

Integrating Steel Production with Mineral CO₂ Sequestration

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Project Title: Integrating Steel Production with Mineral Sequestration
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Timken US Steel
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Concerns over global climate change suggest that the steel industry will face severe constraints on permissible carbon dioxide emissions. The necessity of processing useful iron in the mineral sequestration of carbon dioxide opens up three key opportunities for the Steel Industry.

- 1) It allows the industry to keep carbon disposal as an in-house operation, avoiding competition with larger industries.
- 2) The specifics of the industry could lead to synergies that lower the costs of the sequestration process substantially.
- 3) A carbon dioxide disposal option that exceeds the needs of the steel industry would offer the opportunity to sell carbon dioxide disposal credits to other industries, providing a hedging strategy in case the cost of carbon dioxide disposal rises quickly.

Mineral Carbon Sequestration Overview

- Basic reaction is exothermic:



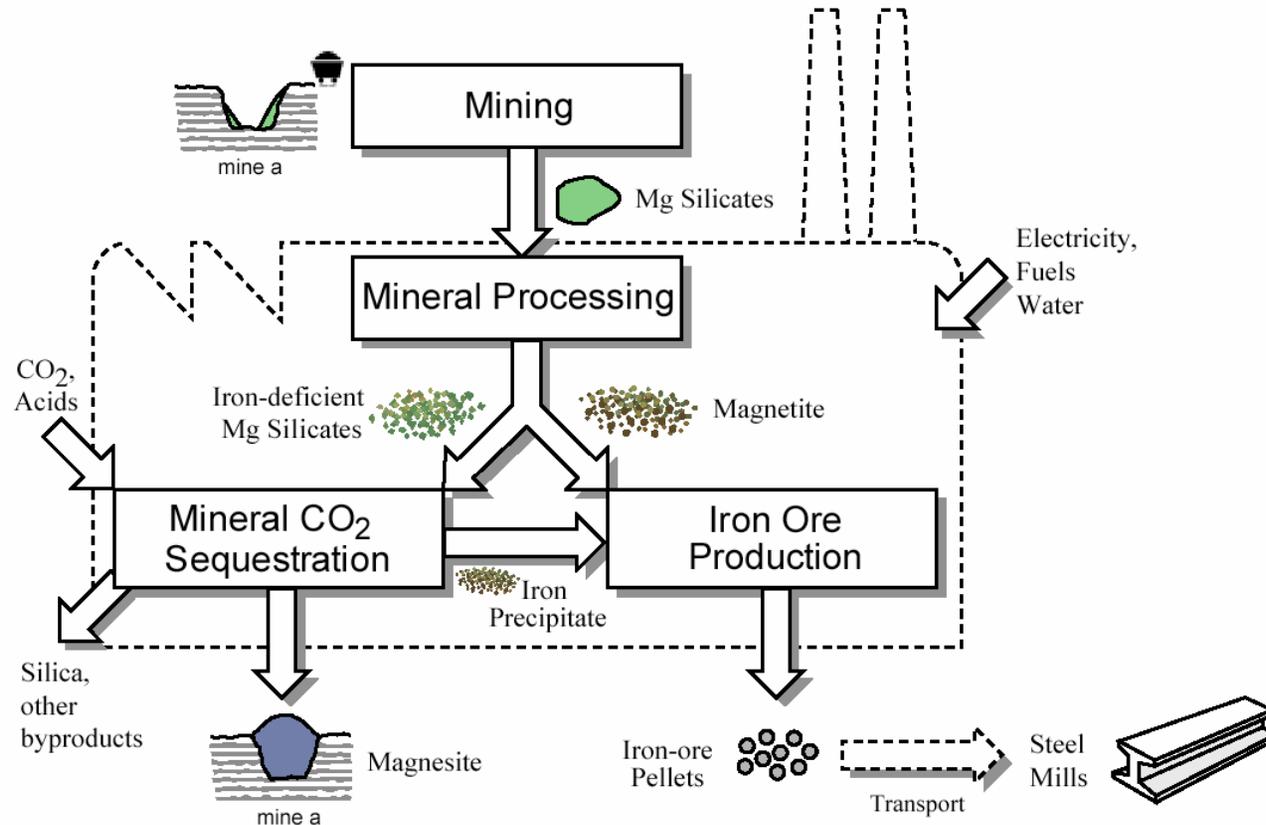
- As are the realistic reactions with abundant Mg-bearing silicate minerals:



The synergy between steel production and mineral CO₂ sequestration comes from the chemical substitution of iron for magnesium in silicate minerals such as serpentine:



