Appendix 4-CC

Waste Rock Management Meeting - February 2018

Crown Mountain Coking Coal Project
Waste Rock Management Meeting

February 15, 2018 – 836 Yates Street, Victoria, BC
10:30-2:30PM

Attendees:

Ministry of Energy, Mines and Petroleum Resources
Andrew Dickinson
Tara Cadeau
Jennifer Brash
Paul Beddoes
Lowell Constable
Sean Shaw
Jennifer McConnachie

Ktunaxa Nation Council
Katrina Caley
Jesse Sinclair (LGL Limited)
Andrea Walter (Waterline)

Environment and Climate Change Canada
David Leung
Christie Spry
Ute Pott
Catherine Ponsford (*via teleconference*)

BC Environmental Assessment Office
Terry Pratt
Alex Denis

NWP Coal Canada
Richard Pope (Dillon Consulting)
Art Palm (NWP)
Lisa Kirk (Enviromin)
Stephen Day (SRK Consulting)

Canadian Environmental Assessment Agency
Fraser Ross

Ministry of Environment
Alison Neufeld (*via teleconference*)

Department of Fisheries and Oceans
Kevin Esseltine (*via teleconference*)

Ministry of Forests, Lands and Natural Resource Operations
Nicole Pyett (*via teleconference)*

Discussion Summary

	Question / Comment /Clarification	Initial response/follow-up discussion / etc.
Slides 1 to 8 - Art Palm **- Introduction/Overview into of team, project overview, project objectives, etc.**		
Slides 9 -58 - Lisa Kirk **- Biogeochemistry of Unsaturated Rock Piles** **- Theoretical underpinnings of the design (microbial, temperature, moisture, etc.)**		
1	With regards to the microbes, are we looking at different organisms?	Yes, there is a variety of microbes, each with different requirements. Iron reducers, iron oxidizers, selenium reducers, etc.
2	Which is the most bioavailable form of selenium?	Jesse Sinclair (LGL/KNC) commented that Selenite is taken up most efficiently (of the two forms noted).
3	Page 14 of presentation – Selenium Biogeochemistry - What are the neutralizing materials?	Calcite and dolomite.
4	Not all microbial reactions can be beneficial	Sulfate reduction, iron reduction - need to make an environment to have selenite reduce all the way through. Do not want to create sulphide gas which is a potential hazard.
5	What happens to nitrogen gas that is produced?	Very low levels of nitrogen gas generated.
6	Clarification re: increasing water content	Full saturation is not required as a dump with water saturated layers is not being proposed. Other projects in the Elk Valley looking at saturated conditions and the use of microbes.
7	Are there seasonal changes?	Typically sub-surface does not freeze. There may be changes with freshet (increased oxygen infiltration, etc.)
8	Clarification re: acid rock drainage generation potential?	Below the lowest coal seam, the Moose Mountain Member has the potential to produce acid. These areas will generally not be mined, with minor exception where some benching may occur to stabilize the footwall.
9	What is the highest temperature for Sulphur oxidation?	16 degrees.
10	Is selenium speciation being evaluated as part of the project?	Yes it is. Pathway depends on carbon source and the availability of carbon.
11	Changes in microbial ecology observed are based on carbon and oxygen environment - which affects more?	Oxygen environment. A number of factors go into choosing the carbon, something that doesn't freeze.

	Question / Comment /Clarification	Initial response/follow-up discussion / etc.
Slides 59 - end – Stephen Day **-Crown Mountain Design**		
12	What is the level of reduction for Teck reactors? Why were they having problems?	Unsure, could potentially be due to oxygen levels? In the work on Crown Mountain, will need to ensure we get to reduced phases.
13	Process question – what are the next steps?	Have not completed lab work yet - modelling only. Column work will occur in the near future. Analyzing materials to get an idea of what materials to place in columns. Columns will be unsaturated (dripped water). Phase 1 was positive - Phase 2 will start shortly. Until Phase 2 complete we will not have a definitive plan moving forward.
14	Dealing with a combination of parameters - how to tie together? How to deal with on-site? Will there be monitoring on site? If so how will it be implemented?	There will be in-situ monitoring, although at this point not sure what monitoring will look like. Understand that this will be key once we move out of the laboratory. Currently trying to refine model inputs.
15	Do the findings rely on water flowing vertically through the pile?	Yes. But there is a way to manage water movement through construction design.
16	Sequencing of rock - how will it be dealt with?	There will be multiple benches which will allow us to deal with spoil sources (overburden, plant reject) as they are produced and disposed of in various stages of pile construction.
17	Will you be able to estimate residence time in the columns?	Yes - with the use of tracers. Based on rates will have to scale up for bigger scale facility.
18	Does it scale well?	Yes - but may not be linear.
19	How to scale?	Scale flow based on what we see in the field. Have some strong evidence moving forward. Problem is dripping water slow enough.
20	Time scale on phases?	Phase 1 - approximately 6 months. Phase 2 - estimated 6 months but could be longer to gather additional information (incremental level of effort low as the columns constructed).
21	Where will be in the waste management assessment process when we submit an Application?	As discussed, a high level of confidence is required before an application is submitted. Specialists and Working Group should agree.
22	After you receive the oxygen profile is it linked back to selenium?	We predict oxygen is low enough, predict it would happen given the inputs.
23	What degree of water management are	Still to be finalized. Expected to include a large

	Question / Comment /Clarification	Initial response/follow-up discussion / etc.
	you going to use for the waste rock management areas?	number of diversion ditches/channels. The intent is that any water introduced will be from natural precipitation. Low oxygen conditions in both refuse and rock layers.
24	Will the climate station go back up?	Information from the previous climate station was used and scaled; a longer set of records over a longer period will be required. A permanent climate station will be installed during project construction or before.
25	Re: Moisture content in the reject layer - what happens with moisture content with snow cover - is there still infiltration? Does it influence levels?	Still some infiltration, but not a concern. The comment regarding adding 2 m layer of waste rock over top primarily to control evaporation.
26	How long would the mine be in operation?	16 years.
27	What happens in the long-term?	This is not a static feature, and the long term will be addressed in detail during permitting.
28	What if oxygen does not deplete as fast as expected?	Will be part of the assessment. There are options to address this if encountered.
29	Is NWP aware of proposed changes to federal coal mining effluent regulations (ECCC)?	Yes, NWP is aware of that discussion.
30	What is the source of groundwater used in the initial assessment? Which depth was used for groundwater collection?	Well 13-06. GW is associated with the 9 and 10 seams (of the Mist Mountain formation). It terminates in the basal sandstone directly below the lowest seam member to be mined (the 10 seam). Borehole log is available on request (was provided in the 2013 Coal Assessment Report on Crown Mountain). Open bore holes were used. At the time of collection of the water sample, the initial depth to water was 22.7m. Depth to bottom of well = 35.47m. Top of screen = 31.7 m and bottom of screen = 34.7 m.
31	What is groundwater being used for? As a proxy?	Influent to the columns to reflect the biology of water and equilibrium community. Coal reject had very little nucleic acid to work with and it is important to have some site specific organisms. Trying to understand the effect during storage as it is difficult on the front end of a greenfield coal project.
32	Test conditions at 10°C – what is the basis of the selection of the temperature?	10°C is considered a good average for sub-surface conditions encountered within waste rock in the Elk Valley.
33	Is the temperature representative of	Yes, a representative temperature.

	Question / Comment /Clarification	Initial response/follow-up discussion / etc.
	what we might expect in the waste rock management piles and does it affect microbial communities?	Yes, it will influence microbial communities.
34	Does temperature matter? Will a significant shift influence things?	Yes, temperature does influence microbial communities – but there will always be some activity. Monitoring down the road will occur once we get to an in situ demonstration.
35	Use of respirators – will they give an estimate for the depletion rate for carbon?	Yes – but will be a long term experiment. With respect to the long term carbon depletion, we can make some simplifying assumptions and calculate long term availability of carbon. The study team will be completing respirometry tests and will calculate a rate of oxygen consumption via biotic activity - with corresponding carbon consumption based on stoichiometry. This will allow us to compare the consumption rate to total carbon for the samples. It is expected that this assessment will show an enormous excess of carbon.
36	Column Test – methods for controlling rates?	Working on methodology. Demonstration columns were built to provide information.
37	What is the influent rate for the proposed Phase 2 Column test design and how this would compare to the expected site infiltration rates (e.g. mm/yr).	The final column design is being determined including proposed column flow rates. It is expected that the rate will be as slow as the pumps will allow, with the intent of trying to remain within the predicted range of flow for the site while maintaining unsaturated flow. The key is ensuring enough sample is obtained to analyze key parameters (e.g., NO3, total selenium, DOC, etc.).
38	What is being proposed for effluent characterization?	Will include selenium speciation.
39	Is water treatment being considered in the interim until the pile starts working as intended?	NWP considers water treatment to be an option of last resort, and is focused on engineering permanent solutions to the selenium issue. Therefore, NWP is looking at other options to accelerate pile efficiency in the short term. For example, use other coal rejects for carbon source.
40	Comment – EMPR The reality of permitting semi-passive approaches is very difficult, particularly in the Elk Valley. How does NWP intend to backstop until	Acknowledged by NWP and certainly valid points we must address as the process moves forward.

	Question / Comment /Clarification	Initial response/follow-up discussion / etc.
	approach proven? EMPR will be looking for alternatives to be part of the submission.	

Crown Mountain Project Waste Rock Facility Design

Regulatory and KNC Meeting at Victoria BC

February 15, 2018

Enviromin

NWP Coal Canada Ltd
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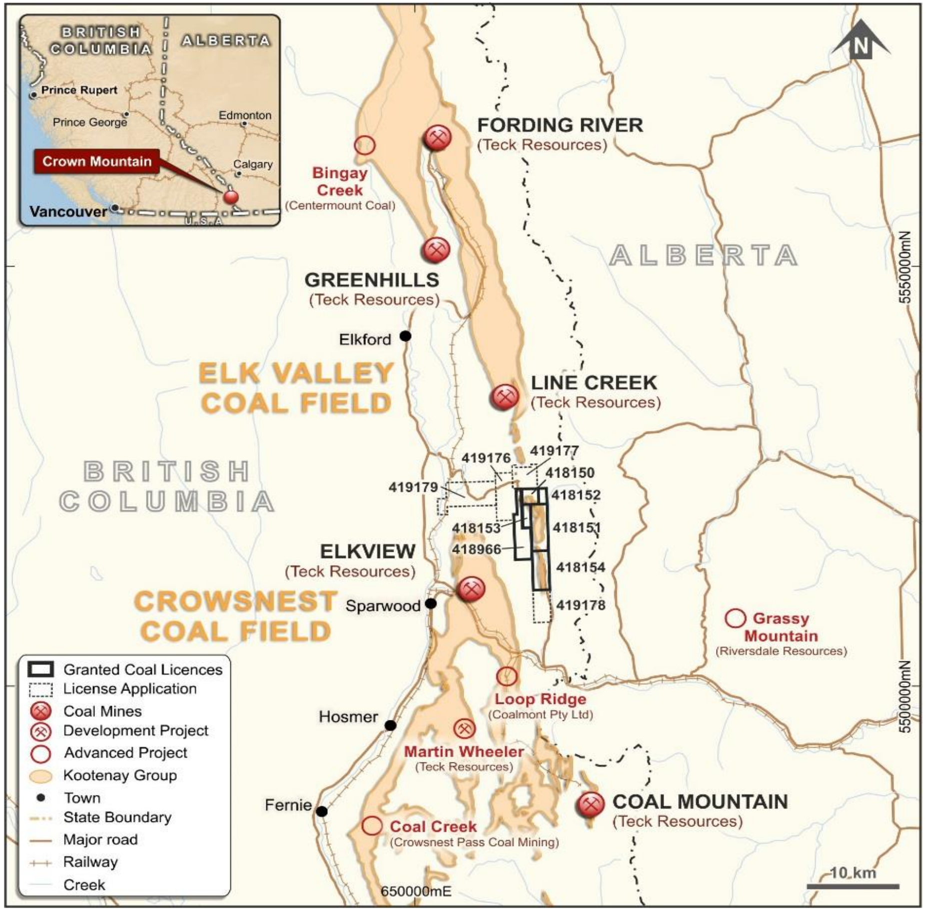
srk consulting

Agenda

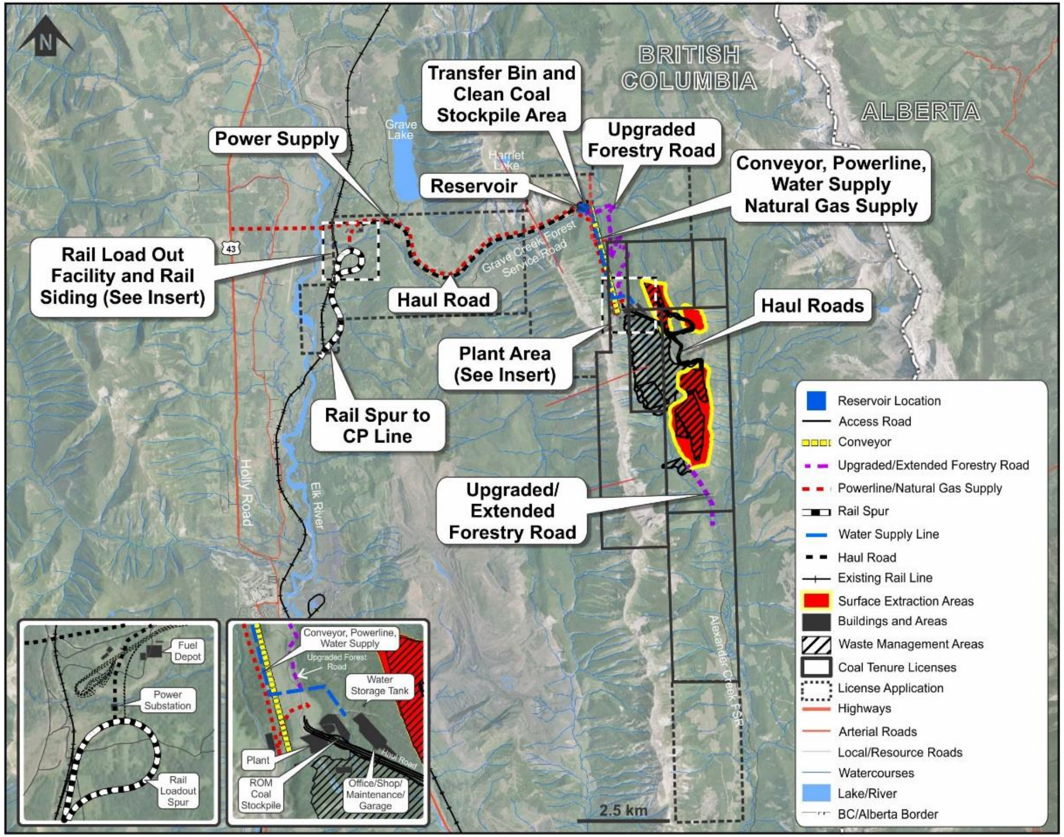
- Project Introduction
    - Project location and history
    - Project components
- Project Objectives
- Biogeochemistry of Unsaturated Coal Rock Piles
- Crown Mountain Proposal
- Site Characteristics
    - Geology, geochemistry, hydrology
- Project Scope and Status
    - Phase I Results
        - Unsaturated flow modelling
        - O2 Transport and Consumption Modelling
        - Implications for Pile Performance
    - Phase 2 Activities
- Next Steps

Crown Mountain

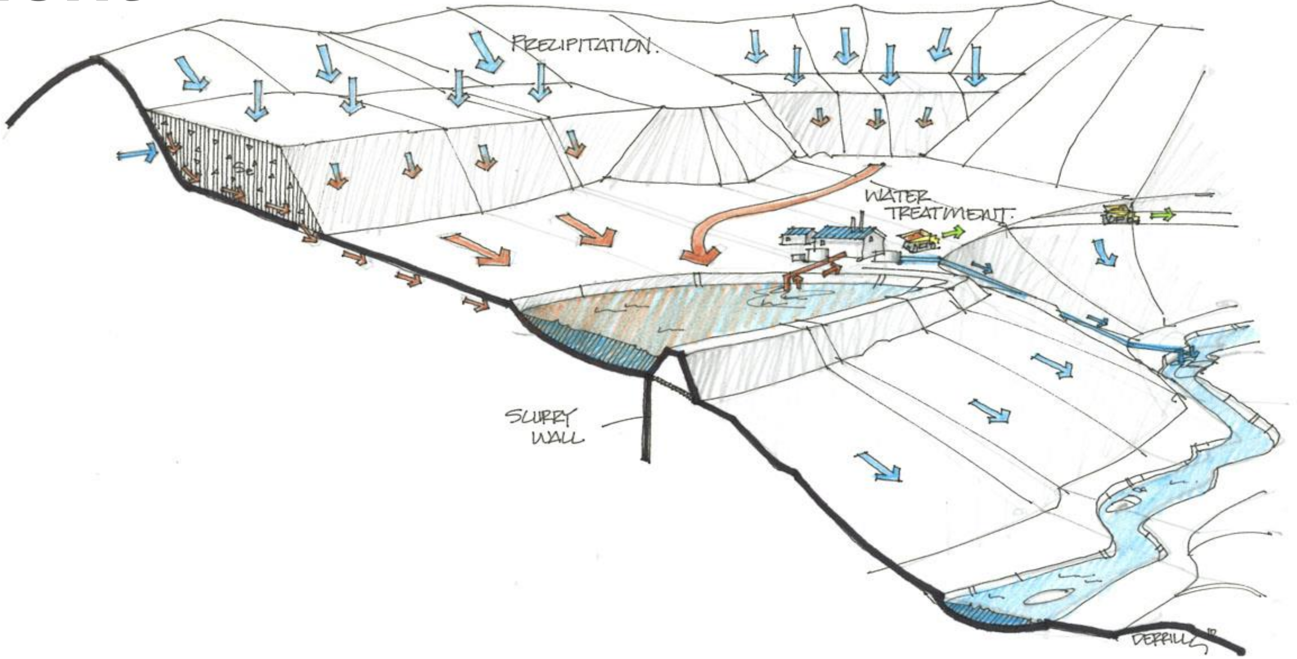
Location



Crown Mountain Plan



Selenium Management



Selenium Mitigation

- Water treatment
  - Treat mine effluent waters
- Water management
  - Reuse Se impacted water
  - Divert clean water around rockdrains
  - Divert clean run-on water away from dumps
  - Reduce infiltration with dump covers
- Dump design to reduce Se loading
  - Selectively handle and encapsulate Se material
- *In situ* microbial source control
  - Interbed CCR/tails with waste rock
  - Control oxygen, moisture, lithology (carbon) to affect reduction
- Mine planning
  - Change from surface to underground mining
  - Design facilities for *both* resource recovery and waste management through selective handling, sequencing, and placement

