Introductory Physical Geology Laboratory Manual – First Canadian Edition (v.3 - Jan 2020)
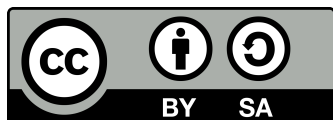
Introductory Physical Geology Laboratory Manual – First Canadian Edition (v.3 - Jan 2020)

Adapted from Laboratory Manual for Introductory Geology (2015) written by Bradley Deline, Randa Harris, & Karen Tefend.

JOYCE MCBETH, KARLA PANCHUK, TIM PROKOPIUK, LYNDSAY HAUBER, AND SEAN LACEY

Contents

Individual chapters of the overview and exercises sections from this lab manual can be downloaded from the links below. You can also read them online, scroll down on the front page of this online open textbook and select the chapter overview or exercises you would like to read. The exercise sections are the important parts for USask GEOL 121 labs this semester, and they are available in a package at the bookstore for you to print for labs.

USask Bookstore price: $15 + tax (January 2020)

There are images in the later labs (Chapter 6, 7, 8, 9) that will not print properly to scale from the web page, so it is best to buy a copy from the bookstore to ensure you have the resources you need for those labs.

–Prof McBeth, January 2020.

PDF copy of lab manual:

Introductory Physical Geology Laboratory Manual (First Canadian Edition, v.3):

pdf of all chapters; maps from end of document (print on 11'x17' paper): Garibaldi Saskatoon

Note: overview sections not included in this pdf, this is the same pdf provided to the bookstore for printing.

PDF copies of individual chapters:

Note: the overview sections are to help support your learning. I have provided pdf copies of both the overview and exercises sections in case you would like to print or download them.

Introduction and Lab Guide for USask GEOL 121 Students PDF

Chapter 1 (Lab 1): Introduction to Canadian Geology. Overview & Exercises

Chapter 2 (Lab 2, 3): Minerals. Overview Exercises

Chapter 3 (Lab 4): Igneous Rocks. Overview Exercises

Chapter 4 (Lab 5): Sedimentary Rocks. Overview Exercises

Chapter 5 (Lab 5): Metamorphic Rocks. Overview Exercises

Lab 6: Rock and Mineral Quiz/Exam Quiz sheet

Chapter 6 (Lab 7): Relative and Absolute Dating. Overview Exercises

Chapter 7 (Lab 7): Topographic Maps. Pre-lab practice questions

Chapter 7 (Lab 7): Topographic Maps. Overview Exercises

Chapter 7 (Lab 7): Topographic Maps. Post-lab practice questions

Chapter 8 (Lab 8, 9): Geological Structures. Overview I & II

Lab 8: Geological Structures I, Exercises I

Lab 9: Geological Structures II, Exercises II (copy and paste the link below)

https://opentextbooks.uregina.ca/app/uploads/sites/81/2020/11/

Chapter8_Structure_II_Exercises_20200108.pdf

Not covered in lab: Practice questions

Chapter 9 (Lab 10): Earthquakes. Overview Exercises

Note: the following chapter(s) are not currently covered in USask GEOL 121.

Chapter 10: Water. Overview Exercises

Introduction

Welcome! Our vision for this project was to create a Canadian introductory physical geology lab manual that is more accessible and affordable for our first-year physical geology students. Since this is an open text, we can also update or modify it quickly to integrate improvements. At the University of Saskatchewan, in addition to our first-year course in physical geology that includes a lab, we offer an introductory physical geology course that does not have a lab component (primarily as a science elective for arts students). Our hope is this manual can be useful to these students too, offering them self-directed hands-on practice with geoscience problems and supplementary text resources.

We were fortunate that we didn't have to start from zero on this project: Bradley Deline, Randa Harris, and Karen Tefend of the University of West Georgia had prepared a [Laboratory Manual for Introductory Geology](#) that we have adapted. Each chapter of this manual is broken down into introduction, overview, and exercises sections. The introduction provides learning objectives and a short vocabulary list, the overview sections provide useful background concepts, and the exercises sections are problems students will (or could) cover in physical geology course labs. Several labs also contain practice or extra questions; these are materials that don't fit in our labs at the University of Saskatchewan but may be useful as supplemental activities for our students. Much of the content for the introduction, overview, and exercises sections of each chapter were based on [Deline, Harris & Tefend's manual](#), but we have extensively rewritten several chapters to align with our programming at USask (specifically the introductory chapter, the exercises on minerals and rocks, and the geological structures chapter). We have also modified the original edition to include more Canadian content and examples, and in most cases, we have changed imperial units to metric.

We are grateful to Bradley Deline, Randa Harris & Karen Tefend for creating the first edition of this text and for helping us along with our questions about the manual – it was a delight to work with the firm foundation you provided! We thank the University of Saskatchewan Gwenna Moss Centre for Teaching and Learning (GMCTL) and the Department of Geological Science for financial support for this project. We are grateful to Jordan Epp at USask Teaching and Learning for his support with PressBooks and Heather Ross at GMCTL for her guidance and encouragement. We are also grateful to Todd LeBlanc for assisting Tim with test-driving the manual in labs before we started the project; his experiences provided critical insights on directions for revisions, particularly for the geological structures chapter. Thank you to our TAs and students for their feedback on the first version of this edition of the manual, we have incorporated numerous edits in this version to address their suggestions.

In the second edition of this manual, we plan to expand the chapters to include others from the first American edition by Deline et al (e.g., plate tectonics) as a resource for our students. If you find errors in the current edition or are interested in contributing images, exercises, examples of Canadian geology or other content to the next edition (or adapting the text for your own use) please let us know. Please direct comments and suggestions to Joyce McBeth at joyce.mcbeth at usask.ca. We hope you find the resources in this manual helpful – please let us know what you think!

–Joyce McBeth, Karla Panchuk, Tim Prokopiuk, Lyndsay Hauber, & Sean Lacey

Department of Geological Sciences, University of Saskatchewan, SK, Canada, January 2020 (v.3).

Cover image: (top) purple garnet sand along a beach at Waskesiu Lake, Prince Albert National Park, Saskatchewan, photo by Scott Colville CC BY 4.0; (bottom) purple sand under the microscope Joyce McBeth CC BY 4.0.

Acknowledgements

This lab manual is an adaptation of the following chapters from [Laboratory Manual for Introductory Geology](#) (2015), First Edition, written by Bradley Deline, Randa Harris, & Karen Tefend.

Original Chapter Number	Original Author	Adaptation Chapter Number(s)
1	Deline	6
3	Tefend & Deline	7
5	Harris	10
7	Harris	2
8	Tefend	3
10	Deline	4
11	Tefend	5
12	Harris & Deline	8
13	Harris	9

Author Biographies

McBeth, Panchuk, Prokopiuk, Hauber, & Lacey (2018) Introductory Physical Geology Laboratory Manual, First Canadian Edition; Adapted from Deline, Harris, and Tefend (2015) Laboratory Manual For Introductory Geology, First Edition.

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Lab Guide For USask GEOL 121 Students

Welcome University of Saskatchewan GEOL 121 Students! We are glad you are joining us to learn about geology this semester, and we hope you enjoy your experience here. Geology is a challenging and rewarding science. You will probably learn things this semester that will stay without you throughout your life and help you understand the world around you more completely.

We have a few rules to help you get the most out of your lab experience this semester and to keep things running smoothly.

Please respect and follow these guidelines:

- attend lab in **your assigned section**.
- you must complete all lab assignments and hand in all assignments that TAs mark in order to pass the course. If you do not, you will get an incomplete in the class. If you hand in assignments late without prior approval you will receive a 0 in that lab.
- if you will be absent from lab, contact the lab coordinator (Michael Cuggy, michael.cuggy at usask.ca) **before** you are absent.
- if you are absent due to illness contact the lab coordinator as soon as possible to arrange to attend an alternative lab. The longer you wait the harder it is to accommodate you so please contact the lab coordinator as soon as you are aware you are going to be (or have been) absent.
- Note that each lab is only offered for one week of the semester, so if you miss a week it will be very difficult to make up.
- Do not lick the rocks! Some of them might have a characteristic taste but remember – hundreds of students handle these samples each year, and if you lick the samples you are probably tasting their sweat, viruses, and bacteria! Your TA can tell you whether the mineral or rock sample has a distinctive taste or not.
- Many of the rock and mineral samples contain metals that you should not ingest. Wash your hands after each lab where you handle rocks and/or mineral samples.
- During quizes and exams, students are explicitly forbidden to talk, share materials, look at exam sheets other than their own, or in any other way participate in activities that could be perceived as cheating. Concerns with students who do any of these things will be resolved according to the student academic misconduct process flow chart. All students should read and be familiar with the Regulations on Academic Student Misconduct.

AES students:

- contact the lab coordinator (Michael Cuggy, michael.cuggy at usask.ca) (not your TA!) at the start of the semester or as soon as possible to arrange to write the rock and mineral quiz at a different time.
- arrange with AES to write the lab final exam. Their standard rules and deadlines apply for writing the lab final exam as for midterms or final exams arranged through AES. If you do not arrange in advance with them we will not be able to accommodate your request for accommodation.

Please be respectful of your TAs' time:

- be punctual – come to labs on time.
- pay attention when they are presenting at the start of each lab.
- Learn your TAs' names.
- read the overview section prior to attending the lab and come to labs prepared to learn.
- if you are struggling, let your TA know as soon as possible – the sooner you let them know, the more they can help

you.

- visit your TA during their office hours or arrange for a mutually-convenient time via email in advance.
- ask lots of questions during the labs and use the time assigned for the labs. A big part of the responsibility for getting the most out of your labs belongs to you, so use the opportunities you are given to learn.

How to succeed in GEOL 121 labs:

- attend all the labs and complete the lab exercises.
- review your lab exercises in preparation for the rock and mineral exam and the lab final exam.
- If you are struggling – get help from your TA as soon as possible, and consider working with a tutor
- geology is a collaborative discipline, so we expect students will work together to learn and complete their lab assignments. However! Be honest with yourself – if you redid the lab on your own, could you do it? If not, spend more time preparing for the quiz and exam, because you will have to work on your own during those tests. Be respectful of your lab partners – contribute equally to lab work as a team.

There are a few things you will need to bring to lab with you:

- rock and mineral identification kit that can be purchased from the bookstore (for Rock and Mineral Labs and quiz)
- pen, pencil, and eraser
- pencil crayons
- geometry set (including protractor, ruler, drafting compass, for Structure and Earthquake Labs)

Good luck with the labs and we hope you enjoy learning about geology this semester!

CHAPTER 1. INTRODUCTION TO CANADIAN GEOLOGY

You can download a pdf copy of this lab to print, and order a copy of the lab manual from the bookstore!

Prepared by Joyce M. McBeth & Lyndsay R. Hauber (2018) University of Saskatchewan. CC BY-SA 4.0.

1.1 INTRODUCTION

Welcome to your physical geology labs! In your first lab, we'll introduce you to Canadian geology and mineral and energy resources across the country.

The objective of this lab to gain an appreciation of the types of mineral and energy resources in Canada and the mineral and energy resources in your province or territory. We will explore how these mineral and energy resources relate to the patterns in the geology and rock ages in your province or territory.

1.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- name several mineral and/or energy resources found across Canada
- describe generally where these resources are found in Canada
- describe how these resources relate to the geology of Canada
- name mineral and/or energy resources found in your province or territory
- describe how these resources are distributed across your province or territory
- describe how these resources relate to the geology in your province or territory

1.1.2 Key Terms

- mineral resources
- energy resources
- geological units
- bedrock geological map
- mineral resource map
- Eon
- Precambrian
- Phanerozoic
- geological provinces
- Canadian Shield
- Interior Platform

Overview of Canadian Geology and Mineral and Energy Resources

Note: this chapter is structured with a brief introduction to general Canadian geology and mineral and energy resources, and then specific information for each province or region of the country. If you are a student, please read the section for the province or region where you are going to university first. Please answer the questions in the exercises section of this chapter based on the province or region where you are attending university.

1.2 CANADIAN GEOLOGY & RESOURCES

The geology of Canada is very diverse (Figure 1.1). In Alberta, Saskatchewan and Manitoba, the prairies are flat because the rocks beneath are flat-lying sedimentary rocks deposited from an inland sea many millennia ago. In mountainous BC and the Yukon Territory, there are volcanoes resulting from plates colliding along the west coast of North America. The iconic beauty of the majestic Rocky Mountains grace BC and Alberta; these rocks are composed of uplifted sedimentary rocks that used to be at the bottom of the ocean. The rocks of the Canadian Shield are the base for the stunning lakes and rocky landscapes of the Northwest Territories, Nunavut, Manitoba, Ontario, and Quebec and represent some of the oldest rocks on Earth and the core of the North American continent. When these rocks formed, the landscape would have appeared much like the Hawaiian Islands today – but it was before plant life evolved! The Appalachian Mountains through southern Quebec used to be as high as the Rockies but have worn away over the many millions of years since they formed. On the East coast, rocks with some of the oldest multicellular fossils in the world jut out from the coast of Newfoundland, and thick layers of sediments coat the continental shelf that extends underwater out into the Atlantic Ocean.

Figure 1.1 | *Geological Map of Canada*
Source: National Resources Canada (1996) [Contains information licensed under the Open Government Licence – Canada.](#) *Geoscan ID 208175.* [view source](#)

This broadly varying geology has generated diverse and plentiful mineral and energy resources across our country. **Mineral resources** include: metals such as gold, silver, and copper; minerals such as diamonds and gypsum; and quarried building materials such as gravel, sand, and limestone. **Energy resources** include oil, gas, and coal deposits. Examples of mineral and energy resources in Canada include the oil and gas deposits of the prairies of Alberta and Saskatchewan and the base metal (e.g., nickel, lead, copper) mines in BC, the Yukon, Ontario, and Quebec. Some of the geology that hosts these resources is special and unusual, for example the nickel deposits mined at Sudbury, ON were formed from an ancient meteorite impact. Other geology is relatively common, for example sand and gravel are mined at quarries across the country for use in building materials.

We encourage you to take some time to explore Canada's Mineral and Energy Resources using the [Interactive Map](#) on the Natural Resources Canada website. As you explore the geological map (Figure 1.1) and interactive mineral resources map of Canada, it is useful to also look at a map of geological provinces in Canada (Figure 1.2) to help understand how Canadian geology broadly varies across the country.
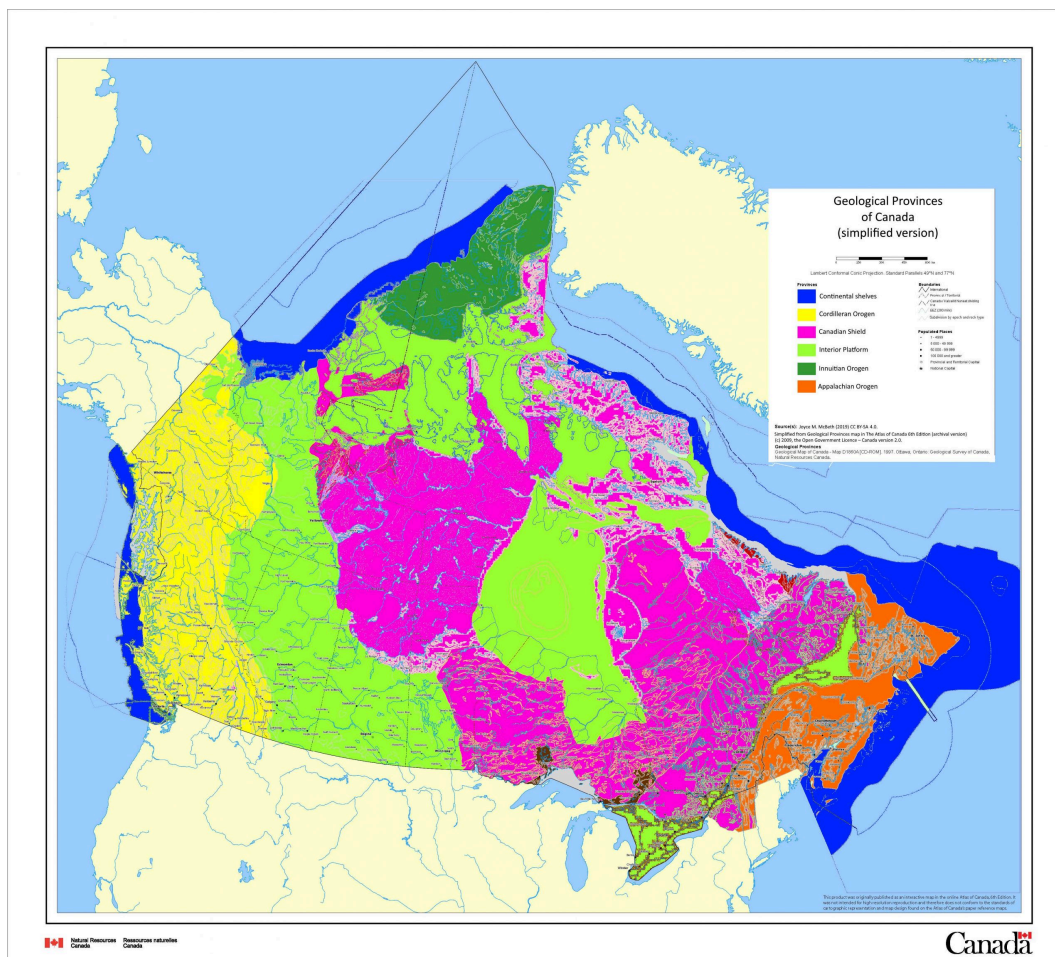
Figure 1.2 | *Geological Provinces of Canada (simplified version). Source: Joyce M. McBeth (2019) CC BY-SA 4.0. Modified from map "Geological Provinces" from the Atlas of Canada 6th Edition © 2009, based on the Geological Map of Canada – Map D1860-A © 1997, Ottawa, ON, Geological Survey of Canada, National Resources Canada. Contains information licensed under the [Open Government Licence – Canada](#). [View source](#)*

Geological provinces are areas where the rocks were formed through similar processes over similar ranges of time. Note that their boundaries are different from the political provinces of Canada. There are 6 geological provinces in Canada: the Canadian Shield, the Interior Platform, the Innuitian Orogen, the Cordilleran Orogen, the Appalachian Orogen, and the Continental Margins.

The rocks of the **Canadian Shield** (pink regions of the map in Figure 1.2) were formed from 4.6 billion to 541 million years ago, a range of time known as the Precambrian. These rocks formed from melted rock that cooled and solidified, and also rocks that were subjected to high pressure and heat after they formed, creating distinctive banded rocks called gneiss (a type of metamorphic rock). At the time the rocks of the Canadian Shield formed, life on earth looked very different – there were no plans or animals, only single-celled organisms! In contrast, the rocks of the **Interior Platform** (green regions on the map in Figure 1.2) were formed in the Phanerozoic Eon (from 514 million years ago until present). These rocks primarily formed from seawater and from the breakdown of older rocks into tiny particles that were deposited into thick deposits of sediments top of older Precambrian rocks.

In the lab, you will use **bedrock geology maps** (maps of the types of rocks in an area) and **mineral resource maps** (maps of where resources are located in an area) to explore the geology and resources across Canada and in your province or territory.

[Map of Canadian Geology](#)
[Map of Canadian Resources](#)

1.3 GEOLOGY & RESOURCE MAPS FOR CANADIAN PROVINCES & TERRITORIES

We have provided links below to bedrock geology and resource maps for each province and territory (if the maps exist).

1.3.1 SASKATCHEWAN GEOLOGY & RESOURCES

Map of Saskatchewan Geology

Map of Saskatchewan Resources

1.3.2 BC GEOLOGY & RESOURCES

Map of BC Geology [link dead :-(]

Map of BC Resources [link dead :-(]

1.3.3 ALBERTA GEOLOGY & RESOURCES

Map of Alberta Geology

Map of Alberta Resources

1.3.4 MANITOBA GEOLOGY & RESOURCES

Map of Manitoba Geology (Adobe Flash Player required)

Map of Manitoba Resources (Adobe Flash Player required)

1.3.5 ONTARIO GEOLOGY & RESOURCES

Map of Ontario Geology (GoogleEarth required)

Map of Ontario Resources (GoogleEarth required)

1.3.6 QUEBEC GEOLOGY & RESOURCES

Map of Quebec geological domains and a geological overview of Quebec

Interactive Map of Quebec Resources

1.3.7 NEW BRUNSWICK GEOLOGY & RESOURCES

Map of New Brunswick Geology

Map of New Brunswick Resources

1.3.8 NOVA SCOTIA GEOLOGY & RESOURCES

Map of Nova Scotia Geology

Map of Nova Scotia Resources

1.3.9 PRINCE EDWARD ISLAND GEOLOGY & RESOURCES

Map of PEI Geology

Map of PEI Resources

1.3.10 NEWFOUNDLAND & LABRADOR GEOLOGY & RESOURCES

Map of Newfoundland & Labrador Geology

Interactive Map of Newfoundland & Labrador Resources

1.3.11 YUKON TERRITORY GEOLOGY & RESOURCES

Map of Yukon Territory Geology

Map of Yukon Territory Resources

1.3.12 NORTHWEST TERRITORY GEOLOGY & RESOURCES

Map of NWT Geology

Map of NWT Resources

1.3.13 NUNAVUT TERRITORY GEOLOGY & RESOURCES

Map of Nunavut Geology [link :-(]

Map of Nunavut Resources

Exercises on Canadian Geology

You can print a copy of this lab using the [pdf version here](#).

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Note: If you are a student, please answer the questions in these exercises based on maps for the province, territory, or region where you are attending university.

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____

Please add your name and email address to the sign-in sheet at the beginning of lab this week to ensure your TAs have contact details to email you about important lab news!

Your TAs will check that you have completed the questions at the end of the lab. Please hold on to your lab notes to help you prepare for your lab final exam.

1-E1 LAB EXERCISES – CANADIAN GEOLOGY & MINERAL AND ENERGY RESOURCES

1. Before you go through the maps provided in this lab, we are curious what you already know about energy and mineral resources in Canada. It is ok if you don't know much about it yet – you will probably know more by the end of this lab! List as many Canadian energy and mineral resources as you can think of and try to think of one for each province and territory.
2. Here is a list of some of the mineral and energy resources in Canada. Each of these resources can be found on the [Atlas of Canada Minerals and Mining Interactive Map](#), and by searching the web. List 1 or 2 provinces or territories where each resource is found. Challenge: try to find a resource from each province and territory in Canada.

Column 1	Column 2	
Energy resources:	**Precious metals and minerals:**	

Column 1

Column 2

Energy resources:
oil _____
gas _____
oil sands _____
coal _____
uranium _____

Base metals:
nickel _____
lead _____
copper _____
zinc _____

Precious metals and minerals:
gold _____
silver _____
diamonds _____

Other metal & mineral resources:
potash _____
niobium _____

Quarried building materials:
aggregate (gravel) _____
limestone _____
sand _____

Table 1-E1 | Canadian Energy and Mineral Resources. Source: Joyce McBeth (2018) CC BY 3.0 original work.

3. Now refer to the Geological Map of Canada alongside the map of the geological provinces of Canada (found in the overview section of this lab). What pattern do you see in the locations of the different resources you identified in question 2 above and the geological provinces of Canada? Give an example of a resource you find in several geological provinces. Give an example of a resource you find mostly in one geological province.

  4. What human factors do you think have (or may have) affected energy and mineral resource development patterns across the country?

1-E2 LAB EXERCISES – REGIONAL GEOLOGY & MINERAL AND ENERGY RESOURCES

1. Refer to your provincial or territorial mineral resource map. What kinds of energy resources (if any) are in your province or territory? Where (roughly) are they located (e.g., near which city)? What kinds of metal or resource mining (if any) occur in your province or territory? Where are they located (roughly)?

2. Looking across your province or territory's resources map. Do you notice any broad patterns in how the resources are distributed across the map? Are there more of one kind of resource (e.g., metal mines) in one area than another than another?

3. Refer to the geological map for your province or territory. Geologic time can be divided into two major parts, the Precambrian (4.6 billion years ago to 541 million years ago) and the Phanerozoic Eon (541 million years to present). Your TA will give you an overview of the ages of rocks (at the Eon scale) throughout your province or territory. Note down the ages of the rocks (Precambrian or Phanerozoic) are in your province or territory. Are there patterns in the colours assigned to the rock units across the map area (e.g., are there lots of green-coloured units in one area, and lots of pink-coloured units in another area)? Is there a relationship between the age of the rock units and the colours assigned to the units?

4. Now refer to both your province or territory's geology map and mineral and resources map. Do you see any broad

patterns in the distribution of mineral and energy resources in relation to the patterns in the geology? Describe any patterns you can see.

5. Now refer to the maps of Canadian mineral resources and Canadian geology. What are 2 or 3 differences between your province or territory's energy and mineral resources and the energy and mineral resources in other areas of Canada?

6. How has this lab changed your awareness of your province or territory's energy and mineral resources and/or energy and mineral resources across Canada?

CHAPTER 2. MINERALS

2.1 INTRODUCTION

Have you used a mineral yet today? While many people may initially say no, answer these questions: Have you brushed your teeth? Have you eaten anything that might contain salt? Did you put on make-up this morning, or do you have painted fingernails or toenails? Have you used a cellphone? What about a car, bike, or public transportation? If you have done any of those things, you have used at least one mineral, and in many cases you have used a great number of minerals. Minerals are very useful and common in everyday products, but most people do not even realize it.

A **mineral** is defined as a naturally occurring, inorganic solid, with a definite chemical composition and a characteristic crystalline structure. By naturally occurring, it means that anything man has created does not count as a mineral (e.g. Figure 2.1). To be an inorganic solid, the mineral must not be composed of the complex carbon molecules that are characteristic of life and must be in the solid state, rather than vapor or liquid. This means that water, a liquid, is not a mineral, while ice, a solid, would be, as long as it is not man-made. A definite chemical composition refers to the chemical formula of a mineral. For most minerals, this does not vary (e.g. halite is NaCl), though some minerals have a range of compositions, since one element can substitute for another of similar size and charge (e.g. olivine is $(Mg,Fe)_2SiO_4$, and the magnesium and iron content can vary). The atoms within minerals are lined up in an orderly fashion, so that the characteristic crystalline structure is just an outward manifestation of the internal atomic arrangement.

Figure 2.1 | *Synthetic Bismuth.*
Source: Philippe Giabbanelli (2010) CC BY-SA 3.0 *view source*

Minerals are not only important for their many uses, but also as the building blocks of rocks. In this lab, you will lay the foundation for all the future rock labs in the course. Correct mineral identification is critical in geology, so work through this lab carefully. There are several thousand minerals, but we will focus on only twenty-one of the most common ones.

2.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Know the definition of a mineral
- Understand the many different physical properties of minerals, and how to apply them to mineral identification
- Be able to distinguish mineral cleavage from mineral fracture
- Identify 21 minerals

2.1.2 Key Terms

- Cleavage
- Crystal Form
- Fracture
- Hardness
- Lustre
- Mineral
- Specific Gravity
- Streak

- Tenacity

Overview of Minerals

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 7 "Minerals" by Randa Harris, CC BY-SA 4.0. [View source.](#) Last edited: 8 Jan 2020

2.2 PHYSICAL PROPERTIES

Identifying a mineral is a little like playing detective. Minerals are identified by their physical properties. How would you describe the mineral in Figure 2.2? You may say that it is shiny, gold, and has a particular shape. Each of these descriptions is a physical property (shiny is lustre, gold is colour, shape is crystal form). Physical properties can vary within the same minerals, so caution should be applied when identifying minerals. For example, colour is a property that is not a very realistic diagnostic tool in many cases, as some minerals, such as Quartz, can come in a variety of colours (e.g. Figure 2.3). Occasionally, colour can be helpful, as in the case of olivine, which is said to be "olive green", a light to dark green (e.g. Figure 2.4). We will cover each of the physical properties in detail to help you identify the minerals.

Figure 2.2 | *Describe this mineral.*
Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

Figure 2.3 | *Examples of the different varieties of quartz (jasper, rose quartz, smoky quartz, agate, amethyst, citrine, and petrified wood), demonstrating the difficulty of identifying this mineral.*
Source: Randa Harris (2017) CC BY-SA 3.0 [view source](#)

Figure 2.4 | *The mineral olivine has an "olive green" colour.*
Source: Joyce M. McBeth (2018) CC BY 4.0 [view source](#)

2.2.1 Hardness

Hardness refers to the resistance of a mineral to being scratched by a different mineral or other material and is a product of the strength of the bonds between the atoms of a mineral. Whatever substance does the scratching is harder; the item scratched is softer. Hardness is based off a scale of 1 to 10 created by a mineralogist named Friedrich Mohs (e.g. Figure 2.5). Mohs' scale lists ten minerals in order of relative hardness. Each mineral on the scale can scratch a mineral of lower number. Your mineral kit comes with several items of a known hardness. The glass plate has a hardness of 5.5, the iron nail has a hardness of 4 , the copper coin has a hardness of 3, and your fingernail has a hardness of 2.5. If you can scratch a mineral, then it would be softer than your fingernail, so therefore its hardness would be <2.5. When trying to scratch a surface, use force, but be cautious with the glass plate. **ALWAYS lay the glass plate on a flat surface rather than holding it in your hand in case it breaks.** Do not confuse mineral powder with a scratch – use your finger to feel for a groove created by a scratch (mineral powder is left behind when a soft mineral scratches a harder surface). Materials of similar hardness have difficulty scratching each other, so that, for example, your fingernail may not be able to always scratch biotite, which has a hardness of 2.5.

Number	Mineral	Relative Hardness
1	Talc	(softest mineral)
2	Gypsum	2.5 – Fingernail
3	Calcite	3 – Copper Coin
4	Fluorite	4 – Nail
5	Apatite	5.5 – Glass Plate
6	Orthoclase Feldspar	
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	(hardest mineral)

Figure 2.5 | *Mohs' Scale of Hardness*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.6 | *An example of a scratch made by the mineral quartz on a streak plate. The red arrow is pointing to the scratch. Quartz, therefore, is harder than glass.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.7 | *An example of a scratch made by a fingernail on the mineral gypsum. The red arrow is pointing to the scratch. Gypsum, therefore, is softer than a fingernail.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

2.2.2 Crystal Form

This property refers to the geometric shape that a crystal naturally grows into, and is a reflection of the orderly internal arrangement of atoms within the mineral. If minerals have space to grow when they are developing, they will display their **crystal form**. These ideal growth conditions do not always occur, however, so many minerals do not display their ideal crystal form due to crowded conditions during growth. Examples of crystal form are shown in Figure 2.8.

Cube   Hexagonal Prism   Rhombohedron

Octahedron (8 faces)   Dodecahedron (12 faces)

Figure 2.8 | *Examples of crystal form.*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 [view source](#)

2.2.3 Cleavage

As minerals are broken, some may cleave, or break, along smooth flat planes known as cleavage. These flat surfaces are parallel to directions of weakness within the crystal. All the bonds among the atoms within a mineral may not be of the same strength, so that when a mineral is broken, it breaks along these zones of weakness. This results in flat cleavage planes. Minerals with perfect cleavage break along a smooth, flat plane, while those with poor cleavage break in a more irregular fashion. Some minerals do not contain zones of weakness either because all of the bonds are the same strength or the weaker bonds are not aligned within a plane. If this is the case it will not have cleavage; instead, it will fracture, similar to the curved fracture of glass when you get crack in a windshield.

Be careful not to confuse cleavage with crystal form. Crystal form occurs as a mineral grows (e.g., cubes of pyrite), while cleavage only forms as a mineral breaks. See Figure 2.9 for the main types of cleavage and an example of each.

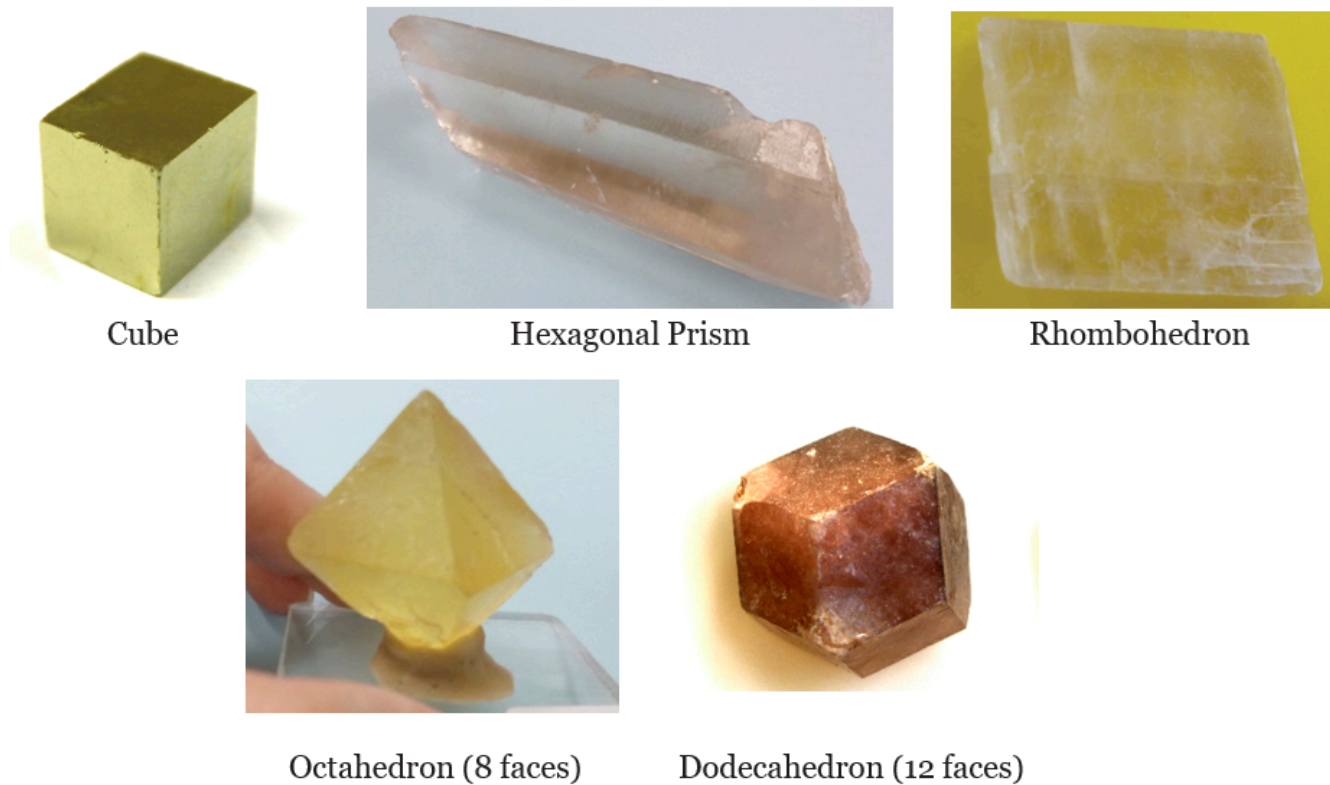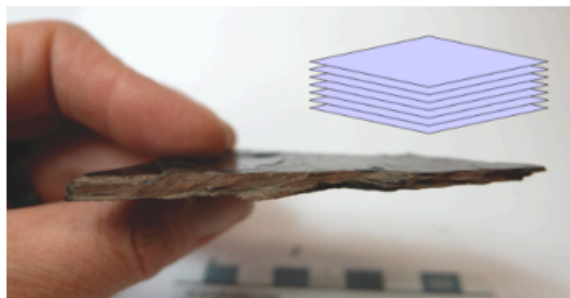**Figure 2.9 |** *Main types of cleavage, along with illustrations indicating the cleavage angles and directions.*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 [*view source*](#)

A mineral may have one or more cleavage planes. Planes that are parallel are considered the same direction of cleavage and should only count as one. One direction of cleavage is termed basal cleavage. Minerals that display this cleavage will break off in flat sheets. Two directions of cleavage is termed prismatic, while three directions of cleavage at 90° is referred to as cubic. A mineral with four directions of cleavage is termed octahedral. With 2 or more cleavage planes present, it is important to pay attention to the angle of the cleavage planes. To determine the angle of cleavage, look at the intersection of cleavage planes. Commonly, cleavage planes will intersect at 60°, 90° (right angles), or 120°. Be cautions when you see a flat surface on a mineral – not every flat surface is a cleavage plane. Crystal faces can be flat, but remember they form as a mineral grows, while cleavage forms as a mineral breaks. The crystal form of quartz is a hexagonal prism, with nice flat sides. But when quartz is hit with a rock hammer, it breaks in an irregular fashion and does not exhibit cleavage. Also use caution when trying to distinguish the minerals pyroxene and amphibole. Both

minerals are black or greenish-black, with similar hardness, making them difficult to tell apart. You must observe the cleavage angles to tell them apart. Cleavage angles in pyroxene are near 90°, so expect it to look boxy and form right angles, while cleavage angles in amphibole are 60° and 120°, so expect a more bladed or pyramid like appearance (e.g. Figure 2.10).

Figure 2.10 | *Comparison of cleavage angles between amphibole and pyroxene. Amphibole has cleavage angles at or near 60° and 120°, and pyroxene has angle at or near 90°.*
Source: Joyce M. McBeth (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 *view source*

2.2.4 Fracture

When minerals do not break along cleavage planes, but rather break irregularly, they are said to **fracture**. Commonly fracture surfaces are either uneven or conchoidal, a ribbed, smoothly curved surface similar to broken glass (e.g. Figure 2.11).

Figure 2.11 | *This piece of igneous rock called obsidian has been hit with a hammer and is displaying conchoidal fracture.*
Source: Joyce M. McBeth (2018) CC BY 4.0 *view source*

2.2.5 Lustre

Lustre refers to the appearance of the reflection of light from a mineral's surface. It is generally broken into two main types: metallic and non-metallic. Minerals with a metallic lustre have the colour of a metal, like silver, gold, copper, or brass (e.g. Figure 2.12). While minerals with a metallic lustre are often shiny, not all shiny minerals are metallic. Make sure you look for the colour of a metal, rather than for just a shine. Minerals with non-metallic lustre do not appear like metals. They may be vitreous or glassy (e.g. Figure 2.13A), earthy or dull (e.g. Figure 2.13B), waxy (e.g. Figure 2.13C), greasy or oily, etc.

Figure 2.12 | Examples of the metallic lustre of pyrite, also known as "fool's gold."
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.13A | *Example of a vitreous, or glassy, lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.13B | *Example of an earthy, or dull. lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.13C | *Example of a waxy lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

2.2.6 Streak

Streak is an easily detectable physical property. It refers to the colour left behind on an unglazed piece of porcelain when a mineral is rubbed along its surface. A streak plate is included in your rock and mineral kit to test this property. Often a mineral will have a streak of a different colour than the colour of the mineral (e.g. pyrite has a dark grey streak, Figure 2.14). Some minerals will have a white streak, which is difficult to see along the white streak plate. If you rub a mineral along the streak plate and do not see an obvious streak, wipe your finger along the streak plate. A mineral with a white streak will leave a white powder behind that will rub on your finger (e.g. Figure 2.15).
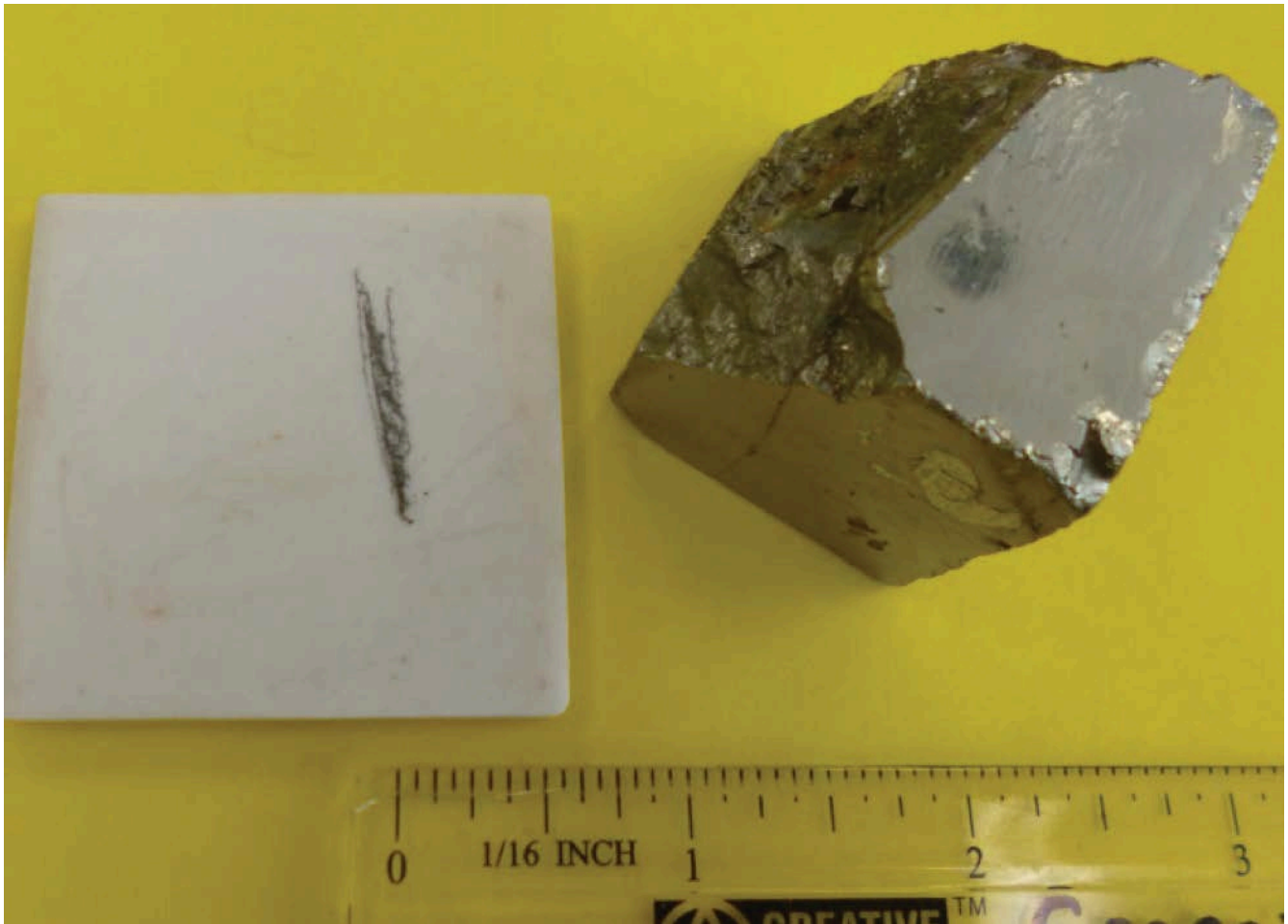
Figure 2.14 | *An example of the dark grey streak left behind when pyrite is rubbed along a streak plate.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.15 | An example of the white streak (on finger) left behind when fluorite is rubbed along a streak plate.
Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

2.2.7 Special Physical Properties

Several minerals have unique properties that aid in their identification. **Tenacity** refers to the way a mineral resists breakage. If a mineral shatters like glass, it is said to be brittle (like quartz), while minerals that can be hammered are malleable (e.g. Figure 2.16).

Figure 2.16 | *Copper, which can be hammered into thin sheets, is malleable.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.17 | *Muscovite mica, which bends but returns to its original shape, is elastic.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Minerals may be elastic, in which they are flexible and bend like a plastic comb, but return to their original shape (e.g., Figure 2.17). Sectile minerals are soft like wax, and can be separated with a knife (e.g., gypsum).

Some minerals react when dilute hydrochloric acid is placed on them. Carbonate minerals (minerals that include CO_3 in their chemical formula) will effervesce or fizz when acid is applied to them. When you test a mineral with acid, be cautious and use just a drop of the acid. Use your magnifying glass to look closely for bubbles (e.g., Figure 2.18). The acid is very dilute and will not burn your skin or clothing, but wash your hands after use. Also make sure that you rinse with water and wipe off the acid from the minerals that you test.

Figure 2.18 | *Note the effervescing acid bubbles at the red arrow on this piece of calcite.*
Source: Randa Harris (2015) CC BY-SA 3.0 [*view source*](view source)

Minerals may be magnetic, and this property is simply tested by seeing if your nail is attracted to a mineral. Magnetite is an example of a magnetic mineral. The mineral halite is simply table salt, so it will taste salty. Sphalerite will release a sulfurous smell when streaked, and talc will feel soapy when touched.

Specific gravity is the ratio of a mineral's weight to the weight of an equal volume of water. A mineral with a specific gravity of 2 would weigh twice as much as water. Most minerals are heavier than water, and the average specific gravity

for all minerals is approximately 2.7. Some minerals are quite heavy, such as pyrite with a specific gravity of 4.9-5.2, native copper, with a specific gravity of 8.8-9.0, and native gold at 19.3, which makes panning useful for gold, as the heavy mineral stays behind as you wash material out of the pan.

Exercises on Minerals

You can of this lab to print, and from the bookstore!

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 7 "Minerals" by Randa Harris, CC BY-SA 4.0. View source. Last edited: 8 Jan 2020

Note: much of the overview material for this chapter is replicated in this exercise section for your reference as you complete the lab. **You will NOT have access to your lab book or notes for the rock and mineral exam!**

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Your TAs will check that you have completed the questions correctly at the end of the lab period. Please hold on to your lab notes to help you prepare for the rock and mineral quiz and your lab final exam.

2.2 PHYSICAL PROPERTIES

Identifying a mineral is a little like playing detective. Minerals are identified by their physical properties. How would you describe the mineral in Figure 2.2? You may say that it is shiny, gold, and has a particular shape. Each of these descriptions is a physical property (shiny is lustre, gold is colour, shape is crystal form). Physical properties can vary within the same minerals, so caution should be applied when identifying minerals. For example, colour is a property that is not a very realistic diagnostic tool in many cases, as some minerals, such as Quartz, can come in a variety of colours (e.g. Figure 2.3). Occasionally, colour can be helpful, as in the case of olivine, which is said to be "olive green", a light to dark green (e.g. Figure 2.4). We will cover each of the physical properties in detail to help you identify the minerals.

Figure 2.2 | *Describe this mineral.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.3 | *Examples of the different varieties of quartz (jasper, rose quartz, smoky quartz, agate, amethyst, citrine, and petrified wood), demonstrating the difficulty of identifying this mineral.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.4 | *The mineral olivine has an "olive green" colour.*
Source: Joyce M. McBeth (2018) CC BY 4.0 *view source*

2.2.1 Hardness

Hardness refers to the resistance of a mineral to being scratched by a different mineral or material and is a product of the strength of the bonds between the atoms of a mineral. Whatever substance does the scratching is harder and the item scratched is softer. Hardness is based off a scale of 1 to 10 created by a mineralogist named Friedrich Mohs (Figure 2.5). Mohs' scale lists ten minerals in order of relative hardness, with each mineral on the scale able to scratch a mineral of lower number.

   Your mineral kit comes with several items of a known hardness. The glass plate has a hardness of 5.5, the iron nail has a hardness of 4, the copper coin has a hardness of 3, and your fingernail has a hardness of 2.5. If you can scratch a mineral, then it would be softer than your fingernail, so therefore its hardness would be <2.5. When trying to scratch a surface, use force, but be cautious with the glass plate. **ALWAYS lay the glass plate on a flat surface rather than holding it in your hand in case it breaks.** Do not confuse mineral powder with a scratch – use your finger to feel for a groove created by a scratch (Figure 2.6). in contrast, mineral powder is left behind when a soft mineral scratches a harder surface. Materials of similar hardness have difficulty scratching each other, so that, for example, your fingernail may not be able to always scratch biotite, which has a hardness of 2.5 or gypsum which has a hardness of 2 (Figure 2.7).

