3.0 GEOLOGICAL SETTING

The geology of the CRRRC Site has been assessed based on a regional, local and Site scale as discussed in the following sections, placing it within the overall context of the Ottawa Valley area geology and taking into consideration the Site-specific investigations that have been carried out. Selected geological literature (Sanford and Arnott, 2010, Bleeker et al, 2011) for the area was reviewed along with geological mapping produced by the Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS), as well as Site-specific investigations carried out by Golder, the Ministry of Transportation of Ontario and other consultants. Information was obtained on deep gas exploration wells from the Ministry of Natural Resources and Forestry (MNRF) Oil, Gas and Salt Resource Library. The MOECC Water Well Information System (WWIS) (MOE, 2013) was reviewed and records of cored boreholes were collected.

Additional detailed information on the Site subsurface conditions is provided in Section 6.0, and on the regional and Site hydrogeological conditions in Section 7.0.

3.1 Regional Geological Conditions

3.1.1 Regional Bedrock Geology

The regional bedrock geology of the Ottawa Valley area is shown on Figure 3-1 taken from Sanford and Arnott, 2010 (Geological Survey of Canada Bulletin 597). The area is underlain by a Paleozoic sedimentary sequence extending from basal quartz sandstone and conglomerate deposits of the Cambrian Period and limestone, dolostone and shale sequences of the Ordovician Period. This area underlain by Paleozoic strata is referred to as the Ottawa Embayment and lies unconformably upon Precambrian basement rocks of Grenville age (approximately 1.2 billion years and older). The Ottawa embayment is structurally bounded by Precambrian rock of the Frontenac Arch to the southwest and west, the Laurentian Arch to the north, the Oka-Beauharnois Arch to the east and the Adirondack Dome to the south as shown on Figure 3-1. These arches have been structurally active areas of uplift at various times during the Paleozoic and Mesozoic Eras (approximately 600 to 100 million years ago) as part of the Ottawa Valley-Nippissing Graben structure, which has affected the sedimentation and structure of the overlying Paleozoic sequences within the embayment.

The Ottawa Valley-Nippissing Graben consists of extensional block fault structures extend from the St Lawrence River north westward through the Ottawa Valley including Lake Timiskaming and the Lake Nippissing valleys. Faulting within the graben commenced in the late Precambrian period (about 600 million years ago) and stratigraphic information indicates that it was active through the Cambrian period associated with the clastic deposition of the basal Covey Hill Formation quartz sandstone and conglomerate. Mid- to late-Ordovician limestone and shale strata were deposited in relatively quiescent environments. Formerly overlying Silurian and Devonian Era (younger) strata have been eroded from the area. The Mesozoic Era saw renewed geological activity including intrusion of alkaline dykes and the Cretaceous age Monteregian calc-alkaline igneous intrusions of the Montreal-St. Lawrence valley area including the Mount Royal, Oka and Saint Andre Est igneous complexes. The major period of faulting within the Ottawa Valley culminated during the Cretaceous Period (145 to 66 million years ago) associated with the dominant period of igneous intrusive activity (Beeker et al, 2011).

The Paleozoic carbonate and shale sedimentation occurred in near flat-lying conditions. Ottawa Valley Graben faulting and uplift associated with the Precambrian arches subsequently gently folded the Paleozoic sequence forming a broad syncline with numerous extensional fault offsets. The locations of the major faults are shown in plan view on Figure 3-1, and the location and amount of vertical displacement along these faults are shown in the cross-sections on Figure 3-2. Displacement along these normal fault structures varies from a few tens of metres to several hundreds of metres and deformational dragging along the fault contacts locally resulted in steeper fold deformation of the bedrock strata. Small scale faults associated with offsets in the range of several metres to several tens of metres are comparatively common throughout the Ottawa Valley, occurring within the intervening areas between the more dominant primary faults such as the Gloucester-Russell, Eardley and Hazeldean Faults. Secondary faults of this nature are typically encountered within the Paleozoic sequence within the Ottawa area. The encountered fault features form comparatively sharp planes associated with localized angular brecciation of wall rock re-cemented in white coarse-grained calcite crystallization. The calcite is also associated with minor pyrite and tremolite mineralization indicating hydrothermal conditions at the time of faulting while the strata was still deeply buried beneath overlying strata, which has since been removed by erosion. The fault planes have been observed to be generally intact in nature (tight) unless opened by penetrative weathering near surface.

Rimando and Benn (2005) studied the origin and development of faults exposed within the Paleozoic rocks of the Ottawa-Bonnechere Graben, including the Queenston Formation shale and underlying interbedded limestone and shale of the Carlsbad Formation. These bedrock formations underlie the CRRRC Site (see Figure 3-1, Figure 3-7 and Figure 3-11).

Rimando and Benn (2005) identified three main periods of deformation events (D_1, D_2 and D_3) represented as in the orientation and slip sense of fault sets in the bedrock units exposed in surface outcrops. Each deformation event is associated with different types of faults, listed below from oldest to youngest:

- D_1 – three families of faults including sinistral and dextral strike-slip faults with north-northwest and northwest strikes, respectively, and northwest-striking normal faults. This oldest generation of faults formed in response to a horizontal maximum principal compressive stress ($\sigma 1$) oriented northwest. The faults are kinematically consistent with the compression direction associated with the Iapetus Ocean.
- D_2 – mostly normal faults with subordinate sinistral and dextral strike-slip faults oriented northwest and west-northwest; normal faults striking west-northwest to west-southwest; and minor thrust faults. Fault patterns indicate a west-northwest-oriented $\sigma 1$. This stress orientation coincides with emplacement of Cretaceous carbonatite dikes.
- D_3 – dextral and sinistral strike-slip faults; northeast-striking normal faults and minor thrust faults with a southwest-oriented $\sigma 1$ consistent with the post-Cretaceous stress field for eastern North America.

