2.1.1 SCOPE

The project is situated in the northeastern portion of the Athabasca oil sands region and is targeting bitumen deposits trapped in the Cretaceous-aged sandstones of the McMurray Formation.

The stratigraphy within the project area (i.e., Muskeg Lease boundary) is shown in:

- Figure 2-1, Stratigraphic Column for the Project Area
- Figure 2-2, Schematic of the Stratigraphic Architecture in the Project Area

Within the project area, the Mannville Group is subdivided into the:

- Grand Rapids Formation
- Clearwater Formation, including the Wabiskaw Member
- McMurray Formation

The Mannville Group unconformably overlies the carbonates of the Devonian Waterways Formation (Beaverhill Lake Group) and underlies the Tertiary and Quaternary deposits that make up the current surface material.

The type well representative of the project area and used for reference throughout this application is 1AA/03-36-093-07W4 (project type well). Figure 2-3 shows the stratigraphy at the project type well location and is annotated with Imperial's subsurface nomenclature. The stratigraphy of the project type well was compared to well 1AA/10-15-095-5W4 (described in Hein 2006) and to the exploration well 1AA/16-14-094-07W4 located in the project area. Figure 2-4 is a comparison of the stratigraphy at these three wells.

2.1.2 AVAILABLE DATA

The development area consists of 14.5 sections (37.6 km^2) located in the central northeastern portion of the project area (see Figure 2-5), with up to 11 oil sands evaluation (OV) wells per section. A total of 140 wells penetrate the McMurray Formation within the project area (see Figure 2-6). All of these wells are vertical. Table 2-1 lists these wells and their associated data, as of March 31, 2013.

2.12 AVAILABLE DATA (cont'd)

Most wells have:

- a standard log suite, including gamma ray, resistivity (shallow, medium and deep), spontaneous potential, density and neutron porosity, caliper
- a sonic log, either borehole compensated or dipole sonic
- formation microimager (FMI) data recorded

Of the 140 wells, 133 were cored through the McMurray Formation. Most of these cores were analyzed in the core lab to measure oil saturation. Selected cores were also analyzed for grain size distribution, porosity and permeability. Formation pressure data was collected from selected wells using either a modular formation dynamics tester (MDT) or Pressure Xpress tool (XPT).

During the 2012 – 2013 drilling season, Imperial drilled 13 appraisal wells in the project area. Of these 13 appraisal wells:

- wells 1F1/04-02-094-07W4 and 102/04-02-094-07W4 were cased and used to evaluate the lower Grand Rapids Formation as a potential water source
- well 1F1/02-17-093-07W4 was cased and used to evaluate the basal McMurray aquifer as a potential water source in the southwestern portion of the project area
- well 1AA/15-03-094-07W4 was used for caprock minifrac testing and a preserved caprock core was collected for geomechanical laboratory testing

The remaining nine wells were drilled to delineate the bitumen resource and to investigate the GSZ that exists in the upper portion of the McMurray Formation.

High-resolution 3-D seismic data recorded over about 90% of the project area compensates for the lower well density at the edges of the project area. Imperial recorded 3-D surveys in 2009 and 2010 covering 46.5 sections of the project area (110 km^2) (see Figure 2-7).

