Deep Earth Academy
CONSORTIUM FOR OCEAN LEADERSHIP

Instructor Version

Window on Arctic Coring

Summary

This suite of short activities opens a window to both the scientific motivation and impact of a coring expedition, using an Arctic Expedition as a case study. The question "Why Drill there?" is addressed at multiple levels, so students can experience the scientific rationale behind drilling the sea floor at a particular location. A subset of research results are also investigated and compared with the current scientific paradigm on Cenozoic climate evolution to demonstrate that science is an evolving process.

Student Learning Goals

Students will be able to:

- Draw reasonable scientific conclusions about regional and global climate evolution by interpreting graphs, tables, photos, and maps.
- Use pre-existing data and scientific theory to articulate a scientific argument for a new drilling expedition.
- Reevaluate previous scientific conclusions given new data.

> ***Literally as well as metaphorically, the man accustomed to inverting lenses has undergone a revolutionary transformation of vision.***
>
> Thomas Kuhn (1922-1996)

- Identify scientific questions that remain unanswered.
- Draw a reasonable scientific conclusion about the tectonic origin of an ocean ridge using core data.

Context for use

- This activity could be used in introductory courses in earth science, historical geology, climate change, oceanography, and upper level courses in marine geology and paleoclimatology.
- This activity could be used before the introduction of topics on Pleistocene epoch, glacial-interglacial cycles, modern climate change.
- This activity could be used after topics on geologic time, marine sediments, plate tectonics.

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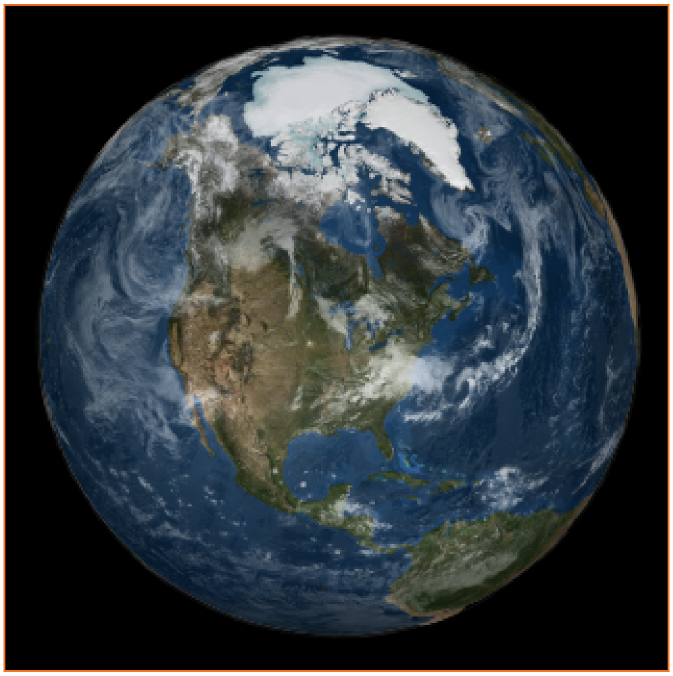
Annotated Student Activity



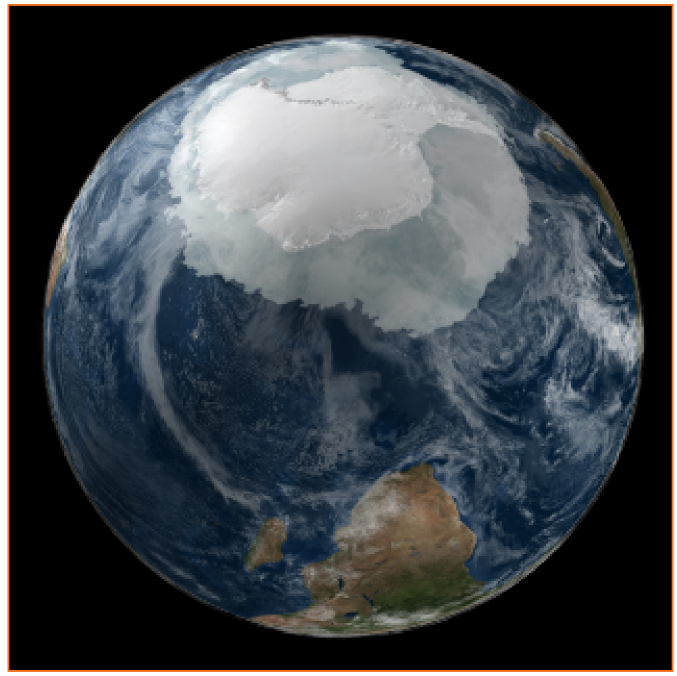


Figure 1. These images show polar views of the Earth on September 21, 2005, the date at which the sea ice was at its minimum extent in the Northern Hemisphere. From: http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003402/index.html.

Initial Inquiry

1. How are the North and South Polar regions (Fig. 1) similar? How are they different?

   Similar:
   high latitudes, cold or Ice, high albedo, low insolation

   Different:
   opposite seasons, continent vs. ocean, sea ice vs. ice sheets, penguins vs. polar bears

2. Predict how sediment cores retrieved from the Arctic Ocean seafloor could be used to infer past climate.

   Student answers may vary a lot depending on their background. If they have already done an exercise on sediment cores and specific paleoclimatic events (e.g., PETM) then their response level will be higher. At the most basic level expect answers like: past environments can be inferred from fossils, or something about the chemistry of the sediments can help tell us if the bottom waters were well oxygenated. Student might say they don't exactly know how the cores can help but that they probably could be used to tell scientists something about how cold it was or how much ice there was at different times in the past. Other reasonable answers might include: composition of the land-derived marine sediment could tell us about climate, weathering, source areas of glacial erosion; geochemistry of microfossils may tell us about sea surface temperatures and salinities, bottom water temperatures.

3. Make a list of what you think might be unique challenges to coring into the sea floor in the Arctic Ocean.

   Keeping on station to drill (staying on one site for days at a time) is very difficult when sea ice is constantly moving with the currents. The cold temperatures can make the mechanics of drilling difficult as well. Being in a remote location makes any re-supply or emergency help difficult.

Share and Discuss

As a group, share and discuss your observations and predictions. Keep these ideas in mind as you delve into the series of activities on Arctic coring.

Consider making a group list of their shared answers to questions 1-3 above. Keep it in the room where students can see it while they work on next activities.

Table 1. Selected Arctic core sites (~1988-2004).

Site/core Identification	Geographic Location	Latitude/ longitude	Water depth (m)	Max coring depth below sea floor (m)	Max age of sediment cored	Reference
NP26-5	Mendeleev Ridge	+78.58/-178.09	1435	2.10	~650,000 yrs [MIS 16]	Polyak et al., 2004
PI-88-AR-P5	Northwind Ridge	+74.37/-157.53	1089	4.76	~1 million yrs [just below Jaramillo event]	Poore et al., 1994
PI-88-AR-P7	Northwind Ridge, Canada Basin	+74.38/-157.23	3513	5.36	~500,000 yrs [MIS 13]	Poore et al., 1994
96/12-1pc	Lomonosov Ridge	+87.06/+144.46	1003	7.22	~900,000 yrs [MIS 22]	Jakobsson et al., 2000, 2001
PS2189-5	Lomonosov Ridge	+88.48/-144.1	1001	10.35	Mid-Pleistocene	Futterer 1992
PS2167-1	Gakkel Ridge	+86.57/-59.1	4434	6.40		
PS2175-5	Amundsen Basin	+87.40/-104.05	4313	16.92		
PS2190-1	Amundsen Basin/ North Pole	+90/	4275	4.27		
PS2159-6	Nansen Basin	+83.60/-30.17	4010	2.18		
PS2200-5	Morris Jessup Rise	+85.19/+14	1073	7.70		
PS2213-6	Yermak Plateau	+80.28/-8.3	853	13.09		
PS2180-2	Makarov Basin	+87.39/-156.58	3991	12.96		
PL-380	Alpha Ridge	+84.37/-128.28	2401	3.45	Mid-Pleistocene, [with older(?) clasts at base]	Clark et al., 2000

Critical thinking/Problem Solving

Part 1 - Making the Case for Arctic Coring I

There are ~700 piston core sites in the Arctic Ocean, 13 of which are included in Table 1. These selected sites are representative of the general geographic distribution of Arctic core sites, as well as the sub-seafloor depth and temporal distribution of the sediment cores recovered.

4. Plot the coring locations given in Table 1 on the physiographic map of the Arctic Ocean (Fig. 2).

   If students don't have much experience plotting latitude and longitude then this task can help build that skill. If on the other hand plotting on a map is easy for them it might be perceived as busywork and you might want to skip this question and move on to #2.

   A reminder that these are only a few of the 700+ piston cores taken in the Arctic, but their locations represent the coring in the deep basin. It does not represent the coring on the wide continental shelves however.

   There is a nice online resource describing what piston cores are at: http://oceanworld.tamu.edu/students/forams/forams_piston_coring.htm.

5. Describe the distribution of the coring locations in terms of geography and water depth.

   The coring tends to focus on bathymetric highs, but this isn't always the case. Given the challenging weather and sea ice conditions in the Arctic it is easy to see that piston coring in the deep basin is less common (because it requires more time on station).

6. What is the maximum sub-sea floor depth reached for the cores listed in Table 1?

   Max sub-seafloor depth is 16.92 mbsf from a core in the Amundsen basin.

7a. What is the maximum age of the sediment in the cores listed in Table 1?

   Many don't have an absolute age, but are listed only with relative ages. It is difficult to date sediments from the Arctic—the preservation of calcareous microfossils is poor, making age determination more challenging. So mid-Pleistocene is the maximum age (about 900,000 years old), although some older clasts may have been recovered on Alpha ridge. The age of these is uncertain.

7b. Calculate the percent of Cenozoic time that the sediment in these cores represents. Note that the Cenozoic Era includes the last 66 million years and the Pleistocene Epoch was between 1.8 million years ago and 10,000 yrs ago.