Number	Mineral	Relative Hardness
1	Talc	(softest mineral)
2	Gypsum	2.5 – Fingernail
3	Calcite	3 – Copper Coin
4	Fluorite	4 – Nail
5	Apatite	5.5 – Glass Plate
6	Orthoclase Feldspar	
7	Quartz	
8	Topaz	
9	Corundum	
10	Diamond	(hardest mineral)

Figure 2.5 | *Mohs' Scale of Hardness*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.6 | *An example of a scratch made by the mineral quartz on a streak plate. The red arrow is pointing to the scratch. Quartz, therefore, is harder than glass.*
Source: Randa Harris (2015) CC BY-SA 3.0 <u>*view source*</u>

Figure 2.7 | *An example of a scratch made by a fingernail on the mineral gypsum. The red arrow is pointing to the scratch. Gypsum, therefore, is softer than a fingernail.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

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This property refers to the geometric shape that a crystal naturally grows into and is a reflection of the orderly internal arrangement of atoms within the mineral. If minerals have space to grow when they are developing, they will display their crystal form. These ideal growth conditions do not always occur, however, so many minerals do not display their ideal crystal form due to crowded conditions during growth. Examples of crystal form are shown in Figure 2.8.

Cube   Hexagonal Prism   Rhombohedron

Octahedron (8 faces)   Dodecahedron (12 faces)

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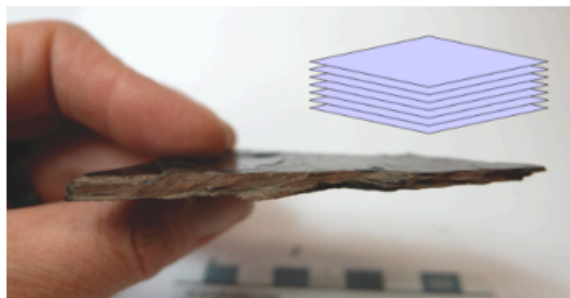
Be careful not to confuse cleavage with crystal form. Crystal form occurs as a mineral grows (e.g., cubes of pyrite), while cleavage only forms as a mineral breaks. See Figure 2.9 for the main types of cleavage and an example of each.

No cleavage; mineral fractures

No cleavage planes

One cleavage plane

Basal cleavage – flat sheets

Two cleavage planes, at or near 90°

90°

Two cleavage planes not at 90°

56°

Three cleavage planes at 90°

Cubic cleavage – cubes

Three cleavage planes not at 90°
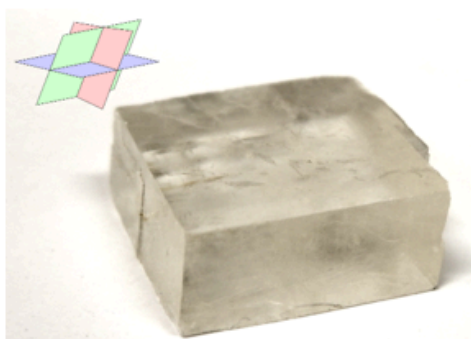
Four cleavage planes

Figure 2.9 | Main types of cleavage, along with illustrations indicating the cleavage angle and direction.
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 view source

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Source: Joyce M. McBeth (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 view source

2.2.4 Fracture

When minerals do not break along cleavage planes, but rather break irregularly, they are said to **fracture**. Commonly, fracture surfaces are either uneven or conchoidal, a ribbed, smoothly curved surface similar to broken glass (e.g. Figure 2.11).

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Figure 2.12 | *Examples of the metallic lustre of pyrite, also known as "fool's gold."*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Figure 2.13A | *Example of a vitreous, or glassy, lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.13B | *Example of an earthy, or dull. lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

Figure 2.13C | *Example of a waxy lustre.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

2.2.6 Streak

Streak is an easily detectable physical property. It refers to the colour left behind on an unglazed piece of porcelain when a mineral is rubbed along its surface. A streak plate is included in your rock and mineral kit to test this property. Often a mineral will have a streak of a different colour than the mineral (e.g. Figure 2.14). Some minerals will have a white streak, which is difficult to see along the white streak plate. If you rub a mineral along the streak plate and do not see an obvious streak, wipe your finger along the streak plate; a mineral with a white streak will leave a white powder behind that will rub on your finger (e.g. Figure 2.15). Alternatively, you may use the black streak plate, which was provided in your mineral identification kit.

Figure 2.14 | *An example of the dark grey streak left behind when pyrite is rubbed along a streak plate.*
Source: Randa Harris (2015) CC BY–SA 3.0 view source

Figure 2.15 | *An example of the white streak (on finger) left behind when fluorite is rubbed along a streak plate.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

2.2.7 Special Physical Properties

Minerals may be magnetic, and this property is simply tested by seeing if your nail is attracted to a mineral. Magnetite is an example of a magnetic mineral. The mineral halite is simply table salt, so it will taste salty. Sphalerite will release a sulfurous smell when streaked, and talc will feel soapy when touched.

  Specific gravity is the ratio of a mineral's weight to the weight of an equal volume of water. A mineral with a specific gravity of 2 would weigh twice as much as water. Most minerals are heavier than water, and the average specific gravity for all minerals is approximately 2.7. Some minerals are quite heavy, such as pyrite with a specific gravity of 4.9-5.2, native copper, with a specific gravity of 8.8-9.0, and native gold at 19.3, which makes panning useful for gold, as the heavy mineral stays behind as you wash material out of the pan.

2-E1 LAB EXERCISES – MINERAL IDENTIFICATION

This lab contains 27 numbered mineral samples, labelled 1 – 27, separated into drawers. Use these instructions to test and identify them. You will test for different properties after learning about them, then work on identification at the end of the lab. As you identify properties of each sample, fill in the table provided in this lab and complete the multiple choice questions to test your knowledge. It is recommended that you obtain a mineral identification kit from the campus bookstore. It will contain:

- A copper coin
- Glass plate (wrapped in paper) – this will be used in testing hardness
- Zinc coated nail
- Unglazed porcelain plate – this will be used as a streak plate
- Black streak plate – this will be used to identify white streaks
- Hydrochloric acid bottle (empty)
- Magnifying glass (10x). To use this, hold it very close to your eye and bring the sample near the glass until it is in focus (approximately one inch from your eye).
- Magnet – this will be used to test for magnetism in minerals

Take the drawers provided by your TA and view the minerals, numbered 1-27; there are 21 different minerals provided, so expect to see some repeat minerals. We will first examine hardness from these samples and will answer more questions about them later in the lab. Look closely at each of the minerals, using the hand lens to observe them.

   You need to experiment with each sample to test for its hardness, using Figure 2.5 for reference. Remember that hardness is determined by scratching the mineral. First, decide which minerals have a hardness greater than 5.5 (the hardness of glass). Lay the glass on a flat surface, then try to scratch it with each mineral by pressing down hard with the mineral. Table 2.1 is provided for you to make notations about each mineral. Note that you do not have to fill in every physical property for every mineral, just fill in the properties you are asked about as you work. Note on the table which minerals have a hardness greater than 5.5. You may also test samples by using materials to scratch them. The copper coin has a hardness of 3; any mineral that it can scratch will have a hardness less than 3. You can further refine this by using your fingernail (only natural fingernails work for this), which has an approximate hardness of 2.5, so if both the copper coin and your fingernail scratches it, you know its hardness must be <2.5. Additionally, you can use a zinc coated nail, which has a hardness of 4, and other minerals to test the hardness. For example, if you have two minerals that have a hardness of <2.5, you can see if one will scratch the other, then you know which mineral is harder.

Lustre	Hardness	Cleavage	Other Properties	Mineral Name
Non-Metallic	> Glass	Poor	Red-brown in colour. H=5-6. SG=5.3. St=red-brown. Dull, earthy lustre.	**Hematite** Fe_2O_3
			Red-brown to brown in colour. H=6-7.5. SG=3.5-4.5. Conchoidal fracture. Vitreous lustre. Crystals are 12-sided and common.	**Garnet** Fe,Mg,Ca,Al, Silicate
			Pale-yellow to olive-green in colour. H=6.5-7. Commonly granular, with glassy grains	**Olivine** $(Fe,Mg)SiO_4$
			Variety of colours. H=7. SG=2.7. Conchoidal fracture. May have a 6-sided prism shape topped with a 6-sided pyramid. Vitreous lustre.	**Quartz** SiO_2
			Variety of colours [grey=chert; black=flint; red=jasper; banded=agate]. H=7. SG=2.7. Conchoidal fracture. Dull lustre.	**Cryptocrystalline Quartz** SiO_2
		Clearly Shows	Black to greenish black in colour. H=5-6.5. SG=3.3 C=2 planes at ~90°. Short, stubby crystals.	**Pyroxene** Ca,Mg,Fe,Al Silicate
			Black to greenish black in colour. H=6. SG=3.3. C=2 planes at ~60° and 120°. Elongated crystals.	**Amphibole** Na,Ca,Mg,Fe,Al Silicate
			Tan-pink, white, green in colour. H=6-6.5. SG=2.6. C=2 planes at 90°. Colour variation lines on cleavage surface.	**Potassium Feldspar** $KAlSi_3O_8$
			White to blue-grey to black in colour. H=6-6.5. SG=2.7. C=2 planes at ~90°. Striations on cleavage plane. Blue play of colours may be present.	**Plagioclase Feldspar** $NaAlSi_3O_8$ to $CaAl_2Si_2O_8$
	< Glass	Poor	White to grey to pale green in colour. H=1. SG=2.7. C=1, though rarely seen. Soapy feel.	**Talc** $Mg_3Si_4O_{10}(OH)_8$
			Yellow to yellow-brown in colour. H=4-5.5. SG=4.5. St=yellow-brown. Earthy lustre.	**Limonite** $Fe_2O_3•nH_2O$
		Clearly Shows	Colourless to white in colour. H=2. SG=2.3. C=3, though 2 directions may be difficult to see.	**Gypsum** $CaSO_42H_2O$
			Colourless to white, blue, yellow, or red in colour. H=2. SG=1.9. C=3 at 90°. Bitterer than halite.	**Sylvite** KCl
			Colourless to white in colour. H=2.5. SG=2.2. C=3 planes at 90°, cubic. Tastes salty.	**Halite** NaCl
			Colourless, light brown, to yellow in colour. H=2.5. SG=2.8. C=1 perfect. Breaks into thin sheets that are elastic.	**Muscovite** $KAl_2(AlSi_3O_{10})(OH)_2$
			Brown to black in colour. H=2.5-3. SG=3. C=1 perfect. Breaks into thin, elastic sheets.	**Biotite** $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$
			Colourless, white, yellow in colour. H=3. SG=2.7. C=3 rhombohedral. Strong effervescence in acid.	**Calcite** $CaCO_3$
			Yellow-brown in colour. H=3.5-4. SG=4. C=6. St=white to pale-yellow. Sulphur odour to streak. Resinous lustre.	**Sphalerite** (Zn,Fe)S
Metallic	> Glass	Poor	Steel grey to black in colour. H=5-6. SG=5.3. St=red-brown. Metallic lustre.	**Hematite** Fe_2O_3
			Black in colour. H=6. SG=5.2. St=black. Strongly magnetic.	**Magnetite** Fe_3O_4
			Brass-yellow in colour. H=6-6.5. SG=5. St=green- or brown-black.	**Pyrite** FeS_2
	< Glass	Poor	Yellow-brown to dark-brown in colour. H=3.5-4. SG=4. C=6. St=yellow-brown to brown-black. Sulphur odour to streak. Resinous and submetallic lustre.	**Sphalerite** (Zn,Fe)S
			Brass-yellow in colour. H=3.5-4.5. SG=4.2. St=greenish black. Tarnishes to green or black in air.	**Chalcopyrite** $CuFeS_2$
			Yellow-brown to dark-brown in colour. H=4-5.5. SG=4.5. St=yellow-brown.	**Limonite** $Fe_2O_3•nH_2O$
		Clearly Shows	Silver grey in colour. H=2.5. SG=7.5. C=3 planes at 90°. Very heavy.	**Galena** PbS

Figure 2.19 | *Mineral Identification Chart. Source: Lyndsay Hauber (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 view source*

Sample	Lustre	Hardness	Cleavage/ Fracture	Streak	Other Notable Properties (include colour when diagnostic)	Mineral Name
0	Non-metallic	2	3 at 90°	white	Bitter taste; key mineral in Potash	Sylvite

Table 2.1 | *Mineral Notation Chart – Fill in this chart as you work through the lab. An example of a mineral you do not have available (#0) is included. You do not have to fill out every column for every mineral – just follow along in the lab and determine the properties you are asked about.*
Source: Lyndsay Hauber (2018) CC BY 4.0, after Randa Harris (2015) CC BY-SA 3.0 view source

1. Sample 11: What is this sample's hardness?

   a. harder than glass
   b. softer than glass but harder than nail
   c. softer than nail but harder than copper
   d. softer than copper but harder than a fingernail
   e. softer than a fingernail

2. Sample 25: What is this sample's hardness?

   a. harder than glass
   b. softer than glass but harder than nail
   c. softer than nail but harder than copper
   d. softer than copper but harder than a fingernail
   e. softer than a fingernail

3. Sample 12: What is this sample's hardness?

   a. harder than glass
   b. softer than glass but harder than nail
   c. softer than nail but harder than copper
   d. softer than copper but harder than a fingernail
   e. softer than a fingernail

4. Sample 26: What is this sample's hardness?

   a. harder than glass
   b. softer than glass but harder than nail
   c. softer than nail but harder than copper
   d. softer than copper but harder than a fingernail
   e. softer than a fingernail

5. Sample 10: What is this sample's hardness?

   a. harder than glass
   b. softer than glass but harder than nail
   c. softer than nail but harder than copper
   d. softer than copper but harder than a fingernail
   e. softer than a fingernail

6. Sample 19. What is this sample's hardness?

   a. harder than glass

    b. softer than glass but harder than nail

    c. softer than nail but harder than copper

    d. softer than copper but harder than a fingernail

    e. softer than a fingernail

7. Sample 27. What is this sample's hardness?

    a. harder than glass

    b. softer than glass but harder than nail

    c. softer than nail but harder than copper

    d. softer than copper but harder than a fingernail

    e. softer than a fingernail

8. Sample 24: This sample has:

    a. no cleavage (it fractures)

    b. 1 cleavage plane

    c. 2 cleavage planes at 90°

    d. 3 cleavage planes at 90° (cubic)

    e. 4 cleavage planes

9. Sample 24: What other unique property does this sample have?

    a. effervescence in acid

    b. it is magnetic

    c. it tastes salty

    d. it feels soapy

    e. it smells like sulfur

10. Sample 21: This sample has:

    a. no cleavage (it fractures)

    b. 1 cleavage plane

    c. 2 cleavage planes at 90°

    d. 3 cleavage planes that are not at 90° (rhombohedral)

    e. 4 cleavage planes

11. Sample 15: This sample has:

    a. no cleavage (it fractures)

    b. 1 cleavage plane

    c. 2 cleavage planes at 90°

    d. 3 cleavage planes at 90°

    e. 4 cleavage planes

12. Sample 13: This sample has:

    a. no cleavage (it fractures)

    b. 1 cleavage plane

    c. 2 cleavage planes at 90°

    d. 3 cleavage planes at 90°

    e. 4 cleavage planes

13. Sample 18: This sample has:

    a. no cleavage (it fractures)

    b. 1 cleavage plane

    c. 2 cleavage planes at 90°

    d. 3 cleavage planes at 90°

    e. 4 cleavage planes

14. Sample 18: What is this sample's hardness?

    a. harder than glass
    b. similar to glass
    c. softer than nail but harder than copper
    d. softer than copper but harder than a fingernail
    e. softer than a fingernail

15. Sample 20: This sample has:

    a. no cleavage (it fractures)
    b. 1 cleavage plane
    c. 2 cleavage planes at 90°
    d. 3 cleavage planes at 90°
    e. 4 cleavage planes

16. Sample 16: This sample has:

    a. no cleavage (it fractures)
    b. 1 cleavage plane
    c. 2 cleavage planes at 90°
    d. 3 cleavage planes at 90°
    e. 2 cleavage planes at $60^o/120^o$

17. Sample 16: What is this sample's hardness?

    a. harder than glass
    b. softer than glass but harder than nail
    c. softer than nail but harder than copper
    d. softer than copper but harder than a fingernail
    e. softer than a fingernail

18. Sample 17: This sample has:

    a. no cleavage (it fractures)
    b. 1 cleavage plane
    c. 2 cleavage planes at 90°
    d. 3 cleavage planes at 90°
    e. 4 cleavage planes

19. Sample 22: What is this sample's hardness?

    a. harder than glass
    b. softer than glass but harder than nail
    c. softer than nail but harder than copper
    d. softer than copper but harder than a fingernail
    e. softer than a fingernail

20. Sample 22: This sample has:

    a. no cleavage (it fractures)
    b. 1 cleavage plane
    c. 2 cleavage planes at 90°
    d. 3 cleavage planes at 90°
    e. 4 cleavage planes

21. Sample 4: What is the streak of this sample?

    a. dark grey streak
    b. white streak

     c. reddish brown streak

     d. pale yellow streak

22. Sample 4: What is the lustre of this sample?

     a. non-metallic, vitreous

     b. non-metallic, earthy

     c. non-metallic, resinous

     d. non-metallic, waxy

     e. metallic

23. Sample 1: What is the lustre of this sample?

     a. non-metallic, vitreous

     b. non-metallic, earthy

     c. non-metallic, resinous

     d. non-metallic, waxy

     e. metallic

24. Sample 6: What is the streak of this sample?

     a. dark grey to black streak

     b. grey streak

     c. reddish brown streak

     d. pale yellow streak

25. Sample 6: Which other item(s) is/are characteristic(s) of this sample?

     a. very heavy

     b. harder than glass

     c. metallic lustre

     d. both a and b

     e. both a and c

26. Sample 8: What is the streak of this sample?

     a. dark grey to black streak

     b. grey streak

     c. reddish brown streak

     d. pale yellow streak

27. Sample 8: What is the lustre of this sample?

     a. non-metallic, vitreous

     b. non-metallic, earthy

     c. non-metallic, greasy

     d. non-metallic, waxy

     e. metallic

28. Sample 9: What is the lustre of this sample?

     a. non-metallic, vitreous

     b. non-metallic, earthy

     c. non-metallic, greasy

     d. non-metallic, waxy

     e. metallic

29. Sample 9: Due to its appearance, this sample has often been confused with native gold, a mineral with a hardness of 2.5-3. How does its hardness compare with that of gold?

     a. Sample 9 is harder than gold.

b. Sample 9 is softer than gold.

30. Sample 14: What is the lustre of this sample?

    a. non-metallic, vitreous
    b. non-metallic, earthy
    c. non-metallic, greasy
    d. non-metallic, waxy
    e. metallic

31. Sample 2: What is the streak of this sample?

    a. dark grey to black streak
    b. grey streak
    c. reddish brown streak
    d. pale yellow streak

32. Sample 2: What another unique property does this sample have?

    a. effervescence in acid
    b. it is magnetic
    c. it tastes salty
    d. it feels soapy
    e. it smells like sulfur

33. Sample 5: Examine this entire sample closely with a hand lens. What is the lustre of this sample?

    a. non-metallic, vitreous
    b. non-metallic, earthy
    c. non-metallic, greasy
    d. non-metallic, waxy
    e. metallic

34. Sample 23: What is the streak of this sample?

    a. dark grey to black streak
    b. white streak
    c. reddish brown streak
    d. pale yellow streak

35. Sample 7: What is the lustre of this sample?

    a. non-metallic, vitreous
    b. non-metallic, earthy
    c. non-metallic, resinous
    d. non-metallic, waxy
    e. metallic

36. Sample 7: What is the streak of this sample?

    a. dark grey to black streak
    b. grey streak
    c. yellow-brown to brown-black streak
    d. pale yellow streak

37. Sample 3: What is the streak of this sample?

    a. dark grey to black streak
    b. grey streak
    c. reddish brown streak
    d. pale yellow streak

38. Sample 3: What is the lustre of this sample?

    a. non-metallic, vitreous
    b. non-metallic, earthy
    c. non-metallic, greasy
    d. non-metallic, waxy
    e. metallic

39. Sample 1: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

40. Sample 2: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

41. Sample 2: What other unique property does this sample have?

    a. effervescence in acid
    b. it is magnetic
    c. it tastes salty
    d. it feels soapy
    e. it smells like sulfur

42. Sample 3: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

43. Sample 4: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

44. Sample 4: What other unique property does this sample have?

    a. effervescence in acid
    b. it is magnetic
    c. it tastes salty
    d. it feels soapy
    e. it smells like sulfur

45. Sample 5: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

46. Sample 6: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

47. Sample 7: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. sphalerite
    e. magnetite
    f. hematite

48. Sample 7: What other unique property does this sample have?

    a. effervescence in acid
    b. it is magnetic
    c. it tastes salty
    d. it feels soapy
    e. it smells like sulfur

49. Sample 8: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. pyrite
    e. magnetite
    f. hematite

50. Sample 9: What is this sample?

    a. chalcopyrite
    b. limonite
    c. galena
    d. pyrite
    e. magnetite
    f. hematite

51. Sample 10: What is this sample?

    a. quartz
    b. muscovite
    c. potassium feldspar
    d. calcite

    e. biotite

    f. plagioclase feldspar

52. Sample 11: What is this sample?

    a. quartz

    b. muscovite

    c. potassium feldspar

    d. calcite

    e. biotite

    f. plagioclase feldspar

53. Sample 12: What is this sample?

    a. quartz

    b. muscovite

    c. potassium feldspar

    d. calcite

    e. biotite

    f. plagioclase feldspar

54. Sample 13: What is this sample?

    a. quartz

    b. muscovite

    c. potassium feldspar

    d. calcite

    e. biotite

    f. plagioclase feldspar

55. Sample 14: What is this sample?

    a. quartz

    b. muscovite

    c. potassium feldspar

    d. calcite

    e. biotite

    f. plagioclase feldspar

56. Sample 15: What is this sample?

    a. quartz

    b. muscovite

    c. potassium feldspar

    d. calcite

    e. biotite

    f. plagioclase feldspar

57. Sample 16: What is this sample?

    a. quartz

    b. amphibole

    c. potassium feldspar

    d. olivine

    e. pyroxene

    f. plagioclase feldspar

58. Sample 17: What is this sample?

    a. quartz

b. amphibole

   c. potassium feldspar

   d. olivine

   e. pyroxene

   f. plagioclase feldspar

59. Sample 18: What is this sample?

   a. quartz

   b. amphibole

   c. potassium feldspar

   d. olivine

   e. pyroxene

   f. plagioclase feldspar

60. Sample 19: What is this sample?

   a. quartz

   b. amphibole

   c. potassium feldspar

   d. olivine

   e. pyroxene

   f. plagioclase feldspar

61. Sample 20: What is this sample?

   a. quartz

   b. amphibole

   c. potassium feldspar

   d. olivine

   e. pyroxene

   f. plagioclase feldspar

62. Sample 21: What is this sample?

   a. quartz

   b. gypsum

   c. cryptocrystalline quartz

   d. calcite

   e. halite

   f. plagioclase feldspar

63. Sample 22: What is this sample?

   a. quartz

   b. gypsum

   c. cryptocrystalline quartz

   d. calcite

   e. halite

   f. plagioclase feldspar

64. Sample 23: What is this sample?

   a. quartz

   b. gypsum

   c. cryptocrystalline quartz

   d. calcite

   e. halite

    f. plagioclase feldspar

65. Sample 24: What is this sample?

    a. talc

    b. gypsum

    c. cryptocrystalline quartz

    d. garnet

    e. halite

    f. plagioclase feldspar

66. Sample 24: What other unique property does this sample have?

    a. it effervescence in acid

    b. it is magnetic

    c. it tastes salty

    d. it feels soapy

    e. it smells like sulfur

67. Sample 25: What is this sample?

    a. talc

    b. gypsum

    c. cryptocrystalline quartz

    d. garnet

    e. halite

    f. plagioclase feldspar

68. Sample 26: What is this sample?

    a. talc

    b. gypsum

    c. cryptocrystalline quartz

    d. garnet

    e. halite

    f. plagioclase feldspar

69. Sample 26: What other unique property does this sample have?

    a. it effervescence in acid

    b. it is magnetic

    c. it tastes salty

    d. it feels soapy

    e. it smells like sulfur

70. Sample 27: What is this sample?

    a. talc

    b. gypsum

    c. cryptocrystalline quartz

    d. garnet

    e. halite

    f. plagioclase feldspar

CHAPTER 3. IGNEOUS ROCKS

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 8 "Igneous Rocks" by Karen Tefend, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

3.1 INTRODUCTION

All rocks found on the Earth are classified into one of three groups: igneous, sedimentary, or metamorphic. This classification is based on the origin of each of the rock types. The focus of this chapter will be on igneous rocks, which are the only rocks that form from what was once a molten or liquid state. Therefore, igneous rocks are defined as those rock types that form by the cooling of magma or lava. Each igneous rock has a name that distinguishes it from other igneous rocks; so, these igneous rocks differ from each other primarily due to:

1. the original composition of the molten material from which the rock is derived, and
2. the cooling process of the molten material that ended up forming the rock.

These two parameters define the classification of igneous rocks, which are simplified into composition and texture. Igneous rock composition refers to what is in the rock (the chemical composition or the minerals that are present), and texture refers to the features that we see in the rock such as the mineral sizes or the presence of glass, fragmented material, or vesicles (holes) in the igneous rock.

3.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Classify igneous rock types based on colour, texture, and mafic colour index
- Identify, when possible, the minerals present in an igneous rock
- Determine the cooling history of the igneous rock

3.1.2 Key Terms

- Amygdaloidal
- Aphanitic
- Extrusive
- Felsic (Silicic)
- Ferromagnesian
- Glassy
- Intermediate

- Intrusive
- Mafic
- Nonferromagnesian
- Phaneritic
- Phenocryst
- Porphyritic
- Ultramafic
- Vesicular

Overview of Igneous Rocks

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 8 "Igneous Rocks" by Karen Tefend, CC BY–SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

3.2 IGNEOUS ROCK ORIGIN

3.2.1 Magma Composition

Before any igneous rock can form, there must be molten material, known as magma, produced; therefore, you must have a rock to melt to make the magma, which then cools to become an igneous rock. There are many factors which may affect the composition of the igneous rock, including the initial rock or rocks that melt to form the magma, the degree of melt, the cooling process of the magma, etc. These are things one should consider when studying the origin of igneous rocks.

Most rocks contain minerals that are crystalline solids composed of the chemical elements. All minerals have a certain set of conditions, such as temperature, at which they can melt; since rocks contain a mixture of minerals, some of the minerals in a rock may melt, while others remain solid. Temperature conditions are important, as only minerals that can melt at "lower" temperatures may experience melting, whereas the temperature would have to increase in order for other minerals to *also* melt and add their chemical components to the magma that is being generated. Therefore, if the same types of rocks are melting, different magma compositions are generated simply by melting at different temperatures!

Eventually, magma will start to rise upward through the Earth's lithosphere, as it is more buoyant than its source rock. This separation of magma from source region will result in new thermal conditions, which results in the magma cooling. As with melting, minerals also have a certain set of conditions at which they form, or crystallize, from within a cooling magma body. The sequence of mineral crystallization is the opposite sequence of crystal melting, which had been experimentally determined by Norman L. Bowen in the early 1900's, and known as Bowen's reaction series (e.g. Figure 3.1)
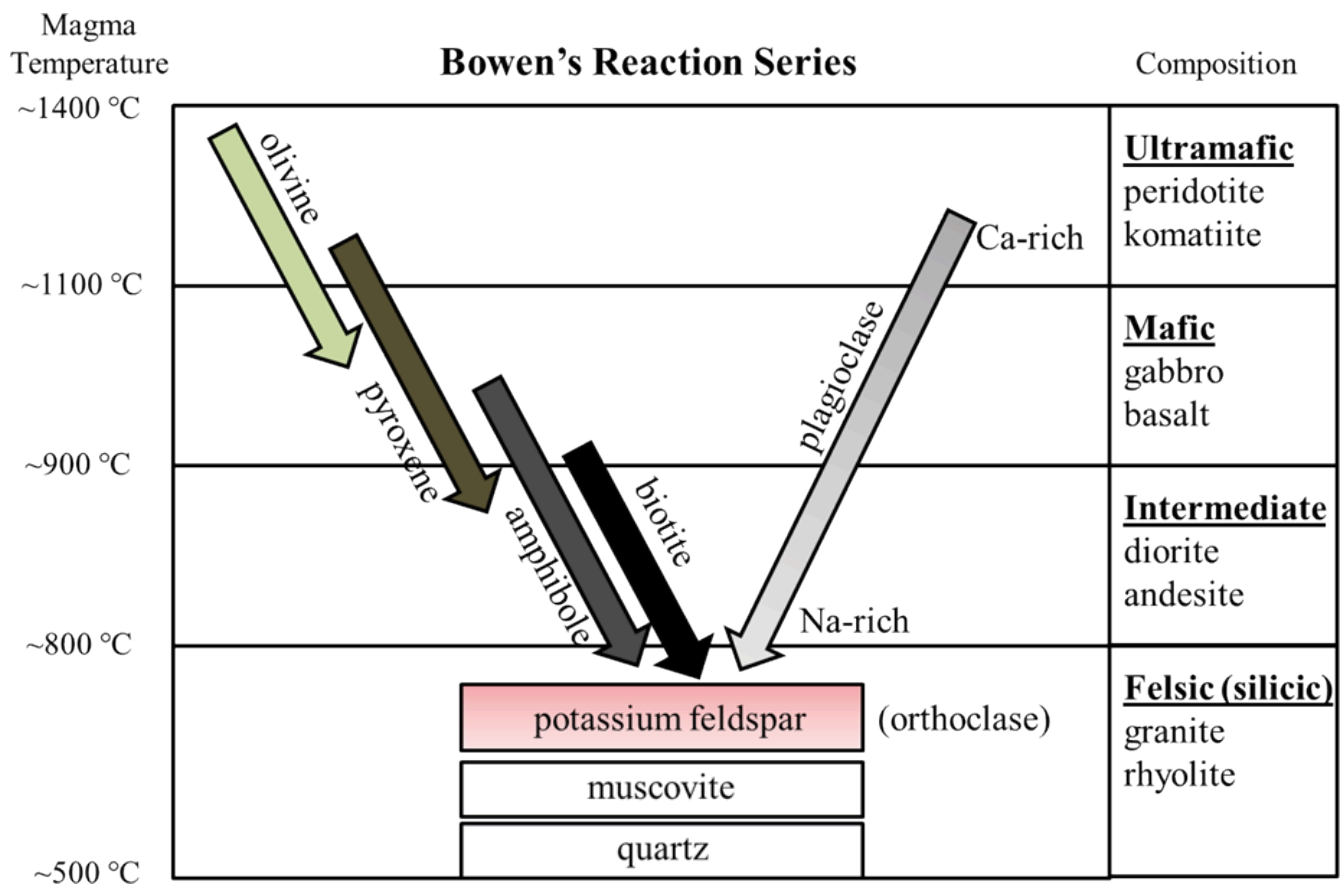
Figure 3.1 | *Bowen's Reaction Series, showing the progression of mineral crystallization as magma temperatures drop from ~1400 °C to ~500 °C. Note the corresponding names for igneous rock composition and some example rock types within each compositional group. Source: Karen Tefend (2015) CC BY-SA 3.0 <u>view source</u>*

This "reaction series" refers to the chemical reactions that are the formation of minerals, through chemical bonding of elements within the magma, in a sequence that is based on falling magma temperatures. Close examination of Figure 3.1 shows that the first mineral to crystallize in a cooling magma of ultramafic composition is olivine; the length of the arrow indicates the range of temperatures at which olivine can form. Once temperatures fall below this range, olivine crystals will no longer form; instead, other minerals such as pyroxene will start to crystallize (a small interval of temperatures exists where both olivine and pyroxene can crystallize). Minerals that form in cooling magma are called crystals, or **phenocrysts**; as these phenocrysts are forming, they are removing chemical elements from the magma. For example, olivine phenocrysts take magnesium (Mg) and iron (Fe) from the magma and incorporate them into their crystal structure. This behavior of mineral phenocrysts to take certain chemical elements into their structure, while excluding other elements, means that the composition of the magma must be changing as phenocrysts are forming!

There can be more than one mineral type crystallizing within the cooling magma, as the arrows in Figure 3.1 demonstrate. The minerals on the left side of Bowen's reaction series are referred to as a discontinuous series, as these minerals (olivine, pyroxene, amphibole, and biotite) all remove the iron (Fe), magnesium (Mg), and manganese (Mn) from the magma during crystallization, but do so at certain temperature ranges. These iron- and magnesium-rich minerals are referred to as **ferromagnesian** minerals (ferro = iron) and are usually green, dark gray, or black in colour due to the absorption of visible light by iron and magnesium atoms. On the right side of Bowen's reaction series is a long arrow labelled plagioclase feldspar. Plagioclase crystallizes over a large temperature interval and represents a continuous series of crystallization even though its composition changes from calcium (Ca) rich to sodium (Na) rich. As the magma

temperature drops and plagioclase first starts to crystallize (form), it will take in the calcium atoms into the crystal structure, but as magma temperatures continue to drop, plagioclase takes in sodium atoms preferentially. As a result, the higher temperature calcium-rich plagioclase is dark gray in colour due to the high calcium content, but the lower temperature sodium-rich plagioclase is white due to the high sodium content. Finally, at the bottom of the graph in Figure 3.1, we see that three more minerals can form as temperatures continue to drop. These minerals (potassium feldspar, muscovite, and quartz) are considered to be the "low temperature minerals", as they are the last to form during cooling, and therefore first to melt as a rock is heated. The previous removal of iron and magnesium from the magma results in the formation of the latest-forming minerals that are deficient in these chemical elements; these minerals are referred to as **nonferromagnesian** minerals, which are much lighter in colour. For example, the potassium-rich feldspar (also known as orthoclase) can be a pale pink or white in colour. The references to mineral colour are necessary, as the colour of any mineral is primarily due to the chemical elements that are in the minerals, and therefore the colour of an igneous rock will be dependent on the mineral content (or chemical composition) of the rock.

3.3   IGNEOUS ROCK COMPOSITION

Often added to the Bowen's reaction series diagram are the igneous rock classifications as well as example igneous rock names that are entirely dependent on the minerals that are found in them. For example, you can expect to find abundant olivine, and maybe some pyroxene and Ca-rich plagioclase, in an **ultramafic** rock called peridotite or komatiite, or that pyroxene, plagioclase, and possibly some olivine or amphibole may be present in a **mafic** rock such as gabbro or basalt. You can also expect to see quartz, muscovite, potassium feldspar, and some biotite and Na-rich plagioclase in a **felsic** (or **silicic**) rock such as granite or rhyolite. Figure 3.1 demonstrates nicely that the classification of an igneous rock depends partly on the minerals that may be present in the rock, and since the minerals have certain colours due to their chemical makeup, then the rocks must have certain colours. For example, a rock composed of mostly olivine will be green in colour due to olivine's green colour; such a rock would be called ultramafic. A rock that has a large amount of ferromagnesian minerals in it will be a dark-coloured rock because the ferromagnesian minerals (other than olivine) tend to be dark coloured; an igneous rock that is dark in colour is called a **mafic** rock ("ma-" comes from magnesium, and "fic" from ferric iron). An igneous rock with a large amount of nonferromagnesian minerals will be light in colour, such as the silicic or felsic rocks ("fel" from feldspar, and "sic" from silica-rich quartz). So, based on colour alone, we've been able to start classifying the igneous rocks.

Figure 3.2 shows examples of igneous rocks representing mafic and felsic rock compositions (Figures 3.2A and 3.2C, respectively), as well as an **intermediate** rock type (Figure 3.2B). Felsic rocks may have small amounts of dark-coloured minerals, but are predominately composed of light-coloured minerals, whereas mafic rocks have a higher percentage of dark-coloured minerals, which results in a darker-coloured rock. A rock that is considered intermediate between the mafic and felsic rocks is truly an intermediate in terms of the colour and mineral composition; such a rock would have less dark minerals than the mafic rocks, yet more dark minerals than the felsic rocks.
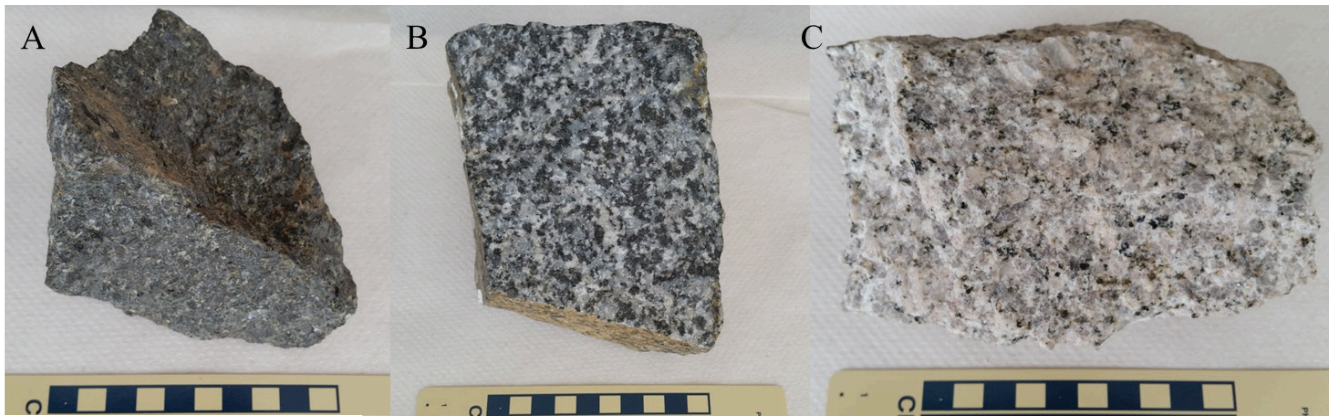
Figure 3.2 | *Examples of igneous rocks from the mafic (A), intermediate (B), and felsic (C) rock compositions. Photo scale on bottom is in centimeters.*
Source: Karen Tefend (2015) CC BY-SA 3.0 *view source*

As previously mentioned, classifying rocks into one of the igneous rock compositions (ultramafic, mafic, intermediate, and felsic) depends on the minerals that each rock contains. Identification of the minerals can be difficult in rocks such as in Figure 3.2A, as the majority of minerals are dark in colour and it can be difficult to distinguish each mineral. An easy method of determining the igneous rock composition is by estimating the percentage of dark-coloured mafic minerals in the rock, without trying to identify the actual minerals present; this method of classification relies on a mafic colour index (MCI), where the term mafic refers to any dark gray, black or green coloured mineral (Figure 3.3). Igneous rocks with 0-15% dark colored minerals (or 0-15% MCI) are the felsic rocks (Figure 3.3A), igneous rocks with 46-85% MCI are the mafic rocks (Figure 3.3C), and igneous rocks with over 85% MCI are considered ultramafic (Figure 3.3D). This means that any rock with an intermediate composition or with a 16-45% MCI is an intermediate igneous rock (Figure 3.3B). Estimating the amount of mafic minerals is only possible if the minerals are large enough to see; in that case, a person can still recognize a mafic rock by its dark-coloured appearance, and a felsic rock by its light-coloured appearance. An intermediate rock will be somewhat lighter than a mafic rock, yet darker than a felsic rock. Finally, an ultramafic rock is typically green in colour, due to the large amount of green-coloured olivine in the rock. Such rocks that contain minerals that are too small to see are shown in Figure 3.4; note that you can still distinguish between mafic (Figure 3.4A), intermediate (Figure 3.4B) and felsic (Figure 3.4C) by the overall colour of the rock. The intermediate igneous rock in Figure 3.4B does have a few visible phenocrysts; this odd texture will be covered later in this chapter.
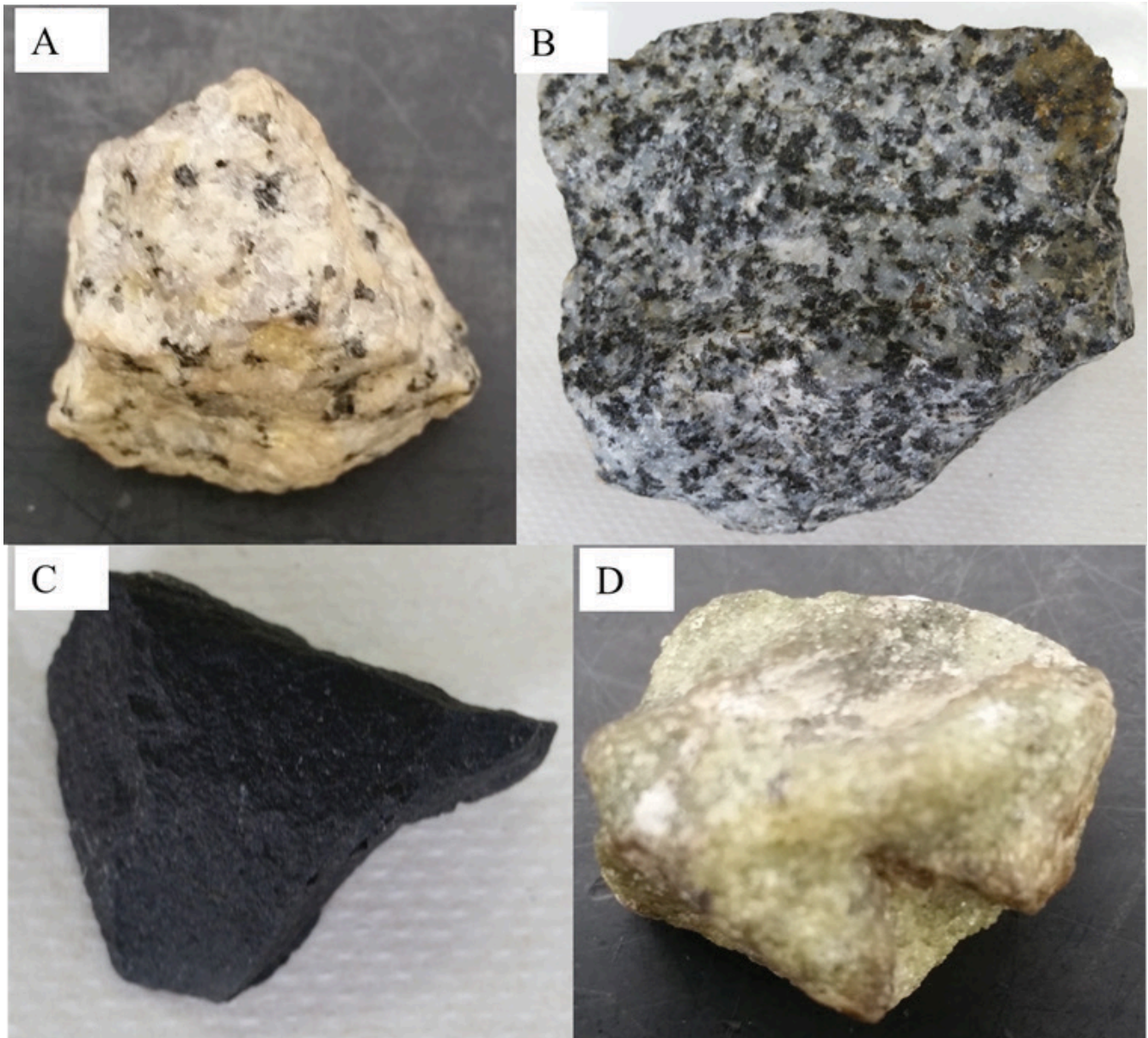
Figure 3.3 | *Examples of how igneous rocks can be classified using the Mafic Colour Index (MCI), which is a visual classification based on the amount of ferromagnesian minerals in the rock: (A) The small amount of tiny black phenocrysts (biotite) gives this rock a 0–15% MCI value; (B) numerous dark phenocrysts (amphibole) gives this rock a 16–45% MCI value; (C) this rock lacks visible phenocrysts, but the black colour in this rock results in a 46–85% MCI value; (D) this rock is entirely green in colour due to the overwhelming amount of olivine. Any rock with this much olivine is always classified as having over 85% MCI values.*
Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)

Figure 3.4 | *Examples of igneous rocks from the mafic (A), intermediate (B), and felsic (C) rock compositions. Notice the difference in appearance between these rocks and those in Figure 3.2.*
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3.4 IGNEOUS ROCK TEXTURE

The classification of igneous rocks is based not just on composition, but also on texture. As mentioned earlier, texture refers to the features that we see in the rock such as the mineral sizes or the presence of glass, fragmented material, or vesicles (holes) in the igneous rock. We will cover mineral crystal sizes and vesicles in this section.

Since the crystals or **phenocrysts** form while the magma is cooling, then the size of the crystals must have something to do with the cooling process. The chemical elements that become part of the mineral must migrate from the liquid magma to bond with other elements in a certain way to form the unique crystal structure for that mineral. When magma cools slowly, the chemical elements needed to form a certain mineral have time to migrate; that mineral can become large enough to see without the aid of a microscope. This igneous rock is said to have a **phaneritic** texture (phan = large). The rock samples shown in Figure 3.2 are all phaneritic rocks; Figure 3.2A is a phaneritic mafic rock called gabbro, Figures 3.2B and 3.4B are a phaneritic intermediate rock called diorite, and the rock in Figure 3.2C is a phaneritic felsic rock known as granite. Magma that cools relatively quickly will result in a different rock; there is less time for the chemical elements to migrate and form large mineral crystals. Therefore, many small, microscopic crystals of a particular mineral will form; these igneous rocks are called **aphanitic** igneous rocks. Figure 3.4A and 3.4C are aphanitic rocks; since Figure 3.4A is dark in colour, it is a mafic aphanitic rock called basalt, and the felsic rock in Figure 3.4C is called rhyolite.

