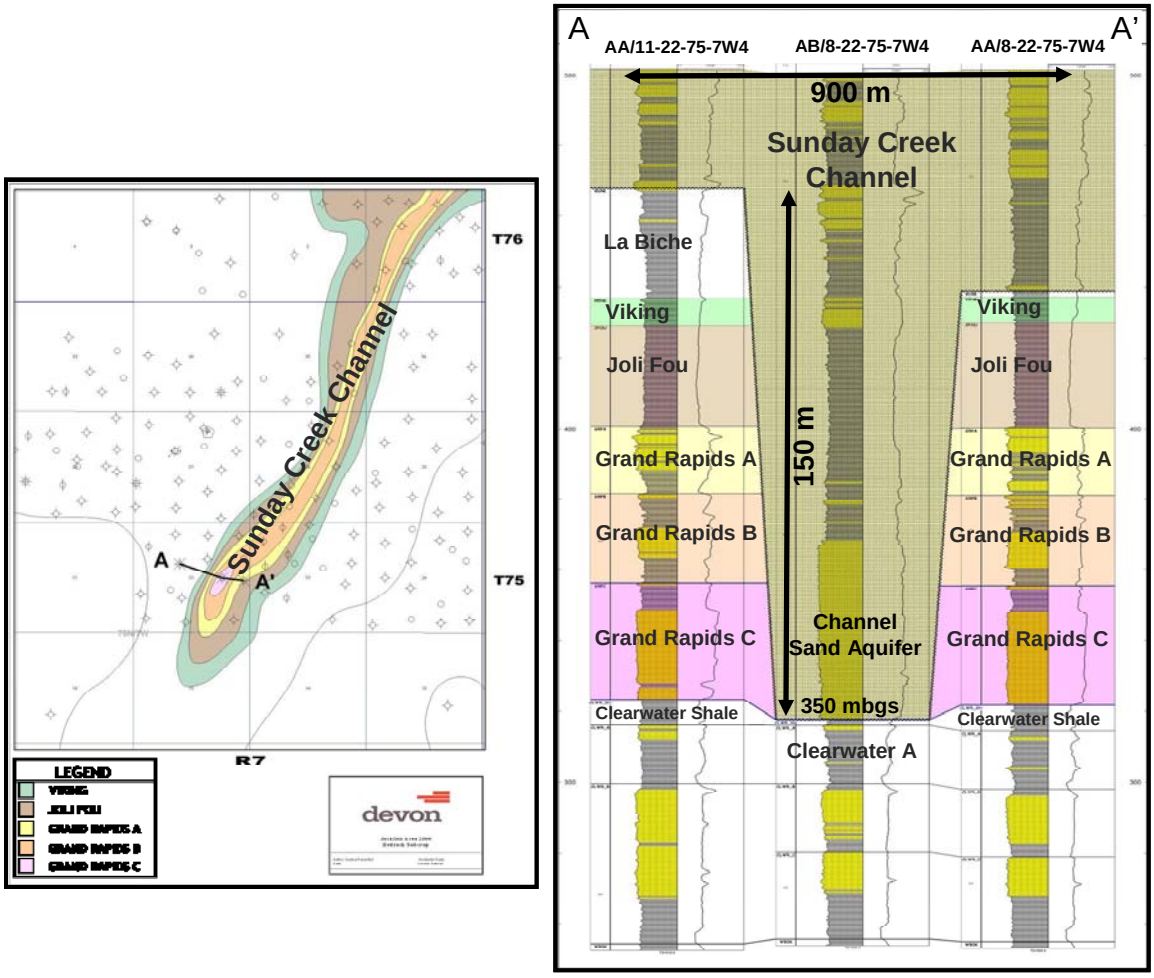

Figure 6: West to east cross-section transecting the Sunday Creek Channel. The cross section length is 900 m through section 22, Township 75, Range 7 west of 4. West and east of the channel, aquitards of the La Biche and Joli Fou are present. In portions of the channel, these aquitards have been eroded and the Grand Rapids C sands are in contact with the sands and gravels of the channel.

