Depositional Environments, Stratigraphic Packages, and Petrography of the Basal Cambrian Sandstone

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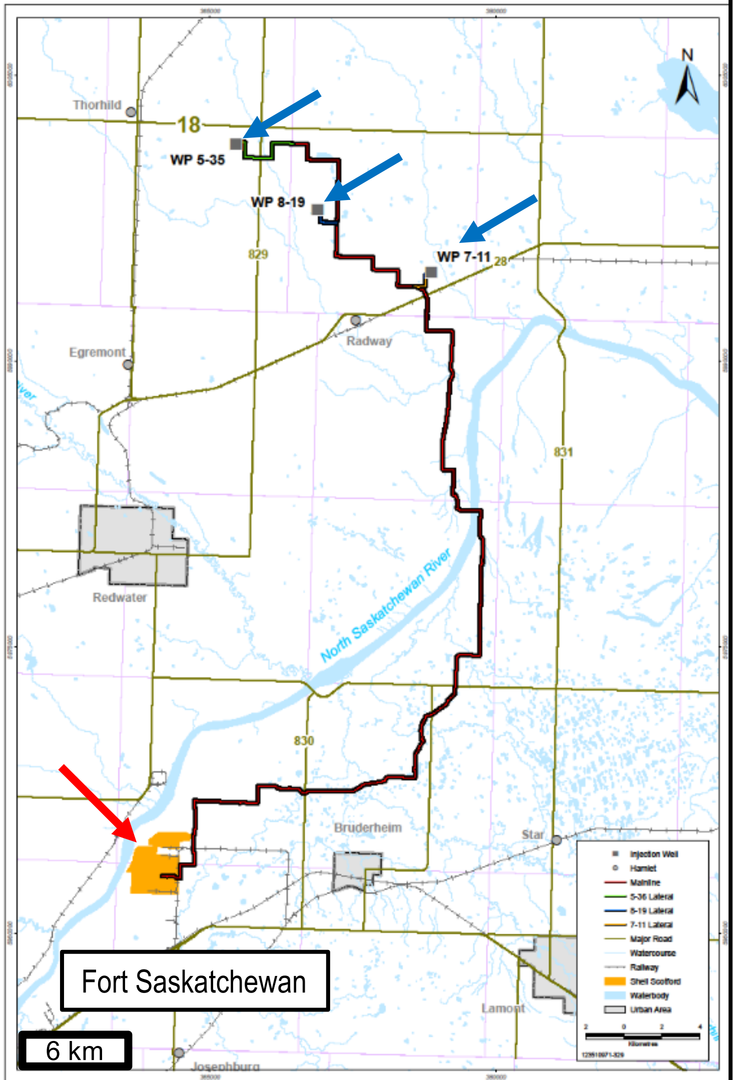
1) Alberta Geological Survey

2) Spectrum Geosciences

Quest CCS Facility

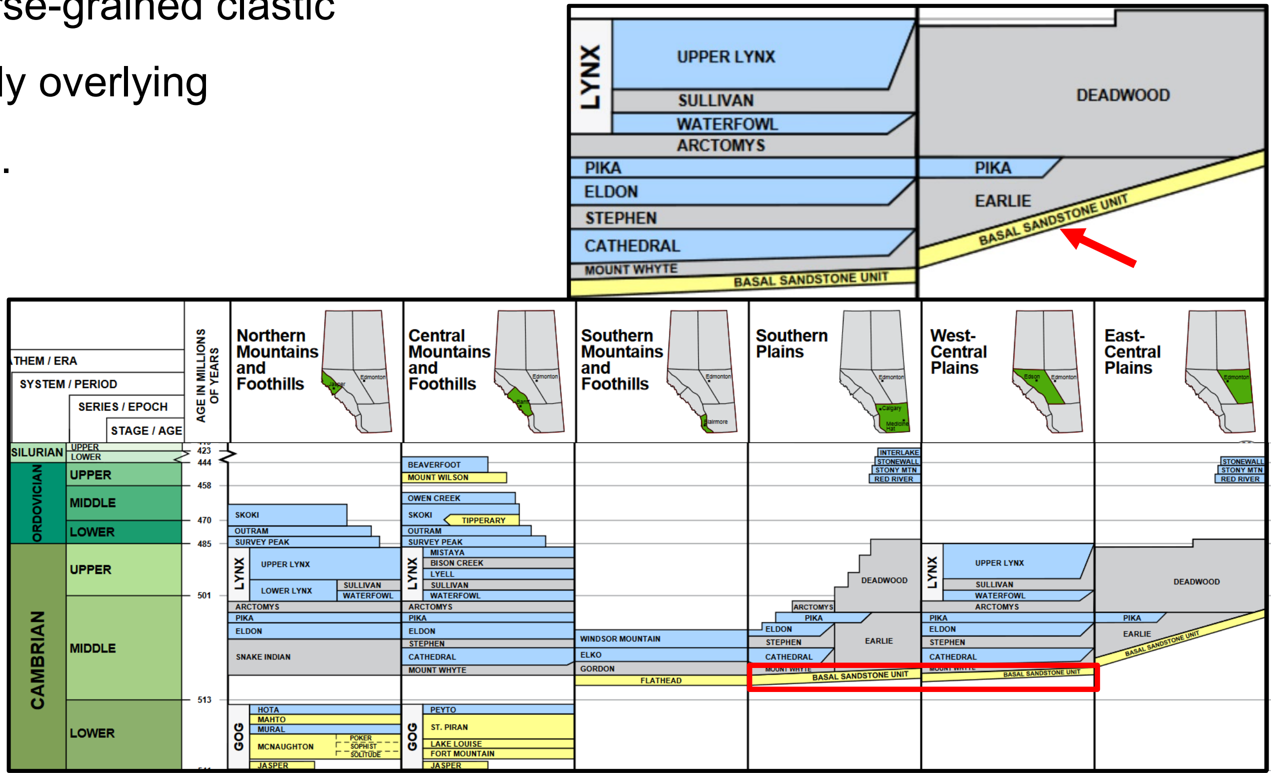
- First commercial scale Carbon Capture and Sequestration (CCS) Facility in Alberta.
  - Over 6 million tonnes of CO_2 has been sequestered from the Scotford Upgrader, ~48% of plant's emissions.
- Sequestering CO_2 into Basal Cambrian Sandstone (BCS).



Quest Annual Summary Report, 2015

Basal Cambrian Sandstone

- Middle Cambrian coarse-grained clastic deposit uncomformably overlying Proterozoic basement.

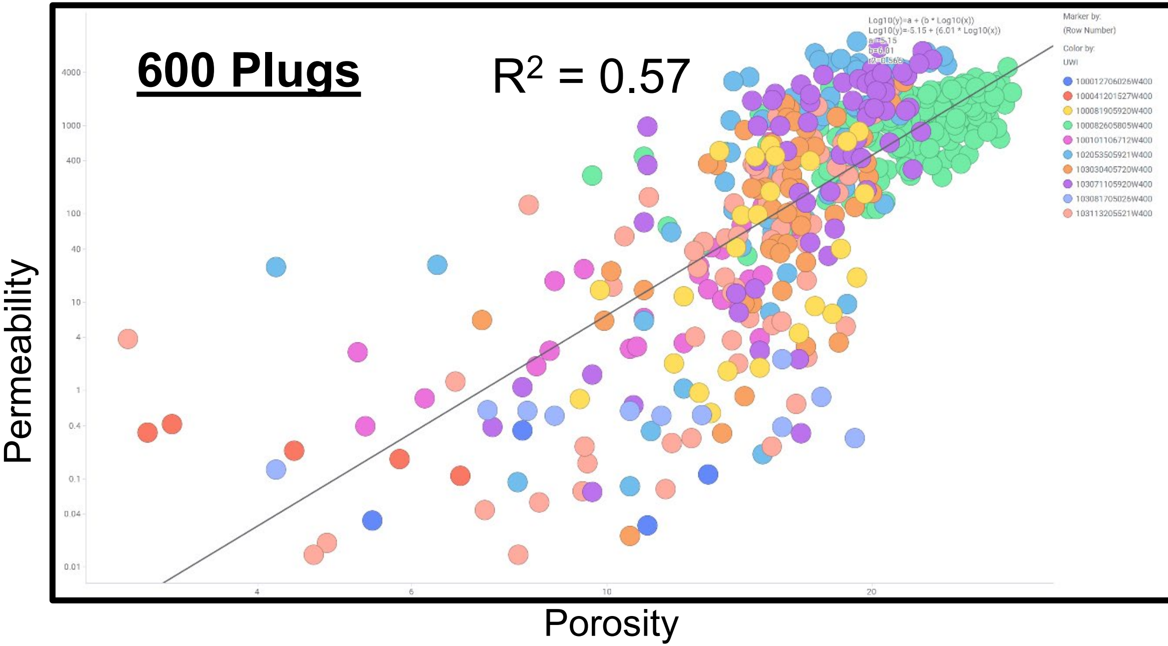


CSPG Canada's Energy Geoscientists

Basal Cambrian Sandstone

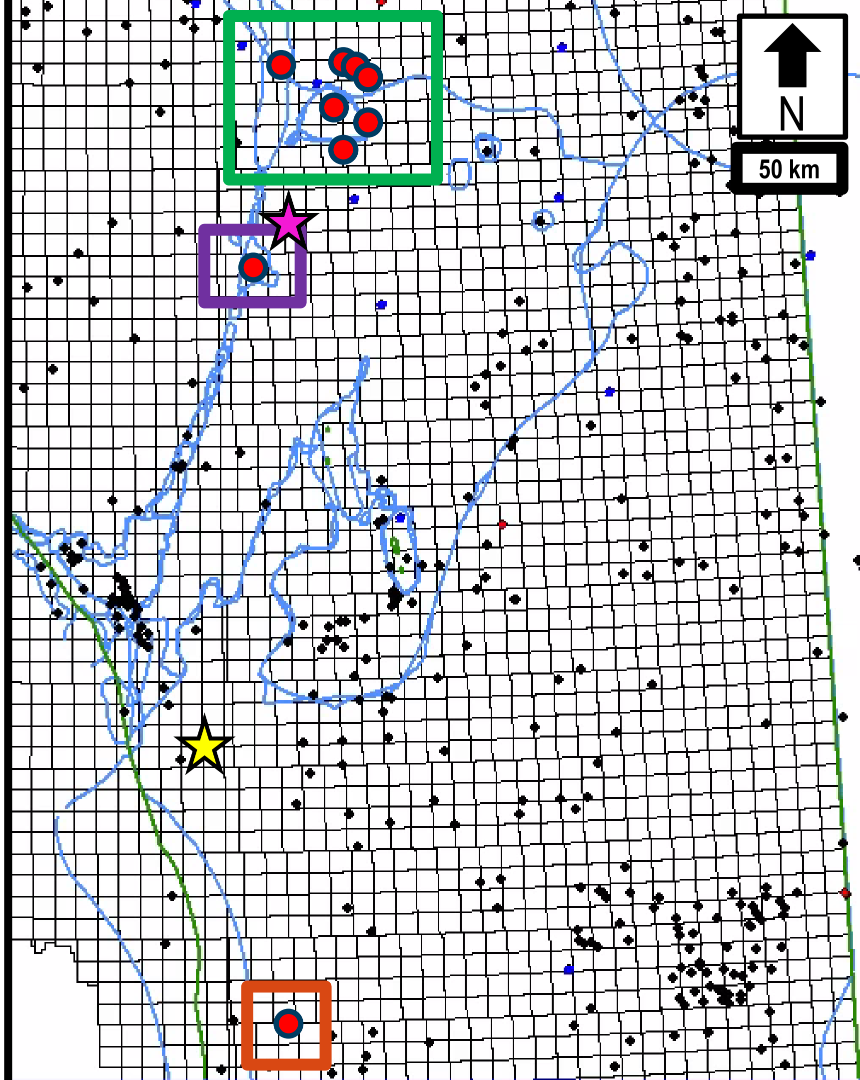
- Middle Cambrian coarse-grained clastic deposit uncomformably overlying Proterozoic basement.
- Good relationship between porosity and permeability.
- Limited wellbore penetrations
  - Reduced wellbore integrity uncertainty.

Permeability Vs Porosity



BCS Cores

- A range (9) of recent and legacy BCS cores. ●
- Cores record burial depths from 1400m-3600m.
- Poor data coverage an issue in evaluating the BCS, few wells go to Proterozoic, even fewer core the BCS.



Industrial Heartland

Leduc Woodbend

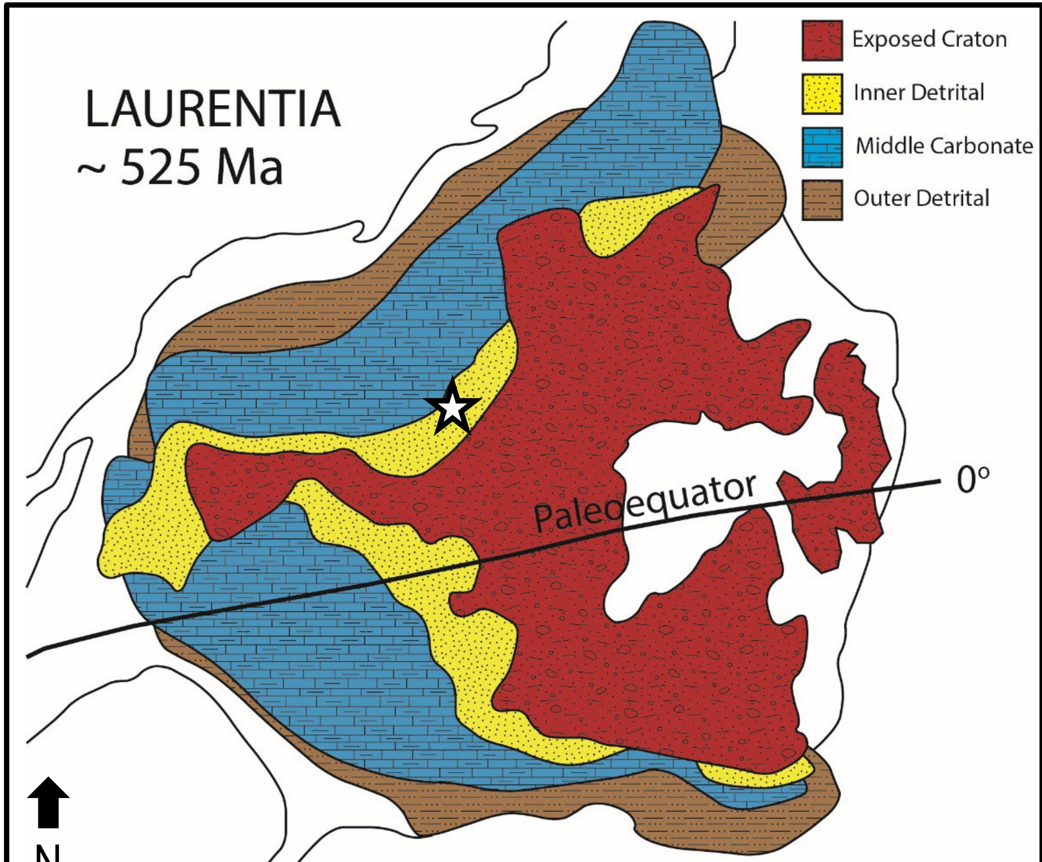
Lethbridge Area

★ Edmonton

★ Calgary

Paleogeography

- Laurentia sitting on the equator, rotated 90*.
- BCS deposited within the Lloydminster Embayment (van Hees, 1964). ☆
- Large ephemeral braided fluvial systems delivering large amounts of sediment to the arid coast.
  - No land vegetation to trap sediment.