Silicate minerals can thus be used as low-grade iron ores

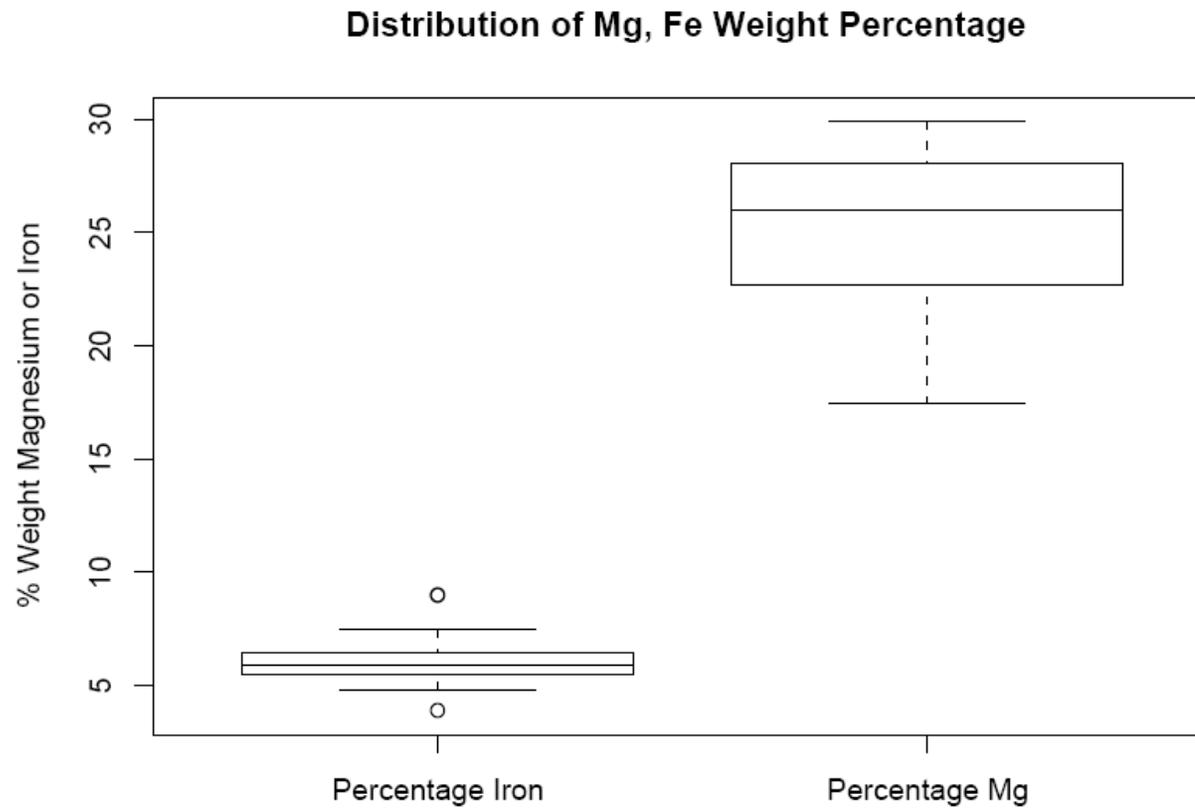


Task 1: Characterization of serpentinite and peridotite rock formations for use as iron ore and magnesium source

Task 2: Magnetic Separation Techniques for the extraction of magnetically separable iron ore.

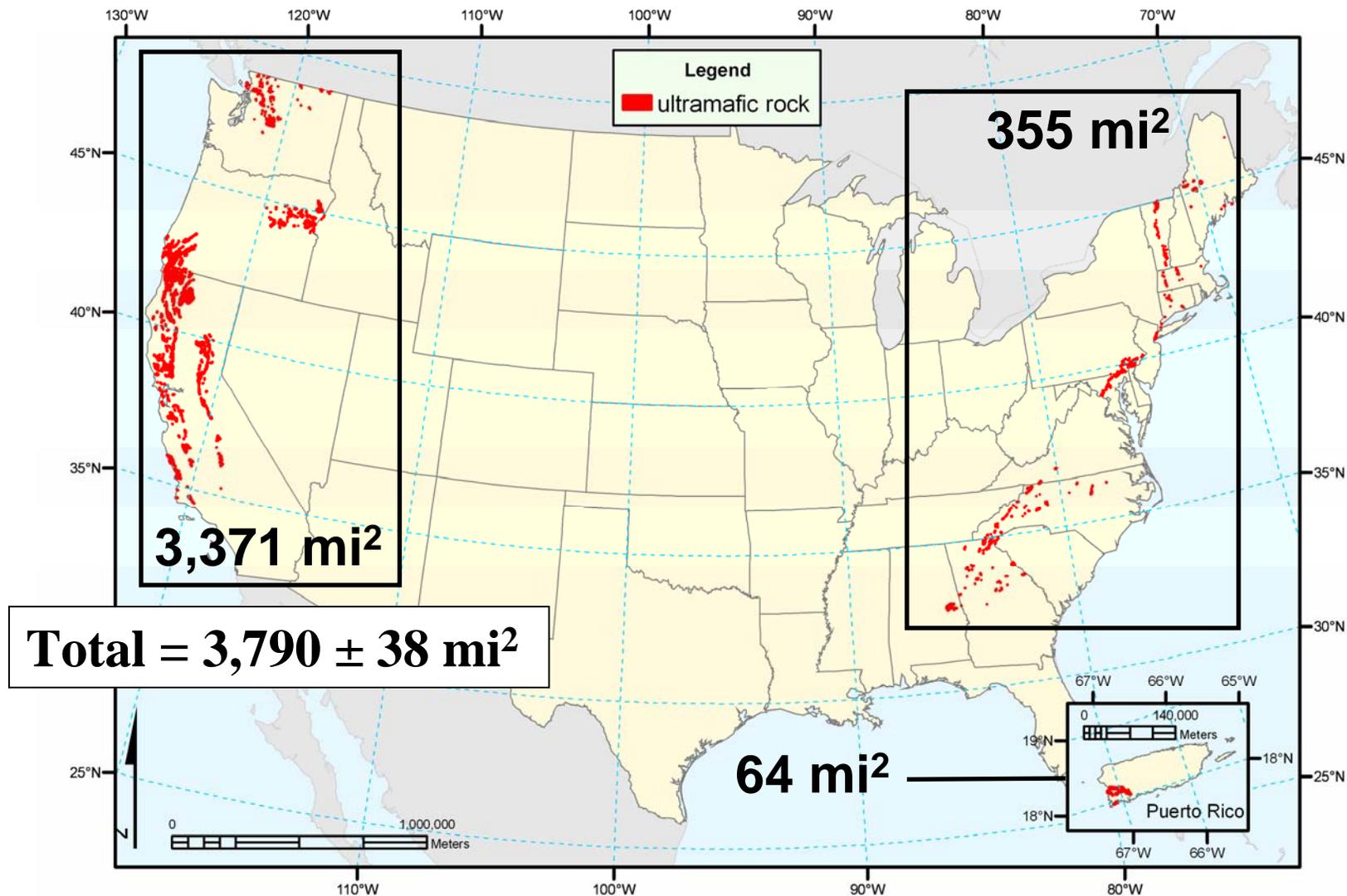
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- Rock types peridotite and serpentinite have been identified as attractive for mineral CO₂ sequestration.
- These rocks generally contain 24-28% by weight magnesium, and 5-7% by weight iron as iron oxide*

*Based on analysis of 56 samples from 33 ore bodies in 9 states



Datasets on the geology of the United States indicate that there may be almost 3,800 square miles of suitable ultramafic material in the United States and PR

1. Total ultramafic area

Ultramafic surface coverage in the Eastern U.S.