Key Hydrostratigraphic Unit Descriptions

As highlighted on the stratigraphic/hydrostratigraphic column, four geologic units are important with respect to the hyrogeologic interaction between the channel sands and gravels and Cretaceous sediments and include: the Grand Rapids 'C', Joli Fou, La Biche and Empress formations.

The Grand Rapids 'C' unit consists primarily of unconsolidated quartzose sands bounded at the top and bottom by shale. The Grand Rapids 'C' is interpreted to be deposited in a fluvial to fluvially-dominated deltaic setting. Core descriptions classify the unit as a silty to medium grained sand that is texturally unconsolidated to friable. As mentioned, the Grand Rapids 'C' is comprised primarily of quartzose sand, however, varying amounts of

chert, lithic fragments, calcareous (shelf) fragments and rock fragments were identified in core. Within the LSA, the top of the Grand Rapids 'C' occurs between 323 and 380 masl. The Grand Rapid 'C' unit was further subdivided on the basis of lithology into an upper shaly/silty portion and a lower porous sand portion (referred to as the Lower Grand Rapids Aquifer). The Lower Grand Rapids Aquifer is the saline groundwater source for the Projects steam generation. The Lower Grand Rapids Aquifer picks were based on cut-offs of greater than 30% porosity, less than 75 API gamma ray and good SP development. The thickness of the Lower Grand Rapids Aquifer (total net porous sand) ranges from 0 to 44 m.

The Joli Fou Formation was deposited in a marine environment and is composed of dark gray fossiliferous shale with increased silt content in the upper beds. Locally, this unit is described as medium grey, blocky soft shale containing pyrite. Differential erosion causes the top elevation of this Formation to vary across the LSA. The Joli Fou Formation subcrops in Christina, Sunday Creek and Kirby channels where the La Biche and Viking Formations are absent and is completely eroded in the thalweg of the Christina and in the northern portions of the Sunday Creek and Kirby channels (Figure 5). The top of the Joli Fou Formation is encountered at depths between 395 and 447 masl in the LSA and is up to 35 m thick.

The La Biche Formation was deposited in a marine environment. The Formation is composed of dark grey shale and silty shale with ironstone partings and concretions, with the lower layers containing fish-scales (Hamilton *et al.*, 1999). Three regional geologic markers are present in the La Biche Formation. These are (from bottom to top) the Fish Scale Zone, the Second White Speckled Shale and the First White Speckled Shale (Mossop and Shetsen, 1994). Beneath the LSA, only the Fish Scale Zone is present. The La Biche Formation subcrops on the Christina-Kirby Interfluve Bench and Wiau-Christina Interfluve Bench and is completely eroded in the Christina Channel and in the northern half of the Sunday Creek and Kirby channels (Figure 5). The La Biche Formation (bedrock to top of the Viking Formation) is up to 77 m thick in the LSA.

The Empress Formation is defined as all stratified sediments that rest on bedrock and are covered by the first occurrence of glacial till in the area (Andriashek, 2003). These drift sediments consist of Tertiary age "stratified gravel, sand, silt and clay of fluvial, lacustrine and colluvial origin" (Whitaker and Christiansen, 1972) and exist within incised channels and on bedrock terraces. Three units of the Empress Formation are identified by Andriashek (2003) on the basis of lithological and petrological properties. The lowermost Unit 1 refers to pre-glacial sand and gravel which characteristically fines upward into Unit 2. The silt and clay of Unit 2 is interpreted to be of fluvial and lacustrine origin and is evidence of the first glaciation in the region. It is interpreted that glacial ice dammed eastward flowing rivers creating a lacustrian environment for fine grain deposition (Andriashek, 2003). Unit 3 consists of glacial sand and gravel which overlie Unit 2. These three units are identified by Andriashek (2003) in the Wiau Channel. However, the Empress Formation deposits in the Christina, Kirby and Sunday Creek channels are classified as "undifferentiated" due to uncertainty regarding the age and origin of the sediments on the channel floor. Within the LSA, the top of the Empress

Formation basal sand and gravel channel deposits (Channel Sand Aquifer) occur between 377 and 476 masl and the thickness of the Channel Sand Aquifer ranges from 3 to 50 m.

