THE STORY OF EARTH - AN OBSERVATIONAL GUIDE



Daniel Hauptvogel and Virginia Sisson
University of Houston

LibreTexts™

The Story of Earth - An Observational Guide (Hauptvogel and Sisson)

This text is disseminated via the Open Education Resource (OER) LibreTexts Project (https://LibreTexts.org) and like the thousands of other texts available within this powerful platform, it is freely available for reading, printing, and "consuming."

The LibreTexts mission is to bring together students, faculty, and scholars in a collaborative effort to provide an accessible, and comprehensive platform that empowers our community to develop, curate, adapt, and adopt openly licensed resources and technologies; through these efforts we can reduce the financial burden born from traditional educational resource costs, ensuring education is more accessible for students and communities worldwide.

Most, but not all, pages in the library have licenses that may allow individuals to make changes, save, and print this book. Carefully consult the applicable license(s) before pursuing such effects. Instructors can adopt existing LibreTexts texts or Remix them to quickly build course-specific resources to meet the needs of their students. Unlike traditional textbooks, LibreTexts' web based origins allow powerful integration of advanced features and new technologies to support learning.



LibreTexts is the adaptable, user-friendly non-profit open education resource platform that educators trust for creating, customizing, and sharing accessible, interactive textbooks, adaptive homework, and ancillary materials. We collaborate with individuals and organizations to champion open education initiatives, support institutional publishing programs, drive curriculum development projects, and more.

The LibreTexts libraries are Powered by NICE CXone Expert and was supported by the Department of Education Open Textbook Pilot Project, the California Education Learning Lab, the UC Davis Office of the Provost, the UC Davis Library, the California State University Affordable Learning Solutions Program, and Merlot. This material is based upon work supported by the National Science Foundation under Grant No. 1246120, 1525057, and 1413739.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation nor the US Department of Education.

Have questions or comments? For information about adoptions or adaptions contact info@LibreTexts.org or visit our main website at https://LibreTexts.org.

This text was compiled on 05/19/2026

TABLE OF CONTENTS

Licensing

Preface

Licensing

1: Labs

- 1.1: Geologic Skills
- 1.2: Plate Tectonics
- 1.3: Earth Materials
- 1.4: Geologic Time
- 1.5: Sedimentary Structures
- 1.6: Stratigraphy
- 1.7: Fossil Preservation
- 1.8: Fossils
- 1.9: Paleoenvironments
- 1.10: Geologic Structures and Mapping
- 1.11: Interpreting Earth's History using Maps
- 1.12: Paleoclimate

Index

Glossary

Copyright

Detailed Licensing

Detailed Licensing

Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

Preface

About the Authors

Drs. Daniel Hauptvogel and Virginia Sisson are instructional faculty in the Department of Earth and Atmospheric Sciences at the University of Houston. We are a team that shares many responsibilities, including the oversight and training of our department's ~64 graduate teaching assistants, directors of our Geoscience Learning Center where our teaching assistants hold their office hours and students come in for tutoring, coordinators for about 15 sections of physical geology lab per semester, and a few sections of historical geology lab per year.



Dr. Daniel Hauptvogel

I'm an Instructional Associate Professor and have been at UH since 2015. I currently teach GEOL 1303 Physical Geology and GEOL 1370 Natural Disasters. I was born and raised in New Jersey, where I attended Montclair State University for my B.S. and M.S. in geology and went to The Graduate School and University Center of the City University of New York for my Ph.D. I didn't start as a geology major though, in fact, I didn't declare geology as my major until my junior year. I sort of floundered around trying to figure out what I wanted to do, and my grades showed it. However, once I joined the geology program, I felt at home, and it has been smooth sailing ever since.

My graduate training in geology was in paleoclimate with a focus on sediment geochemistry, particularly in Antarctica. I began research on Antarctica as an undergraduate after my mineralogy professor suggested I get involved in undergraduate research. I continued to study Antarctica with different projects throughout my Master's and Ph.D. Today, I find myself more interested in geoscience education and student success.

I credit my initial interest in geology to my grandfather, who lived in the Rocky Mountains of northwestern Montana near Glacier National Park. During my visits, we went to various mountains, lakes, parks, etc. The most memorable of which was Hidden Lake in Glacier National Park. I was too young to appreciate the views and the geologic significance of the area, but now I'm longing to return there.



Dr. Virginia Sisson

I'm an Instructional Professor and have been at UH since 2008. My teaching includes GEOL 1303 Physical Geology, and I am the co-director of our summer field geology camp at the Yellowstone Bighorn Research Association camp near Red Lodge, Montana. In 1986, I moved to Houston after finishing my Ph.D. at Princeton University and an A.B. at Bryn Mawr College. At first, I did research and teaching at Rice University before moving across town to UH.

I love to do geology field research and have spent many summers in Alaska, British Columbia, Guatemala, and Venezuela. You might see some of these places in the lab exercises as well as other places that I've done field research such as Appalachians (Maine, New Jersey, and Pennsylvania) and Rocky Mountains (Montana, Wyoming, and Colorado), Grand Canyon, Myanmar,

Malaysia, Norway, India, Costa Rica, Cascades (Washington), California, Utah, and Nevada. In fact, I started majoring in geology when I saw all the places that my physical geology teachers had traveled.

By trade, I'm a metamorphic petrologist (and sometimes igneous rocks as well) who uses tools such as geochronology, geochemistry, fluid inclusions, cathodoluminescence, remote sensing, UAVs (drones), structural geology, and tectonics. Some of my research has touched on global geochemical cycles and how exhumation may influence local climate. Most recently, I've focused on the geology of jade and associated rocks. This led to my Andy Warhol 5 minutes of fame when our rediscovery of Olmec blue jade made the front page of the NY Times.

Other Contributors

Many people contributed to the creation of this lab manual in the form of exercises, images, and editing, including several graduate students from the University of Houston.

Hannah Anderson – UH M.S. student
Carlos Andrade – UH Ph.D. student (Graduated 2021)
Joshua Flores – UH Ph.D. student
Melissa Hansen – Adjunct faculty at Montclair State University and Kean University
Rosalie Maddox – UH Professor
Carolina Ramon – UH Ph.D. student (Graduated 2020)
Ana Vielma – UH Ph.D. student

About this Lab Manual

The idea for this lab manual came from the lack of available texts and resources that we felt suited the needs of our teaching style and class. While there are plenty of options available, we felt that none were truly worth the cost to our students. Hence, we envisioned a completely customized lab manual that speaks to the nature of our teaching philosophy, giving our students a quality education and encouraging them to observe and think about the world around them. Our Earth has a complicated evolution that needs stories and observations for students to understand.

Through our own teaching experiences, we have found that students have difficulty making observations and interpreting them. Perhaps this results from the abundance of standardized tests students must take throughout their primary school career, but nonetheless, it is a problem that we have observed. Perhaps Carl Sagan said it best:

"My experience is, you go talk to kindergarten kids, or first-grade kids, you find a class full of science enthusiasts. And they ask deep questions! What is a dream? Why do we have toes? Why is the moon round? What is the birthday of the world? Why is grass green? These are profound, important questions. They just bubble right out of them! You go and talk to twelfth-grade students and there's none of that. They've become leaden and incurious; something terrible has happened between kindergarten and twelfth grade and it's not just puberty." – Carl Sagan in an interview with Mary Hynes on Canada's TVO, 1995.

Our goal in creating the material for this lab manual was to focus heavily on students making observations of geologic data, whether rocks, minerals, fossils, maps, graphs, and other things. We want students to look at things and wonder why, how, and when. The exercises and examples used in this book are scattered throughout the world. We wanted to make sure that one region of the world was not the sole focus of this work.

As you read the chapters, you'll notice the tone of the text is very casual. This was important to us because many geology texts are dense and, at times, complicated to read because of the vocabulary. Complicated text is more than likely not going to be read by students. Therefore, we have tried to break down concepts and terms into simple explanations and discussions to better engage readers.

We were fortunate enough to have our University Library sponsor our participation in the Rebus Textbook Success Program, a year-long program on creating open-access materials. The experience is a must for anyone wanting to create quality open-access materials.

If you are a faculty member or teaching assistant using this lab book for the first time, please contact us for our guide to teaching and possible answers. Many of the answers are open-ended, with several possible interpretations of the same data. This is part of

our philosophy that data is open to interpretation, and there might not be one correct answer. For students reading this, just try your best and discuss why you believe your interpretation may be right with your professor or TA.

Accessibility

We have designed this lab manual with accessibility in mind using W3C standards. All text has proper headings, text and background coloring meet the highest standards with a contrast ratio of at least 7:1, all images have descriptive alt text, and all hyperlinks open in the same window (you'll need to right-click links to open them in a new tab or window). If you find any accessibility errors or have suggestions to improve accessibility, please contact Daniel Hauptvogel at dwhauptvogel@uh.edu.

Copyright

This manual carries a CC BY-NC-SA license, which means you are free to use and adapt this material as needed provided you give appropriate credit, share it under the same copyright terms, and use it for non-commercial purposes. Most images used in this lab manual are open-access and have some variation of a CC license indicated in their captions. Some images have been used with permission from the original creator, also stated in the captions. For any images and maps that we have created, we can provide the original Adobe Illustrator files and GMT 5.4.5 coding (for most maps) upon request. Please contact Daniel Hauptvogel at dwhauptvogel@uh.edu. It is a violation of our creative commons license to upload any of this material to tutoring sites such as Chegg or Quizlet. Please respect our efforts to create open access material and do not upload material or answers.

Cover Image Credits

Grand Canyon – National Park Service – Public Domain
Siccar Point – Dave Souza – CC BY-SA
Zion National Park – Dr. Igor Smolyar, NOAA/NESDIS/NODC – CC BY
Plant, Fish, Trilobites, and Ammonite Fossil Images – James St. John – CC BY
Partial Geologic Map – USGS – Public Domain

Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

CHAPTER OVERVIEW

1: Labs

1.1: Geologic Skills
1.2: Plate Tectonics
1.3: Earth Materials
1.4: Geologic Time
1.5: Sedimentary Structures
1.6: Stratigraphy
1.7: Fossil Preservation
1.8: Fossils
1.9: Paleoenvironments
1.10: Geologic Structures and Mapping
1.11: Interpreting Earth's History using Maps
1.12: Paleoclimate

This page titled 1: Labs is shared under a not declared license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.1: Geologic Skills

Learning Objectives

The goals of this chapter are to:

- Get to know your classmates
- Summarize the importance of making observations
- Practice sketching for geologic interpretations
- Review the usage of Google Earth
- Create and interpret graphs
- Recognize geologic maps

0.1 – Let's Get Started

"Chapter 0? I've never seen that before; what an odd way to start the book."

Is it unconventional? Yes, but we like to think this is a more effective way of preparing you for the activities in this lab manual because, let's be honest, did you read the Preface? Probably not, and you would have missed all of this handy information to help make your life easier if we had put this material in there.

This lab manual assumes that most users have already taken an introductory geology course, such as Physical Geology or Earth Systems. Can you remember anything from your intro course? What about some of the basic physical processes and vocabulary such as types of **plate boundaries**, rocks and the **rock cycle**, and different classes of minerals such as silicates, carbonates, and oxides? Do you remember much about the geologic time scale or some of the principles that geologists use to date events in Earth's history? If you think you need to review some of these, we recommend browsing through some of those topics at the following open educational resources (OER):

- Physical Geology 2e – An OER textbook for introductory geology developed by faculty from Earth science departments at universities and colleges across British Columbia and elsewhere.
- An Introduction to Geology – An OER textbook for introductory geology developed by a team at Salt Lake Community College.
- Physical Geology Laboratory: Animations and Interactive Questions – An OER lab book by Elizabeth A. Johnson that supplements labs and lets you practice skills you have learned.

In any case, the first few chapters are designed to review this material and do more advanced investigations for these topics. Some of you may be wondering about this, though: Can you complete the exercises in this lab manual without having a previous geology course? If you're the type of student who stays on top of their academic pursuits or easily picks up on new material/concepts, then you most likely won't have an issue. If this doesn't describe you, though, you may find you need to review the material in the OER links above a little more closely.

0.2 – Academic Integrity

As Benjamin Franklin said, "Honesty is the best policy," and we believe students should follow this adage. However, in this digital age, cheating has become easier, and catching it has become harder, especially with large class sizes. Believe it or not, academic integrity (AKA cheating and plagiarism) is a major issue at most universities. The International Center for Academic Integrity conducted a survey of undergraduate and graduate students between 2002 and 2015. They found that 68% of undergraduate students and 43% of graduate students admitted to cheating on exams or other graded work at some point. That's a staggering yet eye-opening statistic. To put that in perspective, if your lab class has 25 students, that means about 17 of your classmates have probably cheated at some point in their college career.

One of the common issues we have found with academic honesty cases is that students don't know they are cheating or plagiarizing. To help you understand this a bit more, we've put together a list of common offenses:

- Plagiarism – presenting someone else's work as your own
- Cheating – getting an unfair advantage in a test

- Misrepresentation of facts – distorting the truth or your data
- Encouraging or helping anyone else do any of these things

In this lab, you may benefit from discussing concepts and exercises with your fellow students, teaching assistants, and professors, which brings us to another gray area: group work. Many of the exercises in this lab manual are best completed in small groups where each member's strengths and weaknesses will shine. This is not a bad thing but rather an opportunity to experience peer-to-peer learning, an effective learning strategy. Working with others will help you solve the exercises in this lab manual, but the answers you turn in must be written in your own words. Similarly, sketches and diagrams must also be your own work, and any data collection, graphs, calculations, or measurements must also be your own.

Learning to write clearly is part of what we hope you learn by answering these questions. So, please be an ethical student and follow these suggestions for academic integrity. These policies may vary depending on your university academic code and are general guidelines for how to succeed during these labs as well as in life. If you are interested in understanding more about plagiarism, consider checking out www.plagiarism.org and their section titled "What is Plagiarism?". Posting images and answers from this lab manual on websites like Chegg and Course Hero violates this work's copyright, and you can be held liable.

0.3 Skill-building

There are many skills you will need to be successful in this lab, including how to make observations, sketching, knowledge of geography and Google Earth, how to compile data, plot it on a graph, and how to interpret that graph. This information may be overwhelming or sound scary right now, but we have designed the exercises in this lab manual to guide you through these skills.

Making Observations

Being able to make observations is a critical skill for most of the exercises in this manual. Through our years of teaching, we've come to realize that students have a difficult time making observations. This is probably a result of the trend in education towards standardized testing, but that's a discussion for another time.

? Exercise 0.1 - Observing and Sketching: Part 1

Before reading any further, let's see where you stand in terms of your observation skills. Using the space below, create a sketch of the photo in Figure 0.1 and annotate any observations you can make. Note: there is no right or wrong answer here; it is merely a means of seeing what you observe.

Sketch Area:

Open your eyes and take note of what is in front of you. It sounds simple, but how do you know what to look at? That's the challenge for students making geologic observations; they don't know what to look for at first. Take a look at Figure 0.1; what do you see? What's the first thing you notice? Is it the clouds? Is it the mountain in the background? Were you able to tell the mountain is a volcano (It's Mount St. Helens)? Did you note the **landscape** around the volcano is **barren**? What about visible features of an area of land, its landforms? Or how about that the landscape appears very smooth for being located in a mountainous region? What about the small valleys carved into the landscape?

Mount St. Helens had a major eruption in 1980 that caused the mountain's northern slope to collapse, creating a major landslide that wiped out all of the vegetation north of the mountain. The landslide was followed by the deposition of **volcanic ash** and other material, which is why the landscape appears smooth. Those valleys are being carved out by rainfall that forms small rivers; they easily erode the loose **volcanic material** and create the valleys. The region has yet to recover from this disaster, but vegetation is slowly making its way back in.



Figure 0.1 – Photograph of Mount St. Helens in Washington state taken in June 2018. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

Most people think taking pictures is the best way to record what they see; however, this is not always true. The lighting may be wrong, or what needs to be observed is under a mineral coating, or there isn't a suitable location to take in the entire **landscape**. Or maybe the opposite; people may need to focus on an area but can't get close enough. To overcome these challenges, geologists use sketches to capture their observations of rocks, fossils, and landscapes.

For a geologist, creating sketches has several distinct advantages over taking photos. When creating sketches, you can remove unimportant details, use shading and colors to highlight different aspects, and easily annotate your sketches on-demand in your field notebook. Figure 0.2 is a sketch of a Triceratops jawbone; the sketch allows us to focus on the important aspects of the fossil, rather than being distracted by the background or other unimportant details.

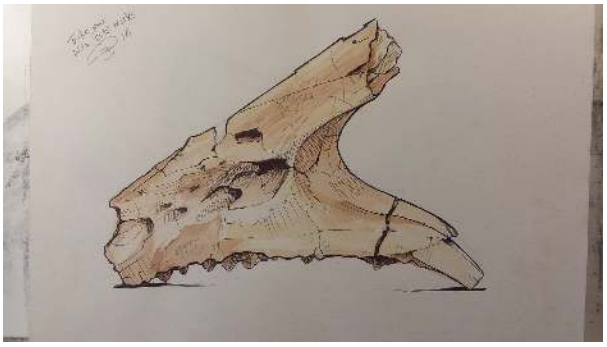


Figure 0.2 – Sketch of a Triceratops maxilla (jawbone) showing bite marks. This fossil is from the Hell Creek Formation in central Montana. The crocodilian bite marks are angular compared to rounded features. When you make sketches, you can consider adding color or shading to show details. The paleontologist omitted other surrounding details to focus on the bite marks. Image credit: Jason Poole, CC BY.

Geologists often find themselves doing fieldwork for weeks at a time in remote areas and don't always have access to reliable electricity to charge camera batteries or laptops. In those circumstances, sketches are the preferred method of recording observations. Does that mean geologists never take photos? Of course not; any geologist has a trove of photos from field locations they visit, but it's the sketches that truly help with their interpretations.

The sketch of the north wall of the Grand Canyon in Figure 0.3 was made by John Wesley Powell, who led the first boat trip through this area in 1869. You can see that he identified three types of rocks and labeled them A, B, and C. Powell was the first to identify the "Great **Unconformity**" between the rocks at the bottom of section A and the tilted rocks in section B. When making sketches, it is important to include a scale. In this sketch of the Grand Canyon, Powell included a riverboat at the bottom. If

possible, use perspective and shading. Finally, annotate your sketches with notes. Annotations can help with the interpretation of parts of your sketch that are difficult to portray correctly.

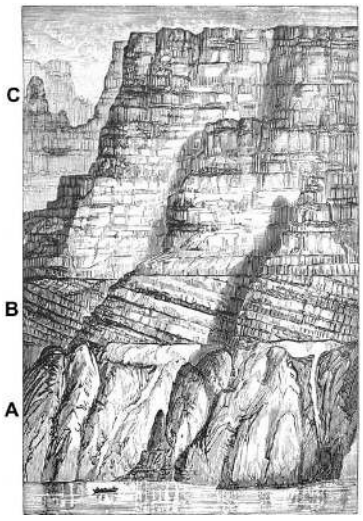


Figure 0.3 – This is a generalized sketch of the Grand Canyon, Arizona, that shows several groups of rocks. Section A is a group of metamorphic rocks (Vishnu schist) intruded by granite (Zoraster granite). Section B is a group of tilted sediments of the Grand Canyon supergroup. Section C is a sequence of Paleozoic sedimentary units. Powell drew this sketch during a time when photographs were not readily available. It gives incredible detail with the horizontal, layered rocks on top, layers of tilted rocks in the middle, and crystalline rock at the bottom. There is also a riverboat drawn to give a sense of scale. Image credit: Modified from the USGS, Public Domain.

With all of that said about sketches, you don't need to be an artist to record what you think is important. And the more practice you get making sketches, the more your sketching skills are going to improve. It is better to sketch quickly instead of spending lots of time making them perfect. If you think some aspects of your sketch are lacking, then make a note of what you are observing.

? Exercise 0.2 - Observing and Sketching: Part 2

Search the internet for a geological feature that inspires you. Websites that you can browse for interesting geology are:

- Pictures that will inspire you to become a geologist
- Smithsonian's list of the ten most spectacular geologic sites
- Awesome geology pictures
- American Southwest geology
- National Geographic's best geology pictures from ordinary people
- Weird geologic formations

Once you find your geologic muse, complete the following:

- Create a sketch of the feature, and be sure to include some type of scale. Scale is important for the viewer to get a sense of what you are sketching. For instance, what is the size of the Triceratops maxilla in Figure 0.2? It could be massive or tiny? You may think that it is massive using your knowledge of dinosaurs that you've seen in museums or elsewhere. But, did you know the smallest dinosaur fossil is ~5 cm (2 inches)? So, add a scale even if there is not one in the picture you are sketching. You can give your best estimate.
- Add some brief comments about any features you can identify. These can be simple comments such as the rocks are red and white. Please note whether these are igneous, sedimentary, metamorphic, or a mix of rock types.

Sketch Area:

Geography

Many students learn some basic geography before college, and almost all seem to forget place names once they no longer need to know them for a test. Perhaps the best way to learn this information is to travel and then have memories associated with these

places. Oh, you're not independently wealthy with enough spare time to travel the world? Not to worry, we have embedded several maps and links to Google Earth in this text to showcase some geology of the world and hope you will learn enough to remember some geography after completing this lab manual. You'll "travel" to the likes of Australia, British Columbia, Eastern Europe, Chile, and Texas, and that's just in Chapter 1! We do assume, though, that you can remember the seven continents (Yes, Antarctica is a continent, a landmass larger than the United States) and the five oceans.

We created many of the maps in this lab manual using Generic Mapping Tools. Most maps are **Mercator projections** and therefore distort the sizes of continents and distances as latitude increases. This is why the United States looks almost as wide as Africa, when, in reality, it is much smaller than Africa (Figure 0.4). In fact, the United States, China, and India can all fit within the area of Africa with room to spare. You can compare true landmass sizes at The True Size.

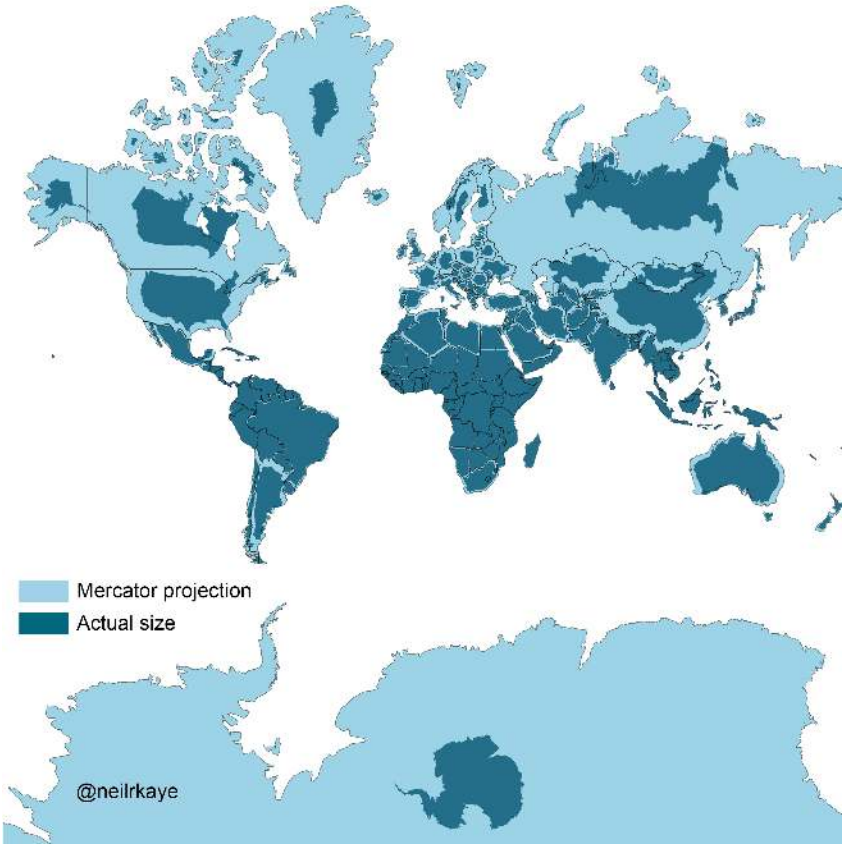


Figure 0.4 – A comparison of country sizes between Mercator projection (light blue) and actual country sizes (dark blue). Mercator projection maps distort the size of continents and distances as latitude increases. Image credit: Neil R. Kaye, CC-BY

Do you remember anything about latitude and longitude? This is the geographic coordinate system to locate any point on Earth; think of it as an address. Latitude is the position north or south of the equator and goes from 0° to 90° north and south. Sometimes negative values are used to represent south. Longitude is the position east or west of the prime meridian, which runs through Greenwich, England, and goes from 0° to 180°. Positive values represent east of the prime meridian, and negative values represent west of the prime meridian.

? Exercise 0.3 - True Sizes of Landmasses

Since we live on a three-dimensional globe that is often projected in two dimensions, it is difficult to appreciate the scale of where you live compared to other countries or states on Earth. An easy way to do this is to use The True Size, a computer visualization tool. Once you are on this website, type in the name of your home state or country, which will highlight the area on the map. Then, drag it around the world, comparing it to other countries or states.

a. Find a country or state that is a similar size to your home state or country. _____

b. How does the latitude affect the size of your home state or country?

_____

c. What countries are the same size as the United States?

_____

Google Earth (Not Google Maps)

There are many ways to find your location, such as a map app on your digital device. This lab book will use the web version of Google Earth to show you all of the locations mentioned throughout this lab manual. Google Earth is a composite of satellite images, aerial photographs, and GIS data on a globe. Coverage includes about 98% of the Earth. The resolution of the images partly depends on how popular the area is. For example, remote areas in British Columbia, Canada, have a poor resolution in mountainous areas except where commercial logging is done. There are many features in the desktop version of Google Earth, such as historical imagery, measurement tools, three-dimensional imagery, night sky, views of the Moon and Mars, and **bathymetry** of the ocean floor. As the web version of Google Earth is updated, we hope many of these tools will be incorporated in future releases. Please note that all links in this lab manual open in the same browser window according to accessibility standards, you may want to open Google Earth links in a separate window or tab.

? Exercise 0.4 - Using Google Earth

Using Google Earth, find a geologic feature of your choosing (a mountain, fault, desert, specific location, anything really) and answer the following questions about it. You can also use your feature from Exercise 0.2 if you know its location.

a. Record the latitude and longitude of your feature.
   i. Latitude: _____
   ii. Longitude: _____

b. Since one degree of latitude is ~110km, how far from the equator is your geologic feature?

_____

c. How about miles? (1km = 0.62 miles) _____

d. Using the ruler tool in Google Earth, how far from your house or dormitory is it to this geologic feature in km and miles? (The ruler tool is the last icon on the left-hand menu.)

_____

Compiling and Plotting Data

In general, data is either quantitative (a measure of how much of something; for example, the temperature is 10°C) or qualitative (a description of something; for example, the temperature is cold). There are many ways to display data, and the type of data you collect will determine the type of data plot you will need. Simple data plots include pie charts, bar charts, timelines, histograms, and scatter plots. Not all data charts are helpful to interpret trends. Often, we have to try different types of plots to discern what is important about the data. A lack of a trend is also informative because it means that your assumptions are incorrect and there is no relationship in your data set.

Let's look at the scatter plot in Figure 0.5. This graph shows a relationship between the time between two eruptions and how long (duration) an eruption lasts. This scatter plot shows two types of eruptions: short eruptions with a short time between them and long eruptions with a long wait time. In this plot, there are not many data eruption durations between 2.5 and 4.0 minutes. So, if we interpolate between these, we can estimate the wait time between eruptions.

Generally, scientists look to see if the data is correlated, meaning they are looking for a relationship or pattern. Suppose there is a positive correlation; as one variable increases, so does the other, just like Old Faithful eruptions (Figure 0.5). In this plot, as the duration of the eruption increases (x-axis), so does the time between eruptions (y-axis). Data can also be negatively or inversely correlated; as one variable increases, the other decreases. For example, as an earthquake's magnitude increases, its frequency (how often it occurs) decreases.

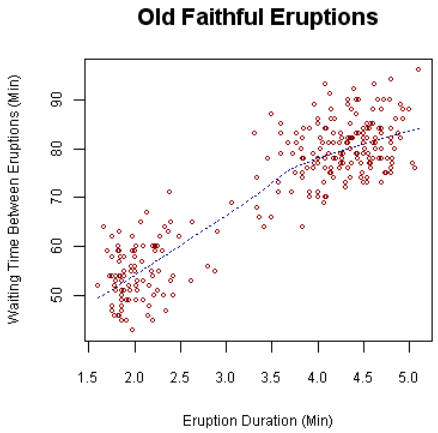


Figure 0.5 – This scatter plot shows two variables: the duration of steam eruptions from the Old Faithful geyser in minutes on the horizontal axis and the time between these eruptions in minutes on the vertical axis. The blue dotted line shows the positive correlation because as one variable increases, so does the other. Image credit: Wikipedia User: Nwstephens, Public Domain.

Most geoscientists use spreadsheet programs such as Microsoft Excel or Google Sheets to analyze their numerical data. You may not yet be familiar with these programs, but there are many tutorials available online. Check out this tutorial at Excel Easy or look at an Excel guide to help you get started. Excel is a powerful program that simplifies many tasks. You will find that many companies and organizations universally use it. Plus, if you learn one program, you will be able to use other programs because many of these software packages are very similar.

In geosciences, we often collect data that has three components, such as grain size in sedimentary rocks and soil, to classify samples using the proportions of sand, silt, and clay-sized particles. These data are displayed on triangular plots (sometimes known as **ternary plots**) (Figure 0.6). For most applications, the three variables (a, b, c) add up to one hundred percent. Since a + b + c = 100 for all components, any one variable is not independent of the other two. Only two variables are on the graph as $c=100-a-b$.

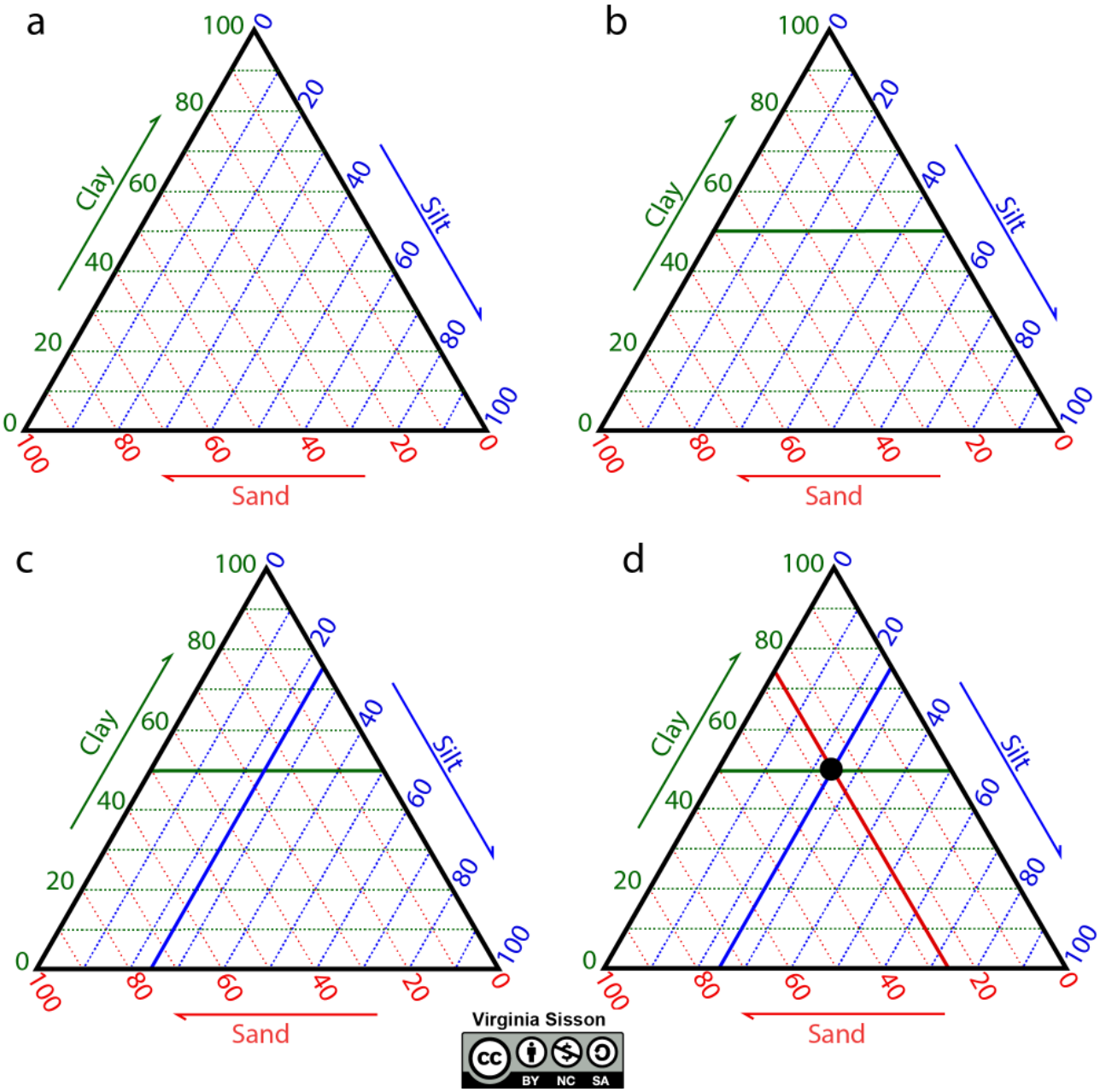


Figure 0.6 – Triangular plots for sand (red), silt (blue), and clay (green). This version of the plot is typically used to classify soil types. The four plots are an example of how to plot a soil sample with 50% clay, 26% silt, and 24% sand. a) blank triangular plot for the relative abundance of clay, silt, and sand; b) First, find the 50 percent line for clay (green horizontal tie lines); c) Next, find the 24 percent line for silt (blue dotted tie lines); d) Check the result by plotting the 26 percent line for sand (red dashed tie lines). Image credit: Virginia Sisson, CC BY-NC-SA.

? Exercise 0.5 - Plotting Data

Collect some data from your classmates. This is up to you as a class to decide on at least two items. Examples are: how far from school do they live, what is their major, height, favorite color, how many have dark hair versus blonde or red hair, how many steps do they take in an average day, how many letters in their names (first, last, nickname, all three), what kind of pet do they have, what is their resting heart rate, etc. Record your data in the space below.

There are many ways to display data. In general, data is either quantitative related to counts of something or qualitative about information that can't be measured. Make a graph of your data using one of the blank graphs in Figure 0.7. If you have two

quantitative (numerical) items, you should make a scatter plot. If you have only quantitative data, you can create a pie chart, bar chart, or histogram.

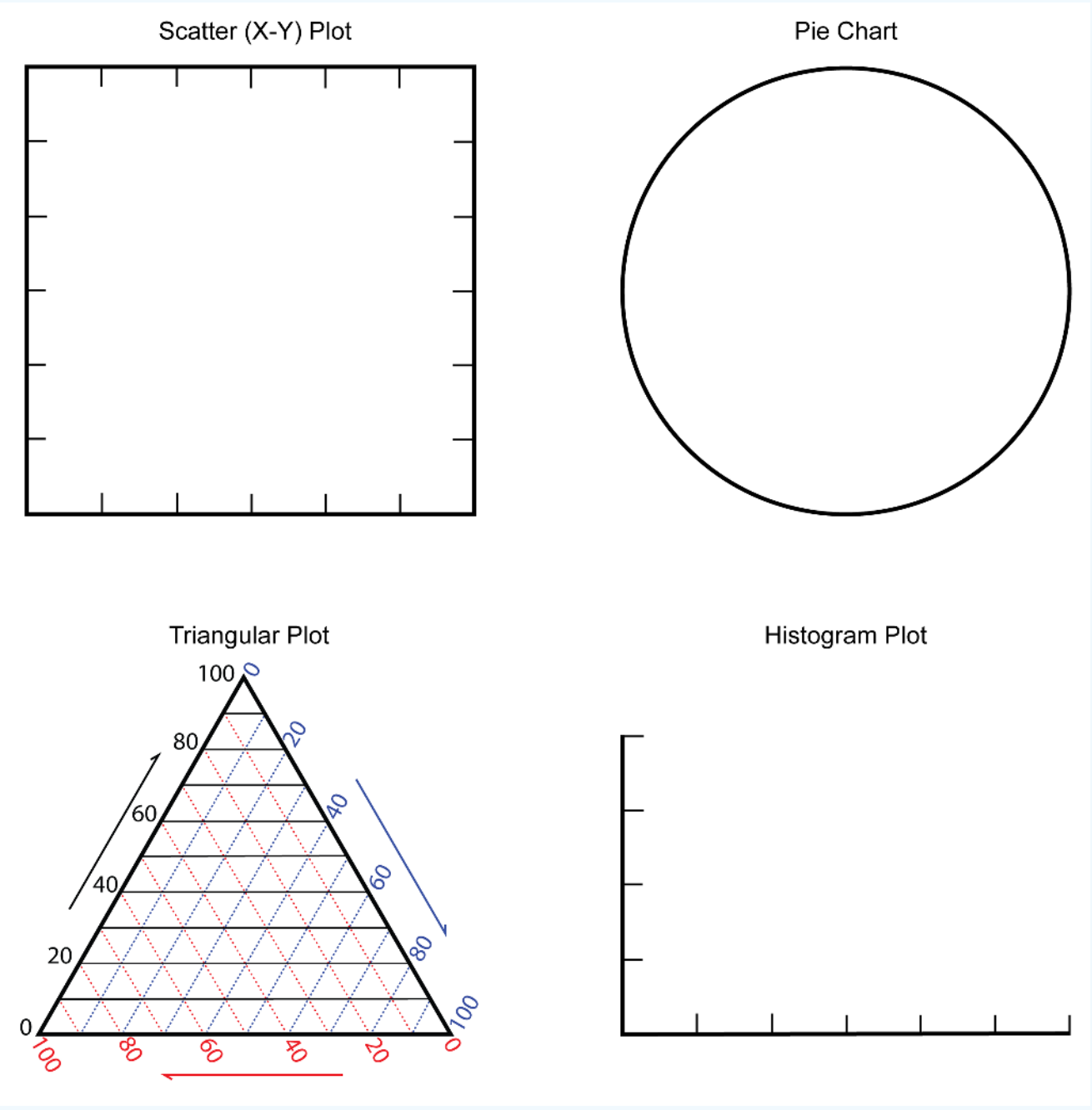


Figure 0.7 – Blank graphs to be used in Exercise 0.4.

a. What does your graph(s) tell you about your classmates?

0.4 Reading and Creating Geologic Maps

The ability to read a geologic map will be necessary, especially for the second half of this lab manual. A geologic map contains stories about the region that is covered. Maps contain information about what is on Earth's surface as well as below. You can use

them to make a three-dimensional picture of your surroundings. Another way to think about it is a geologic map is to a geology major as a wrench is to a mechanic.

Figure 0.8 shows the first geologic map of the U.S. published by William Maclure in 1809. He subdivided the rocks into five types based on the Werner classification. This classification, however, is no longer accepted, and not many people know about this map. Despite this, Maclure made a heroic effort to produce this map. He supposedly crossed the mountains over fifty times to get the details correct, with walking and horseback as his only means of transportation.



Figure 0.8 – The first known geological map of the eastern and central parts of the United States by William Maclure. The colors indicate where primitive (red), transitional (pink), secondary (light blue), alluvial (yellow), Old Red sandstone (dark blue), and salt and gypsum (green) are located. Even though his understanding of geologic formations was different from what is used today, the general distributions of different rock types were fairly accurate. Image credit: David Rumsey, after William Maclure, CC BY-NC.

To an untrained eye, a modern geologic map (Figure 0.9) is a maze of colors in fantastical patterns. We purposefully did not include a legend for this map because it would be too complicated for most geology padawans. By the end of this book, though, you will have everything you need to be a geology master. For now, the colors represent geologic units, which are subdivided by time and rock types. Many geologic maps use a standard color scheme with colors related to the **geologic time scale**, such as shades of yellow for Quaternary units and blues for Paleozoic units. Still, sometimes the colors used are unique to the kind of geologic map. The geologic map on this lab book's cover is for the Grand Canyon region and is mostly blue. So, you can easily guess that most of this area is made of Paleozoic rock units. The standard color scheme used in the United States is available on the USGS website. Between these colored units are lines or **contacts**. The width and type of line designate the type of contact, such as fault (solid line), intrusive contact (dashed line), or contact that is covered by unconsolidated rocks (dotted line). Typically, there is a legend that identifies the type of line with different types of contacts.

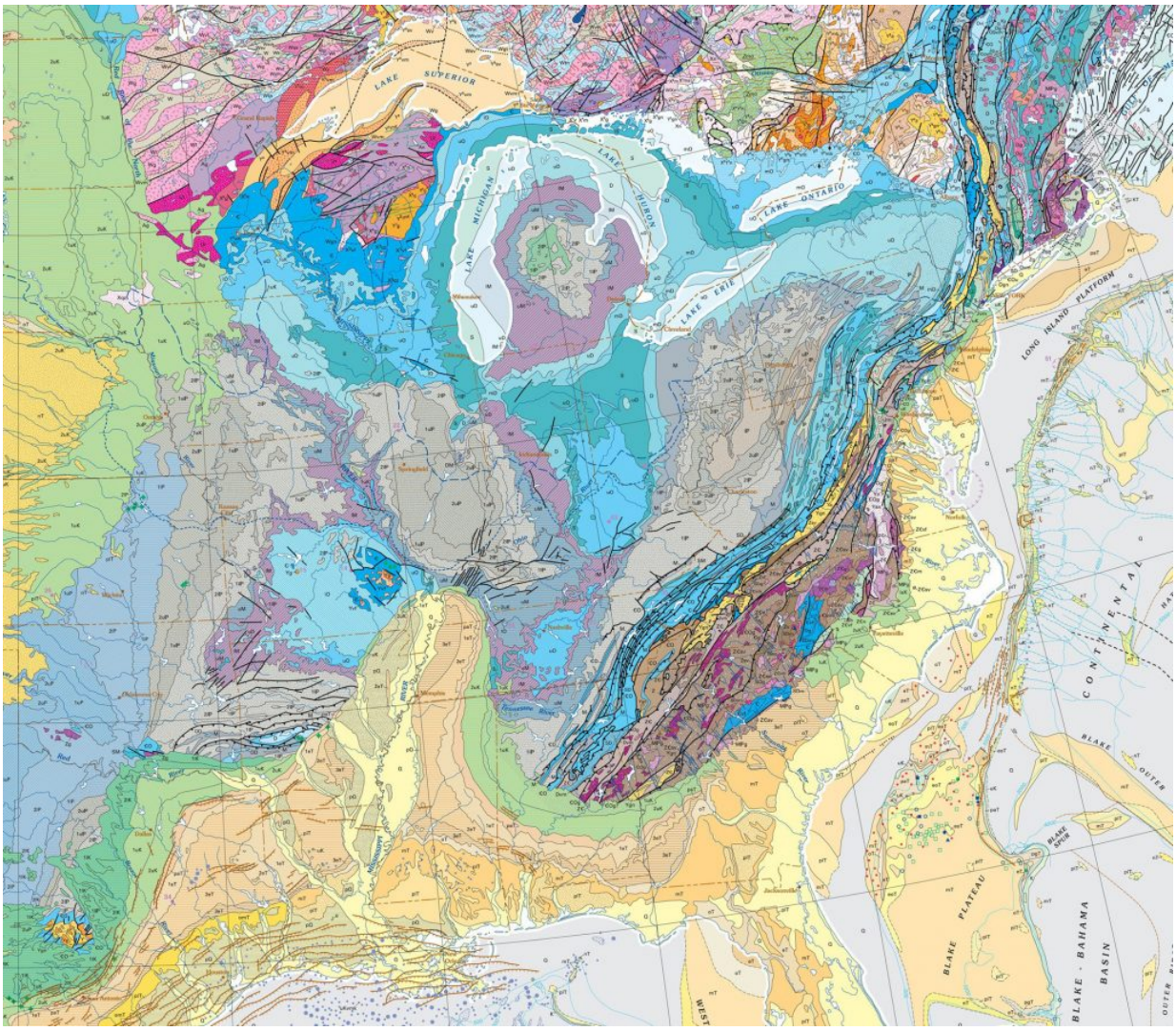


Figure 0.9 – Modern geologic map of the eastern United States. Note that this map covers about the same area as William Maclure's map in Figure 0.8. Image credit: Adapted from the USGS, Public Domain.

Do geologic maps intimidate you? Not to worry, we will break them down for you later on so you can walk away from this class like a map-reading pro. Now, on to Chapter 1.

Additional Information

Exercise Contributions

Virginia Sisson, Daniel Hauptvogel, and Ana Vielma

Google Earth Locations

Click or Scan to View all Chapter 0 Locations on Google Earth

This page titled 1.1: Geologic Skills is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.2: Plate Tectonics

Learning Objectives

The goals of this chapter are to:

- Identify types of plate boundaries and compare their characteristic earthquake and volcanic activities
- Assess the basic lines of evidence supporting plate tectonics
- Explain how ancient plate boundaries affect modern topography

1.1 Introduction

Plate tectonics is the grand unifying theory in geology. It gets that title because many topics in geology can be explained, in some way, by the movement of tectonic plates. Tectonic plates are composed of Earth's crust and the uppermost, rigid portion of the mantle. Together they are called the **lithosphere**. Earth's crust comes in 2 "flavors": oceanic and continental (Table 1.1).

Table 1.1 – Comparison of oceanic and continental crust

Property	Oceanic Crust	Continental Crust
Thickness	7-10 km	25-80 km
Density	3.0g/ cm^3	2.7g/ cm^3
Silica (SiO_2) Content	50%	60%
Composition	Fe, Mg, and Ca silicates	K, Na, and Al silicates
Color	Dark	Light

Lithospheric plates move around the globe in different directions and come in many different shapes and sizes. Their movement rate is millimeters to a few centimeters per year, similar to the rate that your fingernails grow. Motion between tectonic plates can be **divergent**, **convergent**, or **transform**. In divergent boundaries, plates are moving away from each other; in convergent boundaries, plates are moving toward each other; and in transform boundaries, plates are sliding past each other. The type of crust on each plate determines the geologic behavior of the boundary (Figure 1.1).

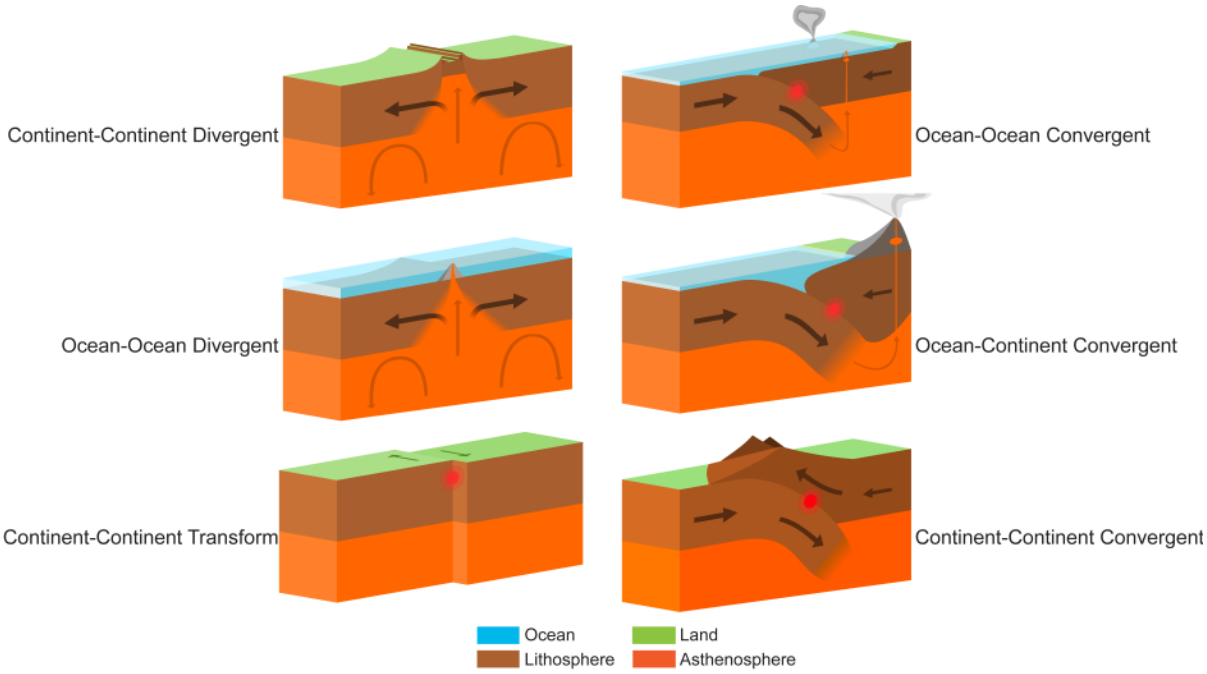


Figure 1.1 – These models show 6 main types of plate tectonic boundaries. Blue indicates ocean, green indicates land, brown indicates the lithosphere, and orange is the asthenosphere. The bold arrows on the plates indicate their relative motion. Also shown are gray volcanoes. Ocean-ocean transform boundaries (not shown) exist on a small scale associated with spreading at mid-ocean ridges, and continent-ocean transform and divergent boundaries are rare (former) or don't exist (latter). Image credit: Adapted from Wikimedia Commons user Domdomegg, CC BY.

The foundations of plate tectonics began with a German scientist named Alfred Wegener, who proposed the idea of **continental drift** in 1915. Think about it, 1915. What kind of evidence could someone possibly have to propose such a big idea? It turns out that Wegener had 4 pieces of evidence that he claimed supported his idea: 1) The continents looked like they fit together like pieces of a puzzle; 2) There were matching fossils on continents that were separated by oceans; 3) There were matching mountain ranges on continents that were separated by oceans; 4) There was **paleoclimate** evidence that suggested that in the past some continents were closer to the polar regions and some were close to the equator. Wegener took his idea one step further and proposed that all of the continents were together in one giant supercontinent 200 million years ago called **Pangea**. Like many great ideas in science, Wegener's idea of continental drift was not accepted by his peers, in part because he did not have a well-developed hypothesis to explain what was causing the continents to drift. It wasn't until the 1960's that his idea was expanded upon by scientists like Harry Hess.

? Exercise 1.1 – Reconstructing Positions of Continents Using Wegener's Evidence

When Alfred Wegener came up with his continental drift hypothesis in the early 1900s, he used several lines of evidence to support his idea. He also proposed that 200 million years ago, all continents were together in a single supercontinent called Pangea. In this exercise, you will use the fit of the continents and matching fossil evidence to piece together Pangea. This exercise is adapted from "This Dynamic Planet" by the USGS.

a. Individually or as a group, piece together the supercontinent Pangea.
   i. Label the landmasses of each continent in Figure 1.2.
   ii. Color the fossil areas to match the legend below.
   iii. Cut out each of the continents along the edge of the continental shelf (the outermost dark line).
   iv. Try to logically piece the continents together so that they form a giant supercontinent.
   v. When you are satisfied with the fit of the continents, discuss the evidence with your classmates and decide if the evidence is compelling or not. Explain your decision and reasoning on the evidence.

b. Pangea began to break apart about 200 Ma resulting in the formation of the Atlantic Ocean. Using the map in Figure 1.3, calculate the spreading rate of the Mid-Atlantic Ridge in mm/yr. (Hint: measure the distance from the easternmost tip of South America to the inside curve of western Africa).

_____

Table 1.2 – Symbol key to Figure 1.2

Symbol	Description
	The continents are surrounded by the continental shelf (stippled pattern), which extends beyond the continent until there is a large change in slope.
	By about 300 million years ago, a unique community of plants had evolved, known as the European ora. Fossils of these plants are found in Europe and other areas. Color the areas with these fossils yellow.
	Fossils of the fern Glossopteris have been found in these locations. Color the areas with these fossils green.
	Fossil remains of the half-meter-long fresh or brackish water (reptile) Mesosaurus. Mesosaurs flourished in the early Mesozoic Era, about 240 million years ago. Mesosaurs had limbs for swimming but could also walk on land. Other fossil evidence found in rocks along with Mesosaurs indicates that they lived in lakes and coastal bays or estuaries. Color the areas with these fossils blue.
	Fossil remains of Cynognathus, a land reptile approximately 3 meters long that lived during the Early Mesozoic Era about 230 million years ago. It was a weak swimmer. Color the areas with these fossils orange.
	Fossil evidence of the Early Mesozoic, land-dwelling reptile Lystrosaurus. They reproduced by laying eggs on land. Also, their anatomy suggests that these animals were probably very poor swimmers. Color the areas with these fossils brown.

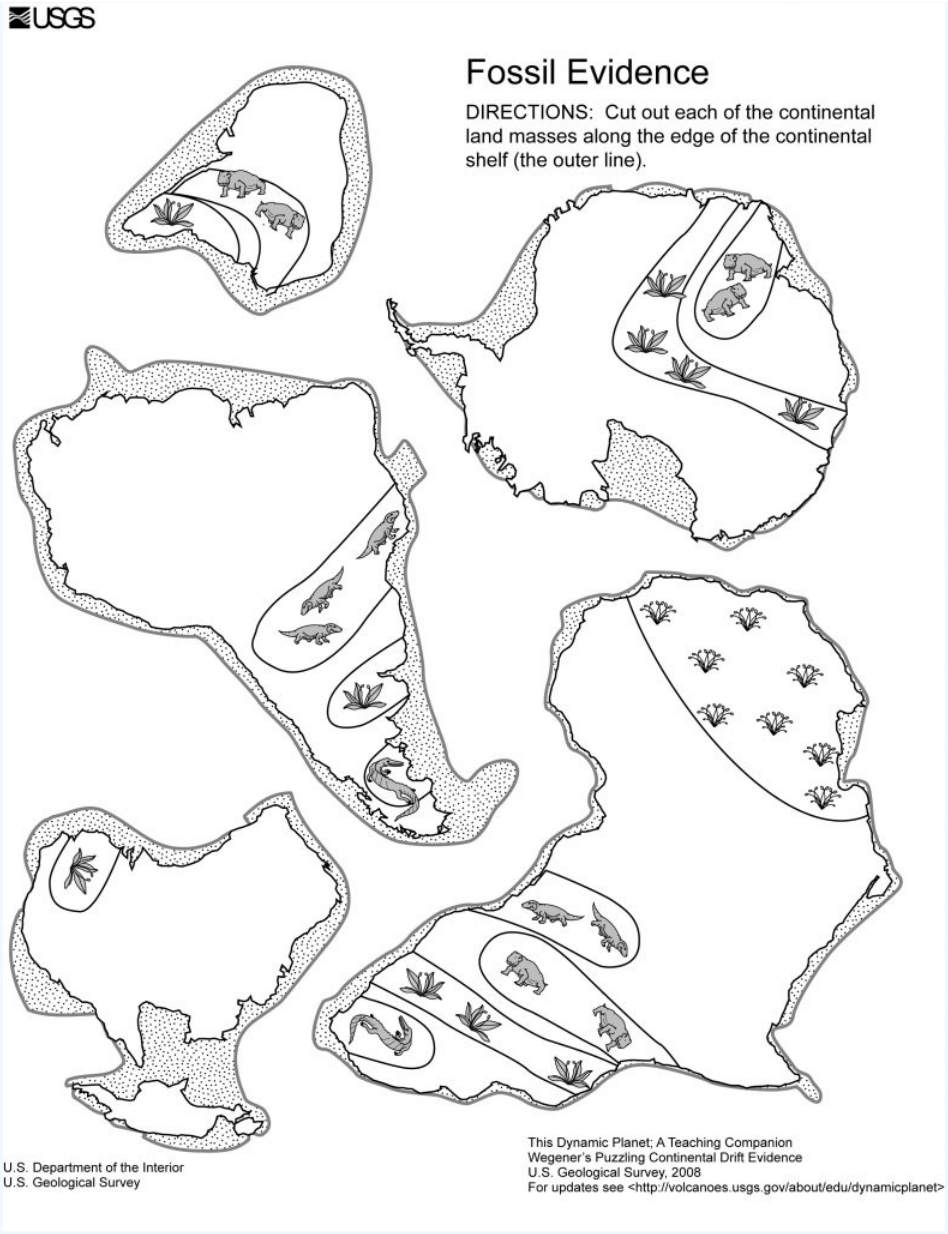


Figure 1.2 – Continent cut-outs for Exercise 1.1. Image credit: From the USGS, Public Domain.

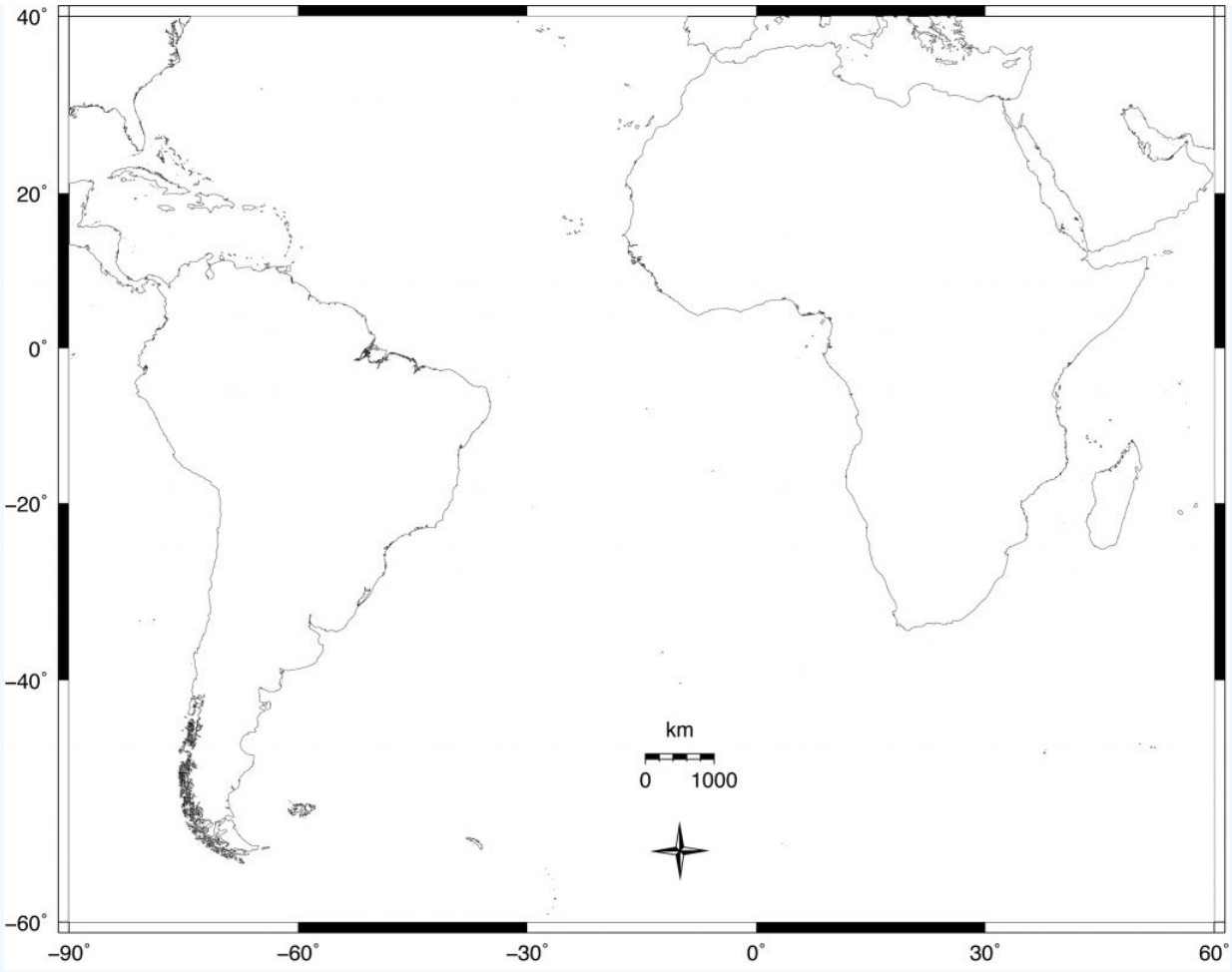


Figure 1.3 – Blank map of the South Atlantic Ocean for Exercise 1.1. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

1.2 Plate Tectonics, Earthquakes, and Volcanoes

Plate tectonic boundaries are often associated with earthquakes and volcanic activity. By looking at maps for the distribution of earthquakes and volcanoes worldwide (Figures 1.4-1.5), you can interpret the boundaries between the major tectonic plates. Generally, divergent plate boundaries are characterized by shallow earthquakes and some volcanism. Convergent boundaries have a range of earthquake depths from shallow to deep, and many have volcanoes as a result of **subduction**. Subduction occurs in convergent boundaries where the denser, oceanic plate descends into the mantle beneath the overriding plate. Convergent boundaries also tend to produce linear and curved **mountain belts**. Transform boundaries typically have shallow earthquakes and no volcanoes.

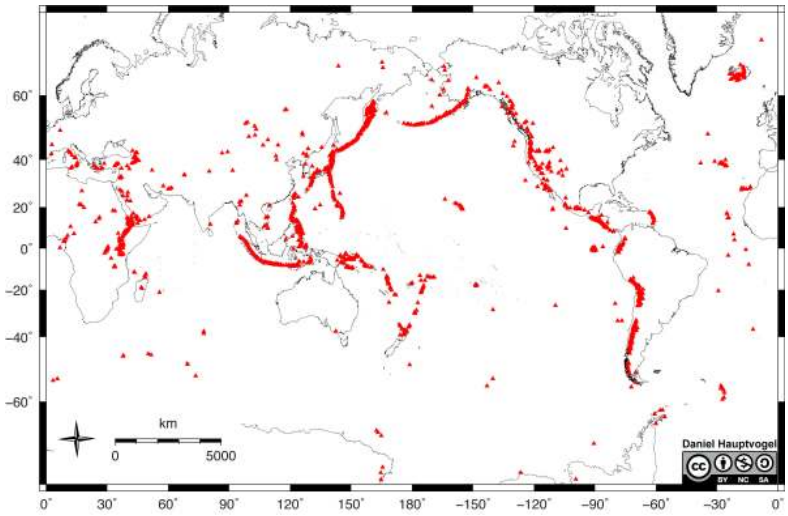


Figure 1.4 – This map shows the location of volcanoes that have been active within the past 10,000 years (red triangles). Map scale reference is 30° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

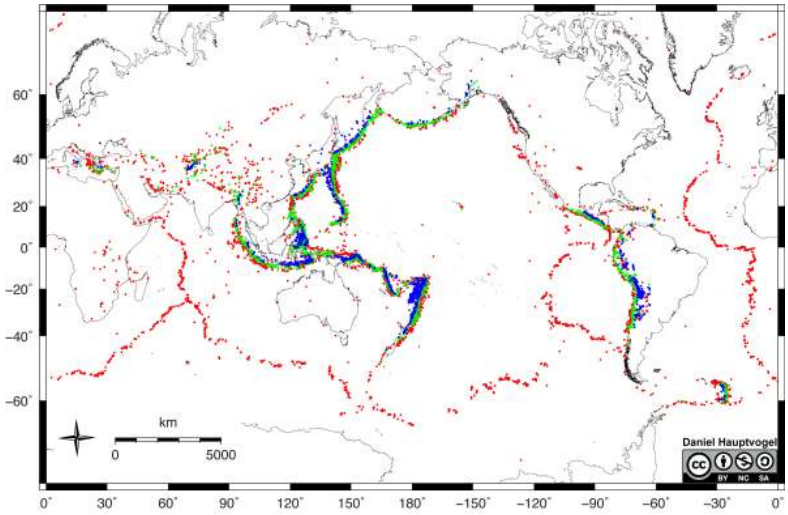


Figure 1.5 – This map shows the locations of all earthquakes with a magnitude greater than 4.5 for the years 2015 and 2016. The colors indicate earthquake depth; red <35 km, green 35-100 km, and blue >100 km. Please note that many red dots are overlaid by green dots on this map. Map scale reference is 30° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

? Exercise 1.2 – Modern Examples of Plate Tectonic Boundaries

Each type of plate boundary has distinct earthquake and volcanic patterns. Using observational and critical thinking skills, answer the following questions:

a. Observe the patterns amongst the earthquake and volcano location maps (Figures 1.4-1.5). Hypothesize where you think the major plate boundaries exist and draw those boundaries on the blank map in Figure 1.6 using three different colors to identify the type of motion for each boundary (example: red for divergent boundaries, blue for convergent boundaries, and green for transform boundaries).

b. Which type of boundary (divergent, convergent, or transform) is the most abundant?

_____

c. On the same map where you drew in plate boundaries (Figure 1.6), identify locations where each type of these boundaries are located:

i. Continent-Continent Convergence (CCC)
ii. Ocean-Ocean Convergence (OOC)
iii. Continent-Ocean Convergence (COC)
iv. Continent-Continent Divergence (CCD)

v. Ocean-Ocean Divergence (OOD)
vi. Continent-Continent Transform (CCT)

d. What type of plate boundary is associated with most of the deep earthquakes?_____

e. Describe the pattern in earthquake depth from the coast to inland at subduction zones.

f. **Critical Thinking:** The San Andreas Fault in California is a transform fault. Is there any evidence in the earthquake and volcanic activity that suggests this fault did not always have transform motion? Explain.

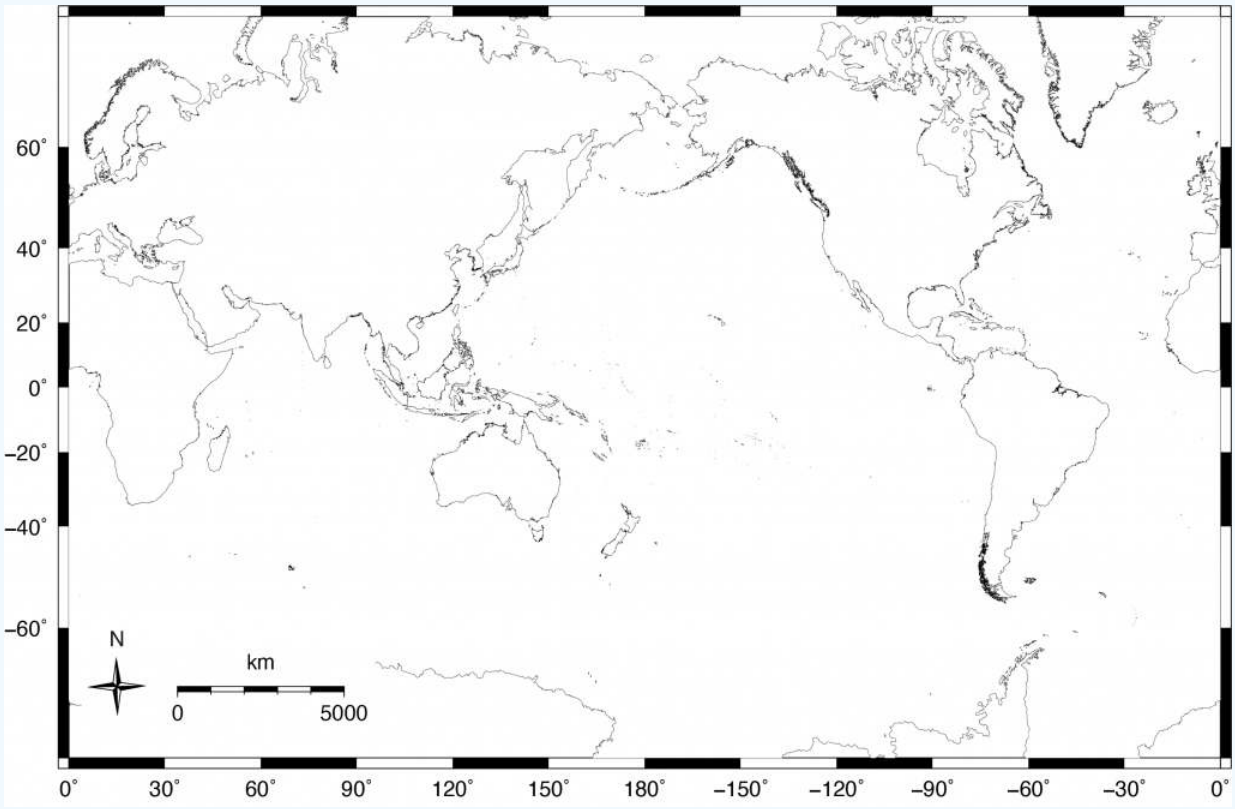


Figure 1.6 – This is a blank map of the world to be used in Exercise 1.2. Map scale reference is 30° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

Earthquake locations can tell you more about an area than what type of plate boundary is there. For example, in subduction zones, most earthquakes occur along the boundary between the subducting slab and the overriding slab. The angle of subduction is not always constant and can vary from one boundary to the next and can even vary along the same boundary. When a plate subducts at a low angle, it is called flat-slab subduction. The effects of flat-slab subduction are many, including shallower earthquakes, uplifting of mountains, and the location and activity of volcanoes.

? Exercise 1.3 – Interpreting Subduction Angle from Earthquake Data

The Western margin of South America is a tectonically active region where the Nazca Plate subducts under the South American Plate (Figure 1.7), creating the Andes Mountains. Even though the entire coast is part of the same subduction zone, the subduction process doesn't look the same throughout. Tables 1.3 and 1.4 contain earthquake data from two different locations of the subduction zone, one from central Chile and another near the Chile-Peru border. The location data are the distance each earthquake was from the **trench** and how deep within the Earth it was.

a. Using the graph paper provided by your instructor, plot the distance of the earthquake foci (hypocenters) from the trench on the horizontal axis and the depth of the earthquakes on the vertical axis; the recommended scale is 1 cm = 10 km. Connect the plotted points to create an approximate cross-section of the subduction zone at the two locations.

b. Look at the graph you made, which region has a steeper subduction angle, the Chile-Peru border or central Chile?

_____

c. Partial melting of the asthenosphere above the subducting slab occurs at a certain depth and leads to volcanism. In which location do you think volcanoes are closer to the coastline? Why?

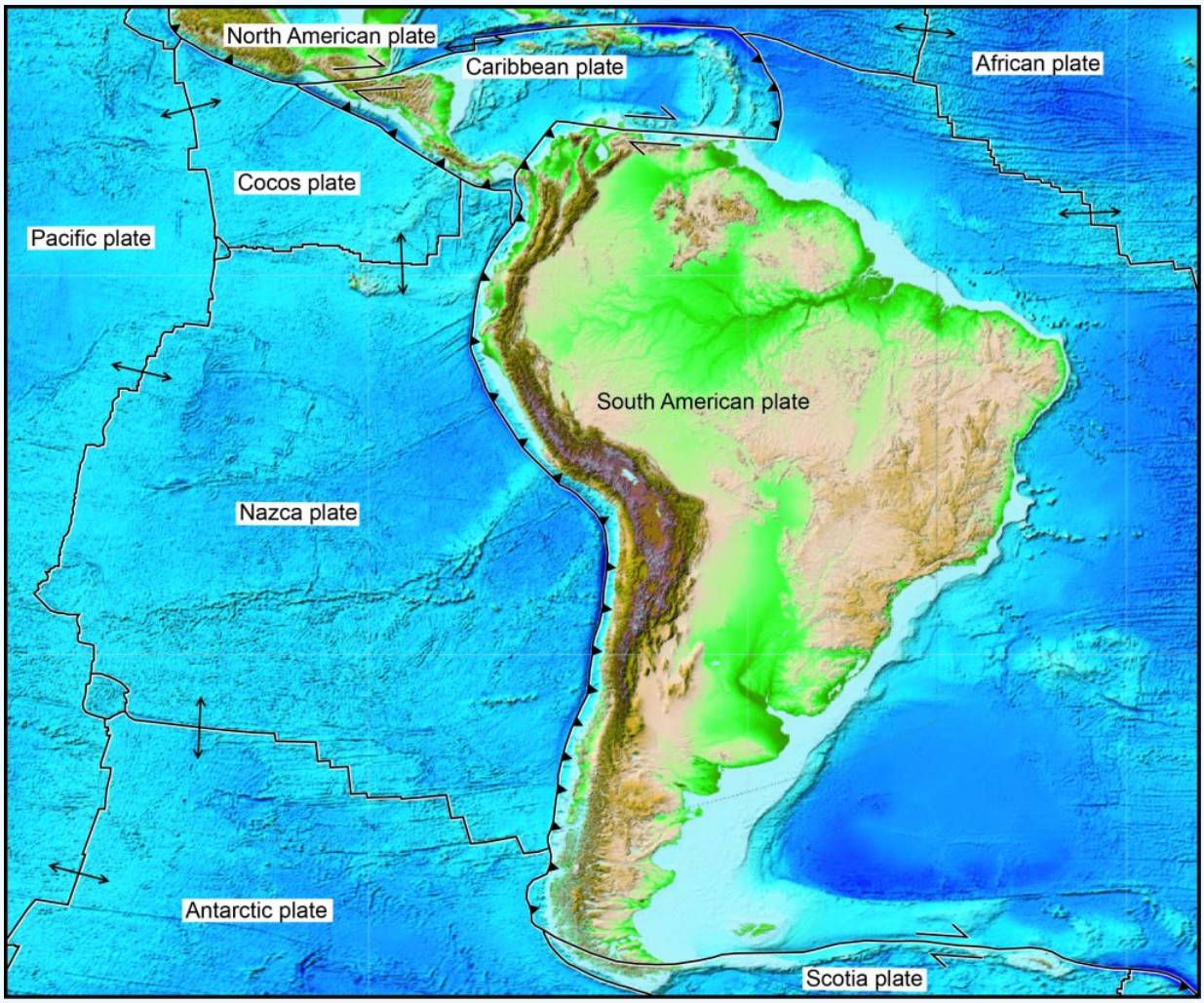


Figure 1.7 – Plate tectonic map of South America and adjacent plates. Boundaries marked with triangles represent convergent zones. Two arrows in opposing directions indicate divergent boundaries. Transform boundaries have arrows showing motion to both right and left. Red and white colors represent high elevations, greens and yellow represent lower elevations, and purple and blue represent areas below sea level. Image credit: Tectonic boundary map drawn using GPlates software.

Table 1.3 – Earthquake location data from the Chile-Peru Border (data from Martinod et al., 2010)

Distance from trench (km)	Depth (km)
160	10
200	30
220	50
300	65
370	125
500	190
300	100
250	65
210	40
280	80
450	175
400	140
410	150

Table 1.4 – Earthquake location data from central Chile (data from Martinod et al., 2010)

Distance from trench (km)	Depth (km)
100	10
170	40
220	65
400	90
200	50
120	20
500	110
350	85
300	75
250	60
280	75
200	55
250	90

1.3 Plate Tectonics and Topography

Geologists can observe most of the processes occurring at plate tectonic boundaries today (earthquakes, volcanoes, mountain building, etc.). However, understanding the plate tectonic activity of the geologic past is more difficult because the events have already happened. Hence, geologists use processes that occur in the present to interpret processes that occurred in the past. This is known as **uniformitarianism**. One way geologists can interpret ancient plate tectonic activity is to look at the topography of an

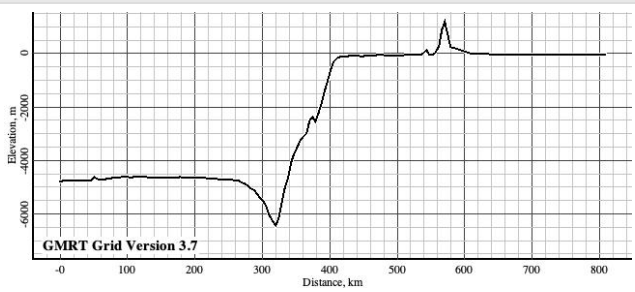
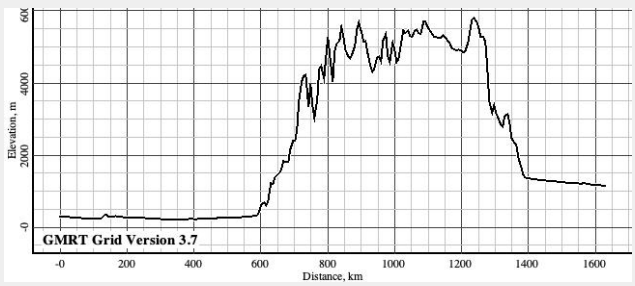
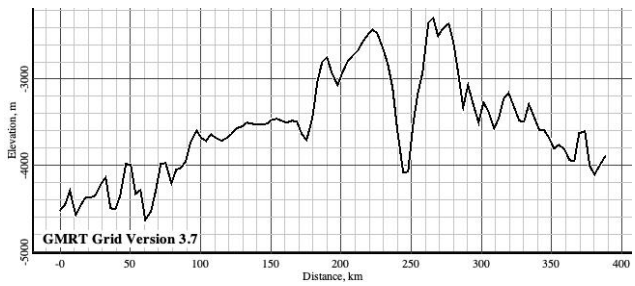
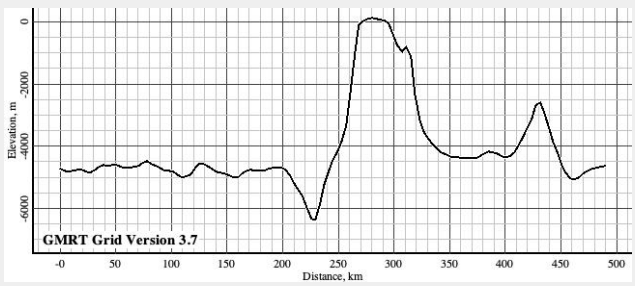
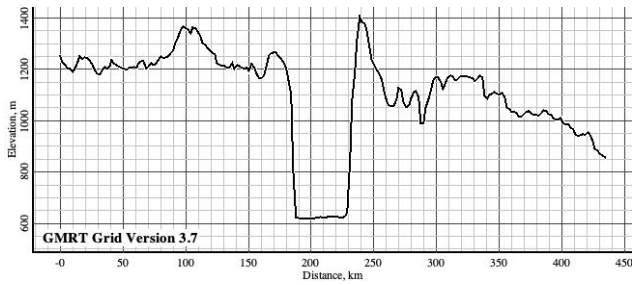
area. Topography is the study of shapes and features of the land surface. When studying features on the seafloor, the topography is instead referred to as bathymetry because this data is referencing how deep a feature is. There are numerous ways of looking at the topography of Earth's surface, including satellite imagery, topographic maps, shaded relief maps, and digital elevation models.

? Exercise 1.4 – Interpreting Plate Boundaries from Topographic Profiles

Below are five topographic profiles showing different plate boundary configurations. A topographic profile is a graph that shows elevation changes as you walk from one point on the Earth to another. These are all made with vertical exaggeration (length/elevation) of 50:1. This overemphasizes the changes in topography. In all of these profiles, the 0 value on the vertical axis is at sea level.

a. For the topographic profiles in Table 1.4, identify what types of plate boundaries are shown using the names from Figure 1.1. Pay close attention to the y-axis versus x-axis.
b. On each profile, draw the location of the boundary between the two plates. You can show this as a single line.
c. For each profile, label features such as oceanic and/or continental crust, mid-ocean ridges, volcanoes, mountain belts, and trenches.
d. Indicate which direction each tectonic plate is moving (you can use arrows for this).

Table 1.5 – Unknown topographic profiles and answer area for Exercise 1.4

Profile	Type of Boundary
	
	
	
	
	

Geologists can use topography to get a broad sense of the tectonic history of an area. Generally speaking, plate tectonic activity tends to produce elevation changes at or near the plate boundary, especially in convergent settings. The collision of two plates leads to **suturing**; the two plates become one when the collision ends. Evidence of these ancient boundaries is most commonly in the form of linear mountain belts that are not currently near a plate tectonic boundary. For example, an eroded, linear mountain belt in the middle of a continent would indicate that area was part of a convergent boundary deep in the geologic past and likely a

continent-continent collision. The Ural Mountains in Russia fit this description (Figure 1.8). They formed during an **orogeny** 240 to 300 million years ago and now serve as the boundary between Europe and Asia.

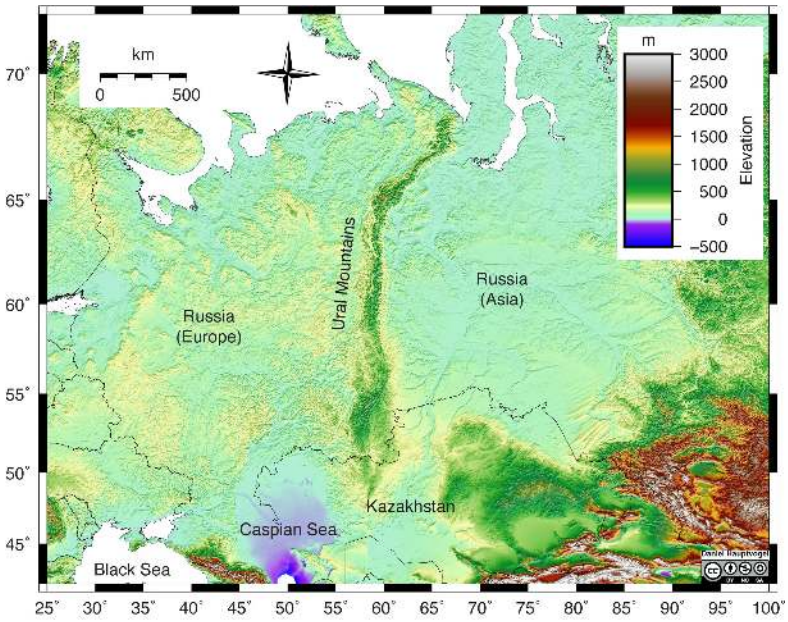


Figure 1.8 – Shaded relief map of the Ural Mountains in Russia. Red and white colors represent high elevations, greens and yellow represent lower elevation, and purple and blue represent areas below sea level. The Ural Mountains are a narrow, linear chain of mountains that trend north-south through Russia. Map scale reference is 60° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

? Exercise 1.5 – Interpreting Ancient Plate Tectonic Boundaries

a. Over time mountain ranges are weathered and eroded, and the topography slowly goes back to base level. Which do you think is more likely to be older, a mountain belt with higher elevations or a mountain belt with lower elevations? Explain your reasoning.
b. Look at the topographic map for part of North America (Figure 1.9). Mark two areas that you think have been through major convergence of tectonic plates.
c. Which of the two areas do you think is older? What evidence from the map supports your hypothesis?
d. Look closely at the western portion of the North American continent. You should be able to notice differences in the patterns that make up the mountains. Each pattern represents a different geologic region. Draw boundaries on the map that separate these different geologic regions and then describe the patterns you observed to distinguish them (Hint: There are at least three).
e. Tectonic plate activity is often associated with mountain building. Based on Australia's topography (Figure 1.10), explain whether or not you think the region is tectonically active today?
f. On the topographic map of Australia (Figure 1.10), mark an area that you think was a plate boundary in the geologic past but is no longer active today. Explain your reasoning for marking this area.
g. **Critical Thinking**: Both of these maps contain areas on continents that are below sea level. Come up with a hypothesis that explains how this can happen.

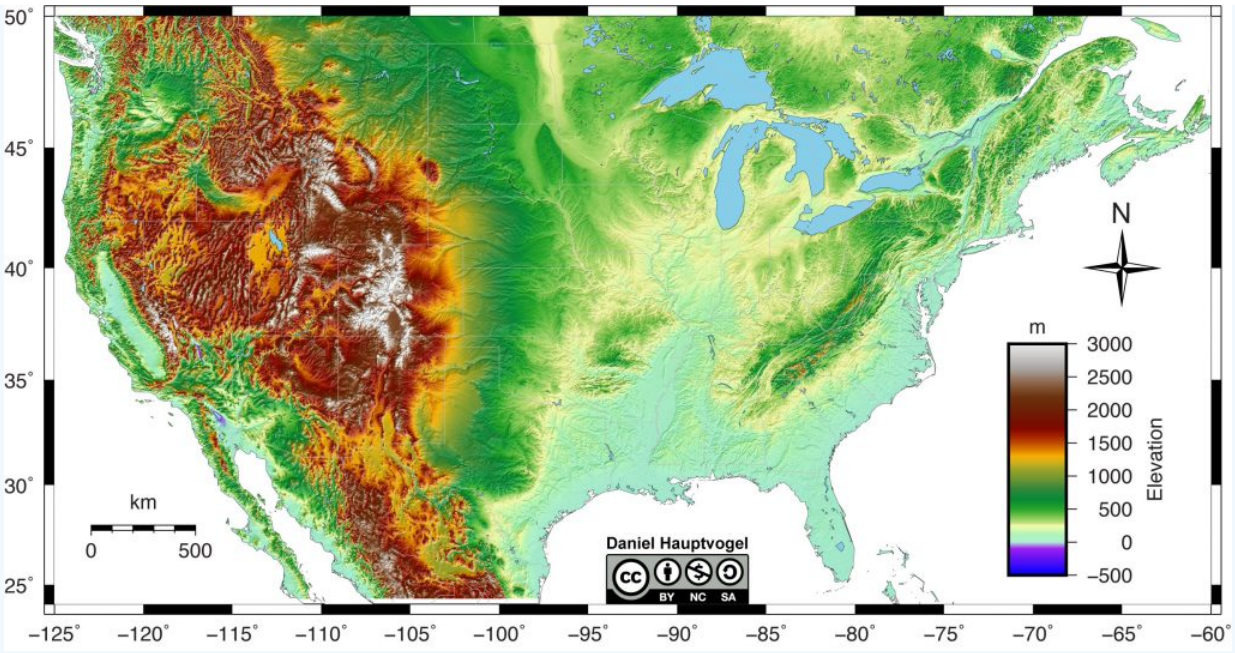


Figure 1.9 – Shaded relief map of the United States. Red and white colors represent high elevations, greens and yellow represent lower elevation, and purple and blue represent areas below sea level. Map scale reference is 40° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

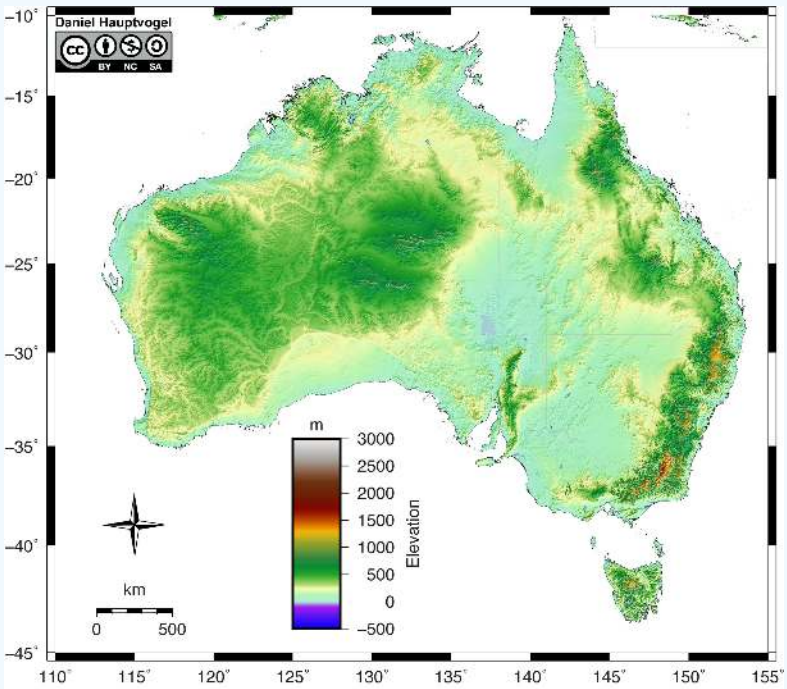


Figure 1.10 – Shaded relief map of Australia. Red and white colors represent high elevations, greens and yellow represent lower elevations, and purple and blue represent areas below sea level. Map scale reference is -20° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

When most people think about tectonic plate boundaries, they often visualize parallel, symmetric lines separating the plates. This is not always the case in the real world as many plate boundaries are curved or segmented; this is because Earth is a sphere. Think about this: if you had a ball and tried to wrap it with a flat sheet of paper, would the paper wrap around it perfectly smooth? The answer is no; the paper will want to fold in some places and tear in other places. The tectonic plates behave similarly to the paper. Of course, other factors affect the shape of a boundary. Evidence of these plate boundaries is also contained in the topography of continents because not all mountain belts are straight lines.