SAPSM, 2010

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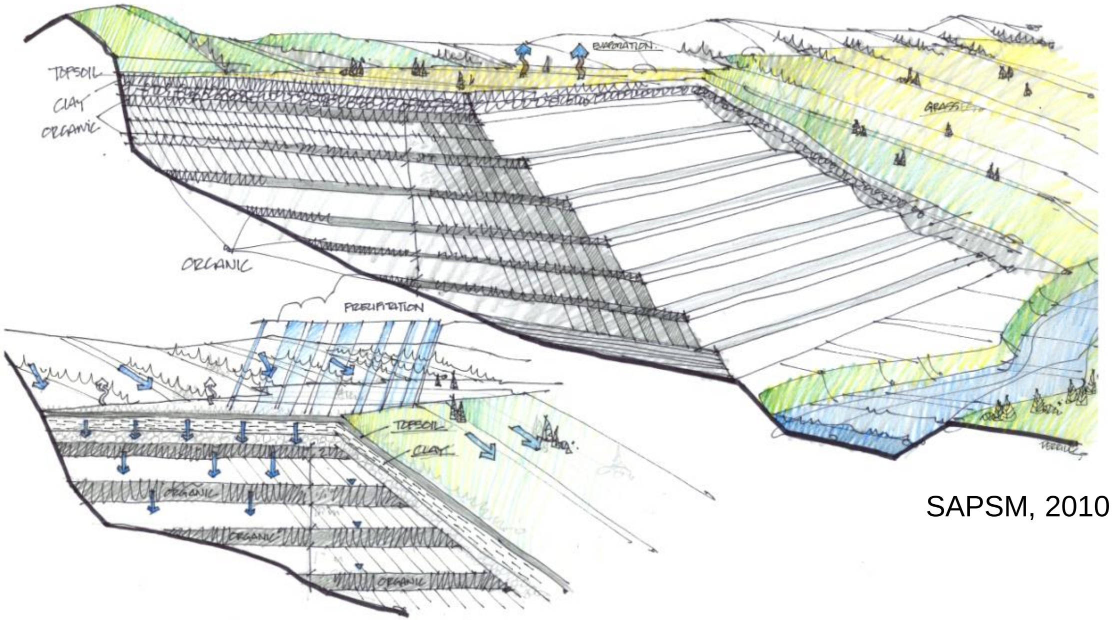
Suboxic Waste Rock Dump Design

Attenuation (biotic and abiotic) >> Release (oxidation/desorption)



SAPSM, 2010

Crown Mountain

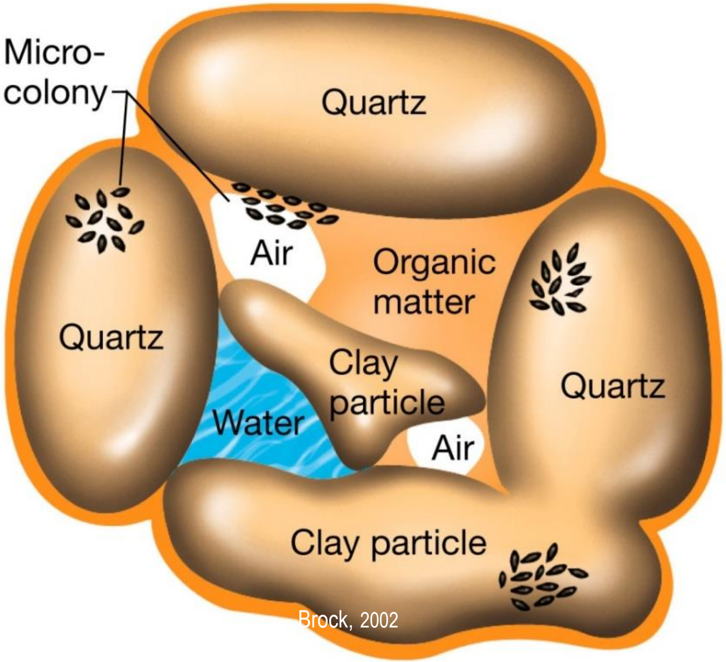
Project Objectives

- Evaluate conditions needed to drive O_2 to suboxic (<0.5 mg/L) levels required for nitrate and selenate reduction
  - Material characteristics
  - Material placement
  - Gas and water flux
  - Microbial community capacity
  - DOC availability
- Goal - design a dump to achieve suboxic conditions sufficient residence time to allow for denitrification and selenium reduction to occur

Biogeochemistry of Unsaturated Rock Piles

Dr. Lisa Kirk
Principal Biogeochemist
Enviromin, Inc., Bozeman MT

What are the key factors influencing microbial metabolism?



Brock, 2002

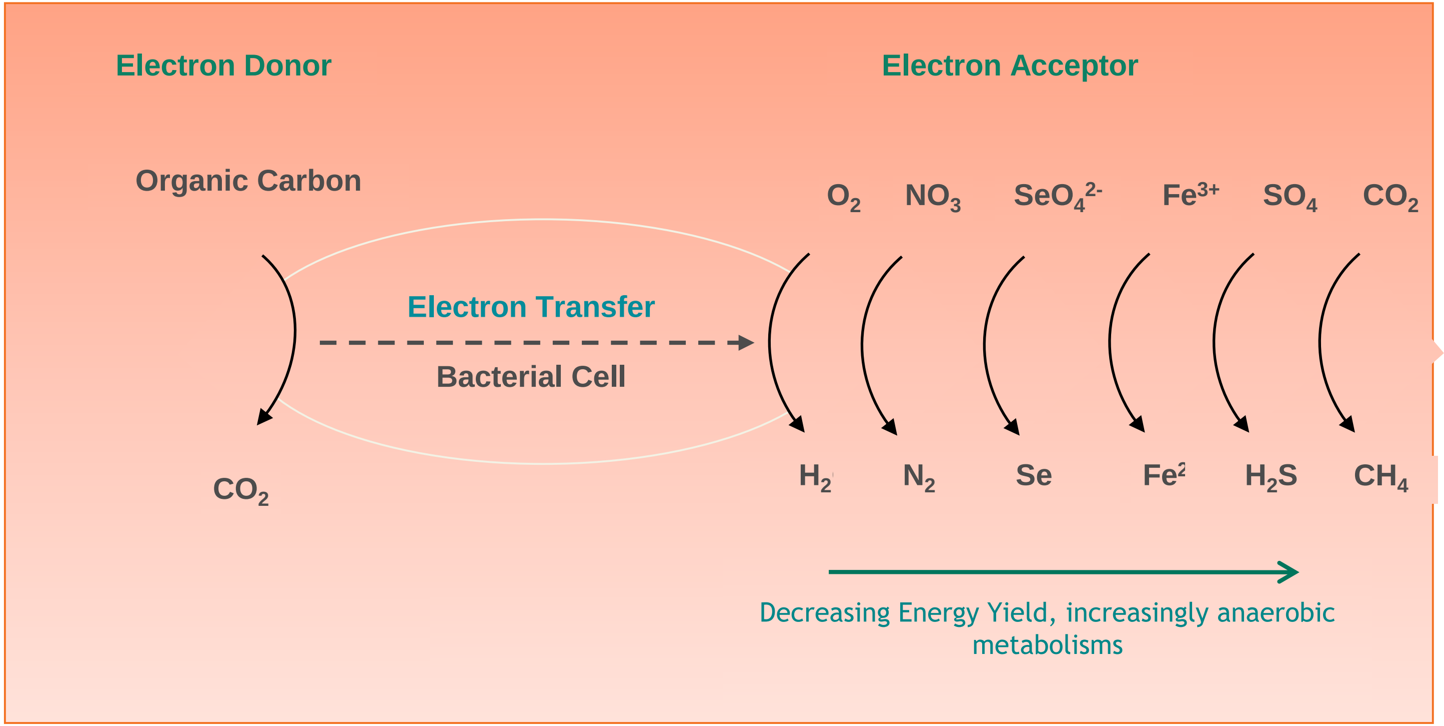
- Electron Donor
  - Carbon
- Electron Acceptor
  - Fe^{III}, Se^{VI}, As^{V}
- Enzymes – proteins that catalyze reactions
- Nutrients
- Moisture
- Temperature
- Gas – aerobic v. anaerobic
- Inhibitors - NO_3, SO_4, salinity, other metals

Redox Biogeochemistry

- In mined materials, native microbes biochemically oxidize or reduce nutrients (e.g., NO_3^-), various metals/metalloids (e.g., Se, Fe), and S –
    - To make energy
    - To detoxify their own environments
- Microbes drive rates of reactions between minerals and water (kinetics)
    - Oxidation (e.g., FeS_2 to ARD)
    - Reduction (formation of sulphide or insoluble Se minerals)

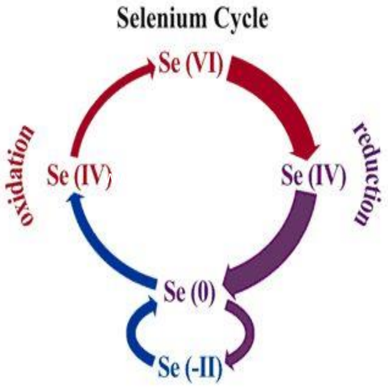
- Electron exchange during oxidation or reduction, from
    - reduced carbon (DOC, e.g. methanol, acetate, etc.) Oxidation – electrons lost
    - Fe^{2+} to Fe^{3+} (1 e- removed)
  - Reduction – electrons gained
    - Fe^{3+} to Fe^{2+} (1 e- gained)
  - Elemental cycling
    - Fe^{3+} to Fe^{2+} to Fe^{3+} to Fe^{2+} , etc.

Microbial Metabolism



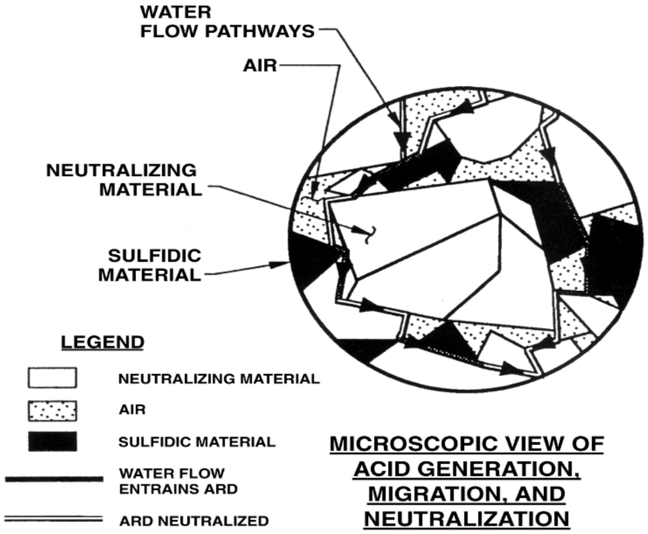
Selenium

- Redox-sensitive metalloid
  - Mobile under oxidizing, alkaline conditions
  - Immobile under reducing, moderately acidic conditions
- Four valence states: +VI,+IV, 0, -II
  - $Se^{+VI}O_4^{2-}$ selenate
  - $Se^{+IV}O_3^{2-}$ selenite
  - Se^{o} elemental selenium
  - H_2Se^{-II} selenide gas, metal selenide
- Attenuation Mechanisms
  - Sorption – selenite to iron oxides, clays, calcite
  - Mineral precipitation – selenite/selenate salts ($BaSO_4(SeO_3){\bullet}2H_2O$, metal selenide minerals, elemental selenium
  - Degassing as H_2Se or methylated Se



Selenium Biogeochemistry

- Mineralogy – Se residence, habit (surface area), composition, sorption or precipitation, remobilization
- Aqueous Geochemistry – solubility and sorption controls on mobile Se – Eh/pH, DO
- Water – flushing mineral surfaces, transporting O_2, limiting gas flux
- Oxygen – sulphide oxidation, aerobic v. anaerobic microbial metabolism
- Microbial activity – S oxidation, Se reduction, NO_3 inhibition
- Scale – affects of gas and solute diffusion, convection, surface area and kinetics.



MICROSCOPIC VIEW OF ACID GENERATION, MIGRATION, AND NEUTRALIZATION

From Hutchison, 1992

Se cycling – abiotic and biotic

- Abiotic oxidation, release, mobility

$Se^o + 3/2O_2 = SeO_3^{2-} + 1/2O_2 = SeO_4^{2-}$

- Biotic selenate reduction

$4CH_2COO- + 3SeO_4^{2-} = 3Se^o + 8CO_2 + 4H_2O$

  - Kinetic constraints for selenate reduction
  - Non specific/detox – nitrate reductase enzymes
  - Growth – selenate reductase enzymes

- Selenite and elemental selenium can be further reduced via biotic or abiotic pathways

Abiotic $Se^{VI}O_4$ Reduction

- Abiotic reduction of $Se^{VI}O_4$ to $Se^{IV}O_3$ occurs very slowly except
  - Green rust (Fe^{II}-Fe^{III} hydroxysulphate)

Myneni et al, 1997

- Abiotic reduction of $Se^{IV}O_3$ to Se^{o} more common

Chakraborty, 2010

  - FAST (24 hrs) siderite, mackinawite, magnetite
  - SLOW (weeks) pyrite, troilite, green rust , Fe(II)-adsorbed montmorillonite, and zerovalent iron Fe(II) sorbed on or coprecipitated with calcite
  - reduction products can differ with a variety of elemental Se (red, gray) and iron selenides (e.g., FeSe)

Is SeO_4 reduction the same as SO_4 reduction?? NO!

Sulphate

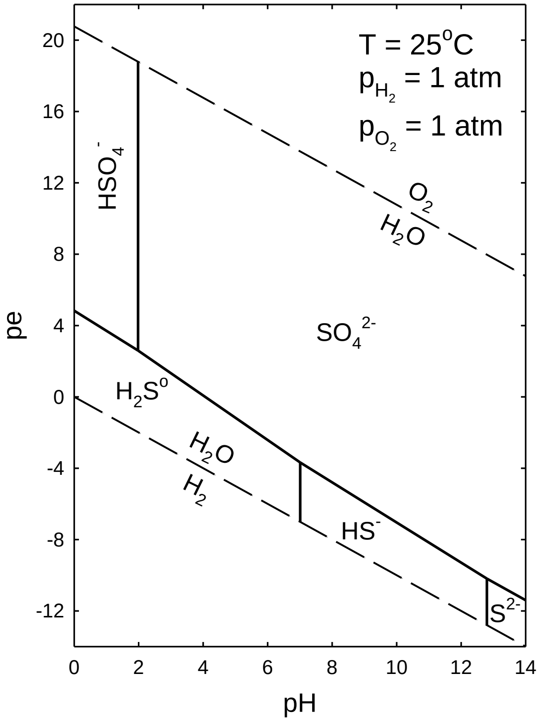
- Obligate Anaerobes
- Delta Proteobacteria
- Some sulphate reducers will reduce selenate to selenite
- Limited suite of C substrates: Lactate, fatty acids, alcohols, H_2
- SO_4 respiration yields -0.1 kcal/mol/e
- Can’t tolerate oxygen

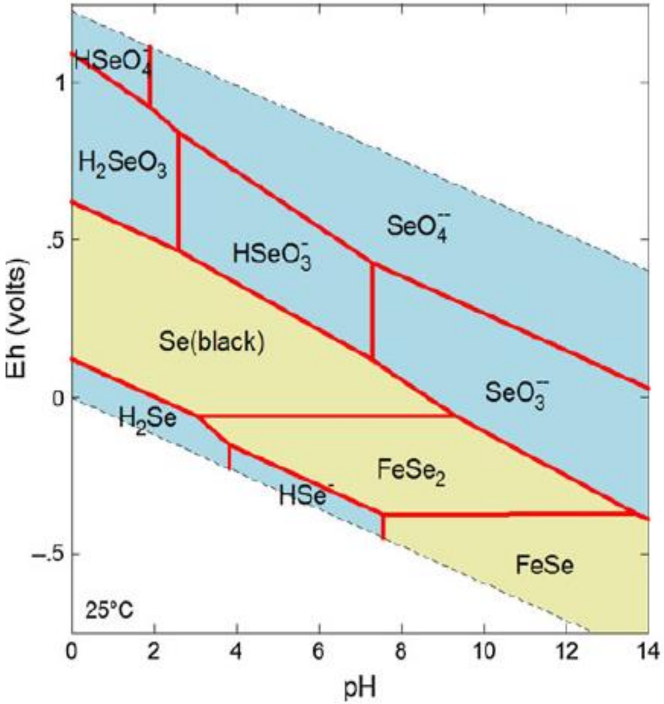
Selenate

- Diverse Anaerobes, Facultative Anaerobes, Aerobes
- SeO_4 respirers do not respire SO_4
- Broad spectrum of carbon
- Denitrification associated
- SeO_4 respiration yields -15.53 kcal/mol/e
- Can tolerate oxygen