Hydrogeology

A south to north schematic hydrostratigraphic cross section through the RSA (Figure 7) illustrates the regional extent of the Lower Grand Rapids Aquifer, Joli Fou Aquitard, La Biche Aquitard and the variable geometries of buried bedrock channels such as the Wiau, Sunday Creek and Christina.

Groundwater Flow

Pressure mapping completed for this project and regional mapping completed by Ozoray (1974), Hitchon et al. (1989) and Bachu et al. (1993) suggest that a downward directed flow potential from ground surface to Devonian bedrock is present throughout the majority of the RSA. A west to east cross section through the LSA (Figures 8) illustrates the interpreted hydraulic head contours in the Quaternary, Tertiary and Cretaceous sediments and highlights the presence of a downward directed vertical hydraulic gradient.

The Channel Sand Aquifer is present and interpreted to be hydraulically connected between the Christina, Sunday Creek, and Wiau channels. The Channel Sand Aquifer is also present in the Kirby Channel, however, it is interpreted that the Kirby Channel is only in direct hydraulic connection with the Christina Channel. The Channel Sand Aquifer hydraulic head map is presented in Figure 9. Hydraulic head data are available for the Wiau and Christina channels. As presented in Figure 9, groundwater in the Wiau Channel flows to the west towards the Athabasca River valley where the Channel Sand Aquifer outcrops and discharges. As reported by Stewart (2003), a series of springs discharge water from the Wiau Channel Empress Formation (Channel Sand Aquifer) within the Athabasca River valley. The total discharge from the springs was estimated to be greater than 7,680 m^3/day (Stewart, 2003). Some groundwater in the Wiau Channel is interpreted to flow into the Christina Channel. It is hypothesized that the relatively low hydraulic head values observed in the Christina Channel at WSW 9-17 (Township 76, Range 6) is due to leakance from the Channel Sand Aquifer to the underlying Grand Rapids Formation. The occurrence of this leakance is also evidenced by groundwater mounding in the underlying Grand Rapids Formation.

Hydraulic head data from the Grand Rapids Formation indicates that groundwater flow is primarily directed north and west towards the Clearwater and Athabasca rivers where the unit outcrops and discharges. This is consistent with mapping completed by Bachu *et al.*, (1993). Regionally, groundwater mounding is evident below the Stony Mountain Uplands. Local groundwater mounding in the LSA is evident in the area of the Christina, Kirby, Sunday Creek and Wiau channels where aquitards of the Colorado group have been eroded. The groundwater mounding is also evident in the west to east cross section (Figure 8) that transects the Kirby and Sunday Creek channels.

