Applying Geochemical Signals and Statistical Tools to Ensure CO_2 Storage Through Water Monitoring

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Carbon Sequestration

Importance of Monitoring

- Ensures CO_2 storage
- Protects valuable assets
- Provides assurance to the community

Geochemical Monitoring

- Utilizes existing infrastructure
- Employs developed tools
- Provides source attribution

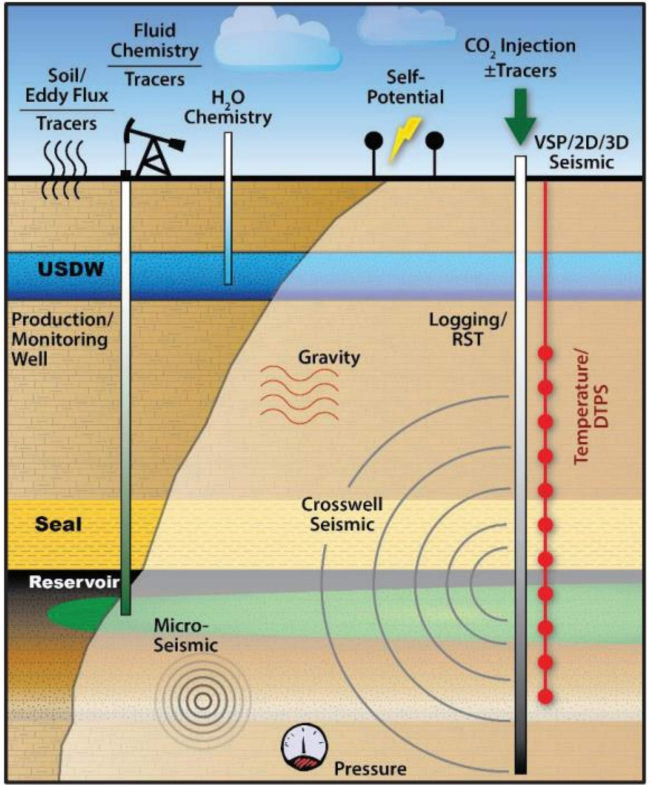

Figure from Balch et al., 2017

Field Studies

Samples

- Ogallala Fm. groundwater
- Santa Rosa Fm. groundwater
- San Andres Fm. produced water

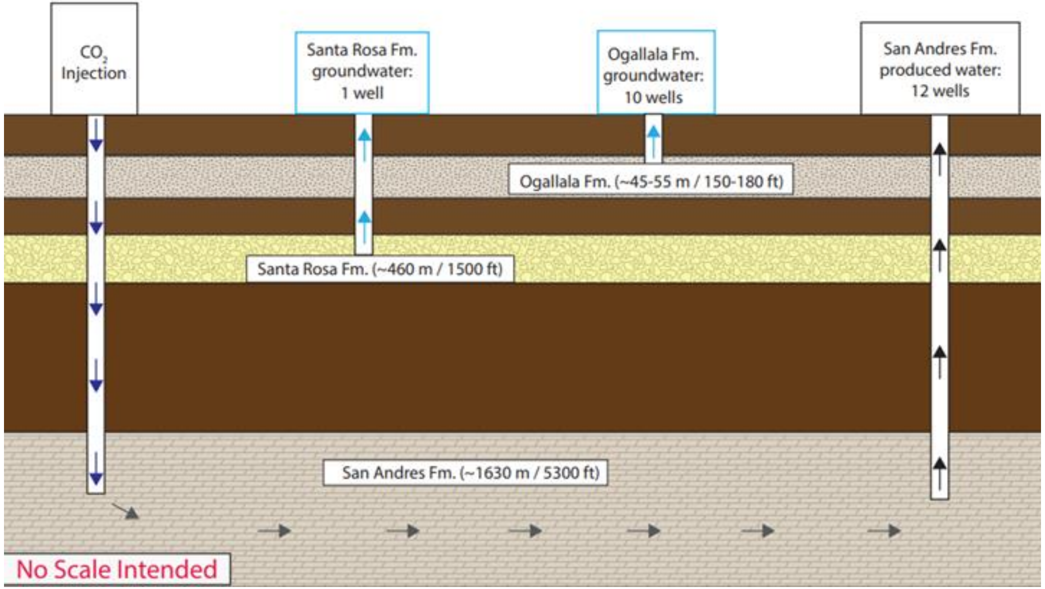

Figure from Miller et al., 2022

Application of Field Results: GILD

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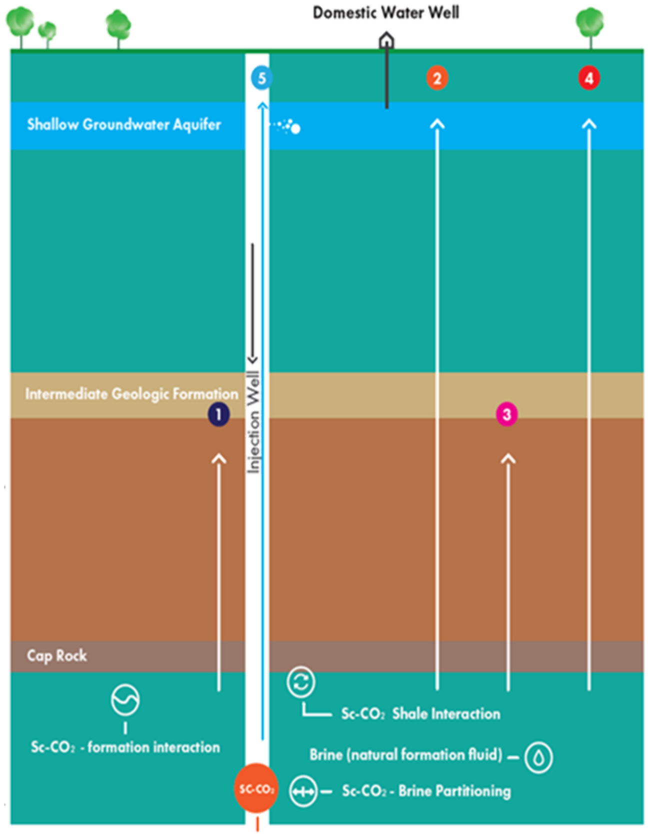
- **Problem Definition**
  - Need for a low-cost, easily implementable monitoring strategy for carbon storage reservoir leak detection
- **Proposed Solution**
  - Geochemically Informed Leak Detection (GILD)

GEOCHEMICALLY INFORMED GILD LEAK DETECTION



Leakage Pathways

1. Wellbore to intermediate formation
2. Wellbore to shallow groundwater
3. Geologic conduit to intermediate formation
4. Geologic conduit to shallow groundwater
5. Well to shallow aquifer