Erlich and Newman, 2009

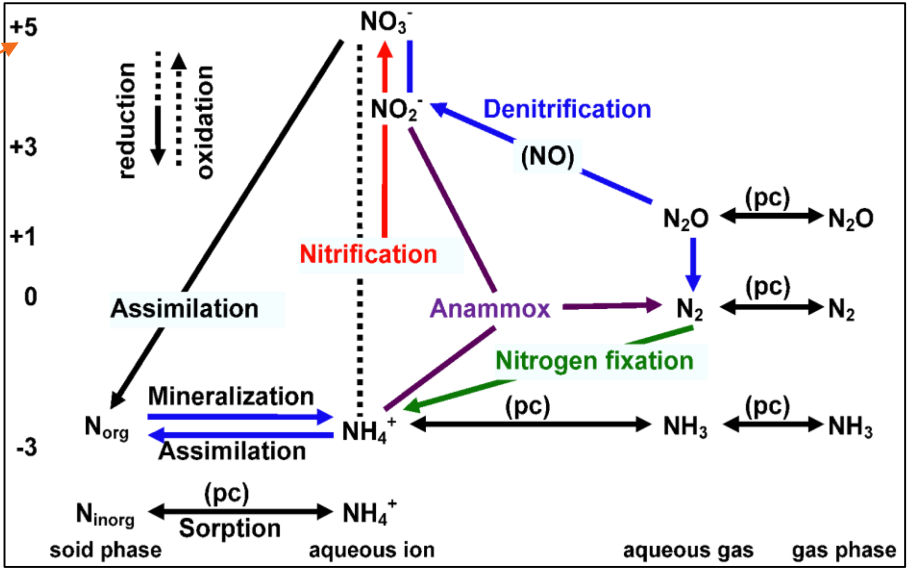
Sulphate vs. Selenate reduction





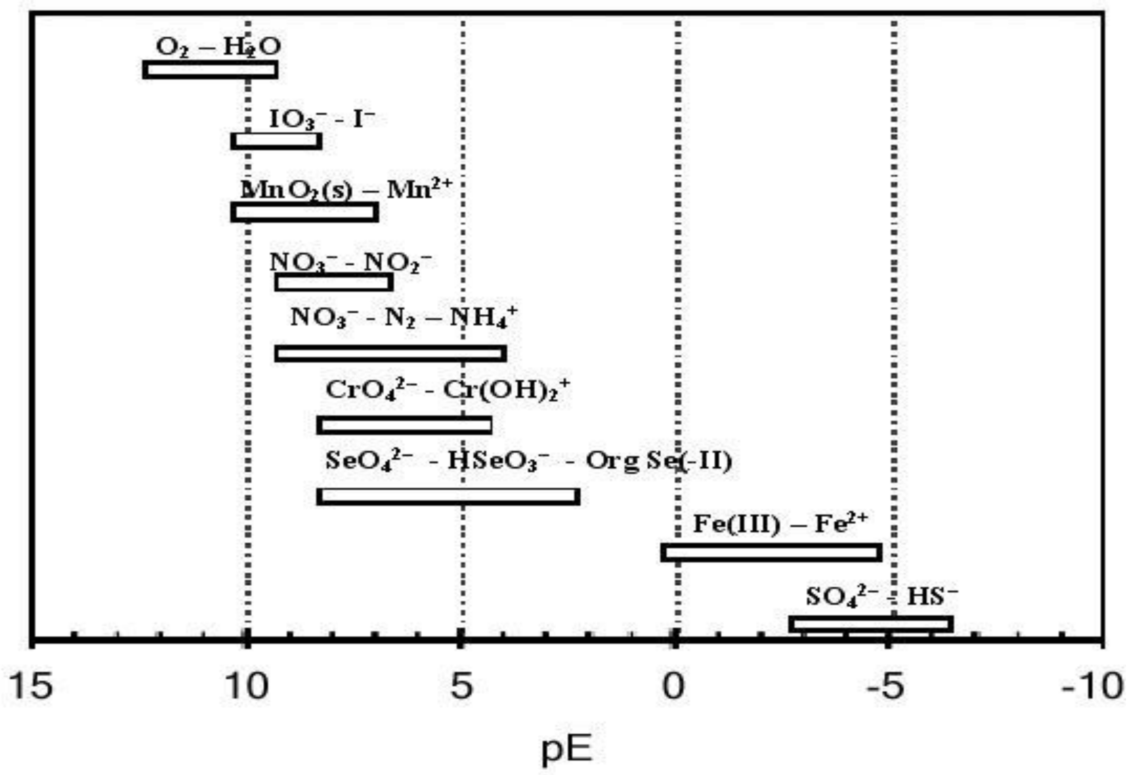
Nitrate

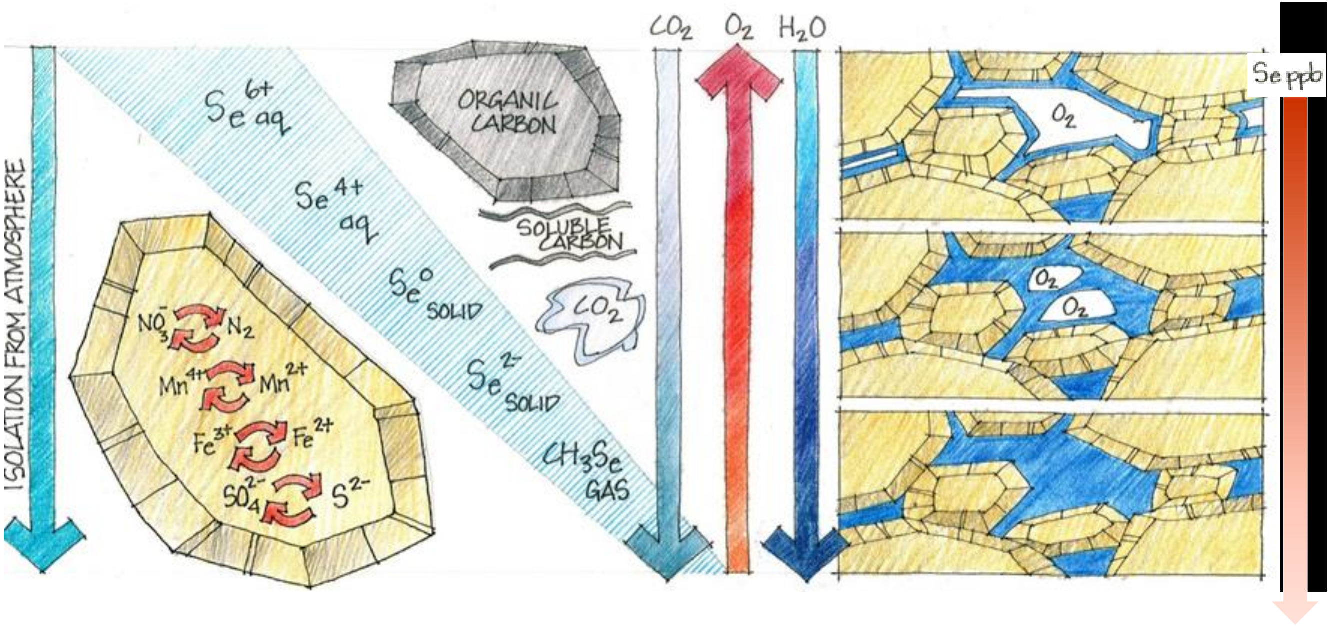
- Released during blasting
- Nitrogen has 5 redox states
- Like Se, N redox biogeochemistry is complex.
- <u>Key inhibitor of selenate reduction</u>
  - Competition for nitrate reductase enzyme substrate
- Readily reduced biologically to nitrite and nitrogen gas under suboxic conditions



Concurrent biological nitrate and selenate reduction is possible via multiple enzyme substrates in mixed microbial community

Microbial metabolism - energetics

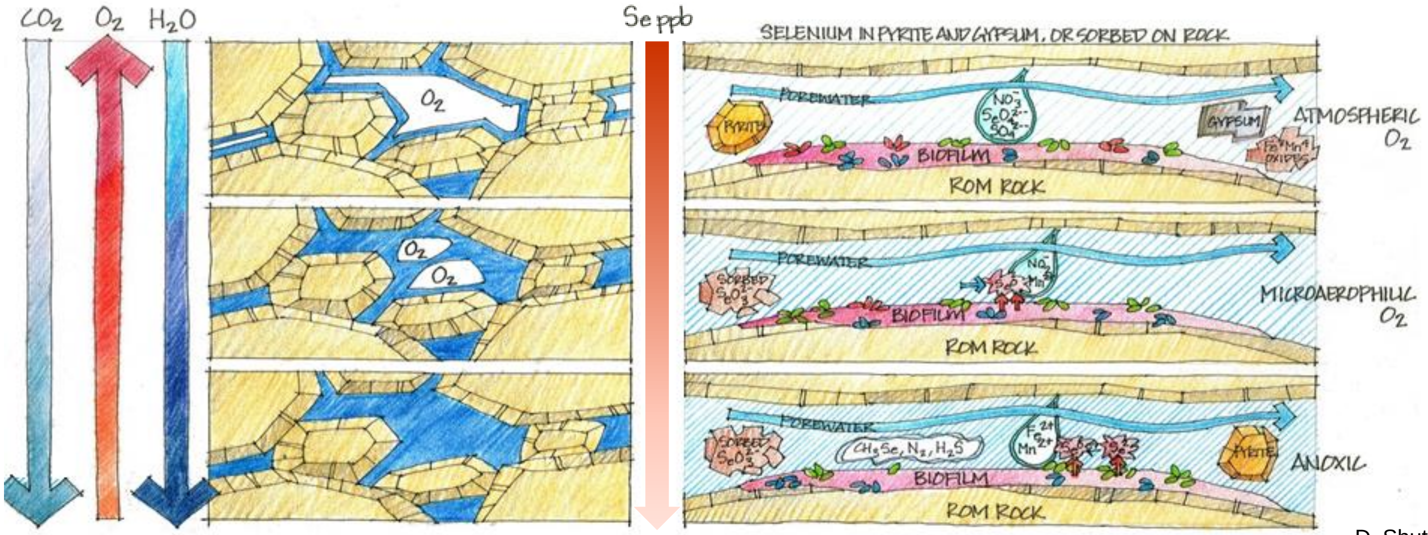




D. Shuttleworth

- SeO_4^{2-} is released during sulphide oxidation
- Reduced SeO_3^{2-}, Se^0, & Se^{2-} are less soluble than SeO_4^{2-}

Conceptual Selenium Biogeochemical Model

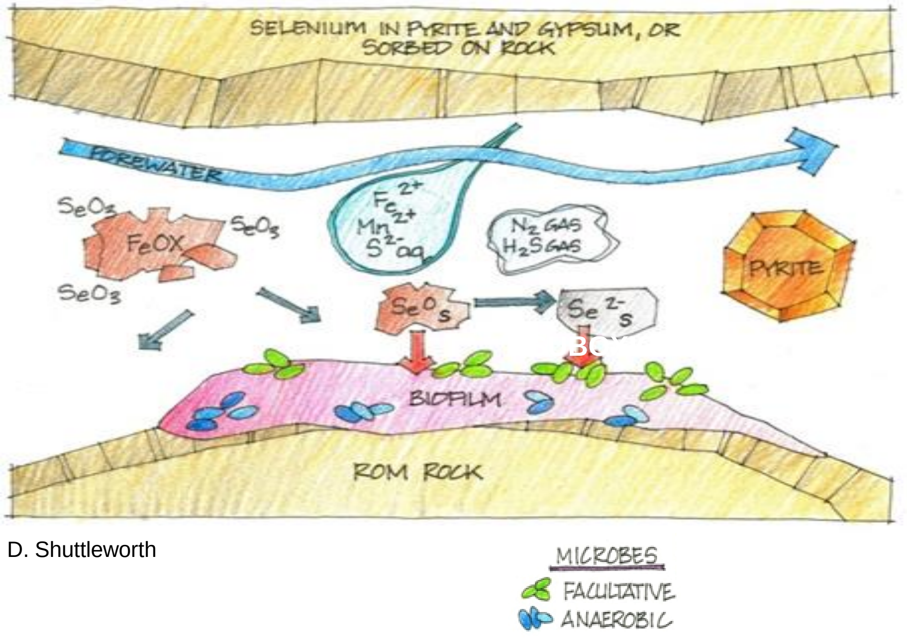


D. Shuttleworth

- Soluble SeO_4^{2-} is associated with O_2 , NO_3^-, & SO_4^{2-}
- Microbial community changes with O_2 availability
- O_2 & NO_3^- reduction reduces inhibition of Se reduction

What conditions are needed to make microbes reduce Se?

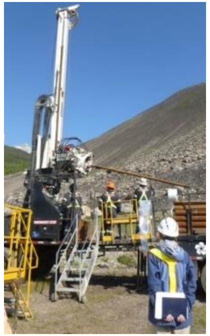
- **Low O_2**
  Promotes the growth of anaerobic and facultative Se-reducing populations
- **Available C**
  Is coal enough?
  What's the longevity of C supply?
- **Ideal H_2O flux**
  Water brings food, takes away waste, but also brings O_2
- **Nutrients**
  NO_3^- & PO_4^{3-} are necessary but also inhibitory



D. Shuttleworth

Understanding the Biology of Waste Management – Who's Home?

Field sampling

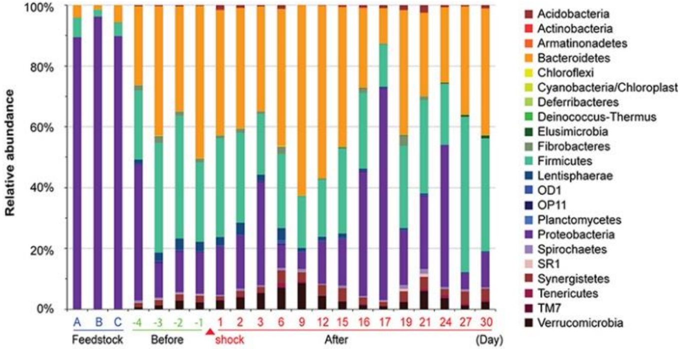


Processing/Preservation

Extraction of genomic DNA

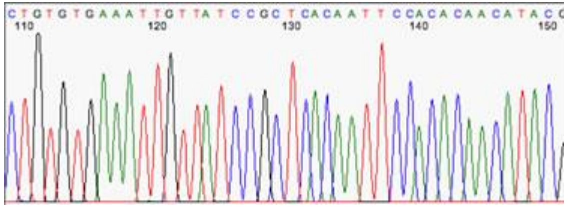
Amplification of target DNA

Community Characterization



DNA Sequencing

Cleanup/Analysis



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Understanding the Biology of Waste Management – What are they doing?

Monitor geochemistry parameters
Controlled changes to conditions
Evaluate changes to the microbial community

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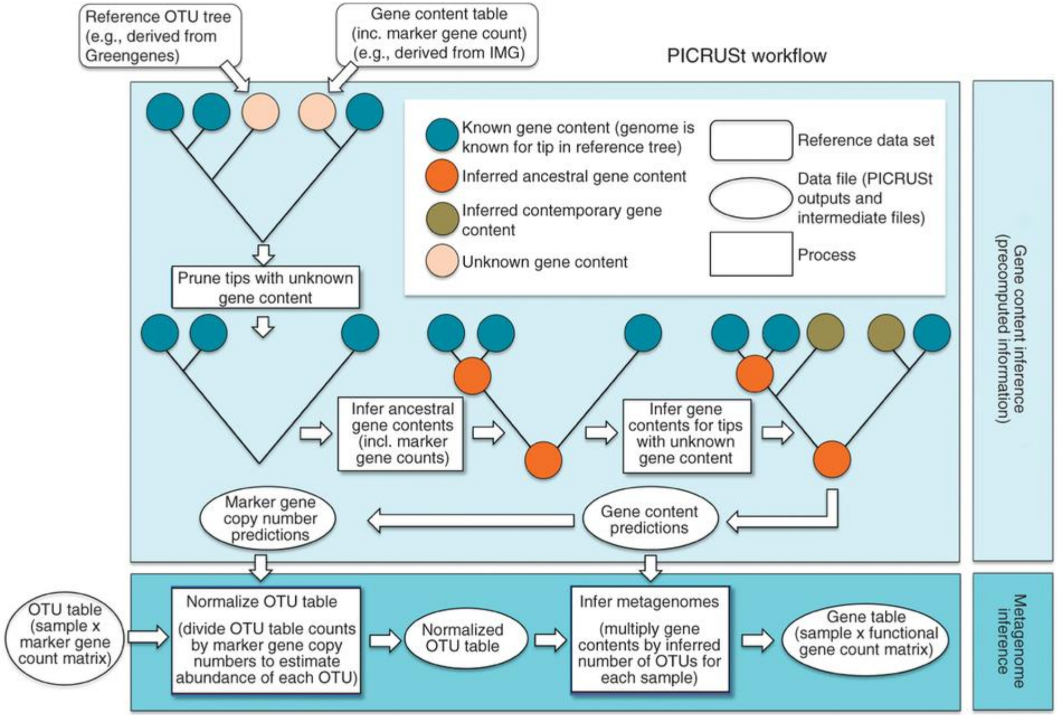
Understanding the Biology of Waste Management – What are they capable of?

Phylogeny-Based

Bacteria **Aerobes, facultative anaerobes**	**Metabolism**
Dechloromonas	Aromatic HC NO3, SeO4 reduction
Pseudomonas	Heterotrophs using O2, NO3, SeO4
Actinobacter	
Cellulomonas	
Stenotrophomonas	
Thiothrix	S oxidation
Pelosinus	Fe reducer clays
Polaromonas	PAH degradation with O2
Rhodoferax Ferrireducens	Fe, Mn reduction

Genomics-based



Langille et al. 2013. *Nature Biotechnology*

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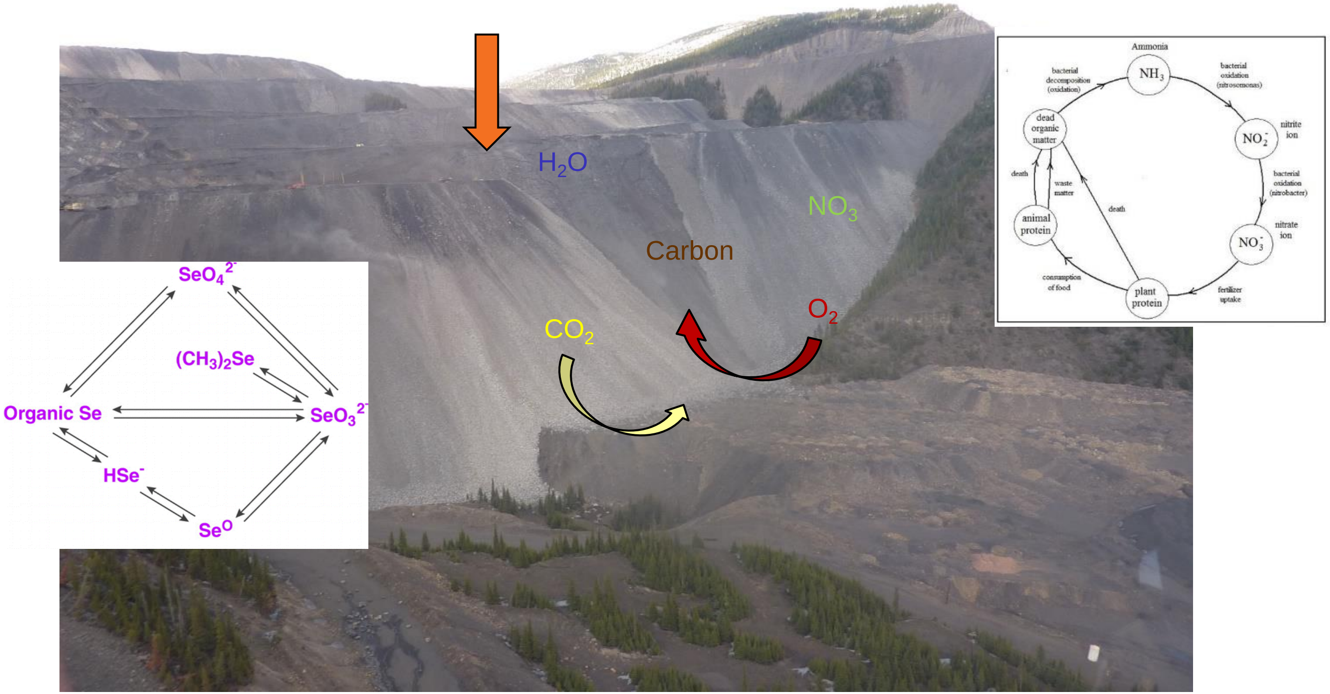
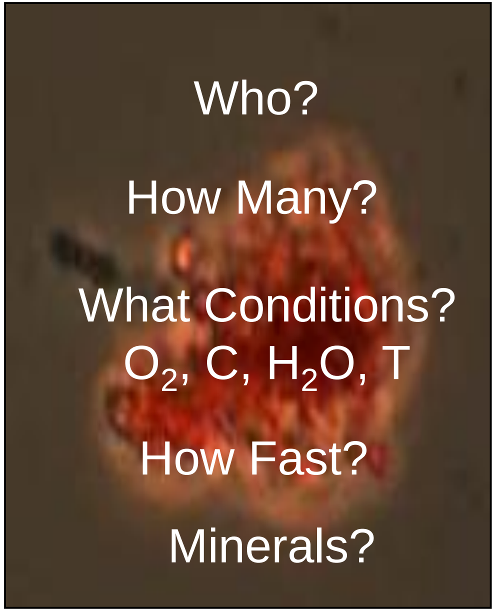
Gas, water, and elemental cycling



Can native microbes at Crown Mountain stabilize Se within mined waste rock, providing source control?



Who?

How Many?

What Conditions?
O_2, C, H_2O, T

How Fast?

Minerals?