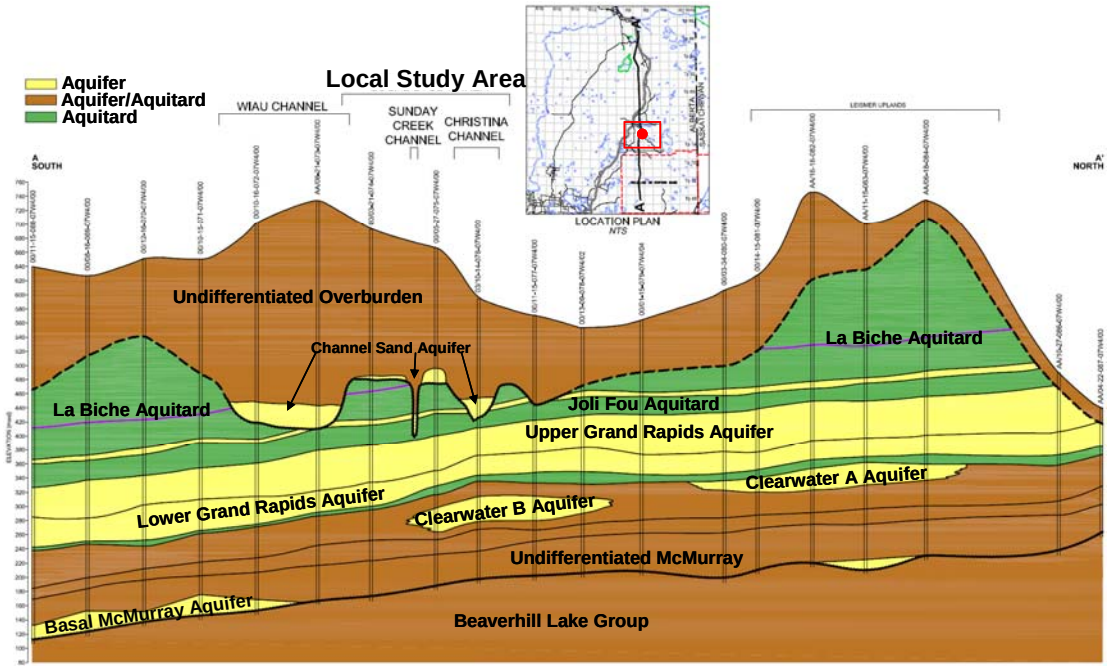

Figure 7: South to north regional schematic hydrostratigraphic cross section illustrating the regional extent of the Lower Grand Rapids Aquifer, Joli Fou Aquitard, La Biche Aquitard and the variable geometries of buried bedrock channels such as the Wiau, Sunday Creek and Christina.

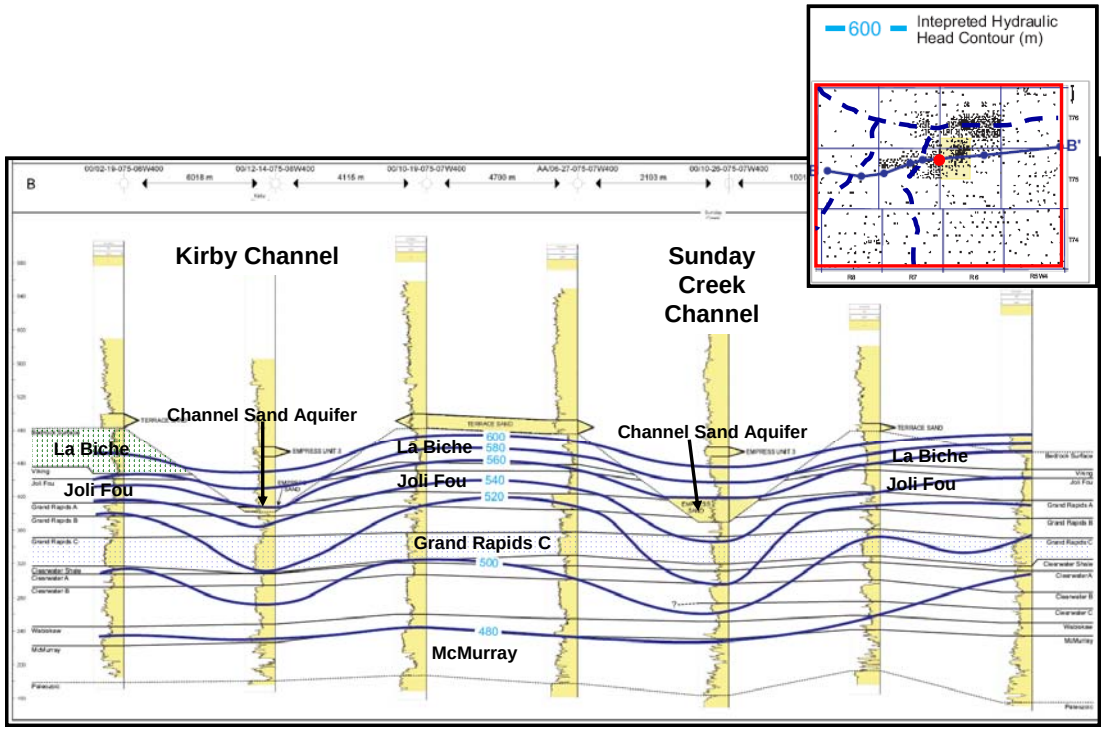

Figure 8: West to east cross section transecting the LSA, Kirby Channel and Sunday Creek Channel with interpreted hydraulic head contours. Groundwater mounding below the Kirby and Sunday Creek channels and a downward directed hydraulic gradient are evident.