There can be equivalent extrusive and intrusive rocks, which appear to different but are chemically identical. For example, basalt and gabbro are both mafic rocks and have the same composition, but basalt represents a magma that cooled fast, and gabbro represents a magma that cooled slowly. The same can be said for the other rock compositions: the felsic rocks rhyolite and granite have identical compositions but rhyolite cooled fast and granite cooled slower. The intermediate rocks diorite (Figure 3.2B) and andesite (Figure 3.4B) also represent magmas that cooled slowly or a bit faster, respectively. Sometimes there are some visible crystals in an otherwise aphanitic rock, such as the andesite in Figure 3.4B. The texture of such a rock is referred to as **porphyritic**, or more accurately porphyritic-aphanitic since it is a porphyritic andesite, and all andesites are aphanitic. Two different crystal sizes within an igneous rock indicates that the cooling rate of the magma increased; while the magma was cooling slowly, larger crystals can form, but if the magma starts to cool faster, then only small crystals can form. A phaneritic rock can also be referred to as a porphyritic-phaneritic rock if the phaneritic rock contains some very large crystals in addition to the other visible crystals. In Figure 3.5 are two porphyritic rocks: a porphyritic-aphanitic basalt, and a porphyritic-phaneritic granite.
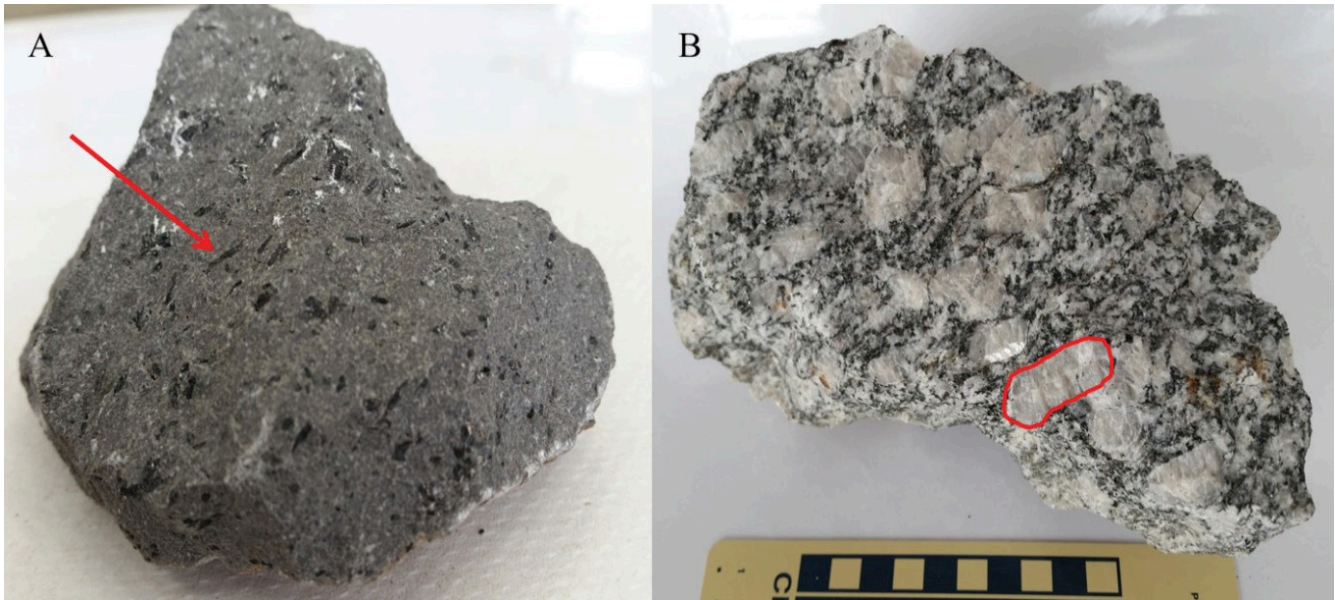
Figure 3.5 | (A) *An example of a porphyritic-aphanitic mafic rock with needle-shaped amphibole phenocrysts (arrow points to one phenocryst that is 1cm in length); No other minerals in (A) are large enough to see. (B) An example of a porphyritic-phaneritic felsic rock with large feldspars (outlined phenocryst is 3 cm length). Surrounding these large feldspars are smaller (yet still visible) dark and light coloured minerals.*
Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)

Sometimes, the magma cools so quickly there isn't time to form minerals, as the chemical elements in the magma have no time to migrate into a crystal structure. When this happens, the magma becomes a dense glass called obsidian (Figure 3.6A). By definition, glass is a chaotic arrangement of the chemical elements, and therefore not considered to be a mineral; igneous rocks composed primarily of glass are said to have a **glassy** texture. The identification of a glassy rock such as obsidian is easy once you recall the properties of glass; any thick glass pane or a glass bottle that is broken will have this smooth, curve shaped pattern on the broken edge called conchoidal fracture. Even though obsidian is naturally occurring, and not man made, it still breaks in this conchoidal pattern. If you look closely at the obsidian in Figure 3.5A, you will see the curved surfaces on the rock. Obsidian appears quite dark in colour regardless of its composition because it is a dense glass, and light cannot pass through this thick glass.
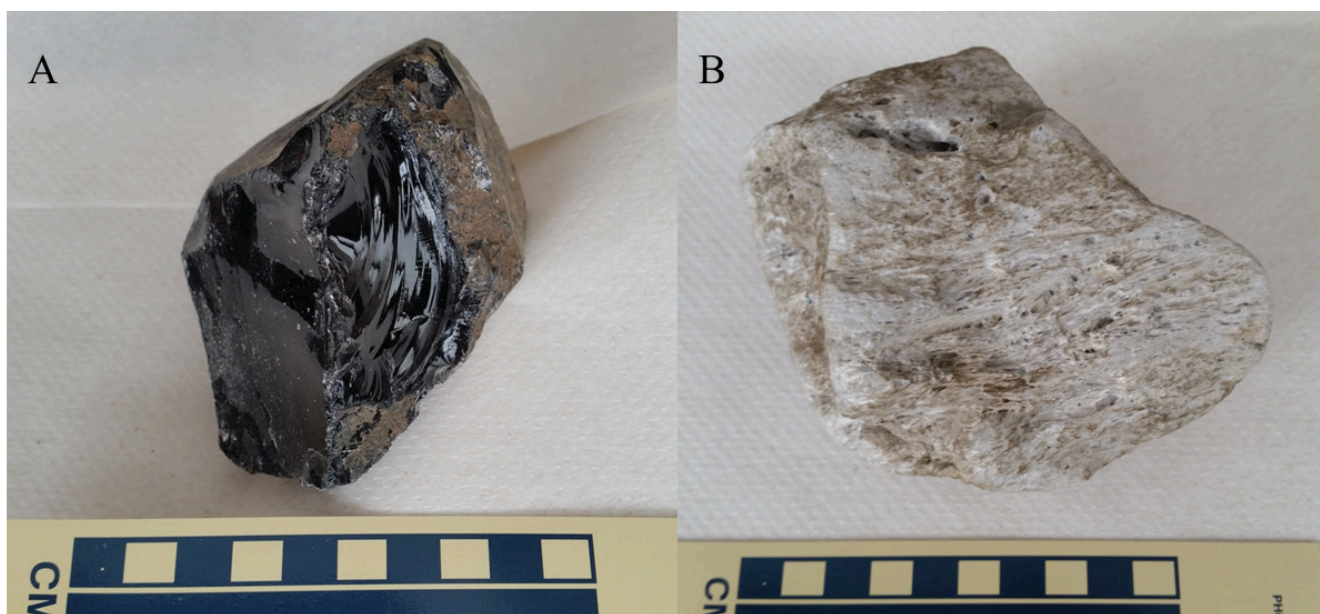
Figure 3.6 | *Igneous rocks with glassy texture: obsidian (A) and pumice (B).*
Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)

In Figure 3.6B, there is another igneous rock that is also composed primarily of glass due to a very fast rate of magma cooling. This rock is called pumice, and is commonly known as the rock that floats on water due to its low density. The glass in this rock is stretched out into very fine fibers of glass which formed during the eruptive phase of a volcano. Because these fibers are so thin, they are easy to break and any conchoidal fractures on these fibers are too small to see without the aid of a microscope. Pumice can have any composition (felsic to mafic), but, unlike obsidian, the colour of the pumice can be used to determine the magma composition, as felsic pumice is always light in colour and mafic pumice will be dark in colour. Mafic pumice with a dark grey, red or black colour is also known as scoria.

3.5 IGNEOUS ROCK FORMATION—INTRUSIVE VS. EXTRUSIVE

The different crystal sizes and presence or absence of glass in an igneous rock is primarily controlled by the rate of magma cooling. Magmas that cool below the surface of the earth tend to cool slowly, as the surrounding rock acts as an insulator, which slows the rate of cooling. Magma that stays below the surface of the earth can take tens of thousands of years to completely crystallize, depending on the size of the magma body. Upon inspection of this rock, you would see that it is composed of minerals that are large enough to see without the aid of a microscope. Any igneous rock sample that is considered to have a phaneritic texture (or porphyritic-phaneritic), is referred to as an **intrusive** rock, as it is derived from magma that intruded the rock layers but never reached the earth's surface.

If magma reaches the earth's surface, it is no longer insulated by the rocks around it and will cool rapidly. Magma that reaches the earth's surface through a fissure or central vent will lose some of its dissolved gas and becomes lava, and any rock that forms from lava will have either an aphanitic texture due to fast cooling, or a glassy texture due to very fast cooling. Flowing lava may continue to release gas while cooling; this is typical of mafic lava flows. If the lava hardens while these gases are bubbling out of the lava, a small hole or vesicle may form in the rock, the term "**vesicular**" is given to the rock to indicate the presence of these vesicles. For example, a basalt with vesicles is called vesicular basalt (Figure

3.7). These vesicles can be filled with a secondary mineral, such as quartz or calcite, long after the rock was formed; these filled vesicles are known as "amygdaloids", giving an **amygdaloidal** texture (e.g. Figure 3.8).

Figure 3.7 | *An aphanitic mafic rock (basalt), with gas escape structures called vesicles. Arrow points to one vesicle that is ~1cm in diameter. This is an example of another texture type, called vesicular texture, and the name of this rock is a vesicular basalt.*
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

Figure 3.8 | *An aphanitic mafic rock (basalt) with amygdaloids, which are vesicles filled with a secondary mineral. Arrows point to amygdaloids that are both partially and completely filled. This is an example of another texture type, called amygdaloidal texture, and the name of this rock is an amygdaloidal basalt.*
Source: Joyce M. McBeth (2018) CC BY 4.0 view source

Aphanitic rocks and rocks with a glassy texture are also known as **extrusive** igneous rocks, as the magma was extruded onto the surface of the earth. Porphyritic-aphanitic rocks are also considered to be extrusive rocks, as these rocks began crystallizing under the earth's surface, forming visible crystals, but this magma later emerged onto the surface as lava, crystallizing to form an extrusive igneous rock with a porphyritic-aphanitic texture.

Composition

	Felsic	**Intermediate**	**Mafic**
	0-15% MCI	16-45% MCI	46-85% MCI
Phaneritic visible minerals, slow cooling (plutonic)	granite	diorite	gabbro
Aphanitic No visible crystals, fast cooling (volcanic)	rhyolite	andesite*	basalt
Porphyritic	Use this term if there are visible crystals in basalt or andesite, or if there are very large crystals in granite		
Glassy	Dense glass that is dark in color (obsidian), or Glass froth that is light or intermediate in color (pumice)		

(left margin, rotated:) **Texture**

*this andesite is porphyritic-aphanitic.

Figure 3.9 | Chart showing some common igneous rock textures and compositions. MCI is the mafic colour index, or the percentage of dark coloured ferromagnesian minerals present. Recall that any composition can be phaneritic, aphanitic, porphyritic or glassy. Vesicular texture is not as common and is only seen in some aphanitic rocks.
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

A summary of the terms used to classify the igneous rocks are provided in Figure 3.9 in order to help with the identification of the igneous rock in this lab. Refer to the preceding figures for further help.

Exercises on Igneous Rocks

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 8 "Igneous Rocks" by Karen Tefend, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

Note: much of the overview material for this chapter is replicated in this exercise section for your reference as you complete the lab. **You will NOT have access to your lab book or notes for the rock and mineral exam!**

Name: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

NSID and student number: _ _ _ _ _ _ _ _ _ _ _ _

Date and lab section time: _ _ _ _ _ _ _ _ _ _ _ _ _

TAs' names: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _   _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Your TAs will check that you have completed the questions at the end of the lab. Please hold on to your lab notes to help you prepare for the rock and mineral quiz and your lab final exam.

3.2 IGNEOUS ROCK ORIGIN

3.2.1 Magma Composition

Before any igneous rock can form, there must be molten material, known as magma, produced; therefore, you must have a rock to melt to make the magma, which then cools to become an igneous rock. There are many factors which may affect the composition of the igneous rock, including the initial rock or rocks that melt to form the magma, the degree of melt, the cooling process of the magma, etc. These are things one should consider when studying the origin of igneous rocks.

Most rocks contain minerals that are crystalline solids composed of the chemical elements. All minerals have a certain set of conditions, such as temperature, at which they can melt; since rocks contain a mixture of minerals, some of the minerals in a rock may melt, while others remain solid. Temperature conditions are important, as only minerals that can melt at "lower" temperatures may experience melting, whereas the temperature would have to increase in order for other minerals to *also* melt and add their chemical components to the magma that is being generated. Therefore, if the same types of rocks are melting, different magma compositions are generated simply by melting at different temperatures!

As the magma cools, mafic minerals tend to crystallize first at relatively high temperatures; these minerals (olivine, pyroxene, amphibole, biotite, calcium-rich plagioclase feldspar) tend to crystallize in a specific sequence and remove iron, magnesium and calcium from the magma during crystallization. Iron- and magnesium-rich minerals are referred to as **ferromagnesian** minerals (ferro = iron) and are usually green, dark gray, or black in colour. The removal of iron and magnesium from the magma results in the formation of minerals that are deficient in these elements; as such, these minerals are referred to as **nonferromagnesian** minerals. They generally crystallize at lower temperatures to form pale-coloured minerals (quartz, muscovite, sodium-rich plagioclase feldspar, potassium feldspar), which are richer in silica, sodium, and potassium.

3.3 IGNEOUS ROCK COMPOSITION

Igneous rocks created in different environments typically have certain characteristics. For example, you can expect to find abundant olivine, and maybe some pyroxene and Ca-rich plagioclase, in an **ultramafic** rock called peridotite or komatiite, or that pyroxene, plagioclase, and possibly some olivine or amphibole may be present in a **mafic** rock such as gabbro or basalt. You can also expect to see quartz, muscovite, potassium feldspar, and some biotite and Na-rich plagioclase in a **felsic** (or **silicic**) rock such as granite or rhyolite. The classification of an igneous rock depends partly on the minerals that may be present in the rock, and since the minerals have certain colours due to their chemical makeup, then the rocks must have certain colours. For example, a rock composed of mostly olivine will be green in colour due to olivine's green colour; such a rock would be called ultramafic. A rock that has a large amount of ferromagnesian minerals in it will be a dark-coloured rock because the ferromagnesian minerals (other than olivine) tend to be dark coloured; an igneous rock that is dark in colour is called a **mafic** rock ("ma-" comes from magnesium, and "fic" from ferric iron). An igneous rock with a large amount of nonferromagnesian minerals will be light in colour, such as the silicic or felsic rocks ("fel" from feldspar, and "sic" from silica-rich quartz). So, based on colour alone, we've been able to start classifying the igneous rocks.

Figure 3.2 shows examples of igneous rocks representing mafic and felsic rock compositions (Figures 3.2A and 3.2C, respectively), as well as an **intermediate** rock type (Figure 3.2B). Felsic rocks may have small amounts of dark-coloured minerals, but are predominately composed of light-coloured minerals, whereas mafic rocks have a higher percentage of dark-coloured minerals, which results in a darker-coloured rock. A rock that is considered intermediate between the mafic and felsic rocks is truly an intermediate in terms of the colour and mineral composition; such a rock would have less dark minerals than the mafic rocks, yet more dark minerals than the felsic rocks.
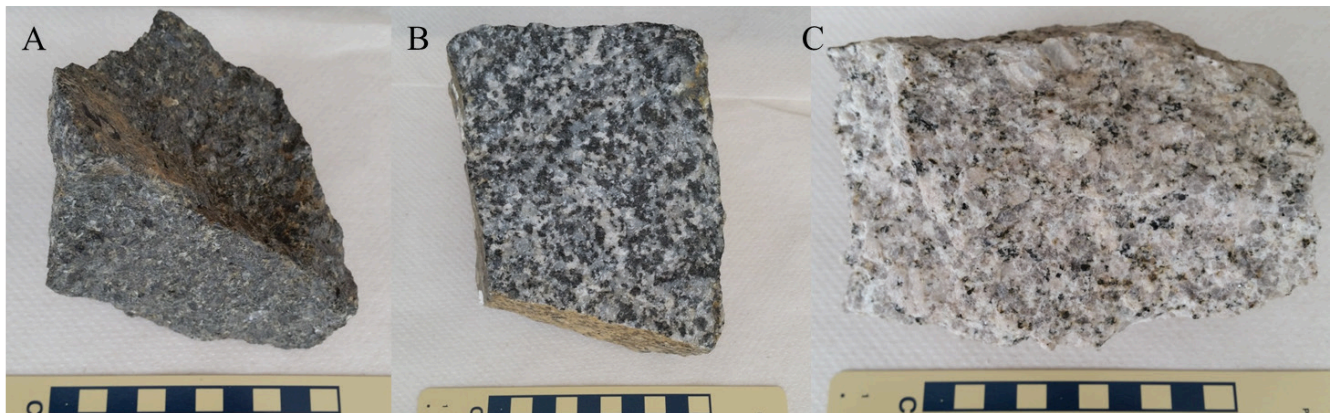

Figure 3.2 | *Examples of igneous rocks from the mafic (A), intermediate (B), and felsic (C) rock compositions. Photo scale on bottom is in centimeters. Source: Karen Tefend (2015) CC BY-SA 3.0* [view source](#)

As previously mentioned, classifying rocks into one of the igneous rock compositions (ultramafic, mafic, intermediate, and felsic) depends on the minerals that each rock contains. Identification of the minerals can be difficult in rocks such as in Figure 3.2A, as the majority of minerals are dark in colour and it can be difficult to distinguish each mineral. An easy method of determining the igneous rock composition is by estimating the percentage of dark-coloured minerals in the rock, without trying to identify the actual minerals present. Estimating the percentage of dark-coloured minerals is only possible if the minerals are large enough to see; in that case a person can still recognize a mafic rock by its dark-coloured appearance, and a felsic rock by its light-coloured appearance. An intermediate rock will be somewhat lighter than a mafic rock, yet darker than a felsic rock. Finally, an ultramafic rock is typically green in colour, due to the large amount of green-coloured olivine in the rock. Such rocks that contain minerals that are too small to see are shown in Figure 3.4; note that you can still distinguish between mafic (Figure 3.4A), intermediate (Figure 3.4B) and felsic (Figure

3.4C) by the overall colour of the rock. The intermediate igneous rock in Figure 3.3B does have a few visible phenocrysts; this odd texture will be covered later in this chapter.
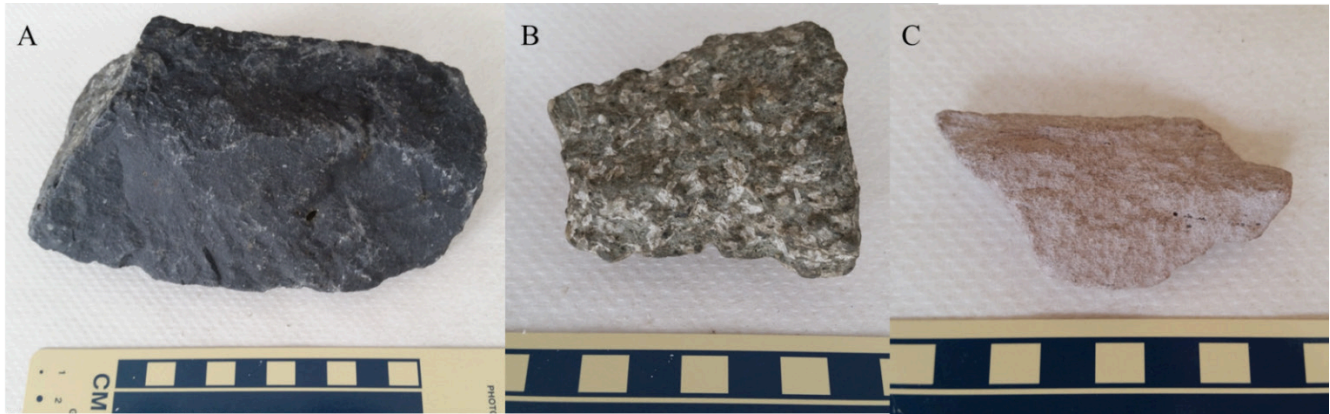

Figure 3.4 | Examples of igneous rocks from the mafic (A), intermediate (B), and felsic (C) rock compositions. Notice the difference in appearance between these rocks and those in Figure 3.2.
Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)

3.4 IGNEOUS ROCK TEXTURE

The classification of igneous rocks is based not just on composition, but also on texture. As mentioned earlier, texture refers to the features that we see in the rock such as the mineral sizes or the presence of glass, fragmented material, or vesicles (holes) in the igneous rock. We will cover mineral crystal sizes and vesicles in this section.

Since the crystals or **phenocrysts** form while the magma is cooling, then the size of the crystals must have something to do with the cooling process. The chemical elements that become part of the mineral must migrate from the liquid magma to bond with other elements in a certain way to form the unique crystal structure for that mineral. When magma cools slowly, the chemical elements needed to form a certain mineral have time to migrate; that mineral can become large enough to see without the aid of a microscope. This igneous rock is said to have a **phaneritic** texture (phan = large). The rock samples shown in Figure 3.2 are all phaneritic rocks; Figure 3.2A is a phaneritic mafic rock called gabbro, Figures 3.2B and 3.4B are a phaneritic intermediate rock called diorite, and the rock in Figure 3.2C is a phaneritic felsic rock known as granite. Magma that cools relatively quickly will result in a different rock; there is less time for the chemical elements to migrate and form large mineral crystals. Therefore, many small, microscopic crystals of a particular mineral will form; these igneous rocks are called **aphanitic** igneous rocks. Figure 3.4A and 3.4C are aphanitic rocks; since Figure 3.4A is dark in colour, it is a mafic aphanitic rock called basalt, and the felsic rock in Figure 3.4C is called rhyolite.

There can be equivalent extrusive and intrusive rocks, which appear to different but are chemically identical. For example, basalt and gabbro are both mafic rocks and have the same composition, but basalt represents a magma that cooled fast, and gabbro represents a magma that cooled slowly. The same can be said for the other rock compositions: the felsic rocks rhyolite and granite have identical compositions but rhyolite cooled fast and granite cooled slower. The intermediate rocks diorite (Figure 3.2B) and andesite (Figure 3.4B) also represent magmas that cooled slowly or a bit faster, respectively. Sometimes there are some visible crystals in an otherwise aphanitic rock, such as the andesite in Figure 3.4B. The texture of such a rock is referred to as **porphyritic**, or more accurately porphyritic-aphanitic since it is a porphyritic andesite, and all andesites are aphanitic. Two different crystal sizes within an igneous rock indicates that the cooling rate of the magma increased; while the magma was cooling slowly, larger crystals can form, but if the magma starts to cool faster, then only small crystals can form. A phaneritic rock can also be referred to as a porphyritic-

phaneritic rock if the phaneritic rock contains some very large crystals in addition to the other visible crystals. In Figure 3.5 are two porphyritic rocks: a porphyritic-aphanitic basalt, and a porphyritic-phaneritic granite.
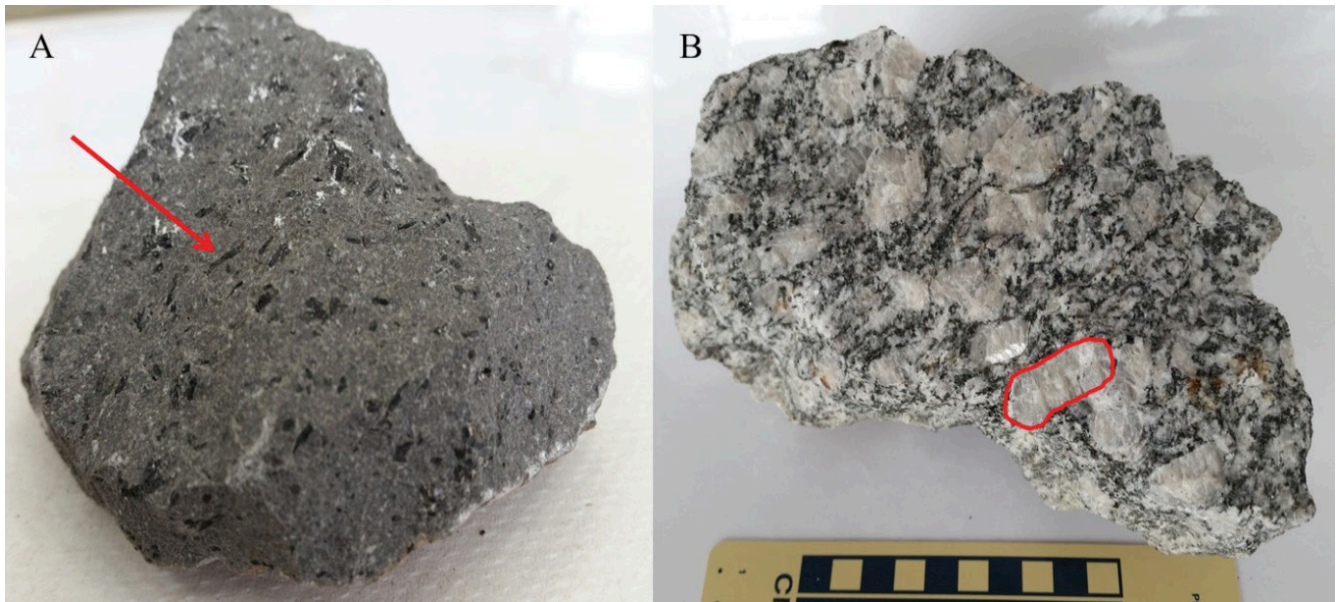

Figure 3.5 | *(A) An example of a porphyritic-aphanitic mafic rock with needle-shaped amphibole phenocrysts (arrow points to one phenocryst that is 1cm in length); No other minerals in (A) are large enough to see. (B) An example of a porphyritic-phaneritic felsic rock with large feldspars (outlined phenocryst is 3 cm length). Surrounding these large feldspars are smaller (yet still visible) dark and light coloured minerals.*
Source: Karen Tefend (2015) CC BY-SA 3.0 <u>view source</u>

Sometimes, the magma cools so quickly there isn't time to form minerals, as the chemical elements in the magma have no time to migrate into a crystal structure. When this happens, the magma becomes a dense glass called **obsidian** (Figure 3.6A). By definition, glass is a chaotic arrangement of the chemical elements, and therefore not considered to be a mineral; igneous rocks composed primarily of glass are said to have a **glassy** texture. The identification of a glassy rock such as obsidian is easy once you recall the properties of glass; any thick glass pane or a glass bottle that is broken will have this smooth, curve shaped pattern on the broken edge called conchoidal fracture. Even though obsidian is naturally occurring, and not man made, it still breaks in this conchoidal pattern. If you look closely at the obsidian in Figure 3.6A, you will see the curved surfaces on the rock. Obsidian appears quite dark in colour regardless of its composition because it is a dense glass, and light cannot pass through this thick glass.
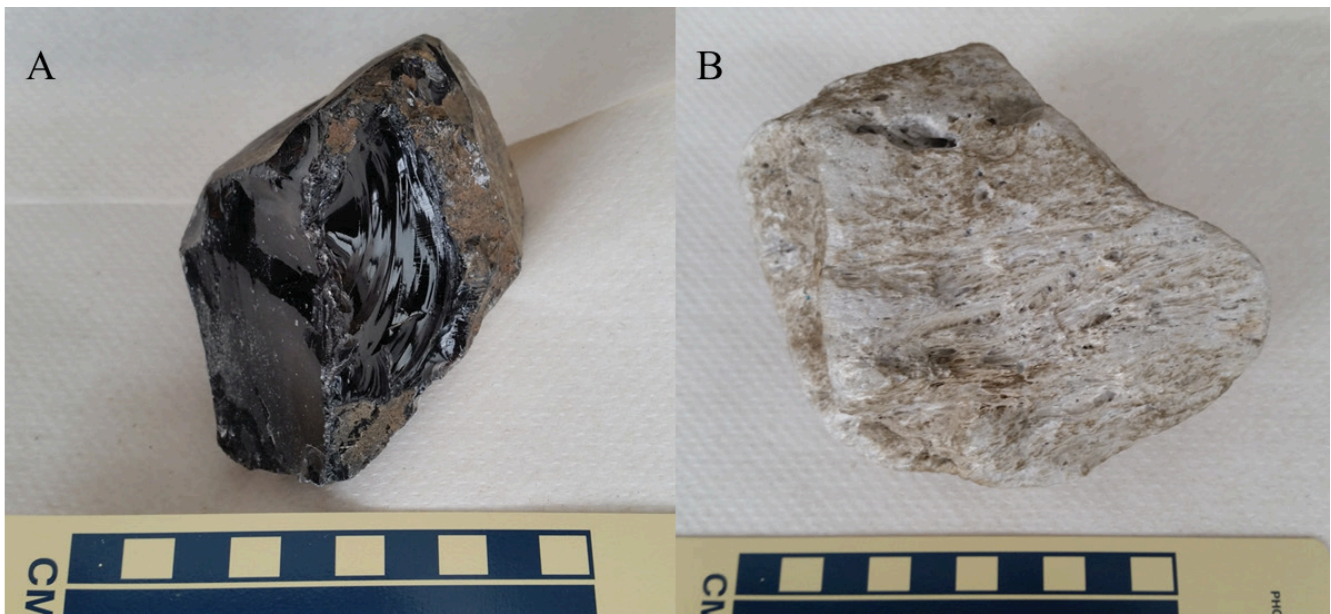
Figure 3.6 | *Igneous rocks with glassy texture: obsidian (A) and pumice (B).*
Source: Karen Tefend (2015) CC BY-SA 3.0 *view source*

In Figure 3.6B, there is another igneous rock that is also composed primarily of glass due to a very fast rate of magma cooling. This rock is called pumice and is commonly known as the rock that floats on water due to its low density. The glass in this rock is stretched out into very fine fibers of glass which formed during the eruptive phase of a volcano. Because these fibers are so thin, they are easy to break and any conchoidal fractures on these fibers are too small to see without the aid of a microscope. Pumice can have any composition (felsic to mafic), but, unlike obsidian, the colour of the pumice can be used to determine the magma composition, as felsic pumice is always light in colour and mafic pumice will be dark in colour. Mafic pumice with a dark grey, red or black colour is also known as scoria.

3.5 IGNEOUS ROCK FORMATION—INTRUSIVE VS. EXTRUSIVE

The different crystal sizes and presence or absence of glass in an igneous rock is primarily controlled by the rate of magma cooling. Magmas that cool below the surface of the earth tend to cool slowly, as the surrounding rock acts as an insulator, which slows the rate of cooling. Magma that stays below the surface of the earth can take tens of thousands of years to completely crystallize, depending on the size of the magma body. Upon inspection of this rock, you would see that it is composed of minerals that are large enough to see without the aid of a microscope. Any igneous rock sample that is considered to have a phaneritic texture (or porphyritic-phaneritic), is referred to as an **intrusive** rock, as it is derived from magma that intruded the rock layers but never reached the earth's surface.

If magma reaches the earth's surface, it is no longer insulated by the rocks around it and will cool rapidly. Magma that reaches the earth's surface through a fissure or central vent will lose some of its dissolved gas and becomes lava, and any rock that forms from lava will have either an aphanitic texture due to fast cooling, or a glassy texture due to very fast cooling. Flowing lava may continue to release gas while cooling; this is typical of mafic lava flows. If the lava hardens while these gases are bubbling out of the lava, a small hole or vesicle may form in the rock, the term "**vesicular**" is given to the rock to indicate the presence of these vesicles. For example, a basalt with vesicles is called vesicular basalt (Figure

3.7). These vesicles can be filled with a secondary mineral, such as quartz or calcite, long after the rock was formed; these filled vesicles are known as "amygdaloids", giving an **amygdaloidal** texture (e.g. Figure 3.8).

Figure 3.7 | An aphanitic mafic rock (basalt), with gas escape structures called vesicles. Arrow points to one vesicle that is ~1cm in diameter. This is an example of another texture type, called vesicular texture, and the name of this rock is a vesicular basalt.
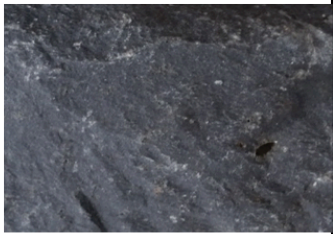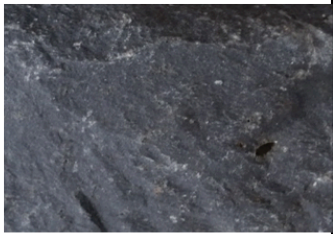*Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)*

Figure 3.8 | An aphanitic mafic rock (basalt) with amygdaloids, which are vesicles filled with a secondary mineral. Arrows point to amygdaloids that are both partially and completely filled. This is an example of another texture type, called amygdaloidal texture, and the name of this rock is an amygdaloidal basalt.
Source: Joyce M. McBeth (2018) CC BY 4.0 view source

Aphanitic rocks and rocks with a glassy texture are also known as **extrusive** igneous rocks, as the magma was extruded onto the surface of the earth. Porphyritic-aphanitic rocks are also considered to be extrusive rocks, as these rocks began crystallizing under the earth's surface, forming visible crystals, but this magma later emerged onto the surface as lava, crystallizing to form an extrusive igneous rock with a porphyritic-aphanitic texture.

Composition

	Felsic	**Intermediate**	**Mafic**
	0-15% MCI	16-45% MCI	46-85% MCI
Phaneritic visible minerals, slow cooling (plutonic)	granite	diorite	gabbro
Aphanitic No visible crystals, fast cooling (volcanic)	rhyolite	andesite*	basalt
Porphyritic	Use this term if there are visible crystals in basalt or andesite, or if there are very large crystals in granite		
Glassy	Dense glass that is dark in color (obsidian), or Glass froth that is light or intermediate in color (pumice)		

*this andesite is porphyritic-aphanitic.

Figure 3.9 | *Chart showing some common igneous rock textures and compositions. MCI is the mafic colour index, or the percentage of dark coloured ferromagnesian minerals present. Recall that any composition can be phaneritic, aphanitic, porphyritic or glassy. Vesicular texture is not as common and is only seen in some aphanitic rocks.*
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

A summary of the terms used to classify the igneous rocks are provided in Figure 3.9 in order to help with the identification of the igneous rock in this lab. Refer to the preceding figures for further help.

3.6 LAB EXERCISES – IGNEOUS ROCK IDENTIFICATION

Before attempting to answer the following questions, obtain the 13 rock samples from the drawers provided by your TA; they will be numbered 28-40. As you work through the questions fill in Chart 5-E1 (link to pdf below). You do not have to fill out every column for every rock – just follow along in the lab and determine the properties you are asked about.

Separate the samples into three groups based on their color (dark, light or intermediate). Take a close look at the dark

colored rocks; how are they different? When you hold them closer to a light source, notice how they reflect light; they may be dull looking, they may have small shiny surfaces, or they may be extremely shiny and smooth. The rock that is very smooth and shiny is not a mafic rock, even though it is dark in color. This particular rock is an example of that rock type that lacks mineral crystals; instead, it is almost entirely made of glass, and is most probably felsic in composition. Separate this rock into its own group. Now take a close look at the light-colored rocks. Some may have several minerals visible that you will see as different colors. Others may be fairly uniform in color; some may be composed of very tiny minerals that require a microscope to view them, while another may seem to be fragile and light-weight. The fragile appearing rock is another example of rock that is again almost entirely glass with a very few, tiny phenocrysts; set this rock aside with the other glassy rock.

Now you should have four piles, please answer the following questions. Refer to the images in figures 3.2-3.9 to help with identification.

Sample #	Textures	Chemical Composition	Colour	Major Minerals Present	Name
0	Phaneritic	Ultra-mafic	Dark; green	Olivine, Pyroxene	Peridotite

Table 3-E1 | *Igneous Rock Notation Chart – Download and fill in this chart as you work through the lab, similar to the chart you completed in the minerals lab. An example of a rock you do not have available (#0) is included. You do not have to fill out every column for every rock – just follow along in the lab and determine the properties you are asked about.*
Source: Lyndsay Hauber (2018) CC BY 4.0

1. Sample 28: The pink coloured minerals are most likely _____.

   a. quartz
   b. biotite
   c. orthoclase
   d. Ca-rich plagioclase

2. Sample 28: The small, dark colored minerals are most likely _____.

   a. quartz
   b. biotite
   c. orthoclase
   d. Na-rich plagioclase

3. Sample 28: This rock belongs to which igneous rock classification?

   a. mafic
   b. intermediate
   c. felsic
   d. any of the above

4. Sample 29: This rock belongs to which igneous rock classification?

   a. mafic
   b. intermediate
   c. felsic
   d. any of the above

5. Sample 32: This rock belongs to which igneous rock classification?

   a. mafic

     b. intermediate

     c. felsic

     d. any of the above

6. Sample 32: According to Figure 3.1, this rock must contain which mineral?

     a. olivine

     b. pyroxene

     c. amphibole

     d. quartz

7. Sample 33: The white minerals are most likely _____.

     a. quartz

     b. biotite

     c. orthoclase

     d. plagioclase

8. Sample 33: This rock belongs to which igneous rock classification?

     a. mafic

     b. intermediate

     c. felsic

     d. any of the above

9. Sample 35: This rock belongs to which igneous rock classification?

     a. mafic

     b. intermediate

     c. felsic

     d. any of the above

10. Sample 35: According to Figure 3.1, which mineral would you NOT expect to find in this rock?

     a. olivine

     b. pyroxene

     c. amphibole

     d. quartz

11. Sample 36: This rock belongs to which igneous rock classification?

     a. mafic

     b. intermediate

     c. felsic

     d. any of the above

12. Sample 29: This rock has which textures? (choose 2)

     a. phaneritic

     b. aphanitic

     c. porphyritic-aphanitic

     d. glassy

     e. vesicular

     f. amygdaloidal

13. Sample 29: What is this rock called?

     a. obsidian

     b. pumice

     c. granite

     d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

14.   Sample 31: This rock has what texture?

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

15.   Sample 31: How did this rock form?

    a. by magma that cooled very slowly

    b. by magma that cooled slowly

    c. by a very fast cooling of a magma

16.   Sample 31: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

17.   Sample 33: This rock has what texture?

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

18.   Sample 33: How did this rock form?

    a. by magma that cooled slowly

    b. by fast cooling lava

    c. by a very fast cooling of a lava

    d. by a very fast cooling magma during a volcanic eruption

    e. by magma that was cooling slowly, then as a lava that cooled quickly

19.   Sample 33: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

20. Sample 33: This rock can also be called _____.

    a. extrusive
    b. intrusive

21. Sample 34: This rock has what texture?

    a. phaneritic
    b. aphanitic
    c. porphyritic-aphanitic
    d. glassy
    e. vesicular
    f. amygdaloidal

22. Sample 34: How did this rock form?

    a. by magma that cooled slowly
    b. by fast cooling lava
    c. by a very fast cooling of a lava
    d. by a very fast cooling magma during a volcanic eruption
    e. by magma that was cooling slowly, then as a lava that cooled quickly

23. Sample 34: What is this rock called?

    a. obsidian
    b. pumice
    c. granite
    d. rhyolite
    e. diorite
    f. andesite
    g. gabbro
    h. basalt

24. Sample 34: This rock can also be called _____.

    a. extrusive
    b. intrusive

25. Sample 36: This rock has what texture?

    a. phaneritic
    b. aphanitic
    c. porphyritic-aphanitic
    d. glassy
    e. vesicular
    f. amygdaloidal

26. Sample 36: How did this rock form?

    a. by magma that cooled slowly
    b. by fast cooling lava
    c. by a very fast cooling of a lava
    d. by a very fast cooling magma during a volcanic eruption
    e. by magma that was cooling slowly, then as a lava that cooled quickly

27. Sample 36: What is this rock called?

    a. obsidian
    b. pumice
    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

28. Sample 37: This rock has what texture?

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

29. Sample 37: How did this rock form?

    a. by magma that cooled slowly

    b. by fast cooling lava

    c. by a very fast cooling of a lava

    d. by a very fast cooling magma during a volcanic eruption

    e. by magma that was cooling slowly, then as a lava that cooled quickly

30. Sample 37: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

31. Sample 37: This rock can also be called _____.

    a. extrusive

    b. intrusive

32. Sample 38: This rock has what texture?

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

33. Sample 38: This rock has what composition?

    a. felsic

    b. intermediate

    c. mafic

    d. any of the above

34. Sample 38: How did this rock form?

    a. by magma that cooled slowly

    b. by fast cooling lava

    c. by a very fast cooling of a lava

    d. by a very fast cooling magma during a volcanic eruption

    e. by magma that was cooling slowly, then as a lava that cooled quickly

35. Sample 38: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

36. Sample 39: This rock has which textures? (choose 2)

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

37. Sample 39: How did this rock initially form?

    a. by magma that cooled slowly

    b. by fast cooling lava

    c. by a very fast cooling of a lava

    d. by a very fast cooling magma during a volcanic eruption

    e. by magma that was cooling slowly, then as a lava that cooled quickly

38. Sample 39: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

39. Sample 39: This rock can also be called _____.

    a. extrusive

    b. intrusive

40. Sample 40: This rock has what texture?

    a. phaneritic

    b. aphanitic

    c. porphyritic-aphanitic

    d. glassy

    e. vesicular

    f. amygdaloidal

41. Sample 40: How did this rock form?

    a. by magma that cooled slowly

    b. by fast cooling lava

    c. by a very fast cooling of a lava

    d. by a very fast cooling magma during a volcanic eruption

    e. by magma that was cooling slowly, then as a lava that cooled quickly

42. Sample 40: What is this rock called?

    a. obsidian

    b. pumice

    c. granite

    d. rhyolite

    e. diorite

    f. andesite

    g. gabbro

    h. basalt

CHAPTER 4. SEDIMENTARY ROCKS

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 10 "Sedimentary Rocks" by Bradley Deline, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

4.1 INTRODUCTION

We are particularly interested in the history and events that occur on the surface of the Earth because it is easier to directly observe and test, and has direct relevance to our lives and history. Sedimentary rocks are the pages in which history is written, since they contain powerful environmental indicators, traces of life, and chemical signatures that can inform us about many subjects, from the occurrence of ancient catastrophes to the productivity of life.

The identification of sedimentary rocks is more than applying names, since each name is a loaded term that conveys information regarding its history, where it was formed, potentially when it was formed, and the processes that lead to its formation. Each sedimentary rock is a puzzle, and by identifying a set of rocks, how they are layered, the fossils within, and patterns in the rocks, a geologist can reconstruct an entire environment and ecosystem. Solving these puzzles is both an academic exercise to better understand the world around us and a tool for finding the resources that are important to our lives. In particular, fossil fuels and other natural resources are, or are contained within, sedimentary rocks such as coal, natural gas, petroleum, salt, and the materials that go into wallboard or in the making of cement. Therefore, a better understanding of sedimentary rocks and how and where they are formed directly influences your everyday life.

4.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Describe how erosion and weathering relate to the formation of sedimentary rocks
- Identify sedimentary rocks and their features
- Describe the formation and history of different types of sedimentary rocks

4.1.2 Key Terms

- Biochemical Sedimentary Rocks
- Chemical Sedimentary Rocks
- Chemical Weathering
- Clast
- Clastic Sedimentary Rocks
- Dissolution

- Erosion
- Hydrolysis
- Maturity
- Mechanical Weathering
- Oxidation
- Sorting

Overview of Sedimentary Rocks

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 10 "Sedimentary Rocks" by Bradley Deline, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

4.2 WEATHERING AND EROSION

Sedimentary rocks are formed by the weathering, erosion, deposition, and lithification of sediments. Sedimentary rocks are composed of pieces of other rocks, which are broken down by a process called weathering. There are two basic ways that weathering occurs in nature. First, rocks can be physically broken into smaller pieces (e.g. hitting a rock with a hammer), which is called **mechanical weathering**. Alternatively, rocks can be broken down and altered at the atomic level (e.g. dissolving salt in water), which is called **chemical weathering**. There are multiple ways each type of weathering can occur and, therefore, both the rate that rocks break down and how they break down varies dramatically depending on the area and environment.

The most prevalent type of mechanical weathering is the collision, breaking, and grinding of rock by the movement of a fluid, either water or air. The size of the carried sediment depends on the type of fluid and speed of the movement. A fast fluid (e.g. a rapidly flowing river) can carry large particles and cause immense amounts of weathering, while a slow fluid (e.g. a calm stream) would hardly cause any weathering. The density of the fluid also controls the size of particle that can be transported; for instance, a denser fluid, like water, can carry larger particles than a less dense fluid, like air. Another common method of mechanical weathering is called frost wedging, which occurs when water seeps into cracks in the rock and freezes. Water expands when frozen, which puts pressure on the rock and can potentially split boulders. The addition and subtraction of heat or pressure can also cause rock to break, which can cause rocks to shatter when cooled very quickly or immense pressure is released. Finally, plants, animals, and humans can cause significant amounts of weathering. These sediments then undergo **erosion**, which is the transport of sediment from where it is weathered to where it will be deposited and turned into a rock.

Rocks can also be chemically weathered, most commonly by one of three processes. The first is called **dissolution**, where a mineral or rock is completely broken apart in water into individual atoms or molecules. These ions can then be transported with the water and redeposited as the concentration of ions increases, generally due to evaporation. Chemical weathering can also change the mineralogy and weaken the original material, which is also caused by water. A mineral can undergo **hydrolysis**, where a hydrogen atom from the water molecule replaces the cation in a mineral; this normally alters minerals like feldspar into a softer clay mineral. Additionally, a mineral can undergo **oxidation**, where oxygen atoms alter the valence state of a cation; this normally occurs on a metal and is commonly known as rusting.

Chemical and mechanical weathering can work together to increase the overall rate of weathering. Chemical weathering weakens rocks, making them more prone to breaking physically, while mechanical weathering increases the surface area of the sediment, which increases the surface area that is exposed to chemical weathering. Therefore, environments with multiple types of weathering can erode very quickly.

4.3 IDENTIFYING SEDIMENTARY ROCKS

Classification of sedimentary rocks is largely based on differentiating the processes that lead to their formation. The biggest division in sedimentary rock types is based on the primary type of weathering that leads to the material building the sedimentary rock. If the rock is largely made from pieces of rock (called **clasts**) that have been mechanically weathered, the rocks are referred to as Detrital or **Clastic Sedimentary Rocks**. These rocks are composed of broken pieces of other rocks. In this case, the mineralogy of the clasts is not important, but we need to note the properties of the sediment itself. Alternatively, if the rock is largely the product of chemical weathering, the classification is based on the composition of the material and the processes involved in the materials precipitation from solution. **Chemical Sedimentary Rocks** form from the inorganic precipitation of minerals from a fluid. Crystals begin to form if the ions present within a fluid, such as water, become very concentrated, either by the addition of more ions or the removal of water by freezing or evaporation. In this case, the identification of the type of sedimentary rocks is based on the minerals present. If organisms facilitate the precipitation of these minerals from water we refer to the rocks as **Biochemical Sedimentary Rocks.** An example of biochemical precipitation is the formation of skeletal minerals in many organisms: from starfish and clams that grow calcite, to sponges that grow silica-based material, to humans that have bones made of hydroxyapatite. Now we can discuss the identification and formation of particular sedimentary rocks.

4.3.1 Clastic Sedimentary Rocks

Weathering and erosion occur normally in areas that are at high elevation, such as mountains, while deposition occurs in lower areas such as valleys, lakes, or the ocean. The sediment is transported from the area of erosion (e.g. the "source") to area of deposition (e.g. the "sink") by ice, water, or air. The sediment changes during its journey; we can recognize the amount of change, the distance traveled, and the transport mechanism, by looking at its maturity (e.g. Figure 4.1). **Maturity** is defined as the texture and composition of a sedimentary rock resulting from varying amounts of erosion or sedimentary transport. Imagine a mountain composed of granite, and let us explore how the sediment from this mountain changes as it makes the long journey via river to the ocean. First, the rock is mechanically breaking down into smaller pieces, which creates sediment that has jagged large and small clasts, and all of the minerals remain. The sizes of clasts in these rocks can range from large boulders, to cobbles, to pebbles, to the smallest particles, clay. As this sediment is transported in the river, the clasts collide with each other and the rocks get smaller and the sharp edges are broken off. Also, as the slope of the land decreases the river slows, leaving behind the large boulders and cobbles, while carrying away the smaller particles. Now, sediments further from the source will be more uniform in size, which is a process called **sorting**. Chemical weathering also occurs, altering the feldspars into clay-sized particles. In the end, the granite is reduced from boulders and cobbles close to the mountain, to pebbles in the rivers, to pure and uniform quartz sand at the beach, and miniscule clay grains on the ocean floor. Therefore, different clastic rocks are found in different areas and have traveled different distances.