   *Using 900,000 yr BP as the oldest age of sediments from the chart (which also represents a mid-Pleistocene age) then: (900,000 yrs/ 66,000,000 yrs) *100 = 1.4% of Cenozoic time that the Arctic cores have penetrated.*

7c. Do you think the Cenozoic geologic history of the Arctic Ocean is well understood? Explain.

   Not well at all for anything older than the mid-Pleistocene - it is a black hole, so to speak. For mid-Pleistocene and younger though, the geologic history of the Arctic should be reasonably well reconstructed (700 + cores).

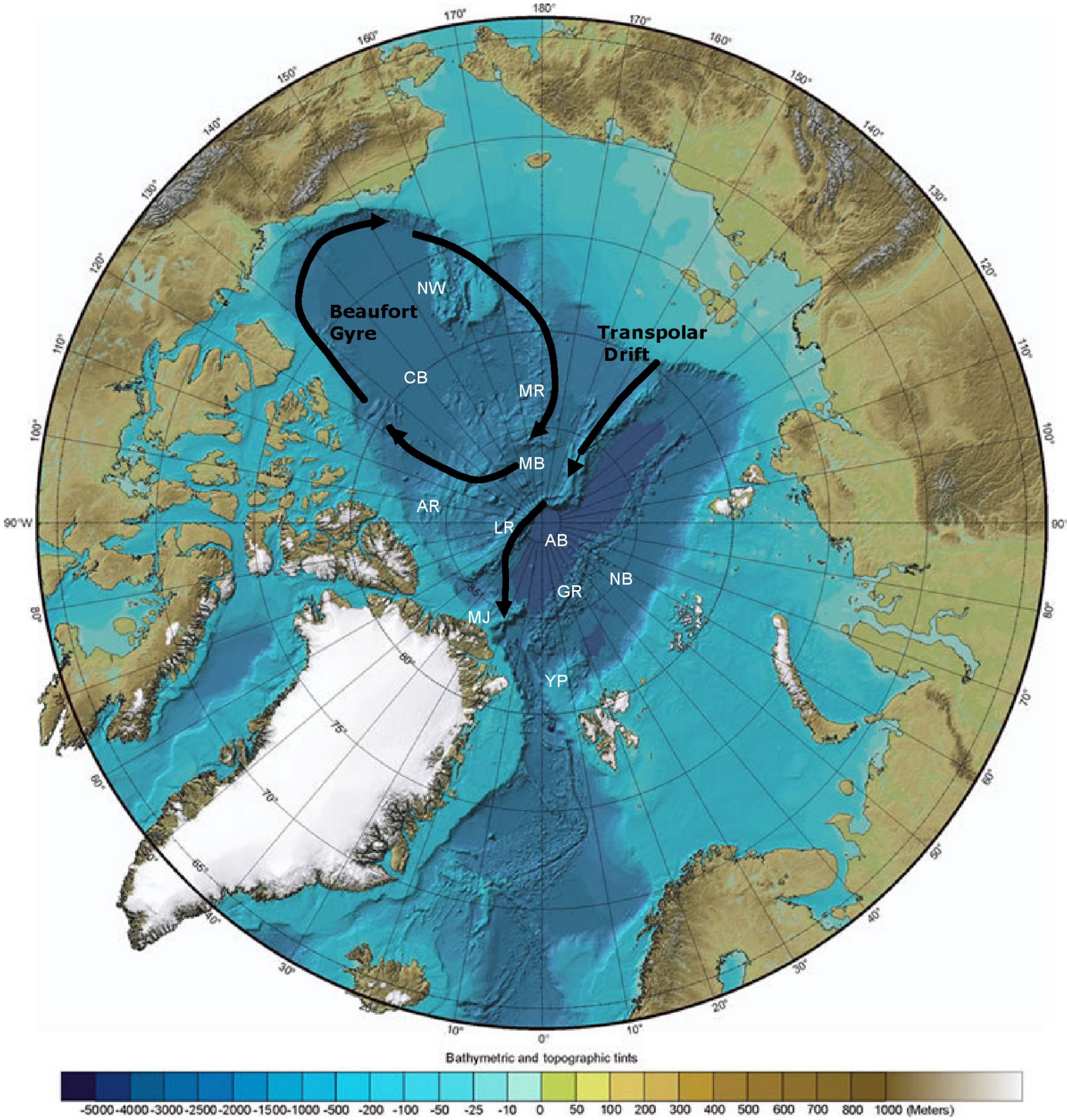


Figure 2. The International Bathymetric Chart of the Arctic Ocean, produced by a team of investigators from Canada, Denmark, Germany, Iceland, Norway, Russia, Sweden, and the USA. It is a physiographic map of the Artic Ocean as it shows the bathymetry, ridges and basins that are part of the Arctic. AB = Amundsen Basin, AR = Alpha Ridge, CB = Canada Basin, GR= Gakkel Ridge, LR = Lomonosov Ridge, MB = Makarov Basin, MJ = Morris Jessup Rise, MR = Mendeleev Ridge, NB = Nansen Basin, NW = Northwind Ridge, YP = Yermak Palteau. Map modified from: http://geology.com/world/arctic-ocean-map.shtml. Black arrows show modern major surface currents of the Beaufort Gyre and Transpolar drift.

Part 2 - Making the Case for Arctic Coring II

Examine Figure 3 adapted from Zachos and others (2001) that shows global climatic, tectonic, and biotic events and trends for the last 66 million years (the Cenozoic Era). The oxygen and carbon isotope data are derived from geochemical analyses of calcite in benthic foraminifera shells. The oxygen isotope data is an indirect indicator (or "proxy") of bottom ocean water temperatures and glacial ice volume on land. The summary data shown in this figure supports the theory that Earth has experienced times of global warmth, so warm that even in the polar regions long-lived ice could not exist. These times are coined "Greenhouse Worlds" (Ruddiman, 2008). In contrast, the Earth has also experienced "Icehouse World" conditions. These are times when temperatures are cool enough to sustain ice sheets. Sometimes these ice sheets are small (like today) and sometimes the ice sheets are more extensive (like during the height of the last ice age, 20,000 yrs ago).

In small groups discuss and answer the following questions based on the information in this summary figure.

8. How would you describe the nature of changing climate during the Cenozoic? What is the general trend of climate change? Is this record smooth and gradual and unidirectional, or some other pattern? Comment on specific intervals of the Cenozoic to support your ideas.

   No introduction is given here to oxygen isotopes. It isn't necessary to have a primer on $\delta^{18}O$ or $\delta^{13}C$ to do this part of the exercise. The figure is annotated to give meaning to the relative direction of $\delta^{18}O$ change (see top of figure).

   From about 50 myr to the present the general trend was cooling. This isn't a smooth trend however. There were several abrupt events of both warming (e.g., PETM at 55 Ma, late Oligocene warming at ~26 Ma) and cooling (e.g., the early Oligocene glaciation at ~34 Ma, the early Miocene glaciation at 24 Ma).

   Not directly on topic but some students ask about the red line vs the black "scatter" in the oxygen-isotope (and carbon isotope) curves. The red line represents the mean values. The black data spots show the variability from the mean. Notice that there is a lot of scatter in the Plio-Pleistocene. This indicates there was a lot of variability in $\delta^{18}O$ values (and thus temperature and ice volume).

9. What was the warmest time of the Cenozoic? When did the southern Hemisphere transition to Icehouse conditions? When did the Northern Hemisphere first transition to Icehouse conditions?

   Warmest time of Cenozoic = 55 Ma, PETM

   Southern Hemisphere transition to Icehouse = ~40 Ma and by 38 Ma (small ice sheets appear)

   Northern Hemisphere transition to Icehouse = late Miocene 7-8 Ma.

   So it is an important take away point that there was a general consensus that the Northern Hemisphere lagged the Southern Hemisphere in the transition from Greenhouse to Icehouse conditions.

10. What physical evidence do you think there is for the existence of the earliest Cenozoic ice sheets? Which would offer a more complete record of ice formation and expansion – sedimentary records on land or sedimentary records from the sub-sea floor? Why?

    Students may think of glacial deposits on land as the primary evidence for the earliest ice sheets. However, these deposits often get eroded by subsequent ice sheet advances so they really are not very common or undisturbed. Glaciomarine sediments are generally more complete records of ice on land – with the caveat that this is ice that has reached sea level so that icebergs can calve off and transport debris to the marine depositional environment.

Thick sediment sequences of the ocean floor can be excellent archives of past climatic and environmental change. Marine sediment records are often more complete than sedimentary records on land because of the geologic processes of erosion. Eroded sediment will be transported by rivers, wind, and ice to the low spots on Earth's surface where it will accumulate. The ultimate low spot on Earth's surface is the global ocean basin. Thus coring into the ocean basins can reveal not only changes in oceanic environments through time but also changes in terrestrial environments through time.