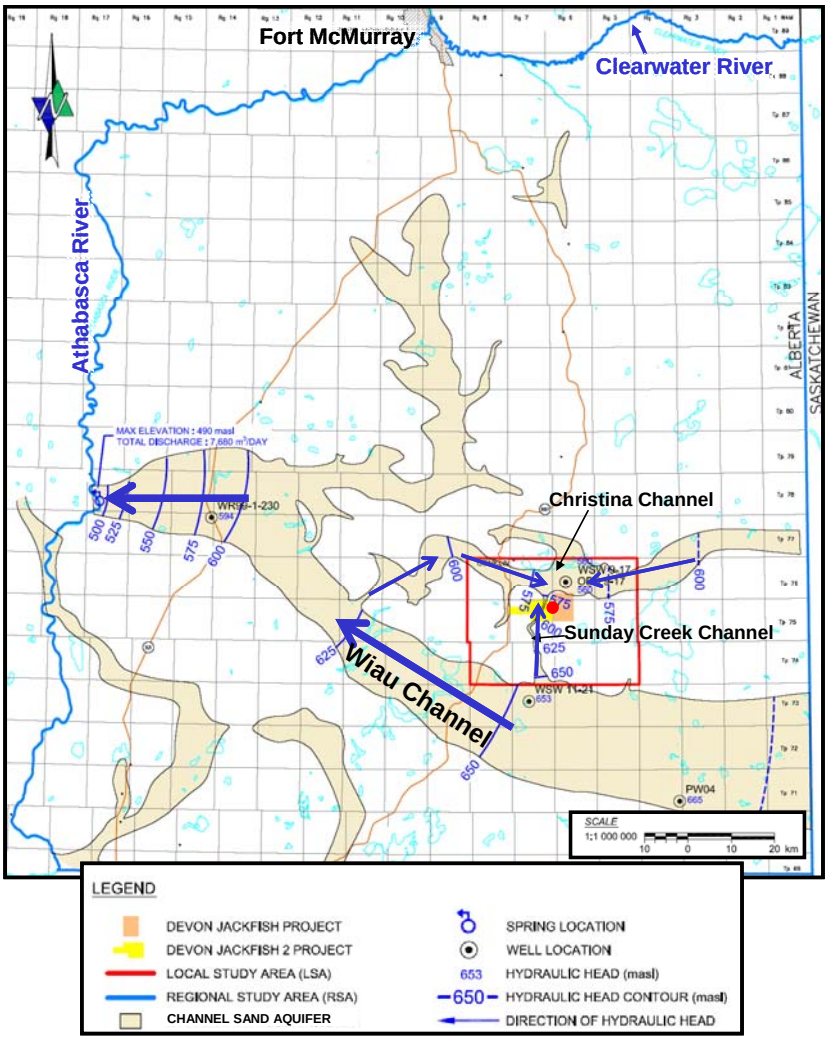

Figure 9: Channel Sand Aquifer hydraulic head distribution.

Groundwater Chemistry

Groundwater chemistry in the LSA supports the presence of a downward directed vertical gradient. This is evidenced by the evolution of major ions with depth and increased TDS concentrations with depth. The ratio of major anions and cations evolves from a calcium-bicarbonate ($CaHCO_3$) type water reflecting meteoric water in the uppermost Quaternary sediments (less than 100 mbgs) to a sodium-bicarbonate ($NaHCO_3$) type water in Tertiary/Quaternary sediments greater than 100 mbgs to a sodium-chloride (NaCl) type water reflecting formation water in the Cretaceous bedrock units (Figure 10). An increase in groundwater salinity (TDS) with depth is present within the RSA and LSA and has also been observed by Bachu et al. (1993).