In the lab, we will look at four types of clastic rocks, conglomerate, breccia, sandstone, and shale. Conglomerate is an immature sedimentary rock (e.g. it has been transported a short distance) that is a poorly sorted mixture of clay, sand, and rounded pebbles. The mineralogy of the sand and pebbles (also called clasts) can vary depending on its source. These rocks would be found on the continent in several types of deposits, such as ancient landslides or pebble beds in rivers. Breccia is an immature sedimentary rock that is a poorly sorted mixture of clay, sand, and angular pebbles. The mineralogy of the clasts can vary depending on its source. These rocks would be found on the continent in several types of deposits, such as next to fault zones and debris flows. Sandstone is defined as a clastic sedimentary rock that consists of sand-sized clasts. These clasts can vary from jagged to rounded, and can contain many minerals or just quartz. Therefore, sandstone ranges from being relatively immature to mature, which makes sense, since we can find

layers of sand associated with mountain rivers, to pure white quartz beaches. Last we have shale, which is composed of clay particles and has a finely layered or fissile appearance. This extremely mature sedimentary rock is made from the smallest particles that can be carried by wind or barely moving water and can be found thousands of miles away from the original source.
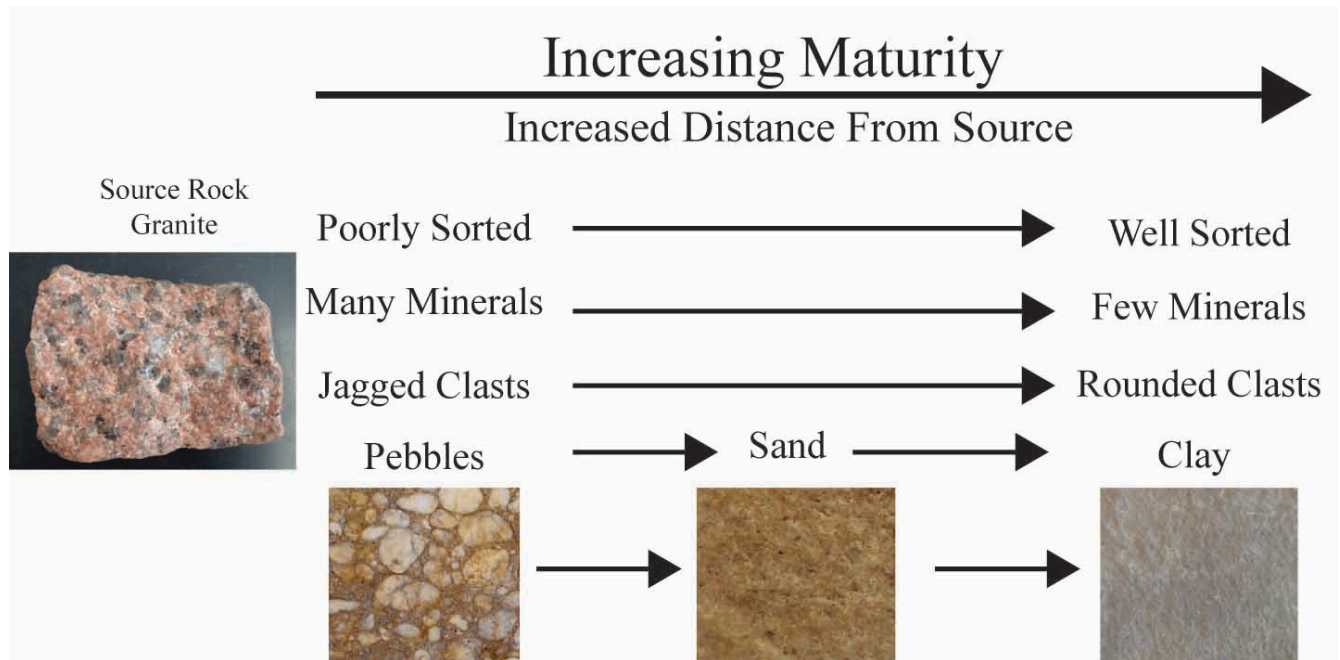

Figure 4.1 | *Maturity in clastic sedimentary rocks showing how the sediments change as they are eroded further from their source.*
Source: Bradley Deline (2015) CC BY-SA 3.0 view source

4.3.2 Biochemical and Chemical Sedimentary Rocks

As mentioned before, biochemical and chemical sedimentary rocks either precipitated directly from water or by organisms. The most recognizable chemical sedimentary rocks are evaporites, which are minerals that are formed by the precipitation of minerals from the evaporation of water. You have already examined multiple examples of evaporites in a previous lab, such as halite and gypsum. In this lab, we will focus on siliceous and carbonate biochemical sedimentary rocks. Chert is a rock composed of microcrystalline varieties of quartz, and thus it has properties that are associated with quartz itself, such as conchoidal fracturing and hardness greater than glass. Chert is often formed deep in the ocean from silicious material that is either inorganic (e.g. silica clay) or biologic (e.g. skeletons of sponges and single-celled organisms) in origin. Carbonates are one of the most important groups of sedimentary rocks and can result in distinctive landscapes (e.g. karst) and human hazards (e.g. sinkholes). Limestone is a sedimentary rock composed of the carbonate mineral calcite and can vary greatly in its appearance, depending on how it is formed, but can easily be identified by its chemical weathering. Limestone composed of calcite undergoes dissolution in acids, meaning it effervesces dramatically when we apply dilute HCl. As with chert, limestone can be formed inorganically from a supersaturation of calcium and carbonate ions in water in varying environments, from caves to tropical beaches. Limestone that consists of crystals of calcite or microcrystalline masses of calcite is called crystalline limestone. Alternatively, limestone can be formed biologically with the most striking example called a fossiliferous limestone, which are rocks made of fragmented carbonate (calcite or its polymorph aragonite) shells or coral.

	Composition	Texture and Properties	

Detrital Sedimentary Rocks

	Composition	Texture and Properties	
Shale	Fine rock fragments smaller than 1/16 mm	Clay-sized particles that cannot be differentiated by the naked eye. May be fissile, splits into distinctive layers	
Sandstone	Medium rock fragments between 1/16 mm and 2 mm	Composed of sand-sized rock fragments. The fragments can vary in mineralogy, including mainly quartz, along with feldspar, and clay	
Breccia	Coarse, angular rock fragments ranging in size, with the largest >2 mm	Poorly sorted mixture of rock fragments, including angular or sub-angular pebbles	
Conglomerate	Coarse, rounded rock fragments ranging in size, with the largest >2 mm	Poorly sorted mixture of rock fragments, including rounded or sub-rounded pebbles	

Chemical and Biochemical Rocks

	Composition	Texture and Properties	
Limestone	Calcite crystals or microcrystalline calcite	Masses of large, interlocking calcite crystals or microscopic crystals not visible with the naked eye	
Fossiliferous Limestone	Calcareous skeletal fragments of coral or shells	Consisting of fossils or fossil fragments	
Oolitic Limestone	Calcite concretions, formed around sand or shell fragments	Aggregates of oolites, small spherical calcite concretions	
Chert	Cryptocrystalline Quartz	Microcrystalline polymorphs of quartz, formed by the recrystallization of siliceous skeletons. Conchoidal fracturing; scratches glass	
Rock Salt	Halite and sylvite crystals	Fine- to coarse-grained crystalline structure, with a salty taste and cubic cleavage	

Table 4.1 | *Classification of Sedimentary rocks.*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0 after Bradley Deline (2015) CC BY-SA 3.0 view source

Exercises on Sedimentary Rocks

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Note: much of the overview material for this chapter is replicated in this exercise section for your reference as you complete the lab. **You will NOT have access to your lab book or notes for the rock and mineral exam!**

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Your TAs will check that you have completed the questions at the end of the lab. Please hold on to your lab notes to help you prepare for the rock and mineral quiz and your lab final exam.

4.2 WEATHERING AND EROSION

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normally alters minerals like feldspar into a softer clay mineral. Additionally, a mineral can undergo **oxidation**, where oxygen atoms alter the valence state of a cation; this normally occurs on a metal and is commonly known as rusting.

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Classification of sedimentary rocks is largely based on differentiating the processes that lead to their formation. The biggest division in sedimentary rock types is based on the primary type of weathering that leads to the material building the sedimentary rock. If the rock is largely made from pieces of rock (called **clasts**) that have been mechanically weathered, the rocks are referred to as Detrital or **Clastic Sedimentary Rocks**. These rocks are composed of broken pieces of other rocks. In this case, the mineralogy of the clasts is not important, but we need to note the properties of the sediment itself. Alternatively, if the rock is largely the product of chemical weathering, the classification is based on the composition of the material and the processes involved in the materials precipitation from solution. **Chemical Sedimentary Rocks** form from the inorganic precipitation of minerals from a fluid. Crystals begin to form if the ions present within a fluid, such as water, become very concentrated, either by the addition of more ions or the removal of water by freezing or evaporation. In this case, the identification of the type of sedimentary rocks is based on the minerals present. If organisms facilitate the precipitation of these minerals from water we refer to the rocks as **Biochemical Sedimentary Rocks.** An example of biochemical precipitation is the formation of skeletal minerals in many organisms: from starfish and clams that grow calcite, to sponges that grow silica-based material, to humans that have bones made of hydroxyapatite. Now we can discuss the identification and formation of particular sedimentary rocks.

4.3.1 Clastic Sedimentary Rocks

Weathering and erosion occur normally in areas that are at high elevation, such as mountains, while deposition occurs in lower areas such as valleys, lakes, or the ocean. The sediment is transported from the area of erosion (e.g. the "source") to area of deposition (e.g. the "sink") by ice, water, or air. The sediment changes during its journey; we can recognize the amount of change, the distance traveled, and the transport mechanism, by looking at its maturity (e.g. Figure 4.1). **Maturity** is defined as the texture and composition of a sedimentary rock resulting from varying amounts of erosion or sedimentary transport. Imagine a mountain composed of granite, and let us explore how the sediment from this mountain changes as it makes the long journey via river to the ocean. First, the rock is mechanically breaking down into smaller pieces, which creates sediment that has jagged large and small clasts, and all of the minerals remain. The sizes of clasts in these rocks can range from large boulders, to cobbles, to pebbles, to the smallest particles, clay. As this sediment is transported in the river, the clasts collide with each other and the rocks get smaller and the sharp edges are broken off. Also, as the slope of the land decreases the river slows, leaving behind the large boulders and cobbles, while carrying away the smaller particles. Now, sediments further from the source will be more uniform in size, which is a process called **sorting**. Chemical weathering also occurs, altering the feldspars into clay-sized particles. In the end, the granite is reduced from boulders and cobbles close to the mountain, to pebbles in the rivers, to pure and uniform quartz sand at the beach, and miniscule clay grains on the ocean floor. Therefore, different clastic rocks are found in different areas and have traveled different distances.

In the lab, we will look at four types of clastic rocks, conglomerate, breccia, sandstone, and shale. Conglomerate is an immature sedimentary rock (e.g. it has been transported a short distance) that is a poorly sorted mixture of clay,

sand, and rounded pebbles. The mineralogy of the sand and pebbles (also called clasts) can vary depending on its source. These rocks would be found on the continent in several types of deposits, such as ancient landslides or pebble beds in rivers. Breccia is an immature sedimentary rock that is a poorly sorted mixture of clay, sand, and angular pebbles. The mineralogy of the clasts can vary depending on its source. These rocks would be found on the continent in several types of deposits, such as next to fault zones and debris flows. Sandstone is defined as a clastic sedimentary rock that consists of sand-sized clasts. These clasts can vary from jagged to rounded, and can contain many minerals or just quartz. Therefore, sandstone ranges from being relatively immature to mature, which makes sense, since we can find layers of sand associated with mountain rivers, to pure white quartz beaches. Last we have shale, which is composed of clay particles and has a finely layered or fissile appearance. This extremely mature sedimentary rock is made from the smallest particles that can be carried by wind or barely moving water and can be found thousands of miles away from the original source.

Figure 4.1 | *Maturity in clastic sedimentary rocks showing how the sediments change as they are eroded further from their source.*
Source: Bradley Deline (2015) CC BY-SA 3.0 _view source_

4.3.2 Biochemical and Chemical Sedimentary Rocks

As mentioned before, biochemical and chemical sedimentary rocks either precipitated directly from water or by organisms. The most recognizable chemical sedimentary rocks are evaporites, which are minerals that are formed by the precipitation of minerals from the evaporation of water. You have already

examined multiple examples of evaporites in a previous lab, such as halite and gypsum. In this lab, we will focus on siliceous and carbonate biochemical sedimentary rocks. Chert is a rock composed of microcrystalline varieties of quartz, and thus it has properties that are associated with quartz itself, such as conchoidal fracturing and hardness greater than glass. Chert is often formed deep in the ocean from silicious material that is either inorganic (e.g. silica clay) or biologic (e.g. skeletons of sponges and single-celled organisms) in origin. Carbonates are one of the most important groups of sedimentary rocks and can result in distinctive landscapes (e.g. karst) and human hazards (e.g. sinkholes). Limestone is a sedimentary rock composed of the carbonate mineral calcite and can vary greatly in its appearance, depending on how it is formed, but can easily be identified by its chemical weathering. Limestone composed of calcite undergoes dissolution in acids, meaning it effervesces dramatically when we apply dilute HCl. As with chert, limestone

can be formed inorganically from a supersaturation of calcium and carbonate ions in water in varying environments, from caves to tropical beaches. Limestone that consists of crystals of calcite or microcrystalline masses of calcite is called crystalline limestone. Alternatively, limestone can be formed biologically with the most striking example called a fossiliferous limestone, which are rocks made of fragmented carbonate (calcite or its polymorph aragonite) shells or coral.

	Composition	Texture and Properties	
Detrital Sedimentary Rocks			
Shale	Fine rock fragments smaller than 1/16 mm	Clay-sized particles that cannot be differentiated by the naked eye. May be fissile, splits into distinctive layers	
Sandstone	Medium rock fragments between 1/16 mm and 2 mm	Composed of sand-sized rock fragments. The fragments can vary in mineralogy, including mainly quartz, along with feldspar, and clay	
Breccia	Coarse, angular rock fragments ranging in size, with the largest >2 mm	Poorly sorted mixture of rock fragments, including angular or sub-angular pebbles	
Conglomerate	Coarse, rounded rock fragments ranging in size, with the largest >2 mm	Poorly sorted mixture of rock fragments, including rounded or sub-rounded pebbles	
Chemical and Biochemical Rocks			
Limestone	Calcite crystals or microcrystalline calcite	Masses of large, interlocking calcite crystals or microscopic crystals not visible with the naked eye	
Fossiliferous Limestone	Calcareous skeletal fragments of coral or shells	Consisting of fossils or fossil fragments	
Oolitic Limestone	Calcite concretions, formed around sand or shell fragments	Aggregates of oolites, small spherical calcite concretions	
Chert	Cryptocrystalline Quartz	Microcrystalline polymorphs of quartz, formed by the recrystallization of siliceous skeletons. Conchoidal fracturing; scratches glass	
Rock Salt	Halite and sylvite crystals	Fine- to coarse-grained crystalline structure, with a salty taste and cubic cleavage	

Table 4.1 | *Classification of sedimentary rocks.*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY-SA 4.0 after Bradley Deline (2015) CC BY-SA 3.0 view source

4-E1 LAB EXERCISES – SEDIMENTARY ROCK IDENTIFICATION

Before attempting to answer the following questions, obtain the 10 rock samples from the drawer provided by your TA; they will be numbered 41-50. There will also be metamorphic rocks in this drawer, numbered 51-60; you will require these rocks for the second half of today's lab. It is recommended that you have your glass plate, streak plate, and magnifying glass readily available.

Using Table 4-E1, start identifying the rocks by separating out the chemical and biological sedimentary rocks from the clastic sedimentary rocks. Make sure to use all of the tools available, including the glass plate, to identify the chemical and biochemical sedimentary rocks (chert will be harder than glass). The streak plate can be helpful in identifying rock salt (potash), which will produce a white streak. Finally, use the hand lens to closely examine the size of the grains in the clastic sedimentary rocks. Once you are confident of your identifications, answer the following questions.

Sample #	Texture (clastic, chemical, biochemical)	Composition	Other Properties (maturity, hardness, fracture/cleavage, etc.)	Name

Table 4-E1 | *Sedimentary Rock Notation Chart – Download and fill in this chart as you work through the lab, similar to the chart you completed in the previous labs. You do not have to fill out every column for every rock – just follow along in the lab and determine the properties you are asked about. Source: Lyndsay Hauber (2018) CC BY 4.0*

1. Sample 41: What is this rock called?

    a. Conglomerate
    b. Limestone
    c. Rock Salt
    d. Shale
    e. Sandstone
    f. Oolitic Limestone
    g. Breccia
    h. Chert
    i. Fossiliferous Limestone

2. Sample 41: What is this rock composed of?

    a. fragments of calcite shells
    b. clay-sized sediments
    c. sand-sized sediments
    d. oolites
    e. calcite crystals

3. Sample 41: Closely examine the individual grains in this rock. Which of the following is true about its maturity?

    a. It is mature because it contains a variety of different minerals.
    b. It is immature because it is poorly sorted.

c. It is mature because it contains mostly rounded quartz grains.

    d. It is immature because the grains are jagged.

4. Sample 41: What does the formation of this rock include?

    a. chemical weathering, transport of ions, precipitation of minerals, lithification

    b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

    c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

    d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition, lithification

5. Sample 42: What is this rock called?

    a. Conglomerate

    b. Limestone

    c. Rock Salt

    d. Shale

    e. Sandstone

    f. Oolitic Limestone

    g. Breccia

    h. Chert

    i. Fossiliferous Limestone

6. Sample 42: What is this an example of?

    a. Clastic Sedimentary Rock

    b. Biochemical Sedimentary Rock

    c. Chemical Sedimentary Rock

7. Sample 42: Closely examine the individual grains in this rock. Which of the following is true about its maturity?

    a. It is immature because it is poorly sorted.

    b. It is mature because it is poorly sorted.

    c. It is mature because it contains mostly rounded grains.

    d. It is immature because it contains mostly rounded grains.

    e. It is immature because it has clay-sized particles.

8. Sample 42: What does the formation of this rock include?

    a. chemical weathering, transport of ions, precipitation of minerals, lithification

    b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

    c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

    d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition, lithification

9. Sample 43: What is this rock called?

    a. Conglomerate

    b. Limestone

    c. Rock Salt

    d. Shale

    e. Sandstone

    f. Oolitic Limestone

    g. Breccia

    h. Chert

    i. Fossiliferous Limestone

10. Sample 43: Compared to Sample 41, how mature is this rock?

    a. more mature

    b. less mature

    c. same level of maturity

11. Sample 43: What does this rock consist of?

    a. fragments of calcite shells

    b. clay-sized sediments

    c. sand-sized sediments

    d. oolites

    e. calcite crystals

12. Sample 43: This rock can be easily recognized by which of the following properties?

    a. conchoidal fracturing

    b. shiny, crystalline appearance

    c. fissile appearance

    d. a sandpaper texture

    e. cubic appearance

13. Sample 44: What is this rock called?

    a. Conglomerate

    b. Limestone

    c. Rock Salt

    d. Shale

    e. Sandstone

    f. Oolitic Limestone

    g. Breccia

    h. Chert

    i. Fossiliferous Limestone

14. Sample 44: What is this an example of?

    a. Clastic Sedimentary Rock

    b. Biochemical Sedimentary Rock

    c. Chemical Sedimentary Rock

15. Sample 44: What does the history of the formation of this rock include?

    a. chemical weathering, transport of ions, precipitation of minerals, lithification

    b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

    c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

    d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition, lithification

16. Sample 45: What is this rock called?

    a. Conglomerate

    b. Limestone

    c. Rock Salt

    d. Shale

    e. Sandstone

    f. Oolitic Limestone

    g. Breccia

    h. Chert

    i. Fossiliferous Limestone

17. Sample 45: What is this an example of?

    a. Clastic Sedimentary Rock

b. Biochemical Sedimentary Rock

c. Chemical Sedimentary Rock

18. Sample 45: Closely examine the individual grains in this rock. Which of the following is true about its maturity?

a. It is immature because it is poorly sorted.

b. It is mature because it is poorly sorted.

c. It is mature because it contains mostly angular grains.

d. It is immature because it contains mostly angular grains.

e. It is immature because it has clay-sized particles.

19. Sample 45: What does the formation of this rock include?

a. chemical weathering, transport of ions, precipitation of minerals, lithification

b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition, lithification

20. Sample 46: What is this rock called?

a. Conglomerate

b. Limestone

c. Rock Salt

d. Shale

e. Sandstone

f. Oolitic Limestone

g. Breccia

h. Chert

i. Fossiliferous Limestone

21. Sample 46: What does the history of the formation of this rock include?

a. chemical weathering, transport of ions, precipitation of minerals, lithification

b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition, lithification

22. Sample 46: What is this rock composed of?

a. clastic sediments

b. microcrystalline calcite crystals

c. calcite concretions

d. microcrystalline quartz crystals

23. Sample 46: This rock can be easily recognized by which of the following properties?

a. conchoidal fracturing

b. shiny, crystalline appearance

c. fissile appearance

d. a sandpaper texture

e. cubic appearance

24. Sample 47: What is this rock called?

a. Conglomerate

b. Limestone

c. Rock Salt

d. Shale

 e. Sandstone

 f. Oolitic Limestone

 g. Breccia

 h. Chert

 i. Fossiliferous Limestone

25. Sample 47: What is this rock an example of?

 a. Clastic Sedimentary Rock

 b. Biochemical Sedimentary Rock

 c. Chemical Sedimentary Rock

26. Sample 47: What is this rock composed of?

 a. clastic sediments

 b. microcrystalline calcite crystals

 c. calcite concretions

 d. microcrystalline quartz crystals

27. Sample 47: Which of the following characteristic(s) does this rock have?

 a. contains aggregates of oolites

 b. salty taste and cubic cleavage

 c. contains fossil shells

 d. contains pebbles and finer sediments

 e. scratches glass and has conchoidal fracturing

28. Sample 48: What is this rock called?

 a. Conglomerate

 b. Limestone

 c. Rock Salt

 d. Shale

 e. Sandstone

 f. Oolitic Limestone

 g. Breccia

 h. Chert

 i. Fossiliferous Limestone

29. Sample 48: What is this rock composed of?

 a. clastic sediments

 b. microcrystalline calcite crystals

 c. calcite concretions

 d. microcrystalline quartz crystals

30. Sample 48: This rock can be easily recognized by which of the following properties?

 a. conchoidal fracturing

 b. shiny, crystalline appearance

 c. fissile appearance

 d. a sandpaper texture

 e. cubic appearance

31. Sample 48: What does the formation of this rock include?

 a. chemical weathering, transport of ions, precipitation of minerals, lithification

 b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification

 c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification

 d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition,

lithification

32. Sample 49: What is this rock called?

    a. Conglomerate
    b. Limestone
    c. Rock Salt
    d. Shale
    e. Sandstone
    f. Oolitic Limestone
    g. Breccia
    h. Chert
    i. Fossiliferous Limestone

33. Sample 49: What is this rock an example of?

    a. Clastic Sedimentary Rock
    b. Biochemical Sedimentary Rock
    c. Chemical Sedimentary Rock

34. Sample 49: This rock can be easily recognized by which of the following properties?

    a. conchoidal fracturing
    b. shiny, crystalline appearance
    c. fissile appearance
    d. a sandpaper texture
    e. cubic appearance

35. Sample 50: What is this rock called?

    a. Conglomerate
    b. Limestone
    c. Rock Salt
    d. Shale
    e. Sandstone
    f. Oolitic Limestone
    g. Breccia
    h. Chert
    i. Fossiliferous Limestone

36. Sample 50: What is this rock an example of?

    a. Clastic Sedimentary Rock
    b. Biochemical Sedimentary Rock
    c. Chemical Sedimentary Rock

37. Sample 50: This rock has which of the following characteristic(s)?

    a. contains aggregates of oolites
    b. salty taste and cubic cleavage
    c. contains fossil shells
    d. contains pebbles and finer sediments
    e. scratches glass and has conchoidal fracturing

38. Sample 50: What does the history of the formation of this rock include?

    a. chemical weathering, transport of ions, precipitation of minerals, lithification
    b. mechanical weathering, transport of sediment a long distance, deposition of sediment, lithification
    c. mechanical weathering, transport of sediment a very short distance, deposition of sediment, lithification
    d. chemical weathering, transport of ions, precipitation of minerals as shells by organisms, deposition,

lithification

PART V

CHAPTER 5. METAMORPHIC ROCKS

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 11 "Metamorphic Rocks" by Karen Tefend, CC BY-SA 4.0. [View source.](#)

5.1 INTRODUCTION

Metamorphic rocks form by the physical, and sometimes chemical, alteration of a pre-existing rock, whether it is igneous or sedimentary. In some cases, even metamorphic rocks can be altered into a completely different metamorphic rock. With igneous rocks forming from the melt produced by any rock type and a sedimentary rock forming from the weathered product of any rock type, the alteration of any rock to produce a metamorphic one completes the components of what is known as the rock cycle. Basically, the rocks we encounter today that we classify as either igneous, metamorphic, or sedimentary, could have belonged to a different rock classification in the past, as rocks are recycled throughout geologic time, driven by the motion of the tectonic plates. It is easy to see that increasing the temperature of a rock can produce magma, and that rocks on the surface of the earth can break up into sediment that can ultimately lithify into a sedimentary rock. But how can we alter a solid rock into a new rock, without melting it or making it become sediment?

All rocks are formed at certain temperatures and pressures on or more commonly, beneath the earth's surface, and these rocks are the most stable at the conditions under which they form. Therefore, changing the temperature and/or pressure conditions may lead to a different rock, one that changed in order to be stable under new external conditions. This new rock that forms in response to changes in its physical and chemical environment is called a metamorphic rock; **metamorphism** means to change form, and for rocks this means a recrystallization of minerals under subsolidus conditions (e.g. temperatures too low for melt production). A metamorphic change can also occur if the rock's composition is altered by hot, chemically reactive fluids, causing a change in the mineral content of the rock. To distinguish between the pre-existing rock and the new metamorphic one, the term **protolith** or parent rock is used to describe the pre-existing rock, and all metamorphic rocks have at least one protolith that has altered during metamorphism. In this chapter you will learn that all metamorphic rocks are identified by the mineral content and texture of the rock; for metamorphic rocks, texture refers to the orientation of the minerals in the rock, although crystal size does convey important information regarding the temperature conditions during metamorphism.

To summarize, metamorphism is the process by which a pre-existing rock (the protolith) is altered by a change in temperature, pressure, or by contact with chemically reactive fluids, or by any combination of these three parameters. The alteration process is a **recrystallization** event, where the initial rock's minerals (crystals) have changed size, shape, and/or composition in response to these new external conditions. The end result is a new metamorphic rock that has an altered appearance, sometimes strikingly different from what it used to look like before metamorphism occurred. The metamorphic rock you end up with is strongly dependent on the rock you started with before the metamorphic event. Of secondary importance is the agent of metamorphic change: was recrystallization due to increased temperature, pressure, or both, or were chemically reactive fluids involved? We must also consider how high the temperatures and pressures were, as metamorphism can occur in a range of temperature and pressure conditions. However, as mentioned in the preceding paragraph, metamorphism occurs under subsolidus conditions, meaning that elevated temperatures that promote the recrystallization of a rock are not high enough to cause melting.

5.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Correctly identify the metamorphic rocks and their distinguishing features
- Identify foliated metamorphic rocks, and the type of foliation
- Determine the grade of metamorphism based on foliation and possible index minerals
- Recognize metamorphic environments and types of metamorphism

5.1.2 Key Terms

- Chemical replacement
- Contact metamorphism
- Differential pressure
- Foliation
- Gneissic banding
- Hydrothermal metamorphism
- Index mineral
- Lineation
- Metamorphism
- Non-foliated
- Phyllitic foliation
- Protolith
- Recrystallization
- Regional metamorphism
- Schistose foliation
- Slaty cleavage
- Thermal metamorphism
- Thermodynamic metamorphism

Overview of Metamorphic Rocks

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 11 "Metamorphic Rocks" by Karen Tefend, CC BY-SA 4.0. [View source.](#) *Last edited: 28 Dec 2019*

5.2 AGENTS OF METAMORPHISM

5.2.1 Pressure

All rocks beneath the surface of the earth experience an increase in pressure due to the weight of the overlying sediment and rock layers, and with increasing depth there is a corresponding increase in pressure. This increased pressure does not necessarily cause a rock to become metamorphic, because this particular pressure is typically equal in all directions and is known as lithostatic pressure. Lithostatic pressure on rocks below the earth's surface may have a change in overall rock volume, but will not cause a change in the shape. An example of decreasing volume due to lithostatic pressure would be a closer packing of clasts and reduction of pore space within a clastic sedimentary rock. **Differential pressure** occurs when the pressure on a rock is unequal, and it can result in a significant change in the appearance of a rock. Figure 5.1 demonstrates how a mineral can change shape due to differential pressure, in this case with the greatest pressures from the top and bottom. Two initially rounded mineral grains (e.g. Figure 5.1A) within a sedimentary rock are experiencing the greatest amount of pressure at the contact between the grains (see red arrows in the figure), and the bonds linking the atoms in this grain will break. The atoms will migrate into the area of lesser pressure and reform a bond with other atoms in the mineral grain (e.g. Figure 5.1B). As a result, the grains have a flattened shape that is perpendicular to the direction of greatest pressure (e.g. Figure 5.1C).
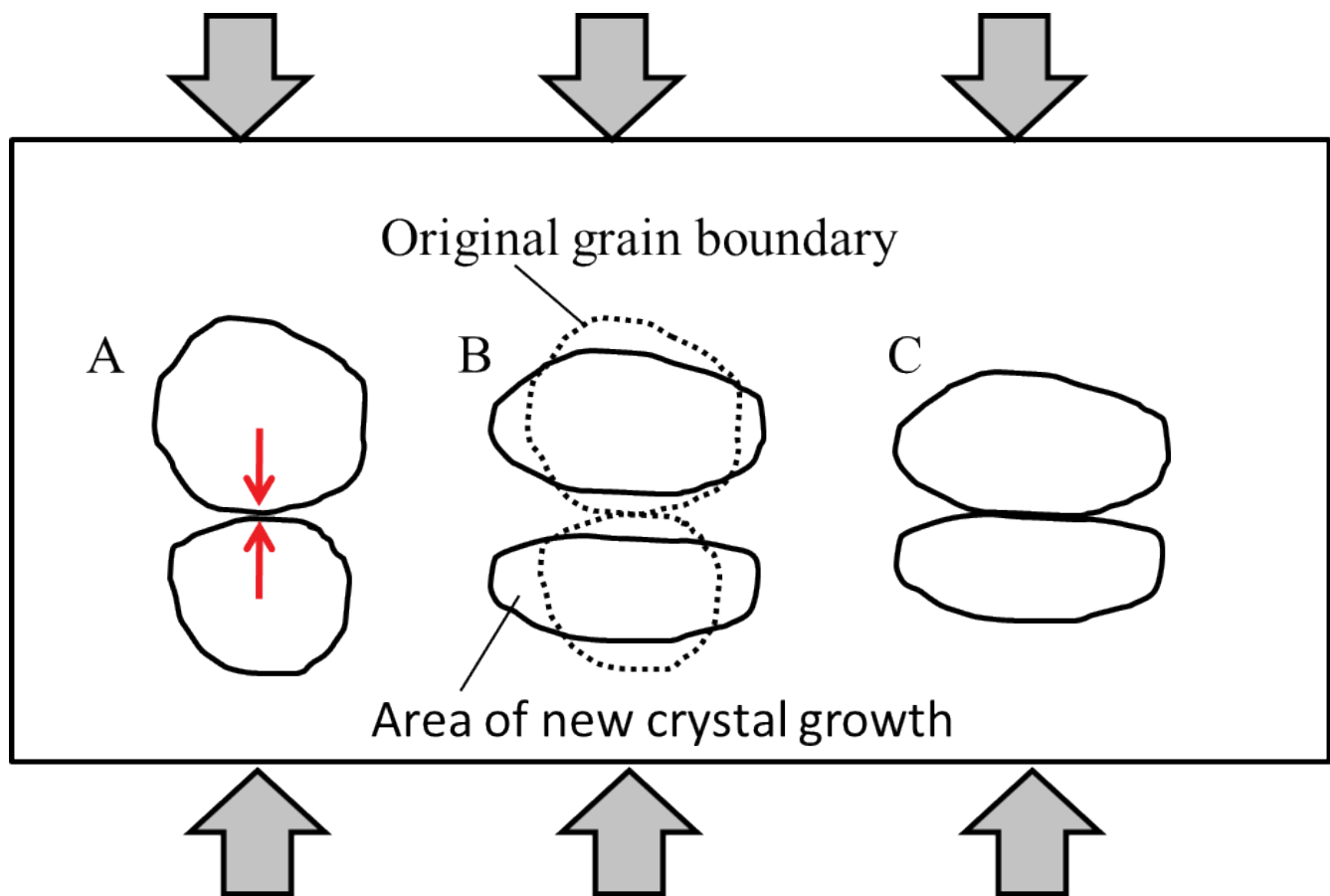
Figure 5.1 | *Example of mineral grain deformation due to differential pressure: A) Rounded grains experience the greatest pressure at the contact between the two grains due to the greatest applied pressure as indicated by the large gray arrows. B) The grains change shape by bonds breaking in the high pressure areas, and atoms migrate laterally into the lower pressure areas (the area of new crystal growth). C) The final shape of these two grains. Note that the grains are flattened perpendicular to the direction of greatest pressure.*
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

Figure 5.1 only shows the deformation of two grains; imagine that this is happening to all of the grains in the sedimentary rock, or to all of the phenocrysts (crystals) in an igneous rock. In that case, you will end up with the entire rock having minerals aligned in a certain direction, all by the breaking of bonds between atoms in a mineral, and reforming (recrystallizing) in the lower pressure areas among the grains or crystals in the rock. The end result is a rock with a metamorphic pattern called a **foliation**. Metamorphic foliations are the patterns seen in a rock that has experienced differential pressure; these foliations may be fairly flat, or have a wavy appearance possibly due to more than one direction of greatest pressure. Some rocks may also develop what is called a **lineation**, which can be formed by an elongation of minerals that form a linear feature through the rock. To understand the difference between a foliation and a lineation, let us use some food analogies: a stack of pancakes demonstrates a foliation in your breakfast food, with each pancake layer representing flattened minerals. If you look at the top of the pancakes, you will not see a pattern, but if you view the stack of pancakes from the side, or cut through the stack with your knife in any orientation other than parallel to the pancake layers, you will see the layering or foliation. However, if within that pancake stack, there existed a slice of bacon (yum), the bacon would be the lineation in your breakfast "rock", and you may or may not see it when you cut through the pancake stack. We will discuss foliations, and the different types of foliations, in a later section of this chapter.

5.2.2 Temperature

Probably the most common cause of metamorphism is a change in temperature. Often times metamorphism involves both an increase in temperature along with the pressure changes as described in the above section. Higher temperatures are often associated with metamorphism due to chemically reactive fluids. The broad classification for metamorphism into low, medium and high grades of metamorphic change exists mainly due to temperature conditions.

Higher temperatures increase the vibrational energy between the bonds linking atoms in the mineral structure, making it easier for bonds to be broken in order for the recrystallization of the minerals into new crystal shapes and sometimes the development of foliations and lineations as described in the previous section. However, recrystallization can be due to just temperature changes without any differential pressure conditions, and when temperatures are increased, there can be a corresponding increase in mineral sizes as initially small minerals become fused into larger crystals. This fusing of numerous smaller mineral sizes into fewer, yet larger, mineral sizes is known as annealing in metallurgy, but for metamorphic rocks it is still referred to as recrystallization.

In order to understand why increasing temperatures lead to increased grain sizes, we need to address stability. In general, a mineral grain or crystal is most stable when it has a low surface area to volume ratio; therefore, large grains are more stable than small grains, since increasing the grain size results in a greater increase in volume as opposed to a smaller increase in the surface area. Stability is important because it is the reason rocks undergo metamorphism. Rocks become unstable when their environment changes, and by a recrystallization processes (metamorphism), they can return to a stable form once again. Figure 5.2 demonstrates the recrystallization process in a sedimentary rock in response to elevated temperature. In this example, the original grains are smaller and rounded, but recrystallization resulted in larger grains that are interlocking; the pore spaces are gone and instead larger crystals exist.
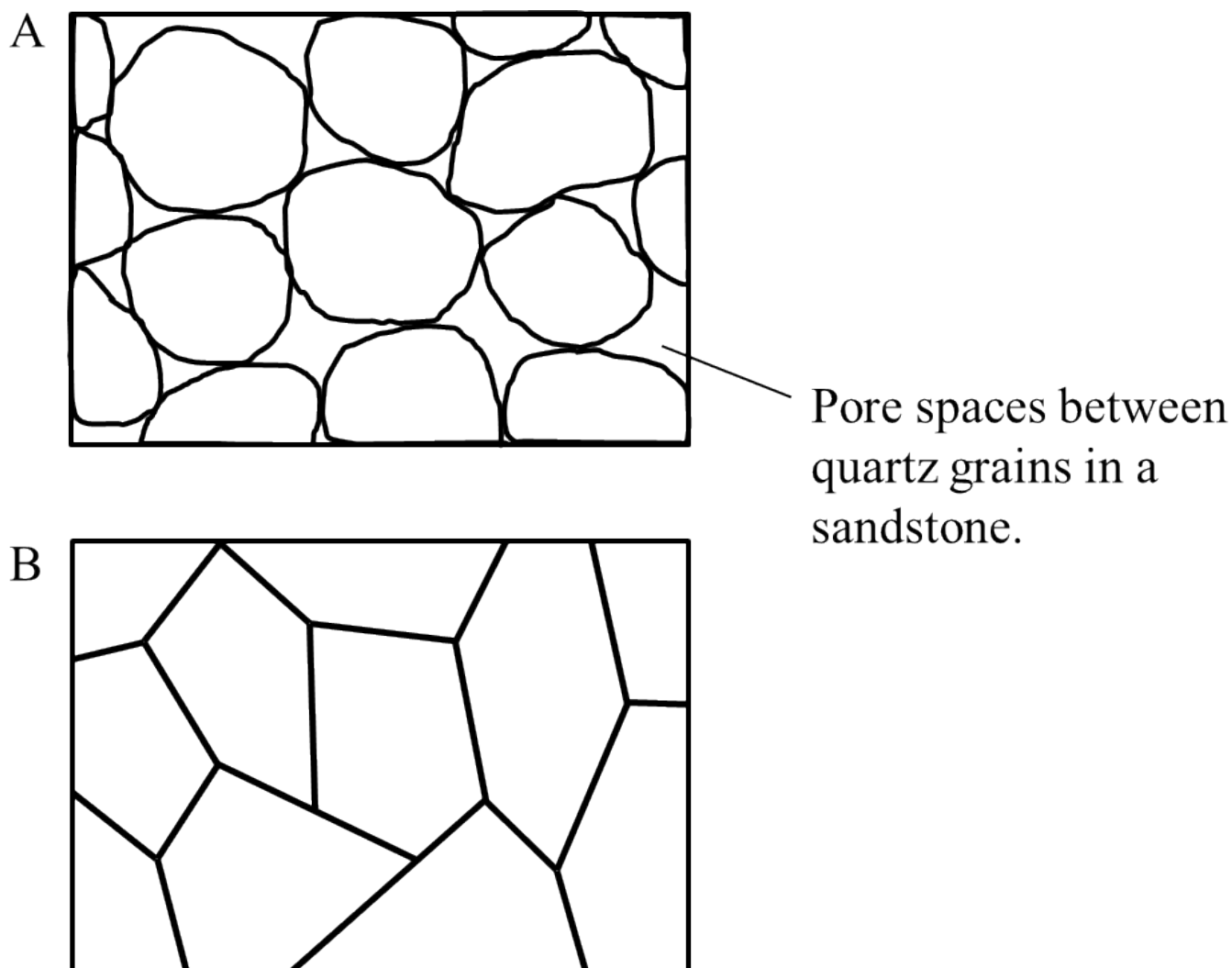
Figure 5.2 | *An example of the recrystallization of crystals into larger sizes due to increased temperature: A) a sedimentary rock with rounded quartz grains, and pore spaces between the grains. B) a metamorphic rock with larger, interlocking quartz crystals due to increased temperature conditions.*
Source: Karen Tefend (2015) CC BY-SA 3.0 *view source*

In addition to increased grain size with increased temperature, occasionally a new mineral forms during metamorphism. These new minerals form at certain temperatures and are called **index minerals**, which can be used to determine the temperature of metamorphism.

5.2.3 Chemically Reactive Fluids

The phrase chemically reactive refers to the dissolved ions in a fluid phase that may react with minerals in a rock; **chemical replacement** occurs when these ions take the place of some atoms in the mineral's structure, which may lead to a significant change in the rock's chemical composition. These fluids can be quite hot, especially if they are released from a nearby igneous intrusion. Metamorphism due to such fluids is known as **hydrothermal metamorphism**.

5.3 METAMORPHIC ROCK NAMES

5.3.1 Foliated Metamorphic Rocks

Differential pressures can cause a metamorphic pattern known as foliation to develop in metamorphosed rocks. There are a few types of foliations that are commonly seen in metamorphic rocks, each foliation type is dependent on the minerals that define the foliation. **Gneissic banding** (e.g. Figure 5.3) is defined as alternating dark and light mineral bands throughout the rock; the metamorphic rock with this type of foliation is called gneiss (pronounced "nice"). In Figure 5.3A, the layering in this gneiss is horizontal, and the greatest pressures were at right angles to the gneissic bands. Note that these bands are not always flat, but may be seen contorted as in Figure 5.3B; this rock still is considered to have gneissic banding even though the bands are not horizontal. The typical minerals seen in the dark coloured bands are biotite and/or amphiboles, whereas the light-coloured bands are typically quartz or light-coloured feldspars. The protoliths for gneiss can be any rock that contains more than one mineral, such as shale with its clay minerals and clay-sized quartz and feldspar, or an igneous rock with both dark-coloured ferromagnesian minerals and light-coloured non-ferromagnesian minerals (see Chapter 3 for review). In order for gneissic foliation to develop, temperatures and pressures need to be quite high; for this reason, gneiss rocks represent a high grade of metamorphism.

Figure 5.3 | *Two examples of the metamorphic rock, gneiss. Each rock exhibits the alternating dark and light mineral bands throughout the rock.*
Source: Karen Tefend (2015) CC BY-SA 3.0 [view source](#)

Another type of foliation is defined by the presence of flat or platy minerals, such as muscovite or biotite micas. Metamorphic rocks with a foliation pattern defined by the layering of platy minerals are called schist; the rock name is commonly modified to indicate what mica is present. For example, Figure 5.4 is a photo of a muscovite schist, with garnet present, so the correct name for this rock is a garnet muscovite schist. By convention, when naming a metamorphic rock the mineral in the lowest quantity is mentioned first. The muscovite micas define a very wavy foliation in the rock; this textural pattern of wavy micas is called a **schistose foliation** (e.g. Figure 5.4B). Shale is usually the protolith for schist; during metamorphism, the very tiny clay minerals in shale recrystallize into micas that are large enough to see unaided. Temperatures and pressures necessary for schistose foliation are not as high as those for gneiss; therefore schists represent an intermediate grade of metamorphism.
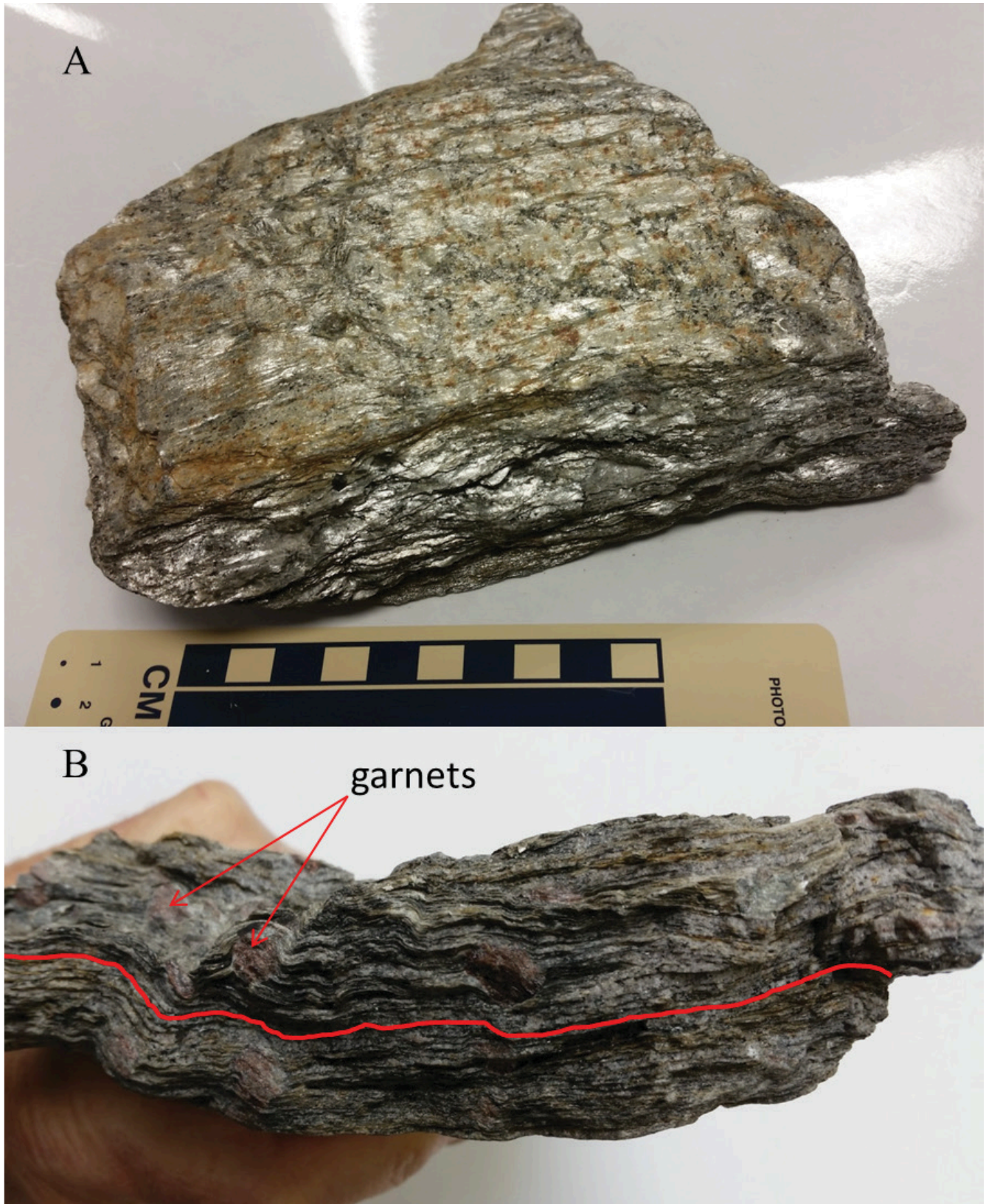
Figure 5.4 | *Photo of a garnet muscovite schist. A) The muscovite micas are large enough to be seen as very shiny minerals in the top photograph. B) Side view of the schist shows the distinctive wavy foliation made by the platy micas. This metamorphic rock also contains the index mineral, garnet.*
Source: Karen Tefend (2015) CC BY-SA 3.0 *view source*

Another metamorphic rock is called phyllite, which is made up of fine crystals that give the rock a shiny appearance. This rock displays **phyllitic foliation**, which has good, sometimes wrinkled or folded, cleavage. Phyllites are generally formed from a shale protolith, with the clay minerals in the shale aligning and recrystallizing as small mica minerals. This foliation was formed under temperatures and pressures less than those for schist and represents a low to intermediate grade of metamorphism.

The next type of foliation is only seen in the metamorphic rock called slate, which forms by the low temperature and pressure alteration of a shale protolith. The clay sized minerals in the shale recrystallize into very tiny micas, which are larger than the clay minerals, but still too small to be visible. The alignment of these micas control how the slate breaks, and it tends to break parallel to the mica alignment. Since we are unable to see the aligned micas, we can use the alignment of the rock fracture pattern to define the foliation, as the rock is cleaved or split. This is called **slaty cleavage**, and a rock displaying this foliation type is called a slate. Figure 5.5 is an example of the foliated slate displaying slaty cleavage; notice that this rock has retained its original sedimentary layering, which is quite different from the foliation direction. Slate is an example of a low grade metamorphic rock, as the original sedimentary features and, occasionally, fossils may be preserved due to the low temperatures and pressures barely altering the shale protolith.

