# McDonald Lake- Surface Water, Groundwater and Sediments Geochemistry


Francisco Castrillon Munoz, P.Geol

Principal Hydrogeologist

S2 Environmental JV Inc.

James T. Freeman

Program Director

S2 Environmental JV Inc.



Presented at:

REMTECH Conference Banff, Alberta

October 17, 2024


ENVIRONMENTAL

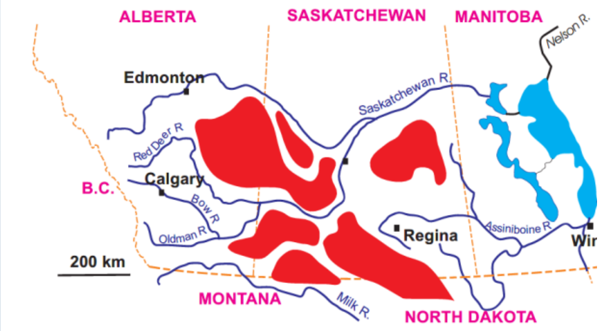
*Driving the Path to Closure*

# Presentation Talking Points

- Integrate climate, water levels, and chemistry data from lake, sediments and groundwater.
- Investigate the mechanisms for sulfate sequestration.
- Validate the hydrochemical conceptual model with a geochemical model to support hypothesis of sulphate sequestration.

# INTRODUCTION

# Regional Perspective

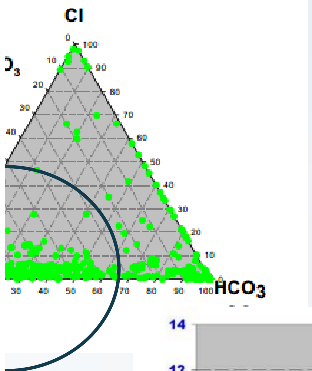


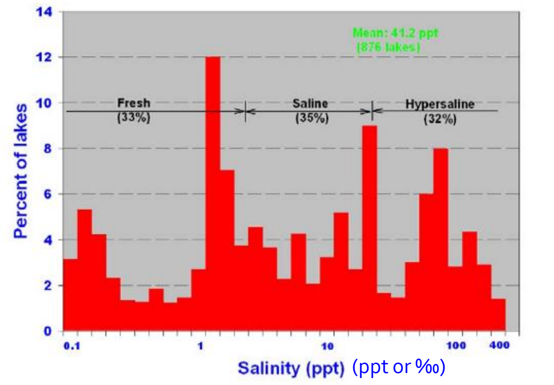

## Closed basins


Table 2: Endogenic and authigenic minerals in saline lakes of the northern Great Plains; modified from [10, 59, 116].

| Mineral Name | Composition | Occurrence |
|---|---|---|
| **Carbonate Minerals** | | |
| Aragonite | $CaCO_3$ | very common |
| Artinite | $Mg_2CO_3(OH)_2 3H_2O$ | very rare |
| Ankerite | $Ca(Fe,Mg)(CO_3)_2$ | rare |
| Benstonite | $Ca_7Ba_6(CO_3)_{13}$ | very rare |
| Calcite | $CaCO_3$ | very common |
| Gaylussite | $Na_2Ca(CO_3)_2 5H_2O$ | rare |
| Kutnohorite | $Ca(Mn,Mg)(CO_3)_2$ | very rare |
| Magnesite[1] | $MgCO_3$ | common |
| Magnesian Calcite | $(Mg_xCa_{1-x})CO_3$ | very common |
| Minrecordite | $CaZn(CO3)_2$ | very rare |
| Protodolomite | $CaMg(CO_3)_2$ | common |
| Zemkorite | $Na_2Ca(CO_3)_2$ | very rare |
| **Sulfate Minerals** | | |
| Arcanite | $(K,NH_4)_2SO_4$ | rare |
| Bloedite | $Na_2Mg(SO_4)_2 4H_2O$ | very common |
| Despujolsite | $Ca_3Mn(SO_4)_2(OH)3(H_2O)$ | rare |
| Epsomite | $MgSO_4 7H_2O$ | common |
| Eugsterite | $Na_2Ca(SO_4)_3 2H_2O$ | very rare |
| Gypsum | $CaSO_4 2H_2O$ | very common |
| Hexahydrite | $MgSO_4 4H_2O$ | common |
| Kieserite | $MgSO_4 H_2O$ | common |
| Krausite | $Fe_2(SO_4)_3 2H_2O$ | very rare |
| Mercallite | $KHSO_4$ | very rare |
| Mirabilite | $Na_2SO_4 10H_2O$ | very common |
| Potassium alum | $KAl(SO_4)_2 12H_2O$ | very rare |
| Thenardite | $Na_2SO_4$ | very common |
| Wattevilleite | $Na_2Ca(SO_4)_2 4H_2O$ | very rare |
| **Carbonate-Sulfate, Carbonate-Sulfate-Chloride, and Carbonate-Phosphate Minerals** | | |
| Bonshtedite | $Na_3Fe(PO_4)(CO_3)$ | very rare |
| Bradleyite | $Na_3Mg(PO_4)(CO_3)$ | very rare |
| Burkeite | $Na_4(SO_4)CO_3$ | very rare |
| Rapidcreekite | $Ca_2(CO_3)SO_4 4H_2O$ | very rare |
| Tychite | $Na_6Mg_2SO_4(CO_3)$ | very rare |
| **Chloride Minerals** | | |
| Bischofite | $MgCl_2 6H_2O$ | Very rare |
| Halite | NaCl | rare |
| **Nitrate and Borate Minerals** | | |
| Inderborite | $CaMgB_6O_{11}H_2O$ | rare |
| Niter | $KNO_3$ | rare |
| Soda Niter | $NaNO_3$ | rare |
| Nitrobarite | $Ba(NO_3)_2$ | rare |
| **Other** | | |
| Pyrite | $FeS_2$ | common |
| Ranciete | $Ca_{0.75}Mn_4O_9{\cdot}3(H_2O)$ | very rare |
| Sepiolite | $Mg_4Si_6O_{15}(OH)_2 6H_2O$ | very rare |

[1]Includes hydromagnesite and psuedohydromagnesite.




tems

BioMed Central

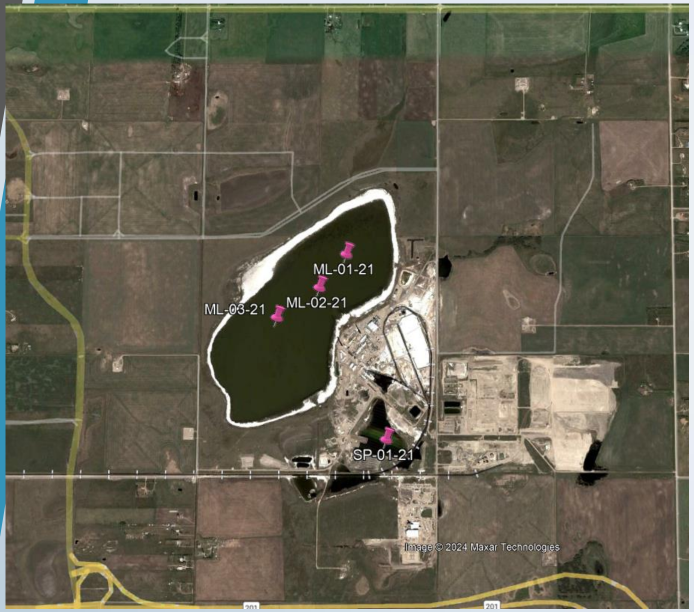
Open Access

the Great Plains of western Canada: an overview
gy and paleolimnology

d Fawn M Ginn[2]
iences, University of Manitoba Winnipeg, R3T 2N2 Canada and [2]Department of Microbiology, University
nanitoba.ca; Fawn M Ginn - fm_ginn@umanitoba.ca

