Deep Earth Academy
CONSORTIUM FOR OCEAN LEADERSHIP

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

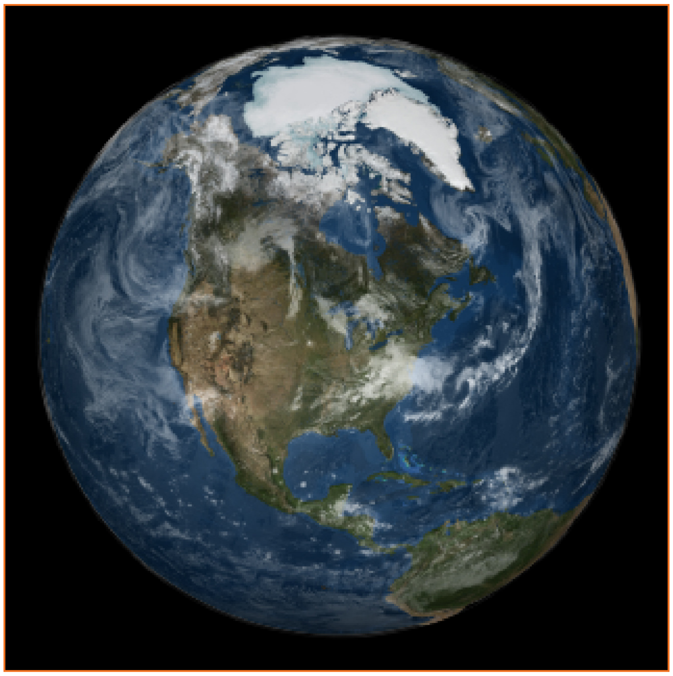
> ***Literally as well as metaphorically, the man accustomed to inverting lenses has undergone a revolutionary transformation of vision.***
>
> Thomas Kuhn (1922-1996)

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.

Activity by: Mark Leckie (mleckie@geo.umass.edu) and Kristen St. John (stjohnke@jmu.edu)

Student Activity



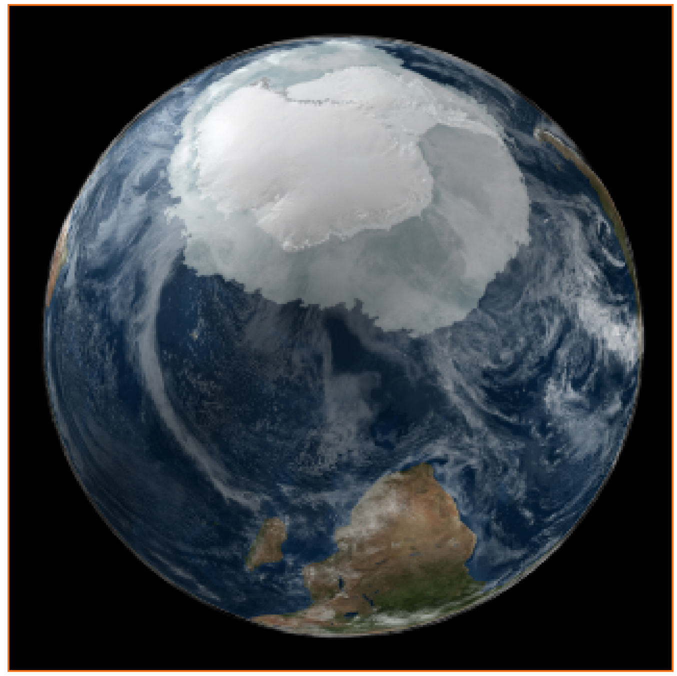


Figure 1. These images show polar views of the Earth on September 21, 2005, the date at which the sea ice was at its minimum extent in the Northern Hemisphere. From: http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003402/index.html.

Initial Inquiry

1. How are the North and South Polar regions (Fig 1.) similar? How are they different?
2. Predict how sediment cores retrieved from the Arctic Ocean seafloor could be used to infer past climate.
3. Make a list of what you think might be unique challenges to coring into the sea floor in the Arctic Ocean.

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.

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).
5. Describe the distribution of the coring locations in terms of geography and water depth.
6. What is the maximum sub-sea floor depth reached for the cores listed in Table 1?
7. Consider the history of the Arctic Ocean.
   a. What is the maximum age of the sediment in the cores listed in Table 1?
   b. 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.
   c. Do you think the Cenozoic geologic history of the Arctic Ocean is well understood? Explain.