One of the pieces of evidence used to infer the existence of past glaciers is anomalously coarse mineral grains and rock fragments in marine sediments. Pebbles and even sand grains in sediment cores drilled offshore on bathymetric highs are interpreted to be ice-rafted debris (or IRD for short). You can see IRD in

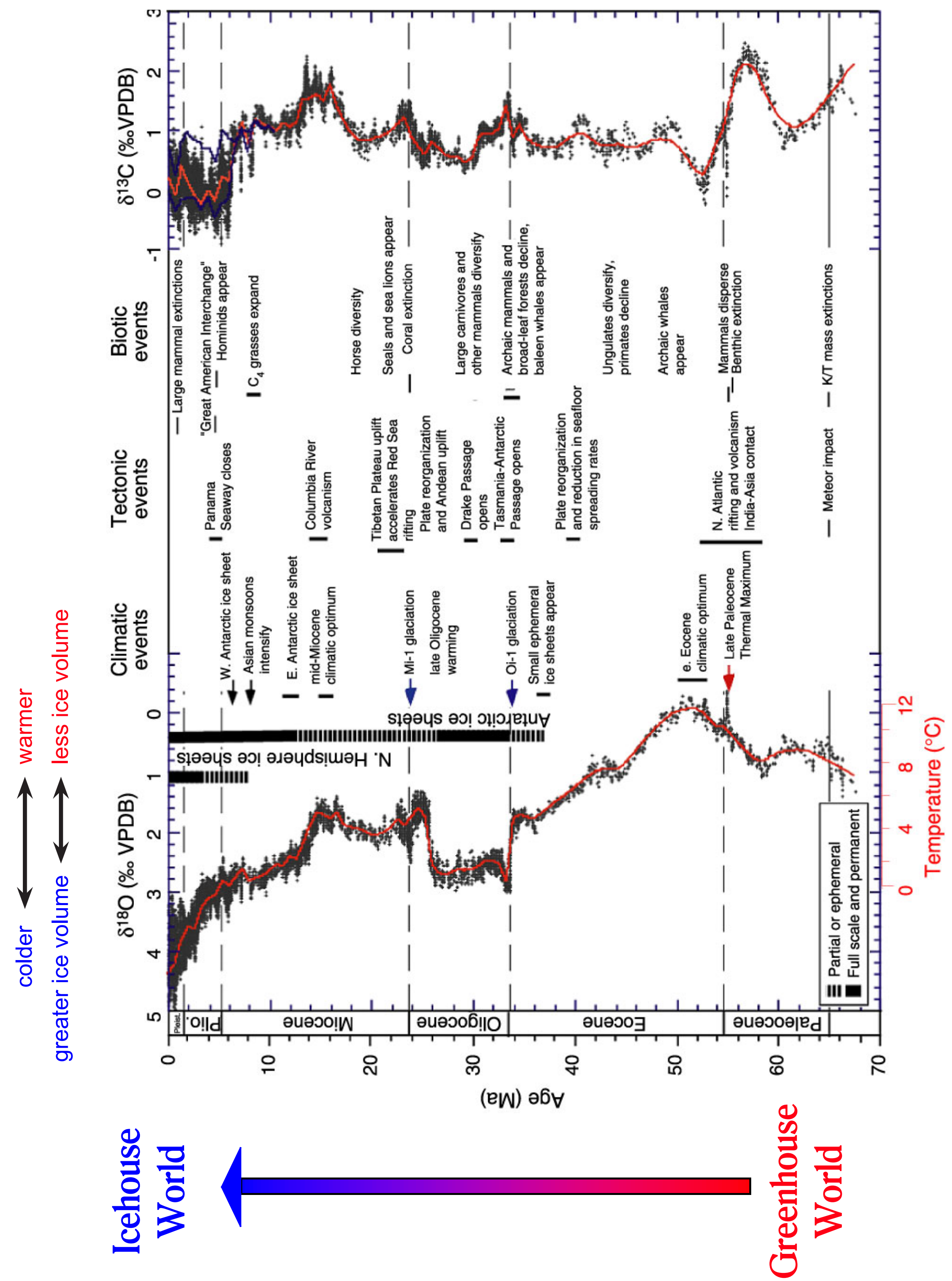


Figure 3. Cenozoic events in climate, tectonics, and biota vs. $\delta^{18}O$ and $\delta^{13}C$ in benthic foraminiferal calcite (modified from Zachos et al., 2001). VPDB = Vienna Peedee belemnite (http://odp.pangaea.de/publications/207_IR/chap_01/c1_f7.htm#6036). Antarctic ephemeral ice sheets extended into Eocene based on data from Lear et al., 2000.

the core photo (Fig. 4, look at Section 5, 110-125 cm). Such rock fragments and mineral grains are the products of weathering and erosion on land, but are too large or heavy to have been transported to the sea by wind. Their location on a bathymetric high also rules out the possibility that these were transported off shore by river systems and related underwater debris flows. By process of elimination the interpretation of ice-transport is reasonable.

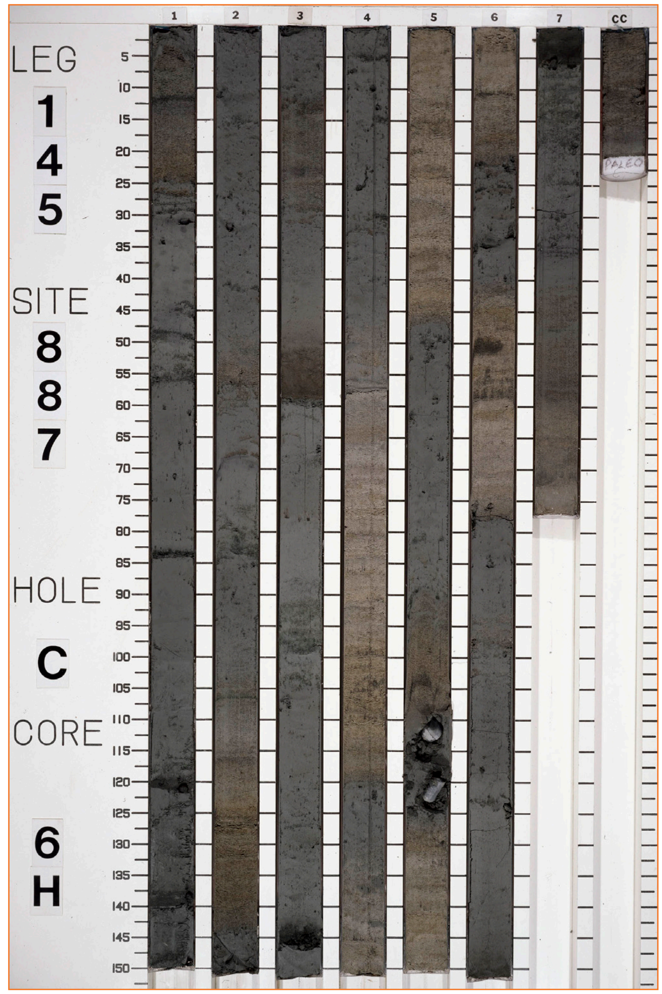
11. Let's bring in some data from Part 1 now. Draw a line along the vertical axis of Figure 3 showing the geologic time intervals that Arctic coring has recovered. Could the Arctic cores have contributed data on the Cenozoic Greenhouse to Icehouse transition of the Northern Hemisphere?

    This line will be short - only from today (0) to the mid-Pleistocene (~1 Ma, given the scale.)

    The Arctic cores couldn't have contributed much data on this topic, except for good regional coverage for the Pleistocene-Holocene; really nothing on the transition time from greenhouse to icehouse. See additional notes below that are also included in the student version:

That was perhaps a rhetorical question. But also a profound recognition—the paradigm of understanding about Cenozoic climate change from a Greenhouse to an Icehouse World lacks any long-term data sets from the Arctic Ocean, the Northern Hemisphere's polar region. Rather, it is long cores from the sub-Arctic that have defined the onset of ice-rafting for the Northern Hemisphere, as shown in Figure 5 below.

Figure 4. Core Photo from 887C-6H, Patten-Murray Seamount, NE Pacific Ocean (Rea et al., 1993).



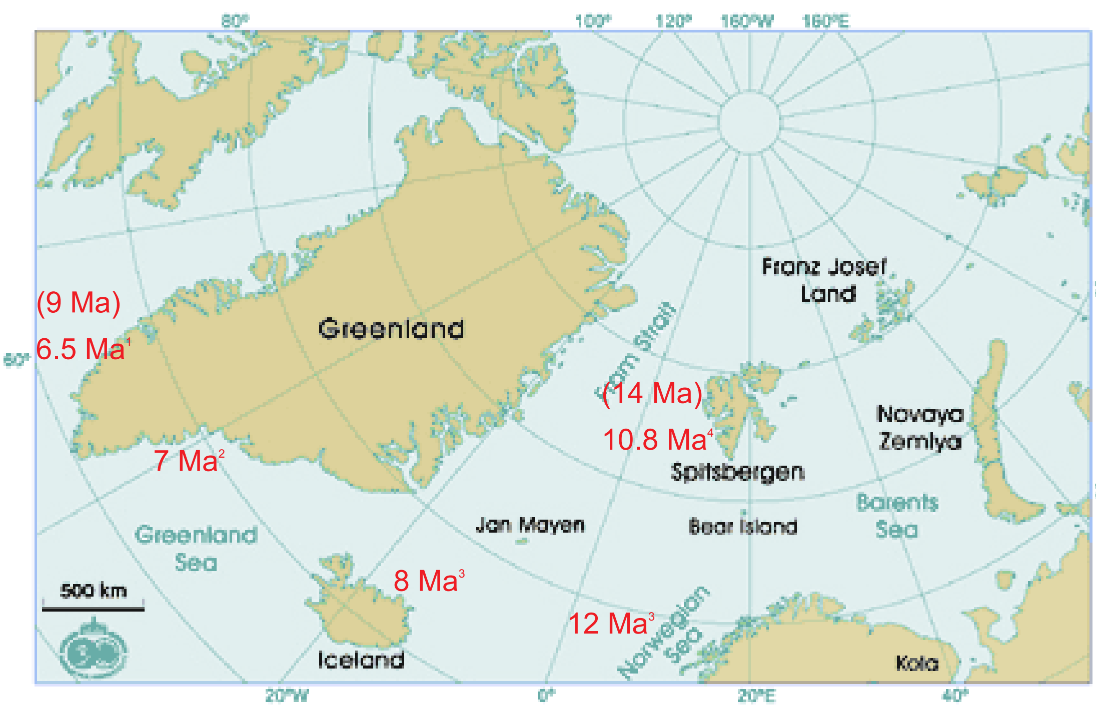


Figure 5. Age of ice-onset based in IRD records in northern North Atlantic core locations. Ages in parentheses are considered ephemeral ice, whereas no parentheses indicate onset of more permanent ice. [1]Wolf and Thiede, 1991; [2]St. John and Krissek, 2002; [3]Fronval and Jansen, 1996; [4]Wolf-Welling et al., 1996.

12. What geographic trends are there in the timing of earliest IRD in the sub-Arctic records (see Figure 5 map)?

    Consider the lines of latitude as contour lines and there is a general (not perfect) trend of earlier ice rafting at higher latitudes.

13. Based on what you have completed in Parts 1 and 2 so far, make a scientific argument for drilling a long core in the Arctic Ocean. Propose some scientific questions that a long sediment core from the Arctic could potentially answer.

