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The Clearwater Formation: A Facies Study for SAGD Water Source in the Athabasca Oil Sands

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Introduction

Water source has become an increasingly important issue recently with the acceleration of SAGD (steam assisted gravity drainage) operations coming online in the Athabasca Oil Sands. In addition to finding enough water to support these operations, the salinity of the water must also be non-potable (>4000 tds – total dissolved solids) which is considered not acceptable for domestic usage. A fundamental understanding of each aquifer and associated aquitards is essential to assess sustained deliverability and long term use. When searching for appropriate aquifers, rock type is paramount. Porosity, permeability and grain size must all be considered and analyzed. This study looks at the relationships between good reservoirs and their link to facies, rock properties (porosity, permeability, grain size) and rock type.

Backround

In 2010, eight wells were drilled and cored in the Clearwater Fm. for potential water source. The Clearwater 'B' was targeted, interpreted and mapped in the Leismer and Corner areas to understand the distribution of water sand resource in this area.

Analysis and Observations

A facies scheme was developed by looking at the following indicators:

- stratigraphy
- bioturbation intensity
- ichnology
- grain size
- sedimentary structures

Six facies were identified and follow an idealized shoreface profile. The facies are:

- Facies 1: offshore organic mudstone
- Facies 2: heavily bioturbated silty-mudstone
- Facies 3: lam-scram silty-mudstone with common bioturbation
- Facies 4: hummocky-cross-stratified sand with mud stringers
- Facies 5: hummocky-cross-stratified sand with abundant glauconite
- Facies 6: structureless, massive sand

<u>Facies 1:</u> **Offshore organic mudstone**

Figure 1: Facies 1

<u>Description:</u> Dark grey to black, locally waxy, low density organic mudstone. Common mm to cm-scale laminations, sharp-based normally graded, silty interbeds and rare, small syneresis cracks. The unit is lightly to moderately bioturbated with *Phycosiphon* and *Chondrites* and possible *Zoophycos*. Sparse authigenic pyritic concretions, possibly around shell fragments, are present.

<u>Interpretation:</u> The erosive nature of the low angle bedded silts suggests rapid bed load deposition, possibly by hyperpycnal flows. The restricted trace fossil assemblage in the muds and the relationship to the silty hyperpycnites are consistent with episodic deposition in a restricted, distal marine setting. Interpreted to represent maximum flooding surface (MFS) and a large scale marine incursion.

<u>Depositional Environment:</u> Restricted distal lower shoreface to proximal offshore or distal prodelta. Sediment starved deep water setting. Accumulation in low oxygen conditions is likely due to the presence of pyrite and dark nature of the sediment.

<u>Stratigraphic Context:</u> This facies constitutes several regionally correlatable low density markers. It marks the top of the Wabiskaw and occurs both within and throughout the Clearwater.

<u>Facies 2:</u> **Heavily bioturbated silty-mudstone**

Figure 2: Facies 2

<u>Description:</u> Heavily bioturbated medium to dark grey silty to sandy mudstone. The unit has largely been biogenically homogenized and primary sedimentary structures are rare. The trace fossil assemblage consists of *Zoophycos*, *Teichichnus*, *Thalassinoides* and *Chondrites* with an overprint of variable-sized *Phycosiphon* and *Scalaratuba*.

<u>Interpretation:</u> The diversity and degree of bioturbation suggests deposition in an open marine setting. The unit is interpreted as representing deposition at distal lower shoreface to offshore transition bathymetries.

<u>Depositional Environment:</u> The gradational change from the underlying Facies 1 and the significant increase in sand content suggest deposition in a more proximal depositional setting than the underlying Facies 1.

<u>Stratigraphic Context:</u> This facies occurs above (and gradationally passes into) Facies 1. It probably represents the initial progradation and shallowing of the basin accompanied by increasing oxygenation.

Facies 3: Lam-scram silty-mudstone with common bioturbation

Figure 3: Facies 3

Description: Heavily bioturbated, interbedded sharp-based wave-rippled, very fine-grained sandstone and silty mud. The sandier interbeds are often cm-scale truncated wave-ripple lamination (HCS). The facies is variably glauconitic and contains common organics. Rare, small thin-shelled bivalves are present. Trace fossils consist of dense *Chondrites*, abundant *Scalaratuba* (larger muddy fills), *Phycosiphon* (with pronounced white halos), possible *Scolicia* and muddy *Zoophycos* burrow fills.

