Hugh Abercrombie and Ken Baxter

# Saline Inflows, Biodegradation and Gas Generation in the Basal Water Sand Aquifer, Athabasca Oil Sands Region, Alberta

WATERtech2012

Golder Associates

# Outline

- Introduction
- Geology
- Hydrogeology
- Geochemistry
- Industrial Significance
  - Biodegradation
  - Gas Generation
  - Saline Inflows
- Summary

Archives, Government of Canada

# Key Messages – Basal Water Sand (BWS)

## Geology

- Deposited on a highly dissected erosion surface cut into a limestone karst terrain; distribution influenced by both pre- and post-depositional structure

## Hydrogeology

- Regional recharge of the BWS east and west of the Athabasca River
- Regional discharge along the Athabasca River where the BWS experiences upward flow of basinal Devonian brines

## Geochemistry

- The BWS occurs within the interface between:
  - A hypersaline, oxidized Paleozoic geochemical network, and
  - A fresh to brackish, reducing Mesozoic geochemical network
- In the discharge region, secondary minerals record vertical movement and progressive reduction of oxidized saline brines

# Significance to Industry

**Oil sands mining**

- Saline inflows
- BWS depressuring
- On-site water storage / transfer

**In situ**

- Brackish groundwater resource
- Potential thief zone

**Geochemical Processes**

- A locus for water-rock-microbial interactions:
  - Reduced bitumen saturations
  - Biodegradation in discharge (upflow) areas
  - $H_2S$ generation associated with biodegradation

# Basal Water Sand

## Oil Sand

## Basal Water Sand

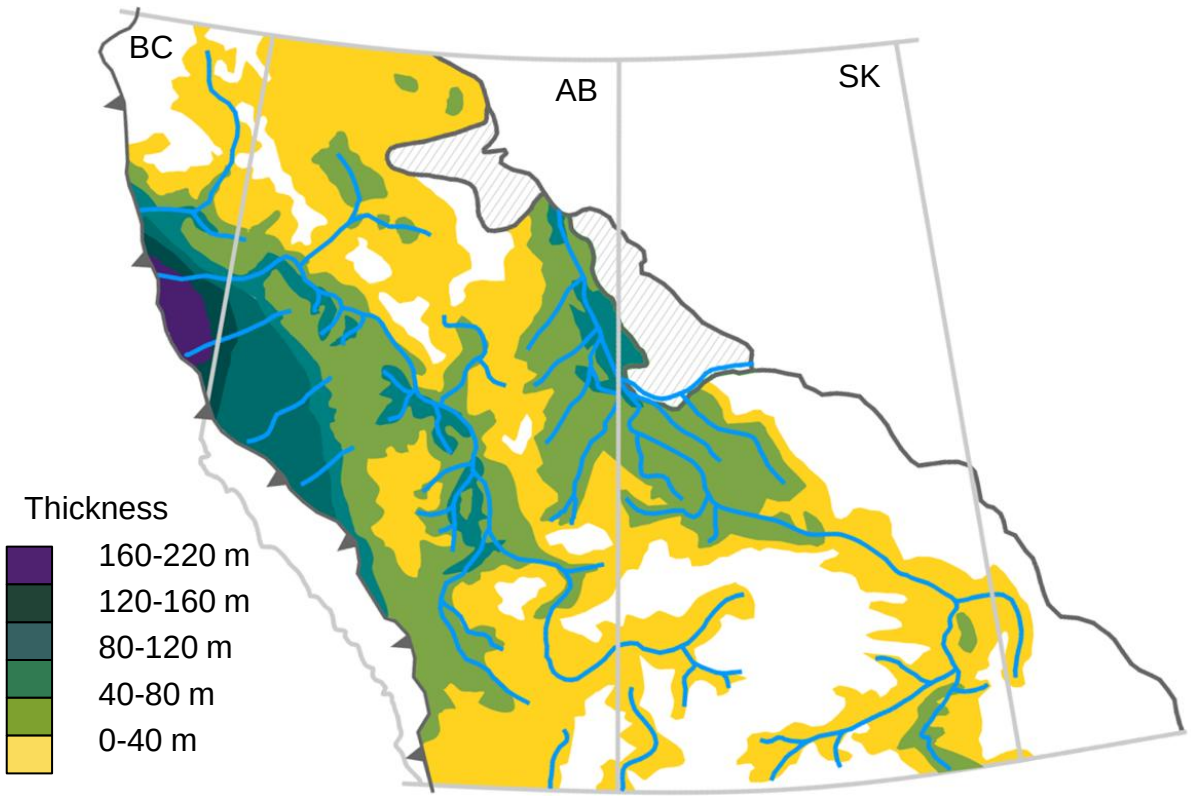
# Location

- Basal Water Sand (BWS) aquifer located in the surface mineable oil sands area
- The BWS may or may not be present in the Athabasca south region and other areas