GILD Overview

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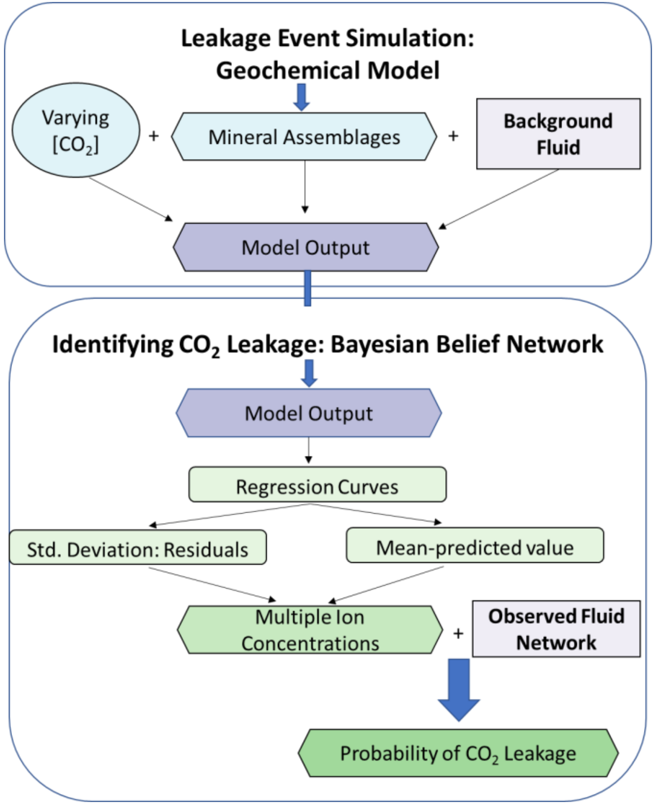
GILD

1) Assess fluid chemistry and mineral compositions of monitoring formation
2) Simulate leakage events with a geochemical model
3) Identify CO_2 leakage with a Bayesian Belief Network (BBN)



Bayesian Belief Network (BBN)

- Decision support tool
- Probabilistic inference from multiple sources of evidence
- Application for leak detection - given monitoring parameters, compute the probabilities of the presence of leakage

Geochemical Modeling

Sandstone minerals: quartz 80 g, kaolinite 10 g, multiple minor minerals

	Carbonate	Feldspar		Mica		Chlorite
No.	Calcite(g)	Albite(g)	Anorthite(g)	Annite(g)	Phlogopite(g)	ipidolit-14A(g
1	0	0	1	0	1	0
2	0	0	1	0	1	1
3	0	0	1	1	0	0
4	0	0	1	1	0	1
5	0	1	0	0	1	0
6	0	1	0	0	1	1
7	0	1	0	1	0	0
8	0	1	0	1	0	1
9	1	0	1	0	1	0
10	1	0	1	0	1	1
11	1	0	1	1	0	0
12	1	0	1	1	0	1
13	1	1	0	0	1	0
14	1	1	0	0	1	1
15	1	1	0	1	0	0
16	1	1	0	1	0	1
17	1	1	1	1	1	1
18	0	1	1	1	1	1

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Mineral Variance

15% porosity 100 g rock, 2.5 g/cm^3 density
6 g of water in pores
25 C
Fixed CO_2(aq) from 0.00003–0.30003 mol/kg
Reaction time 2 hrs
Reactive surface 1000 cm^2/g

Rate	mol/cm2/s
Quartz	1.02E-18
Kaolinite	6.61E-18
Calcite	1.55E-10
Albite	9.12E-17
Anorthite	7.08E-16
Annite	8.51E-18
Phlogopite	3.98E-17
Ripidolit-14A	3.02E-17

Rate constants from Palandri and Kharaka, 2014

Geochemical Modeling

Fluid Variance

Santa Rosa ground water samples

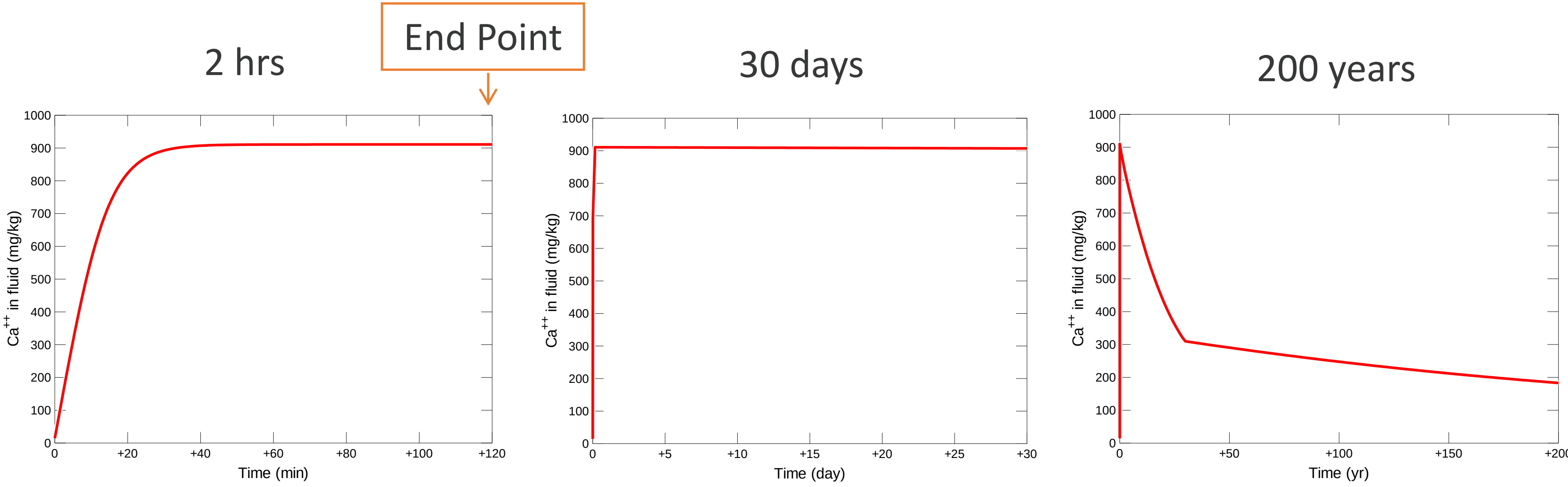
ID	Date	pH	Na	Ca	Mg	K	Cl	SO_4	Br	HCO_3	TDS	Charge balance
			- - -	- - -	- - -	- - -	- - -	mg/L	- - -	- - -	- - -	
Santa Rosa Fm. groundwater - depth of 460 m												
B1	Jun-13	8.0	1410	26.5	12.6	4.88	440	2200		372	4460	-0.38%
B1	Jan-14	9.1	1090	9.73	9.07	6.12	242	2120		385	3860	-9.02%
B1#	May-14	8.2	1490	20.7	8.51	7.87	456	2030		459	4480	3.17%
B1	Sep-15	8.8	1420	1.21	7.71	4.66	449	2060	2.17		3950	6.17%
B1	May-16	9.5	1450	3.75	1.32	4.60	488	2010	2.24	389	4350	-0.04%
B1	Nov-16	8.4	1470	21.1	11.3	4.84	458	2180	2.16	205	4350	3.54%
B1	Jul-17	7.7	1490	20.9	11.1	4.73	454	2160	2.11	449	4590	1.55%
	Average	8.5	1400	14.8	8.81	5.39	427	2110	2.17	377	4290	0.71%

