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New Zealand American Submarine Ring of Fire 2007

It Looks Like Champagne
[adapted from the New Zealand American Submarine Ring of Fire 2005]

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 Submarine Ring of Fire is an arc of active volcanoes that partially encircles the Pacific Ocean Basin, including the Kermadec and Mariana Islands in the western Pacific, the Aleutian Islands between the Pacific and Bering Sea, the Cascade Mountains in western North America, and numerous volcanoes on the western coasts of Central America and South America. These volcanoes result from the motion of large pieces of the Earth's crust known as tectonic plates.

Tectonic plates are 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 called a "plate boundary." Three major types of plate boundaries are produced by tectonic plate movements. If two tectonic plates collide more or less head-on they form a convergent plate boundary. Usually, one of the converging plates will move beneath the other, which is known as subduction. Deep trenches are often formed where tectonic plates are being subducted, and earthquakes are common. As the sinking plate moves deeper into the mantle, fluids are released from the rock causing the overlying mantle to partially melt. The new magma (molten rock) rises and may erupt violently to form volcanoes, often forming arcs of islands along the convergent boundary. These island arcs are always landward of the neighboring trenches. For a 3-dimensional view of a subduction zone, visit: http://oceanexplorer.noaa.gov/explorations/03fire/logs/subduction.html.

The junction of two tectonic plates that are moving apart is called a divergent plate boundary. Magma 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. While the process is volcanic, volcanoes and earthquakes along oceanic spreading ridges are not as violent as they are at convergent plate boundaries. View the 3-dimensional structure of a mid-ocean ridge at: http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html

The third type of plate boundary occurs where tectonic plates slide horizontally past each other, and is known as a transform plate boundary. As the plates rub against each other, huge stresses are set up that can cause portions of the rock to break, resulting in 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. See animations of different types of plate boundaries at: http://www.seed.slb.com/en/scictr/watch/living_planet/plate_boundaries/plate_move.htm.

The volcanoes of the Submarine Ring of Fire result from the motion of several major tectonic plates. The Pacific Ocean Basin lies on top of the Pacific Plate. To the east, along the East Pacific Rise, new crust is formed at the oceanic spreading center between the Pacific Plate and the western side of the Nazca Plate. Farther to the east, the eastern side of the Nazca Plate is being subducted beneath the South American Plate, giving rise to active volcanoes in the Andes. Similarly, convergence of the Cocos and Caribbean Plates produces active volcanoes on the western coast of Central America, and convergence of the North American and Juan de Fuca Plates causes the volcanoes of the Cascades in the Pacific Northwest.

On the western side of the Pacific Ocean, the Pacific Plate converges against the Philippine Plate and Australian Plate. Subduction of the Pacific Plate creates the Mariana Trench (which includes the Challenger Deep, the deepest known area of the Earth's ocean) and the Kermadec Trench. As the sinking plate moves deeper into the mantle, new magma is formed as described above, and erupts along the convergent boundary to form volcanoes. The Mariana and Kermadec Islands are the result of this volcanic activity, which frequently causes earthquakes as well. The movement of the Pacific Ocean tectonic plate has been likened to 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 of the western Pacific. For more information on plate tectonics, visit the NOAA

Learning Objects Web site (http://www.learningdemo.com/noaa/). Click on the links to Lessons 1, 2 and 4 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean Ridges, and Subduction Zones. See the satellite and sonar survey animation of the Mariana Arc Volcanic Chain at:
http://oceanexplorer.noaa.gov/explorations/04fire/background/marianaarc/media/sat_em_islands_video.html

Beginning in 2002, Ocean Exploration expeditions have undertaken systematic mapping and study in previously-unexplored areas of the Submarine Ring of Fire. Visit

- http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/;
- http://www.oceanexplorer.noaa.gov/explorations/03fire/;
- http://www.oceanexplorer.noaa.gov/explorations/04fire/;
- http://www.oceanexplorer.noaa.gov/explorations/05fire/; and
- http://oceanexplorer.noaa.gov/explorations/06fire/welcome.html

for more information about the many discoveries, as well as still and video imagery, from these expeditions. The New Zealand American Submarine Ring of Fire 2007 Expedition is focused on detailed exploration of hydrothermal systems at Brothers Volcano 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, review:
   - Introductory essays for the New Zealand American Submarine Ring of Fire 2007 Expedition at http://oceanexplorer.noaa.gov/explorations/07fire/welcome.html
   - Submarine Ring of Fire 2004 daily logs for April 6 and April 10 (http://oceanexplorer.noaa.gov/explorations/04fire/logs/april06/april06.html and http://oceanexplorer.noaa.gov/explorations/04fire/logs/april10/april10.html);
   - Submarine Ring of Fire 2006 daily log for April 25 log (http://www.oceanexplorer.noaa.gov/explorations/06fire/logs/april25/april25.html); and
   - "Vent Chemistry" essay (http://www.oceanexplorer.noaa.gov/explorations/06fire/background/chemistry/chemistry.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/index.html) and NOAA Learning Objects 1, 2, and 4 (http://www.

