Building Core Knowledge
Reconstructing Earth History

Chapter 12 Interpreting Antarctic Sediment Cores: A Record of Dynamic Neogene Climate

FIGURE 12.1. ANDRILL Scientists discussing a part of the ANDRILL-1B core in the Core Lab, McMurdo Station Season 2006/7. Courtesy of the ANDRILL Program.

Reconstructing Earth's Climate History: Inquiry-Based Exercises for Lab and Class,
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SUMMARY

This set of investigations focuses on the **use of sedimentary facies** (lithologies interpreted to record particular depositional environments) **to interpret paleoenvironmental and paleoclimatic changes in Neogene sediment cores from the Antarctic margin**. Particular attention will be given to characteristics of settings close to the ice (ice-proximal) and far from the ice (ice-distal) in high-latitude settings. In **Part 12.1,** you will build your knowledge of polar sediment lithologies and the corresponding facies through conceptual diagrams, geological reasoning, and use of core images and core logs (a graphical summary of the sediments). In **Part 12.2,** the core log for the entire 1285 m ANDRILL 1-B core is presented. You will characterize each of the key lithostratigraphic subdivisions and use your knowledge of depositional facies to write a brief history of the Neogene climatic and environmental conditions in the Ross Sea region. In **Part 12.3,** you will use your core log reading skills and facies knowledge to evaluate patterns in the Pliocene sediments from ANDRILL 1-B. You will correlate quantitatively patterns in your dataset with cycles in insolation, influenced by changes in the Earth's orbit during the Pliocene.

Interpreting Antarctic Sediment Cores: A Record of Dynamic Neogene Climate

Part 12.1. What Sediment Facies are Common on the Antarctic Margin?

Figures 12.2 & 12.3 illustrate the variety of **depositional environments** and **sediment types** possible at the margin of a glacially influenced land mass, such as in the Ross Sea region, Antarctica. Figure 12.2 shows outlet glaciers from the East Antarctic Ice Sheet (EAIS, upper left) cutting through the rocks of the Trans Antarctic Mountains to the Ross Sea (lower right). Note that *Nothofagus* trees would have only been present during a period of temperate or warmer conditions. In Figure 12.3 the glacier (stippled) is flowing from right to left, into Antarctic Ocean waters. The different sediment lithologies are labeled (e.g., diamict).

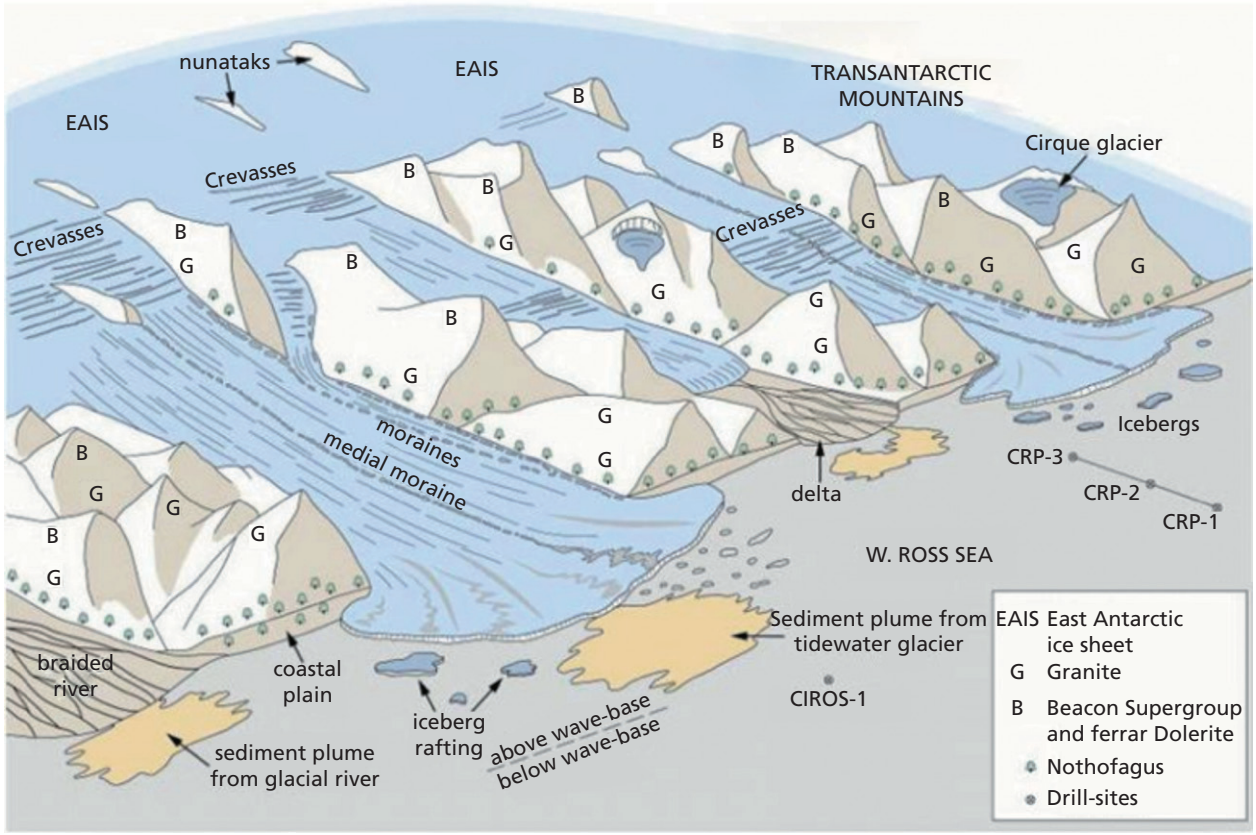

FIGURE 12.2. General paleoenvironmental setting for sedimentation along the flanks of the Trans Antarctic Mountains in late Oligocene time. From Hambrey et al., 2002. *Nothofagus* refers to southern beeches (Genus *Nothofagus*, Family Nothofagaceae) which are native to temperate oceanic to tropical regions in the southern hemisphere.