Rimando and Benn (2005) related each deformation event to the regional stress field developed from major, continental-scale tectonic events such as closing of the Paleozoic Iapetus Ocean toward the end of the Hadrynian approximately 850 to 542 million years ago (D_1) Mesozoic opening of the Atlantic Ocean and associated dyke intrusion about 120 million years ago (D_2); and post-Cretaceous westward drift of the North American plate 66 million years to the present day (D_3). Structural analysis indicates that these faults developed and underwent much of their total displacement more than about 66 million years ago, when the bedrock was in a different stress regime compared to that of the present day.

Major faults that affect the CRRRC study area include the northwest-southeast trending Gloucester Fault and the northeasterly trending Russell-Rigaud Fault branching off from the Gloucester Fault near the Village of Russell (Figure 3-1). These faults have preserved the Billings-Carlsbad-Queenston Formation shale sequences on the north down-dropped side of the faults. The small area of Queenston Formation red shale preserved between the CRRRC Site and Village of Russell represents the youngest strata and hence thickest area of Paleozoic sequence within the Ottawa Valley, up to approximately 850 metres above the Precambrian basement rock (Figure 3-2). Bedrock surface topographic relief associated with faulting has locally developed due to erosion associated with hardness contrasts such as between the harder Precambrian igneous terrain and the softer limestone or between limestone and shale. This is quite evident along the north side of the Ottawa Valley where the Precambrian igneous terrain of the Laurentian Arch rises steeply 100 metres to 150 metres above the Paleozoic terrain to the south along the Eardley Fault located across the river from Ottawa, and to a lesser degree with the Hazeldean Fault west of Ottawa (Figure 3-1).

3.1.2 Regional Surficial Geology

The regional scale surficial geology of the Ottawa Valley is shown on Figure 3-3 taken from the Ontario Ministry of Northern Development and Mines (Map 2556 – Quaternary Geology of Ontario – Southern Sheet). The valley terrain is largely flat associated with the extensive deposition of marine clay during the post-glacial period when the Champlain Sea inundated the area directly following the retreat of the glaciers. The clay soils infilled the former glaciated topography and built up an aerially extensive deposit whose thickness presently varies from a few metres to greater than 30 metres to 50 metres.

The clay thins or is absent within areas where the underlying glacial till deposits formed more prominent relief. The glacial till typically overlies bedrock and bedrock outcrops occur infrequently. Areas of glaciomarine sand and gravel beach deposits developed above the clay deposit during the retreat of the Champlain Sea from the valley, and the subsequent Ottawa River followed former meander channels associated with fluvial granular deposits. The river cut down into the underlying clay as the area continued to isostatically uplift during the post-glacial period until the present Ottawa River course was established. Relatively extensive areas of organic bog deposits have developed due to the flat, poorly drained terrain associated with the marine clays and former river channels.

3.2 Local Geological Conditions

3.2.1 Local Bedrock Geology

The bedrock geological conditions within the local study area around the CRRRC Site are shown on Figures 3-5, 3-6 and 3-7. The local study area includes the CRRRC Site and approximately 12 kilometres towards the east, 9.5 kilometres towards the south, 10.5 kilometres towards the west, and 5 kilometres towards the north. For general context, the extent of the local study area is shown on the regional bedrock geology map (Figure 3-1).

The local study area is overburden covered and bedrock outcrop is limited to a few comparatively isolated areas of shale outcrop at the Russell Shale Quarry approximately 5 kilometres to the southeast of the CRRRC Site and isolated limestone outcrops along the southern edge of the map area, typically south of the Gloucester Fault. An assessment of the bedrock geological conditions within this area was carried out by Golder through a review of the 1:50,000 scale Ontario OGS bedrock mapping (OGS Map P.2717 Paleozoic Geology Russell – Thurso Area, Southern Ontario dated 1985), a review of available site-specific investigation borehole and water well information.

The information included 1,176 MOECC water well records, 70 site-specific investigation cored boreholes drilled by Golder, Ministry of Transportation and other consultants, one deep core hole drilled by the GSC (GSC #2).

The OGS Russell-Thurso Area geology map identified 25 deep gas exploration wells within the local study area and the deep GSC #2 core hole that vary in depth between 300 metres and 890 metres. Ten of the gas exploration wells were completed in the Precambrian basement. The OGS map designated the wells RU-1 to RU-26 and that nomenclature has been retained in this document. The wells also have well names and Well IDs specified on the well cards, providing three references per well as summarized in Table A-1 of Appendix A. The locations of the wells designated RU-01 to RU-26 (GSC #2 = RU-24) are shown on Figure 3-4. The records for the 26 wells were obtained from the MNRF Oil, Gas and Salt Resource Library in London, Ontario. The records obtained included scanned copies of the well card summary sheets including generalized stratigraphy and well completion details, and scanned copies of the original natural gamma and neutron borehole geophysical records. Digitized copies of the natural gamma and neutron logs were also acquired. The majority of the exploration gas wells (23) were drilled by Consumers Gas between 1967 and 1969 and located within approximately 8 km northwest of the community of Russell. The exploration wells were drilled to assess the natural gas production potential within this deep part of the Paleozoic basin. No wells were put into production. Two wells (RU-25 and RU-26) were drilled by the Standard Oil Company in 1910 and 1911 according to the well card records. These two holes were geophysically logged by Consumers Gas in 1968. They are located approximately three kilometres to the east and three kilometres to the north of the CRRRC site, while the GSC #2 core hole is located approximately three kilometres to the southeast of the Site. The exploration gas wells were all plugged and abandoned between 1968 and 1971 in accordance with the MNRF regulations for abandonment of oil and gas wells. The GSC #2 hole was plugged and abandoned in 1966.