State	area (km ²)	% of total
AL	97.45	9.0%
CT	0.56	0.1%
GA	148.33	13.7%
MA	10.08	0.9%
MD*	212.63	19.6%
ME	177.79	16.4%
NC	86.47	8.0%
NJ	3.89	0.4%
NY	40.33	3.7%
PA	62.64	5.8%
VA*	52.71	4.9%
VT	27.60	2.5%
Puerto Rico	165.95	15.3%
Total	1086.44	100.0%

2. Filter out owned lands and urban areas

Unusable land area of ultramafics in the Eastern US

Land Jurisdiction	area (km ²)	% of total ultramafic area
Air Force DOD	0.00	0.0%
Army DOD	0.00	0.0%
Native American Reservation	0.00	0.0%
National Monument BLM	0.00	0.0%
National Park NPS	0.00	0.0%
National Recreation Area FS	0.00	0.0%
National Recreation Area NPS	0.00	0.0%
National Scenic Area FS	0.00	0.0%
Wilderness BLM	0.00	0.0%
Wilderness FS	1.79	0.2%
Wilderness NPS	0.00	0.0%
Wilderness Study Area BLM	0.00	0.0%
Urban areas	32.83	3.0%
Total	34.62	3.2%

3. Filter out uneconomical deposits by size

Exclusion of small deposits not worthwhile to mine

Previously usable ultramafic area	1051.82 km ²
Total area of ultramafic deposits with >1 km ² area	976.10 km ²
% Still Suitable	92.8%

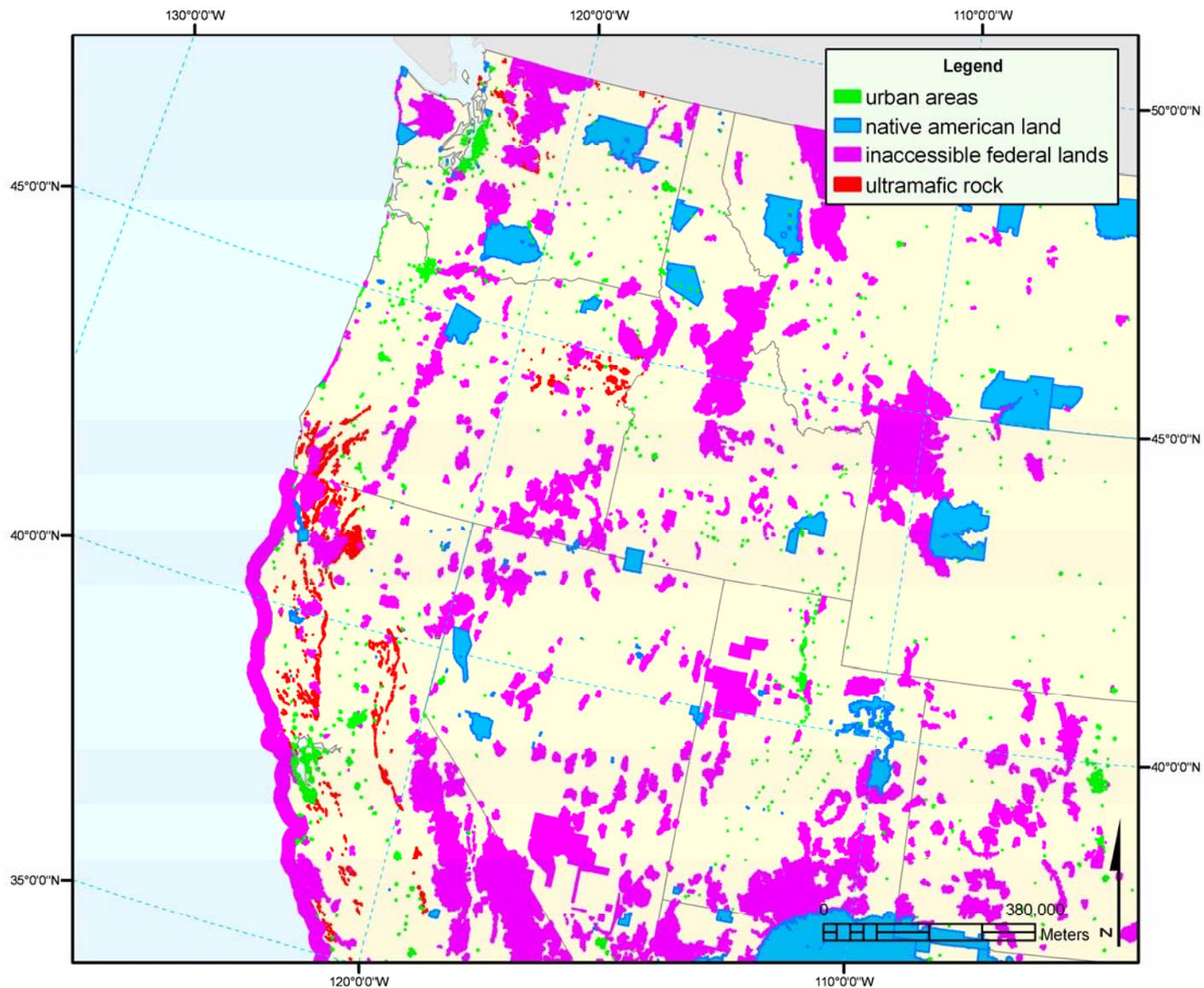
At this point, the useable ultramafic area corresponds to U.S. sequestration ability if CO₂ had no transport limits via pipeline.

