Geological and Geotechnical Site Investigations for the Design of a CO_2 Rich Flue Gas Direct Injection Facility

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Paul Metz

Department of Mining & Geological Engineering

University of Alaska Fairbanks

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National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

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Presentation Outline

- Presentation Outline
- Benefit to the Program
- Project Overview: Goals and Objectives
- Technical Status
- Accomplishments to Date
- Summary
- Appendix: Not Included in Presentation

Benefit to the Program

- Carbon Storage Program Major Goals:
  - Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within +/- 30 percent.
  - Develop technologies to demonstrate that 99 percent of the injected CO_2 remains in injection zones
  - Conduct field tests through 2030 to support the development BPMs for site selection, characterization, site operations, and closure practices.
- Program Goals one and two above are being addressed by the project. The third major goal of the Program is beyond the funding period of the project.
- Project benefits statement:

Project Overview: Goals and Objectives

- Project Objectives
  - Develop a site characterization methodology for CO_2 direct injection into large underground cavities in mafic volcanic rocks for permanent sequestration through mineral carbonation.
  - Characterization of underground mines in Keweenaw Copper Belt (KCB), Midcontinental Rift System as potential sites for small demonstration project.
  - Examine mine tailings sites in KCB for secondary hydrous carbonates formed from atmospheric CO_2.
  - Estimate volumes, if any, of sequestered atmospheric CO_2 sequestered.
  - Estimate the capital and operating cost of a small demonstration project to sequester 100 tons of CO_2 in one of the existing underground mines in the KCB.

Project Overview:
Goals and Objectives, continued

- Describe the goals and objectives in the Statement of Project Objectives.
  - Present information on how the project goals and objectives relate to the program goals and objectives.
    - See presentation guidelines for a list of project goals
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.

Technical Status

- Focus the remaining slides, logically walking through the project. Focus on telling the story of your project and highlighting the key points as described in the Presentation Guidelines
- When providing graphs or a table of results from testing or systems analyses, also indicate the baseline or targets that need to be met in order to achieve the project and program goals.

Technical Status

- Geological and geotechnical site characterization begins with an overview of the design of the engineering work for which the site is being assessed.
- The second step in the process is to assess the critical design parameters for the engineering work that would be impacted by the site geology including geologic hazards and conversely what impacts the engineering work would have on the environmental geology of the site.