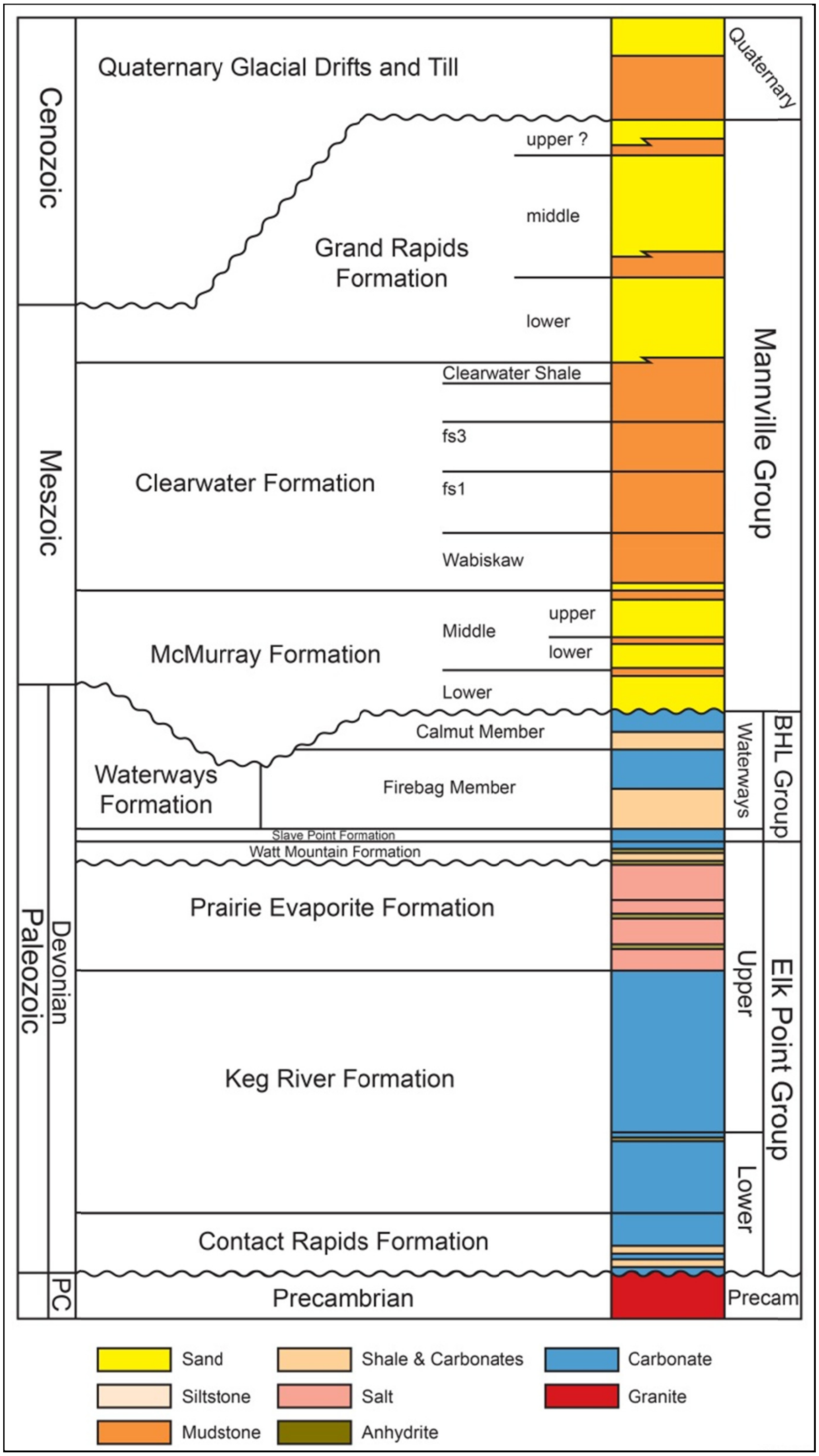


Figure 2-1: Stratigraphic Column for the Project Area

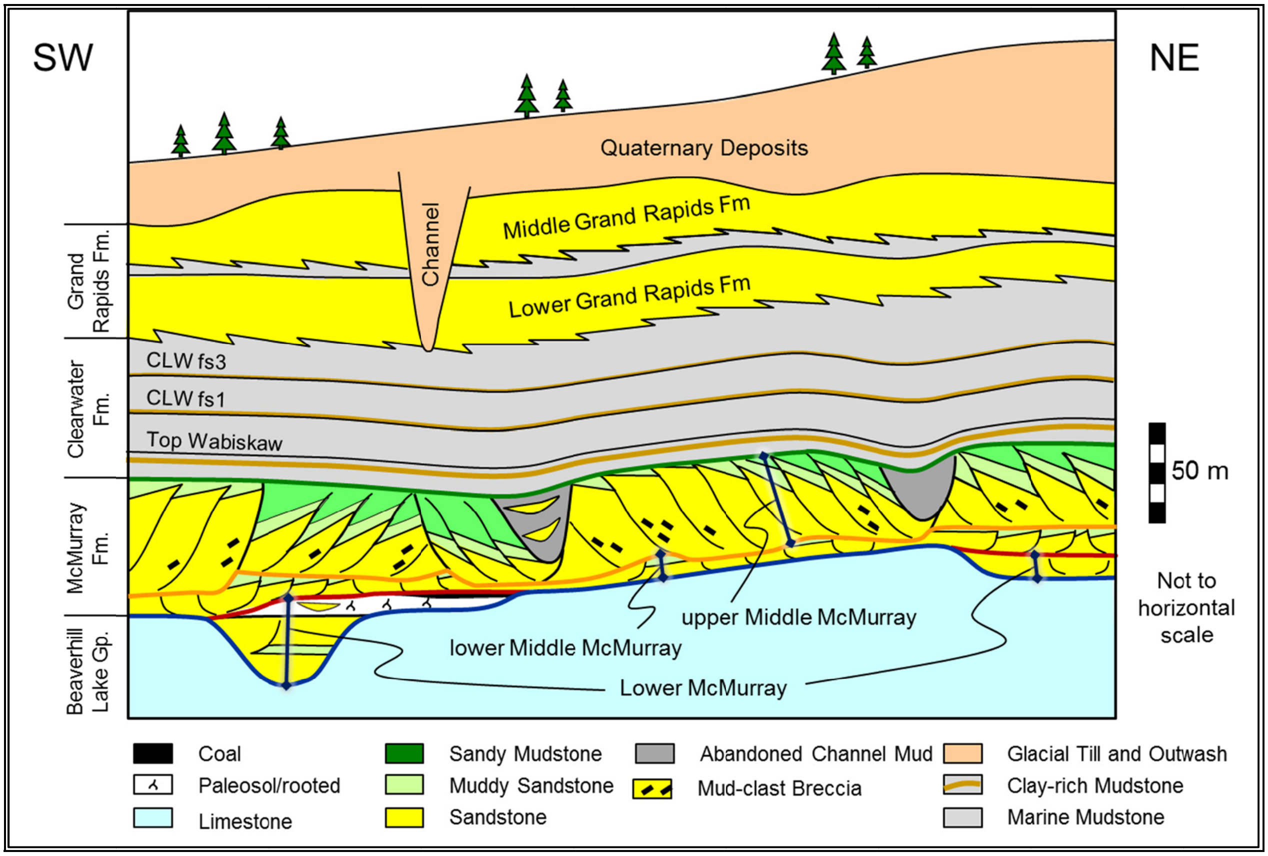


Figure 2-2: Schematic of the Stratigraphic Architecture in the Project Area

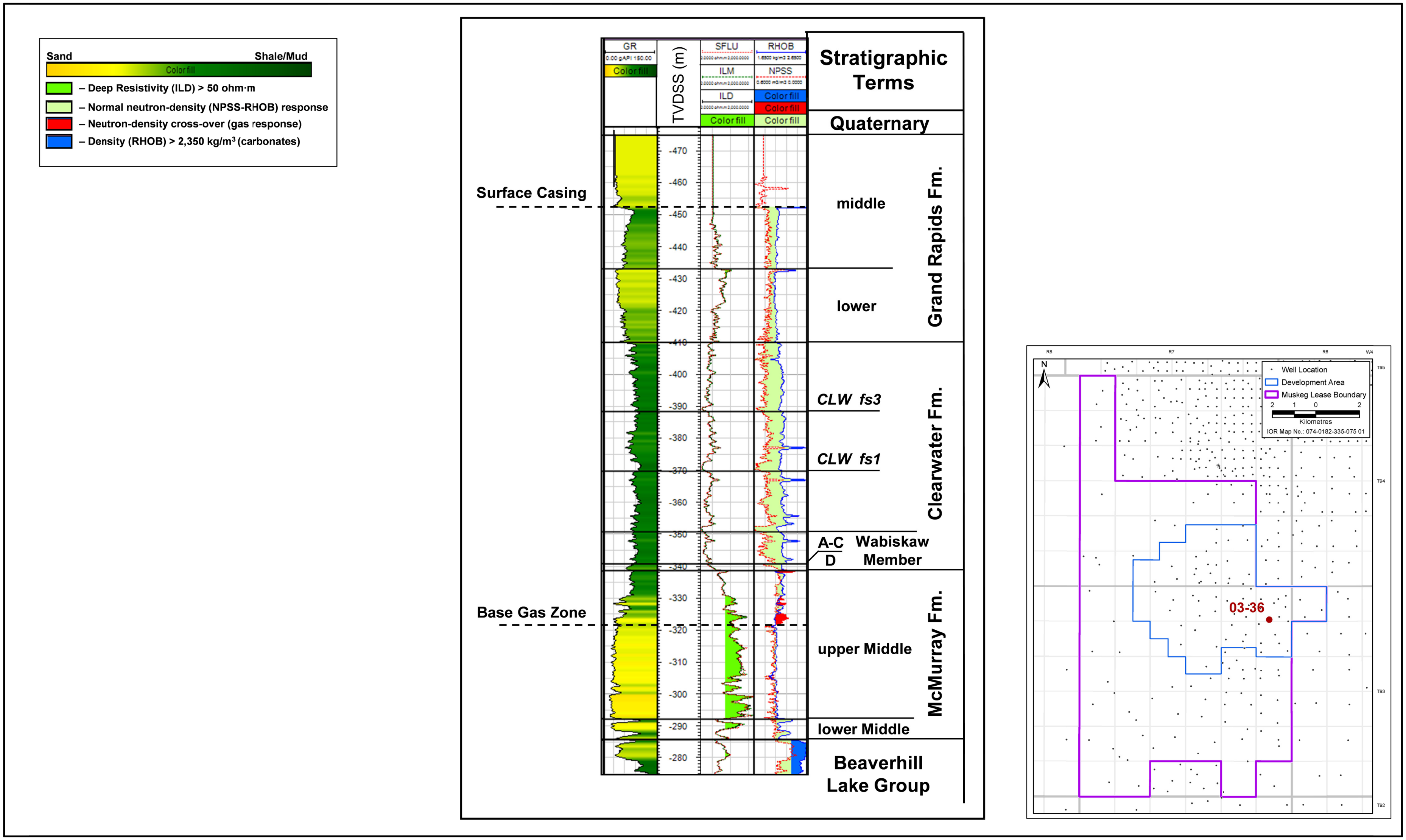


Figure 2-3: Project Type Well (1AA/03-36-093-07W4)

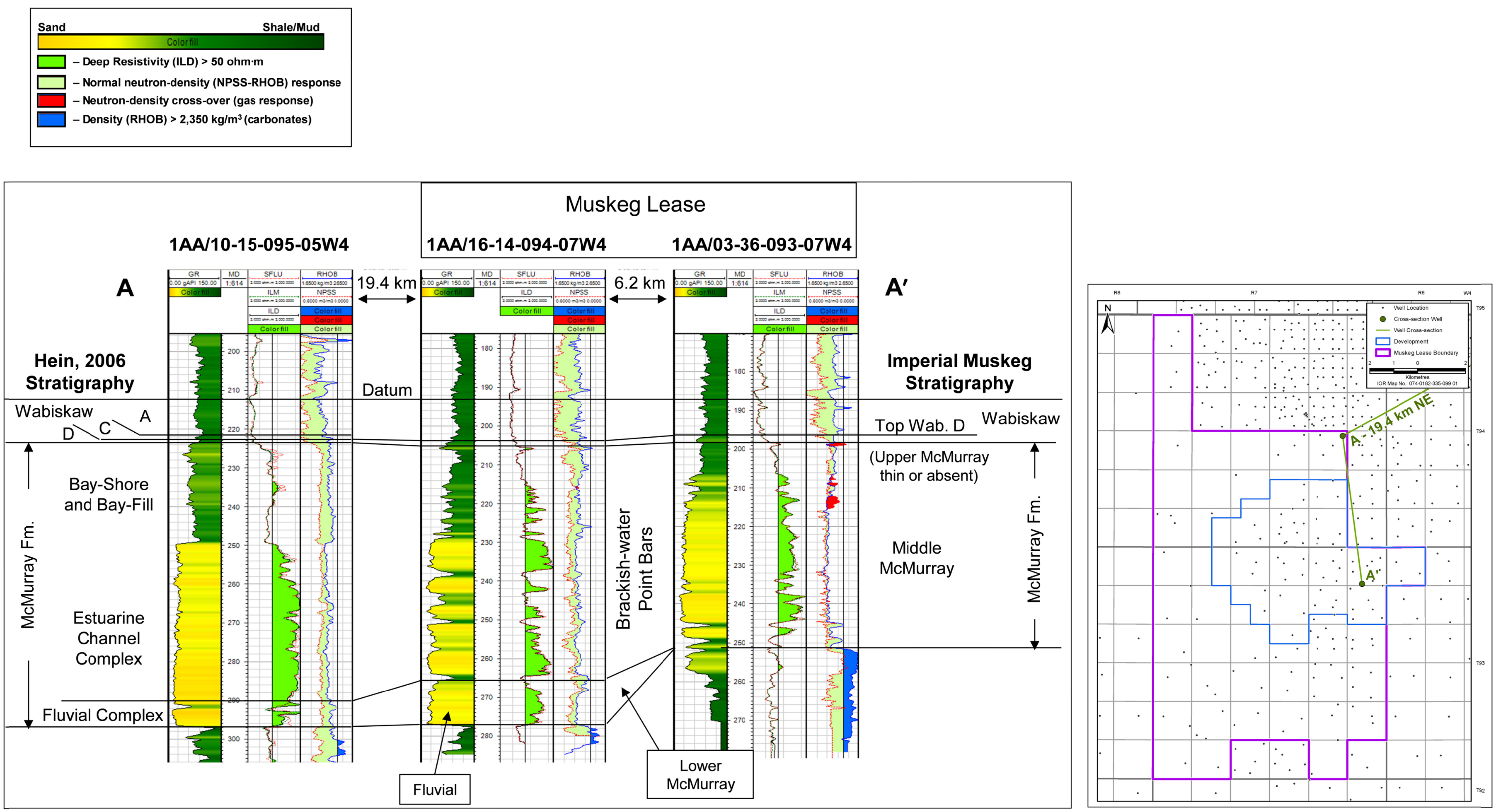


Figure 2-4: Comparison of the Stratigraphy in the Project Area to Hein 2006 Stratigraphy