Government of Alberta

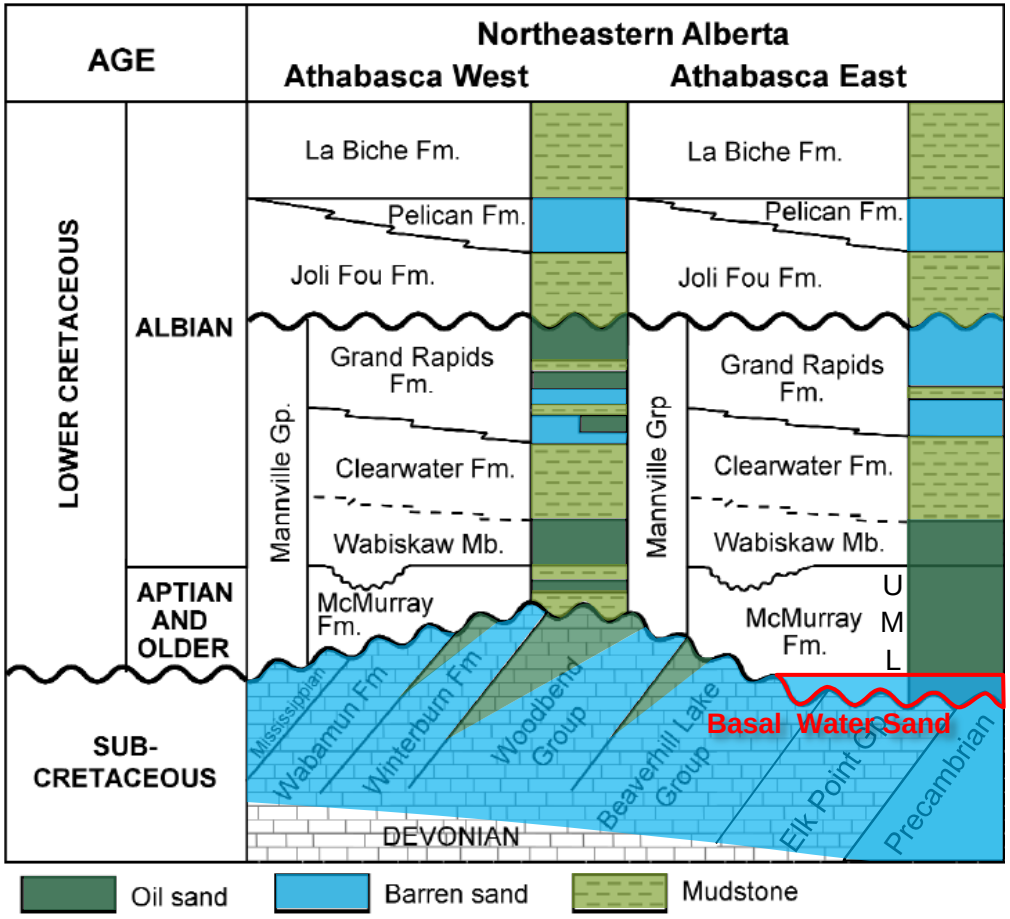
# Lower Mannville Isopach

- LMnv deposition controlled by salt dissolution (east) and flexural subsidence (west)
- LMnv in NE Alberta includes Basal Water Sands deposited in N prograding delta
- LMnv sediments predominantly supermature quartz derived from the Precambrian Shield



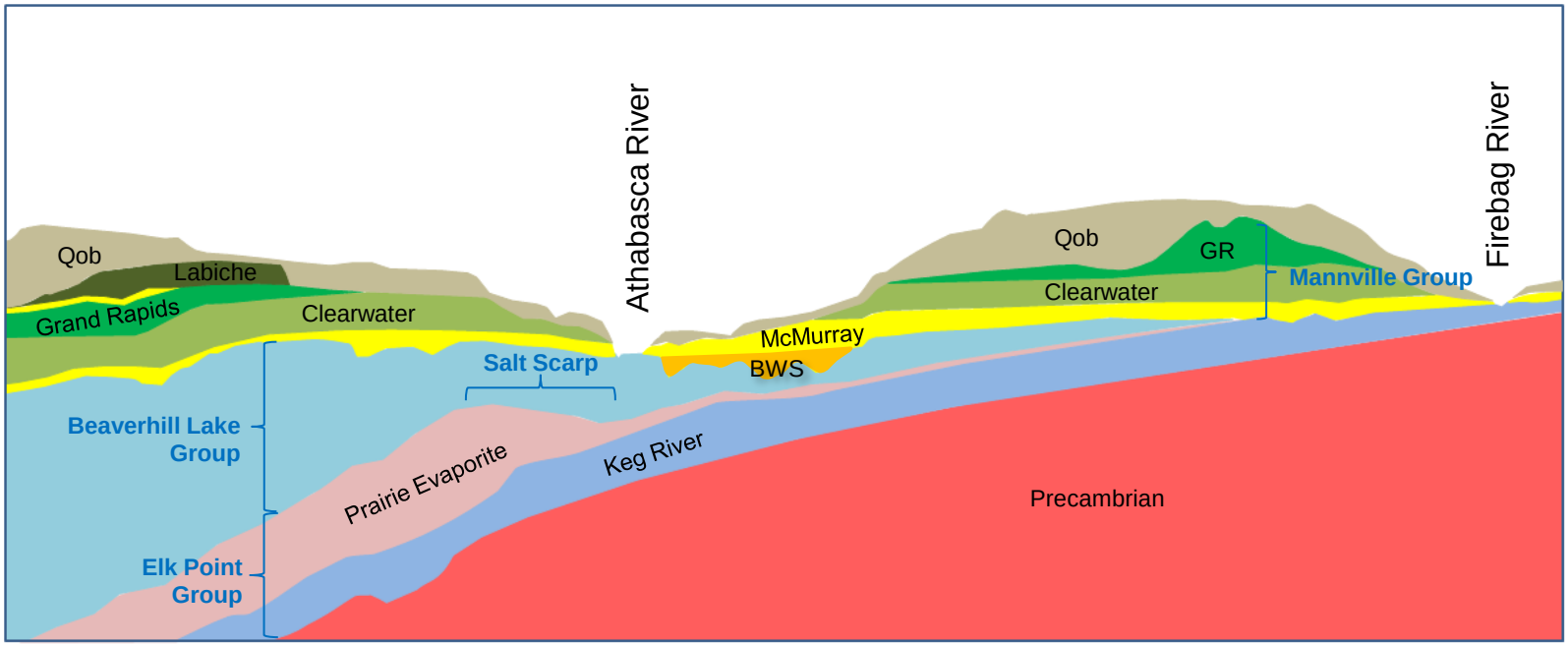

After Cant and Abrahamson (1996)

# Stratigraphic Column, Northeast Alberta



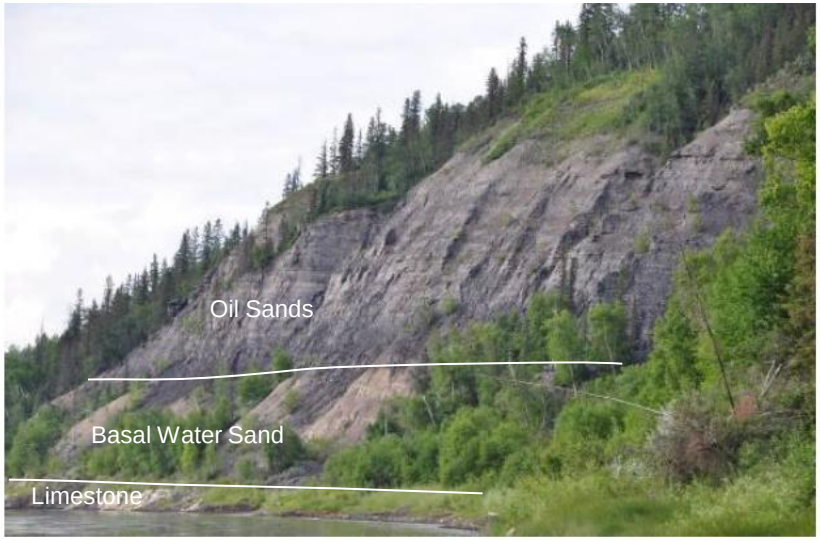

After EUB/AGS Earth Sciences Report 2001-06

# Schematic Geological Cross Section




- Simplified geological cross section north of Fort McMurray
- BWS aquifer sits unconformably on structured Devonian limestone

