

Abrupt Events of the Past 70 Million Years

Examples from Scientific Ocean Drilling

Since 1968, scientific ocean drilling has tapped into a considerable archive of Earth history, and in doing so has revealed much about the processes that drive our planet's dynamic character. For one, our understanding of the ancient ocean-climate system has greatly advanced because of the findings of deep-sea drilling. These advances have benefited from improved coring technologies, utilization of a wide variety of techniques for non-destructive characterization of cored material, creative scientific drilling proposals, generation of high resolution geochemical records (e.g., stable isotopes), and building upon earlier drilling results.

One of the major take-away messages from this facet of scientific ocean drilling is that the ocean-climate system is not always characterized by the slow, gradual, continuous change predicted by James Hutton, Charles Lyell, and Charles Darwin. Rather, it has been perturbed by rapid changes many times in the past. Some perturbations were caused by rare events, such as the bolide impact that likely triggered the last great mass extinction event at the end of the Cretaceous Period (65.5 Ma), which heralded new opportunities for biotic evolution in the Paleogene and Neogene Periods. In addition, we have come to appreciate the importance of positive and negative feedbacks in the climate system, Milankovitch orbital forcing, opening and closing of oceanic gateways, growth of major mountain belts, and large-scale volcanism as agents of global change. At times, these varied influences have culminated in an abrupt change in the ocean-climate system caused by the crossing of some critical threshold, thereby triggering a rapid disruption to the steady-state climate system.

We do not yet fully understand all the linkages among these variables. The

deep-sea sedimentary record has provided stunning examples of just how quickly the Earth's interconnected systems can be perturbed. The latest Cretaceous and Paleogene Periods contain several prominent examples of abrupt changes in the ocean-climate system, including the Cretaceous/Paleogene (K/P) boundary, the Paleocene/Eocene Thermal Maximum (PETM), and the earliest Oligocene glaciation (Oi1 event) of Antarctica. The Neogene has witnessed the rapid Oligocene/Miocene glaciation (Mi1 event) of Antarctica, the mid-Miocene climatic optimum, the middle Miocene glaciation (Mi3-Mi4 event) of Antarctica, and the onset of Northern Hemisphere glaciation.

Paleoceanography using Stable Isotopic Analysis

Paleoceanography is the study of the ancient ocean-climate system, ranging from its physical, chemical, and biological characteristics and behavior, to the internal feedbacks and orbital influences that force changes in the ocean-climate system. Paleoceanographers use a variety of proxies (indirect evidence) to reconstruct the past, including the composition and geochemistry of the sediments, geochemistry of organic matter and specific organic molecules, geochemistry of planktic (surface water) and benthic (bottom-dwelling) microfossil shells, plankton assemblage analysis, and patterns of cyclicity in the sedimentary record, just to mention a few of the diverse areas of inquiry.

Stable isotopes of oxygen and carbon (the ratios of $^{18}\text{O}:^{16}\text{O}$, and $^{13}\text{C}:^{12}\text{C}$) are a commonly used proxy record in paleoceanography. The calcite hard parts of plankton, particularly calcareous nannofossils (autotrophic protists) and planktic and benthic foraminifers (heterotrophic protists) can be studied isotopically by dissolving the calcite

(CaCO₃) in acid to liberate CO₂ gas, and then measuring the isotopic composition of the collected gas in a mass spectrometer. A “mass spec” is an instrument used to separate and measure the relative proportions of the different masses of CO₂ in the sample being analyzed (mass 44: ¹²C¹⁶O¹⁶O, 45: ¹³C¹⁶O¹⁶O, 46: ¹²C¹⁶O¹⁸O).

Stable isotopes of oxygen and carbon in a sample are measured by comparing the ratios of ¹⁸O/¹⁶O and ¹³C/¹²C in a sample relative to a known standard. These “del” values (δ) are reported in units of parts per thousand (‰), or “per mil” (in contrast to units of parts per hundred, or percent). The following equation summarizes how stable isotope values are computed, where R is the ratio of the heavier stable isotope over the lighter isotope:

$$\delta \text{ (in ‰)} = (R_{\text{sample}} / R_{\text{standard}} - 1) \times 1000$$

The measured ratios will be either higher (enriched) or lower (depleted) relative to the standard. What is often as important as the absolute values of δ¹⁸O and δ¹³C, are the trends in the isotopic values through time (a stratigraphic section of analyses called a time series) and the magnitude of any positive or negative excursions. An excursion refers to rapid changes in isotopic values.