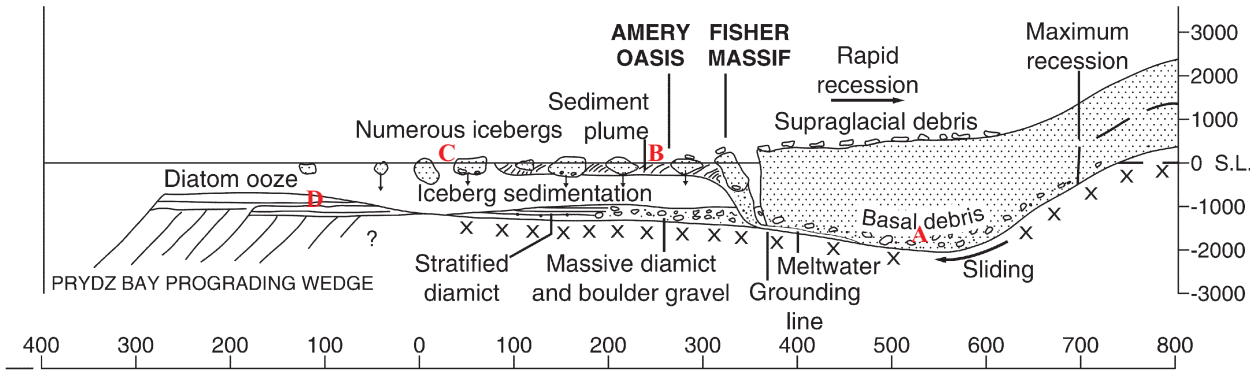

FIGURE 12.3. Cross section showing a conceptual model for growth and decay of a tidewater glacier in Lambert Graben Fjord, Lambert Glacier Region, Antarctica. From Hambrey and McKelvey, 2000. The vertical scale is in meters and the horizontal scale is in kilometers. Letters A–D are explained in Question 1.

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1 Match locations A–D in the conceptual model (Figure 12.3) to locations within the paleonvironmental setting (Figure 12.2). Do this by **writing letters A–D on Figure 12.2**. In the following table, **explain** why you placed each letter where you did.

Location	Your Reasoning
A. On the surface of, and beneath, grounded outlet glacier	
B. Region where a braided river, or subglacial meltwater, enters ocean waters	
C. Marine region characterized by icebergs	
D. Marine region below wave base and seaward of melting icebergs	

The following section introduces several important lithologies that are diagnostic of ice-distal to ice-proximal depositional settings in polar regions. Note that these lithologies are more specific than the general marine lithologies (e.g., siliceous ooze, glaciomarine) of the global ocean that were introduced in Chapter 2.

Answer Questions 2–5, based on:

- The **information on sediment type** in the boxes below
- Figures 12.2 & 12.3
- The short videos '5:Telling Time' (2007) and '6:Cenozoic Global Climate' (2007) from http://www.andrill.org/iceberg/videos/2007/index.html

SEDIMENT TYPE: DIATOMITE

Diatoms are an important group of single-celled free-floating photosynthetic protists (i.e., phytoplankton) that precipitate an opaline silica shell. They are particularly important in areas of open water around Antarctica. Some species of diatoms thrive in the ocean waters under ice shelves. Sediment made up of diatoms is called **diatom ooze** or **siliceous ooze** if it is unlithified, and **diatomite** if it is lithified. These sediments are typically a pale yellowish brown or greenish grayish yellow in color and may be bedded or laminated; sometimes they are bioturbated.

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2 If you are interpreting the history of depositional conditions on the continental margin of Antarctica, what important piece of **environmental information about a location** would you gain from the presence of diatom-rich sediments at that site?

SEDIMENT TYPE: SEDIMENT CONTAINING ICEBERG-RAFTED DEBRIS

When a glacier terminates in the ocean, icebergs can break off (or 'calve') from the front of that glacier or ice shelf, and drift out to sea. The icebergs carry sediment particles that were eroded by and embedded in the glacier as it moved across the land. The particles range from clay- to gravel-sized. As the iceberg melts, the sediment particles are released and settle on the seafloor. The most noticeable particles deposited by this process are the larger gravel-sized particles, which are called **iceberg-rafted debris** (**IRD**); these particles are particularly noticeable as isolated large grains within finer grained sediment (terrigenous sands, silts, and muds). The finer grained sediment containing the IRD may also contain a low concentration of diatoms, particularly at locations further from the end of the glacier as open-marine conditions become more dominant.

3 If you are interpreting the history of depositional conditions on the continental margin of Antarctica, what important piece of **environmental information about a location** would you gain from the presence of a mud that contains a few percent of diatoms, as well as isolated gravel-sized (or larger) grains?

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SEDIMENT TYPE: DIAMICTITE

A diamictite is a deposit of poorly sorted clastic sediments – in other words, it contains a mixture of particles ranging in size from very small ("clay") to very large ("gravel"). In addition, diamictites contain little or no internal pattern of layering (i.e., they are unstratified or poorly stratified). Diamictites can be deposited by several processes, including glacial activity and landslides. A **diamictite** that was deposited directly from glacial ice is called **till**. Most tills are deposited beneath a glacier, rather than along the glacier's sides.

4 If you are interpreting the history of depositional conditions on the continental margin of Antarctica, what important **environmental information about a location** would you gain from the presence of a till at that location?

SEDIMENT TYPE: WELL-SORTED SANDS AND/OR GRAVELS

In some places at the base of a glacier, large quantities of meltwater form subglacial streams. Where these subglacial streams flow out into the ocean from the glacier's front, the flowing water can remove the smaller sediment particles from the glacial till. This process of removing the smaller particles is called "winnowing" and leaves a deposit of **well-sorted sands and/or gravels** close to the end of the glacier. The smaller particles are carried away from the glacier front as clouds of muddy water (also known as "sediment plumes") and are deposited at more distant locations where turbidity current deposits, IRD, and diatoms may be present.