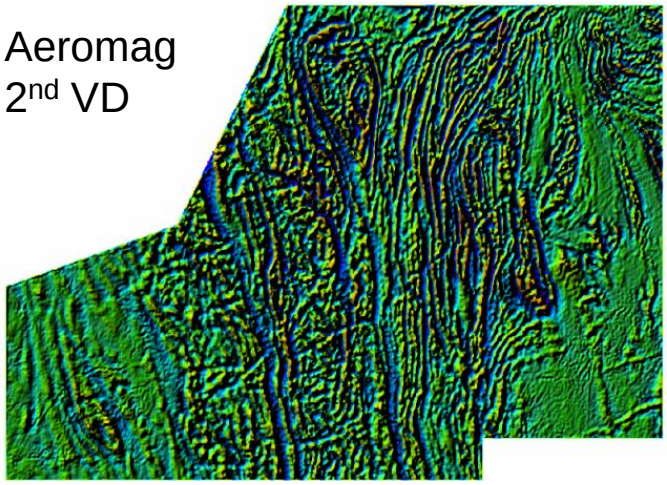
# Basal Water Sand in Outcrop


Gibson et al., OSRIN (2011)

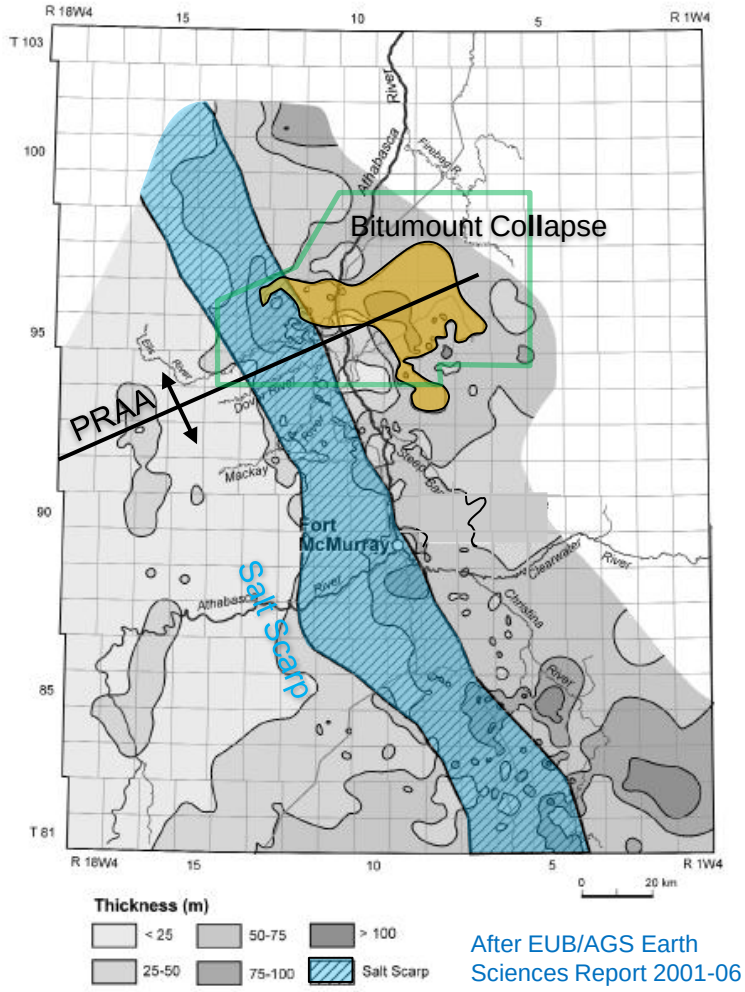
- Cretaceous McMurray Formation of the Mannville Group exposed along the bank of the Athabasca River
- The McMurray Formation sits unconformably above Devonian limestone of the Waterways Formation, Beaverhill Lake Group

# Regional Structural Elements




Birch Mountain Resources (1997)

- Abundant evidence for structural control of BWS distribution
- Salt solution collapse
- Potential basement involvement

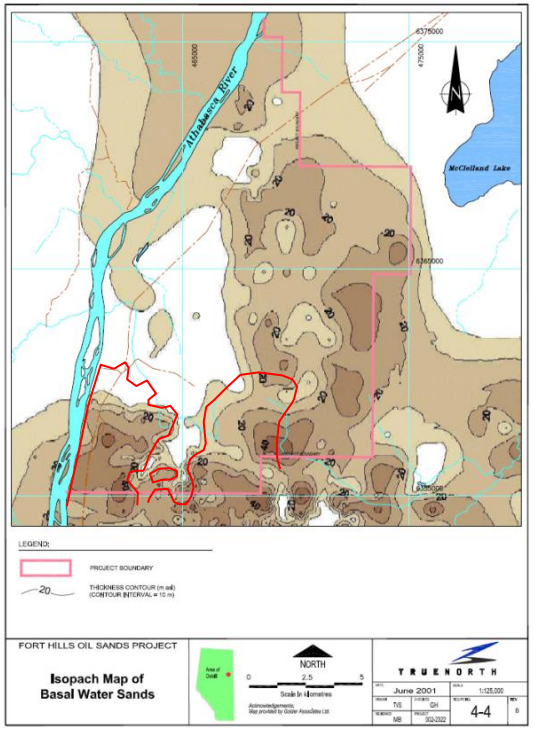



After EUB/AGS Earth Sciences Report 2001-06

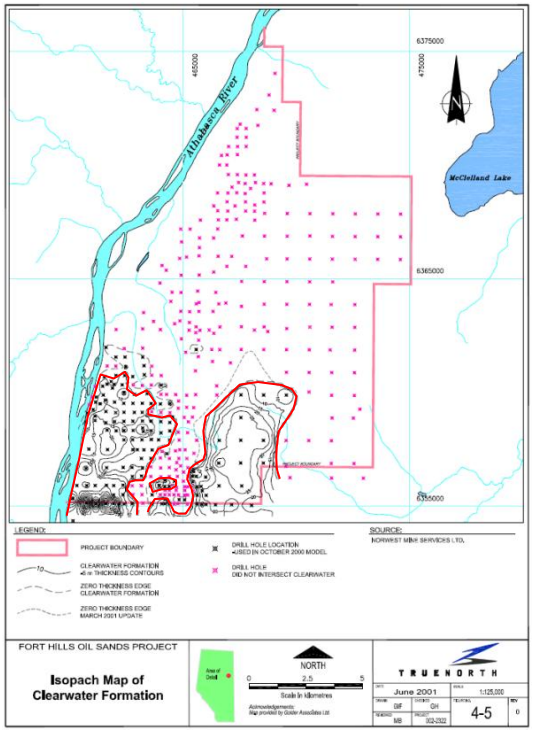
# Structural Control of Basal Water Sand