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”

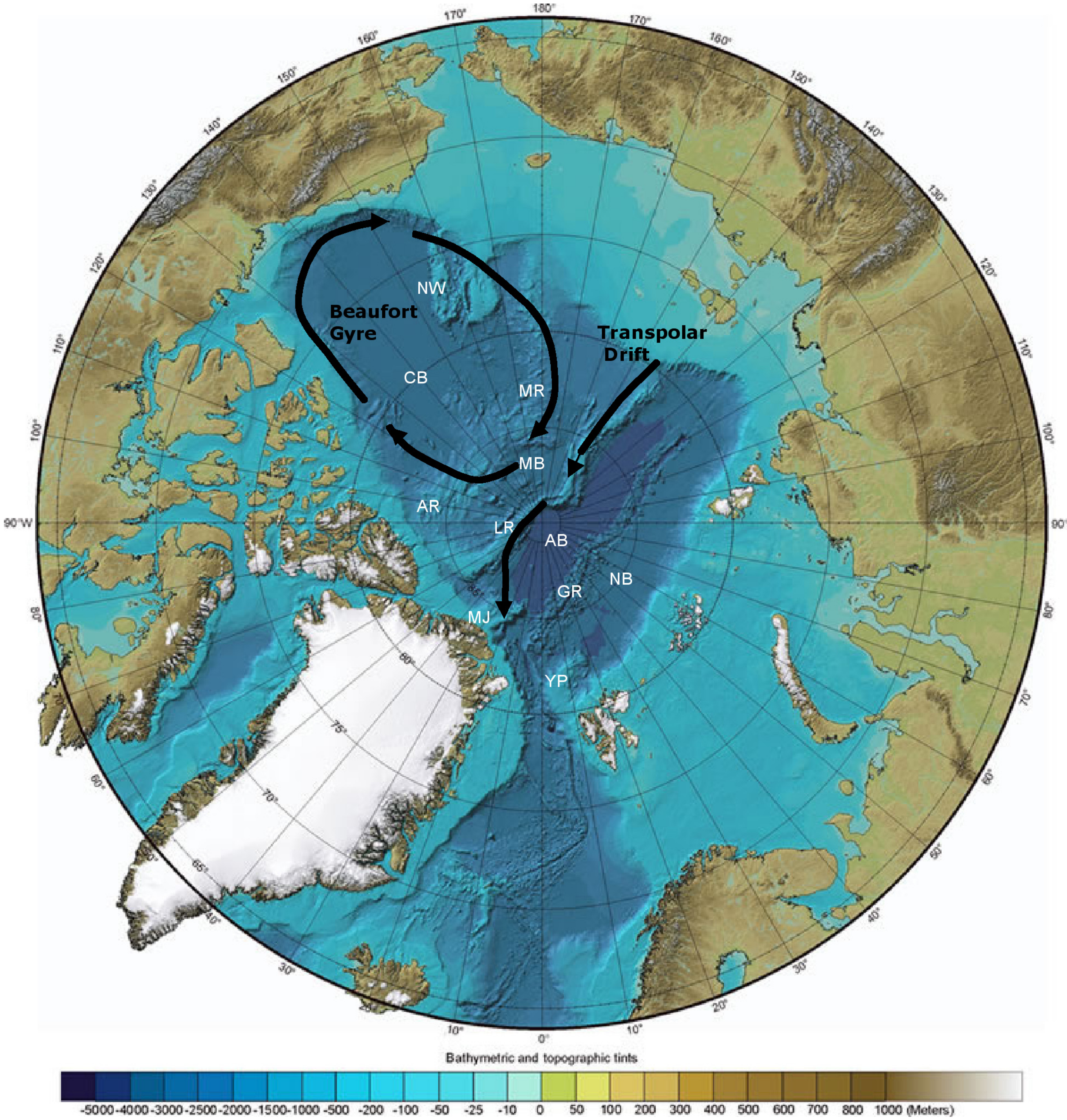


Figure 2. The International Bathymetric Chart of the Arctic Ocean, produced by a team of investigators from Canada, Denmark, Germany, Iceland, Norway, Russia, Sweden, and the USA. It is a physiographic map of the Artic Ocean as it shows the bathymetry, ridges and basins that are part of the Arctic. AB = 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.

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

(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.
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?
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?

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 terrestrial environmental change 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 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?

That was perhaps a rhetorical question. But also a profound recognition—the paradigm of understanding about Cenozoic climate change from a