5 If you are interpreting the history of environmental conditions on the continental margin of Antarctica, what important **environmental information about a location** would you gain from the presence of well-sorted sands and gravels at that location?

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6 In the table below, **name and describe the sediment type (e.g., diamictite) expected for each depositional environment listed**. Use the information in Figures 12.2 & 12.3, the lithologic information in the text boxes, and your answers to Questions 1–5. Succinctly **explain the environmental processes** that produce those sediment characteristics.

Depositional Environment	Sediment Type and Description	Environmental Processes Producing the Lithologies
Open ocean, beyond iceberg influence		
Open ocean, within iceberg influence		
Glacial front, near the exit of a subglacial stream		
Subglacial (i.e., underneath the glacier)		

7 Images of four core intervals are shown in Figure 12.4. Compare them with your summary of sediment characteristics (Question 6) and the information presented in the boxes describing **Sediment types**. In the table on the next page match each of the sediment images/descriptions to one of the depositional environments you described in Question 6, explain your reasoning and ask question(s) about features you observe that do not seem to fit the "model".

NAME

Sediment Core	Sediment Name and Depositional Environment	Reasoning and Questions
ANDRILL 1-B 424.67–425.67 mbsf	Name: Environment:	
ANDRILL 1-B 133.07–133.88 mbsf	Name: Environment:	
ANDRILL 1-B 792.25–793.25 mbsf	Name: Environment:	
ANDRILL 1-B 80.50–81.50 mbsf	Name: Environment:	

NAME

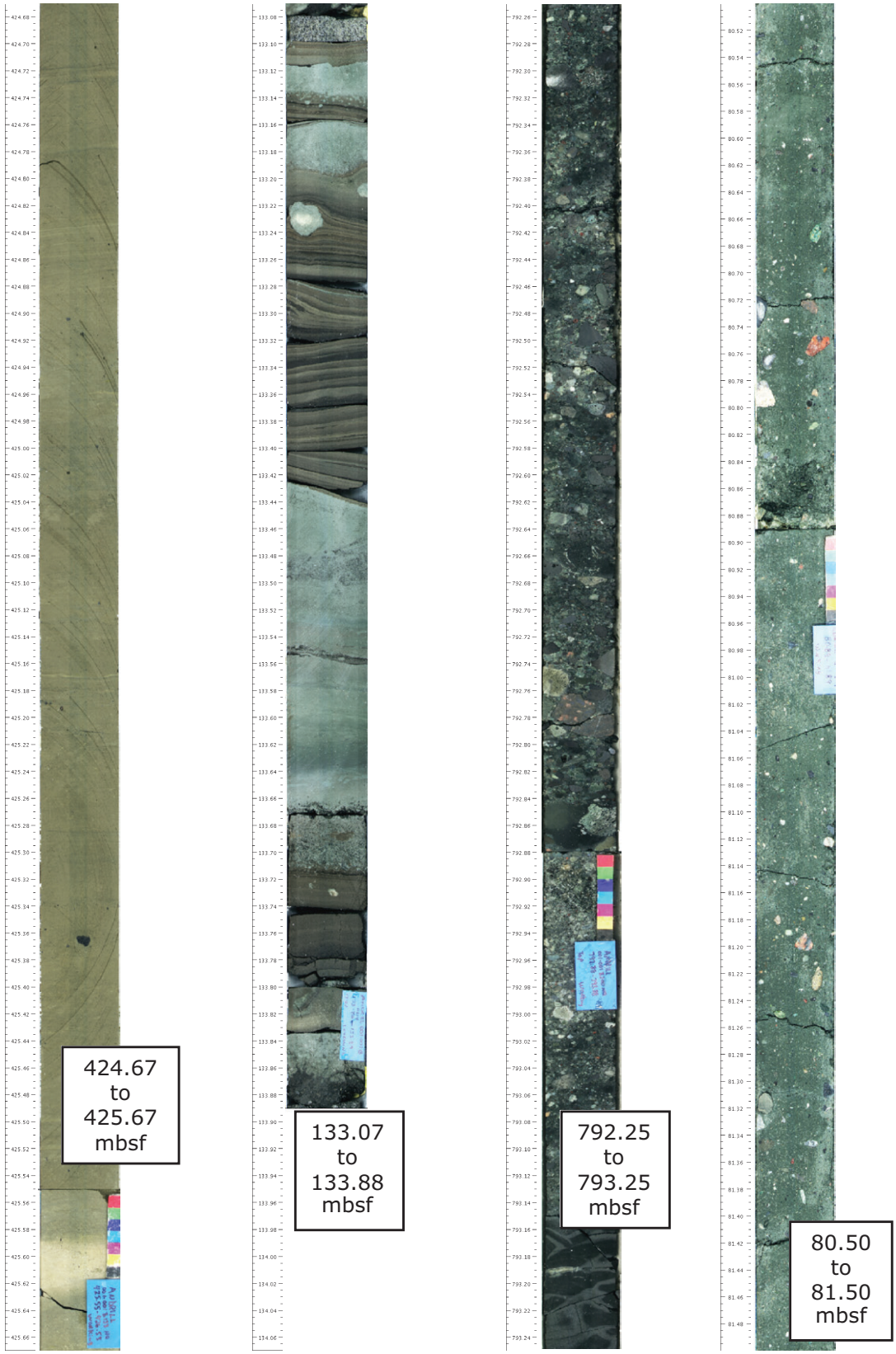


FIGURE 12.4. Four core intervals from ANDRILL 1-B. Photos courtesy of the ANDRILL Program.