Groundwater chemistry data within the LSA also supports the hypothesis that hydrogeologic conditions in the Lower Grand Rapids Aquifer appears strongly influenced by the presence of the buried bedrock channels where aquitards of the Colorado Group have been eroded. Figure 11 presents contoured average resistivity (R_t) values derived from wire-line well logs. Bulk electrical resistivity (the inverse of electrical

conductivity) is generally a function of the composition of the geological material, the porosity of the unit and the geochemistry of the fluid in the saturated pore space. Therefore, if the geological material and its porosity are more or less constant, inferences can be made about the saturating fluid in the pore space. If the saturating fluid is water, bulk resistivity values should increase if the TDS of the water decreases and vice-versa. Resisitivity values in the Lower Grand Rapids Aquifer adjacent to and below the Christina, Kirby and Sunday Creek channels are higher than those below the Wiau-Christina Interfluve Bench, suggesting an increase in TDS to the southeast.

Also posted and contoured on Figure 11 are Lower Grand Rapids Aquifer TDS concentrations. Within the Lower Grand Rapids Aquifer, high resistivity and low TDS values are present adjacent to and below the Christina, Kirby and Sunday Creek channels where non-saline water from the channels mixes with more saline Cretaceous formation water. Relatively low resistivity and high TDS values are present in areas where the Joli Fou and La Biche Aquitards were not eroded by the Tertiary/Quaternary channels such as on the Wiau-Christina Interfluve Bench, southwest of the Christina and Sunday Creek channels.

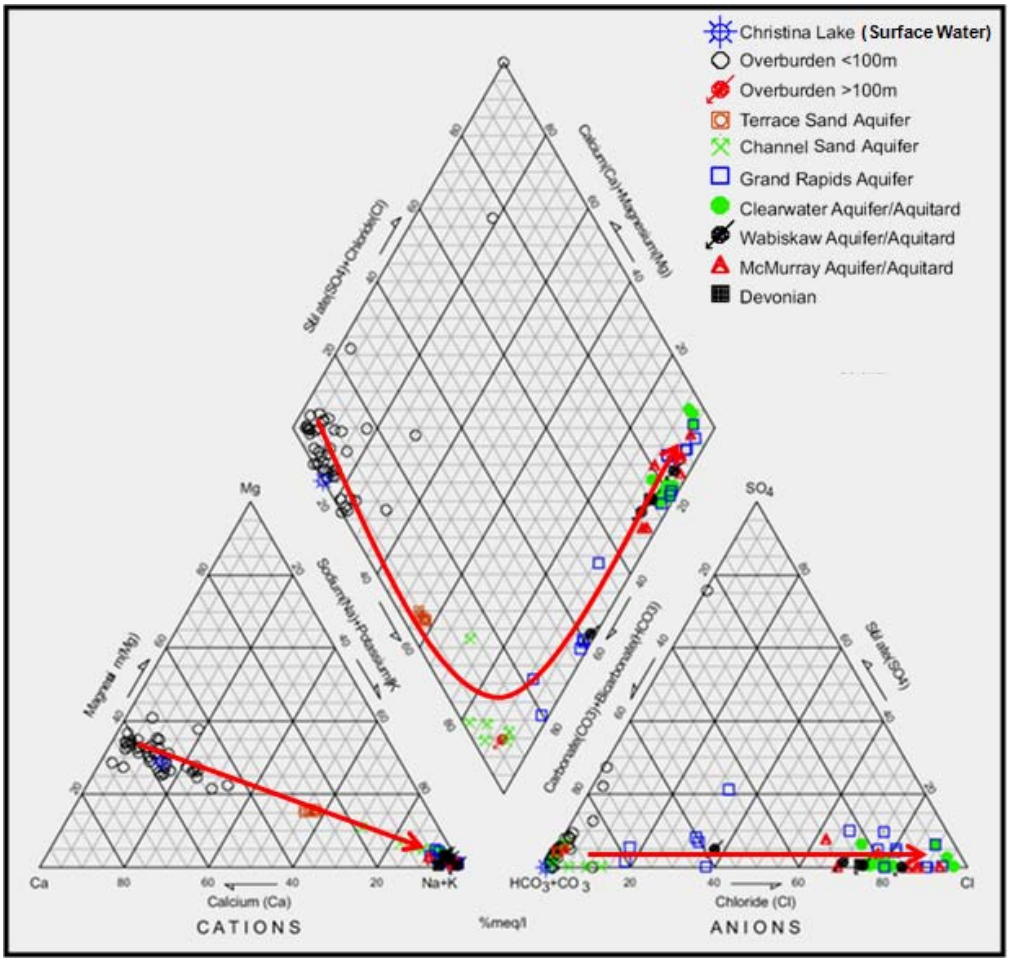

Figure 10: Piper plot illustrating the evolution of groundwater chemistry with depth from a calcium-bicarbonate (or meteoric type) to a sodium-chloride type reflecting formation water.