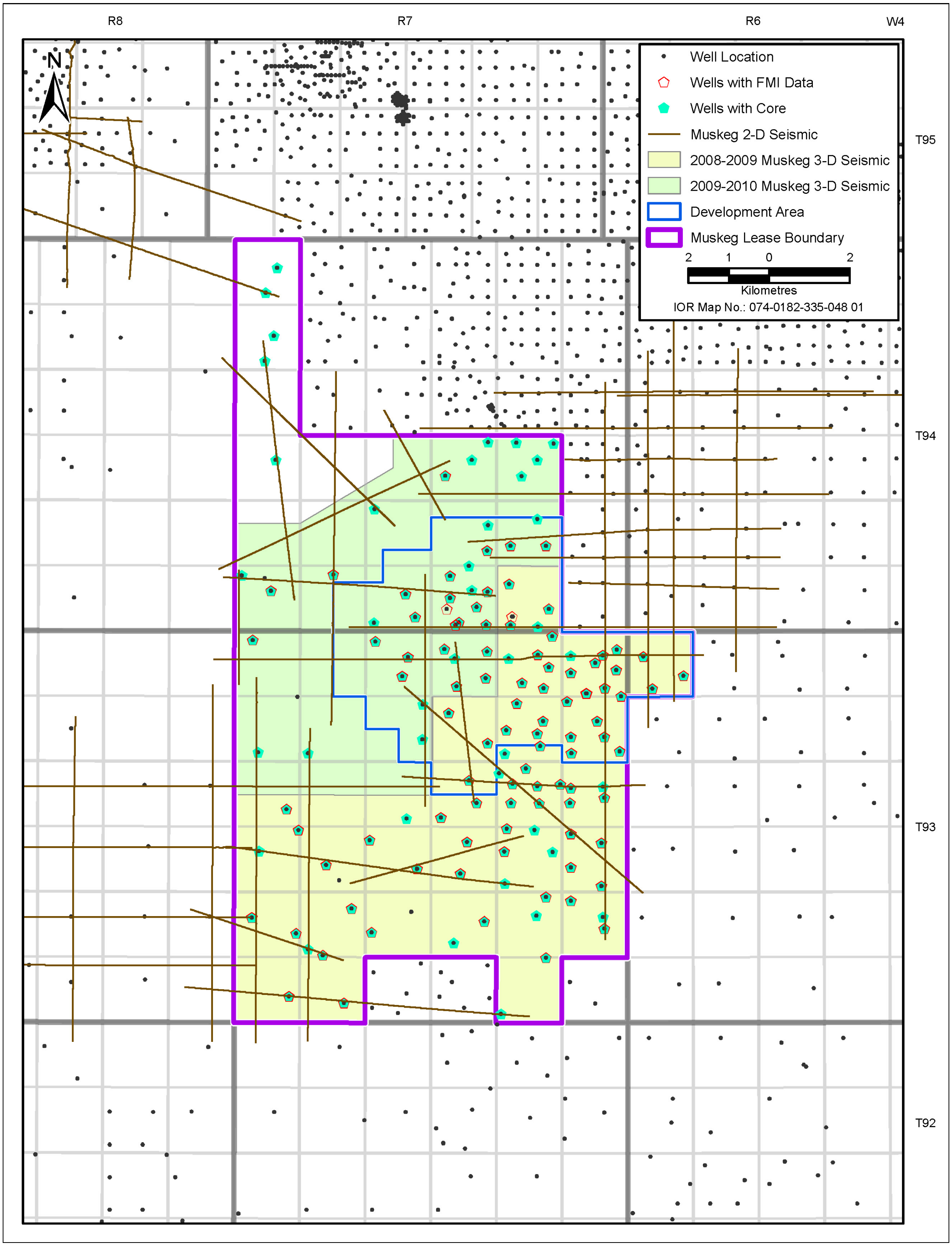


Figure 2-7: Seismic Coverage, Core and FMI Data in the Project Area

2.2.1 PALEOZOIC

The Paleozoic stratigraphy unconformably overlies crystalline Precambrian basement (see Figure 2-1, shown previously). To date, one well in the project area (103/04-02-094-07W4) has been drilled through the Devonian section, reaching the Precambrian granitic basement at total depth (TD) and cored from the Lower Watt Mountain Formation to Precambrian (see Figure 2-8).

Based on well 103/04-02-094-07W4, the Paleozoic stratigraphy in the project area in ascending order is as follows:

- Granite Wash – although absent in this well it might occur elsewhere in the project area in structurally low areas on the top Precambrian surface. In that case, it is expected the Granite Wash would be feldspathic sandstone.
- Contact Rapids Formation – 19 m thick, consisting of variegated red and green siltstone at base, overlain by green siltstone, overlain by nodular anhydrite, capped by a dark grey mudstone. This interval has abundant horizontal to sub-horizontal fractures filled with gypsum. No discernible porosity is present over the project area.
- Keg River Formation – a grey and cream-coloured dolostone and minor limestone and interpreted to be 53 m thick. It contains brachiopods and crinoids in the basal 10 m and the remainder is stromatoporoid-rich with intervals of limestone breccia filled with calcite. Vuggy porosity is present in zones.
- Prairie Evaporite Formation – 19 m thick (pending petrographic confirmation), comprised of laminated grey dolostone that is dedolomitized (i.e., converted to calcite) in the upper part and brecciated at the top. Vuggy porosity occurs in zones.
- Watt Mountain Formation – 23 m thick, the lower part of which was cored. Based on the core and regional observations, it is a light green-grey dolomitic mudstone with minor anhydrite. No discernible porosity is present in the well.
- Slave Point Formation – 2 m thick, and based on log response and regional core observations it is brown to grey limestone and dolomitic limestone, occasionally fossiliferous. This formation was not cored. No discernible porosity is present over the project area.

2.2.1 PALEOZOIC (cont'd)

- Waterways Formation – 64 m thick, with the Calumet Member at subcrop beneath the McMurray Formation. Elsewhere in the project area seismic data indicated that the pre-Cretaceous erosion cuts down to the stratigraphic level of the Firebag middle marker. Based on regional core observations and core in OV wells, the Waterways Formation consists of multiple cycles of green-grey shaly lime mudstone overlain by cleaner light grey lime mudstone. The top of the Waterways Formation is an erosional unconformity representing the end of Paleozoic time. No discernible porosity is present in the well.

2.2.2 MCMURRAY FORMATION

The McMurray Formation is the lowest part of the Mannville Group and unconformably overlies the Devonian Waterways Formation (see Figure 2-9 and Figure 2-1, shown previously). Figure 2-10 shows a McMurray Formation isopach map with variations in thickness of 45 to 115 m, primarily because of relief on the pre-Cretaceous unconformity. An elongated northwest to southeast trending thick area is prominent in the southwest part of the project area and is the result of a combination of erosion and dissolution or collapse of the Devonian section. The elevation of the top McMurray Formation surface ranges from roughly 300 to 340 m above sea level in the project area (see Figure 2-11). Relief on the McMurray structure was caused by dissolution of the underlying Devonian section and compaction of muddy abandoned channel fill within the McMurray Formation. An arcuate (i.e., curved or bowed) depression in the central part of the project area overlies an abandoned channel that is the principal defining feature for the development area boundary.

In the project area, Imperial has subdivided the McMurray Formation into three units (Figure 2-1, shown previously) that are useful for mapping the bitumen resource:

- Lower McMurray
- lower Middle McMurray
- upper Middle McMurray

The Upper McMurray is thin-to-absent in the project area and has not been split out as a separate unit.

Cross-sections of wells showing the structure and stratigraphy of the entire section within the project area are shown in:

- Figure 2-12 for a south-north cross-section
- Figure 2-13 for a west-east cross-section

The Lower McMurray occurs mainly in low areas of the top Devonian surface and appears to be consistent with the Lower McMurray as identified by Hein (2006) in this region. Imperial also interprets the thick sands of the Lower McMurray to be of fluvial origin. The main occurrence of Lower McMurray is in the thick area that trends north-northwest to south-southeast in the southwest corner of the project area and another thick area extending beyond the project area in the northeast. The Lower McMurray in the southwest area contains the basal aquifer at well 1AA/09-08-093-07W4.

The Lower McMurray in the northeast area has a mix of high-bitumen saturated sandstone and high-water saturated sandstone at well 1AA/16-14-094-07W4.

The upper part of the Lower McMurray is generally muddier than the lower (fluvial) part. In places where the lower fluvial section has pinched out, the upper part lies directly on Devonian strata, as indicated at well 1AA/02-21-093-07W4. The upper part is typified by paleosols or coaly deposits or both. Within this muddy interval there might be fining-upward sandy intervals 5 to 10 m thick interpreted as small channel fill packages.

Trace fossils are absent to rare in the Lower McMurray within the project area and sands are typically medium to coarse-grained and cross-bedded. This is consistent with a fluvial origin. The character of the muddy upper part (coaly deposits, discolouration and slickensides) suggests it is a coastal plain deposit that was subaerially exposed to create paleosols.