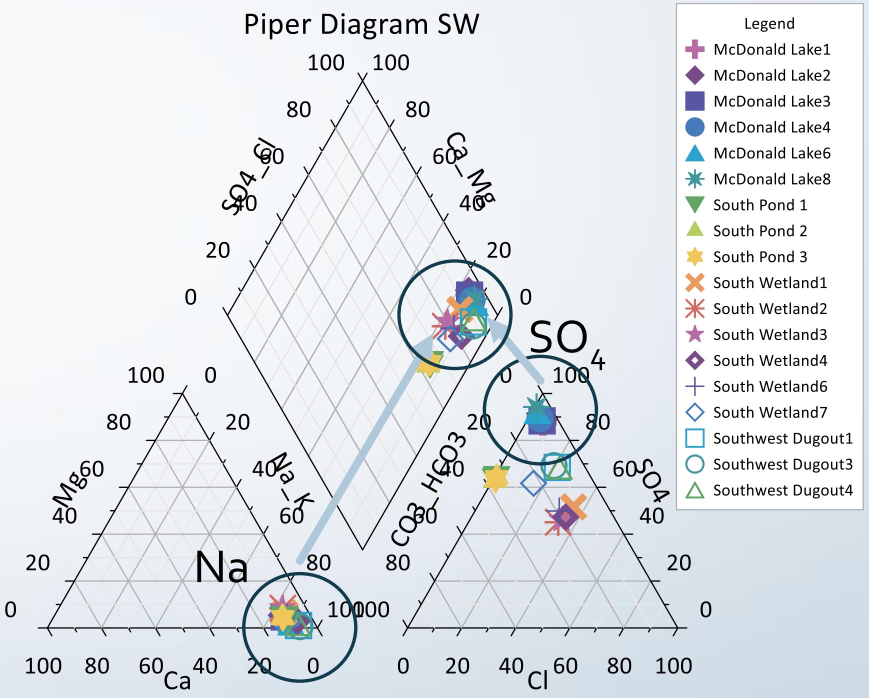
Received: 06 July 2005
Accepted: 18 November 2005
746-1448-1-10
salinesystems.org/content/1/1/10

# McDonald Lake
# (small and shallow Na-$SO_4$ playa lake)




**2002 drought year**

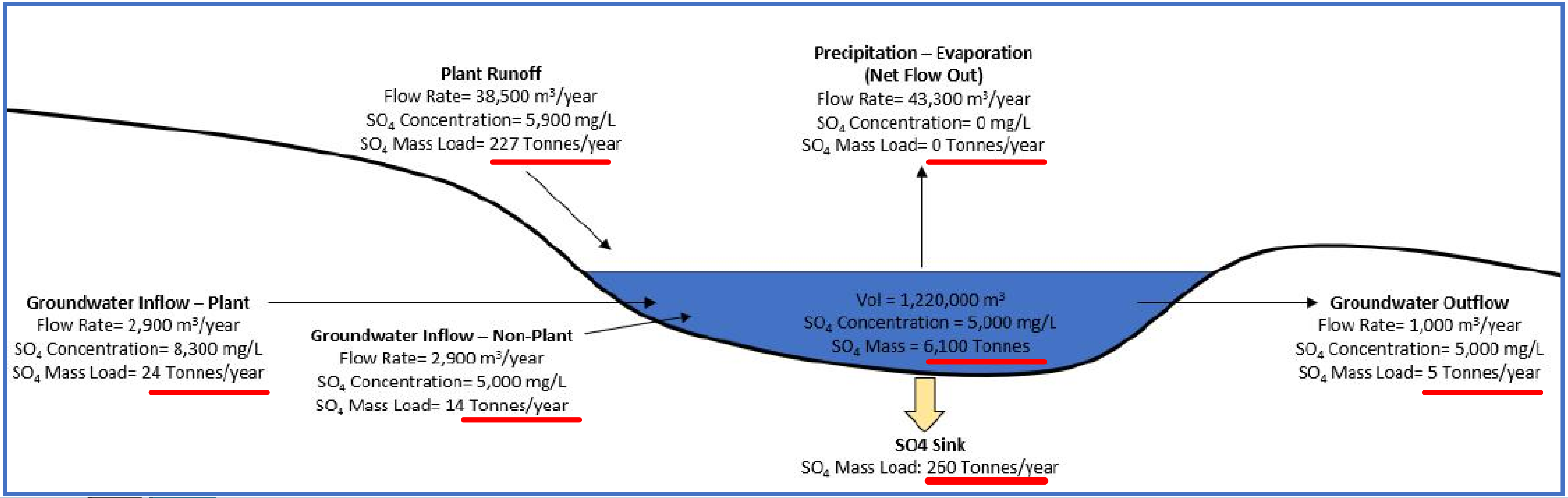

**2023 normal year**




The Lake is saline and Na-$SO_4$ in composition

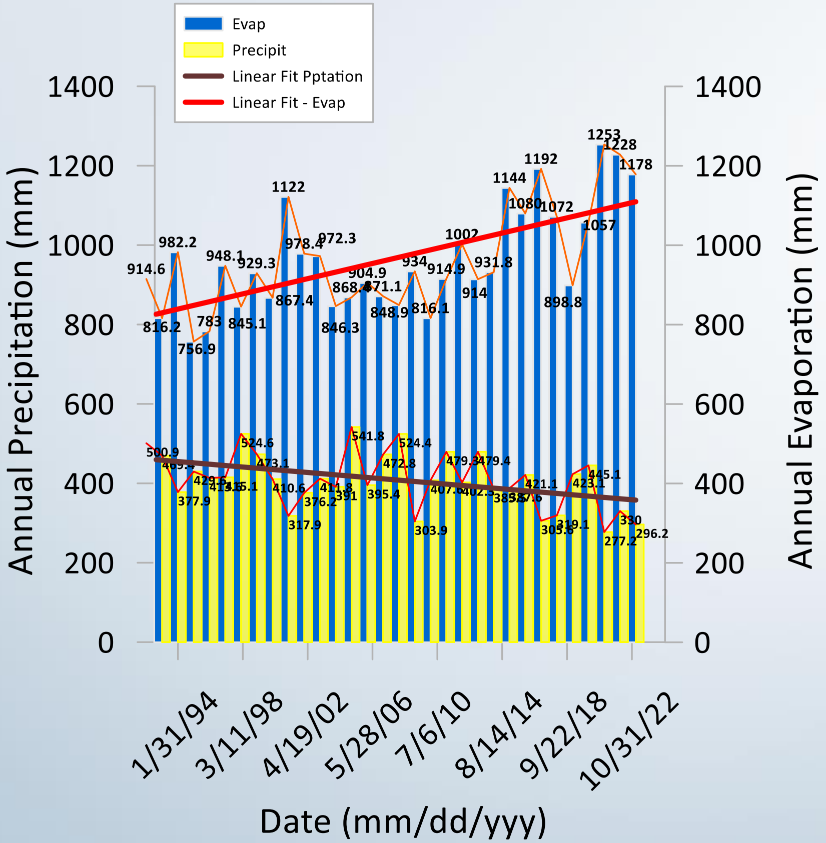
Lake area: 1.3 km²
Lake max depth: 1.3 m