4. Determine economical sequestration potential

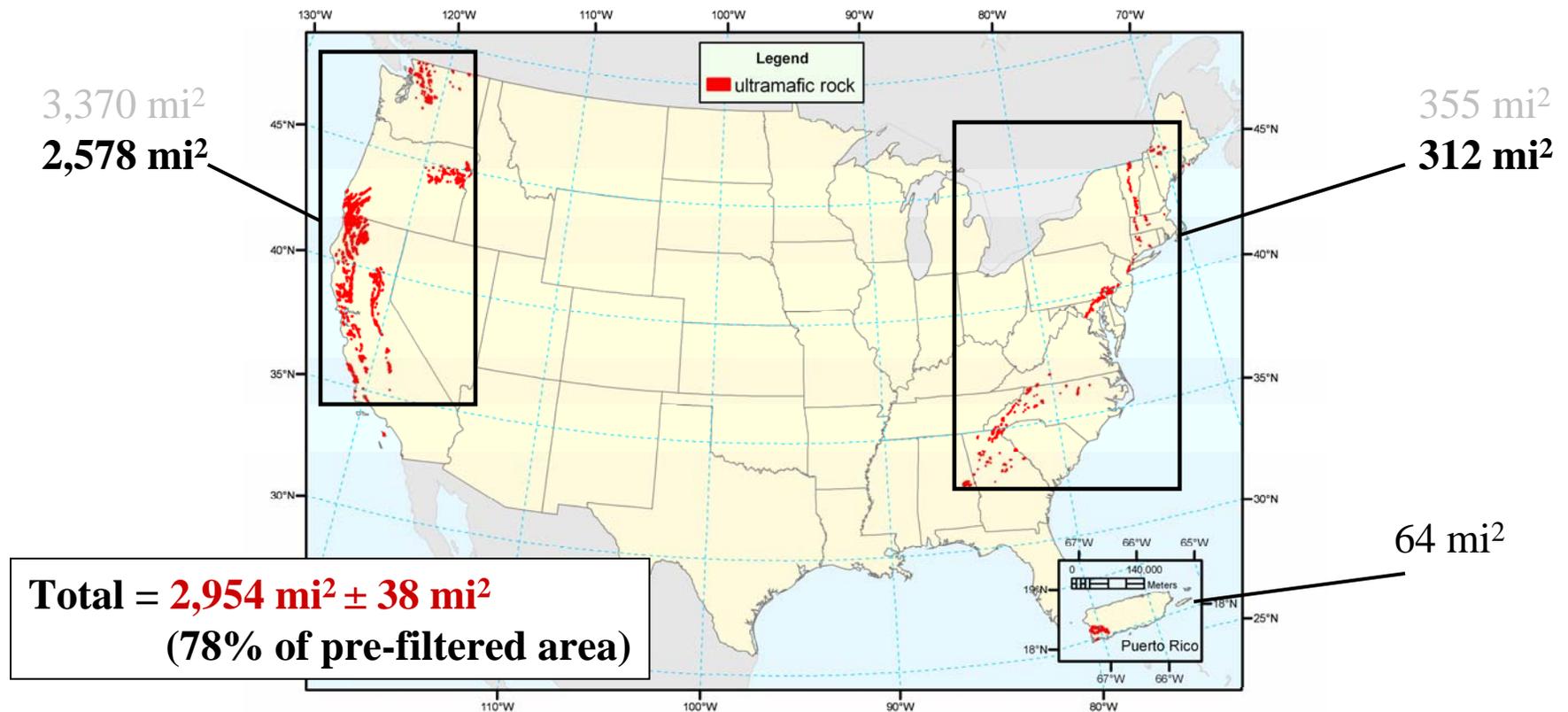
CO₂ emissions of point sources within 200 miles of ultramafics in the eastern U.S.

Sector	CO ₂ emissions (kt/yr)	% of total
Ammonia	580.82	0.07%
Cement	20920.00	2.38%
Ethanol	284.69	0.03%
Ethylene	1339.86	0.15%
Hydrogen	475.74	0.05%
Iron & Steel	22608.00	2.57%
power	784123.00	89.21%
Refineries	23973.00	2.73%
Gas proc	24619.60	2.80%
Total	878924.71	100.00%

Various datasets were used to eliminate areas where deposits were inaccessible or uneconomic



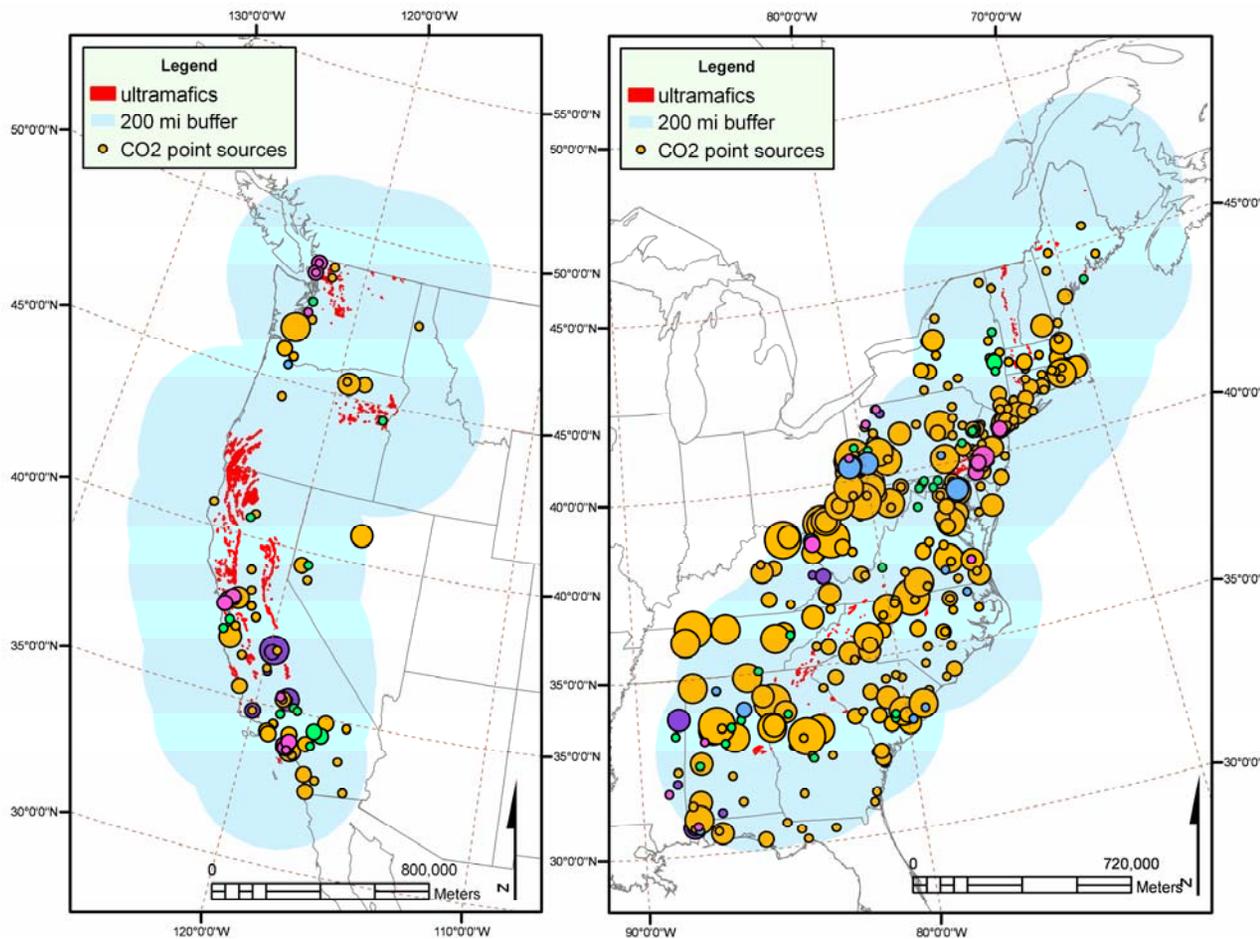
Datasets showing land use in the United States allowed us to see locations where the material would not be accessible for mining



After eliminating small deposits and those in inaccessible areas, 78% of the area remains