Figure 5.5 | *Slaty cleavage in the metamorphic rock, slate. The alignment of very tiny micas controls how this rock breaks or cleaves. Note the banded appearance on the top of this rock, which is the depositional layering of the original rock, shale.*
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

5.3.1 Non-Foliated Metamorphic Rocks

The other class of metamorphic rocks is **non-foliated**; the lack of foliation may be due to a lack of differential pressure involved in the metamorphic process; however, this is not necessarily the case for all non-foliated metamorphic rocks.

If the protolith rock is only composed of one mineral type, such as limestone or a sandstone with only quartz sands, then a foliation will not develop, even with differential pressure. The calcite mineral in limestone and the quartz sands in sandstone are neither platy minerals, nor are there different coloured minerals in these rocks. The calcite and quartz minerals recrystallize into equigranular, coarse crystals (e.g. Figure 5.2B), and the metamorphic rocks that they make are named by their composition, not by foliation type. For example, Figure 5.6 is quartzite, a metamorphosed quartz-rich sandstone, while Figure 5.7 shows two examples of marble; note that colour can vary for both marble and quartzite. Quartzite and marble may be hard to identify based on appearance, therefore, you must rely on the properties of the minerals that comprise these rocks; you may recall that quartz is harder than glass, while limestone is softer than glass. If you zoom in for a close view of the marble in Figure 5.7, you will see the calcite crystals are fairly large compared to the quartz crystals in the quartzite in Figure 5.6; this can be attributed to the temperature of metamorphism, as higher temperatures result in larger crystals.

Figure 5.6 | An example of quartzite; a non-foliated metamorphic rock. Quartzite can appear in a variety of colours, but most are fairly light in colour.
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

Figure 5.7 | *Examples of the non-foliated rock, marble. The pink and white colours are common, however some marbles are darker in colour, and others may be white with dark gray markings (like the famous Carrara marble from Italy).*
Source: Karen Tefend (2015) CC BY-SA 3.0 [*view source*](#)

In order to identify and name metamorphic rocks, a logical first step would be to examine the rock for evidence of any pattern or foliation, and if present, identify which minerals are making the foliation pattern. Non-foliated metamorphic rocks can be identified by the properties defined by their mineral composition. Below is a table summarizing the metamorphic rock types, foliation names, and protolith rock types.

Texture		Characteristics	Protolith	Metamorphic Rock Name	
Foliated	Increasing Temperature & Pressure	Very fine-grained rock, tends to split in parallel fragments (known as slaty cleavage)	Shale	**Slate**	
		Fine-grained rock, with the grains only visible as a satin sheen. Similar to slate, but with a satin lustre and may have wrinkled cleavage	Shale	**Phyllite**	
		Contains shiny muscovite (light) or biotite (dark) micas, may see other minerals, such as quartz, talc, garnet (note arrow), and amphibole. Has schistose pattern of foliation	Shale	**Schist**	
		Contains alternating bands of light- and dark-coloured minerals (usually biotite or amphibole), called gneissic banding	Shale or Igneous Rock	**Gneiss**	
Non-foliated		Equigranular grains of quartz, which has a hardness of 7	Sandstone or Siltstone	**Quartzite**	
		Equigranular grains of calcite, which has a hardness of 4, reacts freely with dilute HCl	Limestone	**Marble**	

Table 5.1|| Summary chart of metamorphic rocks discussed in this chapter, including the names of some of the possible sedimentary rock and igneous rock protoliths for each metamorphic rock. A metamorphic rock can also be a protolith (e.g. a slate can be a protolith for a schist).
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0 after Karen Tefend (2015) CC BY-SA 3.0 *view source*

5.4 TYPES OF METAMORPHISM

5.4.1 Regional Metamorphism

Metamorphism that affects entire rock bodies over a broad region is referred to as **regional metamorphism**. There is a wide range of conditions in temperature and pressure that produce a wide range of metamorphic rock types; for example, all of the foliated rocks fall into this metamorphic category and some non-foliated rocks as well. The main point is that a large area is affected by changes in temperature and/or pressure. One type of regional metamorphism occurs at convergent plate boundaries, where rocks are subjected to a variety of pressures and temperatures, resulting in a **thermodynamic metamorphism** ("thermo-" for increased temperature, and "dynamic" for increased pressure). Mountain ranges that form by the converging of tectonic plates are classic examples of thermodynamic metamorphism. Regional metamorphism also occurs along plate boundaries where an oceanic plate descends (subducts) back into the mantle as a result of plate convergence; oceanic plates that subduct into the mantle will form a deep ocean trench, such as the trench along the western margin of South America. With increased pressure in these regions metamorphic foliations can get quite pronounced, as we saw in the development of slate to schist to gneiss; with increased temperature we see increases in grain size as well as the introduction of new minerals in the metamorphosed rock.

5.4.2 Contact Metamorphism

As mentioned previously, recrystallization due to increased temperature results in the formation of larger minerals, or sometimes in the formation of new minerals (Figure 5.11). **Contact metamorphism** describes the type of metamorphism attributed to increased temperature, usually from proximity to a heat source such as an intrusive magma body or a lava flow, and the rock undergoes a **thermal metamorphism**. The rocks that are in closer contact to the magma will form larger crystals due to the higher heat. Rocks that are in contact with hot, chemically reactive fluids can also fall within the contact metamorphism category; recrystallization due to this type of contact is called **hydrothermal metamorphism**. Unlike the regional metamorphism described in the previous section, both types of contact metamorphism are confided to smaller areas near the heat source (magma, lava, or hydrothermal fluids). Since differential pressures are not involved, contact metamorphism results in the formation of non-foliated rocks. The non-foliated rock types that were covered previously included marble, quartzite, amphibolite, and anthracite coal.

1. Exercises on Metamorphic Rocks

Adapted by Lyndsay R. Hauber & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 11 "Metamorphic Rocks" by Karen Tefend, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

Note: much of the overview material for this chapter is replicated in this exercise section for your reference as you complete the lab. **You will NOT have access to your lab book or notes for the rock and mineral exam!**

Your name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Your TAs will check that you have completed the questions at the end of the lab. Please hold on to your lab notes to help you prepare for the rock and mineral quiz and your lab final exam.

5.3   METAMORPHIC ROCK NAMES

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Figure 5.3 | *Two examples of the metamorphic rock, gneiss. Each rock exhibits the alternating dark and light mineral bands throughout the rock.*
Source: Karen Tefend (2015) CC BY-SA 3.0 *view source*

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		Fine-grained rock, with the grains only visible as a satin sheen. Similar to slate, but with a satin lustre and may have wrinkled cleavage	Shale	**Phyllite**
		Contains shiny muscovite (light) or biotite (dark) micas, may see other minerals, such as quartz, talc, garnet (note arrow), and amphibole. Has schistose pattern of foliation	Shale	**Schist**
		Contains alternating bands of light- and dark-coloured minerals (usually biotite or amphibole), called gneissic banding	Shale or Igneous Rock	**Gneiss**
Non-foliated		Equigranular grains of quartz, which has a hardness of 7	Sandstone or Siltstone	**Quartzite**
		Equigranular grains of calcite, which has a hardness of 4, reacts freely with dilute HCl	Limestone	**Marble**

Table 5.1 | *Summary chart of metamorphic rocks discussed in this chapter, including the names of some of the possible sedimentary rock and igneous rock protoliths for each metamorphic rock. A metamorphic rock can also be a protolith (e.g. a slate can be a protolith for a schist).*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0 after Karen Tefend (2015) CC BY-SA 3.0 *view source*

5.4 LAB EXERCISES – METAMORPHIC ROCK IDENTIFICATION

In the sedimentary lab exercise, you had previously obtained the 10 metamorphic rock samples from the drawer provided by your TA; they are numbered 51-60. It is recommended that you have your glass plate, streak plate, and magnifying glass readily available.

Fill in chart 5-E1 as you work through the lab, similar to the charts you completed in the previous labs. You do not have to fill out every column for every rock – just follow along in the lab and determine the properties you are asked about. Work through the following questions, they will help guide you in learning the properties and characteristics of the rocks in this lab.

Sample #	Texture	Minerals Present	Other Properties (metamorphic grade, protolith, hardness, etc.)	Name

Table 5-E1 | *Metamorphic Rock Notation Chart – Download and fill in this chart as you work through the lab, similar to the charts you completed in the previous labs. You do not have to fill out every column for every rock – just follow along in the lab and determine the properties you are asked about. Source: Lyndsay Hauber (2018) CC BY 4.0*

1. Sample 51: This rock has which texture?

    a. slaty cleavage
    b. schistose foliation
    c. gneissic banding
    d. phyllitic foliation
    e. non-foliated

2. Sample 51: What is this rock called?

    a. marble
    b. quartzite
    c. schist
    d. slate
    e. gneiss
    f. phyllite

3. Sample 52: This rock has which texture?

    a. slaty cleavage
    b. schistose foliation
    c. gneissic banding
    d. phyllitic foliation
    e. non-foliated

4. Sample 52: What is this rock called?

    a. marble

    b. quartzite

    c. schist

    d. slate

    e. gneiss

    f. phyllite

5. Sample 52: What kind of mineral crystals does this rock mainly contain?

    a. biotite

    b. amphibole

    c. muscovite

    d. calcite

    e. quartz

6. Sample 52: What is this rock an example of?

    a. high grade of metamorphism

    b. intermediate grade of metamorphism

    c. low grade of metamorphism

    d. any of the above

7. Sample 53: This rock has which texture?

    a. slaty cleavage

    b. schistose foliation

    c. gneissic banding

    d. phyllitic foliation

    e. non-foliated

8. Sample 53: What is this rock called?

    a. marble

    b. quartzite

    c. schist

    d. slate

    e. gneiss

    f. phyllite

9. Sample 53: What is a possible protolith for this rock?

    a. basalt

    b. granite

    c. sandstone

    d. limestone

    e. shale

10. Sample 54: This rock has which texture?

    a. slaty cleavage

    b. schistose foliation

    c. gneissic banding

    d. phyllitic foliation

    e. non-foliated

11. Sample 54: What is this rock called?

    a. marble

    b. quartzite

    c. schist

    d. slate

    e. gneiss

    f. phyllite

12. Sample 54: What are the dark minerals in this rock?

    a. flat biotite micas

    b. tabular amphiboles

    c. flat muscovite micas

    d. tabular feldspars

13. Sample 54: What is a possible protolith for this rock?

    a. an ultramafic rock

    b. basalt

    c. limestone

    d. granite

    e. sandstone

14. Sample 55: This rock has which texture?

    a. slaty cleavage

    b. schistose foliation

    c. gneissic banding

    d. phyllitic foliation

    e. non-foliated

15. Sample 55: What is this rock called?

    a. marble

    b. quartzite

    c. schist

    d. slate

    e. gneiss

    f. phyllite

16. Sample 55: What mineral is this rock mainly composed of ?

    a. biotite

    b. amphibole

    c. muscovite

    d. calcite

    e. quartz

17. Sample 55: What is a possible protolith for this rock?

    a. basalt

    b. granite

    c. sandstone

    d. limestone

    e. shale

18. Sample 56: This rock has which texture?

    a. slaty cleavage

    b. schistose foliation

    c. gneissic banding

    d. phyllitic foliation

    e. non-foliated

19. Sample 56: What is this rock called?

a. marble
b. quartzite
c. schist
d. slate
e. gneiss
f. phyllite

20. Sample 56: What is a possible protolith for this rock?

    a. basalt clay
    b. sandstone
    c. rhyolite
    d. shale

21. Sample 57: This rock has which texture?

    a. slaty cleavage
    b. schistose foliation
    c. gneissic banding
    d. phyllitic foliation
    e. non-foliated

22. Sample 57: What is this rock called?

    a. marble quartzite
    b. schist
    c. slate
    d. gneiss
    e. phyllite

23. Sample 58: This rock has which texture?

    a. slaty cleavage
    b. schistose foliation
    c. gneissic banding
    d. phyllitic foliation
    e. non-foliated

24. Sample 58: What is this rock called?

    a. marble
    b. quartzite
    c. schist
    d. slate
    e. gneiss
    f. phyllite

25. Sample 58: What is this rock an example of?

    a. high grade of metamorphism
    b. intermediate grade of metamorphism
    c. low grade of metamorphism
    d. any of the above

26. Sample 59: This rock has which texture?

    a. slaty cleavage
    b. schistose foliation
    c. gneissic banding
    d. phyllitic foliation

    e.   non-foliated

27. Sample 59: What is this rock called?

    a.   marble

    b.   quartzite

    c.   schist

    d.   slate

    e.   gneiss

    f.   phyllite

28. Sample 59: What mineral is this rock mainly composed of?

    a.   biotite

    b.   amphibole

    c.   muscovite

    d.   calcite

    e.   quartz

29. Sample 59: What is this rock an example of?

    a.   high grade of metamorphism

    b.   intermediate grade of metamorphism

    c.   low grade of metamorphism

    d.   any of the above

30. Sample 60: This rock has which texture?

    a.   slaty cleavage

    b.   schistose foliation

    c.   gneissic banding

    d.   phyllitic foliation

    e.   non-foliated

31. Sample 60: What is this rock called:

    a.   marble

    b.   quartzite

    c.   schist

    d.   slate

    e.   gneiss

    f.   phyllite

32. Sample 60: What is a possible protolith for this rock?

    a.   basalt

    b.   granite

    c.   sandstone

    d.   limestone

    e.   shale

CHAPTER 6. RELATIVE AND ABSOLUTE DATING

6. Relative and Absolute Dating

Adapted by Sean W. Lacey & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 1 "Relative and Absolute Dating" by Bradley Deline, CC BY-SA 4.0. [View Source](#).

6.1 INTRODUCTION

To develop a history of how geologic events have acted on the Earth through time, we need to understand what and when geological processes have occurred through Earth's history. Geologists learn about *what* processes occur on Earth through studying the rock record and observing geologic processes in modern environments. To understand *when* these processes have acted during Earth's geologic time, geologists make observations about the relationships of rocks to one another in the rock record, using a process called **relative dating**. Geologists use this information to construct models for how these relationships developed. For example, if the rock record in an area contains sedimentary rocks that are folded, a model to explain those relationships would start with a region where sediments were deposited, followed by lithification of the sediments to form rock, then the rocks would be subjected to tectonic pressures that folded the rocks. Using relative dating techniques, we know those events occurred in that order, but not when they occurred precisely in time. To add specific dates for the events in the model, geologists can use **absolute dating** techniques to **date** the rocks (determine their age). Geologists develop models such as this at locations all across Canada, North America, and around the globe. Each location geologists study may only provide information on Earth history from a short window in time; collectively, however, the information in these models can be used to develop our understanding of processes that have acted on Earth since it first formed.

In this chapter, you will learn about how to determine the relative ages of rocks and calculate the absolute ages of rocks.

6.1.2 Learning Outcomes

After completing this chapter, you should be able to:
• Discuss the importance of time in the study of geology
• Discuss the difference between relative dates and absolute dates
• Apply geologic laws and stratigraphic principles in the relative dating of geologic events
• Use radiometric dating data and calculations to determine the absolute date of rock units

6.1.3 Key Terms

- Absolute dating
- Angular unconformity
- Radiometric (Carbon-14) dating
- Daughter atom

- Disconformity
- Geologic laws and stratigraphic principles
- Geologic time scale
- Half-life
- Isotope
- Law of superposition
- Nonconformity
- Principle of cross-cutting relationships
- Principle of faunal succession
- Principle of original horizontality
- Principle of lateral continuity
- Parent atom
- Potassium-Argon (K-Ar) dating
- Radiometric dating
- Relative dating
- Unconformity
- Uranium-Lead (U-Pb) dating

Overview of Relative and Absolute Dating

Adapted by Sean W. Lacey & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 1 "Relative and Absolute Dating" by Bradley Deline, CC BY-SA 4.0. [View Source](#).

6.2 Geologic Time

The methods that geologists use to establish relative time scales are based on geologic laws and principles. A scientific law is something that we understand and is proven, and a principle is a guide we use to help us evaluate a system. Geologic laws and principles are generally easy to understand and simple. Geologists use stratigraphic principles – rules that help us interpret relationships between rocks – to describe and interpret relationships between layers and types of rock and determine the relative ages of rocks and geologic events (i.e., the order in which they formed or occurred).

To provide context for the stratigraphic principles, we'll begin this section with a review of the different rock types. Sedimentary rocks (e.g., sandstone) are made from broken pieces of other rock that are eroded in the high areas of the earth and transported by wind, ice, and water to lower areas where they are deposited. Igneous rocks form through cooling and crystallizing of molten rock. Metamorphic rocks form when heat and pressure cause recrystallization within rocks, which can alter the mineralogy and/or texture. This distinction is important because these three rock types are formed differently and therefore, the events that lead to their formation are interpreted differently when assessing the rock record using geologic laws and principles.

To interpret stratigraphic relationships between **geological units** (types and layers of rock), geologists use **geologic cross-section diagrams** (e.g., Figure 6.1). These are drawings that illustrate the relationships between rocks if you cut into the earth and look at the layers of rock below the surface. A useful analogy for a cross-section is a piece of layered cake: if you cut a piece of the cake and remove it, viewed from the side you will see the top layer of icing, the cake layer beneath it, and then layers of filling and cake alternating as you go deeper into the cake (moving down the slice from the surface at the top of the cake). Geologists use data including maps based on rock outcrops at the surface, cores drilled from the rock, and geophysical data (e.g., seismic data) to help construct cross-sections.

There are 7 stratigraphic principles that geologists use to relatively date rock units:

- law of superposition
- principle of original horizontality
- principle of lateral continuity
- principle of cross-cutting relationships
- principle of unconformities
- principle of inclusions
- principle of faunal succession

The **law of superposition** states that in an undeformed sequence of sedimentary rocks the oldest rocks will be at the bottom of the sequence while the youngest will be on top. Imagine a river carrying sand into an ocean, the sand will spill out and come to rest on top of the seafloor. This sand was deposited after the sand of the seafloor was already deposited, so it is deposited above the seafloor sediments. Over time, more layers can be deposited on top of the sand as sediments are carried into the ocean by rivers and deposited. We can then create a relative time scale of rock layers from the oldest rocks at the bottom (labeled#1 in Figure 6.1) to the youngest at the top of an outcrop (labeled #7 in Figure 6.1).
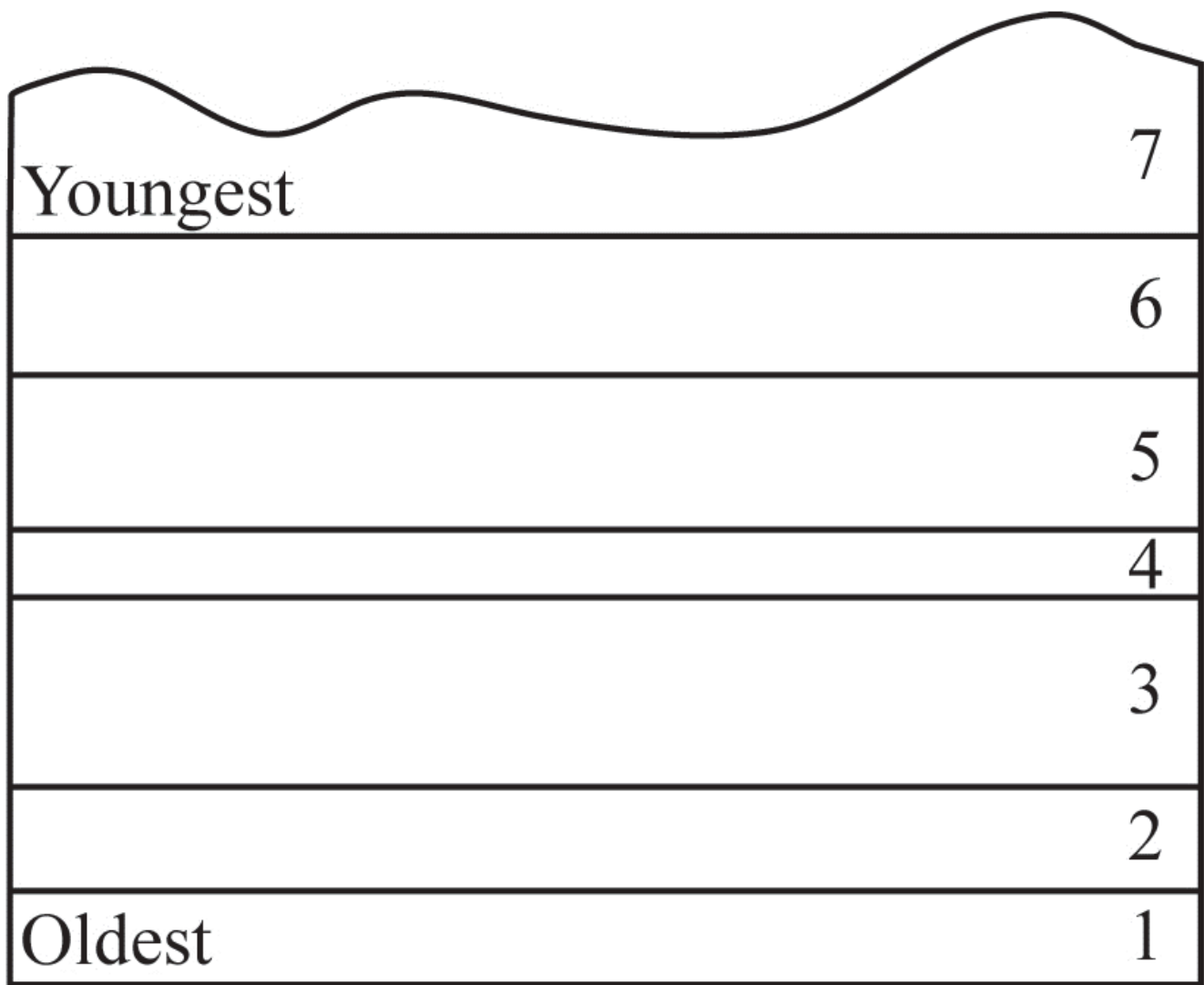
Figure 6.1 | *This block diagram shows the relative age of sedimentary layers based on the Law of Superposition.*
Source: Bradley Deline (2015) CC BY-SA 3.0 view source

The principle of **original horizontality** states that undeformed sedimentary rock are deposited horizontally. The deposition of sediment is controlled by gravity and will pull it downward. If you have muddy water on a slope, the water will flow down the slope and pool flat at the base rather than depositing on the slope itself. This means that if we see sedimentary rock that is tilted or folded it was first deposited flat, then folded or tilted afterward (Figure 6.2).

Uplift and tilting
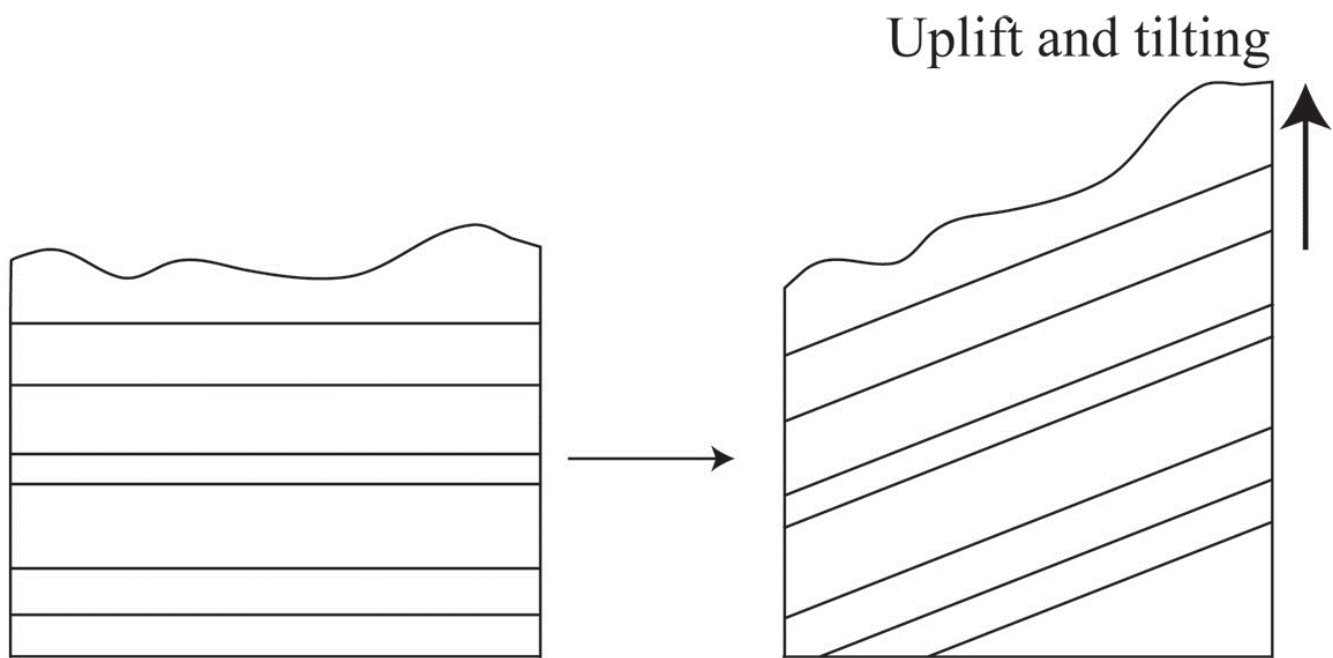
Figure 6.2 | *The principle of original horizontality states sedimentary rocks are deposited horizontally, so if the sedimentary layers are tilted or folded this must have occurred following deposition.*
Source: Bradley Deline (2015) CC BY-SA 3.0 *view source*

Sedimentary rock are generally deposited continuously in all directions. Sometimes erosion can lead to lateral gaps forming in layers of the rock. For example, when a stream erodes through a rock layer. The **principle of lateral continuity** states that even though the rocks are separated from one another by a gap, they were originally part of the same unit (layer) of rock.

The **principle of cross-cutting relationships** states that when two geologic features intersect, the one that cuts across the other is younger. In essence, a feature has to be present before something can affect it. For example, if a fault fractures through a series of sedimentary rocks those sedimentary rocks must be older than the fault (Figure 6.3).
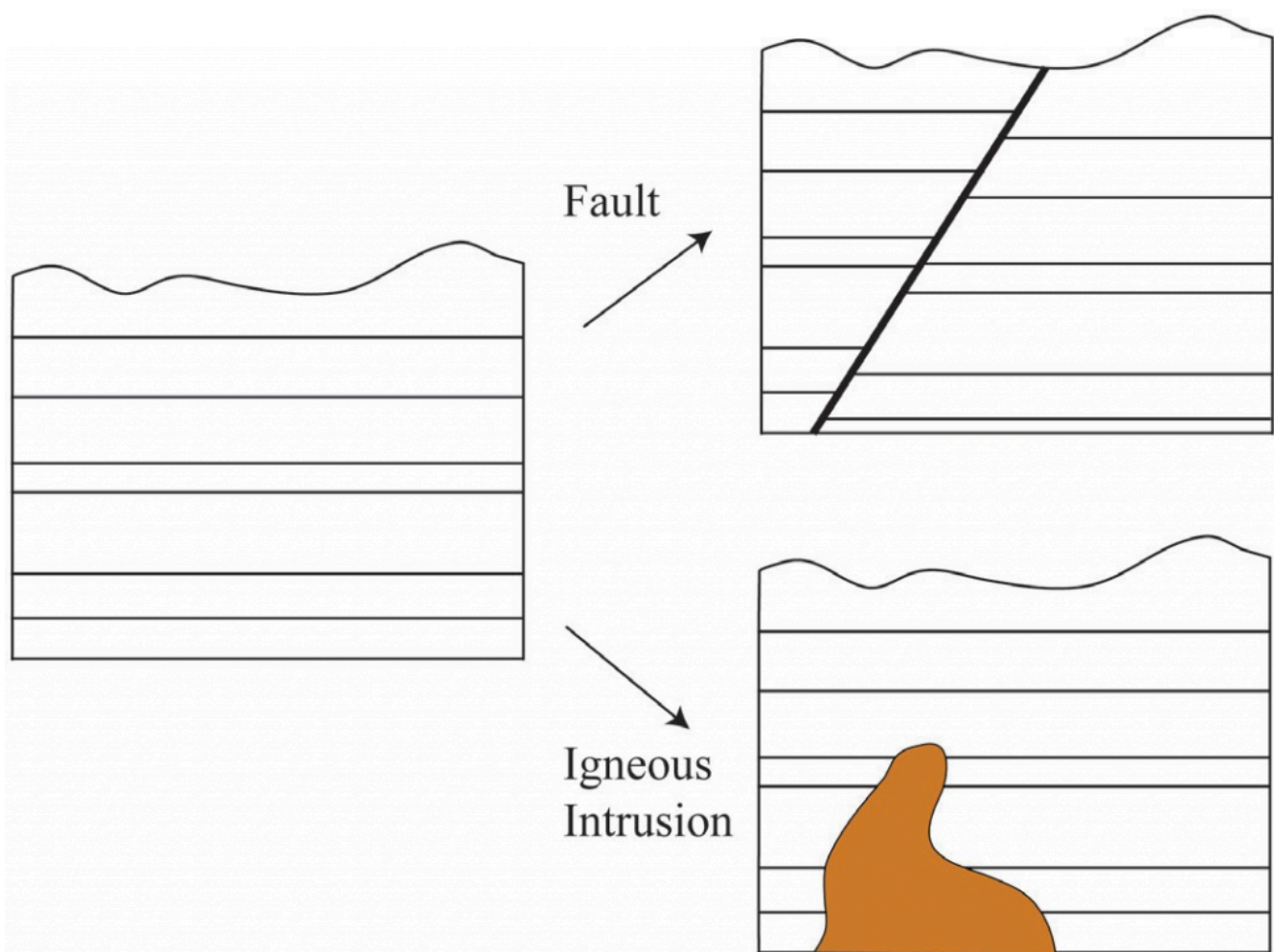
Figure 6.3 | *Block diagrams showing the law of cross-cutting relationships. In both instances on the right the geological features (fault or igneous intrusion) cuts across the sedimentary layers and must then be younger.*
Source: Bradley Deline (2015) CC BY-SA 3.0 *view source*

In geology, rocks that are missing are sometimes as important as rocks that still exist in the rock record; what is missing is very important for building a complete geologic history! **Unconformities** are surfaces that represent significant weathering and erosion (the breakdown of rock and movement of sediment) which result in missing or erased time in the rock record. Erosion often occurs in elevated areas like continents or mountains. **Uplift**, which often occurs when rocks are pushed up by tectonic activity, results in erosion. This will destroy a part of the rock record sequence. Much older rocks are then exposed at the earth's surface, with a gap where the younger rocks were previously. If the area sinks (called **subsidence**), then much younger rocks will be deposited on top of these exposed rocks. The amount of time missing can be relatively short or may represent billions of years.

There are three types of unconformities based on the types of rocks present above and below the unconformity (Figure 6.4)**.** A n**onconformity** is an unconformity where the rock type is different above and below the unconformity (Figure 6.4). For example, if uplifted intrusive igneous rocks are exposed at the surface and then covered with sedimentary rock, the boundary between the two rock types is a nonconformity. If the rocks above and below the erosion surface are both sedimentary, then the orientation of the layers is important. If the rocks below the erosion surface are not parallel with those above, the surface is called an **angular unconformity** (Figure 6.4). This is often the result of the rocks below

being tilted or folded prior to the erosion and deposition of the younger rocks. If the rocks above and below the erosion surface are parallel, the surface is called a **disconformity**. This type of surface is often difficult to detect, but can often be recognized using other information such as the fossils discussed in the next section. Paraconformity is a term used to describe a disconformity where the unconformity surface is very difficult to detect and can only be detected using absolute dating techniques (e.g., radiometric dating of zircons).

Nonconformity

Intrusion of igneous rock into sedimentary rocks
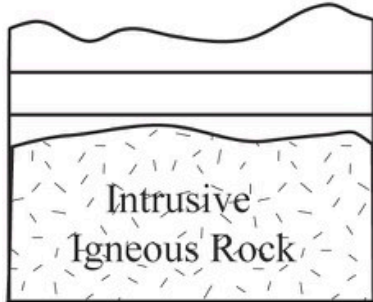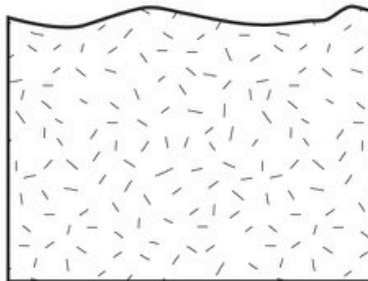
Uplift and erosion

Subsidence and deposition
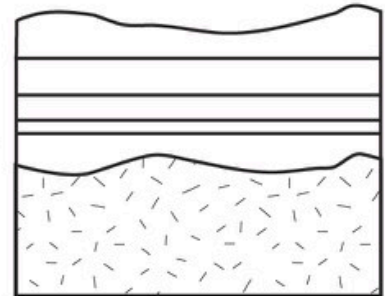
Angular Unconformity

Deposition of sedimentary rocks
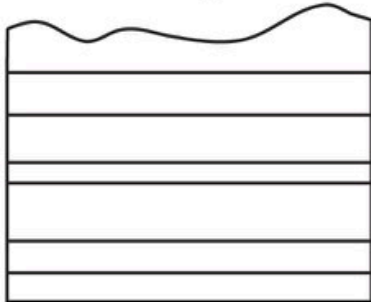
Uplift, tilting, and erosion
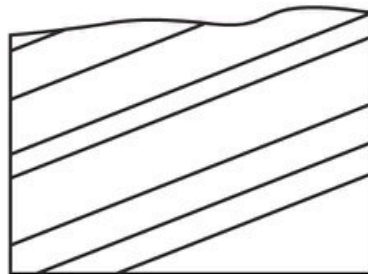
Subsidence and deposition
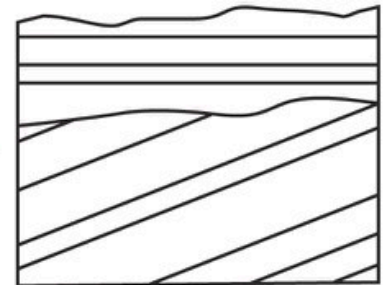
Disconformity

Deposition of sedimentary rocks
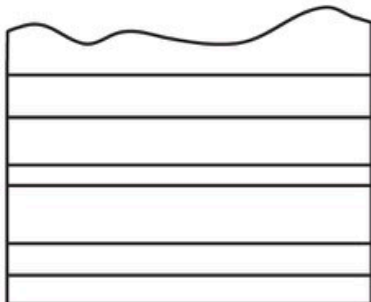
Uplift and erosion
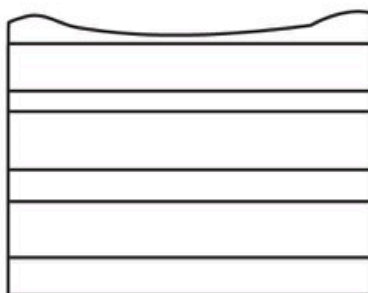
Subsidence and deposition
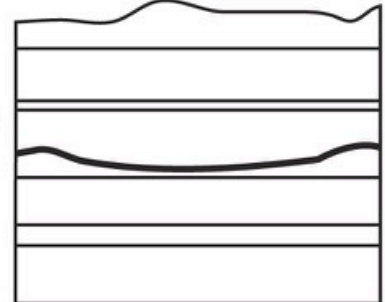
Figure 6.4 | *Block diagrams showing the formation of the three types of Unconformities. The three unconformities differ based on the type of rock underneath the erosion surface.*
Source: Bradley Deline (2015) CC BY-SA 3.0 *view source*

There are two other stratigraphic principles to be aware of, though we won't practice applying these two principles in the lab exercises for this chapter. The p**rinciple of inclusions** states that if inclusions (pieces of rock) are found within a rock formation, those inclusions must be older than the formation they are included within. For example, conglomerates are sedimentary rocks with gravel or cobble sized stones cemented together; the stones within the conglomerate are composed of rock that are older than the conglomerate. The **principle of faunal succession** is a stratigraphic principle where geologists use fossils in the rock to help interpret the relative ages of the rock.

We can use these principles to determine the relative ages of a series of rocks in a geologic cross-section. We can also use this information to create a hypothesis about the series of geologic events that created and affected the rocks in the cross-section through time. Common events that are often preserved as evidence in the rock record include: (1) deposition of sedimentary layers, (2) tilting or folding of rocks, (3) uplift and erosion of rocks, (4) intrusion of magma that solidifies into intrusive igneous rocks, and (5) fracturing of rock (faulting). Figures 6.5 and 6.6 show how to piece together a series of geologic events using relative dating.
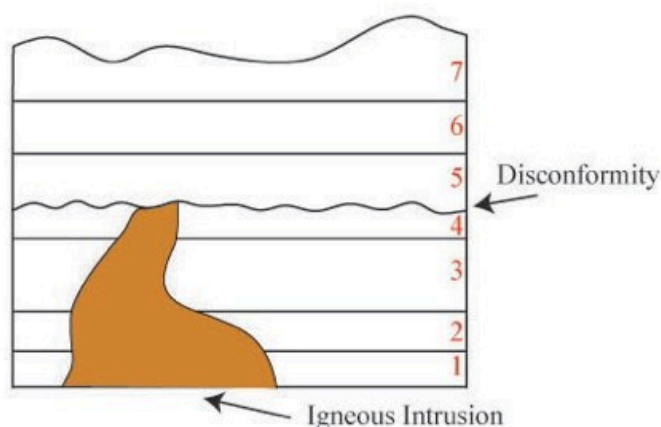

Figure 6.5 | *An example showing how to determine a relative dating sequence of events from a block diagram.*
Source: Bradley Deline (2015) CC BY-SA 3.0 *view source*
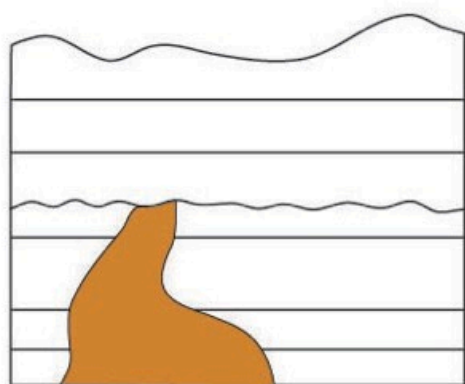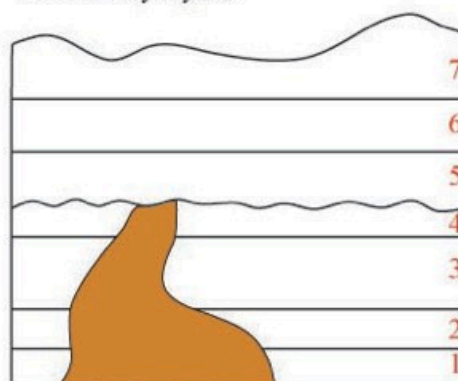
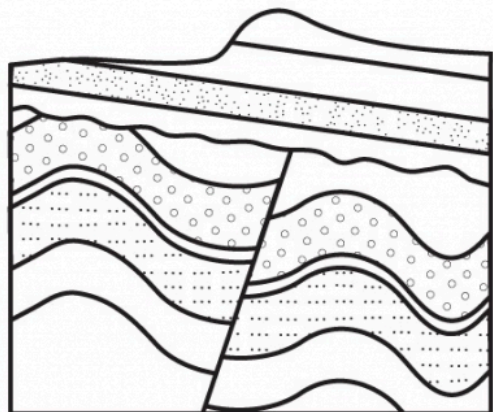Step 2. Identify any other geologic events

Tilting

Angular Unconformity

Folding

Faulting
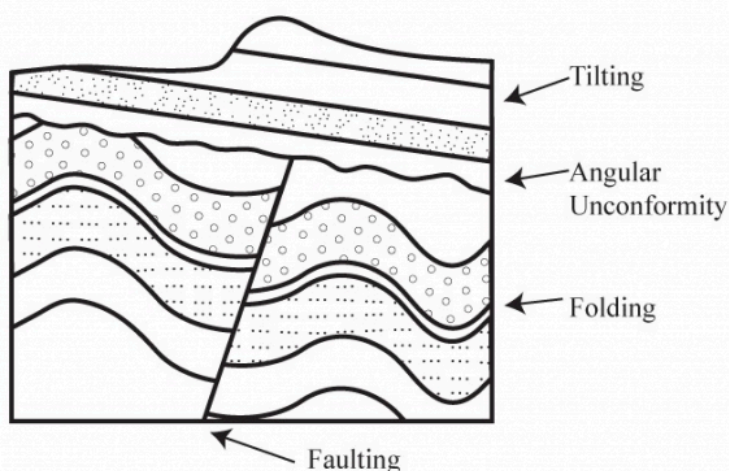
Step 3. Place the sedimentary Layers and geologic events in order based on the Geologic Laws.

1. Deposit sedimentary layers 1-6.
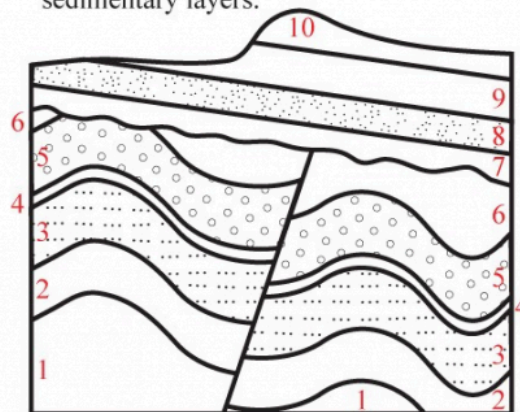2. Fold and Fault layers 1-6.
3. Uplift and Erode - Angular Unconformity
4. Subsidence and Deposit layers 7-10
5. Tilt Layers 1-10.
6. Uplift and Erode.

Figure 6.6 | *An example showing how to determine a relative dating sequence of events from a block diagram.*
Source: Bradley Deline (2015) CC BY-SA 3.0 <u>*view source*</u>

6.3 ABSOLUTE AGE AND RADIOMETRIC DATING

Absolute age of a rock or object is different from relative age. With absolute age dating, scientists determine the absolute age of a rock in millions of years before present rather than just the age of the rock relative to the rock units around it. This information helps geologists develop more precise geological history models for the rocks and regions they study. Absolute age is generally determined using a technique called **radiometric dating**, which uses **radioactive isotopes** of elements in the rock to estimate the age of the rock.

Atoms are made of three particles: protons, electrons, and neutrons. All three of these particles are important to the study of geology: the number of protons defines the identity of a particular element (e.g., carbon has 6 protons), the number of electrons control how that element bonds to other elements to make compounds, and the number of neutrons changes the atomic weight of an element. **Isotopes** are atoms of an element that differ in the number of neutrons in their nucleus and, therefore, their atomic weight.

Some isotopes are unstable and decay (break down into other isotopes) over time. This process is called **radioactive decay**. In radioactive decay, a particle (e.g., a neutron, electron, or x-ray photon) is emitted from a radioactive atom, called the **parent atom.** After the particle is emitted the parent atom is altered to form a different isotope (often a different element) called the **daughter atom**. To be useful for radiometric dating, the daughter isotope atom should not be radioactive (i.e., it should not disappear once it has formed).

Scientists have studied and measure the radioactivity of different elements in the lab to calculate the rate of decay for each isotope. Though the rate of decay varies between isotopes from milliseconds to billions of years, each isotope decays at a regular and predictable rate. This is called the **half-life** of the isotope. The half-life is defined as the amount of time it takes for half of the atoms of the radioactive parent isotope to decay to atoms of the daughter isotope. The half-life is independent of the amount of atoms at a given time; for example, it takes the same amount of time for the amount of parent isotope to decrease from 100% to 50% as it takes for the amount of the parent isotope to decrease from 50% to 25% of its original value. If we plot this pattern as a plot of time vs atoms remaining, we get a radioactive decay curve. When a rock initially forms there are generally very few daughter atoms present in the rock; thus, if we know the length of the half-life for a particular radioactive isotope and we measure the amount of parent and daughter isotope in a rock, we can then calculate the age of the rock. This is the basis for radiometric dating. The concentrations of the different isotopes are measured using an instrument called an isotope ratio mass spectrometer. Given the shape of the radioactive decay curve, a material theoretically never completely runs out of the parent isotope. In practice, scientists can only effectively measure the concentration of remaining parent isotope up to 10-15 elapsed half-lives; after that the concentration of parent isotope remaining is generally too low in concentration to measure.

6.4 RADIOMETRIC DATING SYSTEMS

There are several different pairs of radioactive isotope parent and daughter atoms that are commonly used to absolutely date rocks. Each of these **radiometric dating systems** (or **isotopic dating methods**) has different uses within geology; due to the differences in the half-lives and chemistry of the isotopes they are useful for dating objects over certain age ranges or composed of certain materials.

For example, **radiocarbon (Carbon-14) dating** is of limited use within geology because of the relatively short half-life of Carbon-14 in comparison with the scale of geologic time. However, more people have heard of this radiometric dating system than the others used in geology, because radiocarbon dating is used extensively in archaeology. Carbon-14 (the parent isotope) is found in organic material including bone, tissue, plants, and fiber. This isotope is found naturally in small amounts in the atmosphere within CO_2 and is incorporated into plants when they grow. The plants are consumed by animals, which are consumed by other animals and so on, and thus the carbon-14 thus moves throughout the food chain. You currently have carbon-14 in your body that is decaying to nitrogen-14 (the daughter isotope). As we eat, we replace any carbon-14 we excrete. When an animal stops eating or a plant stops growing (e.g., when a tree is cut down to use for building a home), the radioactive carbon starts to decay without being replaced. This change in carbon-14 concentration can be measured using radiometric dating techniques to determine how long it has been since the animal or plant died (and in the case of a house, this will probably coincide with when it was built). Carbon-14 has a very short half-life of 5,730 years and can thus only be used to date materials up to approximately 70,000 years old. Over that age, there would not be enough parent isotope atoms left to get accurate dating information using this isotopic dating method. Given the age of the Earth is 4.54 billion years, carbon-14 can only be used to date very recent materials.

Uranium-lead (U-Pb) dating – also known as **U-Pb geochronology** – involves decay of the isotope Uranium-238 through many different daughter isotopes that are also radioactive until the atom reaches the non-radioactive lead-206 isotope. Surprising to most students, uranium can be found in many places, but it is normally present in miniscule amounts so does not pose a radioactive hazard. One challenge with this system is that the daughter isotope lead-206 is also found naturally in many different places; this makes it difficult to differentiate between lead formed from radioactive decay

and lead found naturally in the environment. The mineral zircon solves both of these issues, by concentrating uranium and excluding lead from its mineral structure. Therefore, we use uranium dating on zircons found within igneous rocks (such as volcanic ash or rocks formed deep in the Earth). Uranium has a very long half-life of 4.5 billion years, which is more than long enough to date most rocks on Earth, though it is not reliable for dating rocks under 1 million years old.

Potassium-Argon (K-Ar) dating is also a useful method of dating rocks. Potassium-40 decays into two daughter isotopes, argon-40 and calcium-40. The daughter atom scientists use for radiometric dating is the argon-40 because (unlike calcium) it is rare within minerals. The reason for this is that argon is a noble gas and doesn't normally bond with other elements; therefore, any argon-40 within a mineral is most likely from potassium-40 decay. The use of argon also has drawbacks. For instance a gas can easily escape from a rock. Therefore, special care needs to be taken in the lab to capture the argon-40 for analysis. The K-Ar radiometric dating system works well when dating rocks with potassium-rich mineral grains to analyze. For example, the igneous rock type granite is full of the potassium-rich pink mineral K-feldspar. A scientist dating K-feldspar in granite using K-Ar dating would date numerous mineral crystals in the rock to get their final estimated date for the rock. The half-life of potassium is 702 million years so the K-Ar system is most useful for dating older rocks (much like the U-Pb radiometric dating system).