Figure 1. Block Caving Model for Direct Injection Facility

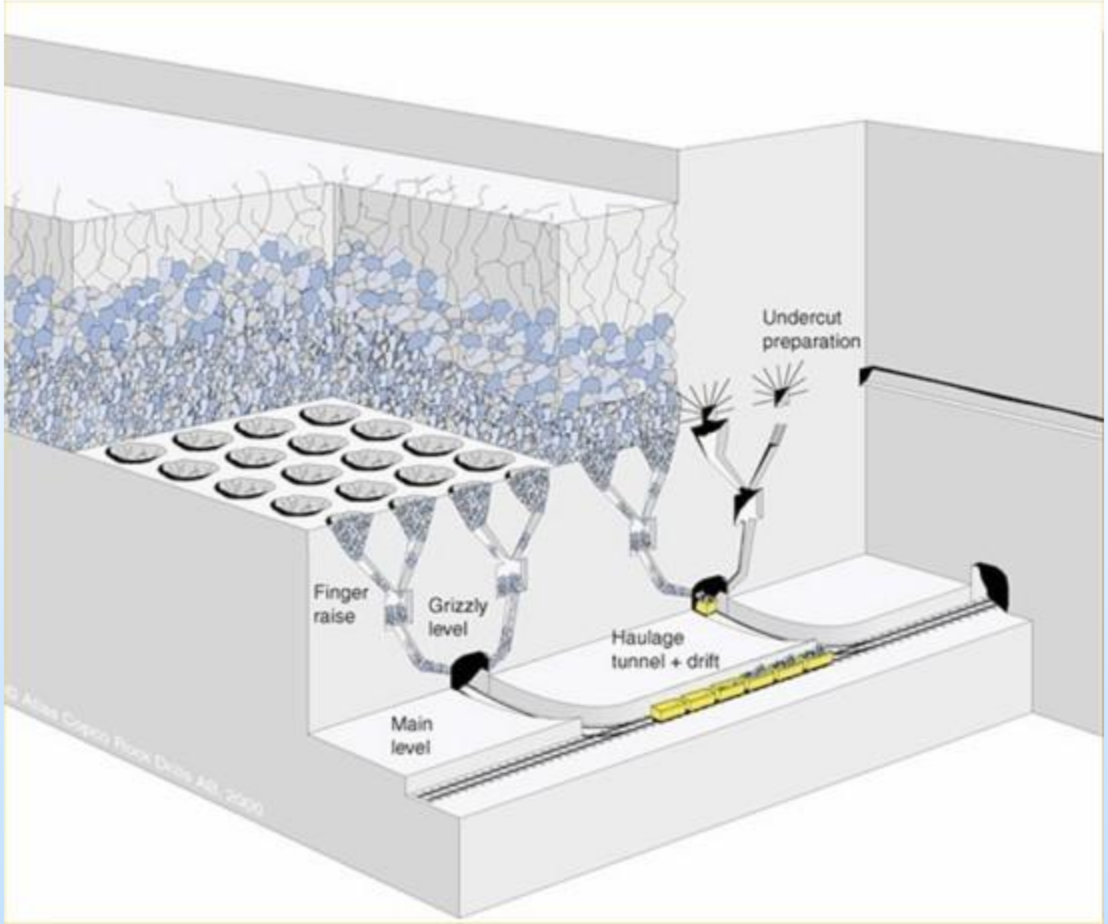
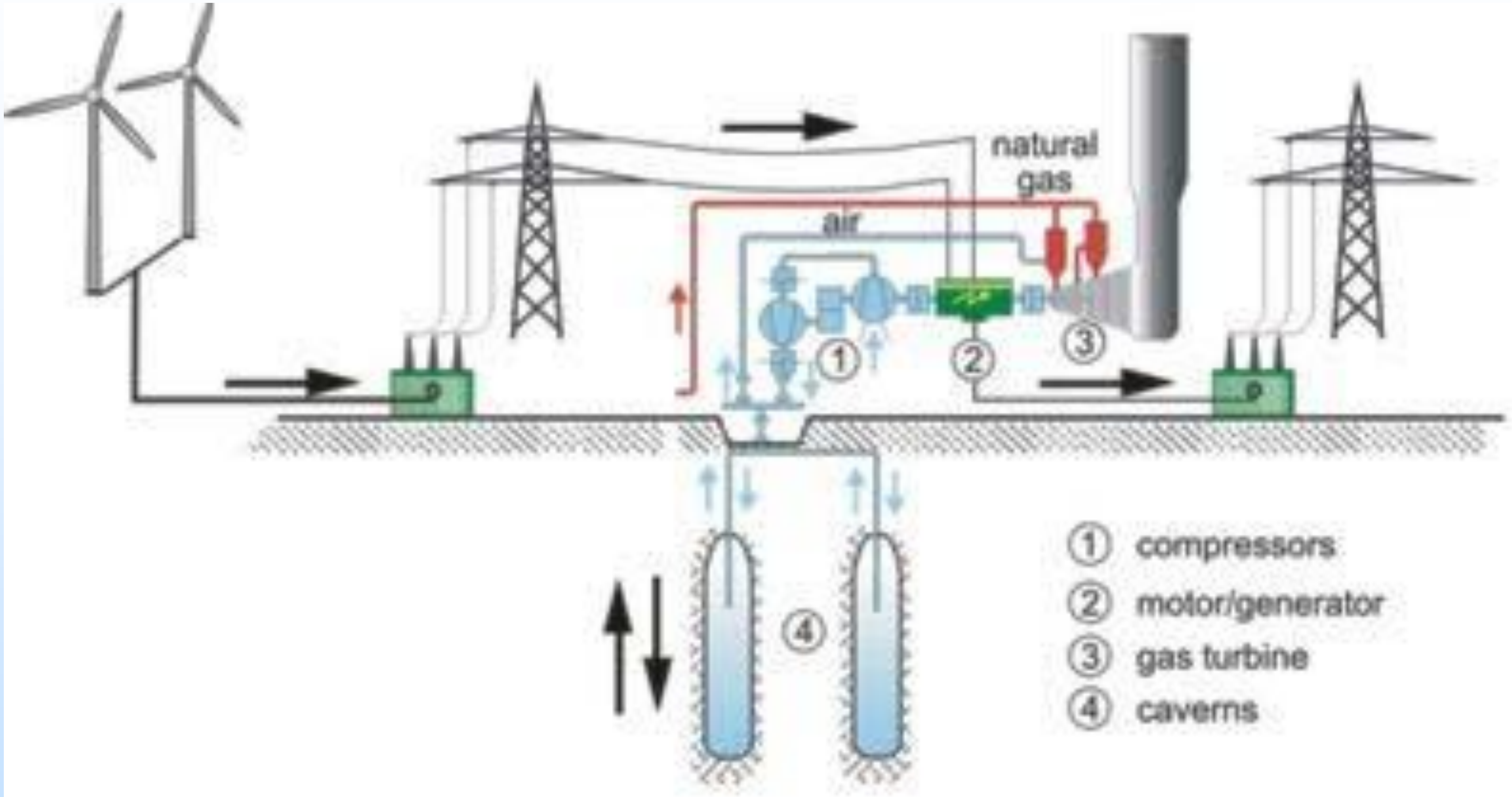