The location coordinates of the gas exploration wells are provided on the MNRF well cards in degrees, minutes and seconds of latitude and longitude. The well cards also include offsets from the Concession/Lot boundaries. It was noted that some of the indicated locations were at variance to the locations shown on the OGS Russell-Thurso geology map; for example, RU-24 (GSC #2) locates approximately 1.5 kilometres north of the location shown on the OGS geology map based on the well card location, which has been used in this study.

The digital records for natural gamma and neutron logs were used to interpret the stratigraphy encountered in the exploration gas wells, including the depths to the top of formations and the elevations of the formation tops as summarized on Tables A-2 and A-3 in Appendix A. The interpretation was carried out formation by formation based upon Golder's considerable experience with the interpretation of geophysical records for core holes throughout the Ottawa Valley. The gas well geophysical records vary somewhat in signal intensity between holes, likely reflecting different tools and logging rates. Casing effects on dampening gamma and neutron signals were also evident in wells RU-2, RU-7, RU-10, RU-24 and RU-25 (Figure 3-7). Overall the available records have enabled a comparatively detailed interpretation of the subsurface stratigraphy as discussed further in Section 3.2.1.3. The detailed stratigraphic interpretation has enabled the identification of faults based on formational displacements as discussed in Section 3.2.1.4.

Seven gas exploration wells (RU-2, RU-5, RU-7, RU-10, RU-23, RU-25 and RU-26) and the deep GSC #2 (RU-24) core hole were used to construct a north-south structural geological section though the local study area (Figure 3-7) extending from ground surface to the Precambrian basement encountered at depths between 700 metres and 850 metres. More detailed records of the borehole geophysics with the stratigraphic interpretation are provided on Figures A-1, A-2 and A-3 of Appendix A.

3.2.1.1 Bedrock Surface Topography

The combined file of site-specific investigation boreholes and MOECC water well information (1,274 data points) and 26 exploration gas wells was used to interpret the bedrock surface topography beneath the local study area as shown on Figure 3-5. The bedrock surface varies over a vertical range of approximately 90 metres within the local study area. In the southwestern corner of the area where bedrock is at or near surface, bedrock occurs at elevations of approximately 75 metres above sea level (m ASL) to 105 m ASL. In the northwestern corner of the local study area where the ground surface is between approximately 65 m ASL to 75 m ASL, the bedrock elevation occurs at approximately 15 m ASL to 25 m ASL. The areas of higher bedrock topography typically coincide with more erosional resistant limestone and dolostone bedrock along or south of the Gloucester Fault while the low areas tend to be underlain by less resistant shaley strata. Beneath the CRRRC Site, the shale bedrock surface occurs at an elevation of approximately 40 m ASL to 45 m ASL compared to ground surface between 75 to76 m ASL.

A buried bedrock ridge trending north-northeast occurs approximately six kilometres east of the Site where the bedrock surface rises approximately 20 metres to between elevations of approximately 60 to 80 m ASL, which coincides with a low topographic ridge at ground surface. The Russell Quarry occurs along this ridge where the Queenston shale is locally exposed at surface.

3.2.1.2 Local Bedrock Geology Map

The interpretation of the geology of the bedrock surface and locations of the Gloucester and Russell-Rigaud Faults is provided on Figure 3-6. The Gloucester and Russell-Rigaud Faults are stratigraphically definable primary faults that pass through the southern portion of the local study area. These faults separate the Upper Ordovician shales of the Queenston and Carlsbad Formations to the north of the faults from the Middle and Lower Ordovician limestone of the Bobcaygeon and Gull River Formations and dolostone of the older Oxford Formation to the south. The total vertical displacement associated with the Gloucester Fault is approximately 500 m (Figure 3-7).

The position of the Gloucester Fault shown on Figure 3-6 approximately coincides with a 5 metre to 20 metres change in bedrock surface elevation as shown on Figure 3-5, the shales to the north of the fault being less resistant to erosion and occurring at lower elevations than the limestone and dolostone south of the fault. There are additional secondary faults with displacements in the range of a few metres to tens of metres that occur beneath the local study area, but there is little stratigraphic information to define their potential positions. Faults of this nature can be recognized by reference to 6 of the 26 gas exploration wells (RU-4, RU-7, RU-8, RU-11, RU-14 and RU-17) based on stratigraphic interpretation of the borehole geophysics.

