

EOS 240: Lab Assignment 8

Cenozoic Climate

Due: 2:30 pm March 26, 2026 (Th section)

Due: 1:30 pm March 27, 2026 (F section)

You have one week to complete this assignment. You should submit your response to the course Brightspace page as a single PDF file. **Additionally, we ask that you upload a copy of the scripts, code, or spreadsheets you used to complete the assignment. These documents will help us track down mistakes.** Responses to questions should be typed, using complete sentences and standard grammar. If you choose to support your answers with hand-drawn illustrations or hand-written calculations, you should scan or photograph the written work and integrate it into your PDF file as a figure. Double check that your image resolution is high enough to read. A google search of 'PDF combiner' will return a number of webpages that allow you to upload individual images and combine them into a single .pdf file (example: combinepdf.com). There are also a number of good apps for mobile phones. If you write your response in a word processor, please export to .PDF before submitting your response.

You are not excluded from working with others (pairs are recommended), but each person will submit their own copy of the assignment. In your submission, include the names of anyone you worked with on the assignment.

To answer the questions, you can perform calculations and make figures using Excel (an open source alternative: www.libreoffice.com), or with a program or programming language of choice.

Name : _____

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Marks:	6	3	9	2	20
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INTRODUCTION

In this lab you will use $\delta^{18}\text{O}$ observations and sea-level records to constrain the history of land based ice during the early Cenozoic and the most recent glacial cycle.

Question 1 (20) $\delta^{18}\text{O}$ AND PAST CLIMATE

The table below lists the isotopic composition, mass, and equivalent global mean sea-level change for Earth's three major ice sheets. For the calculations in this lab, **assume that sea-level rise scales linearly with mass loss for each ice sheet.** *In reality, the amount of sea-level rise produced per unit mass loss differs among ice sheets because some ice rests below sea level, and because glacial isostatic adjustment varies among regions.*

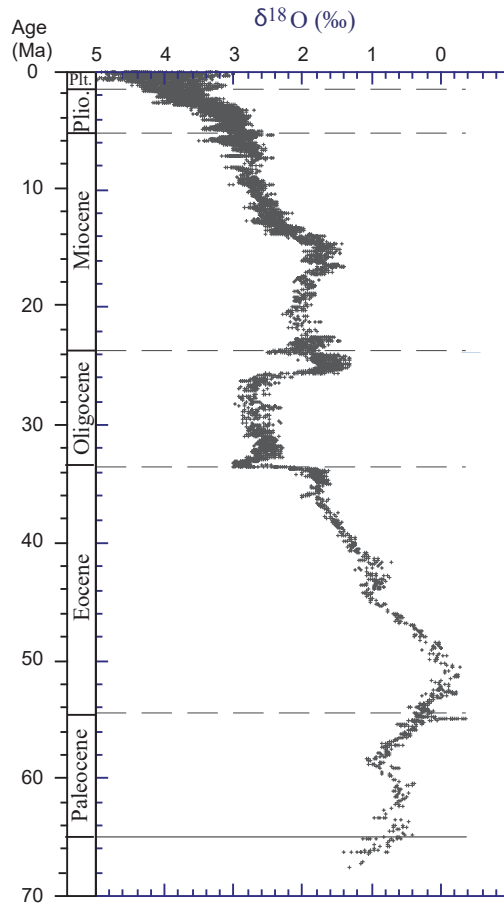
	$\delta^{18}\text{O}$ (‰)	Mass (10^{18} kg)	Sea-level (m)
Ocean	0	1358	–
Greenland Ice Sheet	-35	2.66	7.3
West Antarctic Ice Sheet	-41	2.75	4.3
East Antarctic Ice Sheet	-56.5	21.55	53.3