Size of circle ~ amount of CO₂ per year

Ammonia
Cement
Ethanol
Ethylene
Gas processing
Hydrogen
Iron and steel
Power
Refineries



Over 3,500 million tons of CO₂ is emitted annually from point sources within 200 miles of large ultramafic deposits.

conservative assumptions:		value:	basis:
rock surface area		7653 km ² (= A _{surf})	<ul style="list-style-type: none"> ultramafic area accessible for economical mining
rock density		2.55 gm/cm ³ (= ρ _{rock})	<ul style="list-style-type: none"> low end of range: 2.55 (serpentinite) to 3.15 (dunite), from literature
rock composition		35% by weight MgO (= wt%MgO)	<ul style="list-style-type: none"> reasonable serpentinite, see above
mineral carbonation conversion efficiency		50% silicate converted (= η _{conv})	<ul style="list-style-type: none"> low end of economical range of 60%-80% of current and planned processes
mining and beneficiation losses		8% mass removed (= f _{losses})	<ul style="list-style-type: none"> assumes iron removal for other uses (7%) and small transport and milling losses
variables:		range:	basis:
average mine depth		200 to 800 m (= z _{mine})	<ul style="list-style-type: none"> deposit depths from literature of 100-1500 m for deposits with surface area > 1km², common economic surface mining depths
rate of CO ₂ emissions to sequester		1028 Mt/yr ¹ (18%) 3773 Mt/yr ² (66%) 5725 Mt/yr ³ (100%)	<ul style="list-style-type: none"> (= \dot{m}_{CO_2}) ; • see table footnotes (fraction of total U.S. CO₂ emissions)

Using conservative assumptions about the process and material availability, one can calculate the CO₂ sequestration potential of ultramafic minerals in the United States

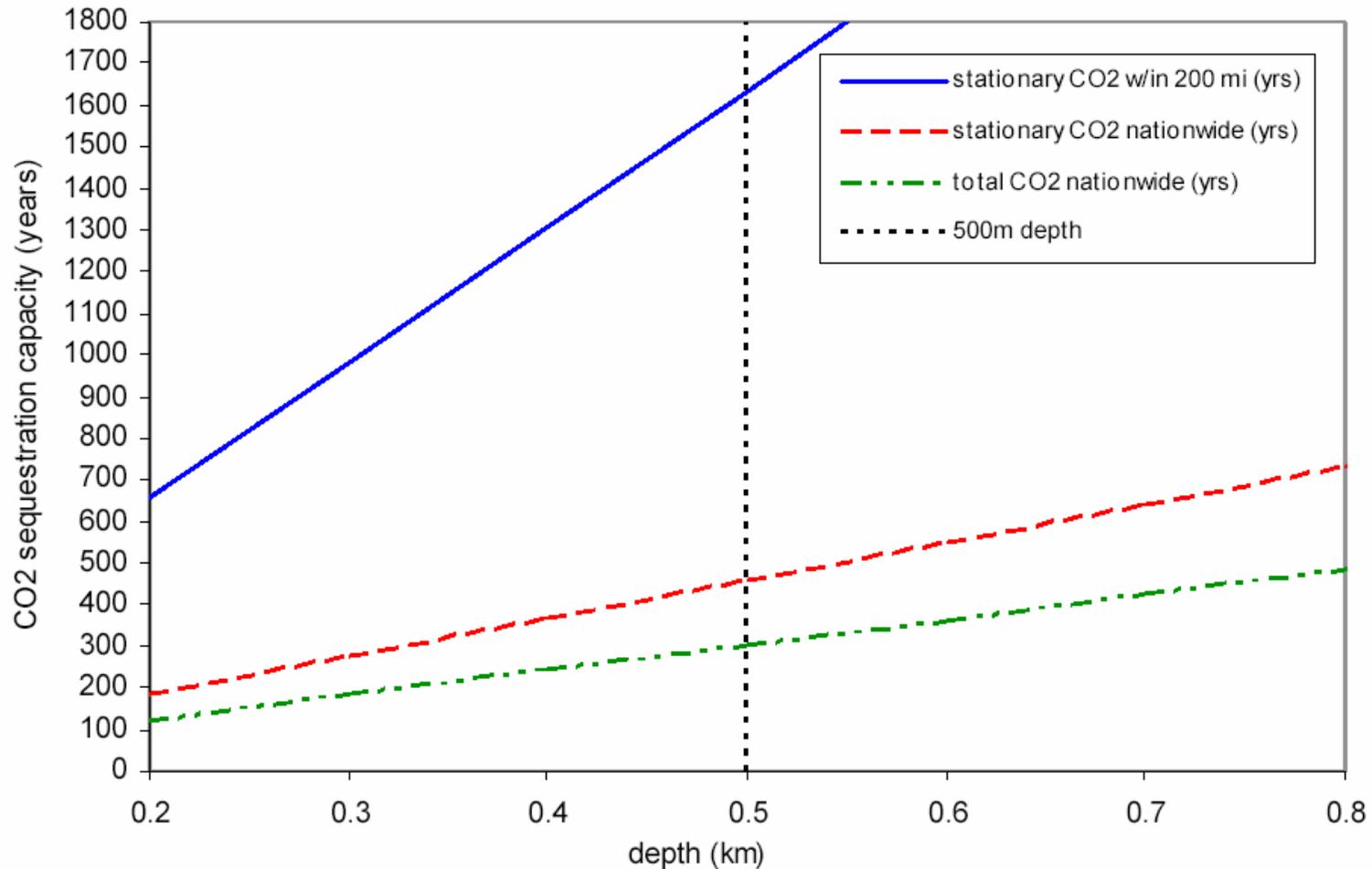
$$m_{\text{rock}} = A_{\text{surf}} \cdot z_{\text{mine}} \cdot \rho_{\text{rock}}$$

$$t_{\text{seq}} = \frac{m_{\text{rock}} \cdot \eta_{\text{conv}} \cdot (1 - f_{\text{losses}})}{R_{\text{CO}_2} \cdot \dot{m}_{\text{CO}_2}}$$

where R_{CO_2} is the ideal ratio of rock mined to CO_2 based on Mg content

$$R_{\text{CO}_2} = \frac{1 \text{ mol MgO}}{1 \text{ mol CO}_2} \cdot \frac{\text{MW}_{\text{MgO}}}{\text{MW}_{\text{CO}_2}} \frac{1}{\text{wt\% MgO}} = 2.62$$

assuming a wt% MgO of 35%.



By any accounting metric, there is enough ultramafic material in the U.S. to sequester large percentages or even all of the U.S. output for centuries. There will be no shortage for the Iron and Steel Industry.