The bulk sediment can be analyzed, or individual shells of foraminifera (i.e., individual species or genera of planktic and/or benthic forams) can be picked from the sample and analyzed. In general, organisms precipitate their calcium carbonate shells in isotopic equilibrium with the seawater (δ_w) in which they live. For oxygen isotopes of foraminifers, the oxygen isotope ratio of the water itself is important, for carbon isotopes it is the dissolved inorganic carbon (HCO³⁻). There are some “vital” (biological) effects that vary from one species to another, but if the isotopic composition of the surface water or deep ocean changes over time, the microfossil shells will faithfully record such changes.

One important influence on the isotopic composition of seawater is ice volume. The snow that falls in the high latitudes to form ice originated from the ocean by way of the hydrologic cycle (evaporation and precipitation). The process of evaporation preferentially removes molecules of water with the lighter isotope of oxygen. As continental ice sheets expand, the ocean becomes more enriched in ¹⁸O. Therefore, microfossils that lived during glacial times have calcite shells with higher δ¹⁸O values compared with interglacial times. Evaporation and precipitation also influence

sea surface salinity. Therefore, the isotopic composition of seawater varies regionally with higher values in the subtropics where evaporation exceeds precipitation, and lower values near the equator and in the high latitudes where precipitation exceeds evaporation.

Seawater temperature also affects how much ¹⁸O and ¹⁶O will be incorporated into the CaCO₃. This thermodynamic fractionation of oxygen isotopes causes calcite precipitated in cooler temperatures to be relatively enriched in δ¹⁸O (higher values), while calcite precipitated in warmer temperatures are relatively depleted (lower values). Carbon isotopes are minimally affected by thermodynamic fractionation.

Climate Change of the Cenozoic

This exercise is based on the composite stable isotope record of deep-sea benthic foraminifers (δ¹⁸O and δ¹³C) recovered from sediments cored by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (Zachos et al, 2001. Trends, Rhythms, and Aberrations in Global Climate Change 65 Ma to Present, Science, 292:686-693).

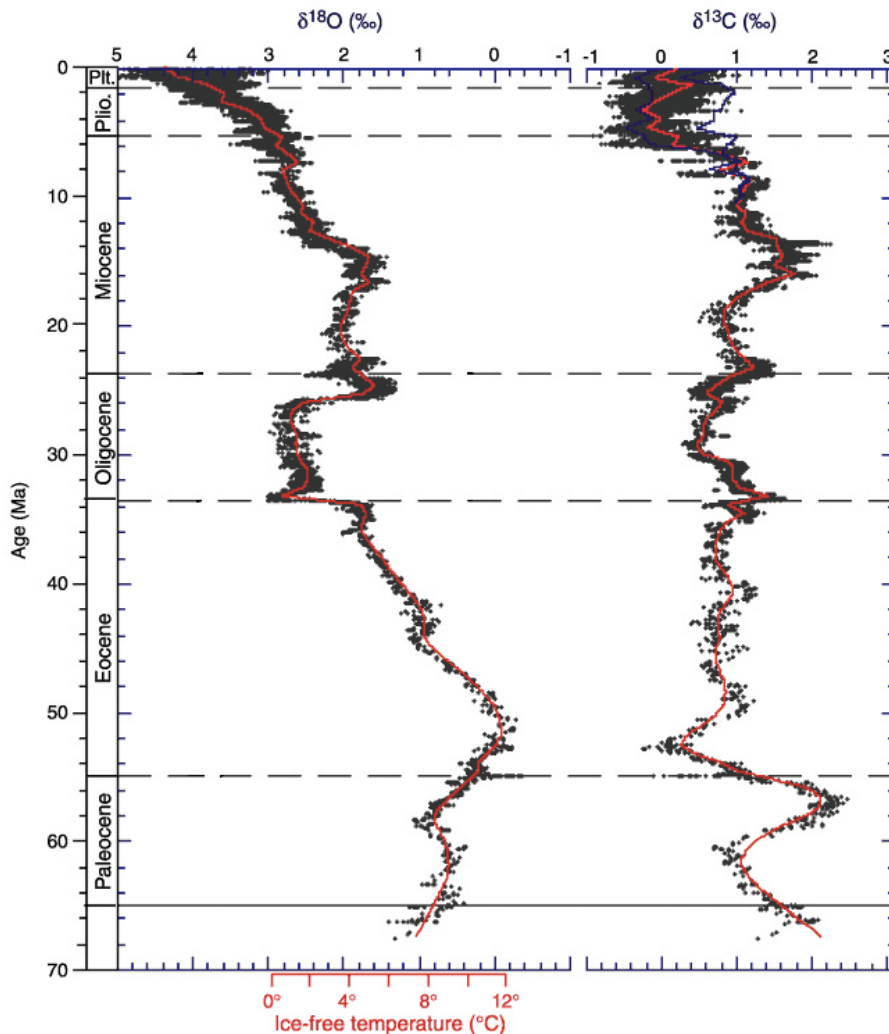
General principles for interpreting stable isotope changes:

