Oxygen Isotopes Reveal Ancient Climates

LESSON SUMMARY

SCIENTIFIC OCEAN DRILLING

In this lesson, students will join scientists as they explore how deep ocean sediment cores are used to study microfossils, their ages, and their oxygen isotope ratios to study past climate change and make predictions about future patterns of change. During the course of their exploration, students will gain a basic understanding of ocean sediment core drilling, use microscopes/microscopic images to explore calcareous microfossils, conduct a graphical analysis of oxygen isotope ratios, and use their analysis to make claims about historical climate change and make evidence-based claims about future trends. This lesson can be part of a unit on climate change. It can also be part of a unit on the coevolution of Earth and life.

Standards and Dimensions

NGSS: HS-ESS2-2, **HS-ESS2-4**, **HS-ESS2-7**, **HS-ESS3-5**

Science Engineering Practices: Analyzing & Interpreting Data; Developing & using models; Engaging in Argument from Evidence

Cross-Cutting Concepts: Cause & Effect; Stability & Change

Disciplinary Core Ideas: ESS2.A: Earth Materials and Systems; ESS2:D: Weather and Climate; ESS2:E: Biogeology

Connections to 2050 Science Framework

Strategic Objectives: Habitability of Life on Earth; Earth's Climate System; Tipping Points in Earth's History.

Flagship Initiatives: Ground Truthing Future Climate Change.

Enabling Elements: Broader Impacts and Outreach.

Ocean Literacy Principle(s)

OLP 2: The ocean and life in the ocean shape the features of Earth. (2A)

OLP 3: The ocean is a major influence on weather and climate. (3C)

OLP 4: The ocean made Earth habitable. (4A)

Suggested Time

120–150 minutes

Preparation of Materials

Per Group

- Computer with internet access

Per Student

- Graphing supplies or program

For Teacher Demonstration

- Computer with internet access
- Helium-filled balloon
- Empty, capped water bottle

Acknowledgments

Lesson Contributors: Nicoline Chambers, based on the original lesson, "Secret of the Sediment," by Ramona Smith. Edited by Lindsay Mossa.

Scientific Acknowledgment

Expedition: Leg 146 was conducted for the purpose of sampling the Cascadia continental margin, specifically to measure the water content of the crust in the subduction zone between the Pacific and North American Plates.

Data source: Kennett, James, 1995. Latest Quaternary Benthic Oxygen and Carbon Isotope Stratigraphy: Hole 893A, Santa Barbara, California. Proceedings of the Ocean Drilling Program Scientific Results, v. 146, 16pp.

AGI Developed in collaboration with the American Geosciences Institute

BACKGROUND FOR THE INSTRUCTOR

Oxygen levels in Earth's atmosphere have fluctuated significantly over geological time, with critical implications for climate and life on the planet. Initially, during the early stages of Earth's history, the atmosphere contained very little oxygen. The first significant increase in oxygen levels occurred around 2.4 billion years ago during the Great Oxygenation Event (GOE), when photosynthetic organisms, particularly cyanobacteria, began producing oxygen as a byproduct. This increase in atmospheric oxygen had a profound effect on life, as it allowed for the evolution of aerobic (oxygen-dependent) organisms. However, this oxygen buildup also caused a mass extinction of anaerobic organisms that thrived in oxygen-poor environments. The rise in oxygen levels eventually helped form the ozone layer, which protected Earth from harmful ultraviolet radiation, allowing life to thrive on land.

As oxygen levels continued to increase, they played a crucial role in shaping Earth's climate and ecosystems. During the Phanerozoic Eon, which began around 541 million years ago, oxygen levels fluctuated, particularly during periods like the Carboniferous, when oxygen levels were higher than today, fostering the growth of large plants and insects. This higher oxygen concentration contributed to cooler global temperatures by enhancing the formation of the ozone layer and supporting the development of forests, which in turn impacted carbon dioxide levels. Over time, oxygen levels stabilized, but changes in the carbon cycle, such as volcanic activity or the rise and fall of plant life, have continued to influence both oxygen concentrations and Earth's climate. The balance of oxygen and other gases in the atmosphere remains vital in regulating Earth's climate, supporting diverse life forms, and sustaining the conditions that allow life to flourish.