The lateral extent of the bedrock formations beneath the local study area as shown on Figure 3-6 has taken into consideration the OGS mapping and the available site-specific investigation borehole information. In addition, the MOECC WWIS (MOE, 2013) provided well driller's brief descriptions of the bedrock encountered during drilling domestic water wells. The wells/boreholes shown on Figure 3-6 are colour coded to take the bedrock descriptions into consideration. Red-coloured bedrock (Queenston shale) was consistently described, while areas underlain by the Carlsbad Formation were variously described by water well drillers as grey to black shale or limestone. The driller's reference to limestone in the same areas may reflect the presence of limestone layers interbedded in the shale that caught the driller's attention.

Through taking the water wells, site-specific investigation boreholes and gas wells into consideration, the general area underlain by the Queenston Formation shale, the uppermost and youngest Paleozoic sequence in the Ottawa Valley, has been defined as shown on Figure 3-6. This area differs from that shown on the published bedrock geology map of the area (OGS Map P.2717) and the Sanford GSC map (Figure 3-1) by being significantly reduced in extent to the east and greater in extent to the west based upon the benefit of the additional information on bedrock from the boreholes compiled for this study. The OGS interpretation indicated that the extent of the Queenston shale was fault bounded representing a down-dropped block. However the results of work carried out for this investigation indicate that the main body of the shale occurs as a conformable sequence within a broad synclinal basin (Figure 3-7). The OGS mapping recognized slivers of the Queenston Formation apparently encountered by water well drillers within the Gloucester-Russell fault zone where they are preserved as down-dropped blocks (Figure 3-6).

The MNRF well cards for gas exploration wells RU-07, RU-08 and RU-17 located near the Village of Russell report Queenston shale at the bedrock surface without definition of the underlying Carlsbad-Billings sequence. The MNRF well cards for gas exploration wells RU-1, RU-2 and RU-4 also indicate the presence of Queenston Formation shale at the bedrock surface where the well cards define a comparatively consistent thickness to the formation. However, examination of the geophysical records for these wells indicates that there is insufficient stratigraphic thickness in the Carlsbad/Billings shale sequences above the Trenton Group limestone to accommodate the Queenston shale at these well locations when compared to the record for RU-24 (GSC #2). In RU-24 approximately 235 metres of Carlsbad and Billings Formation shale occurs between the Queenston shale contact and the underlying Trenton Group limestone. Accordingly, these specific exploration well records are not considered representative with respect to the occurrence of the Queenston Formation.

The RU-6 well card reports Queenston Formation at the bedrock surface but did not define a thickness. There is approximately 306 metres of shale sequence in this well. When compared to RU-24, the projected Queenston shale contact in RU-6 would occur at a depth of approximately 73 metres. This represents the thickest intersection of Queenston shale in the area.

The red shale of the Queenston Formation is locally exposed within the Russell Shale Quarry where previous site-specific investigation core drilling by Golder identified up to 35 metres of Queenston Formation red shale/mudstone overlying the grey shale and limestone of the Carlsbad Formation. The transition from the Queenston Formation to the Carlsbad Formation shale was found to be marked by a laterally continuous fine grained, non-porous limestone layer with minor shale interbeds forming the caprock on the Carlsbad Formation. This limestone caprock varies in thickness from approximately 6.4 metres to 8.3 metres at the Russell Shale Quarry. A five metre thick section of the same limestone caprock with approximately 10% interbedded shale and calcareous shale was encountered in borehole BH12-2-3 at the southwest end of the CRRRC Site, indicating that this limestone caprock is a comparatively continuous stratigraphic horizon associated with the Queenston Formation/Carlsbad Formation contact. The caprock also underlies the eastern slope of the north-northeast trending bedrock ridge in the Russell Shale Quarry area, which is likely in part responsible for this erosional resistant bedrock topographic feature.

At the Russell Shale Quarry site, elevation contours of the Carlsbad limestone caprock/Queenston Formation contact horizon indicate a gentle synclinal fold as shown on Figure 3-8. The axis of the fold gently plunges westward at approximately 1.0% to 1.5% with inward sloping north and south limbs at approximately 2% to 3%. This fold is likely a localized sympathetic fold within the overall gentle synclinal structure represented by the Queenston shale sub-crop (the interpreted extent of which is shown on Figure 3-6), and indicates the scale of fold related bedding dip that can locally occur.

3.2.1.3 Bedrock Stratigraphic Sequence

The subsurface stratigraphy and structure beneath the local study area is shown in cross-section on Figure 3-7. This cross-section has been largely developed from interpretation of the stratigraphic sequence encountered by the deep gas exploration wells and the comparatively shallow site-specific investigation core holes. The section reflects the approximately 700 metres to 850 metres thick Paleozoic sequence unconformably overlying the Precambrian basement. The natural gamma and neutron geophysical records for the gas wells are shown on the section to indicate the positions of the major formation contacts. For example, the contact between the Billings Formation shale and the underlying Eastview Member of the Lindsay Formation limestone provides a pronounced regression in the natural gamma and neutron signal for correlation purposes. Detailed records of the interpreted geophysical signatures are provided on Figures A-1 to A-3 in Appendix A.

Shale Sequence

As indicated on Figure 3-7, the Upper Ordovician shale sequence that forms the bedrock surface north of the Gloucester Fault includes the red shale of the Queenston Formation, the underlying dark grey shale and secondary interbedded limestone of the Carlsbad Formation and the Billings Formation dark grey to black shale. The thickness of this shale sequence shown in the section varies between approximately 200 metres and 260 metres overlying limestone of the Trenton Group. The thickness variation reflects the depth of bedrock surface erosion and the very gentle dip of the strata. A few kilometres further west at well RU-6 (see location on Figure 3-4) the combined shale sequence thickens to approximately 306 metres.