32 scenarios

17	all minerals	1	1	1	1	1	1
18	all except calcite	0	1	1	1	1	1

Ca^{2+} Change over Time

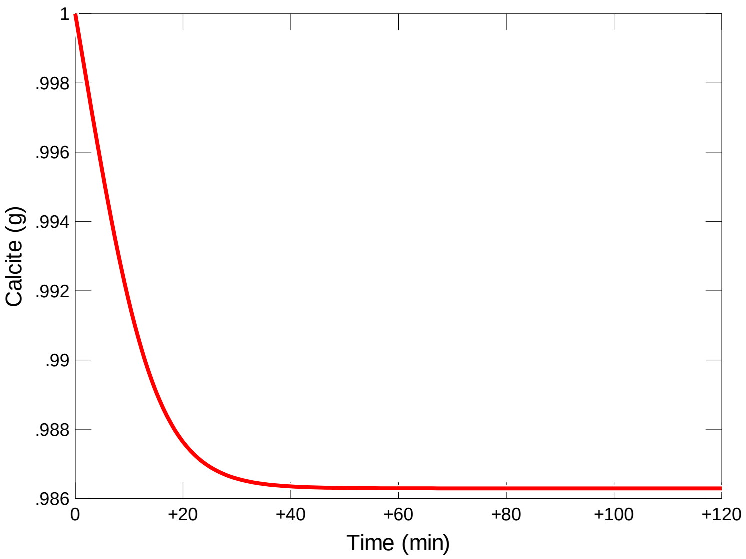
CO_2 = 0.30003 mol/kg, Scenario 17, all minor minerals, average fluid



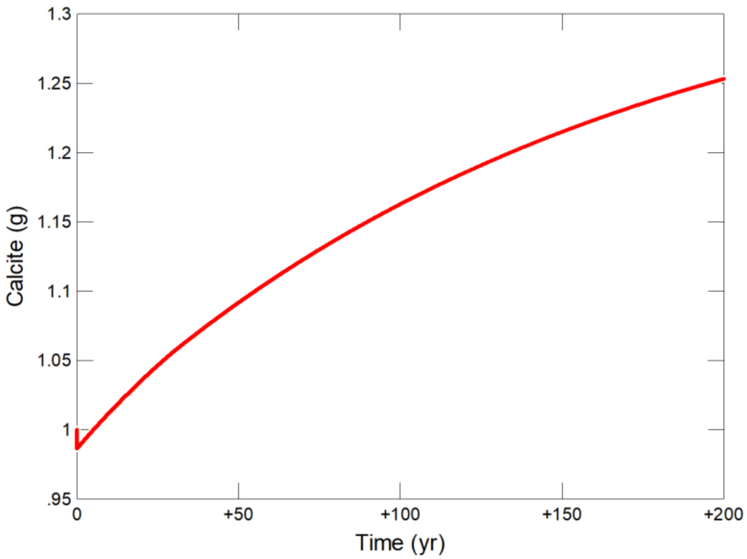
Rapid and significant Ca+ concentration increases only hours after the reaction. The concentration remains at a high level for days, weeks, even months, making it possible to detect this huge increase in a short monitoring period.

Minimal Calcite is Needed

2 hr



200 years



Minimal calcite (<2%) dissolution results in high Ca^{2+} concentration increase.

Calcite reprecipitation due to excessive CO_2 dissolution over time.

Geochemical Model Output Example

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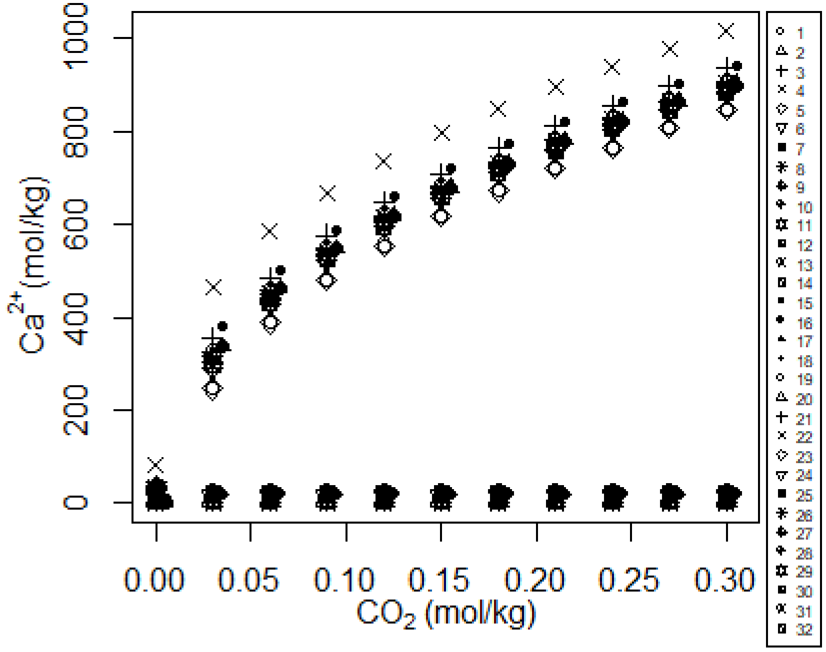
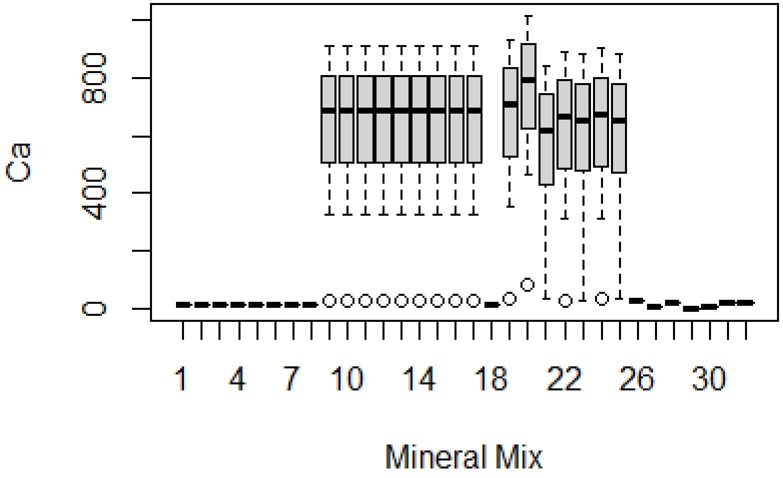
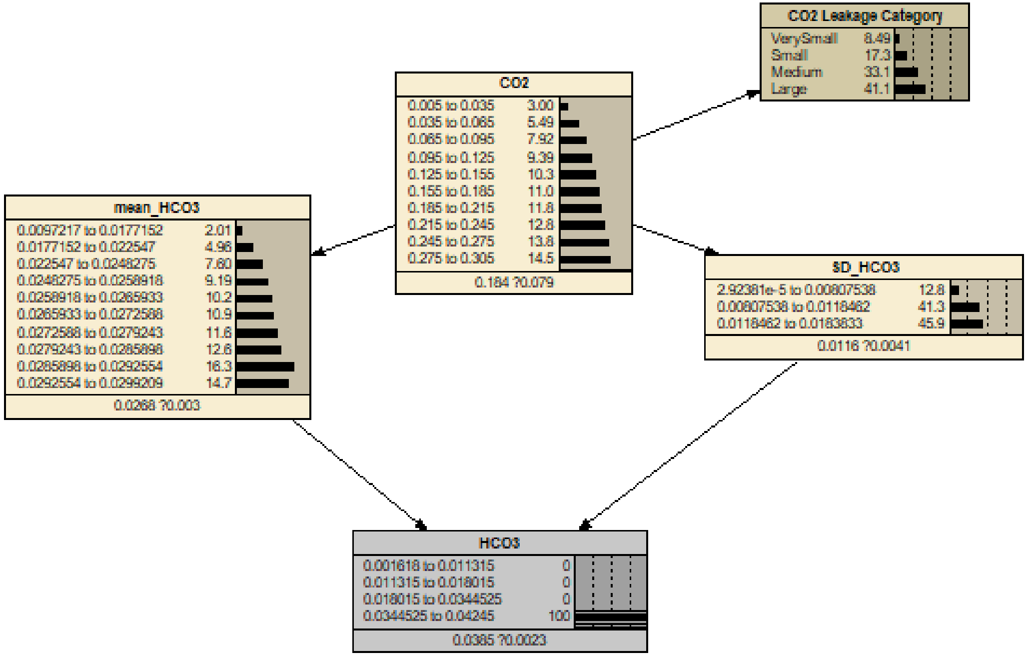