# Mass balance (Fluid Domains 2021)

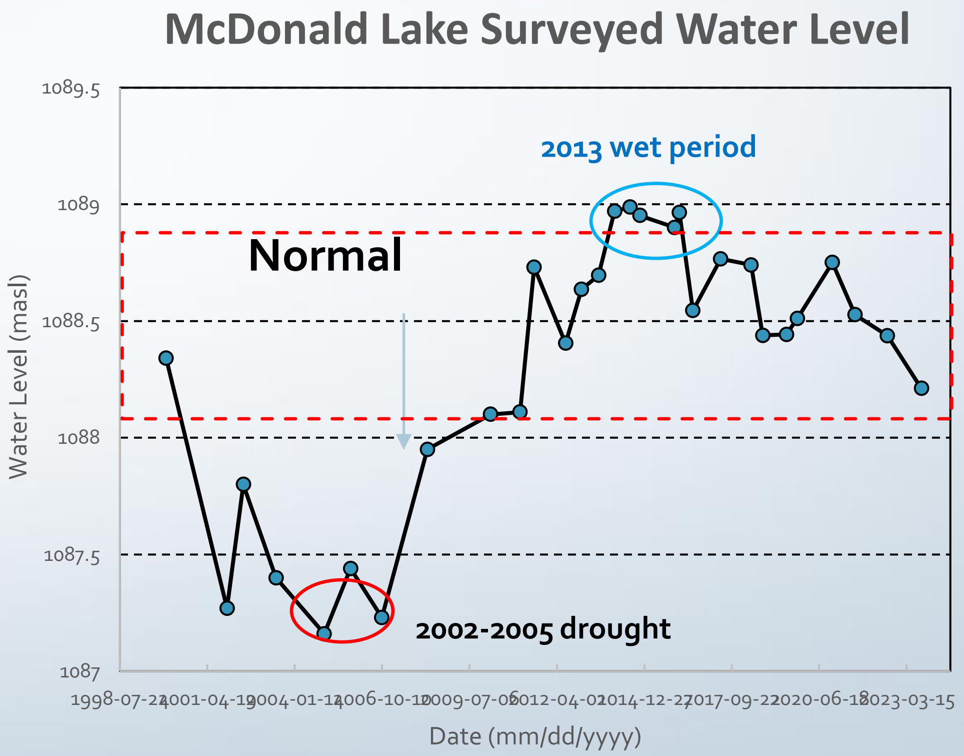


# S2 Water deficit assessment 1992-2023

$$E_L = K_M(e_w - e_a)\left[1 + \frac{U_g}{16}\right]$$ Meyer's Eqn




**Precipitation, evaporation - T026R29W4 Station**

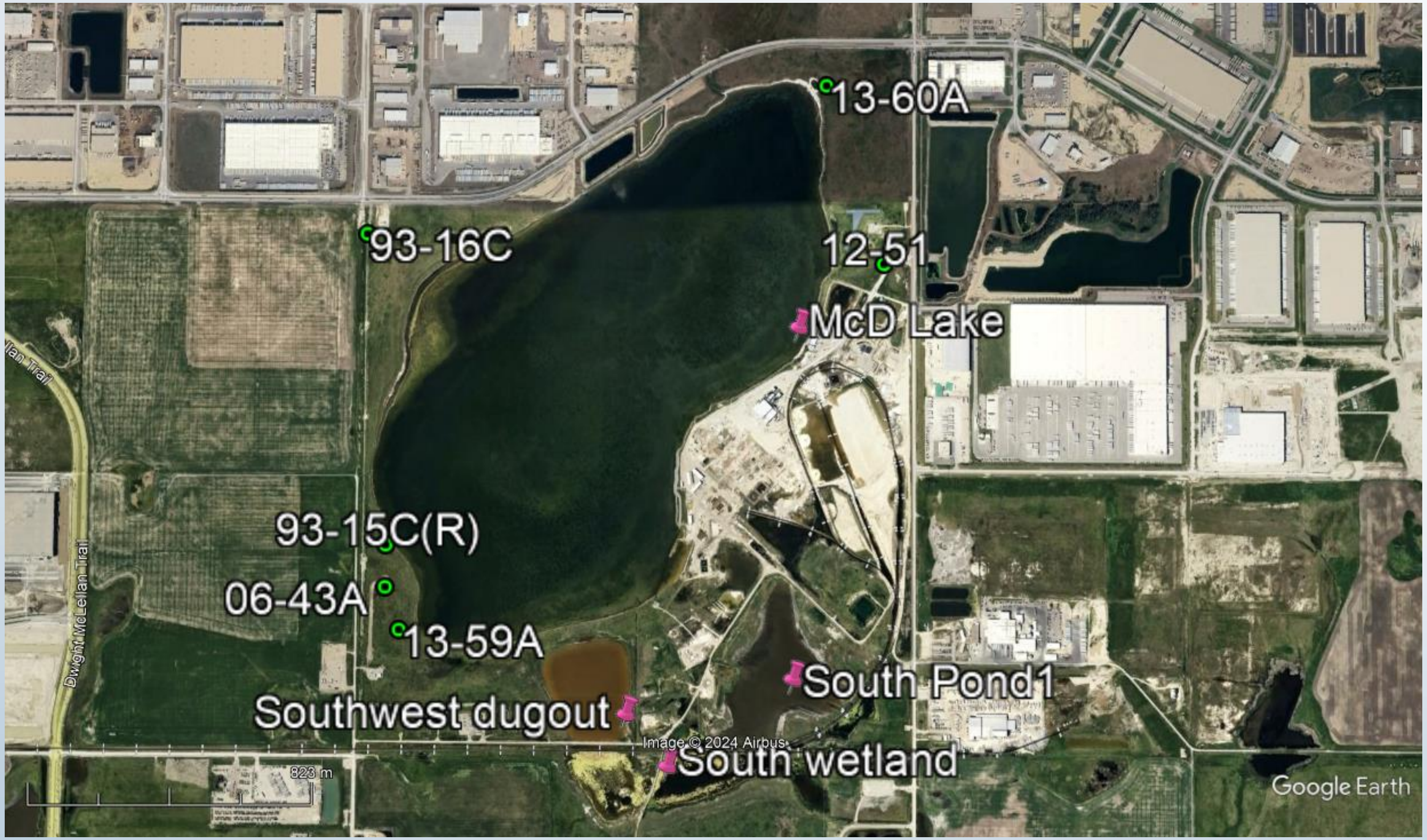


# BGP Geochemistry database

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2925 | Operations | SW | .phur Vat Discha | 294670 | 5675430 | | 1.22E+08 | 7/4/2018 |
| 2926 | Operations | SW | .phur Vat Discha | 294670 | 5675430 | | 1.22E+08 | 7/4/2018 |
| 2927 | Operations | SW | .phur Vat Discha | 294670 | 5675430 | | 1.22E+08 | 7/4/2018 |
| 2928 | Operations | SW | ›hur Vat Pond (Ba | 294687 | 5675430 | | 1.22E+08 | 7/5/2018 |
| 2929 | Operations | SW | ›hur Vat Pond (Ba | 294687 | 5675430 | | 1.22E+08 | 7/5/2018 |
| 2930 | Operations | SW | ıur Vat Pond (Sur | 294678 | 5675431 | | 1.22E+08 | 7/4/2018 |
| 2931 | Operations | SW | ıur Vat Pond (Sur | 294678 | 5675431 | | 1.22E+08 | 7/4/2018 |
| 2932 | Operations | SW | ıur Vat Pond (Sur | 294740.7 | 5675628 | | 2753991 | 7/19/2021 |
| 2933 | Operations | SW | ıur Vat Pond (Sur | 294687 | 5675430 | | 2988107 | 9/17/2021 |
| 2934 | Operations | SW | ıur Vat Pond (Sur | 294687 | 5675430 | | 22C950947 | 9/26/2022 |
| 2935 | Operations | SW | West Sulphur Pit | 294304 | 5675198 | | 1.22E+08 | 7/5/2018 |
| 2936 | Operations | SW | West Sulphur Pit | 294304 | 5675198 | | 1.22E+08 | 7/5/2018 |
| 2937 | Operations | SW | West Sulphur Pit | 294304 | 5675198 | | 1.25E+08 | 9/14/2018 |
| 2938 | BGP Surface | SW | West Base Pad | 294630 | 5675353 | | 1.22E+08 | 7/4/2018 |
| 2940 | | | | | | | | |

The database includes field parameters, routine chemistry, dissolved metals, and isotopes from 200 SW & GW stations, 66 parameters and 2,938 records.

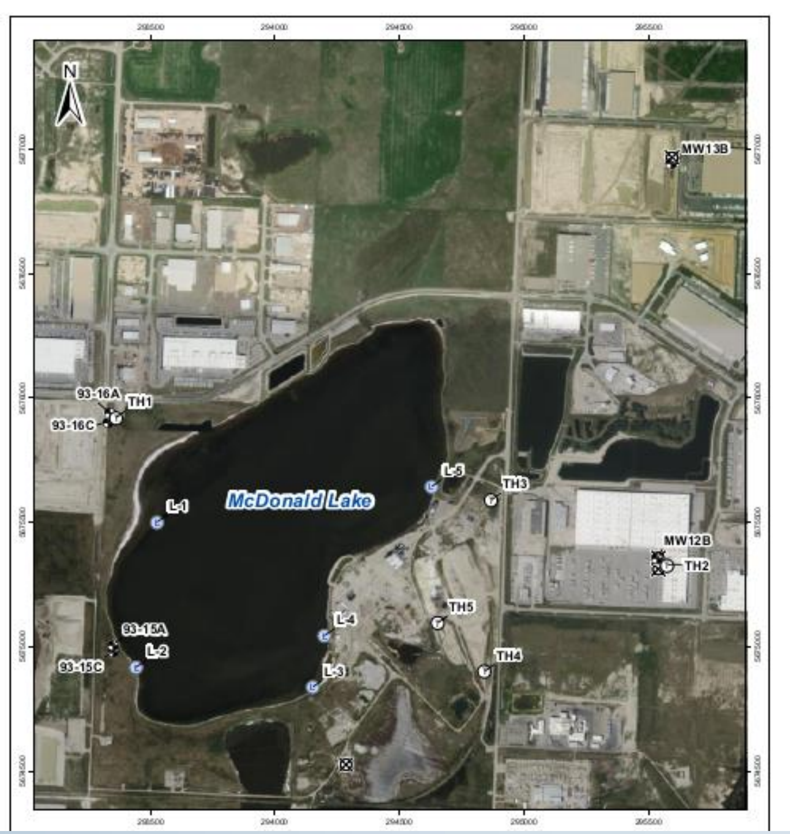
# Background GW and SW Sampling points




These sampling points were selected to reflect background conditions not affected by anthropogenic activities

Sampling locations: the Lake, the Pond, the South dugout, the South wetland and background monitoring wells 12-51, 93-16C, 06-43A, 93-15C(R), 13-59A and 13-60A

# Lake sediment
# Isotopic sampling 1995&2021




**McDonald Lake stable isotopes sampling locations**

Max depth of evaluation: 0.9 mbss

Table I. Stable isotopes in McDonald Lake and sediments at different depths (Komex 1995)