- Clearwater Formation isopach appears to template thickest BWS at Fort Hills
- Clearwater Formation is preserved as an inlier
- Structural down-dropping of Clearwater may have led to thicker BWS development

Basal Water Sand

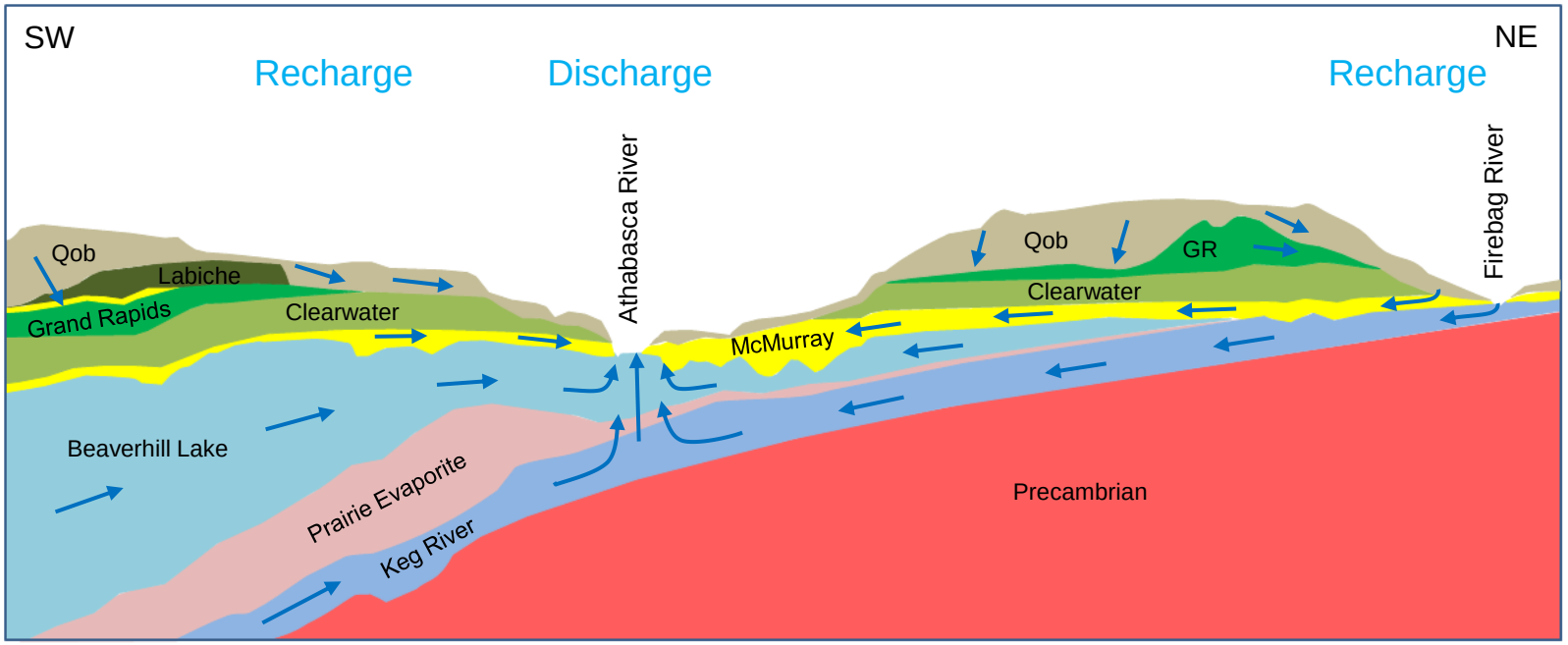



Clearwater Formation



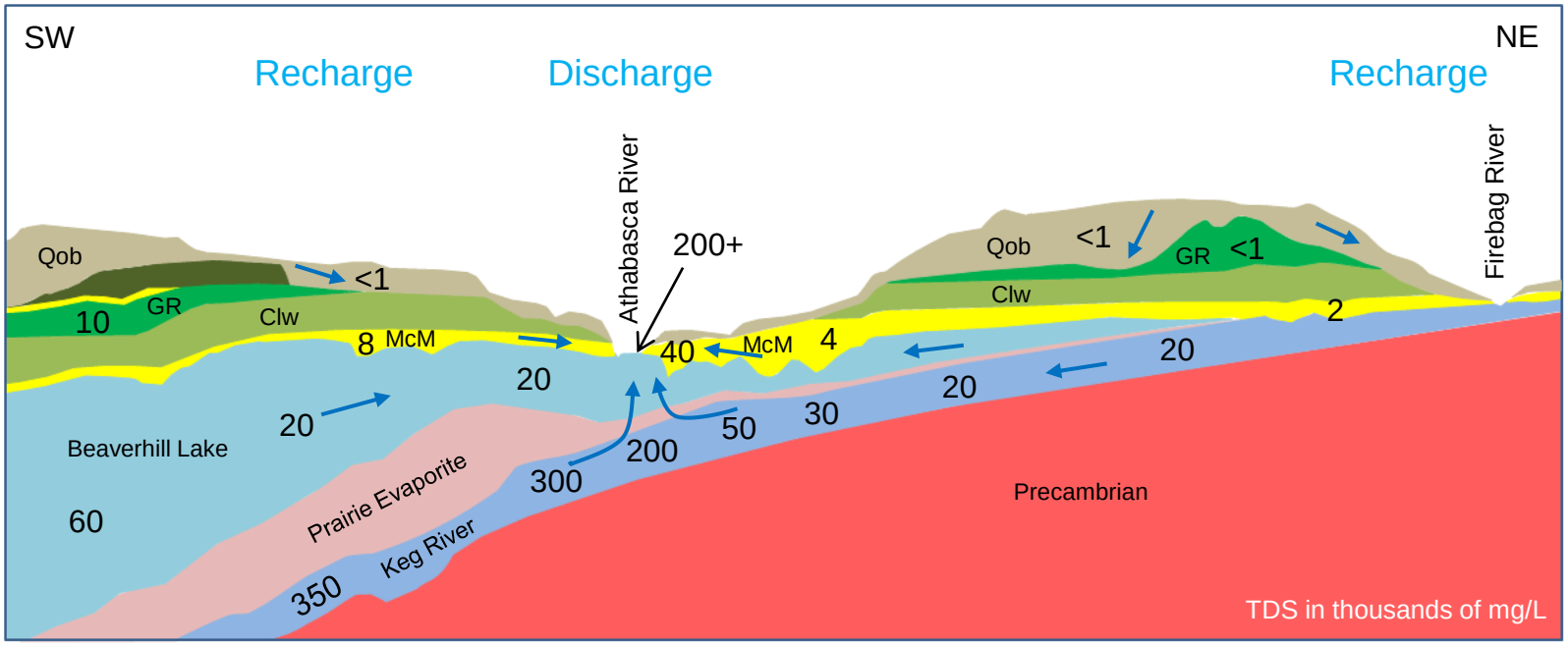

Deer Creek Energy (2001)