Sc 1-8 no calcite
Sc 9-16 with calcite
Sc 17 all minerals with calcite
Sc 18 all minerals except calcite
Sc 19-25: Sc17 with fluid variance
Sc 26-32: Sc18 with fluid variance



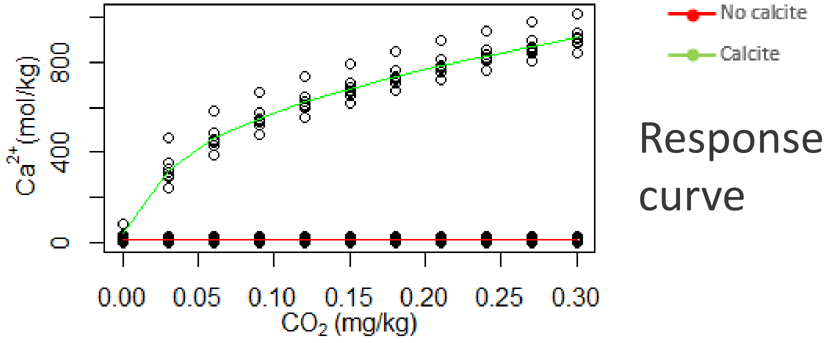
BBN for Leak Detection

- **Upstream node**
  - CO_2 added concentration
- **Arrows**
  - Causal effect
- **Downstream nodes**
  - Monitoring parameters
- **Bars of each node**
  - Probability of a particular range
- **Conditional probability**
  - Probability of downstream given upstream
- **Purpose**
  - Back inference

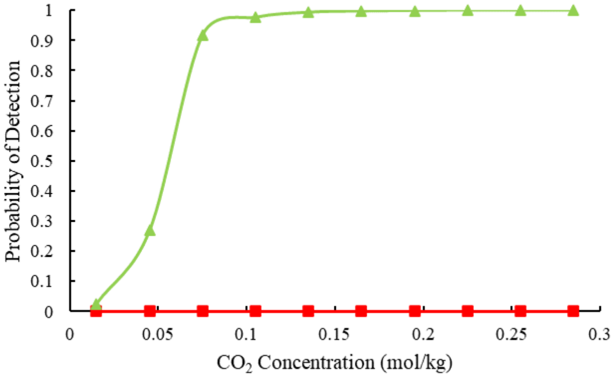


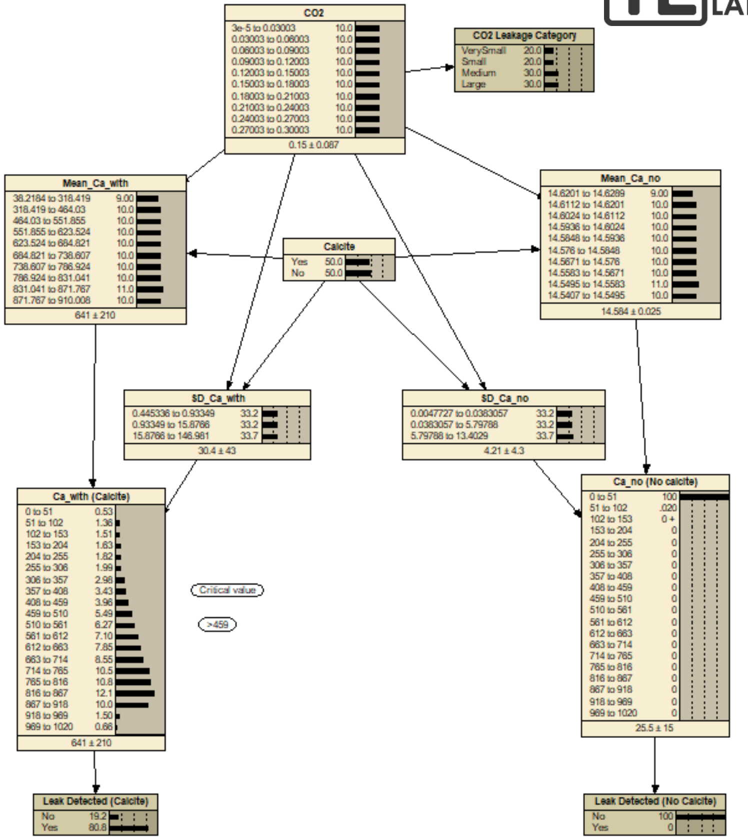
Single-Index BBN Example

Single-index (Ca^{2+}) example



Response curve





Other Indices for Single-Index BBN

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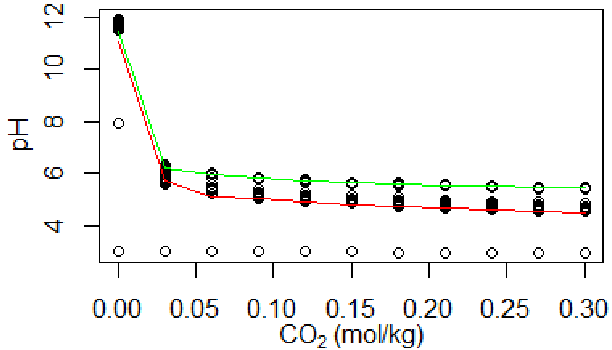
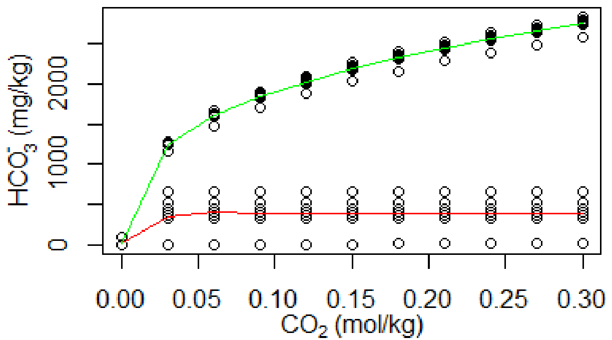
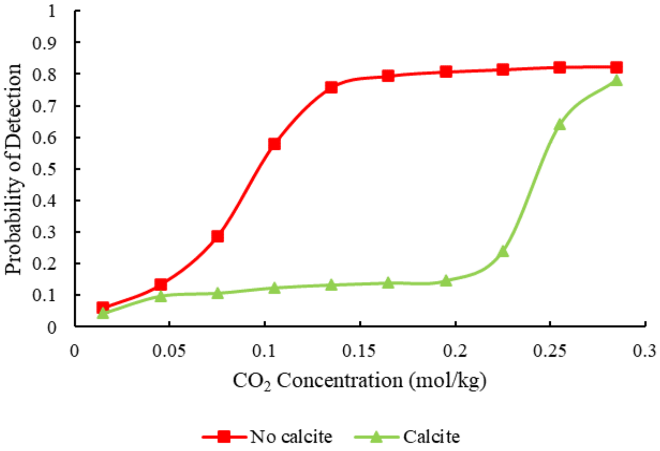
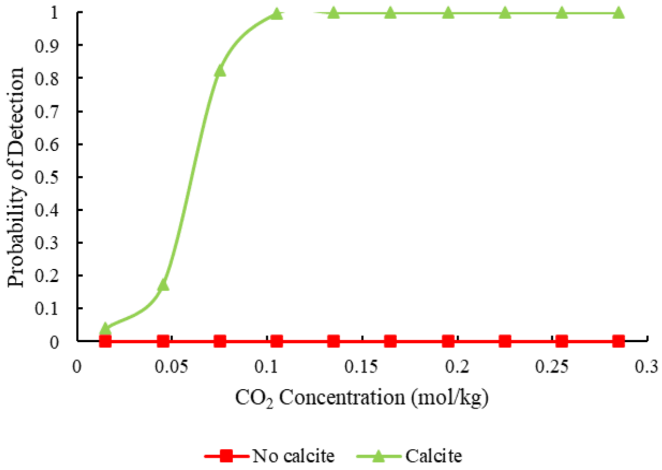