Modified from Saltzman *et al.*, 2004

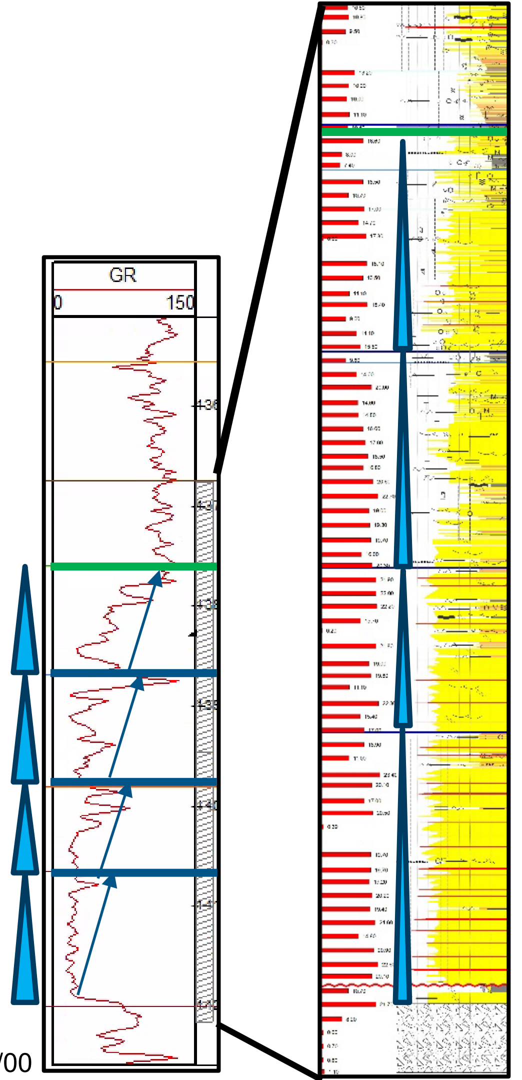
Basal Cambrian Sandstone

- BCS deposited within a fluvio-tidal compound dune field with 3 partitions.

  1. Core — Proximal
  2. Front
  3. Margin — Distal

- 4 progressively transgressive cycles identified.

- BCS deposition terminated by a significant maximum flooding surface (MFSx).



103/07-11-059-20W4/00

Compound Dune Field Core

- Thick accumulations of trough-cross stratified (TCS) medium- to very-coarse sandstone with trace mudstone.
- Abundant wavy muddy laminae (couplets), commonly demarcating TCS bed set boundaries.
- Prolific grain size striping.
- Well to poorly sorted.
- Sporadic fluid muds
- High net to gross sand.

103/07-11-059-20W4/00, 2056m

Compound Dune Field Core

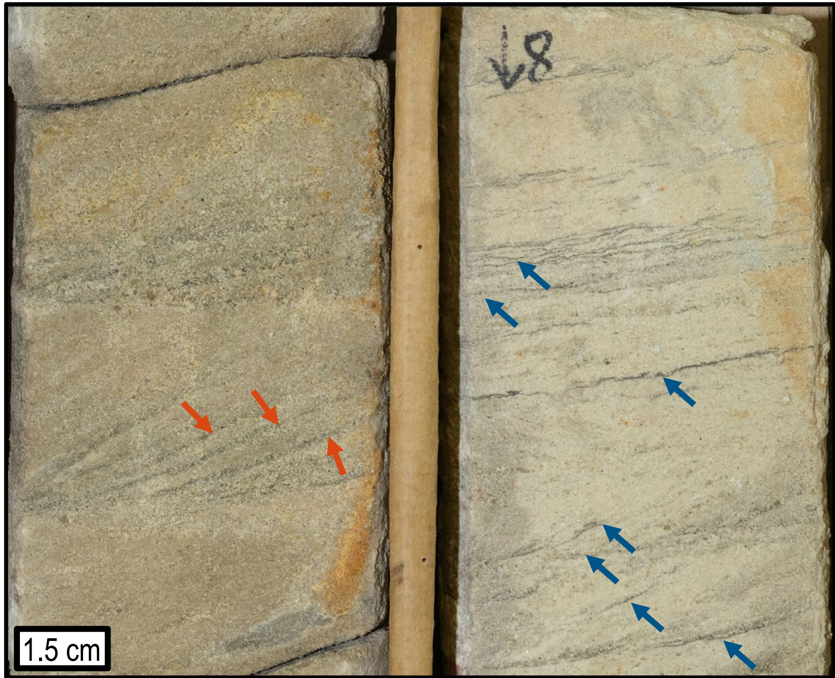
- Thick accumulations of trough-cross stratified (TCS) medium to very coarse sandstone with trace mudstone.
- Abundant wavy muddy laminae (couplets), commonly demarcating TCS bed-set boundaries. ←
- Prolific grain size striping.
- Well to poorly sorted.
- Sporadic fluid muds
- High net to gross sand.

103/07-11-059-20W4/00, 2050m

Compound Dune Field Core

- Thick accumulations of trough-cross stratified (TCS) medium to very coarse sandstone with trace mudstone.
- Abundant wavy muddy laminae (couplets), commonly demarcating TCS bed set boundaries. ⟵
- Prolific grain size striping. ⟵
  - Alternating coarser-finer laminae.
- Well to poorly sorted.
- Sporadic fluid muds
- High net to gross sand.

100/08-19-059-20W4/00, 2081.5m



Compound Dune Field Core

- Thick accumulations of trough-cross stratified (TCS) medium to very coarse sandstone with trace mudstone.
- Abundant wavy muddy laminae (couplets), commonly demarcating TCS bed set boundaries.
- Prolific grain size striping.
- Moderate to poorly sorted. ←
  - Interpreted to record adjacency to immature fluvio-tidal mouth bars.
- Sporadic fluid muds
- High net to gross sand.

100/01-27-060-26W4/00, 2064.4m

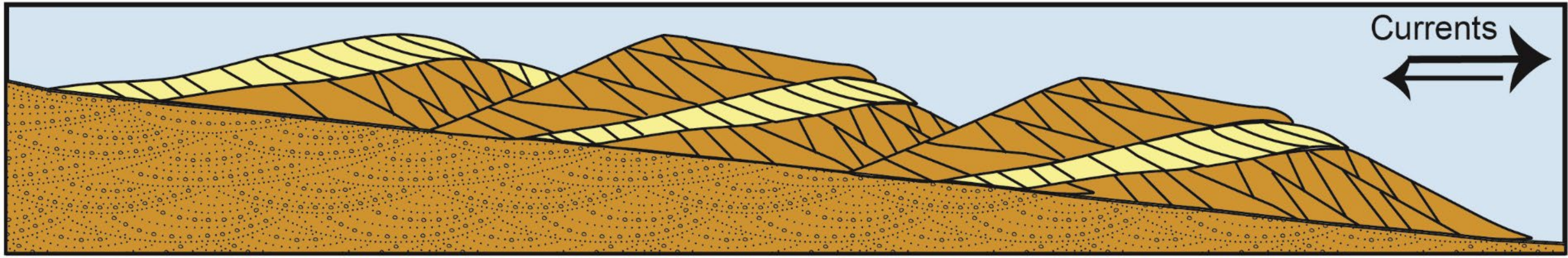
Compound Dune Field Core

- Thick accumulations of trough-cross stratified (TCS) medium to very coarse sandstone with trace mudstone.
- Abundant wavy muddy laminae (couplets), commonly demarcating TCS bed set boundaries.
- Prolific grain size striping.
- Well to poorly sorted.
- Sporadic fluid mud beds.
  - Reflect the episodic and rapid deposition of fluvially derived suspended mud.
  - Mantle and swirl (swimming) biogenic structures indicate soupground conditions.

103/11-32-055-21W4/00 2182.4m
100/08-19-059-20W4/00 2070.7m

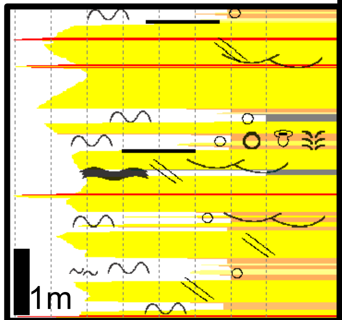
Compound Dune Field Core

- Intense hydraulic currents coupled with prolific sediment supply result in an abundance of clean TCS sandstone.
- Tidal currents rework coarse clastic material cannibalized from fluvial derived mouth bars.
- High net-gross sand, ~0.97 (Winkler, 2011).

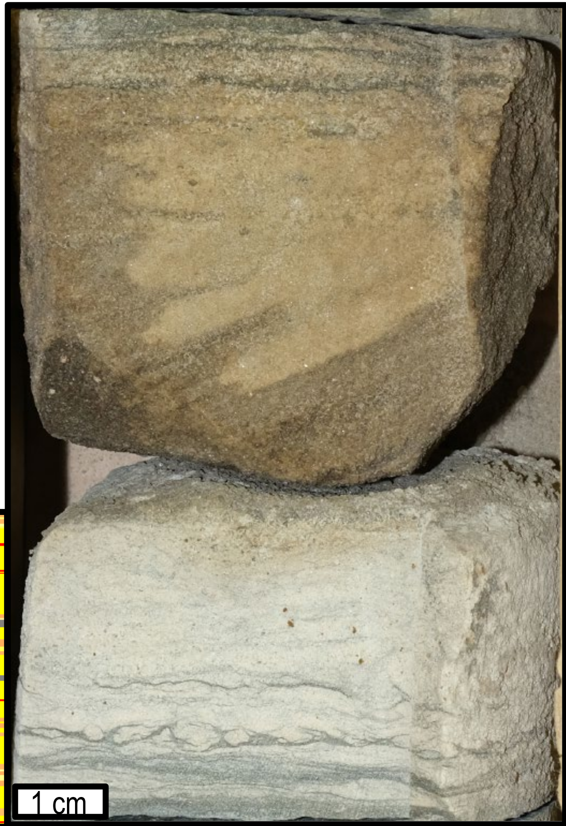


Compound Dune Field Front

- Medium to coarse grained TCS sandstone interbedded with bioturbated (BI 3-5) muddier fine-medium grained sandstone.
- Abundant wavy mud laminae, often found in couplets or rhythmites.
- Rare herringbone cross-stratification.
- Sporadic tubular tidalites.



103/07-11-059-20W4/00, 2047.6m



Compound Dune Field Front

- Thickly bedded fine-medium grained sandstone with minor mudstone.
- Intercalated bioturbated (BI 3-5) and TCS sandstone.
- Abundant wavy mud laminae, often found in couplets or rhythmites.
  - Diagnostic of tidal environments.
- Mud draped foresets on dunes and ripples common.
  - Interpreted to record slack water periods.
- Rare herringbone cross-stratification.
- Sporadic tubular tidalites.

103/11-32-055-21W4/00, 2178.8m

102/05-35-059-21W4/00, 2066m

Compound Dune Field Front

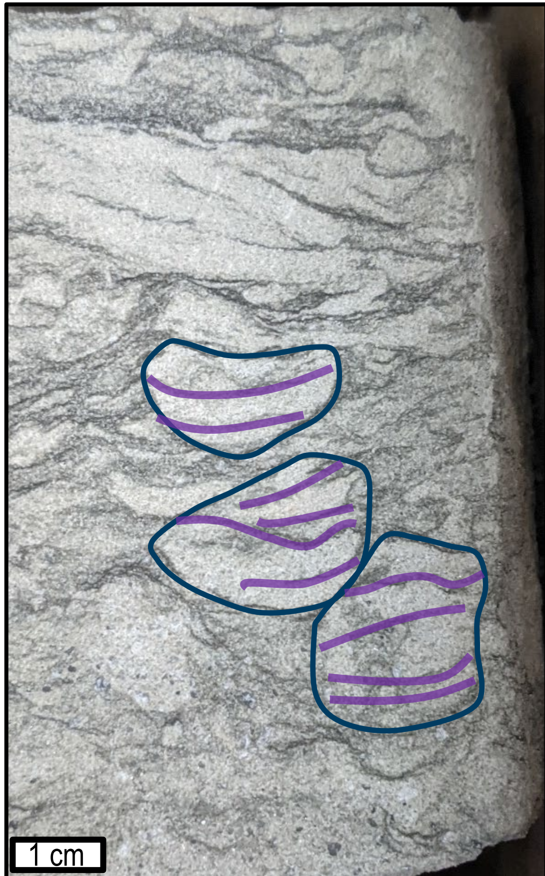
- Thickly bedded fine-medium grained sandstone with minor mudstone.
- Intercalated bioturbated (BI 3-5) and TCS sandstone.
- Abundant wavy mud laminae, often found in couplets or rhythmites.
- Rare herringbone cross-stratification.
  - Indicates bi-directional currents, diagnostic of tidal environments.
- Sporadic tubular tidalites.

102/05-35-059-21W4/00, 2064.1m

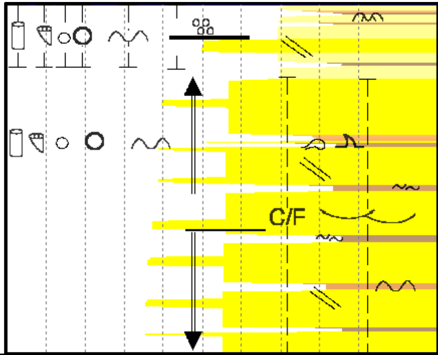
Compound Dune Field Front

- ➢ Thickly bedded fine-medium grained sandstone with minor mudstone.
- ➢ Intercalated bioturbated (BI 3-5) and TCS sandstone.
- ➢ Abundant wavy mud laminae, often found in couplets or rhythmites.
- ➢ Rare herringbone cross-stratification.
- ➢ Sporadic tubular tidalites.
  - ➢ Rhythmic mud laminae preserved within *Thalassinoides*-like arthropod burrows (likely trilobites).
  - ➢ Combined physical and biogenic sedimentary structures that are unique to tidal environments.

100/08-19-059-20W4, 2038.7m

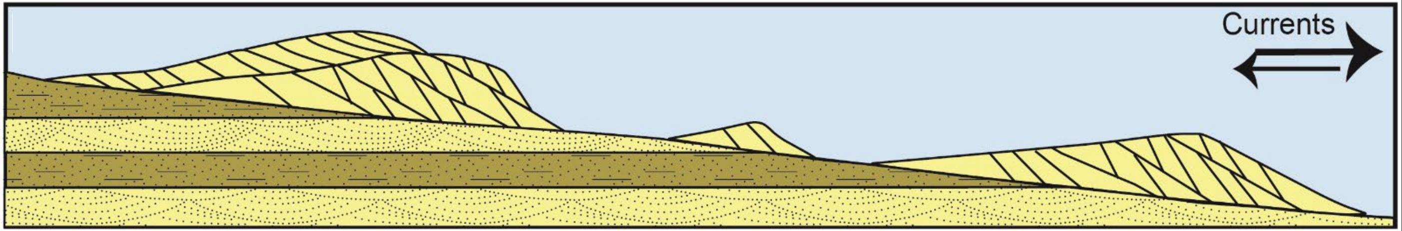


Compound Dune Field Front



- Medial position within the compound dune field.
- Reduced sediment supply and tidal energy result in an increased percentage of bioturbated lithosomes.
  - Dunes migrating across bioturbated troughs.
- Lower net-gross sand when compared with the core part of the system, ~0.93 (Winkler, 2011).