# Regional Hydrogeological Setting




- Two major flow systems discharge to the Athabasca River
  - Deep basin flow system (Devonian)
  - Shallow surface flow system (Cretaceous to Quaternary)

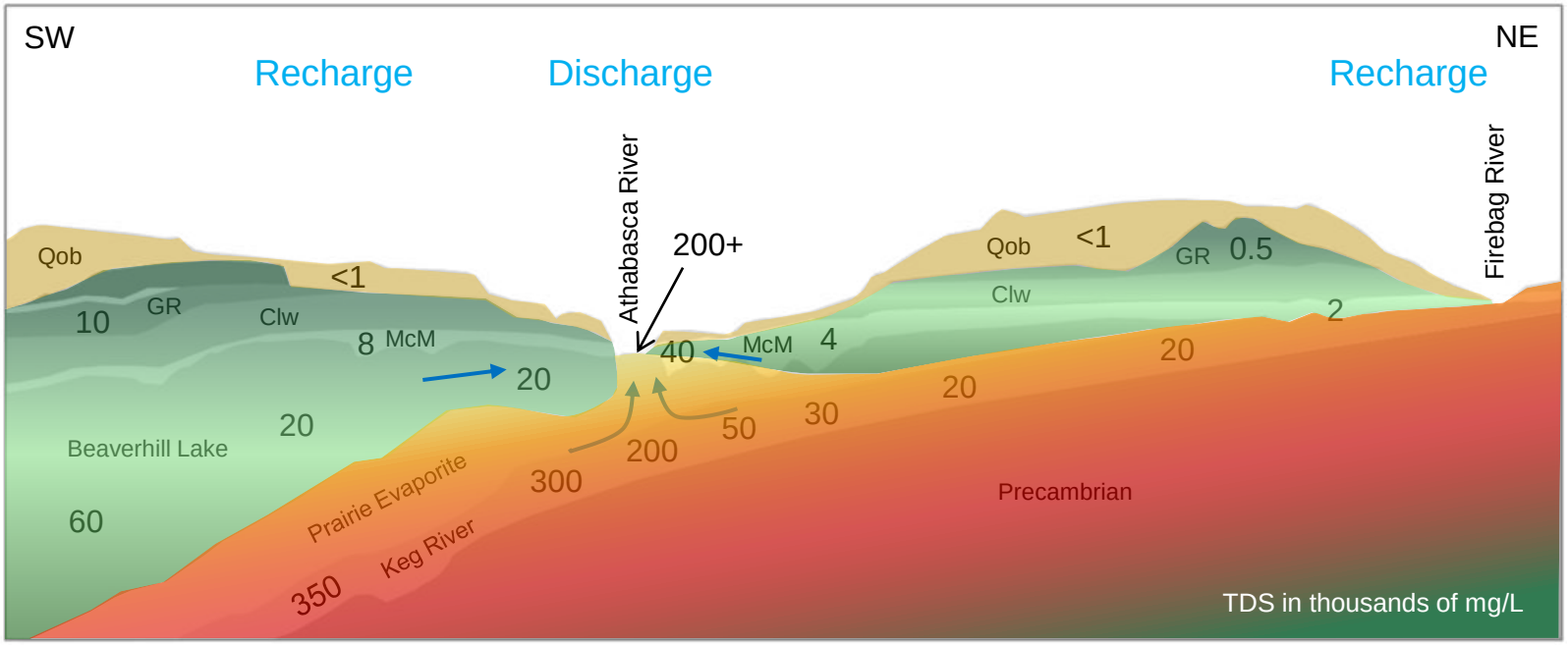
# Regional Hydrochemical Setting




- Westward flow of meteoric and glacial/interglacial recharge waters
- Eastward flow of low TDS water in upper section; eastward flow of high TDS basinal brines in lower section

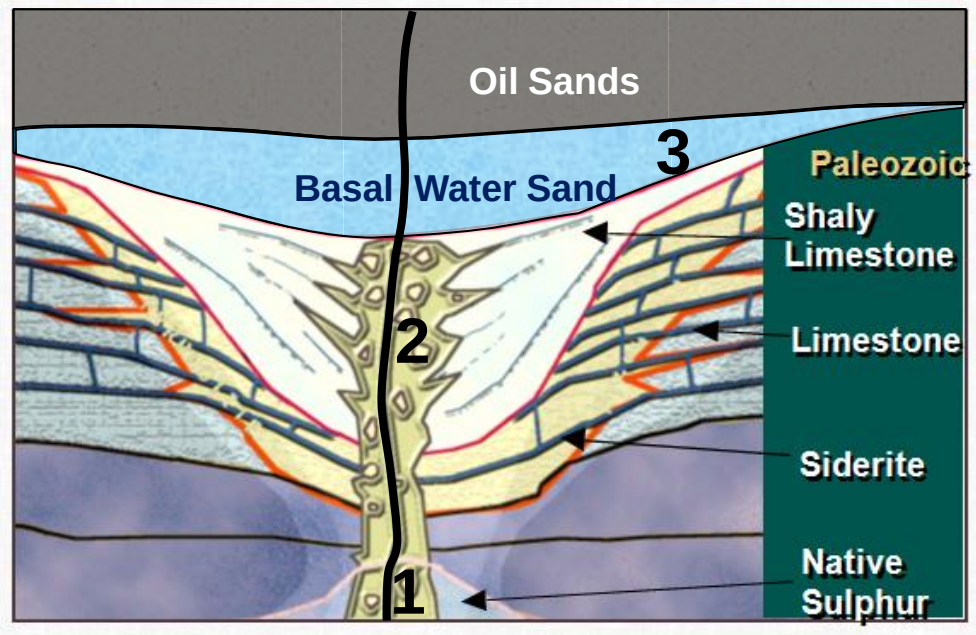
# Brine Discharge at La Saline Springs

# Simplified Redox Stratigraphy




- Oxidized Elk Point brines (red) and surface waters
- Reduced conditions (green) in rocks in contact with bitumen and deep in basement