Supplemental Resources

Oceanic Drilling

- **Introducing the International Ocean Discovery Program**
- **Holes in the Bottom of the Sea: History, Revolutions, and Future Opportunities**
- **Highlights of IODP Discoveries**
- **How do you measure a core?**

Lesson-specific

- **Paleoclimatology: The Oxygen Balance**
- **A Brief Explanation of Oxygen Isotopes in Paleoclimate studies**
- **Stable Isotopes and Isotope Stratigraphy as Indicators of Changing Climate and Biosphere**

Initial Inquiry

1. Hold an empty water bottle (empty of water, at least!) and a helium filled balloon up for students to see, but try to hold the balloon so it is not obvious that it contains helium.

2. Ask students to predict what will happen when you let both objects go at the exact same time.

3. Discuss students' responses, then drop both items. Students will likely understand right away that the balloon is filled with helium. Use this as a means to discuss that lighter gases float. Note: This does not mean the air particles in the water bottle would not also float, but they have a greater mass and so cannot "carry extra weight" like the helium can carry the balloon.

4. Show students **an image of how the mass of isotopes** can affect their accumulation in different parts of the atmosphere and hydrosphere when the climate changes.

   a. Allow students time to make observations of the images, then discuss the similarities and differences in where the different oxygen isotopes accumulate.

Teacher Note: Observations you may want to direct students toward or discuss if they bring up: in warmer periods, rain will allow for more terrestrial erosion, which washes different types of sediment into the ocean than if it is a colder period. In colder climates, there is more consistent deposition of microorganisms.

   b. If needed, draw an oxygen-16 isotope and an oxygen-18 isotope to show why oxygen-18 is heavier.

   c. Tell students that oxygen taken in by aquatic microorganisms called foraminifera (you may want to show **images of some of these organisms**), incorporate the oxygen into their shells. Ask students to look again at the image and describe how they might use the shells of dead foraminifera to determine if they lived in a cold or warm climate.

   d. Suggested Response: Foraminifera that live in colder climates are exposed to a greater concentration of heavy oxygen (oxygen-18), and so would have more of this in their shells than oxygen-16. Foraminifera living in warmer climates would have a more equal amount of the two isotopes.

ANNOTATED STUDENT ACTIVITY

Objective(s)/Outcome(s)

Students will be able to:

1. analyze data taken from microfossils in seafloor cores to describe patterns in climate fluctuation during the last 150,000 years of Earth's history.
2. Evaluate how past climate data can be used to predict future climate change patterns.

Materials

Per Group

- Computer with internet access

Per Student

- Graphing supplies or program

Background

Ocean sediment cores are cylinders of mud, sand, and rock that scientists drill from the ocean floor to learn about Earth's past, including climate. These cores contain tiny organisms, like foraminifera (also known as forams), which are small marine creatures with hard shells made of calcium carbonate. When foraminifera die, their shells sink to the ocean floor and get buried in the sediment. Scientists can look at these shells to understand past climate conditions. The oxygen in the shells can appear as two different isotopes: oxygen-16 (^{16}O) and oxygen-18 (^{18}O). When the water is warmer, there is more of the lighter oxygen-16 in the shells, and when the water is colder, there is more of the heavier oxygen-18. By measuring the ratio of these isotopes in foraminifera shells, scientists can figure out the temperature of the ocean when the organisms lived, giving them clues about past climate.

In addition to studying oxygen isotopes, scientists also examine the type of sediment in the core to learn more about Earth's climate. Sediment types can tell us if the climate was dry or wet, hot or cold. For example, if the core has a lot of land-based sediment, it may indicate higher rates of erosion, which is often associated with more rain or ice melting. By combining information from both the oxygen isotopes in foraminifera shells and the types of sediment layers, scientists can create a picture of Earth's past climate. This helps us understand how the climate has changed over thousands or even millions of years, and how factors like temperature and rainfall have impacted life on Earth.