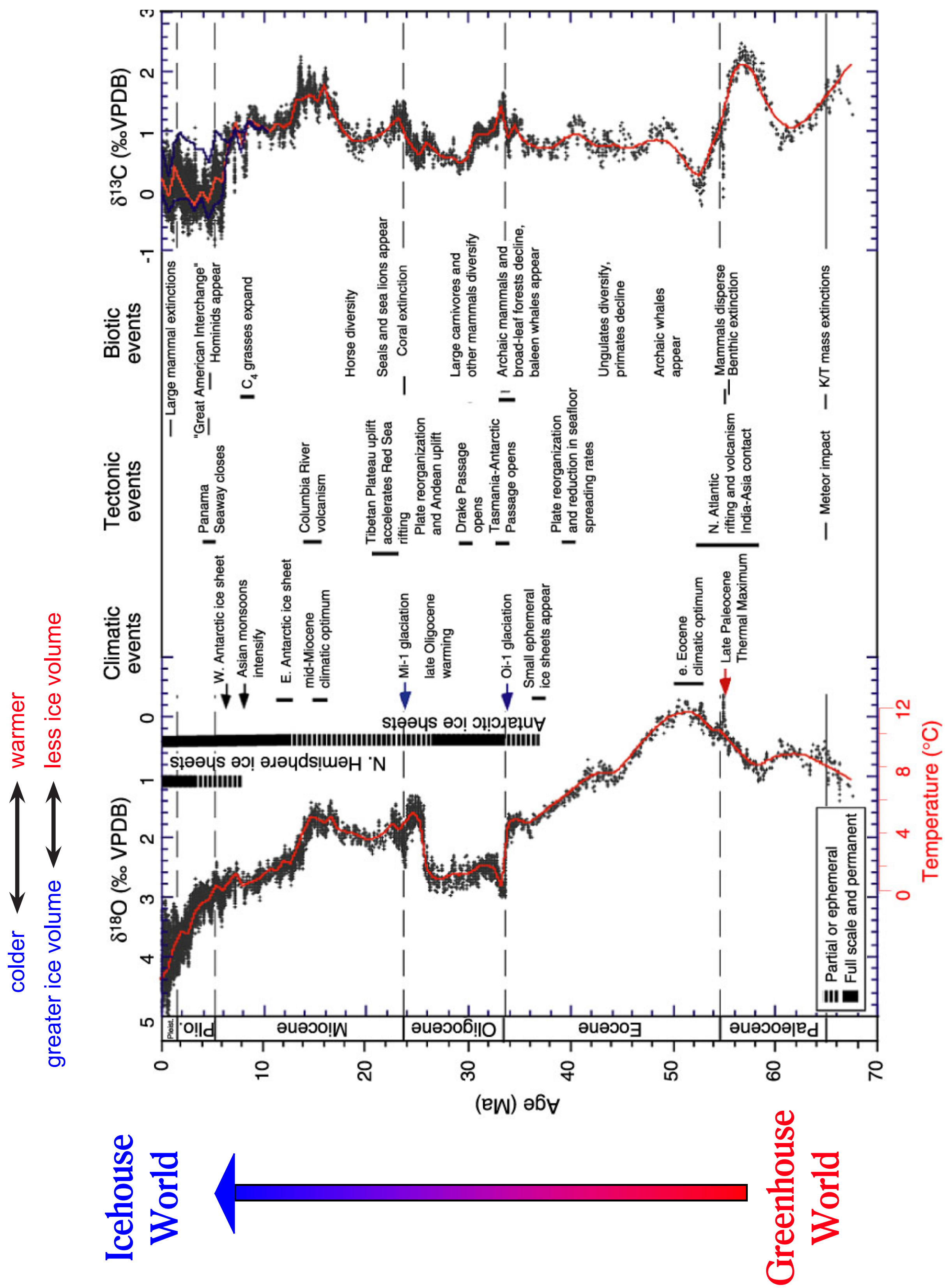


Figure 3. Cenozoic events in climate, tectonics, and biota vs. $\delta^{18}O$ and $\delta^{13}C$ in benthic foraminiferal calcite (modified from Zachos et al., 2001). VPDB = Vienna Peedee belemnite (http://odp.pangaea.de/publications/207_IR/chap_01/c1_f7.htm#6036). Antarctic ephemeral ice sheets extended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

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.

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

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?