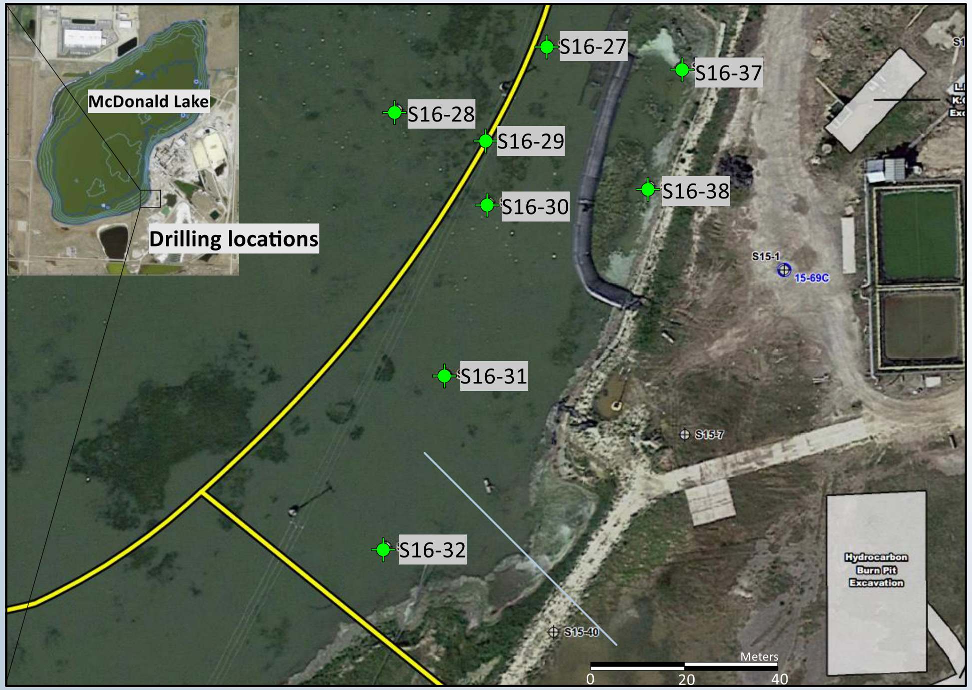
| | Testhole | Depth (cm) | $\delta^{34}S(SO_4)$ (‰) | $\delta^{18}O(SO_4)$ (‰) |
|---|---|---|---|---|
| ID | **Lake sediments** | | | |
| L1 | McDonald Lake | 0.0-20 | 8.1 | |
| | (background) | 20-40 | 5.1 | |
| | | 40-60 | 3.9 | |
| L2 | McDonald Lake | 0.0-20 | 12.2 | 8.6 |
| | (by 15A/B) | 20-40 | 15.2 | 8.7 |
| | | 40-60 | 11.3 | 8.4 |
| L3 | SW Outfall | 0.0-30 | 2.1 | |
| | | 30-60 | -5.4 | |
| | | 60-90 | -4.8 | |
| L4 | West of Flare Area | 0.0-30 | 0.6 | |
| | | 30-60 | -3.6 | |
| | | 60-90 | -4.9 | |
| L-5 | NW of Sulphur VAT | 0.0-30 | 11.6 | |
| | Treated Water Pond | 30-60 | 14.5 | |
| | | 60-90 | 8.8 | |

Sediment $\delta^{34}S$ positive values: Sulphate reduction

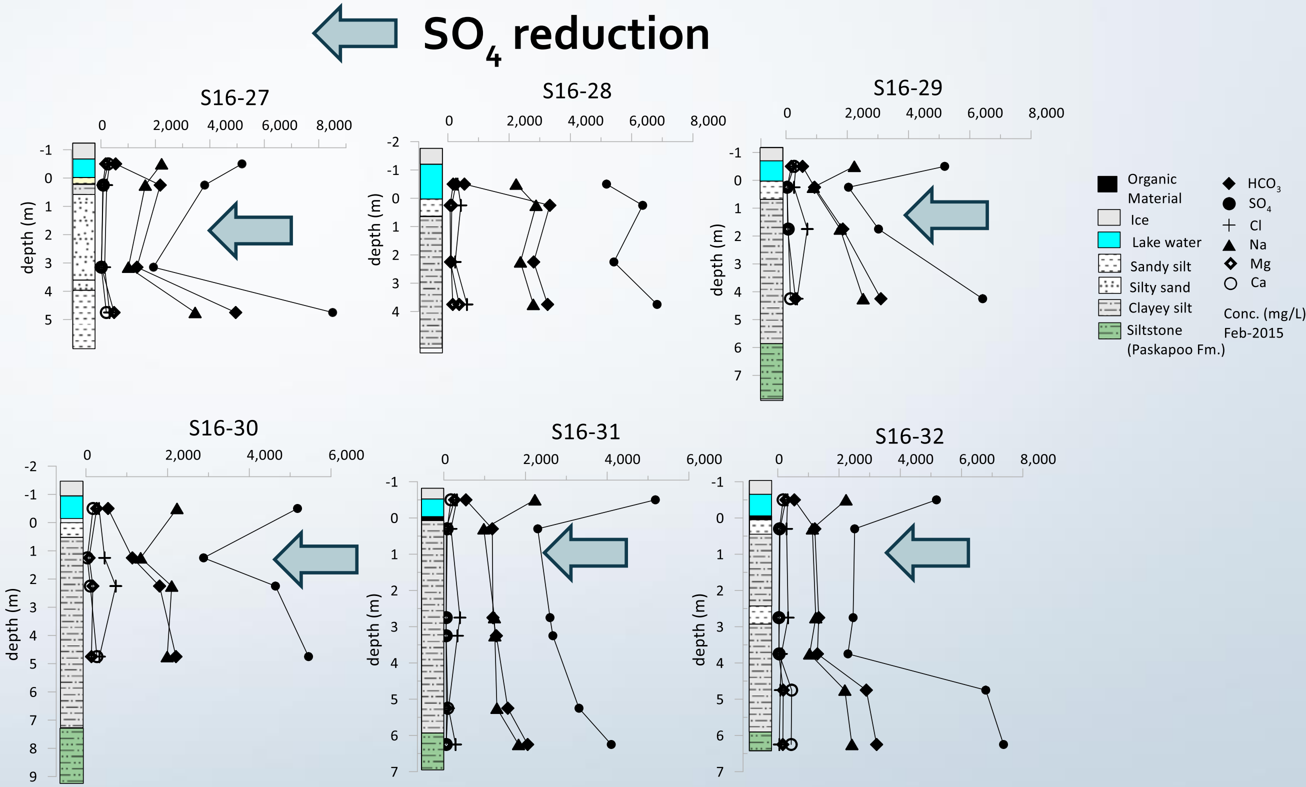
$\delta^{34}S$ negative values: Pyrite ox. or Gyp diss.

# Lake sediment chemistry

Lithological and soluble chemistry samples from the lake sediments collected in 2015 up to 9.0 m of depth.



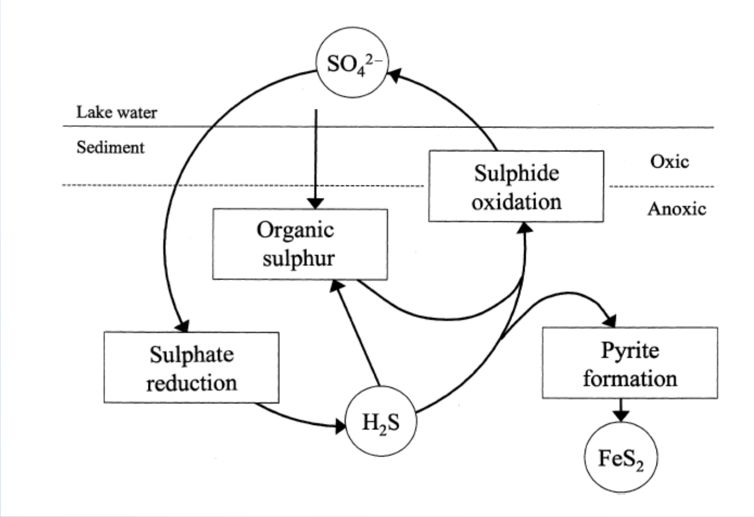

Borehole locations at McDonald Lake offshore from the Flare area in February 2015




The drilling columns comprise ice, water, sediments primarily clayey silts and bedrock below 6.0-7.0 m of depth. **Organic matter was intercepted at the top of two drilling locations.**