Exercise 1.6 – Ancient Plate Boundaries in Texas, Oklahoma, New Mexico, and Northeastern Mexico

Below is a topographic map of Texas, Oklahoma, New Mexico, and northeastern Mexico (Figure 1.11). This area is not near an active plate tectonic boundary today; the closest boundary is in the Gulf of Mexico. However, there is evidence in this topography to indicate it was part of a plate tectonic boundary at least twice in the geologic past.

a. Based on the topography, mark two areas that have been part of a plate tectonic boundary in the geologic past. Topographic changes do not need to be symmetric as some tectonic processes are not symmetric.
b. One of these boundaries is older than the other. Label the old and young boundaries.
c. One of these boundaries has highs and lows within the belt. What tectonic process creates low topography?
d. One of these boundaries splits into two branches. What is the angle between these branches?

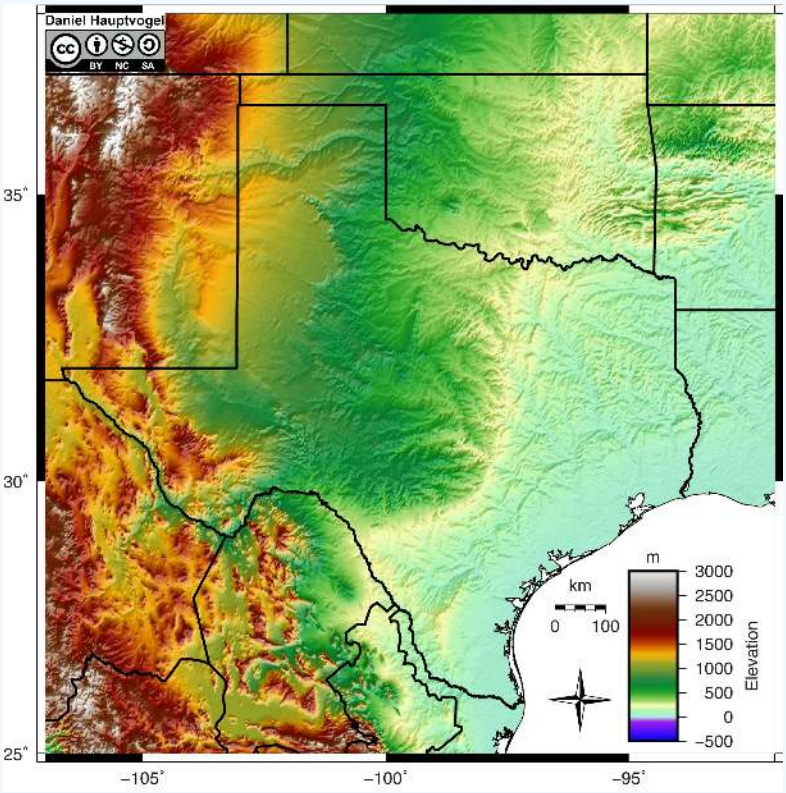


Figure 1.11 – Shaded relief map of Texas. Red and white colors represent high elevations, greens and yellow represent lower elevations, and purple and blue represent areas below sea level. Map scale reference is 30° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

As tectonic plates move, they ride over stationary "**hotspots**" of heat from the **mantle**. Hotspots are still a poorly understood geologic phenomenon, but they allow extremely hot mantle material to rise close to the surface. Hotspots are marked by volcanoes, which come from melting of the mantle and crust directly above a hotspot. If they occur under oceanic crust, they produce basalts. On the other hand, if they are under continental crust, they form both basalts and rhyolites, often called bimodal volcanism. Under North America, there are two hotspots: The Yellowstone hotspot, which is currently under Yellowstone National Park in Wyoming and Montana, and the Anahim hotspot in central British Columbia, Canada. As the North American Plate moves over these hotspots, calderas form from volcanic activity; one of the largest volcanic eruptions ever occurred when the Gray's Landing volcanics erupted 8.72 million years ago above the Yellowstone hotspot. One of the controversies is whether the hot spot is still capable of supereruptions or whether the volume of eruptive material is waning.

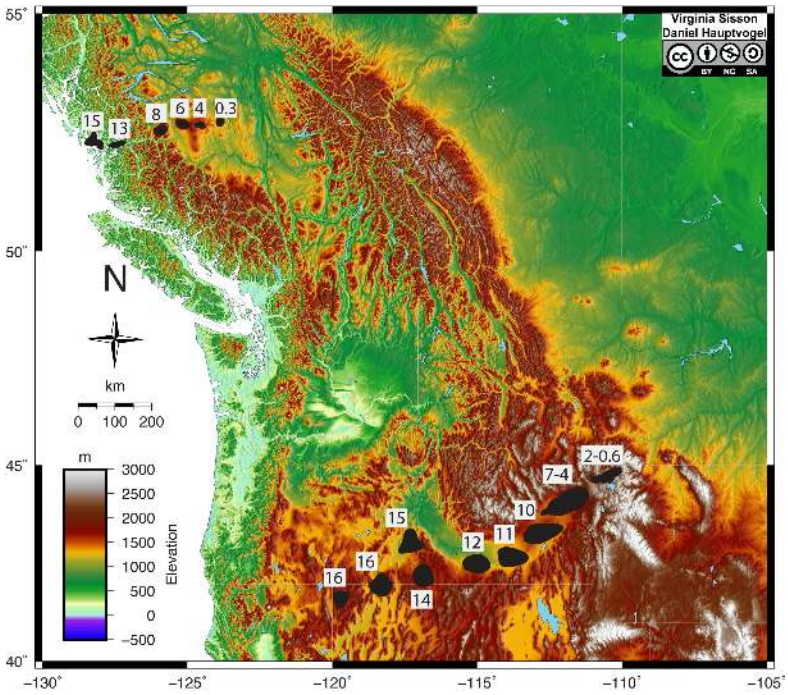


Figure 1.12. – A topographic map for the northwestern United States and southwestern Canada. Superimposed is the distribution of volcanic activity (black areas) for both the Anahim (northern chain of volcanoes and plutons) and Yellowstone (southern chain of volcanoes). These chains of volcanoes are called hotspot tracks. Next to each volcanic area is the age of the initial volcanism in millions of years. Some of these locations have more than one caldera; these overlap in space and time. Red and white colors represent high elevations, greens and yellow represent lower elevation, and purple and blue represent areas below sea level. Map scale reference is 45° latitude. Image credit: Virginia Sisson and Daniel Hauptvogel, CC BY-NC-SA. Location of volcanic centers adapted from Wikimedia Commons Sémhur CC BY-SA for the Anahim hotspot and Kelvin Case CC BY for the Yellowstone hotspot.

? Exercise 1.7 – Tracking North American Hotspots

Use Figure 1.12 to answer the following questions about North American hotspots.

a. Use a protractor to measure the direction of the plate motion for each hotspot track. This is called the azimuth and is usually measured clockwise from the north.

   i. Angle for Yellowstone: _____

   ii. Angle for Anahim: _____

b. How fast is the North American plate moving over these hotspots? Measure the length of the hotspot eruptions from the youngest to oldest. If you divide the length by the maximum age, this will give you the rate of plate motion. Convert this to mm/year (km/my) as most plate motions are low-velocity rates.

   i. Rate of plate motion for Yellowstone: _____

   ii. Rate of plate motion for Anahim: _____

   iii. Are these the same for the two hotspots? _____

   iv. If not, why are the azimuth and the rates different if North America is a rigid plate tectonic block?

   The answer may not be apparent as we don't often move things around on a sphere. Instead, we think of motion as a straight line from point a to point b. These hotspots are on the North American plate which means the plate rotates around a point in the middle of northern Quebec. Since they rotate around a point on a sphere, different locations on the plate move at dissimilar speeds and directions. Geoscientists call this an Euler pole.

c. Geoscientists have measured instantaneous global plate motions through various techniques such as global positioning satellites (GPS) and very-long baseline interferometry (VLBI). This data is used to calculate the rates of motion between two plates. There are several online plate motion calculators available; we will use the one created by UNAVCO. Use the

latitude and longitude for the young end of each hotspot and calculate the rate and direction of plate motion. Fill this out in Table 1.6. This website will give you other information that is not relevant to this lab exercise.

Table 1.6 – Answer area for Exercise 1.7c

Hotspot	Speed (mm/yr)	Azimuth Direction
Yellowstone		
Anahim		

d. **Critical Thinking:** Are the UNAVCO results similar to your calculated results from *b*? If not, why might you get different answers?
e. Has the rate of motion of the North American plate been constant along the hotspot track?
f. Which hotspot track has more volcanism? Yellowstone or Anahim? Be sure to compare the volcanism over the same time period. Consider the size of the calderas when you answer this question.
g. **Critical Thinking:** Can you explain why one of these has larger volcanic eruptions? You may be able to use the topography to help you understand each area's tectonic history to help you answer this question.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Carlos Andrade, Melissa Hansen

References

Knott, T.R., Branney, M.J., Reichow, M.K., Finn, D.R., Tapster, S., and Coe, R.S., 2020, Discovery of two new super-eruptions from the Yellowstone hotspot track (USA) Is the Yellowstone hotspot waning? Geology, v. 48, p. 934-938. doi.org/10.1130/G47384.1

Martinod, J., Husson, L., Roperch, P., Guillaume, B., and Espurt, N., 2010, Horizontal subduction zones, convergence velocity and the building of the Andes. Earth and Planetary Science Letters, v. 299, pp. 299-309. DOI:10.1016/j.epsl.2010.09.010.

Google Earth Locations

Click or Scan to View all Chapter 1 Locations on Google Earth

This page titled 1.2: Plate Tectonics is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.3: Earth Materials

Learning Objectives

The goals of this chapter are to:

- Identify common minerals based on physical properties
- Classify rocks based on texture and mineral composition
- Interpret environments in which igneous, sedimentary, and metamorphic rocks are formed
- Reconstruct the transport and depositional history of sedimentary rocks

2.1 Introduction

Minerals are the basic building blocks of rocks, which means rocks are made up of different combinations of minerals or just one mineral in some cases. Figure 2.1a is an example of a rock called **granite**, which is made up of a combination minerals. A mineral is a naturally occurring, usually inorganic, solid that can be defined by a chemical formula and a crystal structure. Figures 2.1b and 2.1c are two other types of rocks, **sandstone** and **gneiss**, that contain the same minerals as the granite in Figure 2.1a. Even though they contain the same minerals, all three of these rocks formed in different ways. We'll get to that a little later, so for now, let's focus on minerals.

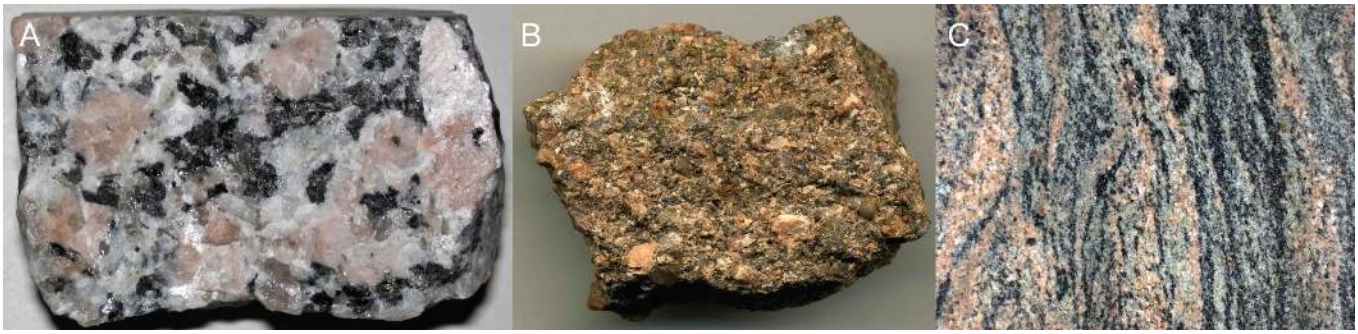


Figure 2.1 – These are three different types of rocks that contain the same minerals: A) granite; B) arkose sandstone; C) gneiss. Pink minerals are K-feldspar, clear minerals are quartz, white minerals are plagioclase feldspar, and black minerals are biotite. Image Credit: James St. John, A, B, and C.

2.2 Minerals

According to the International Mineralogical Association, there are 5,575 known minerals, but most rocks are composed of just a few common minerals. In fact, only seven minerals make up 84% of Earth's crust (Figure 2.2). So when you find an unknown rock, there is a good chance that at least one of those seven minerals will be present.

https://geo.libretexts.org/@go/page/18710

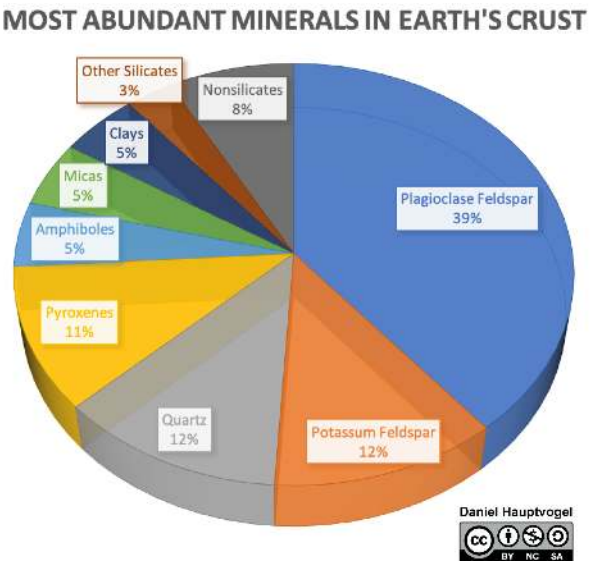


Figure 2.2 – This pie chart shows the distribution of minerals in continental crust. Silicate minerals, structures based around the silicon-oxygen tetrahedron, are the most abundant, making up 92% of all minerals in Earth's crust. Image Credit: Daniel Hauptvogel, CC BY-NC-SA.

Geologists can take rocks and minerals back to their laboratories and run in-depth chemical analyses to determine what minerals they have collected. You don't have that luxury when you're working in the field or the classroom, though. Instead, many minerals can be identified based on a few observable properties that don't require high-tech, expensive equipment. So, distinguishing these seven common minerals and others is easier than you think. The common, observable properties of minerals are:

- Color
- Luster
- Streak
- Hardness
- Cleavage/Fracture

Color

The color of minerals comes from small impurities in the chemical composition. Sometimes elements substitute for one another in the atomic structure of minerals, leading to significant changes in color. It is perhaps the most straightforward observable property, but it is rarely a diagnostic property for most minerals because the same mineral can come in various colors. Quartz, for example, can come in just about any color (Figure 2.3).



Figure 2.3 – Quartz in six color varieties. Color may not be a diagnostic property for mineral identification. Other quartz colors include green, red, orange, and brown. Image credit: Karla Panchuck, CC BY-NC-SA.

Luster

The term **luster** describes how light interacts with the surface of a mineral. There are many different terms used to describe the luster of a mineral, but for this lab manual, we are only concerned with metallic and non-metallic lusters (does it look like a metal or does it not look like a metal, respectively; Figures 2.4a and 2.4b). Be careful, though, because shiny doesn't always mean it's

metallic. The technical difference between metallic and non-metallic is that metallic minerals do not allow light to pass through the atomic structure, and non-metallic minerals do allow some light to pass through.



Figure 2.4a – Pyrite, a mineral with a metallic luster. Image credit: Wikimedia Commons user JJ Harrison, CC BY-SA.



Figure 2.4b – Quartz, a mineral with a non-metallic luster and six-sided crystal form. Image credit: Wikimedia Commons user Didier Descouens, CC BY-SA.

Streak

Streak is the color of a mineral in powdered form, which is observed by scratching the mineral across a ceramic streak plate (Figure 2.5). The powder color can be different from the mineral color because, when in powdered form, the mineral's impurities do not significantly affect the absorption of light. The way light is absorbed and reflected is what gives things color. Streak is only a diagnostic property for metallic minerals because most other minerals have the same streak color as the hand-sample color or the streak is white.



Figure 2.5 – Four different dark gray metallic minerals with varying streak colors. The minerals are from the upper left clockwise: hematite (red-brown), magnetite (black), sphalerite (honey-brown), and galena (dark gray). Image credit: Karla Panchuck, CC BY-NC-SA.

Hardness

The **hardness** of a mineral is a mineral's ability to resist abrasion or scratching. Hardness is determined using the Mohs' scale of mineral hardness (Figure 2.6), developed by Frederich Mohs in 1822. Mohs' scale is qualitative, which means there is no quantitative relationship between hardness values; a 10 on the Mohs scale is not 10 times harder than a 1. The scale is based on the relative relationship between 10 different minerals.

How do you determine mineral hardness? When identifying mineral hardness in the classroom, you can use common objects with a hardness value defined on the Mohs scale. These common objects and their hardness are located on the right side of Figure 2.6.

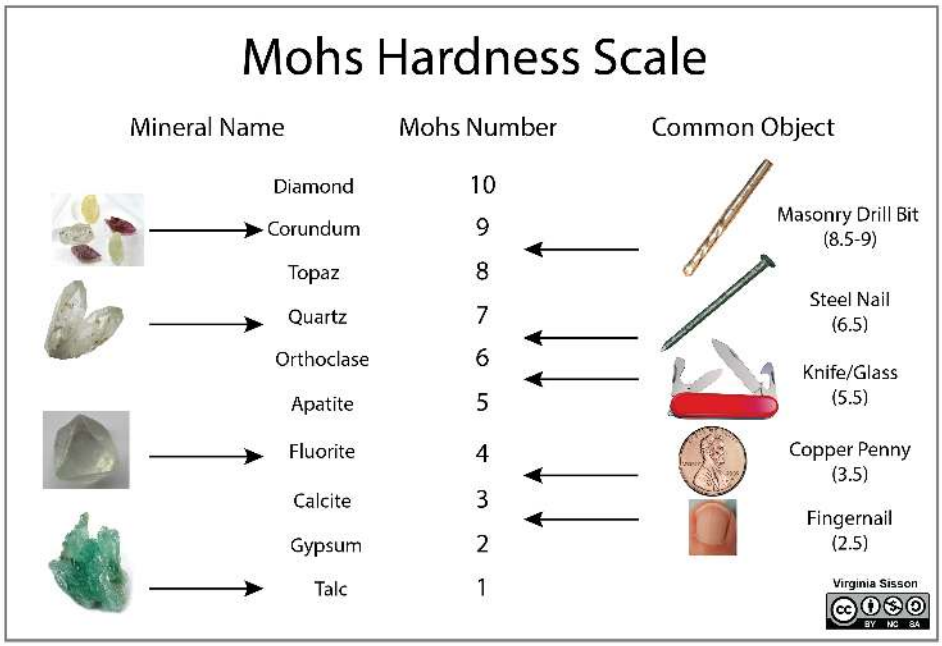


Figure 2.6 – This is the Mohs scale of relative mineral hardness that uses 10 minerals with no quantitative relationship between the values. Lower numbers mean softer minerals; higher numbers mean harder minerals. On the right side is a list of common objects and their Mohs hardness used to test unknown minerals. Note: manufacturing differences can make the hardness of these common objects vary slightly. Image credit: Virginia Sisson, CC BY-NC-SA.

Cleavage/Fracture

Cleavage is a term used to describe minerals that break in a predictable way. When minerals break along planes in which chemical bonds are weak, they produce flat surfaces called cleavage planes. Minerals can have 1, 2, 3, or more planes of cleavage (Figure 2.7). When there is more than one plane, the angle between the planes can also be described. Cleavage is one of the most challenging concepts for introductory geology students, but it is a useful property to identify minerals. For example, amphibole and pyroxene have the same physical properties except for cleavage. Knowing whether a rock contains amphibole or pyroxene could reveal a lot about that rock's geologic history, such as where and how it most likely formed.

While the concept of mineral cleavage is difficult, identifying cleavage in minerals doesn't have to be. When looking at a mineral, the easiest way to identify cleavage is to shine a light on its surface. If that surface brilliantly reflects light, then you most likely have a cleavage plane. Today, just about everyone has a cell phone with a flashlight that can be used to identify cleavage. In the absence of that, you can move the mineral around underneath an overhead light or use sunlight.

Minerals don't always break in predictable ways, and that's when we use the term fracture. Fracture describes irregular breakage in minerals, which usually occurs on mineral planes that don't have any weak bonds. This sounds easy enough; flat surfaces mean cleavage, and uneven surfaces mean fracture, but the truth is that it can be messy. Minerals can appear to have flat surfaces that are not actually cleavage, and fracturing can occur along planes of cleavage. This is why you need to look closely at the surface of a mineral using a hand lens.

A hand lens is a magnifying glass to help geologists look closely at rocks and minerals. To use the hand lens properly, you need to place the lens up against your face and then move the mineral or rock sample back and forth to get it into focus. A common mistake students make is holding the mineral or rock still and moving the hand lens; this is incorrect and will not help you see small-scale features in rocks and minerals.

Another thing that makes identifying cleavage difficult is the entire mineral sample does not have to take on the shape of the cleavages. The minerals in Figure 2.7 are examples where the samples do take on the cleavage shape, but this is not the case for most minerals. Instead, you need to use a hand lens to look at the small details of a single side of the mineral. There will be slight changes in the heights of the surface that you wouldn't be able to see without the hand lens. It is along those "elevation" changes that you should be looking for signs of cleavage. Then repeat your examination on the other sides.

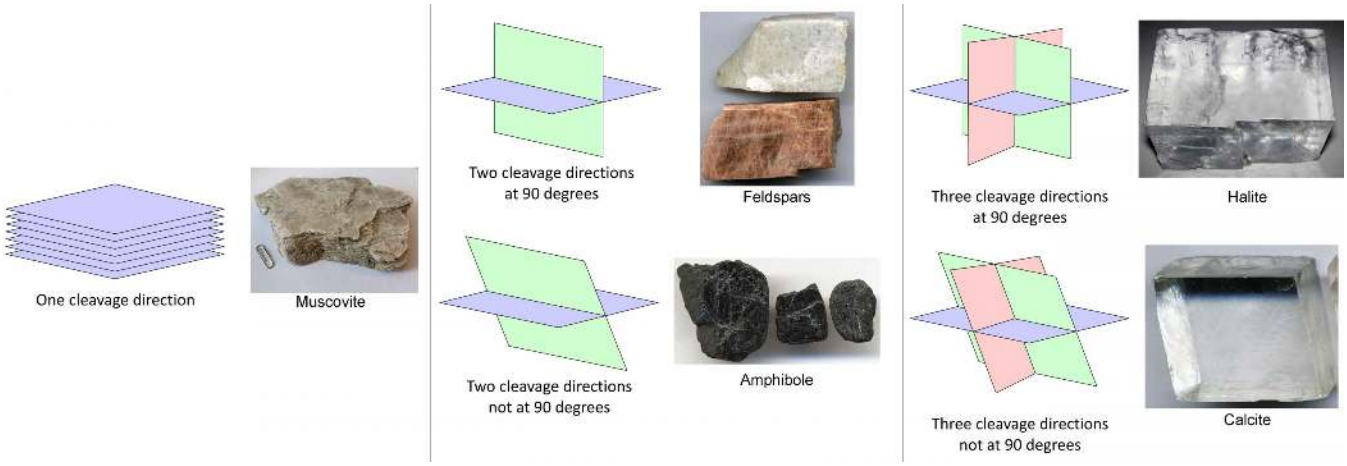


Figure 2.7 – Types of cleavage with mineral examples. Cleavage differs by the number and angle between cleavage planes. Image credit: cleavage models adapted from M.C. Rygel; muscovite from Daniel Hauptvogel, all other minerals from James St. John, CC BY-SA.

? Exercise 2.1 – Identifying Common Minerals

Your instructor will provide you with a set of unknown minerals. Identify each mineral based on its physical properties using either Table 2.1 as your guide or the mineral flow charts in Figures 2.8, 2.9, and 2.10. Fill in this information in Table 2.2. There are also many online guides to help you identify minerals, such as MineralID, Smart Geology (Android), or the app Mineral Identifier (Apple).

Table 2.1 – Physical properties of common minerals

Hardness	Color	Cleavage	Other	Mineral Name
1-2	Colorless	One plane	“Chewy”	Clays
2-2.5	Colorless, light tan, yellow	One plane	Can be peeled into transparent, flexible sheets	Muscovite
2-2.5	Brown, black, green	One plane	Can be peeled into thin, flexible sheets	Biotite
2.5	Colorless, white	Three directions at 90°	Cubic crystals, salty taste	Halite
3	Colorless, white	Three directions not at 90°	Rhombic crystals, reacts with HCl, double refraction	Calcite
5-6	Dark green to black	Two directions at ~60° and ~120°	Elongated crystals	Hornblende (Amphibole)
5-6	Dark green to black	Two directions at ~90°	Elongated crystals	Augite (Pyroxene)
6	Colorless, pink, gray	Two directions at 90°	Stubby, prismatic crystals	Potassium Feldspar
6	Colorless, white, gray, black	Two directions at 90°	Can have small grooves on one of the cleavages called striations	Plagioclase Feldspar
6.5-7	Green	No cleavage, can have conchoidal fracture	Stubby crystals or granular masses	Olivine
7	Mainly red and black	Conchoidal fracture	May occur in 12-sided, circular crystals	Garnet
7	Varied	Conchoidal fracture	May occur in six-sided, elongated crystals	Quartz

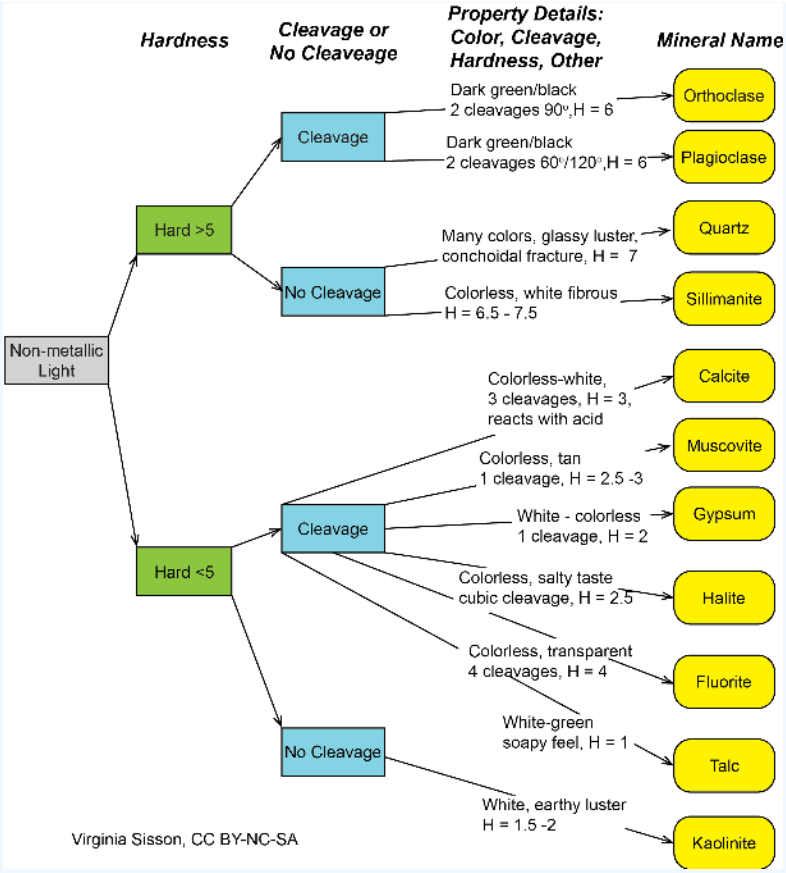


Figure 2.8 – Flowchart for light-colored minerals with nonmetallic luster. Image credit: Virginia Sisson, CC BY-NC-SA.

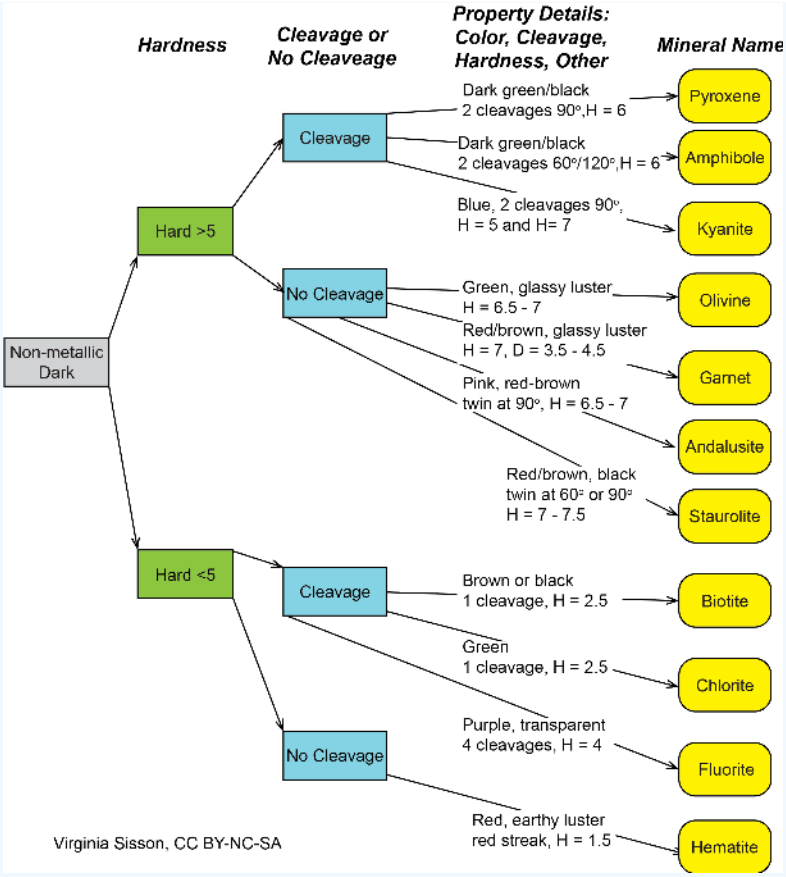


Figure 2.9 – Flowchart for dark-colored minerals with non-metallic luster. Image credit: Virginia Sisson, CC BY-NC-SA.

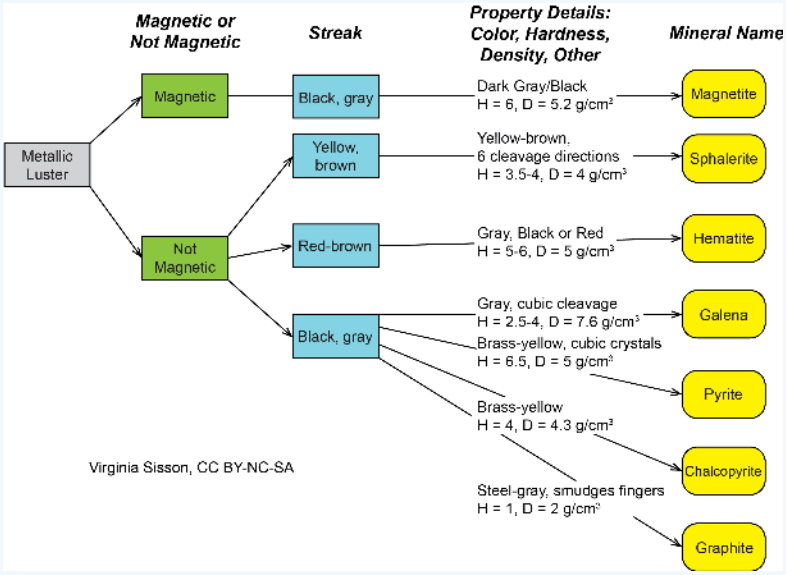


Figure 2.10 – Flowchart for minerals with metallic luster. Image credit: Virginia Sisson, CC BY-NC-SA.

Table 2.2 – Worksheet for Exercise 2.1

Sample ID	Color	Hardness	Cleavage	Mineral Name

2.3 Rocks

Rocks are what most people think of when they hear “geology.” Rocks are made up of different minerals, and in some cases, just one mineral. Minerals in rocks can be difficult to identify, though. Even upper-level geology majors and practicing geoscientists can have trouble identifying minerals in rocks. Nonetheless, it is an essential skill to practice because it serves as one of the primary ways to identify rocks. When geologists go into the field to study rocks, one of the first things they do is get up close and personal with the rock, usually with a hand lens, and identify what minerals are present. Let’s practice with a simple exercise on identifying some common minerals in rocks in Exercise 2.2.

? Exercise 2.2 – Identifying Minerals in Rocks

Your instructor will provide you with a selection of different rock samples. From the list of minerals in Table 2.3 below, indicate which rock sample(s) contain those minerals by filling out the “Rock Sample” column.

Table 2.3 – Worksheet for Exercise 2.2

Mineral	Rock Sample
K-feldspar	
Plagioclase feldspar	
Quartz	
Biotite	
Hornblende	

Based on how rocks are formed, geologists classify them into three basic types: igneous, sedimentary, and metamorphic. Igneous rocks form when **magma** or lava cools and solidifies. Minerals start to crystallize as the magma cools, and they interlock with each other in random orientations. Sedimentary rocks form when broken pieces of other rocks from weathering processes get cemented together. They can also form when minerals precipitate out of a solution, typically water, and are cemented together through sedimentary processes. Metamorphic rocks are pre-existing rocks that are altered by heat and pressure. Metamorphism often results in some type of pattern or orientation to the minerals, called foliation.

Exercise 2.3- Identifying Types of Rocks

Your instructor will provide you with a selection of unknown rocks. Using what you know about how each rock type forms, determine the rock type for each of your unknown samples and fill in Table 2.4.

Table 2.4 – Worksheet for Exercise 2.3

Rock Type	Sample
Igneous	
Sedimentary	
Metamorphic	

2.4 Igneous Rocks

The classification of igneous rocks is based on chemistry and texture, which means it's based on what minerals they have and how large the mineral grains are (Figures 2.11 and 2.12). The magma's chemistry and temperature determine which minerals will form, and the size of the mineral grains is determined by how quickly the magma cools. Slow cooling rates (thousands to millions of years) make larger mineral grains. Fast cooling rates (days to hundreds of years) produce smaller grains. Igneous rocks with large grains are called **intrusive** or plutonic rocks, which means the magma cooled slowly within the Earth. Igneous rocks with tiny grains are called **extrusive** or volcanic because the lava cooled on the surface of the Earth. The distinction between small and large grains is whether you (or a well-trained geologist) can identify the minerals without using any magnification. Using this information, if you had a coarse-grained igneous rock that contained 10% quartz, 10% potassium feldspar, 50% plagioclase feldspar, 20% pyroxene, and 10% amphibole, it would be called a diorite. If the mineral grains were fine (small), the rock would be called andesite.

How would you identify minerals in an extrusive igneous rock if the grains are too small to see? There are a couple of tricks that geologists use to identify which type of igneous rock they have. Do you remember how color was not a diagnostic property for minerals? Well, color in an igneous rock can be diagnostic! Iron and magnesium-bearing minerals are darker in color, like olivine and pyroxene, and they are the primary minerals that makeup **mafic** and ultramafic igneous rocks. Potassium, aluminum, and silica-rich minerals, like quartz and potassium feldspar, are lighter in color and make up intermediate and **felsic** igneous rocks. Geologists can use the color of igneous rocks and the relative amount of light- vs. dark-colored minerals to help identify them (Figure 2.12).

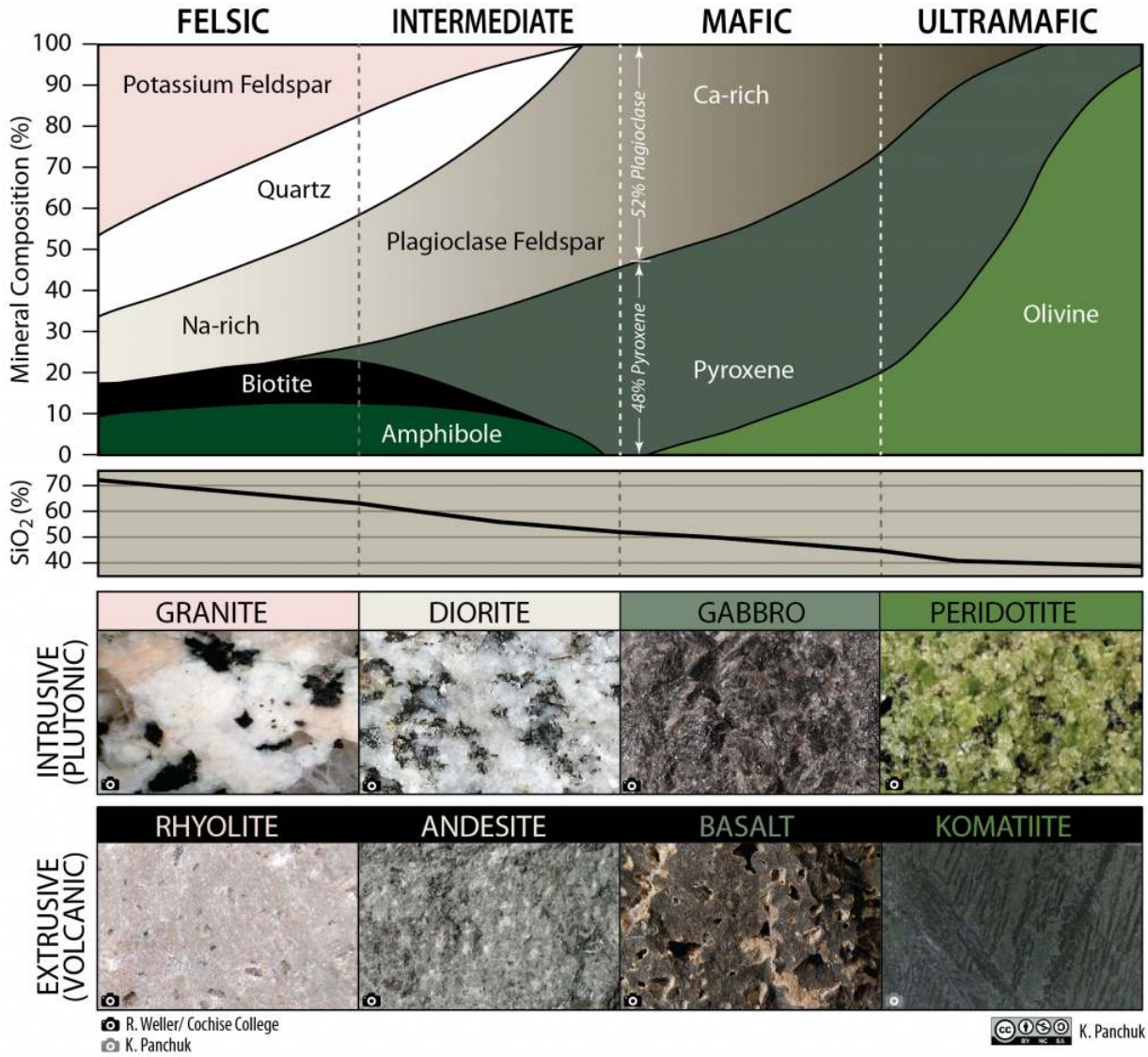


Figure 2.11 – Classification chart of igneous rocks based on the mineral content. The top part is a graphical comparison of silica content and mineral content for both extrusive and igneous rocks. To use this graph, you will need to determine the relative abundance of seven common minerals found in igneous rocks. The bottom two rows compare rocks with the same mineral composition but different names based on whether they formed intrusively or extrusively. Image credit: Karla Panchuk after Steven Earle, CC BY-SA-NC.

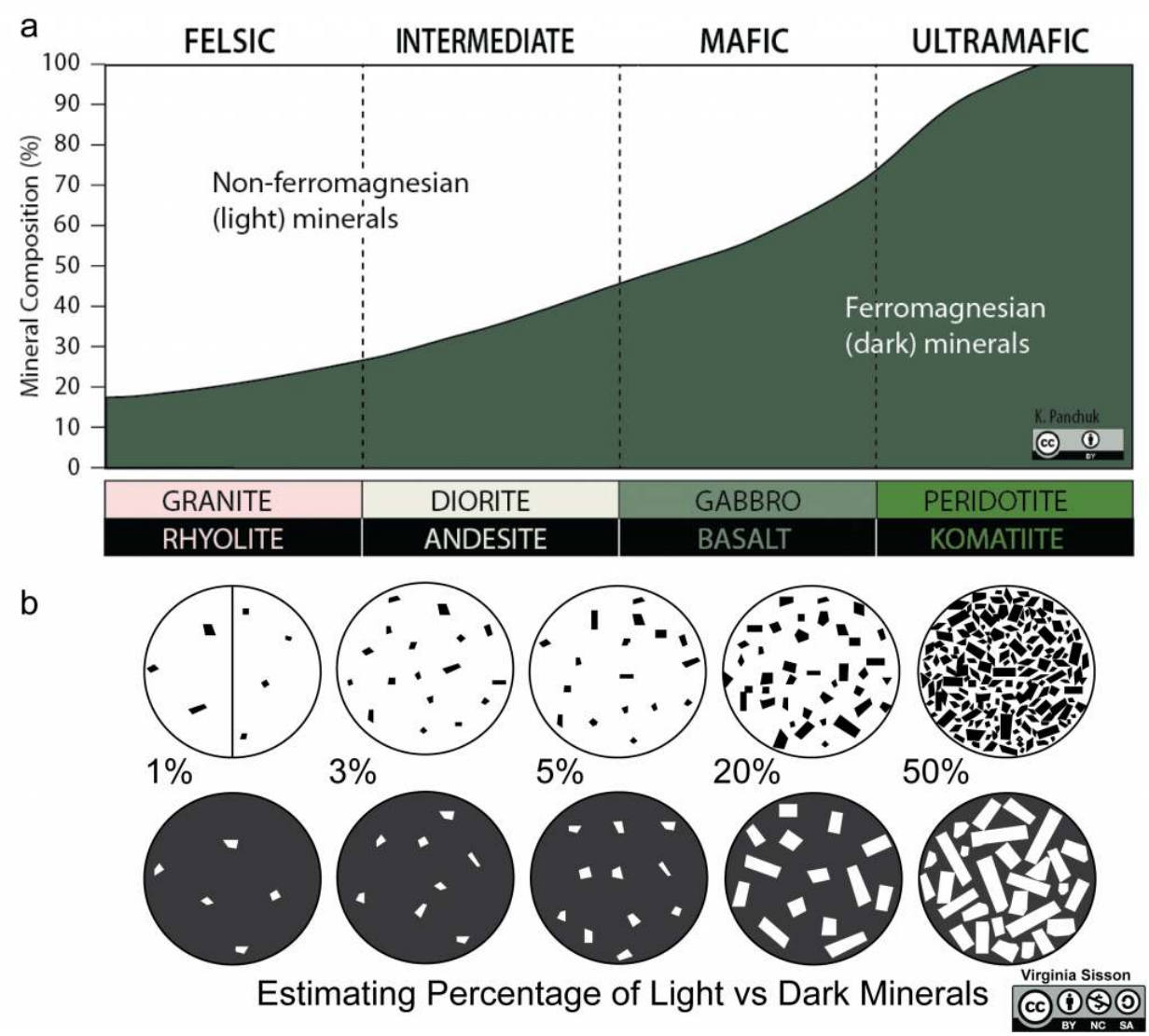


Figure 2.12 – Identifying igneous rocks using mineral color. a) The relative percentages of light (felsic) and dark-colored (mafic – iron and magnesium-rich) minerals, b) Images you can use to estimate percentages of light- and dark-colored minerals. Note: our eyes tend to overestimate the amount of dark colors, so be careful of this when looking at the rocks. Also, for low abundances of accessory minerals, their size will influence your results. Image credit: a) Karla Panchuk after Steven Earle, CC BY; b) Virginia Sisson, CC BY-NC-SA.

? Exercise 2.4 – Identifying Igneous Rocks

Your instructor will provide you with a set of unknown igneous rocks to identify. Use Figures 2.11 and 2.12 to fill out the information in Table 2.5.

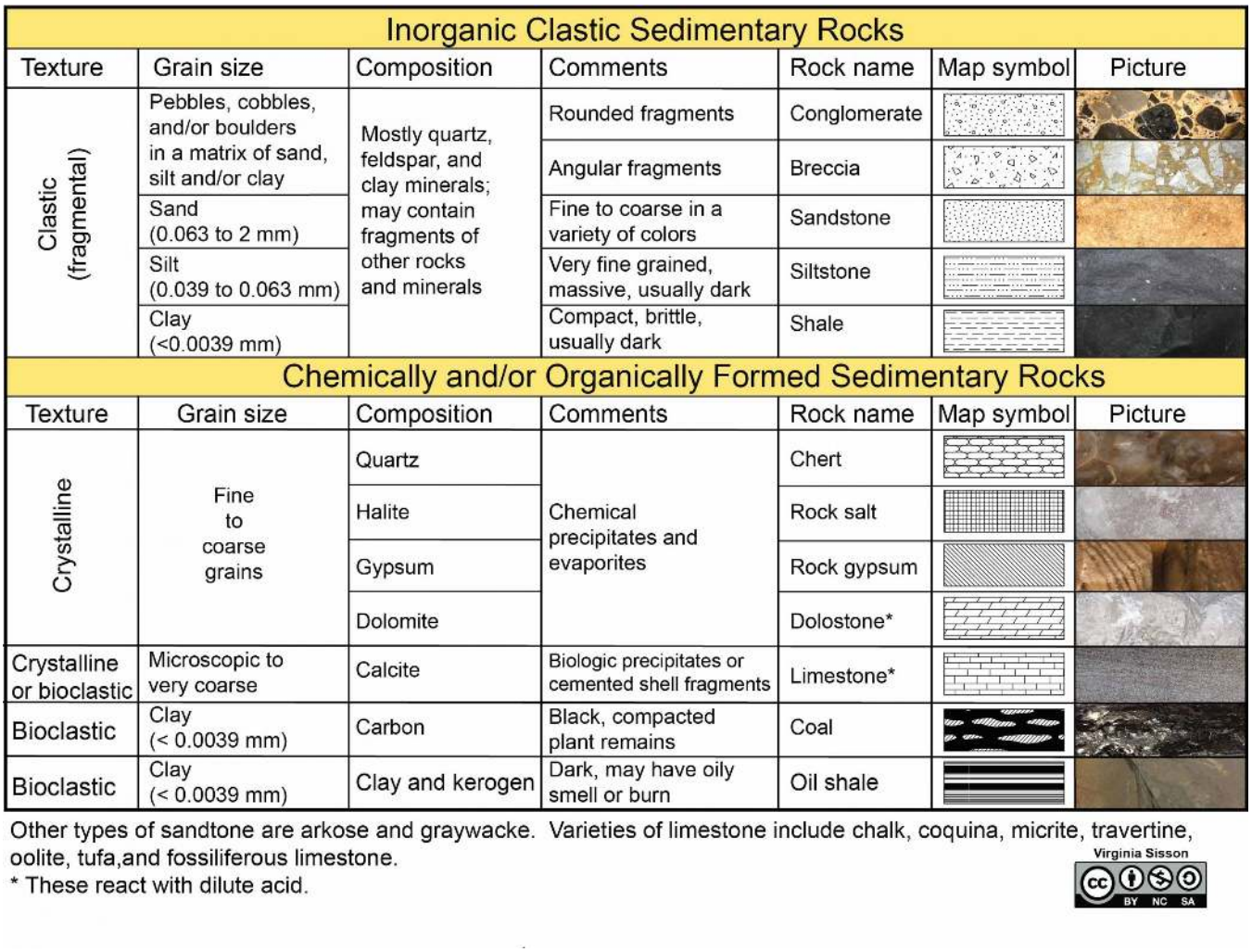
Table 2.5 – Worksheet for Exercise 2.4

Sample	Intrusive or Extrusive	% Light vs. Dark Minerals (for intrusive) or Rock Color (for extrusive)	Rock Name

2.5 Sedimentary Rocks

Sedimentary rocks can form in several ways (Figure 2.13) and are classified as **clastic**, **chemical**, and **organic** based on how they form. The most common way sedimentary rocks form is when other rocks weather into small particles and are transported by wind, water, or ice to an area where they are deposited and form layers. These are called clastic sedimentary rocks and are primarily classified based on their grain size. Sedimentary rocks can also form through chemical or organic processes. If you have a body of water containing dissolved salt and then that water evaporates, it will leave behind the salt as a solid mineral form called a precipitate, which is a chemical sedimentary rock. Organic sedimentary rocks form from the accumulation of organic debris. This organic material would need to be buried very quickly, so it doesn't decay. Organic material in sedimentary rocks is where coal, oil, and natural gas come from. Then, there are sedimentary rocks that we can classify as biochemical. For example, foraminifera are tiny, single-celled organisms that build shells out of calcium carbonate. When they die, their shells can sink to the bottom of the ocean and accumulate to form a sedimentary rock. In this case, biological processes caused the chemical precipitation of the mineral for the shell, but it doesn't contain organic compounds, so we call it bio-chemical.

In all cases, sediments need to be buried so the **lithification** process can take place. There are two steps involved in turning sediment into sedimentary rock; compaction and **cementation**. When grains are deposited, they typically have empty spaces between them called pores (porosity). Compaction reduces porosity by bringing the grains closer together. The best analogy to think about is your garbage can at home. When the garbage can is full, do you change the bag right away, or do you push down on it to create more room? By pushing down on trash, you reduce the space between the pieces of garbage and create more room at the top; this is compaction. Sediments work the same way, but what's causing the compaction is the accumulation of more sediment on top of the previously deposited material. The more sediment that gets piled on top, the more compact the sediment beneath it becomes. Cementation is a process that happens during compaction. As sediments become compacted, water is squeezed out of the pore spaces. As the water leaves the sediment, it precipitates minerals into those pore spaces acting as a glue that holds the sediment together. The common minerals that make up the cement are **calcite**, **quartz**, and **pyrite**.



Inorganic Clastic Sedimentary Rocks						
Texture	Grain size	Composition	Comments	Rock name	Map symbol	Picture
Clastic (fragmental)	Pebbles, cobbles, and/or boulders in a matrix of sand, silt and/or clay	Mostly quartz, feldspar, and clay minerals; may contain fragments of other rocks and minerals	Rounded fragments	Conglomerate		
			Angular fragments	Breccia		
	Sand (0.063 to 2 mm)		Fine to coarse in a variety of colors	Sandstone		
	Silt (0.039 to 0.063 mm)		Very fine grained, massive, usually dark	Siltstone		
	Clay (<0.0039 mm)		Compact, brittle, usually dark	Shale		
Chemically and/or Organically Formed Sedimentary Rocks						
Texture	Grain size	Composition	Comments	Rock name	Map symbol	Picture
Crystalline	Fine to coarse grains	Quartz	Chemical precipitates and evaporites	Chert		
		Halite		Rock salt		
		Gypsum		Rock gypsum		
		Dolomite		Dolostone*		
Crystalline or bioclastic	Microscopic to very coarse	Calcite	Biologic precipitates or cemented shell fragments	Limestone*		
Bioclastic	Clay (< 0.0039 mm)	Carbon	Black, compacted plant remains	Coal		
Bioclastic	Clay (< 0.0039 mm)	Clay and kerogen	Dark, may have oily smell or burn	Oil shale		

Other types of sandtone are arkose and graywacke. Varieties of limestone include chalk, coquina, micrite, travertine, oolite, tufa,and fossiliferous limestone.
* These react with dilute acid.

Virginia Sisson
CC BY NC SA

Figure 2.13 – Sedimentary rock classification table. To use this table, you will need to determine whether the rock is clastic or chemical/organic. Also, you need to determine both the grain size and mineral composition. For clastic rocks, you also need to know the roundness of the grains. Also shown are the US Geological Survey standard patterns for these rock types. These will be used in both stratigraphic columns and maps throughout this lab manual.

The locations where sediments are deposited are called depositional environments. There are a variety of depositional environments (Figure 2.14) that can be grouped into three broad categories: continental, marine, and transitional. Continental environments are areas where sediments are deposited on continents, marine environments are areas where sediments are deposited in the ocean, and transitional environments are coastal and tidal locations between continental and marine environments. Table 2.6 contains the most common environments, a brief description of them, and the common sedimentary rocks that can form in those environments.

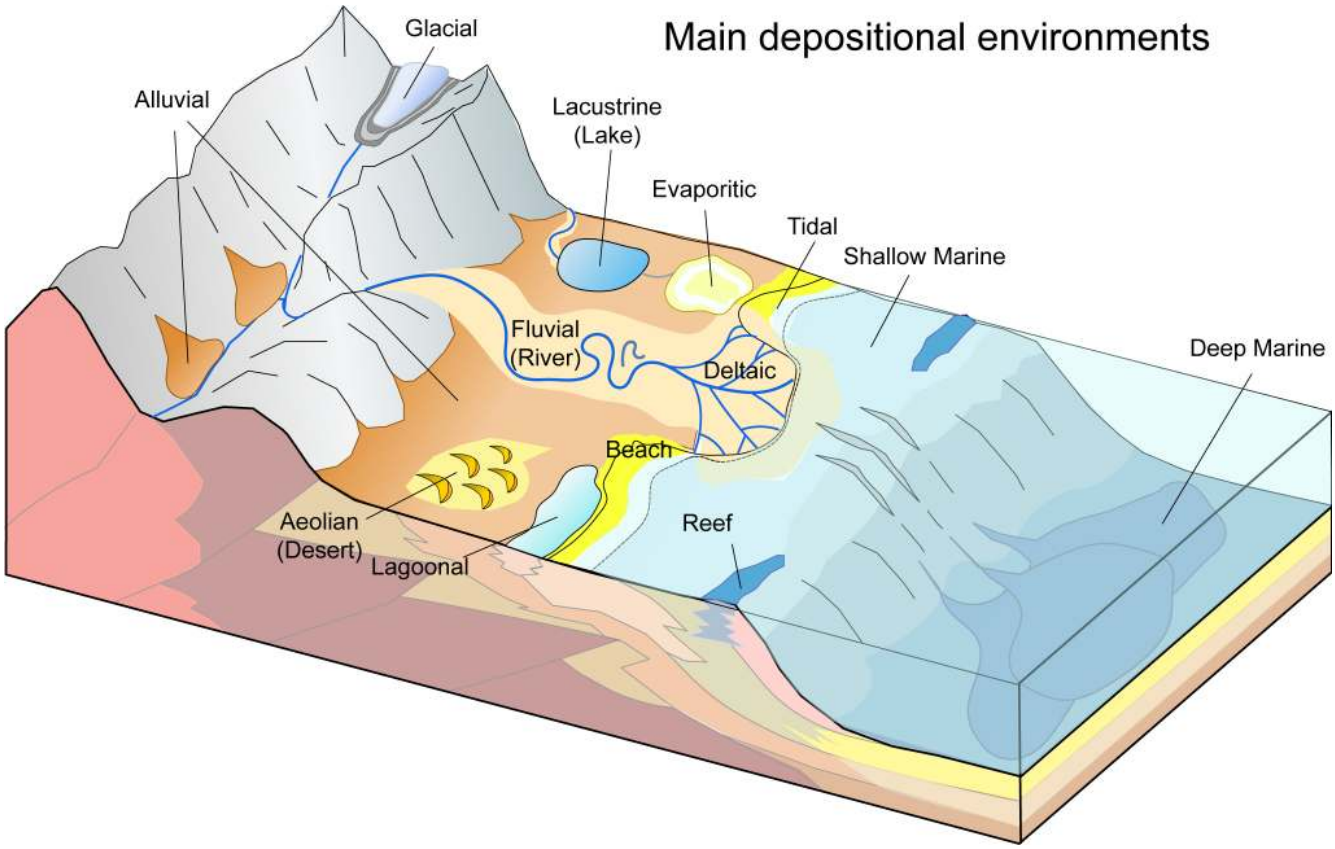


Figure 2.14 – Common depositional environments for sediments ranging from continental to marine settings. Image credit: Modified from PePeEfe after Mikenorton, CC BY-SA.

Table 2.6 – Depositional environments for sedimentary rocks

Environment	Description	Common Types of Sedimentary Rocks

https://geo.libretexts.org/@go/page/18710

Environment	Description	Common Types of Sedimentary Rocks
Continental		
Aeolian	Sediment deposited by wind; primarily deserts and coastal regions; well-sorted sand; typically red in color; variable energy. Example in Google Earth: Algeria.	Sandstone
Alluvial	Fan-shaped deposits caused by moving water; usually found in arid or semi-arid regions; contains gravel, sand, silt, and/or clay; poorly sorted; high energy; creates alluvial fans. Example in Google Earth: Death Valley National Park, California.	Conglomerate, breccia, sandstone, shale
Fluvial	Sediment deposited by moving water, primarily rivers; can contain gravel, sand, silt, and/or clay depending on how fast the water moves; variable energy; commonly red in color from oxidation. Example in Google Earth: Upper Mississippi River in Illinois/Missouri.	Conglomerate, sandstone, shale
Lacustrine	Lake settings that can contain sand, silt, or clay; generally low energy. Example in Google Earth: Lake Winnipesaukee, New Hampshire.	Sandstone, shale
Glacial	Sediment deposited by glaciers; variable grain sizes; poorly sorted. Example in Google Earth: Southern Patagonia, Argentina.	Conglomerate, breccia, sandstone, shale
Evaporitic	Forms where water evaporates and leaves behind mineral precipitates. Example in Google Earth: Utah.	Limestone, rock salt, rock gypsum.

Environment	Description	Common Types of Sedimentary Rocks
Transitional		
Beach	Along coastlines, sediment transported by wave action; contains well-sorted gravel and sand; high energy. Example in Google Earth: Island Beach State Park, New Jersey.	Sandstone
Deltaic	Where a river empties into a body of water; contains gravel, sand, and silt; low energy. Example in Google Earth: Yukon River, Alaska.	Sandstone, shale
Lagoonal	A shallow body of water separated from a larger body of water by barrier islands or reefs; very low energy; contains silt and clay. Example in Google Earth: East Matagorda Bay, Texas.	Limestone, shale, coal (swamps)
Tidal	Affected by the tides; mainly silt and clay; can create tidal flats; low energy. Example in Google Earth: Bay of Fundy, Nova Scotia.	Shale
Marine		
Shallow	Located on the continental shelf; mainly sand and silt; energy decreases with distance from shore. Example in Google Earth: Eastern Gulf of Mexico.	Sandstone, shale, limestone
Deep	The deep ocean; very low energy; mainly clay; can contain turbidite deposits of variable sediment sizes. Example in Google Earth: Pacific Ocean.	Shale, chert, limestone
Reef	A bar of rock, sand, or coral. Example in Google Earth: Great Barrier Reef, Australia.	Limestone

You'll notice that the same type of sedimentary rock can be found in many different settings, making it difficult to determine the depositional environment. Sometimes, the color of a sedimentary rock can indicate the depositional environment because the color is largely determined by how much oxygen is available as the sediment is buried and lithified (Figure 2.15). Reddish colors can indicate oxygen-rich continental environments, like a flowing river or desert. Green and light gray colors mean low oxygen, which can be found in shallow marine environments. Black color means no oxygen, which would indicate a deep marine or swamp environment. Color is not always a good indicator, though, because the sediment only alters its color after **burial**. The conditions affecting buried sediment may not always match the environment on the surface above it.

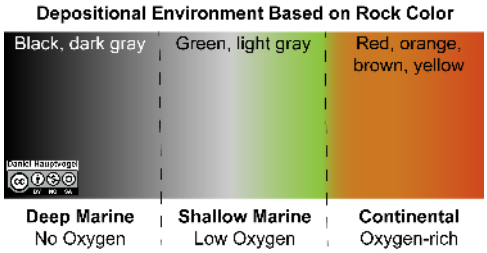


Figure 2.15 – Typical colors of sedimentary rocks based on their depositional environment and oxygen availability during burial and lithification. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

The size and shape of grains within sedimentary rocks can also help you interpret that sediment's history (Figure 2.16). When all of the grains in the rock are about the same size, it is called well-sorted. Usually, sediment needs to travel a far distance from its source to be well-sorted. In contrast, poorly sorted sediment is very close to its source. The rounding of sediment grains is also an indicator of how far the sediment traveled. Grains that have smooth edges are considered well-rounded and have traveled a far distance. These grains start out with rough edges and become smoother as they travel further and further. In contrast, grains with sharp edges are considered angular and have not traveled a far distance.

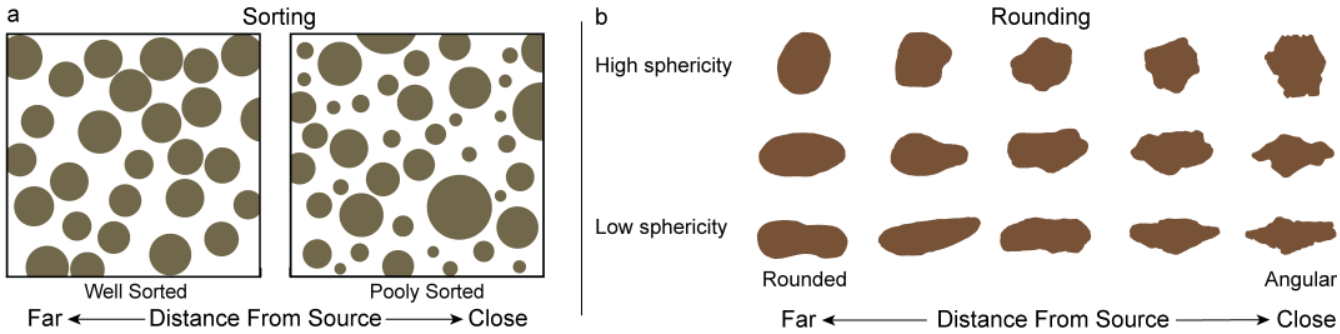


Figure 2.16 – Grain characteristics used to infer the relative distance that sediments have traveled from their source rock. a) Sorting of sediment; b) Sediment roundness, often called sphericity. Image credit: a) Adapted from Wikimedia user Woudloper, CC BY-SA; b) Adapted from Wikimedia user Woudloper, CC BY-SA.

? Exercise 2.5 – Identifying Sedimentary Rocks

Your instructor will provide you with a set of unknown sedimentary rocks to identify. Use Figures 2.13 to 2.17 and Table 2.2 to fill out the information in Table 2.7 below.

Table 2.7 – Worksheet for Exercise 2.5

Sample	Clastic, (Bio-) Chemical, or Organic	Rock Name	Possible Depositional Environments

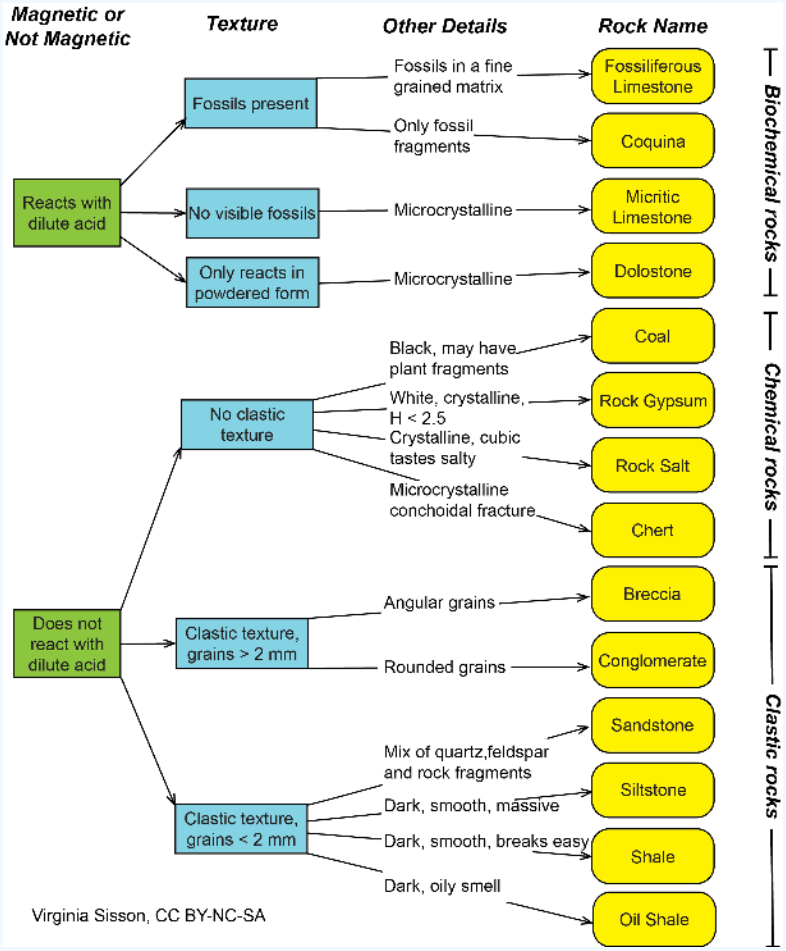


Figure 2.17 – Flowchart for identifying sedimentary rocks. Image credit: Virginia Sisson, CC BY-NC-SA.

2.6 Metamorphic Rocks

Metamorphic rocks (Figure 2.18) form when any pre-existing rock is altered by heat and/or pressure. The two sources of heat for metamorphism are the heat from a magma chamber and the **geothermal gradient**, which is the natural increase in temperature

when getting deeper into the Earth. Pressure also increases with depth in the Earth, but intense pressure also occurs during tectonic plate collisions. This is why most of the world's metamorphic rocks are found in mountain belts or ancient mountain belts.

Heat and pressure can cause several changes in rocks, such as recrystallizing minerals, creating new minerals, and orientating minerals in a direction perpendicular to pressure. The orientation of minerals is the most noticeable feature when recognizing metamorphic rocks. Heat works to "soften" minerals, allowing ions to begin migrating in and out of crystal structures. Then pressure forces the minerals to re-orientate. Heat is the most important factor, though; without heat, the rock would just break under intense pressure. When minerals take on some type of orientation due to metamorphism, it's called **foliation**. As pressure increases, so does the degree of foliation. Not all metamorphic rocks exhibit foliation because some minerals change very little under metamorphic conditions (quartz, for example); these types of metamorphic rocks are called non-foliated or massive and can be very difficult to tell apart from igneous rocks.

The pre-existing rock, before metamorphism occurred, is called the **protolith**. If you've taken an introductory Physical Geology class, you learned to differentiate metamorphic rocks mostly by their texture and classified them as slate, phyllite, schist, and gneiss. You may have even been introduced to the term **migmatite** for rocks that had both igneous and metamorphic textures as these were starting to undergo partial melting. These textural terms are associated with changes in metamorphic temperature and pressure, often referred to as the metamorphic grade or just grade.

Confused by metamorphism? Don't feel alone, as many students and even professional geoscientists have difficulties describing and interpreting metamorphic rocks. First, you need to understand all factors affecting igneous and sedimentary rocks. Then, you add the effects of heat and/or pressure, but unlike other rocks, this can vary dramatically across a region. Often there has been more than one tectonic event in that region, adding even more complications for you to interpret. It is akin to understanding a four- or five- dimensional image and difficult to comprehend all the factors at once. You may want to review your Physical Geology lab and text before tackling metamorphic rocks and these exercises.

Texture		Grain Size	Composition	Metamorphic Type	Comments	Rock name	Map symbol	Picture
Foliated	Minerals are aligned	Fine	Mica, Quartz, Feldspar, Garnet, Amphibole, Pyroxene	Regional (Heat and pressure increase)	Metamorphism of shale breaks along slaty cleavage	Slate		
		Fine to medium			Shiny, micas barely visible breaks along wavy surfaces	Phyllite		
					Mica visible with bumps of silicate minerals*	Schist		
	Banded	Medium to coarse			Minerals segregated into light and dark bands	Gneiss		
					Mixed igneous and metamorphic textures	Migmatite		
Nonfoliated		Fine	Carbon	Regional	Metamorphism of bituminous coal	Anthracite coal		
		Fine	Various minerals	Contact (heating)	Various rocks changed by heating by magma/lava	Hornfels		
		Fine to coarse	Quartz	Regional or contact	Metamorphism of quartz sandstone	Quartzite		
		Fine to coarse	Calcite and/or dolomite		Metamorphism of limestone or dolostone	Marble		
		Coarse	Various minerals	Regional	Pebbles will be distorted or stretched	Meta-conglomerate		
		Coarse	Basalt	Regional	>75% amphibole and feldspar	Amphibolite		
		Coarse	Basalt	Regional	Subduction metamorphism garnet and pyroxene	Eclogite		
		Fine	Ultramafic	Regional	Serpentine minerals	Serpentinite		

Not shown are greenstone, mylonite, metasandstone, blueschist, talc schist, jadeitite, augen gneiss, granulite and many more.
* Silicate minerals typically include garnet, andalusite, sillimanite, kyanite, staurolite, and cordierite.

Virginia Sisson

Figure 2.18 – Metamorphic rock classification by texture, protolith, mineralogy, and type of metamorphism. Map symbols refer to the standard symbols used by the US Geological Survey for each rock type. However, there are no standard patterns for amphibolite and eclogite, so we have designed and included patterns for these two rocks using the first letter of each rock name. The rocks in the sample pictures are from the Wards Classic American rock collection at the University of Houston, except for gneiss, migmatite, hornfels, and eclogite, which are all unpublished photos from VB Sisson. Image credit: Virginia Sisson, CC BY-NC-SA.

? Exercise 2.6 – Identifying Metamorphic Rocks

Your instructor will provide you with a set of unknown metamorphic rocks to identify. Use Figures 2.18 and 2.19 to fill out the information in Table 2.8.

Table 2.8 – Worksheet for Exercise 2.6

Sample	Foliated or Non-foliated	Rock Name	Protolith

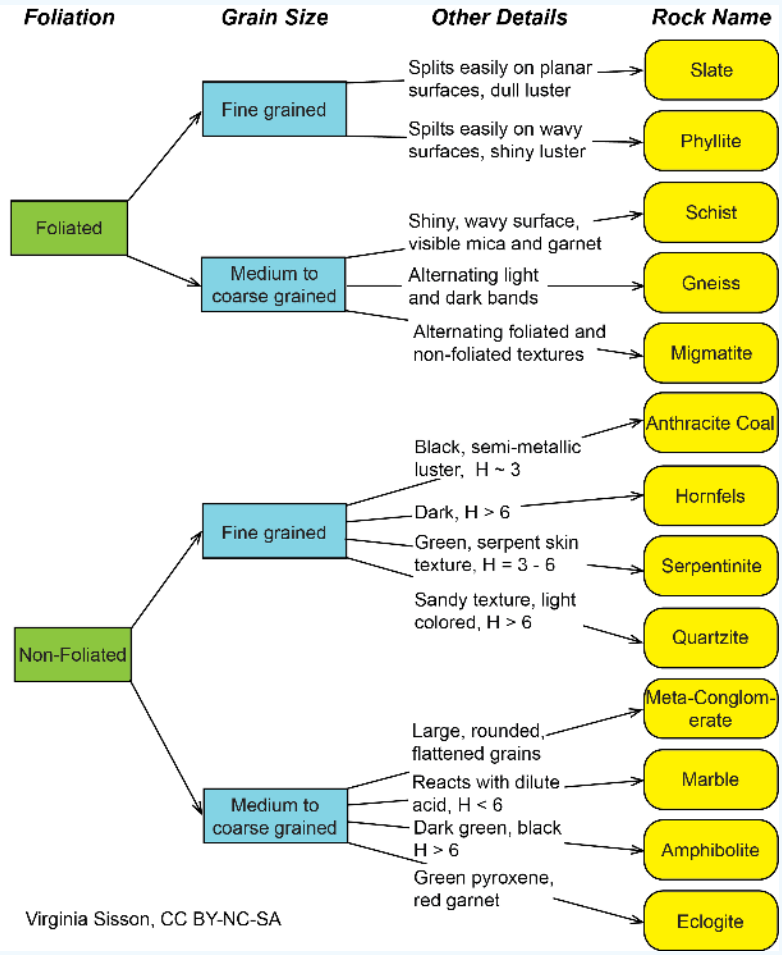


Figure 2.19 – Flowchart for identifying metamorphic rocks. Begin by deciding if the metamorphic rock exhibits any type of foliation. Then determine the grain size. Next, look at other features such as mineralogy, hardness, and how the rock breaks. Image credit: Virginia Sisson, CC BY-NC-SA.

Let's build on your metamorphic rock foundation and start to interpret metamorphic rocks using mineral assemblages. To do this, you have to start by knowing the protolith (parent) material for the metamorphic rock. If you can distinguish mafic (basaltic protoliths) from shale (sedimentary protoliths), this will be easy.

During metamorphism, rocks with a shale protolith will always have quartz, feldspar, and muscovite mica. So, you are on the lookout for new minerals, often seen as **porphyroblast**s. Most of these are not taught in Physical Geology, so here are some minerals you will need to know: chlorite (a dark green mica), biotite, cordierite, garnet, staurolite, sillimanite, kyanite, and andalusite (Figure 2.20). The last three minerals on this list you may remember are **polymorph**s: minerals with the same composition but unique internal structures (Figure 2.21). If you can identify these alumino-silicate minerals in a schist or gneiss, then you can determine the pressure-temperature conditions for that terrane. In general, rocks with kyanite and sillimanite are found in areas that have undergone continent-continent collision and are considered medium-pressure terranes. In contrast, areas with andalusite and sillimanite have an elevated geothermal gradient in response to either divergent zones or unusual ocean-continent collision zones called low-pressure terranes.

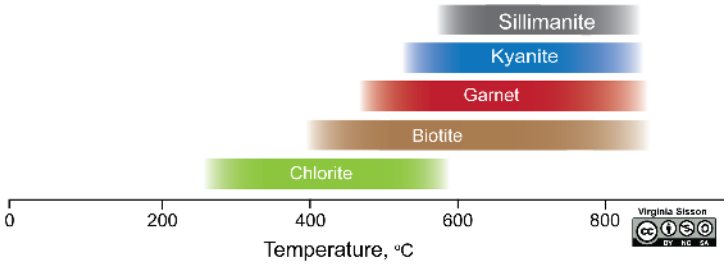


Figure 2.20 – Index minerals used to interpret temperature ranges of metamorphic rocks. These index minerals are for metamorphosed shales (pelites). These rocks all have quartz, feldspar, and muscovite mica in addition to other index minerals. Green is for low-grade rocks that have chlorite. As temperature increases, biotite (brown) begins to form. As the temperature continues to increase, medium-grade rocks will have garnet (red) and kyanite (blue). These are easy to distinguish as these minerals grow as porphyroblasts and often form bumps in the rocks. Finally, at the highest grade, sillimanite appears, and then the rocks begin to melt, forming migmatites. Image credit: Virginia Sisson, CC BY-NC-SA.

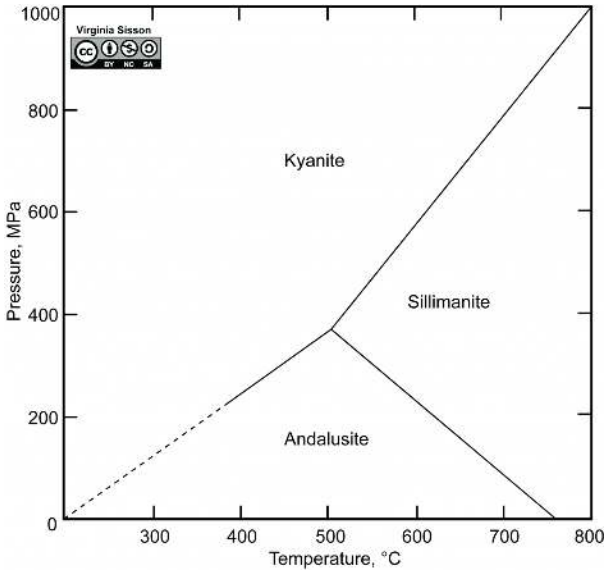


Figure 2.21 – Pressure temperature diagram for aluminosilicate minerals showing the stability fields for andalusite, kyanite, and sillimanite. The dashed line is defined by the stability of pyrophyllite and limits the lower temperature of andalusite and kyanite. This diagram was calculated using the data of Berman (1991). Image credit: Virginia Sisson, CC BY-NC-SA.

During a continental collision, the sequence of metamorphic rocks that form can be predictable by following the **Barrovian sequence** (Figure 2.22). Basically, the further away from the collision or the higher up in the crust the rock is, the lower the grade of metamorphism, while the closer and deeper the rocks are, the higher the grade. So, how do these deeper, high-grade metamorphic rocks become exposed at the surface? The answer is erosion; the low-grade rocks above need to be removed to expose the high-grade rocks below. This is relatively easy for an uplifting mountain belt because the increased surface area of the mountain allows more weathering and erosion to occur. If you are looking for exposures of high-grade metamorphic rocks, your best chance of finding them is near the center of the collision, where much of the uplift and erosion took place. The Barrovian sequence pattern is when the grade of metamorphic rocks increases as you approach the collision center, reaching the highest grade near the center and then decreasing in grade as you move to the other side (like a mirror image). Of course, this perfect, mirror-

image pattern is not always seen because the rocks may not be exposed, or maybe faults have moved rocks from their original positions, or there was significant variability in pressure-temperature conditions.

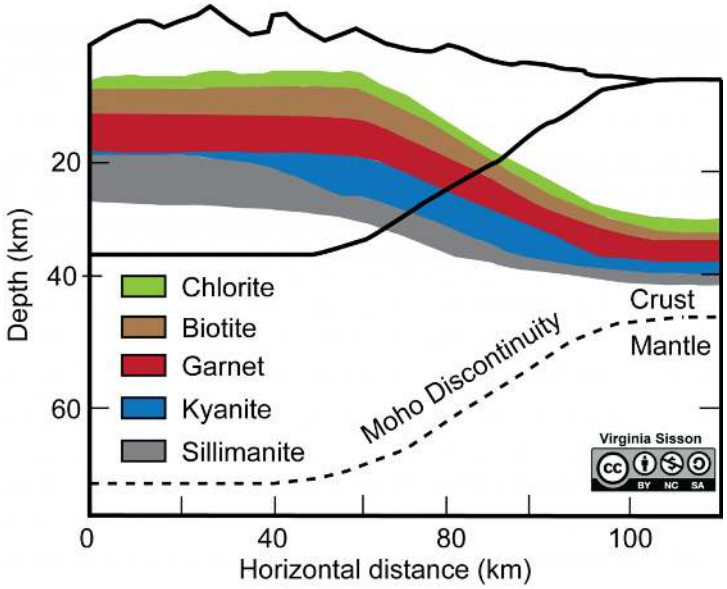


Figure 2.22 – Metamorphic zones in continental convergence. The colored areas are the metamorphic zones; these use the same scheme as in Figure 2.20. Green is chlorite, brown is for biotite, red is for garnet, blue is for kyanite, and gray is for sillimanite. This scheme does not include andalusite as a separate zone; it would overlap the kyanite zone. The dashed line is the boundary between the continental crust and mantle, called the Moho. It is shortened from the term Mohorovičić discontinuity after the Croatian seismologist Andrija Mohorovičić (1857-1936) who discovered this. This figure was simplified from numerical models by Lyubetskaya and Ague (2010). The position of the Moho shows the initial temperature gradient, and the metamorphic zones reflect the temperature 30 million years after continental collision. Image credit: Virginia Sisson, CC BY-NC-SA.

? Exercise 2.7 – Understanding the Barrovian Sequence

Continental collision and closure of the Iapetus Ocean in the Ordovician and early Devonian resulted in the Caledonide Orogeny. By the way, Caledonia is Latin for Scotland. One of the hallmarks of continental collision are suites of metamorphic rocks such as you've been looking at in Exercise 2.6.

Now let's put together information from the rocks you've looked at with a map of the metamorphism of the Scottish Highlands. British geologist George Barrow mapped the area in Figure 2.23 in the 1890s. He realized that he could distinguish metamorphic zones by using their mineral assemblages. One more clue you need to solve this exercise is that there is a relationship between pressure and depth in the Earth as 300 MPa corresponds to approximately 10 km depth. So, you can convert the depths in Figure 2.22 to pressure with this approximation.

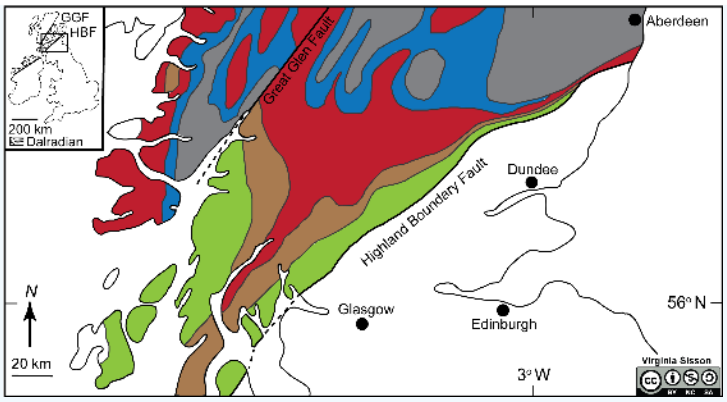


Figure 2.23 – Barrovian metamorphic zones in northern Scotland. The colors used for the different metamorphic zones are the same as in Figure 2.20. Green is chlorite, brown is for biotite, red is for garnet, blue is for kyanite, and gray is for sillimanite. Barrow also mapped a staurolite zone which is not shown here. The black circles indicate the location of major Scottish cities. The area is bound by two faults, the Great Glen strike-slip fault to the northwest and the Highland Boundary reverse fault to the southeast. Image credit: Virginia Sisson, CC BY-NC-SA; simplified from Wikimedia user Woudloper, CC BY-SA.

a. Label the colored areas on the map with the mineral present according to the scheme used in Figure 2.20.
b. Where on this map do you think your samples from Exercise 2.6 occur?
c. On the map, mark which areas you think represent the shallowest and deepest during metamorphism.
d. Draw a line on the map that corresponds to only a change in temperature.
e. On the cross-section shown in Figure 2.22, plot an approximate path through the metamorphic zones. It will be up to you to decide how your metamorphic rocks evolved and your path may be different from a colleague's.
f. To help understand the metamorphic history of a region, geologists will construct geodynamic models of how heat and pressure in the Earth evolve through time. These models start with an initial set of conditions for the area. In Figure 2.22, the heavy black lines show two continental plates colliding; each has an initial lithosphere thickness of ~ 35 km. The convergence causes deflection of the Moho (Mohorovičić) discontinuity between the crust and mantle. Over time, the temperature readjusts. The colored areas on this plot show the metamorphic assemblages about ~35 million years after collision (Lyubetskaya and Ague, 2010). The first step to using this diagram is to convert metamorphic depths to pressures. A good rule of thumb is that 3 km depth is ~100 MPa. Use your results from part *e* to fill in Table 2.9.

Table 2.9 – Worksheet for Exercise 2.7f

Metamorphic Zone	Depth	Pressure	Temperature
Chlorite			
Biotite			
Garnet			
Kyanite			
Sillimanite			

g. Using your calculated pressures from Table 2.9, draw a line on Figure 2.21 that corresponds to your sequence of metamorphic assemblages from the map. This is called a pressure-temperature (PT) path. Geologists now like to add geochronology constraints (t), deformation (d) or compositional constraints (x), so you'll hear them discuss PTt, PTtd or PTx paths when trying to determine the tectonic history of a region.

2.7 Using Rocks to Interpret Earth's History

Igneous, sedimentary, and metamorphic rocks can all be used to interpret Earth's history. Igneous rocks can help determine the plate tectonic setting of an area, sedimentary rocks help determine the environment of an area, and metamorphic rocks provide information about rocks before their deformation and the tectonic setting. All the following exercises will use your critical thinking skills.

Exercise 2.8 – Interpreting Volcanic History

There are a few places on Earth with significant mountainous relief as well as igneous activity. One such place is the western margin of South America, which has been the site of ocean-continent convergence since the Jurassic (~185 Ma). Thus, it has a long history of almost continuous subduction-related volcanism and igneous activity. In the Central Andes Mountains, igneous rocks formed during the Neogene portion of geologic time between 23 and 2.5 million years ago; these include both intrusive and extrusive rocks (Figure 2.24). These volcanic rocks are overlain by more recent volcanoes.