Ca^{2+}, pH, and HCO_3^- are selected as indices for BBN





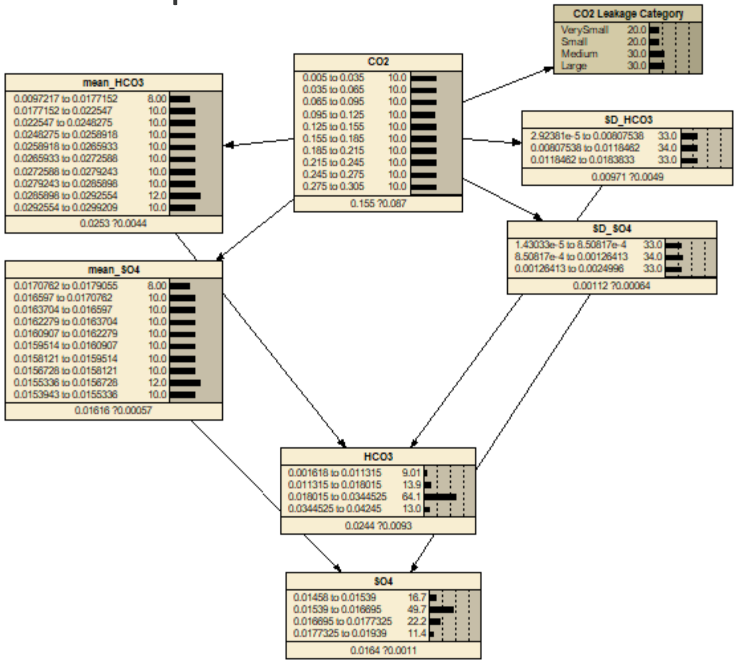
Multi-Index BBN

In progress:

- Combining Ca^{2+}, pH, and HCO_3^- for multi-index BBN model and CO_2(leakage) detection.

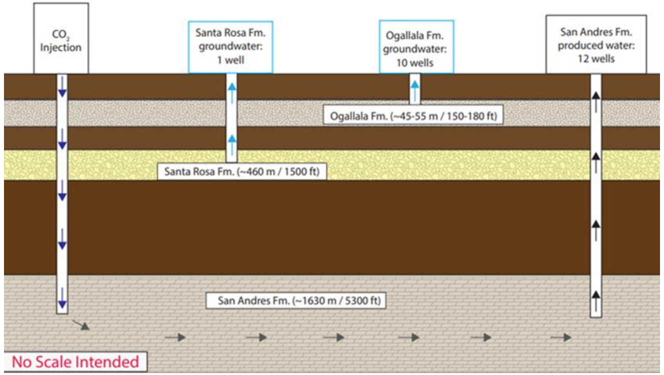
- Manuscript in preparation for *Environmental Science & Technology*.

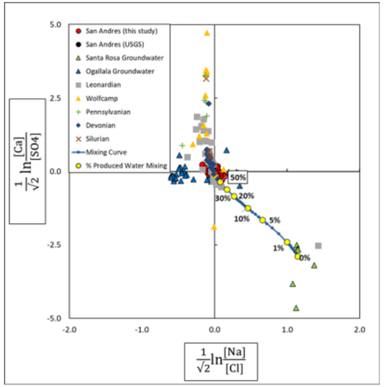
Example:



Conclusions

- **Geochemical monitoring provides insight into groundwaters and target formation reactions**
  - No significant dissolution of the storage reservoir
  - No produced water migration detected in groundwaters
- **Geochemical-statistical models (GILD) can provide CO_2 leakage detection via robust statistical analysis**
  - The current model applies user input via licensed software and researcher knowledge
  - The goal is to create a standalone version that can be used by groundwater observers





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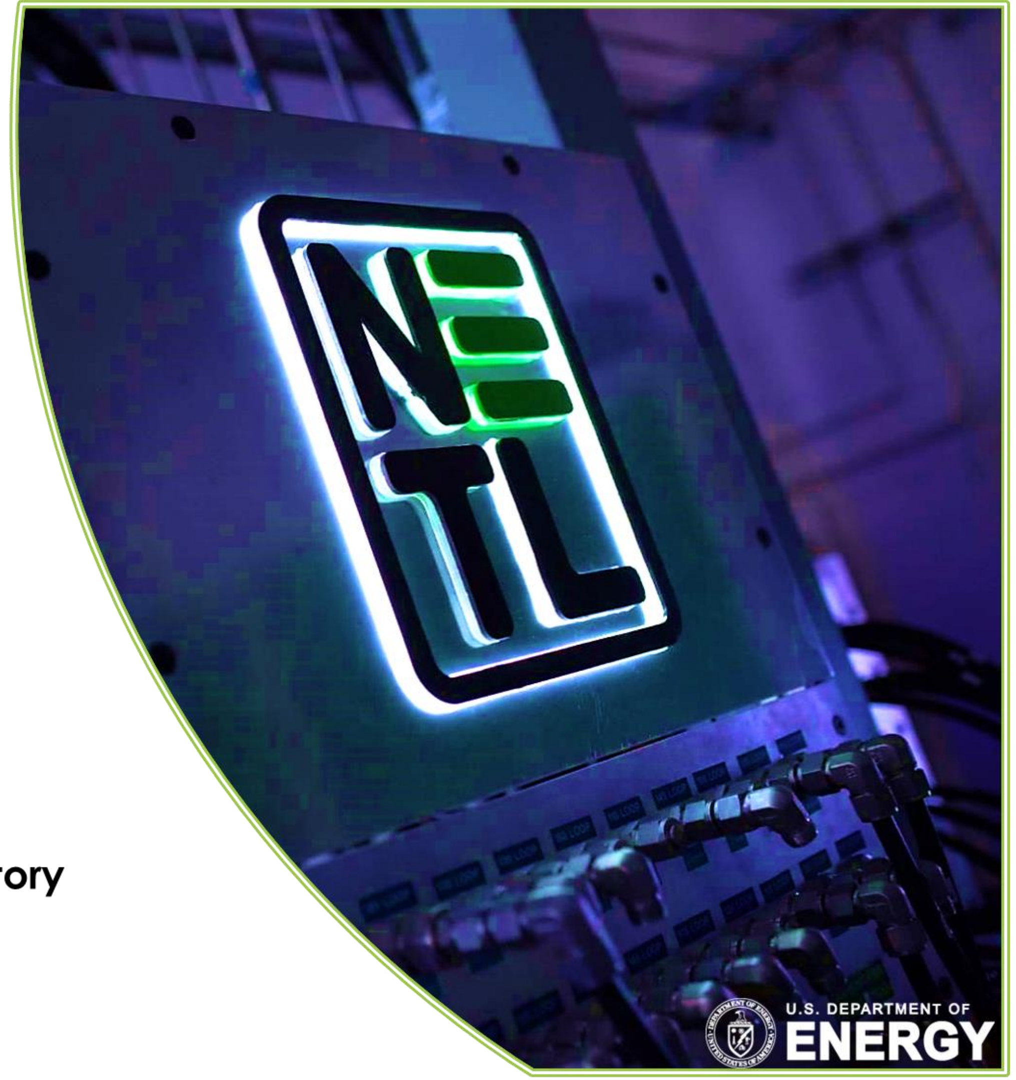
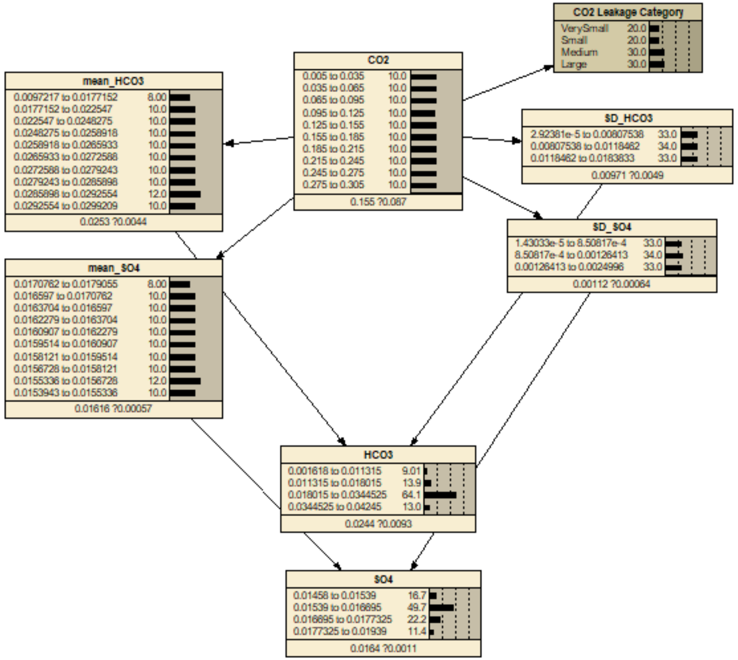