# Hydrochemical Conceptual Model of Sulphate Reduction in Lakes

**Sulfur cycle in freshwater sediments**




Holmer and Storkholm 2001

**Reactions**

**O.M**

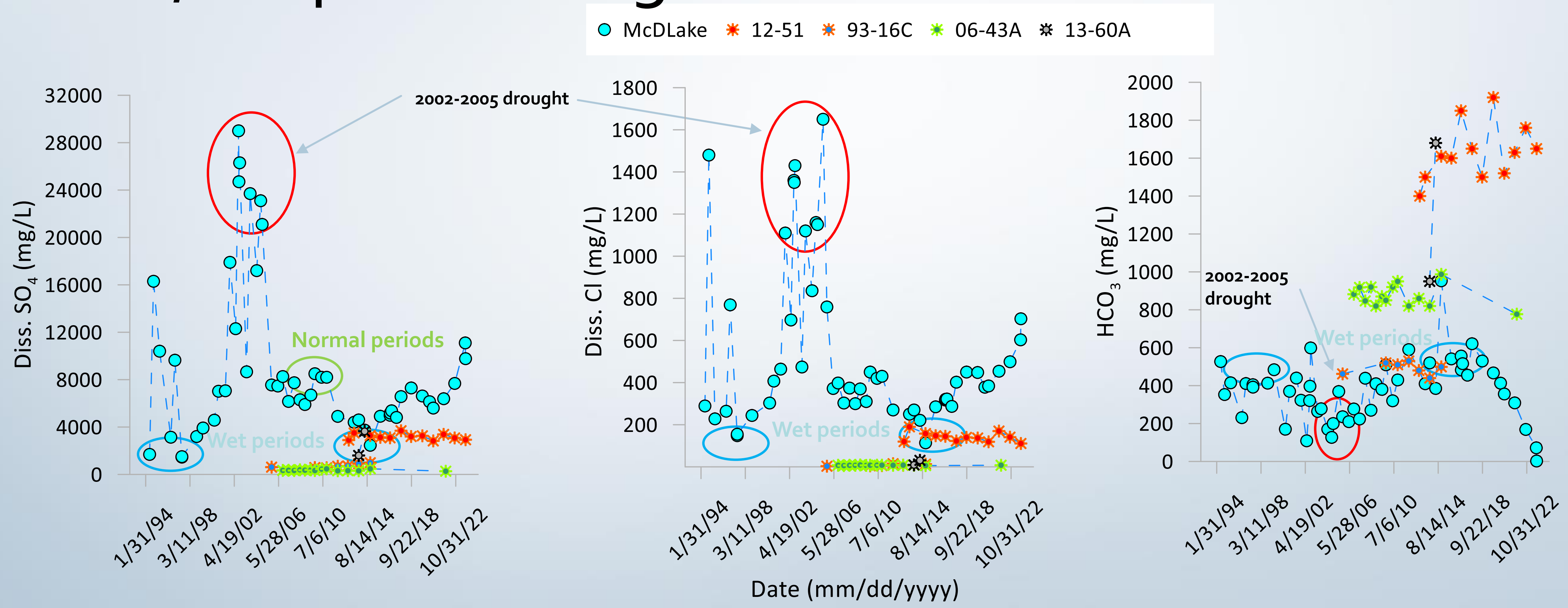
1 $\mathbf{2CH_2O} + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S$

2a $2FeOOH + 3HS^- \rightarrow 2FeS + S^O + H_2O + 3OH^-$ pH=7

**Py**

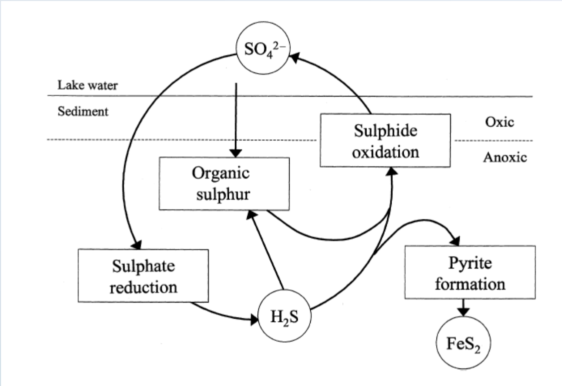
2b $FeS + H_2S \rightarrow 2FeS_2 + H_2$

# Hydrochemical Conceptual Model: Cl/SO4 and HCO3 inverse trends in the Lake

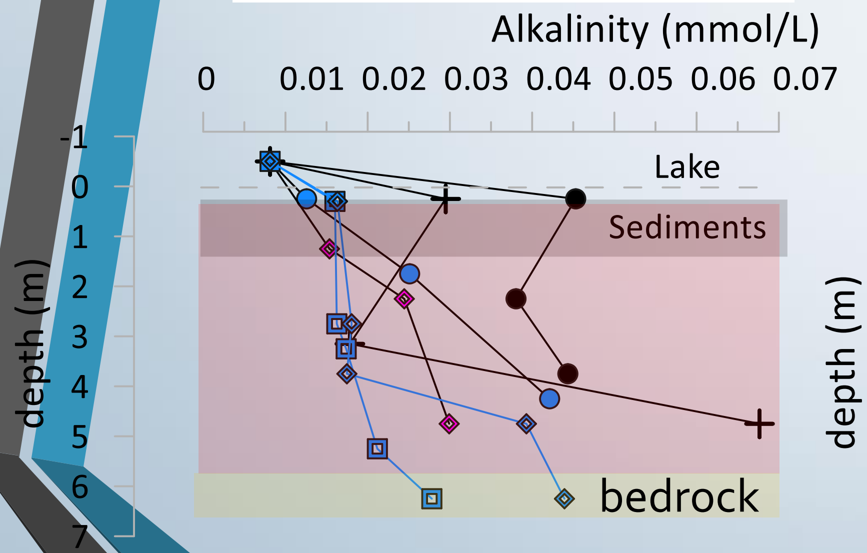


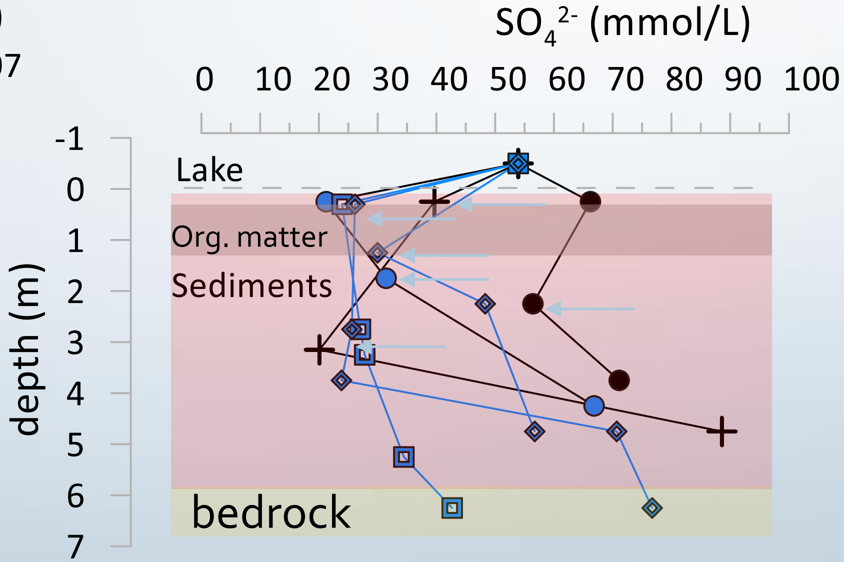

Alkalinity reflected in the $HCO_3$ concentrations show an inverse trend with SO4 data. The groundwater concentrations do not show a correlation with the Lake chemistry.

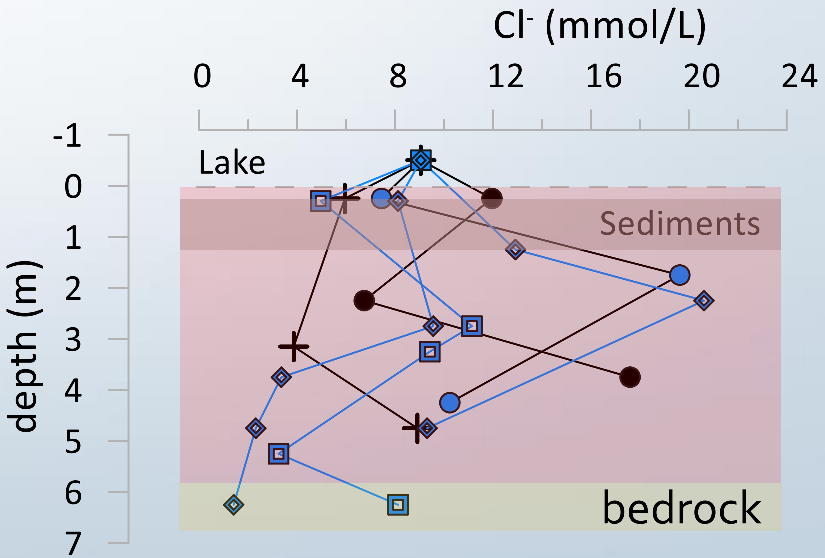
# Hydrochemical conceptual model: Sulphate reduction in the sediments