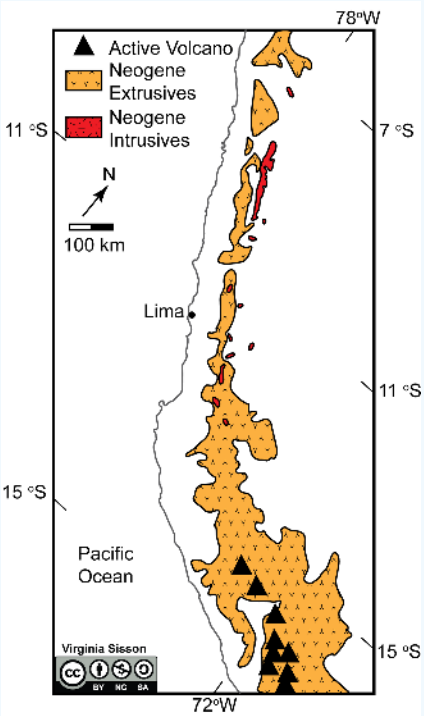


Figure 2.24 – Map of the Neogene igneous rocks of the Peruvian Andes. Intrusive rocks are shown as red areas, and extrusive volcanic rocks are shown in the orange areas. Black triangles are locations of active volcanoes. Note that this map is not oriented north-south. Image credit: Virginia Sisson, CC BY-NC-SA; simplified from Pfiffner and Gonzalez, 2013.

a. In the suite of igneous rocks provided by your instructor, which rocks are most closely associated with the Neogene intrusives?
b. Which rocks would be associated with the Neogene extrusive volcanic rocks?
c. Would the same rock types be found in the active volcanoes?
d. Describe at least three differences between the map patterns of the recent volcanoes, Neogene extrusives, and Neogene intrusives.
e. **Critical Thinking:** What can explain some of these differences in the map patterns?

Exercise 2.9 – Rocks of the Grand Canyon

The Grand Canyon has amazed tourists and geoscientists alike, not only for its beauty but by the fantastic **stratigraphic section**s (layers of sedimentary rock) exposed in its walls. The South Rim of the Grand Canyon is composed of metamorphic, igneous, and various sedimentary rocks. Go here if want to see representative samples of some of these rocks. Figure 2.25 shows a **stratigraphic column** of the Grand-Canyon (see Figure 0.3 for a sketch of the Grand Canyon).

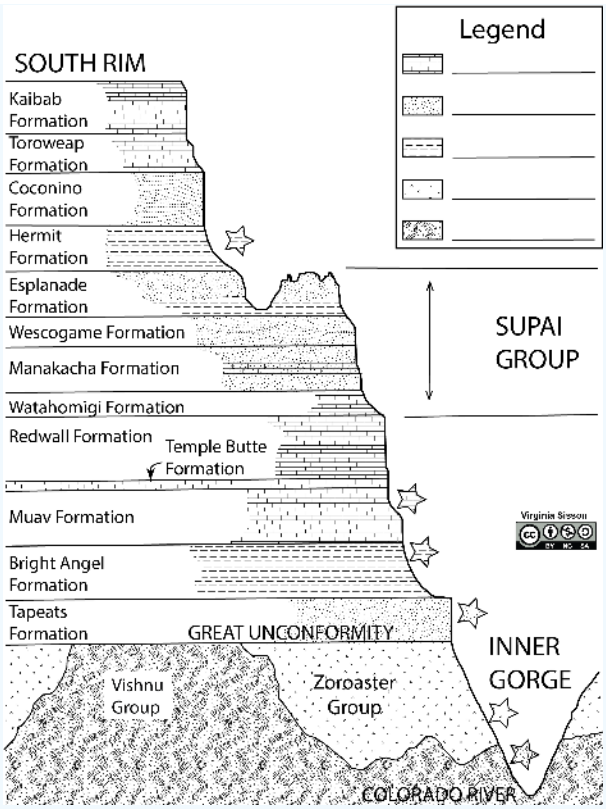


Figure 2.25 – Cross-section of the Grand Canyon. This view shows the inner gorge, Temple Butte, and southern rim on the west bank of the south-flowing Colorado River. Temple Butte's elevation is 1618 m; the maximum depth of the Grand Canyon is over a mile or 1.829 km. This cross-section shows simplified stratigraphy of the sedimentary, igneous, and metamorphic rocks exposed in the cliffs and walls of the canyon. The different formations are shown using patterns for the different rock types commonly used by the U.S. Geological Survey. In other regions of the Grand Canyon, the Grand Canyon Supergroup overlies the Vishnu Schist and Zoraster granite. This is not shown in this figure. The figure is adapted from several publicly available stratigraphic columns, including the National Park Service. Image credit: Virginia Sisson, CC BY-NC-SA.

Table 2.10 contains descriptions of some of the different rocks found in the Grand Canyon.

a. Which rocks from your kit resemble the sedimentary units marked with a star on the Grand Canyon stratigraphic section? Fill this out in the third column of Table 2.10.
b. The symbols used to describe these rocks are standardized. Based on your findings from part *a*, complete the legend in Figure 2.25 by identifying the type of rock each symbol stands for.

Table 2.10 – Rock formations and descriptions for the Grand Canyon for Exercise 2.9a

Rock Formation*	Description	Matching Rock From Your Kit
Vishnu Group	Group of foliated metamorphic rocks that are the result of various rocks, mostly igneous, being exposed to high degree metamorphism.	
Zoroaster Group	Igneous rocks composed of coarse-grained intrusions composed mostly of feldspar and quartz, with minor hornblende and biotite.	
Tapeats Formation	Composed mostly of sand-sized quartz grains with medium roundness. It is mostly massive, but bedding is visible in some areas.	
Bright Angel Formation	Composed of fine-grained shale, and trilobite fossils are common within this unit.	
Muav Formation	Chemical and biochemical sedimentary rocks that react with dilute acid.	
Hermit Formation	Extremely fine-grained, dark-colored sedimentary rocks which have easily observable bedding. Most minerals are clay minerals but can't be observed, even with the help of a hand-lens, due to their extremely fine grain size.	

*See this Wikipedia entry for the differences in stratigraphic unit terminology.

Most of the rocks formed at divergent plate boundaries are igneous, with a thin layer of deep marine sediments on top. Since these sediments accumulate in the deep ocean far from the continents, there are only chert and marine clays. However, there are significant accumulations of igneous rocks derived from the decompression melting of Earth's peridotite mantle. Do you recall what kind of rock forms from the partial melting of an ultramafic rock? It will be a mafic rock, either extrusive or intrusive. The oceanic crust is subdivided into five layers, as shown in Figure 2.26. This entire sequence is called an **ophiolite**. Ophiolites are typically exposed on Earth's surface during the end of the subduction process as two continents move closer together and collide. During these final stages of subduction, the oceanic lithosphere gets stuck in the middle of the continental collision and is uplifted with the newly forming mountain belt. This is why most ophiolites are found in mountains.

? Exercise 2.10 – Ophiolites

Ophiolites offer clues to where oceanic crust used to exist, and they help geologists understand processes at mid-ocean ridges.

a. Your instructor has given you a suite of rocks that represent different layers in an ophiolite sequence. Identify your rocks and complete the legend at the bottom of Figure 2.26 by filling in the compositions and rock names.

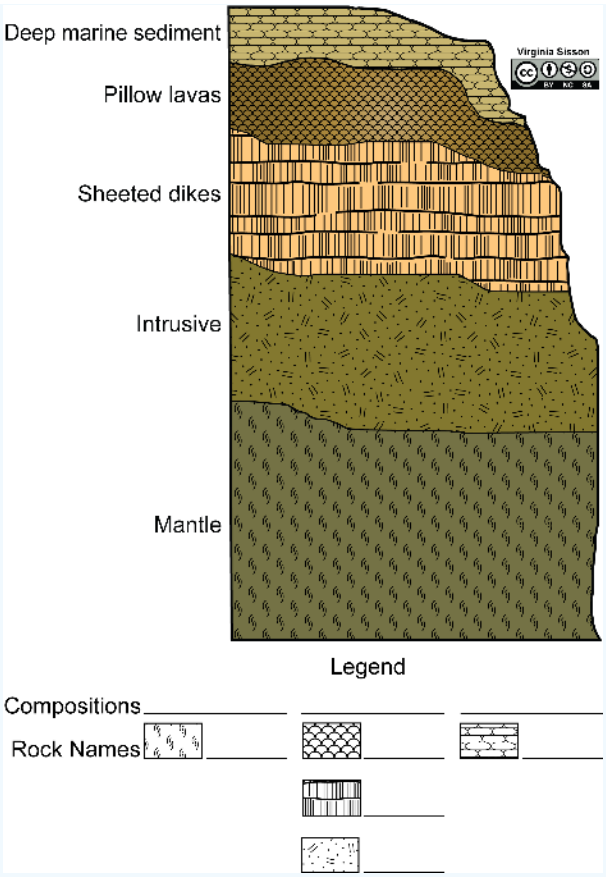


Figure 2.26 – Sequence of rocks in an ophiolite complex. Since it is difficult to find a location with all of these igneous rock types exposed in one outcrop, this is a composite of several different ophiolite exposures. The patterns used for the different units are adapted from the U.S. Geological Survey. Since most ophiolite sequences are composed primarily of mafic to ultramafic igneous rocks underneath deep marine sediment, we used dark green to brown colors for the different rock types. Image credit: Virginia Sisson, CC BY-NC-SA.

a. Explain why ophiolites show a sequence that moves from intrusive rock to extrusive. Hint: Think about relative cooling rates.
b. What do pillow lavas tell you about where they were formed?
c. Now use your knowledge of ophiolites to answer some questions about the geologic history of the Himalayan mountains. In Figure 2.27, name the two tectonic plates. Are these oceanic or continental tectonic plates? What is the thickness of their lithosphere?
d. What type of rocks are shown in the black blobs on this geologic map? _____
e. There are five other groups of rocks in the Himalayan Mountains. Each of these groups has a distinct geologic history.
    i. Why do you think these groups of rocks are distributed as long skinny units?
    ii. If the rock units are elongated in a particular direction, geologists call this their strike direction. Typically strike direction is given as a compass direction. What is the strike direction of these groups? _____
    iii. Does the strike change from east to west along the Himalayan Mountains? _____
    iv. How does the strike of the ophiolites compare to the contacts between the units and to the thrust and normal faults?
    v. What can you infer from your observations of the type of faults and the ophiolites? Hint: do the ophiolite blobs occur next to both the thrust and normal faults?
f. Make some observations about the map patterns of the ophiolites. Are the ophiolite blobs in a continuous or discontinuous belt?
g. Since ophiolites are signatures of previous ocean basins, what happened to all of the oceanic crust that was once between these two continental tectonic plates?

h. **Critical Thinking:** Some geoscientists suggest using the term suture zone to describe where ophiolites occur during continent-continent convergence. Looking at the map, do you think this term is appropriate for the Himalayan Mountains. Explain your answer.

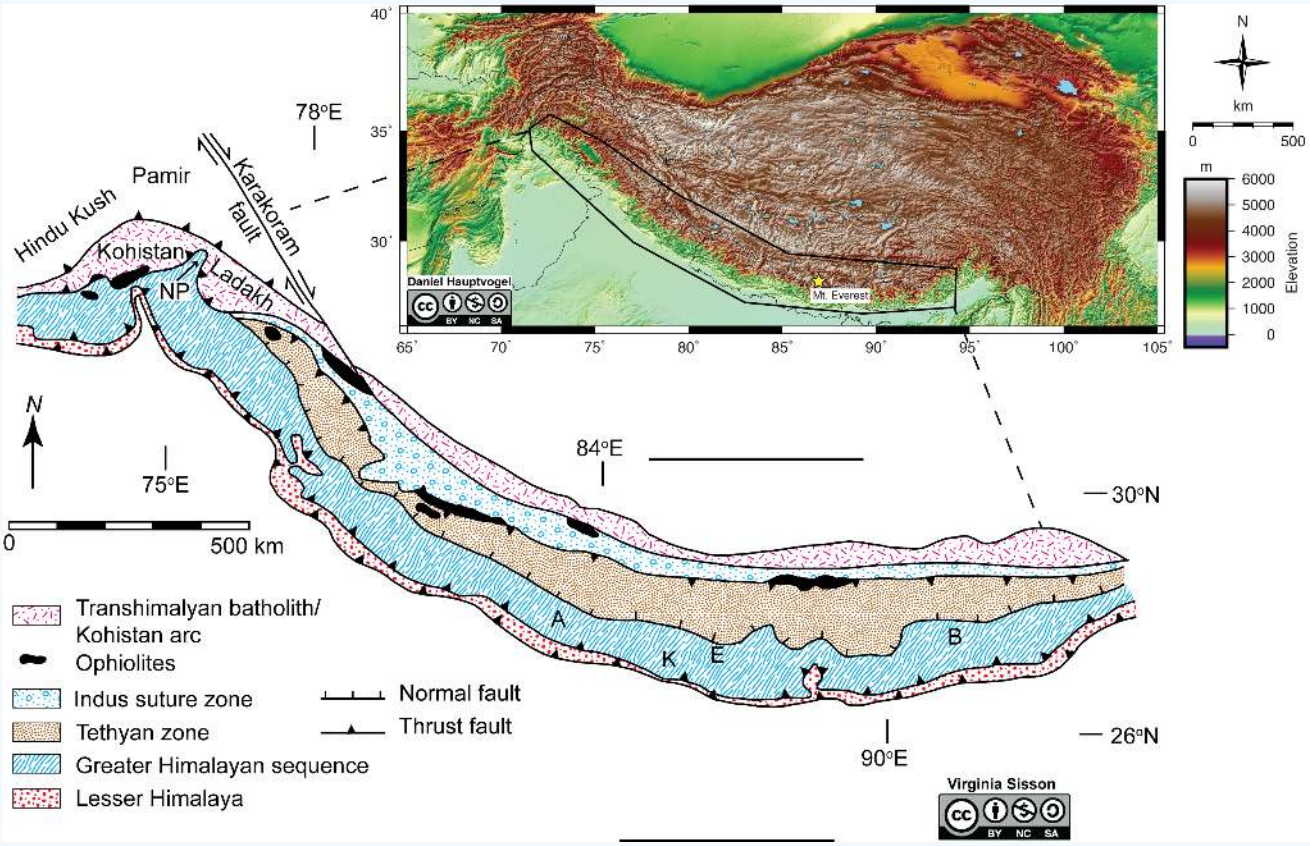


Figure 2.27 – Geologic map of the Himalayan Mountain range. The insert is a shaded relief map of Asia, including Nepal, Bhutan, Pakistan, Afghanistan, China, Russia and India. Most of the high topography is in an area called the Tibetan Plateau. To the south is the low area of India and to the north is Russia and China. Map scale reference is 30° latitude. Within the insert, there is a black box that outlines the area shown below. The location for Mt. Everest (Chomolungma in Tibetan) is shown for reference. The geologic map has six main lithologies. The northernmost unit includes igneous rocks of the Transhimalayan batholith and Kohistan arc shown in a pink, standard crystalline rock pattern. Scattered throughout the map are occurrences of ophiolite sequences indicated as black areas. If you are at the eastern (right) edge of the mountains, the next unit is the Indus suture zone shown in a blue dot and open circle pattern. Next to this is the Tethyan zone in a brown-stippled pattern. The next unit is the Greater Himalayan sequence in wavy blue lines. The southernmost unit is the Lesser Himalaya, shown as red dots. Each unit is separated from the next by either a thrust fault (line with barbed teeth) or a normal fault (line with hatchures). There is a major strike-slip fault (Karakoram) that offsets part of the Himalayan mountains on the northwest side of the range. If you look carefully at the shaded relief map, you can pick out how far this unit goes into the Tibetan Plateau. Abbreviations: NP (Nanga Parbat), A (Annapurna), K (Katmandu), E (Everest), and B (Bhutan). Image credit: This map was simplified from MP Searle and PJ Treloar, 2019.

? Exercise 2.11 – Southern Alaska

There is a sequence of metamorphic rocks in southern Alaska called the Chugach Metamorphic Complex (Figure 2.28). In one area along the Tana River, you can walk upstream from phyllite to gneiss. However, to determine the metamorphic conditions, you need to identify the mineral assemblages. A team of geologists worked along this river for three summers and mapped the distribution of metamorphic minerals and the deformation, textural, and geochronological history. The outcrops occur where a river along a glacier eroded away the glacial sediments and exposed the bedrock. The protoliths for these rocks are graywacke deposited in an **accretionary prism** during the Late Cretaceous. Now that you have the geologic history for this region try to interpret the metamorphic pattern shown in Figure 2.28.

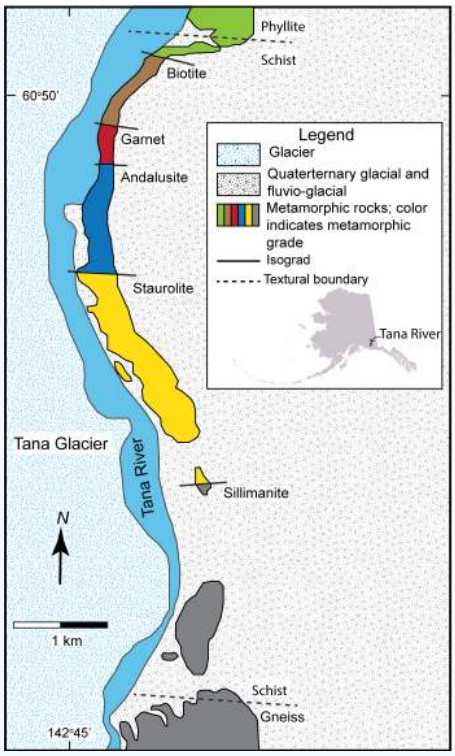


Figure 2.28 – Map of metamorphic zones in southern Alaska along the Tana River. The color scheme is similar to Figure 2.20, except this area has andalusite instead of kyanite. Green is chlorite, brown is for biotite, red is for garnet, blue is for andalusite, yellow for staurolite (a yellow-brown silicate), and gray is for sillimanite. The boundaries between these zones are isograds marked as solid black lines. There are two dashed lines indicating boundaries between rocks with different textures (phyllite, schist, and gneiss). The blue-stippled pattern indicates the position of the Tana Glacier in 1988. The gray stipple pattern represents glacial deposits. The insert map shows an arrow pointing to the location of the Tana River in southern Alaska. Image credit: This map is adapted from Bowman et al. (2003) with unpublished mapping of Sisson.

a. Do the textural boundaries between phyllite, schist, and gneiss correspond to mineralogical changes? If not, why do you suppose they are different?
b. Is this a medium- or low-pressure terrane (consider Figure 2.21)? Did it form as a contact aureole or regional metamorphism?
c. Using a graph of metamorphic temperatures in Figure 2.20, what is the difference in temperature from north to south along the Tana River?
d. What is the geothermal gradient along the Tana River? To determine the horizontal geothermal gradient, determine the distance between the two points you used for estimating the metamorphic temperature.
e. How does the horizontal geothermal gradient compare with vertical geothermal gradients in stable continental crust?
f. What was the heat source for the metamorphism?
g. **Critical Thinking:** This map shows the distribution of another mineral common in metamorphosed shales, staurolite. Using the temperature scale, determine the temperature that the staurolite formed.
h. **Critical Thinking:** Assume this area was at ~10 km depth or ~300 MPa. Then, use your temperature estimates from Exercise 2.7f as well as 2.11g to plot the pressure-temperature history for southern Alaska in Figure 2.21. This will be the path that the highest-grade rocks would have taken through time.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Carlos Andrade

References

Berman, R.G., 1991, Thermobarometry using multi-equilibrium calculations; a new technique, with petrological applications, The Canadian Mineralogist, v. 29 (4), p. 833–855

Bowman, J.R., Sisson, V.B., Pavlis, T.L., and Valley, J.W., 2003, Oxygen isotope constraints on fluid infiltration associated with high temperature–low pressure metamorphism (Chugach Metamorphic Complex) within the Eocene southern Alaska fore-arc, in Sisson, V. B., Roeske, S. M., Pavlis, T. P., editors, Geological consequences of ridge-trench interactions in the northern Pacific, Geological Society of America Special Publication no. 371, p. 237-252

Lyubetskaya, T., and Ague, J.J., 2010, Modeling metamorphism in collisional orogens intruded by magmas: I. Thermal evolution: American Journal of Science, v. 310, p. 427-458, DOI: 10.2475/06.2010.02

Pfiffner, O. A., and Gonzalez, L., 2013, Mesozoic–Cenozoic Evolution of the Western Margin of South America: Case Study of the Peruvian Andes, Geosciences 3, no. 2: 262-310, DOI: 10.3390/geosciences3020262

Searle, M.P., and Treloar, P.J., 2019, Introduction to Himamalyan tectonics: a modern synthesis, in Himalayan Tectonics: A modern synthesis ed by P.J. Treloar and M.P. Searle, Geological Society of London Special Publications, v. 483, p. 1-17 https://doi.org/10.1144/SP483-2019-20

Google Earth Locations

Click or Scan to View all Chapter 2 Locations on Google Earth

This page titled 1.3: Earth Materials is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.4: Geologic Time

Learning Objectives

The goals of this chapter are to:

- Illustrate the immense scale of geologic time
- Summarize the geologic time scale
- Explain the principles of relative dating and unconformities
- Apply principles of relative and absolute dating to determine the ages of rocks

3.1 Introduction

Earth is 4.543 billion years old. That's 4,543,000,000 years, an amount of time so immense that it's challenging to grasp just how long it is. To put this into perspective, if the average human lifespan is 80 years, the Earth has been around for 57,000,000 lifetimes. Or if you have a penny for every year the Earth has been around, you would have $45.4 million! Constantly writing out millions and billions of years is time-consuming, so when geologists talk about ages, they use a few abbreviations. The symbols ka (thousands), Ma (millions), and Ga (billions) refer to points in time like a date. For example, the dinosaur extinction occurred at 66 Ma. Geologists also use other abbreviations for lengths of time, including ky, kya, kyr, and k.y. for thousands of years; my, mya, myr, and m.y. for millions of years; and by, bya, byr, and b.y. for billions of years. All four varieties of abbreviations mean the same thing in this case. Here, you would say the dinosaurs have been extinct for 66 myr. If this sounds confusing, you're not alone because even some geologists use all of the abbreviations interchangeably. There is a debate amongst geologists, and other sciences, over the notation used for geologic time.

Fun fact: The Tyrannosaurus rex was one of the last dinosaurs to evolve about 70.6 Ma (a specific date). The first dinosaurs evolved about 230 Ma (a specific date), 159 myr (a length of time) before T-rex evolved. We are closer in time to the T-rex than the T-rex is to its earliest dinosaur ancestor! See the difference in abbreviations yet?

3.2 Geologic Time

Since 4.54 byr is a large chunk of time, geologists have divided it into more manageable chunks by creating a time scale. The commonly accepted time scale comes from the International Commission on Stratigraphy (Figure 3.1). It is continually revised as new research fine-tunes numbers between time scale divisions. The one in Figure 3.1 is the most up-to-date at the time of this writing and will be referenced throughout this manual. The divisions on the time scale are often based on significant events that have taken place tectonically, biologically, or climatically, and the numerical ages are derived from radiometric dating of rocks, minerals, and fossils.

Geologic time is first divided into **eon**s; these are the Hadean, Archean, Proterozoic, and Phanerozoic. The first three eons are often referred to as the Precambrian, which we'll call a "super" eon. The eons are subdivided into eras, and eras are subdivided into periods, and periods into epochs, and epochs into ages. For the purposes of this lab manual, we will refer to this nomenclature. You'll notice there is a second way to refer to these divisions on the time scale. The difference between the two is discussed here, but it is not important for our purposes. Throughout this lab manual, you will mainly see us referencing periods of geologic time.

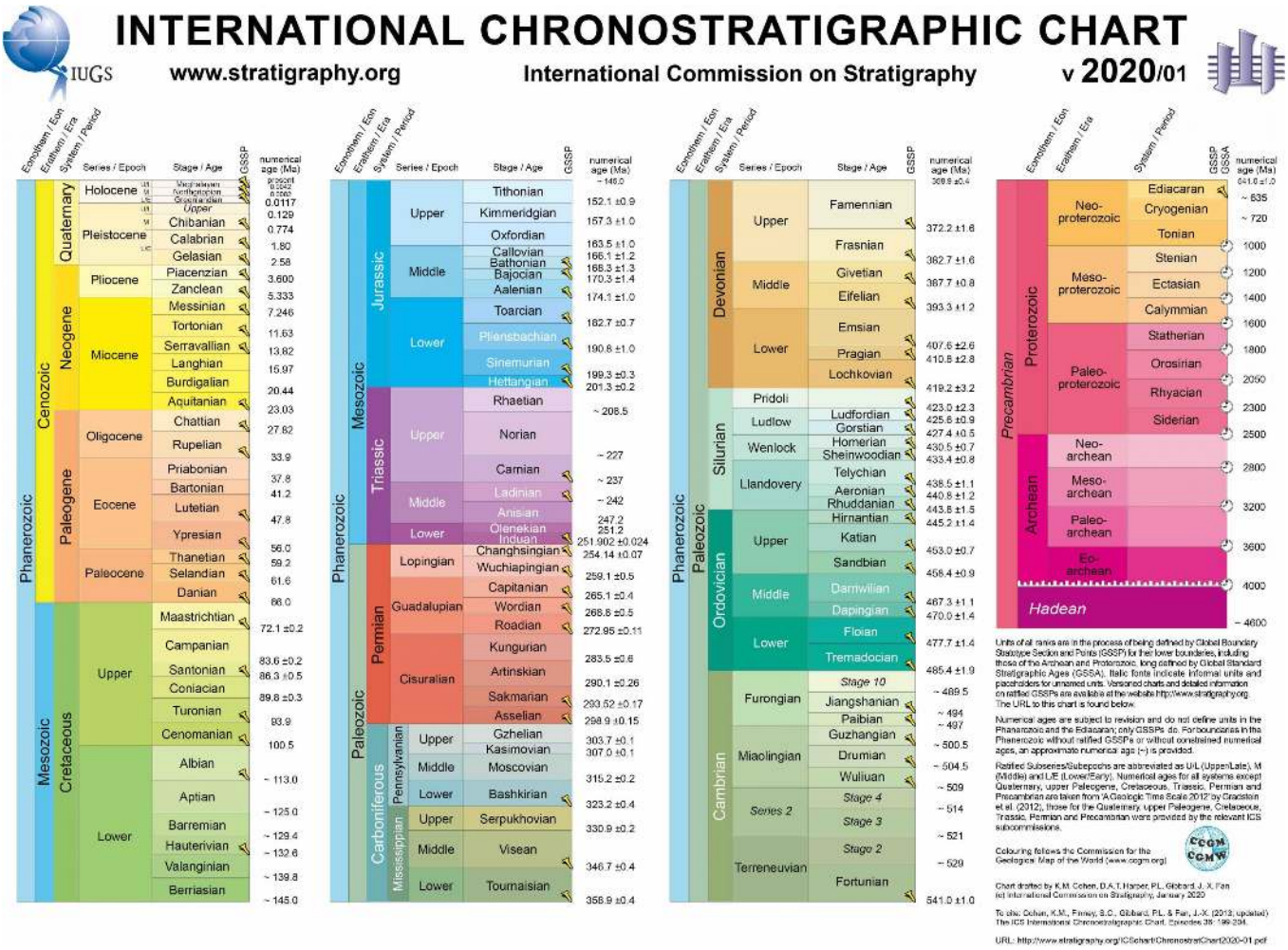


Figure 3.1 – The geologic time scale subdivided by eon, era, system, series, epoch, and stage. What do you observe about each period of time? It is simple; they are color-coded. We will use these standard colors throughout this lab manual. The golden spikes at age boundaries indicate a specific place used to define the age boundary. Image credit: International Commission on Stratigraphy.

? Exercise 3.1 – Making Your Own Geologic Time Scale

Many depictions of the geologic time scale don't show the divisions of geologic time on the same scale. Look at the time scale in Figure 3.1, for example. The far-right column goes from 4.6 Ga to 541 Ma; that's about 4 billion years of history in one small column! The other three columns make up the remaining 500 myrs. The reason for this is that geologists know much more about the last 500 myrs of Earth's history than the first 4 byrs. So, let's make a geologic time scale where all geologic time is shown at the same scale.

a. Using a 2.5 m long roll of paper, create your own geologic time scale using the following scale: 1 cm = 20 million years. For the purpose of this exercise, round Earth's age to 4.6 Ga and use a tick mark spacing of every 100 myrs.
b. Label the Precambrian and its associated eons.
c. Label the Phanerozoic eon and its associated eras and periods.
d. For the Cenozoic era, label the epochs.
e. Table 3.1 is a list of some major events in Earth's history. On one side of your time scale, label when you think these events occurred using a color of your choice.
f. Using a cell phone or laptop, look up when these events actually occurred and label them on the other side of your time scale. Label physical events in one color and biological events in a different color. Some of the events will have a range of ages.
g. How close were your guesses?

https://geo.libretexts.org/@go/page/18711

Table 3.1 – A list of major events in Earth's history

Formation of Earth's Moon	Great oxidation event
Dinosaur extinction	Formation of the Himalayan Mountains
First fossil evidence of life	First homo sapiens
First fish	First mammals
First reptiles	First amphibians
First major glaciation, called Snowball Earth	End of the last ice age
Breakup of Pangea	Formation of Rocky Mountains
Earliest trace of life (bacteria)	Oldest oceanic crust

h. Come up with a mnemonic device to help you remember the periods of geologic time in the Phanerozoic Eon. For example, did you know that the word "scuba," as in scuba divers, is actually a mnemonic device that stands for Self-Contained Underwater Breathing Apparatus?

Table 3.2 – Abbreviations for the Geologic Time Scale

Geologic Time Period	Abbreviation
Quaternary	Q
Neogene	Ng
Paleogene	Pg
Cretaceous	K
Jurassic	J
Triassic	T_R
Permian	P
Carboniferous	C
Devonian	D
Silurian	S
Ordovician	O
Cambrian	Ȼ
Neoproterozoic	Z
Mesoproterozoic	Y
Paleoproterozoic	X
Archean	A

Geologists use abbreviations to refer to the different portions of geologic time (Table 3.2), particularly on geologic maps. A few of these abbreviations may seem puzzling because the abbreviation isn't always the first letter of the name. Carboniferous got the "C", so Cambrian got a C with a slash through it "Ȼ". This left Cretaceous with a "K." Tertiary had originally received the "T", which left Triassic to be symbolized with a T that had an R subscript. In 2003, "Tertiary" was stricken from the geologic timescale and

replaced by the Paleogene and Neogene. You will still see “T” on older maps for Tertiary, and some geologists still use the term today. So, be careful! There were already some M’s and P’s; so, Proterozoic eras were assigned as X, Y, and Z.

Geologists use two methods for dating events in Earth’s history. The first is called relative dating, meaning how events relate to each other in time, or more plainly, they figure out the sequence of events (what came first, second, third, etc.). Relative dating has no regard for numerical ages. The second method is absolute dating, where geologists use radioactive isotopes to figure out the numerical age of a rock or mineral.

3.3 Relative Dating and Correlation

There are several principles geologists use for relative dating. The first four principles were developed in the 17th century by an early geologist named Nicolas Steno, three of which pertain to sedimentary rocks. The first is the law of superposition, which states that in layers of horizontal sedimentary rocks, the oldest rock layer is at the bottom, and the youngest is at the top (Figure 3.2). The second rule is the principle of original horizontality, which says that layers of sediment are originally deposited horizontally (Figure 3.2). So, any tilting or folding of the rock occurred after it was deposited (Figure 3.3). The third principle states that layers of sedimentary rock are continuous, and anything that interrupts the layer (like a river or canyon) happened after the rock formed. This is called the principle of lateral continuity (Figures 3.4 and 3.5).



Figure 3.2 – Horizontal layers of red sedimentary rocks from the Moenkopi and Chinle Formations from the Triassic period in the Virgin River Valley near Zion National Park. Layers of sedimentary rock are originally deposited horizontally, with the oldest layer at the bottom. This shows both the principles of superposition and original horizontality. Image credit: James St. John, CC-BY.



Figure 3.3 – These are tilted layers of the Moenkopi Formation from the Lower Triassic, just south of Split Mountain, Dinosaur National Monument in Utah. They were originally deposited horizontally and were titled at some point in geologic time. Image credit: James St. John, CC BY.

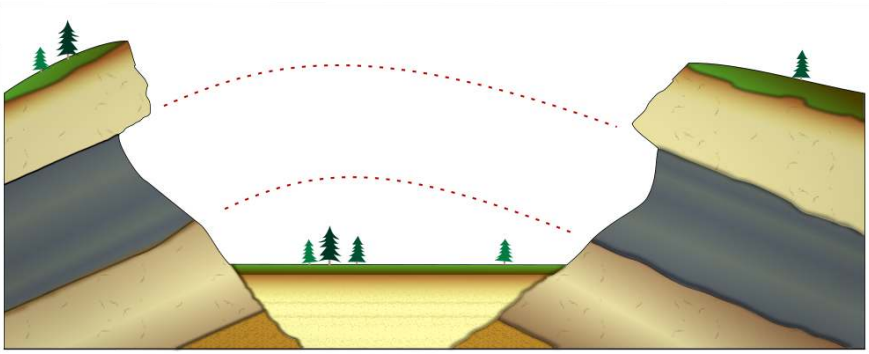


Figure 3.4 – A depiction of the principle of lateral continuity. The layers of rock on one side of this valley were once connected to the same rocks on the other side. The valley was carved after these rocks were deposited. The dashed red lines show how the units were connected. Image credit: Wikimedia user Wouldloper, Public Domain.



Figure 3.5 – A panoramic view of meanders in the San Juan River cutting through layers of sedimentary rock in Goosenecks State Park, southwestern Utah. If you look carefully, you can trace layers of sedimentary rock that have been cut by the river across the entire image; an example of lateral continuity. Image Credit: Gernot Keller, CC BY.

Steno's fourth principle is cross-cutting relationships. This principle is used when other geologic events cut through sedimentary rocks, like an **igneous dike** or a **fault**. This principle basically states that when a geologic event cuts across another, the event doing the cutting is younger than the one being cut (Figure 3.6). For example, if sedimentary rocks are cut by an igneous dike, the

igneous dike is younger than the sedimentary rocks it's cutting through. The same can be said of a fault that cuts through any rock; the fault has to be younger because the rocks had to exist first to be faulted.



Figure 3.6 – A mafic dike (dark rock) cutting through granitic pegmatite (light rock) in Ruggles Mine, New Hampshire. To determine which is younger, look to see which unit cross-cuts the other. Since the mafic dike is cutting through the pegmatite, the dike is younger by the principle of cross-cutting relationships. Image credit: James St. John, CC BY.

Some 200 years later, the fifth principle of relative dating was developed by Charles Lyell called the principle of inclusions. This principle explained that a **clast**, or a different-looking rock that is contained inside of another rock, is older than the rock that contains it (Figure 3.7). How can this happen? Originally, a mafic magma was cooling quickly, producing the finer-grained mafic rock in the middle of Figure 3.7. Then, something happened to change the chemistry of the magma to felsic and slowed the cooling rate to produce the surrounding, coarse-grained granite. The mafic rock formed first, and then the felsic rock formed around it.



Figure 3.7 – A mafic inclusion in granitic rock. Inclusions are older than the surrounding rocks. A penny shows the scale of the image. Image credit: Marli Miller, CC BY.

Unconformities

Simply speaking, an unconformity is a pattern that you look for in a group of rocks that tells you erosion has taken place. Rocks exposed on the Earth's surface are affected by physical and chemical weathering processes that work to break them into smaller pieces or dissolve them in water. This material is then transported away by wind, water, or ice, a process known as erosion. Many people use weathering and erosion interchangeably, but they do mean different things: weathering is the breakdown of rocks, while erosion removes the broken down material.

There are four types of unconformities, and each forms in a slightly different way (Figure 3.8). They all involve sedimentary rocks, changes in sea level, and/or uplift from an orogeny. Each unconformity tells a unique story of the geologic history of the area they've been found.

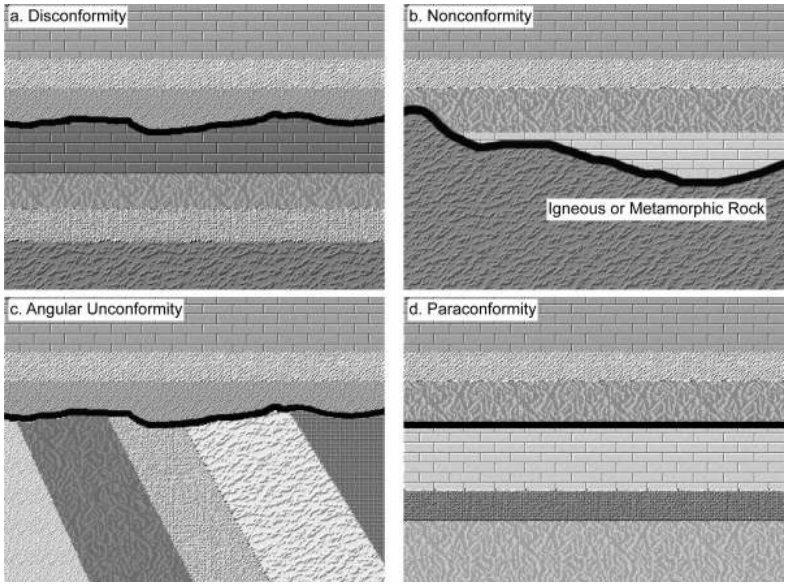


Figure 3.8 – Types of unconformities. (a) Disconformity; (b) Nonconformity; (c) Angular unconformity; (d) Paraconformity. Image credit: Wikimedia user דקי, CC BY-SA.

A disconformity (Figure 3.8a) is an erosional surface where the rocks below the unconformity are much older than the rocks above. This type of unconformity typically forms when horizontal layers of sedimentary rock are deposited in a shallow marine environment; then sea level lowers to expose these rocks and allows erosion to occur; then sea level rises again, and new horizontal layers of sedimentary rock are deposited. Erosion removed some of the original rock, creating a large age gap between the rocks above and below the erosional surface. This age gap is the disconformity and is located at the contact point between the older rock and younger rock. Oftentimes the erosion process leaves behind evidence of river channels or soil development, which provide clues to geologists to locate the unconformity in what looks like a continuous succession of sedimentary layers.

A nonconformity (Figure 3.8b) forms when igneous or metamorphic bedrock is eroded, and then horizontal layers of sedimentary rock are deposited directly on top of it. The unconformity is where the bedrock meets the sedimentary rock. For example, when a mountain belt is eroded below sea level, and afterward sediments are deposited on top of the igneous or metamorphic rock, the contact is a nonconformity.

An angular unconformity (Figure 3.8c) is created when horizontal layers of sedimentary rock lie on top of tilted layers of sedimentary rock. The most famous angular unconformity is from Siccar Point in Scotland. Figure 3.9 shows the process of creating an angular unconformity. For this to occur, sedimentary rocks deposited in the marine environment are lifted above sea level by an **orogeny** or similar event. The orogeny causes the sedimentary rocks to become tilted or folded. Since these rocks are exposed above sea level, erosion takes place. The rocks can either be eroded below sea level, or sea level can rise, which would allow new, horizontal layers of sedimentary rock to be deposited on top of the titled ones. This creates an angle between the younger, horizontal layers on top and the older, tilted layers below.

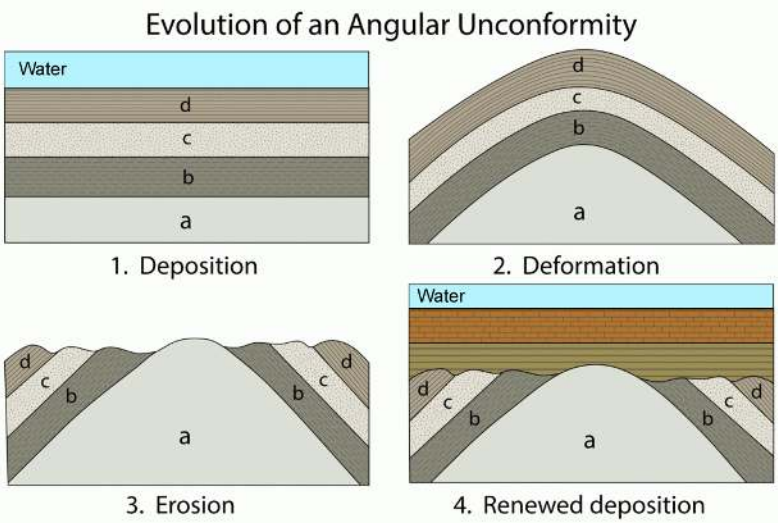


Figure 3.9 – A depiction of how an angular unconformity forms. 1) Deposition of sedimentary rocks; 2) uplift and folding of the sedimentary layers; 3) erosion; 4) resumed deposition on top of the folded layers. Image credit: Utah Geological Survey, Public Domain.

A paraconformity (Figure 3.8d) is very similar to a disconformity, except the evidence for erosion is not present. Either no evidence of the erosion was left behind, or erosion didn't happen, and instead, there was only a pause in sediment deposition. We know these occur because sediment above and below the paraconformity have been radiometrically dated and reveal a large gap in time.

? Exercise 3.2 – Identifying Unconformities

The images in Table 3.3 are different types of unconformities (Figures 3.10-3.12). In the blank spaces provided next to the images, create a sketch for each unconformity, label where you think the unconformity is located, and identify the type of unconformity.

Table 3.3 – Worksheet for Exercise 3.2

 Figure 3.10 – Unconformity #1. Image credit: Marli Miller, CC BY.	
 Figure 3.11 – Unconformity #2. Image credit: Callan Bentley, used with permission.	
 Figure 3.12 – Unconformity #3. Image credit: Marli Miller, CC BY.	

? Exercise 3.3 – Practicing Relative Dating Principles

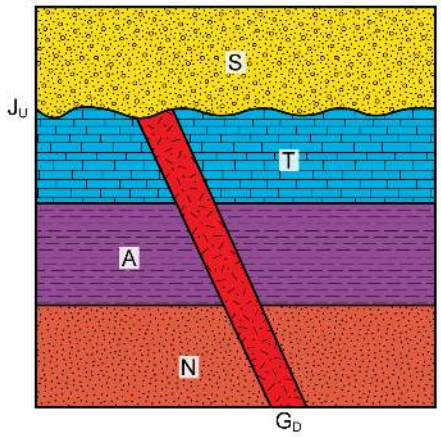
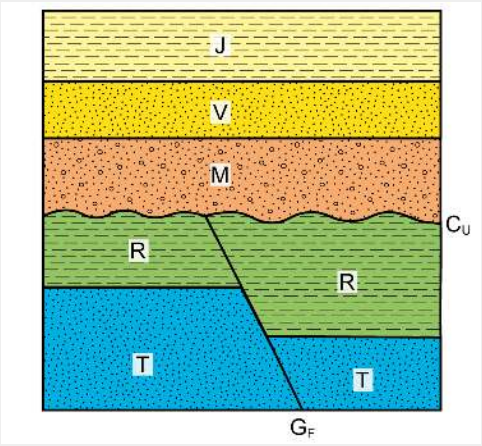
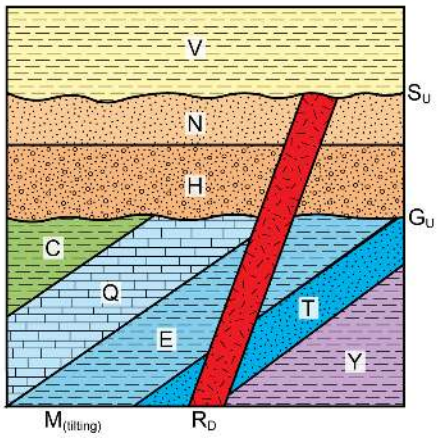
Part I

Now put all of the principles you've learned to work. Below are relative dating outcrop diagrams that represent sections of rock. Each letter represents the deposition of a different layer of sedimentary rock or geologic event.

a. Use the principles of relative dating and unconformities to determine the sequence of events for each diagram in Table 3.4 (Figures 3.13-3.16).
b. Identify the type of each unconformity.

The symbols used to represent common types of rocks are standard USGS symbols. You will only see conglomerate, limestone, sandstone, shale, granite, and gneiss in this exercise. The subscript letters stand for igneous dikes (D), faults (F), and unconformities (U). The colors for each unit are from the geologic time scale shown in Figure 3.1. Hint: it is easier to start with the oldest event and work your way forward through time.

Table 3.4 – Worksheet for Exercise 3.3

 Figure 3.13 – Diagram #1. Image credit: Daniel Hauptvogel, CC BY-NC-SA.	Youngest Oldest
 Figure 3.14 – Diagram #2. Image credit: Daniel Hauptvogel, CC BY-NC-SA.	Youngest Oldest
 Figure 3.15 – Diagram #3. Image credit: Daniel Hauptvogel, CC BY-NC-SA.	Youngest Oldest

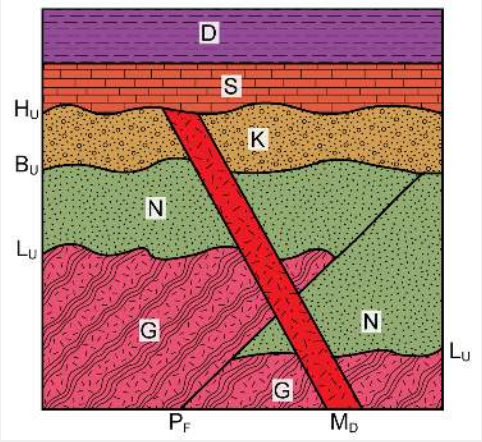


Figure 3.16 – Diagram #4. Image Credit: Daniel Hauptvogel, CC BY-NC-SA.

Youngest
Oldest

Part II

The web program Visible Geology lets you create block models with a complicated geologic history. An example of a diagram made with this website is in Figure 3.17. Answer the following questions using Figure 3.17:

c. Place the following in order from youngest to oldest: Fault, Dike, Folding. _____

d. If the dike is 100 Ma, what is the age of the normal fault? _____

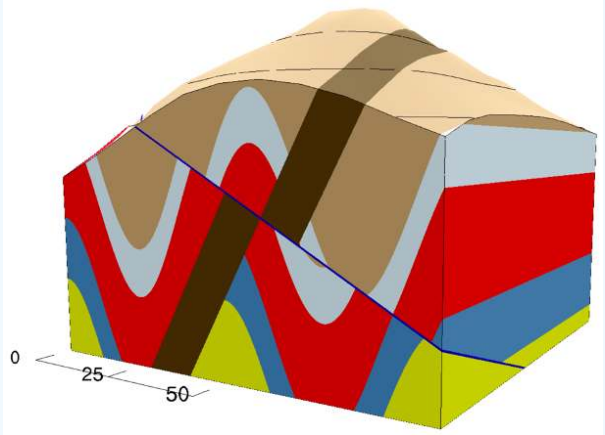


Figure 3.17 – Block diagram created using the website Visible Geology. Sedimentary strata are shown in yellow, blue, red, white, and tan. The dark brown is an igneous dike. The blue line is a fault. The dashed lines represent contour lines.

Part III

Create your own block model using the web program Visible Geology.

- Your model should include 2 to 6 sedimentary layers. You may want to vary their thickness. Each rock type is assigned a unique color. You can also include an unconformity (angular, disconformity, or nonconformity).
- You can include tilting, folds, thrusts, strike-slip faults, and normal faults.
- You may want to include some igneous rocks as sills or dikes. If you include a dike or sill, you may want to assign it a specific age, such as 100 Ma. This numerical age can be used to give specific dates to events in this geologic history.
- Include erosion at some point in your model.

e. When you are done with this, rotate the cube and decide which side has the easiest and most difficult history to assess. Or perhaps you made a model that is easy on all sides? Explain why there is this difference.

f. Create a geologic cross-section through your model from corner to corner. Draw a sketch of one of these cross-sections.

Cross-Section Sketch #1:

g. Sometimes geologists only have cliff faces or road cuts to investigate. Do you think you will get the same geologic history with this cross-section as one of the sides?

h. Now draw a quick sketch of one of the sides. Show it to one of your classmates and see if they can interpret its geologic history. If you included an igneous feature, assign it an age. If your colleague can't get the history, give them some clues to help.

Cross-Section Sketch #2:

? Exercise 3.4 – Using Relative Dating Principles

One of the ways geologists investigate Earth's history is by imaging what is below Earth's surface; this is called a seismic survey. It is done by sending sound waves into the ground or ocean. As these sound waves move through different layers of rock or sediment, some of the waves are reflected back toward the surface and recorded by **geophones**. Different types of sediments or rocks change the characteristics of the wave, such as its velocity. Geologists set up geophones that record these reflected waves and provide an "image" of what the subsurface looks like. The signals recorded are called the seismic amplitudes, a measure of the difference in rock properties between two layers. Seismic data is commonly converted to impedance, or hardness (this is not the same as Mohs hardness). The relative hardness can be positive, negative, or the same. Thus, many seismic sections will use three colors to better distinguish different strata.

Part I

The continental slope off of the north island of New Zealand is called the Hikurangi margin. Geoscientists wanted to explore this area to better understand the plate boundary by drilling a sediment core. The International Ocean Discovery Program (IODP) proposed to put a drill core at Site U1519, but first, they conducted a seismic survey (Figure 3.18) to assess the possibility of active thrust faults in the area.

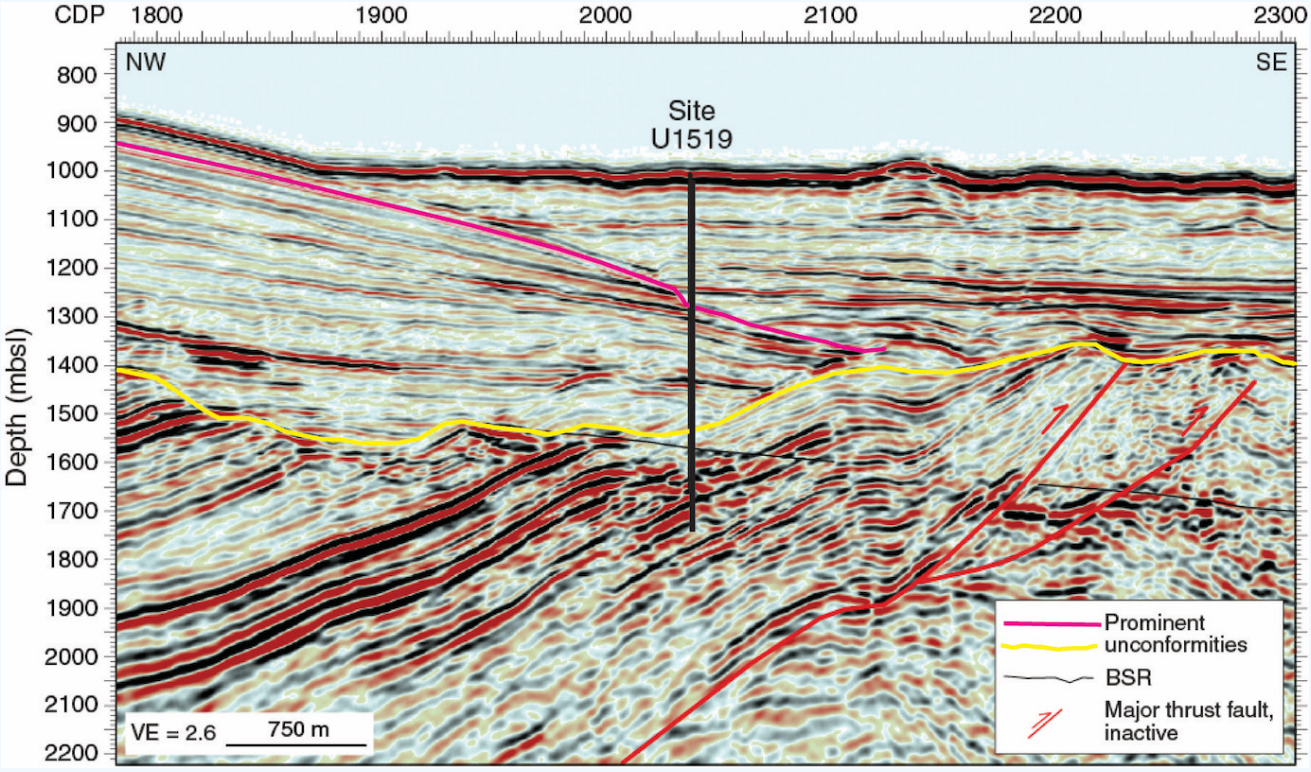


Figure 3.18 – Seismic profile for IODP Site U1519. There are two unconformities shown with yellow and pink lines. Also shown in a thin black line is the bottom simulating reflector (BSR). The black color is used for positive amplitudes, red for negative amplitudes, and white for zero amplitude. Image credit: Wallace et al., 2019 and IODP, CC BY.

a. What type of unconformity is the yellow line? _____
b. What type of unconformity is the pink line? _____
c. **Critical Thinking:** Do you think it would be safe to drill here? Explain your answer.

Part II

As the Pacific plate traveled over numerous hot spots, the basement of the Gulf of Alaska became riddled with seamounts. The seamounts have a variety of ages and sizes, as you can see in Figure 3.19. These are partially covered by a thick blanket of sediments up to 1.5 km thick.

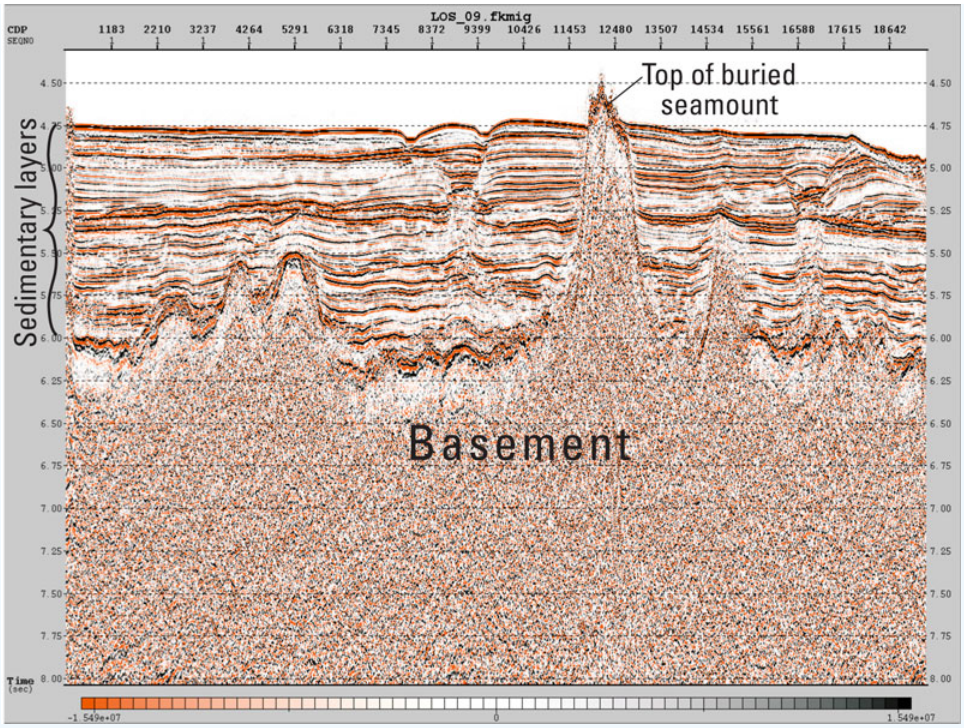


Figure 3.19 – Seismic profile from the Gulf of Alaska. Since this is a preliminary seismic section, it has not been processed to show depth. Instead, it shows two-way travel time in seconds for the seismic energy. The red, black, and white lines indicate sedimentary layers, whereas the red, black, and white dots represent the oceanic crust (basement). The sedimentary layers are more than 1.5 km thick. The same color scheme is used for seismic rock properties as in Figure 3.18. Image credit: USGS, Public Domain.

d. Identify two areas where faulting has taken place by outlining them in Figure 3.19.

e. Why is the contact between the crystalline basement and the sedimentary layers above it not considered unconformity?

Sedimentary Rock Correlation

The principles of relative dating allow geologists to compare seemingly similar groups of rocks separated by some distance. On a small scale, it's as simple as saying that rocks on either side of a canyon are, in fact, the same and were once connected before the canyon formed, as in Figure 3.5. On a larger scale of kilometers to hundreds of kilometers, it can be comparing sets of sedimentary rocks that have similar patterns.

? Exercise 3.5 – Correlating Layers of Sedimentary Rock

Geologists can correlate sedimentary rock units over great distances by matching patterns in the outcrops, called lithostratigraphic correlation. Figure 3.20 below contains two outcrop drawings of sedimentary rock outcrops that are separated by 100 km.

a. Draw lines that correlate the rock units across these two areas. You can color the units to help you.

b. One of these areas contains an unconformity. Mark the location of the unconformity in Figure 3.20.

c. What type of unconformity is it? _____

d. **Critical Thinking:** Are any other sedimentary layers missing from one of the outcrops? If so, explain why.

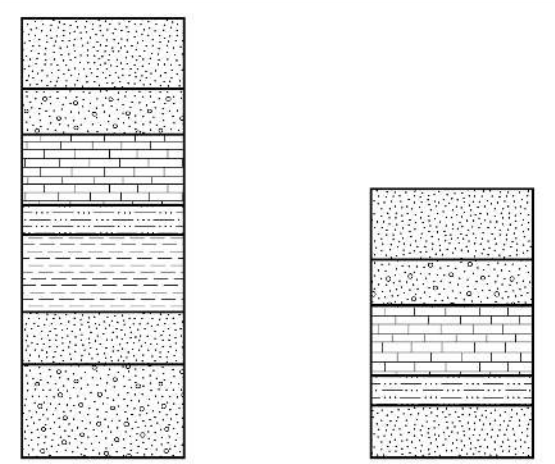


Figure 3.20 – Two stratigraphic columns to be used in Exercise 3.5.

Fossil Correlation

Fossils present in sedimentary rocks can also be used for correlation. This usually involves a fossil assemblage, which is just the group of fossils found in a rock layer. By comparing fossil assemblages from one rock outcrop to another, geologists can determine how the outcrops relate to each other in age. This can tell geologists that layers of rock may have been deposited simultaneously or can be used to identify unconformities.



Figure 3.21 – A sedimentary rock containing multiple belemnite fossils. These cone-shaped shells come from an extinct marine animal similar to a modern squid. Image credit: Wikimedia user PierreSelim, CC BY-SA.

Certain fossils, called index fossils, can be indicative of a narrow span of geologic time. These fossils are easily recognizable, abundant, existed for a short period of time, and had a wide geographic distribution. When you see an index fossil in a rock, it immediately gives you an idea of how old the rock is. For example, Belemnites (Figure 3.21), a type of cephalopod (squid), only existed during the **Mesozoic** era. So if you were to see a belemnite fossil in a rock, you know that rock is from the Mesozoic (between 252 and 66 Ma). We'll have lots more on fossils in later chapters.

? Exercise 3.6 – Using Fossils to Correlate Rocks and Interpret Age

Fossils are very useful for geologic dating and correlation because the type of sediment deposited at a specific time in a region can vary. Sand particles (sandstone) can be deposited in one area, while clay particles (shale) can be deposited in another at the same time. This means that two different sedimentary rocks will have the same age. In this case, correlating the rock units is more difficult because geologists can't tell they are the same age. This is where fossils can help because they can confirm the sedimentary rocks were deposited at the same time, called biostratigraphic correlation. If both rock layers were deposited at the same time, then they should contain the same fossils.

a. Correlate the sedimentary layers in Figure 3.22 based on the fossils they contain.
b. Label where any unconformities could be interpreted.

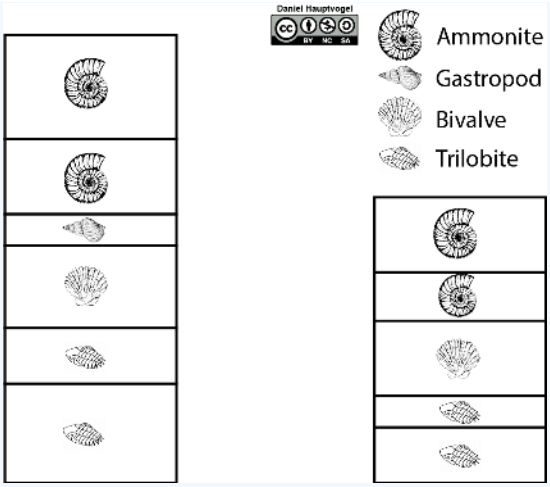


Figure 3.22 – Two stratigraphic columns for Exercise 3.6.

c. You can also use the assemblage of fossils in rocks to correlate sedimentary layers and determine age. Correlate the rock layers in Figure 3.23 based on the groups of fossils that are found.

d. Label where any unconformities could be interpreted.

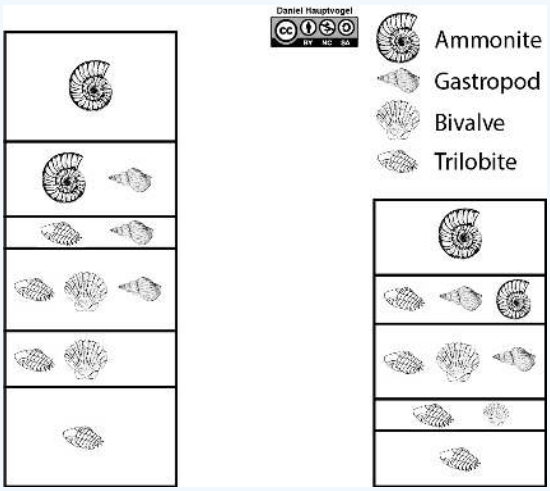


Figure 3.23 – Image for Exercise 3.6.

e. Suppose the fossils have age ranges as shown in Figure 3.24. Label the geologic periods for each layer of sedimentary rock in both columns of Figure 3.23.

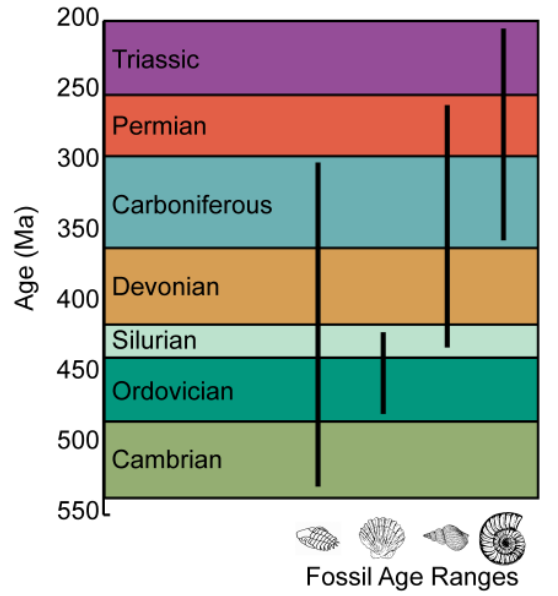


Figure 3.24 – Geologic time scale from Cambrian to Triassic that shows fossil age ranges for Exercise 3.6. The age span for each type of fossil is shown as a black bar above the sketch of the fossil.

f. Which of the fossils is the least useful for dating? _____

g. Which of the fossils is the most useful for dating? _____

*Note the fossil age ranges in this exercise are fictional and used for educational purposes only.

3.4 Radiometric Dating

Geologists can determine numerical ages for the formation of rocks, minerals, and some fossils using **radioactive** isotope systems. Does radioactivity sound scary? It can be, but what we're talking about is happening on such a small scale that you don't have to worry. The next few paragraphs are a bit technical, but we will try to break it down for you.

An isotope is an atom of an element with a different number of neutrons than protons in its nucleus. For example, a typical carbon atom on the periodic table of elements should have six protons and six neutrons in its nucleus, called carbon-12. Some atoms of carbon can have an extra neutron in the nucleus, called carbon-13, and some can have two extra neutrons in the nucleus, called carbon-14. If an atom has too many neutrons in its nucleus, it can become unstable because the nucleus has too much energy; this is called a radioactive isotope. Carbon-14 is a radioactive isotope. Just as the periodic table of elements summarizes the most important information of every element, there are periodic tables of isotopes that include all the possible isotopes for each element and their relative abundance and properties.

Radioactive isotopes **decay** to more stable atoms by way of alpha, beta, and/or gamma decay. We don't need the particulars of these decay processes, but in short, radioactive atoms can gain or lose protons, neutrons, and electrons or release energy in other forms to become stable. Carbon-14 radioactively decays to nitrogen-14, a stable product. This ThoughtCo article gives a very simple explanation of why atoms become radioactive if you want more information.

Table 3.5 – Common isotope systems used for radiometric dating and their half-lives

Parent Isotope	Stable Daughter Product	Half-life
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.0 billion years
Rubidium-87	Strontium-86	48.8 billion years
Potassium-40	Argon-40	1.25 billion years
Samarium-147	Neodymium-143	106 billion years
Carbon-14	Nitrogen-14	5,730 years

Radioactive isotopes don't immediately decay to a stable form because it's a spontaneous process, so it's impossible to predict when and which atom will decay. It's like corn kernels popping in a popcorn maker, you don't know when a kernel will pop, but you know it will happen. Scientists have measured the average rate at which radioactive isotopes decay and describe this rate with the term half-life. Half-life is the time it takes for half of the unstable atoms (parents) to decay to stable forms (daughters). The length of time for a half-life is different for each isotope system. For example, the half-life for carbon-14 is 5,730 years, but the half-life for potassium-40 is 1.25 byrs. In a sample with 1 million atoms of carbon-14, 500,000 of these atoms are expected to decay over the course of 5,730 years. Table 3.5 contains common isotope systems and their half-lives.

Using radioactive isotope systems, geologists can determine quantitative, numerical ages for geological materials and such as rocks, minerals, and fossils. To calculate the age of a geologic material, geologists analyze the material's chemistry and figure out the ratio between parent and daughter atoms. The ratio tells geologists how many half-lives, or what fraction of a half-life, has passed. If you know the ratio between parent and daughter atoms and the rate of decay for that isotope system, you can calculate how old geologic material is.

Geologists use a few assumptions with radiometric dating. One assumption is that when the rock or mineral first formed, there were no daughter atoms present. This means all of the daughter atoms found in the rock had to come from radioactive decay. The second assumption is that the rock or mineral was a closed system. A closed system means there was no addition or removal of elements at any point because that could alter the parent-daughter ratio and therefore affect the age you calculate. With that being said, geologists know that these assumptions may be incorrect for some of the material they work with, and they have methods that can help correct these issues. But that is beyond our scope. That's it for the technical stuff.

Radiometric dating tells you different things depending on which geologic material you're studying. For minerals in igneous rocks, the radiometric age tells you when the mineral crystallized from magma. In metamorphic rocks, the radiometric age of some minerals can give you the age metamorphism took place, but some isotope systems are not affected by metamorphism and can still tell you the age the minerals originally crystallized in the protolith. So, you can determine when the protolith formed and when it became metamorphosed. For minerals in sedimentary rocks, the radiometric age only tells you when that mineral crystallized or metamorphosed in its original rock; it doesn't tell you when the sedimentary rock formed. The only way to determine the age of sedimentary rocks is to combine the principles of relative dating with radiometric dating of igneous or metamorphic events that cross-cut the sedimentary rocks, such as a dike. Ages of sedimentary rocks can also be determined from fossils. Note: It is possible to radiometrically some sedimentary rocks younger than one million years old, but there are no useful isotopes that can be used on older sedimentary rocks.

? Exercise 3.7 – Calculating Radiometric Ages

To determine the age of a mineral or rock, geologists need to know a few things. First, they need to know how long a half-life is for the isotope system being used. Second, they need to know the ratio of parent to daughter isotopes in the mineral, which is measured using scientific instruments like a mass spectrometer.

The standard radiometric age equation is: $t=\ln(1+(D/P))\div\lambda$

- t = time (age of the material)

- ln = natural log (a function on your calculator)
- P = parent ratio (this is measured)
- D = daughter ratio (this is measured)
- λ = lambda is the decay constant (different for each isotope system, a function of the half-life)

Let's get some practice by calculating the ages below:

a. Complete the following calculations to determine the ages of minerals in Table 3.6 (Hint: most cell phones have additional calculator functions when you turn it horizontal. There are also free scientific calculator apps in the Apple and Google stores.)

Table 3.6 – Worksheet for Exercise 3.7

Isotope System	Decay Constant	Parent: Daughter Ratio	Age
Carbon-14	1.21×10^{-4}	1 : 1.3	
Potassium-40	5.34×10^{-10}	1 : 0.25	
Uranium-235	9.72×10^{-10}	1 : 2.34	

a. Look back to Figure 3.16. Let's say a geologist collected a sample of G (gneiss) and M_D (dike) to radiometrically date, with the ultimate goal of trying to constrain ages in this region. She used the potassium-40 isotope system to date metamorphism of hornblende grains and measured a parent-daughter ratio of 1:0.89. She used the uranium-235 isotope system on zircon grains for the igneous dike and measured a parent-daughter ratio of 1:0.28.
   i. How old is the gneiss? _____
   ii. How old is the igneous dike? _____
   iii. What is age range of the fault P_F? _____
   iv. What is the age range of sedimentary layers S and D? _____

3.5 Other Uses for Geologic Dating

Dating in geology has many uses besides determining when a rock or mineral formed. One common use for dating is determining the source rock for sediment, which is called provenance. Interpreting sediment provenance can tell a geologist a lot about the history of an area, including where the sediment came from, where erosion was taking place, and how sediment was transported. Dating of certain sediment grains can also tell geologists when rocks were uplifting during an orogeny. Geologic dating principles can even be used on other planets.

? Exercise 3.8 – Using Geologic Dating to Interpret Sediment Provenance

Even though radiometric dating on mineral grains in sedimentary rocks doesn't give you the age the sedimentary rock formed, it still tells you very useful information about the area's geologic history. One such use is determining the sediment provenance, which is the source rock of the sediment. Remember that the age you determine from sediment grains is the age they formed in their original source rock.

Let's say you collect some biotite grains from the bottom of the lake in Figure 3.25, and you want to figure out where they came from. There are two potential sources for those grains: a set of metamorphic rocks to the west and a set of granites to the south. Little is known about the geology in this area, so you need to figure out the ages of the potential source rocks and determine where the lake sediment came from.



Figure 3.25 – Google Earth image for Exercise 3.8. The yellow star is the location where the sediment was collected. The two potential sources are labeled.

a. You collect five biotite grains from Source 1, five biotite grains from Source 2, and measure them using the potassium-40 system. What are the ages of these source-rock biotite grains? Fill this out in Table 3.7.

Table 3.7 – Worksheet for Exercise 3.8a

Samples from Source 1	Parent : Daughter	Age
1a	1 : 0.808	
1b	2 : 1.706	
1c	1 : 0.825	
1d	3 : 2.349	
1e	2 : 1.596	

Samples from source 2	Parent : Daughter	Age
2a	2 : 0.626	
2b	4 : 1.236	
2c	1 : 0.323	
2d	3 : 0.903	
2e	2 : 0.596	

a. What is the average age of the rocks at Source 1? _____

b. What is the average age of the rocks at Source 2? _____

c. The lake sediment grains you collected have the following ages. Determine which source area they most likely came from by filling out Table 3.8.

Table 3.8 – Worksheet for Exercise 3.8d

Lake Sediment	Age	Source Area
1	523 Ma	
2	1,157 Ma	
3	517 Ma	
4	521 Ma	
5	486 Ma	
6	1,116 Ma	
7	513 Ma	
8	501 Ma	
9	523 Ma	
10	494 Ma	

a. What percentage of the lake sediment is coming from Source 1? _____
b. What percentage of the lake sediment is coming from Source 2? _____
c. **Critical Thinking:** What could be the reason(s) why you see this sediment distribution in the lake?

? Exercise 3.9 – Using Principles of Relative Dating on Other Planets

Cross-cutting relationships is a universal principle. That means it not only applies to our planet but applies to other planets. Let's take a look at some pictures taken from the surface of Mars; these show features such as craters, rivers, and fractures (a type of fault). These types of images are used to decipher the tectonic, volcanic, and impact history.

a. Look at Figure 3.26.
   1. Which is older, Crater B or Crater S? _____
   2. Explain why.

_____

_____

_____

_____

1. Which is older, Fracture F or Crater B? _____
2. Which is older, Fracture F or Crater S? _____
3. **Critical Thinking:** If you wanted to land a rover to investigate Crater B, where would it be safe to land? Consider whether or not you think Fracture F is an active fault.

_____

_____

_____

_____

_____

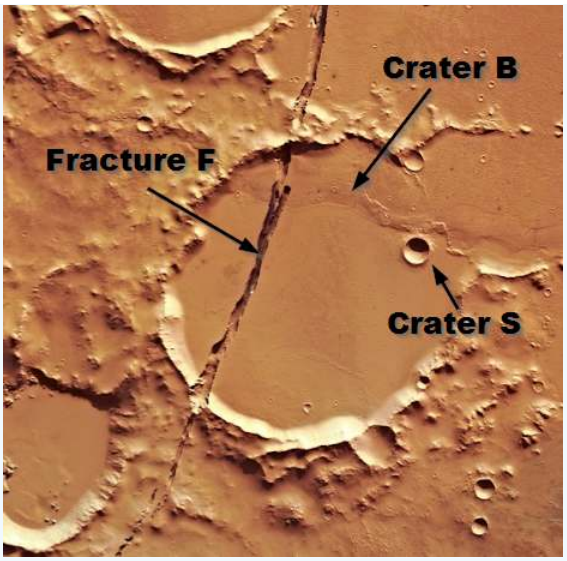


Figure 3.26 – Image for Exercise 3.9a. Martian craters near Cerberus Fossae in the Elysium Planitia region close to the Martian equator. Photo taken January 2018. Image credit: Adapted from ESA/DLR/FU Berlin, CC BY-SA IGO.

b. Look at Figure 3.27. Put the craters in relative order from oldest to youngest. _____

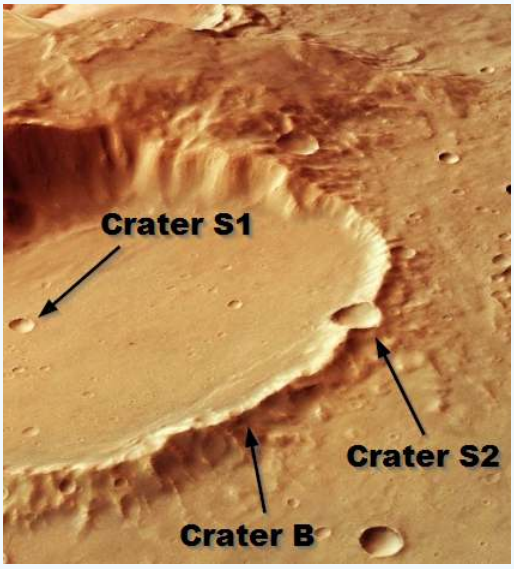


Figure 3.27 – Image of Hadley crater for Exercise 3.9b. This is a composite of several images taken during revolution 10572 on 9 April 2012 by ESA's Mars Express centered around 19°S and 157°E; the image has a ground resolution of about 19 m per pixel. The image shows the main 120 km wide crater, with subsequent impacts within it. Evidence of these subsequent impacts occurring over large time scales is shown by some of the craters being buried. This image shows one of the characteristics of Martian craters as they often have fluidized ejecta that can be seen both in the bottom right and top left craters, the latter crater reaching a depth of around 2600 m. Image credit: Adapted from ESA/DLR/FU Berlin, CC BY-SA IGO.

c. Look at Figure 3.28.

i. Which is older, Crater C1 or River R1? _____

ii. Which is older, Crater C2 or River R2? _____

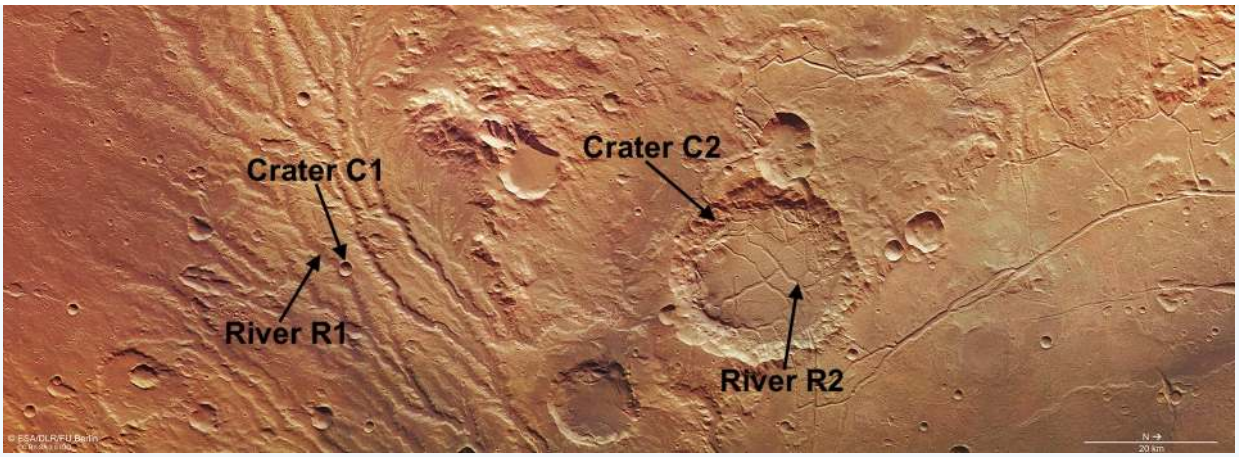


Figure 3.28 – Image from the Arda Valles region of the Martian highlands for Exercise 3.9c. The region was imaged by Mars Express on 20 July 2015 during orbit 14649. The image is centered on 19°S / 327°E; the ground resolution is about 14 m per pixel. Image credit: Adapted from ESA/DLR/FU Berlin, CC BY-SA IGO.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Carlos Andrade

Google Earth Locations

Click or Scan to View all Chapter 3 Locations on Google Earth

This page titled 1.4: Geologic Time is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.5: Sedimentary Structures

Learning Objectives

The goals of this chapter are to:

- Identify types of sedimentary structures
- Explain how sedimentary structures form
- Interpret paleoenvironments using sedimentary structures

4.1 Introduction

Sedimentary structures are features that form in sediment as it is being deposited. These structures are typically an indication of what the sedimentary environment was like. Sedimentary structures can often be identified by observable patterns in the sedimentary bedding or distinct shapes within the sediment. Basically, if the sedimentary rock doesn't look uniform or has a distinctive feature, there's a good chance it's a sedimentary structure.

? Exercise 4.1 – Observing Sedimentary Structures

Part A

For this exercise, your instructor will provide you with a set of sedimentary structures. Look at the samples closely and use a hand lens if necessary. Create a sketch of each sedimentary structure in the blank space below, focusing on what you think are

the most important characteristics of the sample. Then, in full sentences, describe the structure you just sketched. If it helps, pretend you are describing what the structure looks like to someone who can not see it.

Structure #1 Sketch:
Description:

Structure #2 Sketch:
Description:

Structure #3 Sketch:

Description:

Structure #4 Sketch:

Description:

Structure #5 Sketch:

Description:

Part B

Now put your observational and descriptive skills to the test. Read your descriptions to your classmates and see if they can identify which samples you are talking about.

4.2 Types of Sedimentary Structures

The simplest sedimentary structure is **stratification**, which is layering that can be observed in sedimentary rocks (Figure 4.1). Layers of sediment that are thicker than 1 cm are called **beds** and layers thinner than 1 cm are called **laminations**. Laminations are typically composed of fine-grained silt and clay-sized sediment. Structures can be more complex like the wavy pattern seen in ripple marks (Figure 4.2) or chaotic looking patterns in **cross-bedding** (Figure 4.3).

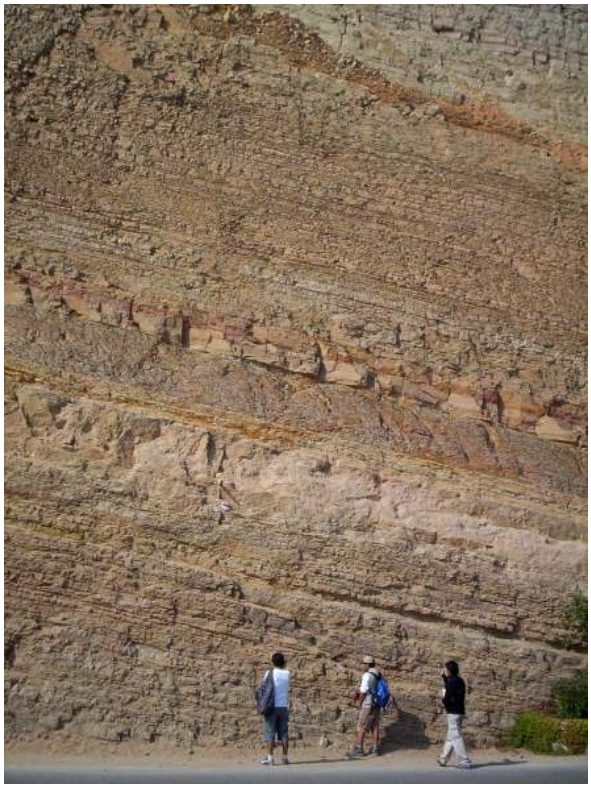


Figure 4.1 – Titled sedimentary beds from Morro Solar near Lima, Peru. Thicker layers are most likely sandstone, and thinner layers are shale. Layering tilts down to the right. Image credit: Miguel Vera León, CC BY.



Figure 4.2 – Ripples caused by waves. This is a view from the top surface and not the side. This rock is Permian in age from Nomgon, Mongolia. Image credit: Matt Affolter, CC BY-SA.



Figure 4.3 – Cross-bedding in sandstone seen on a cliff face in Zion National Park, Utah. You can figure out the scale of the image by looking for trees or other vegetation. Image credit: NOAA, Public Domain.

Sedimentary structures provide a lot of information about the environment in which they formed, including processes that were occurring when sediment was deposited, the environment of deposition, the direction sediment was traveling, and/or the mechanism for transporting the sediment (wind, water, or ice). Some sedimentary structures also help you determine which side of the rock was originally facing upwards, called **way-up indicators**. When outcrops have overturned rocks (rocks that have been tilted so far they are upside down), sedimentary structures can be used to tell which way was originally facing up.

Each structure tells a story that geologists use to interpret Earth's history. For this chapter, only a few of them are discussed: dunes and ripple marks, cross-bedding, graded bedding, mudcracks, raindrop imprints, sole marks, and **trace fossils** and **bioturbation**.

Dunes and Ripple Marks

As water or wind moves across sediment, it can shape the grains into wavy patterns called dunes (>10 cm) and ripples (<10 cm). **Symmetrical ripple marks**, like those seen in Figures 4.2 and 4.4, are formed by the back-and-forth flow of water over sediment. These types of ripples are formed in the shallow marine environment where the back-and-forth motion of waves, or even tides, shape the sediment at the bottom of the ocean. These ripples have symmetrical limbs, meaning that both sides of the ripple dip at about the same angle. This video on symmetrical ripples can help you see how this process works. Symmetrical ripple marks are most commonly found in sandstones from shallow marine environments.



Figure 4.4 – Examples of symmetrical ripple marks with limbs at the same angle on either side of the structure. A) Modern symmetrical ripples from the Bahamas. B, C, and D) Symmetrical ripples in Devonian-Missippian age sandstone from Ohio, USA. These are all views from the top. Image credits: James St. John, CC BY.

Water moving in one direction, like a river, can produce **asymmetrical ripple marks**. The limbs on these ripples are not equal, with one side that is more shallow and one side that is steeper. These types of ripple marks can tell you which direction the river was flowing because sediment moves up the shallow side of the ripple and gets deposited on the steep side (Figures 4.5 and 4.6). The deposition on the steep side of the ripple allows the ripple to move in the same direction that water is flowing, as shown in this video. Wind can also create asymmetrical ripple marks at different scales. Ripple marks at smaller scales can usually be found along a beach. Large-scale ripple marks are called dunes and are common in deserts and some coastal environments.

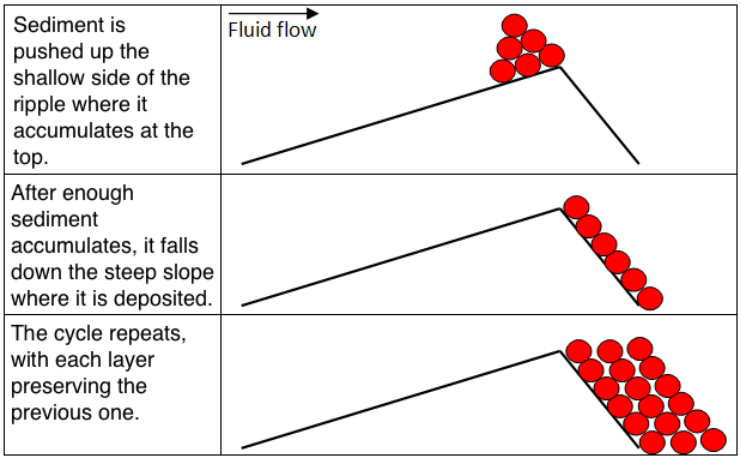


Figure 4.5 – How asymmetrical ripples form. The red circles represent grains of sediment that move up a shallow side and fall down a steep side to form cross-bedding. Image credit: Wikimedia user Nwhit, CC BY-SA.



Figure 4.6 – Examples of asymmetrical ripple marks. The limbs of the ripples dip at different angles, one shallow and one steep. Three views (A, C, and D) are from the top, and B is from the side. A) Modern asymmetrical ripples from the Bahamas. B and C) Asymmetrical ripples in sandstone from Colorado, USA. D) Precambrian asymmetrical ripples in quartzite from Wisconsin. Image credits: James St. John, CC BY.

3D Image 4.1 – Asymmetrical Ripples



Sedimentary Structures - Ripple Marks 2 by **nate_siddle** on **Sketchfab**

Cross-Bedding

The top layer of a ripple or dune is not always preserved in the rock record, so it is rare to find ripples like those seen in Figures 4.3 and 4.7. Dunes and ripples are constantly moving. As one passes and deposits its sediment, another follows right behind it to deposit more sediment on top. Geologists typically find the deposited sediment from the steep side of a series of ripples or dunes in the rock record. The deposition of the steep side of several dunes or ripples creates a sedimentary structure called cross-bedding (Figure 5). One of the most important pieces of information that cross-bedding gives geologists is the direction that wind or water was moving. The steep side of a ripple always angles downward toward the direction the water or wind was moving, as shown by the blue lines in Figure 5b. There are many different types of cross-bedding, and each form in a similar way.



Figure 4.7 – Cross-bedding from ancient sand dunes in Coyote Gulch, part of the Canyons of the Escalante, Utah. The upper image is uninterpreted; the lower image shows interpretations of four dunes as yellow dashed lines and the cross-beds in blue. Image credit: G. Thomas, Public Domain.