Interpretation: The unit consists of lam-scram bedding and represents laminated storm bed deposition interbedded with heavily bioturbated, mud-rich fairweather deposits.

Depositional Environment: Lam scram deposition is common at distal lower shoreface bathymetries in prograding, wave-dominated shorelines. The high bioturbation indicies and the high diversity of trace fossil genera are consistent with deposition in fully marine conditions.

Stratigraphic Context: This facies occurs as part of a coarsening upwards, progradational parasequence and is transitional between Facies 2 and Facies 4.

Facies 4: Hummocky-cross-stratified sand with mud stringers

Figure 4: Facies 4

Description: Very fine-grained hummocky cross-stratified sandstone (HCS) with cm-scale interbeds of dark-grey to black unburrowed mudstone. Abundant organics on bedding planes. The trace fossils are predominately diffuse, “sediment-stirring” structures (*Scolicia*-like locomotory traces) at the tops of the muddy interbeds and *Paramacaronichnus* (*sic*), defined by shunted heavy minerals and organics. Rare, small *Conichnus* and small *Ophiomorpha* are also present. *Zoophycos* and *Chondrites* are commonly associated with the thin mudstone interbeds.

Interpretation: Hummocky cross stratified sandstone with bioturbated mudstone interbeds represents deposition in shallow, storm-dominated marine conditions. The mudstone interbeds represent fairweather conditions.

Depositional Environment: Facies 4 is interpreted to represent deposition in a lower shoreface setting. The increase in sand content is the result of the amalgamantion of storm beds suggesting a shallowing relative to Facies 3.

Stratigraphic Context: This facies occurs as part of a coarsening upwards, progradational parasequence and is transitional between Facies 3 and Facies 5.

<u>Facies 5:</u> Hummocky-cross-stratified sand with abundant glauconite

Figure 5: Facies 5

<u>Description:</u> Consists of sharp, erosively based, fine-grained, low angle bedded to hummocky cross-stratified (HCS) glauconitic sandstone. The facies contains rare cut and fill structures, abundant detritial organics (aligned on bedding planes) and occasional calcareous shell fragments and cm-scale sideritic mudstone clasts on bedding planes.

<u>Interpretation:</u> The predominance of amalgamated and truncated hummocky cross-stratified beds without significant mudstone interbeds suggest an amalgamation of storm beds.

<u>Depositional Environment:</u> The amalgamation of storm beds coupled with abundant glauconite suggests deposition in a proximal lower shoreface setting, below fair-weather wave base.

<u>Stratigraphic Context:</u> No particular significance. This facies occurs near the tops of coarsening upwards, progradational parasequences.

<u>Facies 6:</u> Massive sand

Figure 6: Facies 6

<u>Description:</u> Upper fine to lower medium-grained sandstone with sparse disseminated organics. Common glauconite and sparsely bioturbated with *Palaeophycus* and what appear to be large *Macaronichnus*-like burrows. The unit has a blocky appearance on gamma logs and seems to be sporadically present at the top of coarsening upwards cycles.

<u>Interpretation:</u> The coarser nature of the sediment suggest deposition in a shallower water setting than the rest of the facies encountered. The basal contact of this facies often appears to be gradational with the underlying Facies 5.