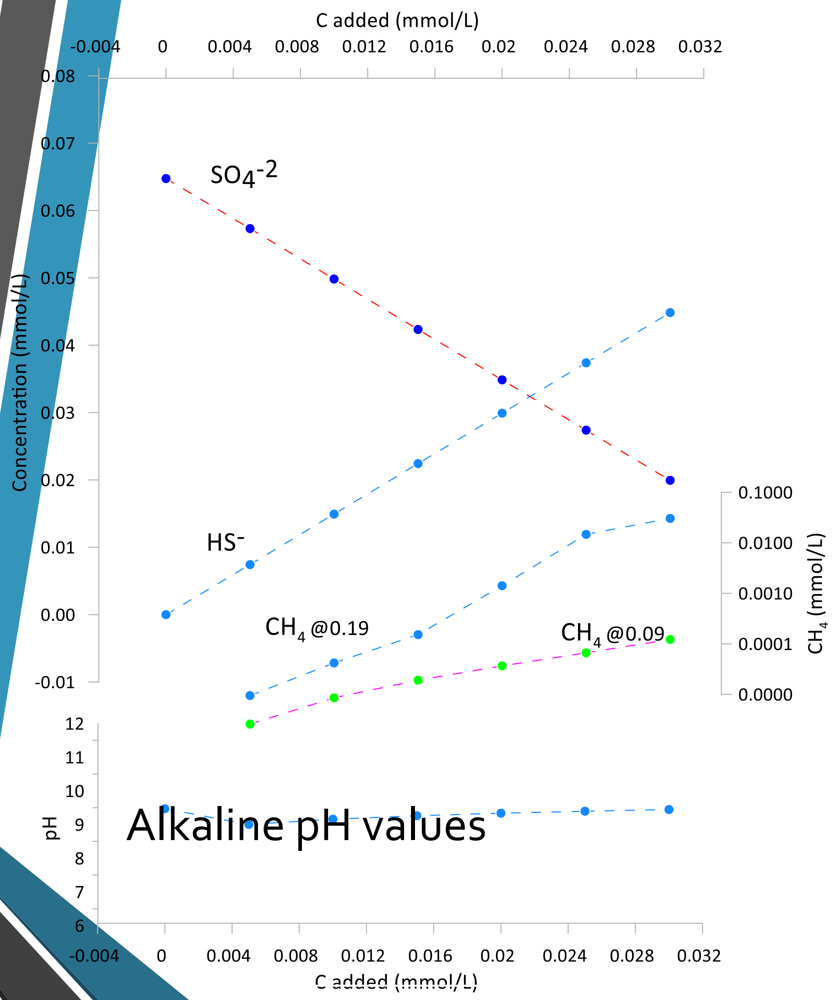

**Sulphate reduction in six sediment profiles at McDonald Lake**



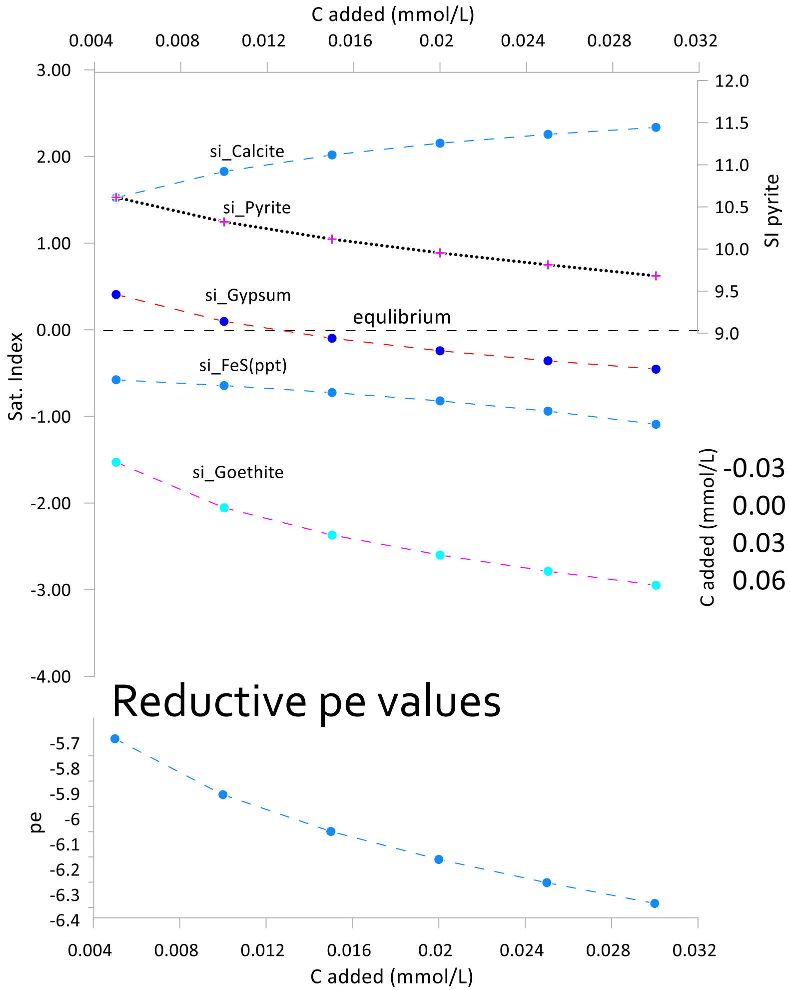



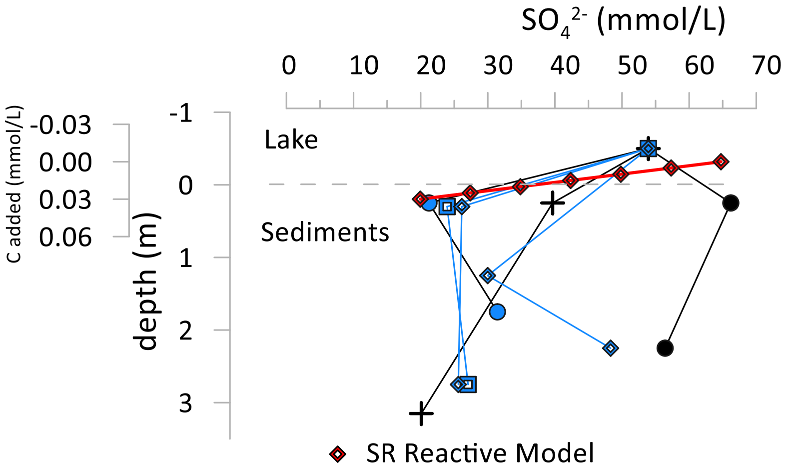
# Sulphate reactive model PHREEQC (normal hydrologic period)