NAME

SEDIMENTARY FACIES

When sedimentologists describe a core or outcrop, they identify distinctive sediment lithologies based on a suite of objective observable properties, such as grain size, sorting, composition, and/or color (see Chapter 2). When lithologies are interpreted in terms of their location within a complex three-dimensional conceptual model of the region's depositional setting, lithologic **facies** are defined. The term facies can also be used in conjunction with the interpreted environment e.g. "ice-proximal facies" or "ice-distal facies".

Each of the sediment types you described and interpreted is one of the facies recognized by sedimentologists as they describe and interpret sediment cores from the Antarctic margin. Because the environment that exists at one location can change through time, the facies being deposited at that location can also change. In other words, **depositional environments (and the facies deposited in those environments) migrate laterally as glacial ice advances and retreats across the area**. Over time, such changes produce a vertical stack of different sedimentary facies; this is known as **Walther's Law**.

8 Examine Figure 12.5, and imagine that you are stuck underneath the glacier at the point labeled "**A**". Over time, as the glacier retreats toward the south (the right side of the diagram), all of the other depositional settings shown in Figure 12.5 will also shift toward the south. When the glacier has retreated furthest to the south, open-marine conditions extend to "**A**". Demonstrate your understanding of Walther's Law (see box on Sedimentary Facies) by making a list of the sedimentary facies you would expect to be deposited at location A in this scenario. Be sure to put the oldest deposit at the bottom and more recent deposits at the top.

NAME

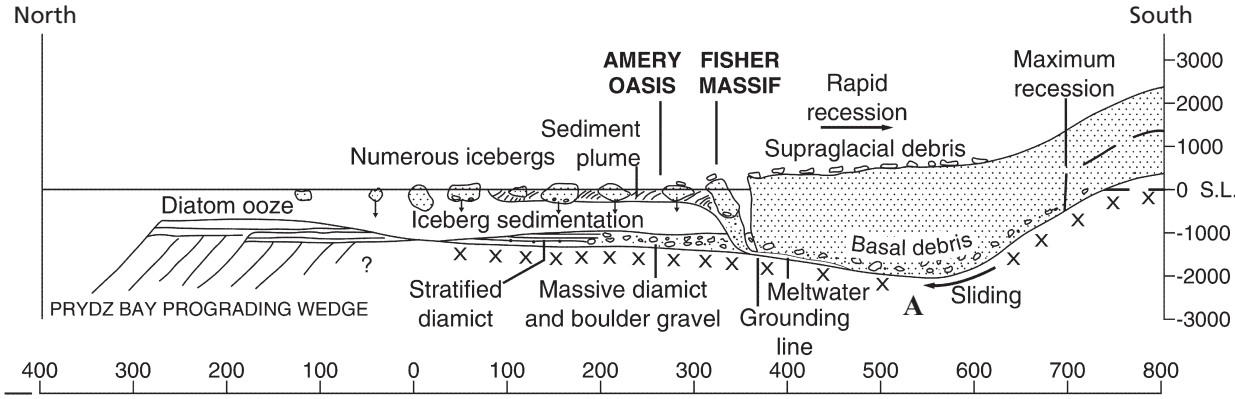
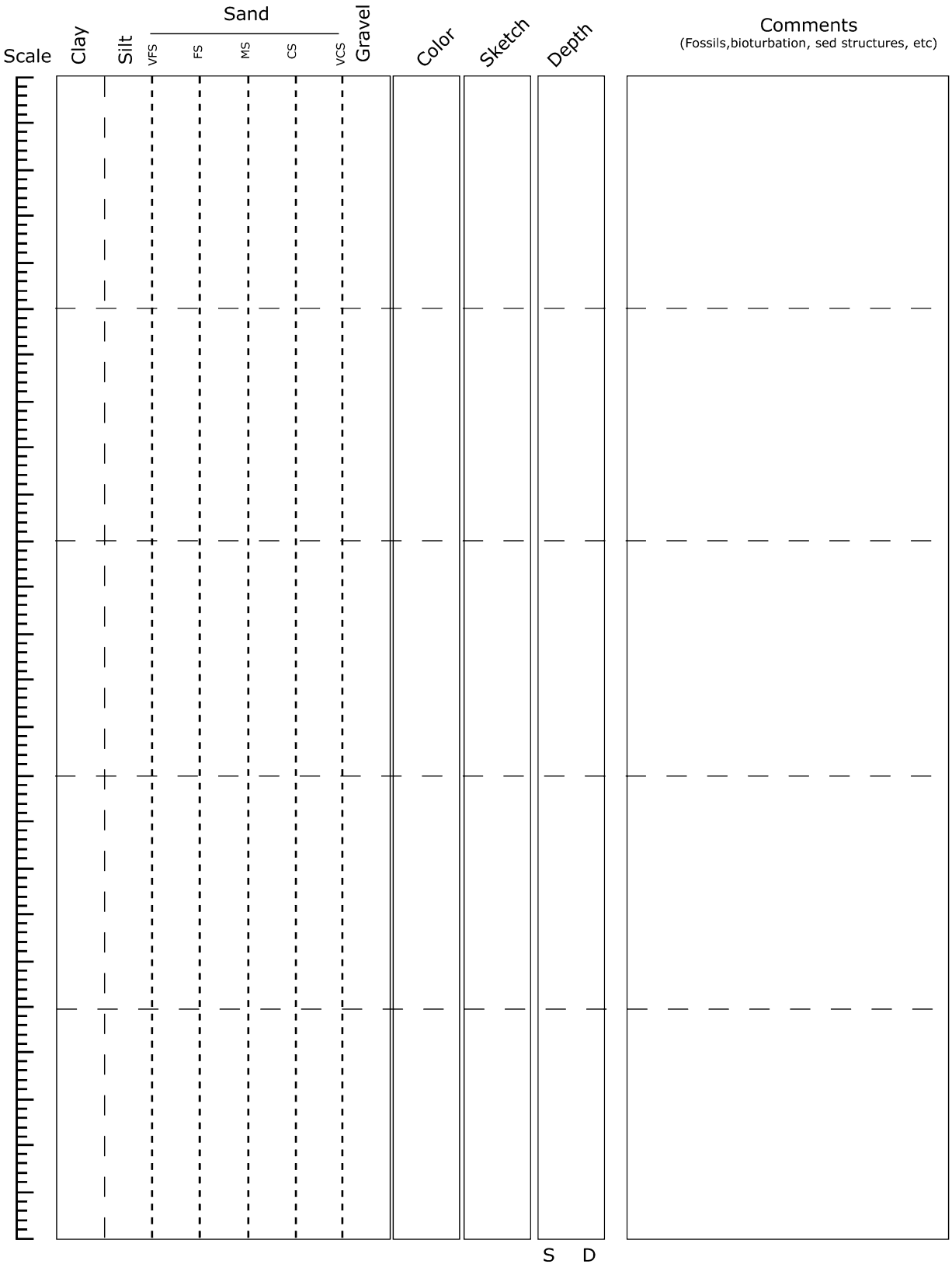