Sedimentary structures are not limited to Earth since similar features have been found on Mars, Venus, and Titan, Saturn's largest moon. Figure 4.8 shows cross-bedding from Mars, and it looks very similar to the wind-blown sand outcrops commonly found in the southwestern U.S. (see Figure 4.7). Do you think the scale is similar between these two images? The size of the cross-bedding can help to determine if these formed in water or air (**aeolian**). Smaller ripples form in water, while larger ones form in terrestrial dunes.

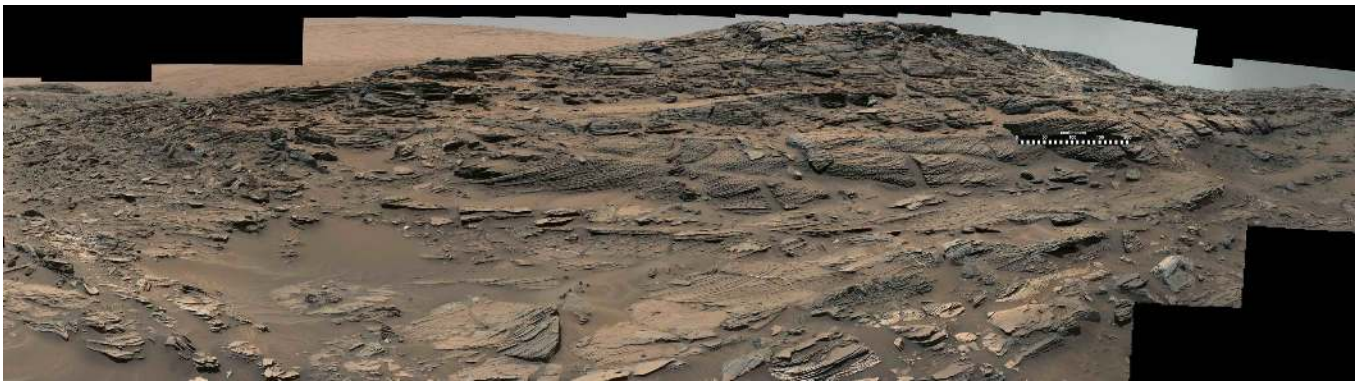


Figure 4.8 – An outcrop of cross-bedded sandstone on the lower slope of Mars' Mount Sharp. The sediment transport direction is interpreted as sediments carried by currents moving down the deltas and into deeper lake water. This photograph was taken by NASA's Mars Rover Curiosity on August 27, 2015, using its mast camera. This area is now known as Whale Rock in the Pahrump Hills and far from where Curiosity found evidence of delta deposits where a stream entered a lake. Image credit: NASA/JPL-Caltech/MSSS.

Graded Bedding

Graded bedding is a common sedimentary structure where a change in grain size can be observed within a single sedimentary bed (Figure 4.9). At the bottom of the bed are mainly coarse particles which get progressively smaller as you move vertically up the bed. Graded beds generally represent depositional environments in which transport energy decreases over time, like the changing water velocity in a river. However, these beds can also form during rapid depositional events, most commonly from turbidity currents. Turbidity currents are essentially underwater avalanches of sediment that move downslope, usually starting at the edge of the continental shelf and flowing down the continental slope. The sediment deposited from a turbidity current is called a **turbidite**, which often has graded bedding with the coarsest particles at the bottom of the bed and the smallest at the top.



Figure 4.9 – A sketch and an example of graded bedding. The left side of the figure is a sketch of graded bedding showing larger grains at the bottom and getting finer towards the top. The right side of the figure is a sample of graded bedding. Image credits: Sketch from Mike Clark, CC BY-SA; example from James St. John, CC BY.

Mudcracks

Mudcracks, also called desiccation cracks, form when wet sediment, typically clay-rich, dries out (Figure 4.10). Clay minerals expand when they get wet and shrink when they dry out. As the sediment shrinks, cracks can develop, which form polygons on the surface of the mud. Today, you can find plenty of modern mudcracks along the margins of rivers or in desert valleys that periodically get inundated with floods. After a mudcrack forms, it can be filled in with new sediment.

Mudcracks are typically wider at the top of the crack and get progressively smaller toward the bottom of the crack. Because of this pattern, mudcracks can be a good **way-up indicator** if you can see a cross-section view of the crack.



Figure 4.10 – A) A modern example of large mudcracks in a dried-up river bed in the Rio San Juan, Argentina. B) An ancient example of mudcracks with sediment filling in the cracks from Maryland. Image credits: A) Daniel Hauptvogel, CC BY-NC-SA; B) James St. John, CC BY.

Mars also has mudcracks (Figure 4.11), one of the pieces of evidence that indicates the red planet used to have liquid water on its surface. These were found in Gale crater in an exposure of Murray Formation mudstone on lower Mount Sharp. The white material in the cracks may be a form of calcium sulfate, either anhydrite or gypsum. This is a guess since the Curiosity rover cannot test the mineral hardness.

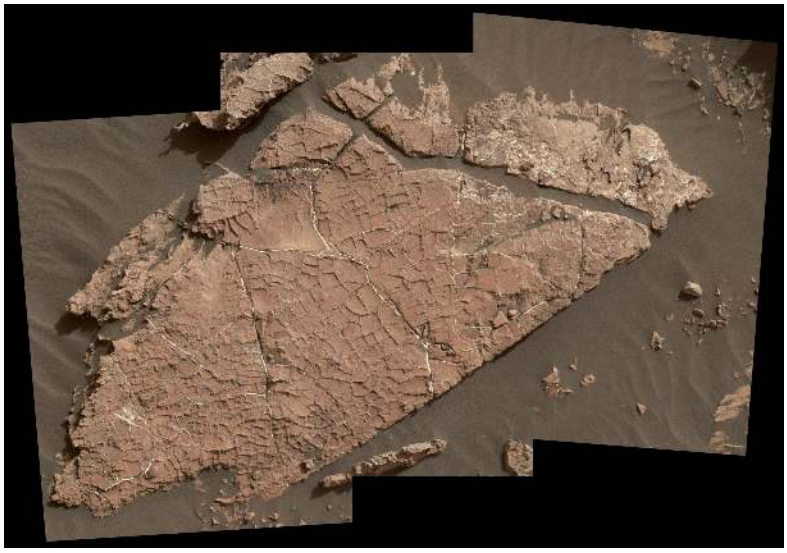


Figure 4.11 – This photograph of mudcracks was taken by NASA's Mars Rover Curiosity on December 31, 2016. The view spans about 4 feet (1.2 meters) left-to-right and combines three images taken by the Mars Hand Lens Imager (MAHLI) camera. The cracks may have formed more than 3 billion years ago. Image credit: NASA/JPL-Caltech/MSSS.

Raindrop Impressions

Raindrop impressions are small, concave imprints made by rain when it falls on soft sediment (Figure 4.12). The impressions or small craters are made from the force of raindrops falling onto the sediment, which makes these structures good way-up indicators. If you were to see only the bottom of the impression, it would look like a raised bump (convex).

Raindrop impressions tend to be found in fine-grained rocks like siltstones and shale but not in coarser-grained sandstones. The impressions likely represent the end of a rainstorm as rain is letting up because any previously formed impressions would be destroyed by subsequent rainfall. That's why most raindrop impressions are very scattered rather than occurring all over the surface. Then the impressions need to be filled in with sediment before the next rainstorm to be preserved.



Figure 4.12 – A) Overhead view of modern raindrop impressions (and mudcracks) from Argentina. B and C) Ancient raindrop impressions from the Lower Permian, Upper Pecos Valley, New Mexico. B is an overhead view, C is the bottom-up view, showing the convex underside of raindrop impressions (not the same sample as B). Image credits: A) Daniel Hauptvogel, CC BY-NC-SA; B and C) James St. John, CC BY.

Sole Marks

Sole marks is a broad term that describes several different sedimentary structures that appear as impressions or grooves in sediment, including flute casts, tool marks, groove casts, and load casts. Typically the cast of the marking (the raised bump) is preserved at the bottom of a sedimentary bed, hence the term "sole" mark, and the mold side (the impression) is filled with sediment. This makes sole marks good way-up indicators since the cast side is facing down.

Flute casts are common structures created by **turbidity currents** (Figure 4.13). The movement of these sediment avalanches underwater can scour the ocean floor, creating an elongated impression. Flute casts are usually closely spaced and can be stacked on top of one another. Not only can they tell you which way is up, but they can also tell you which way the current was flowing. The tapered end of the flute cast points in the direction of flow.



Figure 4.13 – Flute casts from the central Alps, Switzerland. The view is from the underside of the rock. Image credit: Chris Spencer, CC BY-NC-ND.

Tool marks are made when an object, such as a stick, is dragged across sediment by a current and leaves behind what looks like scratches in the soft sediment (Figure 4.14). The elongated scratches can be used as an indicator of the paleocurrent.



Figure 4.14 – Tool marks from Banff National Park. The view is from the underside of the rock. Image credit: Callan Bentley, used with permission.

Groove casts are raised parallel ridges (Figure 4.15). They are spaced closely together, often appearing in sets of 2 and 3, but do not occur on top of one another like flute casts. Interpreting the paleocurrent from groove casts can be difficult because the marking is often symmetrical. Without the addition of other paleocurrent evidence, you may only be able to narrow down the paleocurrent to two directions that are 180° apart.



Figure 4.15 – Groove casts. The yellow arrow indicates the direction of transport. This arrow is double-ended as there is no indication if the water was flowing up or down the river before it was tilted and exposed. The view is from the underside of the rock. Image credit: Brian Ricketts, CC BY.

Load casts form when dense, sandy sediment is deposited on less dense, water-saturated sediment, usually silt or clay (Figure 4.16). The dense sand load pushes into the soft layer below, creating bulb-like impressions.



Figure 4.16 – Load casts in arkose sandstone from the Aquitaine Basin near Nontron, France. The view is from the underside of the rock. Image credit: Rudolf Pohl, CC BY-SA.

? Exercise 4.2 – Identifying Sedimentary Structures

Your instructor will pass around examples of various sedimentary structures. Now that you know what to look for in these structures create a detailed sketch of each one. It may help to sketch the structures from several angles. Identify the sedimentary structures and complete any of the relevant information about them.

Within the sketch area for each structure, provide answers to the following questions:

- What type of sedimentary rock is this sedimentary structure in?
- If your structures can provide the paleocurrent, indicate the direction on your sketch.

- If your structures are way-up indicators, indicate which way is up on your sketch.

Structure #1 Sketch:

Structure #2 Sketch:

Structure #3 Sketch:

Structure #4 Sketch:

https://geo.libretexts.org/@go/page/18712

Structure #5 Sketch:

Structure #6 Sketch:

Structure #7 Sketch:

4.3 Sedimentary Structures and Paleoenvironments

As you may have guessed, sedimentary structures are handy for determining what **paleoenvironments** were like. By combining sedimentary structures and the surrounding geology, a geologist could describe a pretty accurate picture of the environment when these sediments were deposited.

? Exercise 4.3 – Summarizing Sedimentary Structures and Paleoenvironments

a. Using the information you have learned about sedimentary structures, complete Table 4.1.

Table 4.1 – Worksheet for Exercise 4.3

Structure	Type of Rock it Forms in	Environment Description
Symmetrical Ripples		
Asymmetrical Ripples		
Cross-bedding		
Graded Bedding		
Mudcracks		
Raindrop Imprints		
Sole Marks		

b. Below are descriptions of two different environments. Which one is a **braided river** and which is a swamp/wetlands?

i. Mostly sand deposits with some sediment beds having a layer of gravel on the bottom and cross-bedding. _____

ii. Mostly silt and clay deposits with **root structures**, lots of bioturbation, and many coal layers. _____

c. **Critical Thinking:** The global carbon cycle includes the storage of carbon in sedimentary rocks such as limestone or disseminated organic matter (kerogen) in mudrocks. Which sedimentary structures are associated with the accumulation of carbon in clastic rocks?

d. **Critical Thinking:** Can you name two factors that might explain enhanced carbon storage?

Exercise 4.4 – Interpreting Paleoenvironments using Sedimentary Structures and Sedimentary Rocks

Geologists don't only focus on a single rock outcrop to interpret the paleoenvironment of a region; they look at many outcrops so they can see how an environment changes across a region. Figure 4.17 below is a map of an area where sedimentary rocks and structures were described by a geologist. It is divided up into 4 zones with the following descriptions of the rocks and sedimentary structures:

A. Sandstone with large-scale cross-bedding and very well-rounded sand grains.
B. Sandstone and mudstone with **wavy** bedding toward the east and mudcracks toward the west.
C. Fine sandstone with symmetrical ripple marks.
D. Shale with lots of **plankton** fossils and fine laminations.

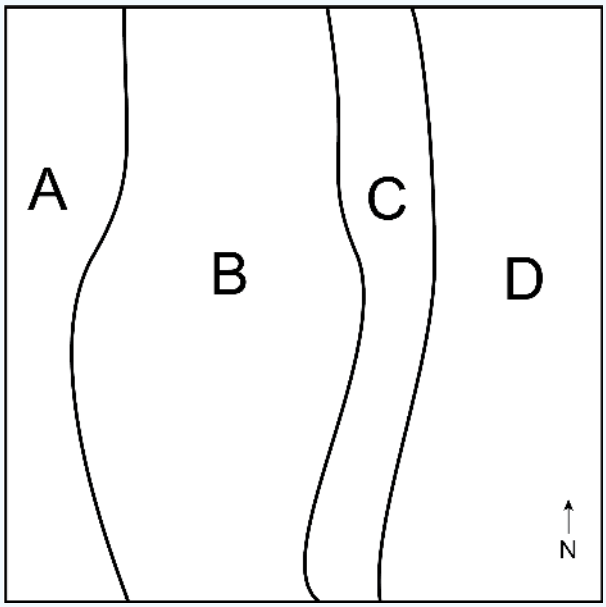


Figure 4.17 – Map for Exercise 4.4.

Answer the following questions:

a. Come up with a brief depositional environmental interpretation for each zone.

i. Zone A:

ii. Zone B:

iii. Zone C:

iv. Zone D:

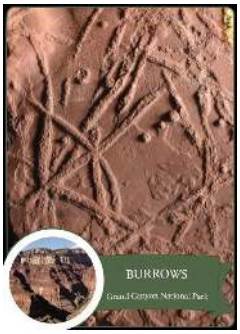
b. **Critical Thinking:** In what direction was the ocean in this paleoenvironment? _____

c. **Critical Thinking:** In what type of tectonic environment would you find this sequence of sedimentary rocks. Explain your answer.

4.4 Trace Fossils and Bioturbation

Organisms burrow and move through sediment on the ocean floor and the bottoms of lakes and rivers; this is called bioturbation. When organisms disturb the sediment by burrowing, their burrows can be preserved when the sediment hardens into rock. In most cases, the burrows will fill with new sediment, but the outline is preserved. It is difficult to assign a specific organism to the creation of a single burrow. Instead, geologists look at different burrows that tend to occur together in the rock record to classify them, a branch of study known as **ichnofacies**. Each ichnofacies is named after the most common trace fossil in the facies. Determining which ichnofacies the trace fossil fits into can tell you about the environment in which the organism lived, including water depth, salinity, energy, and turbidity, and what the substrate was like. Generally, vertical burrows were formed in shallow water environments while horizontal burrows in deeper water environments. Table 4.2 contains a list of ichnofacies, and Figures 4.18-4.25 are images of them.

Table 4.2 – Common ichnofacies

Ichnofacies	Substrate	Paleoenvironment	Description	Image*
Scoyenia	Sandstones, may be associated with red beds	Terrestrial, freshwater, low energy	Horizontal, curved, and rope-like burrows. Unbranching, but can cross each other. Occasional vertical burrows.	 Figure 4.18 – Scoyenia burrows from the Grand Canyon. Image credit: National Park Service, Public Domain.
Psilonichnus	Variable grain size, sand	Coastal, barrier islands, deltas, estuaries, lagoons, bays	Vertical burrows with J, Y, or U shapes. Can also have vertebrate footprints.	 Figure 4.19 – A single Psilonichnus burrow from Holocene beach dunes, San Salvador Island, Bahamas. Cross-bedding is also present. Image credit: James St. John, CC BY.
Trypanites	Hard rock, carbonate, shells	Coastal cliffs, reefs, beachrock	Closely-spaced straight, or slightly curved, vertical burrows.	 Figure 4.20 – Trypanites burrows in Ordovician limestone from Kentucky. Image credit: James St. John, CC BY.
Glossifungites	Firm but not lithified sediment	Shallow marine, marginal marine, delta, estuary	Three-dimensional network of cylindrical burrows and individual, vertical, teardrop-shaped burrows.	

Ichnofacies	Substrate	Paleoenvironment	Description	Image*
				Figure 4.21 – Glossifungites burrows in sandstone from Lima, Peru. Image credit: Miguel Vera León, CC BY.
Skolithos	Sand	Beaches, tidal flats, shallow marine, above wave base	Straight, vertical, burrows that do not branch or cross. Can be slightly angled and J-shaped.	 Figure 4.22 – Skolithos burrows in sandstone from western Maryland. Image credit: James St. John, CC BY.
Cruziana	Sand and silt	Mid to distal continental shelf, below wave base, but above storm wave base	Horizontal and vertical burrows from a wide variety of organisms.	 Figure 4.23 – Cruziana burrows from Portugal. Image credit: Wikimedia user CorreiaPM, Public Domain.
Zoophycos	Sand and silt	Deep water, base of continental shelf, may be associated with turbidites	A series of horizontal burrows curving away from a central point.	 Figure 4.24 – Zoophycos burrows from the Swiss Alps. Image credit: Chris Spencer, CC BY-NC-ND.
Nereites	Silt and clay	Deep water, open ocean	Meandering and spiraling horizontal trails or burrows.	 Figure 4.25 – Nereites trace fossils. Image credit: Wikimedia user Richdebtomdom, CC BY-SA.

*No OER images are available to summarize each ichnofacies, so these are single examples of an ichnofossil that belongs to the ichnofacies. You can find depictions of each facies here and an extensive list of ichnofossils here. You need to select invertebrates on this webpage.

Exercise 4.5 – Determining Ichnofacies

Your instructor will provide you with some samples of ichnofacies or ichnofossils. Sketch each sample, paying special attention to the details of each ichnofossil. Identify the ichnofacies of each sample and the type of sedimentary rock. Based on

https://geo.libretexts.org/@go/page/18712

those identifications, give a brief description of the environment.

Trace Fossil #1 Sketch:

Trace Fossil #2 Sketch:

Trace Fossil #3 Sketch:

Trace Fossil #4 Sketch:

Trace Fossil #5 Sketch:

For one of these ichnofacies samples, answer the following questions:

a. What is the grain size in the surrounding rock compared to the trace fossil?

b. Do you think this trace fossil could be preserved in coarse-grained sediment? Explain.

c. What was the water depth where this fossil lived?

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Carlos Andrade

Google Earth Locations

Click or Scan to View all Chapter 4 Locations on Google Earth

This page titled 1.5: Sedimentary Structures is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.6: Stratigraphy

Learning Objectives

The goals of this chapter are to:

- Evaluate the origin, composition, distribution, and succession of strata to determine past geologic events related to sedimentary environments and tectonic settings
- Apply Walther's Law to marine transgression and regression
- Reconstruct sediment thickness to understand processes of deposition
- Create stratigraphic columns and correlations using multiple techniques

5.1 Introduction

Stratigraphy is the area of geology that deals with sedimentary rocks and layers and how they relate to geologic time; it is a significant part of historical geology. As you learned in Chapters 2 and 4, one of the primary goals of studying sedimentary rocks is to determine their depositional environment; stratigraphy is no different.

Stratigraphy is mainly studied through outcrop observations, the collection of sediment cores, and seismic surveys. Sediment cores are mostly collected from the ocean floor by organizations like the International Ocean Discovery Program (IODP) using a ship dedicated to drilling (Figure 5.1a). Geologists can then study the collected sediment (Figure 5.1b) or send instruments into the drill hole to measure the geologic properties of the surrounding sediment. The cores are then stored at facilities around the world for scientists to request samples from (Figure 5.1c). Another way to study stratigraphy is to conduct seismic surveys by sending sound waves into the seafloor or ground and monitoring how the waves reflect back to the surface (Figure 5.2). Previous seismic surveys were only collected in a line, but now they are typically collected in grids to get three-dimensional data below the earth's surface. Geologists use the patterns of **reflectivity** to help identify the rock types, deformation features, and where there might be water or petroleum and other characteristics in the subsurface. If a seismic survey is repeated over the same area, this gives another dimension of time.

Geologists subdivide stratigraphic columns into **formations**. A formation is a series of sedimentary beds distinct from other beds above and below and is thick enough to be shown on geological maps. Sometimes several formations are lumped together to form a group. If you want to propose a new formation or group, there are strict guidelines set up by the International Commission of Stratigraphy.



Figure 5.1 – A) The JOIDES Resolution, one of the research vessels used by the IODP. B) Scientists studying recovered core during Expedition 378 in the South Pacific. C) An IODP core repository at the University of Bremen in Germany; others are located at Texas A&M University in Texas, Rutgers University in New Jersey, and Kochi University in Japan. Image credit: A) Thomas Ronge and IODP, CC BY; B) Lindy Newman and IODP, CC BY; C) MARUM, CC BY-SA.

An important tool for stratigraphy is to observe seismic characteristics below the surface. Some call this change in seismic response a seismic facies. Just like grain size is important when describing sedimentary rocks, so are the features in a seismic response. So, when looking at a seismic profile, make observations and ask yourself: Do you see areas without many reflectors? This may be related to its lithology. Are the reflectors continuous? If so, they may be well-bedded. Are they thick or thin? Also, what is their shape – flat or curved?

If you look closely at Figure 5.2, the sedimentary **reflectors** are relatively flat and show layering in the Kumano Basin (top left side of the image or NW end; highlighted in green in Figure 5.2b) as well as to the right edge to the SE. Layering is flat and parallel to the ocean floor. This pattern implies the sediment was deposited in relatively quiet, low-energy water. Below these regions, and in the middle of the seismic profile, the layering is disrupted and non-continuous; this probably indicates that these sediments were deformed shortly after deposition and before they were lithified as the sediment was scraped off the downgoing oceanic crust. Towards the bottom, the seismic reflectors are very discontinuous as the oceanic crust has no internal structure. The **seismic character** of the layering lets you know important tectonic and sedimentary history along this profile.

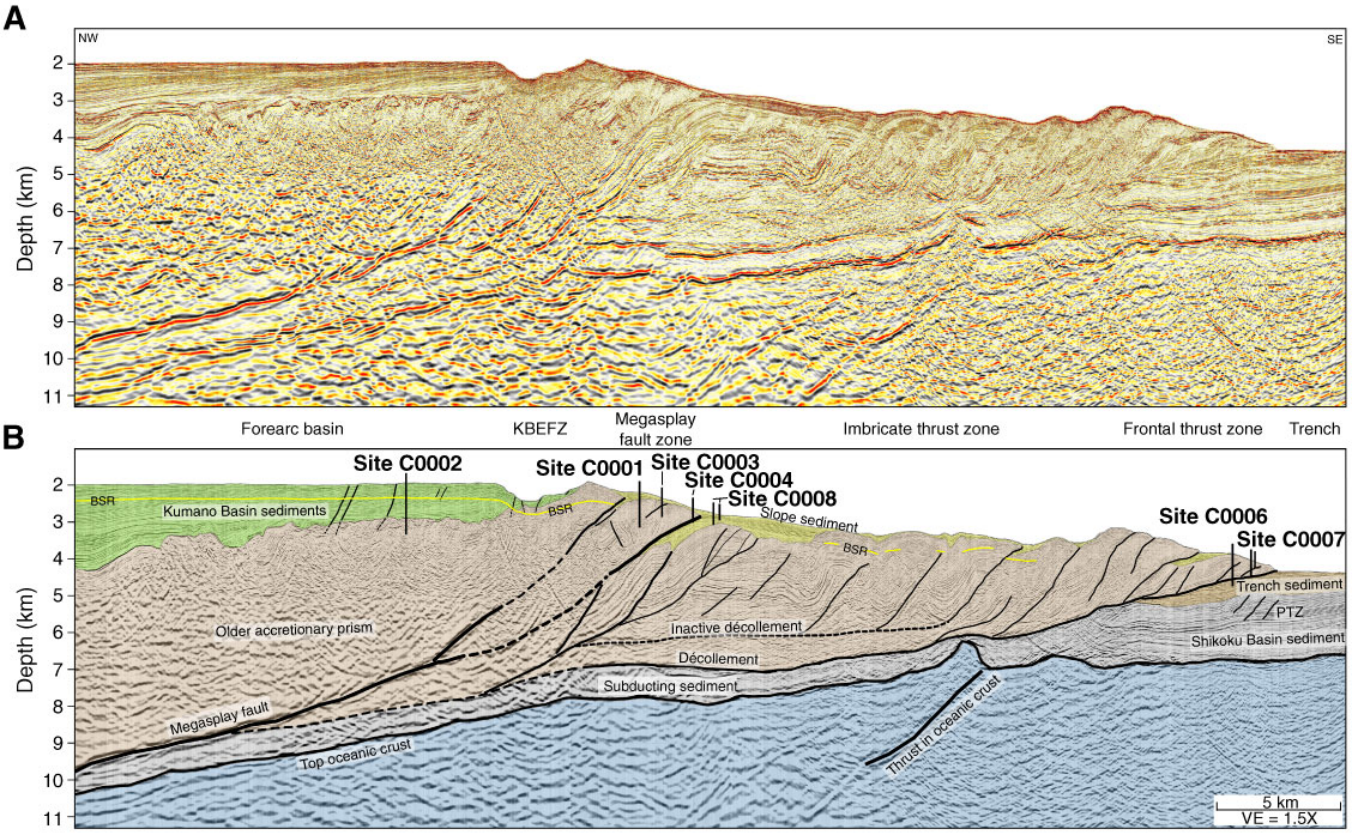


Figure 5.2 – Two seismic images of an accretionary prism near the Nankai trough offshore Japan. Uninterpreted (A) and interpreted (B) seismic data from IODP Expeditions 314, 315, and 316 for the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) in 2009. The interpretations on B show several packages of marine sediments overlying oceanic crust. The yellow line is the bottom simulating reflector (BSR). Image Credit: Moore et al., 2009 and IODP, CC BY.

? Exercise 5.1 – Sediment Coring and Stratigraphic Columns

This exercise is an analogy for how geologists recover sediment cores. Instead of sediment, though, we will use Play-Doh.

1. Using an empty Play-Doh container (or another container), place layers of different colored Play-Doh in the container; don't use more than 10 layers. These layers of Play-Doh will act as our layers of sediment.
2. Take a clear, plastic straw and push it down through the layers of your Play-Doh. This represents geologists drilling into layers of sediment.
3. Pull the plastic straw out. You should see all your layers of "sediment" represented in the straw, which geologists recover when collecting a sediment core.

Depending on the type of coring that is done, geologists will split the sediment core in half. One-half of the core will be sampled and studied by geologists, while the other half will be archived and untouched. One of the first things geologists do on a recovered core is describe the lithology. You are going to create a stratigraphic column of your Play-Doh core. A stratigraphic column is a graphical representation of layers of sediment and sedimentary rock and their characteristics. The bottom of a stratigraphic column is always the oldest rock unit in the area.

a. Measure and record the total length of your Play-Doh core in millimeters. _____

b. Measure and record the thickness of each layer in your Play-Doh core in Table 5.1. Start with the upper-most layer.

Table 5.1 – Play-Doh “sediment” layer characteristics

Layer Color	Thickness (mm)

c. Now let’s visualize this data by creating a stratigraphic column using Figure 5.3. Start with your uppermost layer, use its thickness to fill in the “Lithology” column. For example, if you measured a thickness of 15 mm, draw a horizontal line at the 15 mm mark. Color your layer so that it matches your Play-Doh. This will be your first layer.

d. Now add the second layer to the column. If your second layer is 10 mm, start where the first layer ended and then measure 10 mm down from there. Finish the stratigraphic column with all of your layers.

e. If the sediment at the bottom of your column was deposited 100,000 years ago, what is the sedimentation rate of your core in mm/yr? _____

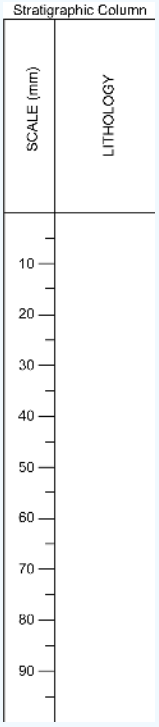


Figure 5.3 – A blank stratigraphic column for Exercise 5.1.

Before you begin the rest of the exercises, you may want to review what you know about classifying sedimentary rocks (Chapter 2) and sedimentary structures (Chapter 4). Remember that **clastic rocks** are subdivided by grain size, rounding, and sorting. Also, how rocks weather is important in these exercises because their differences in weathering resistance make it easier to see the different stratigraphic units. For example, a fissile shale weathers easily compared to sandstone and limestone.

5.2 Grain Size

One of the simplest analyses done on sediment is a grain size analysis. Remember, clastic sedimentary rocks are classified based on their grain size. It can tell you a lot about the transport and depositional history of the sediment. Some geologists use grain size to help determine the geologic history of the sediment; others use it for studying **porosity** and **permeability** to locate fluids (water or oil), or in the case of engineers, how much weight the sedimentary rock can hold before becoming unstable.

? Exercise 5.2 – Grain Size

You can try to visually estimate the distribution of grain size in a sample of sediment, but that can lead to significant error if you over- or underestimate something. Visual estimates are best for field measurements, but you need to be more accurate in the lab. Geologists use quantitative approaches with various particle size analyzers (instruments that can accurately measure grain size and shape), but the traditional way to measure grain size was to separate the sediment into different size ranges using sieves and measure their weights. Computerized particle sizers are probably not available for you to use in your lab, so let's do a grain size analysis on a sample of sediment using sieves.

Note: Grain sizes smaller than 63 µm need to be wet-sieved and dried.

a. Measure the starting weight of the entire sediment sample in grams. _____
b. Now separate the sediment into different fractions using the set of sieves provided by your instructor.
c. Measure and record the weight of each size fraction in the first two columns of Table 5.2.
d. What weight percentage does each fraction make up? Fill in the third column of Table 5.2. Weight percent is the percentage of the entire weight of the sediment that each size fraction takes up. Take the weight of each fraction and divide it by the total weight, then multiply by 100.

Table 5.2 – Grain size analysis

Size fraction range (µm)	Weight (g)	Weight Percent

e. Take your weight percent data and plot it as a bar graph in Figure 5.4.

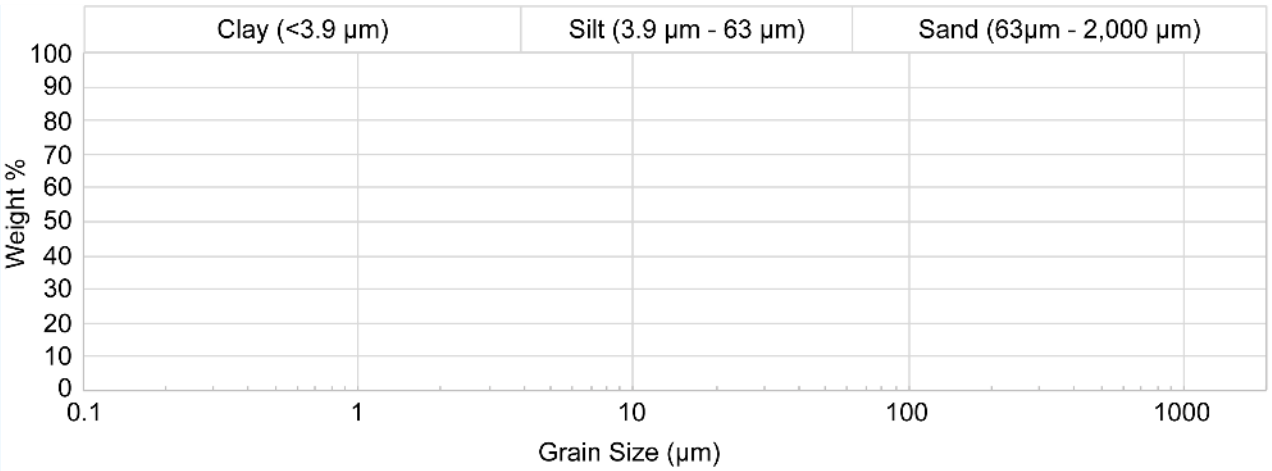


Figure 5.4 – Grain size graph to use in Exercise 5.2.

6. Another way geologists use sediment grain size is to classify and describe the sediment. Do you remember the **triangle (ternary) plot** from Chapter 0? Geologists use ternary plots to compare the sand, silt, and clay content of the sediment. Table 5.3 contains percentages of sand, silt, and clay. Plot these percentages on the triangle graph in Figure 5.5 and record the descriptive term for the sediment size in the last column of Table 5.3.

Sand %	Silt %	Clay %	Sediment Description
55	23	22	
18	27	55	
40	48	12	
23	7	70	

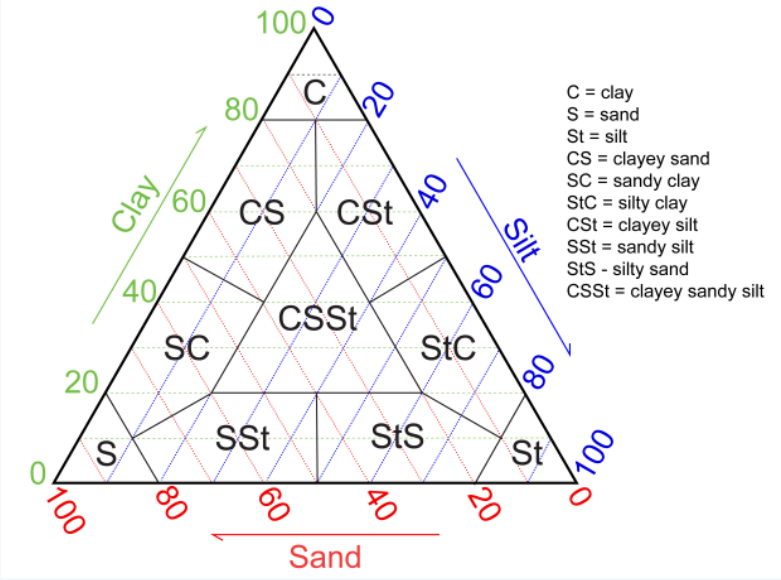


Figure 5.5 – Triangular plot for sedimentary rocks using proportions of sand, silt, and clay. Instructions for how to plot on a triangular plot are given in Figure 0.6. This plot is subdivided into 10 different areas used to assign a rock name to a sample. The abbreviations for each field are given in the figure. Image credit: Adapted from Krumbein, W.C., and Sloss, 1963 by VB Sisson CC BY-NC-SA.

https://geo.libretexts.org/@go/page/18714

Exercise 5.3 – Interpreting Outcrop Stratigraphy

The boundaries between different geologic time periods are often easy to find in the stratigraphic record as a change in sediment type. Sometimes these correspond to major extinction events. One of these occurs at the end of the **Triassic** and beginning of the **Jurassic** time periods (201.3 Ma). At this time, about 25-30% of all marine species died out. The cause for the extinction is debatable, with some geoscientists relating it to increased CO_2 in the atmosphere from volcanic eruption of a **large igneous province** (LIP) in the Atlantic ocean. The Triassic in this region is represented by the Lilstock Formation, deposited in a warm tropical ocean with abundant marine life. Above this is the Blue Lias Formation, well known for its fossil ammonites.

Below is an image created by stitching together many images with software that renders them in three dimensions. Once the image is loaded, you can use your mouse to rotate, tilt, and zoom in on the figure. This image has several numbers that you can click on, highlighting some of the features at the Triassic-Jurassic boundary near Lyme Regis in southern England. There are also two tape measures (inches and feet) draped across the outcrop that you can use to get a sense of the scale of this sea cliff exposure.

An interactive or media element has been excluded from this version of the text. You can view it online here:
https://uhlibraries.pressbooks.pub/historicalgeologylab/?p=80



Triassic - Jurassic Boundary Section by **NHM_Imaging** on **Sketchfab**

a. Sketch a stratigraphic column of Figure 5.6. This is easy to do because the limestones and shales weather differently.

Limestones tend to be more resistant to weathering than shales and thus make prominent layers.

Sketch Area:

b. Is there an unconformity in this stratigraphic column? Explain.

c. What is the dominant lithology in the Triassic? _____

d. What is the dominant lithology in the Jurassic? _____

e. **Critical Thinking:** Can you explain why the lithology changed?

5.3 Facies and Lithostratigraphy

Lithostratigraphy is a sub-discipline of stratigraphy that deals with the type of rock and depositional environment of sediments and sedimentary rocks. One of the fundamental concepts in stratigraphy is Walther's Law (Johannes Walther,1860-1937), which states that depositional environments vary in both space and time such that "the **facies** that occur **conformably** next to one another in a vertical section of rock will be the same as those found in laterally adjacent depositional environments" (Walther, 1894). That's a pretty dense statement, so let's break it down. First, let's tackle two definitions; facies and conformably. A facies is a characteristic rock that represents a certain depositional environment. These characteristics include physical, chemical, and biological aspects. In geology, sedimentary layers are said to lie conformably when there is no unconformity between them. And remember, sediment is deposited in continuous, horizontal layers.

Now for the rest of the law. In the marine environment, sand is deposited close to shore, silt and clay further away, and maybe limestone very far away (Figure 5.7). All three of these sediments are deposited simultaneously and form a single, continuous layer, as in Time 1 in Figure 5.7. The boundary between them is gradational, meaning that the transition from sand to silt, or silt to clay, or clay to limestone is a gradual transition rather than an abrupt boundary (That's what the zig-zag lines in the figure mean). This gradual transition keeps the single-layer continuous and conformable.

Now, what if sea level were to rise (called **transgression**), as in Time 2 in Figure 5.7? As the next layer of sediment is deposited, all sediment types are shifted toward the coastline following the sea-level rise. If sea level continues to rise, the next sediment layer will shift even further, as in Time 3 of Figure 5.7. Looking at Time 3 in Figure 5.7, the shale at the bottom is overlain by limestone, and that limestone is the same facies as the limestone to the left of that original shale. The same could be said about the sandstone and shale. That's what Walther's Law means, vertical changes in the succession of sedimentary rocks reflect lateral (horizontal)

changes in the environment. If sea level were to lower (called **regression**), the facies would move in the other direction, as in Figure 5.8 (Note: if sea level drops enough to expose sediment, erosion will take place).

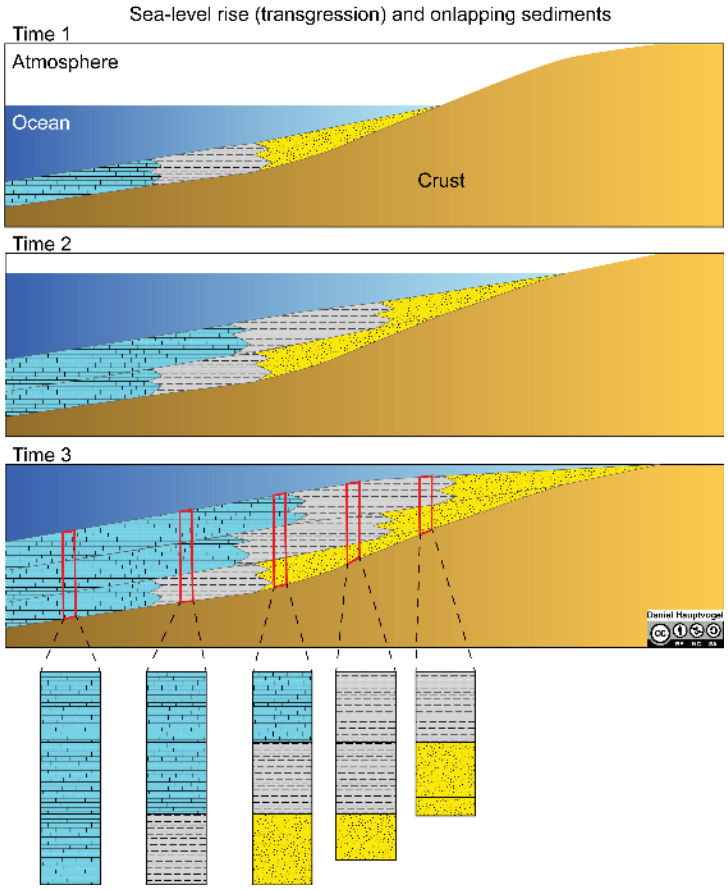


Figure 5.7 – A time-lapse of sea-level rise, also called transgression. At each time interval, the sediment package that is deposited moves in the direction sea level is rising. The sediments are stacking on top of each other toward the coastline, and that pattern is called onlapping. The red boxes in Time 3 represent sediment cores taken at those locations. By looking at the patterns in the sediment cores, you can tell that sea level was rising, and the coastline was to the right. The blue pattern represents limestone, the gray pattern represents shale, and the yellow dotted pattern is for sandstone. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

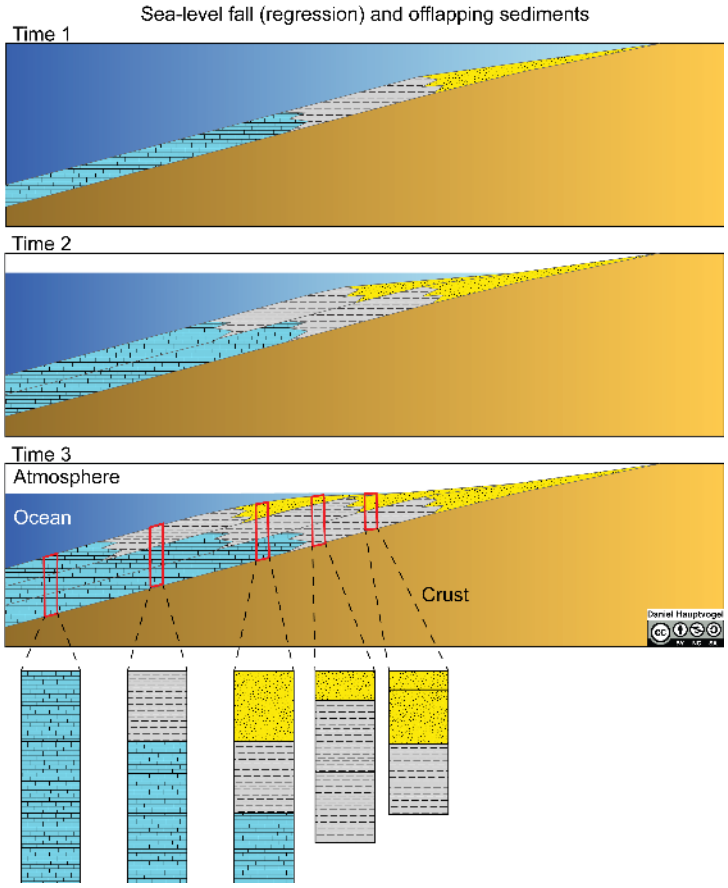


Figure 5.8 – A time-lapse of sea-level fall, also called regression. At each time interval, the sediment package deposited moves in the direction sea level is falling. The sediments are stacking on top of each other away from the coastline, and that pattern is called offlapping. The red boxes in Time 3 represent sediment cores taken at those locations. By looking at the patterns in the sediment cores, you can tell that sea level was falling and the coastline was to the right. Same patterns as in Figure 5.7. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

? Exercise 5.4 – Transgression and Regression

Identifying transgressive (rise) and regressive (fall) cycles in sea level is a key component of lithostratigraphy and sequence stratigraphy. Figure 5.9 is a basic stratigraphic column that contains evidence of transgression and regression.

a. Shade in the facies environment box for each layer of sedimentary rock in the column.
b. Identify where transgression and regression are taking place. You can mark this with vertical arrows on the side of the figure.
c. Can you tell how much sea level has changed? Explain.

d. Can you tell what direction the coastline was in? Explain.

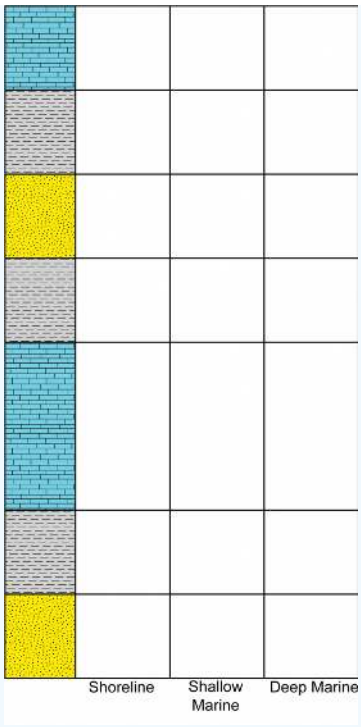


Figure 5.9 – Stratigraphic column for part of Exercise 5.4. The colors and patterns are similar to Figures 5.7 and 5.8. You will need to fill in the columns on the right side of the figure. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

e. Sedimentary layers are laterally continuous, and they transition into other sediment types. This means that a facies can "pinch out" over horizontal distances. Complete the lithologic correlation in Figure 5.10 below of two sediment cores.

f. Which layer pinches out? _____

g. Explain why that layer pinched out.

h. The addition of a second core now lets you interpret the direction of the coastline. Was the coastline to the right or the left? Explain your reasoning.

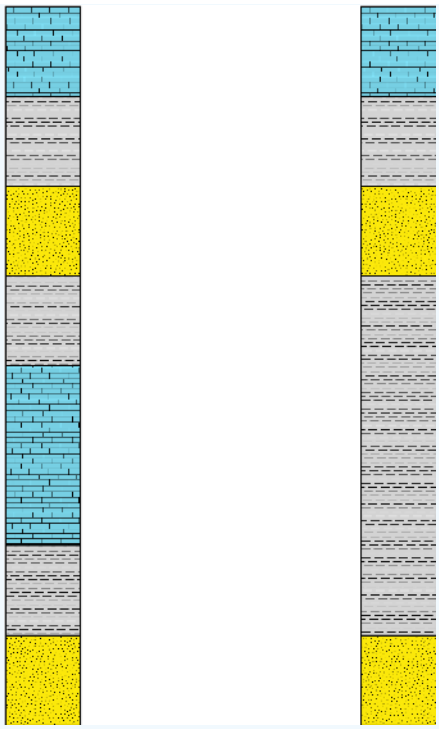


Figure 5.10 – Two stratigraphic columns for part of Exercise 5.4. You will need to correlate the lithology between these two columns. Note, there are no unconformities in these columns. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

i. Imagine a scenario where you're working as a **hydrogeologist**, a type of geologist that deals with water. Your company has assigned you to locate the best source of groundwater for drilling a new water well. Groundwater is contained in rocks with a lot of pore space between the grains. In this area, sandstones make the best **aquifers**. You have found stratigraphic columns for the rocks in the area from wells drilled on nearby properties. The site you are investigating is located between cores 2 and 3. Use this data to create a cross-section to help you understand the thickness of the various layers and potential reservoirs for groundwater at the new well location. To do this, connect layers with similar lithology, and be careful of layers pinching out. The first layer of limestone is already completed for you.

j. **Critical Thinking:** The best aquifers will be laterally continuous sand layers. Label the layer(s) that you think would be the best source of water.

k. **Critical Thinking:** What is the minimum depth you need to drill to install a new water well? _____

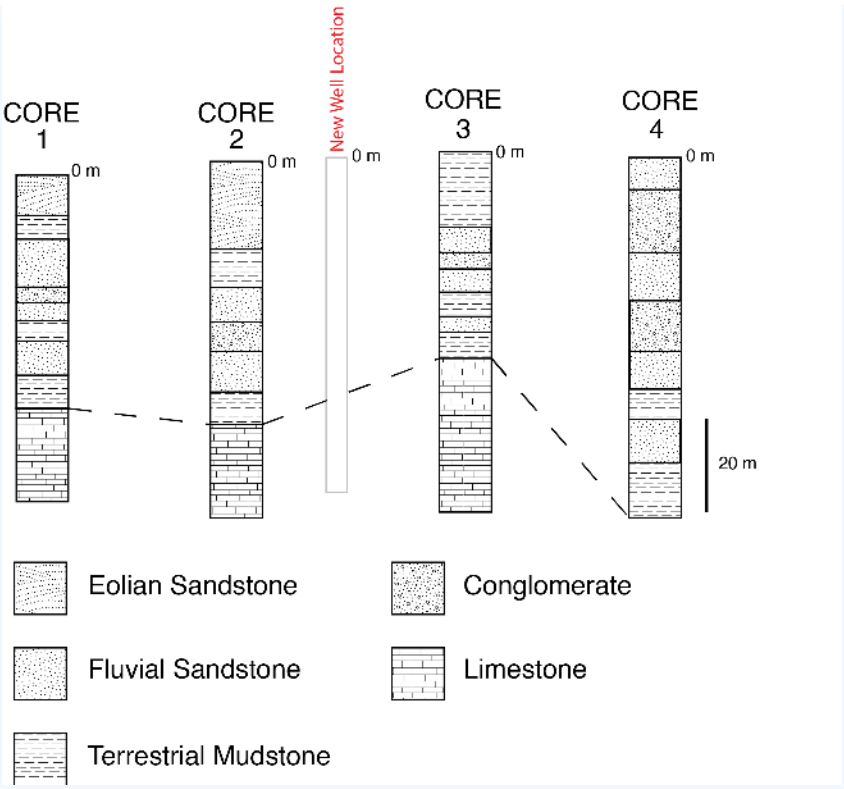


Figure 5.11 – Four stratigraphic columns for part of Exercise 5.3 and the proposed location for a new water well. The height of the columns changes from core to core, representing a small hill. The horizontal scale is not the same as the vertical scale. Image credit: Joshua Flores and Daniel Hauptvogel, CC BY-NC-SA.

Determining facies is an essential part of stratigraphy. In general, there are three main types of facies; marine, coastal, and terrestrial. Many other interpretations of data from sediments and sedimentary rocks rely on an accurate facies analysis. For example, if you are looking at changes in sediment chemistry, they could result from the facies changing. So, you need to have a good and accurate understanding of the facies. You probably discussed rivers and running water in your Physical Geology class. These both erode and deposit sediments. In a meandering river, they can erode their banks and form cut banks or deposit on the opposite shore in a point bar. Further downstream, the sediment transported in the river gets deposited in deltas. Each one of these facies has a distinctive set of sedimentary structures and depending on the velocity of the water a narrow range of grain sizes. Other features of rivers include oxbow lakes, levees, terraces, flood plains, and braided channels. These are all different lithofacies. You may also categorize facies using chemical or biogenic criteria.

? Exercise 5.5 – Facies in a Coastal Environment

In Chapter 2, you learned about different depositional environments. One environment is coastal which is subdivided into beaches and swamps. Well, beach and swamp environments can be further subdivided based on their proximity to the ocean. These coastal environments can have many sedimentary facies (Figure 5.12), and each has something distinctive about it. You'll notice that these facies are mainly sandstone or mudstone, which is not distinctive. Sedimentary rocks have other characteristics besides their particle size, including the abundance of fossils, sedimentary structures, and layering patterns of the strata.

a. Use Figure 5.12 below to match the environments to the lithofacies and descriptions for: **Backshore**, **Dunes**, **Foreshore**, **Bay/Lagoon**, **Marsh**, **Nearshore**, and **Overwash**.

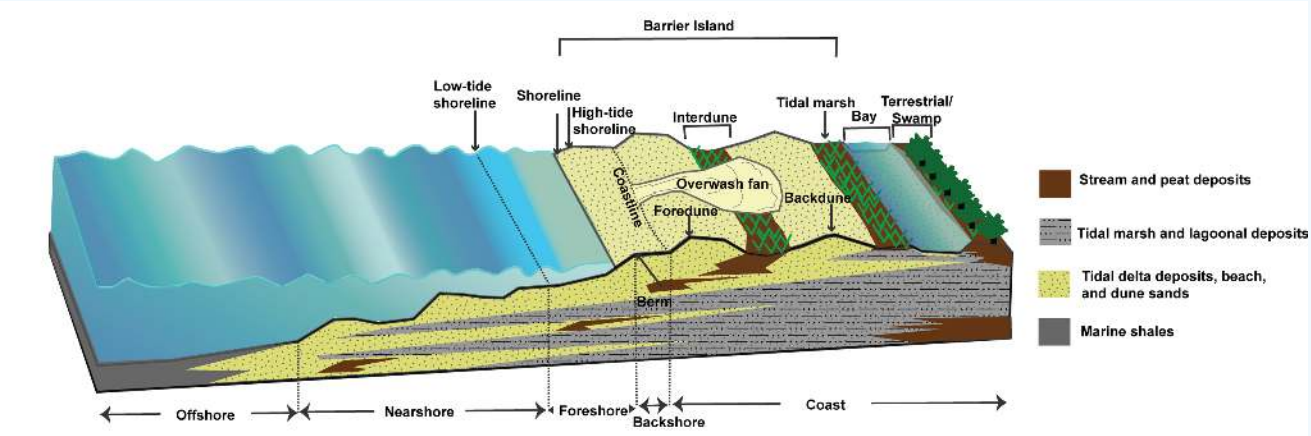


Figure 5.12 – A model of coastal sedimentary environments and facies. Image credit: Carolina Ramón Dueñas, CC BY-NC-SA.

Table 5.4 – Lithofacies descriptions for some environments in Figure 5.12

Environment	Lithofacies	Description
	Sandstone	Coarse sand with abundant shell fragments
	Sandstone	Medium to fine sand and rare shell fragments
	Sandstone	Medium to fine sand and no shell fragments
	Sandstone	Fine to very-fine sand, root structures, and cross-bedding
	Sandstone with mudstone	Horizontal bedding, root structures, and shell fragments
	Mudstone	Bioturbation, root structures, and peat
	Mudstone	Bioturbation, root structures, and shell fragments

b. You have collected a 13 m sediment core from the area. Your team has separated and described the sedimentary layers. Based on your team's descriptions, identify the environment for each layer (using environments from Part I) and fill in the last column of Table 5.5.

Table 5.5 – Descriptions of layers in a sediment core for which you need to interpret the environment

Scale (m)	Lithology	Description	Environment
0.00 – 0.50	Sandstone	Coarse sand with abundant shell fragments	
0.50 – 1.20	Sandstone	Medium sand with occasional shell fragments	
1.20 – 1.90	Sandstone	Coarse, well-sorted sand with abundant shell fragments	
1.90 – 2.20	Sandstone	Medium-grained sand with rare shell fragments	
2.20 – 3.80	Sandstone	Medium-grained sand with rare shell fragments	
3.80 – 4.80	Sandstone	Medium to fine sand, no shell fragments	
4.80 – 5.60	Sandstone	Fine sand, well-sorted, cross-bedded with occasional root structures	
5.60 – 7.00	Sandstone	Medium to fine sand, no root structures or shell fragments	
7.00 – 7.45	Sandstone	Fine sand, well-sorted with cross-beds	
7.45 – 8.05	Sandstone interbedded with mudstone	Unconformity at the base, alternating poorly sorted sand and 1 to 10 cm thick beds of silty clay with bioturbation. Root structures and shell fragments throughout.	
8.05 – 8.60	Mudstone	Silty clay, moderate bioturbation, root structures, shells, and peat	
8.60 – 9.20	Sandstone interbedded with mudstone	Alternating medium- to coarse-grained sand and 1 to 10 cm thick beds of silty clay with root structures	
9.20 – 10.80	Mudstone	Silty clay, moderate bioturbation, root structures, shell fragments, and peat	
10.80 – 13.00	Mudstone	Dark gray silty clay, intense bioturbation, and shells	

c. Use your information to construct your stratigraphic column. If you have computers available, you can do this digitally through the free program Sedlog (Some geologists also use another free program, PSICAT); otherwise, you can use Figure 5.13 to hand-draw your column. Indicate which facies of trace fossil is likely the cause of the bioturbation. Note: a stratigraphic column like this is exactly how geologists present lithologic data from a sedimentary core.

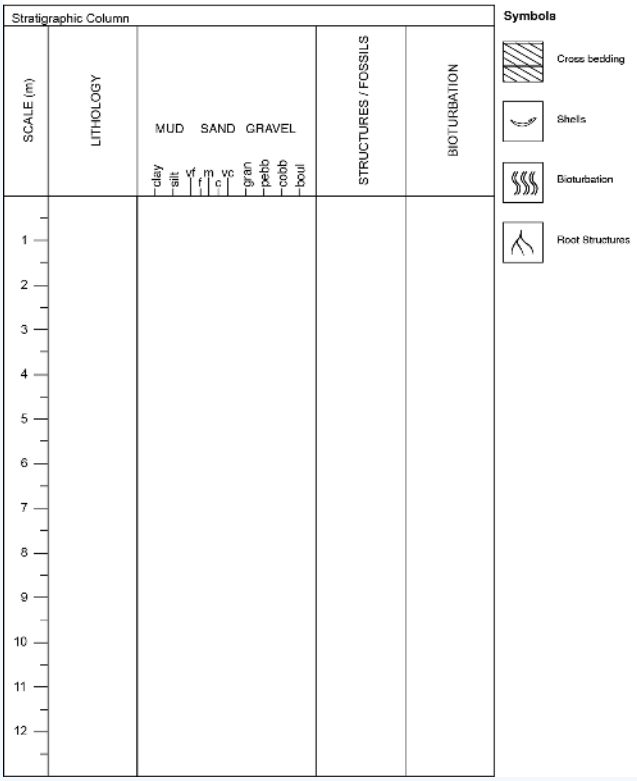


Figure 5.13 – A detailed stratigraphic column that you need to fill out as part of Exercise 5.4. vf=very fine, f=fine, m=medium, c=coarse, vc=very coarse, gran=granule, pebb=pebble, cobb=cobble, boul=boulder.

d. **Geologic History:** Briefly describe the geologic history of this core, starting from the oldest layer.

? Exercise 5.6 – Facies and Biostratigraphy

Remember that not all stratigraphic units are laterally continuous, which can make correlation difficult. In 1820, William Smith noticed that he would occasionally find fossils while digging canals in different parts of England. He noted that the types of fossils changed according to his location. Whenever he found fossils that matched, he assumed the locations were from the same layer and made maps detailing this. From the maps, he predicted the types of rocks and fossils found at different locations while digging more canals. This made it easy to avoid “problem” rock layers and predict the best way to dig a new canal.

The branch of stratigraphy that uses fossils to determine depositional environments and ages of sediment is called **biostratigraphy**. In this exercise, you will use a combination of lithostratigraphy and biostratigraphy.

Background: Your cousin has a small fossil shop that is very popular among tourists, but the location where your cousin has been collecting fossil bivalve shells is no longer accessible. He asked you to help find a new place to collect more fossils and to determine its sedimentary environment. Your cousin told you there are 5 different lithologies in the area. You go to a dozen locations (geologists call these stops) and describe the geology at each place.

To help your cousin, you need to create a geologic map. On your map, you need to use colors to differentiate each unit. On geologic maps colors represent the rock age. For example, rocks from the Cretaceous Period are shown in green, and Quaternary deposits are shown in yellow. Each geologic unit is marked with a label. Geologists typically use an abbreviation for the age and name of the formation. For example, in the Grand Canyon, the label Pk refers to the Permian Kaibab Formation

and label Mr designates the Mississippian Redwall Formation. A geologic map is usually printed over a topographic base map. Many different types of lines and symbols are found on geologic maps (more on this in Chapter 9). The most prevalent are thin black lines that define the contacts between two different mappable units.

Use your notes from Table 5.6 and the map of the stops in Figure 5.14 to see if you can find a new location to collect more fossils.

a. Group the sedimentary rocks from your seven stops into five lithologic units and list these in Table 5.7. Each stop can only belong to one unit.
b. On the map in Figure 5.14, draw contact lines that separate the different units. Color each unit according to its geologic age (see Table 5.7).
c. Circle an area on your map that you would recommend looking for additional fossils.

Table 5.6 – Descriptions of the stops for Exercise 5.6

Stop	Description
Stop 1	This is where your cousin used to collect fossils, specifically a shell that looks like a clam. Fossilization has made it have a variety of colors that are dazzling to the eye.
Stop 2	Here there are lots of fossil imprints of leaves and branches. You don't see any sedimentary structures, and the rock is very dark as well as fine-grained.
Stop 3	This unit is light colored limestone and has some fossil fish. A local geologist has told you that this is the oldest unit in the area.
Stop 4	Cross-bedding! No fossils, but you were fascinated by beautiful cross-bedded sandstone from what look to have been oscillatory waves.
Stop 5	You have found another limestone. There aren't as many fossil fish here, but you have seen a few smaller ones.
Stop 6	So many shell pieces. Unfortunately, everything here is broken up. There are some fragments of the desired fossil.
Stop 7	A well laminated, dark shale with impressions of fern leaves.
Stop 8	You try to scratch this rock with your geologic hammer but it doesn't scratch. The grains are well-rounded and well sorted.
Stop 9	A fissile rock that easily breaks when you try to get a sample with your geologic hammer.
Stop 10	A fine grained rock with molds and casts of bivalve fossils and a few gastropods (snails).
Stop 11	This tan fine-grained rock fizzes when you put a dilute acid on it!
Stop 12	Another rock that fizzes when you put dilute acid on it. However, this one has large, angular, poorly sorted fragments.

Table 5.7 – Worksheet for Exercise 5.6

Unit	Stop(s) within unit
5	
4	
3	
2	
1	

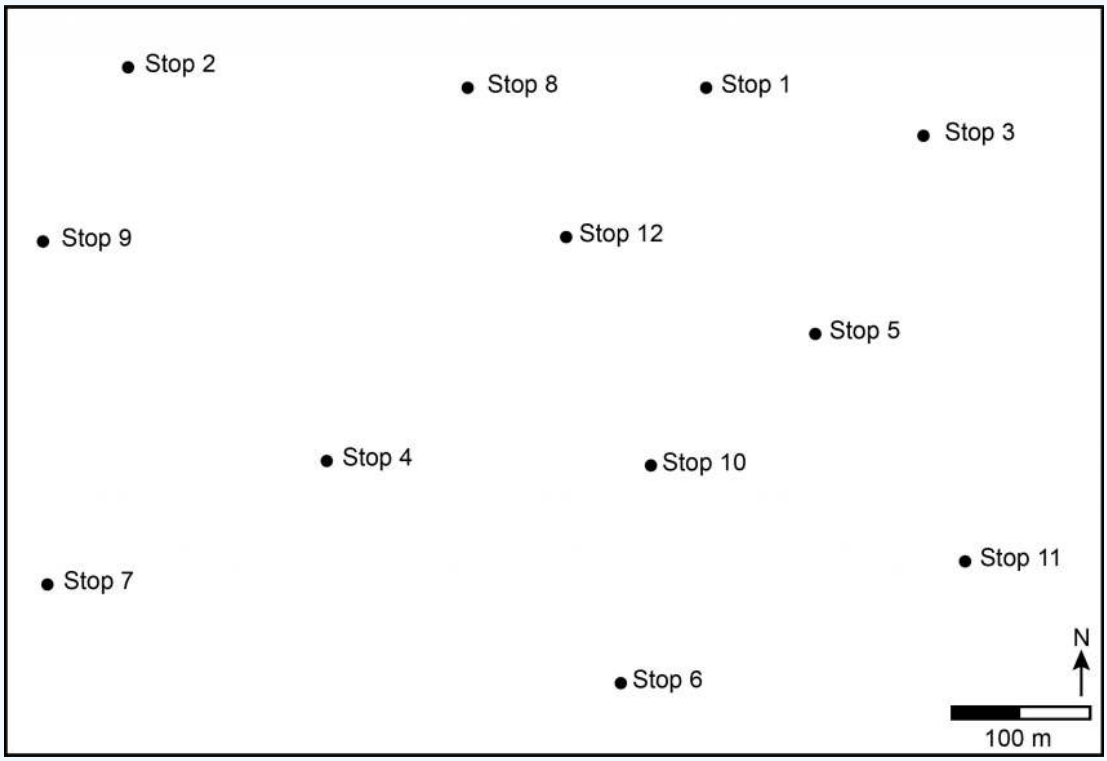


Figure 5.14 – Location map for stops in Exercise 5.6

5.4 Physical Properties

When geologists recover sediment cores, they run an assortment of analyses on the core itself and the hole it came from. After the drilling is completed, geologists will lower an instrument into the hole to take physical property measurements. These measurements can be continuous or occur at specific intervals. Properties that are commonly measured are natural **gamma radiation**, **resistivity**, **conductivity**, density, porosity, and others. These properties are used to give geologists as much information about the rocks or sediment as possible. Physical properties can also be used to correlate sediment cores to each other. Geologists make these correlations to easily compare a section on one core to a section on another.

Exercise 5.7 – Physical Property Correlation

Figure 5.16 below shows the natural gamma radiation logs for two cores recovered by the International Ocean Discovery Program Expedition 369 from the southwestern coast of Australia in the fall of 2017. These two cores were only 20 meters away from each other. The unit for natural gamma radiation is counts per second (CPS). You don't need the details behind this unit's meaning, but the higher the number, the more clay particles there are in the sediment (more shale-like). Geologists use this property to determine and compare lithology; sand versus clay and mud. This property is also used extensively both in oil and gas exploration and hydrogeology.

a. Correlate the two sediment cores to each other using natural gamma radiation data. Draw dashed lines across both columns that match patterns to each other.
b. How many layers did you correlate? _____
c. Compare your answer to *b* to that of your classmates. Did you have the same number of layers? Explain any differences.

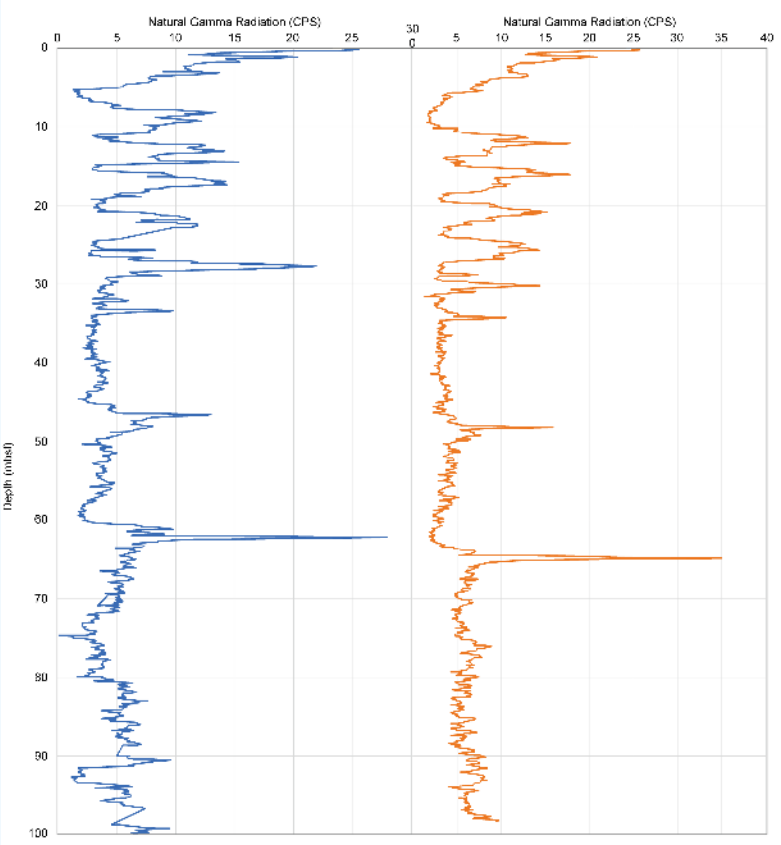


Figure 5.16 – Natural gamma radiation logs for two holes as part of IODP Expedition 369 off the coast of southwestern Australia. mbsf=meters below seafloor. Higher gamma counts generally indicate clay-sized particles and shale, while lower counts indicate silt- and sand-sized grains. The data is from IODP.

Side note: You might be wondering why the IODP collects sediment cores near each other. The reason for this is that the drill rig is only capable of collecting 1.5 m of core at a time, and when there is a section break every 1.5 m, some of the sediment is actually lost where one section ends, and the next one starts. Additionally, several reasons could cause incomplete recovery of sediment. So, the IODP collects a few cores close to each other and slightly offset to ensure they can get a complete record of

the sediment. For example, the first section of the first drill site will start at the seafloor and collect sediment every 1.5 m, but the first section at the second drill site will only go down 1.0 m, and then the rest will be every 1.5 m.

? Exercise 5.8 – Paleomagnetic Properties to Determine Depositional Age

Geologists also analyze magnetic properties of sediment cores for correlation (**magnetostratigraphy**), but they are also used to help determine the age that the sediment was deposited. Do you remember how magnetic minerals in igneous rocks align themselves to Earth's magnetic field as the mineral crystallizes? Well, sediments can align themselves while they are being deposited, too. So, paleomagnetic properties in sediment cores can be correlated to known changes in Earth's magnetic field to determine the sediment's depositional age.

We currently have normal polarity, where the magnetic north pole and the geographic north pole are in the Arctic. During periods of reversed polarity, the magnetic north pole moves to the geographic south pole in the Antarctic. These magnetic reversals are a natural process on Earth, and geologists have developed a time scale of these reversals called the Geomagnetic Polarity Time Scale (GPTS).

a. Use the inclination data from an IODP sediment core in Figure 5.17 to determine periods of normal and reversed polarity. Normal polarity is a positive number, and reversed polarity is a negative number. Fill in the blank polarity column by coloring in the normal polarity intervals in black. Reversed polarity intervals should remain white.
b. Correlate your polarity column to the GPTS to determine depositional ages for this sediment core. You can do this by drawing lines that match your polarity intervals of the sediment core to the polarity intervals of the GPTS.
c. What is the age range of the missing sediment in the core gap? _____

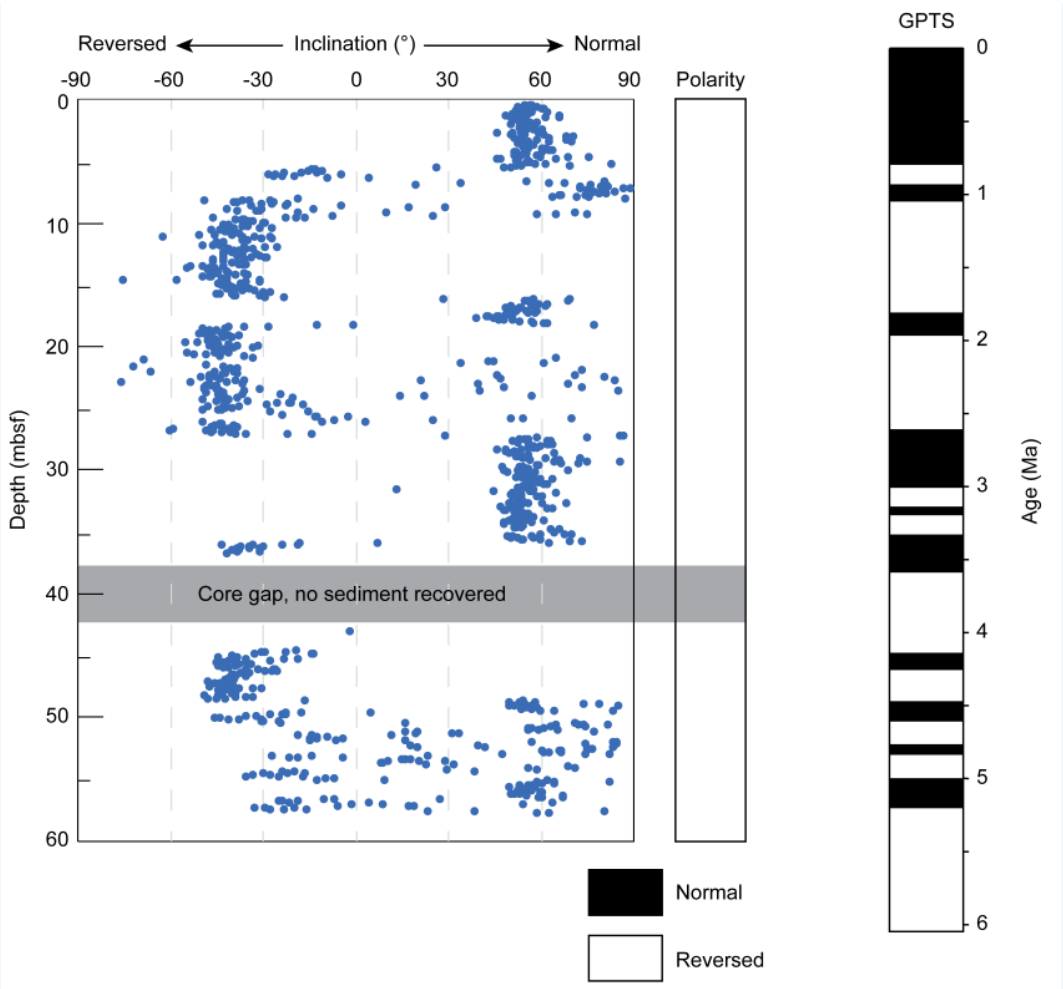


Figure 5.17 – Inclination data (blue dots) from an IODP drill site in the Izu-Bonin-Mariana fore arc drilled during Expedition 352. There is a core gap between 38 m and 42 m (gray bar), which means the sediment was not recovered during the drilling process. Gaps in sediment cores are frequent and can happen for a variety of reasons. Data from IODP.

5.5 Seismic and Sequence Stratigraphy

So far, layers on top of one another have been interpreted as being younger than the layers beneath them. In sequence stratigraphy, age is interpreted from lateral (horizontal) variations of rocks based on the sequence of sedimentary strata in sea-level rise and fall cycles. As sea level rises or lowers, sediment deposition migrates landward or seaward. Sea-level regression is interpreted from (**clinoforms**), which appear to lay somewhat on top of each other at an angle that dips toward the deeper ocean (Figure 5.18). These strata form as land migrates seaward and deposits sediment further away from the original coast. Sea-level rise results in onlapping, where horizontal layers of sediment are deposited against the sloping surface of the clinoforms from the previous sea-level drop. Here is a link to an overview of sequence stratigraphy.

Sequence stratigraphy comes with a slew of new vocabulary words described below and shown in Figure 5.18.

- Base Level – commonly the same as sea level but changes due to basin size and tectonics
- Clinoforms – inclined sedimentary strata tilting toward the deeper ocean
- Downlap – steeply dipping younger strata against a surface or underlying shallowly dipping strata; indicative of sea-level fall
- High Stand – sea level rise and relative increase of onlapping sediment packages
- Low Stand – sea level falls
- Maximum flooding surface – a surface that marks the transition from a transgression to a regression
- Onlap – shallowly dipping, younger strata next to more steeply dipping, older strata; indicative of transgression
- Sequence Boundary – often an unconformity formed by erosion that separates different depositional cycles
- Unconformity – surface separating older from younger rocks and representing a gap in the geologic record

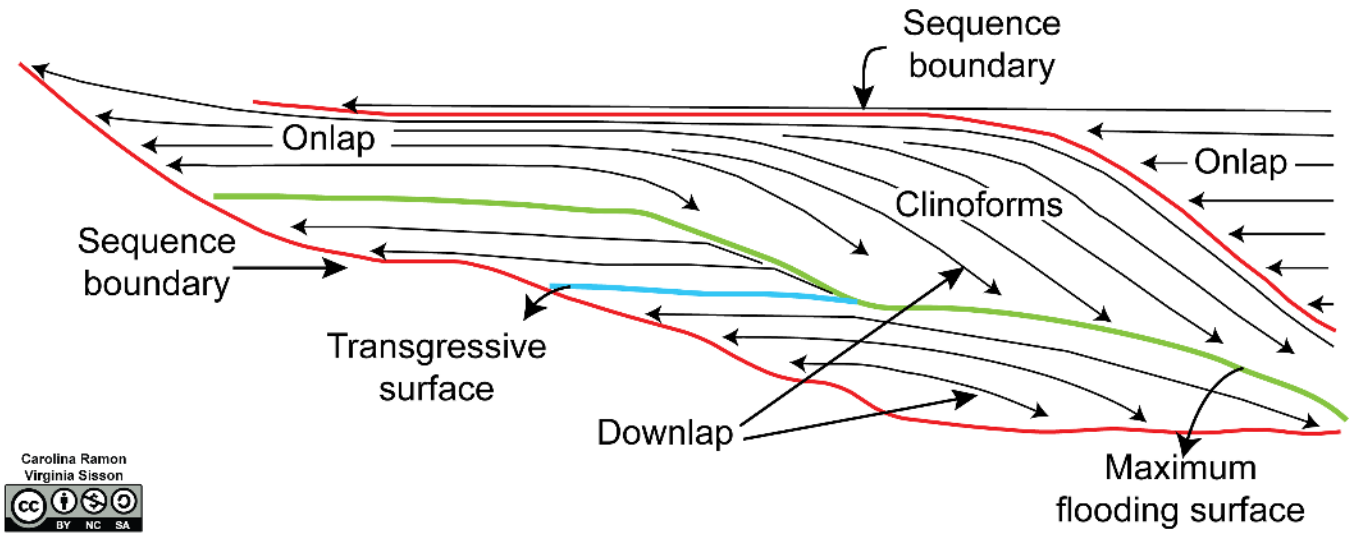


Figure 5.18 – Seismic patterns for a stratigraphic sequence. The lines are seismic reflections. Their shape and how they terminate (shown with the arrowheads) at different locations indicate different geological processes. Image credit: Adapted from Vail et al. (1977) by Virginia Sisson and Carolina Ramon Dueñas, CC BY-NC-SA.

As you look at this figure, there are several things to note. First, clinoforms are not flat. Why you might ask yourself. Well, sediments that are deposited on flat surfaces are flat-lying, whereas those that are deposited on shallowly dipping surfaces are shallowly dipping. New sedimentary layers will mimic the underlying layers until the underlying surface's angle exceeds that of the maximum angle of repose. The angle of repose is the angle at which loose sediments will cascade or landslide down the slope, and it varies depending on the sediment; sandstone is about 30°, and shale is higher than 40°. So, the slope of the clinoforms reflects the underlying sloping strata. Continental margins are where you can commonly find sloping surfaces.

Look carefully at the top sequence boundary. Does it look like a clinoform? Sometimes sequence boundaries look similar to clinoforms as the transition between depositional cycles can be very gradual without significant erosion. You have to look closely to see if there is onlap of the next strata to distinguish a clinoform from a sequence boundary.

? Exercise 5.9 – Sequence Stratigraphy from a Seismic Image

In this exercise, you will work on determining whether sea level influenced the deposition of **Cretaceous** sediments as well as the different features associated with sequence stratigraphy. To do this, you will investigate a stratigraphic section in the Colville Basin, Arctic Alaska (Figure 5.19).

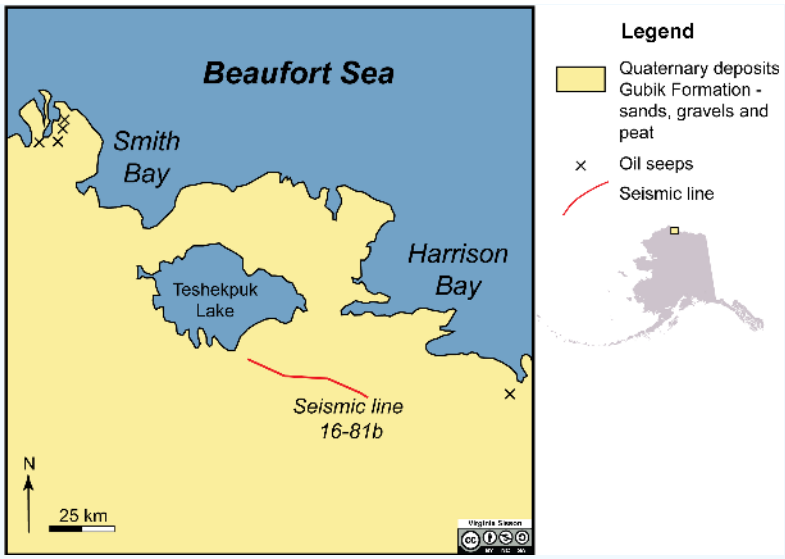


Figure 5.19. Geologic map of part of the National Petroleum Reserve of Alaska (NPRA) west of the Colville River. You may wonder why all the exposure is mapped as Quaternary deposits and not Cretaceous. This is because glaciation and formation of tundra have covered all of the rock exposures. They are only exposed along rivers and seaside cliffs as well as buried beneath the tundra. This is one reason you need to use a seismic line to do this exercise. Image credit: Adapted from the geologic map of Payne (1951) with the location of a seismic line from the U.S. Geological Survey NPRA data archive by Virginia Sisson, CC BY-NC-SA.

Long before Alaska was granted statehood, oil was found seeping from the ground in the Arctic. This oil helped lead to creating the National Petroleum Reserve of Alaska (NPRA – an area the size of Indiana). This area is also known for its coal; some have estimated that this region has ~40% of the U.S. reserves. Arctic Alaska has provided much of the energy resources for the rest of the United States for many years. To help define where the oil was located and how it formed, the U.S. Geological Survey conducted many seismic surveys (often called lines) across the region. We will look at one line for this exercise. Figure 5.20 shows the Cretaceous formations in this section: Pebble Shale unit, Torok Formation, and Nanushuk Formation.

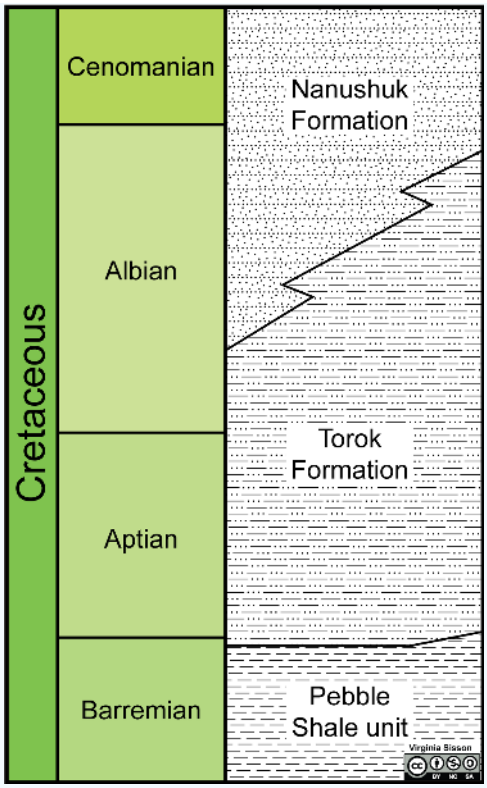


Figure 5.20. Simplified stratigraphic section for the Cretaceous sedimentary sequence in northern Alaska. Image credit: Adapted from Mull et al. (2003) by Virginia Sisson, CC BY-NC-SA.

Before you analyze the seismic section, you should know how sea level is changing worldwide. If you know if the sea level was rising or falling during sediment deposition, this will let you know if you are in a highstand or lowstand environment.

a. We don't know the exact age of these sediments, so first, you must determine the absolute age of these formations using Figure 3.1. Fill out the ages in Table 5.8.

Table 5.8 – Worksheet for Exercise 5.9a

Rock Formation	Absolute Age Range
Nanushuk Formation	
Torok Formation	
Pebble Shale unit	

b. Use the ages you determined in *a* and the sea-level record for the **Phanerozoic** Eon in Figure 5.21 to determine if sea level was rising, falling, or not changing when these three formations were deposited. You might wonder how to do this since this figure has three different sea-level curves. It's up to you to choose one of these to answer this question. Indicate which curve you used to answer this question.

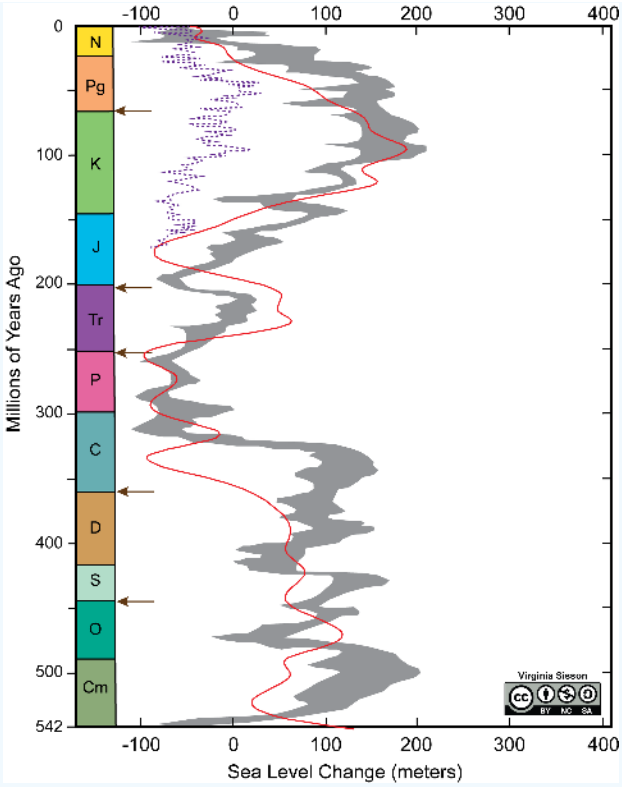


Figure 5.21. Three proposed sea-level curves for the Phanerozoic Eon. The gray area is a compilation of curves proposed by researchers at ExxonMobil. The dashed purple curve considered global ice volumes without tectonic influences on accommodation space. The red curve used a geodynamic model combined with sea level data. Image credit: Simplified by Virginia Sisson CC BY-NC-SA from Vérard et al. (2015).

c. In this exercise, you will identify the age progression of deposition and the different features associated with sequence stratigraphy. In the seismic image (Figure 5.22), identify as many clinoforms as you can. Number them in order of depositional age, with "1" being the oldest. You should be able to identify at least 10 clinoforms. Hint: There is at least one unconformity. Pay attention to the angles at the beginning and end of your features and the angle at which they touch another reflector; if it is at a high angle, this is likely to be either onlap or downlap.