Conclusions

- There is sufficient mineral resource availability in the United States for the operation of a mineral carbonation facility or set of facilities on any scale imaginable

Moving Forward

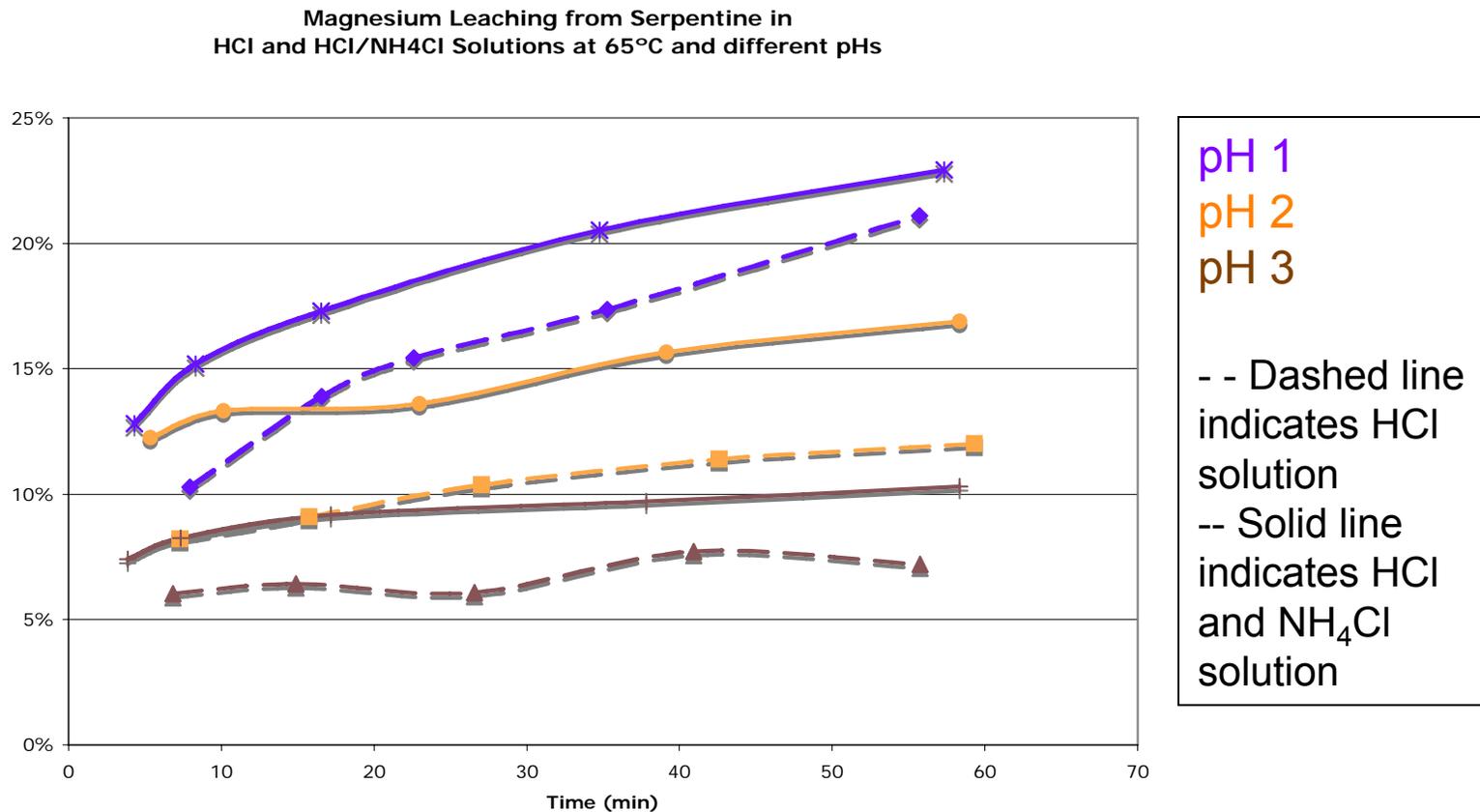
- We are working with the Mineral Resources Division of the USGS to integrate the most up to date information on ultramafic materials in the United States
- After subjecting the assessment to their internal review standards, the information will be published as a mineral resource assessment for mineral carbon dioxide sequestration

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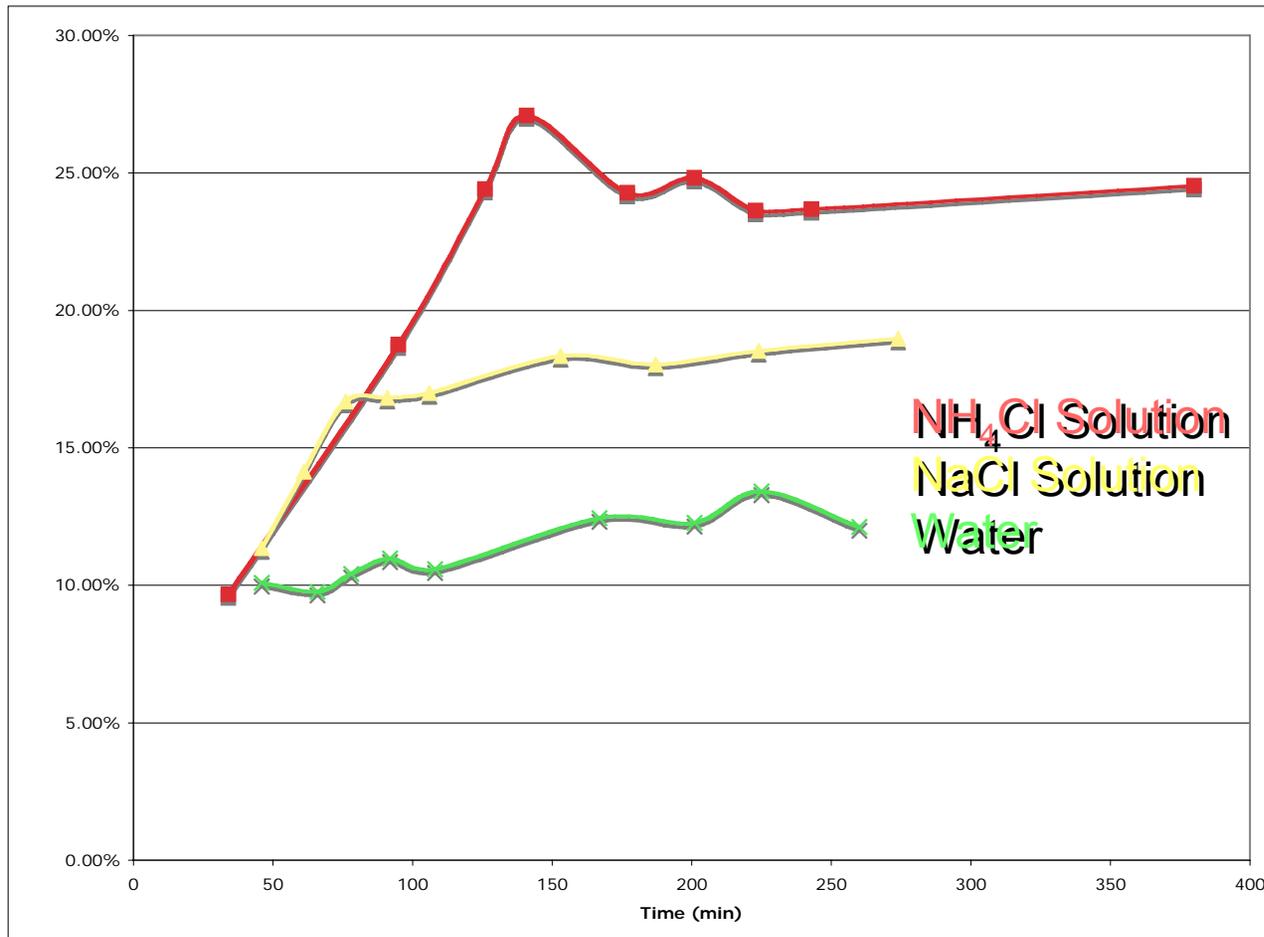
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For varied pH conditions, NH₄Cl in solution was found to significantly enhance the dissolution rate over that of simple HCl solutions