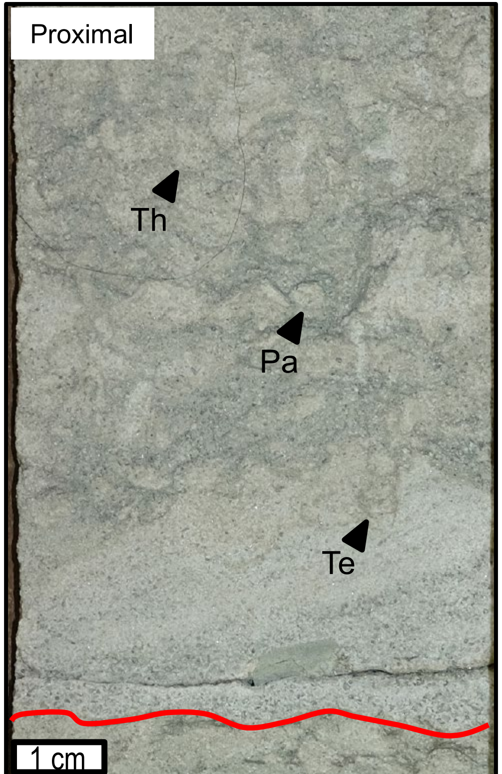
100/08-19-059-20W4, 2059m



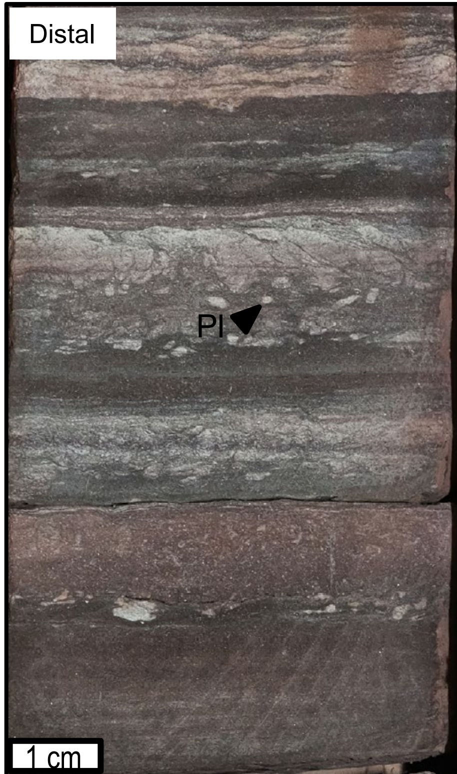
Compound Dune Field Margin

- Thinly laminated to medium-bedded heterolithic sandstone and mudstone. Variable BI, 2-4.
- Background sedimentation dominates.
- Large dune bedforms nearly disappear.
  - Overall greater proportion of mudstone and siltstone.
  - Bioturbation intensity increases. Deposit feeding behaviors dominate. *Thalassinoides*, *Teichichnus*, *Palaeophycus,* and *Planolites.*
  - Impoverished diversity.
  - Dune bedform tops bioturbated and reworked, illustrating sporadic migration. Static long enough for colonization.
- 2 expressions identified, proximal and distal.

103/11-32-059-20W4/00, 2169m



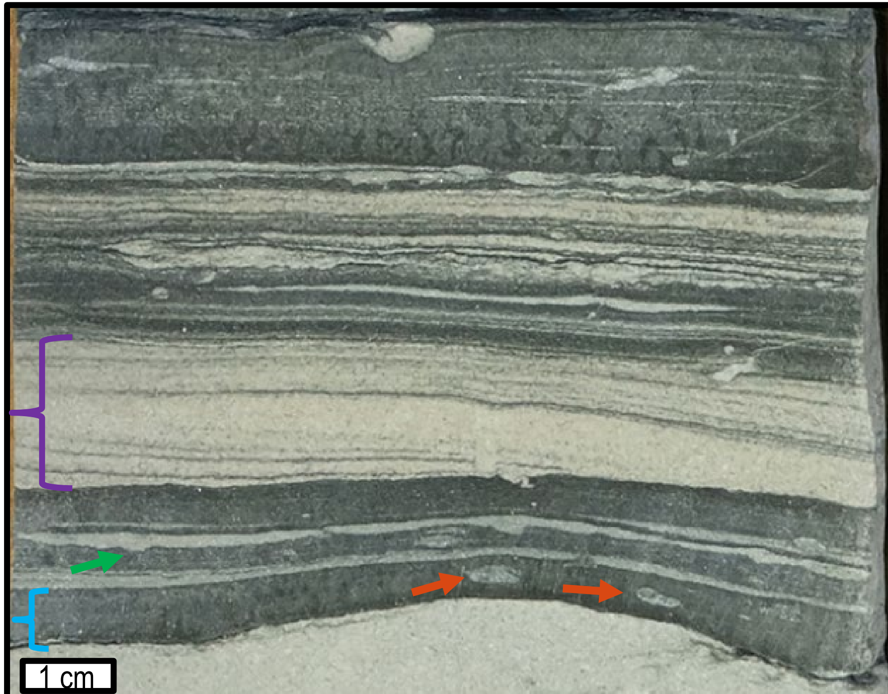
103/11-32-059-20W4/00, 2182m



Compound Dune Field Margin

- Thinly laminated to medium-bedded heterolithic sandstone and mudstone. Variable BI, 1-4.
- Sporadic wave ripples.
- Abundant sediment gravity flow beds.
- Flame, ball and pillow structures common.
- Prevalent fluid mud beds.
- Mantle and swirl biogenic structures, soupground mud conditions.

103/11-32-059-20W4/00, 2166.5m



Compound Dune Field Margin

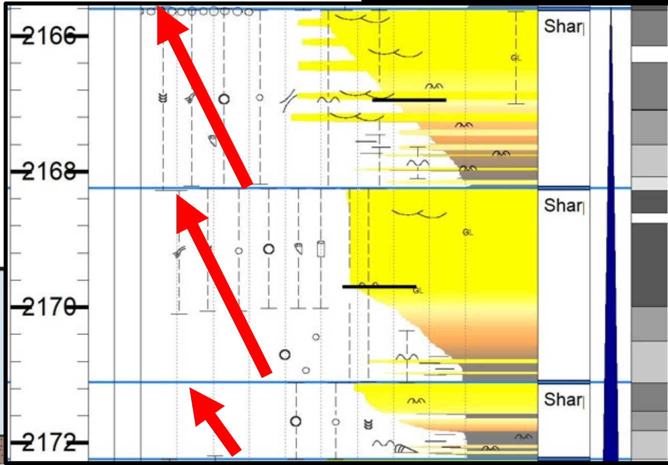
- Thinly laminated to medium bedded heterolithic sandstone and mudstone. Variable BI, 2-4.
- Sporadic wave and current ripples.
- Sediment gravity flow beds are common.
- Prevalent fluid mud beds.
- Episodic sharp-based cross-bedded sand intervals.
  - Significantly coarser (medium) white quartzose cross-bedded intervals.
  - Dune bedforms migrating at the fringes.
  - Background sedimentation dominates deposition.

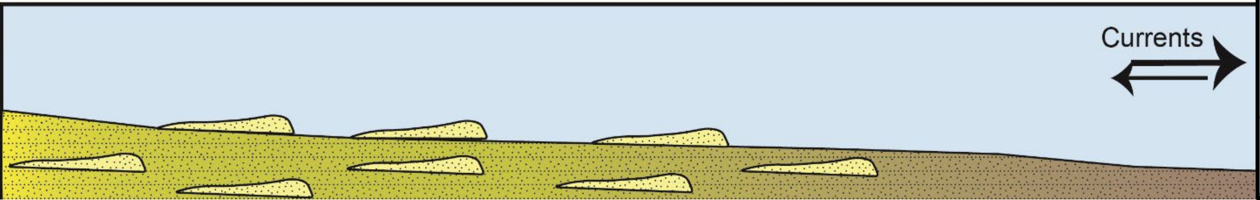
103/11-32-059-20W4/00, 2166.5m

Compound Dune Field Margin

- Most distal position within the compound dune field.
- Sediment starvation and reduced tidal energy result in an increased percentage of bioturbated lithosomes.
  - Sporadic dune bedforms, limited to sediment supply/energy.
- Lower net-gross sand when compared with the core part of the system, ~0.35-0.50 (Winkler, 2011).
- Record the most recognizable parasequences or cycles.
  - Distal to proximal margin facies.

103/11-32-059-20W4/00





Summary

➢ BCS deposited within a fluvio-tidal compound dune field with 3 partitions.

1. Core — Proximal
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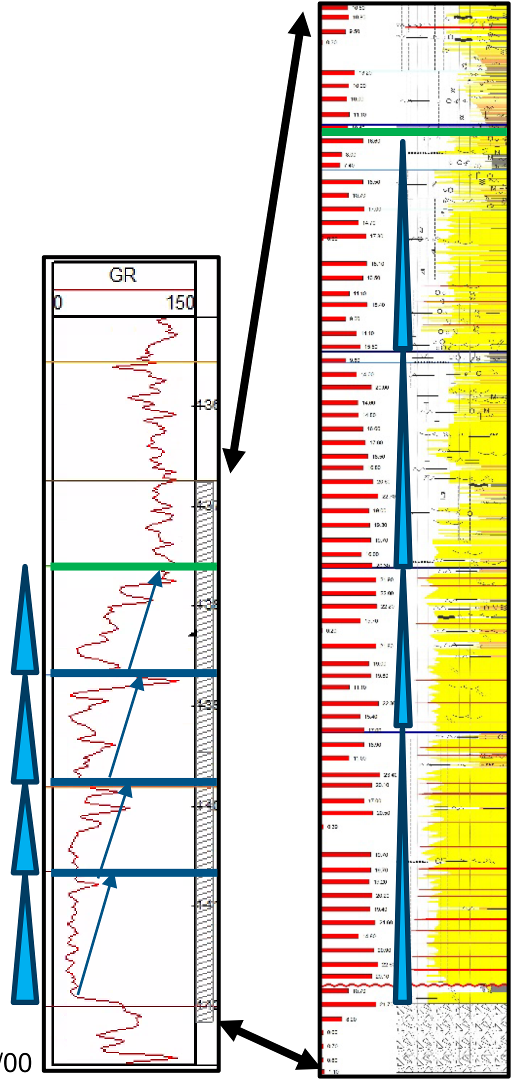
➢ 4 progressively transgressive cycles identified.

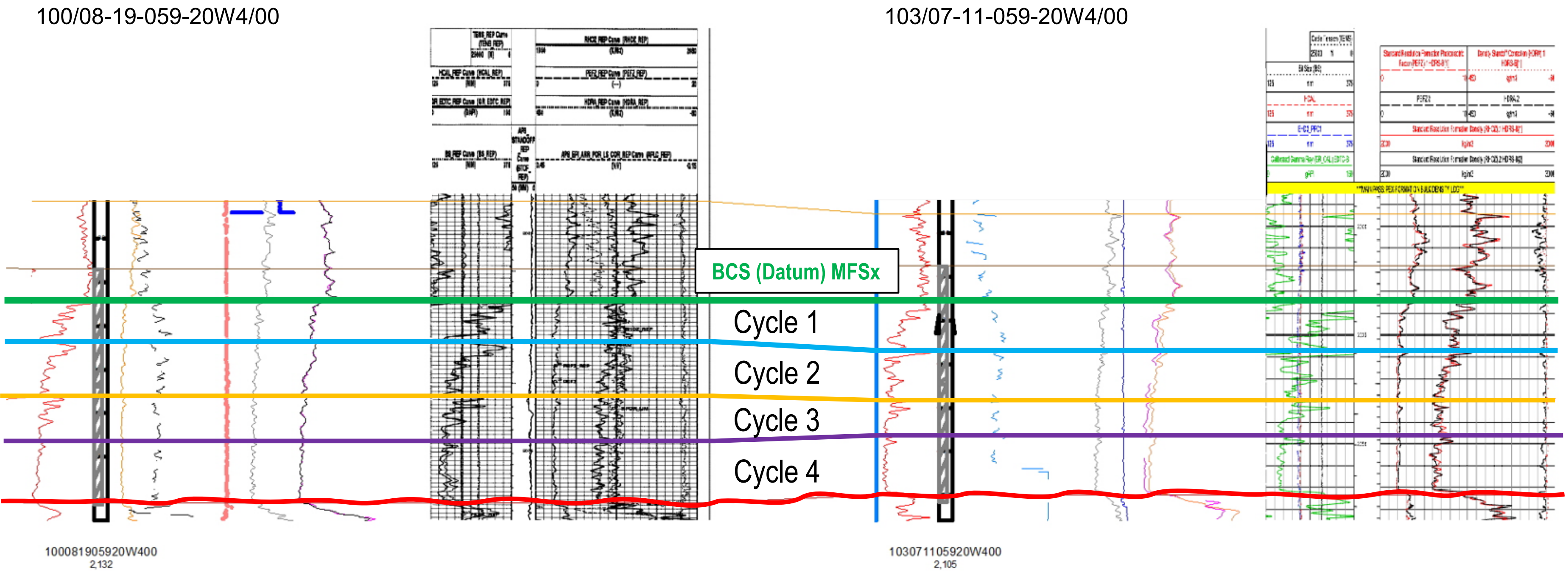
➢ BCS deposition terminated by a significant maximum flooding surface (MFSx).



103/07-11-059-20W4/00

Summary

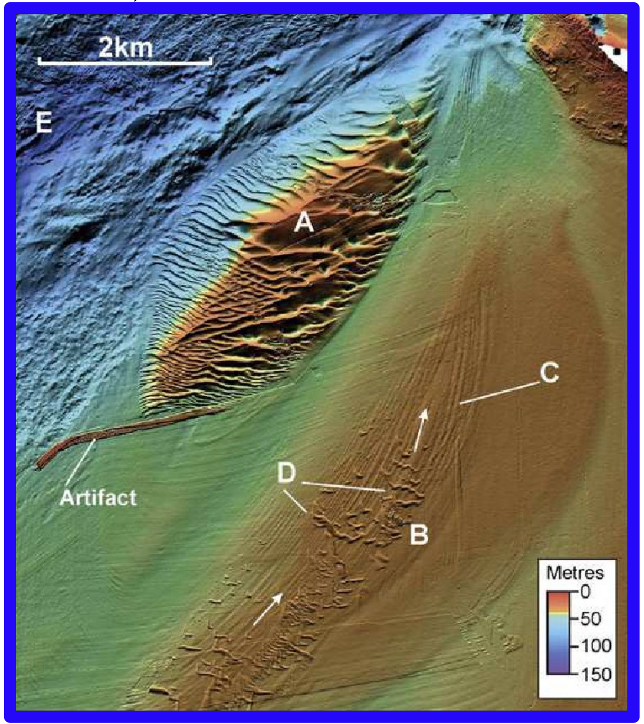
- Core tied to logs: surfaces are correlatable.