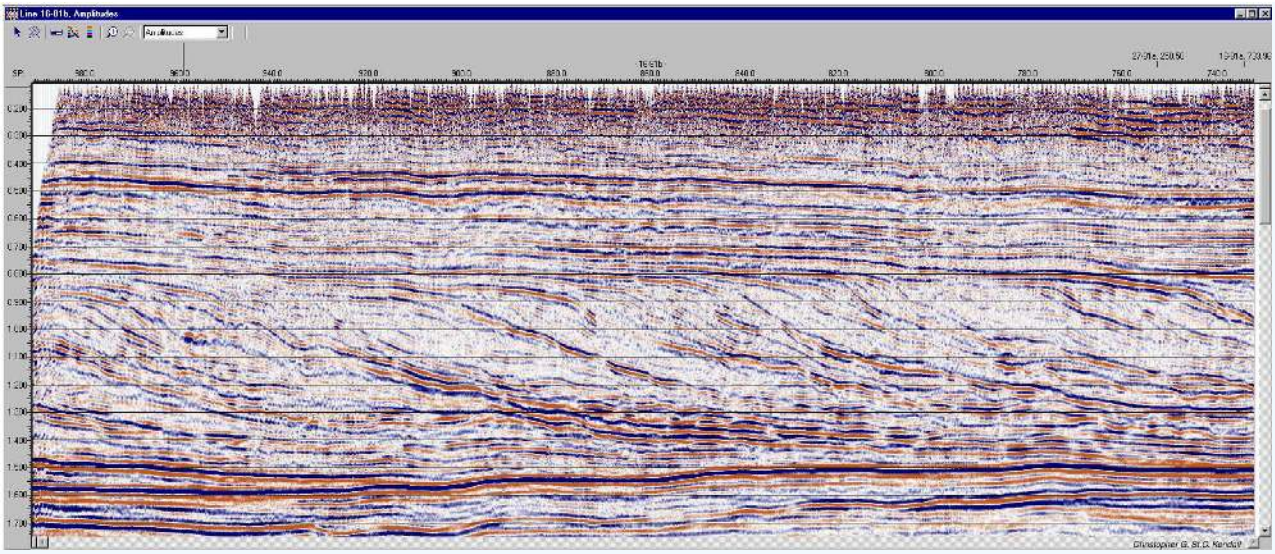


Figure 5.22 Seismic cross-section (line 16-81b) across Cretaceous sediments of the northeastern National Petroleum Reserve of Alaska (NPRA). These sediments filled the Colville foreland basin about 6000′ deep. This view is looking to the north so that the left side is to the west, whereas the right side is to the east. Figure 5.19 shows the location of this seismic line. Blue is for positive amplitude, black for negative amplitude, and white is for no amplitude difference. Image credit: SEPM exercises for sequence stratigraphy with data from U.S. Geological Survey NPRA data archive public domain.

d. Using the seismic features as your guide, which direction would you go to find a marine basin? Explain your reasoning.

e. Based on the seismic section, do you think that sea level was rising or falling during the deposition of this sequence? Explain your reasoning.

f. **Critical Thinking:** Is your answer to *e* the same or different from your answer to *b*, which used the stratigraphic section and the global sea-level curve? If it's different, explain what might cause the discrepancy. Or, if your answers are the same, how does this strengthen your interpretation?

All the previous exercises were aimed at understanding changes in stratigraphy due to environmental conditions and processes. Another component of stratigraphy is the tectonic setting for the sedimentary basin. So, which two tectonic settings are important to consider? The next two exercises will address both convergent and divergent plate boundaries in terms of stratigraphic change. Transform margins may have overlapping faults that create subsidence and small pull-apart basins.

The Appalachian/Caledonide Mountains formed during three separate tectonic events over a period of 220 million years. These events were the **Taconic** (470 to 440 Ma), **Acadian** (420 to 380 Ma), and **Alleghenian** (350 to 250 Ma) orogenies. Between each of these tectonic events, the mountains eroded as they were uplifted. One of the concepts you need to know for this exercise is the effect of increasing the weight on the lithosphere. You may have learned about **isostasy** in Physical Geology and how the lithosphere responds like an iceberg melting in the ocean. Well, during continental collision, the added weight of the continental mass will cause the lithosphere to bend, creating a **foreland** or foredeep basin. For example, the Persian Gulf is a basin formed from the collision of the Asian and Arabian plates creating the Zagros Mountains. These sedimentary basins often form shallow

(30-100 m) repositories for continentally derived sediments. If the area beside the continental collision is wide, it will form a shallow inland ocean (sometimes called an epeiric or epicontinental sea), such as Baffin Bay in northern Canada.

? Exercise 5.10 – Convergent Tectonics in a Sedimentary Record

The Catskill clastic wedge (Figure 5.23) is a Devonian sediment package sourced from the Appalachian Mountains during the Acadian Orogeny. This sediment package extends from New York through Virginia and West Virginia and is part of the larger Appalachian Basin. In western Virginia and eastern West Virginia, the Catskill clastic wedge contains evidence for three phases of the Acadian Orogeny:

Phase 1 – A rapid drop of the seafloor caused by the massive weight of the mountains. The load causes the lithosphere to bend, creating a concave basin in front of the uplifting mountains. It is characterized by a sudden change to deep-water sediments such as shales.

Phase 2 – As the mountains erode, coarse sediment is deposited. These can be deposited in fluvial (rivers) or near-shore marine depositional settings.

Phase 3 – At the end of the mountain building process, there is a return to a stable passive margin sequence ranging from fine sediment deposition to shallow marine carbonates.

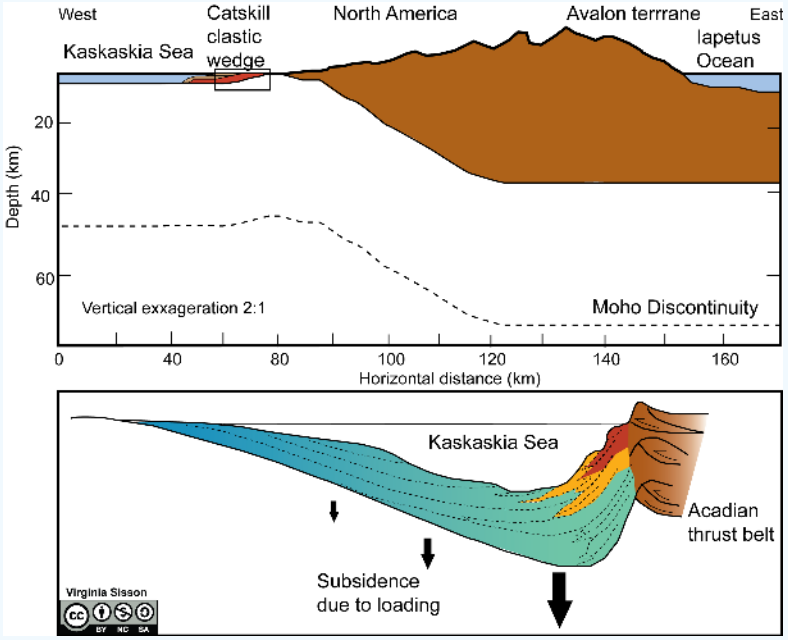


Figure 5.23 Continental collision can result in the formation of inland seas, such as the Kaskaskia Sea and foreland basins. The brown represents the collision of North America with the Avalon terrane. Image credit: Virginia Sisson, CC BY-NC-SA.

Complete the following questions about the Catskill clastic wedge:

a. Figure 5.24 is a roadside outcrop of the Brallier Formation in Pennsylvania, composed of shale and fine sandstone layers. Provide a sketch of this outcrop and identify the layers of sandstone vs. the layers of shale.



Figure 5.24 – Outcrop of Devonian Brallier Formation on the north side of the Pennsylvania Turnpike, central Bedford County, near Mile Marker 138 in Pennsylvania. Sandstone beds near the bottom of the photo are possible turbidites. Image credit: Wikimedia user Jstuby, CC0 Public Domain, photo taken August 2011.

Sketch Area:

b. Figure 5.25 is a roadside outcrop of the Hampshire Formation in Pennsylvania, composed of sandstone and fine-grained siltstone. Provide a sketch of this outcrop.



Figure 5.25 – Point bar deposits in the Hampshire Formation near North Bend, Pennsylvania. Image credit: Wikimedia user Rygel, M. C., CC BY-SA.

Sketch Area:

c. What sedimentary structure is shown in Figure 5.25, and can you tell in which direction sediment was being transported?

d. Figure 5.26 below contains the sequence of sedimentary rocks associated with the Catskill clastic wedge. Based on the rock descriptions, identify the depositional environment for each stratigraphic unit and which orogenic phase it represents.

	Stratigraphic Unit	Dominant Lithology	Depositional Environment(s)	Orogenic Phase
Carboniferous	Mauch Chunk Formation	Coarse sandstone and red siltstone		
	Greenbrier Formation	Limestone		
	Pocono Formation	Quartz sandstone and conglomerate		
Devonian	Hampshire Formation	Sandstone with asymetrical ripple marks		
	Greenland Gap Group	Sandstone with red shale		
	Brallier Formation	Shale with fine sandstone		
	Millboro Formation	Black siltstone with fine sandy layers		
	Needmore Formation	Shale with fine sand and silt layers		

Figure 5.26 – Stratigraphic units of the Catskill clastic wedge and the dominant lithology of each unit. Image credit: Adapted by Carlos Andrade and Virginia Sisson CC BY-NC-SA.

Another dynamic aspect of plate tectonics is continental rifting, a process in which a continental mass splits apart and two separate new landmasses form and drift away from each other. After the last orogeny in the Appalachian mountains, Pangea broke apart into our current continent configuration through continental rifting processes. The Recôncavo basin in Brazil near the city of Salvador (Figure 5.27) is the southernmost basin in northeastern Brazil created by continental rifting of South America and Africa. This rifting process is well recorded in the eastern Brazilian margin and shows different stages of this process:

1. Before rifting begins, continental processes such as fluvial, eolian, and lacustrine deposition dominate the sediment deposition.
2. Then as the rifting begins, igneous activity also begins. In continental rifts, this is usually bimodal (rhyolite and basalt) volcanism. Rifting also causes normal faulting of the continent forming **grabens** and half grabens resulting in lacustrine (lake) deposits. In some areas, very high-energy processes dominate. As the continent starts to split apart, the ocean water will flood the depression caused by the faulting creating shallow-water seas, which sometimes host various shallow marine species.
3. As the shallow seas and lakes are evaporated, massive salt and anhydrite (evaporites) deposits are formed.
4. Rifting completely separates the continent into two new landmasses, which start drifting apart and are marked by a “passive margin system.” Tectonic activity is no longer present, and the sediments are increasingly deeper marine.

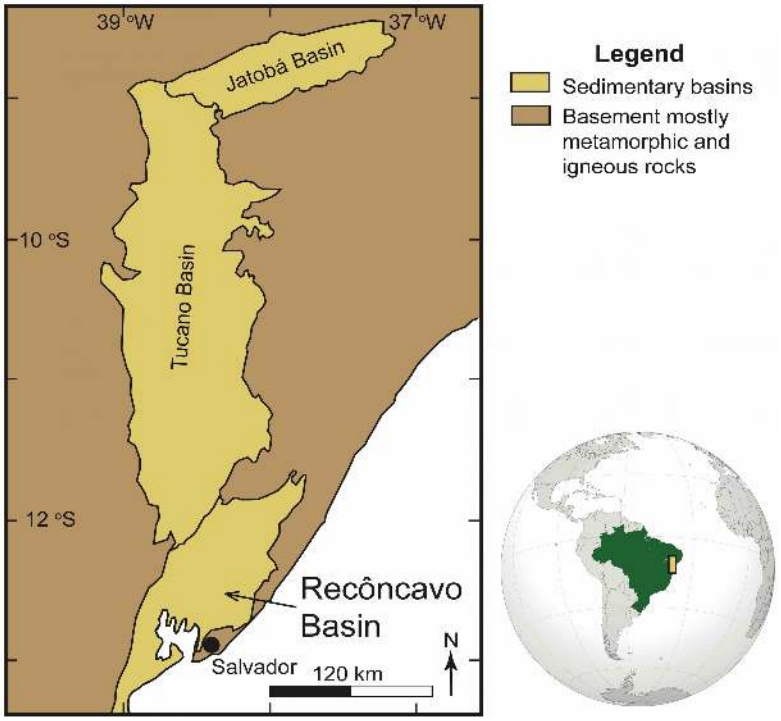


Figure 5.27 – The Recôncavo basin covers 11,500 km^2 and is a prime source of petroleum. Since 1939, 225 wells have been drilled. By 2012, this basin had produced over 1.6 billion barrels of oil and 70 billion km^3 of gas. Image credit: Simplified by Virginia Sisson CC BY-NC-SA from Magnavita et al., 2005 with insert map of Brazil from Wikimedia Commons user Addicted04 CC-SA.

? Exercise 5.11 – Continental Rifting in a Sedimentary Record

Stratigraphic Evidence of Continental Rifting

a. Determine the depositional environments for the different lithologies in the northeastern Brazilian Recôncavo Basin's stratigraphic column in Figure 5.28 below.

b. Identify the 4 stages of rifting (described above Figure 5.28) and mark them 1, 2, 3, and 4 in the right-most column in Figure 5.28. Mark your boundaries between the stages by drawing a thick line at the top of the formation that ends each stage.

	Stratigraphic Unit	Simplified Lithology NW SE	Depositional Environment(s)	Orogenic Phase
Cretaceous	Alagoas	Calcarenites (alternating layers of carbonate and shale)		
	Jiquiá	Halite and anhydrite		
	Buracica	Conglomerate with boulder-size cobbles; Coquina		
	Aratu	Red shales, red siltstones, some bioturbation by roots		
	Rio da Serra	Mafic volcanics interbedded with sandstone		
Jurassic	Dom João	Sandstones, red shales, and siltstones; some have large scale cross-beds and others have ripple marks		

Figure 5.28 – Stratigraphy of the Brazilian Recôncavo Basin with simplified lithology. Image credit: Carlos Andrade and Virginia Sisson CC BY-NC-SA.

c. **Critical Thinking:** What will the sedimentary environment be in this part of Brazil after rifting has stopped?

d. **Critical Thinking:** Today, the Atlantic Ocean marks the rift boundary between Brazil and Africa. At what stage did the rifting stop in the Recôncavo Basin? Why?

Outcrop Interpretations



Figure 5.29 – Sandstones and fossiliferous shales from the Dom João Formation on the southwestern side of the Recôncavo basin at Praia da Pedra Mole (translates approximately to soft rock beach) near Barra do Paraguaçu. These geologists have a rock hammer on the outcrop, and one is about to take a picture. They are standing among large blocks with distinctive white spots, which are oyster shells. Image credit: Luzia Brito via Google Earth.

The following questions refer to Figure 5.29.

e. What sedimentary environment do you find oysters in?

f. Why is the rock in Figure 5.29 black?

g. What is the sedimentary environment of the overlying buff-colored layers?

h. How does this change in sedimentary environments fit with the tectonic setting of the Recôncavo Basin?



Figure 5.30 – Dom João Formation along BR 101, about 14 km southwest of Algoinhas, Brazil. Two processes cause the red color; one is intense tropical weathering creating red soil (the left side of the outcrop is almost completely converted into red soil as is a layer at the top of the outcrop), and two, hematite oxidation during deposition of these sandstones and shales. A fault offsets the bedding in this outcrop along the yellow line. Image credit: Google Street View.

i. What type of fault is present in Figure 5.30? It may help you to draw arrows on either side of the fault showing the sense of motion. _____

j. What is the age of the fault (remember to look at the stratigraphic column for the age of the formation)? _____

k. Is this fault related to continental rifting? How does this help you determine the depositional environment?

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson, Carlos Andrade, Joshua Flores, Melissa Hansen

References

Krumbein, W.C., and Sloss, 1963, Stratigraphy and Sedimentation (2nd edition), W.H. Freeman and Co., 660 p.

Magnavita, L., Da Silva, R.R., and Sanches, C.P., 2005, Field trip guide of the Recôncavo basin, NE Brazil, April 2005, Boletim de Geociencias – Petrobras, 13(2), 301-333.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.E., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic Record of Global Sea-Level Change, Science, 310, 1293-1298. doi: 10.1126/science.1116412

Moore, G.F., Park, J.-O., Bangs, N.L., Gulick, S.P., Tobin, H.J., Nakamura, Y., Sato, S., Tsuji, T., Yoro, T., Tanaka, H., Uraki, S., Kido, Y., Sanada, Y., Kuramoto, S., and Taira, A., 2009. Structural and seismic stratigraphic framework of the NanTroSEIZE Stage 1 transect. *In* Kinoshita, M., Tobin, H., Ashi, J., Kimura, G., Lallemant, S., Screaton, E.J., Curewitz, D., Masago, H., Moe, K.T., and the Expedition 314/315/316 Scientists, *Proc. IODP*, 314/315/316: Washington, DC (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.314315316.102.2009

Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary Stratigraphic Nomenclature in the Colville Basin, Northern Alaska: U.S. Geological Survey Professional Paper 1673, 51 p.

Payne, T.G., 1951, Geology of the Arctic slope of Alaska: U.S. Geological Survey Oil and Gas Investigations Map 126, 3 sheets, scale 1:1,000,000.

Picard, M.D., 1971, Classification of fine-grained sedimentary rocks, Journal of Sedimentary Petrology, 41, 179-195. https://doi.org/10.1306/74D7221B-2B21-11D7-8648000102C1865D

Vail, P.R., Mitchum, R.M., and Thompson, S., 1977, Seismic stratigraphy and global changes of sea level, part 3: Relative changes of sea level from coastal onlap, in C.E. Clayton, ed., Seismic stratigraphy – applications to hydrocarbon exploration: Tulsa, Oklahoma, American Association of Petroleum Geologists Memoir 26, 63–81.

Vérard, C., Hochard, C., Baumgartner, P.O., and Stampfli, G.M., 2015, 3D paleogeographic reconstructions of the Phanerozoic versus sea-level and Sr-ratio variations, Journal of Palaeogeography, 4, 64-84. doi:10.3724/SP.J.1261.2015.00068

Google Earth Locations

Click or Scan to View all Chapter 5 Locations on Google Earth

This page titled 1.6: Stratigraphy is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.7: Fossil Preservation

Learning Objectives

The goals of this chapter are to:

- Explain the different ways organisms become fossilized
- Identify the mode of preservation for fossils

6.1 Introduction

Everyone has heard the word fossil! So, how do you define this term? In this lab, we will define it to mean any evidence for the existence of prehistoric life. What is difficult to explain in this definition is what is meant by prehistoric. For example, would you consider bodies preserved at Pompeii to be fossils, or how about the remains of a frozen mastodon from the Pleistocene that was preserved well enough to be eaten? Some say anything older than 11,000 years is a fossil, but this part of our definition is a matter of semantics. An excellent place to learn more about fossils and fossilization is the Digital Atlas of Ancient Life.

? Exercise 6.1 – Fossilization Probability

We start this chapter on how organisms become fossilized with a quick exercise. Figure 6.1 contains three different organisms.



Figure 6.1 – a) Worms, b) Giant kelp; c) Mussel shells. Image credit: a) Soil-Net, CC BY-NC-SA; b) NPS, Public Domain; c) Linnaea Mallette, Public Domain.

a. Which organism in Figure 6.1 do you think has the highest chance to become a fossil and why?

b. Which organism do you think has the highest chance to leave behind a trace fossil? _____

6.2 Types of Preservation

Taphonomy is the branch of paleontology that focuses on the fossilization process. Fossils are preserved by three main methods: unaltered soft or hard parts, altered hard parts, and trace fossils. You already learned about trace fossils in Chapter 4.

Unaltered fossils are rare except as captured in amber, trapped in tar, dried out, or frozen as a preserved wooly mammoth. Amber is the fossilized tree resin that can trap flowers, worms, insects, and small amphibians and mammals. The father of one of the authors was part of a gold mining operation that discovered a wooly mammoth calf (nicknamed Effie) in Alaska. This was the first mummified mammoth remains found in North America. Even though it was buried about 21,300 years ago, it still consists of tissue and hair. Sometimes, only organic residue is left behind and is detected by molecular, biochemical techniques. Earth's oldest fossils are only preserved as complex organic molecules.

Soft tissue is hard to preserve because it needs to be buried before bacterial decay can occur. This preservation occurs when remains are buried rapidly in an oxygen-free, low-energy sedimentary environment. Since these conditions are uncommon, the preservation of soft tissue rarely happens. Instead, typical examples of unaltered fossils are skeletal material that has been

preserved with little or no change. Many marine invertebrate fossils and microfossils were preserved in this manner. However, paleontologists are now looking closer at fossils and recognizing thin carbon layers in the rock around fossils as soft tissue. Recently, a team led by Mark Norell, a paleontologist at the American Museum of Natural History in New York City, identified a layer of carbon around dinosaur embryos formed over 200 million years ago that they think was a soft eggshell!

Unaltered fossils contain minerals that were biologically produced; these include apatite (in bones and teeth and rarely in exoskeletons, hardness = 5), calcite (calcium carbonate found in many organisms such as shells, hardness = 3, fizzes in acid), aragonite (similar to calcite, but an unstable polymorph) and opal (a type of silica found in marine animals and plants, hardness = 7). In addition, the hard parts (exoskeleton) of some insects and arthropods are made of chitin, a polysaccharide related to cellulose. If you can identify the minerals present in a fossil, you can distinguish if it is original material or altered.

Alteration of hard parts is much more common in fossils and happens when original skeletal material is either permineralized, recrystallized, replaced, carbonized, or dissolved (Table 6.1).

Table 6.1 – Common types of fossil preservation

Type of Preservation	Example
Permineralization occurs in porous tissue such as bone and wood. In this type of preservation, minerals dissolved in water such as quartz, calcite, or pyrite permeate the pore space and crystallize. The addition of these minerals results in denser and more durable fossils. The original bone or wood material may be preserved, or it may be replaced or recrystallized.	 Figure 6.2 – Petrified wood from the Petrified Forest National Park, AZ. Image credit: Jon Sullivan, Public Domain.
Recrystallization involves a change in the crystal structure but not in mineral chemistry, similar to recrystallization in metamorphic rocks. For example, the mineral aragonite, a common mineral of many shells, sometimes changes to calcite, a more geologically stable form of the same chemical composition, $CaCO_3$ (aka a polymorph). Typically, the overall size and shape of a recrystallized fossil do not vary substantially from the original unaltered specimen, but fine details may be lost.	 Figure 6.3 – Recrystallized, Silurian-age coral from Ohio. Image credit: James St. John, CC BY.
Replacement is the substitution of original skeletal material by a secondary mineral. For example, the calcite of an oyster shell may be replaced on a molecule-by-molecule basis by silica. Remarkably, the replaced fossil may retain some of the fine cellular detail present in the original even though its composition changed. In this type of fossilization, pore space is not filled, and the fossils are not as dense. The most common replacement minerals are silica (quartz), pyrite, dolomite, and hematite. Replacement by pyrite creates some spectacular fossils, especially those hosted by black shales!	 Figure 6.4 – Pyritized fossil trilobite with appendages (Triarthrus eatoni) from the Whetstone Gulf Formation, Upper Ordovician; New York State, USA. Image credit: James St. John, CC BY.
Carbonization is a type of fossil preservation in which the organism is preserved as a residual, thin film of carbon instead of the original organic matter. Leaves, fish, and graptolites are commonly preserved in this way. Compression of the original organism results in thin layers of carbon. Carbonization can also result in the formation of coal.	 Figure 6.5 – Carbonization of Silurian-aged graptolites from Poland. Image credit: James St. John, CC BY.
Molds and casts form when the original skeletal material dissolves. The organism leaves behind an impression in the sediment called a mold. If that impression fills with new sediment, it creates a cast. Thus, casts are made from molds.	 Figure 6.6 – A mold (left) and cast (right) of a trilobite fossil. Image credit: Roger Wellner.

Internal molds form when sediment fills the inside of a shell before it dissolves; this occurs inside bivalves, snails, or skulls. Often, people confuse casts and internal molds because both have positive relief. However, internal molds preserve a 3-dimensional mold of the inside of the organism, whereas a cast preserves the structure of the outermost part of the organism.



Figure 6.7 – Dissolution of a gastropod that has left an internal mold of the organism. Fossil from eastern Iowa. Image credit: James St. John, CC BY.

Trace fossils, which we discussed in Chapter 4, are not really fossils but the evidence that organisms affected the sediment by burrowing, walking, or even leaving behind excrement or vomit. No kidding, there is fossil poop; this kind of trace fossil is called a "coprolite," from the Greek word *kopros*, meaning dung. One last rare type of trace fossil is gastroliths, extremely smooth polished stones that aided digestion in dinosaurs and crocodilia. These are more highly polished than stream-worn gravels. Gastroliths found in Jurassic sediments in Wyoming may have been carried by sauropods over 1600 kilometers from their source in Wisconsin.

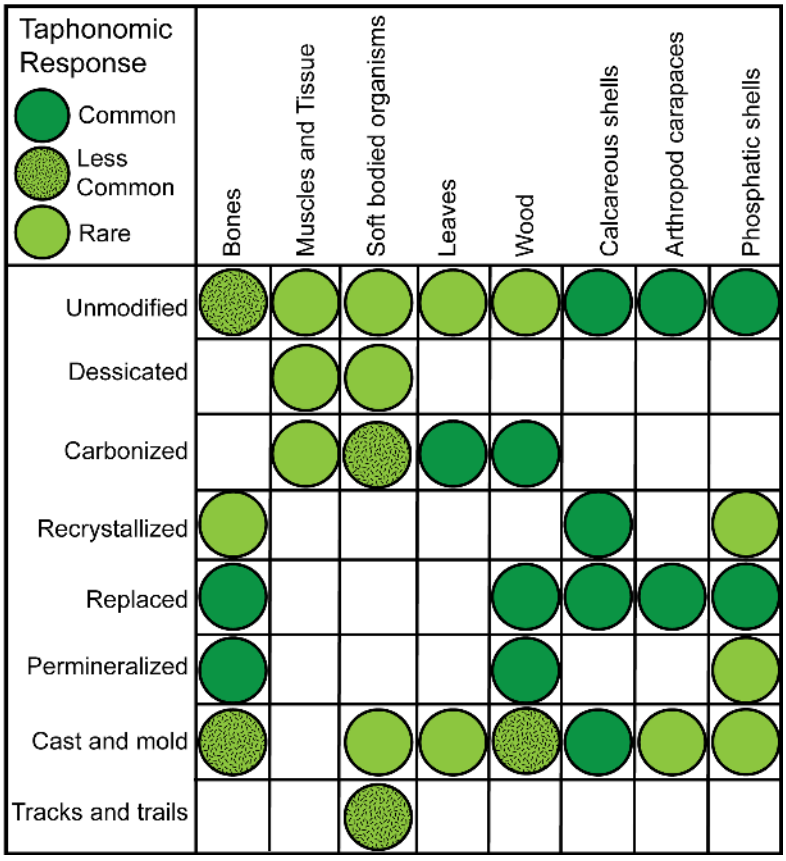


Figure 6.8 – Different parts of organisms compared to how they can be preserved as fossils. The green circles are common types of fossilization, the light green, stippled circles are less common, and the light green circles are uncommon to rare ways. Image credit. VB Sisson modified from Ritter and Peterson (2015) CC-BY-SA-NC.

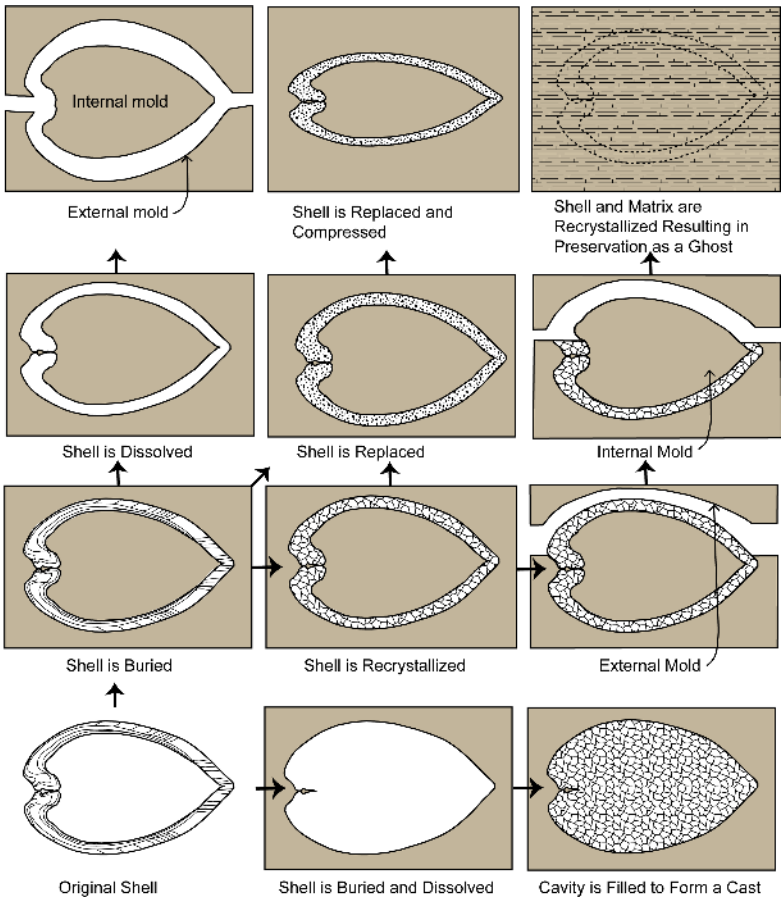


Figure 6.9 – Types of fossilization including alteration and replacement of the original shell. Follow the arrows from box to box to see how different processes can result in molds and casts. The brown color is a sedimentary rock. The random pattern represents recrystallized carbonate, and the stippled pattern represents secondary minerals such as silica or pyrite. Image credit: VB Sisson with a shell showing growth lines and internal structure adapted from Casella et al., 2017 and fossilization processes adapted from Ritter and Peterson (2015) CC-BY-NC-SA.

3-D Model Box 6.1 – Molds

This model shows a preserved fossil shell on the right (not a cast, original) and an external mold on the left of the ammonoid cephalopod Gunnarites sp. from the Cretaceous Lopez de Bertodano Formation of Snow Hill Island, Antarctica. The fossil specimen is from the collections of the Paleontological Research Institution, Ithaca, New York. The diameter of the specimen (not including surrounding rock) is approximately 9 cm.



Cephalopod: Gunnarites sp. (PRI 61543) by **Digital Atlas of Ancient Life** on **Sketchfab**

This is an example of an internal (1) and external (2) mold of the gastropod *Cassidaria mirabilis* from the Cretaceous of Snow Hill Island, Antarctica. The specimen is from the collections of the Paleontological Research Institution, Ithaca, New York. It is approximately 6 cm in length (not including surrounding rock).



Gastropod: Cassidaria mirabilis (PRI 58468) by **Digital Atlas of Ancient Life** on **Sketchfab**

More 3-D models on fossil preservation can be found at the Digital Atlas of Ancient Life.

If you ever get asked by a friend to help identify a fossil, watch out for pseudofossils, which are accidents of diagenesis that look like a fossil but are just weird sedimentary formations. Pseudofossils include septarian nodules that are mistaken for reptile skin or turtle shells, concretions are mistaken for eggs, and manganese oxide dendrites mistaken for ferns moss.

6.3 Handling of Fossils

Some fossils are incredibly fragile. Some delicate samples are prepared by air abrasion with talcum powder to remove the matrix. For some trilobite specimens, this takes thousands of hours to expose their delicate features. Some fossils you will use may be easy to replace and others impossible. Others may be part of a faculty member's personal collection. Only handle the specimens that your instructor says you can. If you are taking this lab when teaching is face-to-face in a lab setting, you will handle both real and replica specimens of fossils. While these may have been around for millions or billions of years and seem like they are now rocks, they need to be treated with respect. Some of the fossils that you may handle may be the only specimen of their kind in the collection. Some of the larger specimens may be heavy, especially those that are molds filled with sediment. Never try to scratch the specimens for hardness. Also, never use acid as a mineral test. Finally, if you break or steal a specimen, you will be charged for its replacement.

You are free to make sketches or photograph the specimens. If you do this, you may want to put a scale in the image, such as a coin or ruler. This will help you remember the size of the object. Some specimens will have labels or numbers written on them, and others will not because they may be too fragile to even be written on. You must put each specimen back in its appropriate box or location in a lab tray. Also, do not move any of the paper labels from the boxes. This will prevent confusion for other lab students.

If you've wondered how to start your own fossil collection, you can either find them on your own or buy them. The price of fossils for sale ranges from cheap to outrageously expensive. For example, in 2020, an anonymous collector bought a fossil Tyrannosaurus rex, nicknamed Stan, for $31.85 million. This specimen only had 188 bones and was one of the most complete of its species. If this is beyond your budget, you can find inexpensive fossils such as fossilized snails from Morocco for only $0.30 each.

? Exercise 6.2 – Identifying Types of Fossil Preservation

Inspect the first set of samples and fill out the table with information about the presence of original biologic material, positive and negative relief, and mineral composition of the samples. Identify the mode of preservation of the fossils. Use the flowchart in Figure 6.10 to help.

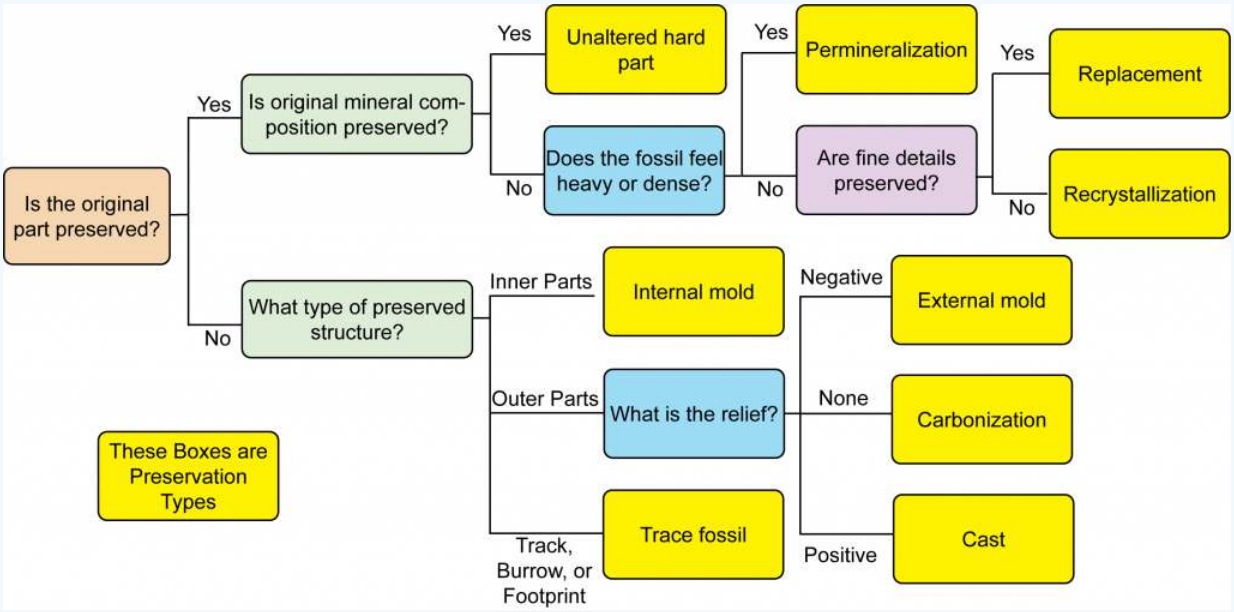


Figure 6.10 – Flowchart for identifying the type of fossil preservation. Image credit: Virginia Sisson and Daniel Hauptvogel CC-BY-NC-SA.

Table 6.1 – Worksheet for Exercise 6.2

Sample	Original Material Present?	Relief*	Mineral Composition*	Type of Preservation

*Note that you may not see relief or be able to identify the mineral. Leave these blank if necessary.

Critical Thinking: Why is replacement the most common mode of preservation?

? Exercise 6.3 – Thinking about Preservation

The way an organism can become fossilized depends on many things. Below are some examples to think about.

a. Examine an external mold in your fossil collection. These commonly preserve details such as the veins in leaves or scales of fish.

i. What is the grain size of the surrounding rock? _____

ii. Do you think these impressions could be preserved in coarse-grained sediment?

b. Look at some examples of carbonization. The dark matter is the remnant of organic carbon that was never oxidized (decayed). Under what conditions might this kind of preservation occur?

c. Your fossil collection may have graptolites, an extinct planktonic, colonial organism that secreted an organic shell of chitin similar to your cellulose. These colonies are usually preserved as two-dimensional impressions, almost always black (indicating carbonization of the chitin).

i. What type of rocks is best suited to finding graptolites?

ii. What were the burial conditions?

d. Some bones and teeth can be preserved, such as unaltered bones or shark teeth.

i. How would you distinguish these from permineralized fossil bones?

ii. Can permineralized wood scratch glass?

e. Now consider the wide range of sedimentary environments.

i. What sedimentary environments are not suitable for preserving fossils?

ii. Which sedimentary environments are good for preserving fossils?

iii. Which depositional environments within continental and marine environments are best for preserving fossils? Explain.

iv. Can volcanic eruptions preserve fossils? Explain.

v. How can the energy of the sedimentary environment affect the preservation of fossils?

vi. Can you find fossils in metamorphic rocks? If so, what factors aid in their preservation?

f. **Critical Thinking:** There are more **invertebrates** than **vertebrate** fossils in this lab exercise. Explain why this is.

? Exercise 6.4 – Modes of Preservation in an Ancient Reef

During the **Permian** time, 299 to 252 million years ago, an extensive reef system grew in west Texas at the edge of a small inland marine basin that extended over 26,000 km² (10,000 square miles). Now it is called the Delaware basin, home to a major oil field (Figure 6.11). This reef is now exposed in three mountain ranges; Apache, Guadalupe, and Glass Mountains. Elsewhere, the reef is now buried around the entire rim of the basin. The northernmost exposure of the reef is part of the Guadalupe Mountains National Park. It is home to Carlsbad Caverns, which has the largest underground chamber in the United

States. The reef was home to many fossils, including ammonoids, bryozoans, algae, sponges, brachiopods, gastropods, pelecypods, echinoids, fusulinids, trilobites, corals, and crinoids.

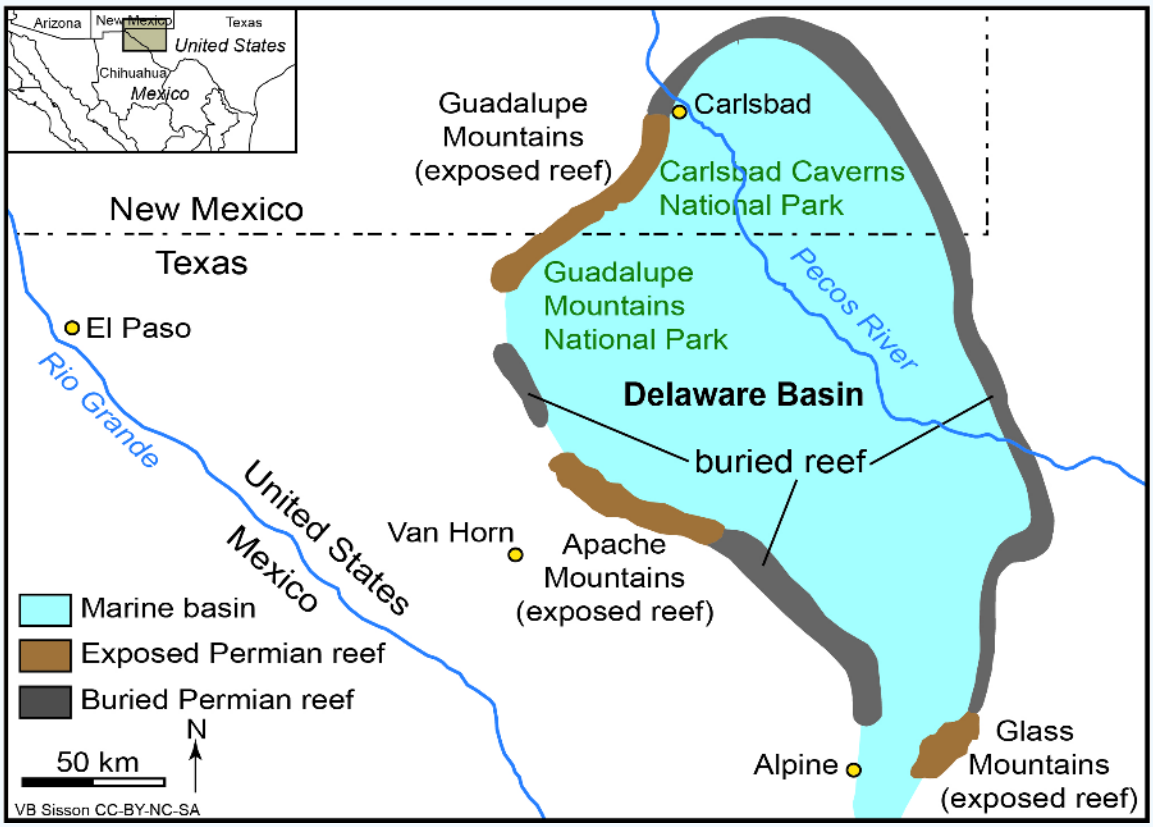


Figure 6.11 – Map of exposed and unexposed Permian reef that encircled the Delaware Basin, an inland sea in Texas and New Mexico. Image credit: Adapted by VB Sisson from National Park Service CC-BY-NC-SA.

Unlike modern coral reefs, such as the Great Barrier reef of Australia or the reefs off the coast of Florida and Belize, it was constructed from **sponge**s, algae, and lacy animals called **bryozoa**. One magnificent exposure of this reef is El Capitan in the Guadalupe Mountains National Park. The reef is subdivided into three parts: back reef, reef, and fore reef. Each had its own unique ecosystem as well as lithology and preservation. The deep part of this basin reached depths of almost 800 meters (½ mile) and is where a lot of organic matter was deposited, leaving black shales – the source of petroleum.

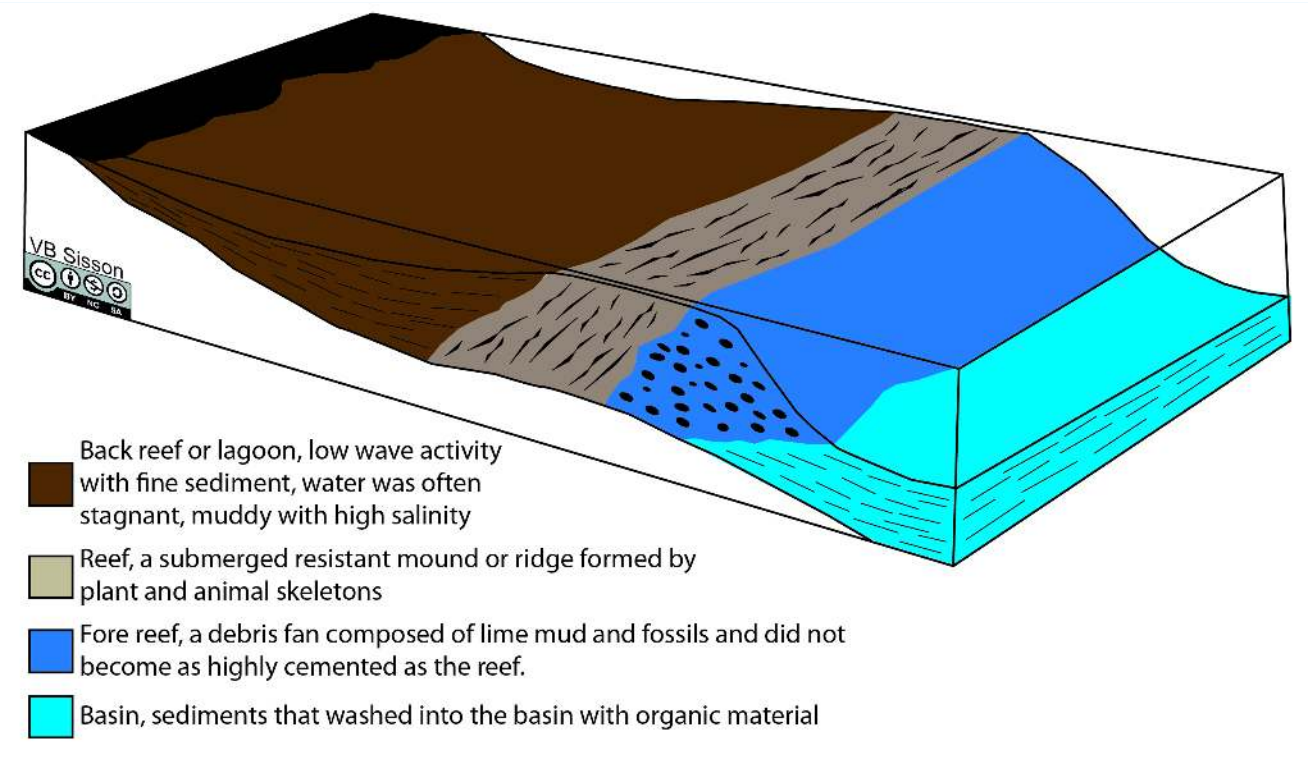


Figure 6.12 – Schematic cross-section across a reef showing the back reef, reef, and fore reef as well as the marine basin. Image credit: Adapted by VB Sisson from National Park System CC-BY-NC-SA.

The Delaware inland sea had a narrow outlet to the **Panthalassan** ocean, much like the Black Sea today. However, after ~30 million years, the entrance got restricted, and the basin started to dry up, forming extensive **evaporite** deposits (Castille and Salado Formations). This created supersaturated, acidic brines that started to dissolve the underlying carbonate reef, forming extensive caves and karst that you can now visit at Carlsbad Caverns National Park and Lechuguilla Cave, the 8th longest explored cave in the world at ~220 km or 138 miles long. These brines also dissolved the silica-rich sponges that formed the reef and affected the fossil preservation in parts of this Permian reef system.

Google Street View in Google Maps has recorded many of the trails in Guadalupe Mountains National Park. Start at either McKittrick Canyon or the trail to Guadalupe Peak and drag the orange person icon onto one of the trails to see views of the massive limestone reef.

The stratigraphy of this basin is complicated because it varies with time and position in the reef. According to recent sequence stratigraphic analysis, there were up to six transgressive-regressive sequences in this basin (Kerans and Kempter, 2002). Figure 6.13 gives a simplified stratigraphy for the basin during the Permian.

	Basin Facies	Dominant Lithology
Permian	Delaware Mtn. Group	deep-water clastic sediment up to 4,500 feet thick
	Bone Spring Fm.	mostly carbonate interbedded with shale up to 4,000 feet thick
	Wolfcamp Fm.	organic-rich shale and argillaceous carbonates varies between 200 to 7,050 feet thick

Figure 6.13 – Simplified stratigraphy for the Delaware Basin. Image credit: Simplified by Virginia Sisson from Kerans and Kempter (2002) CC-BY-NC-SA.

Fossils in the Capitan Formation of the Glass Mountains are uniquely preserved (see Figure 6.4). Paleontologists found that it is easy to dissolve away the host carbonate in weak acid and leave behind spectacular specimens.

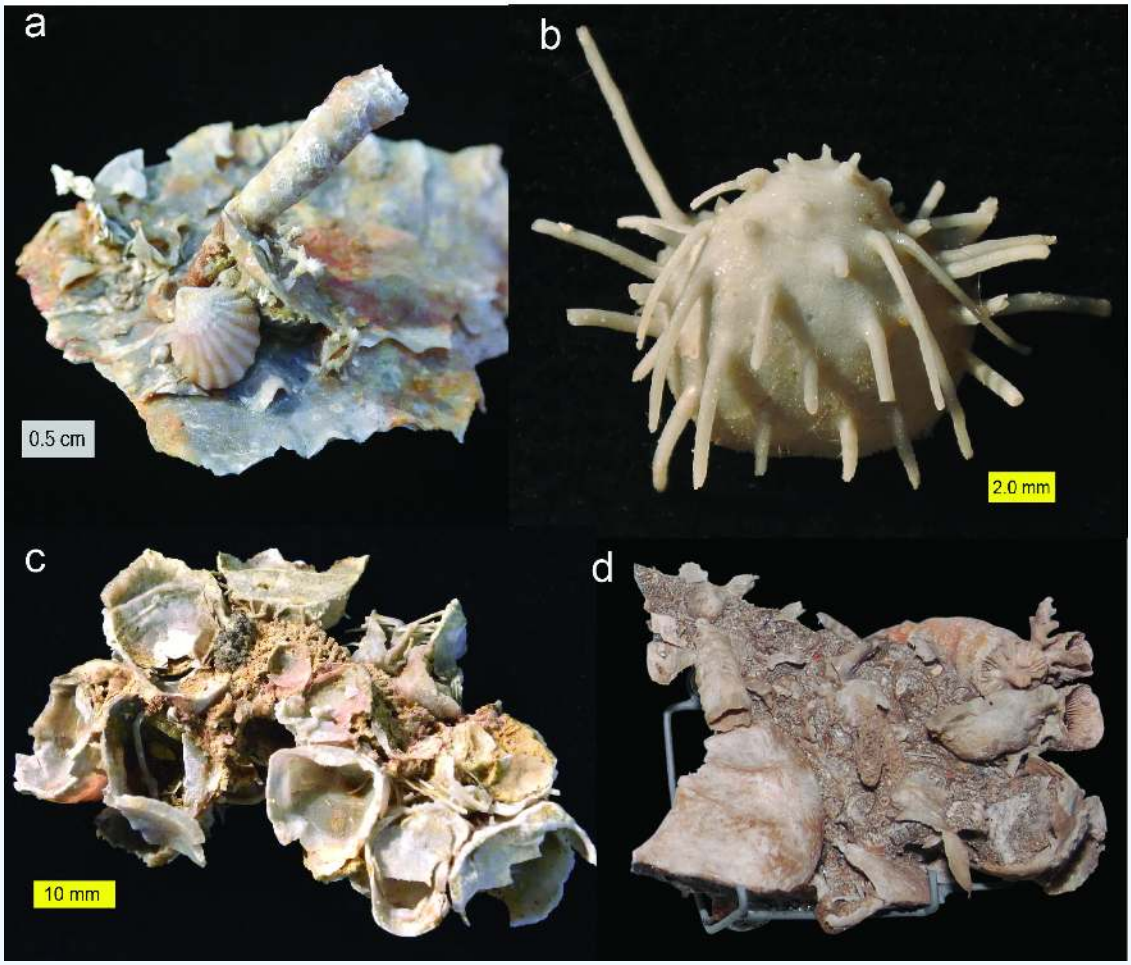


Figure 6.14 – Fossils from the Capitan Formation of the Glass Mountains, Texas. a) silicified fossils including the wavy outer layer of a bivalve shell and attached to it, are encrusting organisms (sclerobionts). Other fossils include a long tube of a rugose coral with a ribbed athyrid brachiopod at its base; b) silicified Productid brachiopod ventral valve; c) silicified Hercosestria cribrosa; d) silicified Anthozoa brachiopoda and bryozoa. Image credits: a) James Wilson, CC0 Public Domain; b) Wikimedia user Wilson44691, CC0 Public Domain; c) Wikimedia user Mark A Wilson Wilson44691, CC0 Public Domain; d) Wikimedia user the paleobear CC BY.

a. The mineral in these fossils is harder than glass and does not fizz as it is no longer a carbonate. Sometimes this mineral is just a coating, and other times the entire fossil is this new mineral.

i. What is the mineral? _____

ii. What is the mode of preservation for these fossils? _____

iii. Were fluids involved in their preservation? If so, what was their composition?

iv. Why do you think this type of preservation is found in this one stratigraphic unit.

v. Which part of the reef were these fossils found? Back reef, reef, fore reef or basin? _____

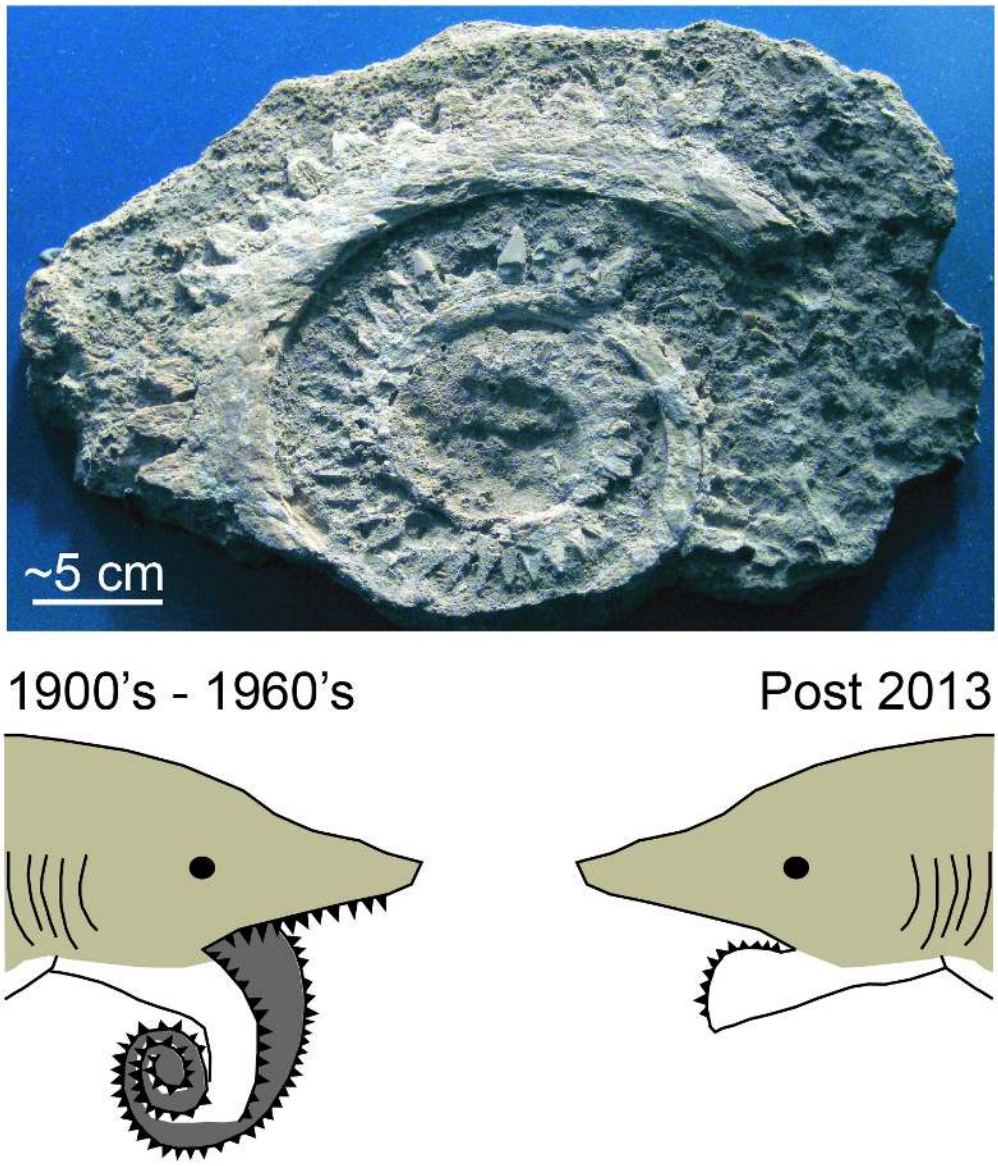


Figure 6.15 – Fossilized jaw with teeth of a Helicoprion ferri. The fish associated with this ~35 cm jaw is estimated to be 4 m (~12') long, but they could reach up to 10 m in length. Also shown are two possible reconstructions envisioned by paleontologists. The first image was common in the 1900s to 1960s. In 2013, CT imaging revealed a different reconstruction. Their primary food source was bottom-dwelling organisms and possibly ammonites. Image credit: Photo is from James St John CC BY 2.0, Reconstructions adapted by VB Sisson from Tapinila et al. 2013 CC-BY-NC-SA.

c. Elsewhere in the Skinner Ranch Formation of the Glass Mountains, fossils include this amazing saw-toothed whorl of teeth from an extinct shark-like fish known as Helicoprion.

i. Using Figure 6.15, what type of sediment is this fossil found in? _____

ii. What is this mode of preservation for this fossil? _____

iii. Where in the reef did Helicoprion live? Back reef, reef, fore reef, or basin? _____

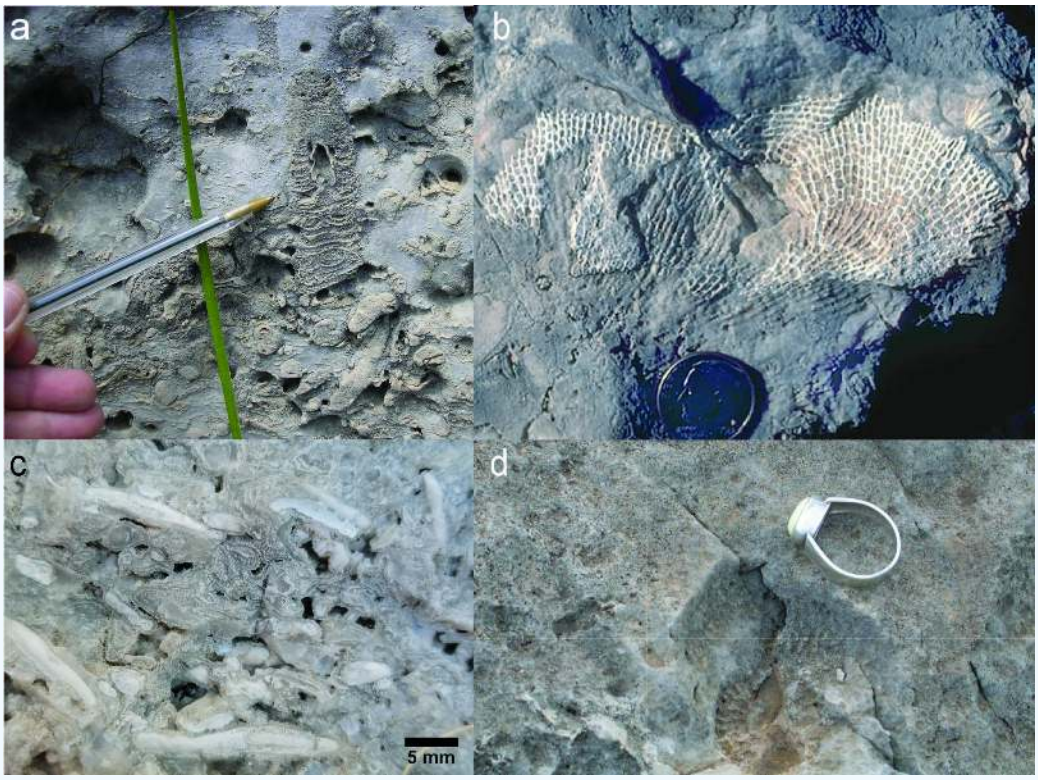


Figure 6.16 – Four fossils from El Capitan reef in Guadalupe Mountain National Park. a) Sponge (Porifera), b) Fennestrate bryozoa, c) Polydiexidina fusulinids with foraminifera, d) Fragment of an ammonite. Image credit: a) Jennifer Trout National Park Service public domain; b) Peter Scholle, used with permission; c) Image from Verydeadthings CC; d) Richard Langford UT El Paso, CC.

d. In the Guadalupe Mountains, you can find thick carbonate layers with many fossils, such as in Figure 6.16:

i. What is the mineral? _____

ii. What is the mode of preservation for these fossils? Note, there could be more than one mode of preservation.

_____

iii. Were fluids involved in their preservation? If so, what was their composition?

iv. Why do you think this type of preservation is found in this portion of the reef?

v. Which part of the reef were these fossils found? Back reef, reef, fore reef or basin? _____

e. **Critical Thinking:** Summarize your observations about the modes of preservation in different parts of the Permian reef system. Can you explain why the preservation is the same or different around the ancient reef?

Additional Information

Exercise Contributions

Virginia Sisson and Daniel Hauptvogel

References

Casella, L.A., Griesshaber, E., Yin, X., Ziegler, A., Mavromatis, V., Müller, D., Ritter, A.-C., Hippler, D., HarperE.M/, Dietzel, M., Immenhauser, A., Schöne, B.R., Angiolini, L., and Schmahl, W.W., 2017, Biogeosciences, 14, 1461–1492, doi:10.5194/bg-14-1461-2017.

Cooper, G.A., and Grant, R.E., 1964, New Permian stratigraphic units in Glass Mountains, West Texas: *American Association of Petroleum Geologists Bulletin* 48: 1581-1588.

Cooper, G.A., and Grant, R.E. 1966. Permian rock units in the Glass Mountains, West Texas, In: Contributions to stratigraphy, 1966: *U.S. Geological Survey Bulletin* 1244-E: E1-E9.

Kerans, C., and Kempter, K., 2002, Hierarchical stratigraphic analysis of a carbonate platform, Permian of the Guadalupe Mountains: The University of Texas at Austin, Bureau of Economic Geology (American Association of Petroleum Geologists/Datapages Discovery Series No. 5), CD-ROM.

Norell, M.A., Weimann, J., Fabbri, M., Yu, C., Marsicano, C.A., Moore-Nall, A., Varricchio, D.J., Pol, D., and Zelinitsky, D.A., 2020, The first dinosaur egg was soft. Nature, 583, 406-410, Published online June 17, 2020. doi: 10.1038/s41586-020-2412-8

Olszewski, T.D. and Erwin, D.H. 2009. Change and stability in Permian brachiopod communities from western Texas. *Palaios* 24: 27-40.

Ritter, S., and Peterson, M., 2015, Interpreting Earth History: A Manual in Historical Geology, Eighth Edition, Waveland Press Inc., 291 pp.

Scholle, P.A., Goldstein, R.H., and Ulmer-Scholle, D.S., 2007, Classic Upper Paleozoic reefs and bioherms of west Texas and New Mexico: A field guide to the Guadalupe and Sacramento Mountains of west Texas and New Mexico. New Mexico Bureau of Geology and Mineral Resources Open File Report 504, 178 pp.

Tapanila, L., Pruitt, J., Pradel, A., Wilga, C.D., Ramsay, J.D., Schlader, R., and Didier, D.D., 2013, Jaws for a spiral-tooth whorl: CT images reveal novel adaptation and phylogeny in fossil *Helicoprion.* Biology Letters, 9, 20130057. http://dx.doi.org/10.1098/rsbl.2013.0057

Google Earth Locations

Click or Scan to View all Chapter 6 locations on Google Earth

This page titled 1.7: Fossil Preservation is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.8: Fossils

Learning Objectives

The goals of this chapter are to:

- Recognize specimens of the most common invertebrate fossils
- Classify the phyla, order, and/or class associated with common fossils
- Compare and contrast symmetry in fossil specimens

Chapter Notes: The main text and much of the imagery from this chapter comes from the Digital Atlas of Ancient Life (CC BY-NC-SA), which the Paleontological Research Institution manages. Exercises in this chapter will heavily rely on sketching, so be sure to review the best practices for sketching from Chapter 0.

7.1 Introduction

Life on Earth has been around for a very long time, at least 3.5 byrs, and organisms have continually evolved and become extinct during this time. Ever since the first fossil was found, paleontologists have studied them to help decipher Earth's history. Early Greek philosophers, such as Xenophanes (570-480 BC) and Herodotus (484-425 BC), recognized fossils as marine organisms. Since then, new discoveries are being found all the time; these change the way we tell Earth's stories. For several centuries, fossils were the only tool geoscientists had to date rocks. Now, fossils are used in a variety of ways. Some of these include determining the origins of life on Earth and possibly other planets, climate change, biodiversity, changes in evolution, massive and small extinctions, and understanding deep time. Paleontology involves science, art, and imagination; it inspires curiosity about ancient life and how the modern world evolved. Paleontology is important to geobiology and is an interdisciplinary bridge between these two fields.

While most paleontologists are paid professionals, there are a large number of citizen scientists who make important paleontological finds. Take the rock shop owner who showed Jack Horner a coffee can filled with tiny fossil bones. He realized that these were fossilized baby dinosaurs. When the two of them went out to the fossil location, Jack Horner discovered the first fossilized dinosaur eggs in the western hemisphere. So, you never know if you'll be the one to discover an interesting fossil that changes the way we think about the Earth.

Recently, paleontologists have embraced the virtual world and computer-aided visualization to look at the three-dimensional structures in fossils. From this, they can better look at the fossil's internal structure. Much like when your doctor needs to look at your organs in detail, paleontologists use computed tomography (CT) with multiple x-ray scans to look through a fossil.

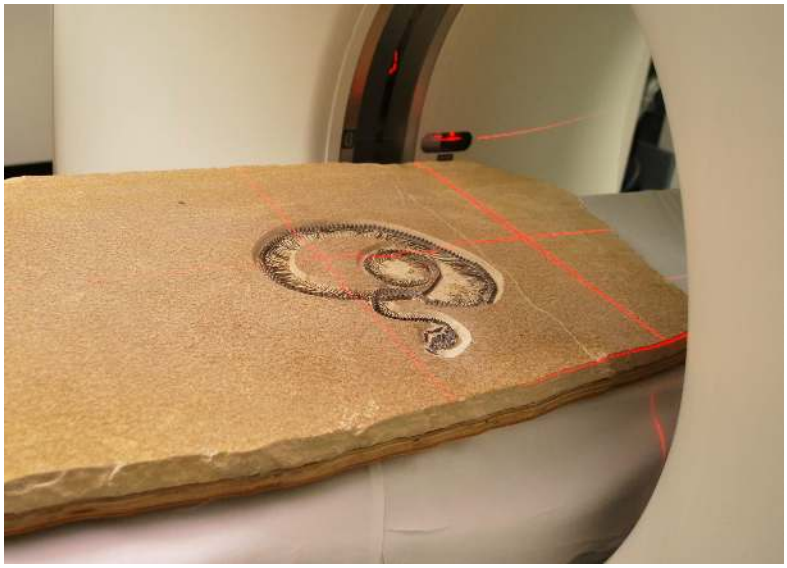


Figure 7.1 – Fossil snake CT scanning at Methodist Hospital in Houston, TX. Image credit: Houston Museum of Natural Science, CC BY-NC-SA.

Using CT images also helps with fossil preparation as paleontologists often spend hours carefully removing rock matrix from a fossil. For example, if you have seen trilobite specimens, these are often prepared by micro air blasting with talc to remove the host limestone. This can take from a few to tens of thousands of hours. CT is much faster at digitally removing the rock matrix (Figure 7.2).

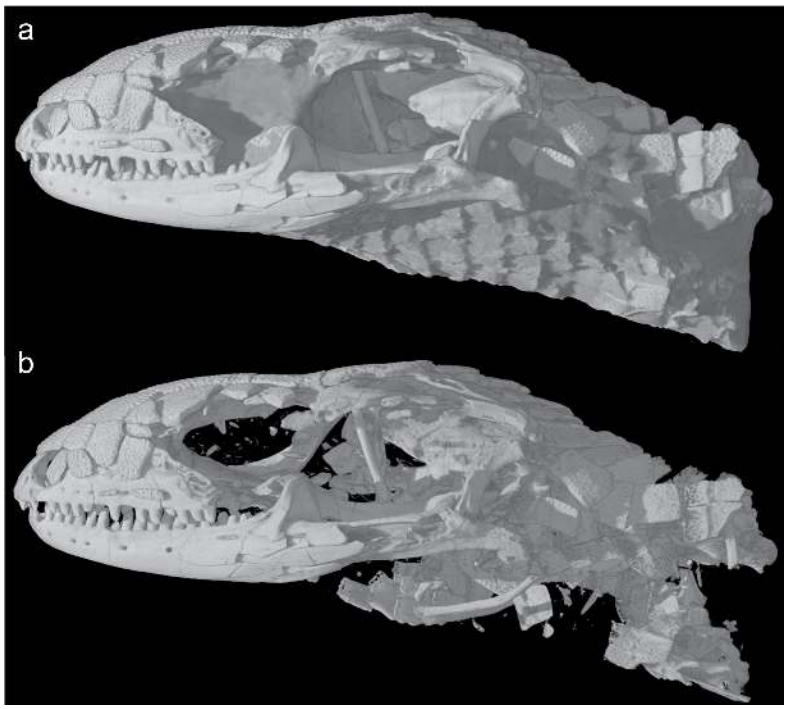


Figure 7.2 – CT images of Peltosaurus granulosus (AMNH FR 8138), a lizard that lived in the Oligocene (White River Fm., Wyoming) and was closely related to today's Texas alligator lizard. The first image is a rendering of the specimen with matrix in left lateral view, and the second image has the matrix digitally removed. This is an excellent example of digital fossil preparation via CT, which takes a fraction of the time that physical preparation takes and can be done without risk of damage to the specimen. The specimen is 56.4 mm long. Image credit: University of Texas High-Resolution X-ray CT Facility and the American Museum of Natural History (AMNH), CC-BY-NC.

Even with newer techniques, the basics of looking at fossils have remained constant for centuries. In fact, some dismiss paleontology as a dead science because simple observations that are the backbone of paleontology are not seen as a credible test you do in a laboratory or model made with advanced machine learning. Paleontology is like a rosetta stone and can help you decipher the tapestry of Earth's history and become a better scientist. If you remember the skills you have been using, such as sketching, data collection, and map interpretation, you'll do well studying fossils.

7.2 Taxonomy

Taxonomy sounds like a big word, but it's just the term used to describe how scientists classify things, which we've been doing throughout this lab manual (e.g. rock and minerals). The classification of fossils is one of the meeting points between geology and biology, and we follow the traditional biology taxonomy when classifying fossils (Figure 7.3). The major ranks are domain, kingdom, **phylum**, **class**, **order**, **family**, **genus**, and **species**. For the fossils in this lab manual, we will focus primarily on the phylum rank, with some organisms at the class and order rankings.

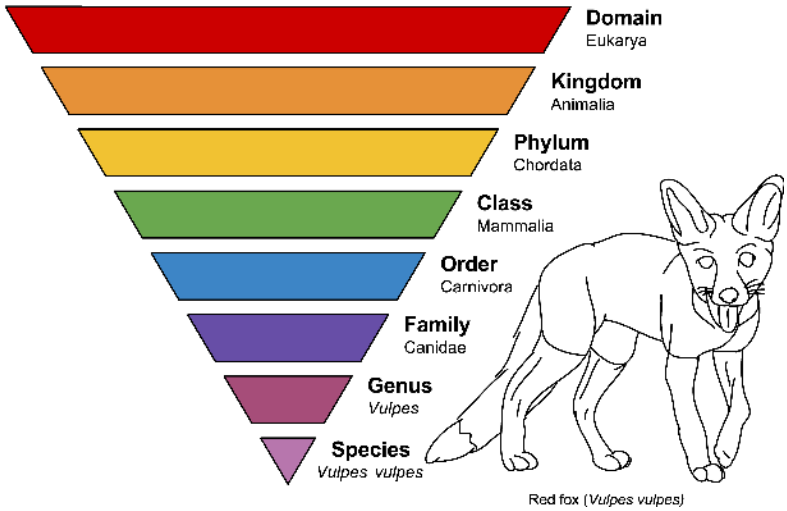


Figure 7.3 – The taxonomic ranks of organisms with the red fox as an example. Rankings start broad at the top with Domain and become more specific toward Species. Image credit: Annina Breen, CC BY-SA.

? Exercise 7.1 – Taxonomic Rankings

Using your phones, laptops, or tablets, look up the taxonomic ranking of the species in Table 7.1.

Table 7.1 – Worksheet for Exercise 7.1

Ranking	Human	Bornean orangutan	Dog	Rice
Domain				
Kingdom				
Phylum				
Class				
Order				
Family				
Genus				
Species	*sapiens*	*pygmaeus*	*lupus familiaris*	*sativa*

You can take an entire course dedicated to paleontology, so we will only cover the more common fossils in the following pages. These fossils have detailed anatomies that are used to differentiate class, order, family, genus, and species. In this chapter, we want you to be able to identify common fossils at a broad level. A detailed study is reserved for upper-level classes. Therefore, for most of these organisms, you will not see a detailed review of their anatomy.

Exercise 7.2 – Comparing Common Fossils

Your instructor will provide you with some common fossils. Create sketches of them and describe the differences that you can observe.

Sketch of first fossil:	Sketch of second fossil:

a. What are the similarities and differences between these fossils?

b. **Critical Thinking:** What evidence from these fossils suggests that they may be organisms that are now extinct?

c. How would you respond to someone who argues that all fossils that are thought to be extinct are actually still alive but haven't been "rediscovered" yet?

The geologic record is full of fossils, from dinosaurs to plants to fish and everything in between. **Invertebrate** animals from the marine environment are the most common branch of fossils you will find because of their abundance and higher probability of fossilization versus land-dwelling organisms, and they will be the focus of this chapter. Table 7.2 contains a list of the major marine invertebrate phyla we will cover, and in some cases, the class and order.

Table 7.2 – Phyla, classes, and orders of organisms to know for this chapter

Phylum	Class	Order	Common Names
Cnidaria	Anthozoa	Rugosa, Tabulata, Scleractinia	Rugose (horn) coral, tabulate coral, scleractinian coral (stony or hard coral)
Bryozoa			Bryozoan
Mollusca	Bivalvia, Cephalopoda, Gastropoda		Clam, squid, snail
Brachiopoda			Brachiopod
Arthropoda	Trilobita		Trilobite
Echinodermata	Echinoidea, Crinoidea, Blastoidea,		Sand dollar, crinoid, blastoid, starfish

7.3 Symmetry

A helpful characteristic in identifying fossils is the symmetry of the organism. Symmetry is an observable pattern in the external or internal structure of organisms that allows you to divide that organism into roughly equal parts that are mirror images of each other. For example, take the face of a human being which has a plane of symmetry down its center, an example of external symmetry. Internal features can also show symmetry. For example, the tubes in the human body, such as your arteries and veins, are cylindrical and have several planes of symmetry. Most multicellular organisms have some form of symmetry.

There are several types of symmetry in biology, but the main ones you will see are **bilateral**, **radial**, and **spherical** (Figure 7.4). Bilateral symmetry is a single plane that divides the organism into two equal, mirror-image halves. Radial symmetry has several subtypes, but they all describe symmetry lines drawn through a central point. The common types of radial symmetry for fossils in this chapter are 5-fold radial symmetry (pentamerous) and 6-fold radial symmetry (hexamerous). Spherical symmetry is when you can draw a line of symmetry through a central point of the organism from any direction so that no matter what the orientation of your symmetry line is, you will always have two equal, mirror-image halves.

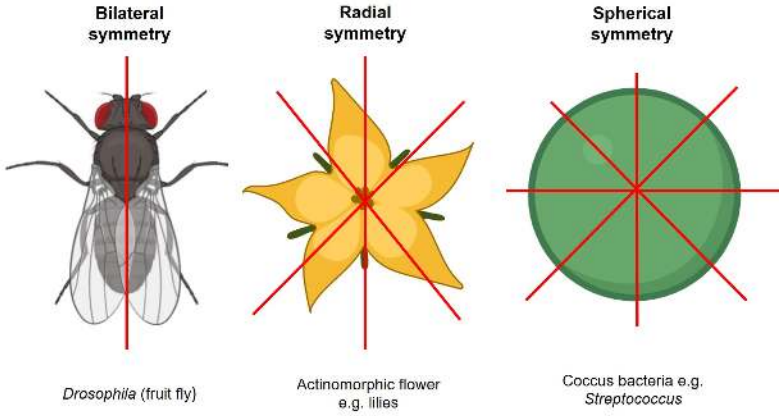


Figure 7.4 – Common types of symmetry. Image credit: Charl Hutchings, CC BY.

? Exercise 7.3 – Identifying Symmetry in Fossils

Let's get some practice identifying and describing the differences in symmetry.

a. Your instructor will provide you with a selection of fossils that exhibit bilateral, radial, spherical, or no symmetry. On a separate sheet of paper, create a sketch of each fossil that highlights its symmetry. Be sure to draw the line(s) of symmetry on your sketch and indicate which type of symmetry each fossil has.

b. **Critical Thinking:** Recently, Evans et al. (2020) described **Ediacaran** fossils of Ikaria wariootia (Figure 7.5) found in South Australia as the first organisms with bilateral symmetry. Ikaria have also been linked to a Nereites-type trace fossil. What would be the benefit of this type of symmetry for these organisms?



Figure 7. 5 – Artist's reconstruction of Ikaria wariootia forming a trace fossil trail. Ikaria are ~5 mm long. Image from Evans et al. (2020).

7.4 Phylum Cnidaria

Cnidaria is a phylum of marine organisms that includes over 11,000 species, including jellyfish, sea anemones, and coral; most have radial symmetry. The soft bodies of jellyfish and sea anemones are rarely preserved, whereas the hard structures of corals are quite commonly preserved as fossils. In the geologic record, three orders of coral are the most abundant: rugose, tabulate, and scleractinian corals. Corals are carnivores, catching **zooplankton** with their tentacles and pulling them into their mouths. Some corals also have a partnership with green algae that live within the coral. As the algae perform photosynthesis, some of the energy they create is transferred to the coral.

Order Rugosa

Rugose corals (Figure 7.6) are an extinct order of coral that originated in the **Ordovician** and went extinct at the end of the Permian. Members of Rugosa are sometimes called horn corals because solitary forms frequently have the shape of a bull's horn (if you like the Harry Potter movies, some say they look like the sorting hat). Rugose corals do have a less common, colonial form that does not have this shape.



Figure 7.6 – Two solitary rugose corals in a slab of Ordovician limestone from near Cincinnati, Ohio. Note the similarity of the left specimen's shape to that of a bull's horn. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

Rugose corals reached their peak diversity during the **Devonian** period when colonial forms were important reef builders (Figure 7.7). They went extinct during the end-Permian mass extinction event. Figure 7.7 is the first of many diversity curves you will see in this chapter. Diversity curves allow paleontologists to graph how many different kinds of fossils existed on earth during different geological time intervals. They are especially important for telling us (a) when a group of animals first evolved on earth, (b) when that group diversified (increased in diversity) and became common on earth, and (c) when that group went extinct.

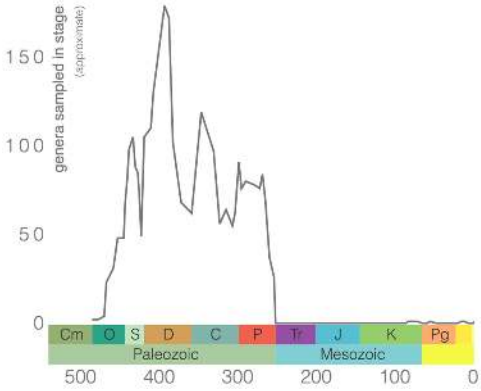


Figure 7.7 – Diversity of Rugosa genera. Image credit: Paleobiology Database, CC BY.

Rugose corals may be either solitary or colonial (Figure 7.8). A solitary coral individual is called a corallum, while an individual within a colony is called a corallite. Rugose corals made their skeletons from calcite; this is a significant difference relative to other corals that make their skeletons out of aragonite, which is more resistant to stress.

The outer part of the corallum (or corallite) is called the theca; think of it as the skeletal wall (Figure 7.8). The theca may, in turn, be covered by an outermost skeletal sheath called the epitheca. Growth lines are often apparent on the epitheca; these are also called rugae ("ruga" is Latin for wrinkled), which gives this group of corals their scientific name (thus, rugose corals are the "wrinkled corals"). Finally, the top of the corallum (or corallite) is called the calice, and it is the portion of the coral occupied by the living organism, called a polyp.

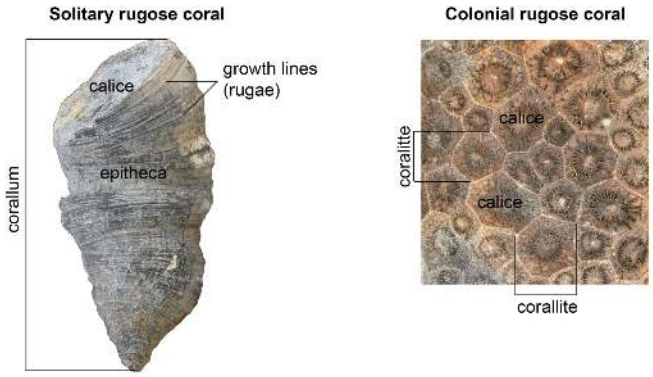


Figure 7.8 – Major features of solitary and colonial rugose corals; labeled features include a corallum, corallites, epitheca, calices, and growth lines. Left: Heliophyllum halli from the Middle Devonian Moscow Fm. of Erie County, New York (PRI 70755). Right: Acrocyathus floriformis from the Mississippian St. Louis Limestone of Monroe County, Illinois (PRI 70756). Both specimens are from the collections of the Paleontological Research Institution, Ithaca, New York. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

The surface of the calice is covered with radiating, vertical structures called **septa** (singular = septum) that resemble the spokes of a bicycle wheel (Figure 7.9). Septa sometimes extend through the theca, forming vertical lines called **costae** (singular = costa). The septa radiate outwards from a central pillar-like structure called the columella. In rugose corals, the septa are added during growth in a manner that ultimately divides them into four quadrants. Spaces between the four quadrants are called fossula. However, it is important to note that fossula are not readily visible in many specimens, especially when they are poorly preserved.

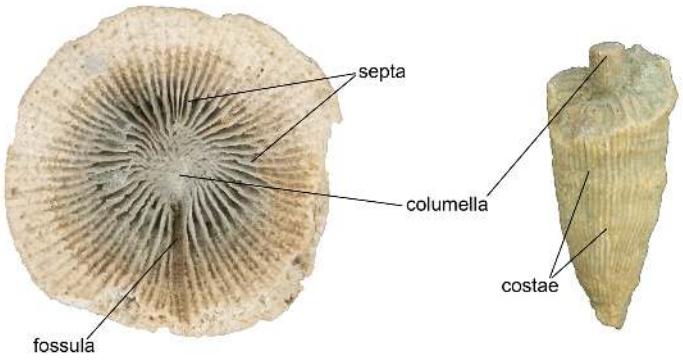


Figure 7.9 – Important features of rugose corals, including a fossula, septa, the columella, and costae. Left: solitary rugose coral Heliophyllum canadense from the Devonian Onondaga Limestone of Mendon, New York (PRI 76809). Right: solitary rugose coral Lophophyllidium proliferum from the Pennsylvanian Graham Formation of Coleman County, Texas (PRI 76802). Both specimens are from the collections of the Paleontological Research Institution, Ithaca, New York. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

As a coral polyp grows upwards, it develops horizontal partitions called tabulae (Figure 7.10).

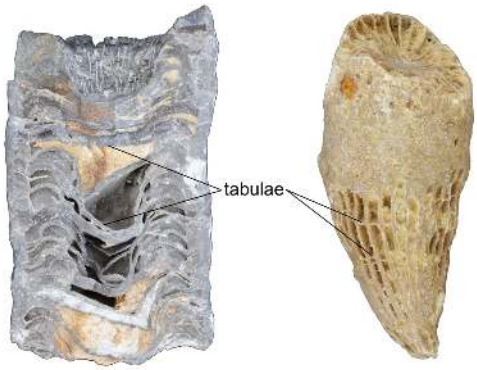


Figure 7.10 – Tabulae observed in hand samples of two solitary rugose corals. Left: Siphonophrentis halli from the Devonian Ludlowville Fm. of Skaneateles Lake, New York (PRI 76806). Right: Amplexizaphrentis pellansis from the Mississippian Pella Beds of Pella, Iowa (most epitheca is eroded away) (PRI 76803). Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

3-D Model 7.1 – Rugose Coral

This is a model of the rugose coral *Heliophyllum halli* from the Middle Devonian from Moscow. The growth lines and costae are clearly visible on the epitheca. Some septa are the only visible features on the calice.



Heliophyllum halli (PRI 70755) by **Digital Atlas of Ancient Life** on **Sketchfab**

More 3-D models of rugose corals can be found at the Digital Atlas of Ancient Life.

Order Tabulata

Tabulate corals originated in the Early Ordovician period and went extinct at the end of the Permian period. All tabulate corals were colonial, and some species were important reef makers during the **Silurian** and Devonian periods. Tabulate corals constructed their skeletons primarily of calcite. Some tabulate corals look superficially like honeycombs (e.g., *Favosites; Figure 7.11a*), while others look like chain links (e.g., *Halysites; Figure 7.11b*) or collections of narrow tubes (e.g., *Syringopora; Figure 7.11c*). Others can be encrusted upon other marine invertebrates (including other corals).

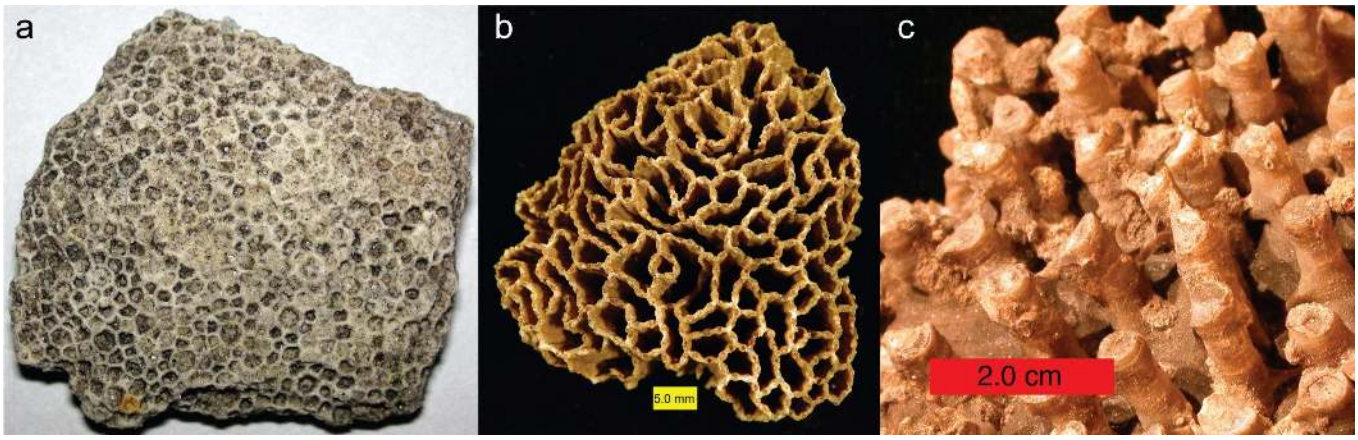


Figure 7.11 – Examples of three genera of tabulate coral. a) Favosites in dolostone from the Silurian of Michigan. Favosites have a distinctive honeycomb shape. b) Halysites corals look like chain links. c) Syringopora corals look like narrow tubes, from the Lower Carboniferous Boone Limestone near Hiwasse, Arkansas. Image credit: a) James St. John, CC BY; b) Wikimedia user Wilson44691, Public domain; c) Wikimedia user Wilson44691, Public domain.