Leaching of Selenium – Unsaturated WR

- Selenide substitutes for sulphide in pyrite, $Fe(S,Se)_2$ (note S>>Se)
- Oxidation of pyrite releases sulphate and selenate, as well as iron and acidity
- Secondary minerals or sorbed surface complexes form
- Desorption of secondary selenite or sorptive substrate (e.g., Fe oxyhydroxides)
- Selenate persists at alkaline pH
- Oxidation of pyrite function of
    - Reactive surface area
    - Neutralization potential
        - pH-driven biological oxidation pH<5
    - Availability of oxygen
- Abiotic oxidation pH>5
- Biological oxidation pH < 5
    - Acidophilic sulphide oxidation

Can dumps be designed to support *in situ* microbial reduction?

- What are the moisture and gas flux requirements for native microbial reduction in Crown Mountain spoil piles?

$$O_2\ _{\text{availability (rate)}} =$$

$$[O_{2\ \text{placed}} + O_{2\ \text{advect}} + O_{2\ \text{diffus}} (T, S, \Theta, \varphi, D_G{}^s)] - [\ O_{2\ \text{BOD (C, moisture, nutrients)}} - O_{2\ \text{COD (temp, surface area, mineralogy)}}]$$

Where

T, temp

S, saturation

Θ , moisture content

Φ, gas filled porosity

$D_G{}^s$, effective diffusivity

BOD, biological oxygen demand respiration

COC, chemical oxygen demand (oxidation C and S)

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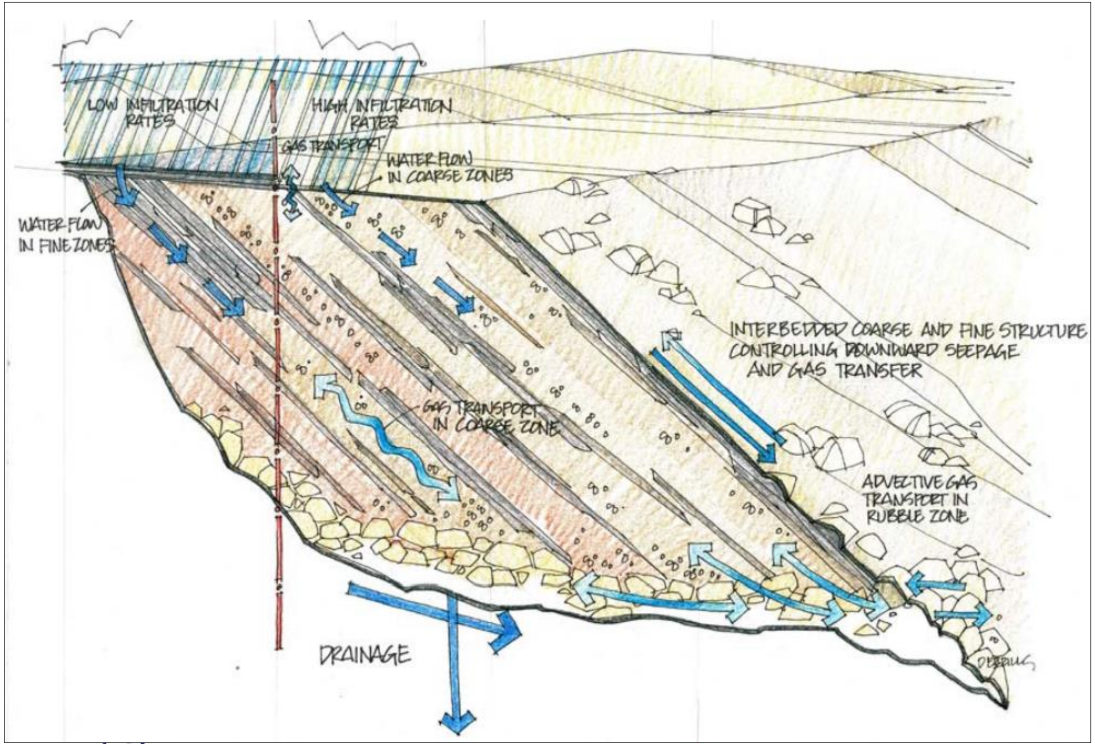
Water Flow in Waste Rock

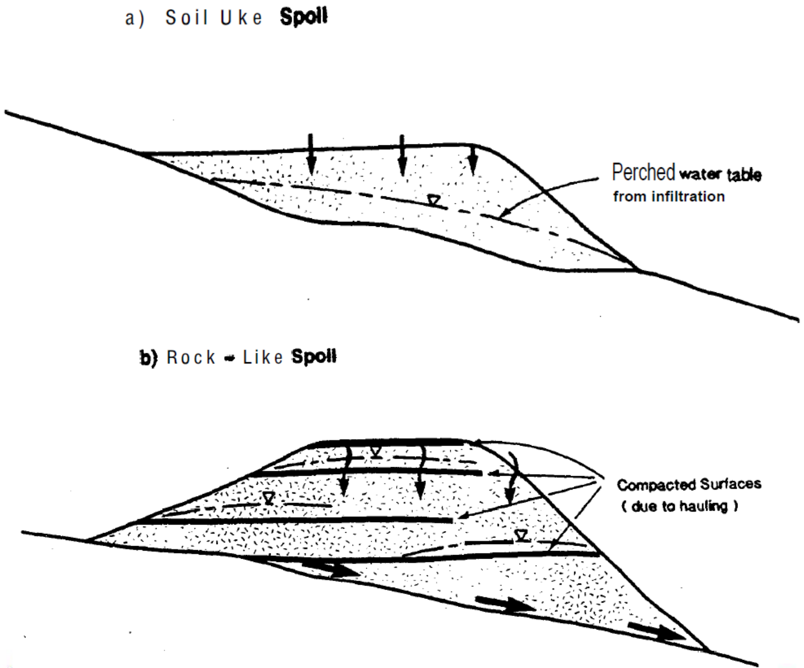


- Infiltration into the dump from rainfall, surface water and snowmelt (if applicable)
- Hydrologic behavior can be complex
- Physical characteristics such as stratification, segregation, particle size and construction method all affect the waste dump permeability and hydrologic behavior

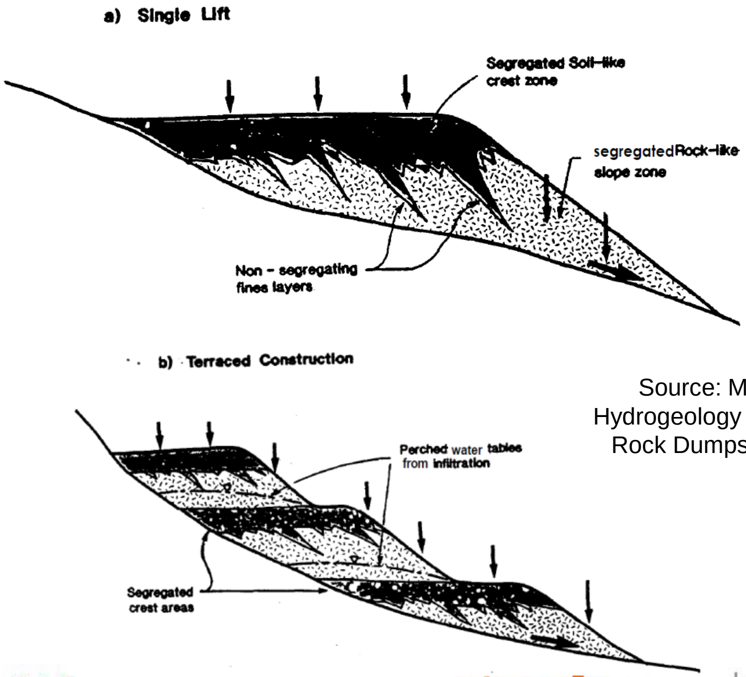
Source: MEND Cold Regions Cover System Design Technical Guide (2012)

Water Flow in Waste Rock

Hydrostratigraphy of **Non-Segregated** Dumps:



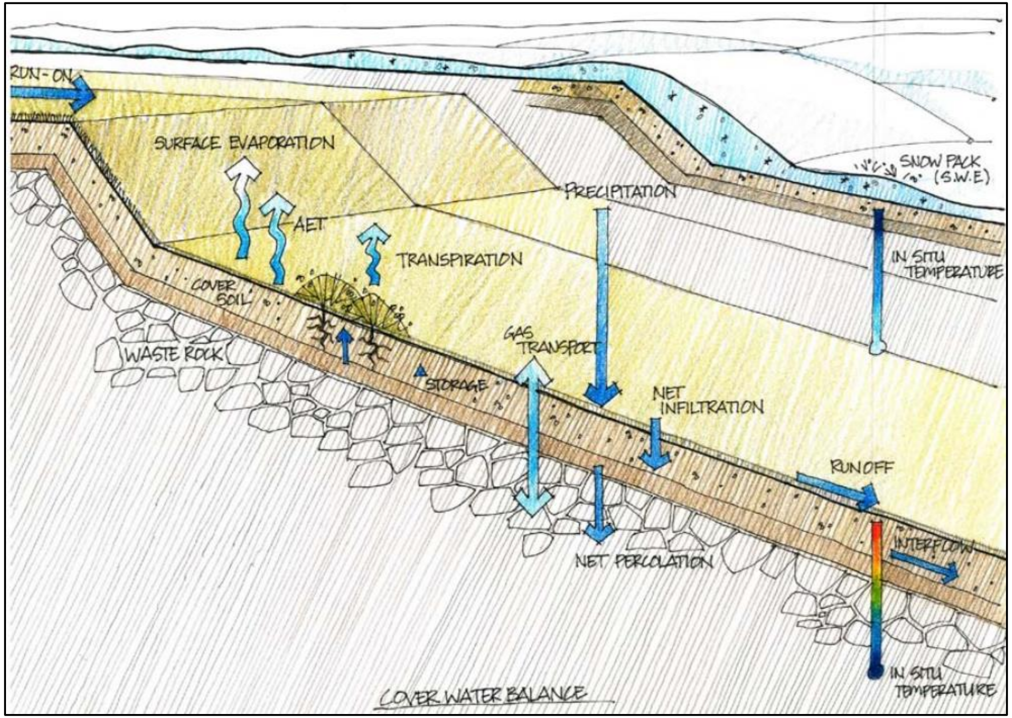
Hydrostratigraphy of **Segregated** Dumps:



Source: MEND Hydrogeology of Waste Rock Dumps (1995)

Hydrodynamics for Mine Waste Covers

- Unsaturated flow behavior
- Water balance can be complex
- Key inputs: precipitation, actual evapotranspiration, soil hydraulic parameters (e.g. van Genuchten)



Source: MEND Cold Regions Cover System Design Technical Guide (2012)

Can microaerobic conditions be created in a dump?

- Evidence Sullivan
    - Phillip, Hockley, 2009
  - Low oxygen conditions were successfully developed
  - Hazard associated with discharge of carbon dioxide enriched, oxygen depleted gas within confined space

- Evidence Teck Coal
  - F2 and B5
  - GHO Area A CCR
  - LCO, LC3
- Evidence SE Idaho
  - Dry Valley
    - Saturated low, field capacity above, <0.3 mg/L at 15 ft
  - Enoch Valley, Luxor
    - Unsaturated, <0.3 wt % at 30 feet.

Oxygen Movement in Waste Rock

- Advection
  - Thermally driven
  - Facility scale
  - Can be limited by saturation with water or by creating flow discontinuities with textural breaks, caps, etc.
- Diffusion
  - Gradient driven
  - Small scale
  - Can be limited by saturation of pores with water

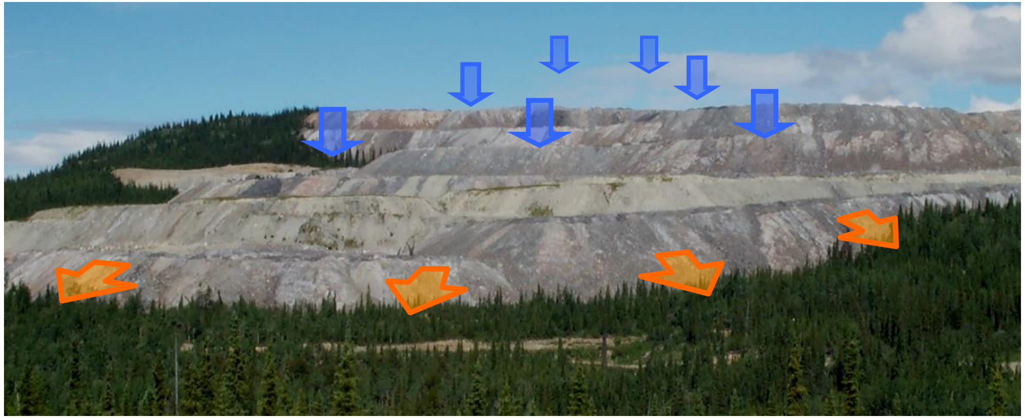
Gas Flow – Simple Terms

- Gas flows upward and out the top surfaces of stockpiles when it is lighter than the surrounding air
  - Less O_2, more H_2O_{vapour}, lower T_{air}

Dawson et al, 2009
Phillip et al, 2009
Lahmira et al 2009
Hockley et al 2009

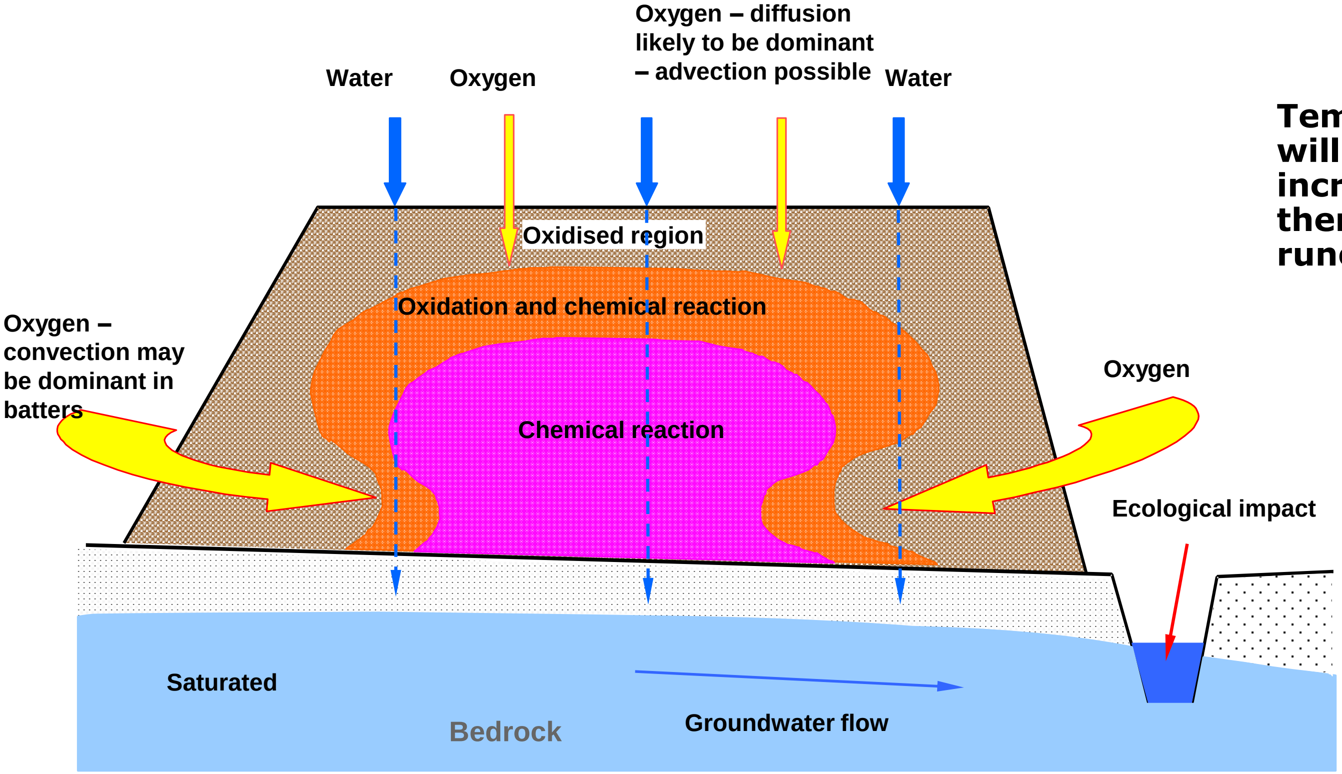
Gas Flow – Simple Terms

- Gas flows downward and out the toe of stockpiles when it is heavier than the surrounding air
  - Increase in CO_2, higher T_{air}



Dawson et al, 2009
Phillip et al, 2009
Lahmira et al 2009
Hockley et al 2009

Processes in Oxidizing Piles



Temperatures will generally increase and there may be runoff

Relationship between Gas Transport and Reactant Consumption

- Convection/advection is driven by total gas pressure differences
- Diffusion is driven by oxygen concentration gradients
- Reactant consumption rate is determined by the material characteristics and a range of parameters. E.g. temperature, oxygen concentration
- Intrinsic permeability - the material parameter that controls the rate of convection/advection of gas
- Oxygen diffusion coefficient – the material parameter that controls the rate of oxygen diffusion
- Construction of dump – compaction to reduce convection/advection & increase water content to reduce the diffusion supply of oxygen

Mathematical Relationship allows Calculation

$$\frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}\bullet\left(\rho\omega_i\boldsymbol{v} - D_{\boldsymbol{i}}\boldsymbol{\nabla}(\rho\omega_i)\right) = IOR$$

Change in O2 density over time

Convection term

Diffusion of oxygen

Consumption rate of reactant e.g. pyrite

Velocity of gas flow

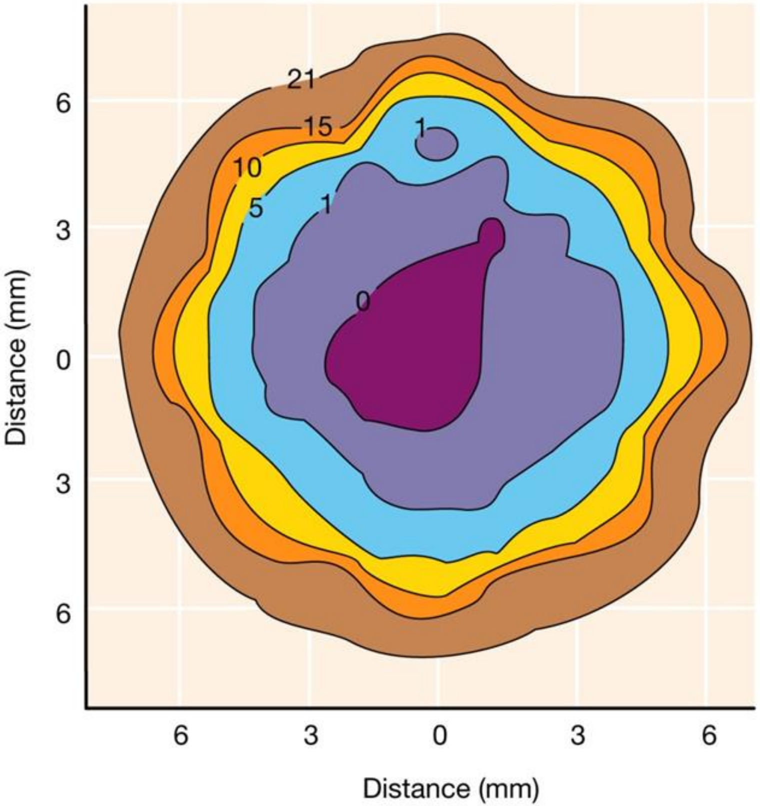
intrinsic permeability

$$\boldsymbol{v} = \frac{-Kk_g(\varepsilon_g)}{\mu\varepsilon_g}(\boldsymbol{\nabla}P + \rho g\boldsymbol{\nabla}z)$$

IOR is the reactant oxidation rate
V = gas velocity
$\boldsymbol{\nabla}P$ = gas pressure gradient
$\rho g\boldsymbol{\nabla}z$ = gas density * acceleration due to gravity * height difference
ω_i = concentration of oxygen

Pore Scale Oxygen

Goal is to prevent convection, limit oxygen flux to diffusion via partial saturation, and consume the remaining oxygen via microbial activity



Selenium Biogeochemistry Case Studies

- Unsaturated waste rock from the Elk Valley
- Unsaturated coal reject from the Elk Valley
- Saturated waste rock from the Elk Valley

Which organisms are present?