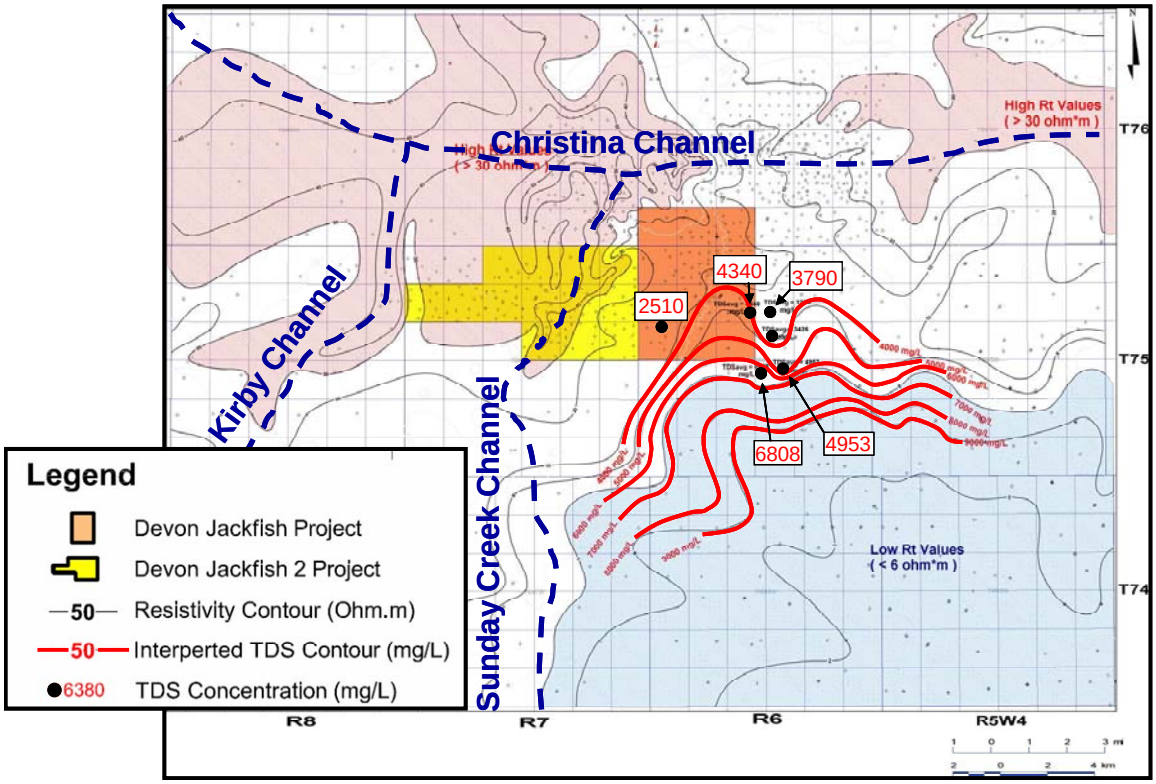

Figure 11: Lower Grand Rapids Aquifer average resistivity (R_t) and TDS Distribution

Implications to Water Supply

The presence of buried bedrock channels adjacent to the Projects has important implications to water supply in terms of deliverability and source water chemistry.

The 20-year safe yield (Q_{20}) or theoretical pumping rate that a well could be pumped for 20 years without exceeding the available drawdown in the aquifer, is used as an analogue for aquifer productive capacity in Alberta. The calculation of the Q_{20} derived by Farvolden (1959) is defined as:

$$Q_{20} = 0.68 * T * H_A * 0.7$$

where:

T = aquifer transmissivity [L2/T];
H_A = available drawdown [L]; and
F_S = safety factor.