The following video from the Paleontological Research Institute gives a great introduction to tabulate corals.



According to the Paleobiology Database, there are 58 families of tabulate corals, 376 genera, and 511 species. As demonstrated by the genus-level plot of their diversity through time (Figure 7.12), tabulate corals suffered badly during the Late Devonian extinction event and never again reclaimed their former levels of diversity. The group went extinct at the end of the Permian period.

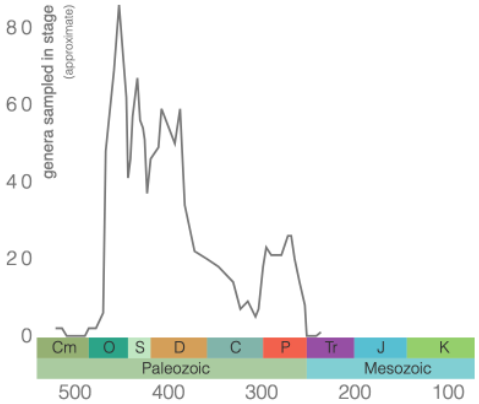


Figure 7.12 – Diversity of tabulate corals. Image credit: Paleobiology Database, CC BY.

A defining feature of most tabulate corals are structures called tabulae, which give them their name. Tabulae (singular, tabula; from the Latin for board or tablet) are horizontal plates that span across individual corallites (Figure 7.13). They are deposited by polyps as they grow, separating the living animal from the space(s) occupied earlier in life. Remarkably, we know something about the soft

polyps of tabulate corals due to the discovery of calcified polyps in specimens of Silurian *Favosites* from the Jupiter Formation of Quebec, Canada. This discovery was reported by Copper (1985), who reported that individual corallites typically had 12 tentacles, though some had 11 or 13. The discovery of these polyps also confirmed that Tabulata are indeed Cnidarians, rejecting the hypothesis of some earlier workers that this group belonged with the sponges.

Unlike rugose and scleractinian corals, most tabulate corals did not have septa. Therefore, as a general rule, identifying whether or not a specimen of colonial Paleozoic coral has septa is a good indication of whether it is a rugose coral (septa always present) or a tabulate coral (septa usually absent).

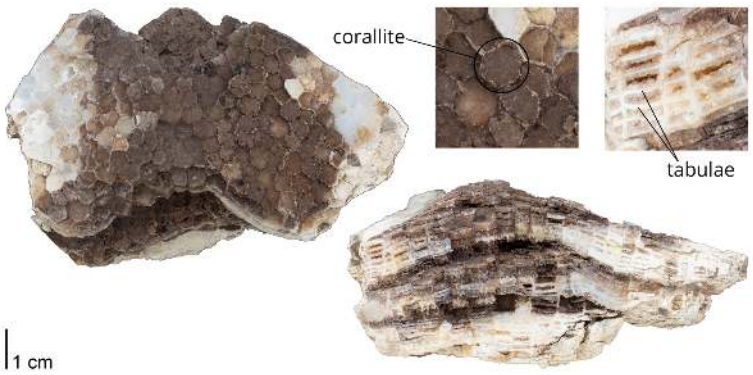
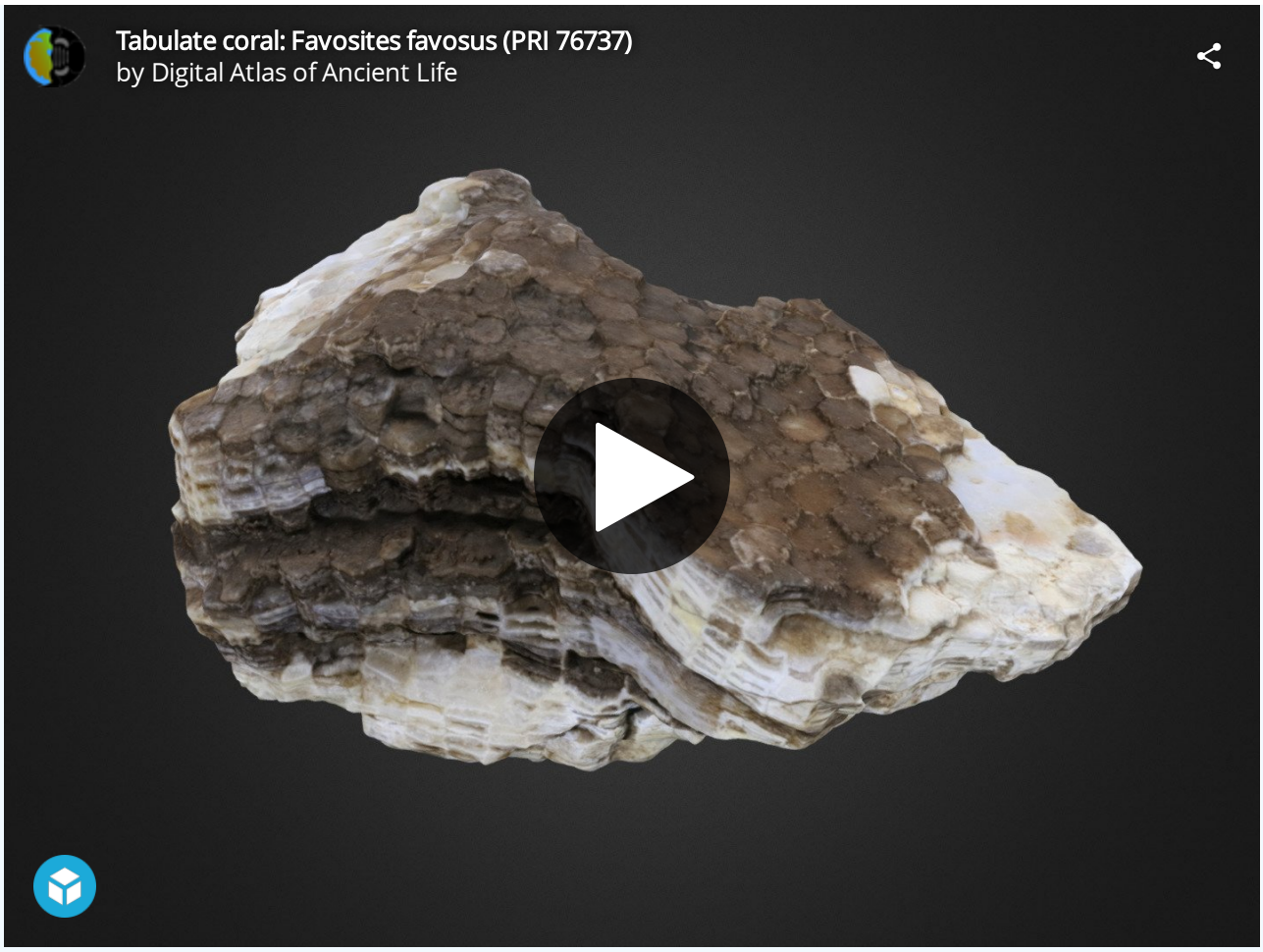


Figure 7.13 – Corallites and tabulae identified on a specimen of Favosites favosus. Note the absence of septa. The specimen is from the collections of the Paleontological Research Institution, Ithaca, New York. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

3-D Model 7.2 – Tabulate Corals

This is a model of the tabulate coral *Favosites favosus* from the Silurian of Delaware County, Iowa (PRI 76737). It is the same one pictured in Figure 7.12. The length of the specimen is approximately 10 cm. The specimen is from the collections of the Paleontological Research Institution, Ithaca, New York. The side view shows the tabulae, and the top view shows the corallites.



Tabulate coral: Favosites favosus (PRI 76737) by **Digital Atlas of Ancient Life** on **Sketchfab**

More 3-D models of tabulate corals can be found at the Digital Atlas of Ancient Life.

Order Scleractinia

The order Scleractinia includes the "true corals" or "stony corals," with about 1,500 living species today. Scleractinians first appeared in the early Middle Triassic (Figure 7.14) and have been the dominant reef-building organisms over the past 240 million years.

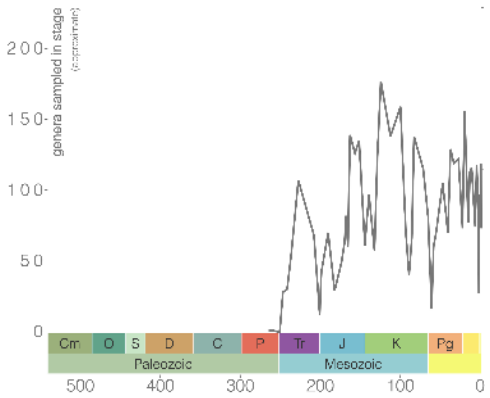


Figure 7.14 – Diversity of Scleractinia genera. Image credit: Paleobiology Database, CC BY.

Scleractinian corals may be either solitary or colonial in form and always have skeletons composed of aragonite. We are going to focus on the colonial forms of Scleractinia corals. An entire colonial coral colony is a corallum; the space occupied by a single

polyp within the colony is called a corallite (Figure 7.15). Individual corallites have their own radial septa, which often attach to a centralized pillar called the columella; all familiar terms from rugose and tabulate corals.

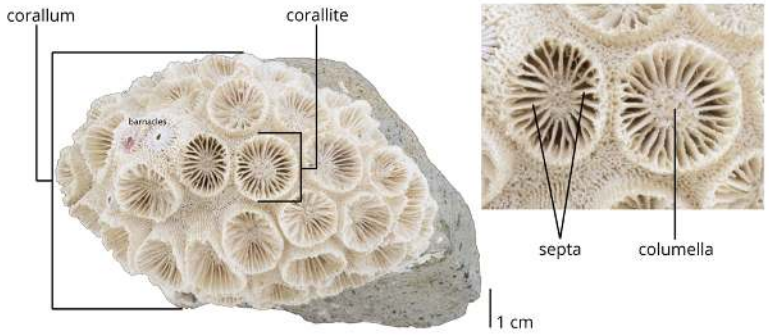


Figure 7.15 – Fossil specimen of the colonial scleractinian coral Astrangia sp. showing the corallites, septa, and columella. The specimen is from the Late Pleistocene Ft. Thompson Fm. of Hillsborough County, Florida (PRI 76863). The specimen is from the research collections of the Paleontological Research Institution, Ithaca, New York. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

The skeletons of colonial corals exhibit a much greater diversity of forms than those of solitary species. Often, their growth forms are dependent upon the habitats in which they live. For example, robust, rounded colonies are often favored in high-energy habitats with lots of wave action (Figure 7.16a), while delicate branching forms are usually associated with quieter environments (Figure 7.16b).

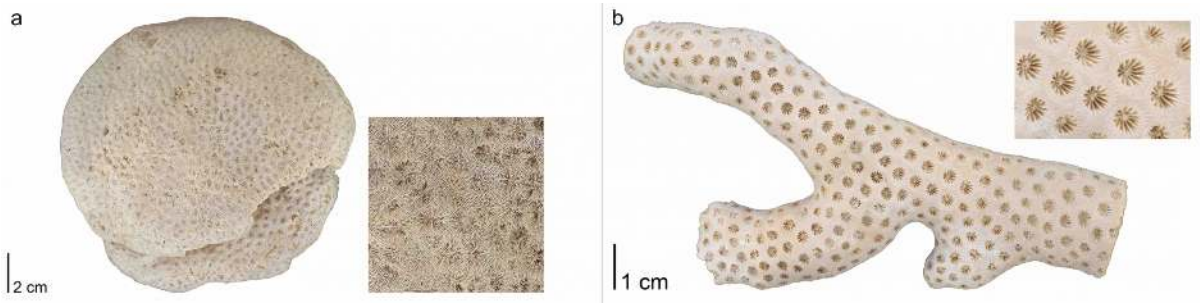


Figure 7.16 – Two types of Scleractinia corals. a) Stacked fossil specimens of the colonial scleractinian coral Siderastrea pliocenica from the Plio-Pleistocene of Lee County, Florida (PRI 76859). The specimen is from the research collections of the Paleontological Research Institution, Ithaca, New York. b) Fossil specimen of the colonial scleractinian coral Oculina sarasotana from the Plio-Pleistocene of Lee County, Florida (PRI 76894). The specimen is from the research collections of the Paleontological Research Institution, Ithaca, New York. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

7.5 Phylum Bryozoa

Bryozoans are filter-feeding invertebrates found in freshwater and marine habitats, where they are often easy to miss because of their small size (Figure 7.17). In almost all species, tiny (<1 mm diameter) bryozoan individuals, called zooids, live together as a colony that often encrusts surfaces, grows branching structures, or, in freshwater species, forms a gelatinous blob. They have bilateral symmetry. Despite their small size, marine bryozoans are abundant in many fossil assemblages thanks to the preservation of their hard calcium carbonate skeletons. Bryozoans first appeared in the Ordovician and are still present in oceans today (Figure 7.18). They were greatly impacted by several mass extinctions with their lowest diversity occurring during the Mesozoic. More than 17,800 species of fossil bryozoans have been described, and more than 6,000 living species are known.



Figure 7.17 – A variety of bryozoan fossils from an Ordovician oil shale from Estonia. Image credit: Mark A. Wilson, Public Domain.

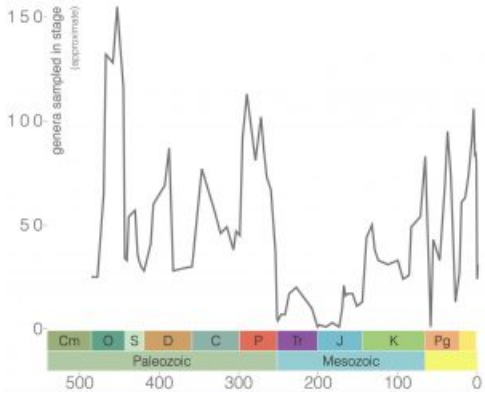


Figure 7.18 – Diversity of Bryozoa genera. Image credit: Paleobiology Database, CC BY.

Bryozoan colonies have highly variable forms (Figure 7.19), from gelatinous blobs to upright branching structures and sheet-like encrusters, but the general morphology of a **zooid** is similar across the classes. Zooids can take several forms, but the most common forms in each class are autozooids, which function in feeding the colony and excreting waste. Branching bryozoans may look similar to branching corals, but the zooids in bryozoa do not have septa or a columella as corallites do in corals.

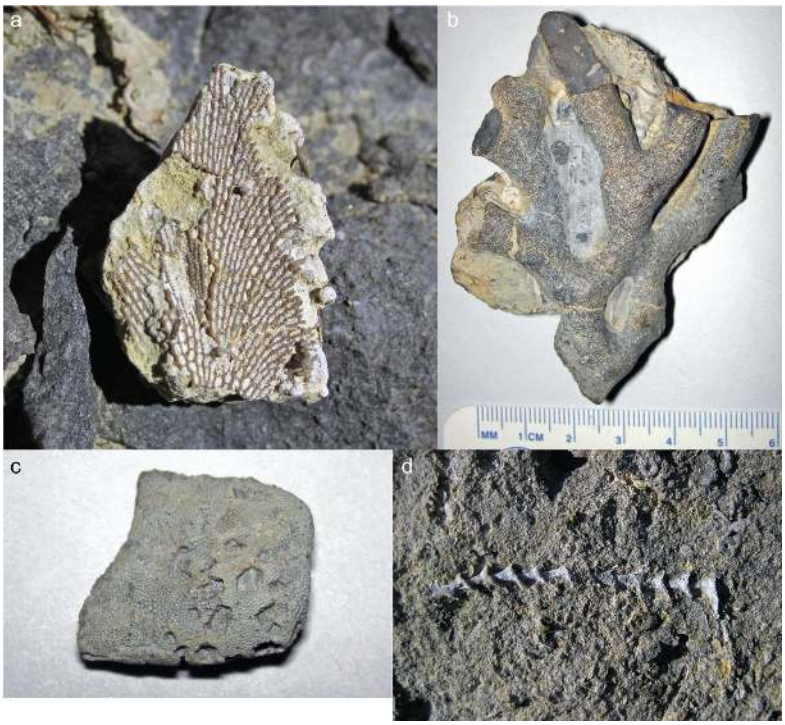


Figure 7.19 – Common bryozoan fossils. a) fenestrate; b) branching; c) trepostome; d) archimedes. Image credit: compiled from James St. John, CC BY.

7.6 Phylum Mollusca

Mollusks are a phylum of marine invertebrates that comprise about 23% of all marine organisms. There are several classes of mollusks, but we will focus on gastropods, cephalopods, and bivalves. All have bilateral symmetry, but it's more complicated for gastropods.

Class Gastropoda

Gastropods are one of the most evolutionarily successful groups of animals; you may commonly know them as snails and slugs. They occupy the world's oceans, freshwater lakes and streams, and terrestrial ecosystems, including many backyards. Some are algae-eating herbivores, while others are venomous hunters of fish. Their strong, single-valved shells (Figure 7.20) have left behind a rich **Cambrian** to Recent fossil record and are the focus of many paleobiological studies (Figure 7.21). These shells are primarily made of calcium carbonate. Gastropods have many different shell shapes, and some with no shell, but one of the defining characteristics of gastropods is the rotation of their body during their development, a process called torsion. Torsion does not refer to the coiling shells you are familiar with and only relates to the gastropod's coiled body. Before rotation, gastropods exhibit bilateral symmetry, but they lose that symmetry as they mature.



Figure 7.20 – A variety of gastropod shell shapes. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

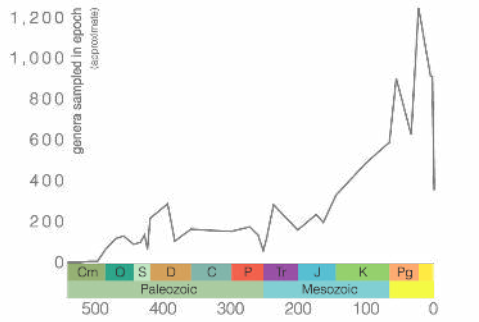


Figure 7.21 – Diversity of Gastropoda genera. Image credit: Paleobiology Database, CC BY.

Class Cephalopoda

Cephalopods are marine organisms with bilateral body symmetry, a prominent head, and a set of tentacles. You may be familiar with some of them, like squids and octopuses. While most modern cephalopods are completely soft-bodied or have only thin internal shells, their ancient shelled cousins left behind a detailed fossil record with a remarkable diversity of shell shapes. Cephalopods became abundant during the Ordovician Period, and many went extinct by the end of the Mesozoic Era with the dinosaurs (Figure 7.22).

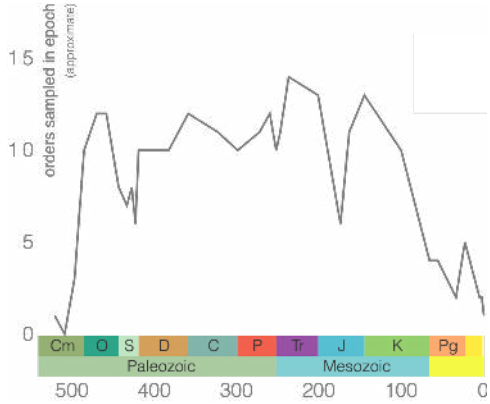


Figure 7.22 – Diversity of Cephalopoda orders. Image credit: Paleobiology Database, CC BY.

One of the most well-known index fossils for cephalopods is the belemnite (Figure 7.23). The belemnite is an extinct order of mollusk that only lived during the Mesozoic. It had a characteristic elongated, cone-shaped shell called a guard (Figure 7.23b). The guard is thought to have been a counterbalance that allowed the belemnite to move horizontally through the water.



Figure 7.23 – Belemnite fossils. a) The entire organism, including the guard and carbonized and preserved soft parts. The cone-shape on the left side is the guard. Please note it is extremely rare to find any fossilization of the soft parts. b) Belemnite guard. Image credit: a) Wikimedia user Ghedoghedo, CC BY-SA; b) California Academy of Sciences, CC BY-NC-ND.

Other well-known cephalopod index fossils are from the subclass Ammonoidea, commonly referred to as ammonites (Figure 7.24). They are extinct mollusks that lived from the Devonian to the end of the Cretaceous (Figure 7.25). These are ideal for

biostratigraphy as there are over 8,000 species of ammonoids, and they occur over a large geographic range.



Figure 7.24 – Examples of different shapes of ammonoid shells. Image credit: Digital Atlas of Ancient Life, Jonathan R. Hendricks, CC BY-NC-SA.

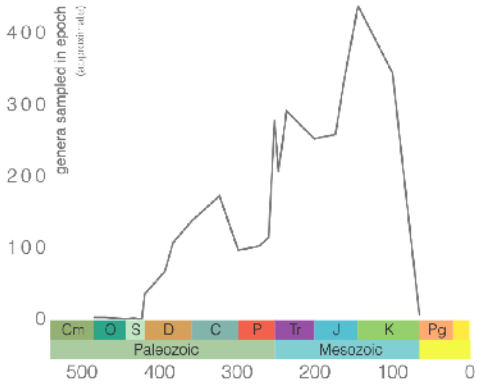


Figure 7.25 – Diversity of Ammonoidea genera. Image credit: Paleobiology Database, CC BY.

One of the ways to distinguish orders of ammonoids is the suture pattern of their shells (Figure 7.26). Ammonoid sutures fall into three main groups: goniatites, ceratites, and ammonites. As you go from goniatites to ceratites to ammonites, the suture patterns become more complex. Goniatitic sutures do not have subdivided saddles or lobes. Saddles are convex toward the opening of the shell, and lobes are convex in the other direction. Ceratitic sutures have subdivided lobes but undivided saddles. Finally, both the saddles and lobes of ammonitic sutures are subdivided, sometimes in an amazingly complex fashion.

One of the oft-quoted principles of evolutionary theory is, "ontogeny recapitulates phylogeny." This a historical hypothesis from Ernst Haeckel that states the development of the embryo of an animal, from fertilization to gestation or hatching (ontogeny), goes through stages resembling or representing successive adult stages (recapitulates) in the evolution (phylogeny) of the animal's remote ancestors. It means that as an animal develops, different stages of growth may give you hints of the evolution that their ancestors went through. Modern biology is full of examples of this theory.

Well, for the fossil record, this theory is hard to prove because of incomplete preservation. One of the best examples in the fossil record that supports this quote is the suture patterns in ammonite shells. These sutures form at the intersection of the shell wall and the interior septa (walls dividing the interior cavity). These patterns started as mere wavy lines in the Cambrian and became more complex through time. Through time, the sutures acquired additional saddles and lobes. Later, paleontologists recognized that within some species, such as a Permian ammonoid (*Perrinites*), the sutures are simple patterns in young animals and get more complex as the animal gets older. Thus, the suture patterns in the young animals resemble their ancestors.

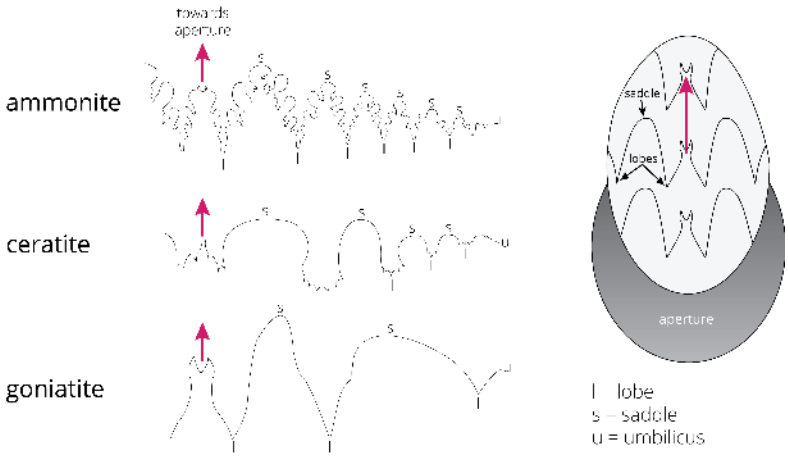


Figure 7.26 – Examples of ammonoid order sutures: goniatites, ceratites, and ammonites. Image credit: Digital Atlas of Ancient Life, Jonathan R. Hendricks, CC BY-NC-SA.

? Exercise 7.4 – Stratigraphic Analysis and Fossil Evolution

On a class field trip to the Guadalupe Mountains in west Texas (Exercise 6.4), you are taken to a stratigraphic section that goes through the Carboniferous to Permian up to the Capitanian extinction, which was an extinction event that occurred in the late Permian about 260 Ma. Your field trip leader has given you a guide to some of the important ammonite species used for relative age dating in this area. In addition, she has given you the patterns for several ammonite species. You prefer looking at fossils compared to stratigraphic sections and have found two fossils just randomly on the ground. Can you place these on the stratigraphic column?

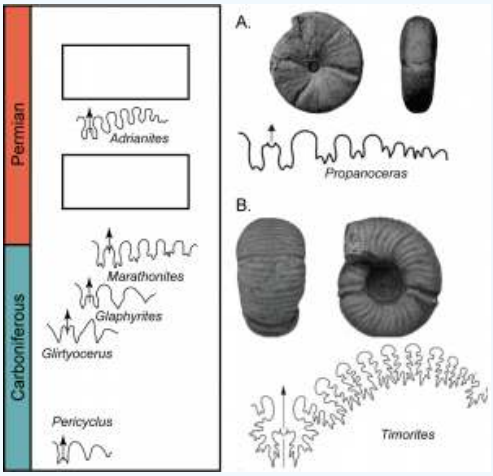


Figure 7.27 – Suture patterns for Carboniferous to Permian ammonoids, specifically for Goniatitida (goniatites). The arrow bisects the umbilicus and points towards the suture of the ammonoid. Image Credit: VB Sisson adapted the stratigraphic column from Leonova (2018) with unknown ammonites from Miller and Furnish (1940) CC.

a. Describe how the sutures of species in this stratigraphic column evolve through time.

b. Based on the evolution of the suture patterns, place these two unknown fossils in the column. You can sketch the sutures in the blank boxes.

c. Explain your answer.

Class Bivalvia

Bivalves refer to a diverse Mollusca class that typically has bilateral symmetry where the upper shell and inner parts of the organism are a mirror image of the bottom half. Clams, oysters, and mussels belong to this class. Their shells are made of calcium carbonate and typically have growth lines (Figure 7.28). Bivalves first appeared in the fossil record in the Cambrian and are still around today (Figure 7.29).

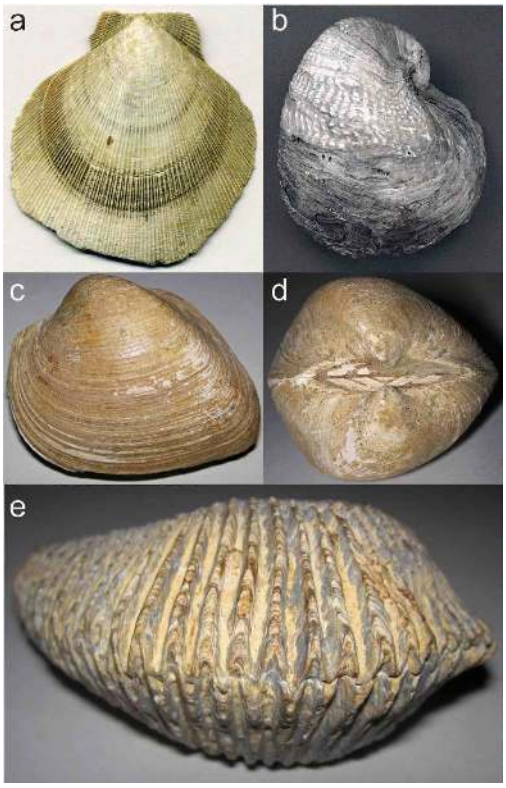


Figure 7.28 – Examples of bivalves. a) Placopecten clintonius (a type of scallop) from the Pliocene of North Carolina; b) Exogyra costata (a type of oyster) from the Cretaceous of South Carolina; c and d) two views of Idonearca vulgaris (a type of clam) from the Cretaceous of Tennessee; e) Rastellum carinatum (a type of oyster) from the Cretaceous of Texas. Image credit: all images from James St. John, CC BY.

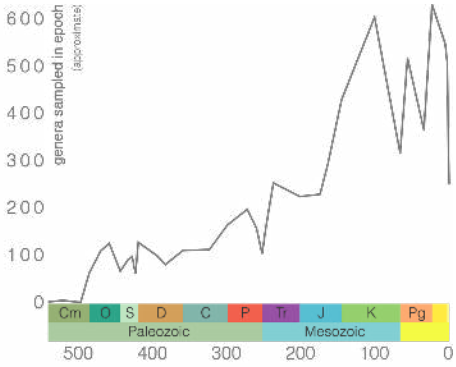


Figure 7.29 – Diversity of Bivalvia genera. Image credit: Paleobiology Database, CC BY.

7.7 Phylum Brachiopoda

Brachiopods are shelled, filter-feeding marine organisms (Figure 7.30) that inhabit the seafloor and come in various shapes and sizes. They have been around since the Cambrian with incredible diversity during the Paleozoic Era (Figure 7.31). Brachiopods are still around today, but their diversity is greatly diminished.



Figure 7.30 – Examples of brachiopods. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

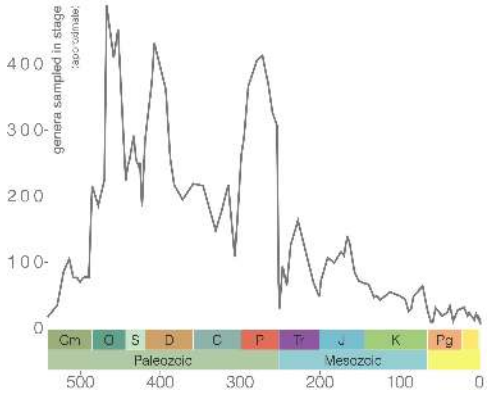


Figure 7.31 – Diversity of Brachiopoda genera. Image credit: Paleobiology Database, CC BY.

Superficially, brachiopods may look like bivalves, but the two are not related. One of the biggest differences between brachiopods and bivalves lies in their symmetry. Both have bilateral symmetry, but the plane of symmetry in brachiopods is vertical rather than horizontal (Figure 7.32). This means that the left half of a brachiopod is a mirror image to the right half. In bivalves, the plane of symmetry is horizontal, and the upper half is a mirror image of the lower half.

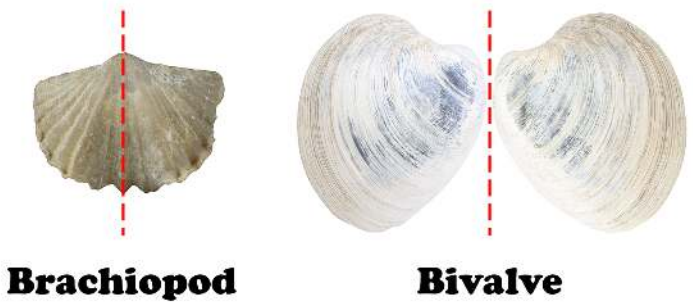


Figure 7.32 – Differences in symmetries between a brachiopod (left) and a bivalve (right). Image credit: Jaleigh Q. Pier, CC BY-SA.

Brachiopod shells have two valves that are distinct in both size and shape (Figure 7.33). The brachial valve is usually the smaller of the two valves and has a ridge, or fold, down the middle of the valve. The pedicle valve is usually larger than the brachial valve and has a valley down the middle. It also has a hole through which the pedicle passes. The pedicle is a fleshy, stalk-like feature which some groups use to attach themselves to hard rocky seafloor. It is rarely preserved, but brachiopod shells will often have a pedicle opening preserved along the hinge-line that varies in shape from rounded to triangular.

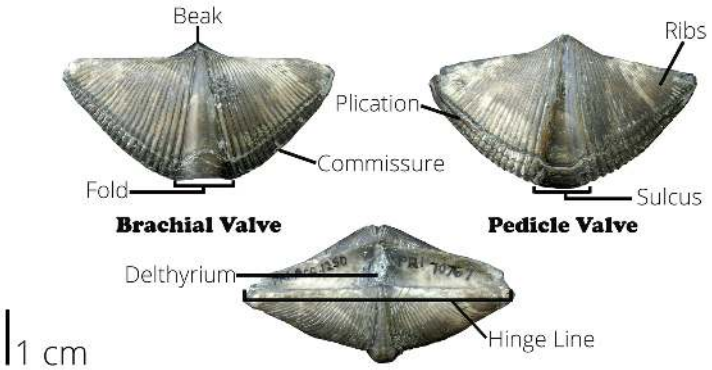


Figure 7.33 – Brachiopod morphology. Image credit: Jaleigh Q. Pier, CC BY-SA.

7.8 Phylum Arthropoda

Arthropods are an extremely diverse and abundant phylum of animals. They include organisms such as spiders, scorpions, crabs, barnacles, and insects. Unfortunately, most of these are not abundant in the fossil record because of poor preservation, but one class of arthropods does stand out in the fossil record, the trilobite.

Class Trilobita

Trilobites are among the most well-known fossils, thanks largely to their abundance, diversity, and broad distribution during the Paleozoic (Figure 7.34). These emblematic arthropods first appeared in the fossil record 521 million years ago and survived until the end-Permian extinction approximately 250 million years ago (Figure 7.35). Even when they first appeared, trilobites were diverse and widespread, suggesting a long history before the first fossils, likely extending as far back as 700 Ma. During the Cambrian, trilobites were a dominant marine ecosystem component, but many of the Cambrian trilobite species died out during the extinction at the end of the Ordovician. Though the class did survive this extinction, their diversity never matched their earlier history. Because they evolved rapidly and were relatively widespread, trilobite species are often used to provide relative ages of the rocks in which they are found.



Figure 7.34 – Trilobite fossils. Image credit: Digital Atlas of Ancient Life, CC BY-NC-SA.

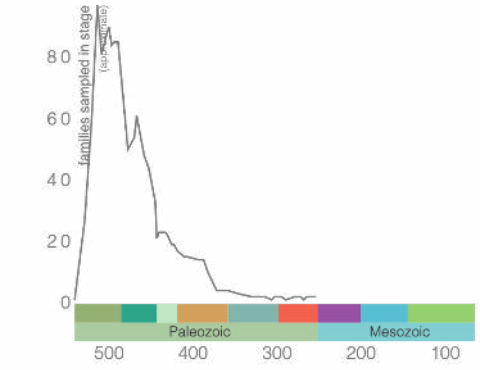


Figure 7.35 – Diversity of Trilobite families. Image credit: Paleobiology Database, CC BY.

Trilobites get their name because their bodies exhibit three distinct, longitudinal sections, and they also have three segments from "head to toe" (Figure 7.36) and have bilateral symmetry. They fed in several ways, including moving across the ocean floor as predators, scavengers, or filter feeders, and some swam to feed on plankton. They ranged in size up to 45 centimeters long (about 1.5 feet).

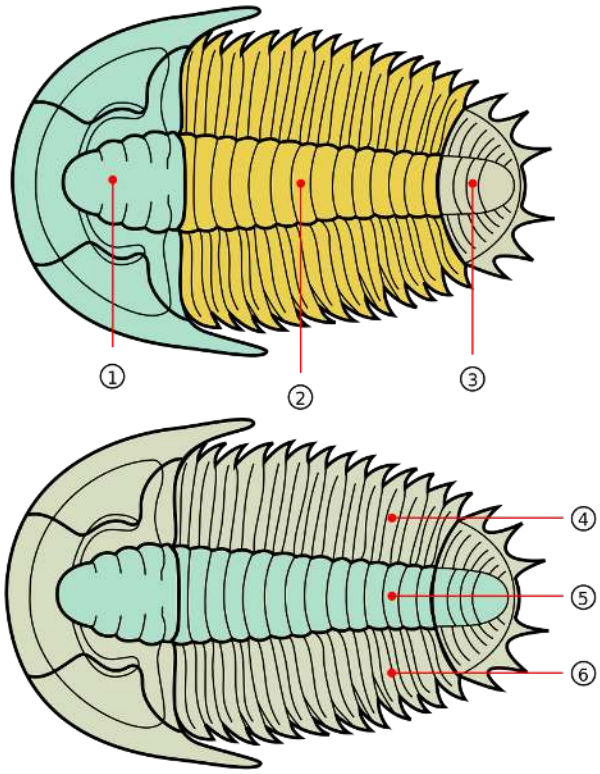


Figure 7.36 – Trilobites have three major body sections, from anterior to posterior, called the cephalon (1), thorax (2), and pygidium (3). The body can also be divided into three longitudinal lobes, called the right pleural lobe (4), axial lobe (5), and left pleural lobe (6). Image credit: Sam Gon III, CC0 Public Domain.

7.9 Phylum Echinodermata

Echinoderms represent the largest marine animal phylum and include starfish, sea cucumbers, sand dollars, blastoids, and crinoids. They first appeared in the fossil record in the Cambrian and are still around today. One of the key features of this group is five-part, radial symmetry (Figure 7.37). There are many classes of echinoderms, and we will focus on Echinoidea, Crinoidea, and Blastoidea.

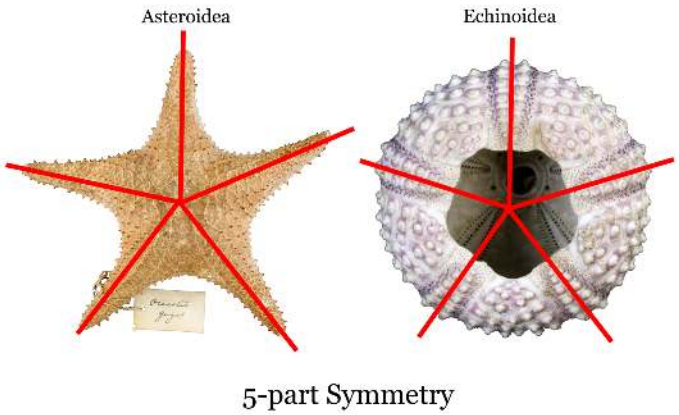


Figure 7.37 – Five-part, radial symmetry of two echinoderms. Image credit: Jaleigh Q. Pier, CC BY-SA.

Class Echinoidea

Echinoids are the most diverse echinoderm class (Figure 7.38). They include spiny-looking sea urchins (**regular echinoids**) and organisms commonly known as sand dollars (**irregular echinoids**). Regular echinoids live on the ocean floor and can be herbivores (eating kelp and algae) or carnivores (eating bryozoans). Irregular echinoids live in the sediment on the ocean floor and eat tiny food particles in that sediment. All modern echinoids have a hard, calcareous, internal skeleton.

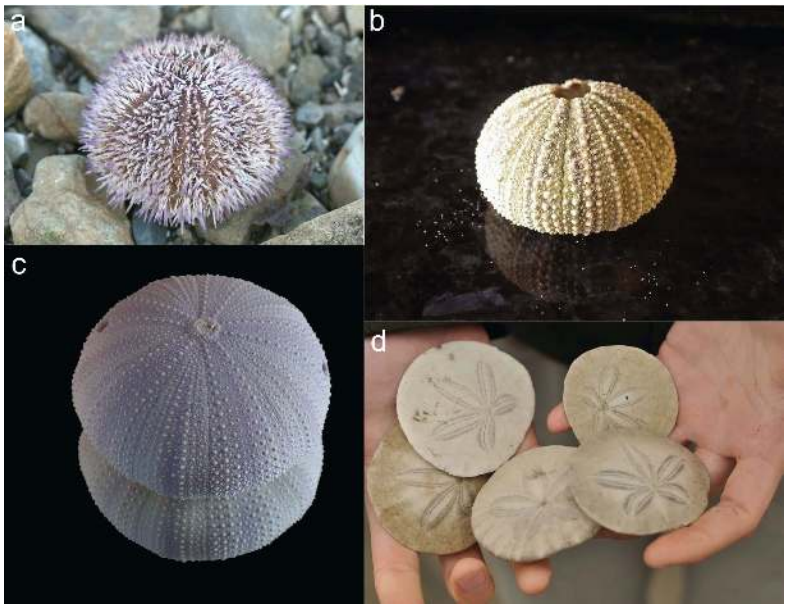


Figure 7.38 – Examples of Echinoidea. a) a living sea urchin; b) sea urchin fossil; c) sea urchin fossil from the Caribbean; d) sand dollars. Image credit: a) S. Rae, CC BY; b) Marian Garcia, CC BY-NC-ND; c) Tim Sackton, CC BY-SA; d) Rachel Hathaway, CC BY.

Echinoids first appear in the fossil record in the Upper Ordovician, approximately 460 million years ago, but they didn't really diversify until the Jurassic (Figure 7.39).

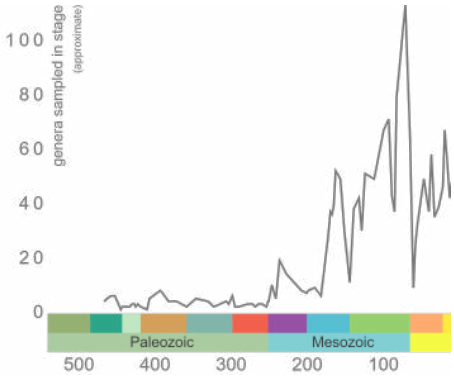


Figure 7.39 – Diversity of Echinoidea genera. Image credit: Paleobiology Database, CC BY.

Class Crinoidea

Crinoids, often referred to as “sea lilies,” may resemble plants (Figure 7.40), but they are actually suspension-feeding animals that have been around since the Ordovician (Figure 7.41). They use their arms to catch floating food particles and transfers them to the base of their **crown**. The crinoid “stem” contains numerous ring-like elements made of magnesium-rich calcite and is held together by a combination of ligaments and muscles. The stem of crinoids is most often found in the geologic record (Figure 7.42). The crown resembles a flower, and this soft tissue is rarely fossilized.



Figure 7.40 – a) Basic anatomy of a crinoid; b) A crinoid fossil from the Permian; c) A living crinoid from Sumilon Island, Philippines. Image credit: a) William I. Ausich, CC BY; b and c) Klaus Stiefel, CC BY-NC.

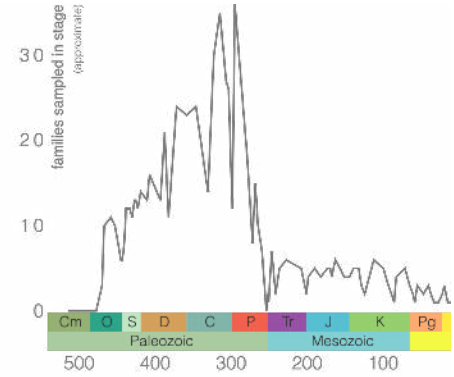


Figure 7.41 – Diversity of Crinoidea families. Image credit: Paleobiology Database, CC BY.



Figure 7.42 – Crinoid stems in limestone from the Ordovician of Kentucky. Image credit: James St. John, CC BY.

Class Blastoidea

Blastoids are an extinct class of echinoderm. Similar to crinoids, blastoids had a stalk and were suspension feeders. The main body is the theca, which was protected by interlocking plates made of calcium carbonate (Figure 7.43). Blastoids evolved in the Ordovician and went extinct during the End Permian extinction event (Figure 7.44).

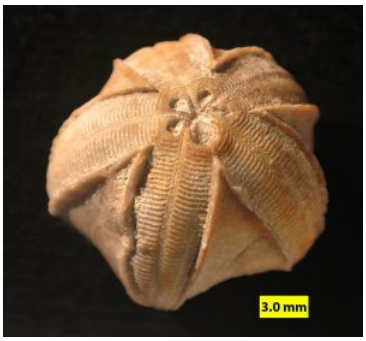


Figure 7.43 – Blastoid from the Lower Carboniferous of Illinois. Image credit: Wikimedia user Wilson44691, CC0 Public Domain.

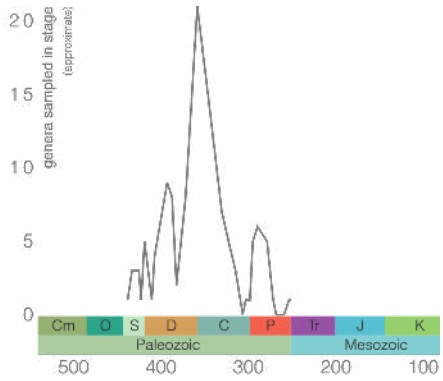


Figure 7.44 – Diversity of Blastoidea genera. Image credit: Paleobiology Database, CC BY.

? Exercise 7.5 – Fossil Identification

To help you identify these fossils, here is a flow chart with some of the observations that may help you decide the phylum and class for the specimens.

a. The flow chart has a few blanks. Fill in the blanks with the correct word.

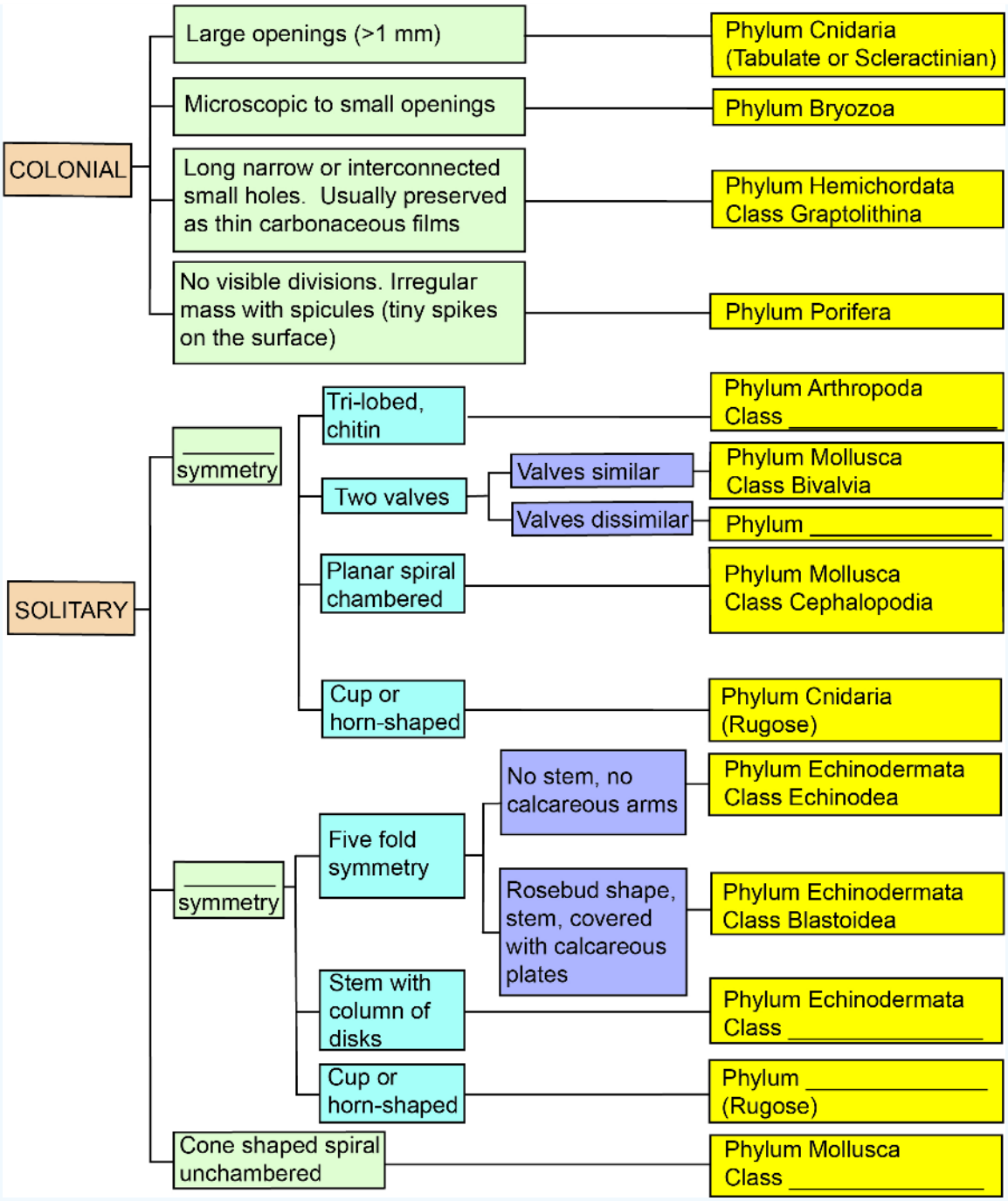


Figure 7.45 – Flow Chart for Fossil Identification. Each color represents different types of observations you should make, with the yellow boxes listing the phylum and class for each type of fossil. You need to fill in a few blanks to be able to use this flow chart. Image credit: VB Sisson.

b. Your instructor will provide you with a selection of fossils for you to identify. On a separate sheet of paper, make detailed sketches for each fossil from at least two different viewpoints. Be sure to label any identifiable parts and then identify the fossils.

7.10 Extinctions

Over Earth's history, many species have gone extinct. Extinction is defined as the death of the last individual of a species. You probably already know about the famous extinction event at the end of the Cretaceous that killed all the dinosaurs and many other species. But, have you ever wondered how and when such enormously successful animals went extinct? Are we undergoing a mass

extinction right now? If you want to know more, Kolbert (2014) offers a good introduction to extinctions and speculates that the Earth is undergoing a sixth massive extinction, the Holocene extinction event caused by human activity.

Some estimate that 99% of all species (~5 billion species) that ever lived on Earth are now extinct. Massive extinction events are rare, whereas local extinctions are quite common.

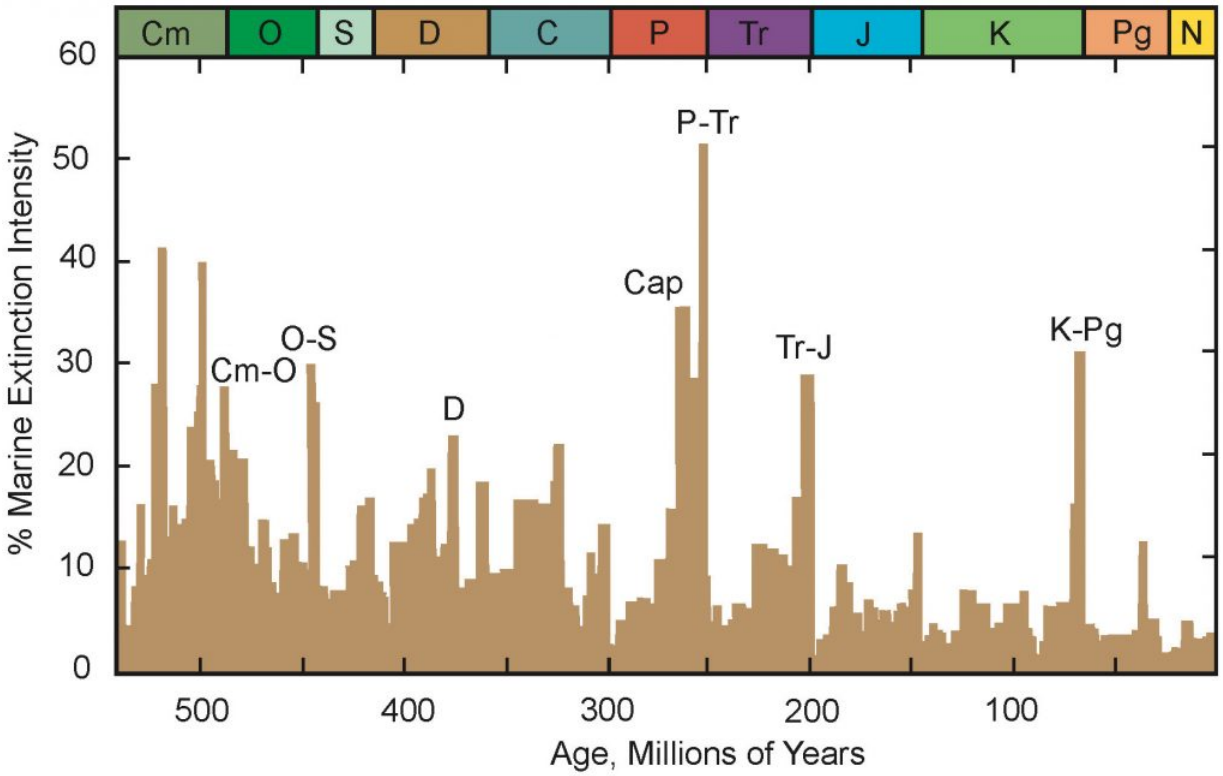


Figure 7.46 – Plot of extinction intensity (percentage of marine genera that are present in each interval of time but do not exist in the following interval) versus time. Geological periods are annotated by abbreviations above. This shows five major and two of the 19 minor extinctions since the beginning of the Cambrian period, including Ordovician-Silurian (O-S), Devonian (D), Permian-Triassic (P-Tr), Triassic-Jurassic (Tr-J), and Cretaceous-Paleogene (K-Pg) with two minor extinctions Cambrian-Ordovician (Cm-O) and Capitanian event (Cap). Image credit: VB Sisson adapted from Rohde and Muller (2005).

Paleontologists postulate that there have been five major mass extinctions in Earth's history (Figure 7.46); these have had an enormous impact on life by quickly killing large numbers of species from land and sea environments. All of these mass extinctions were caused by major environmental catastrophes. The most famous example was the end of the Cretaceous mass extinction caused by a meteorite that crashed to Earth 65 million years ago. It threw so much dust into the atmosphere that the Earth felt like nighttime for many years, preventing algae, plants, and animals from being able to get enough food to survive. The Late Permian mass extinction was the most devastating of all extinctions. Warming of the Earth's climate and changes in ocean chemistry caused by the outpouring of basaltic lava in Siberia may have been responsible for this extinction. These two mass extinctions so dramatically affected life on earth that they are used to define the boundaries surrounding the Paleozoic, Mesozoic, and Cenozoic eras.

? Exercise 7.6 – Extinction Exercise

The Paleobiology Database (PBDB), an online resource for fossil research, will help you investigate your species extinction. Open the PBDB Navigator. The Navigator page has four parts: 1) The map (in the center) shows continents with dots representing fossil data. The color of these dots represents their geologic age. If you click on the dots, you can see all of the information on each fossil locality and the plants, animals, and other fossil life that occur there. 2) The geologic time scale (on the bottom) shows the major eras and periods (and their subdivisions called stages). If you click on the timescale, the map will show you the location of all known fossil localities from that time interval. 3) The most prevalent taxa (on the right) is shown, such as Mollusca, Brachiopoda, etc. 4) The toolbar (on the left) showing the tools you can use to explore the database. Hover

over each tool to see its use. This exercise is inspired by Phil Novack-Gottshall, Benedictine University Evolution of Extinct Animals.

a. Select a group of extinct animals you want to study for this exercise. Your instructor may provide this for you. Which group of extinct animals are you studying? _____

b. On the upper-right corner, type in the name of your extinct group. Next, make a diversity curve for your group by clicking the tool on the left side. You will see a new window show up. The default settings are fine to use. Draw a copy of this graph in the space below.

Sketch Area:

c. The y-axis plots genus diversity, the number of different genera of animals in the fossil record during each time interval. Describe features of your diversity curve through time. Include features such as when the largest diversity was observed, when your animal group first evolved, and what time period your animal group went extinct? (If your group is not extinct yet, then write that it is not yet extinct.) Did your taxa simply increase in diversity and then suddenly extinct? Or was their evolutionary trends have several periods of increased diversity?

d. Some people think extinct animals were evolutionary failures because they are extinct today, or nearly so. Some also claim they were never successful or common animals on earth. Based on the diversity curve, is it fair to claim that your extinct group was a failure? Why or why not? (For comparison, primates have existed for just 16 million years and our species for only 250,000 years.)

e. How were your taxa affected by one of the five major mass extinction events in Earth's history? For each mass extinction, explain whether it (a) had not yet originated, (b) was not affected by the extinction (meaning it did not have a major drop in diversity at this time), (c) was heavily affected by the extinction (meaning diversity drops significantly at this time), or (d) it

went extinct before the mass extinction.

f. Which mass extinction was the most catastrophic for your group? Explain your answer.

g. If your animal group is extinct today, did its extinction occur during a mass extinction? Explain your answer.

Additional Information

Exercise Contributions

Virginia Sisson and Daniel Hauptvogel

References

Evans, S.D., Hughes, I.V., Gehling, J.G., and Droser, M.L., 2020, Discovery of the oldest bilaterian from the Ediacaran of South Australia, Proceedings of the National Academy of Sciences, 117 (14) 7845-7850 doi.org/10.1073/pnas.2001045117

Kolbert, E., 2014, The Sixth Extinction: An Unnatural History, Henry Holt and Co., New York City, 319 p.

Leonova, T.B., 2018, Paleozoic Ammonoids: Historical Pathways of the Development of Morphological Diversity, Paleontological Journal, 52, 1746-1755, DOI: 10.1134/S0031030118140113

Miller, A.K., and Furnish, W.M., 1940, Permian ammonoids of the Guadalupe Mountains region and adjacent areas, Geological Society of America Special Paper, 26, 242 pp.

Rohde, R.A. and Muller, R.A., 2005, Cycles in fossil diversity, Nature, 434, 209-210. doi:10.1038/nature03339

Google Earth Locations

Click or Scan to View all Chapter 7 Locations on Google Earth

This page titled 1.8: Fossils is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.9: Paleoenvironments

Learning Objectives

The goals of this chapter are to:

- Categorize fossil assemblages to determine their habitats
- Develop connections between modern and ancient paleoenvironments
- Evaluate paleoenvironments through time and space

8.1 Introduction

Some geologists use fossils to determine stratigraphy and correlate stratigraphic sequences. Others prefer to study paleoecology to determine ancient **habitats** where both plants and animals co-existed. This avenue leads to discoveries about past climate, predator-prey relationships, and even ocean depth. Using this information, artists create reconstructed paleoenvironments (Figure 8.1) to display these ancient habitats.



Figure 8.1 – Using only fossil pollen, here is a series of reconstructed paleoenvironments for Cretaceous through Paleogene time in Patagonia. Before the Cretaceous-Paleogene mass extinction, there was diverse plant flora (left side). After the meteorite impact near Chicxulub, Mexico, most of the species died (middle). Then as plants started to rebound, the fauna changed (right side). Image credit: Barreda et al. (2012) CC BY.

Remember, fossils are not just exciting curiosities but were once living organisms that reproduced, ate each other, and interacted with their environment just like we do. A fossil's paleoecology depends on many factors of their **paleoenvironment**. These include physical conditions, such as temperature, light, water depth, and energy (calm vs. turbulent), and chemical conditions, such as salinity, pH, oxygen, and toxic chemicals. Some animals will thrive if these variables change, and others will die off. Have you ever been to the beach and seen large piles of seaweed? They came from the middle of the ocean and were brought to shore as ocean currents and winds changed. Some organisms can survive environmental change, such as oysters that can live in both salty and freshwater. Fossils hold the key to determining what the paleoenvironment was like. This ability to reconstruct a fossil's paleoenvironment is one of the most valuable tools that a paleontologist has to offer to broader fields of geology.

Understanding every detail of how a fossil lived is not necessary to help you use fossils to interpret an ancient environment in the rock record. For example, suppose you know that a phylum is exclusively marine or exclusively terrestrial. In that case, this can easily change your interpretation of an otherwise dull sedimentary layer. This is just the beginning of using fossils to determine the paleoenvironment; if you know how it lived, you can determine where it lived.

For any fossil group, ask yourself some basic questions such as the type of the skeleton, its body plan (symmetry), its habitat, and how it fed and behaved. You might find these are hard to determine with fossils but give it a try. Table 8.1 is a list of characteristics that you can use for determining its paleoenvironment:

Where is the skeleton relative to the tissue, as this can be internal, external, or none? Also, look at the number of parts in the skeleton and its construction. This can be either a single element or multiple elements like bivalves (two-part), multivalve (range of 3 to ~15 parts), *plates*, ***ossicles***or bones (many parts from 10's to 100's), or ***spicules***(very many small parts numbering up to 1,000's).

Symmetry is similar to what you described in the last chapter but now consider how it relates to how the organism lived. Bilateral symmetry means that both **locomotory** and sensory organs can be placed efficiently. In contrast, organisms with radial symmetry

tend to be slow or immobile (sessile). They also respond to stimuli from all directions. Organisms with spherical symmetry will live in open water. Finally, those with no symmetry are typically immobile (sessile).

Table 8.1 – Comparison of skeleton types and symmetry between marine fossils. *In colonial forms, symmetry is difficult to identify because of how close together the organisms grow.

	Skeleton Type		Number of Parts in Skeleton			Symmetry	
Organism	Internal	External	Single Element	Multi-Element	Plates or bones	Bilateral	Radial
Ammonite		X	X			X	
Belemnite	X		X			X	
Bivalve		X		X		X	
Blastoid	X				X		X
Brachiopod		X		X		X	
Bryozoa		X	X			X	
Crinoid	X				X		X
Echinoid	X				X		X
Gastropod		X	X			X	
Graptolite		X	X			X	
Rugosa		X	X				X*
Scleractinia		X	X				X*
Tabulata		X	X				X*
Trilobite		X			X	X	

8.2 Marine Paleoenvironments

Most of the fossils you have studied are marine, but remember there are many other environments in the terrestrial, transitional, and marine realms (Table 8.2). Within these environments, organisms can have different modes of life, including not moving (sessile), attached by cement to the bottom, or unattached and able to move (motile) (Table 8.3). Some also categorize organisms as benthic and planktonic. Benthic organisms live at the bottom of the ocean on or in the sediment, and planktonic organisms float or swim.

Table 8.2 – Comparison of habitat between marine organisms

	Habitat		
Organism	Terrestrial	Transitional	Marine
Ammonite			X
Belemnite			X
Bivalve		X	X
Blastoid			X
Brachiopod			X
Bryozoa			X
Crinoid			X
Echinoid			X
Gastropod	X	X	X
Graptolite			X
Rugosa			X
Scleractinia			X
Tabulata			X
Trilobite			X

The way an organism feeds is important for determining its role in the paleoenvironment (Table 8.3). Does it eat by suspension-feeding as it collects small particles from the water column? Or perhaps it eats by deposit-feeding and ingesting sediment to get nutrients. Is it an herbivore that only eats plant material, a carnivore that captures and kills its prey, an omnivore that eats both plants and animals, or a scavenger that only eats dead material? One fascinating debate among paleontologists is whether *Tyrannosaurus rex* was a carnivore or scavenger. Ask yourself: if it was a carnivore, how could it catch its prey with such tiny forearms? Whereas if it was a scavenger, having small arms might be an advantage for just using its large teeth to tear apart the dead meat. The final question is to determine if the organism lived a solitary life or in a colony with others of its own kind. If you can answer some or all of these questions from your observations, you'll be able to address more fascinating aspects of ancient life.

Table 8.3 – Comparison of mobility and feeding characteristics between marine organisms

	Mobility		Feeding				
Organism	Attached	Mobile	Suspension	Deposit (Sediment)	Herbivore	Carnivore	Scavenger
Ammonite		X					
Belemnite		X				X	
Bivalve		X	X				
Blastoid	X		X				
Brachiopod			X				
Bryozoa	X		X				
Crinoid	X		X				
Echinoid		X		X	X		
Gastropod		X		X	X	X	X
Graptolite		X	X				
Rugosa	X					X	
Scleractinia	X					X	
Tabulata	X					X	
Trilobite		X					X

8.3 Continental Paleoenvironments

Depending on the continental paleoenvironment, these can be just as fossiliferous as marine environments. For example, swamps and lagoons can have a wide variety of fish, plant, and insect fossils. In continental paleoenvironments, you commonly do not find **index fossils** as these are not as widespread. Think how quickly the environment can change during a drive through the countryside. Instead these paleoenvironments can record biodiversity and can be used for paleobehavioral analysis. Often these are the fossils more commonly known to the general public as they catch our imagination. What child doesn't know the name of common dinosaurs or ice age mammals?

? Exercise 8.1 – Marine Paleoenvironments

First, review these summaries of the characteristics of Bryozoans and Echinoidea that can be used to determine their paleoenvironments:

Bryozoans: External skeleton. Individuals (zooids) are bilaterally symmetric, but colonies are typically asymmetric. Marine immobile (sessile), typically attached to the substrate, benthic, suspension feeders, and lives in colonies.

Echinoidea: Internal skeleton. Radial (5-fold or pentamerous) symmetry. Marine benthic scavenger or deposit feeder, mobile, and solitary lifestyle.

Using these descriptions as a guide along with your observations, Table 8.1, and material from Chapter 7, characterize a coral (Rugosa) and brachiopod.

a. Summarize the characteristics that will be useful to determine the paleoenvironment of a Rugosa coral.

b. Summarize the characteristics that will be useful to determine the paleoenvironment of a brachiopod.

c. Next, speculate on the paleoenvironment for all four (bryozoans, echinoids, rugosa, and brachiopod) of these organisms. Would all of these four organisms live in the same paleoenvironment?

d. Both bryozoans and echinoids lived throughout the fossil record and thus are not good index fossils. In contrast, rugosa and brachiopods are both more limited in their age range. Using the diversity plots in Chapter 7, what age could a paleoenvironment be if it had both of these fossils?

? Exercise 8.2 – Devonian Reef

Head to the PaleoDB Navigator. A large map of the world should open with many colored circles. The circles represent locations where fossils have been discovered, and the color of the circle corresponds to the geologic timescale at the bottom of the page. You can click through the different time periods to see where fossils of that age have been discovered. On the right side, there is a list of the most abundant fossil groups based on the time period you have selected on your map view. For example, you could zoom in on fossils found in South America from the Ordovician Period. The menu on the right will update with what fossils are found on your map for that period. Depending on your zoom level, you may see that the Trilobita Class is the most abundant, or you may see it broken down into several orders of Trilobita with the Asaphida Order as the most abundant. If there is lower diversity of fossils in your map view and time period, you will see the classification broken down to lower levels. You may find you need to Google some of the names to figure out what phylum, class, or order they belong to. You can clear whatever filters you select on the lower left side of the page.

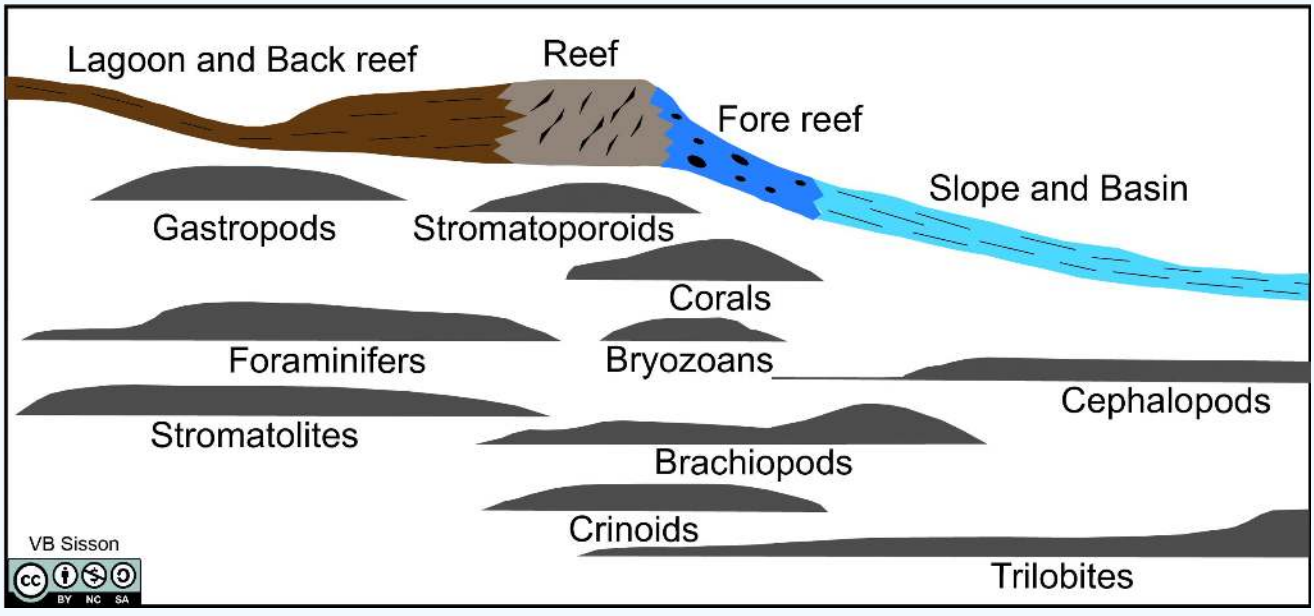


Figure 8.2 – Distribution of organisms in a typical Devonian reef. The thickness of the organism curves represents the relative abundance of the organisms. Image credit: Virginia Sisson, CC BY-NC-SA adapted from Corrandini et al. (2002).

a. In the PaleobioDB Navigator, set your time period to Devonian and zoom in on New York State. What is the most common group of Devonian fossils found in New York? Remember, you may need to search more technical taxonomic names to determine which fossils you're looking at (I'm talking about you, Rhynchonellata and Strophomenata).

b. What are some other organisms that are present?

c. What type of environments are most of these organisms found in?

d. Compare the locations of gastropods and cephalopods. You can do this by clicking on the classes on the right-hand menu. Look at the two locations of these fossils compared to each other. You may find it easier to have two browser windows open for this. Based on the locations from the navigator and the typical locations of fossils around a Devonian reef, what direction was the coastline located?

e. Remove any organism filter and now look at the distribution of all fossils throughout the Devonian in New York. Click on "E", "M", and "L" under Devonian to look at the distribution from early to middle to late Devonian. Was sea level rising or falling in this region during the Devonian (you already know which way the coastline was based on your previous answer)?

? Exercise 8.3 – Himalayan Mountains

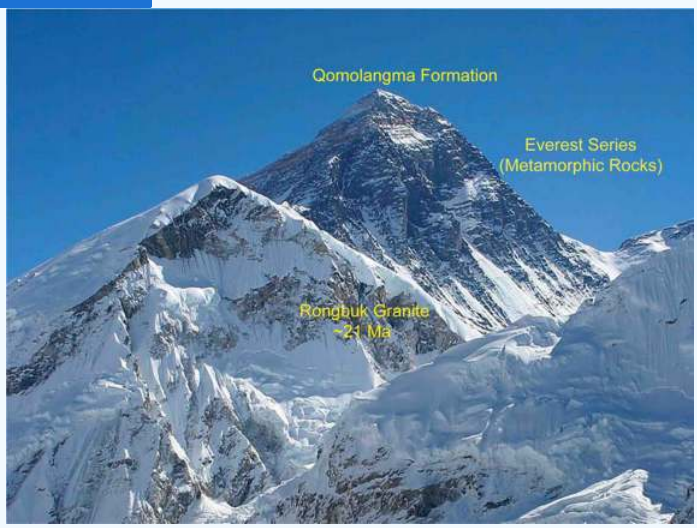


Figure 8.3 – Mount Everest showing geological relationships with the unmetamorphosed Qomolangma Formation overlying the Everest Series metamorphic rocks and the Rongbuk Granite. Image credit: photo of Everest by Pavel Novak CC SA with geology superimposed.

a. Figure 8.3 shows the tallest peak on Earth, Mount Everest, at 8,848 m (29,029 ft) (Tibetan name *Qomolangma*). It has a layer of unaltered limestone from the Ordovician at its summit. What does this tell you about the environment of Mt. Everest during that time?

b. Using the PaleoDB navigator, look at the distribution of fossils for the Himalaya Mountains, particularly near the Nepal/China border. During which two geologic time periods were fossils most abundant?

c. What were the most abundant organisms for each of those periods? The pane on the right side tells you the percentage of each organism found in your current map view. You may need to search the technical taxonomic name to learn which organism it is.

d. Based on the changes in fossils over the time periods, determine whether sea level was rising, falling, or constant. Be sure to explain your answer.

e. **Critical thinking:** Does your sea-level interpretation match the global sea level record from Figure 5.21? Explain your answer.

8.4 Fossils and Paleoenvironments in Movies

We all know that Hollywood stretches the truth (or outright makes it up) when depicting science in movies. Perhaps the most famous movie depicting fossils and paleoenvironments is the Jurassic Park series. For example, in the original movie from 1993, there is a scene where a *Tyrannosaurus rex* chases a Jeep at over 60 mph. At the time of production, some paleontologists thought *T. rex* could only run at a maximum speed of about 45 mph. However, we now know that *T. rex* didn't have the hip structure to support running and was more of a brisk walker. So, you could probably outrun a *T. rex*.

? Exercise 8.4 – Jurassic Park

Using the PaleobioDB Navigator, look up "Dinosauria" (an unranked **clade**). A clade is a group of organisms that share a common ancestor, and cladistics is a way to classify organisms based on common characteristics. You'll notice that one of the groups in the Dinosauria clad is Aves, which is the class comprising birds. Yes, according to cladistics and taxonomic rankings, dinosaurs and birds are related.



Figure 8.4 – Jurassic Park sign at Universal Studios Hollywood. Image credit: HarshLight CC SA.

a. During which geologic time periods were Dinosauria most abundant (excluding Aves)?

b. Which one of those time periods were Dinosaurs (not Aves) most abundant?

c. The movie franchise *Jurassic Park* showcases several different dinosaurs. The table below contains the seven dinosaur genera shown in the original film from 1993. Complete the table below with what geologic time periods these dinosaurs actually lived and what their preferred habitat was (use Google to search for the "[genera] habitat." Remember, the movie depicted all of these dinosaurs living in a tropical climate.

Table 8.4 – Worksheet for Exercise 8.4.

Genera	Geologic Time Period	Preferred Habitat
Tyrannosaurus		
Brachiosaurus		
Triceratops		
Velociraptor*		
Dilophosaurus		
Gallimimus		
Parasaurolophus		

*In the movies and book *Velociraptor* was based on a similar dinosaur, called *Deinonychus*, in almost every detail, and that only the name had been changed to be more dramatic.

d. Does *Jurassic Park* seem like a fitting name based on when these dinosaurs lived? Why or why not?

Additional Information

Exercise Contributions

Daniel Hauptvogel and Virginia Sisson

Exercise 8.1 was inspired by an exercise on Life Mode Characteristics by Steven J. Hageman at Appalachian State University

References

Barreda V.D., Cúneo N.R., Wilf P., Currano E.D., Scasso R.A., Brinkhuis H., 2012, Cretaceous/Paleogene Floral Turnover in Patagonia: Drop in Diversity, Low Extinction, and a *Classopollis* Spike. PLoS ONE 7(12): e52455. https://doi.org/10.1371/journal.pone.0052455

Corradini, C., Pondrelli, M., Corriga, M.G., Simonetto, L., Kido, E., Suttner, T.J., Spalletta, C., and Carta, N., (2012). Geology and stratigraphy of the Cason di Lanza area (Mount Zermula, Carnic Alps, Italy). Berichte des Institutes für Erdwissenschaften, Karl-Franzens-Universität Graz. 17. 83-103.

Google Earth Locations

Click or Scan to View all Chapter 8 Locations on Google Earth

This page titled 1.9: Paleoenvironments is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.10: Geologic Structures and Mapping

Learning Objectives

The goals of this chapter are to:

- Visualize geologic structures in maps and cross-sections
- Identify geologic structures on a geologic map
- Learn how to read a geologic map

Some of the maps in this chapter can be printed on poster paper from large PDF files found here (opens in a new tab).

9.1 Introduction

Do you remember in Chapter 0 how we said you would become an expert at reading and interpreting geologic maps? Now is the time to sharpen this skill. In the past, you probably encountered a variety of types of maps. If you have used a mapping app to get directions somewhere, you have used a map. Maps are a scaled, 2-dimensional representation of the surface of an area. Some maps even attempt to portray 3-dimensional landscape features, such as mountains or canyons. This is one of the great difficulties in geology because geologic maps represent 3-dimensional features in a 2-dimensional format. It can be challenging for someone unfamiliar with these features to look at a geologic map and visualize reality. Maps may represent the surface of the land or areas in and around lakes and oceans, the seafloor, or features known or thought to occur underground. Mapping is also used in astronomy (planet and moons, regions of space, etc.). Anything that has a visual distribution can be mapped.

In previous chapters, you have seen how colors and patterns can be used on maps to distinguish different types of rocks, such as volcanic (orangish) versus plutonic (red) in Figure 2.24. Also, the lines between the different colors represent contacts between different rock types.

Before interpreting or preparing a map, it is important to understand some of the background information about the map. Below is a list of information typically associated with maps.

Table 9.1 – Common map information

Information	What it tells you
Title	Concise information related to geographic information and map contents
Scale	The ratio of distance on the map and distance on the ground. The scale should be relative to both kilometers and miles. Most maps also have a visual scale bar of relative distance on the map.
Orientation	An arrow pointing north and, if possible, latitude and longitude
Explanation or Legend	Explanation of any symbols used on the map, including colors, lines, or icons.
Reference features	Selected reference locations or features such as a town, river, state boundary, mountain, etc.
Source information	A list of authors, compilers, editors, publishers, associated publications (text or guidebook), URL, and any other information so it can be accurately cited in reference list or bibliography.
Base map information	What is the source of the geographic information? For example, is it based on a USGS topographic map, or is it a satellite image? What is the map projection?
Date published	The year the map was released or revised.
Written text	Is there a publication or guidebook associated with this map?

What do you need to know for geologic maps? First, there are lots of standard symbols used to help geologists worldwide use the same terminology. You also need to be able to read **strike and dip** symbols. If you didn't learn about strike and dip in Physical Geology, now is the time to do so. Most geologic maps will have a stratigraphic column with either colors or patterns to distinguish various rock units. Again, there are often standard colors for different ages of rocks and patterns for the rock types. Look at the tables in Chapter 2 Earth Materials to see some common patterns for different rock lithologies. Figure 9.1 shows the common symbols used for geologic structures.

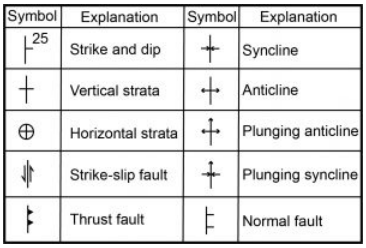


Figure 9.1 – Common map symbols used on geologic maps. These are usually included in the map legend. Image credit: VB Sisson CC-BY.

? Exercise 9.1 – Mississippi River Maps

The Mississippi River has evolved throughout its history as the river **channel** has **meandered** back and forth across the landscape of the central U.S. Different types of maps can provide some insight about previous river channels and how we can distinguish them. What you learn from the Mississippi River will help you understand river systems throughout the world, regardless of their size.

Part 1: Aerial Imagery

Figure 9.1 is a satellite photograph from a section of the Mississippi River from Google Earth. Think of this image as what the ground looks like from an airplane. You can see vegetation that has responded to the river evolving and patterns associated with the river.

a. Trace three previous paths the Mississippi River has taken. It is ok if these channels cross where the river is currently. Label the different paths a, b, and c, and use color to differentiate them.
b. Put the paths that you identified in order from the most recent to the oldest. _____
    i. What is your evidence for this order?

c. Locate and mark at least five features associated with a river system. Examples could include cut bank, point bar, levee, oxbow lake, thalweg, flood plain, terrace, etc.
d. What are some of the difficulties you experienced with completing these two questions?

e. How do you think we could solve some of these problems? What data would you need to accurately assess the true paths and their ages?



Figure 9.2 – Google Earth image of a section of the Mississippi River.

Part 2: LiDAR Imagery

Look at the second image (Figure 9.2). This image was made by using **LiDAR**. This method uses wavelength reflections to produce detailed images of topography. Different wavelengths are susceptible to changes in interference and reflection caused by vegetation and sediment changes, which can help identify previous channels.

f. See if you can locate the channels you found in Part 1. Explain why you agree or disagree with the locations you placed previous river channels?

g. In Figure 9.2, locate and mark three previous paths the Mississippi has taken that are different from those you identified from Figure 9.1. Label them with d, e, and f.

h. Using your three paths from Part 1, and your three paths from this part, try to place the six channels in order from the most recent to the oldest. _____

i. What are some of the problems you are encountering doing this?

i. Explain how this image helped or didn't help you identify the proper paths the Mississippi River has taken.

j. Do you think it is necessary to obtain more data to solve our problem of finding previous paths and ages?



Figure 9.3 – LiDAR image from a section of the Mississippi River. This is the same area as Figure 9.1. Image credit: Daniel Coe, CC BY-NC-ND.

Part 3: Geologic Map

Figure 9.3 is a map of previous river paths the Mississippi has taken. It was made by a geologist before the ability to use Google Earth or LiDAR images.

k. Locate as many paths as you can that you have identified from the previous images. Do you still agree with where you placed the channels you found? Why/why not? Keep in mind that just because a geologist made this map, it may not be 100% correct.

l. See if you can put the paths you've identified from the previous images in order from most recent to the oldest. Explain if you were able to identify a different order, add more paths you hadn't seen before, or if you notice anything else that you think is important.

m. How has this image helped in understanding the proper paths the Mississippi River has taken? Do you think it is necessary to obtain more data, such as drill cores, to solve our problem of finding previous paths and ages for analysis? Explain.

k. **Critical Thinking:** Where would you put a drill core? Explain.

l. **Critical Thinking:** Could you describe how and where the river moved from its creation to now in such a manner that someone could draw snapshots in time? Try it.

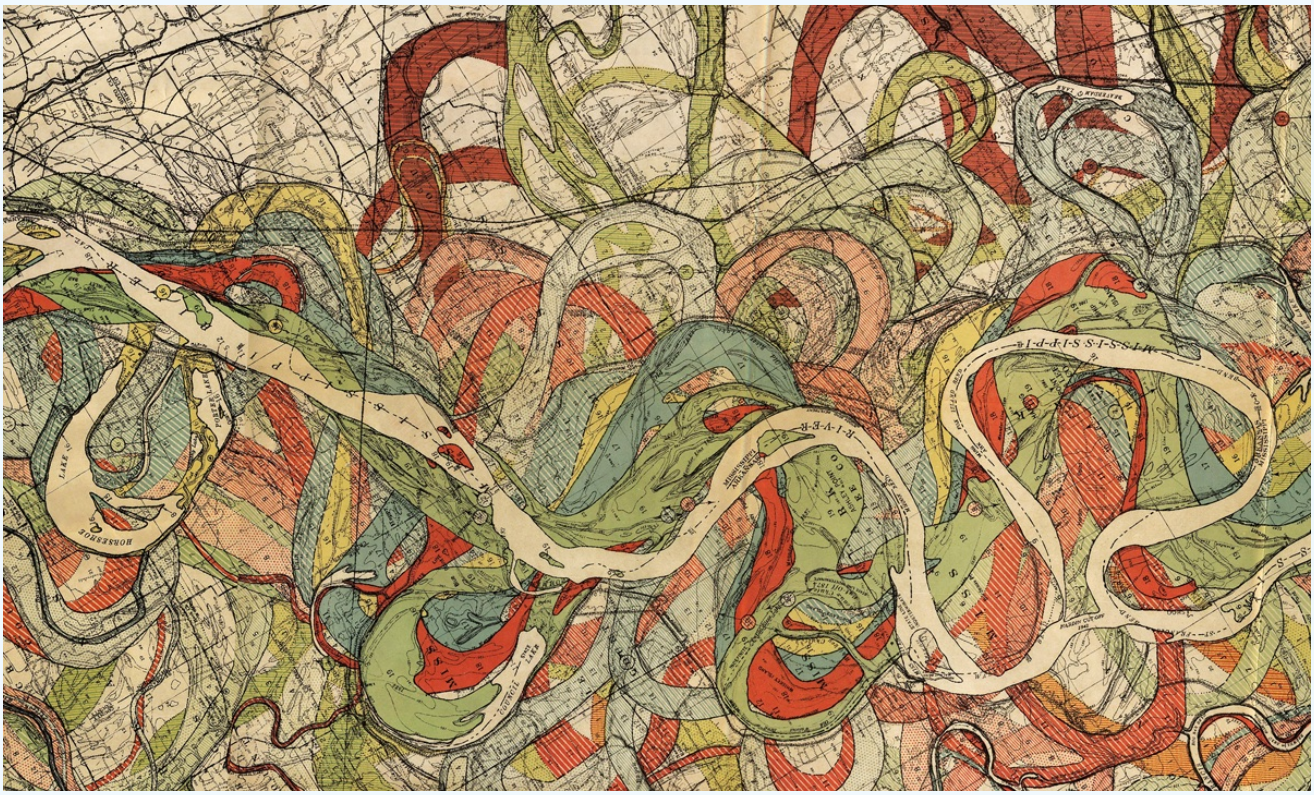


Figure 9.4 – Meander map from a section of the Mississippi River drafted in 1944 by Harold Fisk. Each color and pattern represent a previous path of the Mississippi River. This is the same area as Figures 9.2 and 9.3. Image Credit: Harold Fisk and Army Core of Engineers, Public Domain.

9.2 Geologic Structures

You already know that the Earth is a dynamic place and that plate tectonic forces bend and break rocks. You've already studied this subject in both Physical Geology text and lab books. Here is a short review of some of the concepts you will need for this chapter and the next. Some students have an easy time visualizing in three dimensions. If you have trouble with this, practice with block diagrams.

Remember those lab exercises on geologic time and stratigraphy? While doing these, you looked at vertical sections and views of cliffs, but now you need to be able to decipher geologic patterns on maps. If you need a refresher or perhaps a glimpse of geologic maps with different map patterns, check out these links to flat stratigraphy in Nebraska, three types of unconformities in Saskatchewan, thrust fault in the Olympic Peninsula, plunging anticline in Wyoming, plunging anticlines and synclines, normal faults (core complex in Arizona), and a strike-slip fault in New Zealand.

Strike and Dip

When deformation occurs, sedimentary layers are no longer flat-lying and instead lie at an angle. This angle is called the dip (Figure 9.5). The dip is a measure of the steepest possible slope, sometimes referred to as inclination. You can imagine water running down the surface; it will take the steepest path in the dip direction. It is common for geologists to pour a little water on a rock surface to see how the water runs, telling them the dip direction. The strike of a plane is a bit more complicated. Strike is the horizontal line that forms as a dipping bed intersects with the surface (Figure 9.5) and is always 90° from the dip direction. Geologists measure the orientations of geologic features using a Brunton Compass, a special compass that has a set of levels to take accurate measurements of features. To determine the orientation of these dipping bedding planes, you need to measure both strike and dip.