Activity

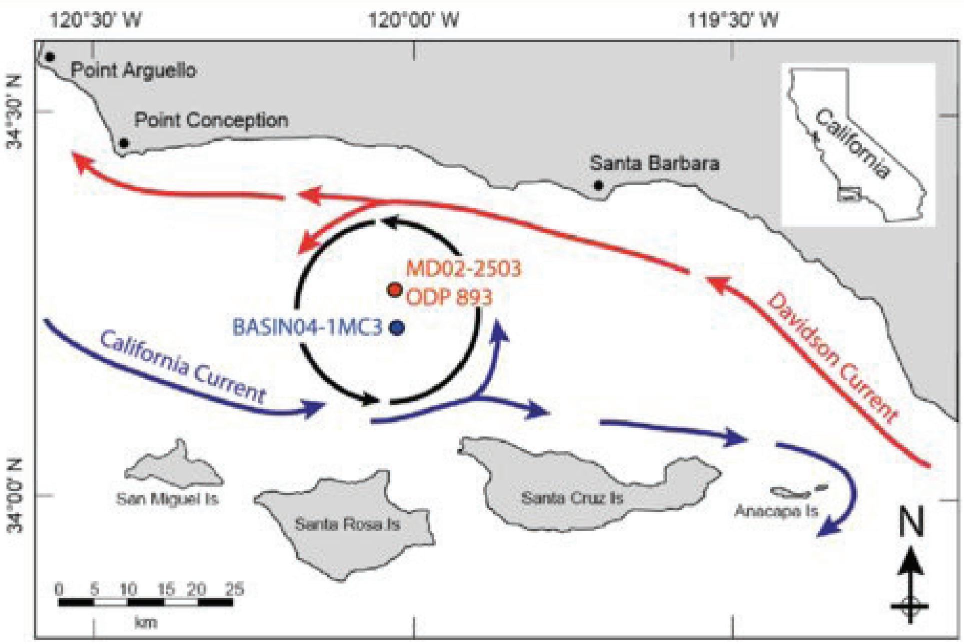
Part 1

1. Look at the data in Table 1. This data is determined by equipment that can measure the amount of each oxygen isotope within foraminifera fossils within an ocean sediment core.

    a. This data was taken from Core 893A during Expedition 146.

    b. Look at a map of the location from which this core was taken (Figure 1).

FIGURE 1: LOCATION OF CORE 893A FROM ODP EXPEDITION 146.



Credit: Beaufort & Grelaud, 2017, **CC BY 4.0**

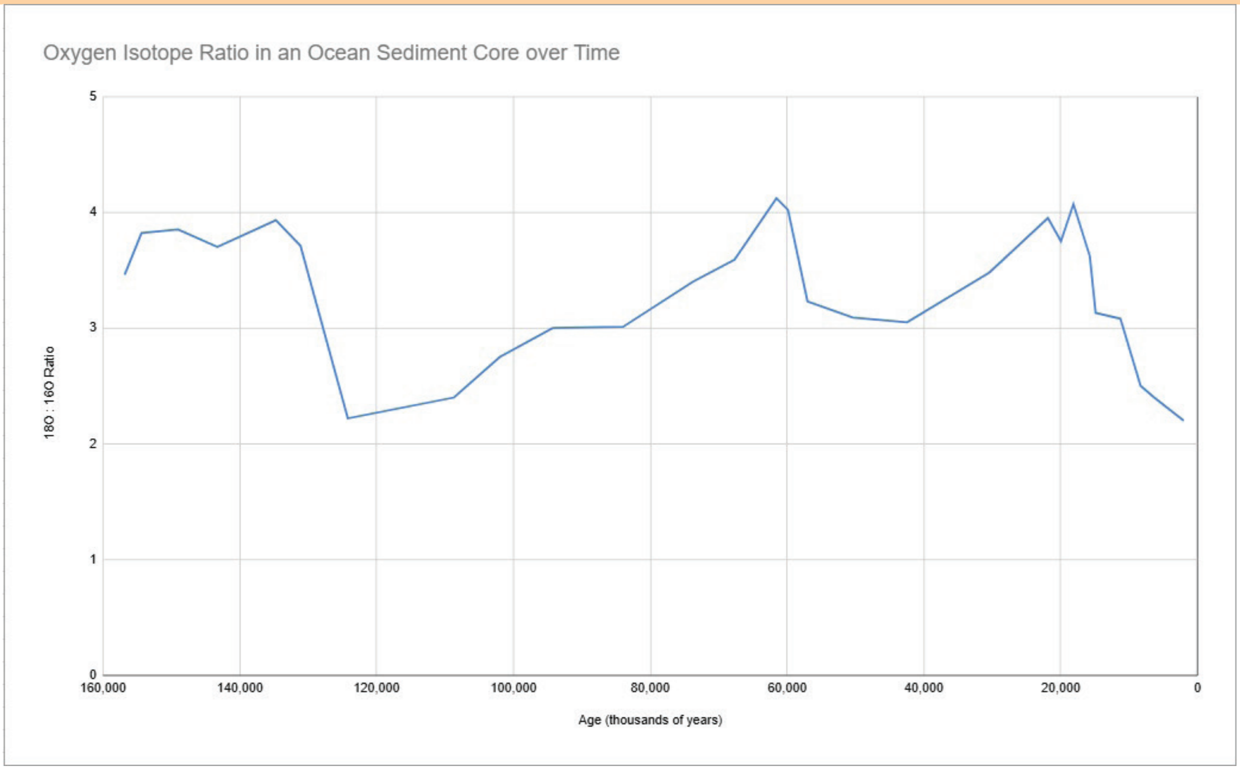
- **c.** Describe how the core's location may have influenced the sediment that accumulated there. Consider all the information on the map, from distance to land to water currents.
- **d.** Name two more pieces of information you would like to know about the location of the core that would help you in determining the environmental conditions that affected sedimentation.