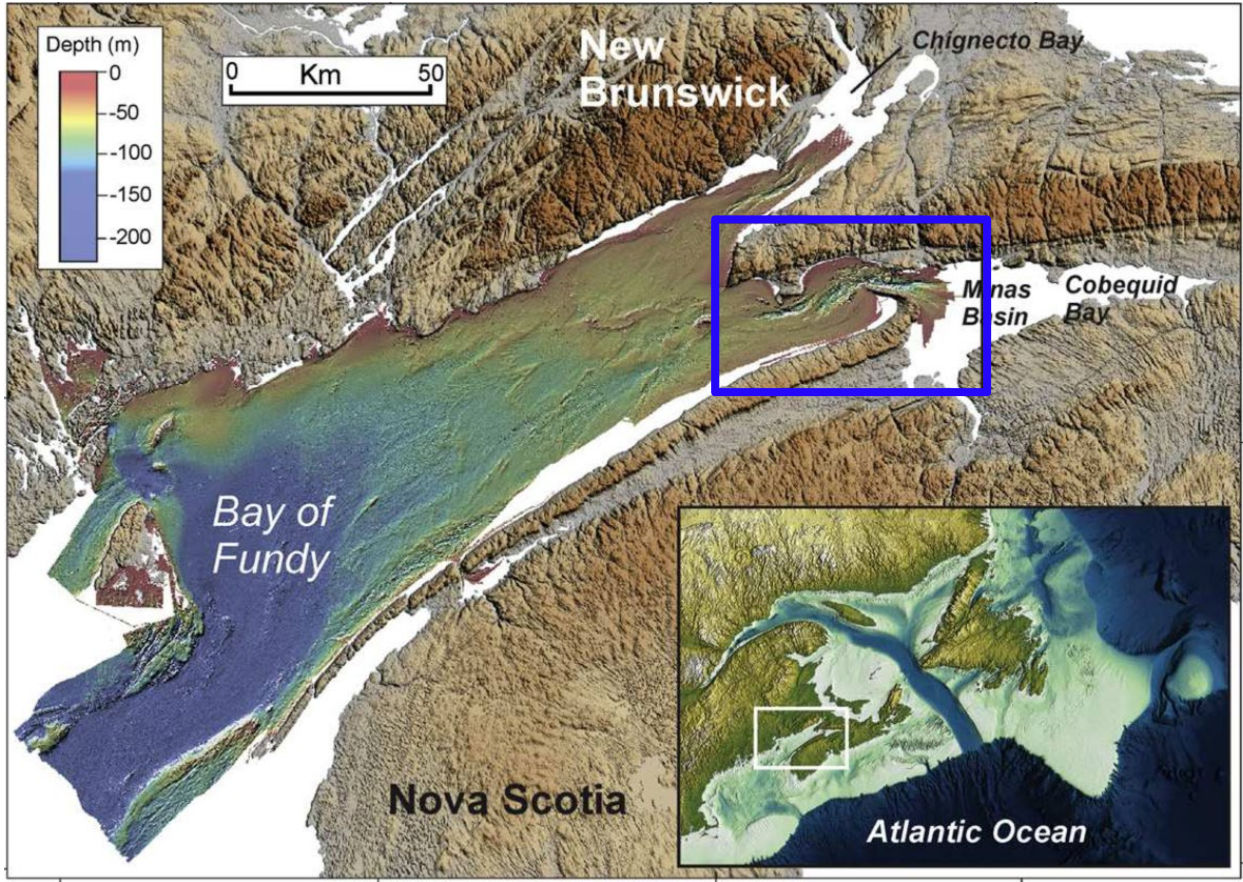


Exploration Model

- Bay of Fundy

Shaw *et al.*, 2012





Fluvio-Tidal Compound Dune Field

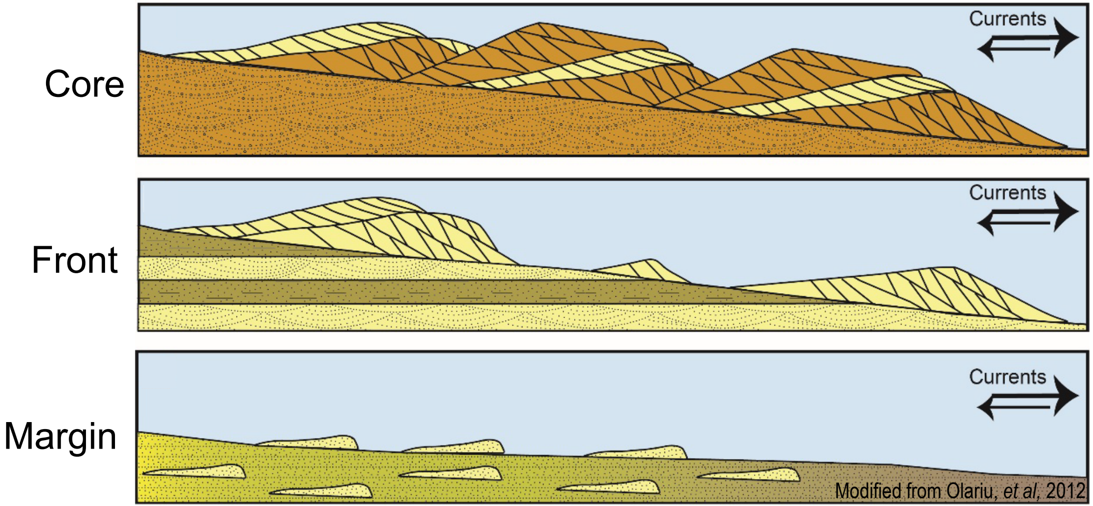
Proximal ⟵⟶ Distal

Net to Gross Sand Ratios (Winkler, 2011)

Core: ~0.97

Front: ~0.93

Margin: ~0.35-0.5



Outcrop: Cambrian Mount Clark Formation, Mackenzie Mountains, NWT

Inset Core Photos: Basal Cambrian Sandstone

Petrography and Mineralogy

- A slew of BCS cores (9) sampled for thin section, XRD, and PoroPerm plugs.
- Cores record burial depths from 1400m-3600m.
- 86 XRD Points
- 64 Thin Sections
- 600 PoroPerm Plugs

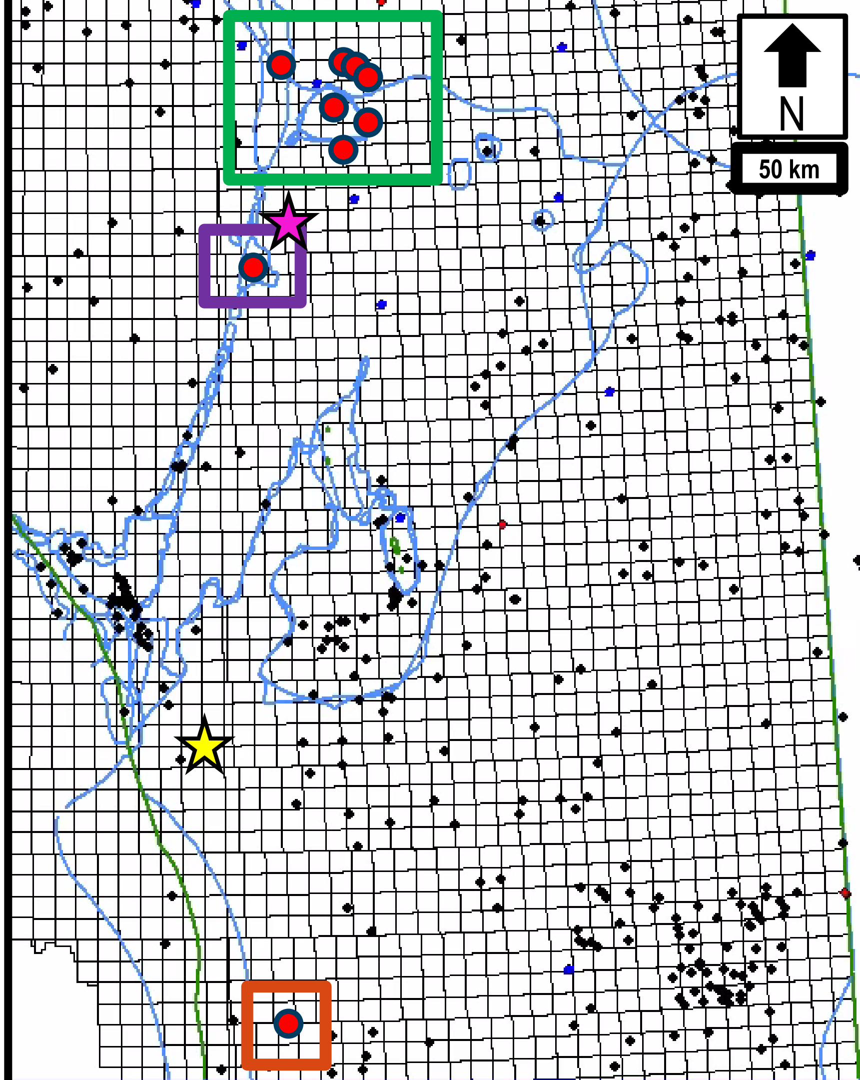
Industrial Heartland

Leduc Woodbend

Lethbridge Area

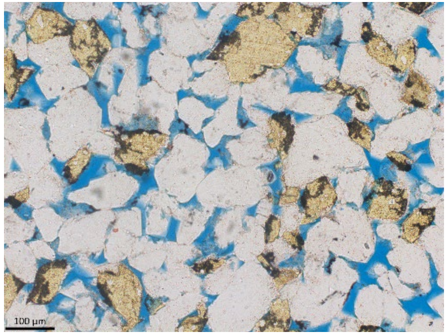
Edmonton

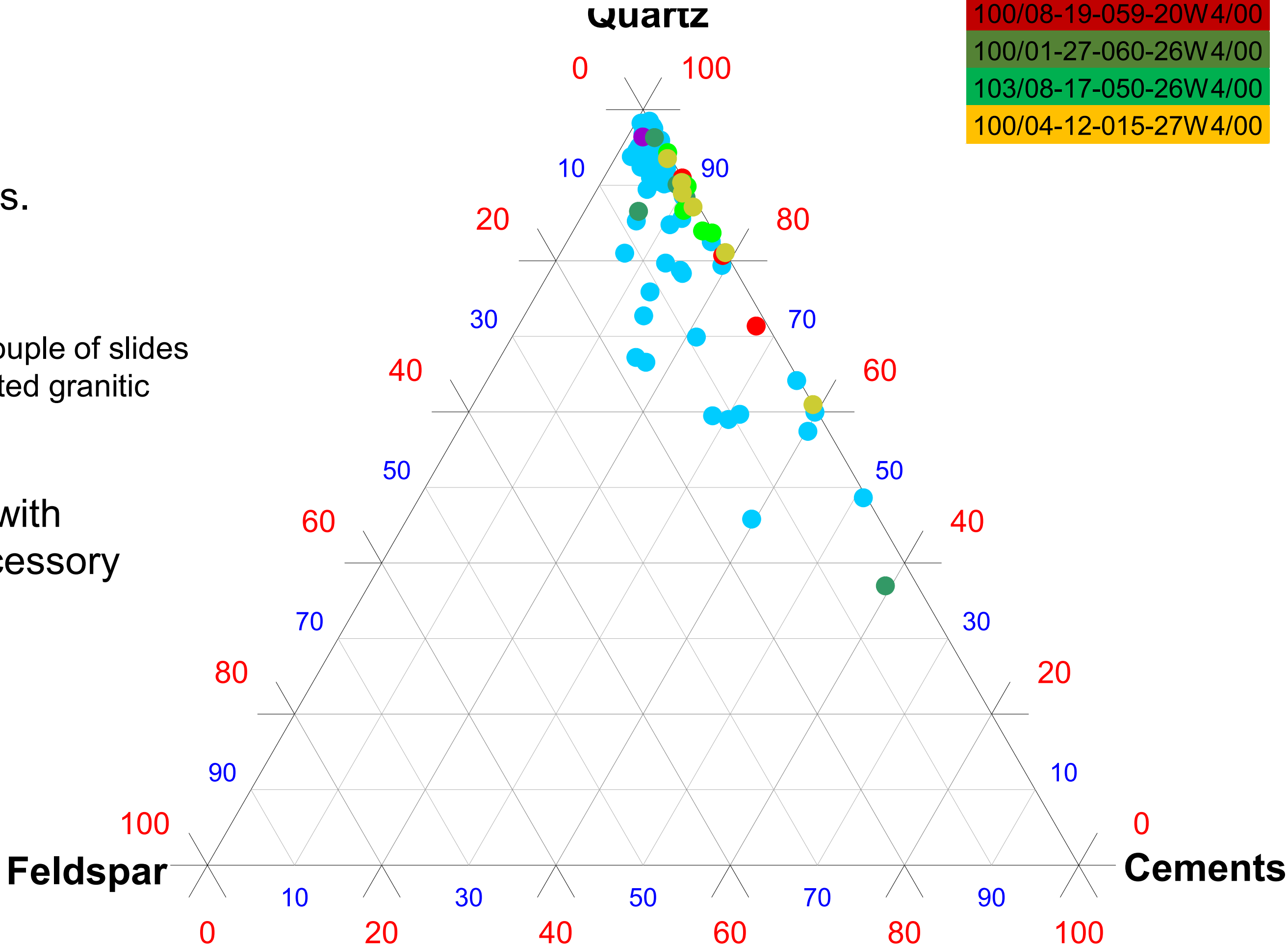
Calgary



XRD Results

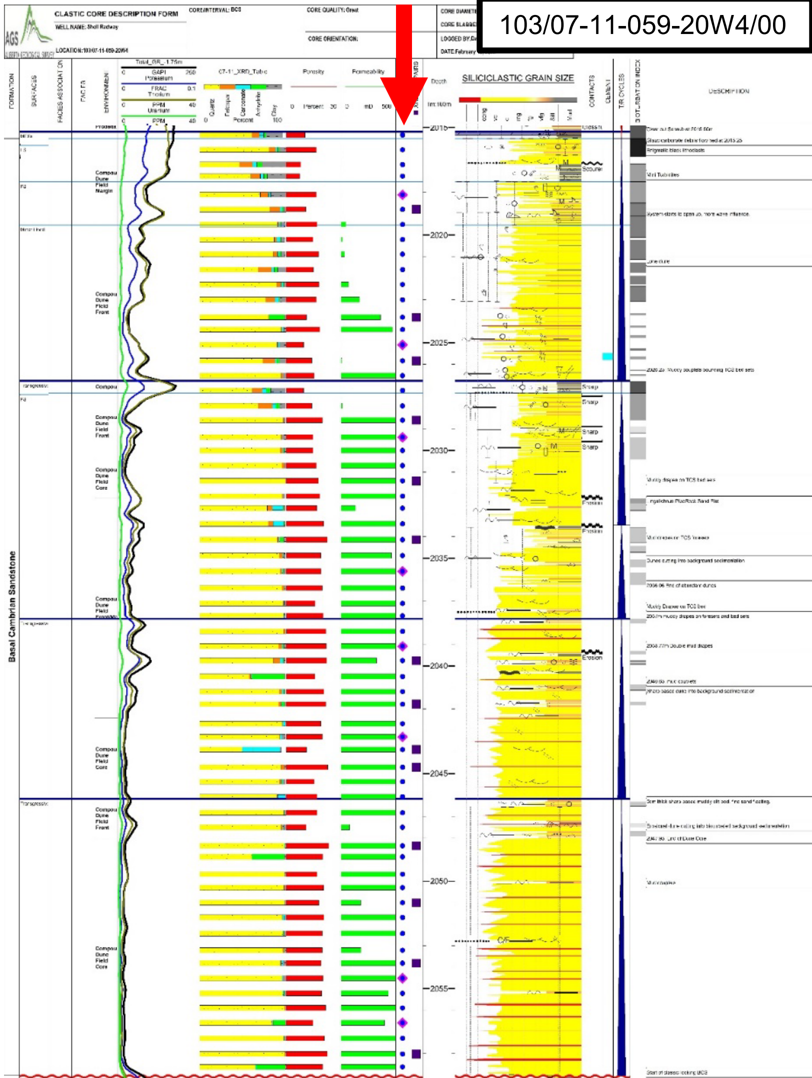
- 86 XRD samples from 6 cores.
- Why not QFL?
  - Lithics are very rare, only a couple of slides had tiny fragments of interpreted granitic basement material.
- BCS is dominated by quartz with potassium feldspar as an accessory mineral.