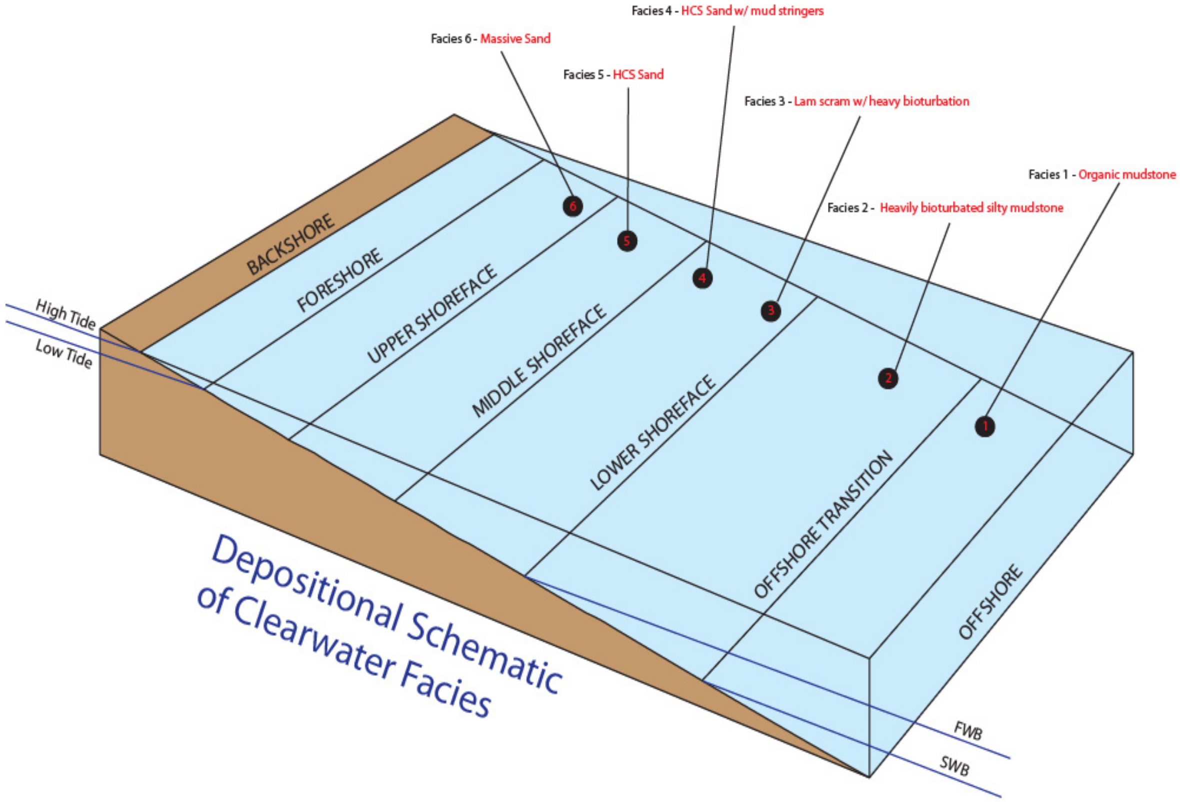
<u>Depositional Environment:</u> The lack of diagnostic sedimentary structures makes precise interpretation of the depositional environment of this facies uncertain. The coarse nature of the sediment, its presence at the tops of coarsening-upwards parasequences and the *Macaronichnus*-like burrows is suggestive of middle to upper shoreface deposition.

<u>Stratigraphic Context:</u> The gradational nature of the basal contact with the underlying units suggest that there is no significant erosional hiatus at the base of the unit. This facies is interpreted to represent the shallowest water facies at the top of mid-Clearwater coarsening upwards shoreface parasequences.

Interpretation

The above six facies can be summarized in the conceptual model below:

Figure 7: Block facies model with idealized shoreface profile *



** Middle Shoreface: defined as an area of overlap of Cruziana and Skolithos ichnofacies*

Facies Summary

- The six facies summarized represent a continuum of deposition from Offshore mudstones (Facies 1) to Middle to Upper Shoreface sandstones (Facies 6).

- The regional extent of the Facies 1 units corresponds to mappable maximum Flooding Surfaces (MFS).

- Facies 6 is genetically related to the underlying Facies 5. There is no erosional disontinuity between the units. The occurrences of Facies 6 would be predicted to occur parallel to regional shoreface trends and do not cut across these trends.

Petrography and Sampling

In concert with the facies, samples were taken from the sandy portions of the core (Facies 4, 5 and 6) and sampled for porosity, permeability and grain size. As well, fluids from the formation were sampled to obtain TDS (total dissolved solids) calculations to ensure the water met requirements.

Figure 8: Example(s) of Porosity/Permeability and Relationship to Facies

Example Well #1 (9518, 9568, 9994 mg/L calculated TDS)

Sample	Facies	Thin Section Porosity (%)	Lab Porosity (%)	Khz (mD)	Kvert (mD)
1	CLW-5	27.5	23.8	479	496
2	CLW-6	29.2	25.2	3650	2447
3	CLW-6	25.6	28.6	2361	2558
4	CLW-6	30.6	28.7	2563	2088
5	CLW-4	20.2	31.4	1085	934
6	CLW-4	23.9	25.3	1537	1098
7	CLW-4	21.3	31.0	346	330
8	CLW-5	24.2	26.1	361	218
9	CLW-5	15.5	28.5	184	121

Example Well #2 (9997, 7473, 12913 mg/L calculated TDS)

Sample	Facies	Thin Section Porosity (%)	Lab Porosity (%)	Khz (mD)	Kvert (mD)
1	CLW-4	18.9	32.7	408	289
2	CLW-6	20.6	34.3	547	412
3	CLW-6	25.7	37.9	1863	1522
4	CLW-6	23.9	38.3	1749	2247
5	CLW-6	21.3	37.7	1578	1239
6	CLW-5	17.6	33.9	382	256
7	CLW-5	15.0	34.1	148	79

The yellow, highlighted portions above in Figure 8, represent desirable permeabilities. Generally, these are confined to Facies 6, but Facies 4 occasionally meets the criteria as well; Facies 5 did not meet requirements in any of the wells analyzed.