The Queenston Formation red shale intersection in the RU-24 (GSC #2) core hole was approximately 25 metres as indicated by Dix and Jolicoeur (2011), while previous Golder borehole drilling at the Russell Quarry site encountered 35 metres of shale. As discussed above, the Queenston shale is directly underlain by the 6- to 8-metre thick limestone caprock of the Carlsbad Formation.

The Carlsbad Formation underlying the limestone caprock at both the Russell Quarry and CRRRC Site is comprised of thinly interbedded dark grey to black slake-susceptible shale with interbeds of calcareous shale, shaley limestone and individual beds of micritic to bioclastic limestone varying between approximately 2 and 20 centimetres thick. Some calcareous beds are cross laminated. The exposed shale tends to weather to a medium grey colour. At the CRRRC Site the percentage of shale and calcareous shale encountered in the cored boreholes was measured and found to vary between approximately 47% and 86% of the sequence, with the balance being interbedded shaley limestone and limestone. Siltstone is often used to describe some of these hard beds but they are all calcareous and readily scratched by knife indicating they are micritic to detrital carbonate beds rather than siliceous clastic beds.

The Carlsbad Formation has a distinct positive gamma spike and negative neutron spike at a depth of approximately 100 metres below the Queenston/Carlsbad contact in the RU-24 core hole as shown on Figure 3-7 (for detail see Figure A3 in Appendix A). This same spike is approximately 130 to 140 metres above the Billings/Eastview contact and was identified within the geophysical signatures of all the gas exploration wells where it provides a distinct stratigraphic marker bed. This thin horizon is reported to be a bentonitic clay layer consistent with an ancient volcanic ash layer (Dix and Jolicoeur, 2011). In exploration gas wells RU-7, RU-8, RU-11, RU-14 and RU-17(all located in the cluster of gas wells just north of the Village of Russell) the shale thickness between the bentonite layer and the Eastview Member varied between approximately 104 and 114 metres indicating the effects of vertical fault offsets in the respective boreholes.

The Billings Formation was not encountered in any of the local site investigations but has been extensively drilled by Golder in the urban Ottawa area as part of sewer and transit tunnel alignment investigations where up to 53 metres of Billings Formation shale sequence has been encountered. The formation consists of black slake-susceptible non-calcareous, bituminous shale. The formation's non-calcareous nature and general absence of hard carbonate interbeds differs significantly from that of the overlying Carlsbad Formation. The basal 10 to 20 metres of the Billings Formation is associated with an elevated natural gamma signature as shown on Figure 3-7, which is also associated with elevated total organic carbon concentrations in the range of 2% to 3% (Dix and Jolicoeur, 2011). The organic carbon content imparts the dark black colouration to the shale, which weathers brownish when exposed. Minor pyrite occurs along bedding partings while occasional thin (5 to 10 centimetres) limestone/siltstone beds occur at intervals of approximately 10 to 15 metres within the lower 53 metres of the section encountered in boreholes drilled in the urban Ottawa area. These thin beds are typically associated with negative natural gamma spikes.

The upward formational change from the Billings Formation to the Carlsbad Formation is transitional noted by the increased frequency of limestone beds. The OGS Russell-Thurso map sheet (map P.2717) reported a Billings shale thickness of approximately 54 metres in the RU-24 core hole. The available geophysical borehole records or the gas exploration wells were not considered to be sufficiently detailed to provide a clear distinction of the contact between the Carlsbad and Billings Formations. Therefore, the Carlsbad and Billings Formations are presented as one combined unit on Figure 3-7 with a thickness of approximately 235 metres.

Previous structural interpretation by Dix and Jolicoeur (2011) based upon limited borehole information (GSC #2/RU-24 and Consumers Gas wells 12417/RU-2 and 1772/RU-25) has suggested that correlation between these three boreholes indicates a localized sin-depositional graben fault feature with approximately 10 metres of offset. This correlation is based mainly upon their core logging of GSC #2/RU-24 borehole compared to the coarsely defined geophysical records of 12417/RU-2 and 1772/RU-25. Based on the geological information compiled and interpreted as presented in this report, the correlation is considered subjective, such that hypothesizing the presence of sin-depositional faulting may not be necessary to interpret the bedrock structure. As shown on Figure 3-7, the boreholes are 2.5 to 3.5 kilometres apart and there is essentially no thickness difference in the intervals between the base of the shale and the bentonite layer. Regardless, post-depositional faults on the scale of several metres to several tens of metres are relatively common throughout the region.

Trenton and Black River Groups

The shale sequence overlies approximately 200 to 215 metres of limestone of the Trenton and Black River Groups. The Trenton group includes the Lindsay and underlying Verulam Formations, which have a comparatively consistent combined thickness of 72 to 74 metres where not influenced by fault offsets (see Figure 3-7). The Eastview Member (former Eastview Formation) of the Lindsay Formation forms the top of the sequence directly beneath the Billings shale. Based on the gas well correlations, the member has a thickness of approximately 10 metres. It is comprised of thinly interbedded dark brownish black bituminous shale and dark brownish grey nodular micritic limestone with fossiliferous debris. The geophysical signature shows a distinct transition from the Lower Lindsay Formation to the Billings Formation (Figure 3-7). The Lower Lindsay Formation consists of medium to dark brownish grey medium thickly bedded micritic to calcarenitic nodular limestone.