- (a) (1 point) Calculate the new $\delta^{18}\text{O}$ value of the ocean after complete melting of the Greenland Ice Sheet. To do this, set up and solve two equations: (1) a conservation of mass equation for the system before and after melting, and (2) an isotopic mass-balance equation for the system before and after melting. *Hint: You can treat the mass balance of isotopes the same way we determined the mass balance of trace element concentrations in solid and liquid phases.*
- (b) (2 points) Starting again with the initial conditions in the table above, calculate the new $\delta^{18}\text{O}$ value of the ocean after enough of the East Antarctic Ice Sheet melts to produce 7.3 m of global mean sea-level rise (for context, 7.3 m is the same sea-level rise expected from complete melting of the Greenland Ice Sheet in part a).
- (c) (1 point) Construct a figure showing the relationship between sea-level rise and the $\delta^{18}\text{O}$ of seawater for the melt scenarios in parts (a) and (b). Use contribution to sea-level rise as the x-axis and seawater $\delta^{18}\text{O}$ as the y-axis.
- (d) (1 point) Based on your figure in part (c), to what extent does a given change in global mean sea level correspond to a single value of seawater $\delta^{18}\text{O}$?
- (e) (1 point) what is the $\delta^{18}\text{O}$ of an ice-free Earth?

The oxygen isotopic composition of benthic foraminiferal shells is linearly related to the temperature of the seawater in which the organisms lived:

$$T = 16.5 - 4.8(\delta^{18}O_s - \delta^{18}O_w)$$

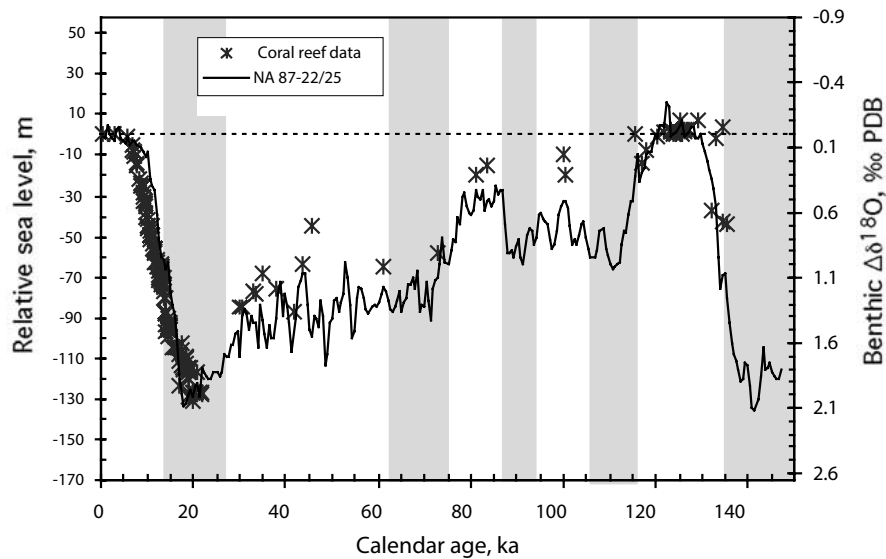
where T is temperature in Celsius, $\delta^{18}O_s$ is the isotopic composition of the foraminiferal shell, and $\delta^{18}O_w$ is the isotopic composition of seawater. The figure below shows a compilation of benthic foraminiferal $\delta^{18}O_s$ spanning the last 70 million years. Use the temperature relationship above and the dataset below to answer the following questions:



- (f) (2 points) Discuss this dataset with at least one other student. Using your combined knowledge of ice-sheet isotopic compositions and the temperature-fractionation equation above, describe at least two major features or trends in Cenozoic climate over the last 65 million years.
- (g) (1 point) Around 50 million years ago, during the Early Eocene Climatic Optimum, tropical plants and animals lived at the poles and there is no evidence for large terrestrial ice sheets. Based on the benthic foraminiferal data, what was the temperature of the bottom water in which these organisms lived?