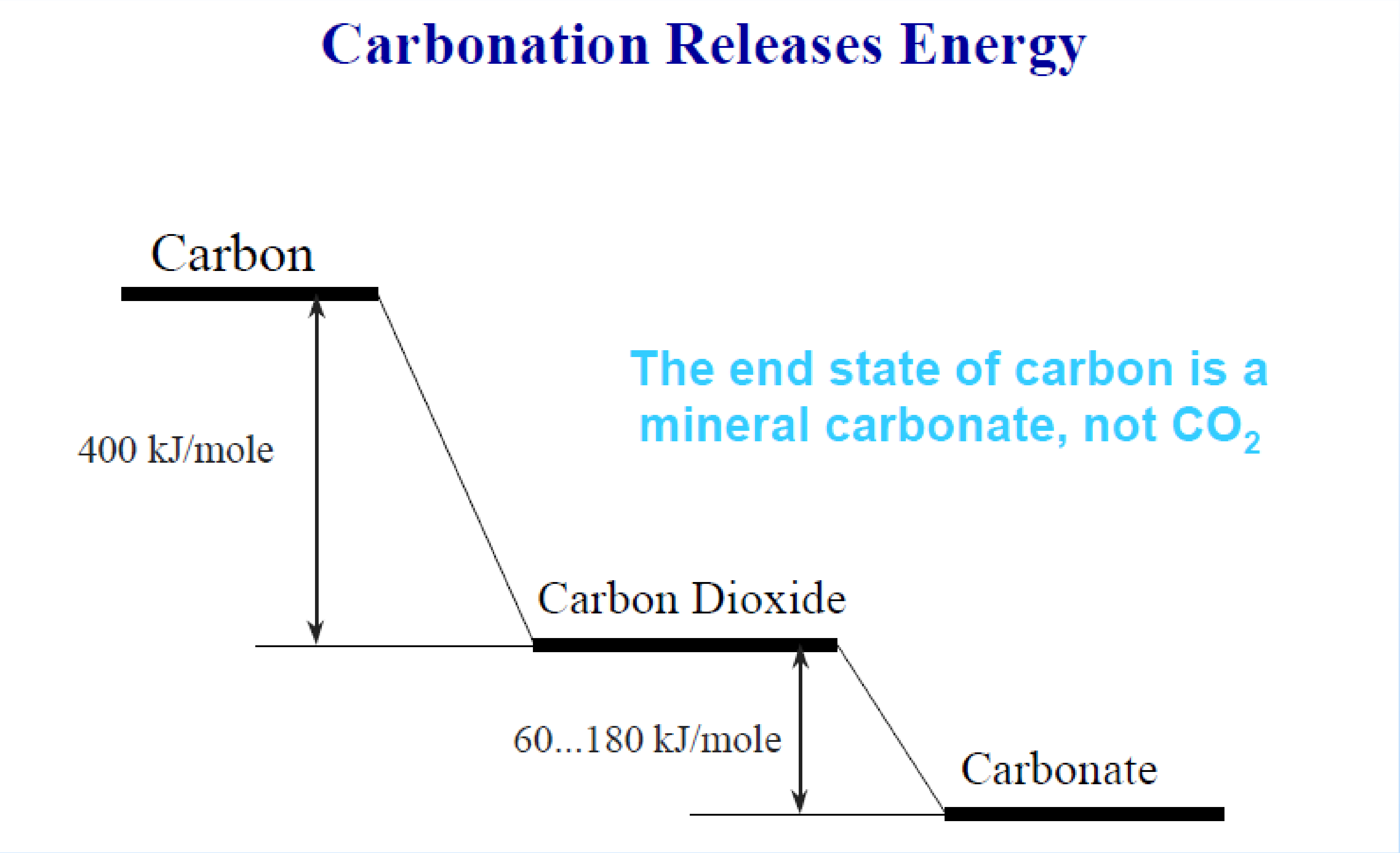
Figure 2. Compressed and Heated Air Returned to Surface for Additional Power Generation



Critical Design Parameters for Direct Injection Facility

1. Reactive mineralogy and petrology of mafic volcanic rocks that are permissible for mineral carbonation.
2. Adequate volume/mass of reactive mafic volcanic for required mass of CO_2 to be sequestered.
3. Rock mechanical properties sufficient for the development of large underground cavities.
4. Potential for secondary heat and mineral recovery to enhance economics of direct injection process.