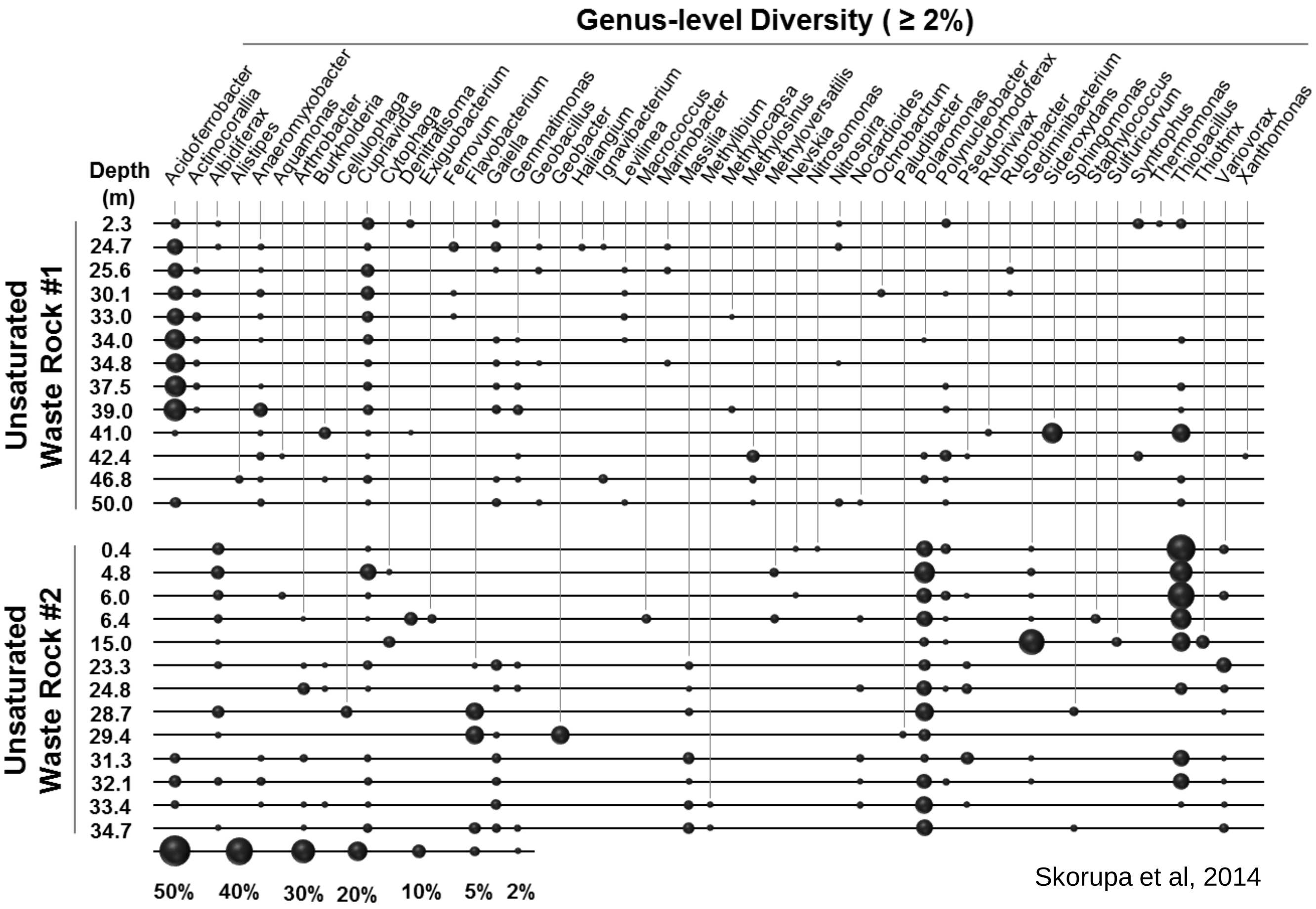
How do they change with environment, depth, chemistry

Elk Valley microbial community structure and function

Mine waste with Se release

Microbial community changes with depth

Geochemistry plays an important role in community structure



Skorupa et al, 2014

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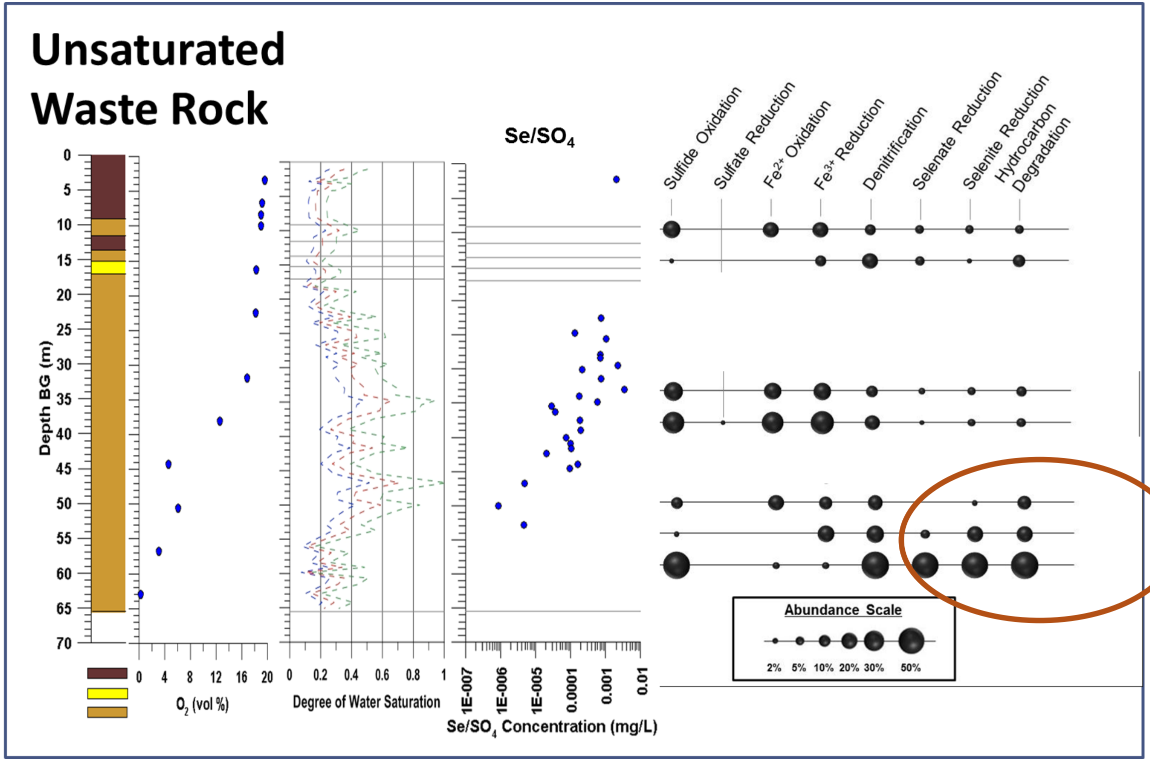
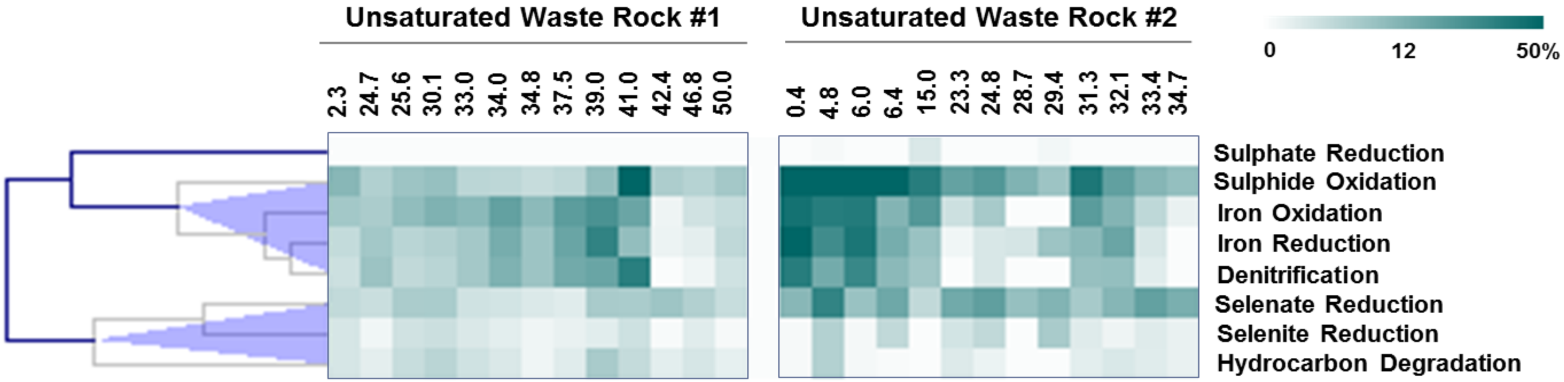
Community analysis supports geochemical evidence



Skorupa et al, 2014

Microbial Characterization: Signatures



Metabolic potential changes spatially

- *Few SO_4^{2-} reducers*
- *S-/Fe-oxidizers and denitrifiers:*
    - *#1: Abundant ≤ 41 m*
    - *#2: Abundant in shallow and mid-depth waste rock*
- *SeO_4^{2-} and SeO_3^{2-} - reducers*
    - *#1 & #2: SeO_4^{2-}-reducers are common, not so for SeO_3^{2-}*
- *Hydrocarbon degraders: abundance tracks most closely with Se*

Skorupa et al, 2014

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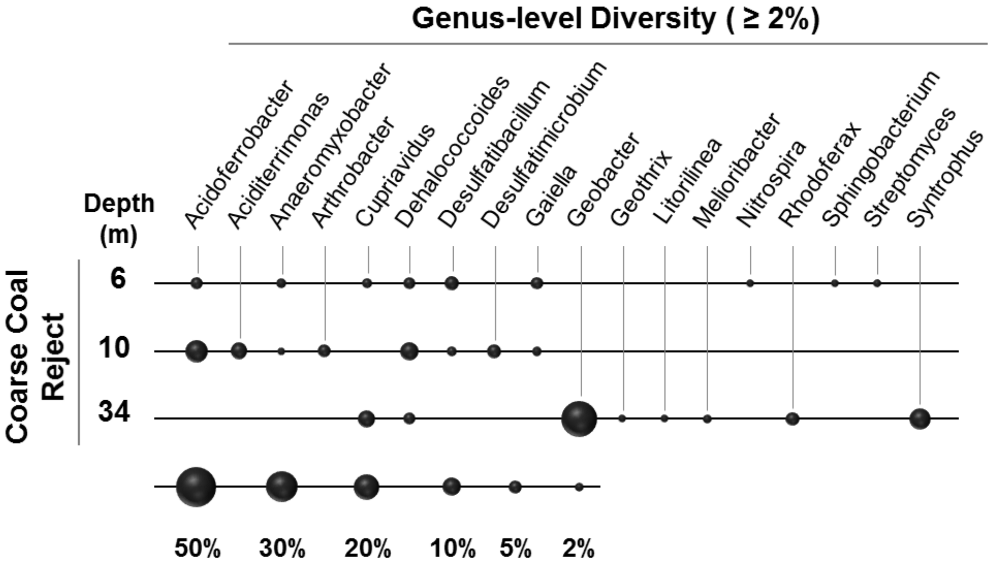
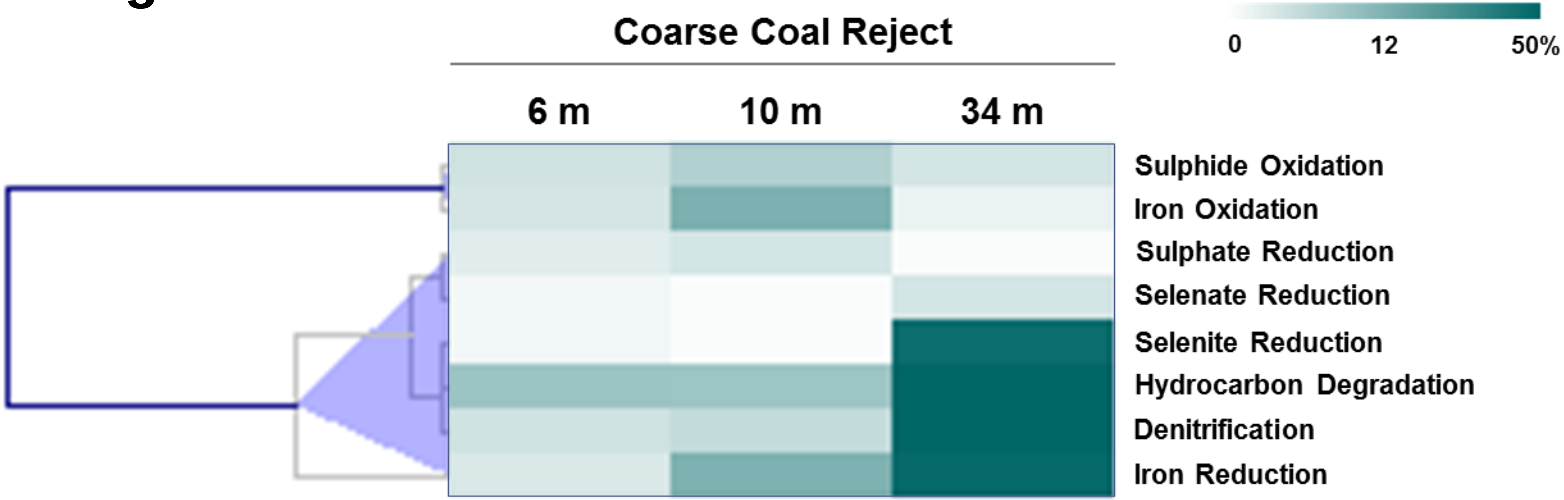
Microbial Community - Coal Reject



- Anaerobic community in the processed waste
- *Geobacter* is rare in other waste, but dominant in the deep CCR
- Is an obligate anaerobe with strong capacity for metal reduction, including Se

Skorupa et al, 2014

Microbial Characterization: Signatures



- *Abundance and diversity of Se-reducing microbial communities were enhanced at the deeper depth*
- *Increased number of SeO_3^{2-}-reducers at 34 m correlates well with drill logs where saturated conditions and decreased Se concentrations were observed*

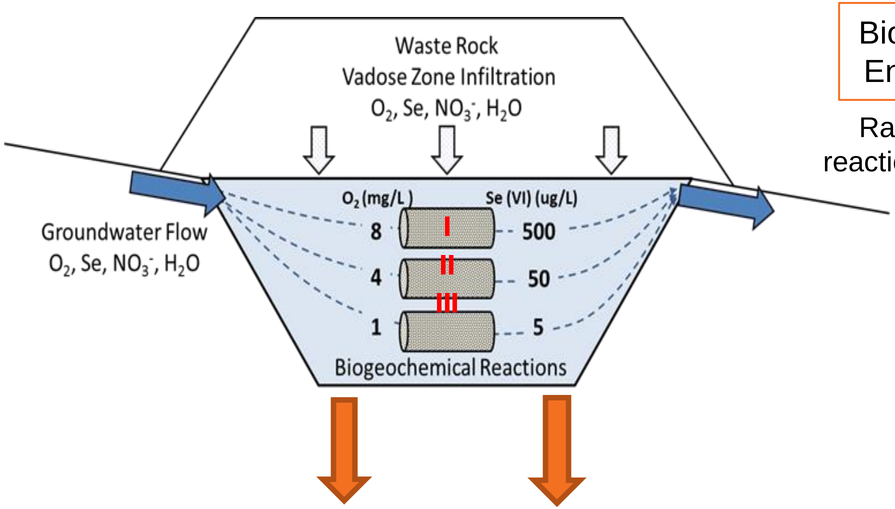
Skorupa et al, 2014

Microbial Process Control of Se in Saturated Fill Systems

Balance flux of oxidants against microbial and chemical reduction rates

Microbial physiology, ecology, and interactions

Microbes-mineral reactions based on key ecological limits (C, O_2, N, Fe, Mn, S)



Non-amended

C amended

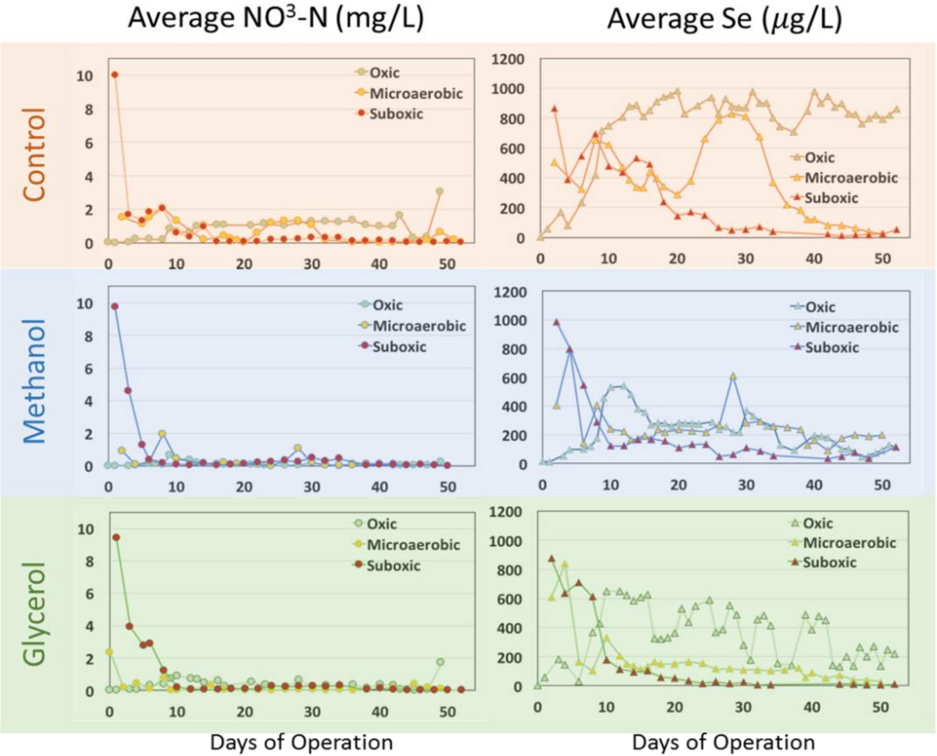
Bio/chemical Engineering

Rates/extent reactions affecting CI’s

Kirk et al, 2017

Saturated (waste rock, process waste)
Columns and targeted field sites (MSU/Enviromin/SRK and others)