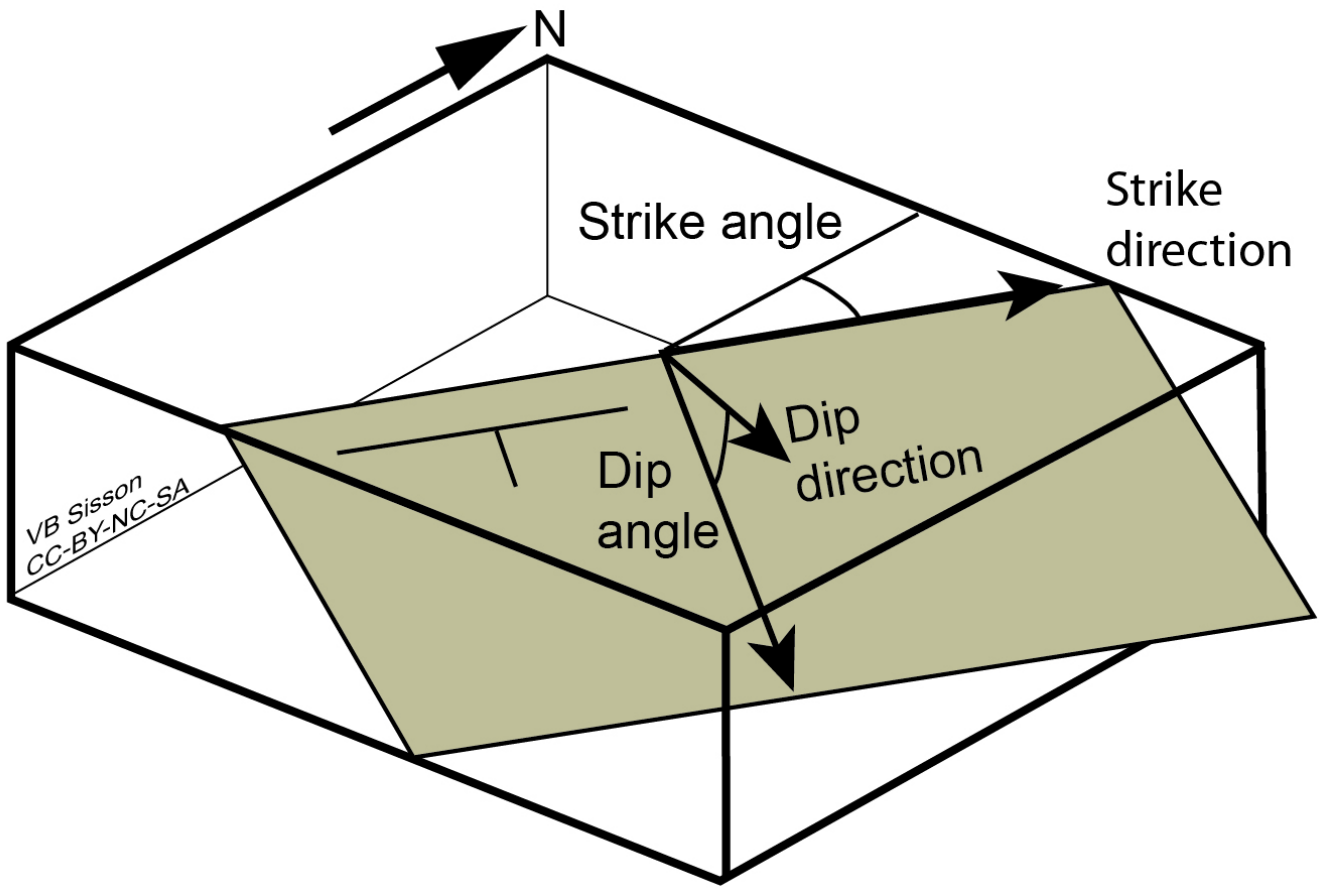


Figure 9.5 – Block diagram showing an inclined plane that strikes ~40º and dips ~30º to the east. Also shows the dip direction. Image credit: VB Sisson CC-BY-NC-SA..

There are two directions you can measure the strike that are 180° apart. The dip direction is clockwise from one and counterclockwise from the other. In most geological fieldwork, the right-hand rule is used. If you place your right hand on the dipping layer with your fingers pointed toward the dip, then your thumb is pointing in the strike direction. In other words, the strike is always 90° counterclockwise from the dip direction.

When writing out the strike and dip, it is a good idea to add the compass direction to the dip measurement, just as a check that you've done the right-hand rule measurement correctly. For example, in Figure 9.5, the strike is 40°, and the dip of the plane is 30°, so this would be written as 040/30 SE. This is a plane that dips at 30° with strike roughly NE. The dip direction is clockwise from the strike, so the dip direction is SE. You can check this since 225/30 would dip to the NW to follow the right-hand rule, not the NE.

Anticlines and Synclines

Folds are some of the most dramatic geologic structures. These form when the Earth's crust is shortened during compression associated with plate tectonic convergence. Folds are important economically as many resources accumulate in the folds, such as petroleum or gold in anticlines. The points of the tightest curvature are called the hinge. In contrast, the limbs are the areas of least curvature. If the limbs dip away from the hinge, this is called an **antiform**. If the limbs dip toward the hinge, this is called a **synform**. Note that if the fold closes on its side, it is impossible to tell if it is an antiform or synform.

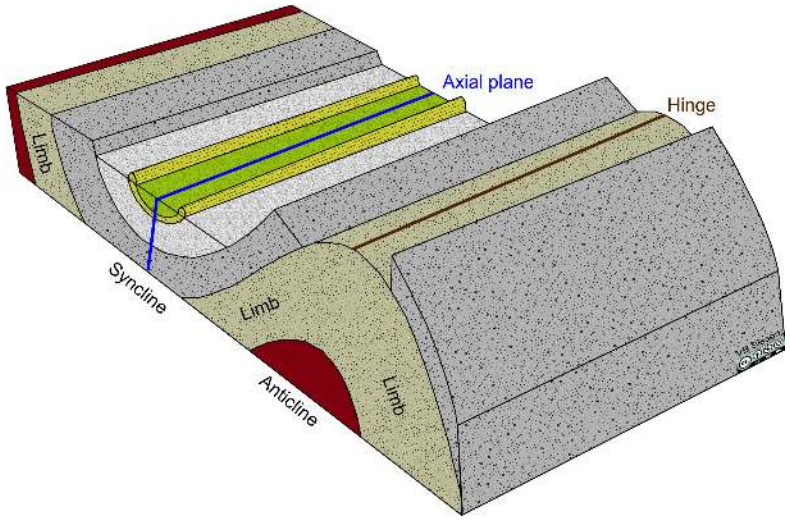


Figure 9.6 – Folded layers with an anticline and syncline pair showing the fold limbs, axial plane, and hinge line. The layers are from oldest red, tan, dark gray, light gray, yellowish, and youngest is green. The top of the folds is eroded, showing the relative ages of the layers. Image credit: VB Sisson.

In a stratigraphic sequence of folded sedimentary rocks, the rocks get younger towards the inside of a syncline and older toward the inside of an anticline, then the fold is a syncline.

The hinges of folds can be connected to create an axial line. If this line is horizontal, the fold is non-plunging. However, if the axial line is tilted, then this is a plunging fold.

If you draw a plane connecting all of the hinges or axial lines of each sedimentary layer in a fold, this plane defines an **axial plane**. This can be oriented vertically, be inclined, or even flat-lying or horizontal. If the axial plane is horizontal, the fold is classified as recumbent. The dip of the axial plane can be used to classify the type of fold (Table 9.2).

Table 9.2 – Fold information

Dip	Fold Type
0-10°	Recumbent
10-30°	Gently inclined
30-60°	Moderately inclined
60-80°	Steeply inclined
80-90°	Upright

Faults

Faults are fractures through rocks that have had a significant amount of movement on them. Strictly speaking, a fault is a single brittle fracture, whereas a fault zone has multiple brittle fractures, and a **shear zone** is a ductile fault (Figure 9.7).

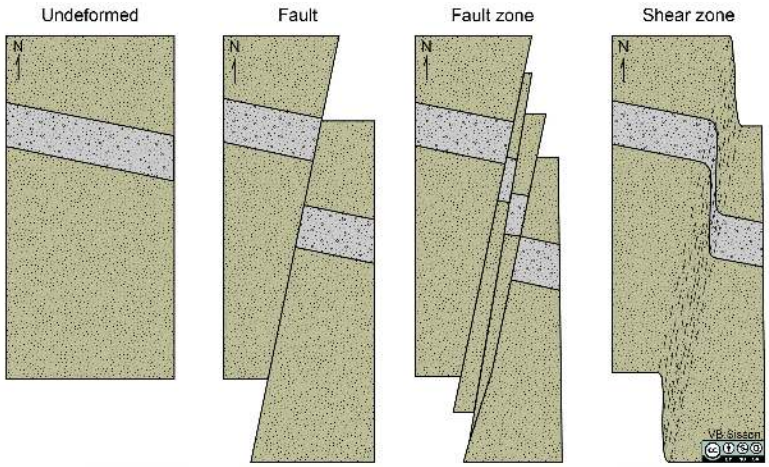


Figure 9.7 – An undeformed block, fault, fault zone, and shear zone. If this is a bird's eye view from above, this is a strike-slip fault with right-lateral motion. Instead, if this is a view of a vertical outcrop, this would be a reverse fault. Image credit: VB Sisson adopted from Weldon and Synder CC BY-NC.

The blocks on either side of a fault are called the walls. If the fault has a vertical orientation, this is a strike-slip fault with horizontal displacement. If the fault has a dip that is not vertical, then one wall is over the other with dip-slip motion. The blocks are defined as either the footwall or hanging wall. There are two types of faults with dip-slip motion: normal faults formed during extension and reverse faults formed during compression and shortening of the Earth. In normal faults, the hanging wall moves down. In reverse faults, the hanging wall moves upwards. There is a special type of reverse fault with a gentle fault that dips less than 30°, called a thrust fault, which is more common than reverse faults (Figure 9.8). For thrust faults, the block that moves is called the **allochthonous** block that is thrust over the **autochthonous** block. Erosion may isolate some of the allochthonous block as a **klippe**. It may also expose the autochthonous material in a window.

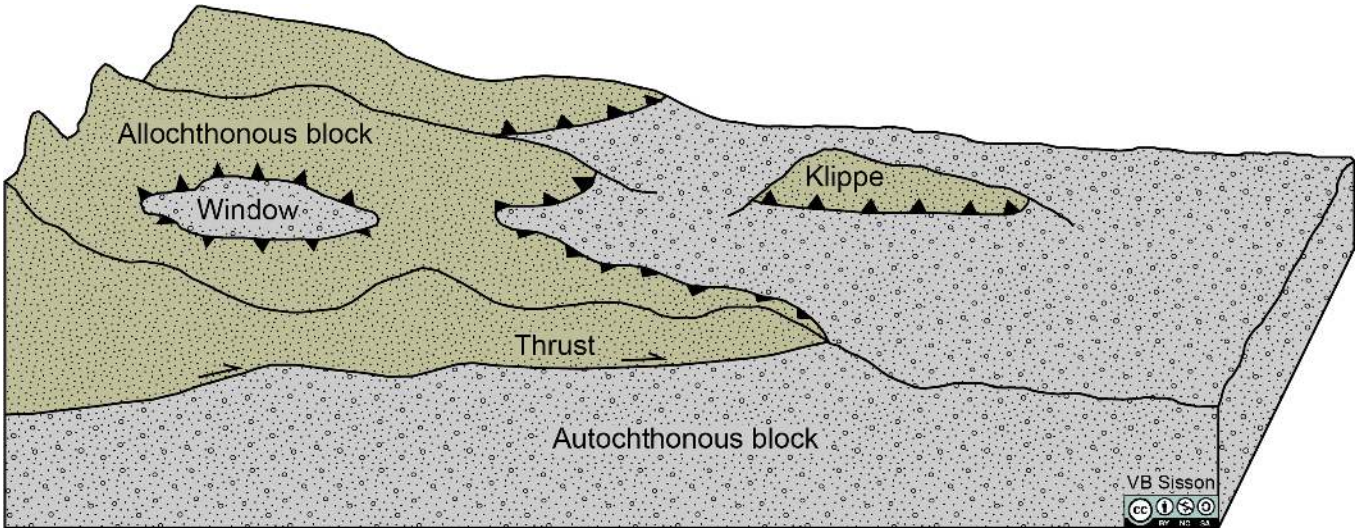


Figure 9.8 – Schematic block diagram of a thrust fault. Also shown are the allochthonous and autochthonous blocks, a window, and a klippe. If you remember the stratigraphy shown in Figure 9.6, you can see that the older tan rocks are thrust over younger gray rocks. Image credit: VB Sisson CC-BY-NC-SA.

9.3 Geologic Maps

To make a geologic map, you need to use your geological skills to fill in the areas between data points, such as outcrops, stratigraphic sections, wells, soil profiles, etc. Often the data is imperfect and doesn't cover 100% of the area in question. For example, figure 9.9 shows an outcrop map and two possible attempts at geological maps. One is made without much understanding of geological processes. Although it satisfies the observations in a simplistic way, it is unlikely to be correct. The other attempt is a more likely interpretation made with some understanding of geological processes. In this case, there are three sedimentary units; these probably have parallel boundaries. Also, there is a basalt which you can see from some of the outcrops that is probably a dike that cross-cuts the sedimentary layers. So, to interpret this outcrop pattern, you have to use your knowledge of sedimentary contacts (Chapter 4) and cross-cutting relationships of basalt dikes since you know that they are often straight (Chapter 3).

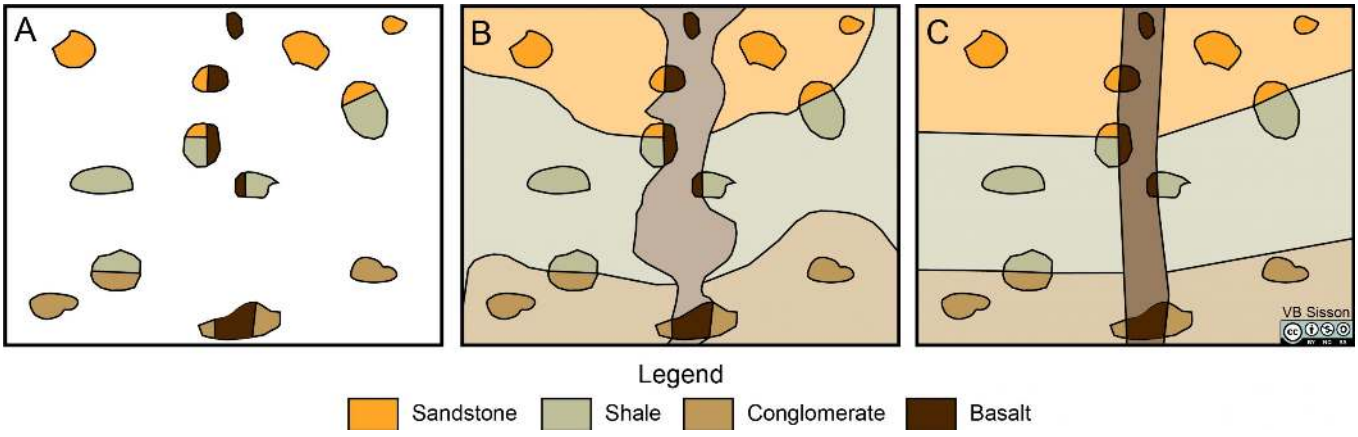


Figure 9.9 – Schematic maps with three sedimentary units and basalt (see Legend) shown in different colors. A. is an outcrop map with different units as well as contacts between them. B. One possible interpretation of the outcrop map made without any geological processes. C. Another interpretation of the same outcrop data made using knowledge of sedimentary and igneous rock types as well as insights about the relative age of the units. Image credit: VB Sisson CC-BY-NC-SA.

Do you remember the rule of V's for maps? There are two different versions of this rule; one for topographic maps and the other for geological maps. If you see a V shape in a topographic map, then the point of the V points upstream toward the source. In geological maps, this rule governs the intersection of the geologic features, such as dikes, sills, faults, bedding planes, fold hinges, etc. with topography. The easiest two features to remember this is that horizontal features such as sedimentary layers and sills will be parallel to topography, whereas vertical features such as dikes will cross-cut topography (Figure 9.10). You can use the angle of

V formed by the intersection of a linear feature and the topography can help you determine the dip of the feature. If you need help seeing these relationships in three dimensions, look at these models.

Cross-sections

You learned how to make topographic profiles and cross-sections in Physical Geology. You may want to review how to do this before starting the exercises. Remember that vertical scale is one of the features in a cross-section, and it may not be the same as the horizontal scale. If these are the same, there is no **vertical exaggeration**. In many cross-sections, the horizontal scale is longer than the vertical scale. This is common in many seismic reflection profiles. This may exaggerate sedimentary layer thickness as well as the dip of some features. In general, the apparent angle of dip increases with increased vertical exaggeration. For example, for a thrust fault dipping at ~25^{o}, it will appear to dip 60^{o} with ~3x vertical exaggeration. This will make it difficult to differentiate a thrust fault from a reverse fault in your cross-section. So, it is important to include the vertical exaggeration for any of the cross-sections you create while interpreting geologic maps.

An important feature on cross-sections is the dip of any contacts, which can range from flat to vertical. If the cross-section is constructed perpendicular to the strike of dipping layers or contacts, then the cross-section will show the true dip of the features. If the cross-section is not perpendicular to the features, the apparent dip of the layers will be less than the true dip.

Another way to visualize cross-sections through an area is to construct slices through a three-dimensional (3D) seismic survey. You may think this is a new technology, but the first 3D survey was made by Exxon across the Friendswood oil field near Houston, Texas, in 1967. For a 3D seismic survey, seismic data is acquired along closely spaced parallel lines that are processed and interpreted as a volume of data. Modern 3D surveys have seismic traces spaced at ~12.5 meters. These seismic volumes are also called seismic cubes.

Figure 9.11 shows a 3D seismic cube through a folded sequence of sedimentary rocks and several two-dimensional cuts through this cube. Cross-sections through the 3D seismic cube are identified relative to the direction that the seismic survey was shot. A cross-section parallel to the direction of the survey is an inline view. A cross-section that is perpendicular to the survey is a crossline. You can also slice horizontally through the seismic cube and create a time slice. Finally, you can make an arbitrary traverse to better show structural features.

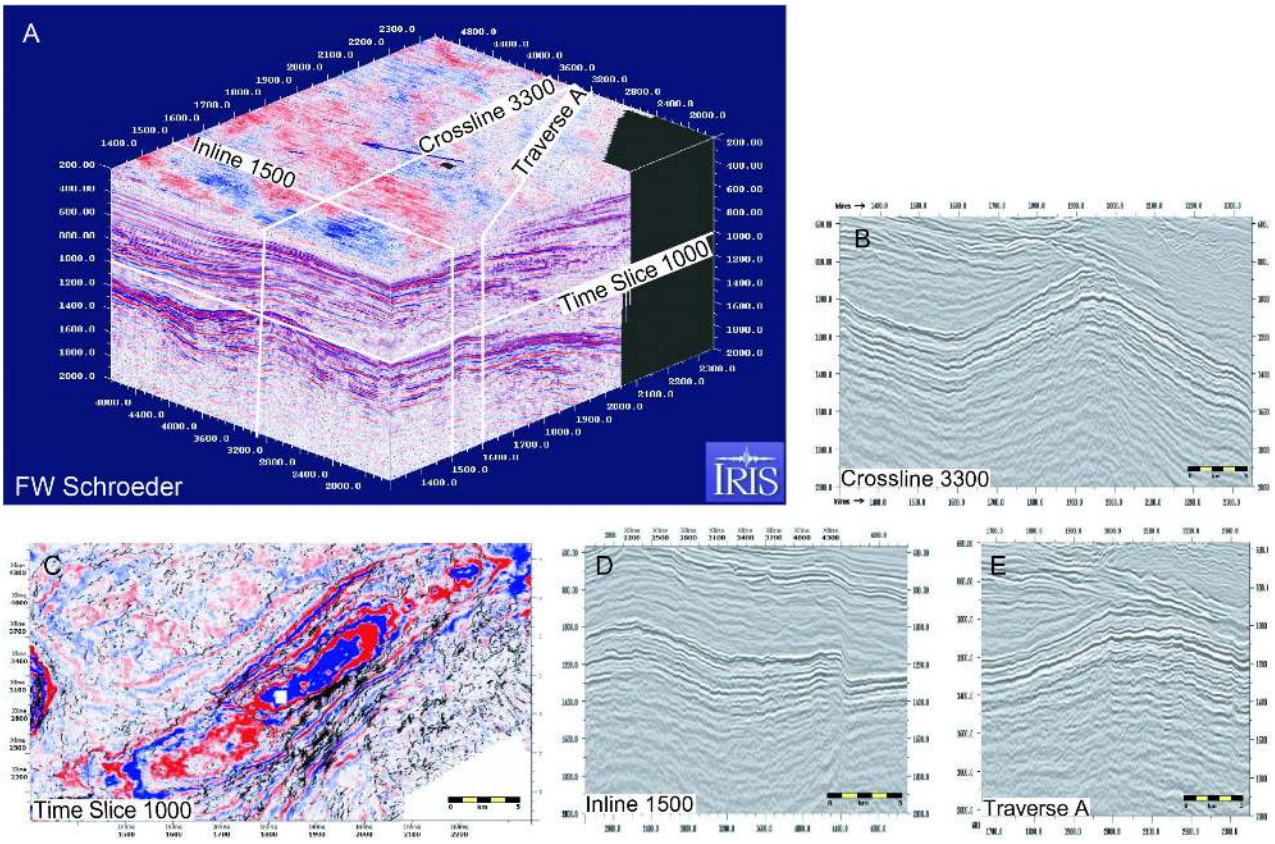


Figure 9.11 – A three-dimensional (3D) seismic cube of folded sedimentary strata that includes both anticlines and synclines. The blue arrow across the top of the cube shows the direction of the seismic survey. The two-dimensional views include (B) a cross-line at 3000, (C) time-slice at 1000 s, (D) an inline section done at 1500, and (E) an arbitrary traverse along line A. Scale bar for B-D is 5 kilometers. Blue is for positive amplitude, black for negative amplitude, and white is for no amplitude difference. Image credit: adapted from FW Schroeder, Incorporated Research Institutions for Seismology (IRIS) Lesson on 3D Seismic Data.

? Exercise 9.2 – Create a Simple Geologic Map and Cross-Section

Your instructor has placed model stations around the classroom. You need to note lithology and collect structural data from each model station. Go around the lab room using the Clino app (free from the Apple app store and Google play store) to measure the strike and dip of the model outcrops and make color-coded notes of their lithology.

a. Make a geologic map using the data points collected from the outcrops you visited in this exercise. Make sure to use appropriate colors for the rock units and appropriate structural notation. Remember that your map should have a scale and a north arrow. Draw contacts between the different rock types. At each station, you should put a strike and dip symbol using the right-hand rule.

Geologic Map:

b. Make a straight line that crosses the contact lines in your map. If possible, the cross-section should be perpendicular to your contacts. This line will be where you construct a cross-section of your map. Label the two ends of the cross-section. Typically cross-sections are labeled as A-A' or A-B. Show the location of your cross-section on your geologic map. Remember that since the desks are flat in the lab, you don't need to worry about the topographic profile for this cross-section. Did you use any vertical exaggeration for your cross-section?

Cross-section:

c. **Critical Thinking:** Imagine you found some fossils in these sedimentary units. Remember your laws of superposition and add into your cross-section which layer would have a *Paradoxides* trilobite and which would have a *Mucrospirifer* brachiopod.

? Exercise 9.3 – Using Google Earth to Interpret Geologic Structures

Head to this Google Earth tour to look at geologic structures in Morocco, a country in northwestern Africa that borders the Atlantic Ocean and the Mediterranean Sea. Morocco is currently part of a passive margin but historically was tectonically active. The geologic history of Morocco started about two billion years ago, in the Paleoproterozoic with the Pan-African orogeny. Then, another tectonic event involved the collision of Euramerica (or Laurussia) with **Gondwana** during the

Hercynian orogeny (in eastern North America, this is the Appalachian orogeny). During the Paleozoic, extensive sedimentary deposits preserved marine fossils. Throughout the Mesozoic, rifting broke up Pangaea forming the Atlantic Ocean. These basins and fault blocks were blanketed in terrestrial and marine sediments. In the Cenozoic, a microcontinent covered in sedimentary rocks from the Triassic and Cretaceous collided with northern Morocco, forming the Rif region. Morocco has extensive phosphate and salt reserves, as well as resources such as lead, zinc, copper, and silver. Morocco is also a fossil hunter's paradise with exquisite trilobites and ammonites.

a. What geologic evidence would you look for to see if an area was tectonically active in the past?

Overview

Start the tour and look at the *Overview* stop. This is the first geologic structure we will look at

b. From this aerial view, how would you describe the appearance of this structure?

c. Do you think this structure is made of igneous, sedimentary, or metamorphic rocks? _____

d. Trace three layers as far as you can on the tour screenshot in Figure 9.12



Figure 9.12 – Screenshot of the Google Earth tour for this exercise.

Views 1 & 2

e. Look at View 1. Are the layers of rock horizontal or tilted? _____

i. If the layers are titled, in what direction are they dipping toward. (HINT: the red triangle on the compass on the bottom-right always points north.) _____

f. Look at View 2. Are the layers of rock horizontal or tilted? _____

i. If the layers are titled, in what direction are they dipping toward. _____

g. What geologic structure are you looking at? _____

h. Look at Rock Layer 1 and Rock Layer 2. Determine and explain which one is older.

i. Look at Rock Layers 3, 4, and 5. What is the age relationship between these layers?

j. Explore the map. Locate similar structures.

Geologic Map and Cross-Section

Figure 9.13 is a geologic map of the region. The location of the structure is right near the town of Imilchil, toward the center of the map. Figure 9.10 is a cross-section along the line labeled Section 2b. There are a couple of items that you need to know to be able to read this map and cross-section. First is that this region was originally mapped by French geologists. So, they used European names for geologic time such as Lias and Dogger. Secondly, a shallow basin formed during Triassic rifting of Pangea; these sediments include salt and **red beds** (hematite-rich sediments). After the basin filled this salt rose, forming **diapirs** and pillars in a wide variety of shapes. Subsequently, the area was deformed by folding and thrusting during the continental collision between the African and European plates.

k. What is the age of the predominate sedimentary rocks exposed along section 2b? _____

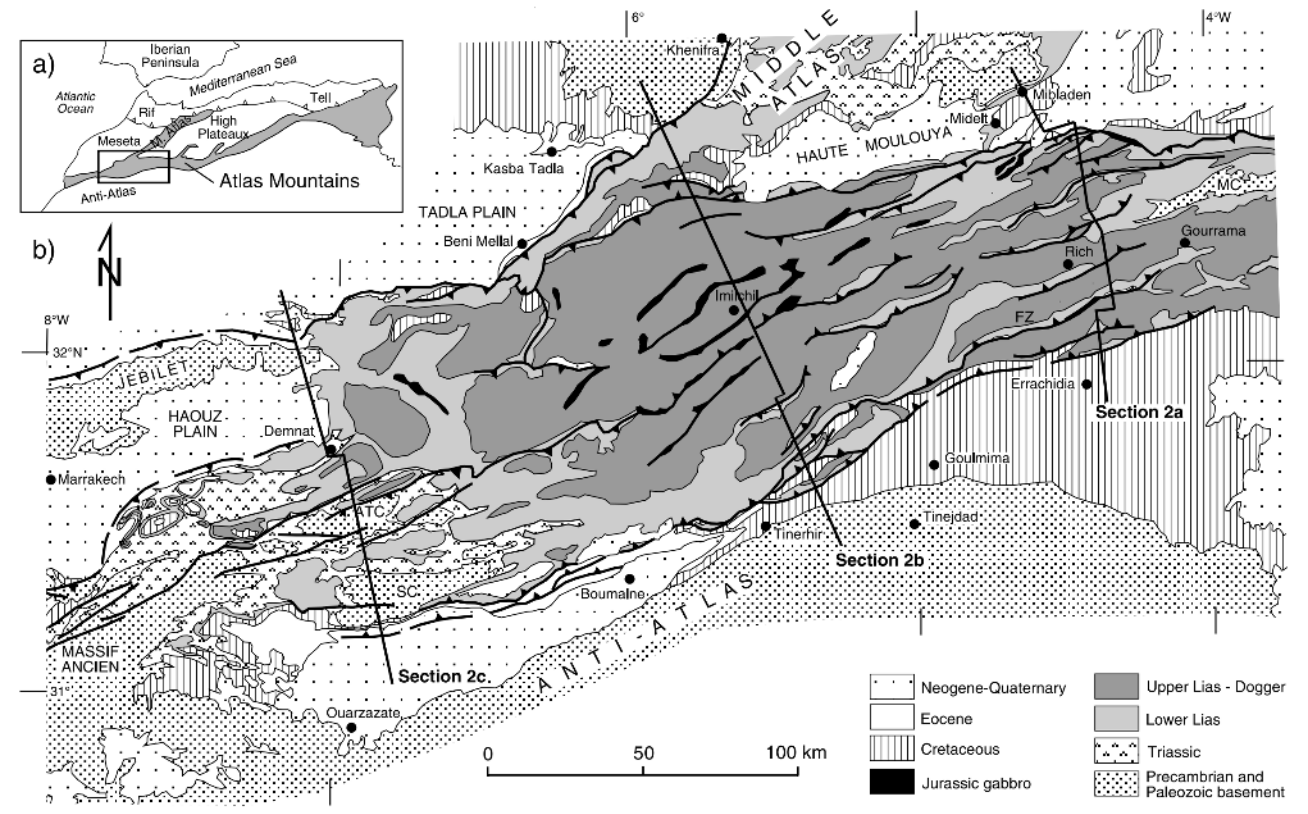


Figure 9.13 – Geologic map of the west-central Atlas Mountains in northern Africa. Insert shows location of this geologic map in the Morocco. The terms Lias and Dogger are European lithostratigraphic units for rocks deposited in the upper Triassic through middle Jurassic. Image Credit: Teixell et al. 2003.

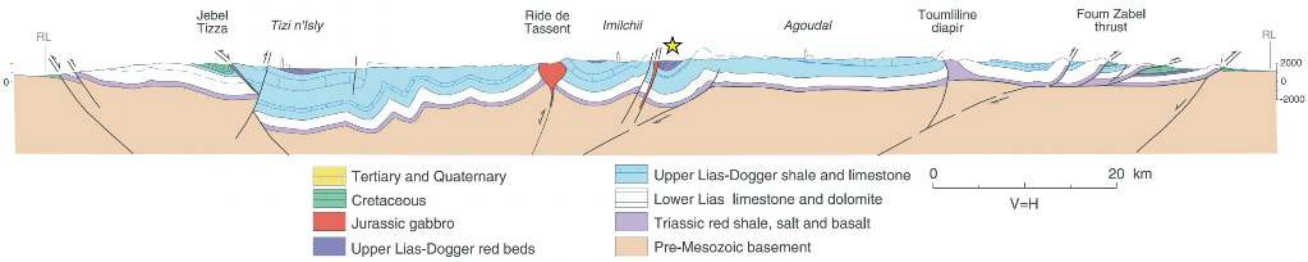


Figure 9.14 – Cross-section of line labeled “Section 2b” on Figure 9.9. The yellow star is the approximate location of the Google Earth tour for this exercise. The terms Lias and Dogger are European lithostratigraphic units for rocks deposited in the upper Triassic through middle Jurassic. Image Credit: after Teixell et al. 2003.

https://geo.libretexts.org/@go/page/18718

l. Find three different sedimentary units, following them across the cross-section. Which unit is the most continuous? Which unit is the least continuous?

m. Is there evidence of an unconformity? If there is, mark on the cross-section where it is. Identify the type of unconformity.

n. On the cross-section, label the anticlines and synclines.

o. Label and identify which kind of faults are present in this area.

p. What type of structure formed the Toumliline diapir?

q. Give a generalized geologic history with the relative stratigraphic, igneous, and deformation events.

The Grand Canyon and adjacent U.S. National Parks cover the entire stratigraphic section from Early Proterozoic to Holocene. This sequence records almost continuous sedimentation with gaps in time (unconformities). This entire section is not exposed in one National Park. In addition to having an awesome exposure of sedimentary rocks, the area has also undergone deformation with faults and folds; this occurred between 70 and 30 Ma ending with the uplift of the Colorado Plateau. If you want to keep track, there are ~40 major sedimentary units in the Grand Canyon.

? Exercise 9.4 – Grand Canyon

One of the most complete records of geologic time is in the Grand Canyon. So, this is an excellent area to learn how to read geologic maps. Before beginning this exercise about the Grand Canyon, you should review the stratigraphic section in Figure 2.25 or look at the sketch by Powell in Figure 0.3.

Getting the Map

If your department has a poster printer, you can print out a large version of the geologic map of the Grand Canyon from this file (opens in a new window). This map is from a USGS poster, but we have removed much of the extra material. Otherwise, you can use this interactive online version of the map.

For fun, you want to look at a 3D geologic map. Another way to look at the Grand Canyon is to use Google Streetview. Start at the South Rim on this map, and drag the orange person icon onto one of the trails to view the rocks from inside the canyon! Or, if you want to do more, you can look at an immersive virtual field trip to see more of the canyon for yourself!

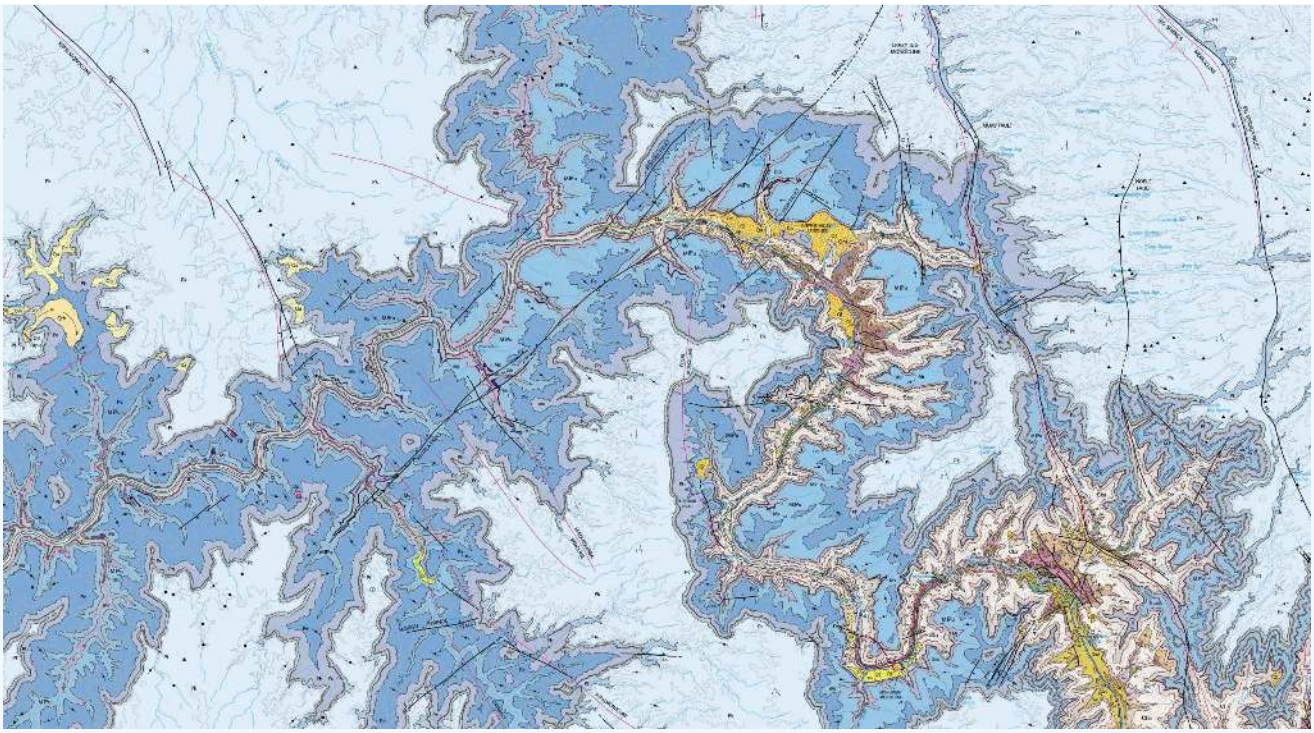


Figure 9.15 – Screenshot of the geologic map of the Grand Canyon. Image credit: Screenshot from USGS map, Public Domain.

Part 1: Map Reading

a. What is the dominant rock type in this map? _____
b. What is the age of about 80% of this map? Give its geologic period. _____
c. Find an example of each type of structure including three types of folds, two types of faults, dipping and horizontal beds, sinkhole, collapse structure, and pyroclastic cones.
d. Which stratigraphic unit is the oldest? Which is the youngest? Give their geologic period and name.

_____

Part 2: Timing

e. Locate on the map the Great Unconformity and estimate its time gap. _____
f. On the map, locate the Greatest Unconformity and estimate its time gap. _____
g. Which of these has the greatest time gap?_____
h. **Critical Thinking:** The Great Unconformity is an iconic geologic feature that marks the boundary between non-fossil-bearing Precambrian rocks and fossiliferous Phanerozoic strata. In North America, it spans from Mexico to Canada. Can you explain why there is this unconformity? What would you look for in either the map pattern or an outcrop (Figure 9.16) to support your hypothesis?



Figure 9.16 – The Great Unconformity in the Grand Canyon with Vishnu schist overlain by Tapeats sandstone. Image credit: Al_HikesAZ CC BY-NC 2.0.

Part 3: Map Patterns

i. Describe or sketch the map pattern for a nonconformity.

j. Describe or sketch the map pattern for an angular unconformity?

k. Using the Rule of V's, describe or sketch the map pattern for flat-lying sedimentary units.

l. **Critical Thinking:** Can you tell from the map pattern which is a resistant rock unit?

Part 4: Critical Thinking about the Geologic History

m. What is the age of the Bright Angel fault? _____

n. There are a series of parallel faults such as the De Motte and Uncle Jim Faults. Using Rule of Vs and their map pattern, are these vertical, horizontal or dipping faults?

_____

o. Is the Kaibab anticline older or younger than these faults? Explain.

p. Some think the Grand Canyon started to form only 5 million years ago when the Colorado River started to cut through the stratigraphy. Others say the Grand Canyon started to form in the Laramide 50 to 70 million years ago. Are there any features on this map that support either hypothesis? Look at the ages of the rocks and faults that are cross-cut by the Colorado River to support your answer.

q. **Critical Thinking:** Using this map, construct a geologic history beginning in the Cambrian and ending in the Holocene. Here is a youtube video of past plate configurations. Anytime the area is blue, it was underwater. Green and brown indicate was landscape and subject to erosion and/ or tectonic uplift.

The Burgess Shale in Yoho National Park in British Columbia, Canada, is a world-famous fossil locality. This locality is famous for its 508 Ma fossils that mark the Cambrian explosion. These are one of the earliest fossil beds that contain soft-bodied imprints of a wide variety of life forms. Many of these are ancestors of higher life forms such as chordates, while others appear unrelated to any living forms. Charles Walcott, Secretary of the Smithsonian Institution, first discovered these in 1909. Walcott collected over 65,000 specimens. Nearby there are other quarries that are still yielding new specimens. There are over seventy similar localities for soft-bodied Cambrian fossils! They were initially described in Vermont 25 years before the Burgess Shale discovery.

One example of a bizarre animal from this location is Opabinia which had five eyes, a backward-facing mouth as well as a proboscis to scoop out prey from the marine muds. Only twenty specimens of this animal have ever been described; they all come from one layer within the Walcott quarry site. No one agrees on what family this carnivore belongs to; some say primitive arthropods and others trilobitoids.

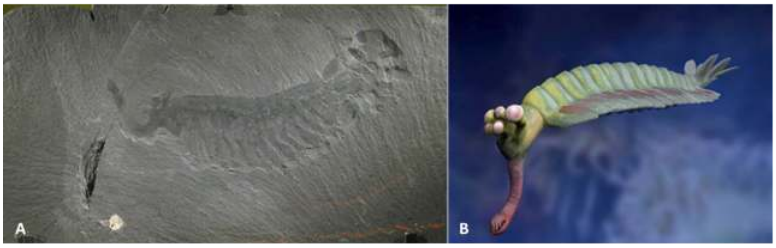


Figure 9.17- Opabinia regalis. (A) Fossil of Opabinia regalis from the Burgess Shale originally collected by Charles Walcott. (B) Restoration of Opabinia regalis. This carnivore was 4-7 cm in length. It is difficult to restore this fossil since it was flattened during fossilization and lithification of the host shale. Image credit: (A) Smithsonian Museum Public Domain. (B) N. Tamura CC BY-SA.

Exercise 9.5 – Burgess Shale

Before you begin to look at the next map, it is useful to remember some of the principles of using a topographic map that you learned in Physical Geology. In this exercise as you'll be using a Canadian map, which uses different scales compared to maps from the U.S. Geological Survey. So, the contour intervals will be different as well as its scale. Contour intervals generally are inversely proportional to the map scale and also depend on whether the area has flat or steep topography. So, by just determining this, you'll be able to judge whether or not you'll be able to easily hike through the area or not.

Look at Lake Louise, west half map by Price et al., 1980. The geologic map (opens in a new tab) and cross-sections (opens in a new tab) can be downloaded and printed on a poster to be able to better view geologic features. This area is very mountainous and has small **valley glaciers**.

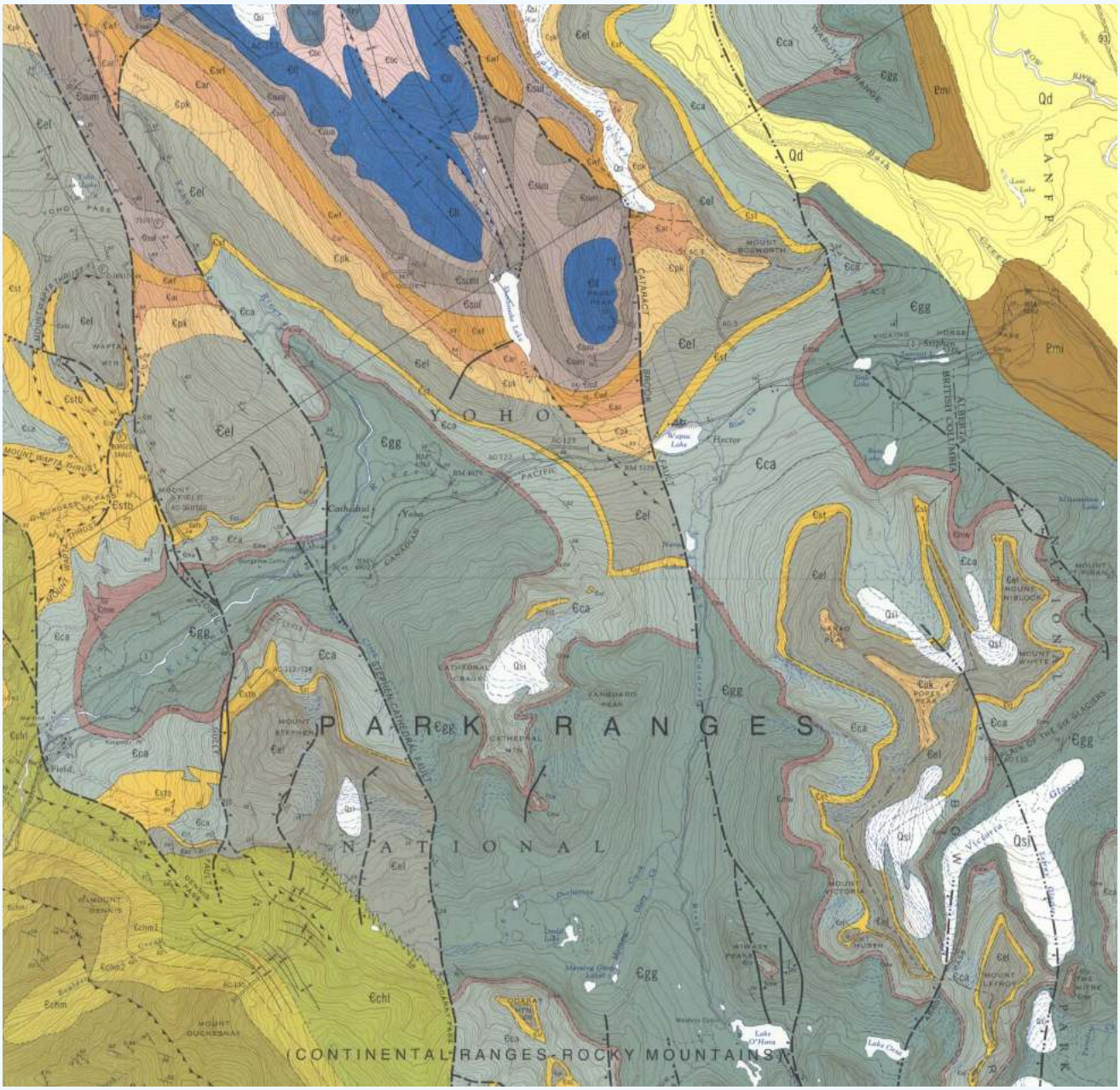


Figure 9.18 – Screenshot of part of Lake Louise (west) map, British Columbia-Alberta Canada. This is the part of the map you'll use for this exercise. Image Credit: Geological Survey of Canada.

Part 1: Map Information

a. What are the contour intervals on this map? _____
b. How would you identify a glacier versus a lake on this map? _____
c. What is the scale of this map? _____

Part 2: Cross-Sections

Find the two cross-section lines. Look at the northernmost cross-section between points labeled "6."

d. What is the highest point along this line? _____
e. What is the name of one prominent mountain along this cross-section?

_____

f. What is the elevation of the lowest point along this line? _____
g. What is the total relief along the line of this cross-section?

_____

Part 3: Stratigraphic Column

g. The Burgess Shale quarry locality is labeled with an F. It occurs north of the town of Field, to the west of Mount Field.
   i. What is the name of this formation? _____
   ii. What is its color? _____
   iii. What is its map symbol? _____
   iv. What is its rock type? _____
   v. What is the general strike of this unit? _____
   vi. What is the general dip of this unit? _____

h. Look another unit either stratigraphically below or above the Burgess Shale location.
   i. What is the name of this formation? _____
   ii. What is its color? _____
   iii. What is its map symbol? _____
   iv. What is its rock type? _____
   v. What is the general strike of this unit? _____
   vi. What is the general dip of this unit? _____

i. Which of these two formations is thicker? _____
j. Which of these is made of resistant rocks? _____

Part 4: Structures and Correlation

p. What type(s) of brittle structures are in the general vicinity of the Walcott quarry in the Burgess Shale unit?

_____

q. What type of natural disaster do you think a gravity fault is associated with?

_____

r. Using the schematic stratigraphic relationships, what formations are time correlative with the Burgess shale?

_____

s. On the eastern edge of the map lies the oldest formation in this map area, the Proterozoic Windermere Group. You may remember a correlative unconformity, the Great Unconformity above the Vishnu Schist and Zoroaster Granite in the Grand Canyon (Figure 2.25) or a similar unconformity in Central Texas seen at Slaughter Gap. What type of unconformity occurs between the Windermere Group and the overlying lower Cambrian Gog Group?

_____

t. **Critical Thinking:** Looking at this map, are there any areas you think might be good to find additional fossils equivalent to the Burgess shale fauna? When you propose an area, you need to consider several factors such as ease of access as even Walcott quarry is about 8 miles from a road and involves a steep climb. Also, avoid outcrops that may be close to faults. In addition, locations down low may be forested and not have any exposed rocks.

_____

Additional Information

Exercise Contributions

Virginia Sisson, Daniel Hauptvogel, Carlos Andrade, and Joshua Flores

References

Billingsley, G. H., 2000, Geologic Map of the Grand Canyon 30' x 60' Quadrangle, Coconino and Mohave counties, northwestern Arizona, U. S. Geological Survey, Geological Investigations I-2688 Map and Pamphlet. Public Domain

Price, R.A., Cook, D.G., Aitken, J.D., and Mountjoy, E.W., 1980, Geology, Lake Louise (west half), west of fifth meridian, British Columbia-Alberta. Geological Survey of Canada, "A" Series Map 1483A, 1980, 2 sheets, https://doi.org/10.4095/108873 (Open Access)

Teixell, A., Arboleya, M.-L., Julivert, M., and Charroud, M. (2003), Tectonic shortening and topography in the central High Atlas (Morocco), *Tectonics*, 22, 1051, doi:10.1029/2002TC001460, 5.

Google Earth Locations

Click or Scan to View all Chapter 9 Locations on Google Earth

This page titled 1.10: Geologic Structures and Mapping is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.11: Interpreting Earth's History using Maps

Learning Objectives

The goals of this chapter are to:

- Understand how fossil locations can be found using geologic maps
- Interpret geologic provinces using maps
- Construct geologic histories using maps

Some of the maps in this chapter can be printed on poster paper from large PDF files found here (opens in a new tab).

10.1 Introduction

Throughout this lab manual, you've been looking at geologic maps for many purposes, such as locating different types of rocks, finding plate boundaries, investigating stratigraphic relationships, and more. However, there are few things you have yet to do. One important skill is using geologic maps to find fossils. This involves using your knowledge of the environment fossil used to live such as deep marine, swamp, or deserts, and the age of the stratigraphic unit. You will need to use your knowledge gained from Chapters 5 to 8.

The other is relating many different features such as magmatic activity, paleoenvironment, deformational history, metamorphism to create geologic provinces that share a common Earth history. Typically a geologic province is many 100's of kilometers in size. They can be a single geologic feature (for example, a sedimentary basin or thrust belt) or a combination of contiguous geologic features. To define geologic provinces, you will use almost all of the concepts you've learned over this course. Why is this important? Well, you can use a geologic province to find resources such as oil and ores. They also will share a similar story of Earth.

You may also identify provinces on other planets, such as Mars, which has three geologic provinces; 1) Tharsis, which is volcanic, 2) northern highlands which have a smooth topography, and 3) southern highlands, which are rugged and heavily cratered (see Golombek and Phillips, 2010). If you were going to go put a settlement on Mars, which of these would you pick to settle just knowing this information?

10.2 How to Locate Fossils

When scouring an area for fossils, the easiest to find are those exposed by weathering from wind or water. In 2020, a California state park ranger was checking out a watershed near the Mokelumne River. He spied a fossilized tree. Then he came back and found that erosion over the year exposed a whole petrified forest and fossilized bones from Miocene mammalian megafauna such as ancestors of horses and rhinos, gomphotheres (similar to elephants but with twice as many tusks), giraffe-sized camels, and many other creatures. Now a team of paleontologists and geologists is excavating the site. You may ask why so many fossils are in one place and why they eroded away so quickly. Well, they were either buried in a mudslide or volcanic ash such as a lahar. Both of these are easy to erode rapidly and expose all the bones of the trapped creatures. So, keep on looking, and perhaps you'll find some of your own fossils.

Once you have found a fossil, what comes next? There are many resources available for amateur fossil collectors. After your initial discovery, if you think you might have an interesting find, you can contact other paleontologists for help or use web resources. If this is a new discovery or unusual specimen, paleontologists will excavate the fossils by removing any overburden and bring them to a museum or other collection. Small fossils such as mammalian teeth are sometimes collected by dry sieving sands.

Many think this is glamorous work similar to what is seen in movies such as Indiana Jones or Jurassic Park. In reality, it often involves tedious work sitting in a dry, hot, dusty quarry removing overburden for many days, especially to expose large fossils. Or you may have to dig a trench around a large specimen to successfully get all of the fossil (Figure 10.1). These large fossils need to be encased in a plaster jacket before bringing them back to the lab. In contrast, delicate fossils are often wrapped in toilet paper to protect them. Plus, Indiana Jones's job performance would not have been viewed favorably by his university.



Figure 10.1 – A paleontologist works to encase Cretaceous dinosaur footprints in a plaster jacket. A plaster jacket is like a cast that a doctor uses to fix a broken bone. This plaster jacket is made of sheets of burlap soaked in plaster-of-Paris. This shows a yellowish sandstone layer below the iron-rich clay layer in which the dinosaur footprints were preserved. Image Credit: NASA/GSFC/Rebecca Roth.

Fossil collecting must be done with proper permission and possibly permits, especially if you are looking for fossils on public lands in the United States and Canada. It is important to know the local laws. For example, you can't collect anything in a National Park. In a National Forest or Bureau of Land Management land, it is illegal to collect fossil bones but okay to take up to 25 pounds of fossilized wood per day, up to 250 pounds per year. So, before you start your own collection, be sure you have proper permission from either the landowner or the proper authorities to collect fossils.

Now that you are using fossils for more than just curiosity, you need to think about how to best preserve them and their future usefulness for others. Many amateur fossil collectors only record the fossil name and the formation. What kind of information do you think is needed?

1. Location from GPS with latitude/longitude
2. Do you need elevation?
3. Additional descriptive details such as collected near a stream
4. Do you need stratigraphic information?
5. Age of formation?
6. Orientation of the fossil relative to layering
7. Labeling – should this be on a separate piece of paper or on the specimen, or both?
8. What other fossils were found at this location?

? Exercise 10.1 – Using Maps to Find Fossils

Now that you have all of the basics for fossil collecting, it's time to go on a search. Fossils in museums are identified by location data and geologic age. Below is a map of all the fossil localities known in the United States from PaleoDB.

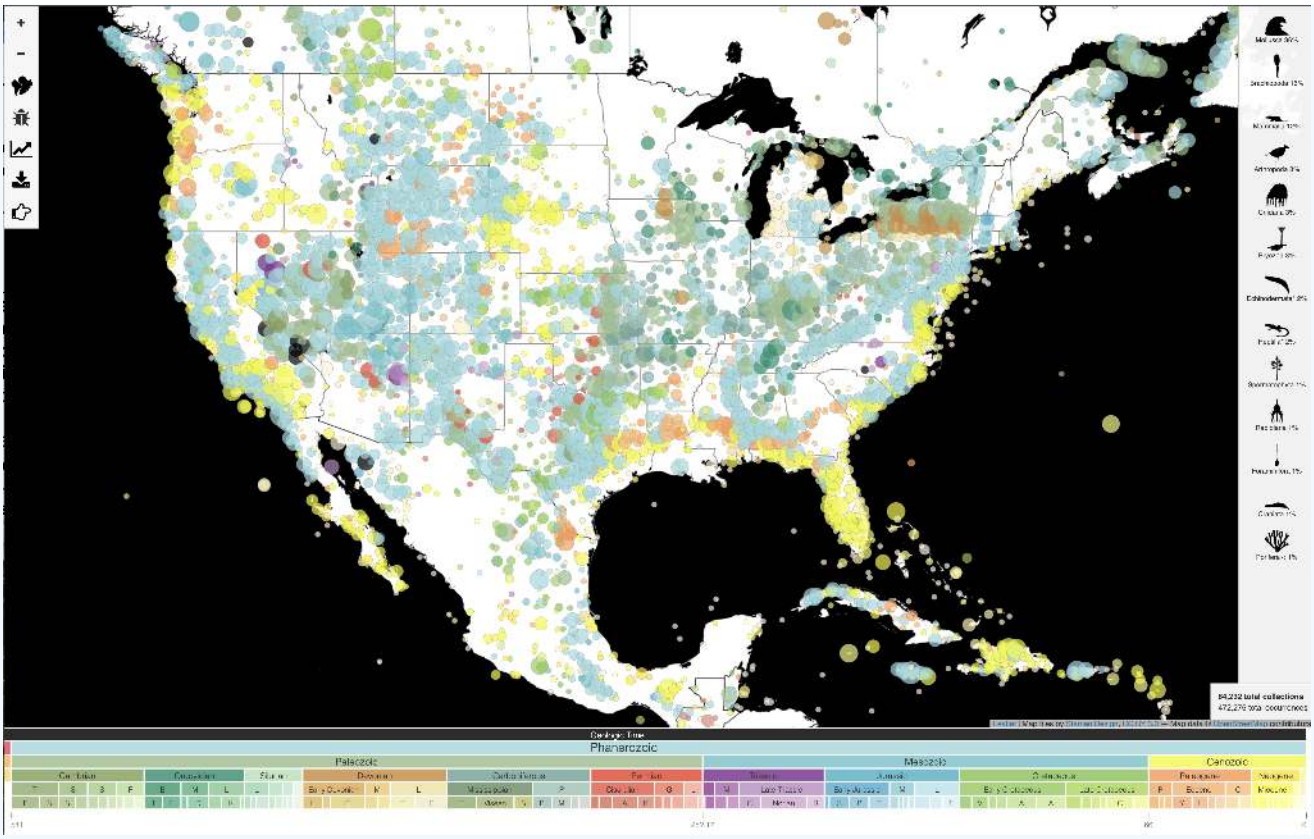


Figure 10.2 – Map of North America and the northern Caribbean showing fossil locations indicated by colored dots. The color correlates with geologic age according to the geologic time scale at the bottom. The size of the dot indicates how many species are found at specific locations. On the left side of the image are the percentages of different fossil phyla for all locations. Image credit: map and data from PaleoDB Navigator world map CC-BY.

a. On the map, mark a few locations that you think would be interesting to go visit. What is the age of the fossils you would find there? _____

b. What type of fossils do you think you might find in these locations? Use your knowledge of fossil diversity through time shown in Chapter 7, such as Figure 7.7 or 7.18. _____

If you search online for the best places in the world to go look at fossils or collect them, the number one locality is the Burgess Shale (Exercise 9.4) to see the first soft-bodied animals (but you can't collect here as it is a protected site). If you want to be in the United States, go to Calvert Cliffs in Maryland to collect shark teeth and more. However, if you want to combine a trip to Europe with this search, go to either the UNESCO World Heritage Site in the Jurassic Coast of the United Kingdom (Exercise 5.3) to collect ammonites or take a trip off the beaten track to Stevns Klint in Denmark. We'll explore what fossils can be found here as well as their geologic history.

To start your exploration of Stevns Klint, first look at the geologic map (Figure 10.3) and then the stratigraphic column (Figure 10.4). To the east and north is Sweden, a part of the Precambrian Fennoscandian Shield made of Archean and Proterozoic gneisses and greenstones. The latest geologic event in southern Sweden was the Sveconorwegian orogen active between 1140 and 960 Ma; too old an area to have any fossils. North-south rifting associated with the break-up of Pangea in the Triassic created the Danish Basin, an extension of the Oslo Graben in Norway. After rifting, marine incursion can be seen as a section of carbonates. A marine setting can host many animals and might be a good place to collect fossils. During the Upper Cretaceous, deep marine carbonates composed of **coccolithophores** (algae) settled in the rift basin as a carbonate ooze and are now lithified as **chalk**. As the basin filled in, carbonates were deposited in bryozoan mounds in shallow water. Today, sea cliffs at Stevns Klint expose chalk at the base, then a clay layer rich in **iridium**, and finally a bryozoan limestone with chert nodules. This boundary between the Cretaceous and Danian (Paleogene) was initially described in 1847 by Desor.

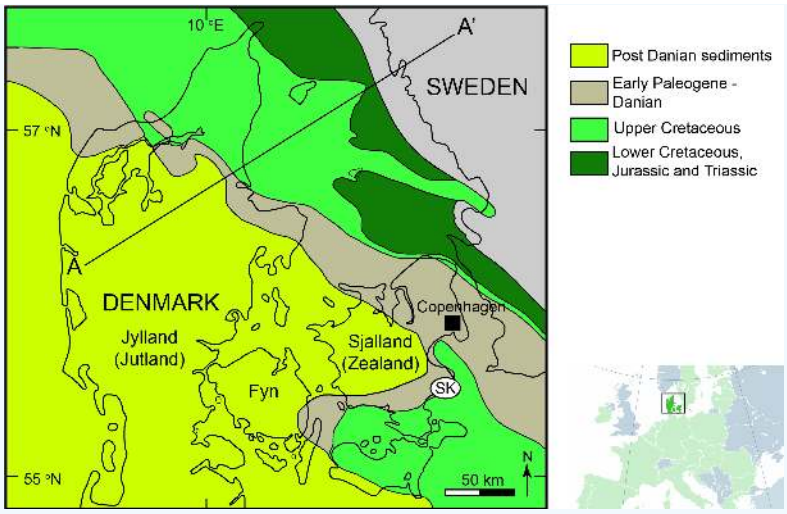


Figure 10.3 – Geologic map of Denmark and Danish Basin. Circle with SK shows the location of Stevns Klint UNESCO World Heritage site. Some geographic location names are given in both Danish and English. Legend indicates the sedimentary units. The gray color represents the Fennoscandian Shield. Image credit: VB Sisson adapted from Adolfssen and Friedman (2017) with index map from NuclearVacuum CC BY-SA 3.0.

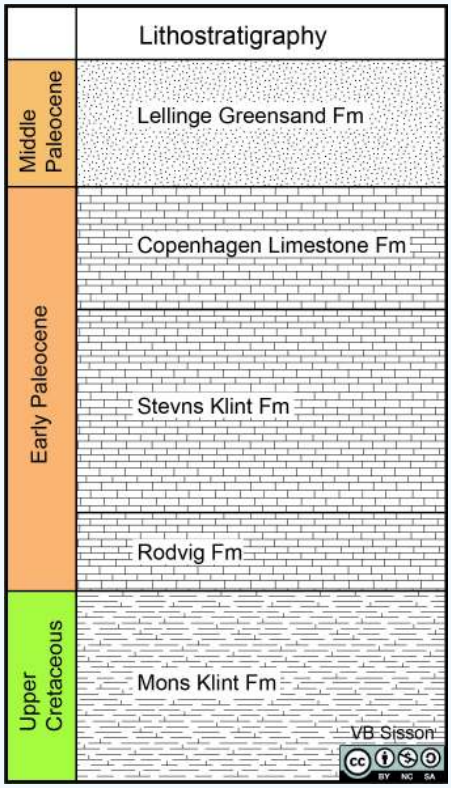


Figure 10.4 – Stratigraphic column for the Danish Basin. This figure has a lithologic pattern you've not seen before that represents chalk (carbonate made of coccolithophores). Note that the geologic time scale uses different colors from the geologic map. Image credit: VB Sisson adapted from Adolfssen and Friedman (2017) CC-BY.

Use the geologic map and stratigraphic section to address the geologic history of this region.

c. What types of unconformity separates the Swedish Fennoscandian Shield from the Danish Basin?

_____

d. What major geologic event occurred in Stevns Klint? Hint: think through all of Earth's history.

_____

e. This boundary is seen at the Stevns Klint location and elsewhere. Circle several other locations on the map that you may go to look for this boundary.

f. What type of fossils would you find in the Mons Klint Formation? _____

g. Do you think the same fossils occur in the Stevns Klint Formation? Explain. _____

h. Would you find Mosasaurs or Plesiosaurs in the Rodvig Formation? _____

i. In which formation would sample to collect echinoderms? _____

j. Draw the boundary between the Cretaceous chalk and the Danian bryozoan mounds on this image. If you could get close to this cliff, this would be marked by a distinctive clay layer rich in iridium.



Figure 10.5 – Photo of Stevns Klint showing the Upper Cretaceous and chalk and Danian bryozoan mounds. Image credit: Lisa Risager CC.

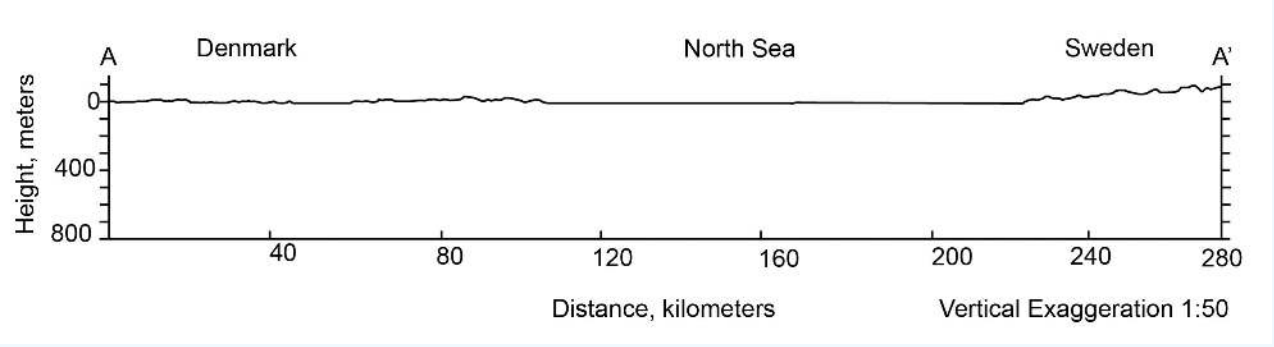


Figure 10.6 – Topographic profile across the Danish Basin. from A-A' . Vertical exaggeration is 1:50. Image Credit: VB Sisson using Google Earth Pro for topography. CC-BY

k. What type of contacts are there between the sedimentary units? _____

l. The Danish Basin geologic map only has formations and does not have any strike and dip symbols (Figure 10.2). The topography in the area is very subtle; even with a very large vertical exaggeration of 1:50, you do not see much in the way of mountains on the cross-section. To make a cross-section, you will need to locate the boundaries between stratigraphic units along the cross-section. Then, using the outcrop picture, the rule of V's, and the vertical exaggeration, you can determine the dip of the units. Draw a schematic cross-section along A-A'. This might be tricky as some of the units are not very thick.

10.3 Geologic Provinces

Have you ever looked at a geologic map of North America? You may not remember it, but part of the map you saw during the first week of lab was North America (Figure 0.9). The age and character of the rocks give rise to landscape characteristics (physiographic) and the types of soil and sediments that cover the surface. The modern landscape of the United States has been shaped by tectonic, climatic, sedimentary, and erosional processes.

On a grand scale, the contiguous United States is divided into eight physiographic regions which are then subdivided into 25 provinces. These are further subdivided into sections. We won't worry about the smallest subdivisions. In comparison, Africa has eight regions with 17 provinces, and South America has only four regions with 27 provinces.

? Exercise 10.2 – Geologic Provinces of the United States)

People tend to be either "lumpers" or "splitters". The "lumpers" like to group things together and join areas with similar characteristics. On the other hand, "splitters" like to subdivide characteristics into smaller and smaller groups. This is why you might find more or fewer physiographic provinces on maps from different geologists.

a. Write a general statement about the topography of North America from the west coast to the east coast. Use Figure 10.7 as your reference.

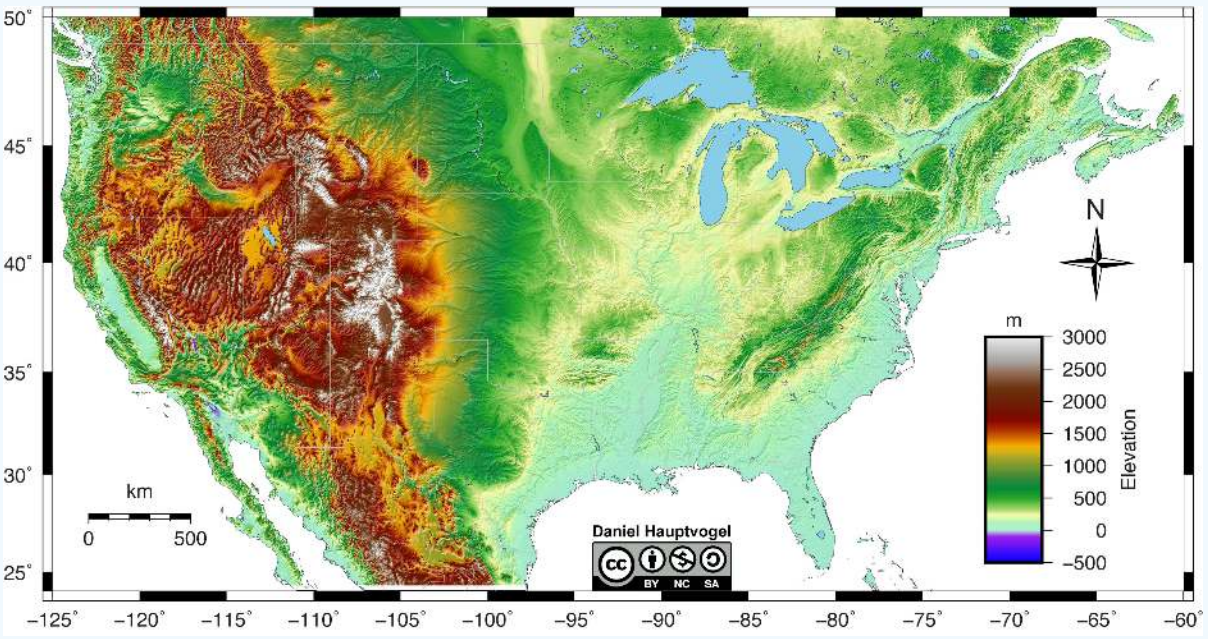


Figure 10.7 – Shaded relief map of the United States. Red and white colors represent high elevations, greens and yellow represent lower elevation, and purple and blue represent areas below sea level. Map scale reference is 40° latitude. Image credit: Daniel Hauptvogel, CC BY-NC-SA

b. On Figure 10.7, roughly draw how you would divide North America into different physiographic provinces based on topography. Use as many provinces as you think necessary. A marker might be best for drawing the boundaries.

Another way to look at geologic provinces is to see the general distribution of rock types. Figure 10.8 shows how igneous (volcanic and plutonic), sedimentary, and metamorphic rocks are located throughout North America. Many sediments and sedimentary rocks are exposed at the surface. These materials typically cover the surface and overly older rocks. Sedimentary rocks exposed throughout North America are of all geologic ages and were often deposited in paleoenvironments different from what exists in the region today.

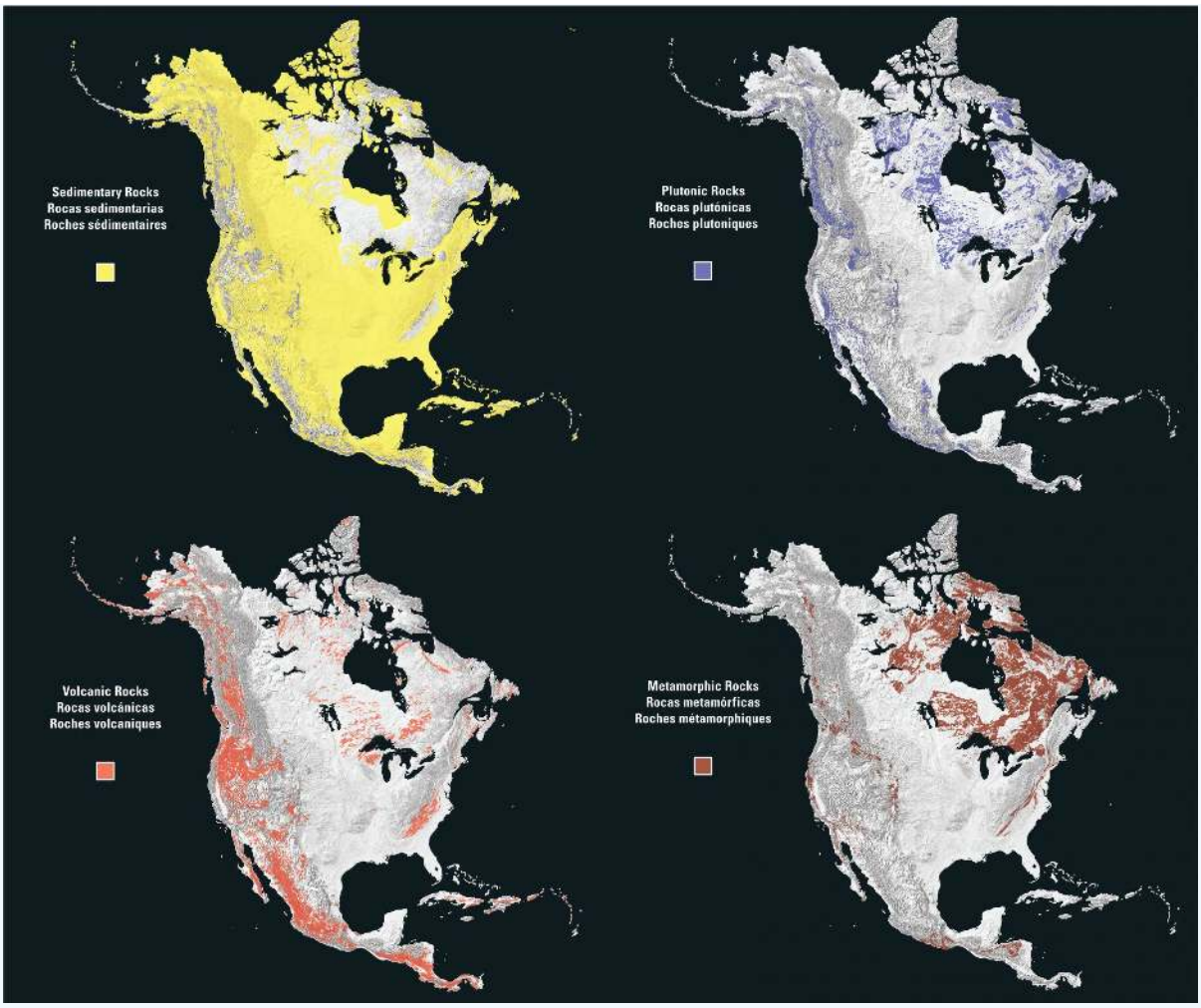


Figure 10.8 – The distribution of rock types on the surface throughout North America. Volcanic rocks are extrusive igneous rocks, and plutonic rocks are intrusive igneous rocks. Image credit: From Kate Barton, David Howell, Jose Vigil, USGS, Public Domain

c. Why do we consider plutonic and volcanic rocks separately when evaluating provinces? Hint: think about the cooling ages of the two types of igneous rocks.

d. Why do we consider the youngest exposed crustal rocks when evaluating provinces (plutonic and/or metamorphic rocks)? Hint: Consider what processes are necessary to expose these deep rocks.

e. Table 10.1 lists 10 major provinces of the United States. Use the map and key in Figures 10.9 and 10.10 to draw where these are located. You may be familiar with the names of some of these provinces, but feel free to search for their general locations to help you.

f. How do the province boundaries you identified in Figure 10.7 (relief map) compare to the ones you identified in Figure

10.9 (geologic map)?

g. Use all the maps provided (Figures 10.7 to 10.10), compile all the different features for each of the tectonic provinces listed in Table 10.1 to look at the characteristics of the ten provinces. Make sure to note observations in the “Topography Patterns” column, such as if the area is mountainous, or what direction are the mountains oriented, or if the hills are flat or gentle.

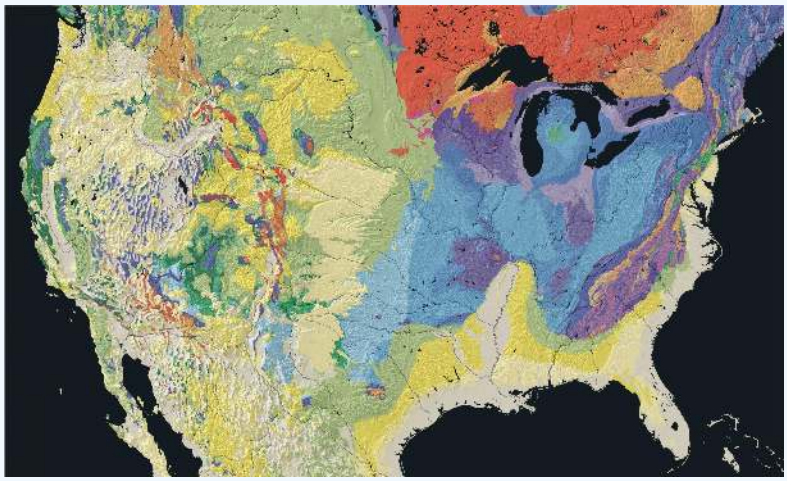


Figure 10.9 – The geologic map of the United States, southern Canada, and northern Mexico. Image credit: From Kate Barton, David Howell, Jose Vigil, USGS, Public Domain.

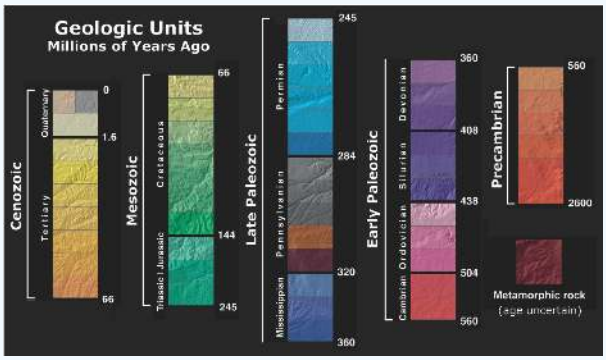


Figure 10.10 – Geologic ages for the map in Figure 10.7. Numbers are in millions of years. Image credit: From Kate Barton, David Howell, Jose Vigil, USGS, Public Domain.

Table 10.1 – Worksheet for Exercise 10.2

Province	Dominant rock type	Youngest plutonic or metamorphic rock	Topographic Patterns	Geologic Structures
Sierra-Nevada				
Columbia Plateau				
Basin and Range				
Colorado Plateau				
Rocky Mountains				
Ozarks/Ouachita				
Great Plains				
Canadian Shield				
Coastal Plains				
Appalachians				

One major issue for society is potential sources of energy. Traditionally this has been coal and petroleum, as well as hydroelectric. Now, there is a push for alternative sources. Have you ever considered just using the temperature of the Earth as an energy source? This can be done using a heat pump to warm or cool a house. Since Vikings first landed in Iceland, they used geothermal energy for bathing, baking bread, and washing clothes. Now, nine out of ten homes in Iceland are powered by geothermal energy. In the United States, the Basin and Range province has great potential for geothermal energy (NREL).

h. **Critical Thinking:** Figure 10.11 is a theoretical cross-section of the Basin and Range province. Why does the Basin and Range Province have a great potential for geothermal resources?

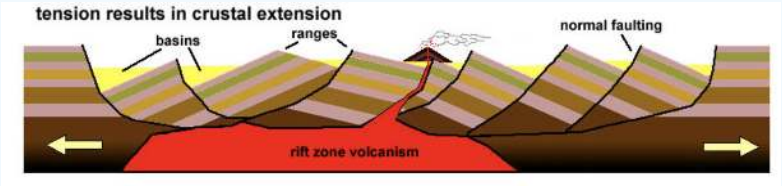


Figure 10.11 – Theoretical geologic structure of the Basin and Range Province. Image credit: from MiraCosta College, CC.

? Exercise 10.3 – Northern New Jersey Map

The geology of northern New Jersey contains a record of the Appalachian Orogenies, including the assembly of Pangea and its subsequent breakup. You can print the geologic map (opens in a new tab) and cross-sections (opens in a new tab) on poster paper. Both maps contain descriptions of the bedrock lithology. The bedrock is either exposed at the surface or sits beneath loose, unconsolidated sediment. Alternatively, you can access digital versions of both maps from the USGS. Use the red arrows in the Map Preview to cycle between each map. The files available for download are on the right-hand side.

Part 1: Separating Geologic Provinces

a. Observe the patterns of colors on the main bedrock map. Divide northern New Jersey into three different regions based on the colors and patterns on this map. Describe the three regions that you can identify using the colors on the map or ages of

the rocks.

Part 2: Valley and Ridge Province

The Valley and Ridge Province formed as a result of deposition and slight deformation of sediments associated with the Taconic and Acadian Orogenies.

b. Do the sedimentary rocks become older or younger as you move northwest? _____

   i. On a regional scale, what does that tell you about the direction these rocks are dipping towards?

c. The Basin and Range province of Nevada is formed through a series of normal faults where basins (valleys) are the hanging walls that dropped down relative to the ranges (mountains) on the footwall. Look at the structures that form the Valley and Ridge Province in New Jersey; how are they different from the Basin and Range Province of Nevada?

   i. For both locations, describe the types of plate boundaries or stresses that would cause these structures.

d. The rock types give geologists clues to what the tectonic setting was. Limestones are typical examples of passive times with little to no tectonic activity. Sandstones, shales, and conglomerates are indicative of active tectonic margins, indicating uplift and then erosion of mountains. Table 10.2 contains a generalized stratigraphic column of the Valley and Ridge Province in northwestern New Jersey.

   i. In Table 10.2, identify the type of rock(s) that comprises each unit. Use terms limestone, shale, sandstone, conglomerate, and quartzite. Quartzite tells you the rock used to be sandstone. You can find all of this information on the 2nd map page.
   ii. Indicate whether the area was an active or passive margin for each unit. Some units contain evidence for both.
   iii. The Valley and Ridge Province contains sedimentary rocks derived from two Appalachian mountain-building events: the Taconic Orogeny and the Acadian Orogeny.
   iv. In Table 10.2, label the rock units you think best represent when these orogenies were active. An orogeny can span more than one unit.

Table 10.2 – Worksheet for Exercise 10.3

Map Symbol	Lithology	Active or Passive	Orogeny
Dm			
Db			
Ds			
De			
Do			
Dp			
Dmn			
Dkc			
DSrd			
Sbv			
Sp			
Sb			
Ss			
Omr			
Omb			
Oj			
Ow			
Obu			
Obl			
O€a			
€l			
€h			
Yu	Igneous and Metamorphic		Grenville

Part 3: The Highlands Province

The New Jersey Highlands lie between the Valley and Ridge Province and the Newark Basin.

e. What two types of rocks are the Highlands primarily made of? _____

f. Are the igneous rocks primarily intrusive or extrusive? _____

g. Are the metamorphic rocks primarily high, medium, or low grade? _____

h. Most of the rocks in this region of New Jersey have the same age. What is it? (Hint: Look for the Mount Even Granite and the Hornblende granite of the Byram Intrusive Suite) _____

i. **Critical Thinking:** Come up with an explanation of how you get these different rocks forming simultaneously. (Hint: Think about the tectonic setting that could have done this)

j. In the middle of the Highlands lie Silurian and Devonian sedimentary rocks (blue and purple colors). You can look at cross-section A-A' to help.

i. Do you think this isolated group of sedimentary rocks could be related to the Silurian and Devonian sedimentary rocks from the Valley and Ridge Province? (Hint: Look at some of the rock descriptions) _____

ii. Explain your answer.

iii. If you thought they were similar, why aren't these two areas connected?

iv. If you thought they were different, explain how you would get these two sets of sedimentary rocks deposited at the same time.

Many of the rocks in this region have an age that corresponds to the Grenville Orogeny and the assembly of the supercontinent called Rodinia. This orogeny is seen on many of the world's continents, including North America, South America, Antarctica, Europe, and Africa, but because this event happened so long ago, much of the evidence has been altered or destroyed by tectonic processes.

You may have noticed there is no evidence of the Alleghenian Orogeny, which was the assembly of the Pangaea about 250 Ma. Any rocks from this orogeny have all been eroded in New Jersey, but much of the faulting and folding of rocks throughout the Valley and Ridge Province and the Highlands occurred during the Alleghenian Orogeny.

Part 4: The Newark Basin

The Newark Basin (Figure 10.12), which is part of the Piedmont Province of the eastern U.S. that extends from New York to Alabama, formed during the breakup of Pangaea during the Jurassic, which eventually led to the opening of the Atlantic Ocean.

k. There is a stark transition from the Highlands Province to the Newark Basin.

i. What is the name of the feature that separates the Newark Basin from the Highlands? _____

ii. What type of structure is this? Use the cross-sections to help. _____

iii. **Critical Thinking:** Look at the cross-sections associated with this map. Why are the sediment layers dipping to the NW?

l. What types of igneous rocks would you expect to find in a rift valley? _____

i. On Figure 10.12, find and mark these igneous rocks. (Hint: look for the Watchung Mountains)

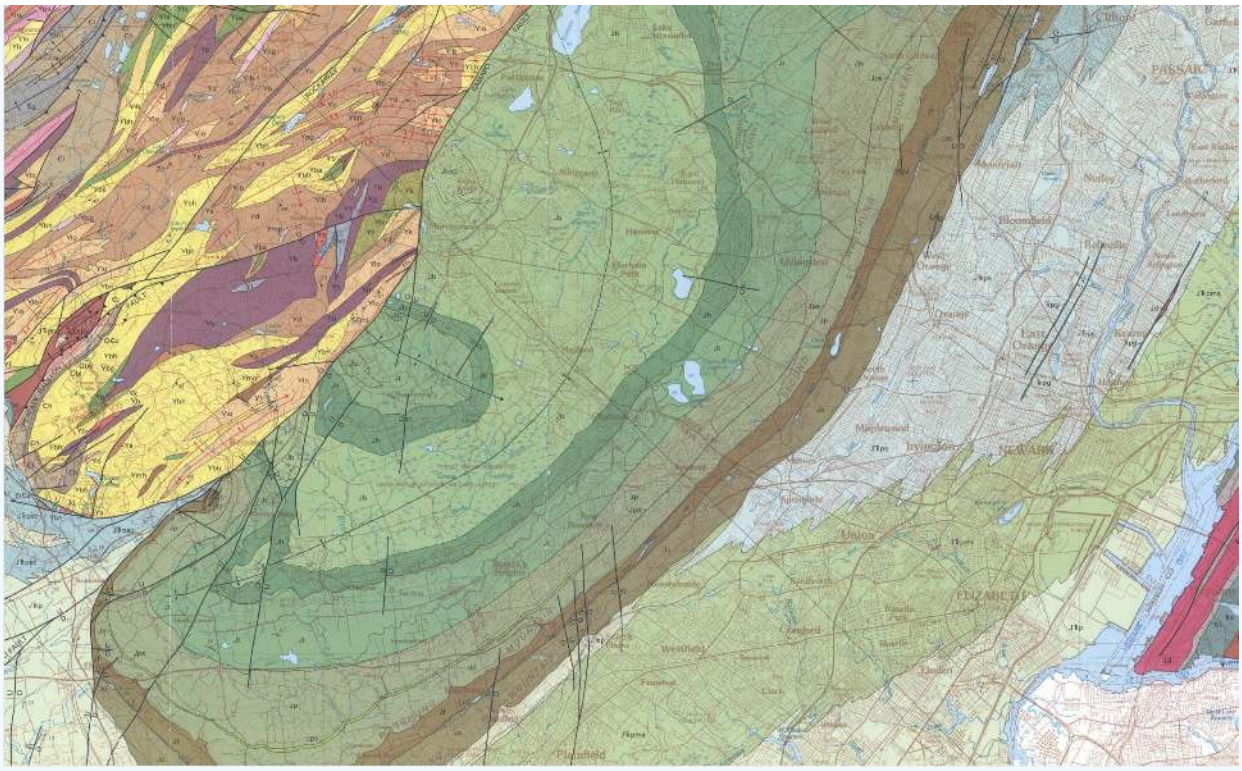


Figure 10.12 – Screenshot of the Newark Basin from the bedrock map of northern New Jersey. Image credit: USGS, Public Domain.

m. **Critical Thinking:** Since this province was associated with rifting and tensional stress, you would not expect to find evidence of compressional stress in a divergent tectonic setting. But if you follow the Ramapo Fault closely, you will see anticlines and synclines connected to it perpendicularly. Explain why these compressional features are here.