Carbonate not CO_2 is Lowest Energy State for Carbon

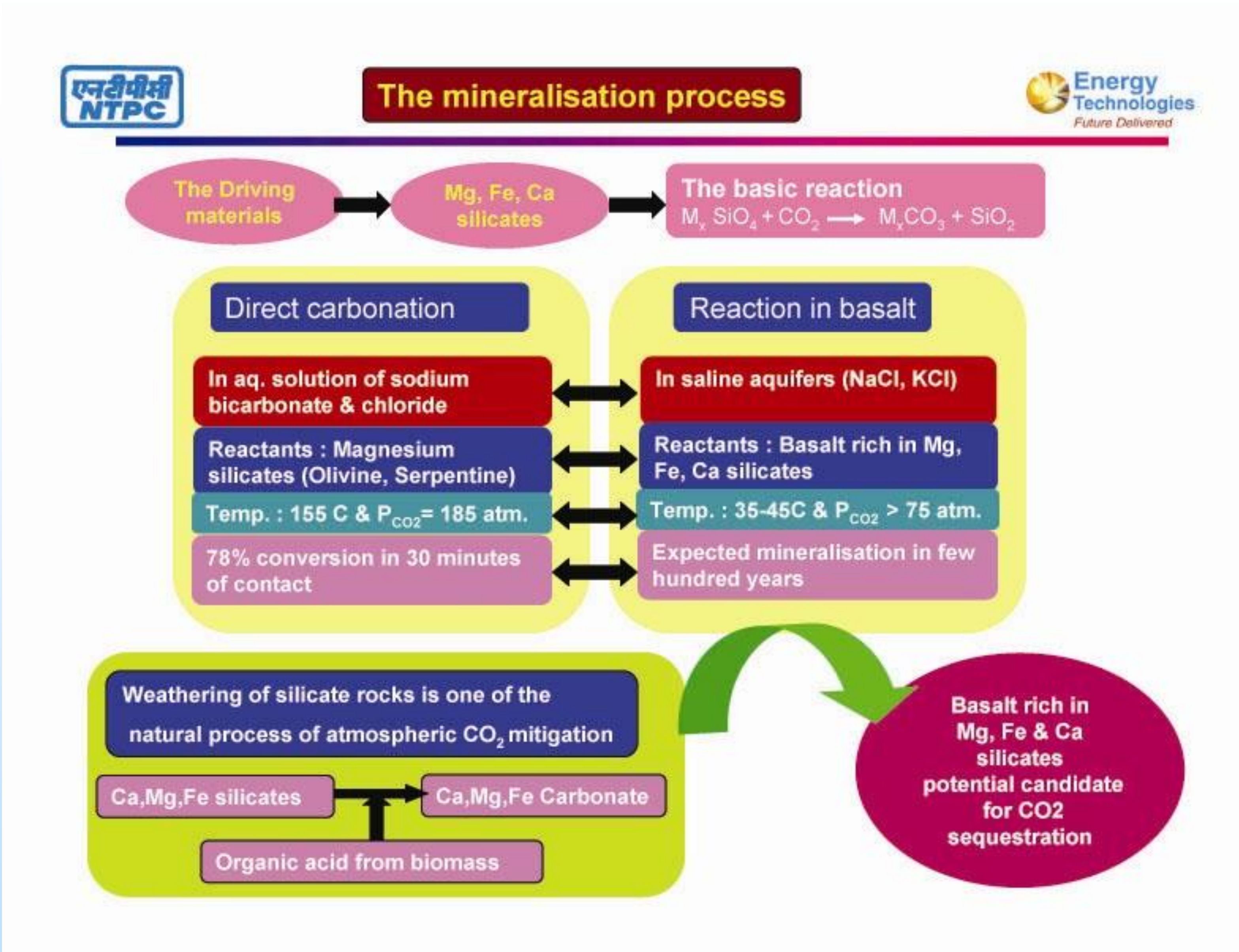


Generalized reaction and mineral specific reactions for the carbonation of magnesium minerals in mafic and ultramafic rocks.

- **Generalized Reaction:**
- $(Mg, Ca)_xSi_yO_{x+2y+z}H_{2z} + xCO_2 \rightarrow x(Mg,Ca)CO_3 + ySiO_2 + zH_2O$

- **Serpentine:**
- $Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
- Exothermic Reaction: + 64 kj/mole
- One ton to dispose of ½ ton of CO_2

- **Forsterite:** $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
- Exothermic Reaction: + 95 kj/mole
- One ton to dispose of 2/3 ton of CO_2