2. Graph the data in the first two columns of Table 1.

- **a.** Note that the years are not evenly spaced.
- **b.** Carefully consider what type of graph to make.

Teacher Note: Students should construct a line graph. While the data would need to be confirmed, because fluctuations can occur, a line will allow them to infer the oxygen isotopes between known times.

Figure TE-1: Example of student-made graph



Credit: L. Mossa

3. On your graph, note at least three areas on the graph that show distinctly different data or trends.
   - a. On Table 1, mark these points, noting the depth at which the data was taken.
   - b. Go to the **database of ocean sediment core images** to view the core from which the data were taken (Core 893A, Expedition 146).
   - c. Go to the segments of the core that contain the depths you marked on Table 1.
   - d. Describe each of the segments you view, noting any trends in their appearance.

Teacher Note: See the suggested responses for the analysis and synthesis questions about the cores for ideas on what students might look for.

Analysis

1. Look at your graph and describe what you see. What overall pattern do you observe?

Suggested Response: The isotope ratios peak and fall at various times over the past 150,000 years. The data cycles between a low and high ratio.

2. During what three times can you find the highest $^{18}O : ^{16}O$ ratios?

> **Suggested Response:** The highest ratios are found at approximately 20,000, 60,000, and 130–150,000 years ago.

3. Describe any trends you saw in the appearance of the cores given what you know about their oxygen ratio content.

> **Suggested Response:** Sections of the core that have lower $^{18}O : ^{16}O$ ratios tend to appear “striped” with alternating layers of light and medium/dark sediment. Sections with higher $^{18}O : ^{16}O$ tend to have consistent coloration and sediment type, as the primary deposit is shelled microorganisms.

Synthesis

1. What might the climate have been like for the three times you noted on your graph in analysis question #1 and the cores sections you observed that match with these times? Do these two pieces of data seem to support the same conclusions? (Think about the hydrological cycle, snow and the formation of large land ice sheets like those covering Greenland and the Antarctic continent. Also, consider how much runoff is coming from the land and going into the oceans.)

> **Suggested Response:** Times of high oxygen isotope ratios suggest that these were periods of glaciation, when water with the lighter oxygen isotope ended up evaporating more readily and precipitating as snow rather than rain. This snow would have accumulated in the large land ice sheets in both hemispheres. The growth of those ice sheets would have influenced deposition in the ocean, with little terrestrial sediment washing into the ocean, but with a lot of shelled organisms drifting down to the seafloor after they died, resulting in a consistent color and texture in the sediment on the seafloor. Times of low oxygen isotope ratio resulted from times when there was more rain, resulting in erosion from the land and different types of sediment eroding from the land and washing into the ocean. This caused different colors and layers of sediment to accumulate on the seafloor.