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

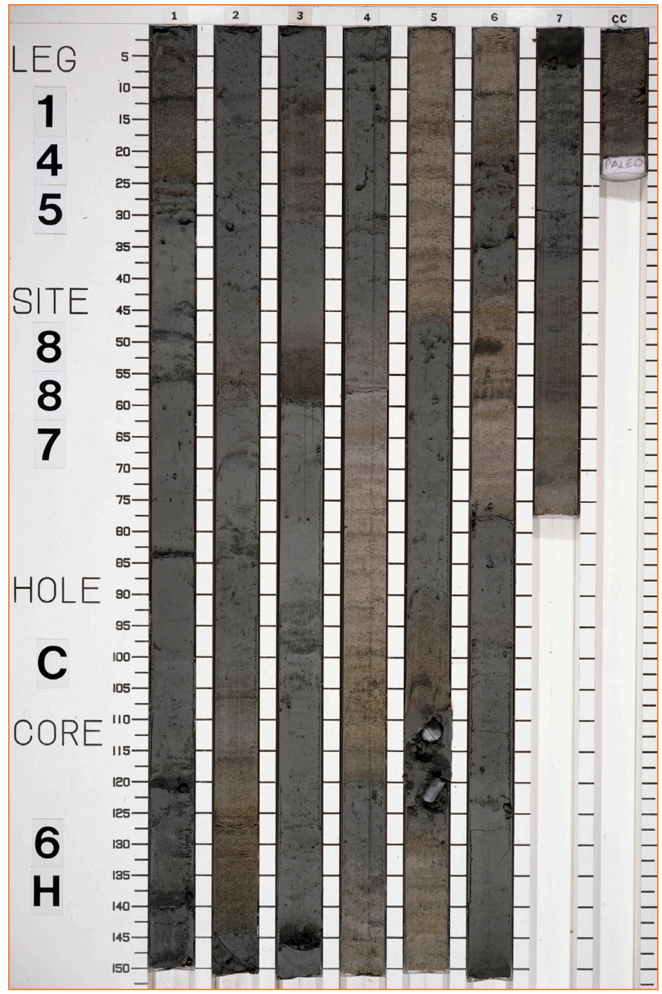


Figure 5. Age of ice-onset based on IRD records in northern North Atlantic core locations.Ages in parentheses are considered ephemeral ice, whereas no parentheses indicate onset of more permanent ice. [1]Wolf and Thiede, 1991; [2]St. John and Krissek, 2002; [3]Fronval and Jansen, 1996; [4]Wolf-Welling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

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

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 with drill site locations indicated.

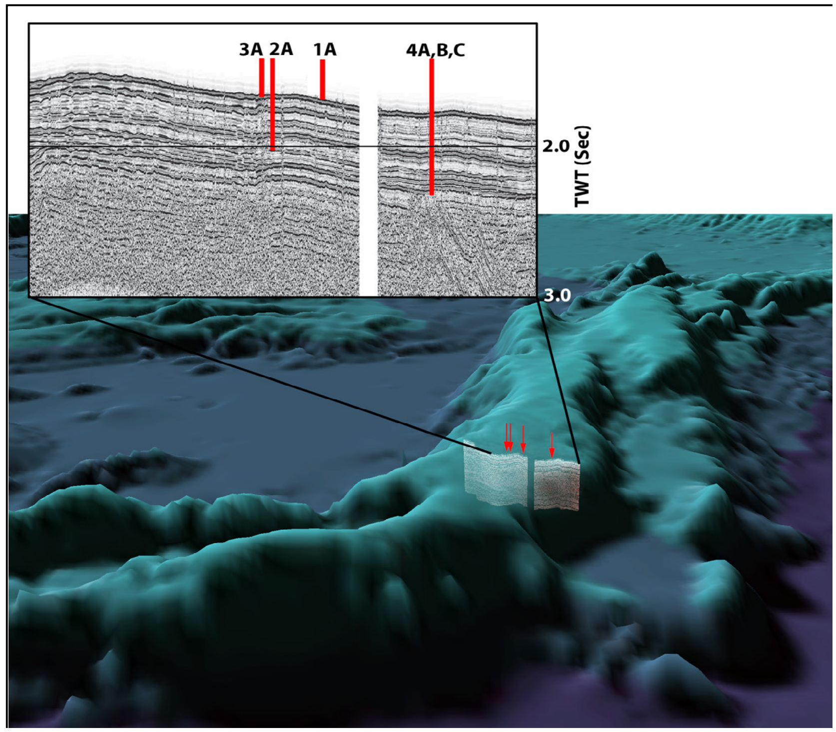


Figure 6. Reflection seismic cross-sections of Lomonosov Ridge (inset figure) from: http://www.eso.ecord.org/expeditions/302/302photo.htm. Modified from Figure 3 in the IODP Expedition 302 Scientific Prospectus: http://publications.iodp.org/scientific_prospectus/302/scip22.html.

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.)

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

    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?

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.

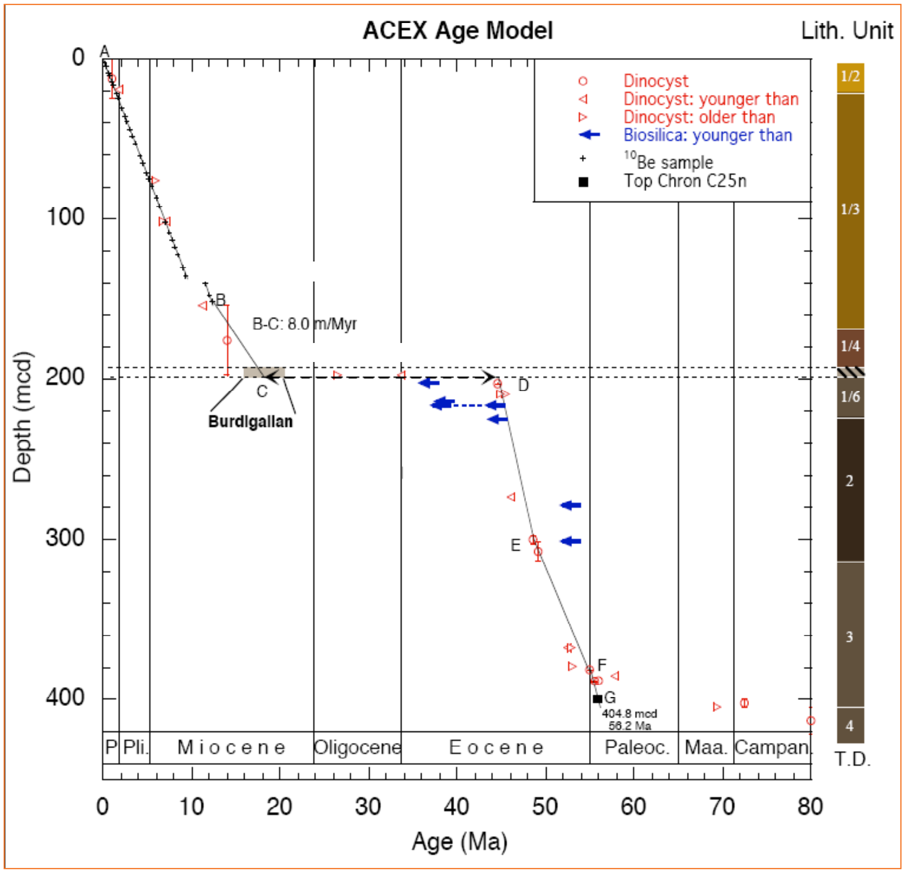
18. Watch the 5-minute video on the technical approach to drilling in the Arctic by going to: *http://recordings.wun.ac.uk/conf/nwo/oceandrilling2006* then selecting "Drilling the Arctic." How was the challenge of staying on site (or "station") long enough to drill a long core solved?

