2005 Submarine Ring of Fire Expedition

It Looks Like Champagne

Focus
Deep ocean carbon dioxide and global climate change

Grade Level
9-12 (Chemistry/Earth Science)

Focus Question
What are some practical implications of the discovery of liquid carbon dioxide in deep-ocean ecosystems?

Learning Objectives
Students will be able to interpret phase diagrams, and explain the meaning of "critical point" and "triple point".

Students will be able to define "supercritical fluid," and will be able to describe two practical uses of supercritical carbon dioxide.

Students will be able to discuss the concept of carbon dioxide sequestration.

Materials
- ❒ Copies of "Supercritical Fluids Worksheet," one copy for each student or student group

Audio/Visual Materials
- ❒ (Optional) computer projection equipment to show downloaded images and video

Teaching Time
One or two 45-minute class periods, plus time for student research

Seating Arrangement
Classroom style if students are working individually, or groups of two to four students

Maximum Number of Students
30

Key Words
Carbon dioxide
Phase diagram
Temperature
Pressure
Sequestration
Supercritical fluid
Critical point
Triple point
Ring of Fire

Background Information
The Ring of Fire is an arc of active volcanoes and earthquake sites that partially encircles the Pacific Ocean Basin.The location of the Ring of Fire coincides with the location of oceanic trenches and volcanic island arcs that result from the motion of large pieces of the Earth's crust (tectonic plates). Tectonic plates consist of portions of the Earth's outer crust (the lithosphere) about 5 km thick, as well as the upper 60 - 75 km of the underlying mantle. The plates move on a hot flowing mantle layer called the asthenosphere, which is several hundred kilometers thick. Heat within the asthenosphere creates convection currents (similar to the currents that can be seen if food coloring is added to a heated container of water). These convection currents cause the tectonic plates to move several

centimeters per year relative to each other.

The junction of two tectonic plates is known as a plate boundary. Where two plates slide horizontally past each other, the junction is known as a transform plate boundary. Movement of the plates causes huge stresses that break portions of the rock and produce earthquakes. Places where these breaks occur are called faults. A well-known example of a transform plate boundary is the San Andreas fault in California.

Where tectonic plates are moving apart, they form a divergent plate boundary. At these boundaries, magma (molten rock) rises from deep within the Earth and erupts to form new crust on the lithosphere. Most divergent plate boundaries are underwater (Iceland is an exception), and form submarine mountain ranges called oceanic spreading ridges.

If two tectonic plates collide more or less head-on, they produce a convergent plate boundary. Usually, one of the converging plates moves beneath the other in a process called subduction. Subduction produces deep trenches, and earthquakes are common. As the sinking plate moves deeper into the mantle, increasing pressure and heat release fluids from the rock causing the overlying mantle to partially melt. The new magma rises and may erupt violently to form volcanoes that often form arcs of islands along the convergent boundary. These island arcs are always landward of the neighboring trenches. This process can be visualized as a huge conveyor belt on which new crust is formed at the oceanic spreading ridges and older crust is recycled to the lower mantle at the convergent plate boundaries. The Ring of Fire marks the location of a series of convergent plate boundaries in the western Pacific Ocean.

The Mariana Arc is part of the Ring of Fire that lies to the north of Guam in the western Pacific. Here, the fast-moving Pacific Plate is subducted beneath the slower-moving Philippine Plate, creating the Marianas Trench (which includes the Challenger Deep, the deepest known area of the Earth's oceans). The Marianas Islands are the result of volcanoes caused by this subduction, which frequently causes earthquakes as well. In 2003, the Ocean Exploration Ring of Fire expedition surveyed more than 50 volcanoes along the Mariana Arc, and discovered that ten of these had active hydrothermal systems (visit http://oceanexplorer.noaa.gov/explorations/03fire/welcome.html for more information on these discoveries). The 2004 Submarine Ring of Fire Expedition focussed specifically on hydrothermal systems of the Mariana Arc volcanoes, and found that these systems are very different from those found along mid-ocean ridges (visit http://oceanexplorer.noaa.gov/explorations/04fire/welcome.html for more information). The 2005 Submarine Ring of Fire Expedition will explore hydrothermally active volcanoes in the Kermadec Arc, an area where tectonic plates are converging more rapidly than any other subduction zone in the world.