The lower Middle McMurray and upper Middle McMurray comprise the remainder of the McMurray Formation in the project area, and either or both can be targets for bitumen production here. The lower Middle McMurray and upper Middle McMurray overlie either the Lower McMurray or lie directly on Devonian carbonate.

The Middle McMurray represents deposition in a fluvial point bar with periods of brackish water conditions.

Interbedded sand and mud intervals exhibit bioturbation to varying degrees, usually in the form of *Planolites* and *Cylindrichnus*, and to a lesser extent *Skolithos* and *Gyrolithes*. The traces are usually small and do not occur in diverse assemblages. Such trace assemblages have been interpreted as being indicative of brackish water depositional conditions in other McMurray Formation sections (Ranger and Pemberton 1992). The muddying-upward succession can have a rooted cap, especially in the upper Middle McMurray sequence.

The muddying-upward stacking pattern and trace fossil assemblage in the Middle McMurray were deposited in point bars by fluvial processes with some degree of brackish water. The arcuate map pattern of depressions on the top McMurray structure (thin areas of the McMurray Formation), coincident with the muddy section in the upper Middle McMurray, suggest an abandoned channel origin. The nearly circular pattern of the abandoned channel marking the boundary of the development area is consistent with formation by a meandering point bar.

In the project area the uppermost part of the McMurray Formation has a variable thickness of 0 to 3 m of deposits that might have formed in a coastal plain or brackish bay setting. These deposits could be considered Upper McMurray, but

2.2.2 MCMURRAY FORMATION (cont'd)

considering their thin-to-absent nature, Imperial included these deposits in the upper Middle McMurray.

2.2.3 CLEARWATER FORMATION

The Clearwater Formation is a mud-rich marine section that ranges in thickness from 65 to 90 m in the project area. Figure 2-14 is an isopach map of the Clearwater Formation.

The Wabiskaw Member at the base of the Clearwater Formation represents a marine transgression over the coastal plain environments of the McMurray Formation. The base of the Wabiskaw Member is a sharp surface overlain by a dark steel blue-grey muddy section with starved ripples of silt or very fine sand and large *Thalassinoides* burrows indicating marine conditions. This basal Wabiskaw mudstone appears to be equivalent to the Wabiskaw D interval described by Hein et al. (2006) and Hein (2006) and is capped by the top Wabiskaw D surface. The Wabiskaw D interval ranges in thickness from 1 to 4 m in the project area (see Figure 2-15).

Overlying the Wabiskaw D is a muddier interval indicating continued marine transgression. This interval has glauconitic sand at its base and marine burrows (*Rhizocorallium*, large *Thalassinoides* and *Planolites*). The glauconitic sandy interval is overlain by light-grey mudstone grading to dark-grey mudstone. Gamma ray and neutron-density logs indicate increasing clay content upward above the glauconitic sandy section. This interval appears equivalent to the Wabiskaw C and A units (Hein et al. 2006) and is capped by the top Wabiskaw surface (see Figure 2-16). This interval (between the top Wabiskaw D and top Wabiskaw) is about 10 m thick over the project area.

The remainder of the Clearwater Formation above the Wabiskaw Member consists of mudstone that is easily correlated on logs and seismic data with calcite-cemented zones and varying clay content. Imperial has subdivided this interval into two surfaces interpreted as marine flooding surfaces (fs), in ascending order, CLW fs1 and CLW fs3. In the project area, the interval capped by CLW fs1 ranges in thickness from 16 to 22 m, and the interval capped by CLW fs3 ranges in thickness from roughly 17 to 21 m. The CLW fs1 and CLW fs3 intervals immediately above the top of the Wabiskaw Member have relatively high clay content as indicated by gamma ray and neutron-density logs and core data.

The top of the Clearwater Formation is a facies transition to the sandy, prograding Grand Rapids Formation (see Figure 2-17). In small areas, 3-D seismic data indicate the base Quaternary unconformity reaches a stratigraphic level near the top of the Clearwater Formation and might erode slightly into Clearwater Formation by about 5 to 10 m. Local erosion does not reach the CLW fs3 surface.

2.2.4 GRAND RAPIDS FORMATION

The Grand Rapids Formation is of Albian age, part of the Manville Group, and overlies the Clearwater Formation with a facies transition relationship. The Grand Rapids Formation consists of a succession of three sandy sequences (lower, middle and upper) separated by muddy units. The sandy sections represent progradation of nearshore environments in a northeast and east direction in the project area. Within the project area, the Grand Rapids Formation is unconformably overlain by Quaternary deposits. The thickness of the Grand Rapids Formation is controlled by erosion by the base Quaternary unconformity and generally ranges from 30 to 110 m in the project area, except along a narrow erosional valley where the entire Grand Rapids Formation is eroded locally (see Figure 2-18).

Three-dimensional seismic interpretation and log correlation indicate two major prograding packages separated by a muddy interval within the Grand Rapids Formation. These packages are termed lower Grand Rapids and middle Grand Rapids. The upper Grand Rapids in the project area is eroded by the base Quaternary unconformity, except for a small, undrilled remnant in the southeast corner at the base of Muskeg Mountain (see Figure 2-19).

The lower Grand Rapids ranges in thickness from 10 to 35 m in the project area excluding the narrow incised area.

2.2.5 QUATERNARY OVERBURDEN

Quaternary sediments overlie the Grand Rapids Formation and consist of multicyclic fills. Nearby mining operations (e.g., Imperial's Kearl mine) have identified a variety of Quaternary lithofacies, including till and glaciofluvial and outwash deposits ranging from clay to boulders. Outcrops of the Birch channel and the North Spruce channel east of the project area show a stratigraphic sequence of glaciolacustrine sediment overlying till, overlying well-graded fluvial sediments, resting on bedrock (Andriashek and Atkinson 2007).

The Grand Rapids Formation is eroded into and incised by large Quaternary channels, which appear to be the southern headlands of the Pemmican Valley channel (Andriashek and Atkinson 2007). These channels locally incise through the entire Grand Rapids thickness and, in places, cut into the uppermost part of the Clearwater Formation. The channels are shown in:

- Figure 2-20, a structure map of the base Quaternary
- Figure 2-21, a map of the subcrop below the Quaternary overburden
- Figure 2-22, a well cross-section

Geologic data for the Quaternary overburden in the project area is limited to petrophysical logs (gamma ray), which are most often recorded through surface casing, and 3-D seismic data. Calibration of log signatures and seismic through core or drill cuttings within the project area is currently not available.

2.2.5 QUATERNARY OVERBURDEN (cont'd)

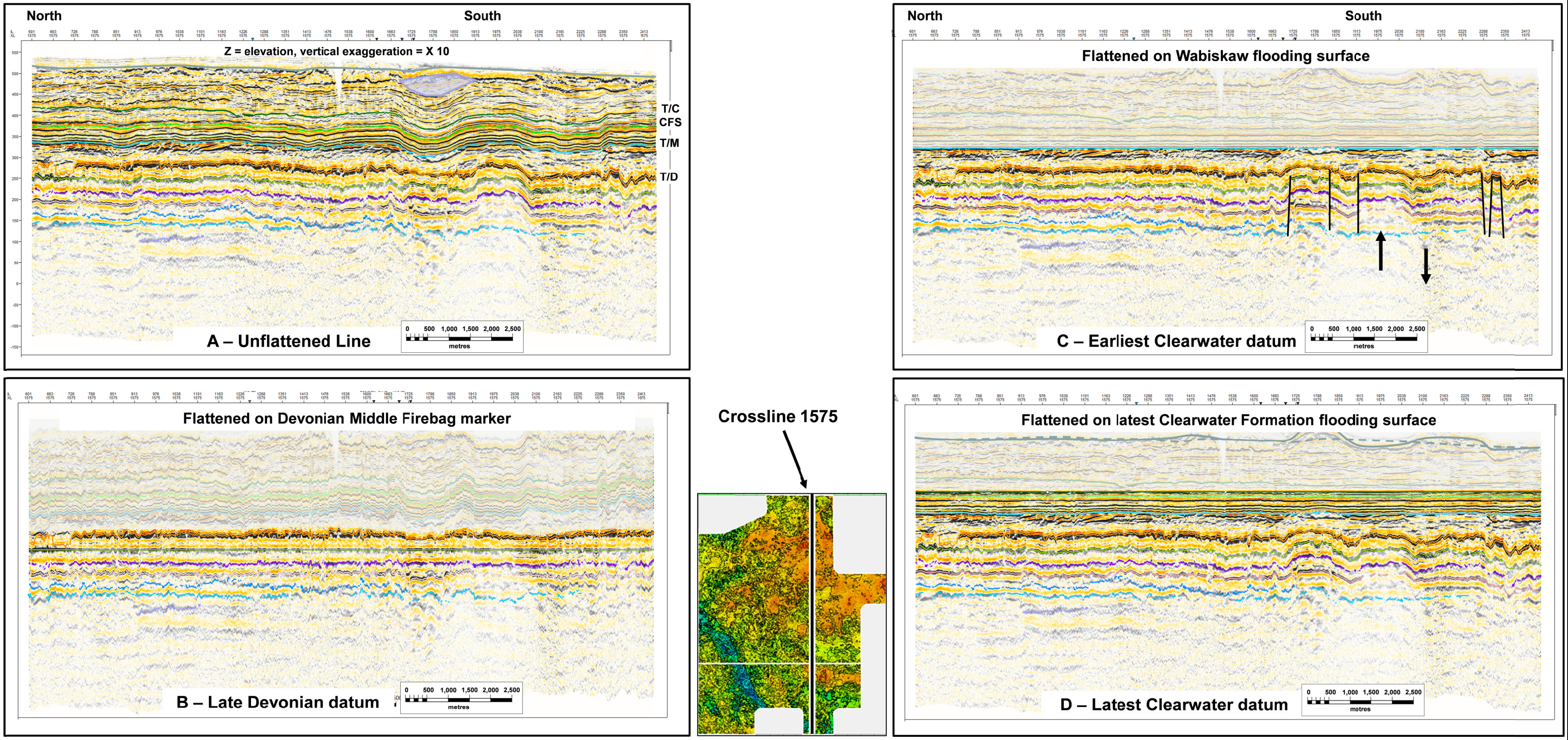
Quaternary deposits range in thickness from 5 to 100 m in the project area, 5 to 60 m outside the channels and 60 to 100 m within the channels (see Figure 2-23).