learningdemo.com/noaa/) to supplement this discussion. Introduce the New Zealand American Submarine Ring of Fire 2007 Expedition, 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 discussion 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 dry-cleaners 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 warming). 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/explorations/07fire/welcome.html to keep up to date with the latest New Zealand American Submarine Ring of Fire 2007 Expedition discoveries, and find out what scientists are learning about hydrothermal systems in the vicinity of Brothers Volcano.

2. Lieu, 1996 (see "Resources") has directions for a simple demonstration of phase changes of carbon dioxide.

Multimedia Learning Objects

http://www.learningdemo.com/noaa/ – Click on the links to Lessons 1, 2, 4, and 5 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean Ridges, Subduction Zones, and Chemosynthesis and Hydrothermal Vent Life.

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

Where Did They Come From? [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.WhereFrom.pdf] (10 pages; 296 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Species variation in hydrothermal vent communities (Life Science)

In this activity, students will define and describe biogeographic provinces of hydrothermal vent communities, identify and discuss processes contributing to isolation and species exchange between hydrothermal vent communities, and discuss characteristics which may contribute to the survival of species inhabiting hydrothermal vent communities.

Hydrothermal Vent Challenge [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.VentChallenge.pdf] (9 pages; 288 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Chemistry of hydrothermal vents (Chemistry)

Students will be able to define hydrothermal vents and explain the overall processes that lead to their formation; explain the origin of mineral-rich fluids associated with hydrothermal vents; explain how "black smokers" and "white smokers" are formed; and hypothesize how properties of hydrothermal fluids might be used to locate undiscovered hydrothermal vents.

Roots of the Mariana Arc [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.Roots.pdf] (11 pages; 312 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Seismology and geological origins of the Mariana Arc (Earth Science)

Students will be able to explain the processes of plate tectonics and volcanism that resulted in the formation of the Mariana Arc and will be able to describe, compare, and contrast S waves and P waves. Students will also be able to explain how seismic data recorded at different locations can be used to determine the epicenter of an earthquake and will infer a probable explanation for the existence of ultra-low velocity zones.

Mystery of the Megaplume [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.Megaplume.pdf] (11 pages; 324 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Hydrothermal vent chemistry (Chemistry, Earth Science, Physical Science)

Students will be able to describe hydrothermal vents and characterize vent plumes in terms of physical and chemical properties, describe tow-yo operations and how data from these operations can provide clues to the location of hydrothermal vents, and interpret temperature anomaly data to recognize a probable plume from a hydrothermal vent.

The Big Balancing Act [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_balancing.pdf] (9 pages, 383Kb) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Hydrothermal vent chemistry at subduction volcanoes (Chemistry/Earth Science)

Students will be able to define and describe hydrothermal circulation systems; explain the overall sequence of chemical reactions that occur in hydrothermal circulation systems; and compare and contrast "black smokers" and "white smokers." Given data on chemical enrichment that occurs in hydrothermal circulation systems, students will be able to make inferences about the relative significance of these systems to ocean chemical balance compared to terrestrial runoff.

Other Links and Resources

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

oceanexplorer.noaa.gov – Web site for NOAA's Ocean Exploration program

http://www.pmel.noaa.gov/vents/index.html – NOAA's hydrothermal vent Web site

http://pubs.usgs.gov/publications/text/dynamic.html#anchor19309449 – On-line version of "This Dynamic Earth," a thorough publication of the U.S. Geological Survey on plate tectonics written for a non-technical audience

http://pubs.usgs.gov/pdf/planet.html – "This Dynamic Planet," map and explanatory text showing Earth's physiographic features, plate movements, and locations of volcanoes, earthquakes, and impact craters

http://www.pbs.org/wgbh/nova/teachers/activities/2609_abyss.html – Nova Teachers Web site, Volcanoes of the Deep Classroom Activity to research and classify symbiotic relationships between individual organisms of different species.

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

http://www.energy.gov/sciencetech/carbonsequestration.htm – U. S. Department of Energy's Carbon Sequestration Product Web page

http://www.chemistry.org/portal/a/c/s/1/resources?id=d2e956aeab9d11d5ebdc4fd8fe800100 – 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 CO_2. 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.