# Redox-Driven Mineral Alteration



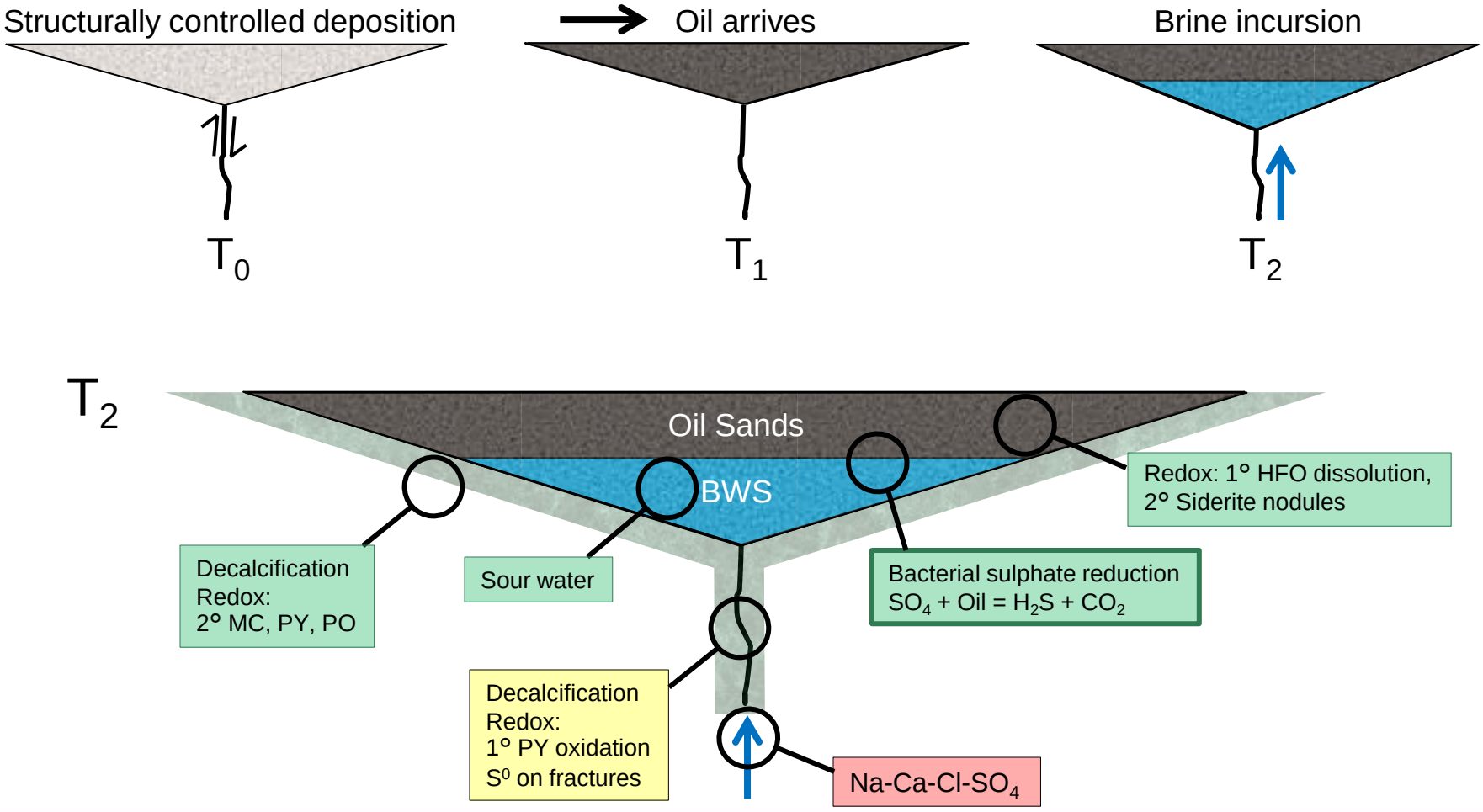

- Vertical flow of oxidizing Na-Ca-Cl-$SO_4$ brines:
  - Oxidation of primary pyrite,
  - In the presence of bitumen, bacterial sulphate reduction produces $H_2S$ and $CO_2$
  - $H_2S$ reacts forming secondary pyrite and pyrrhotite,
  - $CO_2$ reacts to form $H^+$ and $HCO_3^-$, causing decalcification and siderite precipitation




**SECONDARY MINERALS**

1. Native S, Keg River Formation.
2. Pyrrhotite, Waterways Formation.
3. Siderite nodules, Lower McMurray Formation.

# BWS Conceptual Geochemical Model



# Industrial Impact of BWS

**Oil sands mining**

- Saline inflows
- BWS depressuring
- On-site water storage / transfer

**In situ**

- Brackish groundwater resource
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Archives, Government of Alberta

**Geochemical Processes**

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# Hydrochemistry of BWS Aquifer