Figure 9: Example(s) of Grain Size Dstribution with Relation to Facies

Example Well #1 (9518, 9568, 9994 mg/L calculated TDS)

Sample	Facies	Mean (mm)	Min (mm)	Max (mm)
1	CLW-5	0.139	0.071	0.264
2	CLW-6	0.212	0.033	0.455
3	CLW-6	0.221	0.082	0.558
4	CLW-6	0.211	0.082	0.376
5	CLW-4	0.214	0.095	0.383
6	CLW-4	0.185	0.095	0.350
7	CLW-4	0.148	0.068	0.290
8	CLW-5	0.133	0.076	0.221
9	CLW-5	0.124	0.066	0.212

Example Well #2 (9997, 7473, 12913 mg/L calculated TDS)

Sample	Facies	Mean (mm)	Min (mm)	Max (mm)
1	CLW-4	0.141	0.070	0.253
2	CLW-6	0.161	0.076	0.328
3	CLW-6	0.181	0.073	0.321
4	CLW-6	0.187	0.078	0.316
5	CLW-6	0.185	0.080	0.328
6	CLW-5	0.142	0.073	0.221
7	CLW-5	0.123	0.067	0.204

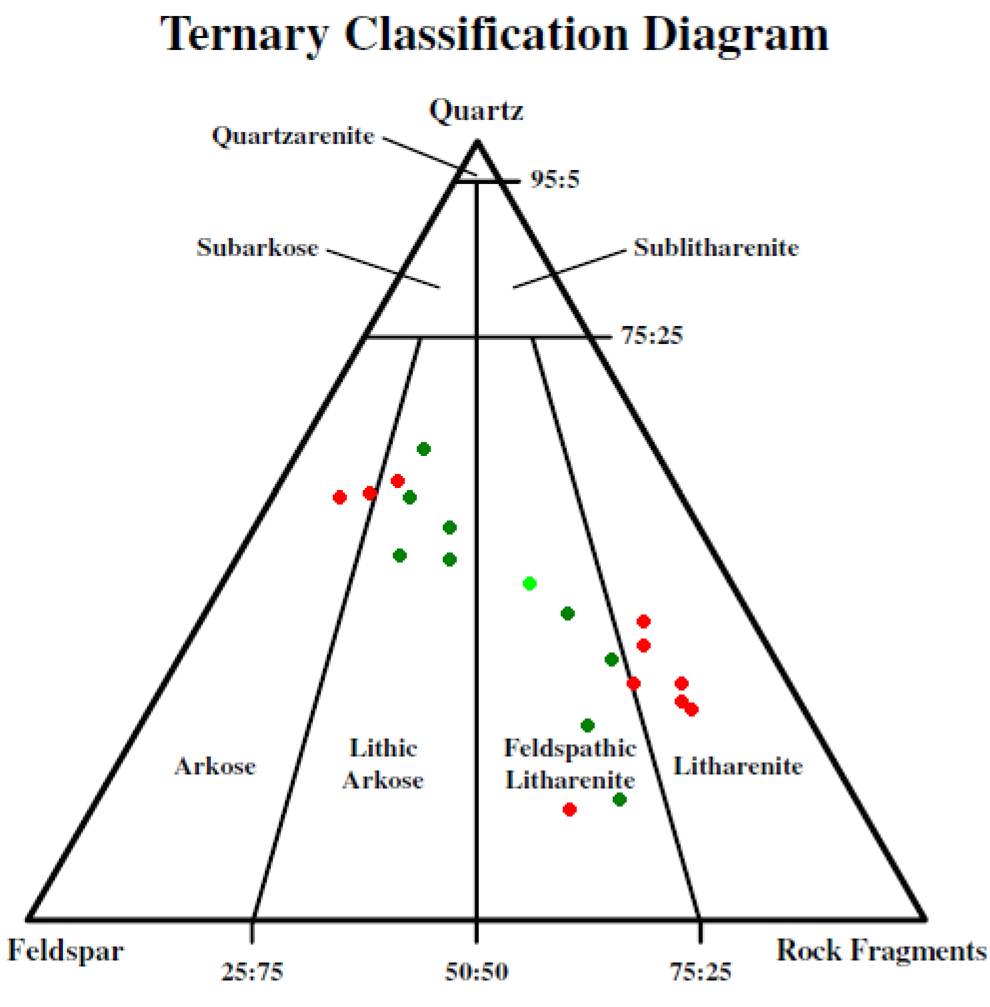
In the above Figure 9, the orange highlighted areas represent desirable permeabilities. Generally, these are confined to Facies 6, but Facies 4 occasionally meets the criteria as well; Facies 5 did not meet requirements in any of the wells analyzed.