2.2.6 STRUCTURAL EVENTS AND TIMING

The degree of structural deformation in the area is minimal. Most of the observed structural deformation (faulting or anomalous interval thicknesses) likely relates to differential vertical movement (subsidence or collapse) within the Devonian interval (see Figure 2-24). The distribution of the zones of vertical displacement appears to be random and follow no particular observable pattern, though a relationship to the Precambrian basement cannot be confirmed.

The timing of the vertical movement within the Devonian ranges from syn-McMurray Formation deposition (i.e., deposited at the same time) through to recent Quaternary-aged collapse. There is little evidence for movement during deposition of the Clearwater Formation.

There are no observable tectonic faults. However, in response to the vertical movement within the Devonian, there has been the development of a small number of faults within the Manville Group, which are observable in the 3-D seismic data. There are few faults that conclusively intersect the McMurray Formation reservoir within the development area (based on observation from the 3-D seismic data), though localized, small-throw faults are observed in the Clearwater Formation.



Structural Events and Timing:

North/South oriented crossline 1575 from the post-stack 3-D-migration volume (merge of 2009 and 2010 surveys).

A) Undatumed section, with seismic markers indicated: 'T/C', Top Clearwater Fm.; 'CFS', latest Clearwater flooding surface; 'T/M', Top McMurray Fm., which would be followed by the Wabiskaw Mbr. flooding surface; 'T/D', Top Devonian unconformity, which overlays the Middle Firebag Mbr. seismic marker (green).

B) Flattening on the Middle Firebag marker (intra-Devonian Waterways Fmn.), a regional marine incursion, demonstrates the relatively minor isochore variation within the internal Devonian units, and the nature of the continental erosion of the pre-Cretaceous unconformity. Little vertical structural movement is evident at this time.

Structural Events and Timing:

C) Where 'B' demonstrated post-Devonian erosional relief, flattening on the flooding surface within the Wabiskaw Mbr. (of the Clearwater Fm.) demonstrates the influence on McMurray isochore variation caused by syn-depositional vertical movement of the basement along both discrete vertical planes (solid black lines) and broader sags (arrows).

D) The activity of the sag-type displacement did not cease with the end of McMurray deposition, but appears to have reactivated in the Quaternary, possibly in response to glacial loading: the present day topography is represented by the dashed line whereas the datumed representation of the present topography is the solid line; the difference between the two represents Quaternary differential vertical displacement.

Figure 2-24: Structural Events and Timing

2.3.1 LITHOGRAPHIC CLASSIFICATION (cont'd)

Lithofacies SS1, SS2, SS3, MC and IBS constitute the primary reservoir rock types. Based on petrophysical analysis integrated with data from core analysis, the average effective porosity of these lithofacies is 33%.

Individually, the lithofacies are not diagnostic of a particular environment of deposition (with the exception of coal indicating a coastal plain). Rather, the environment of deposition is interpreted from the vertical succession of lithofacies and presence or absence of other diagnostic features, such as trace fossils and roots. These lithofacies assemblages are described in the general stratigraphic order they are found, from oldest to youngest.

2.3.2 BRAIDED OR MEANDERING FLUVIAL

This assemblage is dominated by medium to coarse, pebbly cross-bedded sandstone (SS1) and rippled sandstone (SS2), with lesser amounts of interbedded sandstone and mudstone facies preserved. These facies are generally arranged in fining- or muddying-upward successions, and multiple fining-upward successions can occur. The generally coarse-grained nature and vertical succession suggests deposition as bars in a braided fluvial system, although a coarse-grained meandering system is also a viable interpretation. This facies association is common to the Lower McMurray Formation in the project area and also has been observed in the Lower McMurray Formation elsewhere in Athabasca oil sands region (Hein et al. 2006).

2.3.3 COASTAL PLAIN, MARSH AND PALEOSOL

This assemblage consists of mudstone lithofacies (M) that might be rooted or have trace fossils, such as *Cylindrichnus.* Often this lithofacies assemblage shows signs of pedogenesis, including bleached or variegated colour and slickensides. Coal might also occur in this assemblage, usually at the top of the succession.

2.3.4 FLUVIAL POINT BAR, WITH PERIODS OF BRACKISH WATER CONDITIONS

This assemblage is the main target for SAGD production in the project area and is typified by a general fining or muddying-upward.

The upper and lower Middle McMurray have similar lithofacies assemblages and vertical stacking patterns. The generalized stacking pattern is coarse to medium-grained cross-bedded sand (SS1 lithofacies), overlain by sand with mud-clast (MC) breccia, overlain by succession of interbedded current-rippled sand and mud with increasing mud content (IBS-IB-IBM-M, with or without IBL). The stacking pattern is summarized in Table 2-3 (shown previously).

The ideal succession contains lithofacies typical of channel thalweg deposits at base (medium to coarse cross-bedded sandstone [SS1] and mud clast conglomerate [MC]). These thalweg facies are overlain by fine-to-very fine, homogenous or ripple-laminated sandstone (SS2), indicative of weaker currents. Overlying the SS2 facies (in an ideal succession) are an increasingly muddy succession of IBS, IB, IBM and M lithofacies that comprise the inclined heterolithic strata (IHS). The less bioturbated sand and mud interbedded lithofacies (IBL) might also occur within this IHS section as well.

Often variations are observed on this idealized succession. Most commonly seen is that the fining-and-muddying-upward trend is not one smoothly varying progression, but rather consists of multiple fining-upward cycles on a 5 to 15 m scale. These cycles might be because of changes in the pattern of river floods or reorientation of the point-bar system. Other variations from the ideal succession appear to be related to relative position on the point bar in a manner described by Hubbard et al. (2011). Wells that penetrate an upriver position are more likely to have sandy facies, such as SS2 and IBS higher in the succession, and positions farther downriver are more likely to have muddy facies that occur lower in the succession. This lithofacies assemblage often contains trace fossils in varying abundance, but commonly with limited diversity. Common species are *Cylindrichnus*, *Planolites*, small *Skolithos* and *Paleophycus*. This ichnofacies (limited diversity, small forms) is consistent with periods of brackish water conditions during point-bar deposition.

2.3.5 ABANDONED CHANNEL FILL

This lithofacies is typified by laminated mudstone (M) lithofacies, typically grey in colour. In the ideal case, where channel abandonment completely shuts off sand supply to the channel, there is no sand in the abandonment fill. However, sandy intervals were noted within some areas of the abandoned channel fill presumably because of periodic breaches from the newly-active channel or extreme flood events.

2.4.1 GEOPHYSICAL OVERVIEW

Two 3-D seismic surveys were acquired in 2009 and 2010 (see Figure 2-7, shown previously). The high-density (8 x 8 m spacing) 3-D seismic surveys cover 46.5 sections (110 km^2) of the project area.

In 2010, data from two seismic surveys was acquired (see Table 2-4 for acquisition parameters) and processed (see Table 2-5 for a parameter summary). The two surveys were merged together in post-stack migration processing with the average fold of 64 traces per common midpoint. The overall dominant frequency of the seismic data is about 125 Hz, which results in vertical resolution of about 4.5 m.