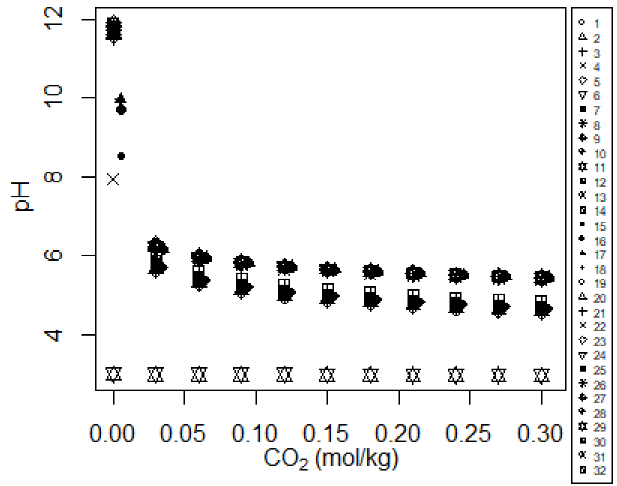
Supplemental Slides

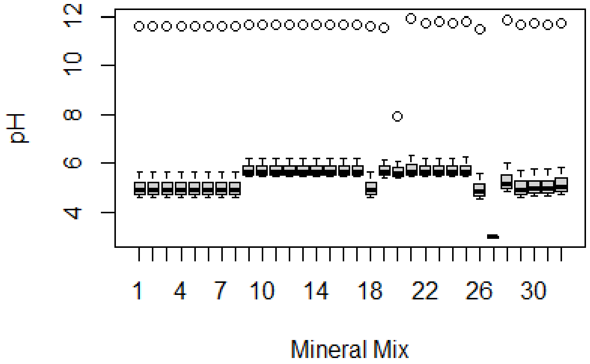
Construction of BBN-Regression Results

- Mean-predicted value from the response function for each CO_2 level
- SD-standard deviation of residuals (geochemical model output-predicted values)
- Ion concentration-normally distributed with mean and SD

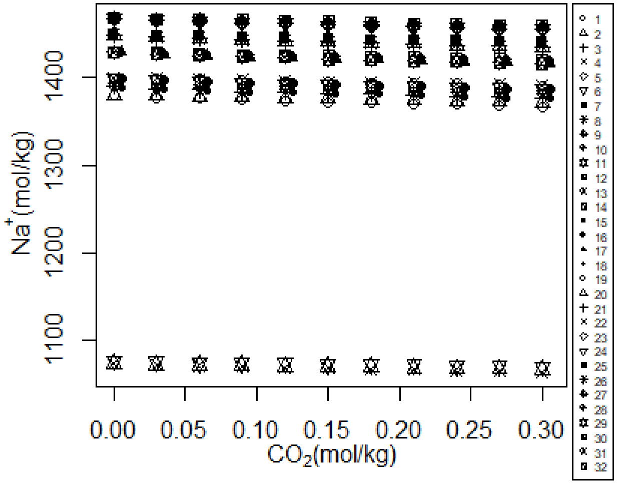


pH

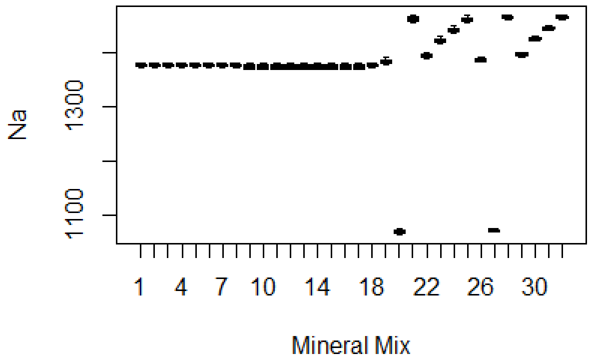

pH
12
10
8
6
4
0.00 0.05 0.10 0.15 0.20 0.25 0.30
CO2 (mol/kg)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32


pH
12
10
8
6
4
1 4 7 10 14 18 22 26 30
Mineral Mix

Na

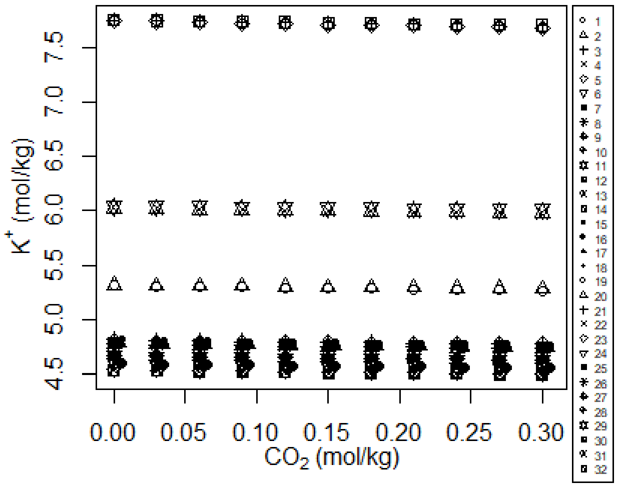


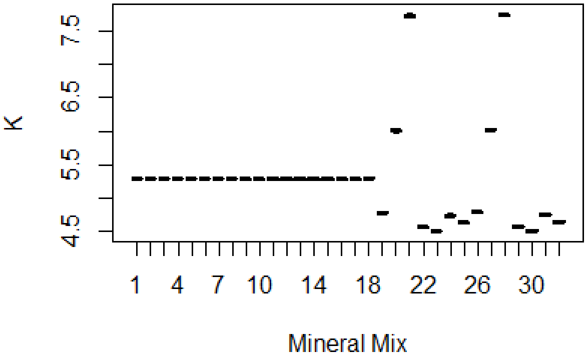
Na^+(mol/kg)
1100
1200
1300
1400
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO_2(mol/kg)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32