The Verulam Formation consists of medium brownish grey thinly to medium bedded shaley calcarenitic limestone with interbeds of nodular limestone, minor thin lithoclastic calcarenite limestone beds and numerous dark gray to black very thin to thin interbeds shale. The formation is transitional from the overlying Lindsay Formation and the contact is considered to be the first shale bed typically identifiable in the natural gamma and neutron geophysical logs, subject to the log quality.

The Black River Group is comprised of the Bobcaygeon Formation and the underlying Gull River Formation. The Bobcaygeon Formation consists of light to medium brownish grey, medium to thickly bedded calcarenitic limestone and interbedded units of argillaceous nodular limestone and shaley limestone. The formation has an average thickness of approximately 92 metres based upon the interpretation of the gas well geophysics. It is associated with a comparatively distinctive geophysical signature, the top contact marked by a drop in gamma and increase in neutron response associated with the transition into a shale free calcarenite. The base of the formation is considered to be the first appearance of faintly to moderately porous dolostone marking the top of the Gull River Formation. This contact is associated with a positive gamma response and negative neutron response. The Bobcaygeon Formation is a clear geophysical marker horizon as shown on Figure 3-7.

The Gull River Formation is approximately 30 to 40 metres thick with the difference largely reflecting the transition into the underlying Rockcliffe Formation. The Gull River Formation is comprised of medium grey, micritic to lithographic limestone, argillaceous to calcareous dolostone and medium to very thickly bedded dolostone, minor interbedded black shale, shaley dolostone, dolomitic siltstone and partly bioturbated quartz sandstone. The top half of the sequence is largely limestone while the lower half is interbedded limestone and dolostone with sandstone interbeds

Rockcliffe Formation

The Rockcliffe Formation is a largely clastic sequence that varies in thickness between approximately 45 metres to 75 metres that can be subdivided into an upper and lower member associated with fairly distinct geophysical signatures. The Upper Member (15-18 metres) is comprised of medium to thick interbedded dolostone and calcareous dolostone, dark grey to black shale, medium grey, argillaceous limestone, and minor light grey calcareous cemented quartz sandstone. The Lower Member (45-60 metres) is composed of light whitish grey, laminar textured to ripple and cross bedded, thin to thick bedded silica cemented quartz sandstone, with minor interbeds of shale.

Oxford and March Formations

The Oxford Formation and the underlying March Formation are dolostone sequences where the thinner March Formation is transitional from the Oxford dolostone noted in core by gradational increase in carbonate cemented quartz sand grains. The geophysical transition from the overlying Rockcliffe Formation is sharply noted by a drop in gamma and increase in neutron responses. There is no distinct geophysical contrast between the Oxford and March Formations and they have been combined as a single unit for the purposes of Figure 3-7. The formations are comprised of fine grained, micritic dolostone, calcareous dolostone, argillaceous nodular dolostone, subordinate beds of lithoclastic dolostone, dark grey to black shale laminations in upper half (Oxford Formation), grading down to sandy dolostone to dolomitic sandstone and carbonate cemented quartz sandstone (March Formation). The thickness of this sequence varies from approximately 110 metres to 125 metres of which the basal 10 to15 metres could be the March Formation.

Nepean Formation

A contact depth for the base of this sequence (top of Nepean Formation) was provided in the MNRF well cards for the gas wells. The contact is associated with an increase in both gamma and neutron responses reflecting an underlying rock unit approximately 35 to 40 metres thick, interpreted to be a calcareous sandstone phase at the top of the Nepean Formation (Nepean Formation Unit 2B on Figure 3-7).

This unit is underlain by a sharp decrease in gamma response consistent with light grey, laminar to cross bedded, silica cemented quartz sandstone typical of the Nepean Formation. The sandstone includes widely spaced interbeds of grey shale and shaley siltstone with individual beds of quartz pebbles and cobbles set in a coarse grained quartz sandstone matrix. This sequence varies in thickness between approximately 100 and 140 metres based on the gas well geophysical interpretation likely reflecting variations in the topography of the underlying Precambrian surface (Nepean Formation Unit 2A on Figure 3-7). The comparatively thin (10 metre) Covey Hill Formation at the base of the Nepean Formation (where present) has not been subdivided.

Precambrian Basement

The Precambrian basement is comprised of undifferentiated igneous and metamorphic rock sequences of the Grenville Province including marble, biotite gneiss and granitic suites.

3.2.1.4 Fault Structures

The results of the geological evaluation have confirmed that the primary fault feature within the Local Study area is the Gloucester and Russell-Rigaud Fault system. As shown on Figure 3-7, the Gloucester Fault is comprised of a series of normal fault slices locally projected to occur within a zone approximately 0.75 kilometres in width where it passes beneath the community of Russell. The combined vertical offset associated with this fault zone is approximately 500 metres downward on the north side, which can be seen by the projected offset of the Oxford/March Formations across the fault zone. The fault zone depicted on Figure 3-7 reflects three individual vertical faults based on projections from sparse formation outcrops at surface. However, the zone is likely comprised of numerous vertical fault slices of varying displacements that collectively make up the total observed formational offset.