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 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?
    b. Where are there time gaps, or hiatuses, in the sedimentary record? How long are these hiatuses?
    c. How do the actual average sedimentation rates compare with the predicted sedimentation rates (question 17a)?
    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.
    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?

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



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
21. Could ice exist at this temperature? Examine the modern sea surface temperature (SST) map (Fig. 9) below, 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?

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 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.

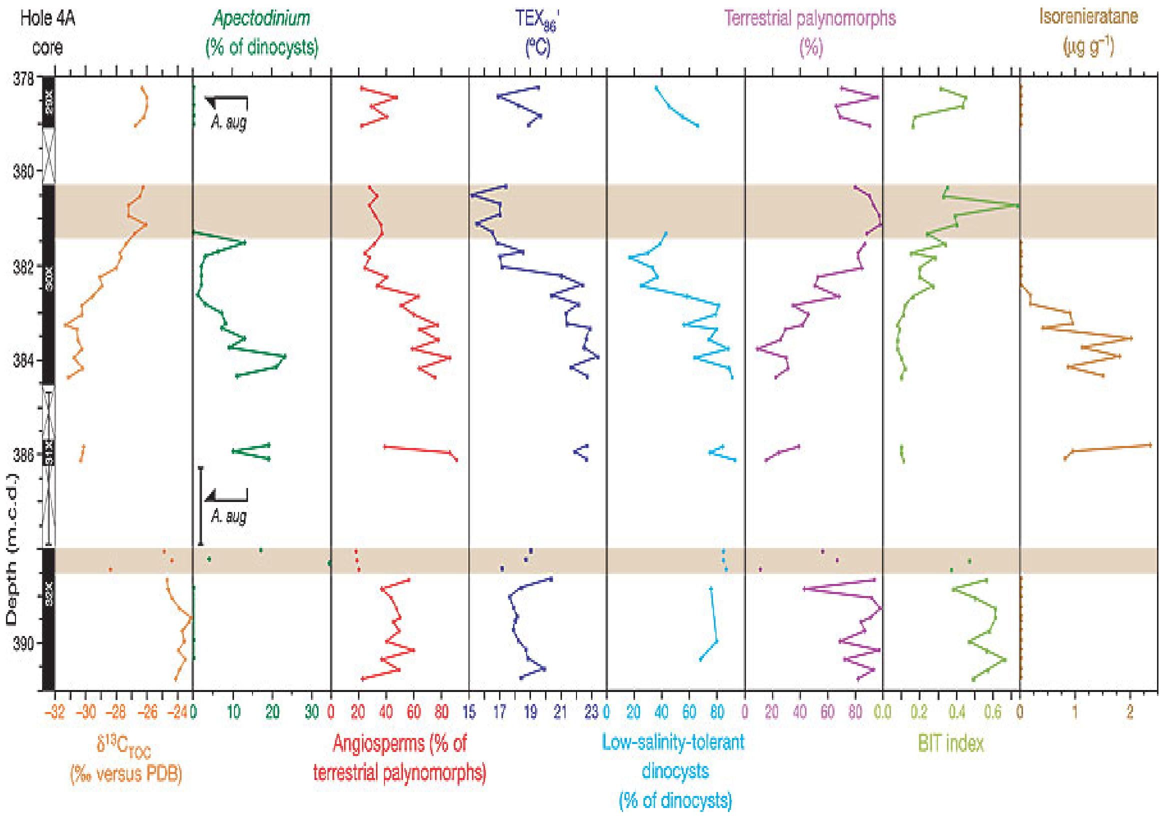
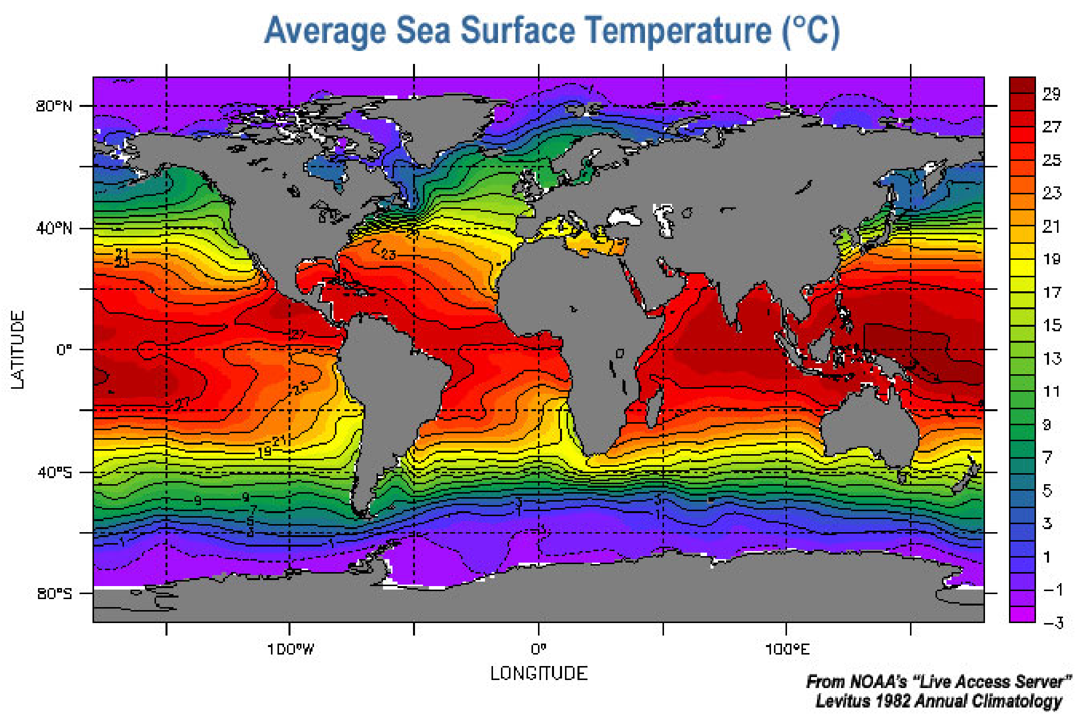