As a result of the groundwater mounding (higher hydraulic head and therefore available drawdown) within the Lower Grand Rapids Aquifer in the vicinity of the Sunday Creek and Christina channels, the theoretical deliverability of the Lower Grand Rapids Aquifer is increased.

The incision of the Sunday Creek and Christina channels into the Lower Grand Rapids Aquifer was also considered from a water quality perspective in terms of securing a saline (TDS concentration greater than 4,000 mg/L) water source for the Projects. Presented on Figure 12 is the thickness of the Lower Grand Rapids Aquifer in the LSA. Highlighted in the isopach map are the general locations of the incisions of the Sunday Creek and Christina channels into the Lower Grand Rapids Aquifer, the source wells and planned/existing observation wells. The source wells for the Projects are located greater than 10 km from the deepest incisions of the Sunday Creek and Christina channels. At this location, the Lower Grand Rapids Aquifer is saline and is expected to remain saline for the duration of the Projects (Devon, 2006). Monitoring of hydraulic head values and/or chemistry will be conducted at the source wells and surrounding observation wells (Figure 12) in the Lower Grand Rapids Aquifer as well as overlying and underlying formations.

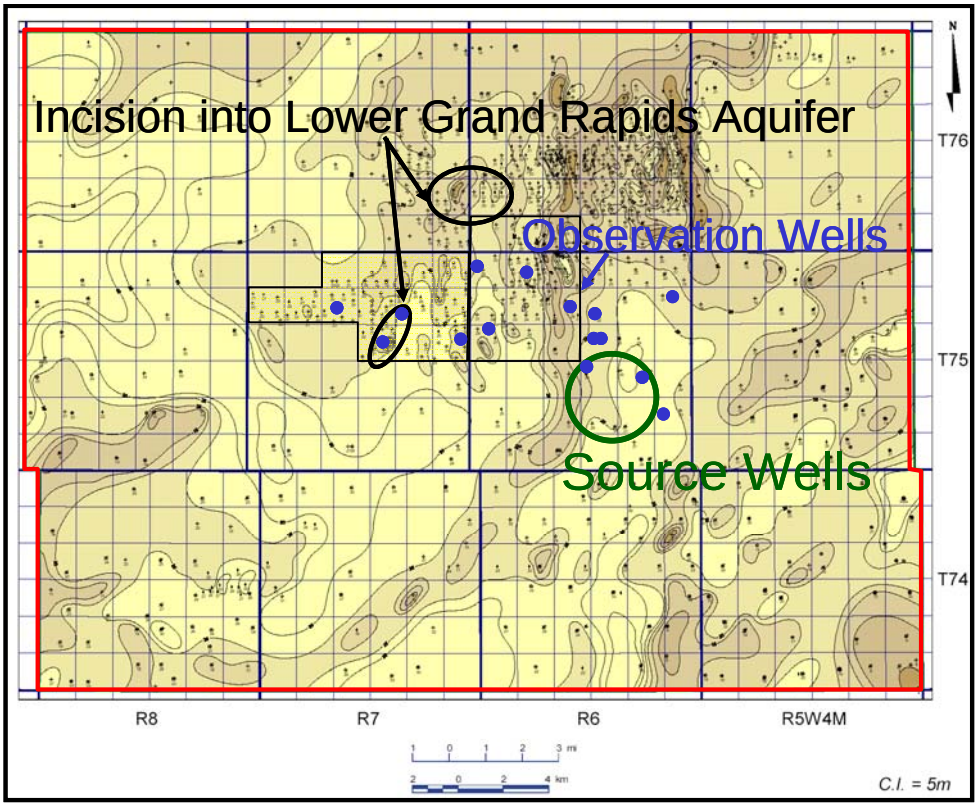

Figure 12: Lower Grand Rapids Aquifer isopach map highlighting the general locations of the channel incisions into the unit, the Projects source wells and planned/existing observation wells.

Summary

The depth of incision and subcropping Cretaceous formations strongly influences: 1) hydraulic head distributions within the buried bedrock channels and Cretaceous formations such as the Grand Rapids and 2) groundwater chemistry of the Cretaceous formations. Therefore, the presence of buried bedrock channels has important implications to water supply in terms of deliverability and source water chemistry.

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