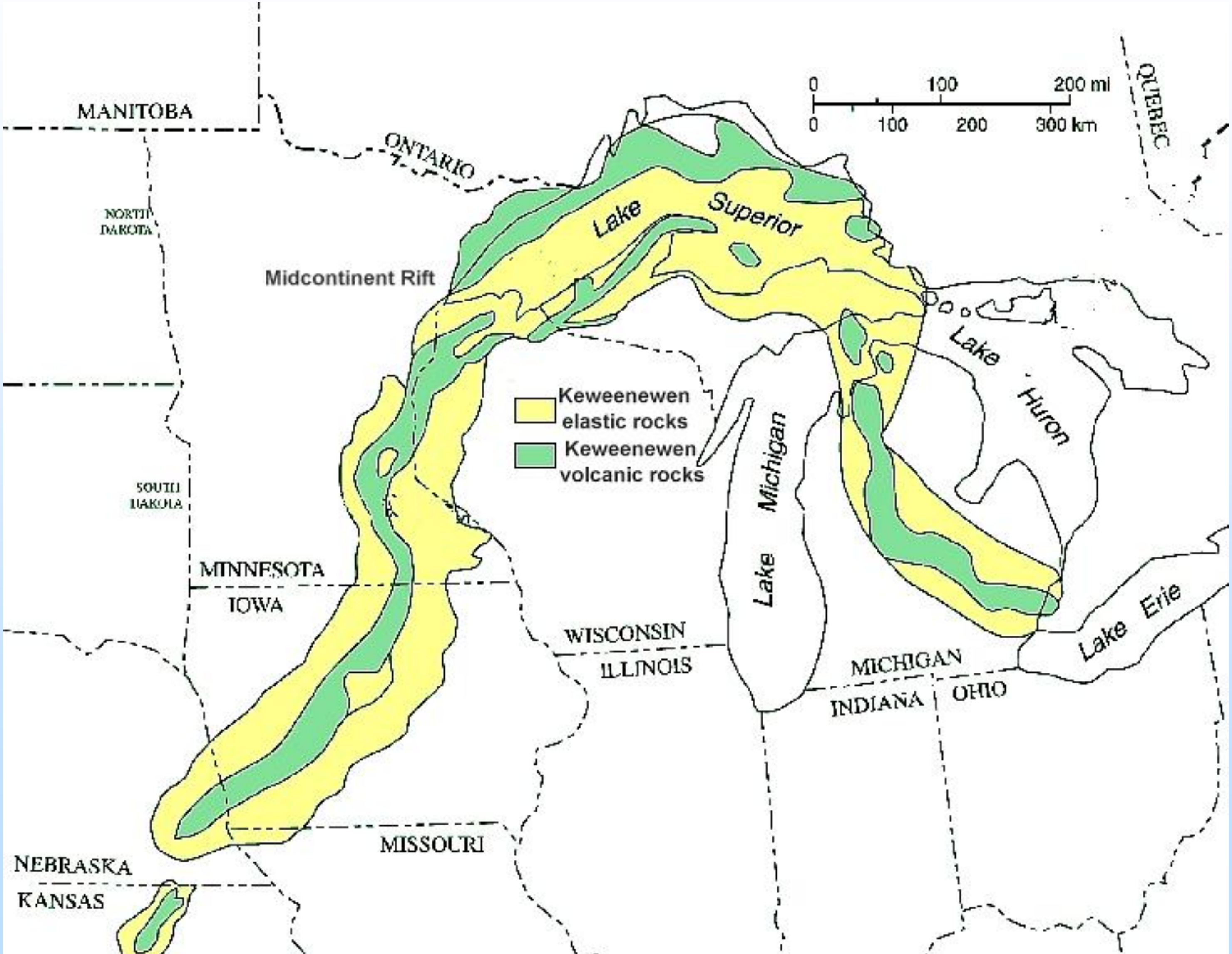

The mineralisation process
NTPC
Energy Technologies
Future Delivered
The Driving materials
Mg, Fe, Ca silicates
The basic reaction
$M_x SiO_4 + CO_2 \longrightarrow M_xCO_3 + SiO_2$
Direct carbonation
Reaction in basalt
In aq. solution of sodium bicarbonate & chloride
In saline aquifers (NaCl, KCl)
Reactants : Magnesium silicates (Olivine, Serpentine)
Reactants : Basalt rich in Mg, Fe, Ca silicates
Temp. : 155 C & P_{CO2}= 185 atm.
Temp. : 35-45C & P_{CO2} > 75 atm.
78% conversion in 30 minutes of contact
Expected mineralisation in few hundred years
Weathering of silicate rocks is one of the natural process of atmospheric CO_2 mitigation
Ca,Mg,Fe silicates
Ca,Mg,Fe Carbonate
Organic acid from biomass
Basalt rich in Mg, Fe & Ca silicates potential candidate for CO2 sequestration