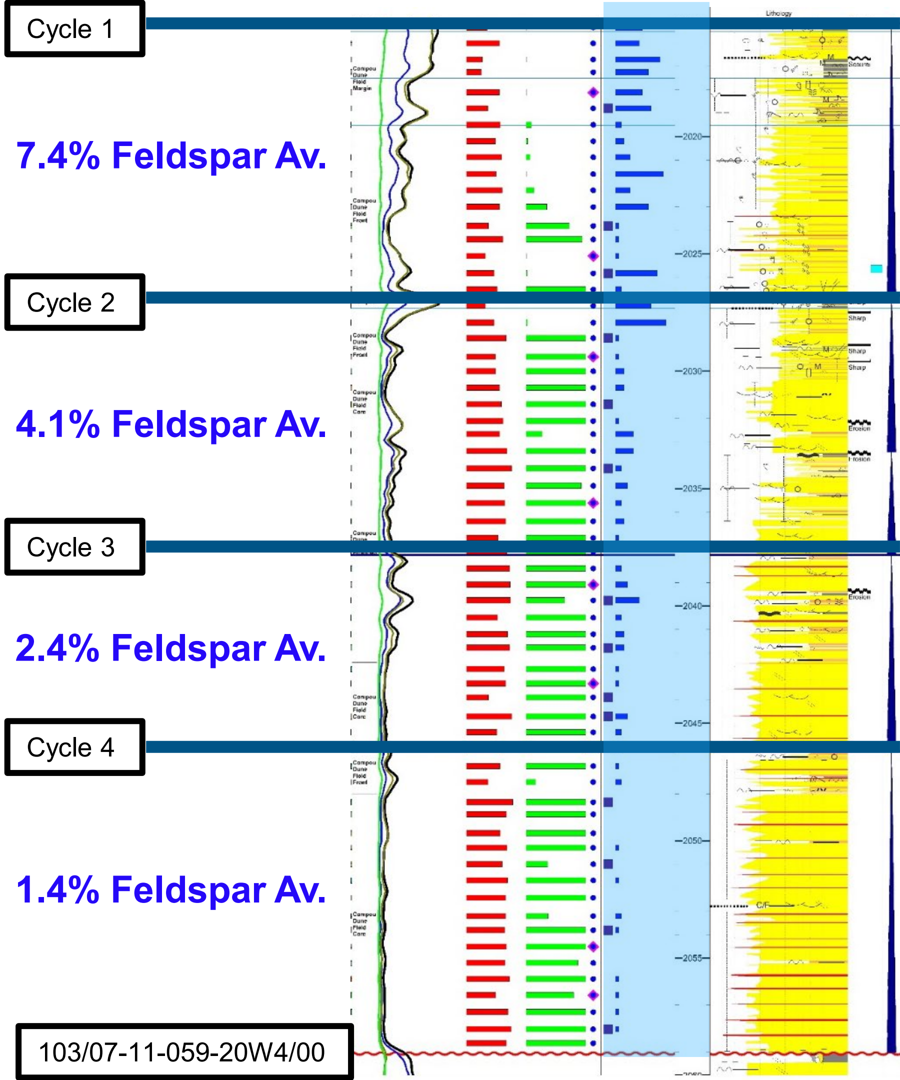
BCS Composition: 07-11 Case Study

- High-resolution XRD study on 07-11, active injection well at Quest.
- This is important because CCUS Hub modeling and forecasting will need to determine potential geochemical reactions with sequestered carbon.
- XRD samples taken on the original core analysis plugs at ~75cm spacing.
  - 62 XRD samples with thin sections spaced in.
  - This gives us a comprehensive mineralogical dataset that can be tied back to the original PoroPerm and grain density data.



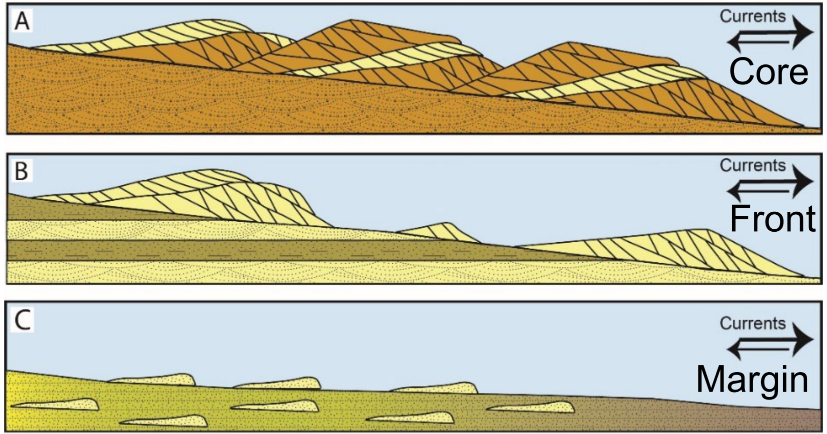
BCS Composition: 07-11 Case Study

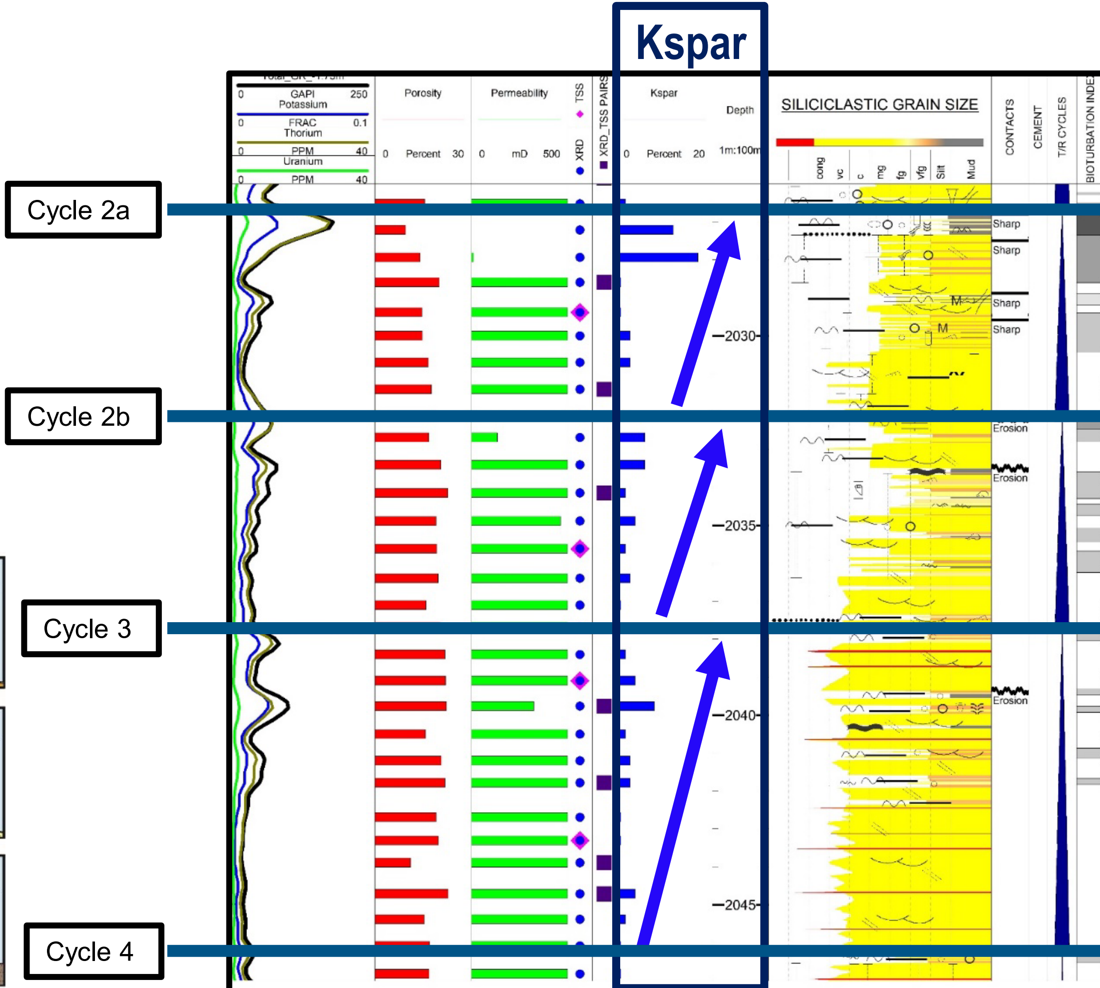
- Distinct mineralogical changes evident in the BCS.
  - BCS becomes more felspathic, less quartzose as we move up.
- Aligns with our progressively transgressive depositional cycles.
- Each transgressive cycle becomes increasingly feldspathic and less quartzose.
- The proximal compound dune core environments contain very little feldspar, too energetic, feldspar isn't as competent as quartz.



BCS Composition: 07-11 Case Study

- Feldspar aligns with smaller scale depositional cycles as well, marking the shifts from dune field core-front-margin environments.

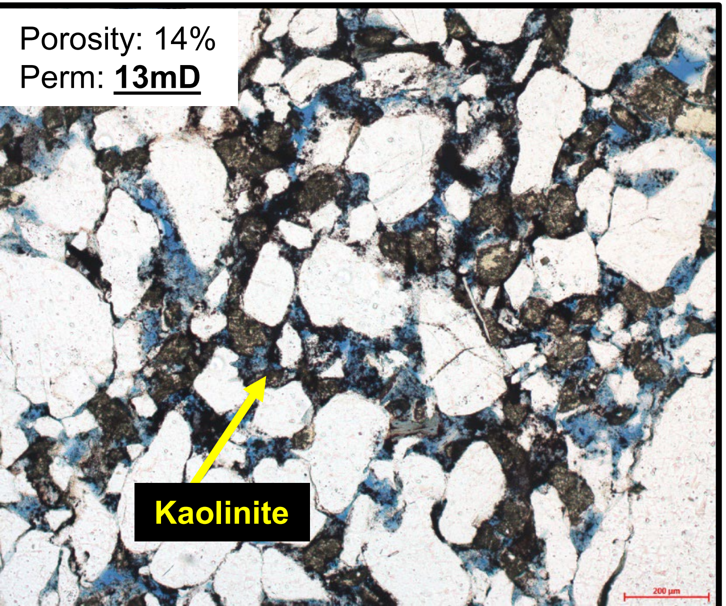


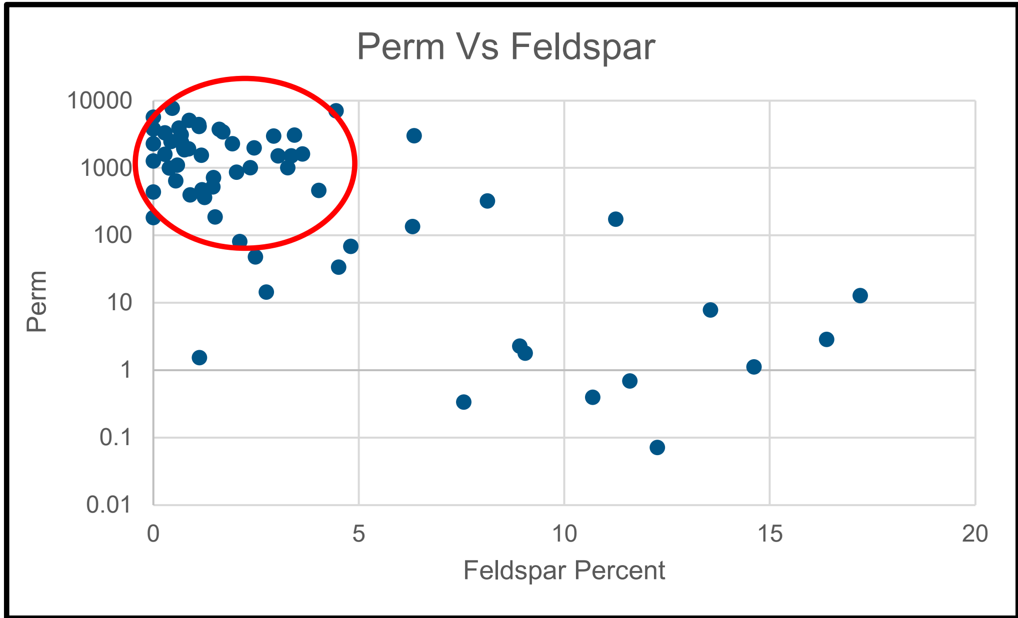


Conclusions: Mineralogy

- Potassium feldspar can significantly degrade the PoroPorm system through alteration to Kaolinite clay.
  - This clay plugs up the pore throats and coats quartz grains.