FIGURE 12.5. Cross section showing part of conceptual model for growth and decay of tidewater glacier in Lambert Graben Fjord, Lambert Glacier Region, Antarctica. Scales are in meters (vertical) and kilometers (horizontal). Vertical scale is in meters above or below sea level. Horizontal scale is in kilometers. This figure is nearly identical to Figure 12.3. From Hambrey & McKelvey, 2000.

9 Use the core logging sheet on the next page to **draw a simple stratigraphic column** that shows the vertical stack of sediments you would expect to be deposited at "A" as the glacier "retreats" landward (i.e. to the south) and then "advances" seaward (i.e. to the north). Note that you will not be able to fill in the columns labeled color, sketch, and depth, so leave these columns blank. In the "comments" section (a) label each facies in the vertical sequence, and (b) indicate the depositional environment present at "A" when that facies was being deposited. For help with development of your predictive model go to the simulation at http://andrill.org/system/files/web/images/edu/iceshelfadvanceretreat.swf

NAME


Scale
Clay
Silt
Sand
VFS
FS
MS
CS
VCS
Gravel
Color
Sketch
Depth
Comments
(Fossils,bioturbation, sed structures, etc)
S
D

NAME

SEQUENCE MOTIFS

Sedimentologists working on the Antarctic continental margin have recognized several typical sedimentary sequences that develop during the advance and retreat of the ice. One example of a typical sequence, called a **"sequence motif"** by the ANDRILL sedimentologists, is shown in Figure 12.6. Note that the phrase "ice-proximal" is used to mean sediments deposited closer to the ice and "ice-distal" to mean sediments deposited further away from the ice.

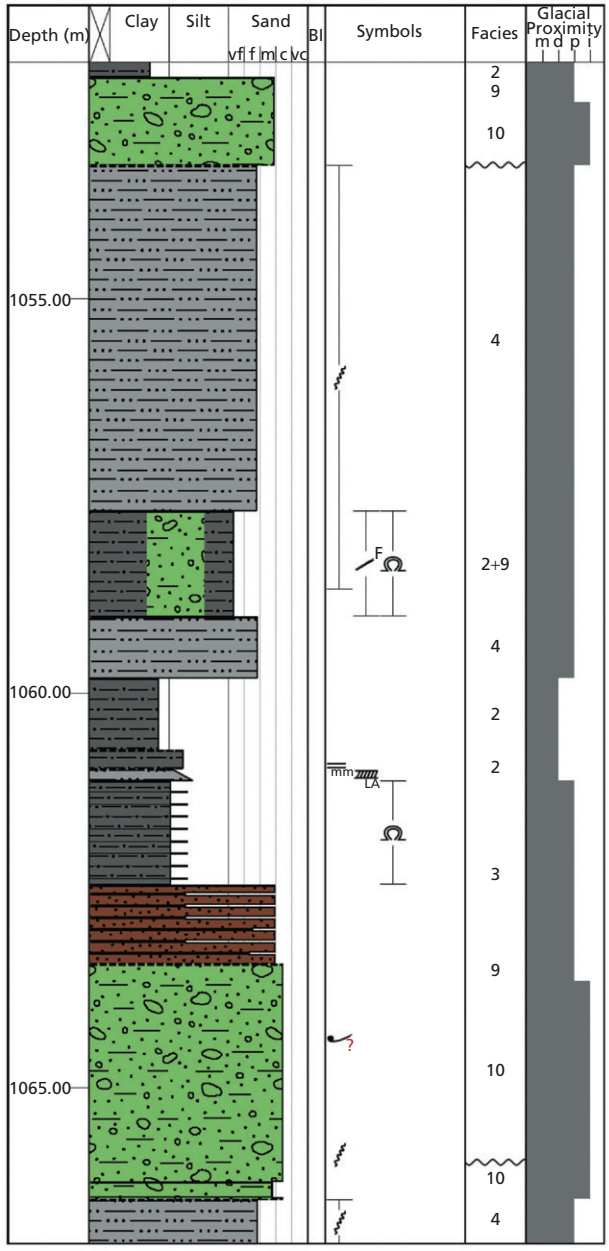


FIGURE 12.6. Example of a **sequence motif** from ANDRILL core 1-B, 1053.3–1066.4 mbsf. Green is diamictite, brown is conglomerate or breccias, gray is terrigenous siltstone and sandstone. The columns on the right of the graphic log show the main sedimentary features by symbols, facies number, and a glacial proximity graph. In the glacial proximity column, the width of the dark bar indicates ice proximity (wider = more proximal). From Krissek et al., 2007.

NAME

10 How does the vertical sequence you proposed for "**A**" in Question 9 compare with the vertical sequence shown in Figure 12.6? What is similar between the two? What is different? What explanations can you propose for any differences?