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson

References

Adolfssen, JS and Friedman, M, 2017, Review of the Danian vertebrate fauna of southern Scandinavia, Bulletin of the Geological Society of Denmark, 65, 1-23. doi: 10.37570/bdsg-2017-65-1

Desor, P.J.E., 1847, Sur le terrain Danien, nouvel étage de la craie. Bulletin de la Societé Géologique de France, 2 (4), 1779-182.

Golombek, M.P., and Phillips, R.J., 2010, Mars Tectonics in Planetary Tectonics, edited by Watters, T.R. and Schultz, R.A., Cambridge University Press, 181-232.

Some background info from https://whc.unesco.org/uploads/nominations/1416.pdf

Google Earth Locations



This page titled 1.11: Interpreting Earth's History using Maps is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

1.12: Paleoclimate

Learning Objectives

The goals of this chapter are to:

- Understand the different sources of evidence used to study past climates
- Recognize the processes influencing natural climate change
- Use geologic evidence to interpret past climates

11.1 Introduction

Earth's climate has constantly changed throughout its existence, with periods that have been much warmer and cooler than today. Evidence of these climate variations is found in the geologic and fossil records, and geologists use them to interpret how climate has changed through time. The study of past climates is called paleoclimatology.

Geologists can't directly observe past climates because they already happened; no temperature or precipitation can be measured. Instead, geologists turn to the geologic record to study things dependent on climate, in a sort of second-hand view. These secondary sources of information are called proxies. The most common proxies used to interpret past climate are fossils, but ice cores, tree rings, and sediment cores are also used. For example, a particular species of foraminifera coils its shell (technically called a test) to the left or right, depending on whether the seawater temperature was cooler or warmer. While this does not give an exact temperature, it gives you a relative idea of the conditions. If you were to find mostly right-coiling fossils in a layer of sediment, you would know that seawater temperature was relatively warm during the time those organisms lived.

? Exercise 11.1 – Foram Morphology as a Climate Signal

Foram fossils are an excellent proxy for paleoclimate because their growth is influenced by climate and ocean conditions. Some species of foraminifera are so sensitive to seawater temperature that they will alter the way they grow their test (hard shell). *Neogloboquadrina pachyderma*, for example, is a species of planktonic foraminifera that will coil its test to the right when ocean water is warmer and coil to the left when ocean water is cooler.

In a sediment core recovered from the North Atlantic Ocean, you counted the number of left- and right-coiling varieties of *N. pachyderma* to help interpret paleoclimate for the past 160,000 years. Samples of the sediment core were taken at 10,000-year intervals.

a. Complete Table 11.1 by calculating the values for the total number of *N. pachyderma* for each sample, the percentage of the right-coiling variety, and the percentage of the left-coiling variety. The first row is done for you.

Table 11.1 – Worksheet for Exercise 11.1

Age (years ago)	Right-coiling *N. pachyderma*	Left-coiling *N. pachyderma*	Total number *N. pachyderma*	% Right-coiling *N. pachyderma*	% Left-coiling *N. pachyderma*
0	230	50	280	82%	18%
10,000	220	75			
20,000	70	230			
30,000	45	300			
40,000	50	302			
50,000	65	389			
60,000	20	140			
70,000	56	287			
80,000	63	267			
90,000	212	56			
100,000	120	23			
110,000	87	45			
120,000	203	66			
130,000	56	205			
140,000	45	332			
150,000	89	135			
160,000	123	166			

b. Plot the percentage of right-coiling N. pachyderma on the blank graph in Figure 11.1 (or make your own graph in Microsoft Excel). The x-axis is the percent of the right coiling variety, and the y-axis is the age of the sediment sample the forams were in.

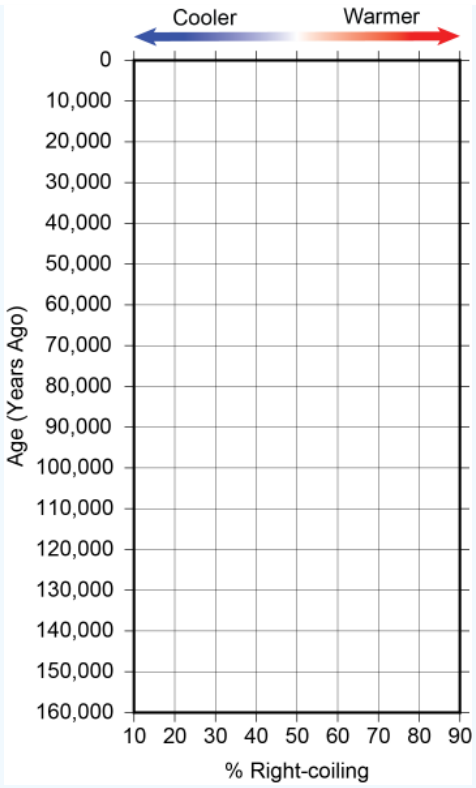


Figure 11.1 – Graph for Exercise 11.1.

c. Has climate changed in the last 160,000 years?

d. On your graph in Figure 11.1, indicate where warm and cold periods occur.

e. How many times has it been warm with a high percentage of *right* coiling forams? You should group several points as one time interval. For example, you could group 0 and 10,000 years as one time interval.

f. Has the length of time that it has been cool (with a low percentage of right coiling forams) been the same each time there has been an ice age?

g. Why does the total number of forams vary between samples? Does the number of forams vary with climate?

h. **Critical Thinking:** How does the length of time of the ice ages compare to the length of time it was hot? Can you think of a reason for this difference?

Exercise adapted from Hilary Clement Olson, Learning from the Fossil Record.

11.2 Causes of Natural Climate Change

Climate change is complex, and many factors affect Earth's climate system. These include Earth's orbital patterns, plate tectonics and the position of continents, changes in solar output, changes in atmospheric greenhouse gases, and others. All operate at various time scales that alter Earth's climate over hundreds, thousands, and millions of years.

On a time scale of millions of years, the movement and location of continents is the biggest influence on Earth's climate system. The position of continents affects ocean and atmospheric circulation, which are the two conveyor belts responsible for taking excess heat from the equatorial regions and moving it to the polar regions.

On time scales of thousands to hundreds of thousands of years, Earth's orbital patterns have the greatest effect on climate. Earth's orbit varies on three different cycles, called Milankovitch cycles. The shape of Earth's orbital path around the sun changes from more circular to more elliptical, completing an entire cycle about every 100,00 years. This is known as eccentricity. Eccentricity changes how close Earth is to the sun, affecting how much solar radiation the planet receives.

A video element has been excluded from this version of the text. You can watch it online here:
https://uhlibraries.pressbooks.pub/historicalgeologylab/?p=92

Earth has a tilt to its axis, and it moves back and forth between 22.1 and 24.5 degrees. This cycle, known as obliquity, takes about 41,000 years. Obliquity changes increase seasonality when the angle is higher and decrease seasonality when the angle is lower. Seasonality refers to the difference between summer and winter temperatures. Higher seasonality means hotter summers and colder winters; decreased seasonality means mild summers and mild winters.

A video element has been excluded from this version of the text. You can watch it online here:
https://uhlibraries.pressbooks.pub/historicalgeologylab/?p=92

The last orbital change is called precession, best described as a wobble around Earth's axis. If you've ever spun a toy top as a kid, you may remember that as the top slows down, it begins to wobble. That wobble is the same as Earth's precessional cycle, which takes nearly 26,000 years. Precession affects the timing of seasons because it changes what time of year the northern hemisphere points toward the sun. Today, the northern hemisphere experiences summer during June-September, but in 13,000 years, the northern hemisphere will have winter during those months.

A video element has been excluded from this version of the text. You can watch it online here:
https://uhlibraries.pressbooks.pub/historicalgeologylab/?p=92

These three cycles can work together to amplify climate change or work against each other to dampen it. They also have much longer versions that affect climate on longer time scales. For example, eccentricity also has 400,000-year and 2.4 million-year cycles and obliquity has a 1.2 million-year cycle.

It's important to note that these natural causes of climate change cannot explain the magnitude of warming and climate change that we see happening today. Current climate change can only be explained by human influences, particularly from the release of greenhouse gases from burning fossil fuels.

11.3 Oxygen Isotopes as a Climate Proxy

There are many ways fossils can be used as proxies. One of the most common uses is stable oxygen isotopes in organisms like forams and diatoms. Forams and diatoms are shelled organisms found in aquatic and marine environments. There are both planktonic forms floating in the water column, benthic forms that are bottom-dwellers. Foram shells are made up of calcium carbonate ($CaCO_3$), while diatom shells are composed of silicon dioxide (SiO_2). Do these formulas look familiar? They are essentially calcite and quartz. These organisms extract these elements from the seawater to build their shells. Oxygen, in particular, is sensitive to global climate and has different isotopes that vary in abundance based on how much ice is on the planet.

Oxygen-16 (^{16}O) is the most common form of oxygen, with 8 protons and 8 neutrons. Oxygen-18 (^{18}O) is less abundant but has two extra neutrons, making it slightly heavier than ^{16}O. Since ^{16}O is lighter, water molecules containing it are preferentially evaporated from the oceans than its heavier counterpart (^{18}O is evaporated too but in smaller quantities, Figure 11.2). When the water vapor begins to condense into rain or snow, heavier ^{18}O isotopes preferentially do so. The remaining water vapor then has even less ^{18}O. If temperatures in the polar regions are cold enough when precipitation falls, the water turns to snow and ice and becomes stuck on the continent in ice sheets instead of flowing back to the ocean. This is important because, during cold times, oceans become relatively enriched in ^{18}O because ^{16}O is being extracted and stored on continents in the ice. When these organisms build their shells, the chemistry of the shell reflects the chemistry of the seawater. Suppose you have a sediment core containing an abundance of these organisms. In that case, you can look at their shell chemistry for changes in ^{18}O to interpret how much ice was on that planet.

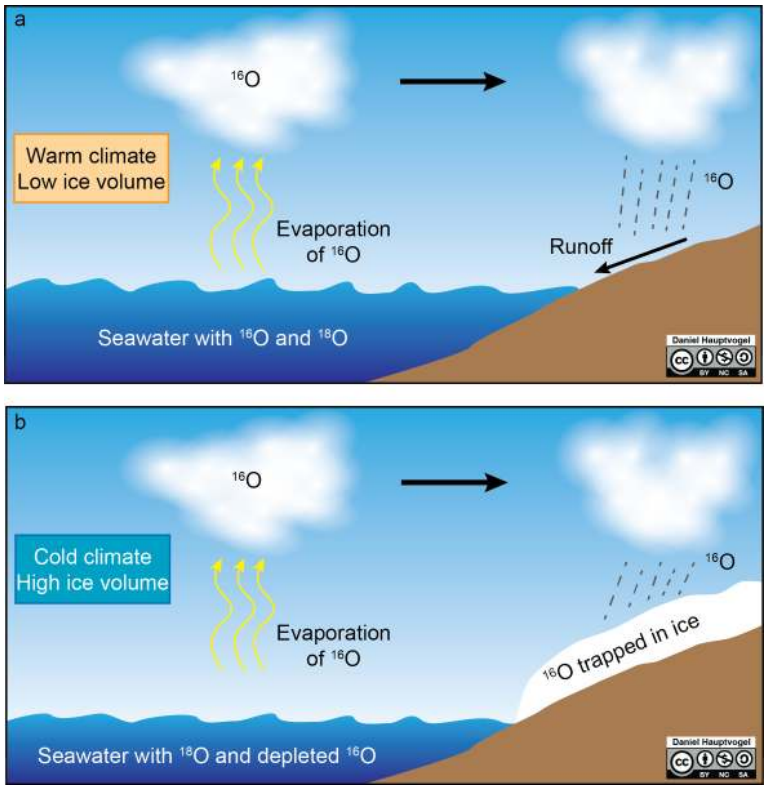


Figure 11.2 – Oxygen isotope changes during a) warmer and b) colder climates. Oxygen-16 preferentially evaporates because it is lighter. During colder times, the ratio of oxygen-18 to oxygen-16 in seawater increases because the evaporated oxygen-16 gets stored in ice sheets on continents.

? Exercise 11.2 – Using Oxygen Isotopes to Interpret Climate

One of the most famous oxygen isotope records in paleoclimatology is from Drs. Lorraine Lisiecki and Maureen Raymo, who published an extremely detailed record of the past 5.3 myrs from foraminifera. Figure 11.3 is a portion of this oxygen isotope record that spans the last 800 kyrs. The notation used for oxygen isotope records is $\delta^{18}O$ (usually pronounced as delta-O-eighteen), which is the ratio of ^{18}O to ^{16}O. The higher the number, the more ^{18}O there is. The unit is per mil (‰), which looks like a percent sign with an extra 0 in the denominator because it is out of a thousand instead of a hundred.

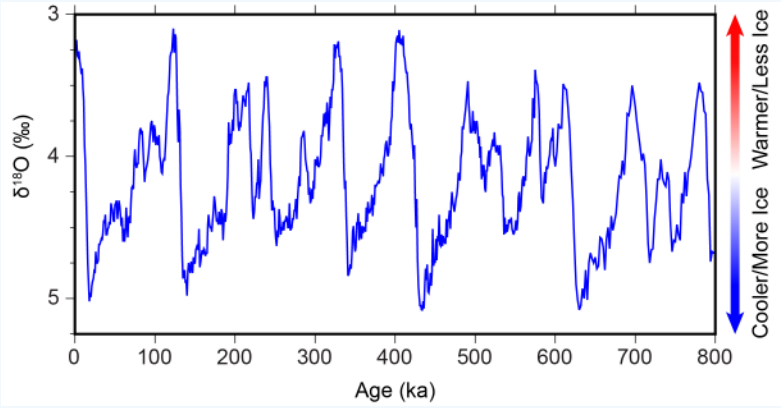


Figure 11.3 – Oxygen isotope record for the past 800,000 years from foraminifera shells. Data from Lisieckie and Raymo, 2005. Image credit: Daniel Hauptvogel, CC BY.

a. How many distinct cold periods can you identify in Figure 11.3? _____

b. About how far apart are these cold periods? _____

c. What do you think has been controlling natural climate change over the past 800,000 years? Explain.

d. Compare and contrast the transitions from warm to cold periods and from cold to warm periods.

e. **Critical Thinking:** If we assume that much of this oxygen isotope signal is a proxy for ice volume, do you think it takes longer for ice sheets to grow or melt? Explain.

Exercise 11.3 – The Climate Record of the Past 65 myr

For Earth's climate record, we know the most about the past 65 myr than we do for the rest of Earth's history. Figure 11.4 contains oxygen isotope and sea-level data for the entire Cenozoic.

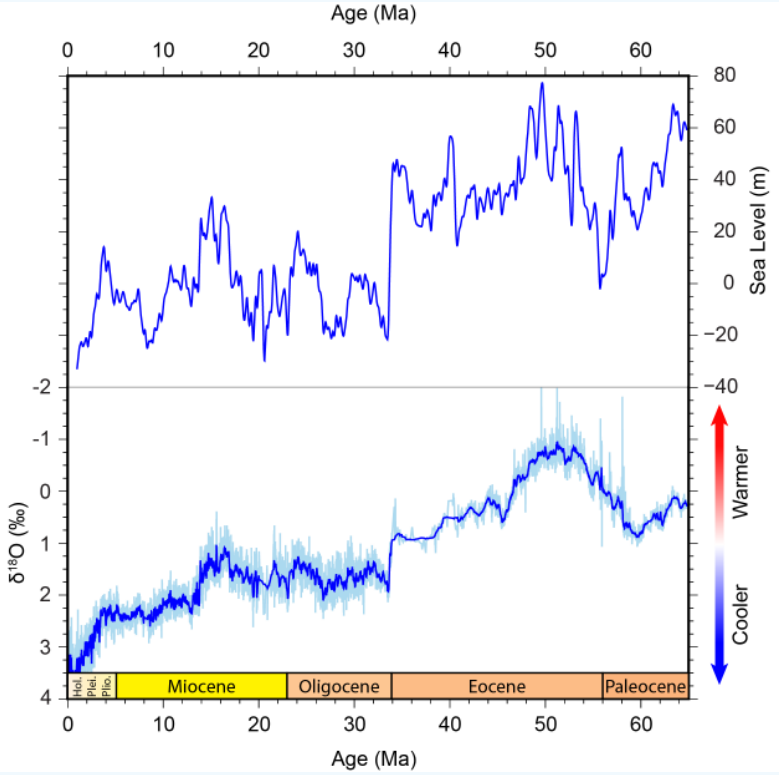


Figure 11.4 – Sea-level and oxygen isotope records for the past 65 myr. 0 in sea level represents modern sea level, positive numbers mean sea level was higher than today, and negative numbers mean sea level was lower. The light blue in the oxygen isotope data is the complete data set, the dark blue line is a 25-pt smoothing. Data from Miller et al. (2020). Image credit: Daniel Hauptvogel, CC BY-NC-SA.

a. Table 11.2 contains major climate events of the past 65 myr. Identify these events in Figure 11.4.

b. Explain why there is a steep drop in sea level during the Eocene-Oligocene transition.

Table 11.2 – Major Cenozoic climate events

https://geo.libretexts.org/@go/page/18720

Event	Description
Paleocene-Eocene Thermal Maximum (PETM)	A short, 200,000 year period where massive amounts of carbon dioxide were released into the atmosphere, and global temperatures increased by 5-8 °C.
Early Eocene Climatic Optimum (EECO)	A 2 myr period of the warmest temperatures of the past 65 myr.
Late Eocene Cooling	A global cooling driven by lowering CO_2.
Eocene-Oligocene Transition	Permanent ice sheets form in Antarctica, driven by CO_2 lowering past a critical threshold and changes in ocean circulation from moving continents.
Middle Miocene Climatic Optimum (MMCO)	A prolonged warm period whose cause is still debated.
Middle Miocene Climate Transition (MMCT)	Antarctic ice sheet expansion and global cooling driven by lower CO2 and changes in ocean circulation.
Pleistocene Glaciations	Repeated glacial cycles in which northern hemisphere continental glaciers reached as far south as 40° latitude.

11.4 Tree Rings as a Climate Proxy

Every year, trees grow taller, and their trunks grow wider. The new growth that makes the trunk wider is called a tree ring. Tree rings are a valuable tool to climate scientists because they contain a record of temperature and precipitation. During dry years, trees hardly grow at all and create narrow rings. However, during rainy years, trees will grow more than usual and have wide rings. Because of this difference in ring size and connection with precipitation, scientists can use tree ring patterns to learn about the climate during the time the tree lived. The science of studying tree rings to see what they tell us about past climates is called dendrochronology.

Each tree ring has a wider light-colored portion and a narrow dark-colored portion (Figure 11.5). The light coloring, called the earlywood, forms during the winter and early spring precipitation as trees grow at their greatest rate. The darker color, called the latewood, forms in late summer during slower growth in anticipation of the dormant season to come. A full year's growth includes both a light, earlywood ring and a dark, latewood ring. Together, they make up one tree ring.

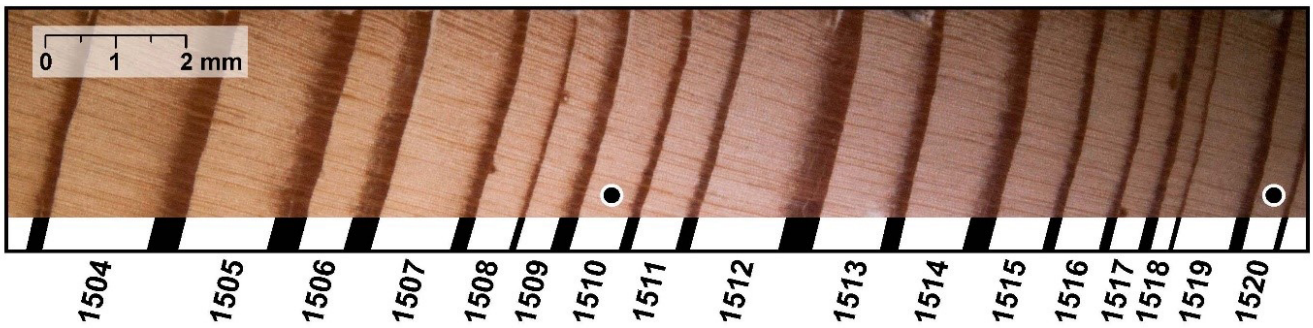


Figure 11.5 – A photomicrograph showing tree rings for years 1504-1520 on a Douglas fir core specimen. The black and white bar across the bottom illustrates which components would be measured as earlywood (white) and latewood (black). Image Credit: USGS, Public Domain.

Data from multiple trees can be combined to create a longer history than a single tree can make. To do this, dendrochronologists match patterns in the rings from each tree (Figure 11.6). For example, if tree A started growing in 1830 and died in 1930, and tree B started growing in 1910 and died in 2010, scientists can combine the records of both trees by matching the patterns for the 20 years that both trees lived. Dendrochronologists rarely cut down trees to analyze rings. Instead, they take a thin coring tool to extract a core about the thickness of a pencil without harming the tree.

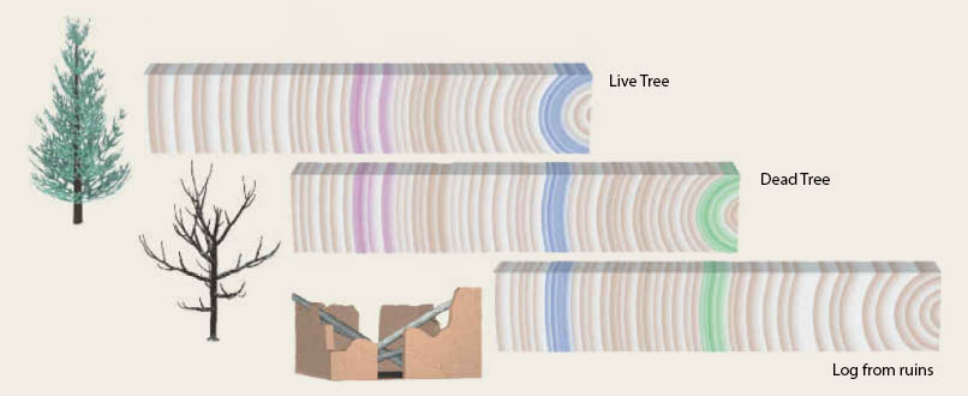


Figure 11.6 – Long tree ring chronologies can be constructed by matching overlapping patterns of different trees. Image credit: Andreas Schmittner, CC BY-NC.

? Exercise 11.4 – Investigating Tree Ring Growth and Climate

You have been given four simulated tree ring cores (Figure 11.7) from the following sources:

- Core Sample 1: From a living tree from the Pinetown Forest in the fall of 2018
- Core Sample 2: From a tree from the Pinetown Christmas Tree Farm a few years ago
- Core Sample 3: From a log found near the main trail in Pinetown Forest
- Core Sample 4: From a barn beam removed from Pinetown Hollow

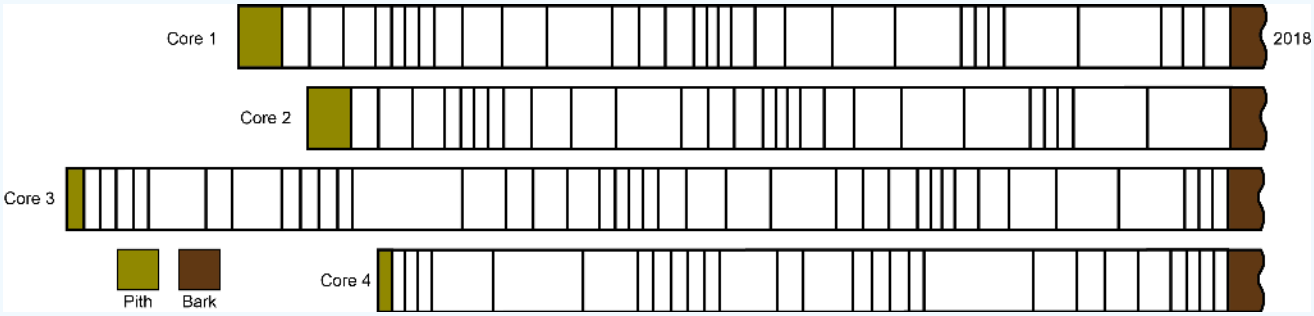


Figure 11.7 – Simulated tree ring cores for Exercise 11.3. Image credit: adapted from the USGS and UCAR.

a. Count the number of tree rings in each core sample. That number is the age of the tree in years. Record the ages in Table 11.3. Don't count the pith, which is a special plant tissue found at the center of tree trunks.
b. Determine the year that tree from core sample 1 started growing. Fill this out in Table 11.3.
c. Cut out the 4 tree ring records. Match the patterns in core sample 1 and core sample 2 by lining up the records and looking at what years overlap in both records. Determine when the tree from core sample 2 started growing and when it was cut/cored.
d. Follow the same steps for core sample 3 and core sample 4.

Table 11.3 – Worksheet for Exercise 11.4

Core Sample	Age of Tree	Year Growth Began	Year Cut or Cored
1			2018
2			
3			
4			

e. Which tree ring matches the year you were born? _____

f. Was the weather in Pinetown the year you were born good for tree growth or not? Explain.

g. Over the entire record, how many years were good for tree growth, and how many were not?

11.5 Fossils as a Climate Proxy

The foraminifera fossils used to construct oxygen isotope records are not the only use of fossils for paleoclimate. Many fossils in the geologic record can provide at least some information about climate. For example, fossils of palm trees from the Green River Formation in Wyoming (Figure 11.8) suggest climate there was subtropical during part of the Eocene 50 Mya, similar to what Florida is like today. If you look at the oxygen isotope record for the past 65 myr in Figure 11.4, you'll notice that at 50 Ma, we had the warmest climate of the Cenozoic. This is an excellent example of using multiple sets of data to support ideas in science.



Figure 11.8 – A palm fossil from the Green River Formation at Fossil Butte National Monument in Wyoming. Image credit: National Park Service, Public Domain.

Pollen fossils are widely used to interpret paleoclimate. Pollen grains (Figure 11.9) have a resistant outer shell that helps to keep them preserved in the geologic record, and they are very common. The study of pollen is called palynology, and palynologists use these fossils from sedimentary records to interpret what climate was like. Each plant species produces a different sized and shaped pollen grain, and palynologists can determine which type of plants were present or trace the migration of plants as climate changes.

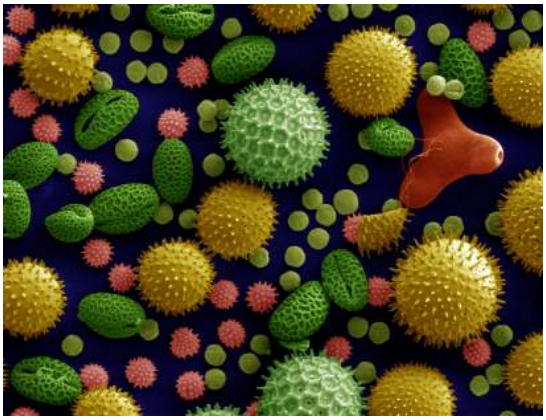


Figure 11.9 – Pollen from a variety of common plants: sunflower (Helianthus annuus, small spiky sphericals, colorized pink), morning glory (Ipomoea purpurea, big sphericals with hexagonal cavities, colorized mint green), hollyhock (Sildalcea malviflora, big spiky sphericals, colorized yellow), lily (Lilium auratum, bean-shaped, colorized dark green), primrose (Oenothera fruticosa, tripod shaped, colorized red) and castor bean (Ricinus communis, small smooth sphericals, colorized light green). The image is magnified some x500, so the bean-shaped grain in the bottom left corner is about 50 μm long. The coloring is artificial. Image credit: Dartmouth Electron Microscope Facility, Dartmouth College, Public Domain.

Exercise 11.5 – Using Fossil Pollen to Track Ice Sheet Movement



Figure 11.10 – Black spruce (Picea mariana) trees at an Arctic home south of Inuvik, NT, Canada. Image credit: Daniel Case, CC BY-SA.

During the late Quaternary, our planet experienced large, rapid changes in climate associated with the growth and retreat of continental ice sheets. These changes were related to major reorganizations of terrestrial habitats, especially in the northern hemisphere. Ice age mammals like the classic mammoths and mastodons had to cope with these changes, as did our own species, *Homo sapiens*, as we expanded out of Africa during this time.

Because plant and animals species often have specific climate requirements, we can use the geographic distribution of fossil species to reconstruct ancient climate parameters and document how these parameters changed over time. The coniferous tree species *Picea mariana* (Figure 11.10) and *Picea glauca*, commonly known as black spruce and white spruce, are the two most abundant and widely distributed *Picea* species in North America. Their migration with changing climate is well-documented through pollen fossils. Their modern habitat, like all spruces, is in boreal forests or mountains, most commonly found in Canada and some parts of the northern U.S.

Part 1

You will document the modern distribution of *Picea mariana* and its preferred climate conditions.

a. Take a close look at Figure 11.11. In terms of geography, what is the extent of *Picea mariana's* habitat?

b. Figure 11.11 also shows *Picea mariana's* modern temperature and precipitation ranges. Describe the type of climate this tree grows in.

c. Predict how the distribution of this tree taxon has changed over the last 21,000 years. Do you think it has remained in the same position, or has it migrated through time?

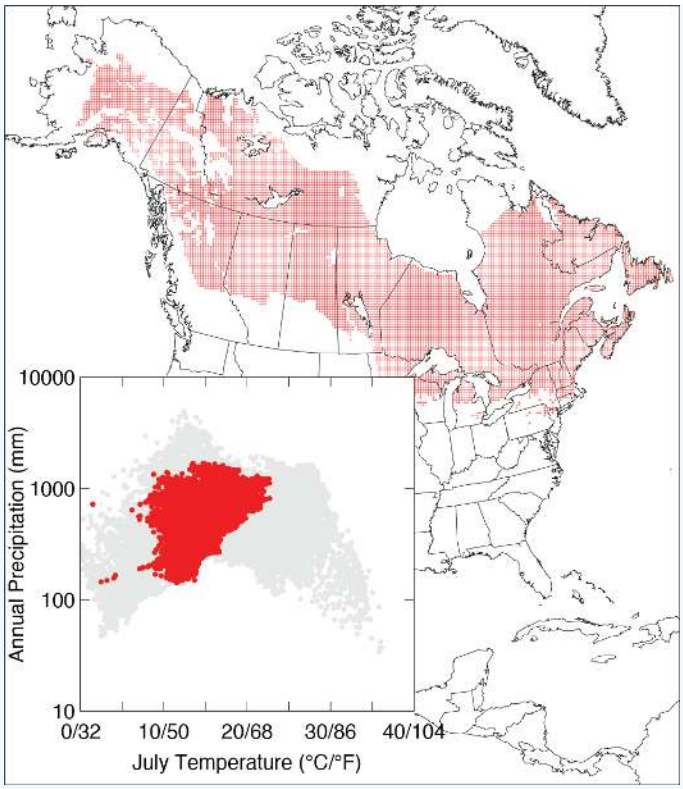


Figure 11.11 – This map shows the regional extent of Picea mariana. The graph shows the range of annual precipitation and average July (warmest month) temperature Picea mariana grows in. Picea glauca has similar distribution and climate parameters. Data from Thompson et al. (2015). Image credit: adapted from Thompson et al. (2015), Public Domain.

Part 2

In this part, you will look at the distribution of all *Picea* species over time using the Neotoma Database, which will show you the locations where its pollen grains have been found. The Neotoma database is a repository for paleoenvironmental data, including pollen fossils.

Follow these steps:

- Go to the Neotoma Database and click on the Explorer icon. The search window should automatically pop up; if it doesn't, click on the binoculars icon.
- For dataset type, select "pollen" from the dropdown menu.
- Click on the gears symbol next to the "Taxon name" box and select "vascular plants" from the Taxa group pull-down menu.
- In the "Search for" box, type "Picea" and click "Go".
- Select all species of Picea and click close (We are using all species because not all scientific studies have separated Picea fossils into different species. Instead, they simply reported the fossil as *Picea* sp. There are only a few species of Picea in North America, and their habitats and climate conditions are similar in boreal forests or mountainous areas.)
- Click the checkbox next to "Abundance/density" and set the abundance to "> 20%".
- Click on time and set the age range to 21,000 (oldest) to 18,000 (youngest) and hit search.

After a few seconds, your map will update with the locations of pollen fossils for *Picea* sp. at the indicated time range.

d. Where in North America did *Picea* sp. exist? How does that compare to the modern distribution of *Picea mariana*?

e. Based on the modern climate conditions and habitat for *Picea*, what was the climate like for the U.S. during this time?

Repeat the search for the following time ranges; you will only need to change the time range, all other options should not have to be selected again:

- 15,000 to 12,000 yr BP
- 10,000 to 7,000 yr BP
- 5,000 to 1,000 yr BP

Observe the patterns for spruce at each time slice on the map. You can change the symbols and colors, rearrange the plotting order, and turn layers on and off using the View Current Search Layers tool (it's next to the binoculars icon)

f. Describe the distribution of *Picea* sp. through time.

g. What climate parameter (temperature or precipitation) do you think is driving the distribution of Picea through time? Explain your reasoning.

h. Compare the distribution of *Picea* through time to the location and size of the Laurentide Ice Sheet in Figure 11.12. How does the position of *Picea* relate to the position of the ice sheets?

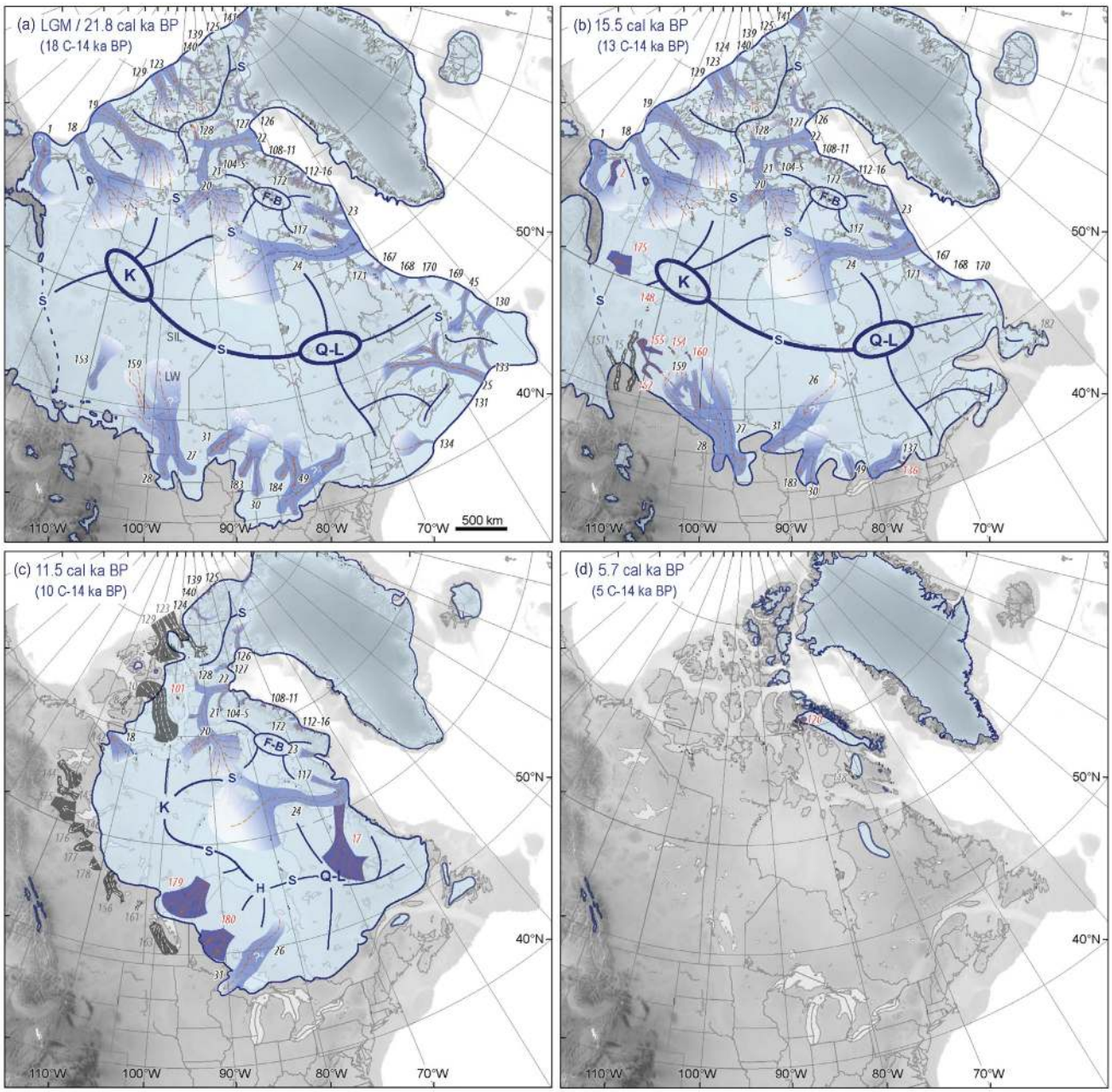


Figure 11.12 – Evolution of the Laurentide Ice Sheet during deglaciation. Numbers represent different ice streams (regions of fast-moving ice) and letters represent ice drainage divides; not relevant to this exercise. Image credit: adapted from Margold et al. (2018), CC BY.

i. **Critical Thinking:** This exercise focused on one species of a conifer. Most conifers are restricted to either high elevation or high latitudes. What types of trees could you use for tracking glacial history in temperate or tropical locations?

This exercise was adapted from Samantha Kaplan, Margaret Yacobucci, and John Williams.

11.6 Sediment as a Climate Proxy

Sediment on the continent or at the bottom of the ocean can give geologists a lot of information about what the climate was like when sediment was deposited. Not only does that sediment contain fossils that provide clues, but the grain size and provenance of

the sediment can help determine temperature and precipitation patterns. In polar regions, geologists can use the sedimentary record to determine how far ice sheets advanced and when they retreated. Those IODP Expeditions we talked about in Chapter 5 are among the primary ways sedimentologists study past climates.

? Exercise 11.6 – Using Sediment Provenance to Determine Paleoclimate in Antarctica

All rocks have a distinct chemical makeup; even rocks of the same type can have slight variations. When sediment is weathered and eroded from rocks, the sediment retains this chemical makeup. Thus, when geologists recover sediment, like drilling a sediment core from the ocean floor, they can analyze the sediment chemistry and match it up with known sources on the continent.

Ice sheets are large ice masses that sit on top of continents. Antarctica, for example, is a continent a bit larger than the U.S., and 98% of it is covered by an ice sheet that is two to three miles high. Ice on continents flows, like water flowing through a series of rivers but at a much slower pace. As the ice moves across the rocky surface, it weathers and erodes sediment. Most of this erosion occurs at the edge of the ice sheet, where the ice is moving fastest. When ice sheets reach the coastline, the sediment is then carried by ocean currents to eventually be deposited. When geologists investigate sediment eroded by glaciers, they can use the geochemical fingerprint of the sediment, match it to rocks that exist on the continent, and determine where the edge of the ice was because that is where the most erosion was taking place.

Figure 11.13 is a map of Antarctica with a focus on a region called the Wilkes Subglacial Basin. A marine sediment drill core was taken from a location just off the coast; the site is labeled U1361A. Layers of sediment recovered from this core were analyzed for two trace element geochemical signals, neodymium (Nd) and strontium (Sr). These trace elements have several uses in geology, but we will use them as indicators of provenance.

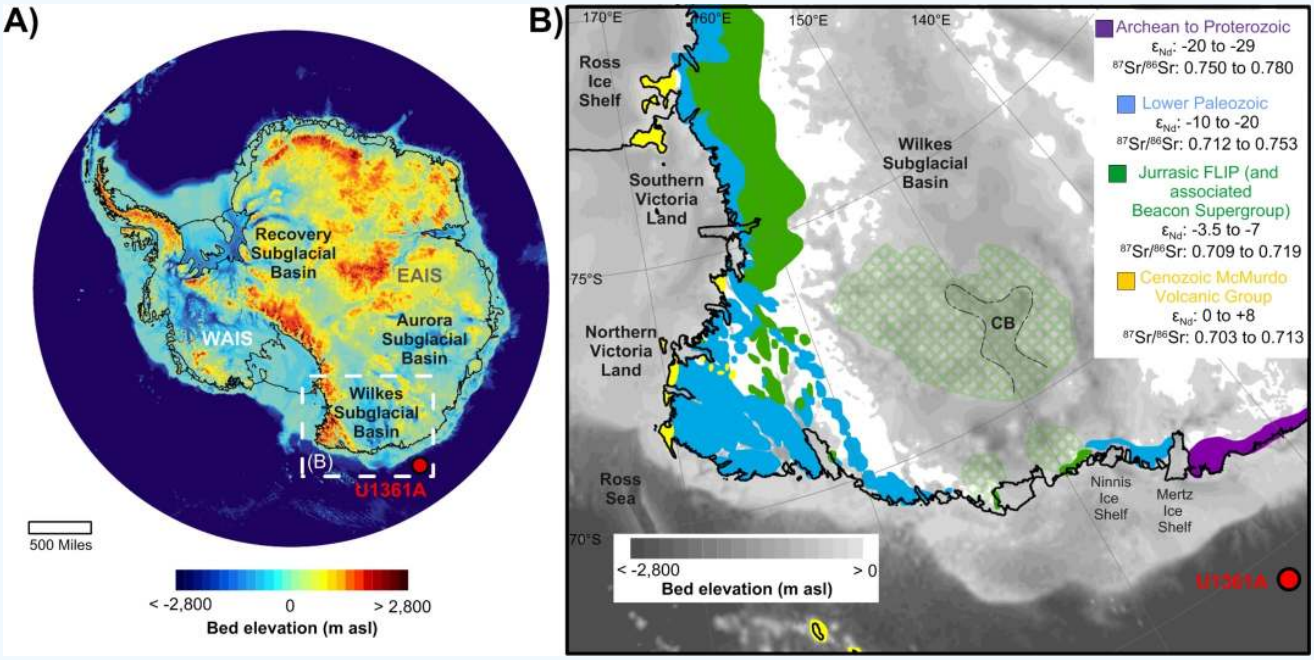


Figure 11.13 – (A) Topography and bathymetry (meters above sea level, m asl) of the Antarctic continent, highlighting areas below sea level, including the three largest subglacial basins in East Antarctica: the Aurora Subglacial Basin, the Recovery Subglacial Basin, and the Wilkes Subglacial Basin. The location of IODP Expedition 318 drill site U1361A offshore of the Wilkes Subglacial Basin is marked in red. (B) Geological map of the area around the Wilkes Subglacial Basin with simplified lithologies and their isotopic characteristics. Areas of inferred Jurassic Ferrar Large Igneous Province (FLIP) from airborne geophysics are shown in hatched marking. CB denotes the Central Basin. Image credit: Bertram et al., 2018, CC BY, adapted from Cook et al., 2013.

Figure 11.14 contains five different types of data collected from the layers of sediment in this core: sediment type, natural gamma radiation, diatom concentration, Sr, and Nd. Diatoms are single-celled, photosynthetic algae that build a body out of silica. Generally speaking, diatoms are more productive when water temperature increases. Use these data sets to answer the following questions.

a. Describe any trends or patterns that you can see in the data in Figure 11.14.

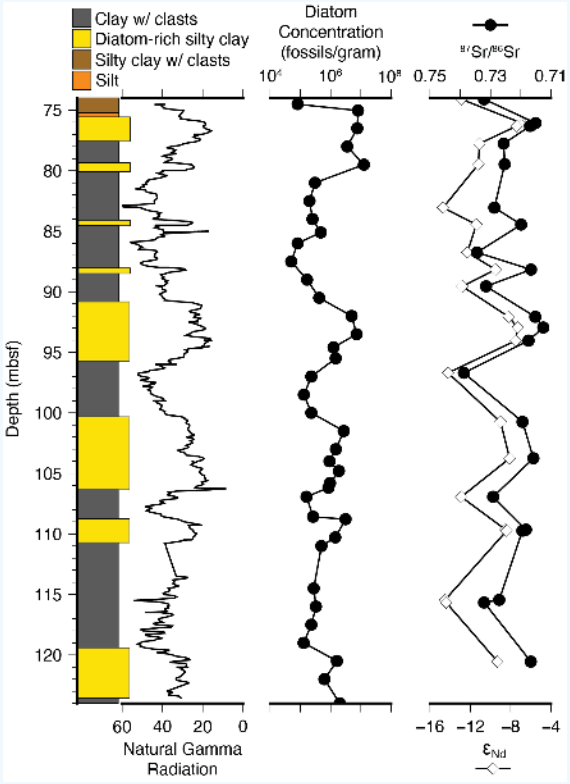


Figure 11.14 – Lithostratigraphy (Escutia et al., 2011), natural gamma radiation, diatom valve concentrations, and Nd and Sr isotopic compositions from Site U1361A. Lithostratigraphy and natural gamma radiation are from Escutia et al. (2011), diatom, Nd, and Sr data are from Cook et al. (2013). mbsf = meters below seafloor. Image credit: Daniel Hauptvogel, CC BY-NC-SA.

b. Table 11.4 contains the Sr and Nd chemical analyses collected from sediment in the drill core (the same data is plotted in Figure 11.14). Using Figure 11.14, note whether each Sr and Nd analysis was from diatom-rich or diatom-poor layers.

Table 11.4 – Sr and Nd isotopic data

https://geo.libretexts.org/@go/page/18720

Depth (mbsf)	$^{87}Sr/^{86}Sr$	ε_{Nd}	Diatom-rich or Diatom-poor
74.09	0.73215	-12.9	
76.07	0.715075	-6.9	
76.27	0.716604	-6.9	
76.31	0.716901	-7.4	
77.77	0.72563	-11.1	
79.47	0.725313	-11.2	
83.05	0.72871	-14.7	
84.45	0.71985	-11.4	
86.75	0.734461	-12.3	
88.17	0.716557	-9.5	
89.55	0.731468	-12.8	
92.07	0.715194	-8.2	
92.95	0.712514	-7.3	
94.03	0.717386	-7.5	
96.7	0.738815	-14.2	
100.75	0.719381	-9	
103.76	0.715787	-8.1	
106.94	0.729142	-12.9	
109.65	0.718272	-8.5	
109.74	0.71947	-8.4	
115.45	0.72711	-14.5	
115.67	0.732095	-14.4	
120.55	0.716649	-9.3	

c. Figure 11.15 is a graph comparing Sr and Nd values for the four potential source areas of the sediment, with colors matching the areas from the regional map in Figure 11.13. Plot the Sr and Nd data on this graph using different colors/shapes for samples from diatom-rich and diatom-poor layers.

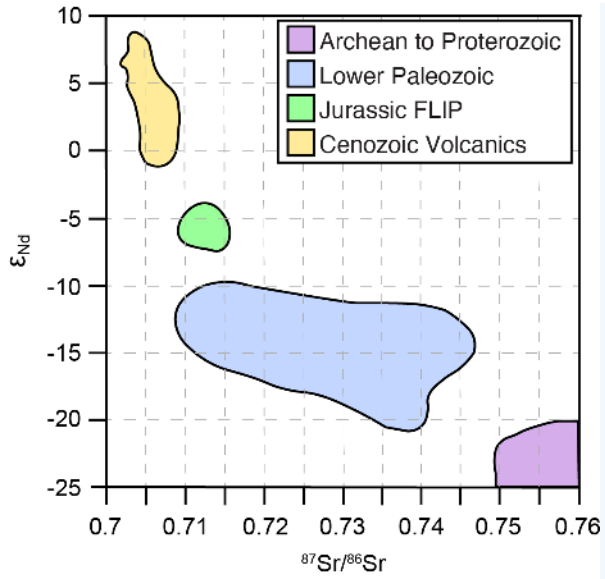


Figure 11.15 – Characteristic geochemical signatures of the different lithological terranes in the Wilkes Subglacial Basin vicinity. Image credit: Daniel Hauptvogel, CC BY-NC-SA, adapted from Bertram et al. (2018).

d. Why do some of the samples plot inside the known chemistry of potential source areas (the colored polygons) and some plot outside of them?

e. Which source(s) are primarily contributing sediment to Site U1361A? _____

f. When the edge of the ice sheet retreats inland, which source area should become more abundant? _____

g. Combining all the data, explain whether diatom-rich or diatom-poor layers represent ice sheet retreat or ice sheet advance toward the coastline.

h. **Critical Thinking:** Site U1361A is closest to the Archean to Proterozoic source. Why don't we see that chemical signature in the sediment?

Additional Information

Exercise Contributions

Daniel Hauptvogel, Virginia Sisson

References

Bertram, R.A., D.J. Wilson, T. van de Flierdt, R.M. McKay, M.O. Patterson, F.J. Jimenez-Espejo, C. Escutia, G.C. Duke, B.I. Taylor-Silva, and C.R. Riesselman, (2018). Pliocene deglacial event timelines and the biogeochemical response offshore Wilkes Subglacial Basin, East Antarctica. Earth and Planetary Science Letters 494, 109–116, DOI:10.1016/j.epsl.2018.04.054.

Cook, C., van de Flierdt, T., Williams, T. *et al.* (2013). Dynamic behaviour of the East Antarctic ice sheet during Pliocene warmth. Nature Geoscience 6**,** 765–769. DOI:10.1038/ngeo1889

Escutia, C., Brinkhuis, H., Klaus, A., and Expedition 318 Scientists, (2011). Proceedings of the Integrated Ocean Drilling Program, 318, Integrated Ocean Drilling Program Management, Inc., Tokyo, DOI:10.2204/iodp.proc,318.2011

Margold, Martin & Stokes, Chris & Clark, Chris. (2018). Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet. Quaternary Science Reviews. 189. DOI:10.1016/j.quascirev.2018.03.013

Miller, K.G., Browning, J.V., Schmelz, W. J., Kopp, R.E., Mountain, G.S., and Wrigth, J.D., (2020). Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. Sciences Advances, 6(20).

DOI: 10.1126/sciadv.aaz1346

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records, Paleoceanography, 20, PA1003, DOI:10.1029/2004PA001071

Thompson, R.S., Anderson, K.H., Pelltier, R.T., Strickland, L.E., Shafer, S.L., Bartlein, P.J., and McFadden, A.K., 2015, Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America—Revisions for all taxa from the United States and Canada and new taxa from the western United States: U.S. Geological Survey Professional Paper 1650–G, DOI:10.3133/pp1650G.

Google Earth Locations

Click or Scan to View all Chapter 11 Locations on Google Earth

This page titled 1.12: Paleoclimate is shared under a CC BY-NC-SA 4.0 license and was authored, remixed, and/or curated by Daniel Hauptvogel and Virginia Sisson via source content that was edited to the style and standards of the LibreTexts platform.

Index

D

dire

Glossary

absolute age | age measured in years and is usually determined by measuring isotopic decay

Acadian | a mountain building period from 420 to 380 Ma

accommodation space | the space that is available for the deposition of sediments. In river systems, changes in accommodation are controlled by the river gradient, water discharge rates, and sediment supply

accretionary prism | a mass of sedimentary material scraped off of oceanic crust during subduction that piles up at the edge of the overriding plate

aeolian | also spelled eolian, wind processes that shape the surface of the Earth (or other planets)

aggradation | growth either vertically or horizontally of morphological features. In coastal areas, these include the beach, dunes, sand banks, tidal flats, and salt marshes

Alleghenian | a mountain building period from 350 to 250 Ma

allochthonous | rock that originated at a distance from its present position

alluvial fan | a landform shaped like a gentle mound or cone with its apex at the mouth of its sedimentary source, typically a mountain stream.

alluvium | unconsolidated detritus (clay, silt, sand, and gravel) deposited by streams and floods

ammonite | a cephalopod (similar to a nautilus) with a sutured shell; commonly it grows in a spiral form. They lived in the Jurassic and Cretaceous and are excellent for biostratigraphy and determining relative age

angle of repose | the maximum angle that a soil, sediment, or other loose material can be placed or accumulate and not move down-slope. This angle varies for different types of material and moisture conditions

anhydrite | an anhydrous calcium sulfate mineral ($CaSO_4$) that is formed in deeply buried evaporite deposits. It absorbs water in near-surface environments to form gypsum

anoxia | characterized by a lack of oxygen; thus, they do not support life such as burrowing or benthic organisms

antiform | A geologic feature which is composed of layers with a convex form

aquifer | a body of rock and/or sediment that holds groundwater

arc | a linear belt of volcanoes that forms where an oceanic plate collides with the either a continental or oceanic plate and subducts beneath it

arkose | a sedimentary rock consisting of sand or gravel with both feldspar and quartz; typically created by rapid weathering of granite

assemblage (of fossils) | a suite of fossils collected from a rock unit. These are assumed to have lived at the same time and environmental conditions

asymmetrical ripple marks | a sedimentary structure produced by fluid flow in one direction in which the limbs of the ripple are at about the different angles

autochthonous | rock formed in its present position

axial plane | a plane that divides a fold as symmetrically as possible. This may be vertical, horizontal, or inclined at any angle

back arc basin | a basin formed near a volcanic arc on the side opposite the oceanic trench; this is the result of extension caused by mantle convection behind a subduction zone and its island arc

back reef | the area behind a reef that may include shallow marine sediments, shoreline, and evaporite sedimentary environments

backdune | a part of the system of dunes that is furthest from the ocean

backshore | the beach between the foreshore and coastline. The backshore is typically dry and does not have vegetation and often characterized by berms or dunes. The backshore is only exposed to waves under extreme events with high tide and storm surge

Baltica | the northern craton of Europe underlying much of Scandinavia that was an independent continent that collided with northeastern North America in the early Paleozoic to form the Taconic, or Caledonian Mountains

barren | a landscape that lacks plant or animal life

barrier island | a coastal landform that is a barrier between the ocean and mainland generally running parallel to the main coastline. They typically occur in a chain and extend from several to 100's of kms

Barrovian sequence | a series of metamorphic zones with both pressure and temperature increase generally due to continental collision

basin | a topographic or bathymetric low area. Structural basins have dipping strata toward the center. Depositional (sedimentary) basins have thick accumulations of sediment compared to adjacent regions

bathymetry | the depth of water in oceans, seas, or lakes

bay/lagoon | area of relatively shallow water in a coastal environment, separated from the open marine conditions by a natural barrier (a sand spit, a barrier island or a coral reef), but with an access to the sea

beach | an area of unconsolidated material that extends from low-tide line to an area with permanent vegetation

bed forms | the ocean bottom is seldom flat and often undulates from the interaction of currents and waves. These include ripples and sand ridges

beds | distinct layers of sediment that have a thickness greater than 1 cm

benthic | related to the seafloor. Benthic organisms live on or in the substrate of the ocean floor

bentonite | a clay-rich rock made of smectite that formed from alteration of volcanic ash. It is mined as a major constituent of drilling mud.

bilateral symmetry | an object that can be divided into two symmetrical parts across a unique plane, sometimes called a mirror plane

biostratigraphy | the branch of stratigraphy that uses fossils to determine relative age and correlate successions of sedimentary rocks

bioturbation | reworking of soil and sediment by animals or plants

bottom simulating reflector | a seismic reflection occurring in the upper few hundred meters of marine sediments mimicking the seafloor

braided river | consists of a network of river channels that split and join. The channels can be separated by small, often temporary, islands.

bryozoan | a type of aquatic invertebrate animals. They are filter feeders that extract food particles out of the water using tentacles.

burial | process in which sedimentary layers are piled up and the sediments beneath are buried, sometimes by hundreds of meters of sediment above

calcite | a carbonate mineral, $CaCO_3$. This is the stable polymorph at the Earth's surface

caliche | a white to reddish brown material ranging from soil to rock produced in a soil in semiarid to arid environments. Caliche can have sand or gravel zones that are cemented by calcium carbonate.

Cambrian | the first period in the Paleozoic era, between the Precambrian eon and the Ordovician period (541 to 485 Ma)

cementation | process of transforming clastic sediments into rocks by the precipitation of mineral matter in their pore spaces

chalk | limestone composed of shells of microscopic marine animals (foraminifera) and marine algae (coccoliths). Chalk is white or light gray, porous, permeable, soft and friable.

channel | the path of a fluid, most commonly a river or river delta

chemical sedimentary rock | form when minerals in solution become supersaturated and inorganically precipitate

clade | a group of organisms believed to have evolved from a common ancesto

class | a principal taxonomic category that ranks above order and below phylum

clast | a fragment of geological detritus broken off other rocks by physical weathering

clastic | sedimentary rocks composed of broken pieces of older rock

clastic rock | composed of fragments or clasts, of geologic detritus including both minerals and rocks

clinoforms | these sedimentary layers are timelines that represent a moment in geological time

coast | a strip of land from the coastline inland to an area that is not influenced by coastal processes

coastal area | both the land and the sea bordering a shoreline

coccolithophore | also called coccoliths are unicellular marine algae; they belong to the kingdom Protista. They have calcite scales that can form chalk.

conductivity | of the amount of electrical current a rock can carry or its ability to carry a current

conformable | parallel strata that have a similar geologic history and were deposited in succession without interruption

contacts | a boundary which separates one rock body from another. These can be depositional, unconformable, and intrusive contacts

continental drift | the hypothesis proposed by Alfred Wegener in 1915 that stated the continents were moving

continental shelf | the submerged portion of continent crust in relatively shallow water. It extends from the shoreline to the drop-off point marked by the shelf break.

convergent | a plate boundary where two plates move towards each other

correlation | process of relating either characteristics, time or stratigraphic position of separated rock units. This can be lithologic (similar rock types), biostratigraphic (similar fossil content), chronostratigraphic (similar ages), or chemostratigraphic (similar chemical signatures)

costa (plural = costae) | Rib or rib-like structures

Cretaceous | a geological period from about 145 to 66 Ma. It is the third and final period of the Mesozoic Era, as well as the longest. The name is derived from the Latin creta, chalk

cross-bedding | groups of inclined layers and sloping layers are known as cross strata. Cross-bedding forms on a sloping surface such as ripple marks and dunes

crown (crinoid) | a cup-like central body with a set of five rays or arms, usually branched and feathery

delta | a low, flat area near the mouth of a river typically with a triangular shape that is crossed by distributaries of the main river. It also includes the shoreline and off shore environments related to the delta plain. These form because the sediment load supplied by the river is too high to be washed away. They are classified by the main source of energy that supply the sediment load such as wave dominated, fluvial (river) dominated, or tide dominated.

depocenter | an area of maximum deposition in a stratigraphic unit

Devonian | the fourth period of the Paleozoic era, between the Silurian and Carboniferous periods (405 to 345 Ma)

diapir | a domed rock formation in which a core of rock has moved upward into overlying strata. These typically form when low-density material such as magma or salt flows upward

diapir (salt) | a mass of salt that has flowed ductilely and has discordant contacts with the rocks above and on its sides

divergent | a linear feature where two plate boundaries move apart from each other

drainage basin | the area of land in which runoff feeds into a stream, lake, or reservoir. A first order drainage basin feeds directly into the ocean

dunes | there are two types of dunes: subaerial and subaqueous. Most only know about the subaerial dunes from trips to the beach and/or a desert. They are made of wind-blown sand and typically are vegetated. Subaqueous dunes are also known as sandwaves.

eclogite | a metamorphic rock composed of garnet and pyroxene. Also, a facies of metamorphism formed at high pressure and temperature.

Ediacaran Period | the uppermost division of the Proterozoic Eon of Precambrian time and latest of the three periods of the Neoproterozoic Era, extending from approximately 635 million to 541 million years ago. Also called Vendian Period

eolian | sedimentary features formed by wind including sand dunes and silt (loess) deposits

eon | longest division of geological time, subdivided into eras

epoch | unit of time that is a component of a period, such as Eocene

era | a unit of time such as Mesoproterozoic, Neoproterozoic, Paleozoic, Mesozoic, and Cenozoic. Eras are divided into periods and epochs.

Euler pole | a mathematical pole of rotation that describes the relative movement of two or more plates on a sphere

eustatic | worldwide changes in sea level due to changes in volume of water in the oceans versus ice sheets

evaporite | a type of sediment that consists of water-soluble minerals deposited after concentration and crystallization by evaporation from an aqueous solution

extrusive | igneous rocks that form when magma cools at or near the Earth's surface

facies | for sedimentary rocks, it is a body of rock with specified characteristics such as type of sediment

family | a principal taxonomic category that ranks above genus and below order

fan | a triangular shaped sedimentary deposit, often called an alluvial fan when it is composed of alluvium or overwash fan when it occurs in a coastal environment

fan delta | a type of alluvial fan that flows into lowlands that is reworked by shoreline and gravity processes

fault | a fracture or zone of fractures between two pieces of rock

felsic | an igneous rock rich in feldspar (fel) and quartz (si)

foliation | planar arrangement of structural or textural features in metamorphic rocks along straight or wavy planes

foredune | the part of a system of dunes closest to the ocean

foreland basin | structural basin that develops adjacent and parallel to a mountain belt formed from the mass created by crustal thickening that causes the lithosphere to bend creating accommodation space

foreshore | this is the zone between low-tide line and high-tide line, also called the beach face. It is typically wet from the tides and waves and can be destroyed by storm surge.

formation | a fundamental rock unit based on similar characteristics in lithology, including characteristics as color, mineralogy, and grain size. Formations may represent deposition over short or long time intervals, may be composed of materials from several sources, and may include breaks in deposition. Formations are named after geographic features where they were first studied.

gamma radiation | gamma (γ) rays come from the radioactive decay of naturally occurring radionuclides

genus | a principal taxonomic category that ranks above species and below family (plural is genera)

geologic time scale | a system that geologists use to relate chronological dating to geological strata (stratigraphy)

geophones | a device that converts ground movement (velocity) into voltage, which is recorded as a seismic response and is analyzed for structure of the earth.

geothermal gradient | change in temperature with respect to increasing depth. Away from the edges of lithospheric plates, it is about 25–30 °C/km

gneiss | a metamorphic rock made up of bands that differ in color and composition; generally there are light-colored bands rich in feldspar and quartz and dark-colored bands rich in mafic minerals such as biotite or amphibole

Gondwana | a supercontinent that existed from the Neoproterozoic and began to break up during the Jurassic and ended in the Eocene

graben | graben and horst refer to regions between normal faults and are either higher (horst) or lower (graben) than the area beyond the faults

graded beds | a sediment consisting of a mixture of coarse and fine detrital material

granite | a coarse-grained, intrusive igneous rock typically composed of quartz, feldspars, and amphibole/biotite.

habitat | the natural home or environment of a plant or animal

hardness | measure of the resistance to scratching by another object or mineral

hornfels | hornfels are formed during contact metamorphism or the baking by heat of intrusive igneous masses. These are often nonfoliated or massive and in some cases very durable

hotspots | linear volcanic regions that are probably fed by underlying mantle that is anomalously hot compared with the surrounding mantle

hydrogeology | area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust

ichnofacies | an assemblage of trace fossils that provide an indication of the paleoenvironment that these organisms inhabited

igneous dike | a sheetlike igneous body that is often oriented vertically or steeply inclined to the bedding or layering

index fossil | a fossil used for both dating and correlating of strata in which it is found. These are typically organisms that lived for a short geologic time period

interdune | the area between the foredune and backdun

intrusive | an igneous rock that forms when magmas cool beneath the Earth's surface

invertebrate | an animal lacking a backbone such as a clam or worm

iridium | a chemical element with the symbol Ir and atomic number 77. Iridium concentrations in meteorites is much higher than any terrestrial rock. Thus, high concentrations of iridium are hypothesized to come from extraterrestrial sources.

irregular echinoid | these have a definite front and back and move in a particular direction

isostasy | the principle that Earth's crust is floating on its mantle

Jurassic | a geologic period that spanned 56 million years from the end of the Triassic Period 201.3 Ma to the beginning of the Cretaceous Period 145 Ma. This constitutes the middle period of the Mesozoic Era, also known as the Age of Reptiles

klippe | a remnant of a nappe after erosion has removed connecting portions of the nappe

lagoon | a relatively shallow, narrow body of water that is parallel to the shoreline between a barrier bar or island and the mainland. It is connected to the ocean by narrow passes. It may have high salinity and significant tides.

laminations | distinct layers of sediment that have a thickness less than 1 cm

landscape | visible features of an area of land and its landforms

large igneous province | an extensive area of predominantly iron- and magnesium-rich (mafic) rock that form by processes other than normal seafloor spreading; they are the dominant form of near-surface magmatism on the terrestrial planets and moons of our solar system

laterite | a soil rich in iron oxide and alumina, poor in silica, and depleted in alkali elements. It forms by intense tropical weathering.

Laurentia | a continental block or craton consisting of most of North America and Greenland that has retained its integrity since late Proterozoic time. Since the collision of Baltica, the resulting continent is Laurasia.

LiDAR | a remote sensing method that uses pulsed laser light to measure distances to the Earth

lithification | process where loose grains of sediment are converted into rock, often by cementation

lithology | the general characteristics of rocks and rock types present in a stratigraphic division of earth

lithosphere | the uppermost layer of the Earth as defined by physical properties. It is composed of the crust and uppermost, rigid part of the mantle.

lithostratigraphy | a sub-discipline of stratigraphy focuses on strata or rock layers

locomotory | having the power of locomotion

logging | sometimes called well logging. Methods to identify characteristics of subsurface formations either by samples of physical responses (geophysical well logging) that are displayed as a function of depth of a borehole.

longshore current | the dominant current in the nearshore zone; typically runs parallel to the shore

lowstand | an interval of time when relative sea level is low and the continental shelf and carbonate platforms are exposed. Extensive deltas form at the margin and a lot of sediment can be transported into deep marine basins.

luster | how light interacts with the surface of a mineral

mafic | an igneous rock that is rich in magnesium (ma) and iron (f), often has abundant pyroxene, olivine and amphibole

magma | molten matter beneath or within the Earth's crust from which igneous rocks are formed

magnetostratigraphy | a branch of stratigraphy in which stratigraphic divisions are made on the basis of changes in magnetic signals

mantle | a layer in the Earth or a planet that is between the core and crust

marl | sedimentary material that is a mixture of carbonate and clay; both present in subequal amounts

marsh | in coastal areas, these are low-lying and often inundated by tidal waters. They tend to be heavily vegetated and low-energy sedimentary environments

meander | have a winding course, in geology used to describe rivers or streams

meandering | the tendency to scour the outer bend of a river channel and deposit sediment on the inner bend

member | a formal stratigraphic unit that is a part of a formation; these need not be mappable

Mercator projections | a map projection of the world onto a cylinder so that all the latitude lines have the same length as the equator

Mesozoic | interval of geological time from 252 to 66 million years ago. Some call it the Age of Reptiles or the Age of Conifers. The Mesozoic is one of three geologic eras of the Phanerozoic Eon, between the Paleozoic and the Cenozoic

metamorphic rocks | the process by which heat, pressure, or fluids transform the minerals and textures of the rock

mid-ocean ridge | an underwater mountain and rift system formed by an oceanic divergent plate boundary

migmatite | heterogeneous rock with properties of both igneous and metamorphic rocks; often formed by partial melting

mineral | a naturally occurring, inorganic, solid that can be defined by a chemical formula and a crystal structure.

minibasin | a small basin typically formed by subsidence in thick salt

mountain belts | an aligned group of mountain ranges that form from the same cause, usually an orogeny or convergent plate boundary

mud | fine grained sediment with a high concentration of clay minerals

natural gas | a mixture of hydrocarbons generally with 1-5 carbon atoms with variable amounts of hydrogen atoms that is gaseous at the surface produced by degradation of organic matter in sedimentary rocks and microbial activity

nearshore | this zone extends from the low-tide line to beyond where waves influence the sedimentation (sometimes called the breaker zone).

nektonic | a organism that actively swims in the water column, compare with benthic and planktonic

novaculite | a sedimentary rock composed of finely crystalline quartz that may form from thermal alteration of bedded chert

offshore | this is not well defined, but is a zone beyond the nearshore. Typically it begins beyond where nearshore currents and waves affect the water column.

onlap |

in geology: the advance of a sea beyond its former shore

in geophysics: pattern of reflections in seismic data that occur during periods of transgression (sea level rise)

oolite | a type of limestone made of sand-size, well-rounded carbonate particles (oolith) with concentric layers formed in a shallow, wave agitated environment that are cemented together

ophiolite | a section of oceanic crust and its underlying upper mantle that has been uplifted and exposed, generally now on continental crust

order | a principal taxonomic category that ranks above family and below order

Ordovician | second period of the Paleozoic era, between the Cambrian (~486 Ma) and Silurian (~444 Ma) periods

organic sedimentary rocks | form from the accumulation and lithification of organic matter, such as leaves and other plant or animal material

orogeny | a mountain-building event typically resulting from a convergent tectonic boundary

ossicle | either a a small piece of a invertebrate skeleton such as an echinoderm or a very small bone in the ear

overwash | caused by waves that rush over a natural or artificial coastal barrier. This term can also be used for the sand deposit on the leeside of the barrier. These typically form during storm events.

paleoclimate | the climate during some past geological time

paleoenvironment | an environment that prevailed at some time in the geologic past

paleoenvironments | an environment that has been preserved in the rock record at some time in the past

Paleozoic | the earliest of three geologic eras of the Phanerozoic Eon. It is the longest of the Phanerozoic eras, lasting from 541 to 252 million years ago

Pangea | a supercontinent that existed from ~300 to 200 Ma and included almost all of Earth's continental crust

Panthalassan | a super ocean that surrounded all of the supercontinent Pangea

patch reef | a small carbonate reef that is moundlike and separated from other patch reefs or bioherms

pelagic | pertaining to the open ocean, often referring to organisms that do not need seafloor or continental environments

period | a unit of time such as the Cretaceous; a component of an era and composed of epochs

permeability | the ability for fluids (including gas) to flow through rocks

Permian | a geologic period that spans 47 million years at the end of the Paleozoic era, from the end of the Carboniferous period (298.9 Ma) to the beginning of the Mesozoic era with Triassic period (251.902 Ma)

petroleum system | involves deposition, generation, migration, entrapment, and preservation of hydrocarbons in sedimentary basins

Phanerozoic | the current geologic eon in the geologic time scale. This has the abundant animal and plant life. It covers 541 million years to the present, and it began with the Cambrian Period

phylum | a principal taxonomic category that ranks above class and below kingdom

plankton | a diverse variety of aquatic organisms that are cannot swim against a currents, tides, and waves. A common group of plankton are foraminifera

planktonic | an organism that drifts in the water column, compare with nektonic and benthic

plate boundaries | the edge of either a continental or oceanic tectonic plate

plateau | a large flat area that covers a large region and is elevated above its surroundings. It is larger than a mesa.

playa | a dry, vegetation free flat area within a desert. It can be filled with ephemeral lakes (playa lakes) during wet seasons that evaporate during dry seasons

polymorph | two or more minerals that have the same chemical composition but differ in their internal atomic arrangement and crystal structure

polymorphism | a solid material that exists in more than one form or crystal structure. Polymorphism can potentially be found in any crystalline material including minerals, polymers, and metals

porosity | the amount of void space in a rock

porphyroblast | a large mineral in a metamorphic rock which has grown in the fine grained matrix

progradation | seaward movement of a shoreline and coastal area, occurs when the rate of sediment supply is more than the rate of relative subsidence

protolith | original, unmetamorphosed rock from which a metamorphic rock was formed; sometimes called the parent rock

pull-apart basin | a basin formed between two adjacent strike-slip faults in a region where subsidence generates accommodation space for the deposition of sediments

pumice | a vesicular felsic igneous extrusive rock with very low density such that it floats in water

pyrite | metallic, yellow mineral made of FeS2 and typically occurring as intersecting cubes. Often called Fool's Gold

quadrangle (quad) | a topographic map sheet published by the United States Geological Survey with boundaries defined by lines of longitude and latitude

quartz | mineral consisting of SiO2, silicon dioxide, found in all rock types, the stable polymorph at the Earth's surface

quartz arenite | a type of sandstone with >95% quartz. This high quartz content is a result of quartz that has been "recycled" during several depositional cycles

quartzite | a metamorphic rock with a sandstone protolith

Quaternary | the current and most recent of the three periods of the Cenozoic Era from 2.588 ± 0.005 million years ago to the present

radial symmetry | symmetry around a central axis

radioactive | emission of energetic particles and/or radiation during radioactive decay

radioactive decay | spontaneous emission of particles (alpha or beta) and gamma rays from the nucleus of an unstable nuclide. The resulting nucleus may be stable or unstable. If it is unstable, decay continues until there is a stable nucleus

radiocarbon dating | a method for determining absolute age by measuring the amount of carbon-14 remaining in organic material. Only used on rocks less than 70,000 years

red beds | sedimentary rocks consisting of sandstone, siltstone, and shale, that are predominantly red in color due to the presence of ferric oxides. These can be deposited in both continental and marine paleoenvironments

reef | a mound or ridge built by calcite-secreting organisms such as coral, rudist mollusks, or sponges. They are resistant to waves and stand above the surrounding seafloor.

reflectivity | another term for reflection coefficient or how much energy is reflected by the stratigraphic units

reflector | a seismic reflector may represent a change in lithology, a fault, or an unconformity

regression | a geological process occurring when areas of previously submerged seafloor are then exposed above sea level

regressive | Areas of submerged seafloor being exposed above the sea level. A marine regression is a geological process occurring when areas of submerged seafloor are exposed above the sea level. The opposite event, marine transgression, occurs when flooding from the sea covers previously-exposed land (transgressive).

regular echinoids | these have no front or back end and can move in any direction

relative age | geologic age of an organism, rock, or event that is defined in relation to other rocks or events rather than in years before present or an absolute age

resistivity | a rock property which represents how strongly it opposes the flow of electric current

restricted shelf | a margin that has restricted flow of seawater, often associated with evaporites and arid conditions

retrogradation | landward retreat of a shoreline that occurs when the rate of sedimentation is slower than the rate of subsidence

rock cycle | a concept in geology that describes transitions among the three main rock types: sedimentary, metamorphic, and igneous

Rodinia | a supercontinent formed in the Proterozoic eon (1000 to 700 million years ago)

root structure | a thin, tubular, near-vertical, and sometimes downward-branching sedimentary structure formed by the filling of a hole left by a root, also called a root cas

rudist | a bivalve mollusk that existed from Late Jurassic to Cretaceous. The two valves (shells) were very unequal. This grew as solitary animals or in reefs.

sag basin | a basin formed by extension of continental crust typically containing lake deposits and evaporites

salt sheet | a salt mass that is longer and wider than its thickness. It is fed by a salt diapir.

salt tectonics | structural features caused by the movement (flow) of salt under geologic stresses. This can include salt domes and canopies and can also effect overlying sedimentary strata

sandstone | a clastic sedimentary rock composed of sand-sized minerals, rock fragments, or organic material

scoria | a vesicular mafic igneous extrusive rock which often forms in cinder cones

sea level rise | a rise of the mean sea level; this causes coastline retreat and increased flooding

seismic character | a set of characteristics with similar seismic reflections including bedforms, their geometry, lateral continuity, amplitude, frequency, and interval velocity

septa | a wall that divides a cavity into smaller sections

septae (corals) | radial internal walls within the chamber of a coral that support their soft tissue

shale | indurated mudstone, usually clay rich, with bedding planes lined with clay which produce fissility (easy separation of the layers)

shear zone | a structural discontinuity in the Earth's crust or upper mantle. It forms as a response to inhomogeneous deformation partitioning strain into high-strain zones. Intervening blocks are relatively undeformed

shelf | the flat part of the continental margin between the shoreline and the shelf margin. Generally it is less than 180 m (600 ft) water depth. They can also occur in intracratonic basins

Silurian | the third period of the Paleozoic era, between the Ordovician and Devonian periods (444 to 416 Ma)

siphuncle | a tube running between the chambers in cephalopods that allows them to adjust their internal pressure and buoyancy

source rock | a term for hydrocarbons that refers to a sedimentary rock that is rich in organic matter and has been subjected to heat that will generate oil or gas

species | a group of organisms that can reproduce with one another and produce fertile offspring

spherical symmetry | a body shaped like a sphere arranged around a central point

spicule | a siliceous or calcareous support that stiffens and supports tissues of various invertebrates, especially siliceous sponges

spicules | part of the skeleton of a sponge that is a small needle-like structure made of calcite or silica

sponge | multicellular organisms with bodies full of pores allowing water to circulate through them. They are made of collagen and some have silica-rich spicules.

starved basin | a sedimentary basin in which the rate of sedimentation is less than the rate of subsidence

storm surge | a sudden rise in sea level in coastal areas during a storm or hurricane caused by strong winds blowing onshore

strata | tabular or sheet-like layers of sedimentary rock. A single layer is called stratum.

stratification | layering in sedimentary rocks and igneous rocks formed at the Earth's surface such as lava flows and volcanic fragmental deposits. These layers can range from several millimetres to many metres in thickness and vary greatly in shape

stratigraphic column | a representation used to describe the vertical sequence of rock units

stratigraphic section | a sequence of rock layers or formations in the order they were deposited

stratigraphy | a branch of geology that focuses on the study of rock layers and layering. It is can cover both sedimentary and layered volcanic rocks. Stratigraphy has two related subfields: lithostratigraphy and biostratigraphy

streak | color of a mineral in a powdered form

strike and dip | used to describe the orientation of a rock bed, fault, fracture, cuestas, igneous dikes, and sills.

subduction | a process that occurs at convergent plate boundaries where one plate descends beneath another into Earth's mantle.

subsidence | downward motion of land; often related to soil compaction, extraction of natural gas or other mineral resources, and ground and water withdrawal. It can also occur with earthquakes, glacial isostatic adjustment, erosion, sinkhole formation, or sediment loading

supercontinent | a large landmass (notably Pangaea, Gondwana, and Laurasia) that then divided to form the present continents

suture | the zone where two plates meet during continent-continent collision

suture pattern | a feature used to classify cephalopods with patterns such as ammonite, ceratite, goniatite, and nautiloid

suturing | the zone where two continental plates meet during convergence

swelling clay | smectite or vermiculite clay minerals that swell by absorbing water

symmetrical ripple marks | a sedimentary structure produced by the back-and-forth motion of waves or tides in which both limbs of the ripple are at about the same angle

synform | A downward closing fold

Taconic | a mountain building period from 550 to 440 million years ago

talus | coarse, angular rock fragments formed by falling or sliding rocks down a slope

ternary plots | a graph that depicts the ratios of the three variables as positions in an equilateral triangle

Tethys Ocean | an ocean that occupied the area along the Alpine to Himalayan mountain belt in the Jurassic. Named after Tethys, the wife of Oceanus in Greek mythology

trace fossil | a fossil that records biological activity but not the preserved remains of the plant or animal

transform | a plate boundary where two plate boundaries move horizontally beside each other

transgression | a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding

transgressive | Areas of land that are covered by a sedimentary basin and are now below sea level. A marine transgression is a geological process occurring when areas of land are submerged below sea level. The opposite event, marine regression, occurs when the sea becomes exposed land (transgressive). Synonym: onlap

trench | a topographic depression of the sea floor, relatively narrow in width, but very long usually associated with convergent plate boundaries

Triassic | a geologic period that spans 50.6 million years from the end of the Permian Period 251.9 Ma, to the beginning of the Jurassic Period 201.3 Ma. This is the first and shortest period of the Mesozoic Era

tundra | a biome where tree growth is shortened by low temperatures and short growing seasons

turbidite | sedimentary deposits on the sea-bottom formed by massive slope failures that result in currents carrying grains sorted by density

turbidity currents | the currents that deposit grains sorted by density

type locality | the geographic locality of site chosen for the description of a geologic unit. Can also be used for the site that a fossil or mineral is first discovered

type section | similar to a type locality, this consists of a representative series of rock units. Once described it can never be changed

U-Pb geochronology | a method of determining absolute age using isotopes of uranium, thorium, and lead typically using the mineral zircon. Yields ages between 4,500 to 5 Ma

unconformity | a buried erosional or non-depositional surface separating two rocks or strata of different ages, indicating that sediment deposition was not continuous

uniformitarianism | the theory that the same natural laws and processes that operate in our present-day scientific observations have always operated in the universe in the past and apply everywhere in the universe. It is sometimes referenced as "The present is the key to the past".

valley glacier | a glacier that begins at cirque at the head of a valley head or in a plateau ice cap and flowes downward between the walls of a valley. This erosion results in U-shaped valleys

valve | shells of animals especially paired shells of brachiopods and bivalves such as clams and oysters

varve | paired light and dark sedimentary layers which may indicate cyclical seasons such as summer and winter

vertebrate | an animal with a backbone such a dog or cat

vertical exaggeration | this is used to emphasize vertical features, which might be too small to identify relative to the horizontal scale. Many geological cross-sections have no vertical exaggeration

volcanic ash | fragments of rock, minerals, and volcanic glass, created during volcanic eruptions and measuring less than 2 mm in diameter

volcanic material | larger fragments of rock, minerals, and volcanic glass created during volcanic eruptions and measuring more than 2 mm in diameter

Walther's Law | this theory states that the vertical succession of facies reflects lateral changes in environment of deposition

wavy bedding | occurs when mud is deposited over the entire bed of rippled and/or cross stratified sand following the alternating concave-convex nature of the ripples creating a wavy appearance

way-up indicators | a characteristic seen in a sedimentary or volcanic rock that makes it possible to determine whether they are still the right way up (i.e. in the attitude in which they were originally deposited)

window | in structural geology, it is an eroded area that shows rocks beneath a thrust sheet

zircon | a zirconium silicate mineral, $ZrSiO_4$, that is present in felsic and intermediate igneous rocks as well as metamorphic and sedimentary rocks. Thus, it is invaluable for U-Pb geochronology

zooid | a single animal that is part of a colony

zooplankton | small and microscopic organisms drifting or floating in the sea or fresh water, consisting chiefly of diatoms, protozoans, small crustaceans, and the eggs and larval stages of larger animals

Copyright

The Story of Earth: An Observational Guide by Daniel Hauptvogel & Virginia Sisson is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License, except where otherwise noted.

Detailed Licensing

Overview

Title: The Story of Earth - An Observational Guide (Hauptvogel and Sisson)

Webpages: 27

Applicable Restrictions: Noncommercial

All licenses found:

- CC BY-NC-SA 4.0: 55.6% (15 pages)
- Undeclared: 44.4% (12 pages)

By Page

- The Story of Earth - An Observational Guide (Hauptvogel and Sisson) - *CC BY-NC-SA 4.0*
  - Front Matter - *Undeclared*
    - TitlePage - *Undeclared*
    - InfoPage - *Undeclared*
    - Table of Contents - *Undeclared*
    - Licensing - *Undeclared*
    - Preface - *CC BY-NC-SA 4.0*
    - Licensing - *Undeclared*
  - 1: Labs - *Undeclared*
    - 1.1: Geologic Skills - *CC BY-NC-SA 4.0*
    - 1.2: Plate Tectonics - *CC BY-NC-SA 4.0*
    - 1.3: Earth Materials - *CC BY-NC-SA 4.0*
    - 1.4: Geologic Time - *CC BY-NC-SA 4.0*
    - 1.5: Sedimentary Structures - *CC BY-NC-SA 4.0*
    - 1.6: Stratigraphy - *CC BY-NC-SA 4.0*
    - 1.7: Fossil Preservation - *CC BY-NC-SA 4.0*
    - 1.8: Fossils - *CC BY-NC-SA 4.0*
    - 1.9: Paleoenvironments - *CC BY-NC-SA 4.0*
    - 1.10: Geologic Structures and Mapping - *CC BY-NC-SA 4.0*
    - 1.11: Interpreting Earth's History using Maps - *CC BY-NC-SA 4.0*
    - 1.12: Paleoclimate - *CC BY-NC-SA 4.0*
  - Back Matter - *Undeclared*
    - Index - *Undeclared*
    - Glossary - *Undeclared*
    - Copyright - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *Undeclared*
    - Detailed Licensing - *Undeclared*

Detailed Licensing

Overview

Title: The Story of Earth - An Observational Guide (Hauptvogel and Sisson)

Webpages: 27

Applicable Restrictions: Noncommercial

All licenses found:

- CC BY-NC-SA 4.0: 55.6% (15 pages)
- Undeclared: 44.4% (12 pages)

By Page

- The Story of Earth - An Observational Guide (Hauptvogel and Sisson) - *CC BY-NC-SA 4.0*
  - Front Matter - *Undeclared*
    - TitlePage - *Undeclared*
    - InfoPage - *Undeclared*
    - Table of Contents - *Undeclared*
    - Licensing - *Undeclared*
    - Preface - *CC BY-NC-SA 4.0*
    - Licensing - *Undeclared*
  - 1: Labs - *Undeclared*
    - 1.1: Geologic Skills - *CC BY-NC-SA 4.0*
    - 1.2: Plate Tectonics - *CC BY-NC-SA 4.0*
    - 1.3: Earth Materials - *CC BY-NC-SA 4.0*
    - 1.4: Geologic Time - *CC BY-NC-SA 4.0*
    - 1.5: Sedimentary Structures - *CC BY-NC-SA 4.0*
    - 1.6: Stratigraphy - *CC BY-NC-SA 4.0*
    - 1.7: Fossil Preservation - *CC BY-NC-SA 4.0*
    - 1.8: Fossils - *CC BY-NC-SA 4.0*
    - 1.9: Paleoenvironments - *CC BY-NC-SA 4.0*
    - 1.10: Geologic Structures and Mapping - *CC BY-NC-SA 4.0*
    - 1.11: Interpreting Earth's History using Maps - *CC BY-NC-SA 4.0*
    - 1.12: Paleoclimate - *CC BY-NC-SA 4.0*
  - Back Matter - *Undeclared*
    - Index - *Undeclared*
    - Glossary - *Undeclared*
    - Copyright - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *Undeclared*
    - Detailed Licensing - *Undeclared*