103/11-32-055-21W4/00: 2192.68m





Burial Diagenesis

- What happens to the BCS as we bury it?
- 3 cores: ●
  - 103/07-11-059-20W4, Quest, ~2000m
  - 103/08-17-050-26W4, Leduc Area, ~2700m
  - 100/04/12-015-27W4, Lethbridge , ~3600m

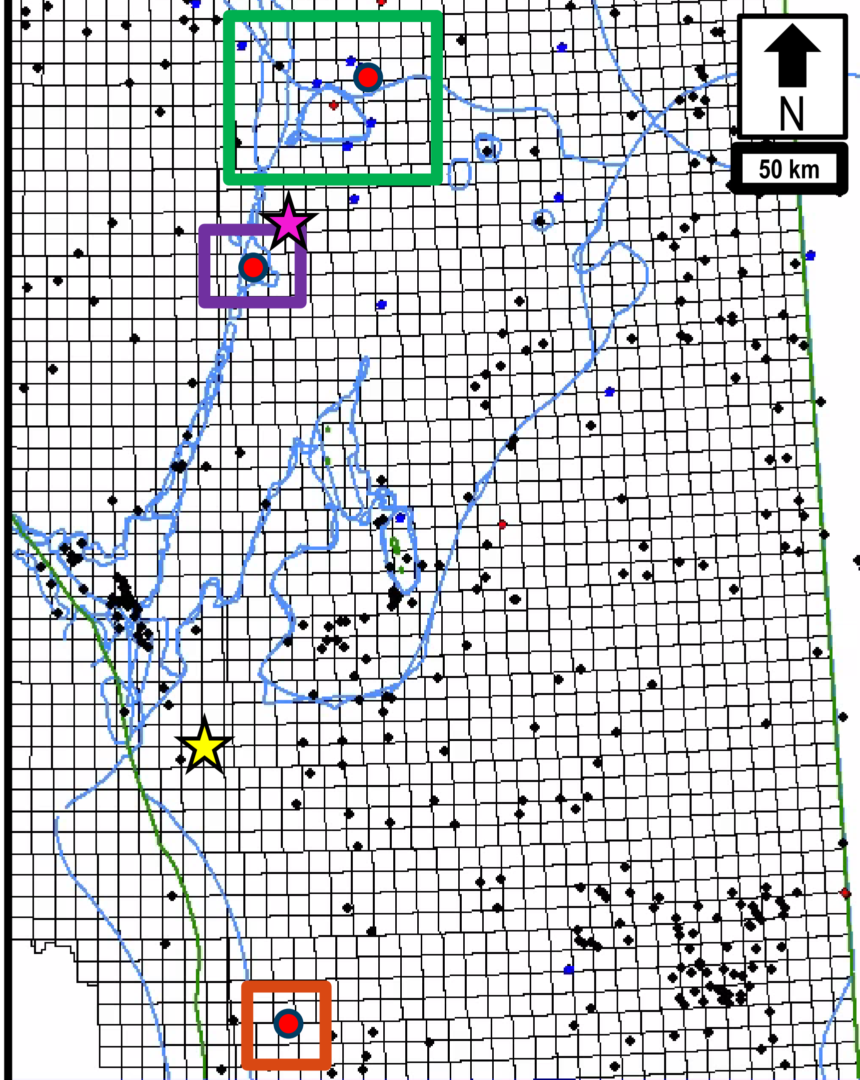
Quest

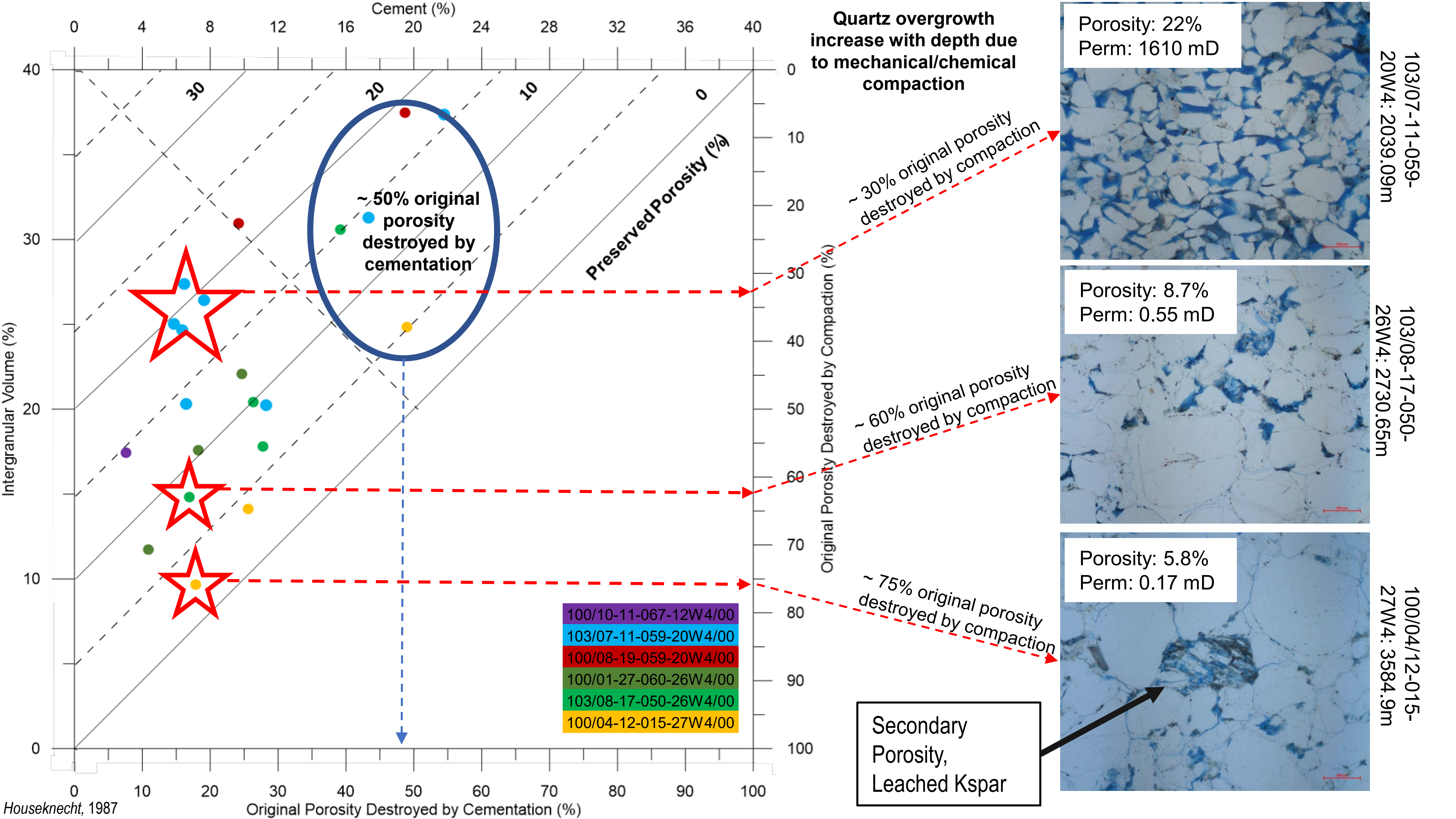
Leduc Woodbend

Lethbridge Area

★ Edmonton

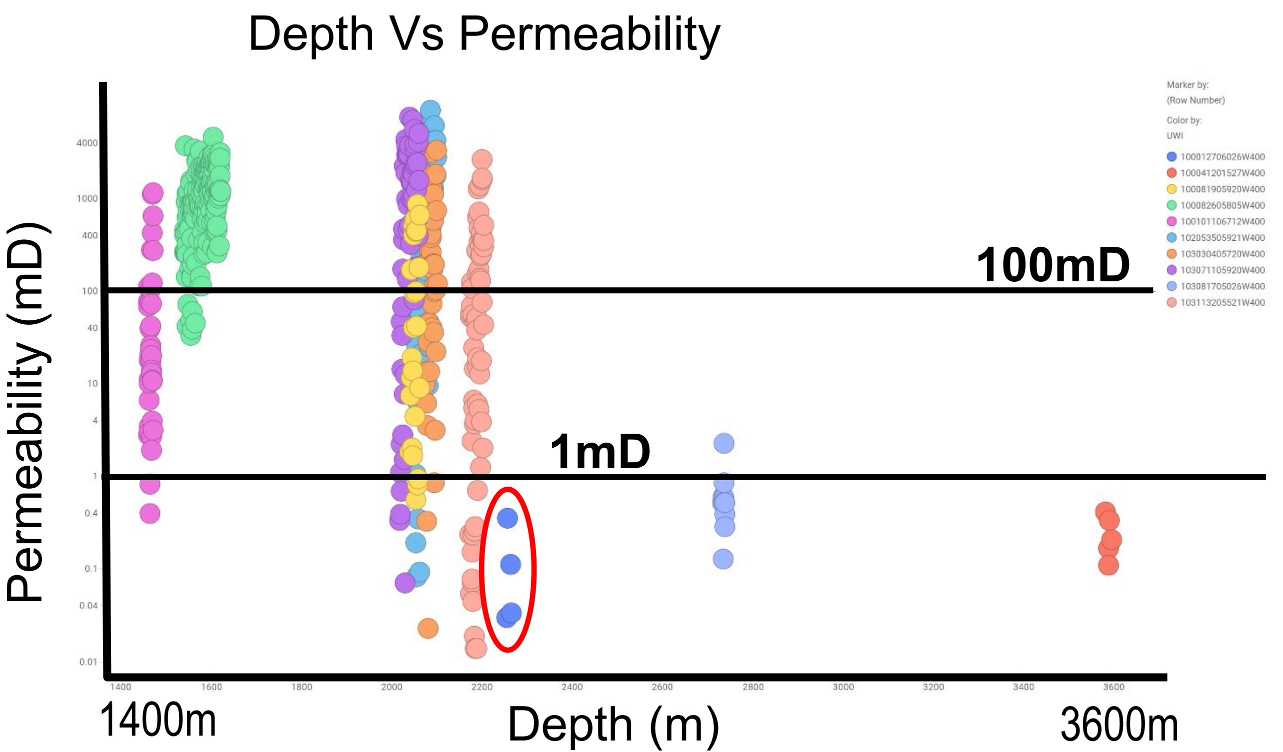
★ Calgary



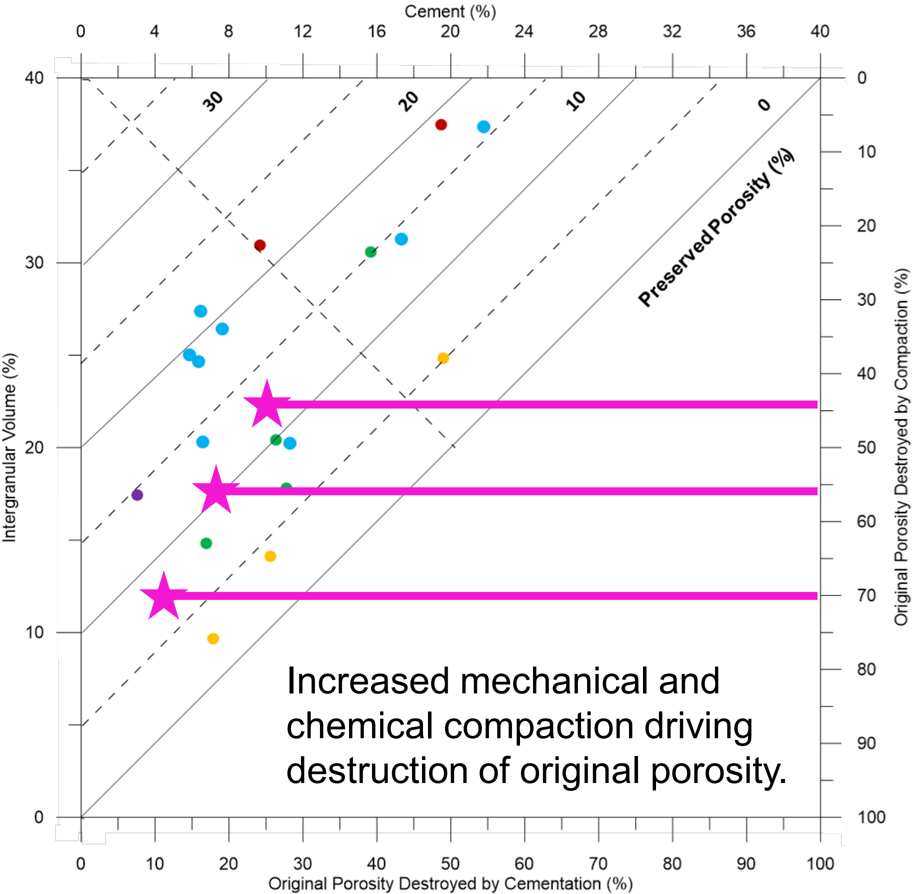

Cement (%)
0
4
8
12
16
20
24
28
32
36
40
30
20
10
0
Preserved Porosity (%)
~ 50% original porosity destroyed by cementation
Intergranular Volume (%)
40
30
20
10
0
Original Porosity Destroyed by Compaction (%)
0
10
20
30
40
50
60
70
80
90
100
Original Porosity Destroyed by Cementation (%)
0
10
20
30
40
50
60
70
80
90
100
Houseknecht, 1987
100/10-11-067-12W4/00
103/07-11-059-20W4/00
100/08-19-059-20W4/00
100/01-27-060-26W4/00
103/08-17-050-26W4/00
100/04-12-015-27W4/00
Quartz overgrowth increase with depth due to mechanical/chemical compaction
~ 30% original porosity destroyed by compaction
~ 60% original porosity destroyed by compaction
~ 75% original porosity destroyed by compaction
Porosity: 22%
Perm: 1610 mD
103/07-11-059-20W4: 2039.09m
Porosity: 8.7%
Perm: 0.55 mD
103/08-17-050-26W4: 2730.65m
Porosity: 5.8%
Perm: 0.17 mD
100/04/12-015-27W4: 3584.9m
Secondary Porosity, Leached Kspar

Petrography and Mineralogy

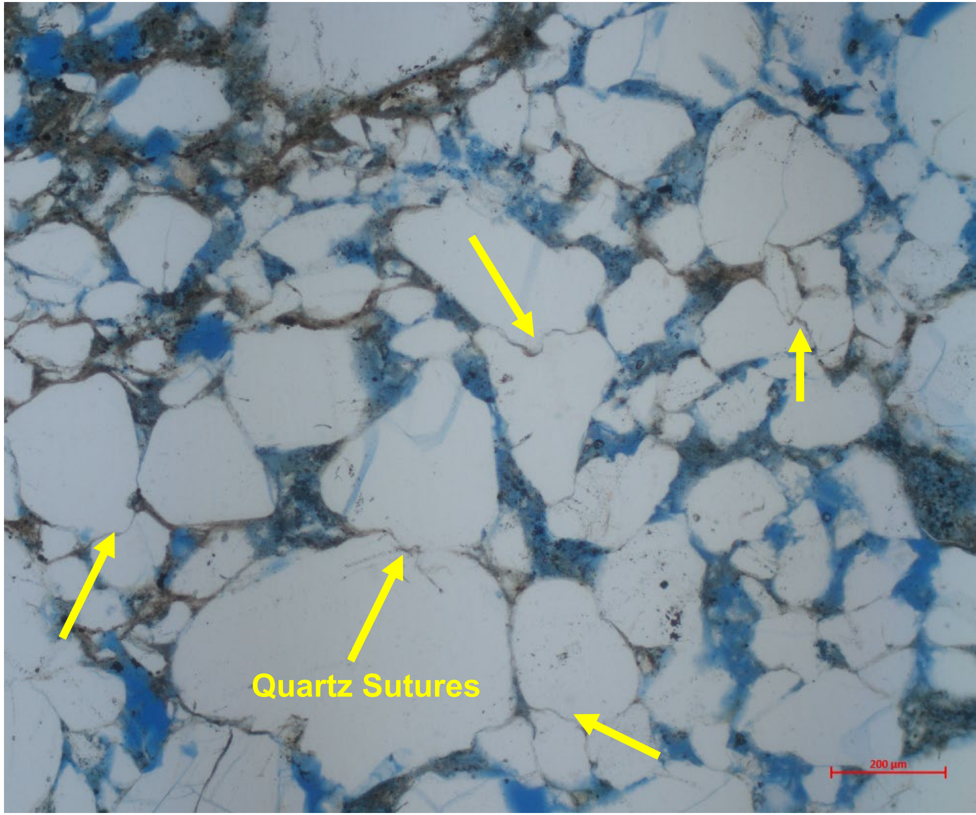
- 01-27-060-26W4 shows significant destruction of PoroPerm system at ~2250m.
- 3 orders of magnitude reduction in permeability, <1mD.
- What is driving this?