Selenium and Nitrate Reduction – Saturated Fills



Kirk et al, 2017

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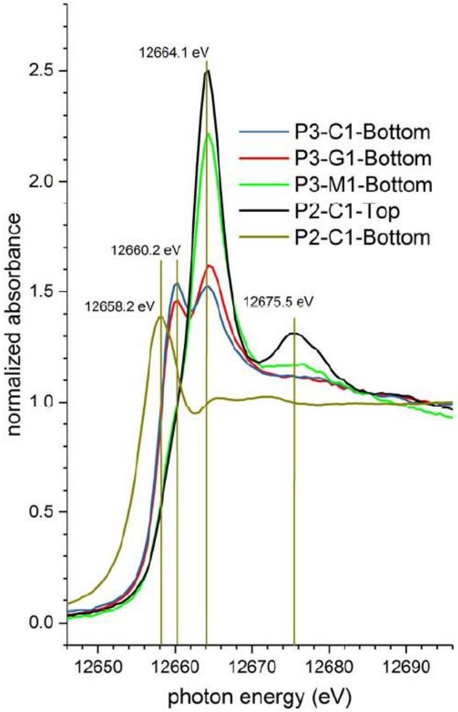
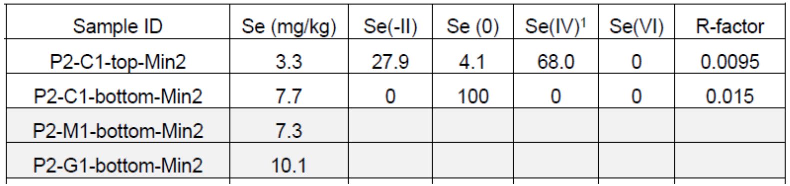
Selenium Biomineralization in Microaerobic Columns



Ratio of Se(IV) to Se(0) and Se(-II) varies depending on location in column

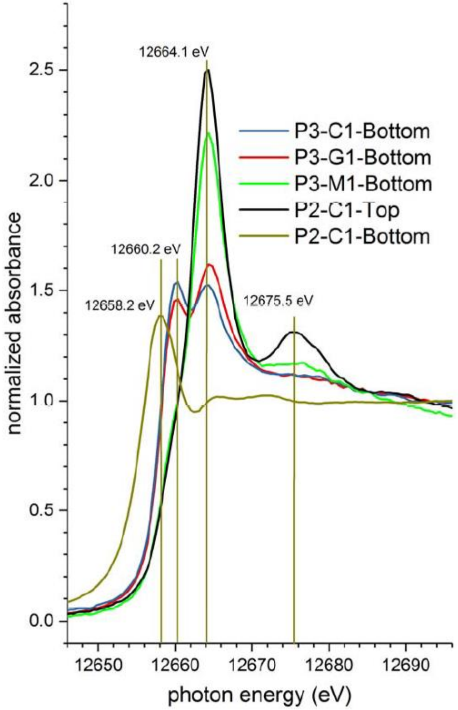
- Mass greater in inflow (bottom) portion of carbon fed columns
  - Pre-test composite 2.2 mg/kg
- Se more reduced in inflow zone
  - Se(0) influent (bottom)zone
  - Se(IV) higher in outflow (top)



Sample ID	Se (mg/kg)	Se(-II)	Se (0)	Se(IV)[1]	Se(VI)	R-factor
P2-C1-top-Min2	3.3	27.9	4.1	68.0	0	0.0095
P2-C1-bottom-Min2	7.7	0	100	0	0	0.015
P2-M1-bottom-Min2	7.3					
P2-G1-bottom-Min2	10.1					

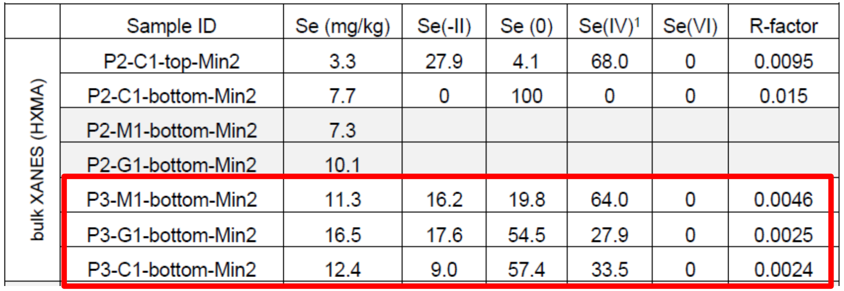
Kirk et al, 2017

Selenium Biomineralization in Suboxic Columns



Ratio of Se(IV) to Se(0) and Se(-II) varies depending on carbon amendment

- Methanol highest Se(IV)
- Glycerol, no carbon highest Se (-II)



	Sample ID	Se (mg/kg)	Se(-II)	Se (0)	Se(IV)^1	Se(VI)	R-factor
bulk XANES (HXMA)	P2-C1-top-Min2	3.3	27.9	4.1	68.0	0	0.0095
	P2-C1-bottom-Min2	7.7	0	100	0	0	0.015
	P2-M1-bottom-Min2	7.3					
	P2-G1-bottom-Min2	10.1					
	P3-M1-bottom-Min2	11.3	16.2	19.8	64.0	0	0.0046
	P3-G1-bottom-Min2	16.5	17.6	54.5	27.9	0	0.0025
	P3-C1-bottom-Min2	12.4	9.0	57.4	33.5	0	0.0024

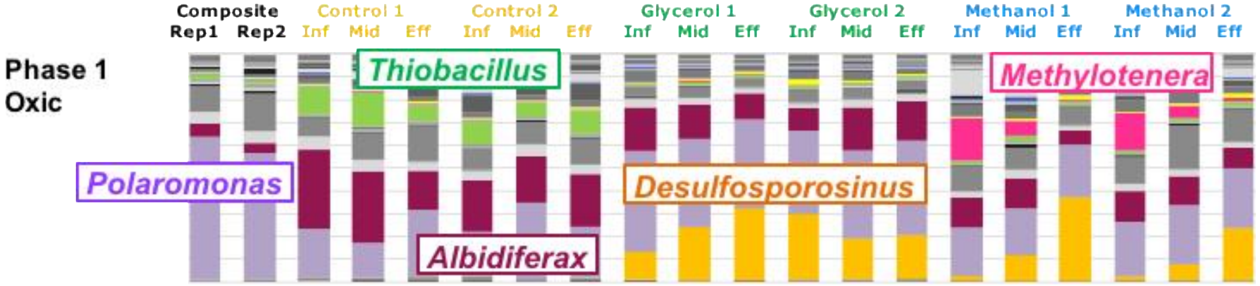
Kirk et al, 2017

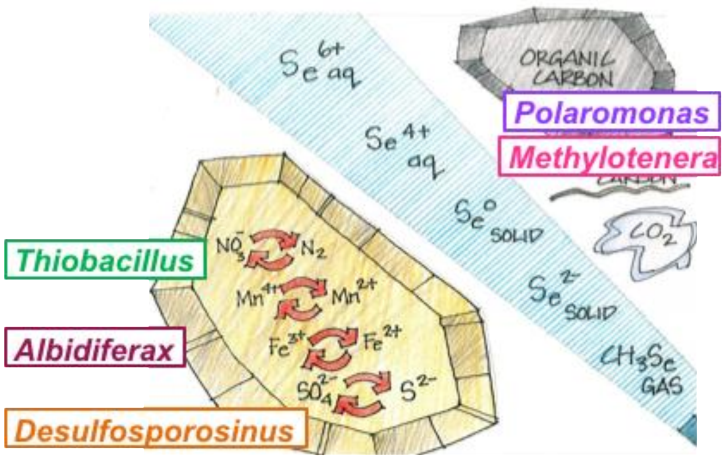
Saturated Fill Column results

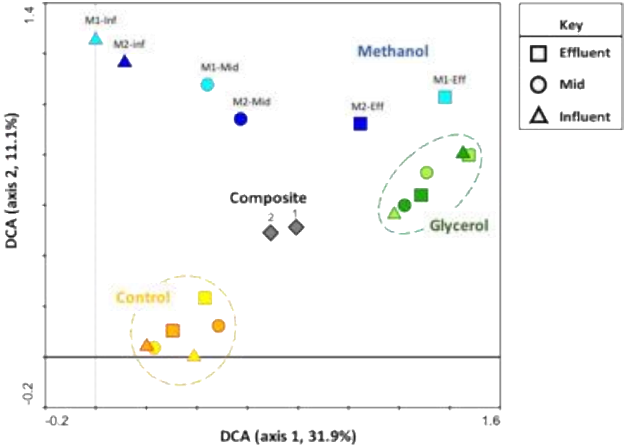
- O_2 and NO_3^- inhibition is overcome via C substrate addition.
  - System responds to changes in O_2.
  - No-carbon control columns showed increasing rates of Se removal with decreasing oxygen, using native C (no addition).
- Attenuation of Se can be promoted through carbon addition to saturated rock fills, under steady state concentrations of 1000 ug/L, with removal of up to 98% of Se and most NO_3^-
  - Under suboxic conditions, carbon is released from the rock in sufficient quantities to support efficient denitrification and selenium reduction.
  - Biomineralization varies in response to oxygen, carbon, and residence time.
    - Se(IV) is converted to Se(0) and Se(-II) with decreasing O_2.

Kirk et al, 2017

Aerobic Microbiology Columns



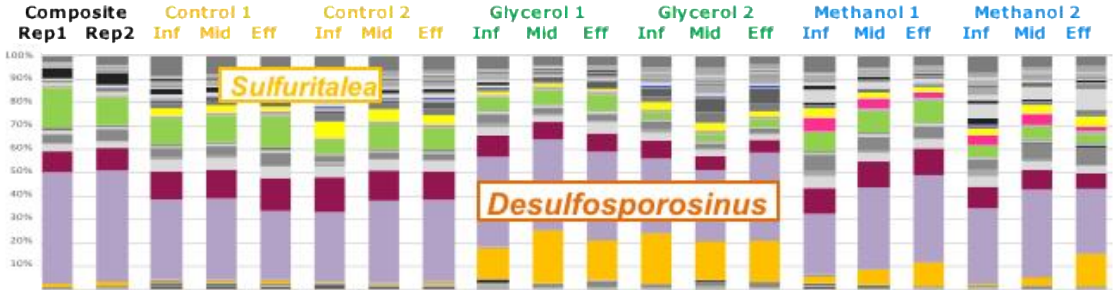


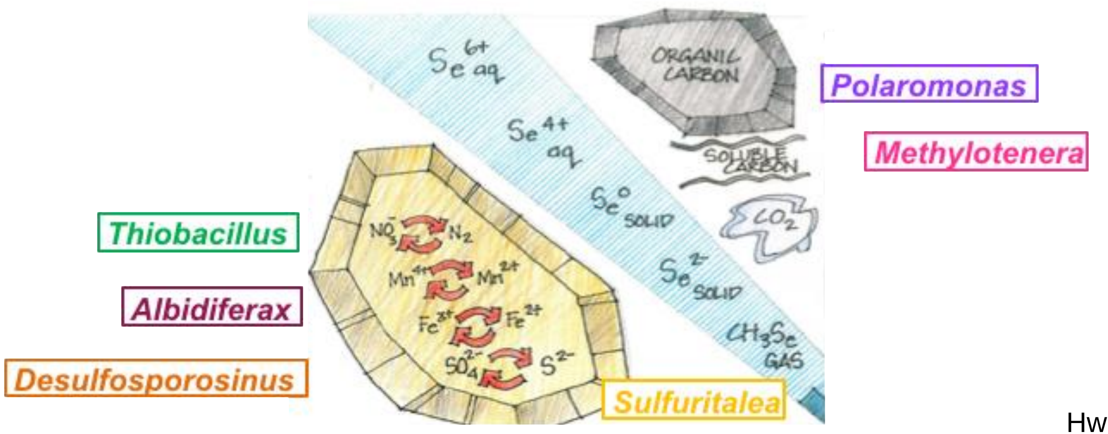


Hwang et al, 2017

Microaerobic Microbiology Columns

Phase 2 Microaerophilic

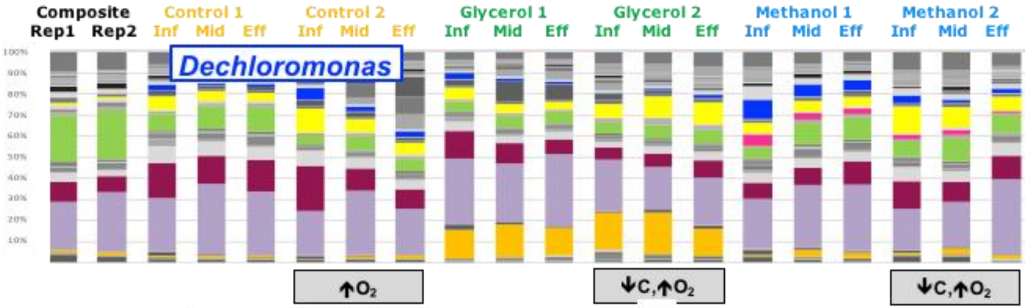


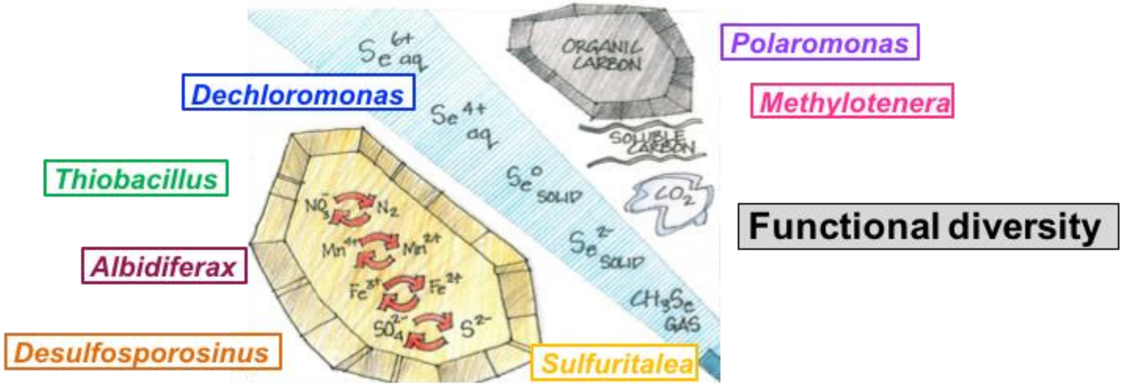


Hwang et al, 2017

Suboxic Microbiology Columns

Phase 3
Sub-oxic





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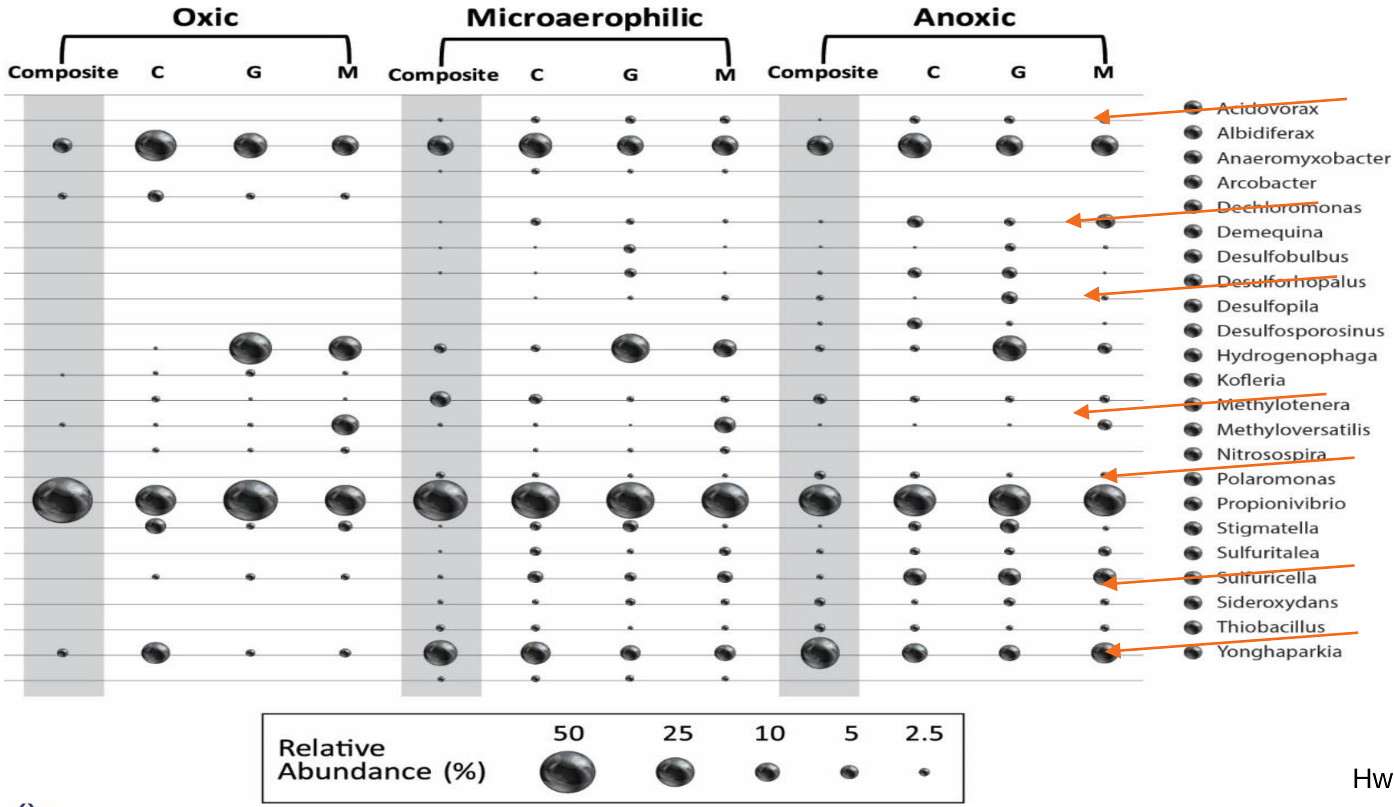
Microbial Community Results