Similarities:

Differences:

Explanation:

NAME

11 In the next section (Part 11.2), you are going to be presented with the entire 1285 m core log for ANDRILL 1-B. Recall that a core log is a graphical summary of the sediments recovered from one location. How could you use the information on depositional environments, facies, and sequence motifs that you learned in this investigation to aid in your interpretation of the 1285 m core log for ANDRILL 1-B? List your strategies.

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Interpreting Antarctic Sediment Cores: A Record of Dynamic Neogene Climate

Part 12.2. ANDRILL 1-B The BIG Picture

ABOUT ANDRILL

ANDRILL (ANtarctic geological DRILLing) is an international program involving scientists, students, engineers, technicians, drillers, and educators from the USA, New Zealand, Italy, and Germany. ANDRILL's goal is to drill and recover sediment cores from the ocean floor beneath the Antarctic ice shelf and sea-ice, where the most complete sedimentary records of Antarctica's glacial, climatic, and environmental history for the past 65 million years are most likely to be found. In order to drill and recover these cores, a new drilling and coring system was developed that could be placed on top of the ice shelf and sea-ice.

Two ANDRILL projects have been completed successfully: the **McMurdo Ice Shelf Project (MIS)** in late 2006 and the **Southern McMurdo Sound Project (SMS)** in late 2007. Studies of the cores recovered during these projects are presently underway and will continue for many years to come.

This investigation will focus on sediments recovered during the MIS Project. As an introduction to ANDRILL operations and sediment core description, watch the short ANDRILL video journals listed below (downloadable from http://www.andrill.org/iceberg/videos/index.html):

ANDRILL Video Journals

4: *Selecting Where to Drill* (2007)
6: *The Drill Rig* (2006)
7: *Physical Properties and Logging* (2006)
8: *Core Curation* (2006)
9: *Sedimentology Team* (2006)
10: *Paleontology* (2006)
11: *Petrology* (2006)
12: *Paleomagnetism* (2006).

NAME

1 Use the information in the video journals to write a paragraph that summarizes the types of observation and data that are collected from the sediment cores before they are shipped to the Antarctic Core Repository in the United States.

LITHOSTRATIGRAPHIC UNITS (LSUs)

Figure 12.7 is a graphic summary (i.e., core log) of the sediments recovered in the 1285-m long ANDRILL MIS core (officially named "AND-1B"). In this graphic summary, glacial tills are shown in green, mudstones (generally containing IRD) are shown in gray, well-sorted sands and gravel are shown in brown, and diatom-rich sediments ("diatomites") are shown in yellow. Volcanic rocks and sediments rich in volcanic material are shown in orange, but will not be considered further here.

As the core was described, the sedimentologists identified "**lithostratigraphic units**" (**LSU**s). The LSUs are intervals of the core that are either:

- Dominated by a single sediment type (i.e., facies) or
- Exhibit a relatively consistent pattern of interbedding of two or more sediment types (i.e., two or more facies).

The LSUs are numbered in **increasing order down-core** and some LSUs are further subdivided (e.g., LSU 2.1, 2.2, 2.3) to highlight more subtle differences in the relative abundance of sediment types.

2 In order to examine the differences between these LSUs, use Figure 12.7 to **complete the table (located after Figure 12.7)** by estimating the contribution of each sedimentary facies (i.e., diatomite, mudstone, till, and sand and gravel) to each LSU. To make each estimate, first identify the LSU number