Table 2-4: Acquisition Parameters for 2009 and 2010 3-D Seismic Surveys

Parameter	2009 Program	2010 Program
Record length	2.0 seconds	2.0 seconds
Sample rate	1 millisecond	1 millisecond
Source	Dynamite, single hole	Dynamite, single hole
Source interval	16 m	16 m
Source line separation	64 m	64 m
Receiver interval	16 m	16 m
Receiver line separation	64 m	64 m
Normal 3-D patch	12 lines x 80 stations	12 lines x 80 stations
3-D grid bin size	8 x 8 m	8 x 8 m

Table 2-5: Processing Flow and Parameter Summary, Project Area 3-D Survey

Surface Consistent Deconvolution
Spectral whitening
Refraction static corrections
Surface-consistent statics
Normal move out correction
CDP stack
Merge 2009 with 2010 seismic survey
F-XY noise reduction
3-D Kirchhoff migration
Bandpass filter, 15/25-220/240 Hz
Trace scaling

2.4.1 GEOPHYSICAL OVERVIEW (cont'd)

Three-dimensional seismic data are helpful to understand the subsurface architecture within the project area. Interpretation and analysis of the seismic data are used to:

- map the structure of all major formations
- interpret the McMurray Formation point-bar environment of deposition and its geometry, see:
  - Figure 2-28, Seismic Time Slice
  - Figure 2-29, Seismic Section (West to East)
  - Figure 2-30, Seismic Section (South to North)
- identify abandoned shale and mud-filled channels (non-reservoir)
- delineate the Devonian salt (Prairie Evaporate Formation) dissolution
- map the rugosity of the Devonian surface, caused by karsting during aerial exposure
- map the GSZ found at the top of the McMurray Formation reservoir
- map the caprock interval and lateral integrity attributes
- map potential formations for water sources and wastewater disposal to facilitate SAGD operations
- reduce the number of the vertical wells required to delineate the reservoir

2.4.2 SEISMIC INTERPRETATION

Well ties are shown on the two depth-converted seismic sections (see Figure 2-29 and Figure 2-30). The following observations were made interpreting the 3-D seismic data:

- The pre-Cretaceous unconformity, or top Devonian, is the strongest seismic reflector because of the high reflectivity contrast between the low-velocity, low-density McMurray Formation sediments and the high-velocity, high-density Devonian carbonates.
- The top McMurray is not a strong seismic marker and varies between positive and negative reflections because of the interbedded sand-mud lithology. In most cases, this horizon is interpreted as a trough, and this trough becomes brighter if gas is present at the top of the McMurray Formation. The top of the gas zone is identified as a strong trough on the seismic sections. The base of gas in clean sand is a strong peak, otherwise the response is variable.
- The lower Clearwater and Wabiskaw Member (caprock) reflectors are continuous throughout the seismic dataset.

- The Clearwater Formation is represented by the offshore marine mudstones, and contains calcite-cemented zones, which correspond to the bright and parallel reflectors on the seismic sections. These high-density, high-velocity zones are located on the top of maximum flooding surfaces within the Clearwater Formation. There is a distal mudstone at the top of the Clearwater Formation, which corresponds to a weak reflectivity zone.
- Well control at the lower Grand Rapids was much sparser because of surface casing sections in the logs. The top of the lower Grand Rapids unit was interpreted by iteratively fitting consistent well picks with consistent reflectors on the depth-converted depth-seismic volume.
- Similarly, the base of the Quaternary overburden was interpreted using a few well picks, but dominated by the erosive character on the seismic data. The most striking feature interpreted was the deep Pemmican Valley channel, which cuts through down to the top of the Clearwater Formation.

Depth slice at 326 m or the Top of the McMurray

South to North cross-section wells:

A. AA/08-06-093-07W4
B. AA/09-08-093-07W4
C. AA/02-21-093-07W4
D. AA/10-22-093-07W4
E. AA/03-03-094-07W4
F. AA/10-11-094-07W4
G. AA/16-14-094-07W4

West to East cross-section wells:

H. AA/10-06-094-07W4
I. AA/10-04-094-07W4
E. AA/03-03-094-07W4
J. AA/10-35-093-07W4
K. AA/03-36-093-07W4

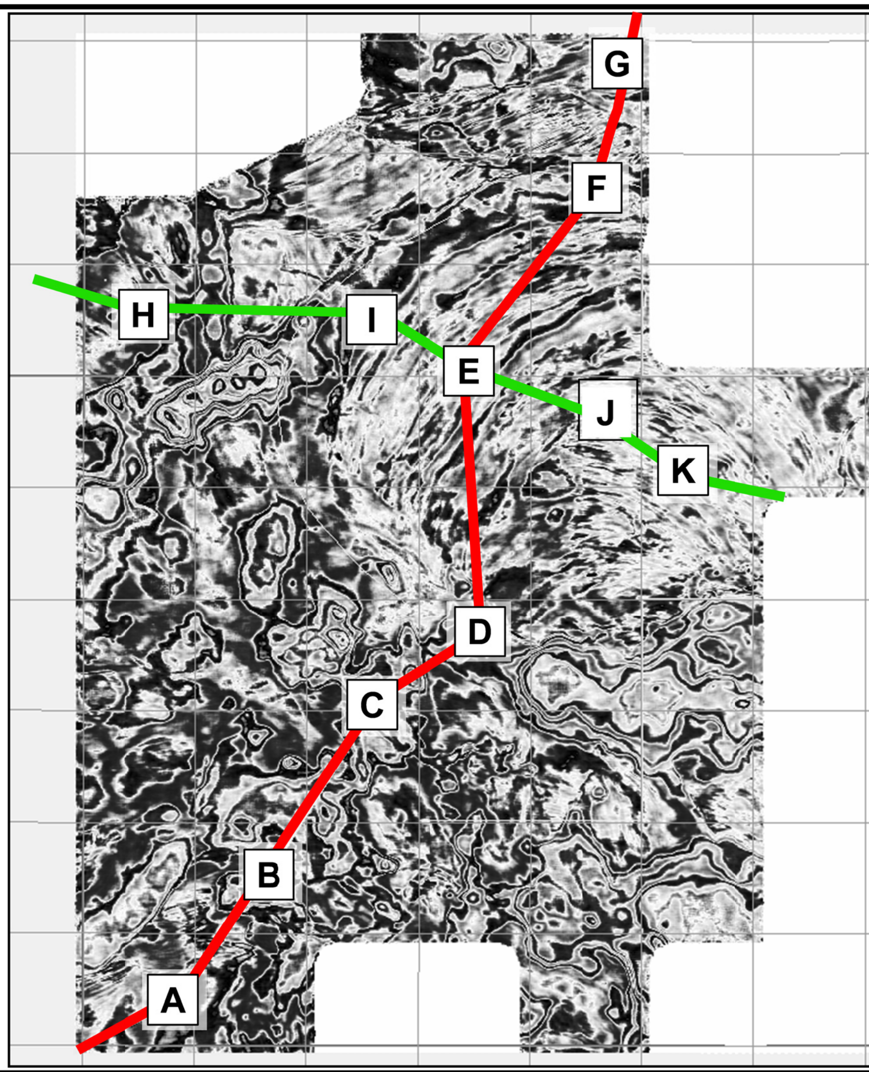


Figure 2-28: Seismic Time Slice

2.5.1 CAPROCK INTEGRITY

Generally, the caprock is represented by the geological formation that acts as a barrier to fluid incursions and seals the reservoir from steam migration into the overlying formations. Over geologic time, the caprock has acted as a trap for fluid migration and has promoted hydrocarbon accumulation in the pay zone.

For the project area, the regional Clearwater Formation, including the Wabiskaw Member acts as an overall or regional caprock for the reservoir as it provides a competent seal for the steam. The primary caprock for the project area is defined by the Lower Clearwater Formation interval, including the Wabiskaw Member (i.e., CLW fs1 to top McMurray Formation).

Figure 2-1, shown previously, shows the stratigraphic column of the project area. Figure 2-31 is a cross-section of the caprock across the project area taken at four wells.

To assess the competency of the caprock in the project area, Imperial has evaluated the mechanical strength of the Clearwater-Wabiskaw intervals through in situ minifrac tests and geomechanical testing of the caprock core.

2.5.2 REGIONAL AND PRIMARY CAPROCK

The Clearwater Formation is part of the Manville Group and is lower Cretaceous in age. This unit conformably overlies the McMurray Formation and is conformably overlain by the Grand Rapids Formation. The Clearwater Formation consists of fine-grained marine clastics, represented by interbeds of clay-rich and silty shales. Petrophysical assessment of logs shows only some minimal porosity in the silty zones.

In the project area, the Clearwater Formation is regionally extensive, with a consistent lateral continuity and thickness of about 65 m or more. The Wabiskaw Member at the base of the Clearwater Formation has an average thickness of 12 m. The structure of the Clearwater Formation at well 1AA/03-36-93-7W4 is shown in:

- Figure 2-17 (shown previously) for the top structure
- Figure 2-11 (shown previously) for the bottom structure along the base of the Wabiskaw Member (top McMurray Formation)

2.5.2 REGIONAL AND PRIMARY CAPROCK (cont'd)

- Figure 2-32 for the depth of the bottom structure in true vertical depth (TVD)

Figure 2-33 is an isopach map of the primary caprock interval (Clearwater fs1 to top McMurray Formation).

The stratigraphic analysis of the logs reveals several regionally correlatable flooding surfaces with high clay content and low permeability within the Clearwater Formation. Imperial has subdivided these flooding surfaces into several correlative units from youngest to oldest (as shown in the caprock test well):

- top Clearwater shale (103.00 to 118.00 m)
- CLW fs3 shale (128.75 to 130.05 m)
- CLW fs1 shale (146.75 to 149.50 m)
- Wabiskaw D shale (174.00 to 175.75 m)

The values shown in parentheses in this list represent the depths of the flooding surfaces recorded in the caprock test well 1AA/15-03-094-07W4. Figure 2-34 shows the stratigraphy of the caprock integrity test well.