P.press $CO_2$(g) @ -3.4

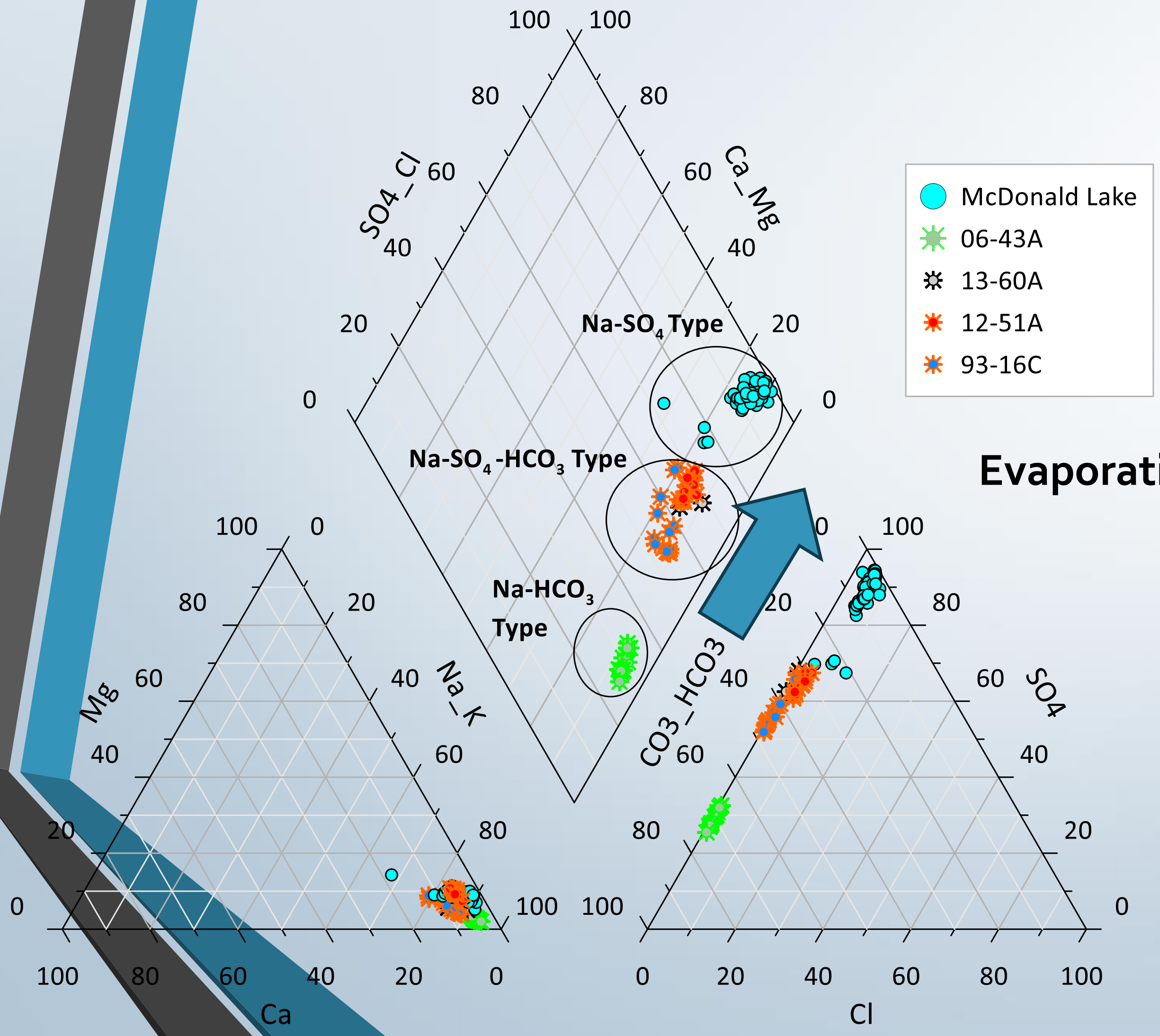



Adding **0.09** Mol C in 6 exponential steps replicates $SO_4$ values similar to the sediments profiles

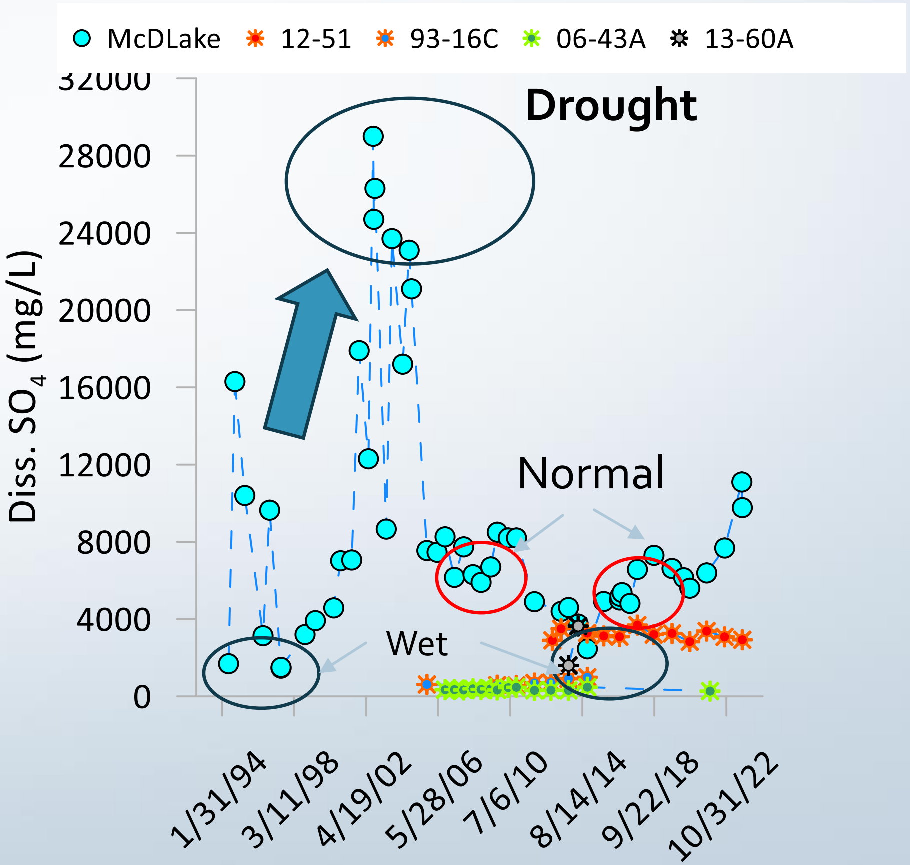



The model suggest that the SR in the lake is highly dependent on the dissolved organic carbon

# Drought – evaporation effect
# Lake and gw chemistry

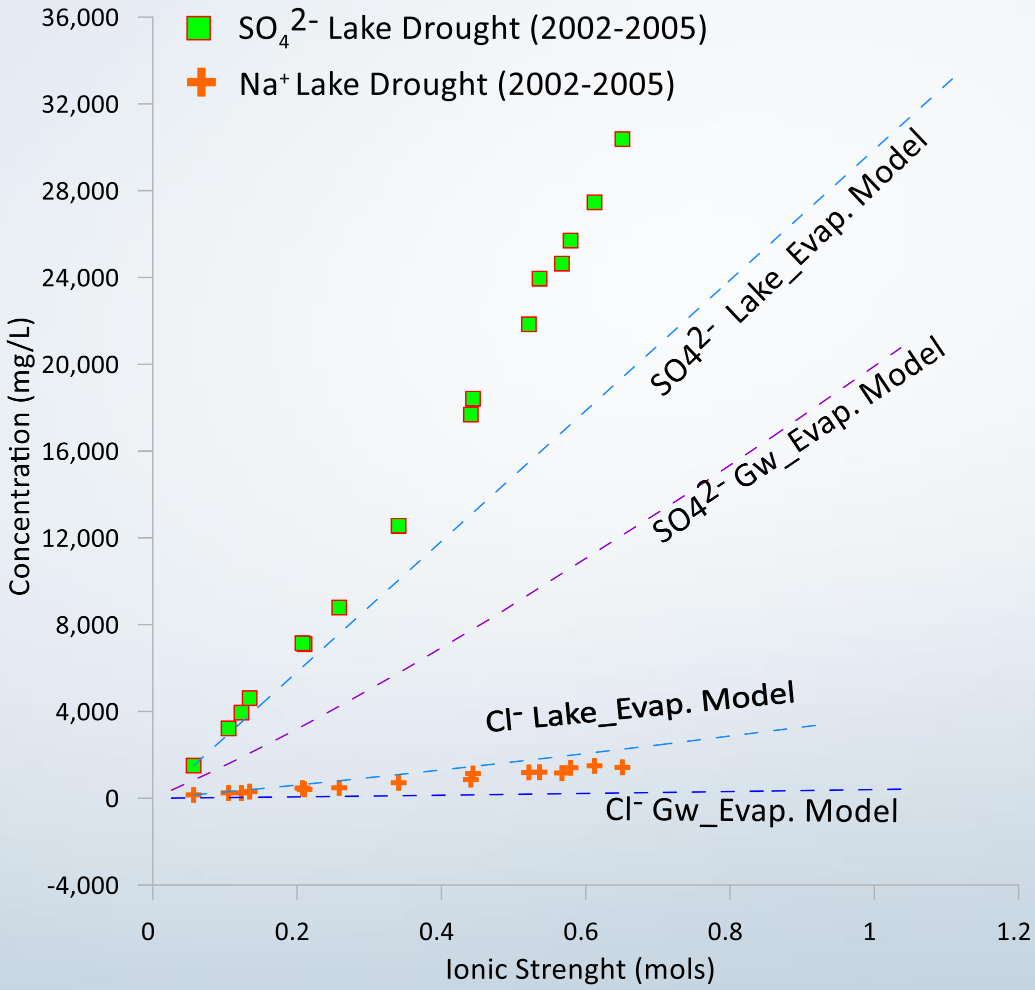



**Evaporation**




Hypothesis 1: the lake chemistry during **drought** is the result of groundwater evaporation; 2 It is the result of lake water evaporation.