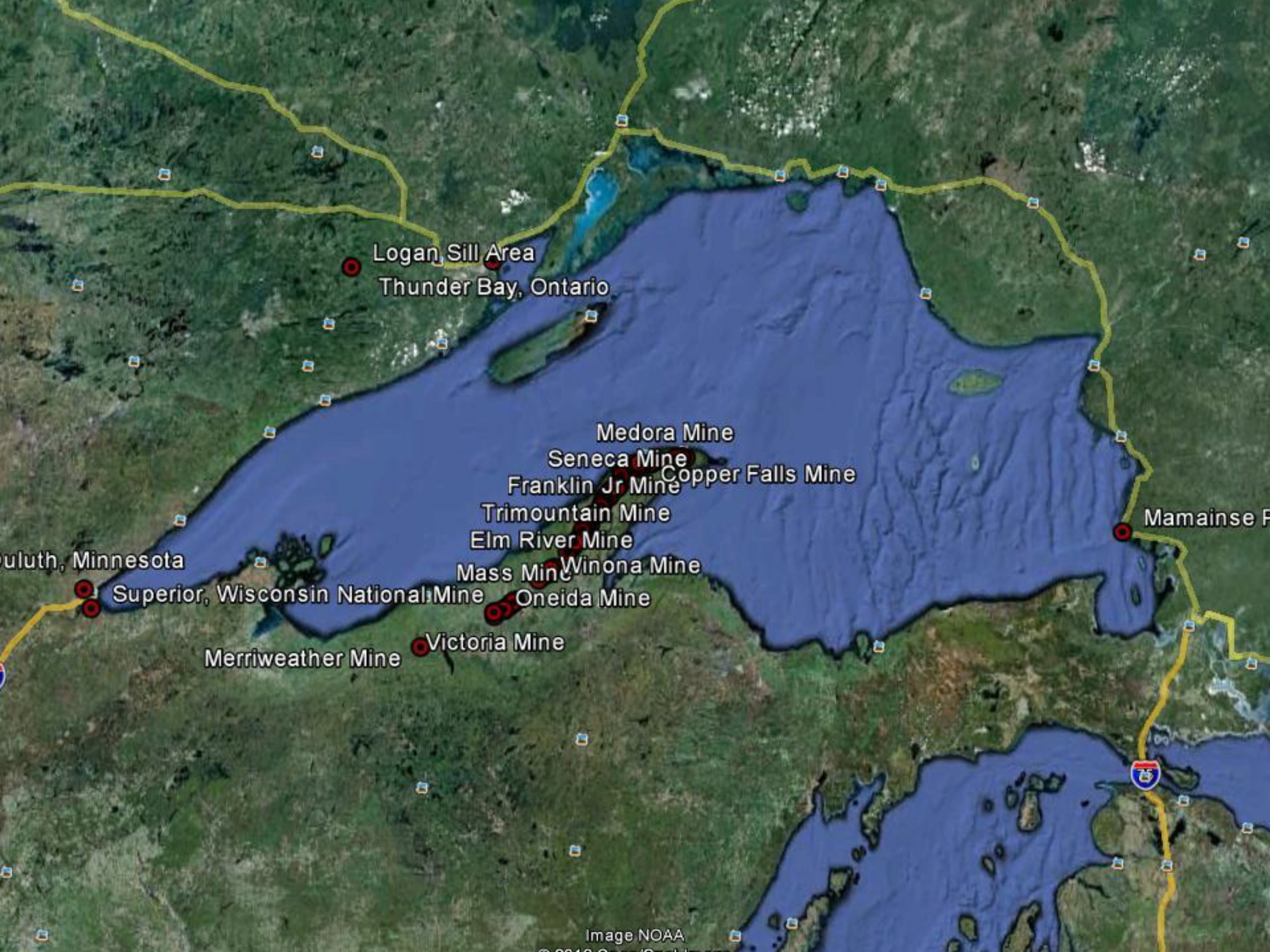
Secondary hydrated magnesium carbonate minerals formed from atmospheric CO_2 at the Clinton Creek and Cassiar chrysotile mine tailings sites in Yukon Territory and British Columbia respectively (from Wilson et al., 2009)

Mineral	Composition
• Dypingite	$Mg_5(CO_3)_4(OH)_2 \cdot 5H_2O$
• Hydromagnesite	$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$
• Lansfordite	$MgCO_3 \cdot 5H_2O$
• Nesquehonite	$MgCO_3 \cdot 3H_2O$

- NOTE: The chrysotile ores were crushed to sand size or finer material thus the mine tailings have large specific surface areas. Estimated volumes of sequestered CO_2 are potentially equivalent to that generated in the mining and milling process.

Mafic Volcanic Rocks of the Midcontint Rift System and the Keweenaw Copper Belt





Logan Sill Area
Thunder Bay, Ontario
Medora Mine
Seneca Mine
Copper Falls Mine
Franklin Jr Mine
Trimountain Mine
Elm River Mine
Mamainse P
uluth, Minnesota
Mass Mine
Winona Mine
Superior, Wisconsin National Mine
Oneida Mine
Victoria Mine
Merriweather Mine
Image NOAA

Mine and Mine Tailing Sites Examined and Sampled

- 25 Sites examined and sampled for:
  - Optical and electron microprobe determinations of mineralogy and petrology of Portage Lake Volcanics of the KCB.
  - Total rock characterization by whole rock, trace element, and rare earth elemental analyses.
  - Rock Uniaxial Compressive Strength
  - Rock Mass Classification (Rock Quality Designation (RQD) Index)

Mineralogy and Petrology

- Portage Lake Volcanics are tholeiitic basalts (200 separate flows) that are host to native copper mineralization.
- Past production of over 10 billion pounds of copper came from altered amygdaloidal flow tops characterized by decalcified plagioclase feldspar and altered augite along with calcite, epidote, prehnite, pumpellyite and zeolites.
- Mineral phases have been attributed to low grade regional metamorphism.
- Inferred metamorphic fluid compositions are low salinity and CO_2 rich.
- In contrast, electron microprobe analyses of the massive centers of the flows indicate that the ophitic basalts and micro-gabbros are relatively unaltered.