- Rapid or sharp changes are called “excursions” and typically represent rapid or abrupt changes in the ocean-climate system. Gradually changing values, either increasing or decreasing, typically represent longer-term trends.
- For oxygen isotopes, increasing values and positive excursions could represent colder conditions and/or greater ice volume (growth of ice sheets). Conversely, decreasing values and negative excursions could signify warmer conditions and/or smaller ice sheets. Salinity also affects oxygen isotopes, but for benthic foraminifera, changes in salinity of the deep ocean are likely insignificant. Therefore, oxygen isotopes are a good proxy for temperature and ice volume.
- For carbon isotopes, increasing values and positive excursions could represent the burial and preservation of abundant organic matter (rich in ¹²C) to the rock record. This could be associated with rising sea level and flooding of continental shelves, vast wetlands, and coastal plains, or it could be due to elevated marine productivity and burial of light depleted carbon. Conversely, decreasing values and negative

excursions could represent the erosion and remineralization (decomposition) of organic carbon due to falling global sea level, or it could be due to the exposure and erosion of previously buried organic matter. Alternatively, the introduction of light carbon from volcanism or the dissociation of methane hydrates would also decrease carbon values. Methane gas is produced by methanogenic bacteria during the anoxic decomposition of organic matter buried along continental margins. This methane is isotopically very depleted in the heavy isotope of C, with very negative $\delta^{13}\text{C}$ values of around -80 per mil as compared to HCO_3^- dissolved in the ocean, which normally has a $\delta^{13}\text{C}$ value of around 0. The methane gas is frozen below the seafloor in deposits called gas hydrates, or clathrates. Gas hydrates are stable under specific temperature and pressure conditions, but it has been hypothesized that these gaseous deposits can be destabilized if the boundary conditions change, such as increasing temperature or decreasing pressure due to falling sea level or a large gravity slide on the seafloor.