On April 10, 2004, scientists exploring the NW Eifuku volcano reported seeing small white chimneys emitting a cloudy white fluid near the volcano's summit, as well as masses of bubbles rising from the sediment around the chimneys. The bubbles were composed of some type of fluid, and were so abundant that the scientists named the site "Champagne." Further investigation revealed that the chimneys were venting a supercritical fluid saturated with carbon dioxide, and that the bubbles were liquid carbon dioxide. The concentration of carbon dioxide in the vent fluid was an order of magnitude higher than in previously studied hydrothermal vents. This discovery has generated widespread interest because it is directly relevant to the idea of injecting carbon dioxide into the deep ocean as a strategy to help control rising levels of carbon dioxide in the atmosphere. A key question surrounding this idea is, what effect will carbon dioxide enrichment have on the deep ocean environment? The Eifuku site may provide a "natural laboratory" to study the effects of high carbon dioxide in the deep ocean.

In this lesson, students will investigate phase diagrams and some properties of supercritical fluids, as well as the idea of sequestering carbon dioxide as a strategy to mitigate global warming.

Learning Procedure

1. To prepare for this lesson, read the Submarine Ring of Fire 2004 daily log for April 10 (http://oceanexplorer.noaa.gov/explorations/04fire/logs/april10/april10.html). You may also want to print copies of the photographs and/or download the video of the champagne site.

2. Briefly review the concepts of plate tectonics and continental drift and how they are related to underwater volcanic activity and hydrothermal vent systems (you may want to use resources from NOAA's hydrothermal vent Web site (http://www.pmel.noaa.gov/vents/home.html) to supplement this discussion). Introduce the Ring of Fire, and describe the processes that produce the island arcs.

3. Show students photographs and videos of the Champagne site, or direct them to the Ocean Explorer Web site. Provide each student or student group with a copy of the "Supercritical Fluids Worksheet." You may want to review the concepts of phases and phase diagrams, or allow students to work through these on their own.

4. Lead a discussions of students' answers to questions on the worksheet. The following points should emerge during this discussion:

   Students should understand that the phase of a substance depends upon temperature as well as pressure. On a phase diagram, the line separating the liquid and solid phases corresponds to the melting point at a specific temperature and pressure. At this point the substance exists as both liquid and solid phases, and the phases are in equilibrium. Similarly, the line separating the liquid and vapor phases corresponds to the boiling point at a specific temperature and pressure, and at this point both phases exist in equilibrium. The melting and boiling points listed for substances in reference tables are those when the pressure is equal to one atmosphere.

   Be sure students understand that the line separating the solid and vapor phases indicates the temperature and pressure at which these two phases exist in equilibrium, and that a solid phase may change to a vapor phase without passing through a liquid phase. This transition between solid and vapor phases is known as sublimation. Dry ice is a familiar example.

   The critical point is the temperature and pressure at which the liquid and gas phases become indistinguishable. If temperature and/or pressure is increased beyond the critical point the substance forms a supercritical fluid, which often has properties that are different from properties of the same substance in solid, liquid, or vapor phases. The critical point of carbon dioxide is 72.8 atm, 31.1°C. At temperature and/or pressure above this point carbon dioxide forms a supercritical fluid. The critical point for water is 218 atm, 374°C.

   The triple point is the temperature and pressure at which solid, liquid, and vapor phases are all in equilibrium. This implies that a substance at the triple point is melting, boiling, subliming, and condensing at the same time. The triple point for water is 0.006 atm, 0.0098°C; in other words, very near what we normally think of as the freezing point, but at a very low pressure. The triple point of carbon dioxide is 5.11 atm, -56.4°C.