    The pre-Pleistocene geologic history of the Arctic is a black hole—there is no empirical data from the ocean (note that there is some from outcrops on land but even these are sparse). Existing cores from the Arctic only give us a glimpse of the last 1.4% of Cenozoic Arctic history. Thus the Northern Hemisphere high latitudes are virtually an unknown in the Greenhouse to Icehouse transition. If the logistical challenges of drilling a long core in the weather and sea ice conditions of the Arctic can be overcome then a long core or set of long cores from the Arctic would be a high priority for scientific drilling.

    Long sediment cores may be able to address the following questions:

    When did ice first form in the Arctic? Was it before or after the sub-Arctic?

    How warm was it in the Greenhouse time? How cold was it in the Icehouse time?

    How was the Arctic environment impacted by this cooling?

    Long sediment cores may also help address many other questions relating to sea level, tectonics, ridge subsidence, ocean circulation, source areas of sediment, sediment types and more.

14. Share and discuss your ideas as a group. As a class refine the collective argument for drilling a long core in the Arctic and articulate one or more scientific objectives.

    Use this as an opportunity for scientific ideas to blossom. Because the Arctic geologic history (including climatic history) is a big unknown, the possibilities for scientific objectives are really quite broad. For your reference the scientific objectives of the IODP Arctic Coring Expedition (more on this expedition in the next few parts) included:

    - *What is the history of ice-rafting? How does this pattern fit with what is known from the sub-Arctic? Did sea ice or glacial ice form first?*
    - *When did local ice sheets develop? Where did ice form first? Are pulses of ice expansion in the sub arctic also seen in the Arctic?*
    - *What was the density structure of the Arctic surface waters? How did this change with the onset of Northern Hemisphere glaciation?*
    - *How connected was the Arctic Ocean deep water circulation to the rest of the world ocean?*
    - *What was the timing and consequence of the opening of the Bering Strait?*
    - *What are the land-sea links and the response of the Arctic to Pliocene warm events known from land records?*
    - *What is the history of biogenic sedimentation? Were biosiliceous sediments always dominant in this region?*

    You can read the actual scientific prospectus for the Arctic Drilling Expedition at: http://publications.iodp.org/scientific_prospectus/302/index.html. This was the document that articulated the scientific arguments and logistical plan for the coring expedition which was successfully funded and executed.

Part 3 – Why Drill There? Site Selection

Assuming your scientific arguments for drilling a long core in the Arctic are sound, its time to propose a specific site for drilling. This would be the first long core in the Arctic so the pressure is on to select a location that will prove to have a successful recovery of several hundred meters of core to provide the first glimpse of pre-Pleistocene history of the Arctic Ocean.

15. Think about your scientific objectives and examine the Arctic Ocean Map (in Part 1). Where would you propose to drill and why? What additional information would you want to have for making this decision?

    This is an open-ended question; students should think about criteria like: deep basin vs bathy high, on shelf or away from shelf; consider safety challenges, They may think of sediment thicknesses, currents, impact of sea level change on record too. They would probably also want specific information on the geology of the piston cores from the regions they are considering targeting for coring. Students may want seismic survey data of the seafloor too. This question aims at getting students to recognize that research always builds on what was done *before and that both scientific and logistical factors must be taken into account in planning a research program.*

16. Share and discuss your ideas and information needs as a group. Can you come to consensus on 2 or 3 sites to propose?

The actual sites proposed are less important than their rationale for choosing those sites – are the scientific arguments strong? Are the logistical arguments reasonable?

Hopefully some of the students will say that since this would be the first long core from the Arctic they would target a bathymetric high (because logistically easier to drill) in the central Arctic - one that is influenced by one or both of the major surface currents. The next section (which is also in the student version) gives information on the actual suite of drill sites proposed.

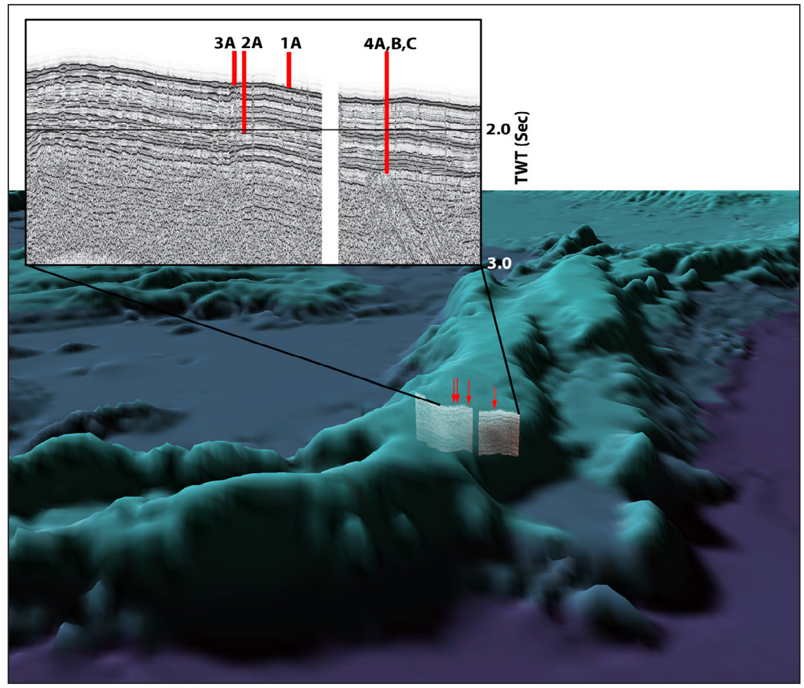


Figure 6. Reflection seismic cross-sections of Lomonosov Ridge (inset figure) from: http://www.eso.ecord.org/expeditions/302/302photo.htm. Modified from Figure 3 in the IODP Expedition 302 Scientific Prospectus: http://publications.iodp.org/scientific_prospectus/302/scip22.html.

In March 2002 a team of scientists led by Jan Backman from Stockholm University proposed to drill five sites along the ridge crest of the Lomonosov Ridge in the central Arctic Ocean. The proposed sites were to be distributed between 88°N and 81°N in water depths between 800 and 1415 m and were all in international waters. Some of the pieces of information that helped Jan and his team select these particular sites were seismic reflection profiles from several seismic survey cruises in this area that suggested sediments along this part of the ridge were ~450 m thick on top of harder basement rock. One of those profiles (Fig. 6) is shown on page 9 with drill site locations indicated.

17. From seismic survey data there is an estimate on the thinkness of the sediment cover. Let's project that drilling is successful here and a full 450 meters of sediment are recovered. What amount of time does this thickness of sediment represent? We can make a first order estimate of the age by using existing data from the piston coring on the Lomonosov Ridge that is included in Table 1:

    a. To determine age we first need to determine the sedimentation rate – this is the rate at which sediment accumulates, or builds up, in this area. Use data from Table 1 to determine the sedimentation rate in meters per million years on the Lomonosov Ridge. Are there any uncertainities about this number? (hint: think about the assumptions you are making.)

    Sedimentation rate = 7.22 m/0.9 Myr = 8 m/Myr

    This assumes a constant or at least average, rate that sediment accumulated on the sea floor over long time periods. It essentially assumes the environment is fairly constant such that the sediment delivered to the sea floor is constant.Since this site is on a bathymetric high then we can at least feel confident that turbidity flows are not impacting the sedimentation rate, but other "events" still could. For example – could sea level lower enough that there is erosion by waves on the ridge?

    b. How much time does 450 m of sediment on the Lomonosov Ridge represent, given that sedimentation rate?

    Time = 450m / 8m per myr = 56 myr

    c. Calculate the percent of Cenozoic time that the 450 m of sediment on the Lomonosov Ridge represents. Compare this to your answer to 7b – would this be a significant improvement in Cenozoic sediment recovery from the Arctic?

    *56 myr / 66myr * 100 = 85% of Cenozoic time*

    Yes, compared to the 1.4% of Cenozoic time that the piston cores recovered.

Part 4 – How to drill there?

Drilling a long core into the sea floor of the Arctic Ocean poses some unique challenges; several of which you probably identified back in Question 3.

18. Watch the 5 minute video on the technical approach to drilling in the Arctic by going to: *http://recordings.wun.ac.uk/conf/nwo/oceandrilling2006* then selecting "Drilling the Arctic." How was the challenge of staying on site (or "station") long enough to drill a long core solved?

    This was met by having two icebreakers accompany the drill ship. Their job was to break up the sea ice into small enough bits so that the drill ship could stay on station and drill.

Part 5 – Arctic Coring Expedition: revising what we know

The scientific and logistical arguments were compelling and the Arctic Coring Expedition (ACEX) was approved and funded by the Integrated Ocean Drilling Program, an international consortium of marine research institutions and universities. The expedition took place from August 7 to September 15, 2004. The drill ship, the *Vidar Viking*, was accompanied by two ice-breakers, the *Oden* and *Sovetskiy Soyuz*. A 428-m–long composite sedimentary section was constructed by combining cores recovered from four holes located <15 km apart along the seismic line (Fig. 6). The cores were transported to the Bremen Core Repository, where in November 2004 the scientific team reconvened to split, describe, and sample them.

19. The vertical axis on Figure 7 below represents down-core composite depth for the ACEX cores. To the right of the figure is a stratigraphic column indicating the major boundaries between geologic units in the suite of cores. The horizontal axis on the figure is sediment age. This is inferred using a combination of paleontological (dinocysts), paleomagnetic (Chron boundaries), and isotopic age-depth data, as indicated by the key in the figure. Using the data in this "age-model" answer the following:

    a. How old is the oldest sediment recovered?

    ~80 million yrs old

    b. Where are there time gaps, or hiatuses, in the sedimentary record? How long are these hiatuses?

    The hiatuses are marked in instructor version Fig 7 but are blocked out of the student version.

    There are three:

    120 mcd (9.4-11.6 Ma), ~2 million yrs long

    198 mcd (18.2-44.5 Ma), ~26 million yrs long

    404 mcd, hard to know – there were several cores with no recovery below this depth then a bit of Cretaceous sediment was recovered.