Dissolution of Serpentine 120 C, 20 bars CO₂



Performing experiments at process conditions has produced similar results but more work is required to quantify the effects of the varying solution compositions

Conclusions

- It is clear that we can obtain improvements in the overall process kinetics without affecting the solution pH through the use of salt additives in solution

Moving Forward

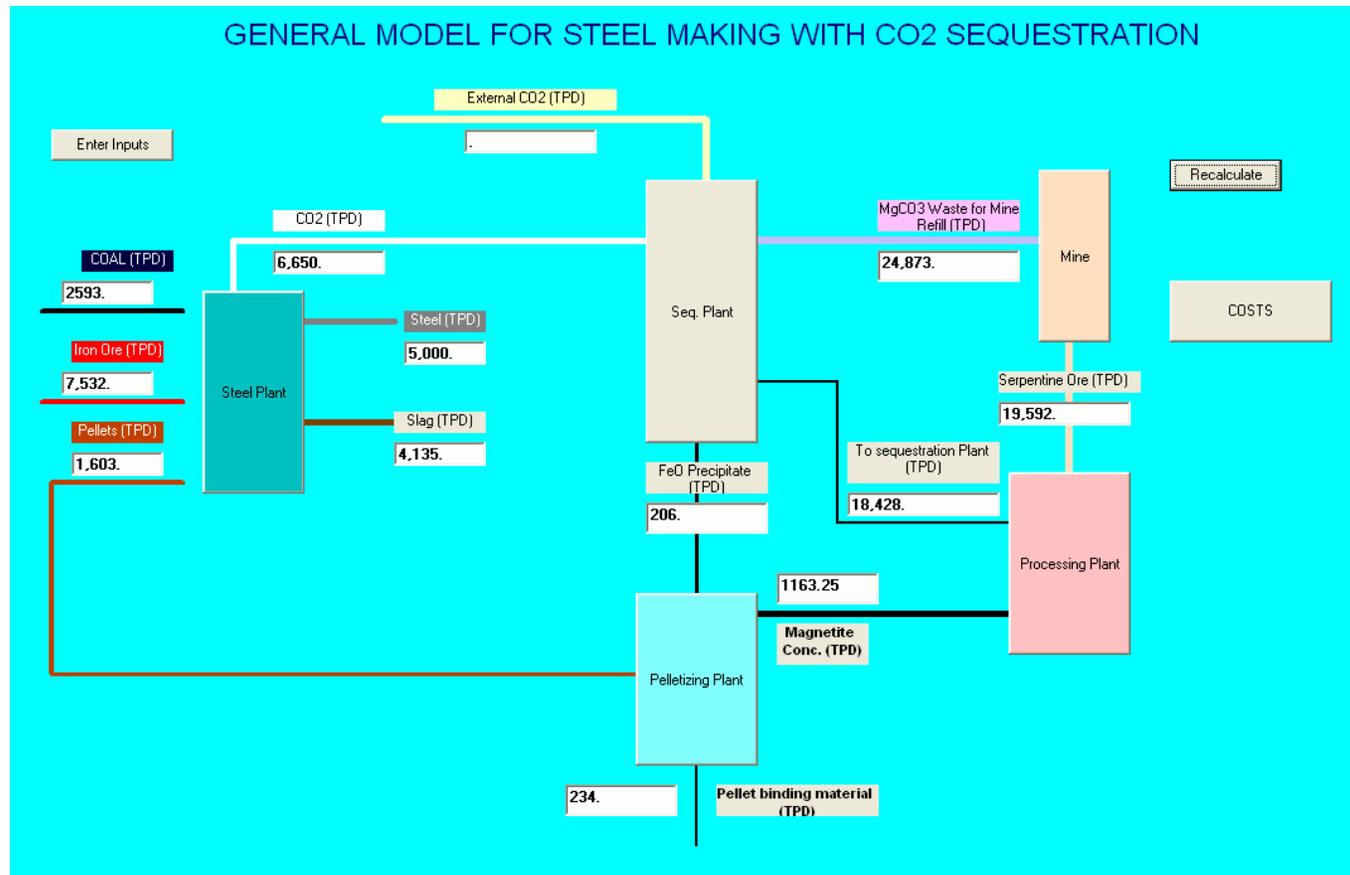
- Using new analytical equipment, we will revisit dissolution studies performed at high temperatures and pressures
- We will integrate dissolution results into a particle balance model describing the dissolution so that a quantitative evaluation may be made on the effectiveness of the salt additives
- We will perform carbonation experiments at conditions found to be optimal by previous studies

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- A stand-alone process model has been developed in Visual Basic.
- The model integrates mineral sequestration with iron and steel production
- The model calculates throughputs and estimates costs