**PROCESS VECTORS**

Decalcification

Dedolomitization

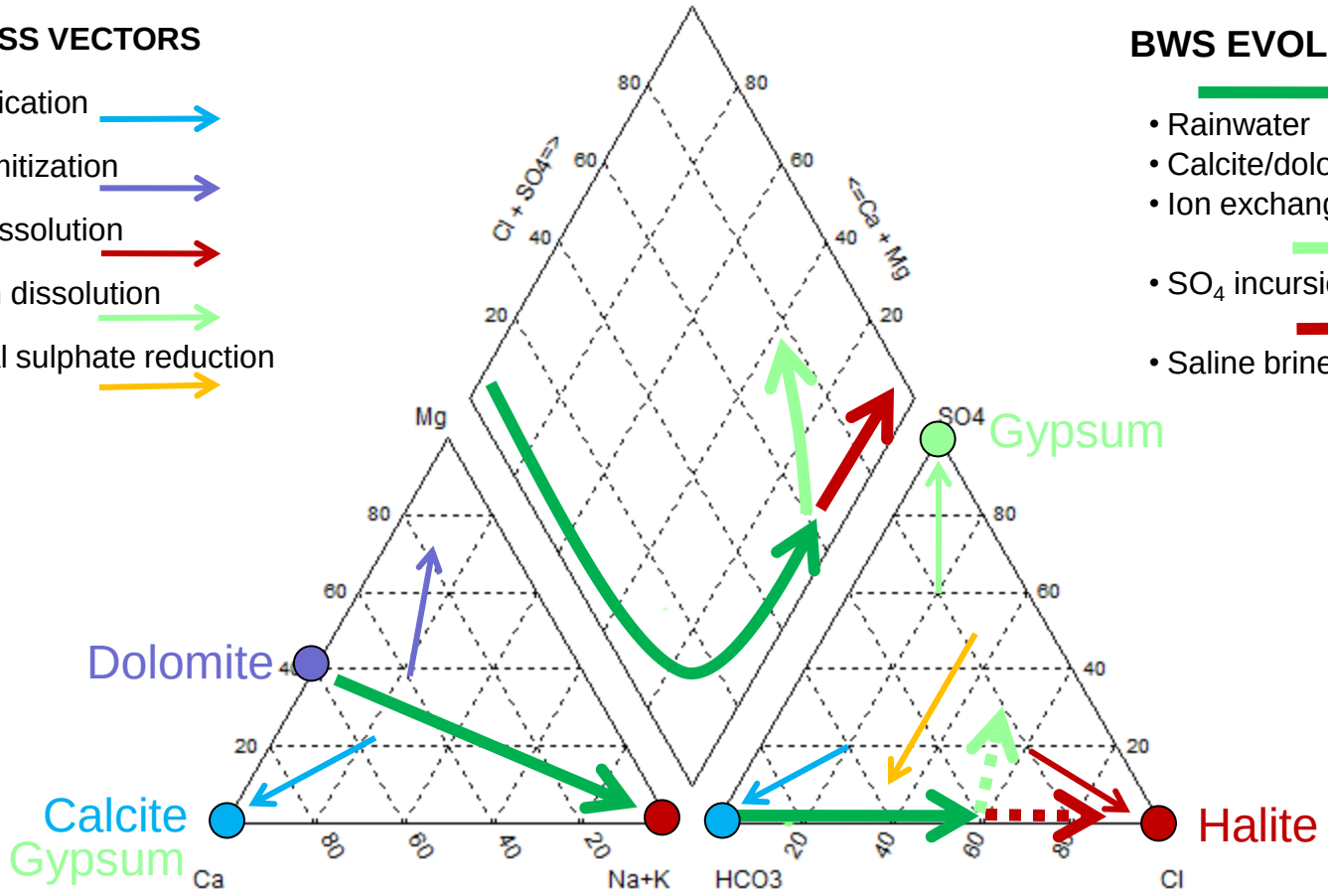
Halite dissolution

Gypsum dissolution

Bacterial sulphate reduction

**BWS EVOLUTION**

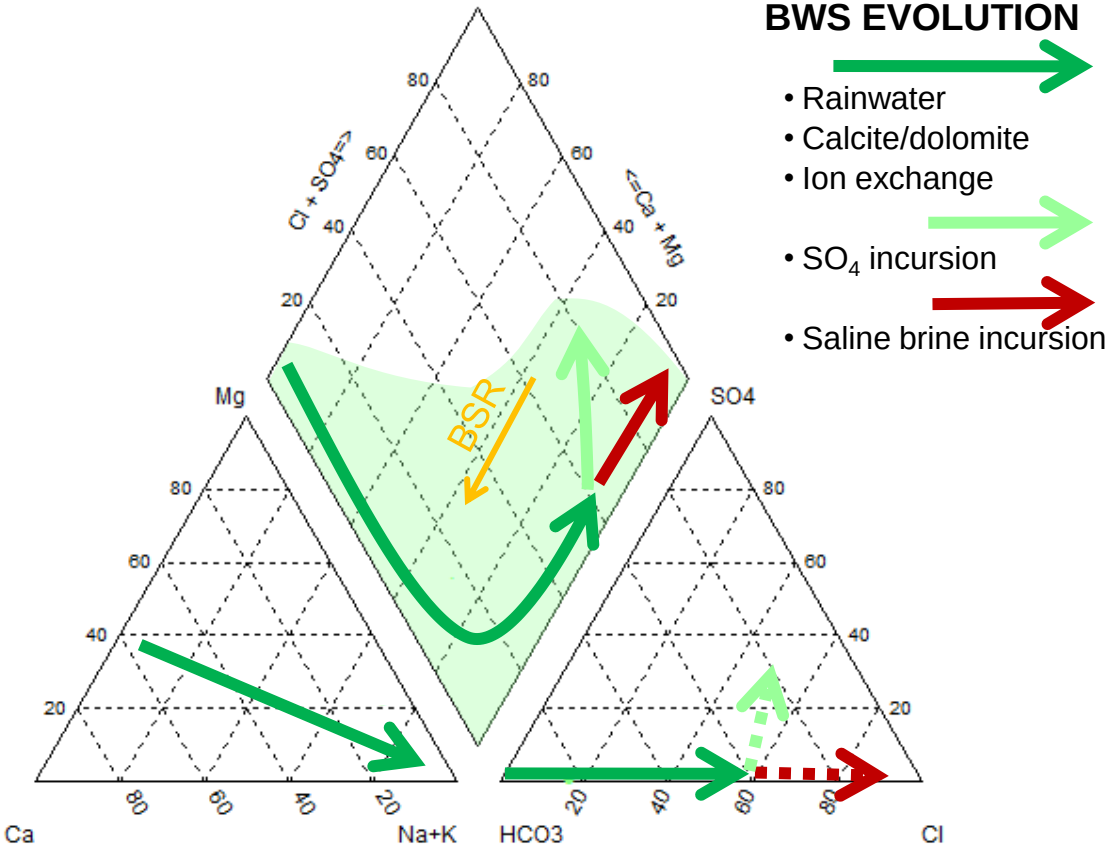
- Rainwater
- Calcite/dolomite
- Ion exchange
- $SO_4$ incursion
- Saline brine incursion




Piper diagram - mass units

# Biodegradation and Water Chemistry

- BWS water compositions record multiple processes
- Site specific processes
- Potential importance of redox over chlorinity as an indication of Devonian incursion