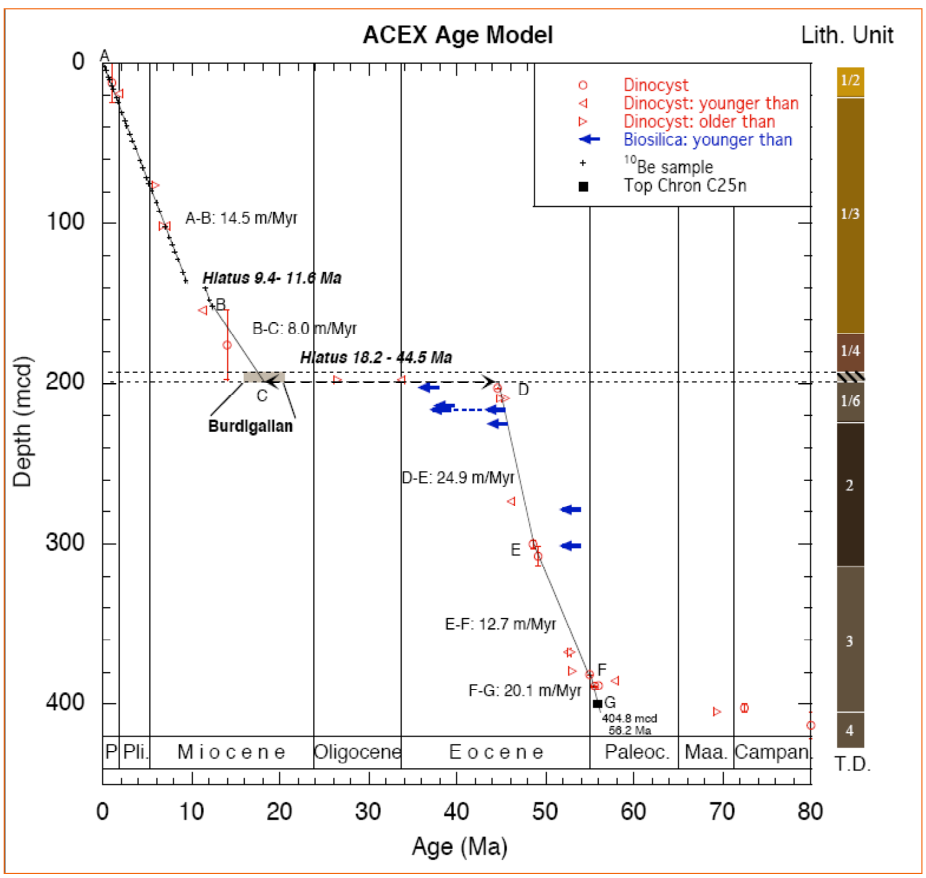
    c. How do the actual average sedimentation rates compare with the predicted sedimentation rates (question 17a)?

    Sedimentation rates are shown in Fig 7 of the instructor version, but are blocked out of the student versions. These can be calculated using the depth range of segments and the age range. Sedimentation rate is essentially the slope of the line segments.

    Sedimentation rates are:14.5 m/Myr in the late Miocene- Pleistocene (A-B)

    8 m/My in the Miocene (B-C)

Figure 7. ACEX age model from Backman et al., 2008.



25 m/Myr in the middle Eocene (D-E)

12.7 m/Myr in the early-middle Eocene (E-F)

20 m/Myr in the Paleocene (F-G)

Considering the predicted sedimentation rates were based on only recent (mid-Pleistocene and younger) data they were a good but overall low prediction. One of the previous general conclusions about the Arctic Ocean was that it was a sediment starved basin—thus low sedimentation rates. This conclusion was in part fed by poor age control on many of the piston core records. The ACEX sedimentary sequence from the Lomonosov Ridge demonstrated that the central Arctic it is NOT sediment starved, but has relatively high sedimentation rates.

d. Revisit Figure 3 and draw a line along the vertical axis showing the geologic time intervals that Arctic coring has recovered. Do you expect these new Arctic cores to be able to contribute data on the Cenozoic Greenhouse to Icehouse transition of the Northern Hemisphere? Explain.

The line should extend from 0-10 Ma, then again from 12-18 Ma, and again from 45-56 Ma. Breaks in the line are due to hiatuses in the record. A dashed lined into the Cretaceous would be an appropriate way to represent the recovery of pre-Cenozoic sediments.

These cores should contain evidence of the Greenhouse to Icehouse transition, but the Oligocene hiatus hinders complete reconstruction.

e. A hiatus in a sedimentary sequence is usually caused by erosion of the sedimentary record or non-deposition. Consider the location, modern water depth, among other factors and propose a hypothesis for what may have caused the large hiatus identified in the ACEX cores. What evidence would you look for to support your hypothesis?

This is really an open ended question and one that scientists are considering now themselves. One possibility is that the Lomonosov Ridge was emergent or at least in very shallow water during some or all of the time of the hiatus, thus resulting in an erosive environment rather than a depositional environment. This could occur by a lowering of sea level and/or uplift of the ridge. Evidence for shallow water or emergent conditions may include shallow water sedimentary structures in the core above the hiatus.

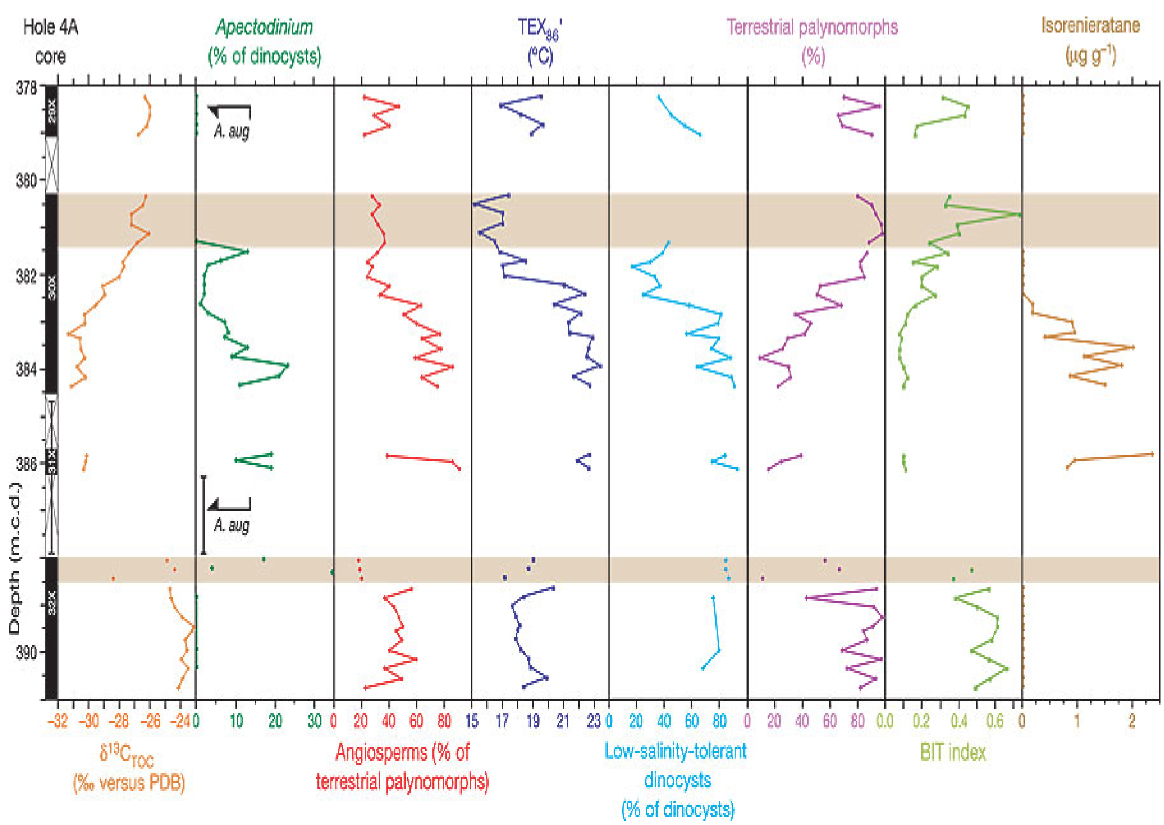
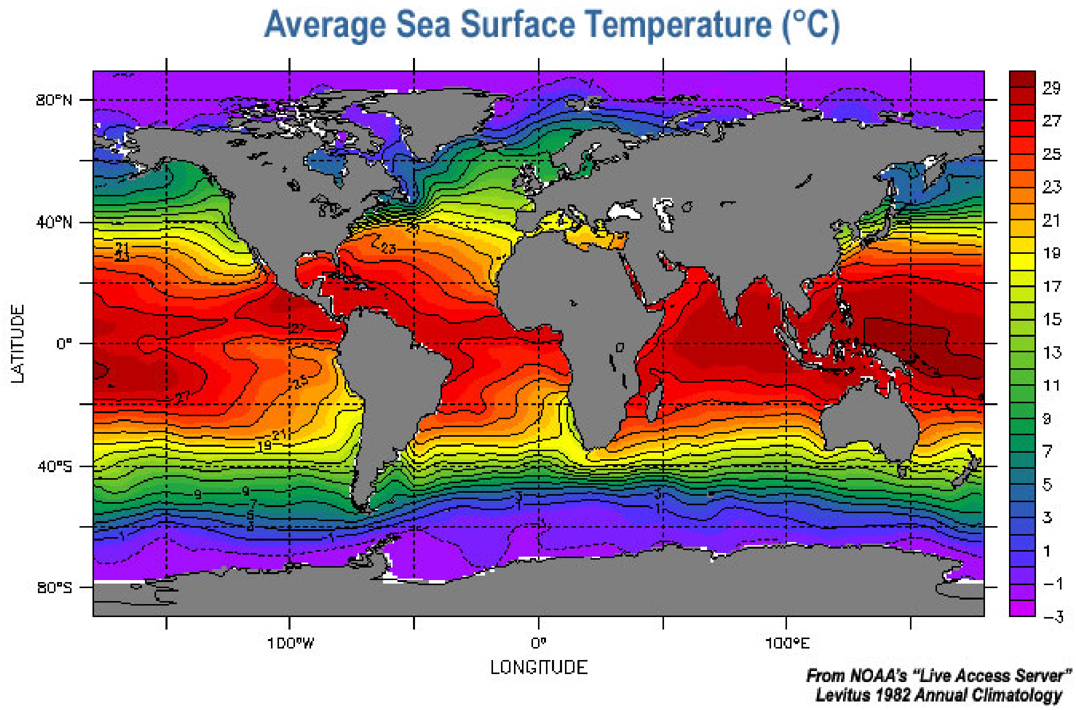