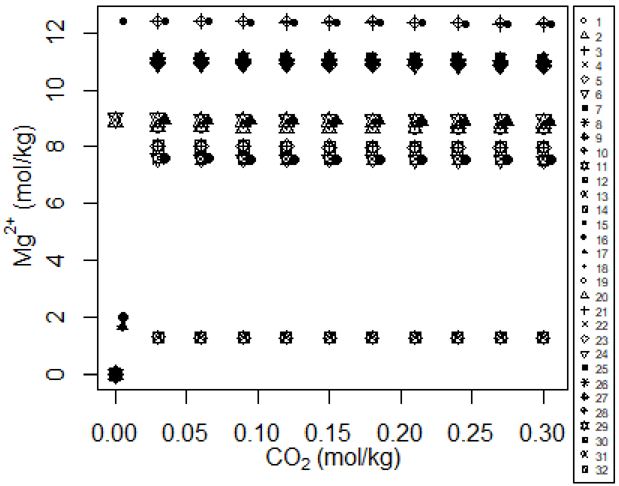
Na
1100
1300
1
4
7
10
14
18
22
26
30
Mineral Mix

K

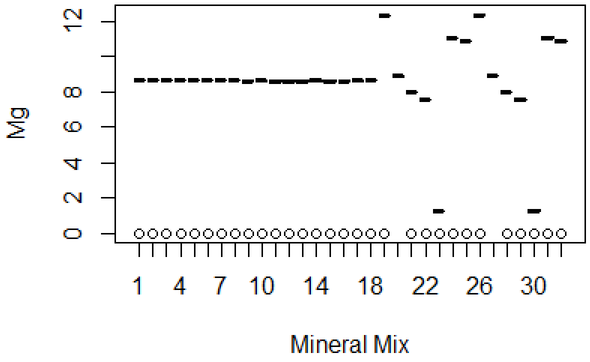

K+ (mol/kg)
4.5
5.0
5.5
6.0
6.5
7.0
7.5
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32


K
4.5
5.5
6.5
7.5
1
4
7
10
14
18
22
26
30
Mineral Mix

Mg

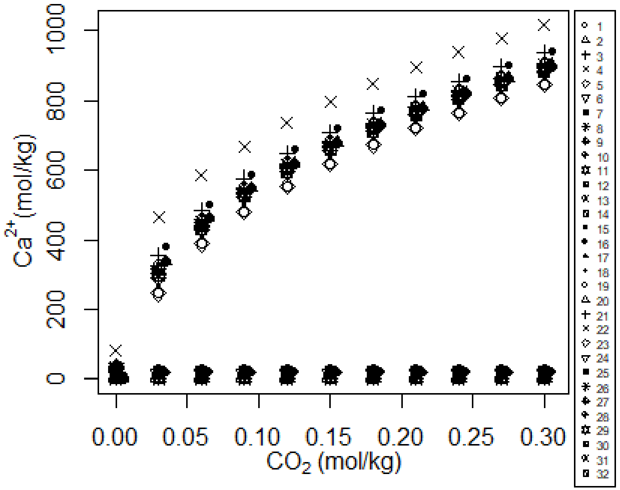


Mg^{2+} (mol/kg)
0
2
4
6
8
10
12
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO_2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

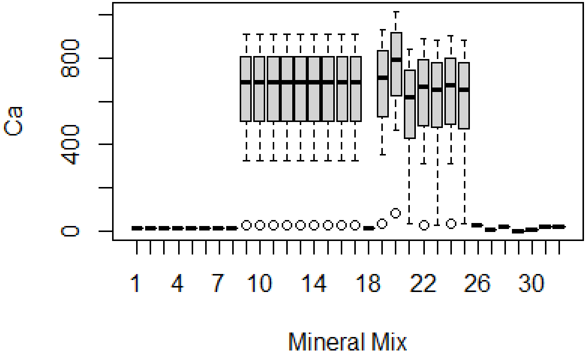


Mg
0
2
4
6
8
12
1
4
7
10
14
18
22
26
30
Mineral Mix

Ca

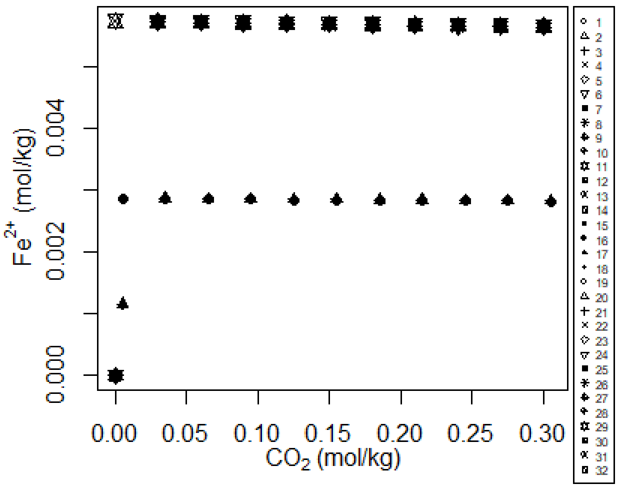


Ca2+(mol/kg)
0
200
400
600
800
1000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

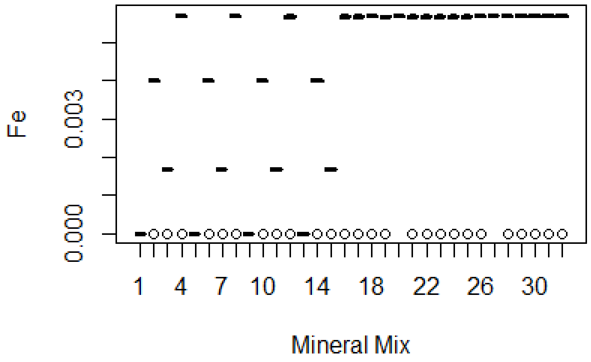


Ca
0
400
800
1
4
7
10
14
18
22
26
30
Mineral Mix

Fe

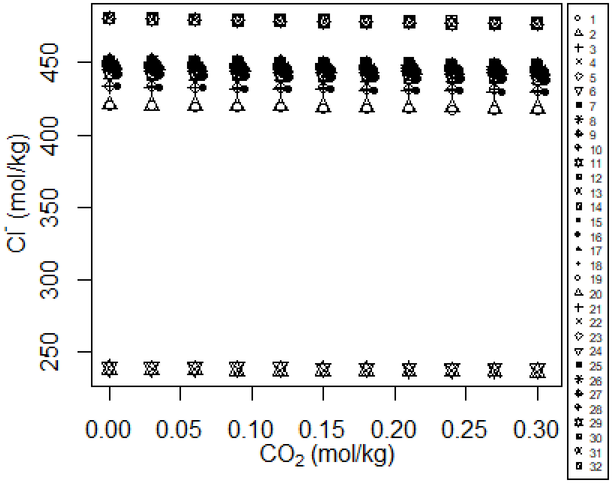


Fe2+ (mol/kg)
0.000
0.002
0.004
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