All radiometric dating systems have **error** associated with them. Error is a term that describes the combination of factors relating to the sample chemistry, preservation, and analyses that can affect how accurate the results of the testing. It is best to think of radiometric dating results as scientific hypotheses that need to be tested further; a date should be supported by numerous additional date analyses to provide certainty in the accuracy. A major source of error for radiometric data analyses is addition or subtraction of either parent isotope atoms or daughter isotope atoms in the rock following its formation. This can occur in several ways; most commonly it happens when the rock is subjected to heat and pressure (metamorphism). There are ways to correct for these issues that allows the scientist to date both the rock and the metamorphic event as long as the geologic history is known. Analytical variability (error associated with quantifying the different isotopes in the rock) can also contribute some error to radiometric dating analyses. When scientists report radiometric dates they also provide a **range of error** (possible range of actual values) associated with their measurements (e.g., 4.10 ± 0.01 Ga, where Ga stands for gigaannum, or billions of years).

It is rare to find a rock that contains an amount of the parent remaining that falls exactly on one of the half-lives. In most cases we need to use a simple formula to calculate the age of a rock using the length of the half-life and the amount of parent remaining.

$$Age = -\left(\frac{t_{1/2}}{0.693}\right)\ln(P)$$

The formula is:

$t_{1/2}$ = The length of the half-life in years

P = The proportion of the parent isotope remaining in decimal form. For example, if there is 50 % of the parent remaining it would equal 0.5.

Let's work through a simple example using this equation that we already know the answer to in advance. You have a sample of bone that has 25% of the carbon-14 (half-life= 5730 years) remaining. How old is the sample? We can answer this question in two ways:

1. We know that if there is 25% remaining, two half-lives have passed and with each half-life being 5730 the bone would be 11,460 years old.
2. We could use the above equation and insert both the length of the half- life and the amount of the parent

$$Age = -\left(\frac{5730}{0.693}\right)\ln(0.25)$$

remaining:

To solve the equation, take the natural Log (ln) of 0.25 and multiply by the term in the parentheses (make sure to include the negative sign). If you do this you will get 11,460 years as well.

2. Exercises on Relative Dating

Adapted by Joyce M. McBeth & Sean W. Lacey (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 1 "Relative and Absolute Dating" by Bradley Deline, CC BY-SA 4.0. View Source. Last edited: 14 July 2020

Note that portions of this lab will require students read through and refer to the "Overview of Relative and Absolute Dating" portion of the lab manual.

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____

Please hand in this lab to your TAs at the end of the lab.

6-E1 LAB EXERCISES – RELATIVE TIME

Relative time is an important tool for geologist to quickly construct a model for a series of geologic events, especially in the field. In the following section, apply what you have learned regarding relative time to the questions below.
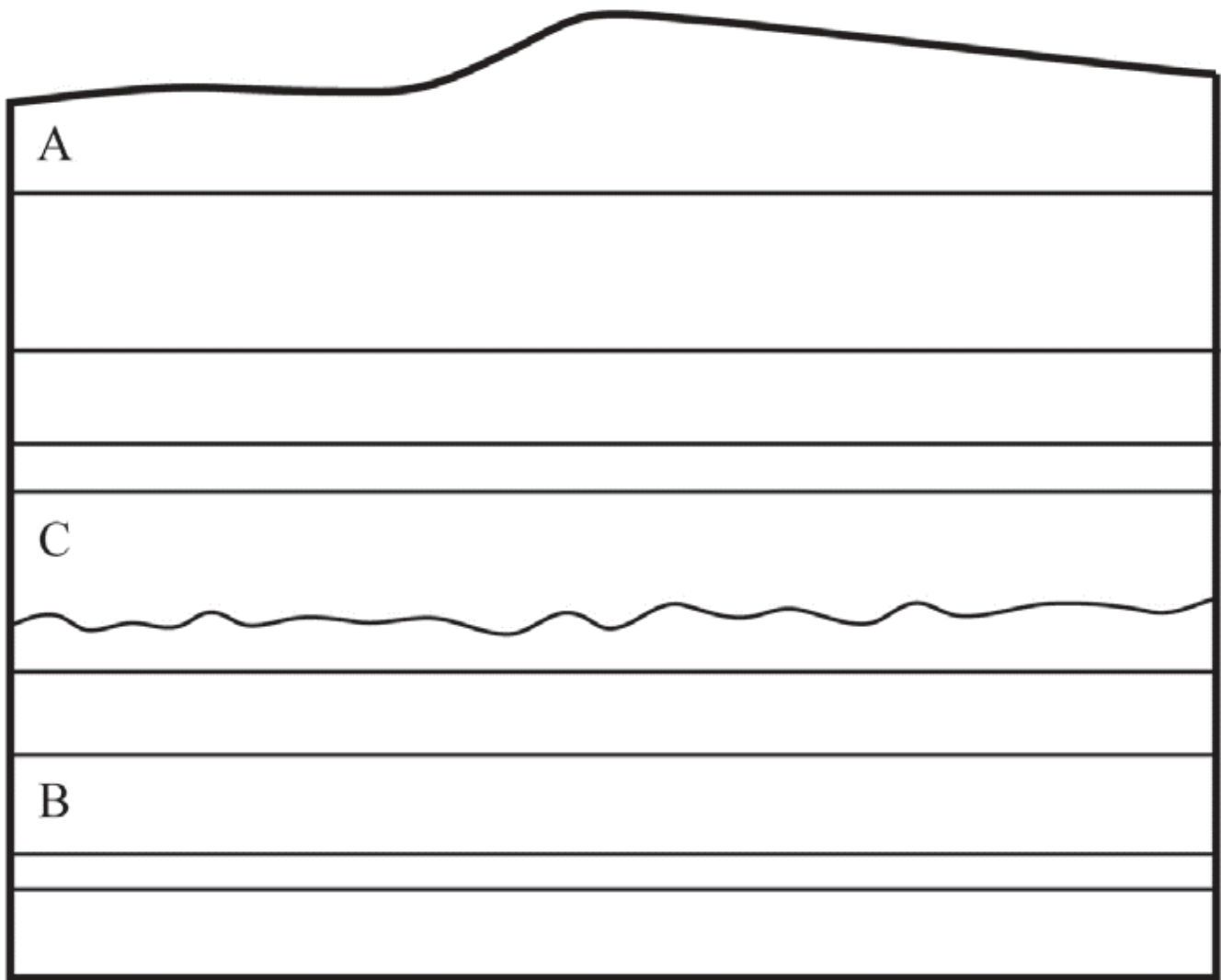
Figure 6-E1 | *Block diagram to use to answer questions 1 and 2.*
Source: Bradley Deline (2015) CC BY-SA 3.0 view source

1. (1 pt) In Figure 6-E1, which of the following rock layers is the oldest?

a. A

b. B

c. C

2. (1 pt) Which geologic law or principle did you use to come to the conclusion you made in the previous question?

a. The law of superposition

b. The principle of cross-cutting relationships

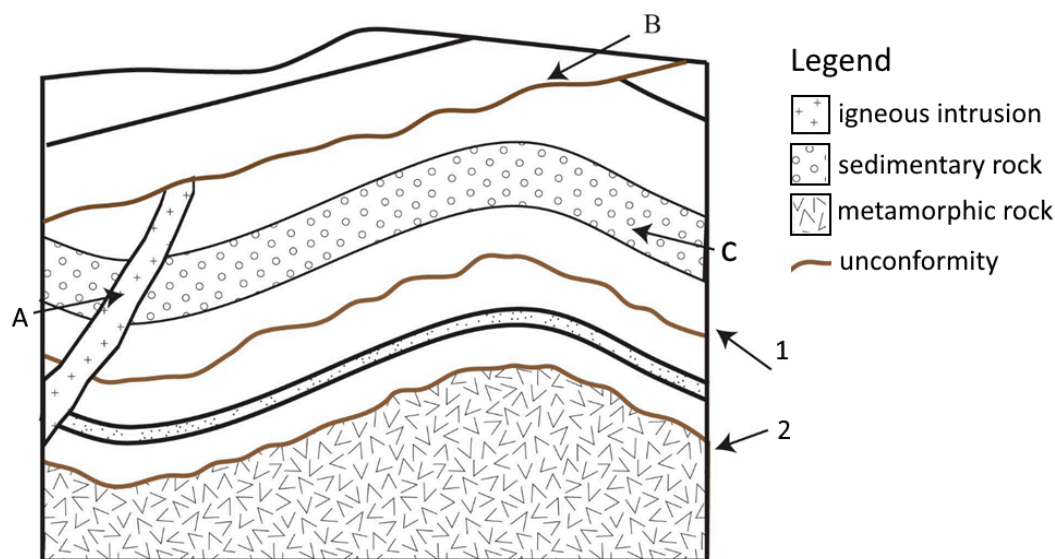c. The principle of original horizontality

d. The principle of unconformities

Legend
- igneous intrusion
- sedimentary rock
- metamorphic rock
- unconformity

Figure 6-E2 | Block diagram to use to answer questions 3, 4, and 5. Unconformities (B, 1, 2) are shown in brown. Source: Joyce M. McBeth (2019) CC BY-SA 4.0; modified from Bradley Deline (2015) CC BY-SA 3.0 view source

3. (1 pt) In Figure 6-E2, which of the following geologic structures is the youngest?

a. A

b. B

c. C

4. (1 pt) Which geologic law or principle did you use to come to the conclusion you made in the previous question?

a. The law of superposition

b. The principle of cross-cutting relationships

c. The principle of original horizontality

d. The principle of unconformities
    e. b and d.

5. (1 pt) Examine unconformities 1 and 2 in Figure 6-E2. Which of the following statements about them is true?
a. The older unconformity is a nonconformity, while the younger is an angular unconformity.
b. The older unconformity is a disconformity, while the younger is a nonconformity.
c. The older unconformity is a nonconformity, while the younger is a disconformity.
d. The older unconformity is an angular unconformity, while the younger is a disconformity.

6. (1 pt) Examine the unconformity shown in Figure 6-E3. What type of unconformity is this?
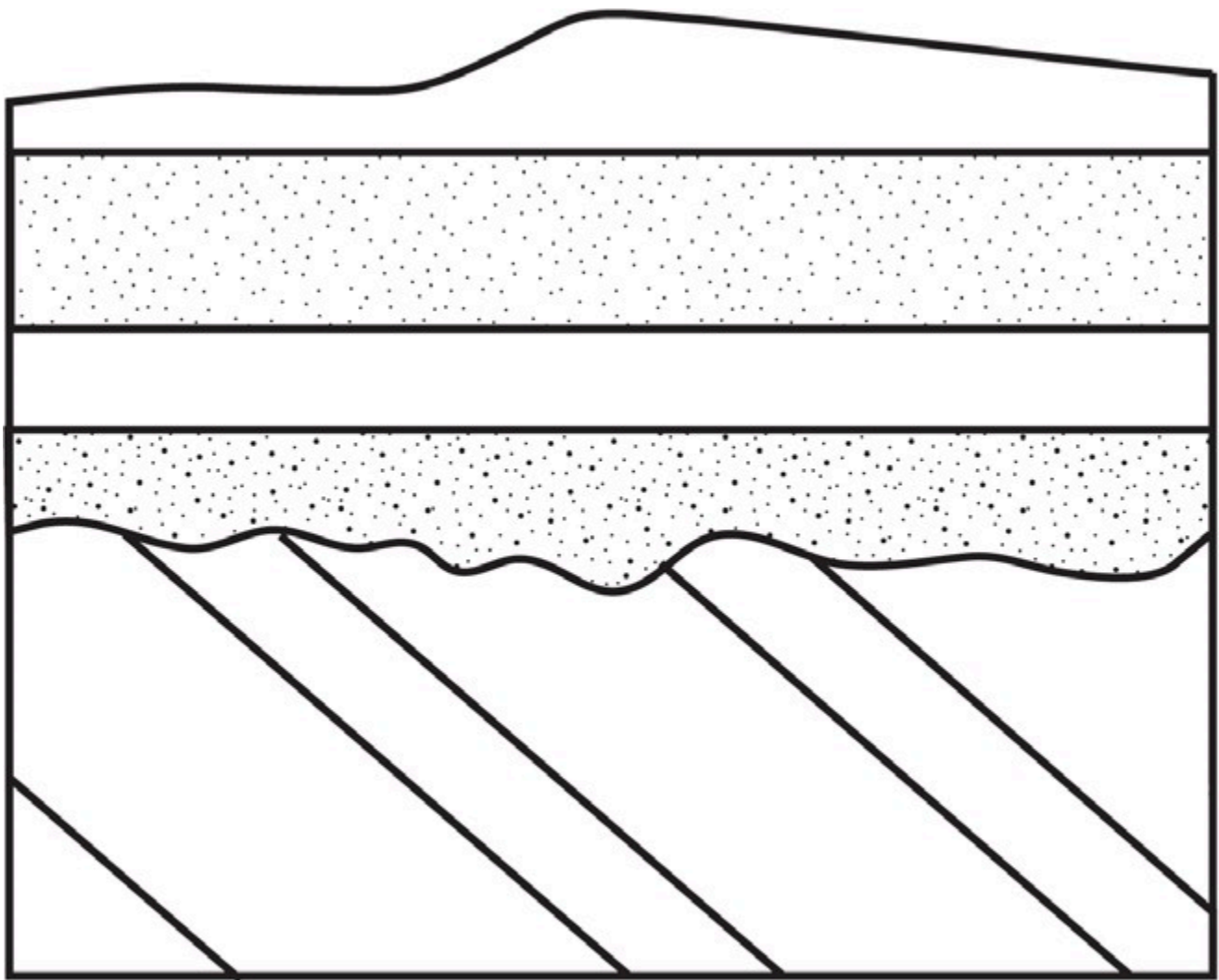
a. Angular unconformity
b. Nonconformity
c. Disconformity

Figure 6-E3 | *Block diagram to use to answer question 6.*
Source: Bradley Deline (2015) CC BY-SA 3.0 view source

To answer questions 7 and 8, examine Figure 6-E4. Note that all layers in this block diagram are composed of sedimentary rock and the unconformities are colored in red. Using Figure 6-E4, the geologic laws and principles discussed earlier, and following the examples shown in the overview section, identify the geologic events that occurred in this area.

7. (4 points) Number the sedimentary layers in order of deposition on the diagram below: from oldest (1) to youngest (13).
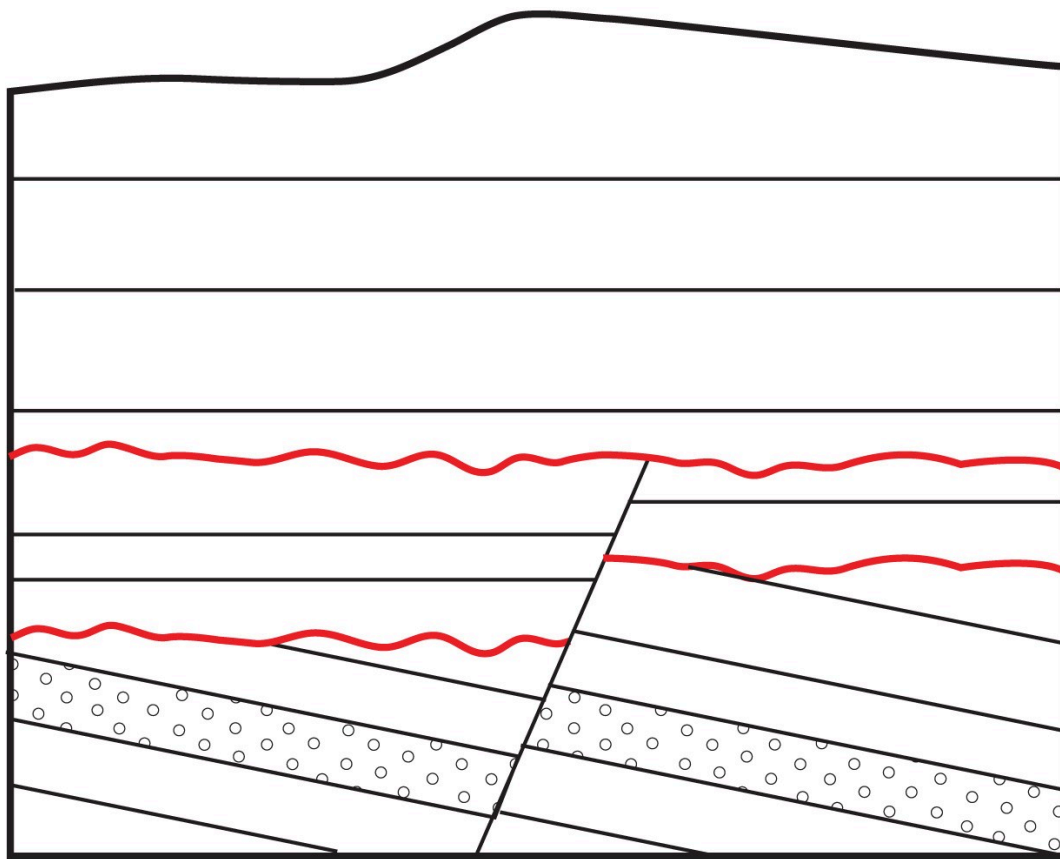
Figure 6-E4 | Block diagram to use to answer questions 7, 8, and 9. Unconformities are shown in red. Source: Bradley Deline (2015) CC BY-SA 3.0 [view source](#)

8. (8 points) Place the geologic events (a-h) in the correct relative time sequence in the table below, in order from oldest (1) to youngest (8).

a. Tilting.

b. Uplift and erosion (angular unconformity).

c. Submergence and deposition of sedimentary layers 10-13.

d. Uplift and erosion to current position.

e. Submergence and deposition of sedimentary layers 7-9.

f. Uplift and erosion (disconformity)

g. Submergence and deposition of sedimentary layers 1-6.

h. Fault.

Event order:

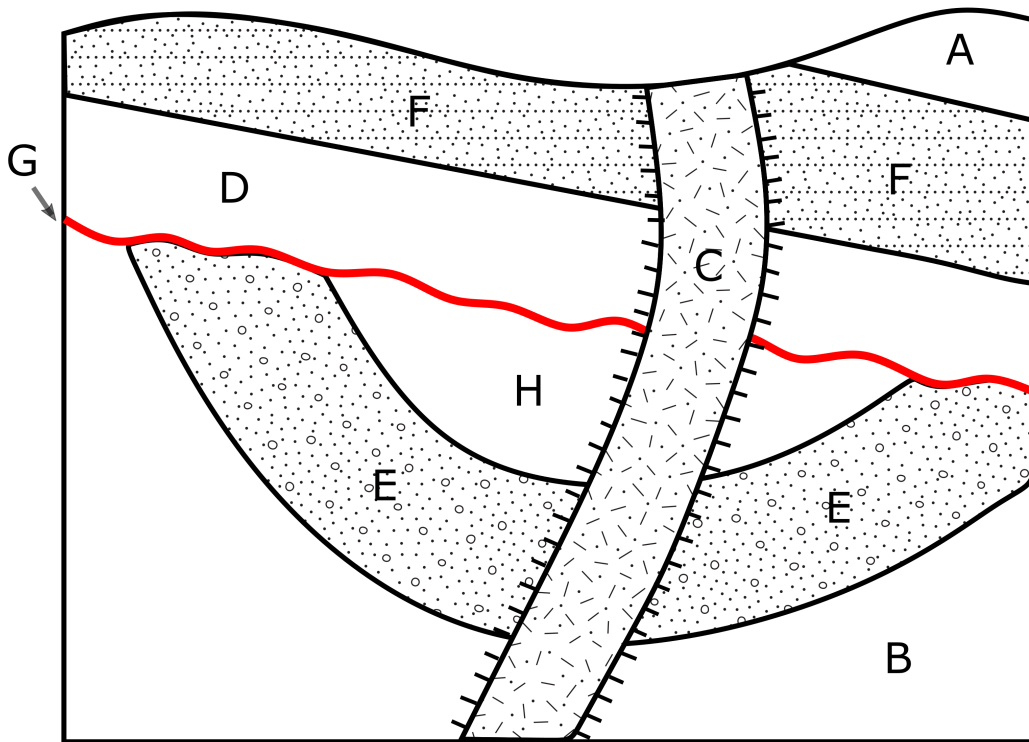| 1	2	3	4	5	6	7	8
Oldest							Youngest

Figure 6-E5 | *Block diagram to use to answer questions 9 & 10. Unconformity is shown in red.*
Source: Joyce McBeth (2020) CC BY 4.0.

Examine Figure 6-E5. Note that all of the layers in this block diagram are composed of sedimentary rock except for unit "C", and the unconformity is colored in red.

9. (7 pts) Using the geologic laws and principles discussed in this lab and that you have practiced in earlier lab questions, identify and list the geologic events that occurred in this area.

10. (3 pts) Place them in the correct time sequence from oldest to youngest event.

11. (8 pts) Using the key below, label the units and unconformity in Figure 6-E5 in order from oldest (1) to youngest (8).

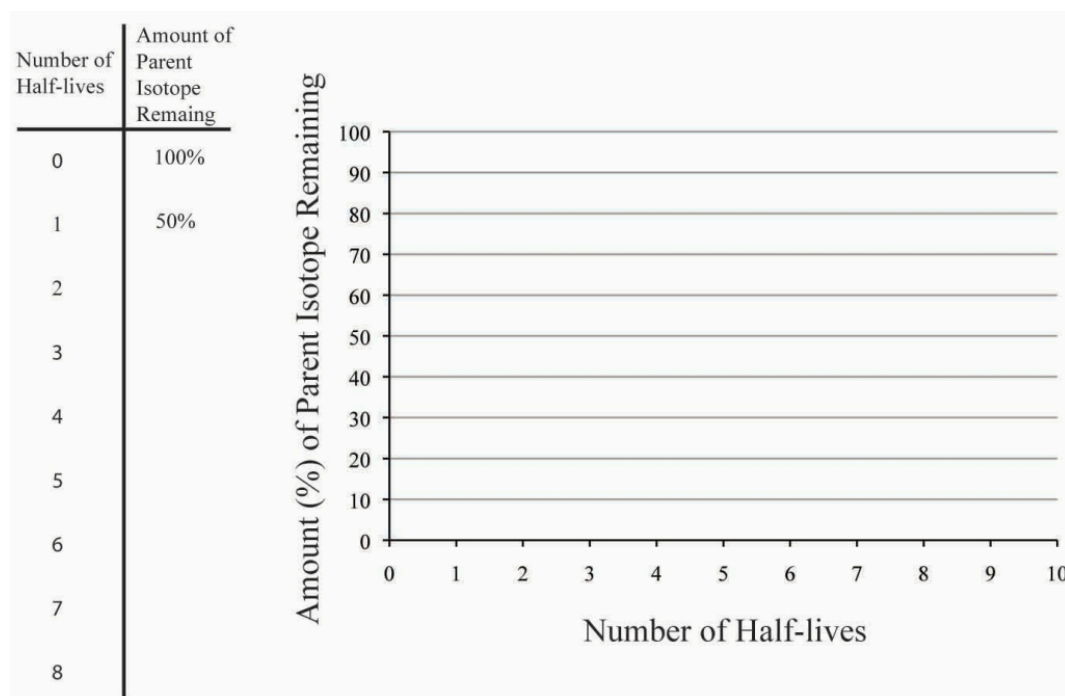| ___ | ___ | ___ | ___ | ___ | ___ | ___ | ___ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Oldest | | | | | | | Youngest |

3. Practice Questions on Absolute Dating

Adapted by Joyce M. McBeth & Sean W. Lacey (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 1 "Relative and Absolute Dating" by Bradley Deline, CC BY-SA 4.0. View Source. Last edited: 8 Jan 2020

Note that portions of these exercises will require students read through and refer to the "Overview of Relative and Absolute Dating" portion of the lab manual.

6-E2 LAB EXERCISES – RADIOMETRIC DATING

Complete the following chart by calculating the amount of parent isotope remaining for each number of elapsed half-lives. Plot your findings on the graph (Figure 6.11). Make sure you connect the data points on the graph by drawing in the decay curve. Use the completed chart and graph to answer the questions below.

Figure 6.11 | *Chart for plotting relationship between remaining amount of parent isotope and time and number of elapsed half-lives of a radioactive isotope. Source: Bradley Deline (2015) CC BY-SA 3.0 view source*

10. How much of the parent isotope would be remaining after 7 half-lives have passed?

a. 6.25 %

b. 1.56 %

c. 0.78 %

d. 0.39 %

11. If a radioactive element has a half-life of 425 years, how old would a rock be that only had 3.125 % of the parent isotope remaining?

a. 2125 years

b. 1700 years

c. 2550 years

d. 3400 years

12. Based on your graph above, approximately how much of the parent isotope would be remaining after 3.5 half-lives?

a. 16 %

b. 12 %

c. 4 %

d. 8 %

13. Based on your graph above, approximately how many half-lives have passed when only 35 % of the parent isotope is remaining?

a. 0.75

b. 1.5

c. 2.1

d. 2.5

6.7 LAB EXERCISE – CHOOSING ABSOLUTE DATING METHODS

Determine the most appropriate absolute dating method to determine the ages of the materials in the following questions. *Hint: refer to the section on* [radiometric dating in the overview section](#) *of this textbook for half-life values for various radiometric dating methods and examples of how to complete these problems.*

14. An Archeologist finds some cotton cloth at a burial site and wants to determine the age of the remains. Which isotopic dating method should they use?

a. Carbon-14

b. Uranium-Lead

c. Potassium-Argon

15. The Archeologist determines there is 16.7 % of the parent isotope remaining in the cloth sample. How old is the burial site? The half-life of carbon-14 is 5730 years.

a. 13,559 years

b. 14,798 years

c. 16,743 years

d. 1.66 billion years

e. 1.81 billion years

f. 2.05 billion years

16. A geologist is trying to date a sequence of sedimentary rocks with abundant fossils. The sedimentary rocks are mostly sandstone. Within the rock sequence there is a distinctive clay layer that under closer inspection is fine-grained volcanic ash. Which of the following is the best way to obtain an absolute date for the sequence of rocks?

a. Carbon date the fossils
b. Potassium-Argon date the sands
c. Uranium-lead date the zircons in the ash
d. Identify the index fossils

17. The geologist determines there is 78.3 % of the parent isotope remaining in the sample that they examine. How old is the sequence of rocks? *Hint: your answer to this question will depend on your answer to the previous question!*

a. 2022 years

b. 247.8 million years

c. 390.7 million years

d. 2.504 billion years

e. 1.588 billion years

f. 1.202 billion years

CHAPTER 7. TOPOGRAPHIC MAPS

7 Topographic Maps

Adapted by Joyce M. McBeth, Sean W. Lacey & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 3 "Topographic Maps" by Karen Tefend and Bradley Deline, CC BY-SA 4.0. [View Source](#).

7.1 INTRODUCTION

A **topographic map** is a useful type of map that adds a third dimension (vertical) to an otherwise two-dimensional map defined by the north, south, east, and west compass directions. This third dimension on a topographic map is represented by contour lines, which are imaginary lines drawn on a map that represent a constant elevation above either average sea level (a.s.l.) or mean sea level (m.s.l.). A map with such elevation lines will provide the map reader with detailed information regarding **topography** (the shape of Earth's surface). Knowledge of how to interpret a topographic map will allow a person to locate and identify features on Earth's surface such as hills, valleys, depressions, steep cliffs and gentle slopes. In addition, the map reader will be able to identify areas that may be prone to geologic hazards such as landslides and flooding. Any person interested in purchasing property, landscaping, planning a hike or camping trip, or who needs to survey an area for construction of a road, dam or building, will want to first consult a topographic map.

7.1.1 Learning Outcomes

After completing this chapter, you should be able to:
• Recognize topographic patterns and geologic patterns
• Read and construct contour lines
• Determine gradients
• Read map scales and convert fractional scales
• Construct a topographic profile

7.1.2 Key Terms

• Bar Scale
• Benchmarks
• Contour interval
• Contour line
• Equator
• Fractional (ratio) scale
• Gradient
• Hachure marks
• Index contour
• Latitude

- Longitude
- Prime Meridian
- Relief
- Topographic profile
- Verbal scale
- Vertical exaggeration

Overview of Topographic Maps

7 Topographic Maps

Adapted by Joyce M. McBeth, Sean W. Lacey & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 3 "Topographic Maps" by Karen Tefend and Bradley Deline, CC BY-SA 4.0. [View Source](#)*.*

The purpose of this chapter is to familiarize students with how to read and use topographic maps. This is a critical skill to prepare students to learn about more complex geologic maps.

7.2 MAP PARTS, ORIENTATION, AND SCALE

A map is a **plan view** (viewed from above, also known as **map view**) representation of an area on Earth's surface. **Topographic maps** are maps that illustrate the topography (vertical relief, such as hills) of the mapped region. **Geological maps** are maps that illustrate the rock types, rock ages and other geological features of the mapped area.

Every map has a:

- **map area** or **data frame**: the part of the map illustrating the map area;
- **legend**: a guide to the different symbols used on the map, such as lines representing roads and streams;
- **scale**: this defines the relationship of distances on the map to real distances in the area that the map represents;
- **north arrow**: indicates the direction of geographic north; and
- **title**: a name that generally describes the location of the map area.

The topographic and geological maps produced by Natural Resources Canada (NRCan, which includes the Geological Survey of Canada, GSC), and the United States Geological Survey (USGS) are oriented with north at the top of the map. Therefore if you move towards the top of the map you are moving in a northerly direction, and if you are moving towards the bottom of the map, you are moving towards the south. Any movement to the right or left will be towards the east or west, respectively.

7.2.1 Coordinate systems

There are two coordinate systems commonly used to define positions on Earth's surface: **geographic** (latitude and longitude, abbreviated lat/long) and **universal transverse mercator** (UTM). Latitude and longitude coordinates are used on NRCan and USGS maps; they are simpler to interpret and plot on a map than UTM coordinates. UTM coordinates are more accurate and are used in navigation and field work. Often geologists will report coordinates of important features using both coordinate systems.

7.2.2 Geographic Coordinates

Geographic coordinates use latitude and longitude to define positions on Earth's surface. The **longitude** is an imaginary

line that circles the globe and is oriented so that it passes through the north and south geographic poles. Starting with the 0° longitude line (zero degrees, known as the Prime Meridian) that passes through the town of Greenwich, England, the lines of longitude increase to 180° in both directions east and west of the Prime Meridian, meeting at a line of 180° longitude that passes through the Pacific Ocean (Figure 7.1). Lines of longitude converge as you move north or south of the equator, eventually intersecting at the geographic poles.It may help to visualize longitude lines if you think of an orange, which when peeled will show the sections of orange oriented like longitude lines that section the Earth into segments.
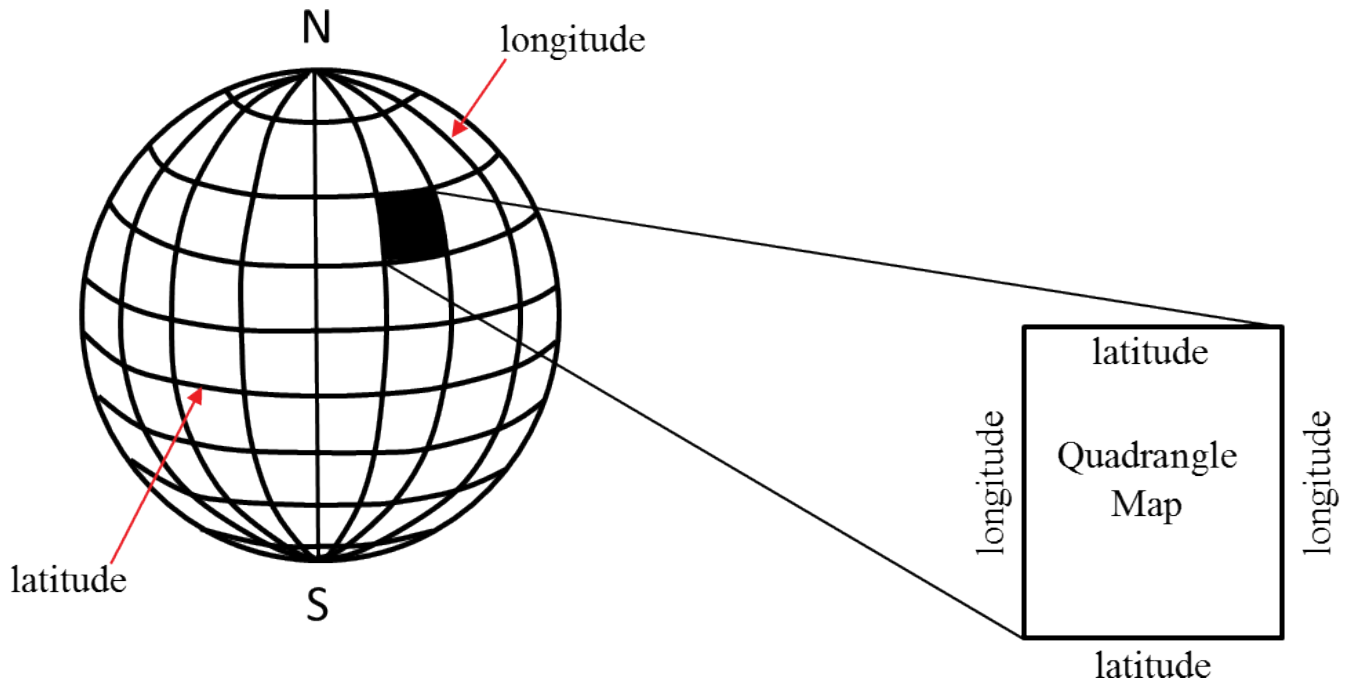
Figure 7.1 | Latitude and longitude grid system of Earth. Note how the regions defined by two adjacent lines of longitude is narrower as the lines approach the poles of Earth.
Source: Karen Tefend (2015) CC BY-SA 3.0 view source

Lines of **latitude** are imaginary lines that circle the globe parallel to Earth's equator (Figure 7.1). The 0° latitude line is the Earth's equator, and latitude lines increase up to 90° north or 90° south of the equator. The North Pole has a latitude of 90°N, and the South Pole has a latitude of 90°S.

This grid system allows a position on Earth to be uniquely defined with a set of longitude and latitude values. The values for latitude are always identified by their position N or S of the equator, and the longitude is identified as E or W of the Prime Meridian. A degree (abbreviated with the symbol "°") of latitude or longitude represents a large distance on Earth, therefore degrees are further subdivided into minutes, which are further subdivided into seconds. Note that a minute or second of distance is not the same as a minute or second of time. There are 60 minutes (abbreviated 60') of distance in 1° of latitude or longitude, and there are 60 seconds (abbreviated 60") of distance in one minute. An example of a precise location on Earth's surface would be 52°07′ 59.00″N, 106°40′ 12.00″W (the coordinates for Saskatoon, SK). This is read as "52 degrees, 7 minutes, 59 seconds north latitude, and 106 degrees, 40 minutes, 12 seconds west longitude." These coordinates are often converted into decimal notation. For the example above, the decimal notation coordinates are 52.133° N, 106.67° W. To convert between decimal degrees and degrees/minutes/seconds notation, use the formula: Decimal Degrees = Degrees + (Minutes / 60) + (Seconds / 3600) or use a converter on the internet (for example, on the US Federal Communications Commission website).

Note that the distance between two degrees of longitude is not the same distance in km when you are at the equator

as when you are at a location in northern Canada. As the lines of longitude approach the poles of Earth, they are closer together (as illustrated in Figure 7.1), and the distance each degree, minute, and second covers is smaller. Longitudinal distances in degrees, minutes and seconds are not absolute distances like metric units are (e.g., metres).

The latitude and longitude coordinates of NRCan maps are found along the edge of a map (for example see the map of Canadian geology we studied in Chapter 1). On USGS topographic maps the latitude and longitude coordinates are found at the corners of the map (Figure 7.2). Often, topographic and geological maps represent an area of Earth that is smaller than one degree of distance. Additional numbers (other than latitude and longitude) are also shown on the edges of the map (e.g., 40 01 in the top right corner of Figure 7.2); these are coordinates in the UTM grid system.

BAT CAVE QUADRANGLE
ARIZONA-MOHAVE CO.
7.5-MINUTE SERIES
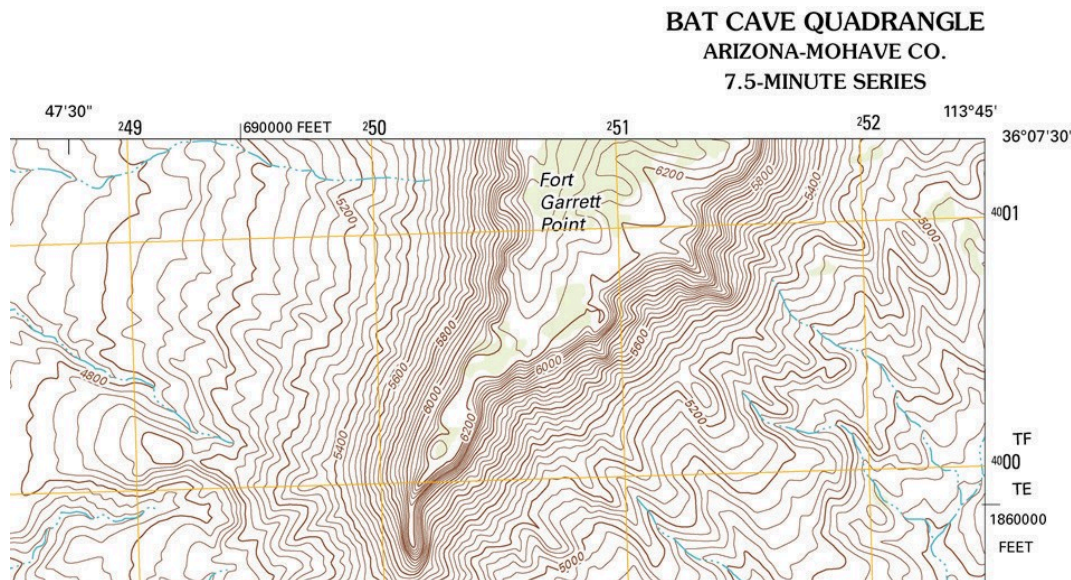
Figure 7.2 | This is the top right corner of a USGS topographic map. Note that the coordinates are written out completely in the corner of the map, but shorthand notation is used for the longitude coordinate on the top edge of the map (47'30", rather than 113˚47'30"). Since the number increases towards the left (by a distance of 2'30"), we know that these are west longitude numbers (meaning the longitude at that tick mark is 113˚47'30" W), since only lines of longitude located west of the Prime Meridian increase with distances to the west. Source: Harris (2015), map originally from USGS Public Domain [view source](#)

The top and bottom edges of USGS topographic maps are oriented parallel to lines of latitude. This is also broadly the case for NRCan maps; however, the closer the map area is to the north pole the more the curve of the lines of latitude will influence the distances between points on the map (since the closer to the pole, the smaller the regions defined by the lines of latitude and longitude). Near the north pole, the map may have quite different distances at the top and the bottom, particularly for maps that cover large areas. In some NRCan maps the lines of latitude curve to prevent distorting the distances between the lines of longitude (e.g., the map of Canada's geology from Chapter 1).

In Figure 7.2, the top edge of the map is a latitude line, so the coordinates that are changing as you move along the top of the map (in an East-West direction) must be longitude coordinates, since the latitude does not change. The bottom edge of this map is not shown, but you can predict what the latitude on the bottom edge should be: this map is of a region in Arizona, and since Arizona is located north of the Equator the latitude lines should increase from the bottom of the map towards the top of the map (as all latitude lines increase as you move north of the Equator).

7.2.3 Projections

To define two-dimensional (2D) coordinates on a three-dimensional (3-D) surface, the three-dimensional surface must

be converted to a 2-D surface representing the 3-D surface. This is called a **projection**. Whenever a 3-D object is rendered in 2-D, there is distortion. In other words, distances between positions will not always be accurate, especially for positions closer to Earth's poles. There are different methods of rendering regions of Earth onto maps that attempt to deal with such distortion, but distortion cannot be eliminated. The typical global map of Earth is generated by wrapping a cylinder around a globe representation of Earth, with the edges of the cylinder oriented vertically, so that the edge of the cylinder touches the globe along the equator. We then imagine a light source at the centre of the globe that casts shadows of all of the globe's features onto the inside surface of the cylinder. These shadows are then traced onto the inner surface. Unwrapping the cylinder then shows a two dimensional map of Earth. This type of projection is called a transverse Mercator map projection.

Since the equator was in contact with the inner surface of the cylinder, there is no distortion of features along the equator. But the further away from the equator you move, the more distorted the map becomes. This can see this distortion by examining a typical world map, which are usually created using a transverse Mercator map projection. On this kind of map, Greenland will appear to be a similar size to South America, but in reality, South America is nine times larger than Greenland. Also note on maps with this kind of projection you never reach 90o latitude either north or south. This is because light emanating from the globe will be moving almost parallel to the edges of the cylinder when it escapes from the globe at and near the geographic poles. Another distortion in these maps is the appearance of Antarctica as a continuous land mass that runs along the southern edge of the map. Antarctica is a circular land mass centred around the south geographic pole, rather than a long narrow island as seems to be indicated on the map.

The scale of the map is another factor that leads to distortion on maps of Earth. As you move northwards or southwards from the equator, the scale of the map expands. For example, if you use a ruler to measure 1 cm of distance at the equator, this will convert to a certain distance on the ground. But 1 cm measured further north or south of the equator will convert to larger and larger distances on the ground, depending upon how far north or south you go.

A strategy used to minimize distortion on maps is to zoom in and only render a small region of Earth's surface into the 2-D map. The smaller the region, the less distortion will occur on the map.

7.2.4 UTM coordinates

The UTM coordinate system is another system for determining points on Earth's surface. You will not use the UTM coordinate system in the lab exercises in this chapter, but it is important to be aware that this other coordinate system exists since it is broadly used by geoscientists in the field and in navigation. The reason the UTM system was developed was to allow for more precise calculations of positions on Earth's surface for navigational purposes. Longitudinal degree distances change as you approach the poles of the Earth due to the curvature of Earth's surface, resulting in distortion of distances on maps in these regions. Thus, it is difficult to make an accurate calculation of positions for navigation using latitude/longitude coordinates in northern regions. The UTM system uses a slightly different approach to map out regions on Earth's surface to decrease the amount of distortion on maps using this grid system.

The UTM system divides the Earth into 60 zones that are 6° of longitude wide. Zones 7 to 22 cover Canada. The polar regions of Earth's surface are not included in the UTM system, so points north of 84°N do not have UTM coordinates (note that this is further north than the most northerly islands in the Canadian Arctic). Within each zone, there is a central meridian (line of longitude) and there are 3° of longitude on either side of this central meridian. Positions within each zone are defined by how far north of the equator they are (their "**northing**" value), and their position relative to the central meridian of each zone (the "**easting**" value). The central meridian of each zone is given a value of 500,000 m. In practice, points east of a zone's central meridian will have easting values that are less than 500,000, and points west of the central meridian will have easting values greater than 500,000.

The most important thing to remember when using UTM coordinates is that you must specify the zone for any position you are reporting, otherwise you will not be able to accurately find the position on Earth's surface, since the

easting position is not measured relative to the Prime Meridian. Here is an example of a UTM coordinate position for the University of Saskatchewan, Saskatoon, SK: UTM Zone 13U, 388107.09 E, 5776949.85 N.

7.2.4 Map scale

All maps are a scaled-down version of the region of the world that they depict; if this were not the case, then the map that a person must carry would be the exact same size as a city (if it is a city map) or the size of a province (if it is a provincial map). The word "scale" refers to the amount of reduction the map represents, and all maps include at least one type of map scale to indicate the relationship between the area on the map and the area of the region it represents in reality. Map scales are provided so that a map reader can determine exactly how much distance is actually represented on their map, or to measure the distance between two points on a map, or even to calculate the **gradient** (slope) of a hill or river. The two commonly used map scales on a topographic map are the **bar scale** (or graphical scale) and the **fractional scale** (also known as the **ratio scale**).

In Figure 7.3 there are three bar scales; each bar is a graphical representation of distance on the map, and it is up to the map reader to decide if they want to measure distances in kilometers, meters, miles, or feet. Notice that each bar scale has the starting point (zero) within the interior of the scale, and not on the end of each scale (Figure 7.3).

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
NORTH AMERICAN VERTICAL DATUM OF 1988
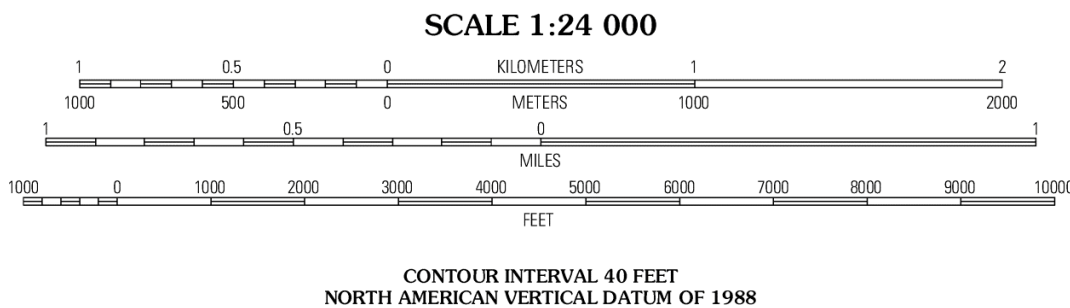
Figure 7.3 | Map scales are typically located on the bottom and/or right side of a topographic map. Note that the bar scales start at zero in the interior of each bar for kilometers, miles, and feet. The bar to the left of zero is further subdivided for more accurate distance determinations. Source: Harris (2015), map originally from USGS Public Domain [view source](#)

The other type of map scale is the fractional scale (e.g., in Figure 7.3 the fractional scale is 1:24,000). No units are reported for fractional scales because the ratio of a fractional scale is valid for any unit of measure, provided that it is the same unit on both sides of the ratio. For example, if using centimetres, then this map scale indicates that 1 cm on the map is equivalent to 24,000 cm on the ground the map represents (the distance between two locations in the real world). If our map was the same size as the area that it is representing (say for example, a map of the room you are currently sitting in), then the fractional scale of your map would be 1:1 and the map would be the exact same size as the room. This brings us again to the definition of a map, which is a scaled-down version of the region it represents. Maps that are greatly scaled down (greatly reduced) are called small scale maps even though they represent large sections of Earth. For example, a 1:500,000 map will show a large section of Earth, but small details are lost (such as building locations or small streets), whereas a 1:12,000 map is a large-scale map even though it shows a much smaller region of Earth's surface, but greater detail can be seen (such as buildings, roads, and other landmarks).

7.3 CONTOUR LINES

Contour lines allow us to add a vertical dimension to a plan view map. Contour lines represent elevations above sea level at specific intervals within a map area. Since each individual contour line connects points of equal elevation, if you were to follow a contour line across a map area in the real world you would be walking at the same elevation while walking along that imaginary line. If you were to move off that line, you would be either walking up or down in elevation.

Let's explore the concept of contour lines with an exercise. You can use a pencil and paper to illustrate this exercise as you do it. Imagine if you are on a small circular island in the ocean, and you walk from the shore up to 10 m above the shoreline. If you were to walk around the island and stay exactly 10 m above shore, you would be walking a contour line that represents 10 m of elevation above sea level. If you move off that line, you are either moving uphill or downhill. If you could walk uphill another 10 m from your first 10 m contour line, and if you stay at that elevation (20 m above sea level) while circling the island, then you have walked the 20 m contour line. The vertical change in elevation between these two adjacent contour lines is called the contour interval, which in this case is 10 m. If you were to transfer these imaginary lines onto a map, you would see three lines forming concentric circles that represent 0 m (the seashore or sea level), 10 m and 20 m, and your map would look like a bull's eye pattern. Congratulations, you've made your first topographic map! If you would like to see what the map should look like, refer to Figure 7.7 at the end of this overview chapter.