Figure 8. Core 31X was plotted 100 cm lower than m.c.d. for illustration purposes. Error bars connected to Core 31X in the recovery column indicate the uncertainty of its stratigraphic position (see Supplementary Information). Orange bars indicate intervals affected by drilling disturbance. Stable carbon isotopes are expressed relative to the PeeDee Belemnite standard. From (Sluijs et al. 2006): http://www.nature.com/nature/journal/v441/n7093/abs/nature04668.html

Figure 9. Sea surfact temperature (SST) map. From: http://aquarius.nasa.gov/images/global_sst_map.jpg



The ACEX cores recovered sediments deposited during the global Greenhouse World, as well as sediments deposited during the global Icehouse World. Let's look at research results from two different studies of early Cenozoic ACEX sediments:

The warmest episode of the Cenozoic Greenhouse World was the Paleocene-Eocene Thermal Maximum (PETM; see Fig. 3), ~55 million years ago. The PETM was a brief period of extreme widespread warmth that was associated with a large transfer of greenhouse gases to the atmosphere. The ACEX coring recovered the first data on the PETM for the Arctic region. Part of that data is shown in Figure 8 below by Appy Sluijs and others (2006). The PETM was identified in the top of core 32X up through the bottom of core 29X. In the ACEX cores it is marked by isotopic changes in carbon-isotopes, abundances of microfossil groups (e.g., dinocysts & angiosperm spores), as well as geochemical changes in lipids from marine Archea, prokaryotic single-celled microfossils. The geochemical changes measured in Archea have been used to infer past sea surface temperatures. This is called the TEX-86 technique.

20. Based on the TEX-86 data shown in Figure 8 below what was the inferred central Arctic sea surface temperature just before the PETM? What was it during the PETM? Convert these Celsius temperatures to degrees Fahrenheit given: degrees F = (9/5 x degrees C) +32

    Before the PETM = 18˚C, 64˚F

    Maximum during the PETM = 23˚C, 73˚F

21. Could ice exist at this temperature? Examine the modern sea surface temperature (SST) map (Fig. 9) above, which is produced by NOAA. How does the maximum PETM SST compare to the the modern SST of the Arctic? How does it compare to the modern SST of ocean waters off the closest coast to where you live?

    While these temperature estimates are annual averages, they most likey represent the conditions at the time when the Archea microorganism were most productive—early summer. These temperatures are too warm for ice to exist.

    According to Figure 9, modern (1982) average SST for the Arctic is between 1 and -3˚C (34-27˚F). These temperatures are increasing due to global warming today. In 2007 SST in parts of the Arctic Ocean reach +4˚C, a 5˚C increase from the average (Steele et al., 2008).

    The modern average SST (1982) off of Virginia is 23˚C. This is the same as the Arctic surface temperature during the PETM. It may be surprising to students to learn how warm the central Arctic was in the past.

The other ACEX research data set we will look at is on ice-rafted debris (IRD) results. Recall from Part 2 that IRD records are one of the primary means of documenting the existance of floating ice in the geologic past. Note that in the Arctic this could be icebergs or it could be sea ice, both of which can transport anomalously coarse-grained terrestrial sediment to offshore marine settings. Examine

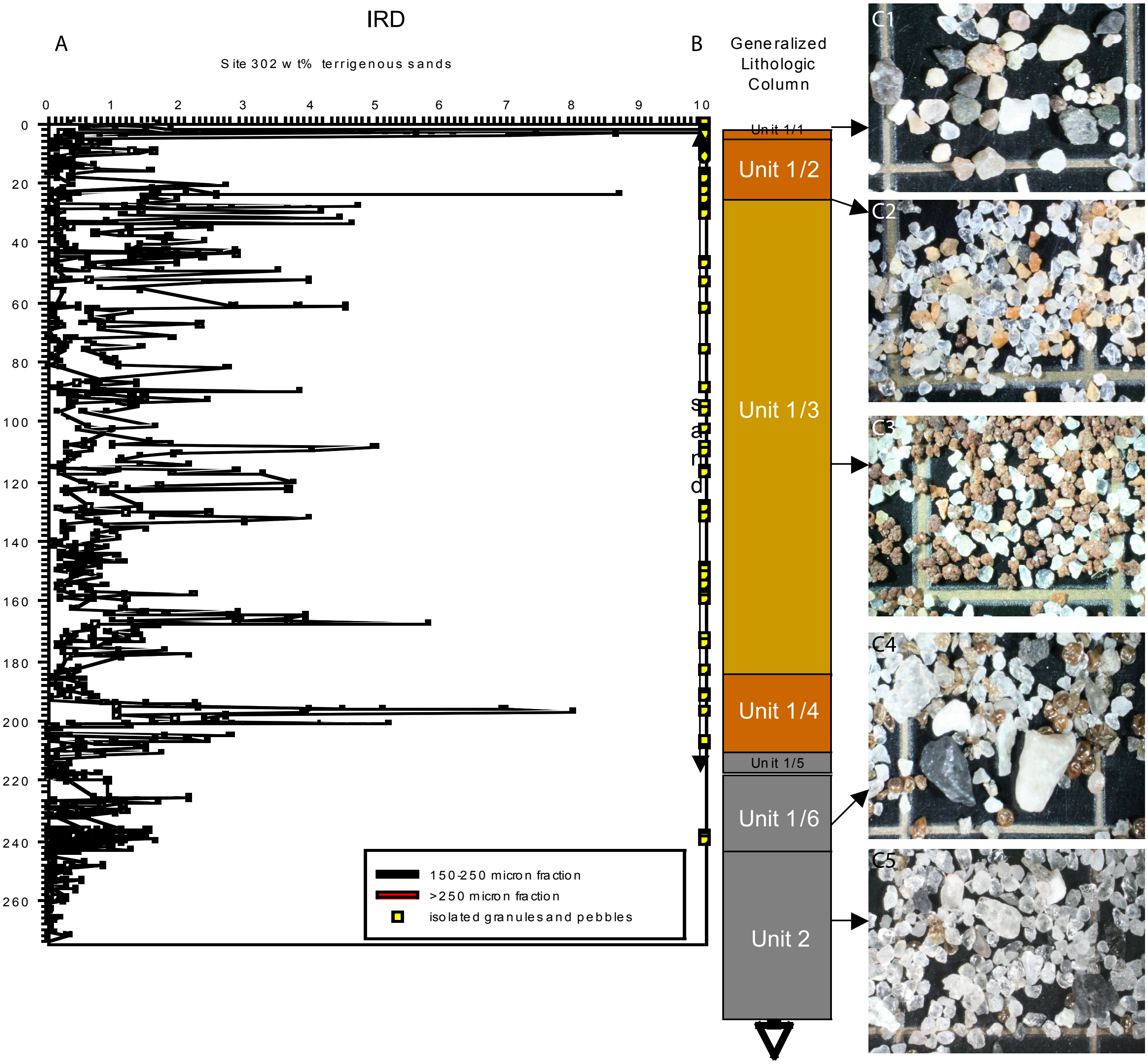


Figure 10.

A. Weight percent abundance of terrigenous sands (= IRD) in the >250 µm (red), and 150-250 µm (black) size fractions, and isolated granules and pebbles (yellow) [from Backman et al., 2006] vs. meters composite depth (mcd) [from O'Regan, et al., 2008].

B. Generalized lithologic column for IOPD 302 0-270 r-mcd [modified from Backman et al., 2006].

C. Representative samples shown are from the >250 micron fraction.C1 = sample 302-4C-1H-1-16 cm (0.16 mcd; 0.01 Ma); C2 = sample 302-2A-5X-1-106 cm (21.4 mcd; 1.63 Ma); C3 = sample 302-2A-24X-3-82 cm (110.02 mcd; 8.4 Ma); C4 = sample 302-2A-49X-4-16 cm (215.64 mcd; 44.29 Ma); sample C5 = sample 302-2A-55X-4-120 cm (240.39 mcd, 45.4 Ma). The grid scale in each photomicrograph is 0.5 cm.

Figure 10 below from St. John (2008) which shows the ACEX IRD record, along with the same stratigraphic column you saw in the ACEX age-model. Also shown are representative photos of the coarse sand in the ACEX cores from different intervals in the cores.

22. Refer to the ACEX age-model (Fig. 7), and draw two horizontal lines on the IRD graph (Fig. 10) to indicate where the two major hiatuses are in the ACEX sedimentary record. What is the age of the deepest pebbles and terrigenous sand peaks? What does this new data indicate about the timing of the Arctic's transition from a Greenhouse world to an Icehouse World (you may want to refer to Fig. 3)?

    Horizontal lines marking the two hiatuses should be drawn in at 120 and 198 mcd.

    The deepest pebble co-occurs with an increase in terrigenous sand at ~245 mcd. Using the age model (see Fig. 9) this equates to ~46 Ma.

    From that point on there appears to be both pebbles (dropstones) and terrigenous sand – both evidence of ice rafting out to the central Arctic from coastal settings where terrigenous debris was entrained in the ice. Since we do not know if it was icebergs or sea ice transporting the debris, we can't assume that the IRD means there were Arctic glaciers 46 million years ago, but we also cannot rule that out. It had to be cold enough for ice at sea level to form in at least the winter months and be transported to the central Arctic by surface currents. This means that the Arctic started to transition into an Icehouse world much earlier than previously recognized (think back to Fig. 3) and much closer to the time when Antarctica began to transition into an Icehouse world. The bi-polar disconnect in timing starts to go away when this new data is taken into account. Given the extreme warmth of the Arctic during the PETM (55 Ma) and the start of ice conditions at 46 Ma, the early and middle Eocene must have been a time of great environmental change in the Arctic. This may also be true for the late Eocene and Oligocene in the Arctic as it was in the Antarctic – but this cannot be addressed with the ACEX cores because of the hiatus at 198 mcd.