By observing the above data set from one particular well, we notice that permeability appears to be related to porosity and grain size. As a general rule, Facies 6 was more likely to have acceptable permeability (>1D), while Facies 4 had ranging permeabilities on the precipice of the 1D cutoff range. When Facies 4 had grain sizes below a mean of 0.155 mm and a lack of larger grains, due to sorting, the facies did not quite meet the proper permeability cutoffs. Also observed was a differential between plug porosity and thin section porosity, with thin section porosity being slightly more useful as the values had greater variability and comparatively matched up better with the permeability and grain size data in this particular case. This is likely due to a differential in clay content and its apparent effect on the former porosities.

A key indicator when looking for these good water source zones is small neutron-density separation which would infer a high sensitivity to mud particulate and filtrate invasion. This indicator can sometimes be more useful than strictly looking for clean API zonations on gamma ray, given the feldspathic mineralogy. A higher gamma count can be attributed to the presence of K-feldspar and not necessarily reflect clay content.

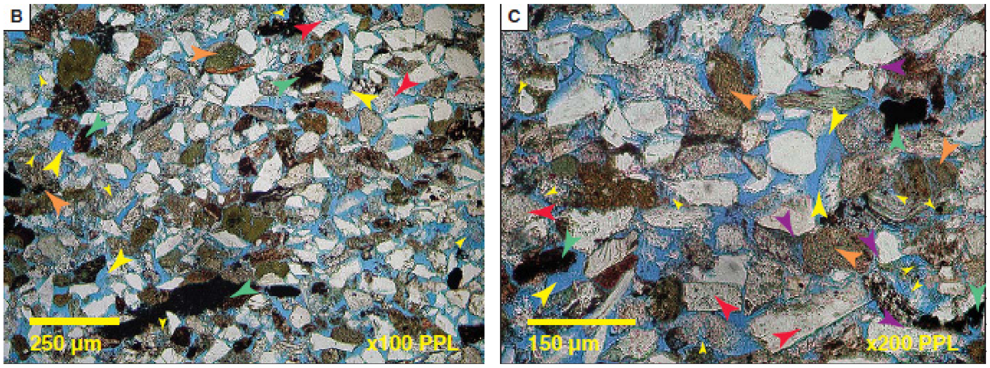
Plotted below (Figure 10) is a combined plot of two wells on a Ternary Diagram looking for relationships between permeability and rock type. Green dots represent permeability of >1D, while the red dots represent plots of facies/samples with <1D permeability. At a quick glance, it is easily to visually identify where the facies/samples plot with regards to the desirable permeabilities.