Figure 2-35 includes logs and high-definition photos from the Clearwater Formation interval taken at the caprock integrity test well. In this well the:

- top Clearwater shale is a 15 m thick, dark grey laminated shale
- CLW fs3 shale is about 1 m thick and is described as a dark grey, laminated shale
- CLW fs1 shale (not cored) is about 2 m thick

The CLW fs1 shale unit is laterally continuous over the entire project area and is considered the top of the primary caprock for the project area. To date, there is no evidence of Quaternary channel erosion into this unit. Figure 2-36 shows the top structure of the CLW fs1 shale unit.

The Wabiskaw Member at the base of the Clearwater Formation is directly overlying the McMurray Formation. The Wabiskaw Member is a sandy shale unit with moderately bioturbated mudstones capped by a transgressive clay-rich, dark fissile shale in a fining-upward sequence. The Wabiskaw D shale unit described in Volume 1, Section 2.3, McMurray Lithographic Units, is laterally continuous over the project area, with no known faults or incising channels undercutting this unit.

A few localized structurally controlled gas zones have been interpreted within the Clearwater Formation at depths ranging from 130 to 135 m TVD, between the CLW fs1 and CLW fs3 markers. The intra-Clearwater gas accumulations have been interpreted using the responses from neutron-density well logs and have been delineated from 3-D seismic amplitude maps. The areal extent of these gas lenses is small and, from the seismic amplitude map, they appear to be disconnected (see yellow regions in Figure 2-37).

Calcite beds are encountered on a regional scale within the caprock. Based on information obtained from the logs, the beds are no more than 1 m thick. The beds have also been visually observed on cores and computerized tomography (CT) scans.

2.5.2.1 Caprock Composition

Imperial has collected and preserved 60 m of core from the caprock integrity test well. The core was collected from two intervals:

- 32 m were collected from the top of the Clearwater (103 to 135 m TVD)
- 28 m were collected in the lower Clearwater-Wabiskaw interval, roughly from CLW fs1 to top McMurray Formation (155 to 183 m TVD)

The mineralogy of the preserved core was tested with X-ray diffraction (XRD) analysis on 52 samples collected on site and in the lab. The overall mineralogical composition of the samples indicates an average clay fraction of 36 wt% and an average quartz fraction of 43 wt%.

The most abundant clay minerals are represented by the illite-smectite mixed layers, with a higher smectite content in the Wabiskaw Member samples. A summary of the results from the XRD analysis showing the mineral composition and the clay minerals present in the shale is provided in Table 2-6 and Table 2-7.

2.5.2.2 Caprock Fracture Analysis

2.5.2.2.1 Fractures from Fresh Cores

The fresh cores taken from the caprock integrity test well were inspected on site for natural fractures, and no fractures were observed. A correlation of natural fractures interpreted from the high-definition photographs of the cores and the FMI data is presented in Volume 1, Attachment 1, BitCan Geosciences and Engineering Inc. (BitCan) report on core preservation.

2.5.2.2.2 Microimage Logs

Imperial commissioned Schlumberger Canada Ltd. to conduct a study of image logs to support the caprock integrity analysis in the project area. The main objectives of the study were to determine the:

- presence of faults, fractures and other features that could affect caprock integrity
- fracture density
- likelihood of interconnected fracture networks in the project area
- likelihood of continuous features over the entire stratigraphic column from the Devonian to the caprock

A total of 39 FMI logs from the project area were selected for this study, with an average of one FMI log per section, where possible, for statistical robustness. The image logs showed horizontal bedding in the Clearwater Formation and localized fractures in the Clearwater Formation were observed in 14 wells. The study showed no preferred orientation of the Clearwater Formation fracture strikes. In addition, there was no evidence of major faulting in the project area, and no cross-cutting relationships were observed between the fractures and faults identified in the Devonian or McMurray Formations and the caprock. The average fracture density for the Clearwater Formation obtained from this analysis is 0.016 fractures/m, or about one fracture for every 100 m. The spatial distribution of natural fractures in the Clearwater Formation is shown in Figure 2-38.

Based on the results of this study, Imperial observed no interconnected fractures that would compromise the integrity of the caprock and no major post-dissolution disturbances in the regional caprock. The caprock study from Schlumberger Canada Ltd. is provided as Volume 1, Attachment 2, IOL Muskeg Lease Fracture Characterization.

2.5.3 GAS AND WATER ZONES BELOW THE REGIONAL CAPROCK

A low-pressure GSZ exists below the caprock in the project area. The average thickness of the net gas sand is 10 m (see Figure 2-39). Currently, there are no gas production wells in the project area, and it is Imperial's understanding that gas was never produced from within the project area.

There is no significant top water present at the top of the McMurray Formation across the project area. See Volume 1, Section 3, Figure 3-4 for an isopach map showing top water in the McMurray Formation within the development area.

The caprock has acted as a geological trap for hydrocarbon accumulation over geologic time. Caprock integrity is not expected to be adversely affected by the pressurized GSZ and SAGD operations. Currently, the low-porosity Wabiskaw Member is naturally maintaining the hydraulic integrity of the seal to contain the low-pressure GSZ in the reservoir.

2.5.4 GEOMECHANICAL TESTING, PRIMARY CAPROCK AND MOP

2.5.4.1 Minifrac Tests

To assess the in situ stress state of the McMurray reservoir and the regional caprock shales, Imperial commissioned BitCan to conduct minifrac tests in the caprock integrity test well. The minifrac tests were done in a cased hole at a low injection rate and volume to open and propagate a fracture in the formation. For practical purposes, the fracture closure pressure after shut-in was equated to the minimum horizontal stress identified in the formation. If the minimum horizontal stress was greater than the vertical stress, then the minimum in situ stress was vertical and an induced fracture would propagate in a horizontal direction within the formation.

The location of the minifrac testing well was determined by choosing a representative caprock structure for the project area. Additionally, the testing well was placed in a zone with seismic amplitude response for the intra-Clearwater gas zone and where the offset well logs displayed clean, reasonably thick, testable shale intervals.

The testing program was designed to test six targets, two in the McMurray Formation, one in the Wabiskaw Member and three in the Clearwater Formation. Based on the minifrac tests:

- the average fracture gradient in the McMurray Formation is 13.0 kPa/m
- the fracture gradient in the caprock is 21.6 kPa/m

For information on the minifrac tests, see Volume 1, Attachment 3, Mini-Frac Tests for Imperial Oil Company at Its Aspen Well: 15-03-094-07W4.

The results from the minifrac tests indicate that induced fractures in the Clearwater Formation (including the Wabiskaw Member) propagate in a horizontal direction, further supporting the competence of the caprock. The fractures induced in the reservoir propagate vertically. The results of the tests are presented in Table 2-8 and in Figure 2-40, where:

- red dashed lines indicate minifrac test depths
- pink squares show the fracture closure pressures at those test intervals
- S_v is the vertical gradient stress
- all stresses are measured in MPag

The methodology of minifracs and the analysis of the specific field data from the tests are summarized in the BitCan report (see Volume 1, Attachment 3).

The results obtained for the in situ stress in the caprock integrity test well are consistent with the results obtained by other operators in the area (e.g., Oak Point Energy’s Lewis reports an average Clearwater Formation fracture gradient of 20.41 kPag/m in test well 1AA/05-03-093-07W4).

Table 2-8: In Situ Stress Interpretation

UWI 1AA/15-03-094-07W4	TVD (m)	Minimum Stress [1]		Vertical Stress [2]		Stress Regime
		MPag	kPa/m	MPag	kPa/m	
McMurray reservoir	214.70	2.93	13.63	4.77	22.20	vertical fracture
McMurray reservoir	202.00	2.47	12.25	4.50	22.29	
Wabiskaw shale	175.00	3.85	22.01	3.95	22.55	horizontal fracture
Clearwater shale	148.50	3.18	21.43	3.37	22.71	
Clearwater shale	130.00	2.77	21.29	2.98	22.89	
Clearwater shale (repeat)	130.00	2.89	22.22	2.98	22.89	
Clearwater shale	115.00	2.40	20.85	2.66	23.11	

Note:
1. Stress interpreted from fracture closure pressure of the minifrac test.
2. Stress interpreted from integration of the density logs in the project area.

2.5.4.2 Triaxial Tests

The mechanical strength of the caprock was tested under unconfined and confined pressure conditions and for different temperatures of the reservoir under SAGD operations. The laboratory work was performed by BitCan as part of the caprock integrity study. The results of the triaxial testing are shown in Table 2-9.

In addition, BitCan performed two shear box tests to determine the friction angle of the caprock materials. The results of the shear box tests are shown in Table 2-10.

2.5.4.3 Geomechanical Simulation Results

As part of the caprock integrity study, Imperial commissioned BitCan to assess the strength of the caprock during SAGD operations through geomechanical simulations. The geomechanical model accounts for different strength parameters for the Wabiskaw Member and the lower Clearwater Formation based on the triaxial tests results for these zones. A schematic of the initial stresses used in the geomechanical model is presented in Figure 2-41.