23. In addition to this new IRD data from the Arctic, Eldrett and others (2007) examined cores from Site 913 in the Greenland Sea (75°29'N, 6°57.'E) and have shown that these cores contain stratigraphically intact ice-rafted debris deposited between 38 and 30 myr, derived from the central east Greenland margin. Add this IRD-onset data from the central Arctic and from the Greenland Sea to Figure 5 - the map of IRD-onset/intensification back in Part 2. Does this new data support your interpretation of geographic trends of the timing of ice-onset (Question 12)? If not, how would you revise your interpretation?

    These new data on the earliest IRD from the Greenland Sea and the central Arctic support the trend described in Question 12 - that ice formation began earlier at higher latitudes.

24. Share and discuss your interpretations of the ACEX research results on the PETM and Cenozoic IRD record. As a group make a list of scientific questions on Arctic and/or Cenozoic geology that remain, or new questions that examination of this new data spurs. List them here:

    This is an opportunity to pull the different working groups together and discuss the results and conclusions from the data provided in Part 5 (if you have not already done so). The new data from ACEX (and ODP Site 913) fill in many gaps in reconstructing Cenozoic climate evolution of the Northern Hemisphere high latitudes, but as is common in science, new knowledge also bring with it new questions. Some of those include:

    - *What were the environmental and tectonic conditions to produce the 26 myr hiatus?*
    - *What environmental changes were occurring in the Arctic as Antarctica experienced the early Oligocene glacial expansion?*
    - *What were the climate drivers that pushed both poles into an Icehouse world?*
    - *How much regional variability was there in the Arctic during the PETM and during the transition to Icehouse conditions?*

The second phase of Arctic drilling is now in its planning stages. There will also be a planning meeting of scientist interested in Arctic drilling in November 2008. This team of scientists will take into account previous Arctic drilling results, including those from ACEX, new seismic survey data, and define key scientific questions to make the base scientific and logistical case for future Arctic drilling. A pre-proposal on Arctic drilling can be downloaded at: *http://www.iodp.org/700/ by selecting proposal #708*. Stay tuned!

Extension: Lomonosov Ridge & Plate Tectonics

1. Re-examine the Arctic Ocean bathymetric map (Fig. 2 in Part 1). Think about what you know of plate tectonics theory and propose a hypothesis for the origin of the Lomonosov Ridge. How could you test your hypothesis?

   Some students may propose that the Lomonosov Ridge is a spreading center, marking a divergent plate boundary. Other students may recognize that the Gakkel Ridge is connected to the Mid-Atlantic Ridge and therefore propose that the Lomonosov ridge is a submerged continental fragment rifted from the Eurasian margin. To test either of these possibilities magnetic survey of the sea floor would be useful data to determine the magnetic anomaly pattern and age of the sea floor. Also cores of the basement rocks (i.e., harder rocks underlying the sediment drape) on the Lomonosov ridge would be helpful. If there is a think sediment cover and the basement rocks are basalts then it would support the Lomonosov ridge being a spreading center. If the basement rocks are not basalt, but something else that matches the geology of the rocks exposed on the Eurasian margin then it would support the Lomonosov Ridge as being a submerged continental fragment rifted from Eurasia.

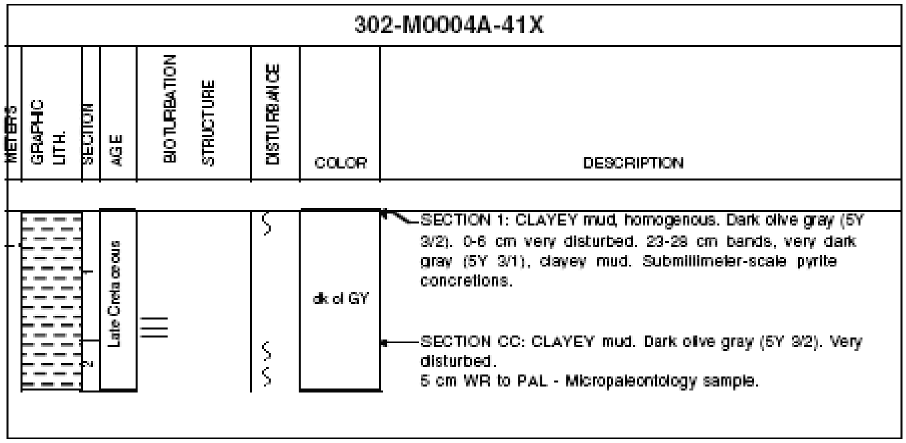


Figure 11a. Visual core description of core 302-4A-41X. From http://publications.iodp.org/proceedings/302/EXP_REPT/CORES/COR_302.PDF.

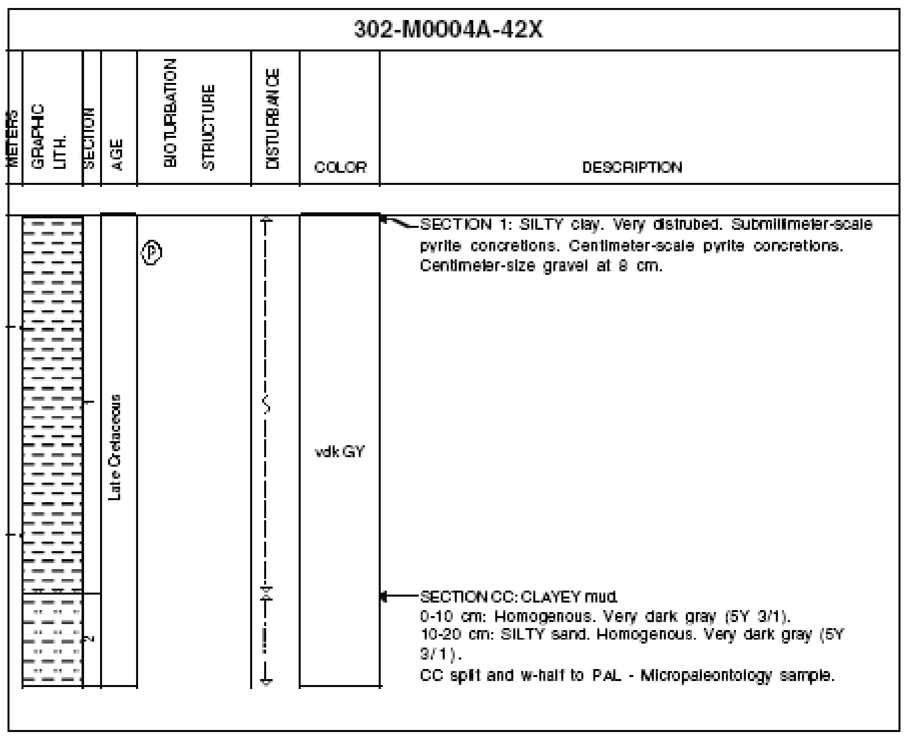


Figure 11b. Visual core description of core 302-4A-42X. From http://publications.iodp.org/proceedings/302/EXP_REPT/CORES/COR_302.PDF.

2. While the primary objective of the Arctic coring expedition was to recover core to reconstruct a paleoceanographic history of the central Arctic Ocean, a secondary objective was to sample the bedrock under the sediment cover to decipher the tectonic history of the Lomonosov Ridge. What would you expect the bedrock to be if the Lomonosov Ridge is a divergent plate boundary?

   If it were a spreading center there should be a thin sediment cover, with basaltic basement rock.

3. Examine the visual core descriptions of the pre-Cenozoic bedrock given in Figure 11 below. Does this data suggest the Lomonosov Ridge is a divergent plate margin? Explain.

   Note that core photos should be included here too but these were not available for download at the time of exercise production. Based on the visual core descriptions given here the Cretaceous units are sedimentary, not igneous basalt. There were several cores with no recovery directly above this Cretaceous unit. This geology of the cores does not support a hypothesis that the Lomonosov Ridge is a spreading center.

4. You might need to revise your hypothesis on the origin of the Lomonosov Ridge at this time. In doing so, take into account this information too: the Gakkel Ridge (see Fig. 2) is a divergent plate margin, recognized by Heezen and Ewing in 1961. Do you have a new hypothesis for the origin of the Lomonosov Ridge? If so, list it here:

   Some students may not need to revise their hypothesis. A reasonable hypothesis given this information would be that the Lomonosov Ridge is a submerged continental fragment rifted from the Eurasian margin.

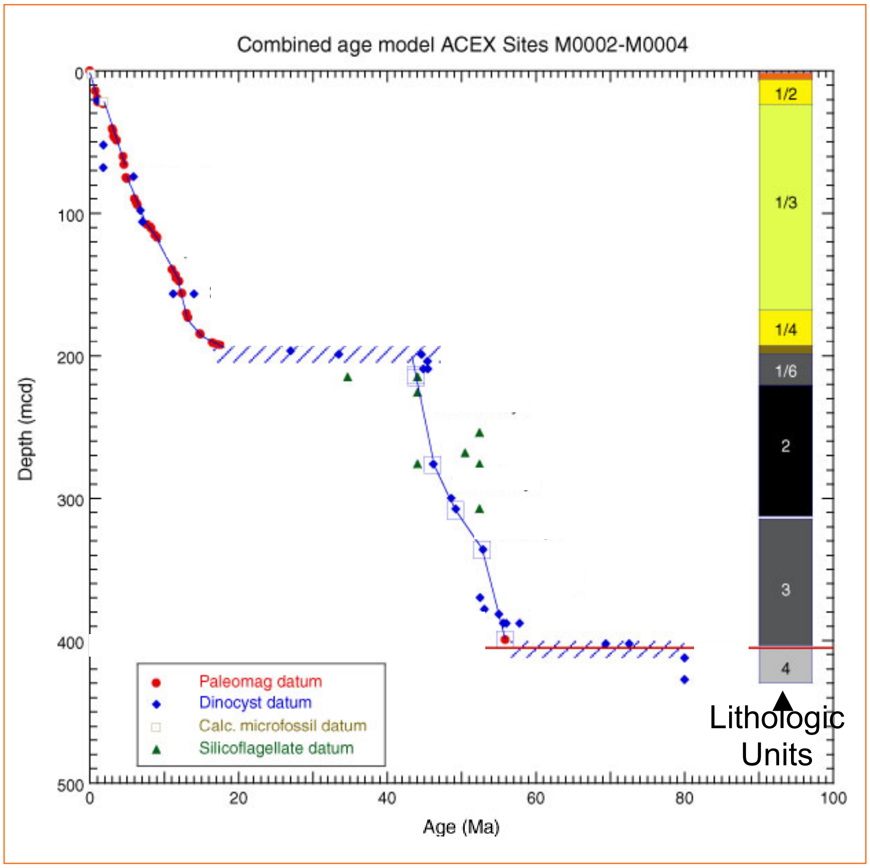


Figure 1. Age-Depth plot from the Arctic coring expedition (ACEX).