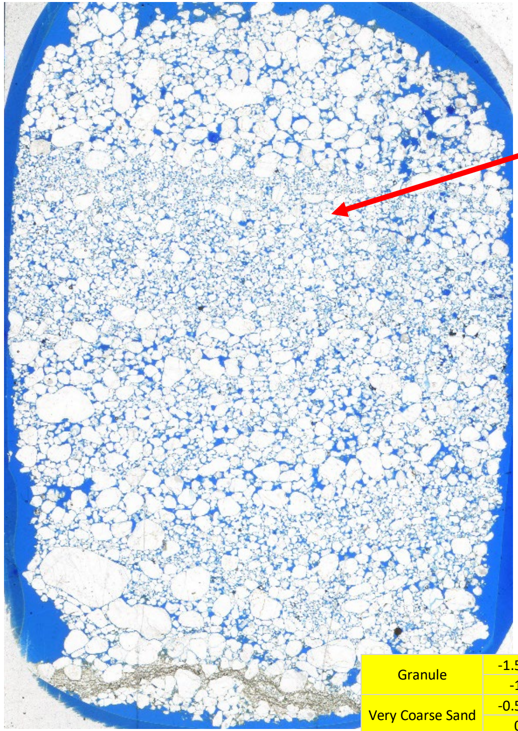
Petrography and Mineralogy



01-27-060-26W4. 2252.9m, 10x



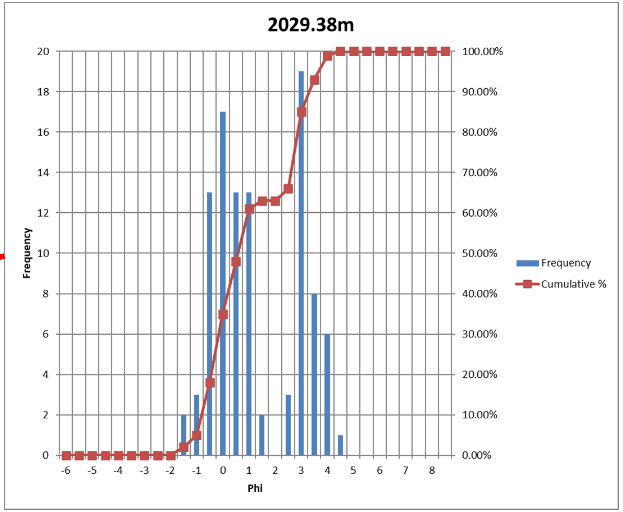
07-11-059-20W4
2029.38m

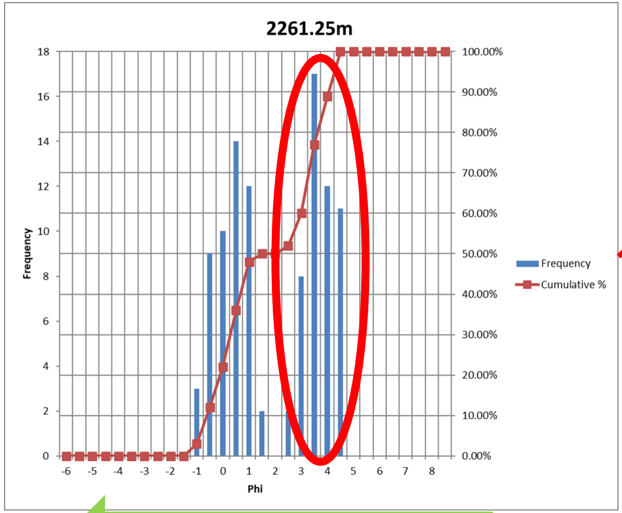


Thin Section Overview

Porosity = 14.6%
Permeability = 1930 mD
5% Clay

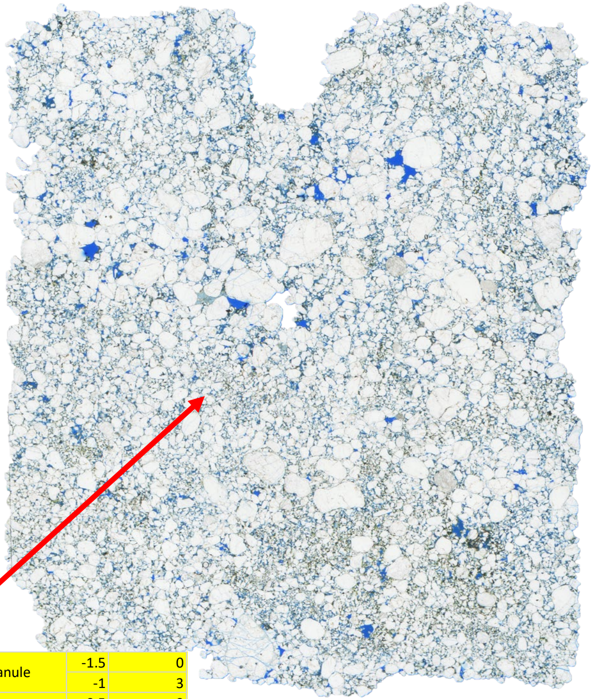
Granule	-1.5	2
	-1	3
Very Coarse Sand	-0.5	13
	0	17
Coarse Sand	0.5	13
	1	13
Medium Sand	1.5	2
	2	0
Fine Sand	2.5	3
	3	19
Very Fine Sand	3.5	8
	4	6
Coarse Silt	4.5	1
	5	0





Coarser Grained

01-27-060-26W4
2261.25m

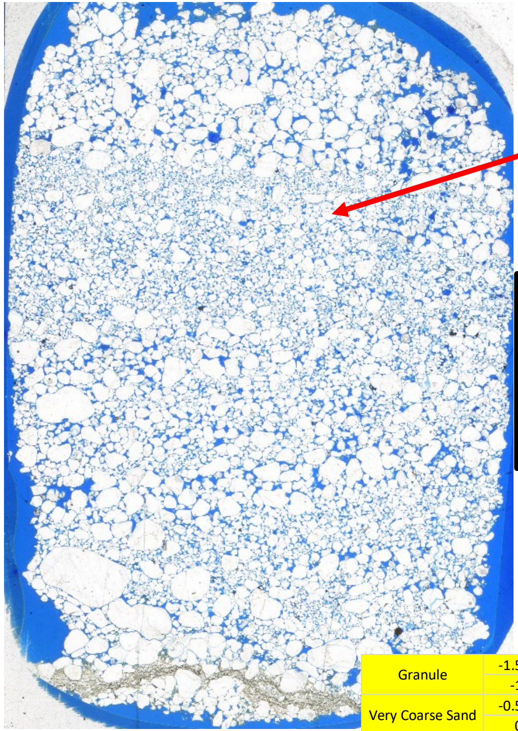


Granule	-1.5	0
	-1	3
Very Coarse Sand	-0.5	9
	0	10
Coarse Sand	0.5	14
	1	12
Medium Sand	1.5	2
	2	0
Fine Sand	2.5	2
	3	8
Very Fine Sand	3.5	17
	4	12
Coarse Silt	4.5	11
	5	0

Thin Section Overview

Porosity = 13.0%
Permeability = 0.11 mD
8% Clay

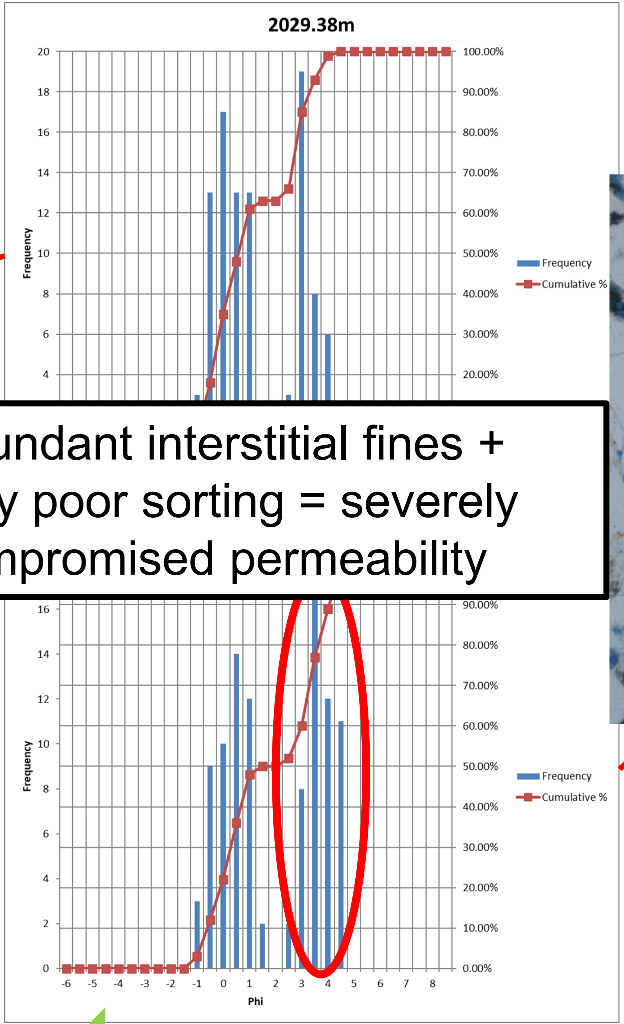
07-11-059-20W4
2029.38m



Thin Section Overview

Porosity = 14.6%
Permeability = 1930 mD
5% Clay

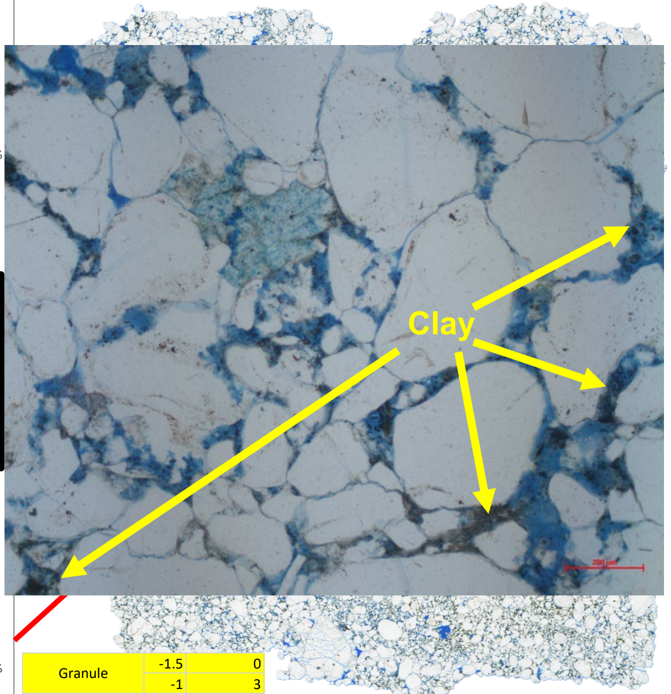
Granule	-1.5	2
	-1	3
Very Coarse Sand	-0.5	13
	0	17
Coarse Sand	0.5	13
	1	13
Medium Sand	1.5	2
	2	0
Fine Sand	2.5	3
	3	19
Very Fine Sand	3.5	8
	4	6
Coarse Silt	4.5	1
	5	0



Abundant interstitial fines + very poor sorting = severely compromised permeability

Coarser Grained

01-27-060-26W4
2261.25m



Granule	-1.5	0
	-1	3
Very Coarse Sand	-0.5	9
	0	10
Coarse Sand	0.5	14
	1	12
Medium Sand	1.5	2
	2	0
Fine Sand	2.5	2
	3	8
Very Fine Sand	3.5	17
	4	12
Coarse Silt	4.5	11
	5	0

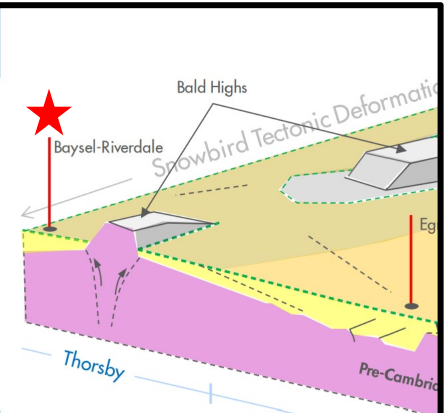
Thin Section Overview

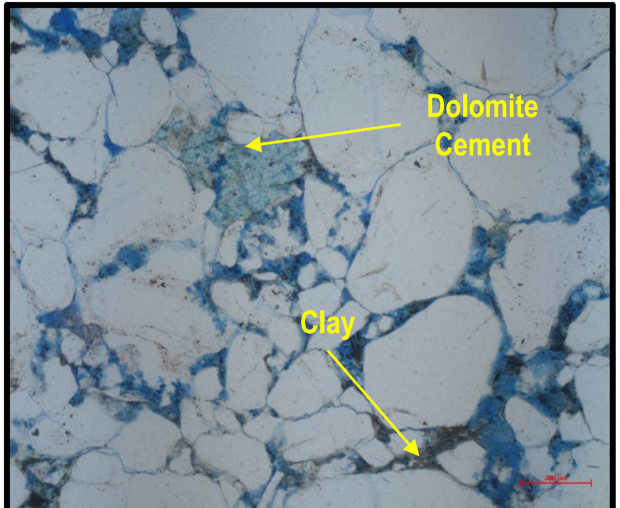
Porosity = 13.0%
Permeability = 0.11 mD
8% Clay

Conclusions: Sorting and Perm

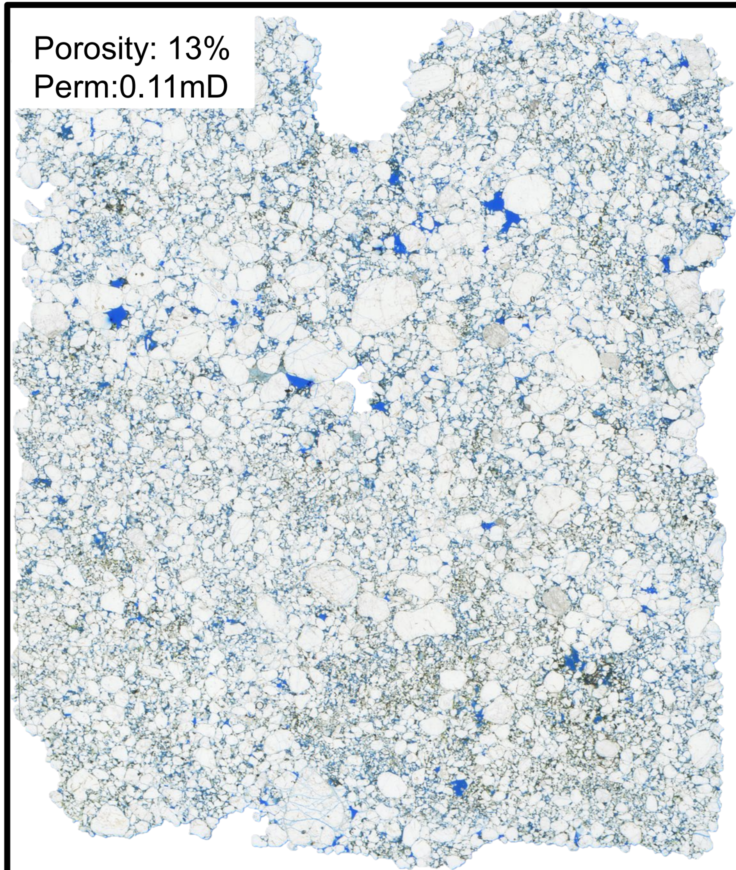
- BCS deposited near syn-depositional basement highs has an elevated risk of permeability destruction due to elevated clays and fines in conjunction with very poor sorting.
  - "Sucker Sand": porosity is excellent, however tortuosity is very high and pore throats are plugged up with fines.