Figure 10: Ternary Plot of Wells with >1D and <1D Permeability

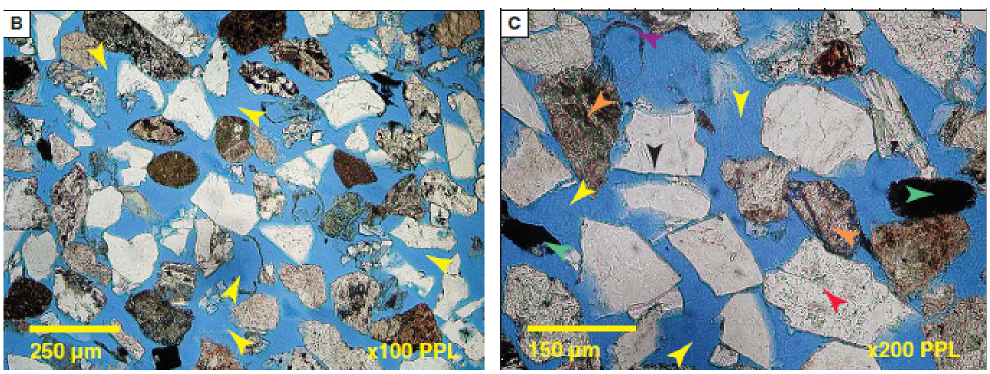


We could expect the plots towards the rock fragment to have poor permeability, but the outlier as seen above was that there were samples that performed poorly as we move towards ‘cleaner’, more mature type sands with an abundance of quartz and less lithics. We found that Facies 5, which accont for the poor permeabilities (upper Arkose), has a grain size that is too fine to allow sufficient flow parameters. Facies 5 is highly glauconitic hummocky-cross-stratified sandstone and the glauconite may have an effect on porosity and permeability due to its malleability around adjacent grains. The ductile nature of the glauconite may partially block pore systems.

Figure 11: Example of Plate with >1D vs. Plate with <1D Permeability



Facies 4: <1D Permeability: note smaller grains. Approximately 75% of total porosity volume is primary intragranular and minor solution enhanced intragranular porosity (large yellow arrows). Sample represents lower quality reservoir, moderately sorted, upper very fine-grained feldspathic litharenite with good estimated total and effective porosity and relatively low estimated permeability (100 – 500mD) (GR Petrology Consultants Inc.)

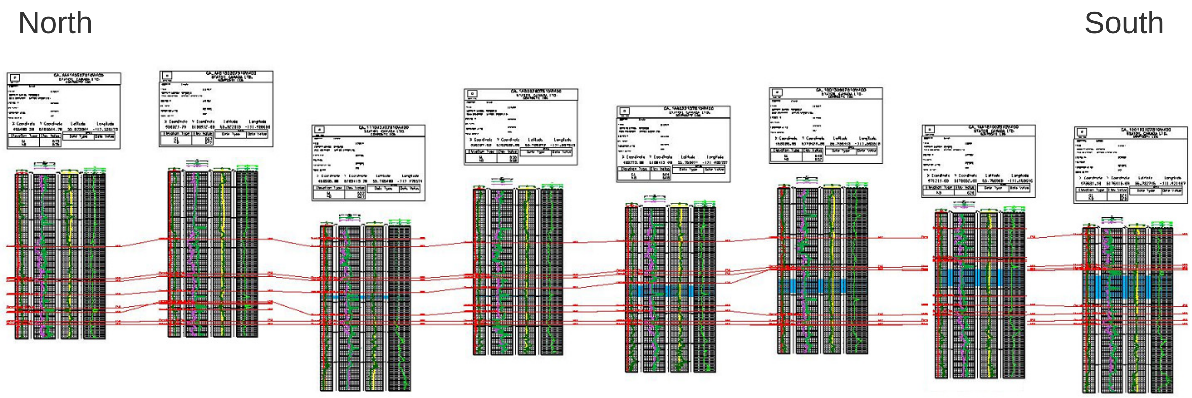


Facies 6: >1D Permeability: note larger grains. Approximately 90% of total pore system comprised of intergranular and grain moldic porosity (large yellow arrows). Sample represents excellent reservoir quality, upper fine-grained feldspathic litharenite with excellent estimated total and effective porosity and excellent estimated permeability (>2500mD). (GR Petrology Consultants Inc.)

Implications and further studies

After the six facies were labeled on the cored Clearwater portions, a map and cross-sections were made and a general trend was observed in the area of study.

Figure 8: Cross-Section of Facies 6 – Potential Water Source (in blue)



In Figure 8, Facies 6 was plotted and mapped and shows an thickening trend as the section moves south. This ties in well with observed clean gamma zones as well as small neutron-density separation. The warping of the transgressive Facies 1 units, as seen above, is most likely due to differential compaction.

Conclusion

Water source in the Clearwater Formation in the Athabasca Oil Sands can be targeted through looking at the following criteria: petrophysics (gamma ray, neutron-density separation), facies and rock properties and type (porosity, permeability, grain size and petrography).

Through first identifying target zones on logs by looking for 'clean' sand zones, coring can help identify whether or not these are sufficient for water source. By first applying facies to the rock, a general understanding of porosity and permeability can be achieved and inferred. The next step is to sample the rock in the coarser and cleaner sands. Thin sections help immensely in accurately predicting effective porosity and permeability.