Formative Assessment

As part of the wrap up section in the student version, have students Answer the following questions:

- What did you find most interesting or helpful in the exercise?
- What was the "Sticky Science," in other words what stuck with you – what are you going to remember a few months from now?
- Does what we did model scientific practice? If so, how and if not, why not?

Summative Assessment

There are several ways the instructor can assess student learning after completion of this exercise. For example, students should be able to answer the following questions after completing this exercise:

The Arctic Coring Expedition (ACEX) was the first drilling expedition to recover deep cores from the high Arctic (only 250 km from the North Pole!). Microfossil occurrences and the record of change in Earth's magnetic field are very useful for establishing the age of ancient sediments. A plot of depth in the core versus age of the sediment provides a useful record of sedimentation history in this area. Note that depth is in meters composite depth (mcd), and changes in sediment character (lithologic units) is summarized on the right side of the plot (Fig. 1). Examine this age-depth plot to answer questions 1 to 6.

1. Which lithologic unit, 1/4 or 1/3, reflects a higher rate of sedimentation? ______

2. Calculate the sedimentation rate between 53 and 56 million years ago in m/myr (meters per million years) and cm/yr (centimeters per year). Show your work.

   ________ m/myr ________cm/yr

3. Where on the age-depth plot is there an age break/missing sediment in the sedimentary sequence (i.e., hiatus or unconformity) cored at this site?
   a. There are no gaps in the sediment record
   b. At 100 mcd
   c. At 200 mcd
   d. At 270 mcd

4. Approximately how much time is "missing" in this break/unconformity?
   a. No time "missing"
   b. 10 million years
   c. 20 million years
   d. 40 million years

5. Using a complete sentence, propose a hypothesis for how a break in sediment record could occur in the ACEX cores. A map of the ACEX coring location is shown below (Fig. 2).

6. What reason might there be for including more than one type of age control data (e.g., paleomagnetic stratigraphy, dinocyst biostratigraphy) for constructing this plot?
   a. Multiple lines of evidence reduce the uncertainty in the interpretation
   b. All were used to see which one created the best fit line
   c. The scientists couldn't agree which data set they should use
   d. All of the above
7. Based on the global $\delta^{18}O$ record (Fig. 3) what is the general trend of climate change since the start of the Paleocene?
   a. Gradual warming
   b. Gradual cooling
   c. Abrupt warming
   d. Abrupt cooling
   e. Gradual trends punctuated by abrupt events of warming or cooling
8. Give the ages of two abrupt changes in climate you can identify on Figure 3.

   ______________ ______________

Read the following research abstract from the peer-reviewed scientific journal *Nature* on the Arctic record of the Paleocene/Eocene Thermal Maximum (PETM) to answer questions 9 to 12.

Nature 441, 610-613 (1 June 2006) | doi:10.1038/nature04668; Sluijs et al., 2006

Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum

The Palaeocene/Eocene thermal maximum, 55 million years ago, was a brief period of widespread, extreme climatic warming that was associated with massive atmospheric greenhouse gas input. Although aspects of the resulting environmental changes are well documented at low latitudes, no data were available to quantify simultaneous changes in the Arctic region. Here we identify the Palaeocene/Eocene thermal maximum in a marine sedimentary sequence obtained during the Arctic Coring Expedition. We show that sea surface temperatures near the North Pole increased from 18°C to over 23°C during this event. Such warm values imply the absence of ice and thus exclude the influence of ice-albedo feedbacks on this Arctic warming. At the same time, sea level rose while anoxic and euxinic conditions developed in the ocean's bottom waters and photic zone, respectively. In-

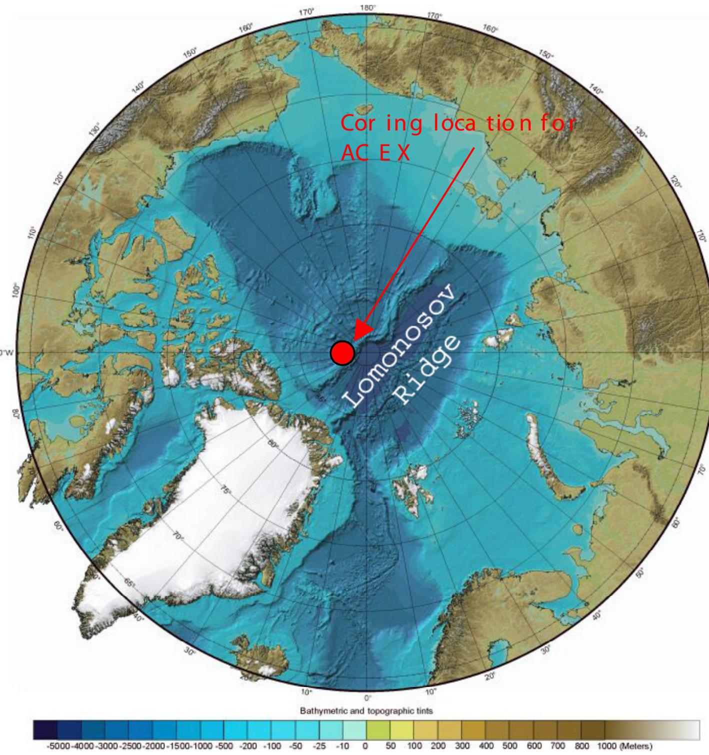


Figure 2. Map showing the Arctic coring expedition drill location on the Lomonosov Ridge. Shading indicates depth: browns are exposed land, light blue is shallow seafloor, deep blue is deep sea floor.

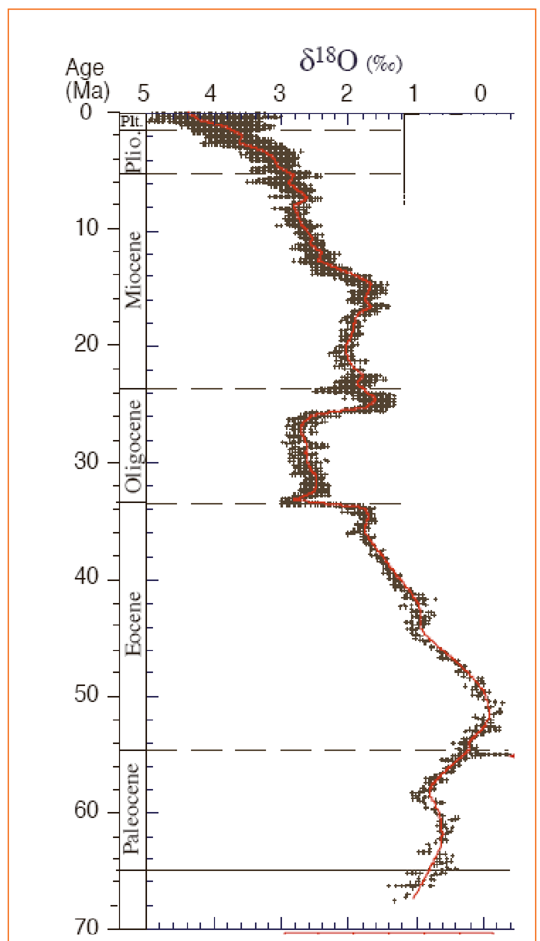


Figure 3. Composite marine benthic foraminifera $\delta^{18}O$ record.

creasing temperature and sea level match expectations based on palaeoclimate model simulations, but the absolute polar temperatures that we derive before, during and after the event are more than 10°C warmer than those model-predicted. This suggests that higher-than-modern greenhouse gas concentrations must have operated in conjunction with other feedback mechanisms—perhaps polar stratospheric clouds or hurricane-induced ocean mixing—to amplify early Palaeogene polar temperatures.

9. List two observations (data) used in this research study.
10. List two interpretations (hypotheses) made in this research study.
11. How warm were the Arctic Ocean surface waters during the PETM?
    a. 5˚C (41˚F)
    b. 10˚C (50˚F)
    c. 18˚C (64˚F)
    d. 23˚C (73˚F)
    e. Not enough information in abstract to determine.
12. Where do you think you would find ocean waters of this temperature today?
    a. around Antarctica
    b. near Florida
    c. near Norway
    d. in the Arctic

Resources

State of the Science

- A pre-proposal for future Arctic drilling can be downloaded at: *http://www.iodp.org/700/ by selecting proposal #708*.

Supplemental Materials

- A menu of several short videos to download on Drilling Extreme Climates, including the Arctic Coring Expedition: *http://recordings.wun.ac.uk/conf/nwo/oceandrilling2006*
- Download this five-minute video to explore the process of ocean drilling science—from proposal ideas all the way to reconstructing Earth's past climate history: *http://www.oceanleadership.org/learning/materials/multimedia*
- To read a paper on the technical challenges and acomplishments of drilling a long core in the Arctic go to: *http://publications.iodp.org/proceedings/302/EXP_REPT/CHAPTERS/302_106.PDF*
- You can read the actual scientific prospectus for the Arctic Drilling Expedition at: *http://publications.iodp.org/scientific_prospectus/302/index.html*. This was the document that articulated the scientific arguments and logistical plan for the coring expedition which was successfully funded and executed.
- To learn more about piston cores go to: *http://oceanworld.tamu.edu/students/forams/forams_piston_coring.htm*

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Acknowledgements

This activity was developed with funding from NSF award number 0737335.