The geomechanical simulations performed by BitCan in Abaqus have been designed to analyze the effects of SAGD operations on the caprock, using the results from field and lab tests as input parameters. The base-case scenario assumes the reservoir is operated at 2,500 kPag for the entire life, while the GSZ is maintained at 2,500 kPag as well. Several other simulation scenarios investigate the effects on the caprock of different operating pressures in the reservoir and GSZ. The sensitivity of the initial pore pressure in the caprock is also discussed. The results from the base-case scenario are presented in Figure 2-42. Figure 2-43 shows the results of a simulation scenario where the reservoir is operated at 1,400 kPag for a long term and the GSZ is pressurized to 1,900 kPag. All of the simulation cases assume 140 m well spacing for the SAGD pads.

The results from the geomechanical simulations show that there is no significant deformation in the caprock after 15 years of SAGD operations for the base-case scenario with a pressurized GSZ. These results show that from the caprock integrity perspective, the project can be safely operated up to 2,500 kPag.

For details of the triaxial work, geomechanical simulations and maximum operating pressure (MOP) discussion, see Volume 1, Attachment 4, Geomechanical Study on Caprock Integrity for Imperial Oil Resources Ltd.'s Aspen SAGD Project.

Table 2-9: Triaxial Test Results from Preserved Core Samples (1AA/15-03-094-07W4)

Temperature	Room-Temperature						150°C	
Sample ID	C23T4S1	C23T1S2	C22T3S1	C15T1S1	C19T1S1	C18T3S1	C15T4S1	C19T2S1
Sample depth (m)	178.91	176.91	175.31	154.61	166.22	164.69	156.25	167.16
Test Condition								
Effective confining (Pc, MPa)	2.00	0.50	0.00	3.00	1.50	0.00	3.00	1.50
Triaxial loading rate (1/s)	3.00E-07	3.00E-07	3.00E-07	3.00E-07	3.00E-07	3.00E-07	3.00E-07	3.00E-07
Axial strain, end of test (%)	5.16	3.02	4.82	5.13	4.92	4.48	5.07	5.11
Geometry/Petrophysical Parameters								
Sample height (mm)	123.21	146.48	144.33	154.72	145.38	142.83	136.77	144.55
Sample diameter (mm)	70.80	71.03	71.01	71.39	70.78	70.70	71.60	71.33
Weight (g)	1050	1234	1187	1318	1249	1215	1174	1213
Density (g/cm^3)	2.16	2.13	2.08	2.13	2.18	2.17	2.13	2.10
Moisture content (%)	12.46	14.84	16.05	15.62	14.01	13.28	13.02	12.83
Summary of Results								
Young's modulus (MPa)	246.76	228.32	199.56	607.37	207.85	90.31	521.93	360.76
Poisson ratio	0.23	0.26	0.21	0.23	0.27	0.29	0.25	0.26
Coefficient of thermal expansion (1/°C)	NA						6.10E-05	2.20E-05
Peak strength (MPa)	2.03	1.72	0.84	8.01	3.81	1.75	7.76	4.33
Permeability (nD)	1,330	818	NA	1,280	643	NA	1,370	4,620
Formation	Wabiskaw			Clearwater			Clearwater	

Table 2-10: Shear Box Test Results from Preserved Core (1AA/15-03-094-07W4)

Sample ID	C23T2S3	C23T2S3
Sample depth (m)	177.08	176.91
Friction Angle (°)	7.4	16.0
Cohesion (kPa)	150	360
Formation	Wabiskaw	Wabiskaw

2.5.4.4 Primary Caprock and Maximum Operating Pressure

The primary caprock over the project area is represented by the interval defined from CLW fs1 shale to the top McMurray Formation. The average thickness of this interval is 30 m. The results presented here support the assessment that this interval is laterally continuous, with no structural or erosional disturbances and is geomechanically strong enough to withhold steam. Therefore, the caprock constitutes a competent regional barrier to vertical steam movement. In addition, the remaining Clearwater Formation lithological column, which has an average thickness of 42 m between the primary caprock and the Grand Rapids Formation, will also contribute to holding steam within the Clearwater Formation. The proposed MOP for the project will be 2,500 kPag, which is less than 80% of the estimated fracture closure pressure at the base of the caprock. This MOP is compatible with the results from the geomechanical simulation study. To reduce the risks of overpressurizing the reservoir, Imperial will ensure that the MOP is not exceeded at any time during start-up, production or circulation. The planned target reservoir operating pressure throughout most of the project’s life is 1,500 kPag.

2.5.5 CAPROCK INTEGRITY MONITORING

Imperial is committed to safe and efficient operations for the project area. The caprock integrity tests and studies performed will allow Imperial to develop a monitoring plan to ensure caprock integrity under SAGD operations in the project area.

Caprock integrity will be demonstrated by monitoring the pressure of the GSZ below the caprock to ensure that the MOP is not exceeded at this interval. A typical SAGD well pad will have one or two observation wells. These wells will be designed individually to monitor pressures in the reservoir and GSZ, temperature in and above the reservoir, or a combination of the capabilities. In addition, the monitoring wells will be instrumented with thermocouples throughout the reservoir and the caprock. Criteria that might be indicative of loss of fluid containment are:

- sudden loss of pressure in the GSZ
- temperatures in the overburden of the reservoir other than those consistent with conductive heating
- unexplained increases in the groundwater pressure

If the monitoring indicates a loss of fluid containment, then Imperial will investigate the cause and take the necessary actions to stop any potential steam loss. An appropriate response protocol will be developed before the start of operations.

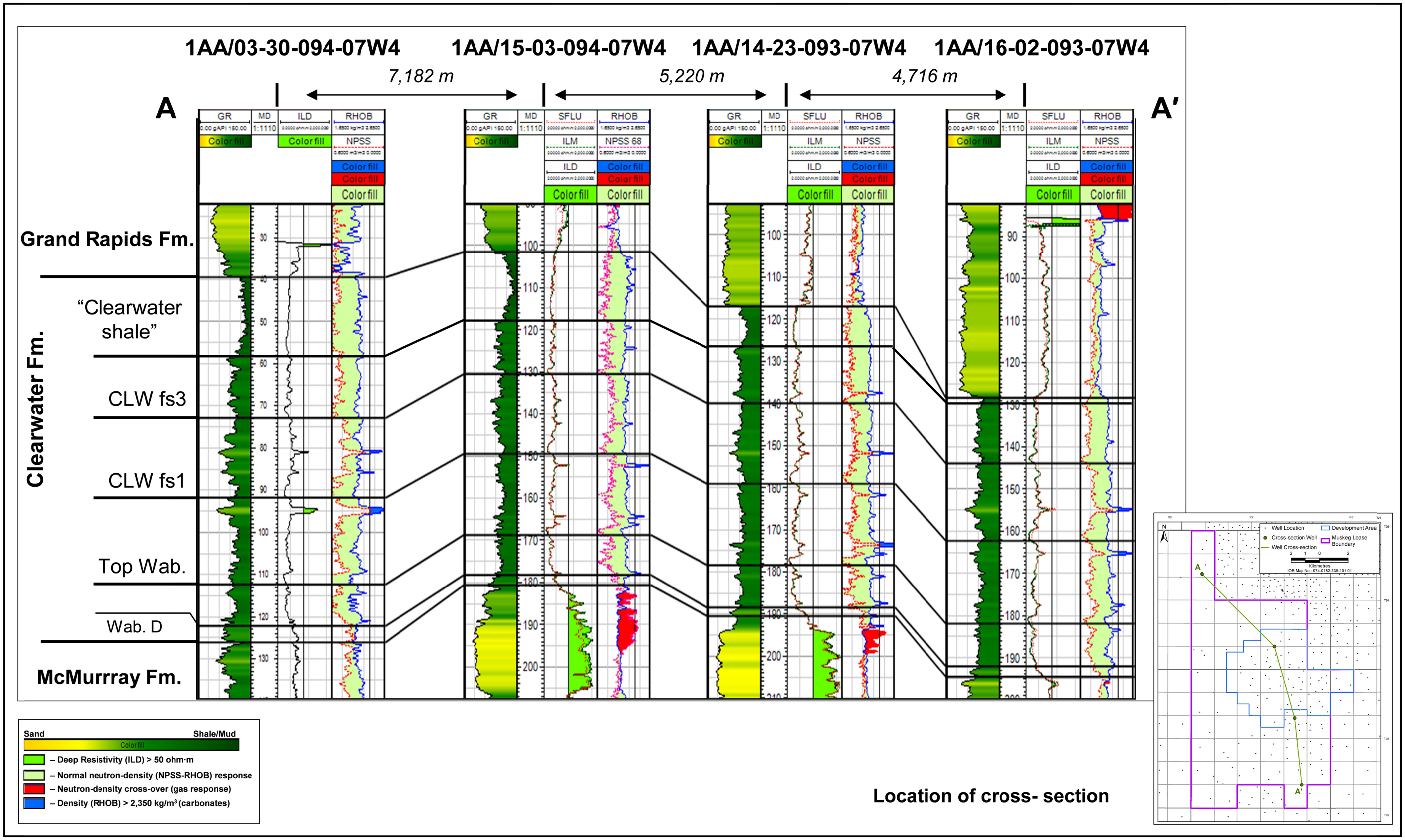


Figure 2-31: Caprock Cross-Section Across the Project Area