Contour lines on topographic maps are shown as brown or black lines, and all maps will have a contour interval that is specific for that map. Note that the elevations represented by the contour lines are not always labeled on each line (e.g., Figure 7.2). Instead, every 5th contour line is labelled with an elevation, and is darker than the contour lines that lie between; these darker contour lines are called index contours. The use of index contours allows a map to be easier to read and is also more appealing visually, especially when the contour lines are numerous and closely spaced to one another. The reason they appear every 5th contour line is because generally index contours are every 10, 50, 100, 500, or 1000 m or feet, so the index contours are evenly spaced between these distances (i.e., every 2, 10, 20, 100, or 200 m or feet, respectively).

To determine the elevation of each contour line you must first know the contour interval for the map. By using the values of two adjacent index contours, one can easily calculate the contour interval between each line. For example, there are four contour lines between the 5200 ft and 5400 ft index contours on Figure 7.2, which means that there are four contour lines separating the 200 ft of elevation between the index contours. These divide up that 200 ft of elevation change into five sections of equal elevation change. If we divide 200 ft by five sections, each intermediate contour interval represents a 40 ft elevation change (in this example, the contours are 5200, 5240, 5280, 5320, 5360, and 5400 ft). To verify this, locate the 5200 ft index contour on the western side of the map in Figure 7.2, and increase the elevation by 40 ft each time you cross a contour line while traveling east (to the right) towards the 5400 ft contour line. Luckily there is no need to do this calculation to find the contour interval on a complete topographic map, as all topographic maps give the contour interval at the bottom of the map near the bar and fractional scales (see Figure 7.3). The contour interval must be obeyed for each contour line on a map. For example, if the contour interval is 50 m, then an example of possible contour lines on such a map would be 50 m, 100 m, 150 m, 200 m, and so on; you would not expect to see the contour interval suddenly switching on the map to 240 m, since that is not a multiple of 50 m.

You may be wondering why some contour lines are closely spaced in some areas of a map (e.g., the central portion of Figure 7.2) and why they are farther apart in other areas of a map (e.g., the western part of Figure 7.2). Let's return to our circular island exercise: if you are standing at 10 m above sea level on the island (on the 10 m contour line) and want to walk up the hill to reach the 20 m elevation contour, how far do you have to walk? The answer is – it depends! If the hill has a gentle slope you may have to walk a long time before you reach a higher elevation of 20 m. On a topographic map, the contour lines for a gently sloping hill would be spaced far apart, because the distances between the contours are further apart horizontally. Conversely, if the hill's slope is very steep, you do not need to walk as far up the hill to reach the 20 m elevation contour. The contour lines representing a steep slope will be closely spaced on a topographic map. Even for a perfectly circular island you could have differences in the slope of the hill between the contours (you can

experiment with drawing different slopes for your island if you want to!) The **slope** (also known as a **gradient** or **grade**) is the change in elevation divided by the distance. you can calculate the slope of a hill or any region on a topographic map if you know the change in elevation between two points, and if you know the distance between those same two points (rise/run). Slope gradients are usually reported in meters per kilometer (m/km) but other units are sometimes used. Two common units often used are the angle of the slope above the horizonal plane (e.g., a slope of 30 degrees) or as a percent (commonly used to describe the slope of roads and in other civil engineering contexts, calculated using the equation 100 % x rise/run). If you are calculating the slope of a hill, remember to use the contour lines to determine the elevation difference, and the bar scale on your map to measure the separating distance.

In addition to contour lines, topographic maps will also have **benchmarks** (**surveyed points**) located in various locations on the map. These points are exact elevations above sea level that surveyors have measured, and they are commonly used to mark the elevations of mountains, hilltops, road intersections and airport runways. These benchmarks are rarely located on a contour line and instead are usually identified by a black "x" or identified with the letters "BM". The benchmark also shows the specific elevation at the point, often in black (in contrast to the generally brown numbers on index contours). Benchmark locations will normally be found in the area between contour lines. For example, on a map with a contour interval of 10 m, a benchmark of 236 m would be found between the 230 m and 240 m contour lines. If the map had a contour interval of 10 m, a benchmark of 236 m would be found between the 235 m and 240 m contour lines. Try placing a 12 m benchmark point on your island map illustration!

In addition to obeying the set contour interval for a map, contour lines should not branch (split) or end at a dead end inside of the mapped region. Instead these lines are continuous, although ending at the edge of the mapped region is allowed, since the edge of the map is cutting off the contour line which would carry on outside of the mapped area. Contour lines also never touch, overlap, or cross, except in certain rare instances such as if there is a vertical or overhanging cliff. In the case of a vertical cliff, the contour lines will appear to merge because they are right on top of each other when viewed from above (plan view).

The span of the third dimension (elevation) represented by contour lines on a topographic map is called the **relief.** The relief for a topographic map is easily calculated by finding the highest and lowest contour line elevations on the map; you then subtract the two values to determine the vertical relief represented in the map. The hardest part of calculating the relief is finding these highest and lowest elevations on the map. Start by finding the highest index contour line and continue counting lines until you reach the lowest contour line. For example, in Figure 7.2 the highest contour line is the line that runs through the letter "r" in Fort (of Fort Garrett Point). This same contour line circles back and goes through the letter "o" in Fort. The elevation of this line is 6360 ft (based on the contour interval of 40 ft). On the map in Figure 7.2, some of the index contours appear to be missing their identifying elevation numbers, however they are still easy to identify because all index contours are in bold (darkened lines). To find the lowest elevation on the map, find the lowest index contour line and continue counting lines in the downhill direction. An easy way to determine which way is downhill is to find a water feature such as a stream on the map; water is coloured blue on topographic maps, and lines representing flowing water such as rivers or streams are coloured blue. A dashed blue line such as that shown in Figure 7.2 implies that the stream is dry part of the year (this is called an intermittent or ephemeral stream). Since water collects in low spots, such as a basin (where ponds, lakes, or oceans are found) or valleys (such as a stream or river valley), then the contour lines should represent decreasing elevation as you move towards a water feature on a map. Referring back to Figure 7.2, if you examine the contours you will see that the highest portion of the map is the central portion where Fort Garrett Point is located, and that any point west, south and east of this is a downhill direction. Note that the streams are flowing away from this Fort Garrett Point region. The lowest elevation will be a contour line that is crossing the stream just before leaving the map area. Close examination of the contour lines reveals that the lowest contour line is in the lower right corner of the map; the contour line that is crossing the stream in this portion of the map represents an elevation of 4560 ft. So, for the map area shown in Figure 7.2, the relief of the map region is 6360 ft (highest contour) − 4560 ft (lowest contour) = 1800 ft.

There is a feature worthy of special note that occurs on topographic maps where flowing water such as streams and rivers erode the landscape creating small or large valleys. There is a deflection of the contour lines on a map as they cross the valley. In Figure 7.2, the contour lines form a "v" shape as they cross the water, and that the pointed end of

this "v" is pointing in the upstream direction. We can use this to easily determine which way water is flowing, even if we don't know the elevation of the contour lines on the map, because the "v" always points upstream. This is known as the **Rule of Vs for Contour Lines**. Notice in Figure 7.2 that the contour lines that cross the streams are pointing toward the central hill (Fort Garrett Point), which means that the streams are all flowing away from the central portion of this map and towards the edges of the map region.

There is another, more complex feature that you may occasionally observe on topographic maps that you should be prepared for: depressions (for example, sinkholes) found on Earth's surface. If we drew contour lines for a sinkhole feature on a map which didn't capture an index contour within it, the sinkhole depression could be misinterpreted by a map reader as a hill top – because of this we need to provide the map reader with a different contour line feature to indicate that there is a depression in the landscape. Contour lines with small perpendicular lines (called **hachure marks**) are used for such depressions on a topographic map. These hachures are directed inwards towards the centre of the depression. The contour interval for the map is still obeyed when contouring a depression. The only difference is that the hachure marks on the contour lines indicate that you should count down in elevation, not up, as you move towards the center of the hachured contour circles. However, if there is a depression at the top of a hill or mountain (for example, a volcanic crater), then the first contour line that is hachured must be the same elevation of the closest contour line that is not hachured. The reason for the repeat is that a person climbing the hill will reach the highest contour line, and walk a little higher still, before descending into the depression (crater), and will therefore encounter the same elevation line again while descending (see Figure 7.4).
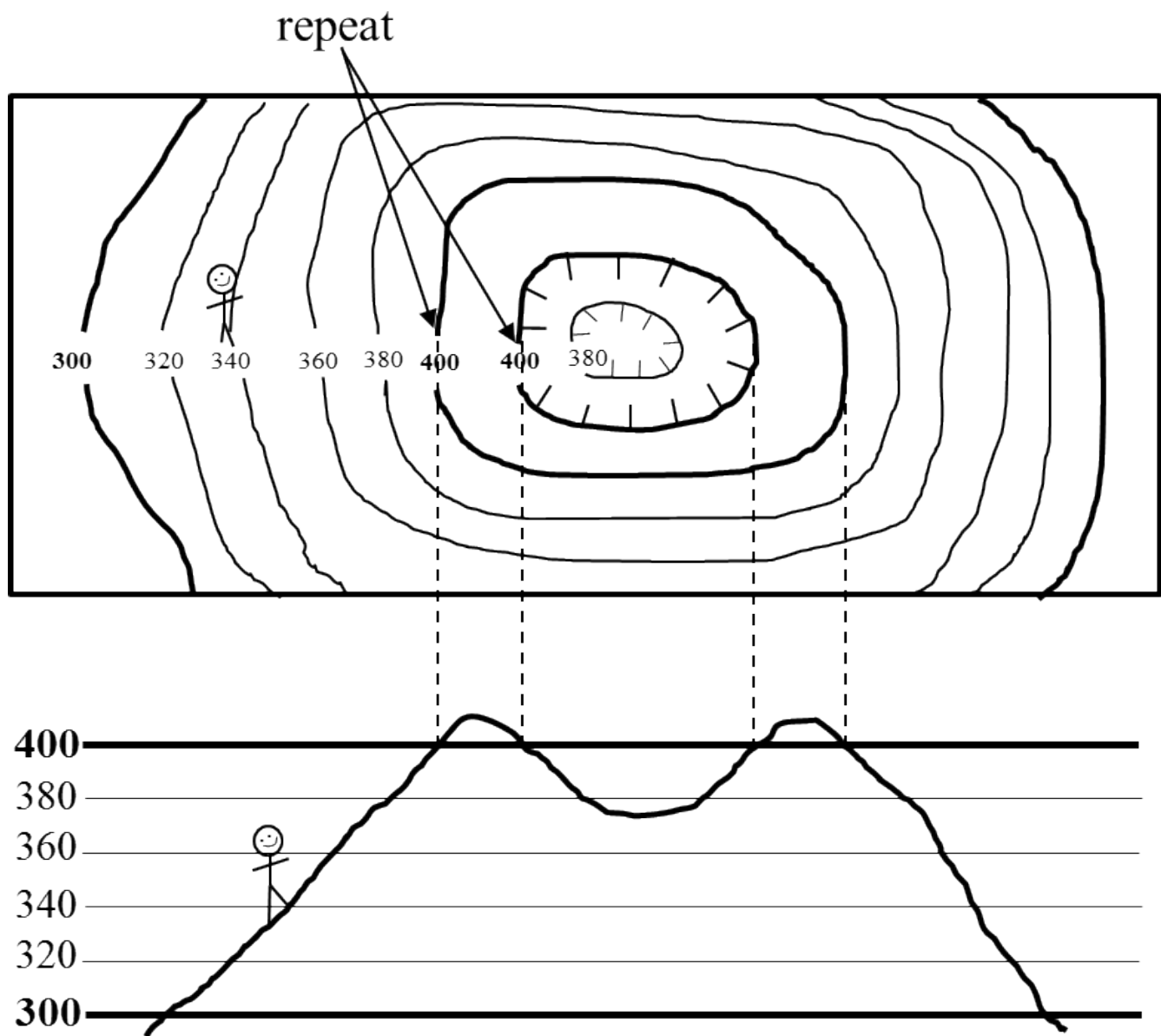
repeat

Figure 7.4 | *Contours and hachured contours for a depression at the top of a hill illustrated on a topographic map and a corresponding topographic profile. Notice that the first hachured depression contour line elevation is a repeat of the closest non-hachured contour line elevation.*
Source: Karen Tefend (2017) CC BY-SA 3.0 view source

7.4 DRAWING CONTOUR LINES AND TOPOGRAPHIC PROFILES

Constructing a topographic map is simple if a person remembers the following rules as they draw in contour lines on their map:

- contour lines represent lines connecting points of equal elevation above sea level;
- contour lines never cross, split, or die off;
- contour intervals must be obeyed, therefore the contour line elevations can only be multiples of the contour interval; and
- contour lines make a "v" pattern as they cross streams and rivers (Rule of Vs for Contour Lines), and the "v" always

points towards the upstream direction.

When working with topographic maps, sometimes it is useful to examine the landscape in profile. A **topographic profile** is a vertical cross-section or side image through a map that allows us to see how the topography varies along a line through the map. Let's consider an example of a profile through a topographic map. The top picture in Figure 7.5 shows a topographic map of a hill that contains two separate hill tops, and the bottom picture shows a topographic profile representing the profile along the line A-B on the map. The topographic profile contains elevation lines at the same intervals as the contour lines on the topographic map, but the contour lines cut through the profile horizontally at regular intervals along the vertical axis. Note how the elevation lines are equal distances vertically as you move up through the profile. If you draw lines from the positions on the topographic profile where the contour lines reach the surface of the hill up to the same positions along the line A-B through the topographic map, they align with the contour intervals on the topographic map. This pattern is a key relationship we can use to construct topographic profiles.

7.4.1. Constructing a topographic profile

To construct a topographic profile, you need graph paper, a ruler and a pencil, and a topographic map. Use the topographic profile in Figure 7.5 as an example. Draw or select a line across the topographic map through a region of interest to you (e.g., through a hill) that you will use to draw your topographic profile (e.g., Figure 7.5 line A-B). Draw a parallel line the length of this line horizontally near the bottom of the piece of graph paper (this is the x-axis of your profile). Then draw y-axis lines on either size of the horizontal line oriented toward the top of the piece of paper. Add horizontal lines joining the two y-axes at the same intervals as the contour intervals, to represent the elevation lines. These marks should generally be at the same scale as the map (e.g., 1 cm per 10 m if the scale of the topographic map is 1:100,000). Place the profile paper between you and the line on the topographic map, with the x-axis of the profile paper parallel to the line on the topographic map (as shown in Figure 7.5). Using a ruler, you can then transfer the elevation points from where the contour lines intersect the line on your topographic map straight down onto your graph paper at the corresponding elevation lines as shown in Figure 7.5 (dashed lines). Be sure to only plot those elevations that are at the intersection of the contour line with line A-B. Once your points are plotted on the topographic profile on your graph paper, connect the dots between each contour point. You should not use straight lines to join the points – real topography is generally smoother than the jagged line produced by joining points as straight lines – use a line that gently curves through the points (Figure 7.5). Note you will have to estimate the position of the line between the points on the profile as best you can, and your line may differ from other students' lines. That is ok if you don't break any of the rules. As a rule, hill tops will be slightly rounded to show a slight increase in elevation to represent the crest of the hill but be careful not to draw the hill top too high on your graph paper or the profile will intersect the next elevation line – if that interval isn't shown on the topographic map you should not go that high in the profile. For example, the first hill on the left has a top contour line of 50 m. Because there isn't a 60 m contour line on this hill top, we know that the hill's highest point (the crest) is some elevation between 50 and 60 m. When connecting the points on your graph paper in the area between the two hills in the Figure 7.5, you again want to round out the area to represent the base of your valley between the hills but be careful not to make the valley floor too deep, as according to the topographic map the elevation is below 40 m, but not as low as 30 m.
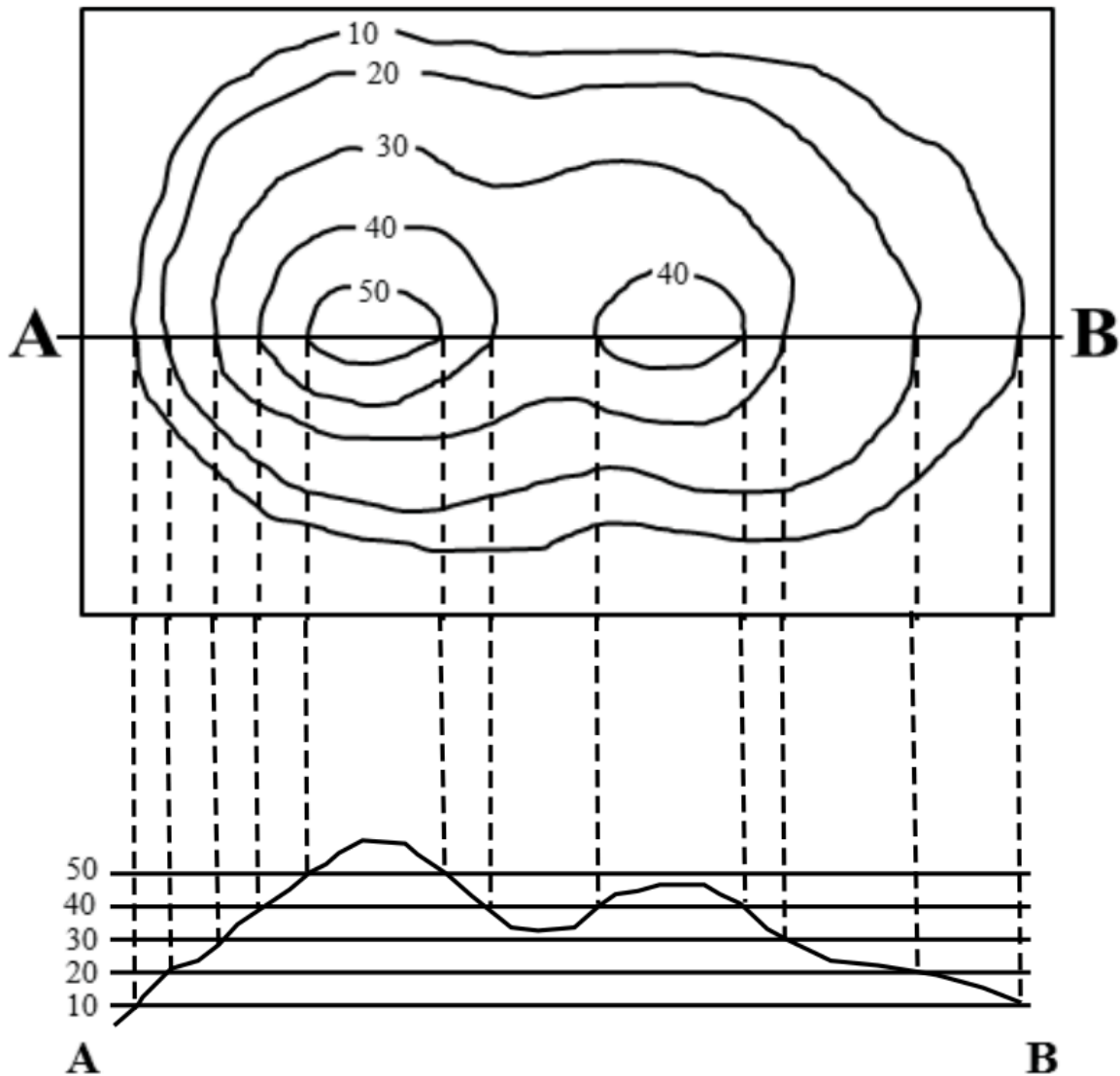
Figure 7.5 | *Contour map and topographic profile of two hills with a valley between them.*
Source: Joyce McBeth (2018) CC BY-SA 4.0, after Karen Tefend (2015) CC BY-SA 3.0 view source

7.4.2.Vertical exaggeration

If you examine the graph showing the topographic profile in Figure 7.5, can you imagine what would happen to the profile if we changed the spacing for the elevation lines along the y-axis? When the vertical scale of the graph is larger than the horizontal scale on the map, you will end up with a graph that shows a vertical exaggeration, and the features of Earth represented by your topographic profile will become distorted. This is illustrated in Figure 7.6 which has a smaller scale for the x-axis (horizontal) than the y-axis (vertical). Sometimes vertical exaggeration is useful for illustrating features that are interesting on the topographic profile but too small to see with equal horizontal and vertical scales (e.g., small hills). To avoid creating a distorted profile, use matching vertical and horizontal scales.

For example, if your map scale is 1 cm = 50 m, and one centimetre on your topographic profile's y-axis represents 50 m of elevation, there will be no vertical exaggeration in your cross-section. If 50 m on the y-axis is represented by a distance longer than 1 cm, there is vertical exaggeration in your cross-section.

Let's explore vertical exaggeration using the topographic profiles in Figure 7.5 and 7.6. Both profiles represent the same topographic profile along line A-B on the topographic map in Figure 7.5. If the topographic map in Figure 7.5 has a fractional scale of 1:2667 then 1 cm is equal to 2667 cm or ~27 m; thus, 1 cm = 27 m for the horizontal scale on this map. If we hold a ruler to the y-axis of the topographic profile in Figure 7.5 (download and print a pdf version of this figure if you want to try this yourself) the vertical scale should also be 1 cm = 27 m since there is no vertical exaggeration in Figure 7.5. If you do the same calculation using the profile in Figure 7.6, you should find that the vertical scale is about 1 cm = 13 m. To calculate the vertical exaggeration in the topographic profile shown in Figure 7.6 we divide the vertical scale by the horizontal scale on this figure: (1 cm/13 m) / (1 cm/27 m) = 2. Therefore, the topographic profile in Figure 7.6 represents a profile along the A-B line in Figure 7.5 that has been vertically exaggerated by 2 times (2X).

Topographic map of Ejemplo Island

Legend

— 10 m contour interval

water

x spot height (BM)

0 m
10 m
x
12 m
20 m
a
b

2 km
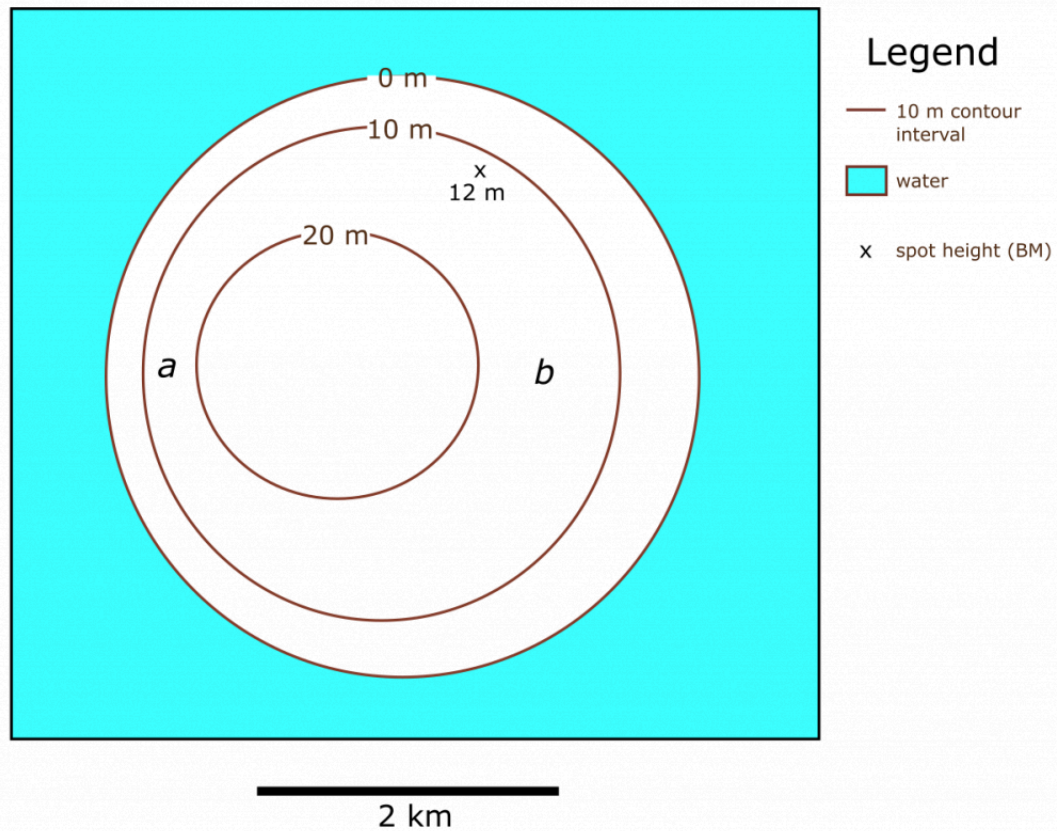
Figure 7.7 | *Topographic map of Ejemplo Island. This is one example of a topographic map students could produce from the instructions provided in section 7.3. Note that the slope in position "a" is steeper than the slope in position "b". Source: Joyce M. McBeth (2018) CC BY 4.0 original work.*

4. Practice questions on Topographic Maps

Adapted by Joyce M. McBeth, Sean W. Lacey, & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 3 "Topographic Maps" by Karen Tefend and Bradley Deline, CC BY-SA 4.0. [View Source](#).

7-E1 PRACTICE QUESTIONS

The questions in section 7-E1 are for practice (they will not be graded). Answers to these questions are provided at the end of the lab.

Please refer to British Columbia Topographic Map [094A018.](#) A thumbnail version of the map is shown in Figure 7-E1. *Hint: the information in the map area legend (on the right hand side of the map) will be very helpful in answering these questions.*
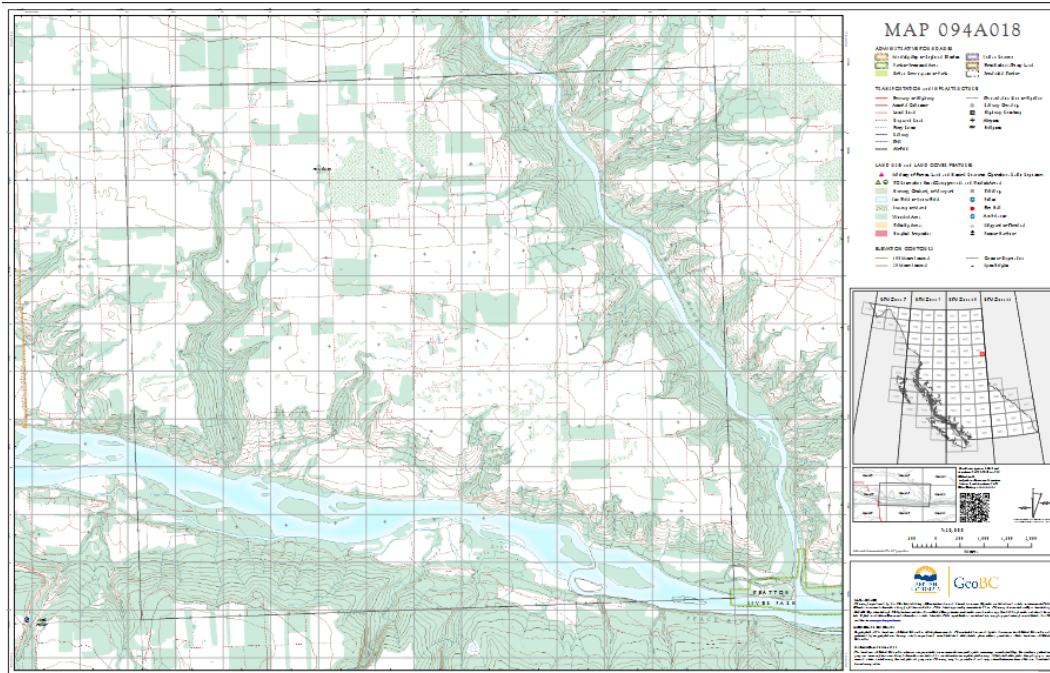
Figure 7-E1 | Two Rivers Topographic Map. Source: British Columbia Topographic Map 094A018, Province of British Columbia © 2016 all rights reserved [view source](#)

1. Is the map area located in northeast (NE), northwest (NW), southeast (SE), or southwest (SW) B.C.?

2. What do the green areas on the map represent?

3. What are the contour intervals of the two types of contour lines used on this map?

4. Note the location of the two rivers running through the map area. What are their names?

5. What happens to the contour lines as you move out in the first 1000 m from the rivers? (Hint: Does the distance between the contour lines change?) How does this pattern differ when you move further from the rivers (such as the NW corner of the map)? What does this tell you about the topography in this area?

6. A fractional scale of 1:20,000 means that 1 centimetre (cm) = _____ metres.

7. A fractional scale of 1:20,000 means that 1 metre (m) = _____ kilometres (km).

8a. The scale of the map will be different if you print it on a larger piece of paper than if you print it on a smaller piece of paper. What size of paper should you print the map on for the map to be at 1:20,000 scale? *Hint: this is specified in the map legend.*

8b. Please comment on which scale (graphical scale or fractional ratio scale) you find easier to work with and why.

For Questions 9 through 13, refer to Figure 7-E2 below, which shows a hill, an intermittent stream, and two index contours (darkened contour lines). Assume the contour interval for this map is 5 m, and the index contour that is crossing the stream has an elevation of 70 m. Review overview section 7.3 prior to doing this exercise.

70 meters

Figure 7-E2 | *Portion of a topographic map showing contour intervals*
Source: Sean Lacey (2018) CC BY 4.0, after Tefend and Deline (2015), map originally from USGS Public Domain [view source](#)

9. Which way is the stream flowing, to the north or to the south?

10. What is the elevation of the highest contour in the map?

11. Calculate the relief of this map. *Hint: it may be helpful to review the "Contour Lines" section in this chapter for instructions on calculating relief.*

12. Calculate the gradient of the stream between the highest and lowest contour lines that cross the stream. These two contour lines are 2 km apart.

13. Which side of the hill shown in Figure 7-E2 is slightly steeper: the west or east side?

Links to Maps Used in this Lab

- British Columbia Topographic Map 094A018. https://pub.data.gov.bc.ca/datasets/177864/pdf/094A/094A018.pdf

Answers to Practice Lab Exercises in section 7-E1

1. NE
2. wooded areas
3. 100 m, 20 m.
4. Beatton River, Peace River.
5. Contour lines are closer together near the river because the slope is steep, very far apart in the NW corner (flatter area).
6. 200 m
7. 20 km
8. 28″ x 44″
9. south
10. 95 m (this is the index contour at the top of the hill)
11. 95 m − 65 m = 30 m
12. (80 m − 65 m)/2 km = 7.5 m/km
13. East

Exercises on Topographic Maps

Adapted by Joyce M. McBeth, Sean W. Lacey, & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 3 "Topographic Maps" by Karen Tefend and Bradley Deline, CC BY-SA 4.0. [View Source](#).

The purpose of this lab is to familiarize students with how to read and use topographic maps. This is a critical skill to prepare students to learn about more complex geologic maps. Note: the maps used in this lab are in colour and the colours have significance in terms of the symbols and patterns used on the maps – it is best to print this lab in colour and from a pdf version.

Name: _____

Student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Please hand in this lab to your TAs at the end of the lab period.

Links to maps used in this lab

- British Columbia Topographic Map 092G095. https://pub.data.gov.bc.ca/datasets/177864/pdf/092G/092G095.pdf
- Saskatoon topographic map: https://opentextbooks.uregina.ca/app/uploads/sites/81/2020/11/SKtopomap_v2-1.pdf

7-E2 LAB EXERCISE – TOPOGRAPHIC MAPS

This is a graded activity, please submit it to your TA at the end of the lab. *Note: This lab is in colour. Therefore, if you print it out in black and white please refer back to the electronic copy to avoid confusion. For all of the following figures, assume north is at the top of the map, and south at the bottom.*

Questions 1 to 9: basic topographic map skills

Overview section 7.3 provides background information on contour lines to prepare you for these exercises.

1. (5 pts) The following topographic map (Map 7-E3) is from a coastal area and features an interesting geological hazard in addition to the ocean. Using a contour interval of 40 m, label the elevation of every contour line on the map below. *Note: elevation is metres above sea level; thus, sea level = _____ m*
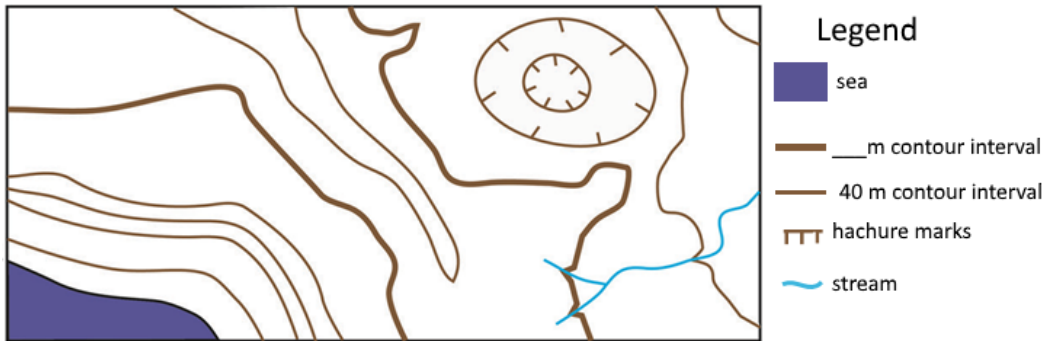
Figure 7-E3 | *Coastal area topographic map. Source: Joyce M. McBeth (2018) CC BY-SA 4.0, after Brad Deline (2017) CC BY-SA 3.0 view source*

2. (5 pts) Figure 7-E4 shows five waypoints (A, B, C, D, and E) on a topographic map. Answer the following questions about these waypoints, based on your best guess estimate of the elevation of each waypoint. *Note: there is technically more than one correct answer for some of these questions. Please use Occam's razor as you answer the questions: use the simplest explanation rather than the most complicated explanation to answer the question.*

 a. Write your estimates for the elevation at each waypoint next to the waypoint.
 b. Describe how you decided on an estimated elevation for points A and E.
 c. Is the elevation of waypoint A > (greater than) or < (less than) waypoint E?
 d. Is the elevation of waypoint D > or < waypoint C?
 e. Is the elevation of waypoint A > or < waypoint B?
 f. Is the elevation of waypoint C > or < waypoint B?
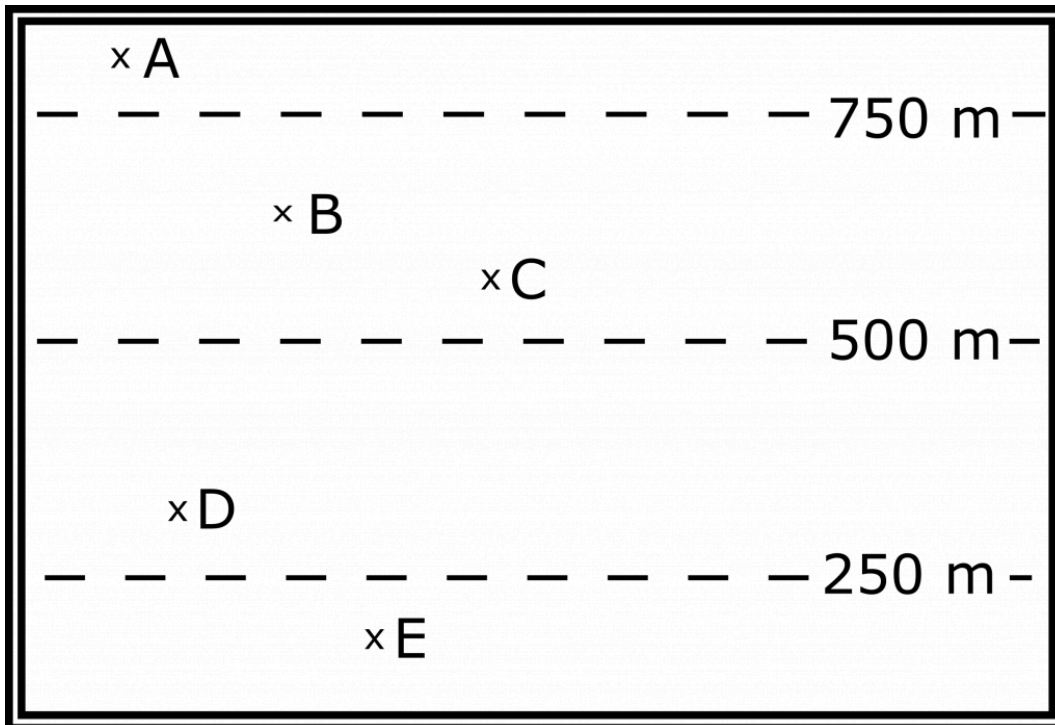
Figure 7-E4 | *Estimating elevations exercise. Note that the double thick line is the edge of the figure, not a part of the topographic map. Source: Joyce M. McBeth (2018) CC BY-SA 4.0*

3. (10 pts) Imagine you are a geologist working for the Geological Survey of Canada. You are tasked with creating your own coastal topographic map, so you hike around a coastal area with a GPS receiver (Global Positioning System) and every so often you record your position along with the elevation in metres at that point, which results in the map below

(Map 7-E5). Complete this map by adding in contour lines using a contour interval of 100 m. Draw the contour lines so that they are continuous: they will either continue to the edge of the map or form an enclosed circle. Refer to the topographic map in Figure 7-E3 for an example of contour lines you can use to help you complete this question. Your contour lines will generally fall between the GPS points on your map, so you will need to estimate many of the contour line positions. Don't forget to add a contour line to the map legend!

Figure 7-E5 | *Elevation measurements and drawing contour maps. Source: Joyce M. McBeth (2019) CC BY-SA 4.0, after Brad Deline (2017) CC BY-SA 3.0 [view source](#)*

The overview section 7.4.2 provides useful background to help you answer questions 4 & 5.

4. (5 pts) Construct a topographic profile for the map in Figure 7-E6 from position A to A' on the graph paper provided in Figure 7-E6 below.
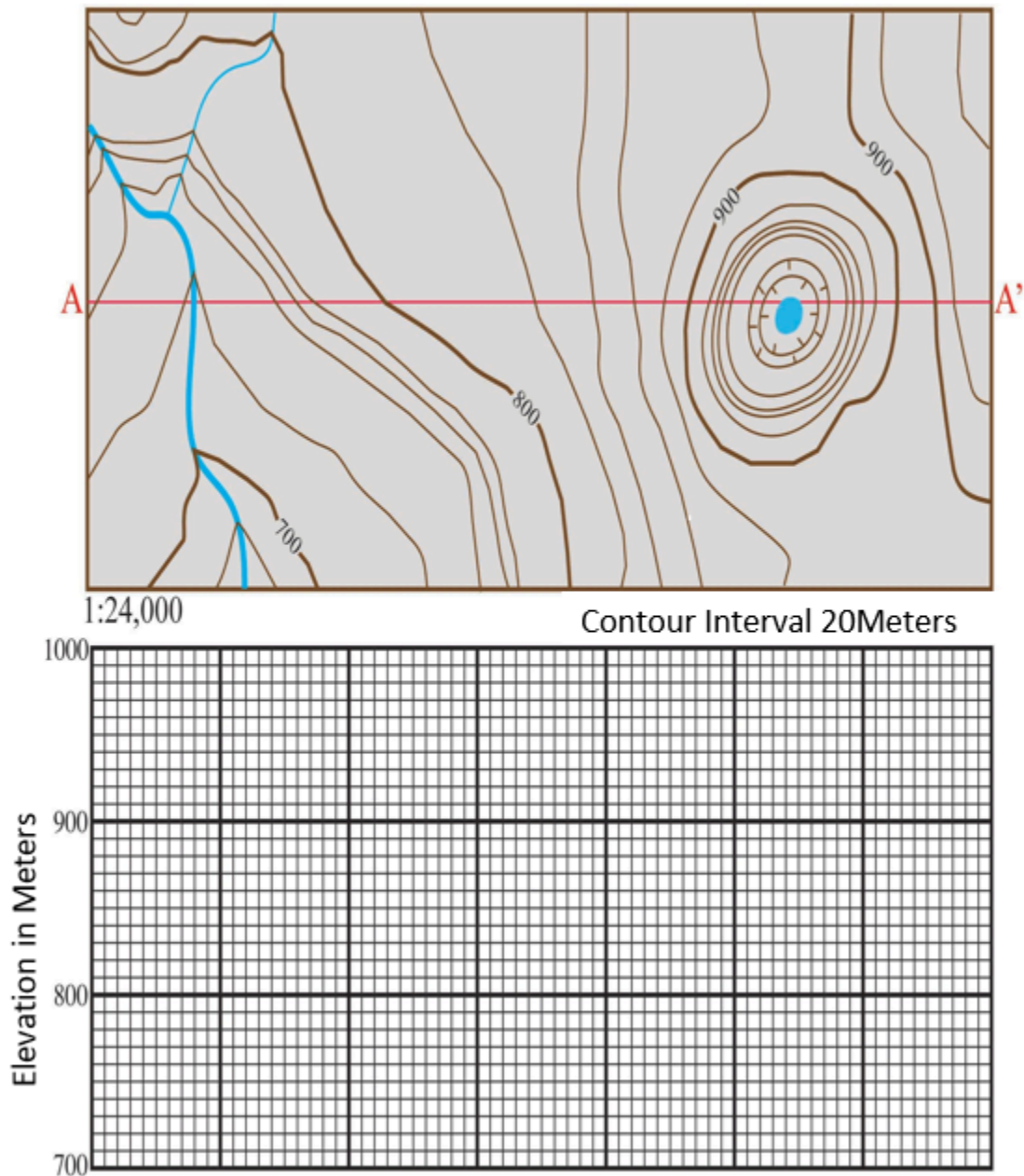
Figure 7-E6 | *Topographic map and cross-section.*
Source: Sean Lacey (2018) CC BY 4.0, after Brad Deline (2017) CC BY-SA 3.0 view source

5. (3 pts) Based on the scale chosen for you for the topography (vertical axis), calculate the amount of vertical exaggeration on the topographic profile you constructed for question 4. Show your work.

Questions 6 to 16: MAP 092G095 Mt. Garibaldi Area, B.C.

For the following exercises, please refer to British Columbia Topographic Map 092G095 of the Mount Garibaldi area in

southern BC. A thumbnail version of the map is shown in Figure 7-E7, a larger copy is provided at the back of this lab manual, and your TA will provide you with a full-scale version of the map in lab.

6. (1 pt) What is the ratio scale of this map?

7. (1 pt) Explain in a sentence how a ratio scale works.

8. (1 pt) Examining your map, you will see there is a black line that outlines a rectangle that takes up most of the map area. What is the latitude on the northern edge of this rectangle?

9. (1 pt) What is the longitude along the eastern edge of this rectangle?
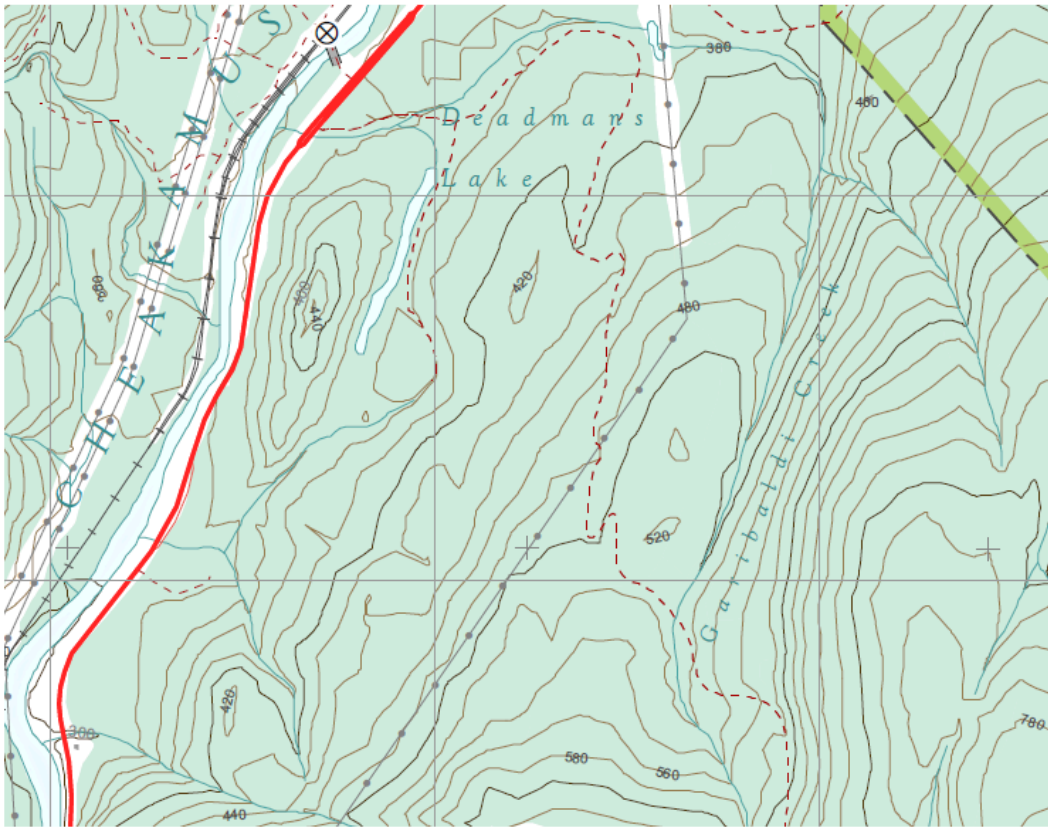
10. (1 pt) Find Deadmans Lake (it is located close to Cheakamus River and south of Daisy Lake; refer to Figure 7-E8 which is a close up from the map area). Using the surrounding contour lines, what is the approximate elevation of Deadmans Lake? Note: *if you are unable to read the contours on the map, view the original map on the web or look at the large printed copy in the lab.*

11. (1 pt) Garibaldi Creek is located east of Deadmans Lake (Figure 7-E8). Using the contour lines, determine the upstream direction of the creek. How were you able to come to this conclusion?
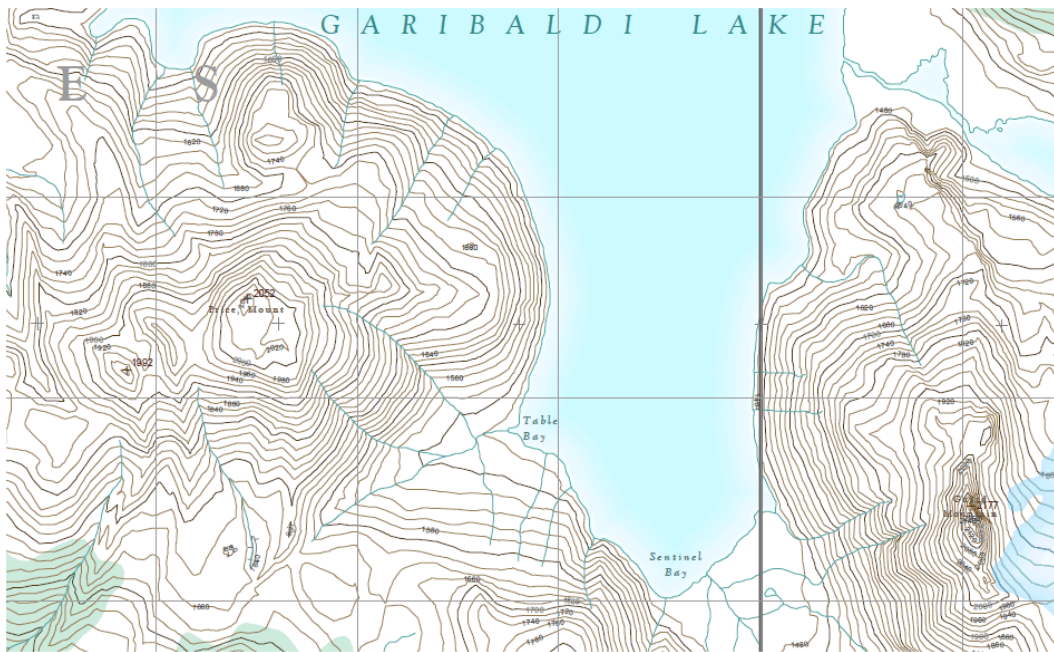
12. (1 pt) Mount Price is located next to Garibaldi Lake (just west of Table Bay, Figure 7-E9 above). Determine the height of Mount Price.

