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Carbon Sequestration Facilities

Let's Just Bury It

Christopher D. Barry
SNAME, Panel EC-12

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Baltimore MD
February 28-29, 2012

Overview

- The Carbon Cycle
- The "Hail Mary" Option
- Economics Needed – Carbon Credits
- Deep Ocean Injection
- Subsea Basalt Injection
- Biological Approaches
  - Fertilization
  - Upwelling
  - OTEC?
- Manufacture of Fuels At Sea
- Big Infrastructure Is Needed

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The Carbon Cycle

- About $7x10^{12}$ kg Anthropogenic Carbon / Yr
  - $5.5x10^{12}$ kg Fossil Fuel
  - $1.5x10^{12}$ kg Agricultural
- About $700x10^{12}$ kg In Atmosphere As CO_2
- Terrestrial Vegetation Roughly Neutral
- Ocean Sequestration: $3x10^{12}$ kg / Yr
  - $100x10^{12}$ In/Yr, $97x10^{12}$ Out
- Deep Ocean Storage: $33,000x10^{12}$ kg
- Sedimentation, $CaC0_3$: $0.1x10^{12}$ kg / Yr
- Net Gain, $4x10^{12}$ kg / Yr – 0.6% Increase
  - (Minus Increased Shallow Ocean Take-up)

The "Hail Mary" Option

- Sequestration Isn't The Best Option

But

- Renewables May Not Come On Line In Time
  - Lots Of Infrastructure Needs To Be Replaced
- May Be More Economical Than Some Renewables
- May Discover That Climate Change Is Proceeding Too Fast
- Probably Will Be Part Of A Mix Of Solutions
- Some Renewables May Include Sequestration

Economics

- Carbon Taxes, Carbon Credits
- 1 kg of CO_2 Produced By 1 kW-hr Coal Power
- Cap And Trade: Prices Rise As Caps Lowered
- Depends On Competing Source Costs, Carbon
  - Price Of Oil, Natural Gas, Nuclear, Other AE
- Low Prices For Carbon Credits: € 8 / Tonne CO_2
  - Means Alternatives Are Working, or ..
  - Economy In The Dumps
- Sequestration Probably Very Expensive
- Think About Business Models

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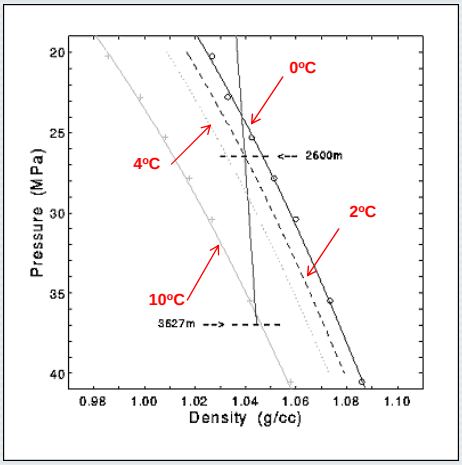
Deep Ocean Injection

- As Liquid: CO_2 At 2º C / 4,000 PSI Is Denser Than Seawater
  - 9,000 Feet Down!
- CO_2 At 2º C Liquefies At 532 PSI
- Energy Cost To Liquefy And Pump
- Leaks - Acidifies



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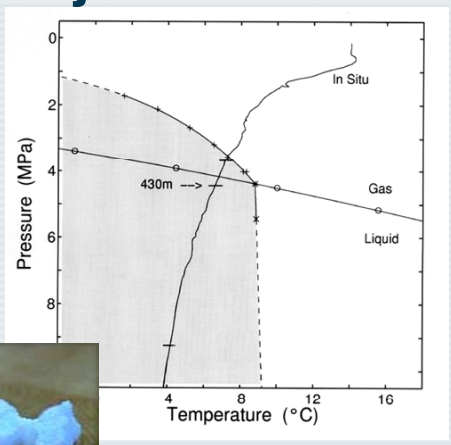
Deep Ocean Injection II

- As Hydrate: CO_2 Trapped In Matrix of Ice - Sinks
- Much Lower Pressure Requirements
- Made By Mixing Liquid CO2 And Water
- Tested At Sea
- May "Leak"



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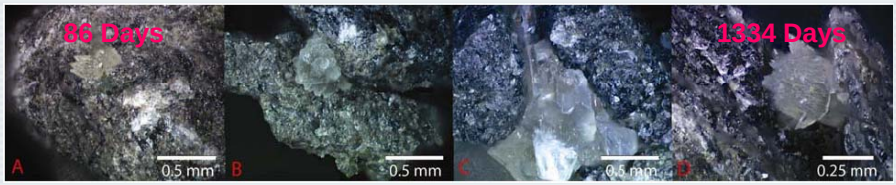
Basalt Injection

- Basalt: Volcanic Ca, Na, K Silicates & Quartz
- Basalt + Seawater + CO2 + Pressure = Carbonate Minerals (Limestone) + Heat
- Deep Sea Basalt = Seawater & Pressure
- Much Less Depth, Much Less Energy Required
- Doesn't Leak: Locked In Mineral Form



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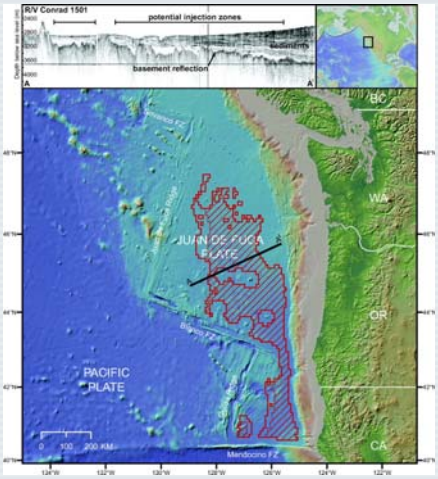
Deep-Sea Basalt Regions