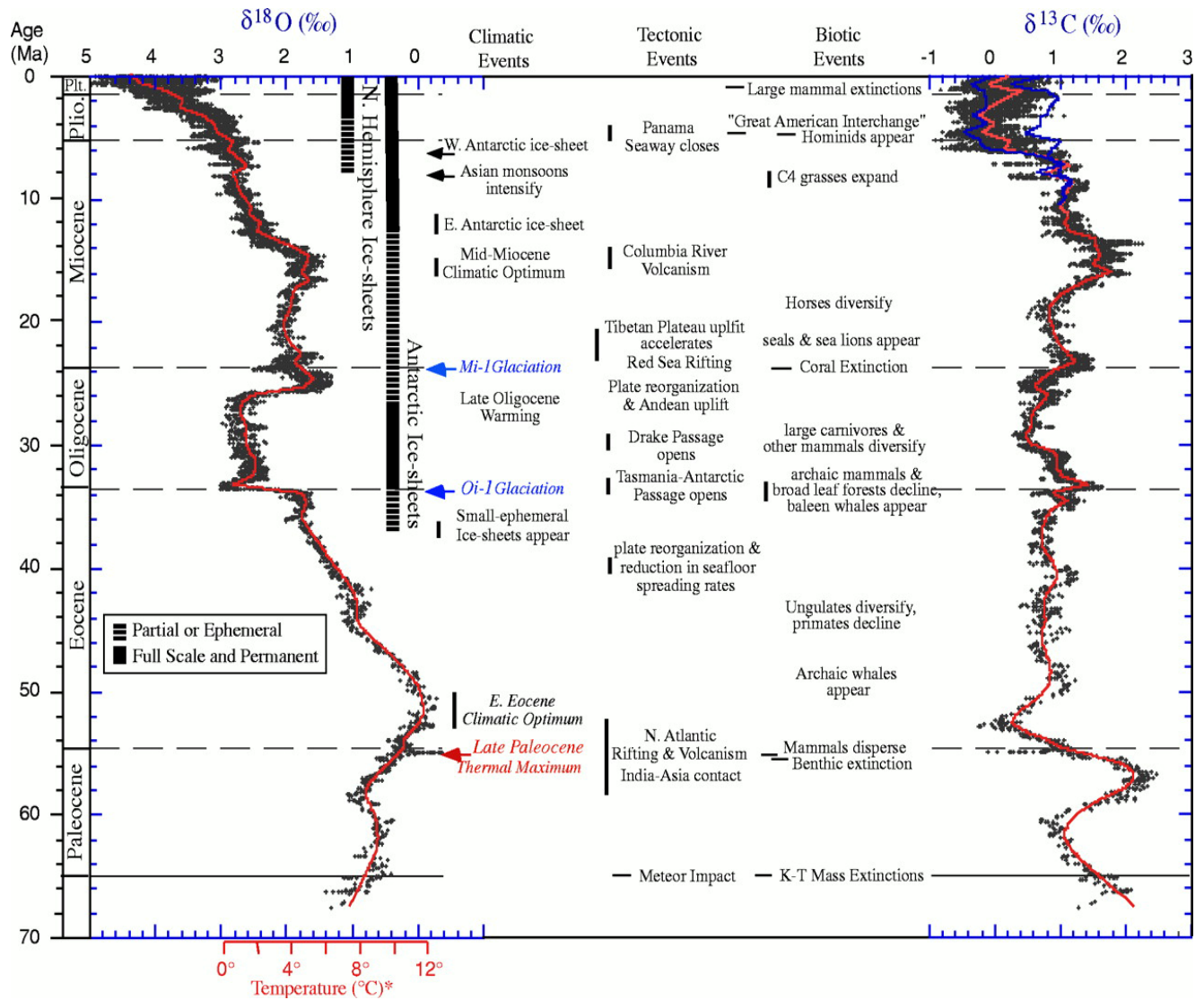
Part 1 – Based on the benthic foraminifer $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records of Zachos et al. (2001), without annotations:

1. What was the warmest time of the Cenozoic? Predict times of ice sheet growth and advance and times of ice sheet retreat.
2. Describe the long-term Cenozoic $\delta^{18}\text{O}_{\text{benthic foram}}$ trends. Describe the nature of changing climate during the Cenozoic. Is the record smooth and gradual and unidirectional, or are there other patterns of change? Comment on specific intervals of the Cenozoic to support your ideas.
3. For the events marked by oxygen isotope excursions (rapid changes in $\delta^{18}\text{O}$ values), how many of these are also associated with $\delta^{13}\text{C}$ excursions? What times show the largest carbon isotope excursions? What happens to the oxygen isotope record during these events? Is there a consistent relationship between oxygen and carbon isotope excursions? In other words, do they always trend in the same directions relative to one another (either higher or lower values, increasing or decreasing trends)? Explain with specific examples.



Part 2 – Based on the interpreted benthic foraminifer $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records of Zachos et al. (2001), with annotations:

1. What events are attributed to oxygen isotope excursions (rapid changes in $\delta^{18}\text{O}$ values)?
2. What was climate like during the middle to late Eocene, the time during which archaic whales were diversifying? What was climate like at the time baleen whales appeared? What other biotic events occurred at this time?
3. Notice that there is a big extinction in deep-sea benthic foraminifers at the same time that land mammals dispersed widely and experienced rapid rates of evolution. Can you speculate about what types of environmental changes could affect organisms in both the deep-sea and on land?
4. Geologists long ago subdivided the geologic record into Periods and Epochs. Speculate about why these early geoscientists may have recognized the Cretaceous/Paleogene (K/P), Paleocene/Eocene, Eocene/Oligocene, Oligocene/Miocene, and Pliocene/Pleistocene boundaries.



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