This won't show up on density logs



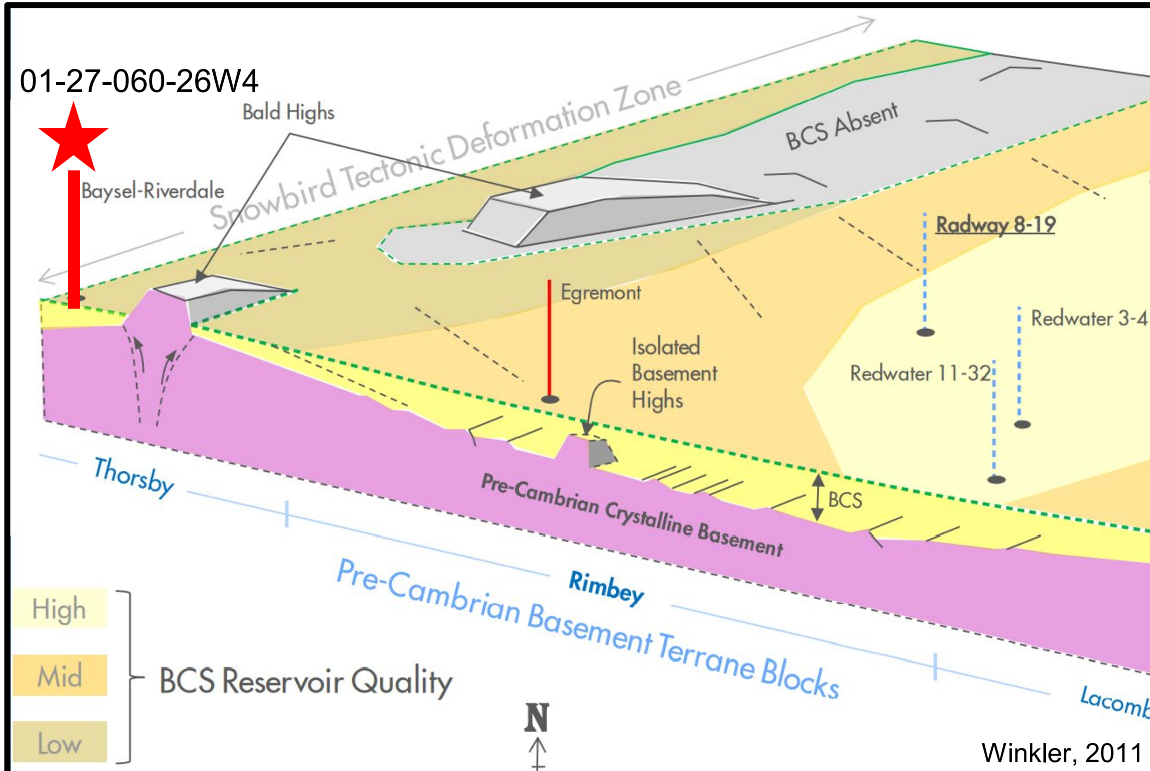


01-27-060-26W4 2261.25m



Petrography Tied to Exploration

- 01-27 happens to be deposited very close to the Snowbird Tectonic Zone, an interpreted paleo-high during BCS deposition.
- Extremely coarse-grained with very poor sorting and an abundance of interstitial fines.
- Interpreted to record deposition closer to the fan deltas interpreted to be supplying sediment to the coast.
- We are out of the "tidal fairway" that is cleaning and winnowing sand.

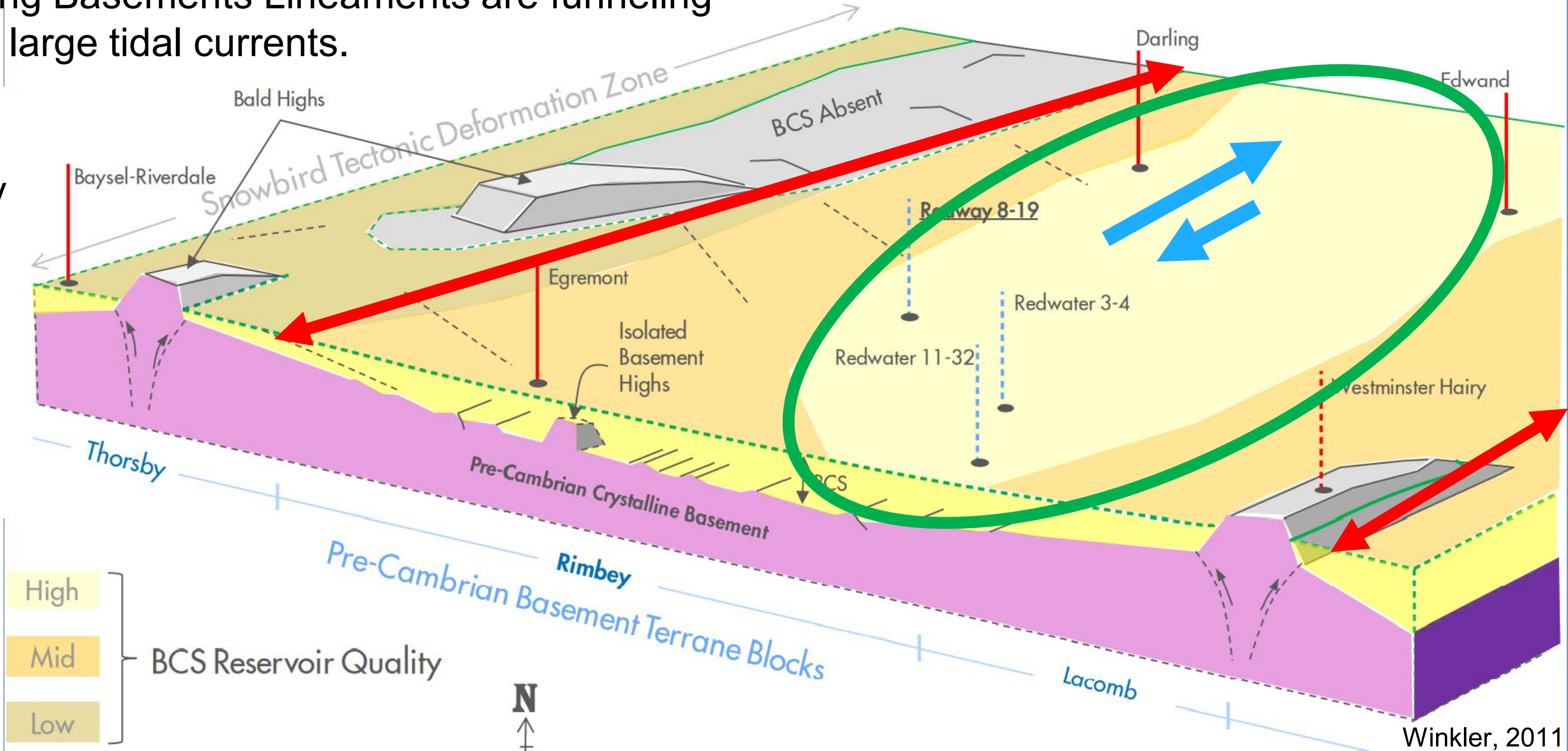


Winkler, 2011

Exploration Model

- SW-NE Trending Basements Lineaments are funneling and amplifying large tidal currents.

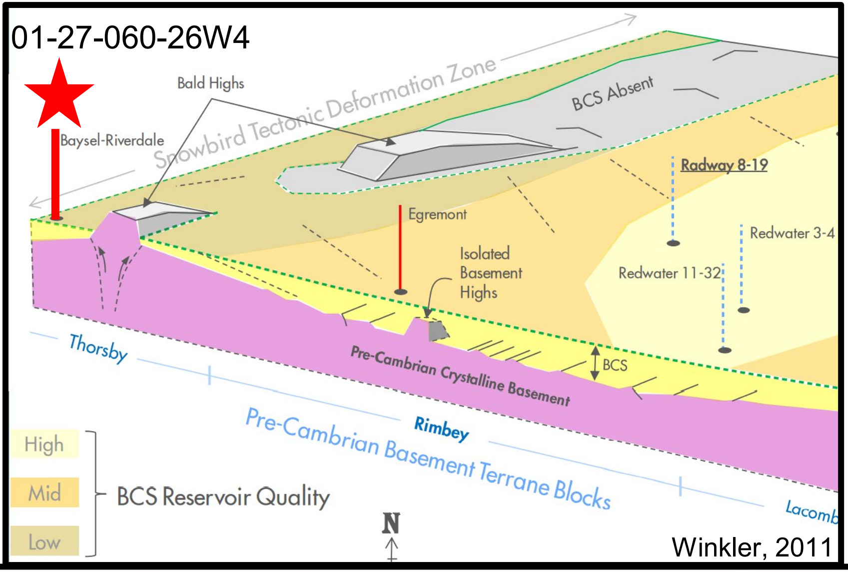
- Develop a sandy fairway where the interstitial fines are sorted out and the feldspar is broken down.



Winkler, 2011

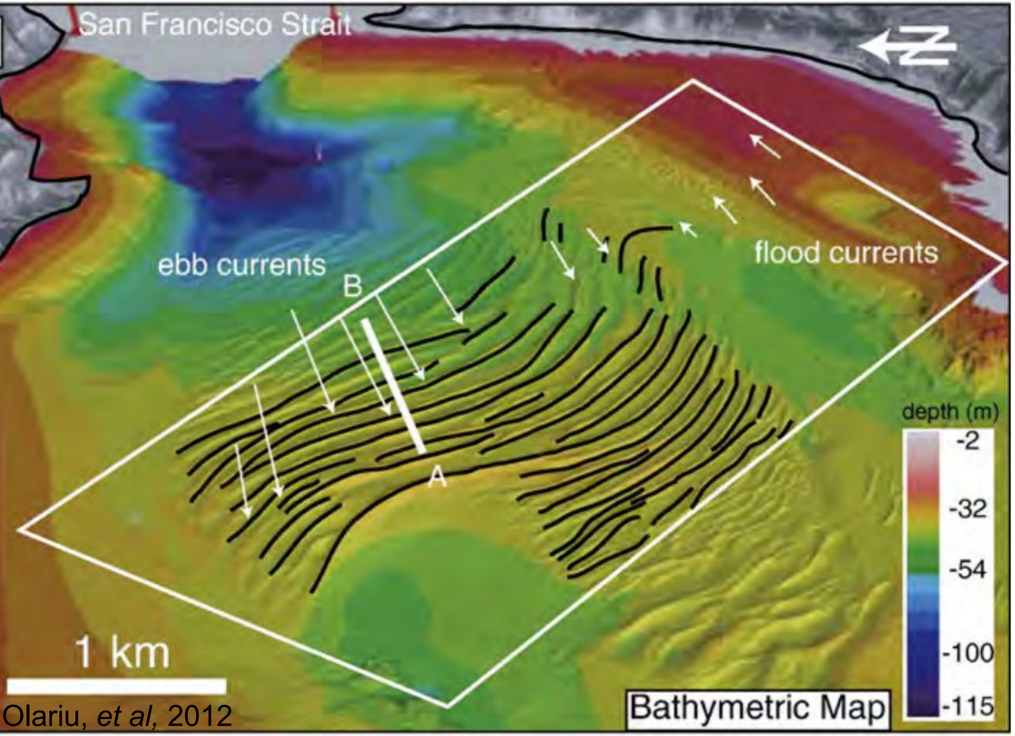
Exploration Model

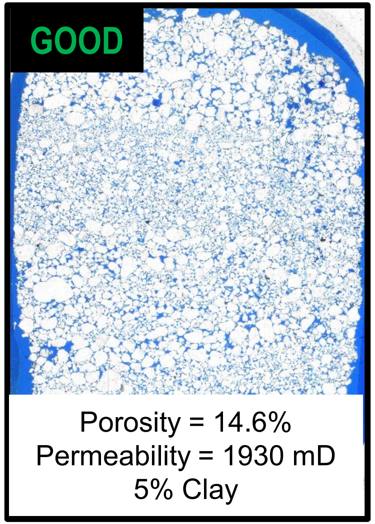
- You're after the "Goldilocks Zone", not too proximal, not too distal, just right.
- Too proximal? You're at 01-27, close to fluvially derived braid mouth bars.
  - Lots of Feldspar and interstitial fines, which degrade permeability.
- Too distal?
  - You're introducing bioturbated lithosomes into the system with a much higher percentage of fines and feldspar.
- You want the depositional environment that is closest to the sediment source while still being actively washed and winnowed by tidal forces.
  - Compound Dune Field Core and Proximal Front.

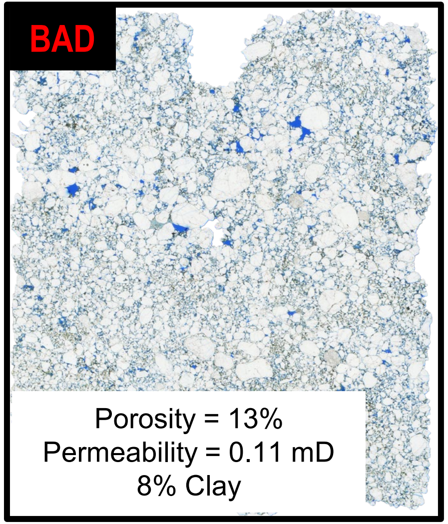


Exploration Model

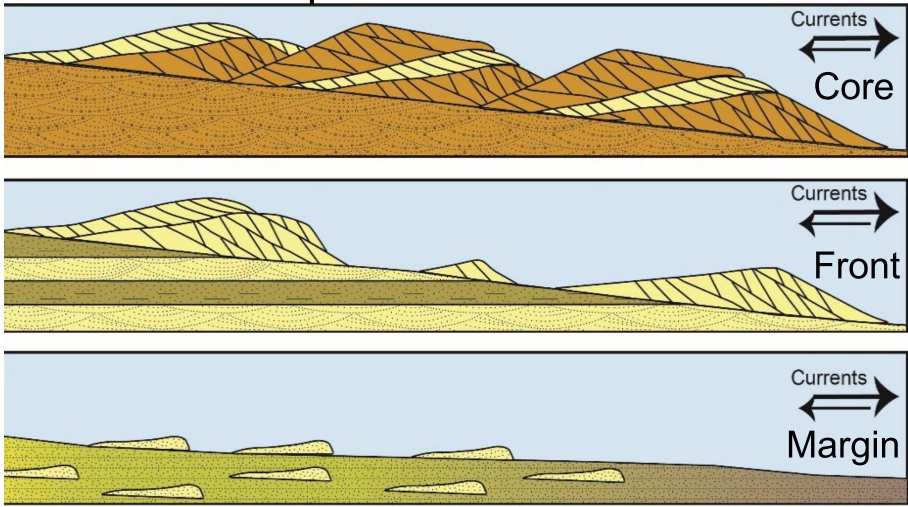
- San Francisco Strait







Tidal Compound Dune Field Model



Take Home Points

- BCS becomes more feldspathic you move up, directly related to the facies and environment encountered.
- Feldspar has a negative effect on PoroPerm through the degradation into Kaolinite clay.
- Spectral gamma logs are worth running on new appraisal wells
- Sorting and grain size matter.
  - Very poor sorting can have great PoroPerm.
  - Very poor sorting with abundant interstitial fines destroys perm.
- It’s not just sorting, it’s what is being sorted.
- Compaction and associated quartz overgrowths become significant around ~2300m depth, PoroPerm begins to significantly degrade.

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Questions, concerns, comments?

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