- Proposed Project In Linden, NJ
  70 NM Offshore,
  600 Ft. Deep
- Other Sites Include Offshore Washington & Oregon Coast
- Hundreds Of Years Of Storage Capacity



Biological Sequestration

- Ocean Is The Major Sink For CO_2
- Biological Uptake Is The Conduit
  - Mainly Via Sedimentation Of Zooplankton
- Tropical Ocean Fertility Very Small
  - 100 mg Carbon Takeup / m^2 / yr
  - Tropical Water Is Nutrient Poor
  - Nitrates, P, Fe Limited
- Two Approaches:
  - "Geritol Option" – Iron Fertilization
  - Upwelling: Lovelock & Rapley (*Nature*, 09/07)

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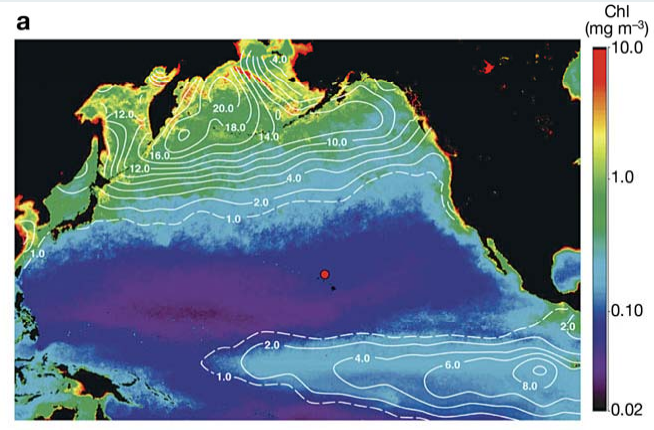
Chlorophyll Levels In The Pacific



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Geritol Option

- Theory Is That Lack Of Iron Is The Problem
- Early Experiments In Iron Fertilization Not Clear Regarding Ultimate Sequestration (Sinking)

"The Iron Hypothesis isn't wrong, but it's much more subtle than usually stated. Achieving optimum carbon sedimentation from plankton growth may require the right "recipe" of iron and other trace nutrients to grow the right kind of phytoplankton, … "You can grow a lot of Brussels sprouts, but kids won't eat it. The same appears to be the case with diatom phytoplankton and zooplankton. It's the zooplankton community that determines carbon sedimentation."

Jim Bishop, Carbon Explorers Project

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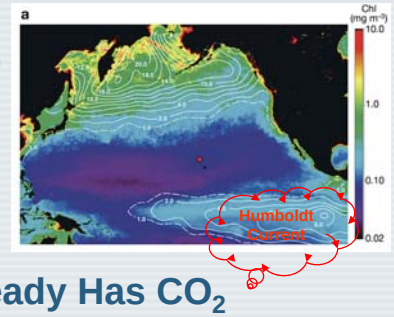
Upwelling

- Tropical Upwelling (Humboldt / Peru Current)
  - 1.8 kg Carbon / m^2 / yr
  - 6.8 kg CO_2 / m^2 / yr
- Artificial Upwelling
- Wave Powered Pumps
- But – Deep Seawater Already Has CO_2
- Redfield Ratio: Carbon To Nitrogen To Phosphorus (106 C : 16 N : 1 P)
- May Just Cycle Up And Down – No Net Takeup
- "Super Redfield Ratio" Growth?



The Questions

- What Is The Level Of Nutrients Vice CO_2 Release?
  - How Does This Vary With Depth?
- How Do The Nutrients Mix?
- What Optimizes Biological Takeup?
  - How Much Becomes $CaCO_3$?
  - How Much Becomes Accessible Carbon?
- What Is The Effect Of Increased BOD?
- How Do We Design & Build Equipment?
- How Much Does It Cost?

OTEC Upwelling - The Opportunity

- Prodigious Amounts Of Cold Water
  15 m^3 / s / MW
- Depending On Dilution Scenarios
  10,000 Tonnes ($1x10^7$ kg) CO_2 / MW / yr
- 1 Billion Tonnes CO_2 / Yr For 100,000 MW (25%)
- OTEC Plant ~ $1,000,000 / MW
  For €80,000 / MW Of Carbon Credits
- Plus Fertilizer And Fish – "Solve World Hunger"
- May Allow Other (Nitrate) Fertilization

Fuel Production At Sea

- Use Ocean Energy (Waves, Wind, OTEC?) To Make Hydrogen
- Use CO_2 In Seawater And Hydrogen To Make Methane Or Alcohols (Ethanol, Butanol)
- Use Methane To Make Hydrocarbon Fuels
- Why?
  - Use Stranded Energy
  - CO_2 Much More Concentrated In Seawater (Especially Deep Water From OTEC)
- No End Of Practical Questions

Opportunities

- Basically Injection Schemes Are Standard Oil Patch Operations / Equipment "Just Making Hole In The Ocean"
  - Where Does The Energy Come From?
- Standard Opportunities For OSV Fleets, Drilling Rigs, Etc.
- Big Pipelines – Possibly At High Pressure
- Biological Schemes:
  - Lots Of Small Units (To Be Installed, Etc.)
  - Big OTEC Plants / Maybe Fuel Carriers

Summary

- May Be Opportunities For The Marine Industry
- Depends On Carbon Credit Economics
- Not Today,
- Maybe Not Tomorrow,
- Maybe Not Ever (We Hope)
- But Be Alert (America Needs More Lerts)

Thank You For Listening
Any Questions?