The geophysical interpretation of the stratigraphy encountered in the gas exploration well identified secondary faults intersecting wells RU-4, RU-7, RU-8, RU-11, RU-14 and RU-17 where displacement was measurable based upon the stratigraphic offsets in the boreholes.

In gas well RU-7, there is approximately 60 metres of vertical displacement associated with a reduction in the thickness of the Carlsbad/Billings sequence, complete displacement of the Lindsay Formation and upper 10 metres of the Verulam Formation, as indicated in section on Figure 3-7. The lower strata extending from the base of the Verulam Formation downward project directly from RU-10, while the upper sequence is displaced and RU-23 is stratigraphically down dropped relative to RU-7. This indicates that the fault passing through RU-7 is down thrown on the south side and probably parallels the local northeast-southwest trend of the adjacent Gloucester-Russell fault zone reflecting a localized downthrown post-depositional graben feature. There are likely other smaller scale faults within this interval as indicated by the projection of the Carlsbad bentonite layer between gas wells RU-7 and RU-23 (Figure 3-7).

Further west at gas well RU-17 (see location on Figure 3-4), the Carlsbad/Billings shale sequence between the bentonite layer and the top of the Eastview Member is approximately 110 metres thick compared to a typical undisturbed thickness of approximately 140 metres, indicating a displacement of 30 metres likely passing through the borehole approximately 10 metres above the Billings/Eastview contact based upon the foreshortened basal Billings geophysical signature.

Gas well RU-11 (see location on Figure 3-4) also has a foreshortening of the Carlsbad/Billings shale sequence between the bentonite layer and the top of the Eastview Member of approximately 35 metres.

Gas well RU-14 directly west of RU-11 has a foreshortening of the Carlsbad/Billings shale sequence between the bentonite layer and the top of the Eastview Member of approximately 26 metres and complete displacement of the Eastview Member and a portion of the underlying Lower Lindsay Formation of 16 metres totalling 42 metres, similar to the displacement in RU-11.

Gas well RU-8, located approximately 650 m south of RU-11 and RU-14 has a foreshortening of the Carlsbad/Billings shale sequence between the bentonite layer and the top of the Eastview Member of approximately 20 to 22 metres. To the northwest at gas well RU-4 (see location on Figure 3-4), there is a minor offset of approximately 10 m associated with foreshortening of the Carlsbad/Billings shale sequence between the bentonite layer and the top of the Eastview Member.

Further structural insight can be gained through a comparison of the formation contact elevations of the gas wells summarized in Table A-3 of Appendix A and the gas well locations shown on Figure 3-4. For example, slope of the contact of the top of the Eastview Member between gas well RU-22 and RU-12 is approximately 2% northward, similar to the local observations of formation slope at the Russell Quarry. There is an offset of approximately 28 to 30 metres between RU-22 and RU-17 to the south, consistent with the offset observed in RU-17 indicating downward displacement on the south side of the fault similar to RU-7. To the west, the projected displacement between RU-14 and RU-8 is approximately 60 metres. These relationships indicate an east-west trending fault or series of parallel faults related to the Gloucester Fault Zone passing between these boreholes with displacements of up to 60 metres down-thrown on the south side of the faults as indicated on Figure 3-7. North of these boreholes the formation contact slopes are comparatively constant and there is little indication of faulting.

The stratigraphic projection shown on Figure 3-7 extending northward beneath the CRRRC Site appears very consistent with no direct indication of discernable fault displacements. Smaller displacement faults (<10 metres) could however be present.

3.2.2 Local Surficial Geology

The thickness of the surficial deposits overlying the bedrock within the local study area is shown on Figure 3-9. This figure represents a subtraction of the bedrock surface shown on Figure 3-5 from the ground surface topography, essentially reflecting an inverse image. As shown, the areas underlain by shale north of the Gloucester Fault have approximately 20 metres to 60 metres of surficial deposits. The north-northeast trending buried bedrock ridge within this area locally has thinner surficial deposits of approximately 0 metres to 10 metres. The deposits are similarly thin (5 metres or less) within the area to the southwest of the Gloucester Fault underlain by Oxford Formation dolostone. The CRRRC Site is underlain by up to approximately 40 metres of soil, representing one of the thicker areas of surficial deposits within the local study area.

GSC mapping of the surficial deposits is shown on Figure 3-10. Much of the area is underlain by deposits of offshore marine silts and clays associated with the former Champlain Sea. The Champlain Sea deposits are thickest within those areas of lower bedrock surface topography. The marine clay deposit overlies glacial till deposits above the bedrock. The till deposits locally come to surface along the north-northeast trending buried bedrock ridge and within the areas of thin overburden above the dolostone bedrock strata to the southwest of the Gloucester Fault. The relationship between the basal till and overlying deposits is shown on Section D-D' Figure 3-11. The till is comparatively thin (2 metres to 9 metres) and follows the bedrock topography. The marine clay deposits have filled in the low areas, and are generally overlain by thin sandy soils.

A buried esker deposit of sand and gravel (Vars-Winchester Esker) occurs directly east of and roughly parallels the trend of the north-northeast trending buried bedrock ridge (Figure 3-11), and is about 8 kilometres east of the CRRRC Site. This esker forms an aquifer beneath the clayey marine deposits. This aquifer is structurally and hydraulically isolated from the CRRRC Site by the thick clay deposits and the buried bedrock ridge as illustrated on Figure 3-11.