Hwang et al, 2017

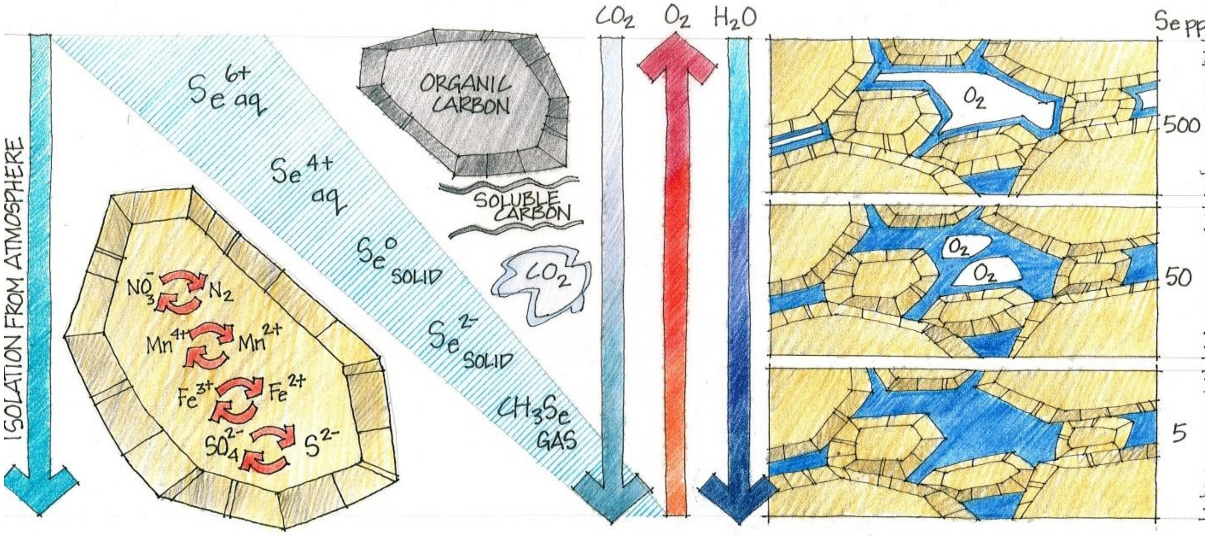
Summary

- O_2 and NO_3^- inhibition is overcome via C substrate addition.
  - Microbial community changes in response to O_2, carbon
- ***Thiobacillus, Albidiferax*** **and** ***Polaromonas*****-like organisms**
  - Cycling N, Fe and hydrocarbon
  - *Methylotenera* in methanol-fed reactors
- ***With decreasing oxygen,***
  - Abundance of *Dechloromonas, Anaeromyxobacter and Acidovorax*-like Se-reducing organisms increased
  - *Desulfurosporinus* and *Sulfuritalea*
    - Less abundant than Fe, N, and S-cycling genera

Hwang et al, 2017

Goal: Control Nitrate and Selenium in Waste Rock Seepage

1. Predict and demonstrate oxygen depletion in an unsaturated waste rock design for the Crown Mountain site
2. Evaluate design alternatives in this context
3. Predict chemistry of leachate from waste rock facility



Crown Mountain Design

Stephen Day
Corporate Consultant - Geochemistry
SRK, Vancouver BC

Enviromin

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Uncertainty

Scale and Process Dependent

Biogeochemistry

- Community Ecology/ characteristics
- Se reduction potential
  - Conditions
  - Rates
- Se reduction products
- Unintended consequences
  - Fe, Mn reduction
  - Shifts in carbonate equilibria
  - Sulphide generation potential

Hydrodynamic Dump Design

- How to construct new dumps
  - Grade, capping, lift height, compaction
    - Oxygen control
    - Water control
  - Permeable barrier
  - Modular design approach

Knowns and Unknowns

Known

- Se^{VI} and Se^{IV} reducers widespread, diverse, present in waste rock
- Function limited by NO_3^- but NO_3^- reduction is widespread
- Carbon is present
- Apparent reduction of SeO_4, not SO_4,
  - saturated zones at Teck Elkview Cardinal River operations
- Zones of low oxygen in waste rock
- Possible

Unknown

- Character of Se-reducing community in unsaturated waste rock
- Capacity of native SeRB
  - Sensitivity to T, O_2, Fe, Mn, SO_4
  - Rate (required residence time)
- Bioavailability of native C from coal reject
- Ability to cost-effectively construct reducing conditions
  - Gradation, moisture
  - Gas and water flux rates
  - Compaction?
  - Lift height
  - Cover ?

NWP Canada Crown Mountain Site Characteristics

- Coal at Crown Mountain is hosted by the Mist Mountain Formation.
- Geological and geochemical characteristics are similar to nearby mining operations:
  - Sulphide content, presence of acid neutralizing minerals, selenium content.
- Climatic conditions are similar.
- Similar mining and coal processing technologies.

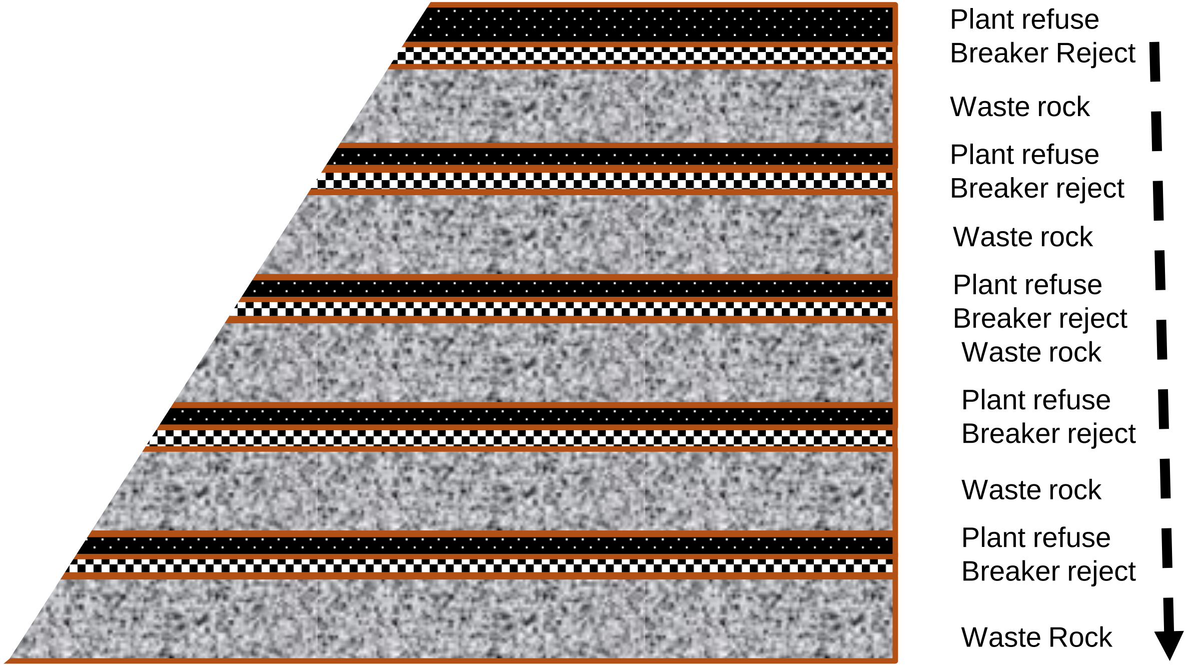
Crown Mountain Waste Rock Design

Conceptual Model For Selenium and Nitrate Attenuation in a Waste Rock Dump

Expected role of plant refuse layers:

- Retain moisture retarding oxygen transport.
- Generate dissolved organic carbon.
- Provide sub-oxic zones where reductive processes could occur.

Oxygen movement by diffusion not advection



Reductive Processes

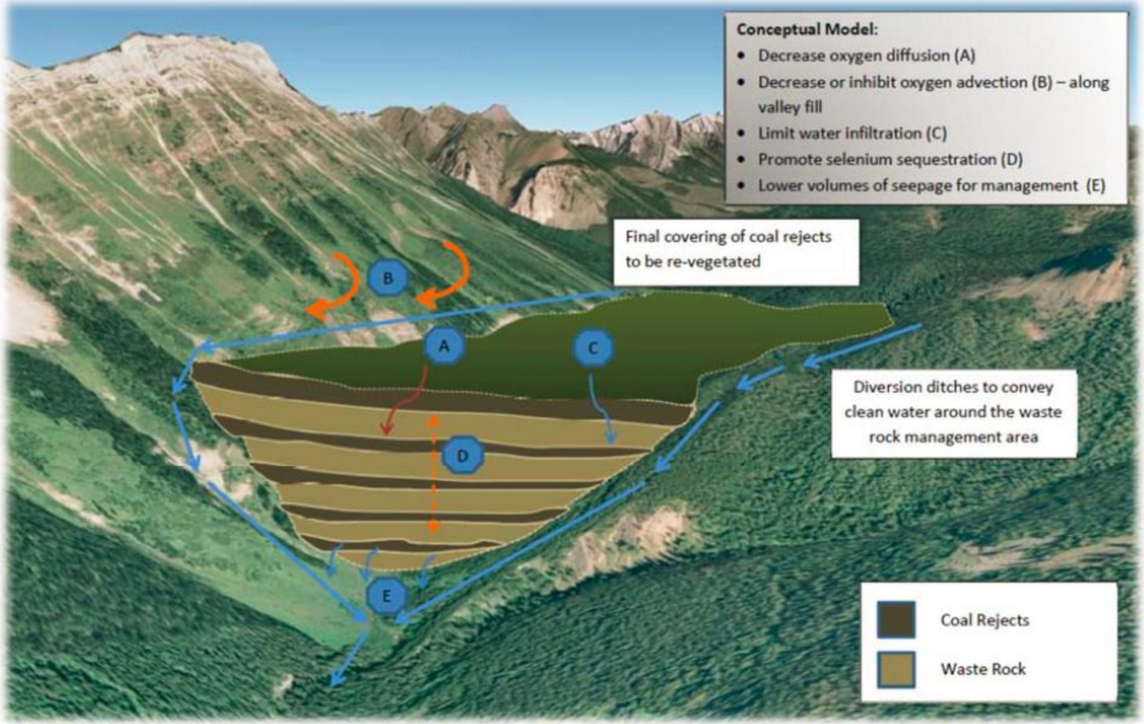
O_2 decreasing

<u>When DO<0.5 mg/L:</u>

$NO_3^- \rightarrow N_2$

$SeO_4^{2-} \rightarrow Se^0$

Waste Rock Management: Layered Approach



Conceptual Model:

- Decrease oxygen diffusion (A)
- Decrease or inhibit oxygen advection (B) – along valley fill
- Limit water infiltration (C)
- Promote selenium sequestration (D)
- Lower volumes of seepage for management (E)

Final covering of coal rejects to be re-vegetated

Diversion ditches to convey clean water around the waste rock management area

■	Coal Rejects
■	Waste Rock

Scope of Work

1. Proof of Concept

- Assemble existing data
  - Material and water balance
  - Published oxygen consumption rates
- Conceptual design model
- Analytical model of oxygen consumption potential

2. Quantitative Evaluation- Lab

- Sampling
  - Groundwater
  - Waste Rock
  - Coal Reject
- Characterize material properties
- Test oxygen consumption rates
- Test denitrification and selenium reduction rates under controlled oxygen exposure, T=10^{o}C, unsaturated flow in columns

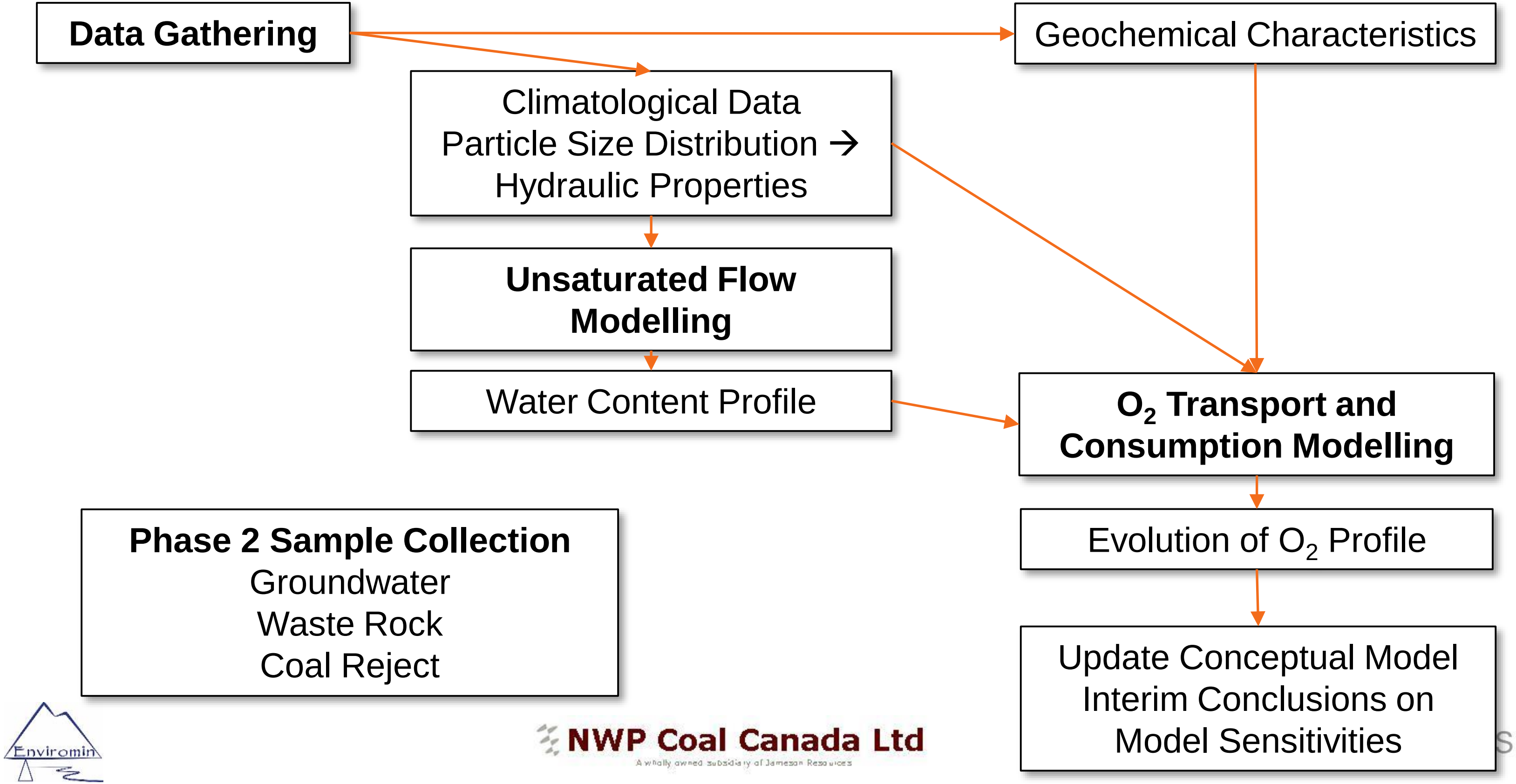
3. Revise Designs for Demonstration

- Numerical Modeling of Phase 2 results
  - Revise oxygen predictions
  - Calculate Se and NO_3 reduction
  - Predict Water Quality
- Update Conceptual design model
- Develop field scale demonstration design

4. Demonstration

- Site Waste Characterization
- Pilot Scale test demonstration
  - Facility design
  - Monitoring
  - Assessment

Phase 1 – Methods and Results



Data Gathering

Geochemical Characteristics

Climatological Data
Particle Size Distribution → Hydraulic Properties

Unsaturated Flow Modelling

Water Content Profile

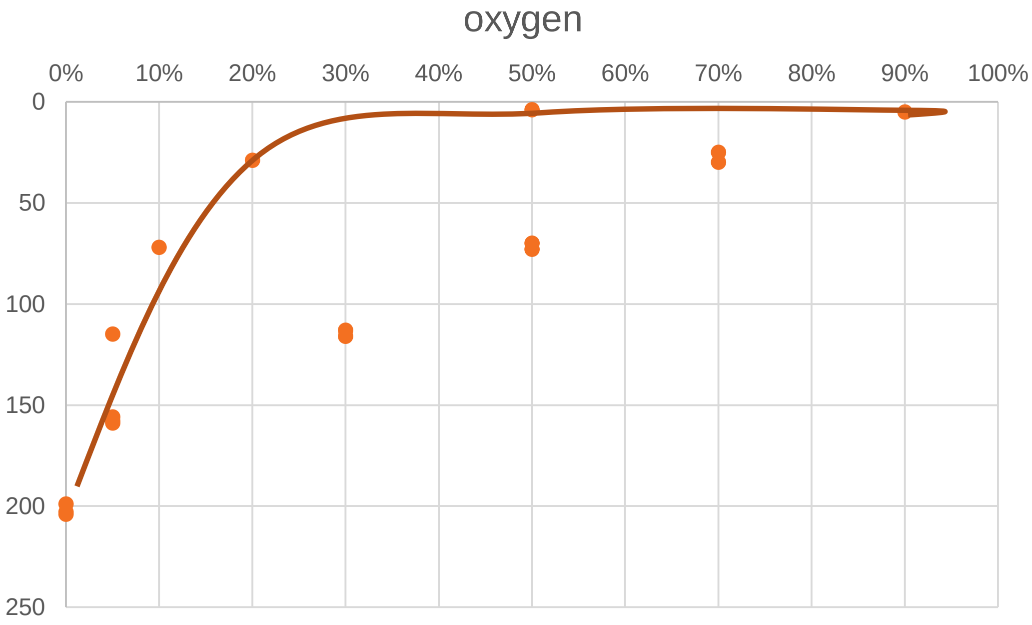
O_2 Transport and Consumption Modelling

Evolution of O_2 Profile

Update Conceptual Model
Interim Conclusions on Model Sensitivities

Phase 2 Sample Collection
Groundwater
Waste Rock
Coal Reject

Targeted oxygen gradient



Unsaturated Flow Modelling

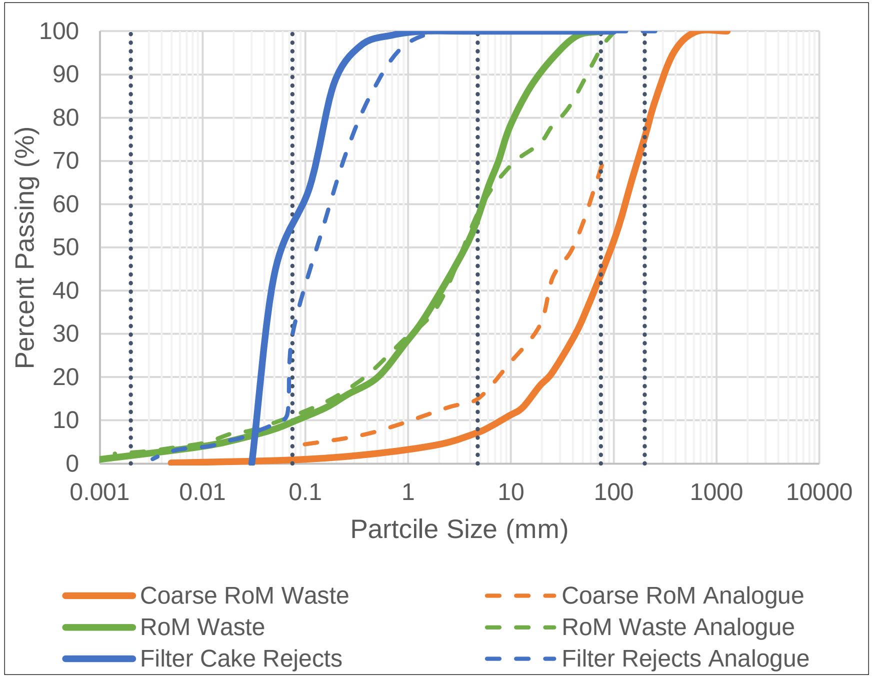
- Inputs
  - Particle size of plant rejects (filter cake and coarse):
    - PFS (Norwest, 2015)
    - Analogous compacted tailings with similar particle size distribution (filter cake only).
  - Particle size of waste rock: Literature for BC Coal deposits
  - Breaker reject: Not included in intermediate layers due to low volume – evaluated as a final cover.
  - Climate: Sparwood station scaled for elevation of site
- Configuration
  - Six 30 m high waste rock lifts, bottom 5 m assumed coarser (due to segregation).
  - Material balance: PFS