   Pressure at a depth of 1,650 meters would be equal to 166 atm:
   (1 atm surface pressure) + (1,650 m ÷ 10 m/atm) = 166 atm

   A temperature of 100°C and pressure of 166 atm is well above the critical point, so carbon dioxide would be expected to exist as a supercritical fluid under these conditions.

Pressure at a depth of 3,000 meters would be equal to 301 atm:
(1 atm surface pressure) + (3,000 m ÷ 10 m/atm) = 301 atm

If water temperature is 0°C, carbon dioxide would be expected to exist in the liquid phase at this depth.

Supercritical carbon dioxide has powerful solvent properties, and is commonly used to remove caffeine from coffee beans. Some drycleaners also use supercritical carbon dioxide as an alternative to toxic organic solvents.

The idea of sequestering carbon dioxide is relatively recent, and its feasibility is still under study. Aside from injection into the deep ocean, other sequestration options include injection into geologic formations (such as underground caverns, mines, or depleted oil wells) and indirect sequestration in terrestrial ecosystems (such as forests). Students should realize that sequestration is being studied as a strategy to deal with additional carbon dioxide emissions to the atmosphere, and that this strategy also requires effective means for capturing carbon dioxide at the sources of emission. You may also want to encourage students to identify other options for reducing carbon dioxide emissions, such as developing energy sources that do not involve combustion of fossil fuels.

The Bridge Connection

www.vims.edu/bridge/ – Type "carbon dioxide" in the "Search" box in the upper right corner to find links to resources about the role of carbon dioxide in global climate change, and other ideas about sequestering carbon dioxide in the ocean.

The "Me" Connection

The potential use of the Champagne site as a natural laboratory for studying the effects of carbon dioxide in deep ocean ecosystems is one example of how deep-sea explorations can be directly relevant to important social issues (such as global climate change). Have students write a brief essay describing other ways in which these explorations might be of personal benefit.

Connections to Other Subjects

English/Language Arts, Geography

Assessment

Worksheet results and class discussions provide opportunities for assessment.

Extensions

1. Have students visit http://oceanexplorer.noaa.gov to keep up to date with the latest Ring of Fire Expedition discoveries.

2. The ChemMatters Teachers Guide (see "Resources") has directions for a simple demonstration of phase changes of carbon dioxide.

Resources

http://oceanexplorer.noaa.gov – Follow the Ring of Fire Expedition daily as documentaries and discoveries are posted each day for your classroom use.

http://www.chemguide.co.uk/physical/phaseeqia/phasediags.html - Tutorial about phase diagrams

http://www.netl.doe.gov/coal/Carbon%20Sequestration/index.html – U. S. Department of Energy's Carbon Sequestration Product Web page

www.chemistry.org/portal/resources/ACSContent/education/curriculum/chemmatters/tg100_A_tg.pdf – ChemMatters Teachers' Guide from the American Chemical Society; click on "Supercritical Clean Machine" for information about practical uses of supercritical carbon dioxide

Brewer, P. G., G. Friederich, E. T. Peltzer, and F. M. Orr, Jr., 1999. Direct experiments on the ocean disposal of fossil fuel CO2. Science.

284:943-945. Technical journal article on some of the first experiments to evaluate the idea of sequestering carbon dioxide in the deep ocean

National Science Education Standards

Content Standard A: Science as Inquiry
- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Content Standard B: Physical Science
- Structure and properties of matter
- Interactions of energy and matter

Content Standard D: Earth and Space Science
- Energy in the earth system
- Geochemical cycles

Content Standard E: Science and Technology
- Abilities of technological design
- Understandings about science and technology

Content Standard F: Science in Personal and Social Perspectives
- Natural resources
- Environmental quality
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