Figure 8. Core 31X was plotted 100 cm lower than m.c.d. for illustration purposes. Error bars connected to Core 31X in the recovery column indicate the uncertainty of its stratigraphic position (see Supplementary Information). Orange bars indicate intervals affected by drilling disturbance. Stable carbon 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



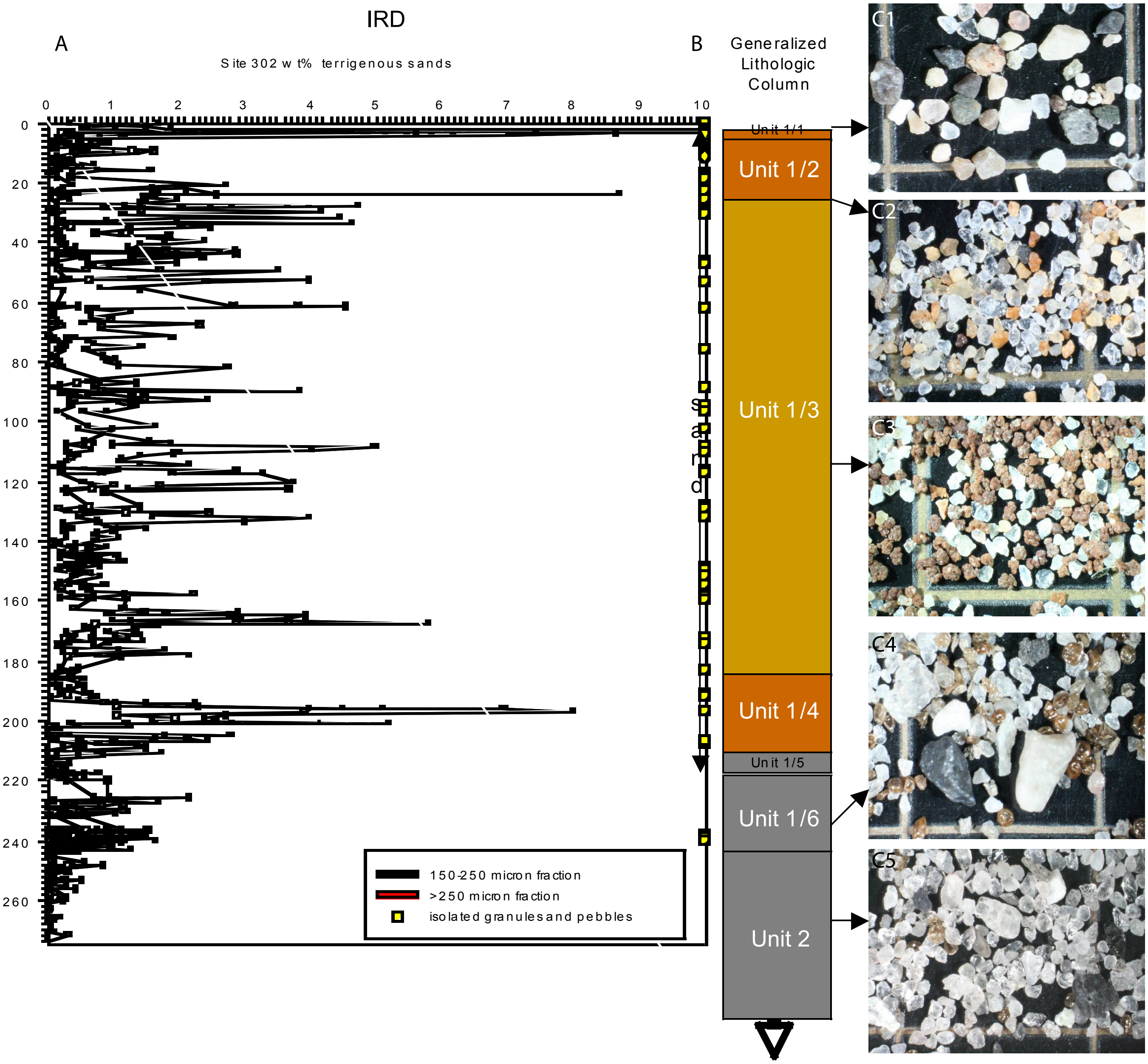


Figure 10.

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.

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)?