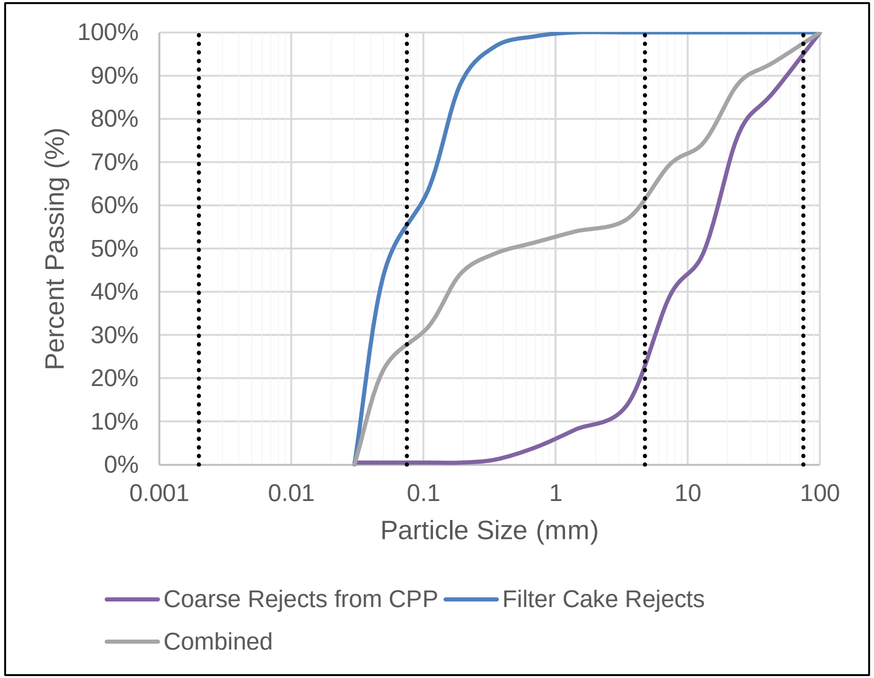
Unsaturated Flow Modelling

Thickness (m)			Cumulative Height (m)
3	Plant Rejects		188.5
0.5	Breaker reject		
25	RoM Waste	Lift 6	
5	Coarse RoM Waste (due to segragation)		
1	Plant Rejects		155
25	RoM Waste	Lift 5	
5	Coarse RoM Waste (due to segragation)		
1	Plant Rejects		124
25	RoM Waste	Lift 4	
5	Coarse RoM Waste (due to segragation)		
1	Plant Rejects		93
25	RoM Waste	Lift 3	
5	Coarse RoM Waste (due to segragation)		
1	Plant Rejects		62
25	RoM Waste	Lift 2	
5	Coarse RoM Waste (due to segragation)		
1	Plant Rejects		31
25	RoM Waste	Lift 1	
5	Coarse RoM Waste (due to segragation)		
	Natural Ground		

- Note the plant rejects here are only filter cake rejects (they are assumed to control hydraulic conductivity).
- Under-conservative as the rejects will have a coarse component.
- The split between filter cake rejects and coarse rejects needs to be confirmed.
- NOTE: model assumed compaction of coal spoils, but not waste rock.

Unsaturated Flow Modelling





- RoM waste PSDs are based on literature.
- Combined plant rejects PSD assumes 50/50 split.

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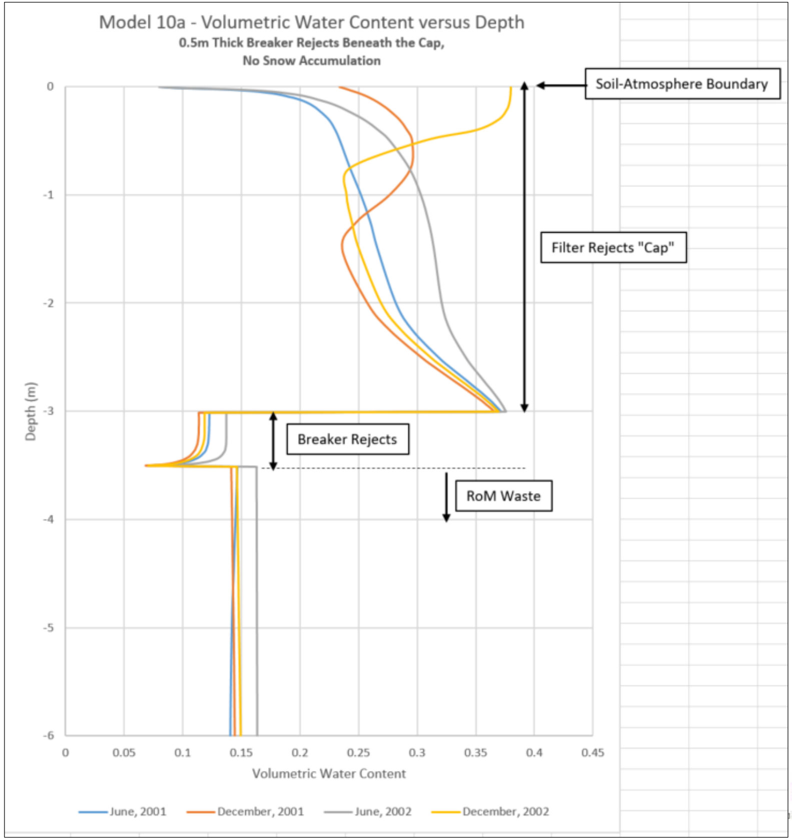
Unsaturated Flow Modelling

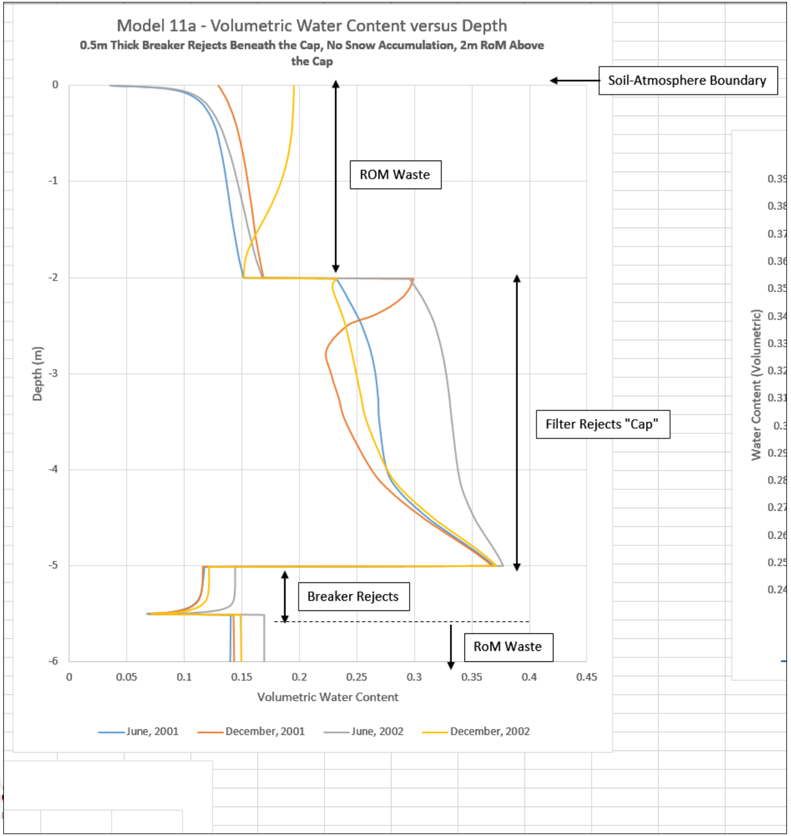
- Model:
  - HYDRUS
- Sensitivities
  - Base case vs compaction
  - Effect of a cover on plant reject to reduce evaporative effects
- Findings
  - Raw plant rejects are not expected to retain sufficient moisture to limit oxygen entry
  - Compaction of rejects appear to achieve the desired characteristics.
    - No compaction of waste rock was modeled
  - 2 m ROM waste rock placed on reject helps with increasing moisture content in the plant rejects cap.

Unsaturated Flow Modelling



Model 10a - Volumetric Water Content versus Depth

0.5m Thick Breaker Rejects Beneath the Cap,
No Snow Accumulation



Model 11a - Volumetric Water Content versus Depth

0.5m Thick Breaker Rejects Beneath the Cap, No Snow Accumulation, 2m RoM Above the Cap

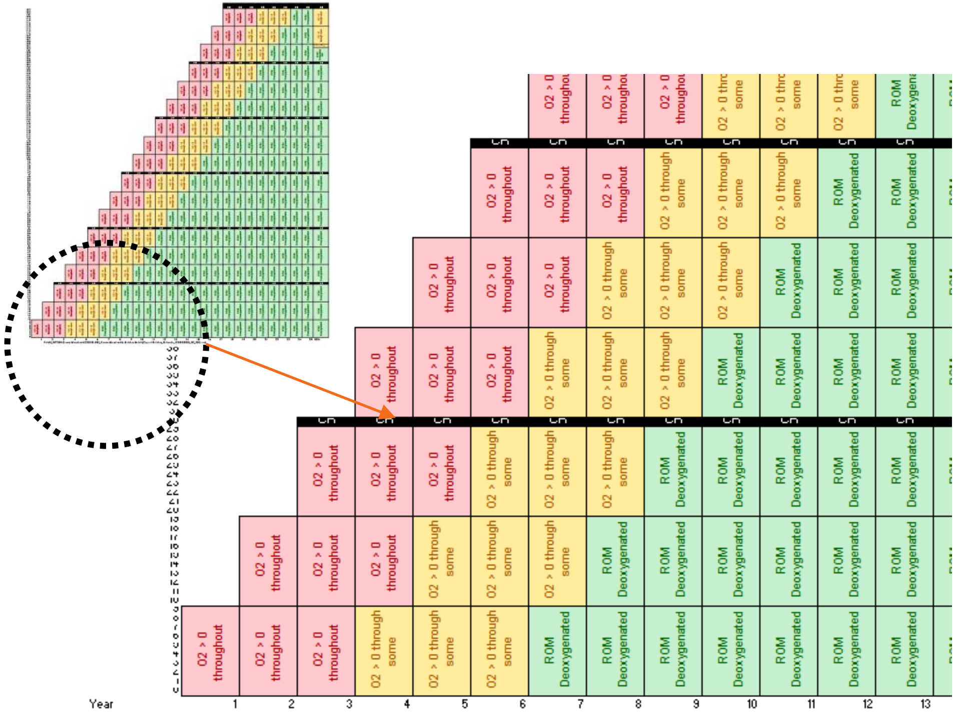
O_2 Transport and Consumption Modelling

- Inputs
  - O_2 diffusion coefficient: Unsaturated flow model
  - Sulphide content: Crown Mountain data
  - Sulphide oxidation rates: Analogous file data
  - Carbon oxidation rate: No data, set to 0 (conservative).
- Model
  - FlexPDE (1D model, accounts for O_2 transport by diffusion, O_2 consumption by sulphides, Arrhenius temp dependence of oxidation rate, heat release due to sulphide oxidation)
  - Configuration
    - One lift (reject on waste rock)
    - No O_2 entry on edges

O_2 Transport and Consumption Modelling

- Findings (assuming compacted plant reject layers)
  - O_2 penetrates 15 m into waste rock
  - Takes about 3 years to consume O_2 in pore spaces (i.e. takes about 3 years to establish O_2 profile)

Implications for Pile Performance



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Time →

- Years 1 to 3
  - Performs as unsaturated.
- Years 4 to 8
  - Parts of first lift become de-oxygenated.
- Year 9 onward
  - First lift de-oxygenated.
- Water quality benefit seen in years 6 to 9.
- Need for water treatment determined by loading

Interim Modeling Conclusions

- Conceptual model demonstrated numerically.
  - Can yield conditions that result in reduction of selenate and nitrate.
  - Results consistent with observations of full-scale facilities.

Particle Size and Compation

- Controls retention of moisture and development of oxygen barrier.
- Very strong sensitivity to the assumed particle size distribution of plant rejects.

Interim Modeling Conclusions (continued)

- Effect on water quality may take 6 to 9 years to be realized.
- Oxygen consumption modelling currently does not account for oxidation of carbon or aerobic microbial consumption of oxygen, which will accelerate and increase development of low oxygen conditions.
- Conservative
  - No compaction of waste rock
  - No aerobic metabolism and oxidation of carbon
  - Further size reduction of coal reject is possible
  - Inclusion would accelerate oxygen depletion and reduce time required

Phase 2

- Sampling
  - Groundwater
  - Waste Rock
  - Coal Reject
- Scoping level water quality assessment
- Characterize material properties
- Test oxygen consumption rates via respirometry
- Test denitrification and selenium reduction rates under controlled oxygen exposure, T=10°C, unsaturated flow in columns
  - Microbial community and biomineralization

Phase 2
Material Characterization and Sampling

- Multiple sources of test materials have been evaluated
  - Blasted Waste Rock: Collected from blasted bulk coal sample test pit.
  - Coal Reject: Created by SGS Metallurgical Laboratory
  - Groundwater: Collected from Crown Mountain "Mona Lisa" well 12-01.
    - Water quality monitoring data from OKC, update prior to testing following storage
    - Microbial community analysis

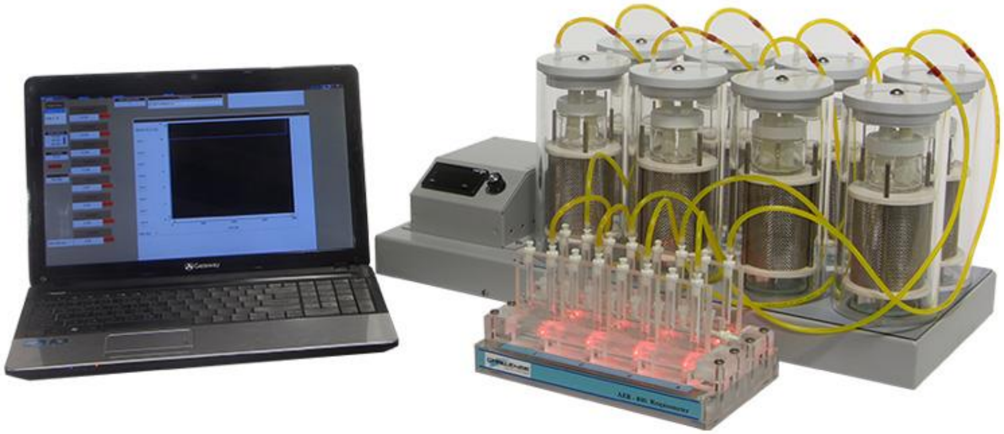
Waste and Coal Reject Characterization

- Hydrodynamic Properties
  - Particle gradation (sieve)
  - Unsaturated hydraulic parameters
    - Van Genuchten

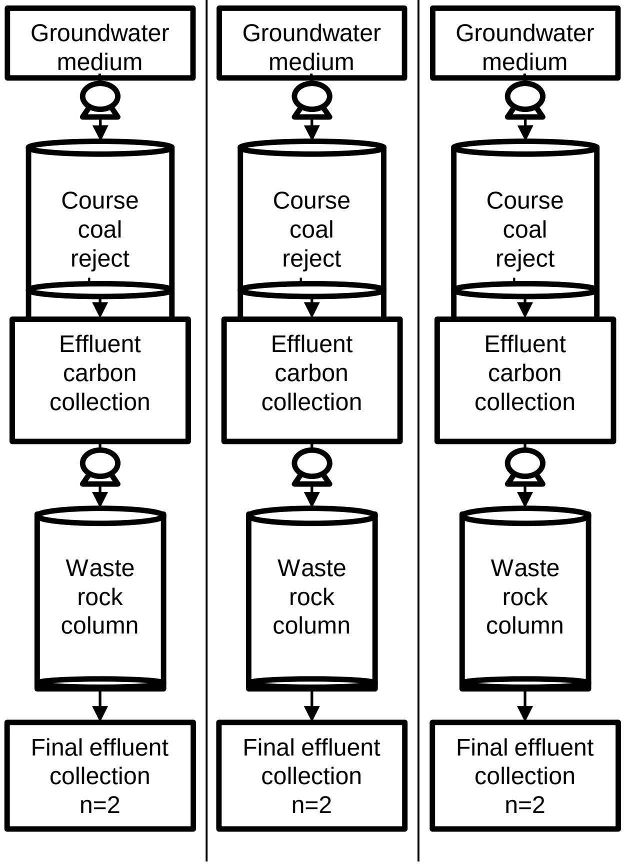
- Biogeochemistry
  - Mineralogy (XRD)
  - Multielement analysis
    - (4 acid/aqua regia)
  - Carbon content and speciation
  - Sulphur content and speciation
  - ABA
  - Microbial Community Analysis

Respirometry

- Measure of oxygen consumption by unsaturated waste and coal reject
- Repeated oxygen measurements in fixed headspace over period of days to weeks.



Proposed Unsaturated Column Test Design



Groundwater medium
Course coal reject
Effluent carbon collection
Waste rock column
Final effluent collection n=2

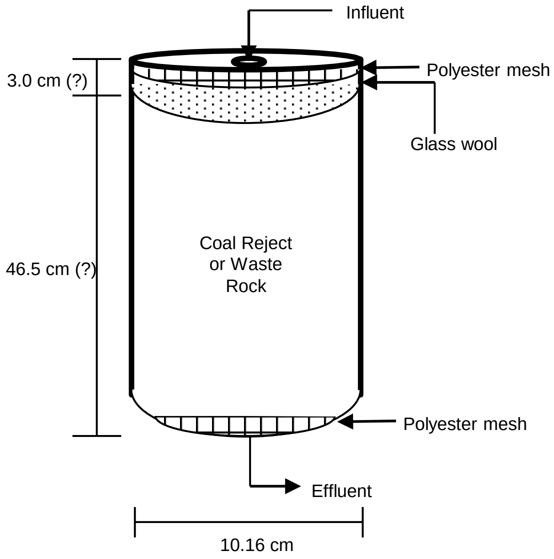
Aerobic conditions

Groundwater medium
Course coal reject
Effluent carbon collection
Waste rock column
Final effluent collection n=2

50% Air-N_2 mix

Groundwater medium
Course coal reject
Effluent carbon collection
Waste rock column
Final effluent collection n=2

Anoxic conditions



Enviromin

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In Situ Operational Demonstration

Microbial Geochemistry

- Se speciation and concentration
- Community Characterization
- Isotope Fractionation
- Mineralogy
- Field scale rates

Hydrodynamic Dump Design

- Changes in T, O_2, CO_2, H_2O based on design
- Changes in vapor phase Se