2. Do some additional research: when are known periods of glaciation in North America during the last 160,000 years? Do these align with your graphed data in any way? Do they support the claim that oxygen isotopes are a useful way to study the history of climate change?

> **Suggested Response:** “From around 150,000 to 130,000 years ago, North America experienced colder and generally more arid than present conditions. About 130,000 years ago, a warm phase slightly moister than the present began, and conditions were at least as warm as the present lasted until about 115,000 years ago. Subsequent cooling and drying of the climate led to a cold, arid maximum about 70,000 years ago, followed by a slight moderation of climate with a second arid maximum around 22,000–13,000 14C years ago.” (**Source: Oak Ridge National Laboratory**) This data aligns well with the graph, and supports the claim that oxygen isotopes are a useful way to study the history of climate change.

3. Based on the trends you see on your graph, predict and explain what will happen to $^{18}O : ^{16}O$ ratios as modern global warming continues. (CAUTION: Oxygen isotopes are simply a record, not a cause of climate change.)

> **Suggested Response:** The isotope ratio could be expected to approach 1:1 as more water molecules are available in liquid form in the ocean.

Extensions

1. Read and discuss "**Fossil Thermometers for Earth's Climate**" by Lear et al. Summarize what the article is saying.

2. Research and describe modern and/or fossil foraminifera (the organisms used in the oxygen isotope studies that generated the data that you graphed).

HANDOUT

TABLE 1. OXYGEN ISOTOPE RATIOS OVER THE LAST 157,000 YEARS

Age (years)	$^{18}O : ^{16}O$ Ratio	Depth in Core (meters below seafloor, mbsf)
2,012	2.20	3.54
6,345	2.40	10.47
8,325	2.50	13.53
11,277	3.08	18.02
14,897	3.13	22.28
15,748	3.62	24.70
18,142	4.07	28.23
19,971	3.75	30.91
21,871	3.95	33.68
30,414	3.48	45.28
42,452	3.05	62.01
50,388	3.09	73.04
57,013	3.23	81.02
59,872	4.02	84.41
61,551	4.12	86.40
67,682	3.59	93.00
73,751	3.40	98.68
83,977	3.01	108.25
94,248	3.00	120.33
101,995	2.75	127.58
108,684	2.4	133.84
124,202	2.22	150.94
131,125	3.71	161.45
134,718	3.93	165.44
143,274	3.70	174.94
149,011	3.85	181.31
154,360	3.82	187.25
156,819	3.46	189.98

Data sampled from: Kennett 1995

CLOSURE

1. Exit ticket:
   a. Would you expect high or low $^{18}O : {}^{16}O$ ratios in ice cores? Explain your answer.

Suggested Response: In ice cores, you would typically expect high $^{18}O : {}^{16}O$ ratios during warmer periods and low ratios during cooler periods. This is because the ratio of oxygen isotopes (^{18}O and ^{16}O) in ice is influenced by temperature. During warmer periods, more of the lighter ^{16}O isotope evaporates from the oceans and is incorporated into the water vapor, leaving behind relatively higher concentrations of the heavier ^{18}O isotope in the remaining ocean water. As this vapor condenses and falls as precipitation (such as snow), the ice that forms will have a higher $^{18}O : {}^{16}O$ ratio. Conversely, during colder periods, more ^{16}O is preferentially locked in ice, leading to a lower $^{18}O : {}^{16}O$ ratio. This relationship between the isotope ratios and temperature is often used in paleoclimate studies to reconstruct past climate conditions based on ice core data.

2. Follow-up lessons:
   a. Climate data analysis;
   b. Climate proxies; or
   c. Causes of climate change throughout Earth's history.

References

Beaufort, L., & Grelaud, M. (2017). A 2700-year record of ENSO and PDO variability from the Californian margin based on coccolithophore assemblages and calcification. Progress in Earth and Planetary Science, 4(1), 5.

Kennett, James, 1995. Latest Quaternary Benthic Oxygen and Carbon Isotope Stratigraphy: Hole 893A, Santa Barbara, California. Proceedings of the Ocean Drilling Program Scientific Results, v. 146, 16pp. **http://www-odp.tamu.edu/publications/146_2_SR/VOLUME/CHAPTERS/sr146pt2_01.pdf**