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?
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.

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?
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

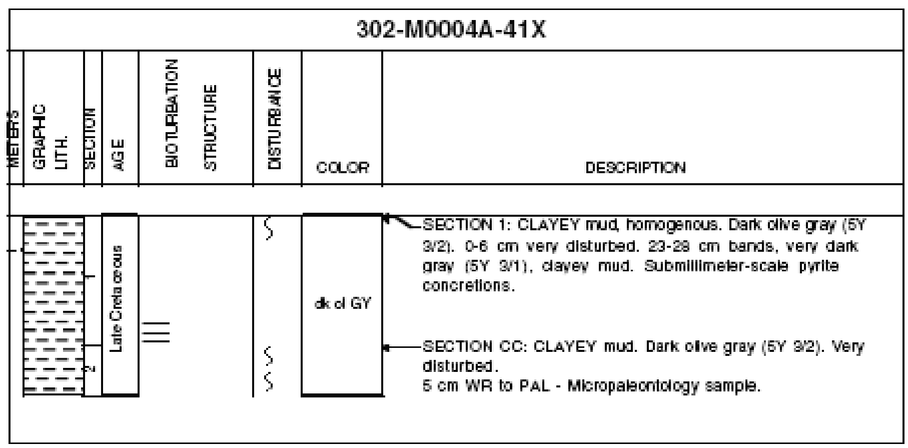


Figure 11a. Visual core description of core 302-4A-41X. From http://publications.iodp.org/proceedings/302/EXP_REPT/CORES/COR_302.PDF.

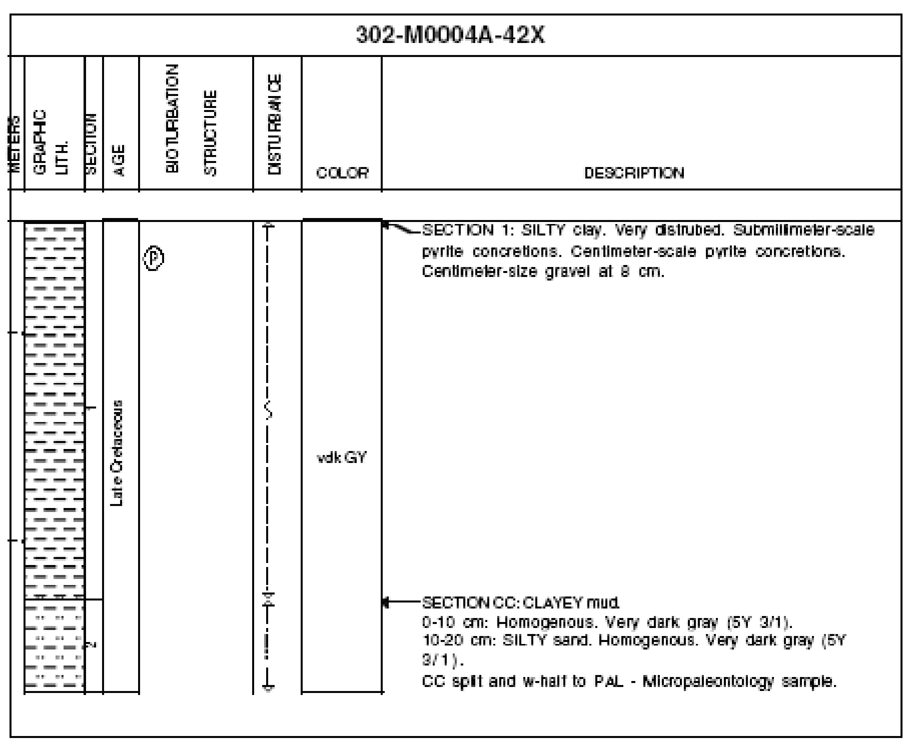


Figure 11b. Visual core description of core 302-4A-42X. From http://publications.iodp.org/proceedings/302/EXP_REPT/CORES/COR_302.PDF.