Lieu, Van T. 1996. A Simple Experiment for Demonstration of Phase Diagram of Carbon Dioxide. J. Chem. Educ. 73:837.

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

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.
The Earth has one big ocean with many features.

Fundamental Concept a. The ocean is the dominant physical feature on our planet Earth—covering approximately 70% of the planet's surface. There is one ocean with many ocean basins, such as the North Pacific, South Pacific, North Atlantic, South Atlantic, Indian and Arctic.

Fundamental Concept b. An ocean basin's size, shape and features (such as islands, trenches, mid-ocean ridges, rift valleys) vary due to the movement of Earth's lithospheric plates. Earth's highest peaks, deepest valleys and flattest vast plains are all in the ocean.

Essential Principle 5.
The ocean supports a great diversity of life and ecosystems.

Fundamental Concept b. Most life in the ocean exists as microbes. Microbes are the most important primary producers in the ocean. Not only are they the most abundant life form in the ocean, they have extremely fast growth rates and life cycles.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.

Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

Send Us Your Feedback

We value your feedback on this lesson.
Please send your comments to:
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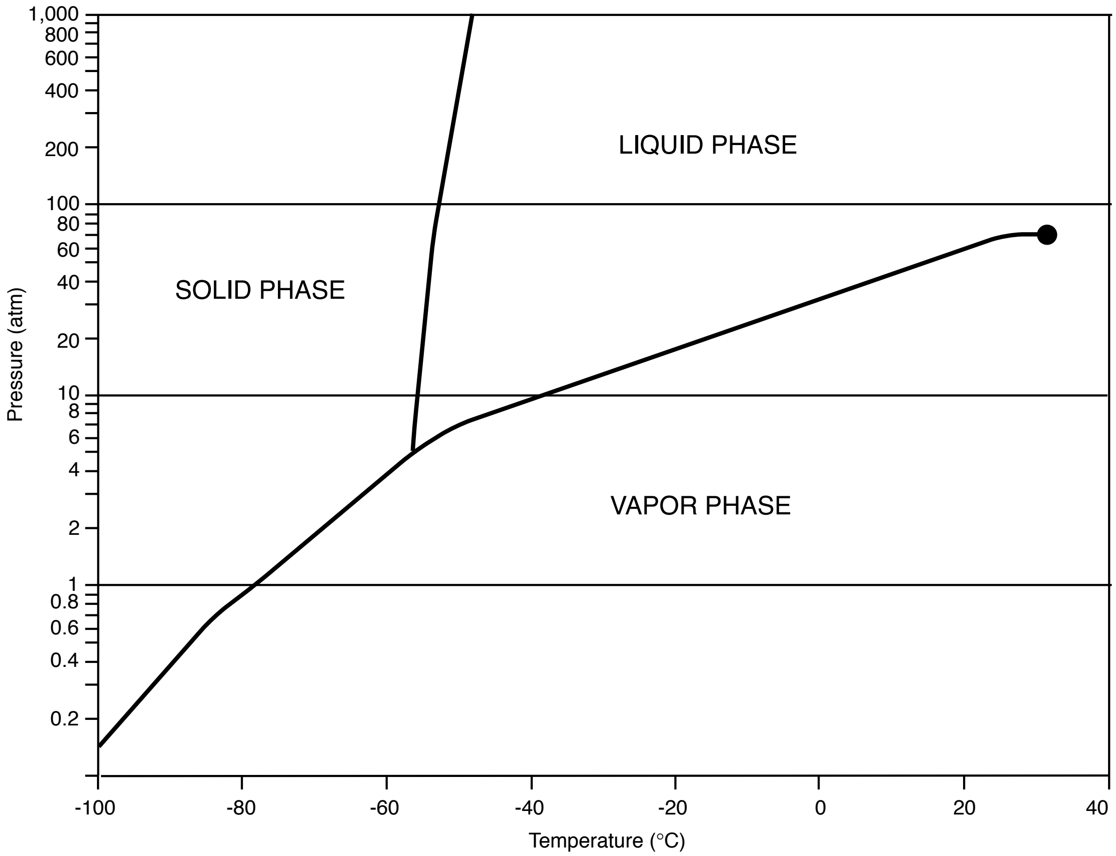
Student Handout

Supercritical Fluids 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.energy.gov/sciencetech/carbonsequestration.htm for information about carbon sequestration; and
- http://www.chemistry.org/portal/a/c/s/1/resources?id=d2e956aeab9d11d5ebdc4fd8fe800100 for information about practical uses of supercritical carbon dioxide.

Use these resources to answer the following questions:

1. What is the critical point?

2. What is a supercritical fluid?

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

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 warming. 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 3,000 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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