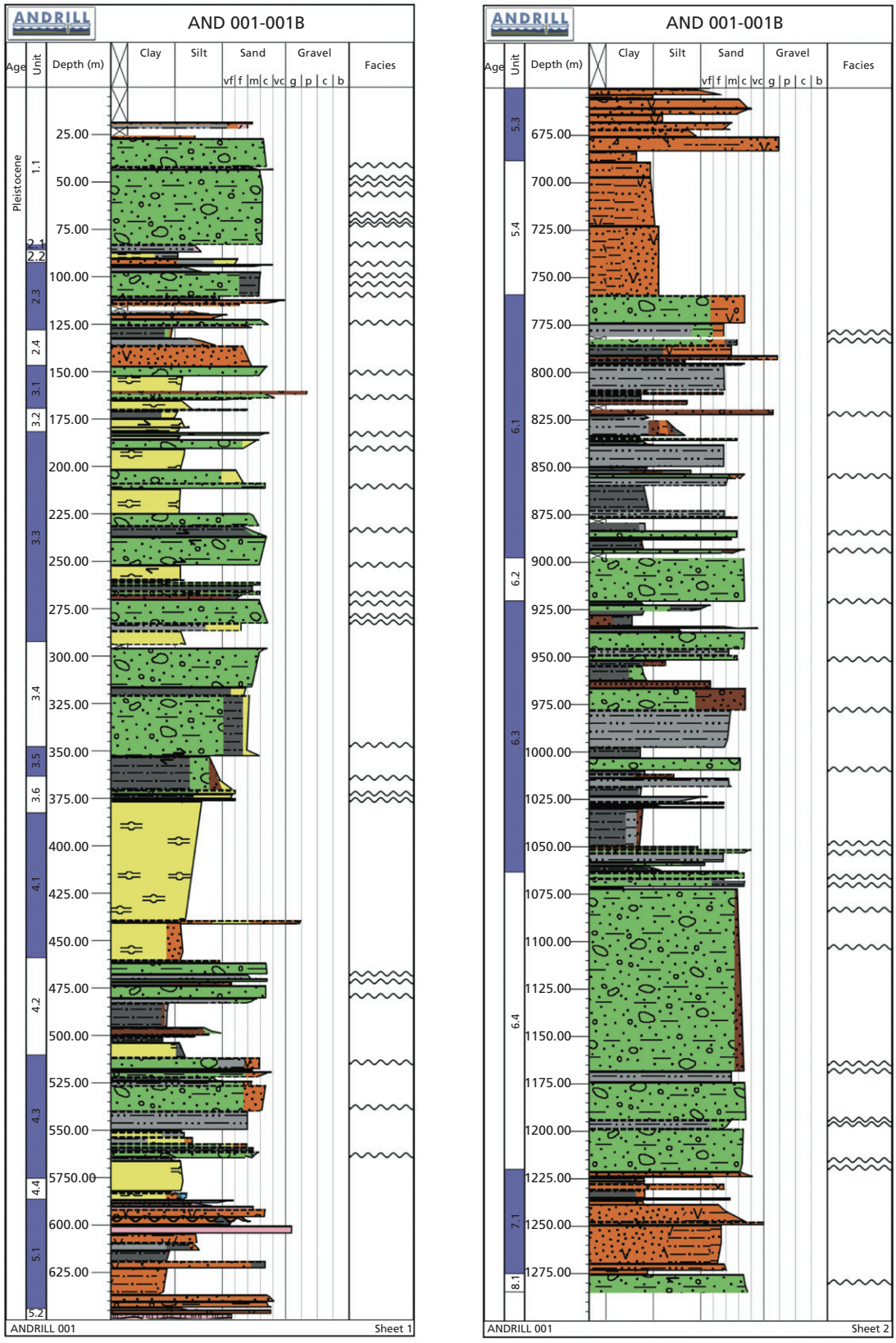

FIGURE 12.7. Core log for ANDRILL 1-B (ANDRILL "MIS"), LSU numbers shown in blue/white column on the left. The wavy lines represent breaks or gaps in the sedimentary sequence caused by erosion by grounded ice. These gaps in the record are called unconformities. Green = diamictite, yellow = diatomite, brown = conglomerate or breccias, grey = terrigenous siltstone and sandstone, orange = volcaniclastic sediment. From Krissek et al., 2007.

from the blue/white column on the left-hand side; then sum the thicknesses of the occurrences of each of the four facies within that LSU and divide by the total vertical thickness of that LSU.

LSU	% Diatomite	% Mudstone	% Sand and Gravel	% Till
LSU 1				
LSU 2				
LSU 3				
LSU 4				
LSU 6.1 + 6.2 + 6.3				
LSU 6.4				

3 The presence (100%) or absence (0%) of diatomite (open marine) compared with the till (sub-glacial) is clearly a key criterion for identifying the LSUs. However, abundance variations of as little as 5–10% in one of the four facies can help distinguish between LSUs. Based on your estimates in Question 2, are there significant differences in facies abundances in the LSUs identified by ANDRILL scientists? What are the significant differences?

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4 Use your answer from Question 2 and Figure 12.7 to summarize the major compositional changes that take place as one moves "up-core" from LSU 6.4 to LSU 1.

As you learned in Part 12.1, the environmental conditions that existed at a location during times in the past can be interpreted from the characteristics of the **sedimentary facies** deposited during those times.

5 In order to develop a general environmental history for the ANDRILL-1B site, use your data from Question 2 (Part 12.2) and notes from Part 12.1 of this chapter to complete the table below.

LSU	Most Abundant Facies	2nd Most Abundant Facies	Most Common Environment	2nd most Common Environment
LSU 1				
LSU 2				
LSU 3				
LSU 4				
LSU 6.1 + 6.2 + 6.3				
LSU 6.4				

NAME

6 Use the data from the table you have just completed to **write a history of climatic and environmental conditions at the site of ANDRILL-1B**, from the time of deposition of LSU 6.4 to the time of deposition of LSU 1. Describe the environments present during deposition of each LSU, the stability or variability of conditions, and whether you would classify that interval as a time dominated by ice (glacials), a time dominated by the absence of ice (interglacials), or a time of repeated glacial–interglacial cycles.

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Part 12.3. Pliocene Sedimentary Patterns in the ANDRILL 1-B Core

Sedimentary sequences that show some kind of repetition or pattern are generally referred to as being **cyclic**. The cyclicity may take place over a regularly repeated time interval. This time interval is referred to as the periodicity of the cycles (see Chapter 8). In this investigation we will analyze the 135–250 mbsf interval of the 1285-m long sediment core recovered by the ANDRILL McMurdo Ice Shelf project in 2006/07 (Figure 12.8). **Facies patterns in this part of the sedimentary sequence will be evaluated qualitatively and quantitatively to identify possible climate cycles**.

In Figure 12.8 the narrow yellow intervals are **diatomites** and the wider intervals in green, brown, and gray are **terrigenous** sediments that contain common to abundant gravel-sized clasts. These terrigenous sediments can be generalized in this investigation as **diamictites** (or tills).

Note that for Question 1, you should consider the dominant lithologic facies in each interval. Sedimentologists use the term facies or lithology somewhat interchangeably for distinctive "packets" of sediment. Recognition of each sedimentary lithology or sediment type is based on a suite of objective, observable properties such as grain size, sorting, composition, and color (see Part 12.2).

1 Starting from 227 mbsf and **working upwards** to 150 mbsf, list the vertical succession of lithologic facies (either diamictite or diatomite) in the table below. Start the list at the bottom of the table, so the oldest intervals are at the bottom and the youngest at the top. List the core interval, the thickness of each interval, and the lithologic facies.

Core Interval (in mbsf)	Interval thickness	Lithologic Facies

Note: The works space for Question 1 continues on page 424.