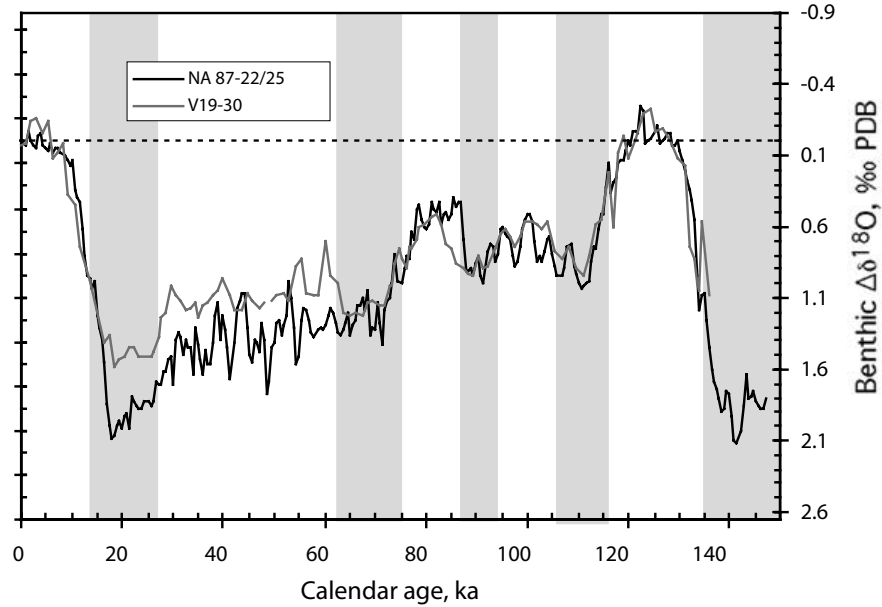
- (h) (1 point) What is the highest benthic foraminiferal shell value, $\delta^{18}O_s$, that would be consistent with an ice-free world? Assume that bottom-water temperature cannot be lower than -1.8°C , and use the appropriate ice-free value of $\delta^{18}O_w$.
- (i) (1 point) Suppose instead that ice sheets begin to form once bottom-water temperature cools to about 4°C . If so, what is the highest $\delta^{18}O_s$ that would still be consistent with an ice-free world? Use the same ice-free value of $\delta^{18}O_w$.
- (j) (2 points) Using the threshold $\delta^{18}O_s$ values you calculated in the previous two questions, describe the evolution of climate through the Cenozoic. Identify intervals for which the isotopic record indicates there *must* have been ice on land, and intervals for which ice on land *may* have been present, and explain why.

For at least the last few million years, continental ice sheets have repeatedly expanded and contracted in response to changes in Earth's orbit. The maximum extent of the most recent glaciation is known as the Last Glacial Maximum, which occurred about 20 thousand years ago. The figure below shows past sea level, as inferred from dated fossil coral reef terraces, together with the change in benthic foraminiferal $\delta^{18}O_s$ relative to the value of organisms living today ($\Delta\delta^{18}O_s$).



- (k) (2 points) Using the sea-level and $\Delta\delta^{18}O_s$ records shown in the figure, describe the major pattern of climate change through time. Identify intervals when Earth was relatively warm and intervals when it was relatively cold. Does the figure suggest that warming and cooling occurred at similar rates?
- (l) (3 points) Using the sea-level fall shown for the Last Glacial Maximum in the figure, calculate what percentage of the benthic foraminiferal $\delta^{18}O_s$ change relative to today can be explained by ice-sheet growth alone. Assume that the mean isotopic composition of the ice added to continental ice sheets was -30‰ and that each 2.4 m of sea-level fall corresponds to the growth of 10^{18} kg of ice.

The following figure shows an additional benthic foraminiferal isotope record spanning the last glacial cycle. This record is from the equatorial Pacific, whereas the first record is from the North Atlantic.



- (m) (2 points) The equatorial Pacific and North Atlantic benthic foraminiferal $\delta^{18}O_s$ records are not identical. Identify one or more key differences between them, and propose the most plausible explanation for those differences in terms of temperature, seawater $\delta^{18}O_w$, and/or deep-ocean circulation. Explain why your interpretation is more convincing than at least one alternative.