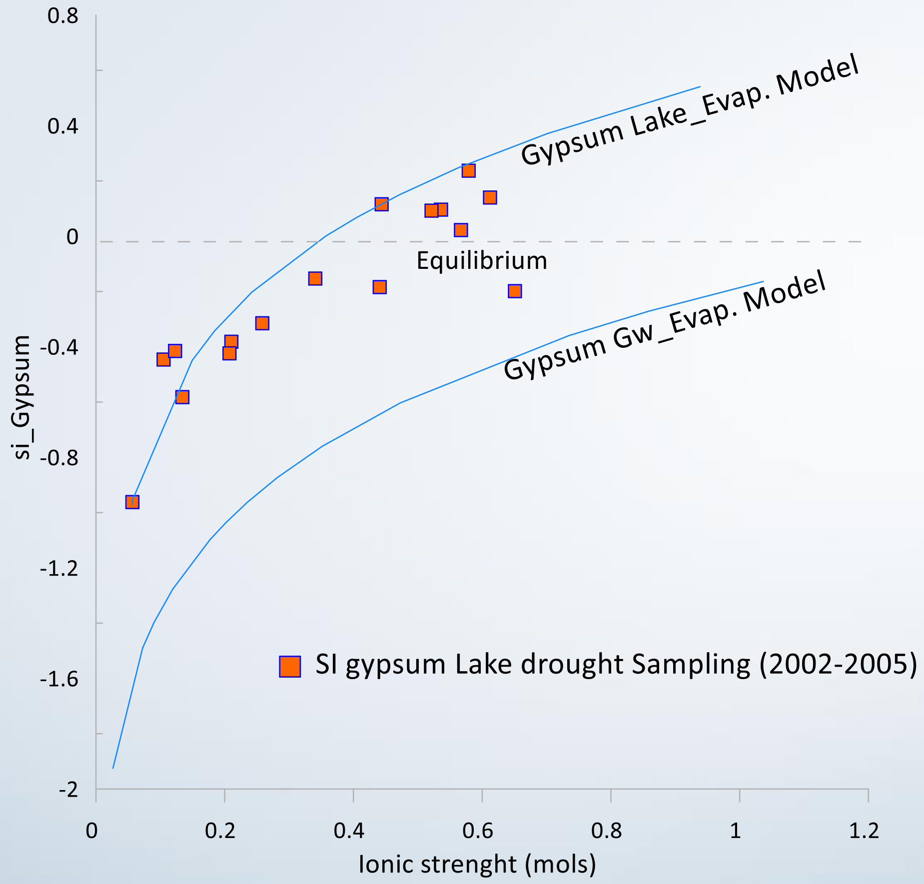
# Sulphate evaporative model PHREEQC (Drought period)




**The lake evaporation results are closer to sulphate concentration in the Lake**

Both models seem to satisfy the chloride concentration in the lake.

# Sulphate evaporative model PHREEQC (Drought period) SI gypsum results in the Lake




**Only the lake evaporation model seems to be able to replicate adequately the gypsum precipitation trend the Lake during the 2002-2005 drought.**

The groundwater concentration seems insufficient to explain the gypsum saturation values estimated for the Lake during drought.

# Sulphate sequestration summary

## 1. Isotope evidence:

Soil $\delta^{34}S$ negative values: Pyrite ox. Or Gyp diss.

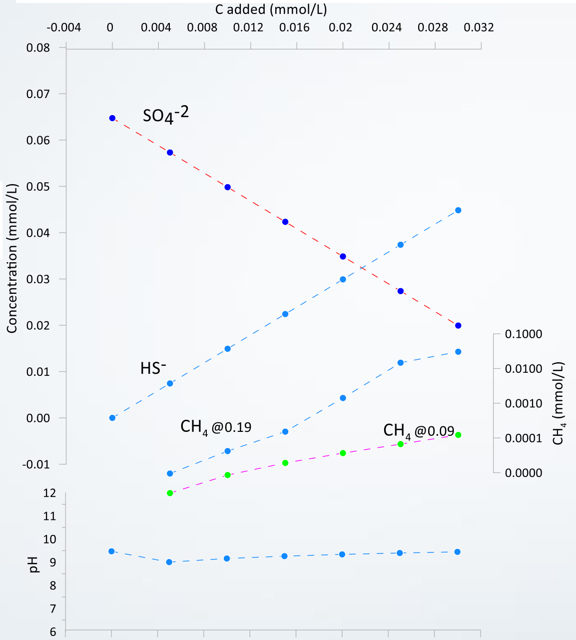
Sediment $\delta^{34}S$ positive values: Sulphate reduction

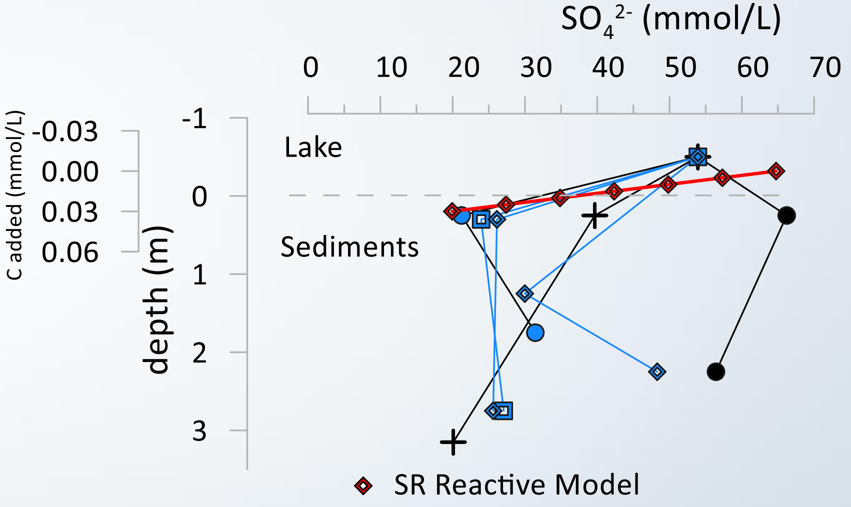
Table I. Stable isotopes in McDonald Lake and sediments at different depths (Komex 1995)

| ID | Testhole | Depth (cm) | $\delta^{34}S(SO_4)$ (‰) | $\delta^{18}O(SO_4)$ (‰) |
|---|---|---|---|---|
| | Lake sediments | | | |
| L1 | McDonald Lake | 0.0-20 | 8.1 | |
| | (background) | 20-40 | 5.1 | |
| | | 40-60 | 3.9 | |
| L2 | McDonald Lake | 0.0-20 | 12.2 | 8.6 |
| | (by 15A/B) | 20-40 | 15.2 | 8.7 |
| | | 40-60 | 11.3 | 8.4 |
| L3 | SW Outfall | 0.0-30 | 2.1 | |
| | | 30-60 | -5.4 | |
| | | 60-90 | -4.8 | |
| L4 | West of Flare Area | 0.0-30 | 0.6 | |
| | | 30-60 | -3.6 | |
| | | 60-90 | -4.9 | |
| L-5 | NW of Sulphur VAT | 0.0-30 | 11.6 | |
| | Treated Water Pond | 30-60 | 14.5 | |
| | | 60-90 | 8.8 | |

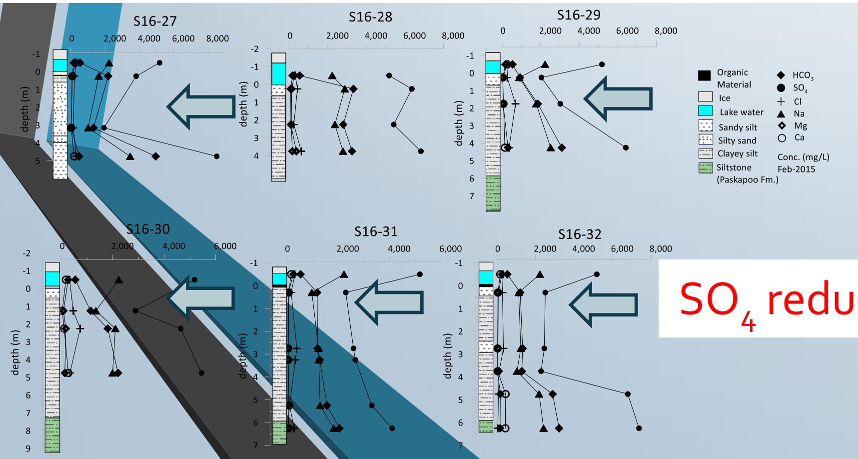
$SO_4$ reduction

## 3. Sulphate reduction reactive geochemical model - Lake and sediment



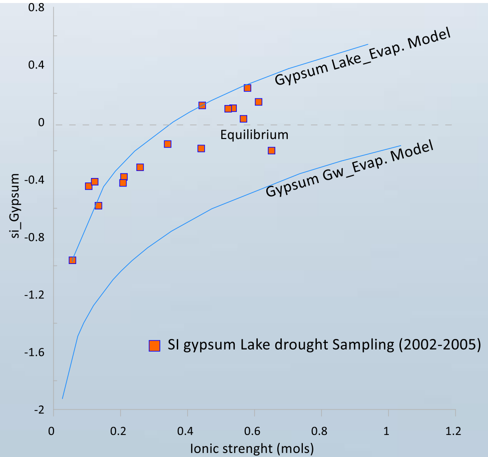




## 2. Sediment cores chemistry evidence




$SO_4$ reduction

## 4. Drought geochemical model




### Sulphate sequesters

- $HS^-$ (aq)
- **FeS - iron sulfide (min)**
- **$FeS_2$ - pyrite (min)**
- $H_2S$(g) – hydrog .sulfide
- $CaSO_4 2H_2o$ -gypsum (min)

Importance

# Acknowledgements

**CNOOC Petroleum North America – funded the investigations and allowed to present this work.**

**S2 field and office staff that contributed to collect this information and participated in technical discussions.**

# Questions?

fcastrillon@summitearth.com

+1 (587) 834-2904