For More Information

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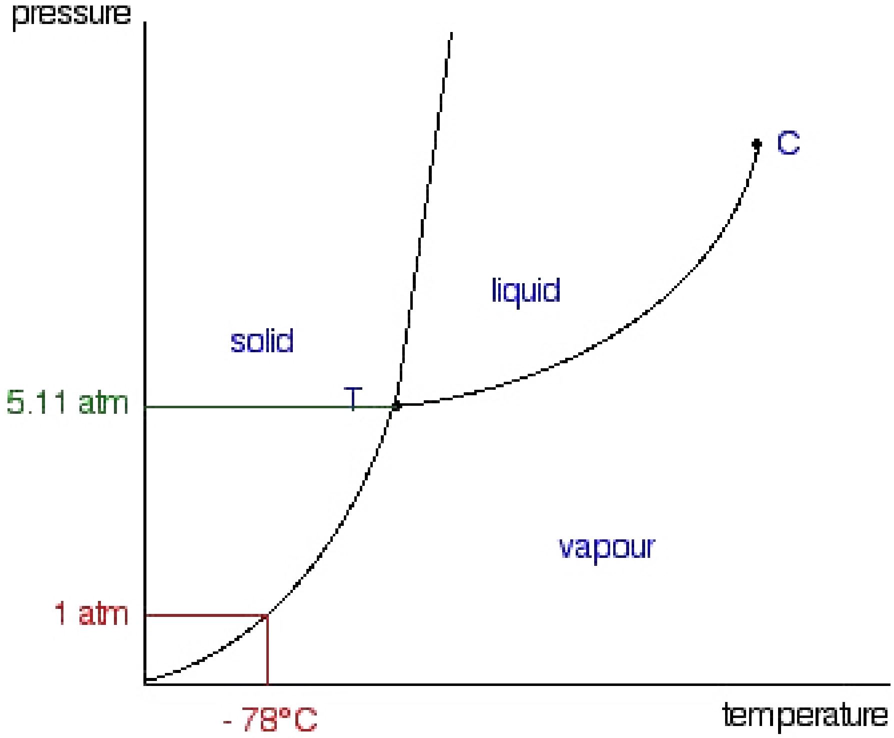
http://oceanexplorer.noaa.gov

Student Worksheet

This is a phase diagram for carbon dioxide.



Visit:

- http://www.chemguide.co.uk/physical/phaseeqia/phasediags.html for a tutorial about phase diagrams;
- http://www.netl.doe.gov/coal/Carbon%20Sequestration/index.html for information about carbon sequestration; and
- www.chemistry.org/portal/resources/ACSContent/education/curriculum/chemmatters/tg100_A_tg.pdf – click on "Supercritical Clean Machine" for information about practical uses of supercritical carbon dioxide.

Use these resources to answer the following questions:

1. What is the critical point?

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2. What is a supercritical fluid?

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3. At what temperature and pressure does carbon dioxide form a supercritical fluid?

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4. What is the triple point?

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5. What is the triple point of carbon dioxide?

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6. The Champagne site is 1,650 meters below sea level. The temperature of the fluid being emitted from the chimneys was 100°C. What is the pressure at this depth? (Hint: Pressure in the ocean increases by 1 atm with every 10 m increase in depth).

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7. What is the expected phase of carbon dioxide under the conditions described in question 6?

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8. Increased levels of carbon dioxide in the atmosphere are widely believed to contribute to global climate change. Direct injection of carbon dioxide into the deep ocean has been proposed as a way to slow its accumulation in the atmosphere. Researchers from the Lawrence Livermore National Laboratory have used mathematical models to simulate CO_2 injections at various depths, and found that 3000 meters was the most effective depth for sequestering carbon dioxide from the atmosphere. Assuming that the water temperature is 0°C, what would be the expected phase of CO_2 at this depth?

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9. What are two practical uses for supercritical carbon dioxide?

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10. Injecting carbon dioxide into the deep ocean is one strategy for keeping carbon emissions out the of atmosphere. What are two other options for sequestering carbon dioxide?

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