Whole Rock Chemistry of Keweenaw Basalts

- Results from 138 of the 187 samples to be analyzed.
- Portage Lake Volcanics are dominantly low TiO_2 (< 2%) tholeiitic basalts.
- Results similar to Nicholson et al., 1997 but much larger number of analyses that also include trace element data.
- Massive fine-grained basalt and micro-gabbros from the center of the flows are less altered than the mineralized flow tops but still contain significant copper concentrations see following slide).
- Rhyolites and High TiO_2 basalts are a minor portion of the sampled population.

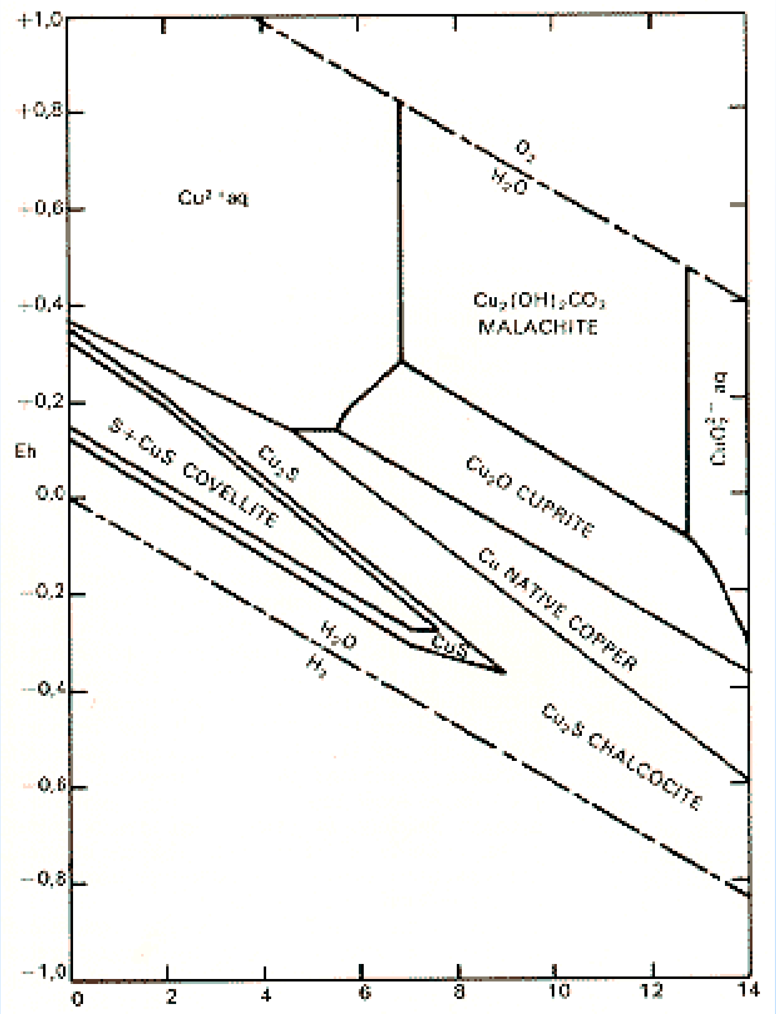
Trace Element Chemistry of Keweenaw Basalts

- Results from 138 of the 187 samples to be analyzed.
- Sample digestion – 4 acid.
- Instrument – ICP-MS.
- Trace Elements – Ag, As, Ba, Bi, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sn, Te, Th, U, V, W, Zn.
- Notable anomalous elements in most samples (111 of 138).
- Copper: 100 - 27,200 ppm.
- Silver: 1 - 15.5 ppm.

Rare Earth Elemental Analyses

- Normalized REE for various flows in the Midcontinent Rift System indicate minor differences in in degree of light vs heavy element distribution that may be a function of magmatic differentiation.
- No major differences in the Portage Lake Volcanics have been determined.

Eh-pH Diagram for Copper



Uniaxial Compressive Strength and Density

- The ophitic textured basalts and micro-gabbros have compressive strengths that range from 58,000 to 63,000 psi.
- Density ranges from 2.9 to 3.1 gm/cc.

RQD data for the Caledonia Mine

- Joint spacing outside the shear zone hosted mineralization and flow tops generally exceeds 100 cm.
- The Rock Quality Designators for the two drifts selected for the potential direct injection demonstration project had RQD's of 100%.
- The blocks are generally equi-dimensional and the estimated minimum block size is approximately 100 x100 x 100 cm.