INPUTS

ORE ASSAY % wt

MgO	39.1
Fe3O4	5.
Fe2O3	2.78
SiO2	37.9
Al2O3	1.02
CaO	.53
Na2O	.05
K2O	.01
MnO	.11
TiO2	.02
P2O5	.01
Cr2O3	.39
Other	13.08
Total	100

STEEL PLANT

Tons/day	
STEEL OUTPUT	5000.
Fe in Steel %	95.
CO2 output	6650.
Iron Ore Grade %	52.
C in Coal	.7
CO2/Ton Steel	1.33

PROCESSING PLANT

Concentrate Grade (Magnetite) % wt.	80.
Efficiency	.95
Plant Life (Years)	15.00
Working Days/year	350.00
Operating Cost A	23.022
Operating Cost B	0.812
Capital Cost A	33407.000
Capital Cost B	0.743

MINE

Mine Life (Years)	15.
Working Days/year	250.
Operating Cost A	52.972
Operating Cost B	0.691
Capital Cost A	88118.000
Capital Cost B	0.606

SEQUESTRATION PLANT

Sequestration Efficiency	.8
Fe recovery Efficiency	.8
External CO2	0
Operating Cost A	50.6840
Operating Cost B	0.9333
Capital Cost A	317984.00
Capital Cost B	0.6962
Plant Life (Years)	15.00
Working Days/year	350.00

PELLETIZING PLANT

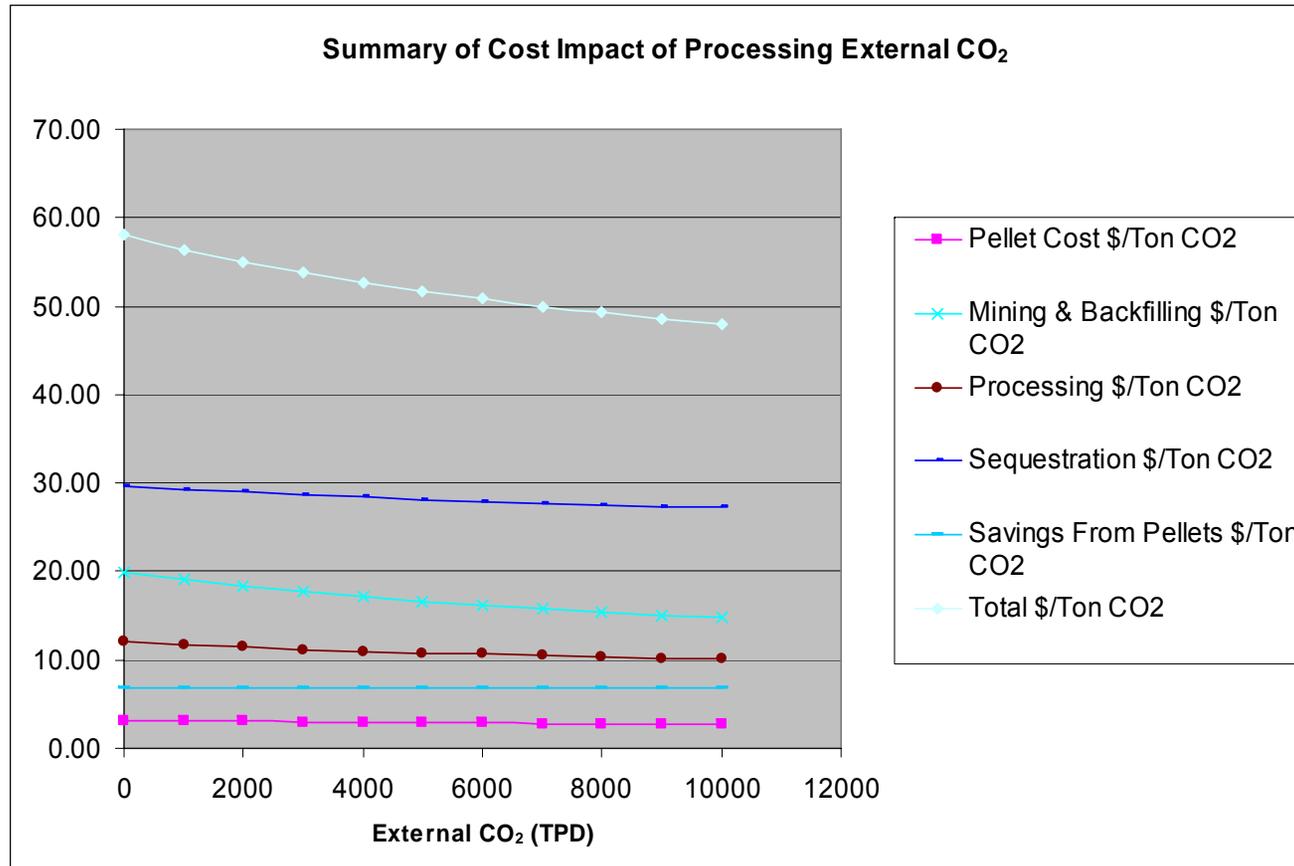
Pellet Grade % Fe	52.
Operating Cost A	46.044
Operating Cost B	0.8117
Capital Cost A	66814.00
Capital Cost B	0.7432
Plant Life (years)	15.00
Working Days/year	360.00

TRANSPORTATION PARAMETERS

	Distances (miles)	Unit Costs \$/mile Ton
Ore and waste		
Mine to Plant	0.0	0.0
Pellets		
Plant to Steel Mill	0.0	0.0
CO2		
Steel Mill to Plant	0.0	0.0
External Source to Plant	0.0	0.0

Cost = A · Capacity^B

- Inputs include the assay for the ore, cost parameters for the various facilities, and efficiency parameters



- Results provide estimates as to the cost of mineral carbonation, broken down by subcategories

Conclusions

- A mineral CO₂ sequestration process will be capital-intensive, but it is not yet clear as to how much enhancing reaction rates may affect this cost

Moving Forward

- The windows-based throughput model will be integrated with an Aspen-based simulation so that sensitivity analyses may be performed on the effects of enhancing the rate of mineral carbonation.
- Energy balances will be more rigorously integrated into the model so as to provide accurate costs per net amount of CO₂ sequestered

Moving Forward

The project has successfully hit key milestones:

- Identification and characterization of the ultramafic mineral resource in the United States
- Identification and demonstration of improvements in the carbonation processing
- Development of cost models for the mineral carbonation process

At the same time, we are behind in a number of key areas:

- Magnetic separation of iron
- Conclusion of the leaching studies
- Integrating energy balances and sensitivity analyses in the process modeling