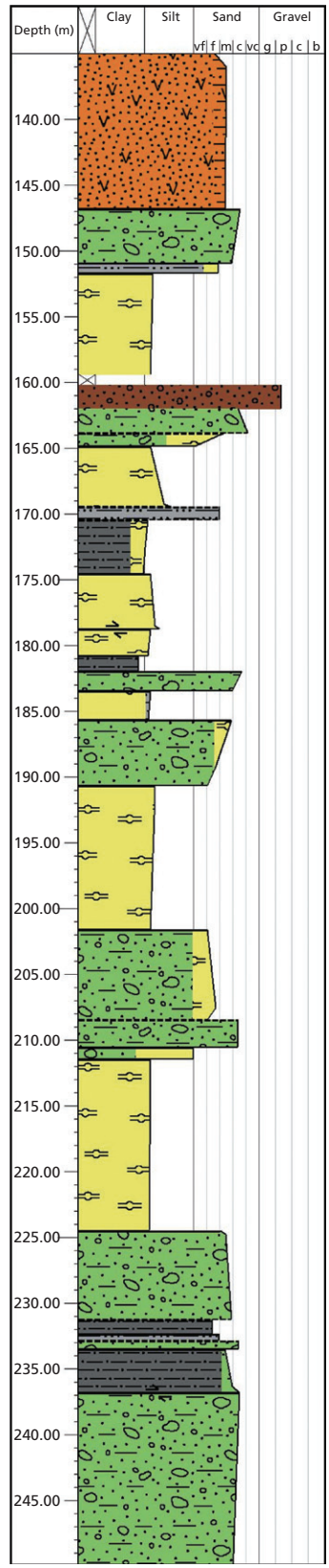

FIGURE 12.8. Graphical log of ANDRILL Core 1-B showing interval from 135–250 mbsf. Yellow intervals are diatomites. Green, brown, and gray intervals are terrigenous sediments. The scale at the top of the column gives grain size. Adapted from Naish et al., 2009.

NAME

2 Describe the general pattern of vertical arrangement of lithologic facies that you listed in Question 1. For example, is the stratigraphic pattern regular or random? Provide some specific details.

3 Let's define a "couplet" of these sediments as an interval of diamictite (till and other terrigenous sediments) overlain by an interval of diatomite. Starting at 227 mbsf and working up to 150 mbsf, how many "couplets" of diamictite overlain by diatomite can you identify?

4 Based on this vertical arrangement of lithologic facies, how did the environmental conditions at this site change as these sediments were deposited?

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5 Based on a combination of biostratigraphic, paleomagnetic, and radiometric data, the estimated age at 150 mbsf is between 1.94 Ma and 2.58 Ma, and the age at 227 mbsf is approximately 2.95 Ma.

(a) Given these data, what is the **fastest sedimentation rate** possible for this interval? Show all your calculations, give the rate in m/myr and cm/yr.

_____m/myr

_____cm/yr

(b) Given these data, what is the **slowest sedimentation rate** possible for the 150–227 mbsf interval? Show all your calculations, give the rate in m/myr and cm/yr.

_____m/myr

_____cm/yr

6 Assuming that the 150–227 mbsf interval represents 1.01 million years, what is the average duration of each couplet? This is the maximum average duration of the couplets. Show all your calculations; give the answer in myr, kyr, and yr.

_____myr

_____kyr

_____yr

7 Assuming that the 150–227 mbsf interval represents 0.37 million years, what is the average duration of each couplet? This is the minimum average duration of the couplets. Show all your calculations; give the answer in myr, kyr, and yr.

_____myr

_____kyr

_____yr

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8 When data are being used to assess large-scale connections (such as links to global-scale patterns of climate variability), averages are often most useful. In this case, use your answers to Questions 6 and 7 to calculate the average duration of each couplet; in other words, calculate the average of the "maximum average duration" from Question 6 and the "minimum average duration" from Question 7. Show all your calculations; give your answer in my, ky, and yr.

_____myr

_____kyr

_____yr

9 Compare the couplet durations you have calculated in Questions 6, 7, and 8 to the periodicities of eccentricity, obliquity, and precession (see Chapter 8). Does the Pliocene sedimentation in the Ross Sea, Antarctica, match any of these global-scale patterns of climate variability? Describe.

_____

_____

_____

_____

_____

10 In order to evaluate the couplet durations that you have calculated, it is important to have a sense of the **completeness of the stratigraphic record**.

(a) Is it likely that all the sediments that initially were deposited at this location have been preserved? Why or why not?

_____

_____

_____

_____

_____

_____

NAME _____

(b) Use your knowledge about age determination (Chapter 3 and 4) to explain how you might you test whether the stratigraphic record is complete.

_____

_____

_____

_____

_____

_____

11 You have already calculated that the sediments presently at 227 mbsf were deposited 0.37–1.01 million years before the sediments present at 150 mbsf. Geoscientists working on the core, however, have estimated that only 36% of that time—0.37 to 1.01 million years—is actually represented by the sediments in this interval; the other 64% of the elapsed time is not represented by sediments. Using this estimate of the time actually represented by sediments (36%) and your answers to Questions 6 and 7, recalculate how much time (in **years**) is actually represented by each couplet if one considers:

(a) The **minimum average** couplet duration for the interval 150–227 mbsf. Show your calculations.

_____yr

(b) The **maximum average** couplet duration for the interval 150–227 mbsf. Show your calculations.

_____yr

(c) Use the results from (a) and (b) to determine the **overall average couplet duration** for the interval 150–227 mbsf. Show your calculations.

_____yr

NAME

12 Do any of the time intervals calculated in Question 11 match global-scale patterns of climate variability (eccentricity, obliquity, precession; see Ch. 8)? If yes, **which global-scale pattern and what is its periodicity?**

13 If you look back to the core log and the table you completed for Question 1 (Part 12.3), you will note the variability in thickness of the individual lithologic facies and couplets. Also look back at the rates that you calculated. If each couplet was deposited during the same length of time, controlled by a global-scale pattern of climate variability (eccentricity, obliquity, or precession), what could account for the variations in couplet thickness observed in this core?

14 What additional datasets from this core might you look at or obtain to test your hypotheses regarding cyclicity? (Hint: think about datasets explored in Ch. 8.)

References

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