Piper diagram - mass units

# Modeling Bacterial Gas Generation

- PHREEQC used to model gas bubble generation via reaction with bitumen
- Henry's Law $K_H$ values used for $CH_4$, $CO_2$, $H_2O$, $H_2S$ and $N_2$
- Incremental addition of bitumen to reach supersaturation with the least soluble gas ($CH_4$)
- Track total mass and volume of gaseous species in the gas phase
- Decrease containing pressure to simulate depressuring

```
Reaction 1.  Irreversible reaction defined in simulation 4.

       3.000e-002 moles of the following reaction have been added:

                            Relative
       Reactant               moles

       (C)2(H)2.93(N)0.01(S)0.04(O)0.02      1.00000

                            Relative
       Element                moles
       C                     2.00000
       H                     2.93000
       N                     0.01000
       O                     0.02000
       S                     0.04000

-----------------------------------Gas phase------------------------------------

Total pressure:  15.0000   atmospheres
    Gas volume:  2.54e-002 liters

                                                        Moles in gas
                                                  ---------------------------------
Component                log P            P       Initial       Final       Delta
CH4(g)                    1.13   1.364e+001   0.000e+000   1.489e-002   1.489e-002
CO2(g)                    0.12   1.332e+000   0.000e+000   1.454e-003   1.454e-003
H2O(g)                   -1.92   1.189e-002   0.000e+000   1.299e-005   1.299e-005
H2S(g)                   -1.69   2.062e-002   0.000e+000   2.251e-005   2.251e-005
N2(g)                    -5.05   8.946e-006   0.000e+000   9.768e-009   9.768e-009
```

30 millimoles of…

…model bitumen…

…titrated into 1 Kg of BWS water…

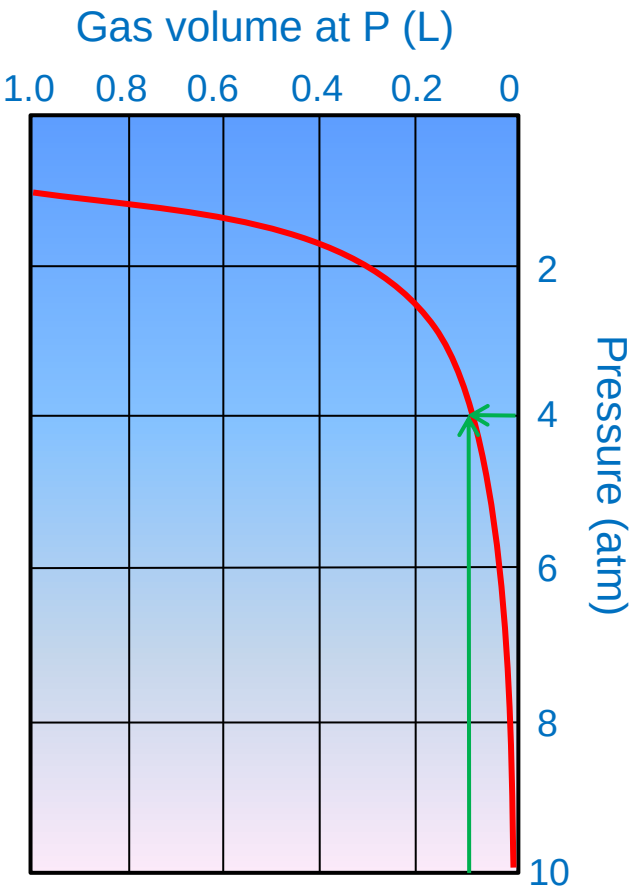
…at 15 bar pressure…

…results in initial bubble formation…

…of $CH_4$ with minor $CO_2$.

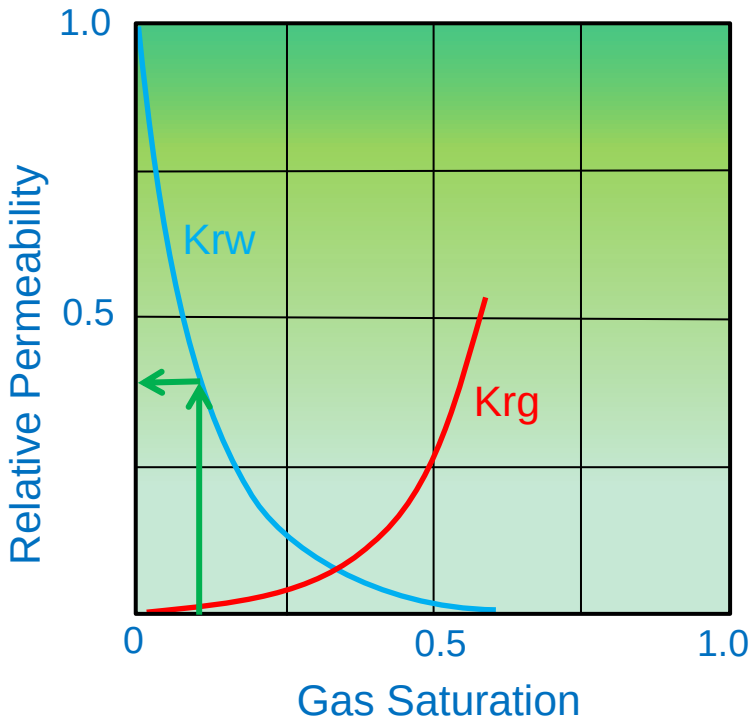
# Depressuring Model Results

- Gas volume at saturation calculated for ~90 m depth (10 atm)
- Gas volume tracked as pressure is reduced; i.e., drawdown
- At ~60 m drawdown gas volume is ~10% of total volume
- This analysis does not consider the salting-out effect which further decreases gas solubilities



# Implications for Depressuring

- Biodegradation of small quantities of bitumen may provide sufficient gas to saturate BWS at depth
- Schematically, a pumping drawdown of 60 m on a gas-saturated BWS water at 90 m depth can result a loss of 60% relative permeability to water
- Analysis is qualitative, but illustrates the importance of understanding BWS, including biodegradation, gas generation and salinity




P. Glover, Formation Evaluation M.Sc. Course Notes.

# Saline Inflows – The Devonian Connection

- Operators in the Mineable Oil Sands area have, from time to time, encountered inflows of saline water inferred to originate in Devonian aquifers
- BWS provides part of the pathway linking Pz and Mz formations
- Present-day salinity distribution suggest little connection between Devonian and McMurray Formations
- Mineralogy, bitumen chemistry and structure imply in the past there may have been connection
- Prior structural / hydrogeological fairways may be reactivated during mining – multiple layered datasets are needed to locate these fairways

# BWS Summary

- Regionally, the BWS is subjected to numerous physical, chemical and biological processes:
  - Meteoric recharge to the east and in elevated areas to the west
  - Interglacial to early post-glacial recharge
  - Upflow of Devonian brines, themselves influenced by
    - Decalcification and dedolomitization
    - Gypsum and/or halite dissolution
  - Bacterial sulphate reduction is expected where upflowing waters carrying sulphate encounter bitumen, leading to:
    - Production of $H_2S$ and $CO_2$
    - Reductive dissolution of hydrous ferric oxide minerals
    - Precipitation of sulphide minerals
- Site-specific knowledge of Devonian and BWS waters is required to address key issues of concern to oil sands industry, regulators

# Questions…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