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?

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

Wrap Up

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?

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*

References

Backman, J., K.Moran, D. B. McInroy, L.Mayer, and Expedition 302 Scientists (2006), *Proc. Integrated Ocean Drill. Program*, 302, doi.10.2204/iodp.proc.302.104.2006.

Backman, J., et al. (2008), Age model and core seismic integration for the Cenozoic ACEX sediments from the Lomonosov Ridge, *Paleoceanography*,23, doi:10.1029/2007PA001476.

Clark, D.L., Kowallis, B.J., Medaris, L.G., and A.L. Deino, 2000. Orphan Arctic Ocean metasediment clasts: Local derivation of from Alpha Ridge or pre-2.6 Ma ice rafting? *Geology*, v. 28: no. 12: 1143-1146.

Eldrett, J. S., I. C. Harding, P. A.Wilson, E. Butler, and A. P. Roberts (2007), Continental ice in Greenland during the Eocene and Oligocene, *Nature*, 446, 176–179.

Fronval, T., and E. Jansen (1996), Late Neogene paleoclimates and paleoceanography in the Iceland-Norwegian Sea: evidence from the Iceland and Voring plateaus, *Proc. Ocean Drill. Program Sci. Results*, 151, 455– 468.

Futterer, D.K., 1992, ARCTIC'91: The expedition ARK-VIII/3 of R/V Polarstern in 1991: Bremerhaven, Germany, Alfred Wegener Institute for Polar and Marine Research, *Report on Polar Research*, v. 107, 267 p.

Heezen, B.C. and M. Ewing (1961). The mid-ocean ridge and its extension thorugh the Arctic basin, Pp. 622-642 in *Geology of the Arctic 1*, G. Raasch, ed. University of Toronto, Canada.

Jakobsson, M., Lovlie, R., Al-Hanbali, H., Arnold, E., Backman, J., and M. Morth, 2000. Manganese and color cycles in Arctic Ocean sediments contrain Pleistocene chronology. *Geology*, 28: 23-26.

Jakobsson, M., Lovlie, R., Arnold, E., Backman, J., Polyak, L., Knudsen, J.-O., and E. Musatov, 2001. Pleistocene stratigraphy and paleoenvironmental variations from Lomonosov Ridge sediments, central Arctic Ocean. *Global Planetary Change*, 31:1-22.

Lear, C. H., H. Elderfield, and P. A. Wilson (2000), Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite, *Science*, 287, 269– 272.

Polyak, L., Curry, W., Darby, D., Bischof, and T. Cronin, 2004. Contrasting glacial/interglacial regimes in the western Arctic Ocean as exemplified by a sedimentary record from the Mendeleev Ridge. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 203:73-93.

Poore, R.Z., Ishman, S. E., Phillips, R.L., and D.H. McNeil, 1994. *Quaternary Stratigraphy and Paleoceanography of the Canada Basin, Western Arctic Ocean. U.S., Geological Survey Bulletin 2080*.

Rea, D.K., Basov, LA., Janecek, T.R., Palmer-Julson, A., et al., 1993. *Proc. ODP, Init. Repts*., 145:College Station, TX (Ocean Drilling Program). Available from the World Wide Web: *http://www-odp.tamu.edu/publications/145_IR/145TOC.HTM*.

Ruddiman, W.F., 2008. *Earths Climate, Past and Future* (2nd edition). W.H. Freeman, New York.

Steele, M., W. Ermold, and J. Zhang (2008), Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, 35, L02614, doi:10.1029/2007GL031651.

St. John, K. (2008), Cenozoic ice-rafting history of the central Arctic Ocean: Terrigenous sands on the Lomonosov Ridge, *Paleoceanography*, 23, PA1S05, doi:10.1029/2007PA001483.

St. John, K., and L. A. Krissek (2002), The late Miocene to Pleistocene ice-rafting history of southeast Greenland, *Boreas*, 31, 28– 35.

Wolf, T. C. W., and J. Thiede (1991), History of terrigenous sedimentation during the past 10m.y. in the North Atlantic (ODP legs 104 and 105 and DSDP Leg 81), *Marine Geology*, 101, 83–102.

Wolf-Welling, T. C. W., M. Cremer, S. O'Connell, A. Winkler, and J. Thiede (1996), Cenozoic Arctic gateway paleoclimate variability: Indications from changes in coarse-fraction compositions, *Proc. Ocean Drill. Program*, 151, 515–525.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups (2001), Trends, rhythms, and aberrations in global climate 65 Ma to present, *Science*, 292, 686–693.

Acknowledgements

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