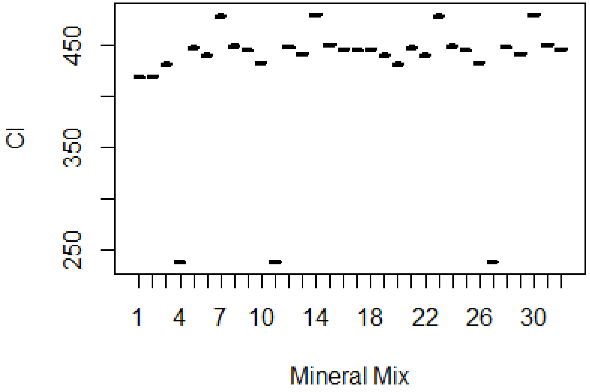


Fe
0.000
0.003
1
4
7
10
14
18
22
26
30
Mineral Mix

Cl

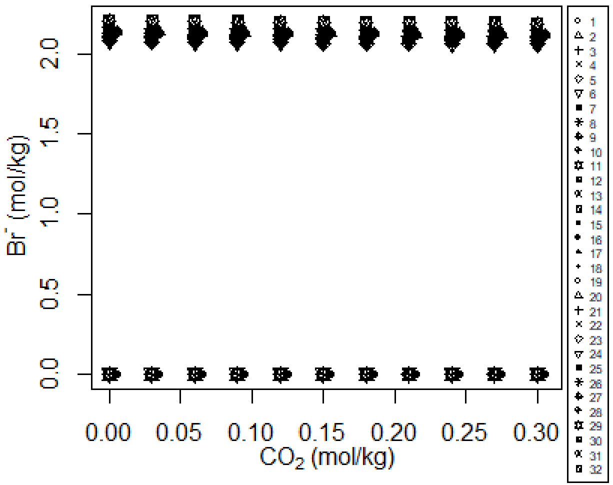


Cl⁻ (mol/kg)
CO2 (mol/kg)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
250
300
350
400
450

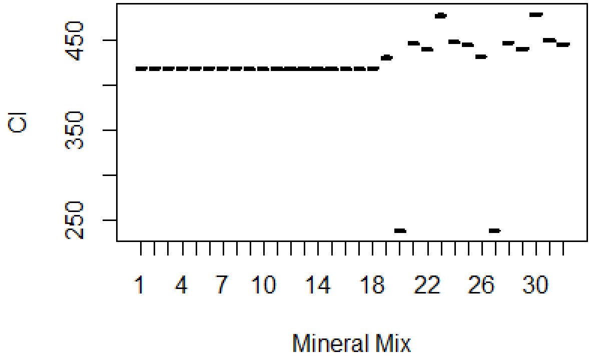


Cl
Mineral Mix
250
350
450
1
4
7
10
14
18
22
26
30

Br

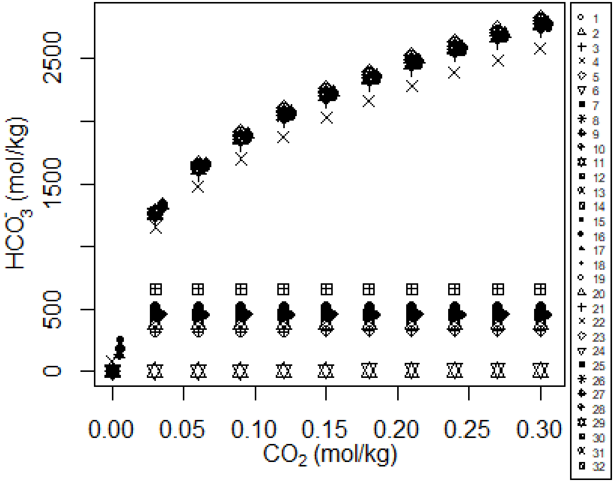


Br⁻ (mol/kg)
0.0
0.5
1.0
1.5
2.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

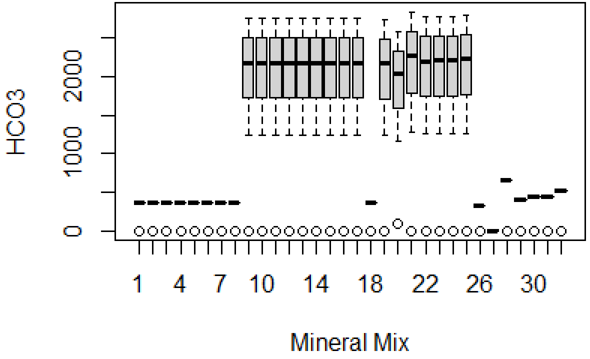


Cl
250
350
450
1
4
7
10
14
18
22
26
30
Mineral Mix

HCO3

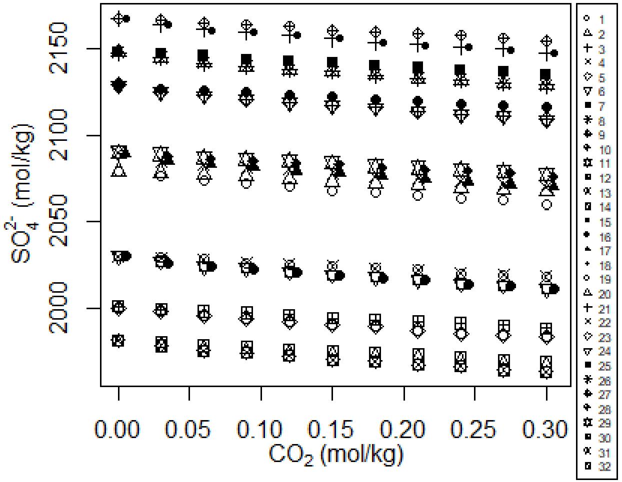


2500
1500
500
0
HCO3- (mol/kg)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

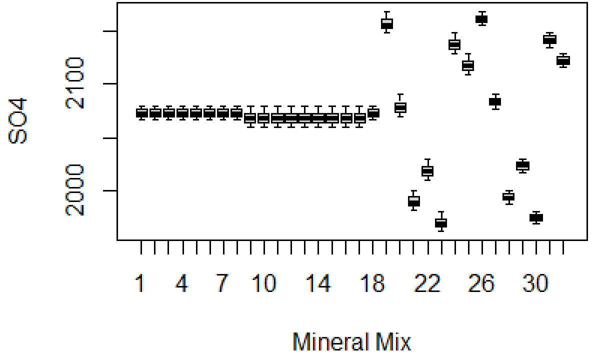


HCO3
0
1000
2000
1
4
7
10
14
18
22
26
30
Mineral Mix

SO4



SO_4^{2-} (mol/kg)
2000
2050
2100
2150
0.00
0.05
0.10
0.15
0.20
0.25
0.30
CO_2 (mol/kg)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32



SO4
2000
2100
1
4
7
10
14
18
22
26
30
Mineral Mix