The clayey marine deposits are locally overlain by a thin layer of sand and silt of near shore deltaic or estuary derivation that was deposited during the retreat of the Champlain Sea from the area. A former channel of the Ottawa River passes through the area directly north of Highway 417. The channel cut linear terrace faces into the marine clays and deposited stratified silts, sands and gravels along the channel bed. Following the retreat of the Ottawa River to its present channel, organic bog deposits accumulated in the low areas such as the extensive Mer Bleue Bog to the north/northwest of the CRRRC Site (see location on Figure 3-10).

3.3 CRRRC Site Geological Conditions

3.3.1 Site Bedrock Geology

The CRRRC Site was investigated by drilling at 25 locations during 2012 and 2013 (the methodology and results of the drilling program are described in detail in Section 2.0 and Section 6.0, respectively). Eight of the boreholes were drilled to bedrock and the rock was cored to depths of approximately 4 metres to 6 metres below the bedrock surface. The bedrock boreholes included BH12-1-3, BH12-1-3-1, BH12-2-3, BH12-3-3, BH12-4-3, BH13-5-3, BH13-6-3 and BH13-7-2, and the borehole locations are shown on Figure 3-12. The bedrock encountered in these boreholes was lithologically logged on a bed-by-bed basis and the individual borehole records are provided in Appendix A. Ten groundwater boreholes were previously drilled on the Site by Water & Earth Sciences Associates (WESA) in 1986-87, but only Test Hole #10 was completed into bedrock.

The location of Test Hole #10 drilled approximately 650 metres east of the southeast corner of the CRRRC Site is shown on Figure 3-12.

The bedrock surface elevation beneath the Site was interpreted from the on-Site boreholes that intersected the bedrock and from adjacent boreholes and water wells as shown on Figure 3-12 Panel A. The bedrock topography forms an irregular bowl shape beneath the Site varying in elevation between approximately 36 m ASL and 46 m ASL compared to a ground surface elevation of approximately 76 m ASL to 77.5 m ASL.

The boreholes cored into bedrock beneath the CRRRC Site all encountered the Carlsbad Formation (Figure 3-12 Panel B). The majority of the Site is underlain by the shaley member of the formation consisting of dark grey, very thinly to thinly interbedded shale and calcareous shale with thin to medium interbeds of argillaceous to shaley limestone and occasional beds of bioclastic limestone typical of the Carlsbad sequence beneath the limestone cap. A comparison of the core logs indicated that the interbeds of limestone could not be correlated between the cored boreholes. The shale and calcareous shale beds comprised approximately 47% to 86% of the bedrock investigated in the 8 core holes, averaging 71%. The shale tended to slake on exposure to wetting and drying.

The limestone caprock layer marking the top of the Carlsbad Formation was encountered at the south end of the CRRRC Site in BH12-2-3 where 5 metres of thinly to medium bedded limestone with approximately 10% shale interbeds was intersected. The limestone caprock was also encountered in the previously drilled Test Hole #10 directly east of the Site, while the red shale of the Queenston Formation was encountered in a water well directly southwest of the Site. Based on these strata intersections, a bedrock geology plan of the Site was constructed as shown on Figure 3-12 Panel B.

The geology plan indicates that the typically 6 metres to 8 metres thick caprock and associated formations dip very gently toward the south in the range of 1% to 2%.

3.3.2 Site Surficial Geology

As indicated on Figure 3-13 Panel A, the CRRRC Site is underlain by approximately 32 metres to 40 metres of surficial deposits; the thickest section is beneath the eastern side of the Site. The soil thickness directly mirrors the bedrock topography considering that the ground surface within the Site is essentially flat.

The majority of the boreholes drilled on-Site encountered a 1 metre to 2 metres thick veneer of silty sand at the surface overlying marine silty clay, while a few of the boreholes encountered the underlying marine silty clay at surface (Figure 3-13 Panel B). Two cross-sections illustrating the subsurface soil stratigraphy are provided on Sections E-E’ and F-F’ on Figures 3-14 and 3-15, respectively. The silty clay is the dominant soil horizon overlying a comparatively thin glacial till layer above the bedrock. A thin (0.1 metres to 0.6 metres), near flat lying layer of sandy silt to silty sand, trace clay (described as the ‘silty layer’) was encountered at a consistent depth of approximately 4 metres to 6 metres below ground surface (Figures 3-14 and 3-15) and was reasonably interpreted to be continuous beneath the Site and assumed to extend off-Site.

The thicknesses of the various soil horizons are shown by isopachs on Figures 3-16 and 3-17. The surficial layer of silty sand varies from not present (0 metres) to a maximum of 2.7 metres in a localized area (Figure 3-16 Panel A), while the underlying marine silty clay varies from approximately 25 metres along the northern edge of the Site to approximately 32 metres to 34 metres in the southwest corner and beneath the east side of the Site (Figure 3-16 Panel B). This trend generally reflects the inverse of the bedrock surface topography.

The silty layer within the upper portion of the silty clay deposit thins to the north and south of the Site and appears to be thickest in a diagonal band passing from northwest to southeast through the central part of the Site where it locally thickens to approximately 0.4 metres to 0.6 metres, possibly reflecting a local erosional pattern in the surface of the clay deposit (Figure 3-17 Panel A).

The thickness contours of the basal glacial till unit vary from 4 metres to 8 metres and reflect a relatively uniform layer given the large scale of the Site (Figure 3-17 Panel B).