Accomplishments to Date

- Mineral and petrologic characterization of Portage Lake Volcanics and definition of reactive mineralogy in the unaltered flows.
- Geochemical characterization of the Portage Lake Volcanics.
- Characterization of the critical rock mechanic properties that indicate large underground cavities can be developed in the Portage Lake Volcanic (demonstrated by large scale past mining to depths in excess of 8500 feet at the Quincy Mine).
- Characterization of the Portage Lake Volcanics in the Caledonia Mine (Horizontal Adit with at least100 meters of back).

Summary

– The Midcontinental Rift System is estimated to contain 1,500,000 km^3 of mafic volcanic rocks.
– The upper portion of the at least 10 km thick sequence is represented by the Portage Lake Volcanics which have the potential for mineral carbonation of the pyroxenes and labradorite feldspars.
– Such carbonation has probably occurred during regional metamorphism and is the probable mechanism for formation of the largest native copper deposits in the world.
– Large underground openings in the rocks have occurred during past mining activities and can be developed for the direct inject of CO_2 rich flue gases.
– Direct inject may significantly decrease the cost of CO_2 sequestration through avoided separation costs and potential additional mineral and energy recovery.

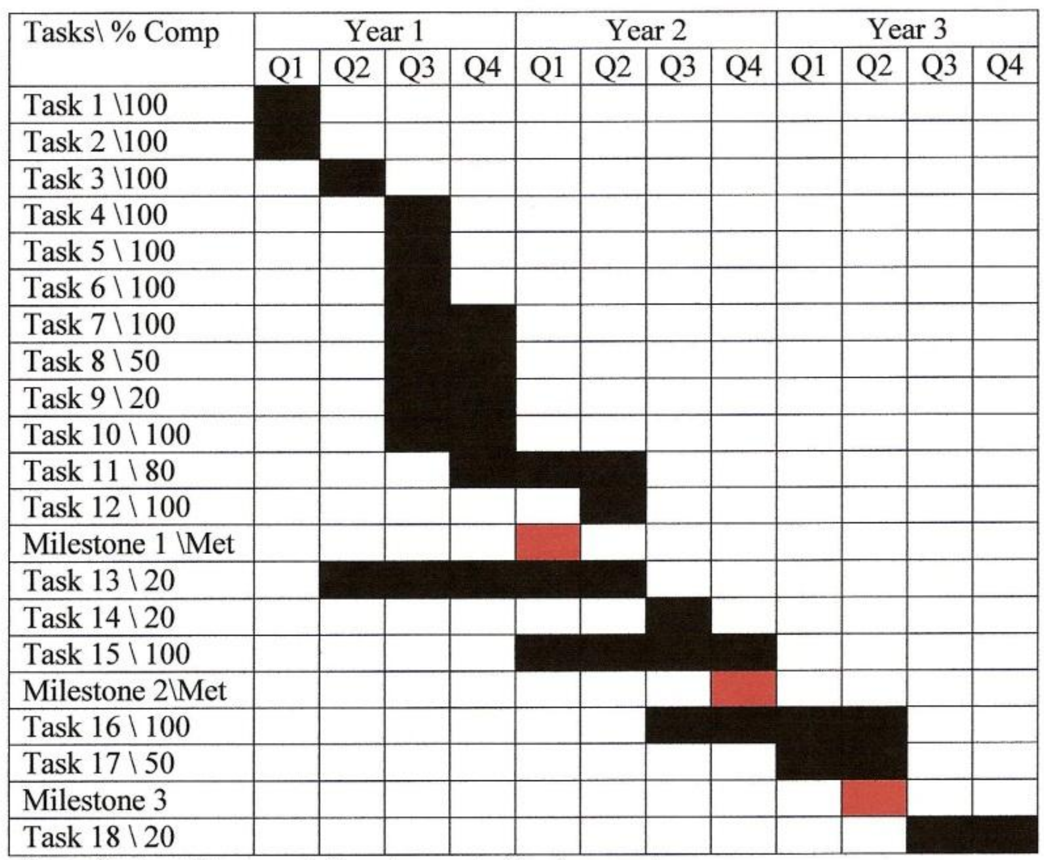
Appendix

- – These slides will not be discussed during the presentation, but are mandatory

Organizational Chart

- Dr. Paul Metz, Principal Investigator,
- Department of Mining & Geological Engineering, UAF
- Dr. Rajive Ganguli, Co-Principal Investigator, Department of Mining & Geological Engineering, UAF
- Dr. Abihijit Dandekar, Co-Principal Investigator, Department of Petroleum Engineering, UAF
- Dr. Shirish Patil, Co-Principal Investigator,
- Department of Petroleum Engineering, UAF
- Patti Bolz – Graduate Student (Geological Engineering, University of Alaska Fairbanks)

Gantt Chart



Note: Project Years and Quarters not calendar quarters.

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