13. (1 pt) How much higher is Mount Price than Garibaldi Lake?

14. (2 pts) What is the gradient between Garibaldi Lake and Mount Price? Show your work below. Mark Figure 7-E9 with a line to indicate the distance you used in your calculation.

15. (2 pts) How would the gradient change if you measured from the peak of Guard Mountain (on the east side of the lake, across from Mount Price) to Garibaldi Lake? Explain why.

16. (1 pt) If someone decided to climb Mount Price, what would be the easiest and safest route to take? Explain why. *Hint: draw a simple map or a rough cross-section sketch to help illustrate your logic.*

Questions 17-19: Saskatoon Area Topographic Map

Please refer to this Saskatoon topographic map to complete the next three questions. A thumbnail version of the map is shown in Figure 7-E10, a larger copy is provided at the back of this lab manual, and your TA will provide you with a full-scale version of the map in lab.

https://opentextbooks.uregina.ca/app/uploads/sites/81/2020/11/SKtopomap_v2-1.pdf
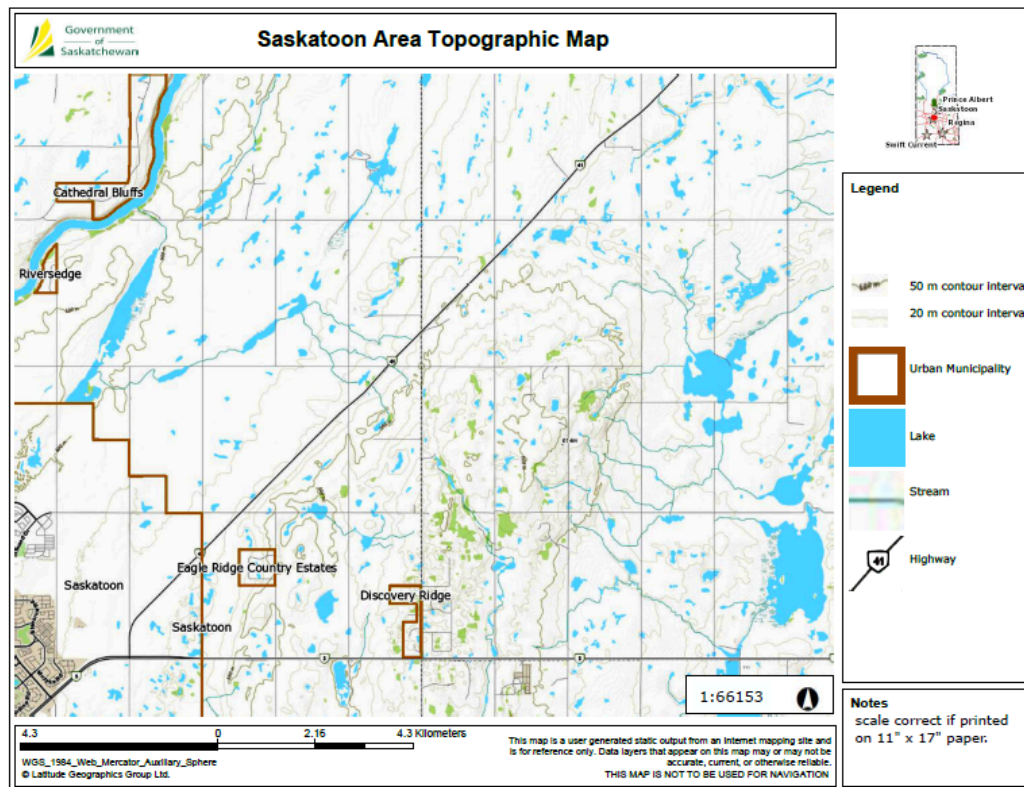
Figure 7-E10 |
Topographic map of Saskatoon area. Source: Government of Saskatchewan © 2018.
View source

17. (2 pts) What is the ratio scale used on this map? Why would a smaller ratio scale be used for this map in comparison to the Garibaldi map?

18. (2 pts) What is the relief on this map? Give the elevation of the highest and lowest contour lines as well as the difference between them.

19. (1 pt) Contour intervals located on this map are few and far between. Why is this so?

5. Extra Practice Question on Topographic Maps

Adapted by Joyce M. McBeth, Sean W. Lacey, & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 3 "Topographic Maps" by Karen Tefend and Bradley Deline, CC BY-SA 4.0. [View Source](.).

7-E3 Extra Practice Exercises – Topographic Maps

For questions 1 to 4 refer to the Map 7-E11. The following topographic map shows an interesting geological feature called a drumlin, which is a pile of sediment left behind by a retreating glacier.
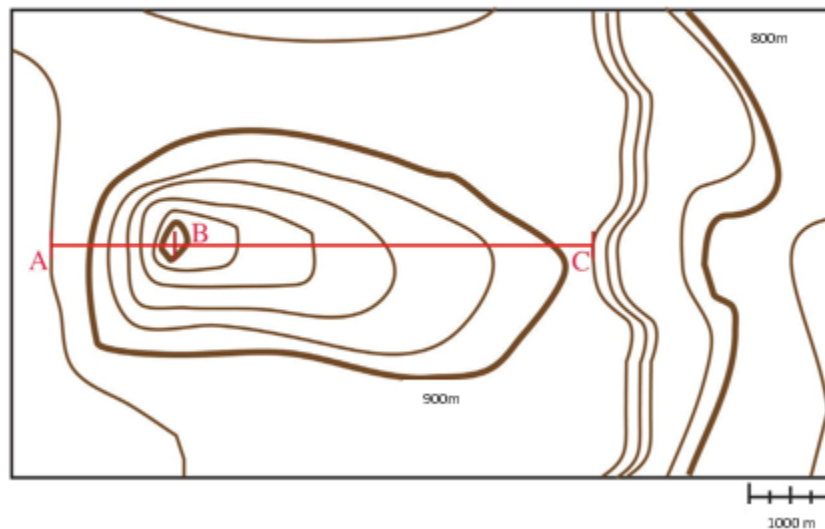
Figure 7-E11 | *Topographic map of a drumlin.*
Source: Sean Lacey (2018) CC BY 4.0, after Brad Deline (2017) CC BY-SA 3.0 [view source](.)

1. What is the contour interval on Map 7-E11?

2. What is the regional relief on Map 7-E11?

3. Using the contour lines on Map 7-E11, which section along the red line through the centre of the map is steeper: A to B *or* B to C? Explain how you came to this conclusion.

4. Calculate the gradients from A to B *and* B to C on Map 7-E11? Show your work.

5. Drumlins can be used to determine the direction of glacier ice flow. The glacier moves in the direction from the steeper side to the shallower (less steep) side of the drumlin. Using your previous answers for Map 7-E11, what direction was the glacier traveling? *Note: assume that the top of the map is north.*

CHAPTER 8. GEOLOGICAL STRUCTURES

Joyce M. McBeth, Karla Panchuk, Lyndsay R. Hauber, Tim C. Prokopiuk, & Sean W. Lacey (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0. [View source.](#) Last edited: 8 Jan 2020

8.1 INTRODUCTION

Earth is an active planet shaped by dynamic forces. Forces generated by plate tectonics and other geological processes can build mountains, and crumple and fold rocks. As rocks respond to these forces, they undergo deformation, which results in changes in shape and/or volume of the rocks. The resulting features are termed geologic structures. This deformation can produce dramatic and beautiful scenery; for example, in Figure 8.1 the originally flat (horizontal) rock layers were deformed to form folds in the rocks. Structural geology is the subfield of geology in which scientists study the relationships between geological structures (such as folds and faults) and the processes (such as plate tectonics) that have shaped Earth's crust through time.

Figure 8.1 | *Deformed rocks along the coast of Italy.*
Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

Why is it important to study structures and deformation within the crust? These studies can provide us with a record of the geologic history in a region, and also give us clues to the broader geological processes happening globally through time. This information can be critical when searching for valuable mineral resources. The correct interpretation of features created during deformation helps geologists find oil and valuable metal ores in the petroleum and mining industry, respectively. It is also essential for engineers to understand the behavior of deformed rocks to create and maintain safely engineered structures (e.g., in open and underground mines, and for roads).

When engineers do not adequately consider geology in their planning – for example by excluding consideration of geological structures – disaster can strike. An example of this is the disaster that occurred at the Vajont Dam, Monte Toc, Italy in the early 1960s. The location was a poor choice for a dam: the valley was steep and narrow with undercut riverbanks at the base and the area surrounding the dam was prone to large landslides due to solution cavities in the limestone canyon walls which could fill with water and interbedded claystones that generated zones of structural weakness in the rocks. Thorough geological tests were not performed prior to construction. Shifting and fracturing of rock that occurred during the filling of the reservoir and faster downhill movement of surface geological deposits were warning signs that went unheeded. In 1963, a massive landslide in the area displaced much of the water in the dam, causing it to override the top of the dam and flood the many villages downstream, resulting in the deaths of almost 2,000 people (Figure 8.2).

Figure 8.2 | *An image of the Vajont reservoir shortly after the massive landslide (landslide scar at right, dam located in foreground on the left).*
Source: Unknown (1963) copyright expired. view source

There are two parts to this chapter overviewing geological structures:

Part I – strike, dip, and structural cross-sections: overview of the methods geologists use to describe geological structures, including strike and dip measurements, representations of geological structures on maps, how to construct geological cross-sections and measure the thicknesses of geologic units; and

Part II – folds, faults, and unconformities: overview of how to interpret and draw more complex geological structures on geological maps and cross-sections.

8.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Demonstrate an understanding of the concepts of strike and dip
- Use block diagrams to display geologic features
- Interpret a geologic map
- Create a geologic cross-section from a geologic map
- Understand the types of stress that rocks undergo, and their responses to stress
- Recognize the different types of folds and faults, and the forces that create them

8.1.2 Key Terms

- Anticline
- Basin
- Compressional forces
- Contact
- Dip
- Dip-slip fault
- Dome
- Geological cross-section
- Geological map
- Horst & graben structure
- Monocline
- Normal fault
- Reverse fault
- Shear forces
- Strain
- Stress
- Strike
- Strike-slip fault
- Syncline
- Tensional forces
- Thrust fault

Overview of Geological Structures Part 1: Strike, Dip, and Structural Cross-Sections

Adapted by Joyce M. McBeth, Karla Panchuk, Lyndsay R. Hauber, Tim C. Prokopiuk, & Sean W. Lacey (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0. [View source.](#) *Last edited: 8 Jan 2020*

In Part I of geological structures, students will learn how to interpret strike and dip information from a geological map, prepare a geological cross-section from a plan-view geological map, and measure the thicknesses of geological units.

8.2 STRIKE & DIP

To learn many of the concepts associated with structural geology, it is useful to look at block diagrams and block models. Block diagrams are images based on three-dimensional (3-D) block models, which are blocks of wood or paper with geological structures marked on them. Block models and block diagrams assist in visualizing how 3-D geological structures in the real world can be represented in two dimensions on a map or in a geological cross-section.

As you examine the block diagrams in the figures in this section, note the different ways that you can view them: from above, or from the sides. If you look at a block from along the side, you are seeing the cross-section view. This is the view of geological structures you also see when you drive through the mountains and the roads have been cut through the rocks, exposing structures in the rock that you wouldn't see otherwise. If you look at the block from directly above, you are looking at the map or plan view (Figure 8.3).

Figure 8.3 | *Map or plan view vs cross-section view. The top block in this image is an area viewed in map view, which is the view from directly above the block. The lower block is from the same rock layers, and you are viewing it in cross-section (or from the side). Note that when you view the rocks in cross-section, you can see how the rock layers are tilted. Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)*

As you look at geological maps and drawings and try to figure out about how rocks have changed when they are tilted and/or deformed, it is useful to remember how they were deposited in the first place. Let's briefly review some of the geological laws that you learned in the chapter on relative and absolute dating. Sedimentary rocks, under the influence of gravity, will deposit in horizontal layers (principle of original horizontality). The oldest rocks will be on the bottom (because they had to be there first for the others to deposit on top of them), and are numbered with the oldest being #1 (law of superposition). The wooden block in Figure 8.4 (a cross-section view of sedimentary layers) provides an example of the principle of original horizontality and the law of superposition.

Figure 8.4 | *Horizontal sedimentary layers viewed in cross-section. In this image, different rock types are given different colors. The oldest rock, on the bottom, is labelled #1. The youngest rock in this image is #4.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

Each of the boundaries between the colored rock units in Figure 8.4 represents a geological **contact**, which is the planar surface between two adjacent rock units. Earth's rock layers are often complicated: rock layers are often tilted at an angle, not horizontal – this indicates that changes have occurred since deposition (e.g., the rocks have been uplifted by tectonic activity and tilted). Figure 8.5 is a block model example of tilted rocks. Which color bed in the block model is the oldest? Given the law of superposition and the principle of original horizontality, it is more likely that the gray bed on the bottom left side of the block was the bottom bed during deposition, and therefore the oldest. In some circumstances, beds can be completely overturned (for example in recumbent folds); if this was the case, the grey bed would be the youngest bed in figure 8.5. In the lab exercises for this chapter we will not have any exercises with overturned beds.

Figure 8.5 | *Tilted rocks in a block model.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

To measure and describe the geometry of geological layers, geologists apply the concepts of strike and dip. **Strike** refers to the line formed by the intersection of a horizontal plane and an inclined surface. This line is called a strike line, and the direction the line points in (either direction, as a line points in two opposite directions) is the strike angle. **Dip** is

the angle between that horizontal plane (such as the top of the block in figure 8.5) and the inclined surface (such as a geological contact between tilted layers) measured perpendicular to the strike line down to the inclined surface. A useful way to think about strike and dip is to look at the roof of a house (Figure 8.6). A house's roof has a ridge along the top, and then sides that slope away from the ridge. The ridge is like a strike line, and the angle that the roof tilts is the dip of the roof.
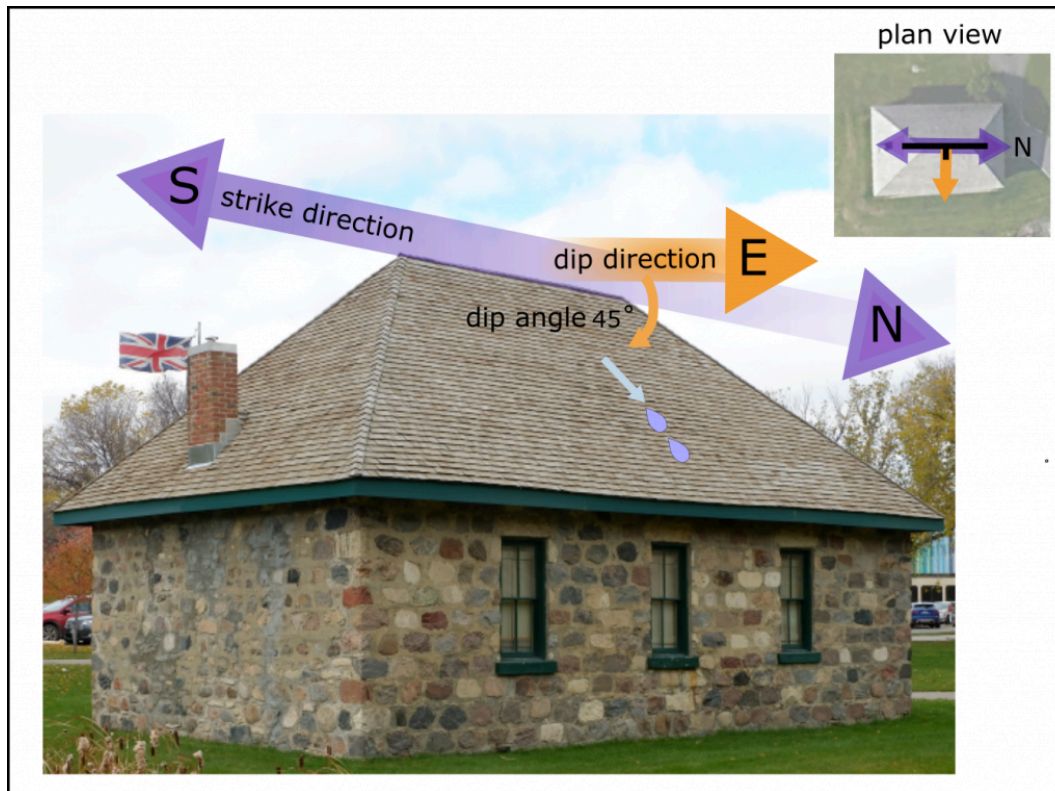

Figure 8.6 | Strike and dip of a roof. The sloping roof of a building is a useful analogy to illustrate strike and dip. The ridge of the roof defines the strike of the roof. The roof dips away from the ridge with a characteristic angle (the dip angle). The inset in the top right corner of the figure shows the roof viewed from above with the strike and dip symbol superimposed on it (symbol explained in the text below). Source: Joyce M. McBeth (2018) CC BY-SA 4.0. Satellite image from © 2018 Google Earth.

Figure 8.7 illustrates strike and dip for tilted flat sedimentary layers. The line of strike is represented by the water line when a lake intersects with the rock along the shoreline (Figure 8.7). The dip angle for the beds is measured from the horizontal surface to the uppermost dipping bed, perpendicular to the strike line.
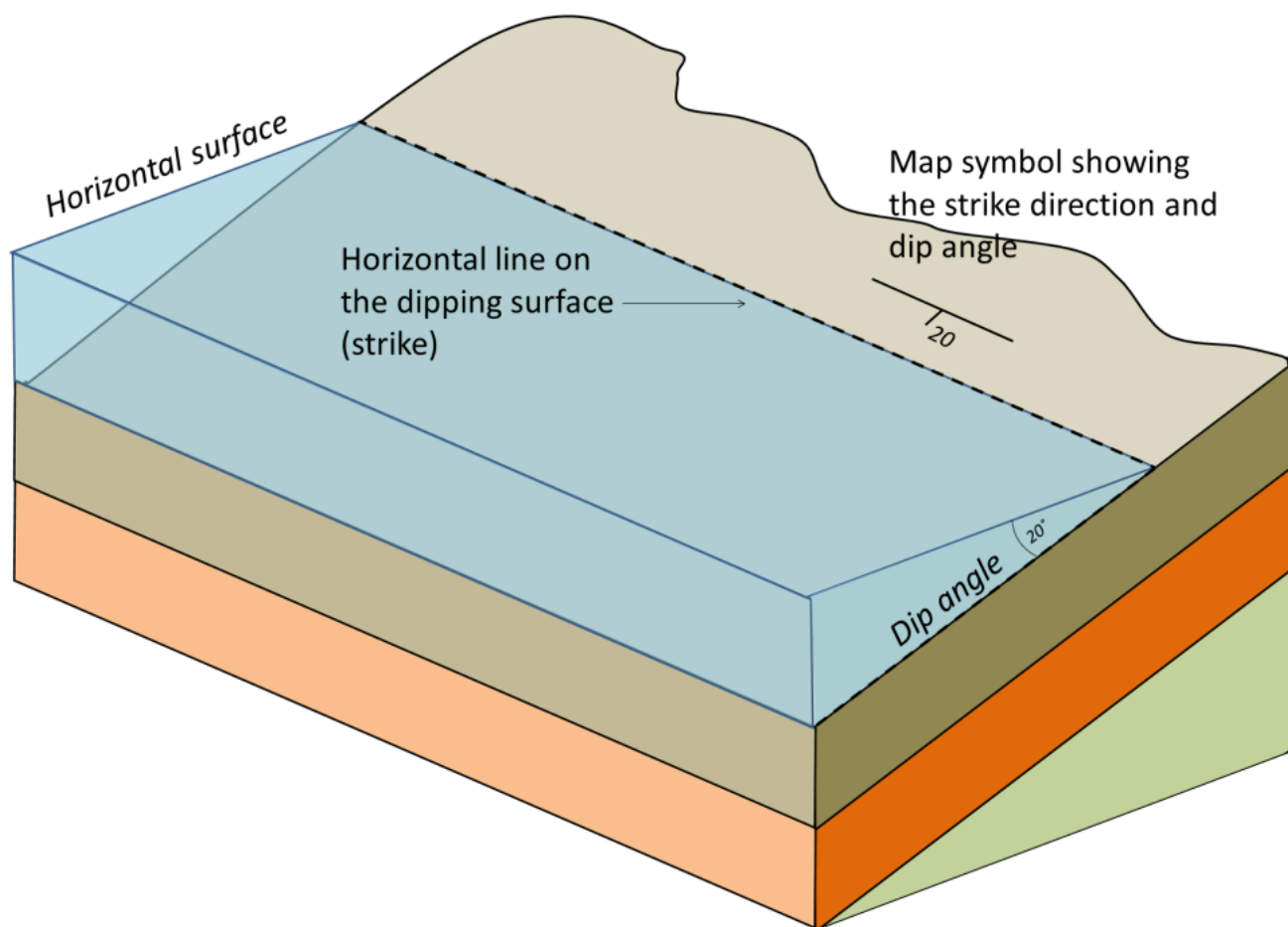
Figure 8.7 | *Strike and dip for tilted sedimentary beds. Water provides a horizontal surface. The strike and dip symbol is a T with the long horizontal bar representing the strike direction, and the small tick mark indicating the dip direction. The dip angle is written next to the tick mark.*
Source: Karla Panchuk (2018) CC BY 4.0. Modified after Steven Earle (2015) CC BY 4.0 *view source*

Now, let's apply this concept to the block of dipping beds in Figure 8.5. To find a strike line, find where a contact intersects the horizontal surface. Each dipping contact intersects the horizontal surface in a horizontal line, so there are many strike lines to choose from. To determine dip, pretend that there is a drop of water between one bed and the next, for example, along the intersection of the pale blue bed and the red bed. In which direction would the water roll if it followed that contact? That is the direction of dip — here, it is towards the right side of the figure. Note that the dip symbol (shorter line) should be drawn perpendicular to the strike symbol, whatever the angle of dip (Figure 8.8).
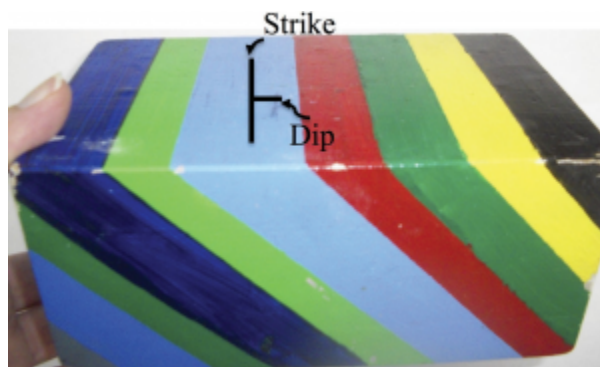
Figure 8.8 | *This image depicts the strike and dip for the pale blue bed in the block. Because the beds are oriented in the same direction, they all have the same strike and dip.*
Source: Randa Harris (2015) CC BY-SA 3.0 <u>*view source*</u>

The rule of Vs for contour lines that we discussed in the topographic maps section of this lab manual is also useful for interpreting the direction that beds and other geological structures (e.g., faults) are tilted on maps. The law of Vs for geological structures is more complicated than the rule of Vs for contour lines since there is an additional layer of complexity when we add in the geology. You can usually determine the dip direction of inclined beds by looking at the direction of the V that forms when the bed crosses a valley on a map. This resulting V may or may not point in the direction the bed dips, depending on the slope of the valley. For vertical beds, no V shape is created in map view: the bed cuts directly across the valley without being deflected in either direction (Figure 8.9 A/B). For inclined beds if the bed dips in the opposite direction as the slope of the valley, the V will point in the direction of dip (Figure 8.9 E/F). The situation is more complex when the beds dip in the same direction that the valley slopes. If the dip of the beds is steeper than the slope of the valley, then the V will point in the direction of dip (8.9 C/D). But if the valley slopes steeper than the dip of the beds, the V will point in the opposite direction of dip (example not shown in Figure 8.9). For horizontal beds the edge of the bed will intersect topography parallel to topographic contours. If the landscape is flat near the valley, the bed will intersect in a straight line along the edge of the valley (Figure 8.9 G/H). If the landscape is sloping near the valley, the bed will generate a V shape parallel to the contour lines in the valley (I/J).
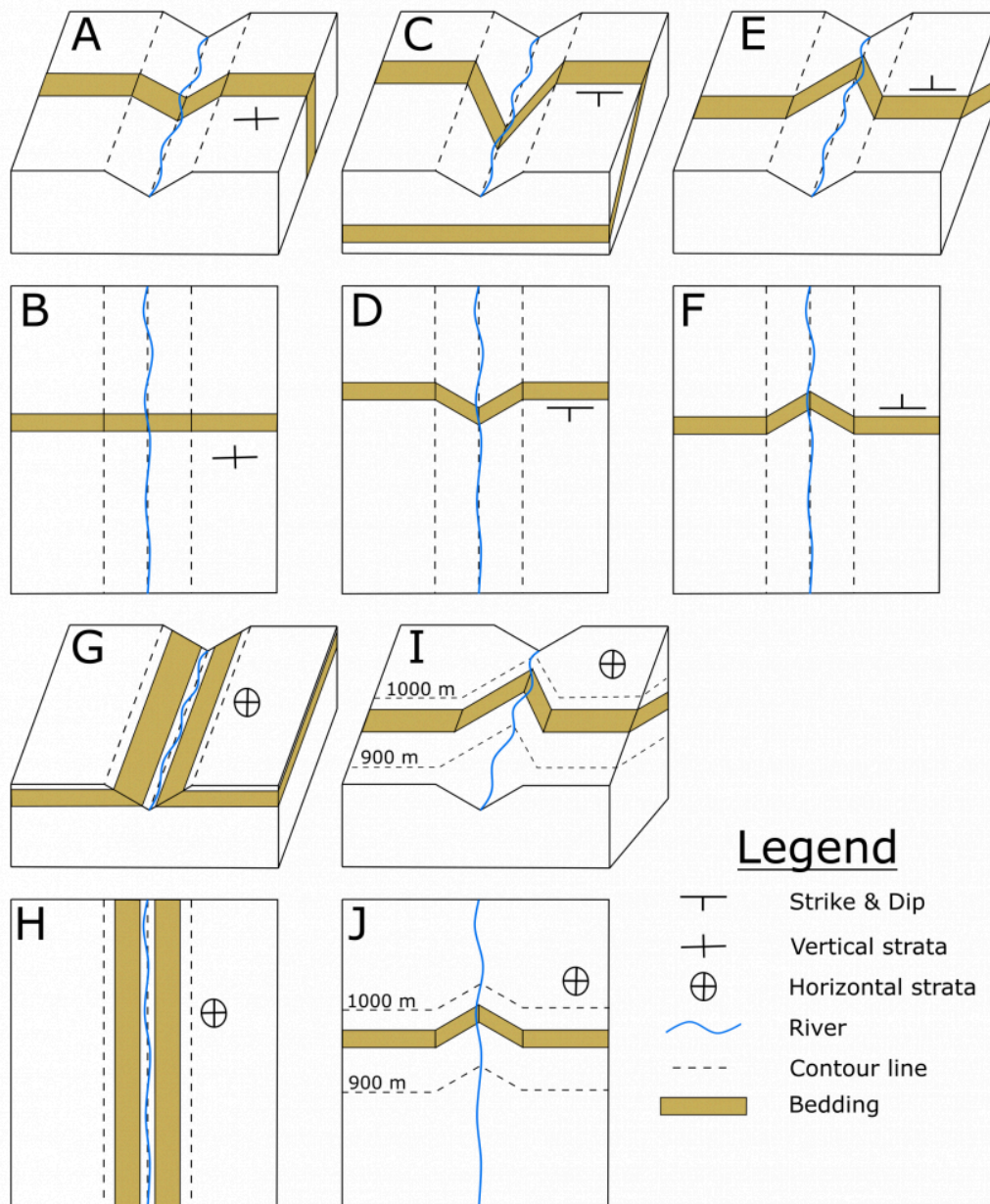
Figure 8.9 | *The Law of Vs are characteristic patterns that develop when inclined strata are cross-cut by streams or gullies in the landscape. In each paired set of images, the top image shows a block diagram and the bottom image shows the plan view for the same block diagram. Note that these examples (aside from panels I and J) are for a valley cutting across a flat landscape; some of these patterns would be different if there was a slope to the topography in addition to the valley. Images A and B in the panel show vertical beds; these do not generate a V shape when cut by a valley on a map, even if the topography is sloping. Image C and D show beds that are inclined and dipping toward the bottom of the page. Images E and F show beds that are inclined and dipping toward the top of the page. Images G and H show beds that are horizontal; in images I and J horizontal beds generate a V pattern when the stream valley is cutting through a slope. In both G/H and I/J, the edge of the bed is always parallel to topographic contours. Source: Lyndsay Hauber & Joyce McBeth (2018) CC BY 4.0, original work.*

In the law of Vs, vertical and horizontal beds generate unique patterns when they intersect with the surface of Earth. Figure 8.10 provides another illustration of these patterns, this time for a symmetrical hill. Not that in the case of the vertical beds (Figure 8.10A), there are no Vs produced in the landscape, and the feature is linear across the landscape despite the changes in the topography. We would see the same pattern in the landscape for vertical faults or other vertical geological features. In the case of horizontal beds (Figure 8.10B), the strata intersect with the topography in lines that are parallel to the contour lines. What pattern would you expect to see if a stream ran through Figure 8.10B and partially eroded into the slope? *Hint: see Figure 8.9 I and J.*
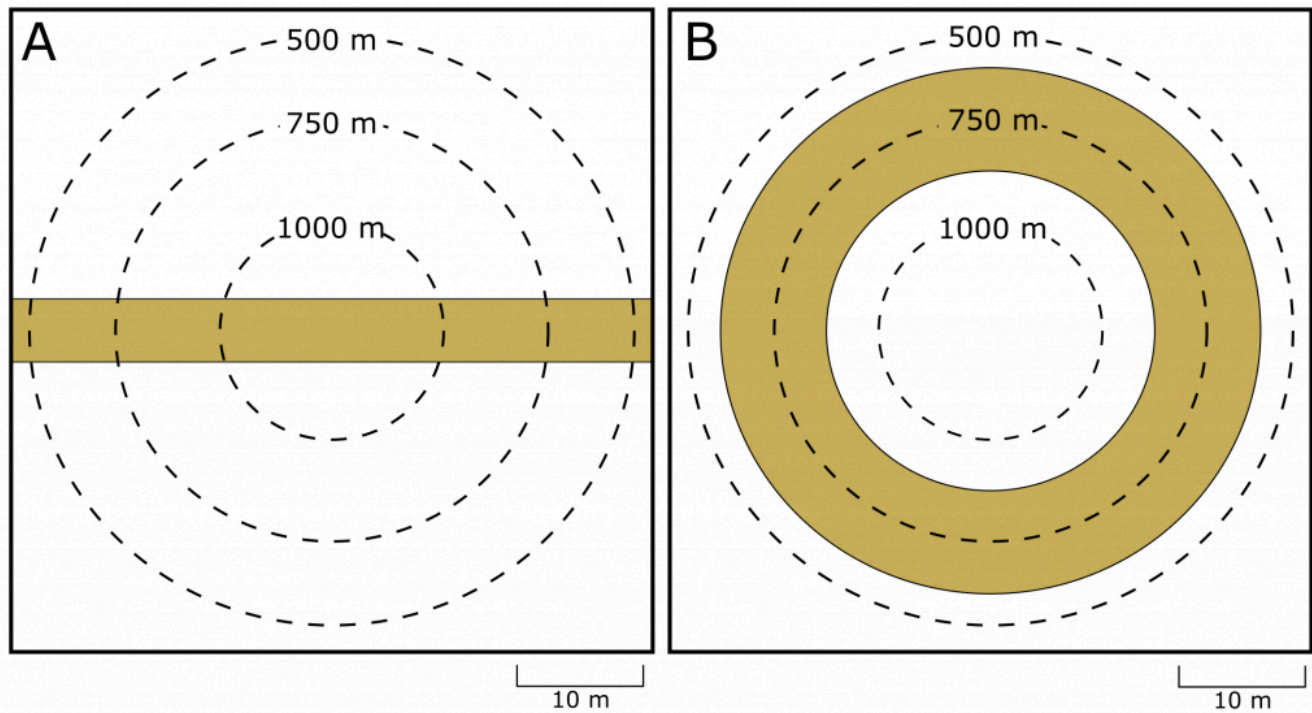
Figure 8.10 | *Vertical (A) and horizontal (B) beds in regions with variable topography, in this case a symmetrical hill.*
Source: Lyndsay Hauber & Joyce M. McBeth (2018) CC BY 4.0 original work.

8.3 GEOLOGICAL MAPS & CROSS-SECTIONS

A **geological map** uses lines, symbols, and colors to communicate information about the nature and distribution of rock units within an area. The map includes information about geological contacts and their strikes and dips. Geologists make these maps by careful field observations at numerous outcrops (exposed rocks at Earth's surface) throughout the mapping area. At each outcrop, geologists record information such as rock type and the strike and dip of the rock layers. They can also include relative age data in their map if they are able to find evidence of relationships between the rocks using the principles of relative dating. Geological maps take practice to understand, because three-dimensional features (including complex features such as folds) are displayed on a two-dimensional surface. Remember that a geological map will be seen in map view, i.e., they are viewed from above. A geological map is analogous to viewing a floor plan to a house – there are many things you can represent in plan view (e.g., doors, appliances, stairs) that will help you visualize what the interior will look like if you were to visit the house in real life.

Geologists use information about rocks that are exposed to visualize how the unseen rocks beneath the surface are oriented. This allows geologists to prepare their best interpretation of the cross-sectional view of the geology below the surface, similar to what we observed in the blocks above.

A **geological cross-section** shows geologic features from the side view (the side views of the block diagrams in Figures 8.3-8.5 are cross-sections). They are similar to the topographic profiles that you created in the topographic maps chapter, but they also show the rock types and geologic structures present beneath Earth's surface.

There are four things to include on every geological cross-section: a legend, the orientation of the line the cross-section represents on the map, a title, and a scale (e.g., Figure 8.11C). To help us remember, we abbreviate these four key parts with the acronym L.O.T.S.

Legend – the legend is a key to the patterns used to identify each unit on the cross-section. The units are ordered from oldest formation at the bottom of the legend to youngest unit at the top of the legend.

Orientation – the orientation of the cross-section is the direction that the cross-section line makes on Earth (the "strike" direction of the cross-section line on the geological map). You can indicate the orientation by writing the corresponding direction at each end of the cross-section (e.g., west and east on Figure 8.11C).

Title – a descriptive title for the cross-section. You can include the letters used to identify the line on the original geological map in the title (e.g., Cross-Section along Line X-Y in Figure 8.11C).

Scale – include a ratio scale and/or a bar scale to show the scale of the cross-section. The vertical and horizonal scales should be the same, so you only need to include one scale on the cross-section.

Figure 8.11 provides an example of a simple geological cross-section. To construct a geological cross-section, follow these steps:

1. Carefully look at the geological map that you are using to construct your cross-section (e.g., Figure 8.11A). Pay close attention to any strike and dip symbols, geological contacts, and ages of the rock types (Figures 8.12 and 8.13 have examples of rock age abbreviations and common structural symbols used on geological maps).
2. Identify the position on the map designated for the cross-section. The line will be indicated by an actual line, or with positions labelled with letters on the edges of the map, e.g., "X" and "Y".
3. Take a clean sheet of paper, and line it up along the line on the plan view map (Figure 8.11B). At each geological contact, make a mark on the edge of the paper.
4. Using any strike and dip symbols on the map, add the dip onto the marks on your piece of paper, showing the direction the rocks are dipping, and note the angle of dip for each position.
5. If strike and dip symbols are not provided but based on the Law of Vs or the ages of the beds you are able to determine that there are dipping or vertical structures present, include these as corresponding marks on your paper. Use your best interpretation of the dip direction if dips are not given on the geological map.
6. Transfer the marks from your paper to the bottom of the cross-section diagram provided (Figure 8.11C). You can prepare your own cross-section diagram based on the example in the exercises section of this chapter. The x-axis of the diagram will be the distance along the line on the map, and the z-axis will be the elevation of the rocks (usually measured relative to sea level or another benchmark).
7. Draw the topography on the cross-section (just as you did in the exercises in the topographic maps chapter). Note that in the example in figure 8.11 the map area is flat.
8. Transfer the marks from along the edge of your piece of paper to the points along the line where they intersect with the topography. These are the points where the geological structures are exposed at the surface.
9. Sketch the structures into your cross-section, starting at the points where the structures meet the topographic surface. Pay careful attention to dip angles (if they were provided). Structures may be drawn in with a dotted line above Earth's surface to indicate rocks that were formerly present but that have since been eroded (e.g., Figure 8.11C). You can also use dashed lines to indicate the position of the bottom of beds when you don't have any evidence for their thickness or if you have some basis to know that they will end within the cross-section, e.g., sedimentary beds overlying metamorphic basement rock that is exposed elsewhere in the region.
10. Don't forget L.O.T.S.! Add a legend, orientation, title, and scale to your cross-section (Figure 8.11C). Ensure your units and legend on the cross-section use the same colour or pattern scheme as on the original geological map.

Map Area Alpha

A

X ———————————————————————— Y

M | D | S | O | S | D | M

N

Legend
- ☐ M
- ☐ D
- ☐ S
- ☐ O

1 km

B

oldest
↓

M | D | S | O | S | D | M

C

Cross-section of Map Area Alpha along line X-Y

W   E
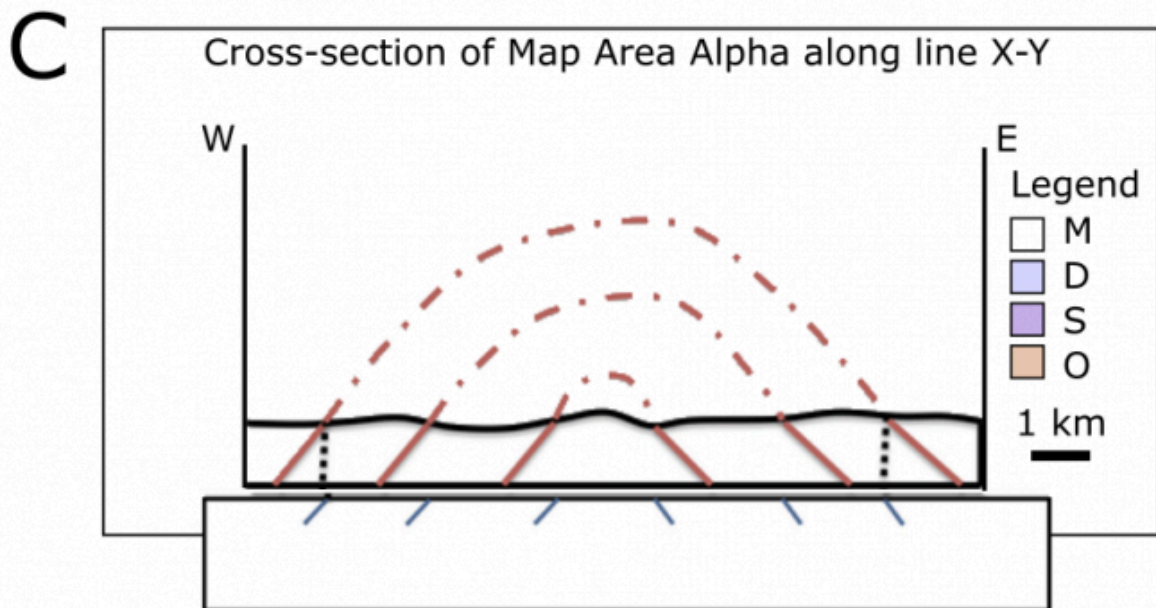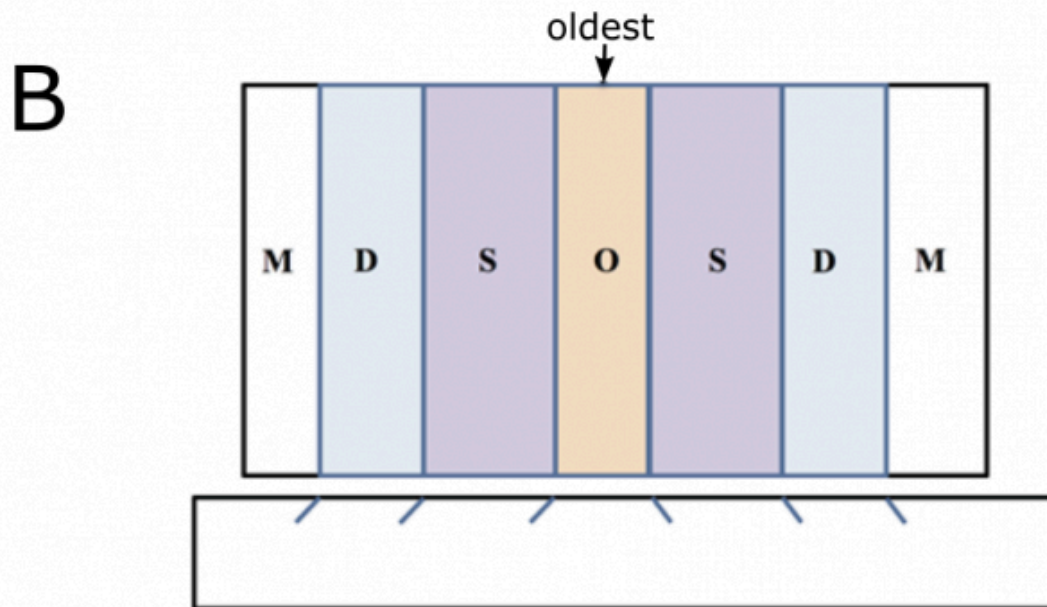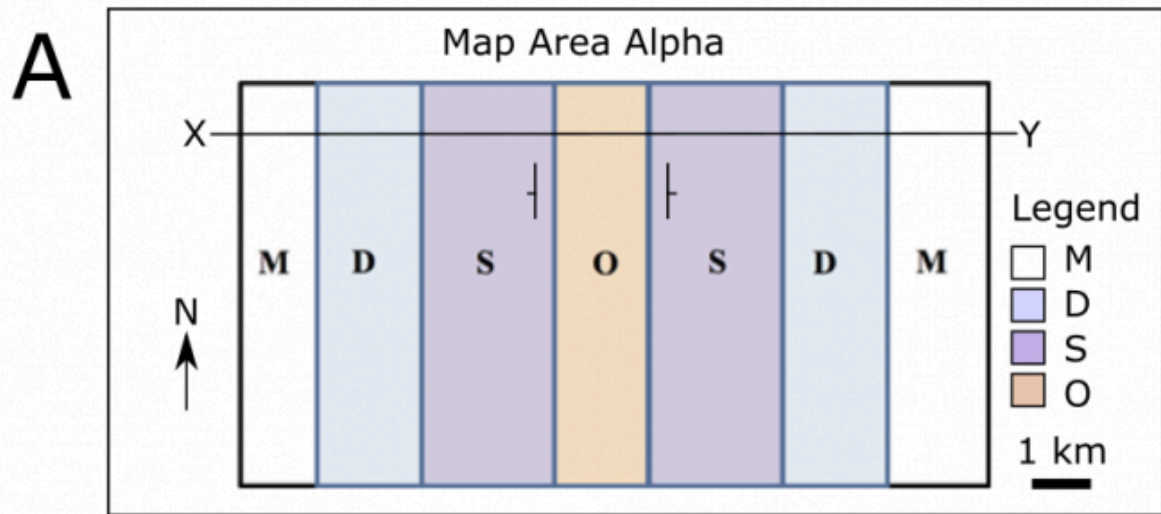
Legend
- ☐ M
- ☐ D
- ☐ S
- ☐ O

1 km

Figure 8.11 | Illustration of how to construct a cross-section from a geological map. A) geological map, with different rock units indicated by different colours, and age information given (see Figure 8.12 for code for rock unit ages). B) A blank sheet of paper is stretched along the bottom of the cross-section, and a mark is made at each geologic contact. Since the oldest bed is in the middle, this indicates that this structure is an anticline (also supported by the strike and dip symbols on the map), so beds have been drawn so that they dip away from each other. C) The paper is aligned with the cross-section diagram and the contact marks are transferred to the cross-section (as indicated by the black dashed lines on each end mark that connect up to the surface expression of the bed). Beneath the surface, contacts have been drawn in using a solid line. The beds above the surface that have since eroded have been drawn in with a dashed line. Note the parts of a cross-section diagram illustrated in C): L.O.T.S.
Source: Joyce M. McBeth (2018) CC BY-SA 4.0, after Randa Harris (2015) CC BY-SA 3.0 view source

Age of Rocks	Geologic Age Symbol	Geologic Time Period
Youngest	Q	Quaternary
	T	Tertiary
	K	Cretaceous
	J	Jurassic
	Tr	Triassic
	P	Permian
	IP	Pennsylvanian
	M	Mississippian
	D	Devonian
	S	Silurian
	O	Ordovician
	-C	Cambrian
Oldest	p-C	PreCambrian

Figure 8.12 | *Guide to rock ages. Source: Randa Harris (2015) CC BY-SA 3.0. View source*

Map Symbol	Explanation
├	Strike & Dip
+	Vertical strata
⊕	Horizontal strata
⊬	Anticline axis
⊢	Syncline axis
✗	Plunging anticline axis
✗	Plunging syncline axis
⫽	Strike-slip fault

Figure 8.13 | *Guide to common map symbols. Source: Randa Harris (2015) CC BY-SA 3.0. [View source](#)*

8.4 CALCULATING BED THICKNESSES

As you study Figure 8.11 and work though the exercises in this lab, you will notice that the thicknesses of the sedimentary beds in the plan-view map (viewed from overhead) are different from the thicknesses of these beds in the cross-section view. Generally, the cross-section view will show that the **true thicknesses** of the beds are thinner than what they appear to be in plan-view, the latter of which would be an **apparent thickness**. But true thicknesses are only displayed in cross-sections that are constructed perpendicular to strike. Any other cross-sectional view will also result in a distorted or apparent thickness that appears thicker than the true thickness of the bed.

Figure 8.14 illustrates why we see this difference. The line marked y-z represents the **upper contact** of the bed (where the sedimentary bed comes in contact with the bed above it), and the line marked x-w represents the **lower contact** (where the sedimentary bed comes in contact with the bed below it). The beds are inclined in the figure, so the length of the distance between x and y (labelled "c") is longer than the shortest distance between the upper and lower contacts (labelled "b"). If you know the angle that the beds are dipping and the distance between x and y, you can calculate the thickness of the beds using trigonometry. Providing that you draw the map to the same scale in all directions (i.e., not exaggerated on the vertical axis) you can also directly measure the distance between the bottom of the bed and the top of the bed using a ruler and the scale of the cross-section to get the true thickness. Remember that when using a cross-section to measure the true thickness of a bed, that the cross-section must be drawn perpendicular to the strike of the beds (illustrated in the plan view map in Figure 8.14).

In situations where the beds are vertical (dip = 90°), the thickness of the bed is equal to the distance between the upper and lower contact of the bed as measured directly on the geological map. If the beds are horizontal (dip = 0°) and there is enough topography that both the upper and lower contacts are exposed, the thickness of the beds can be measured by calculating the difference in elevation between the upper and lower contacts.

Plan view

Cross-section
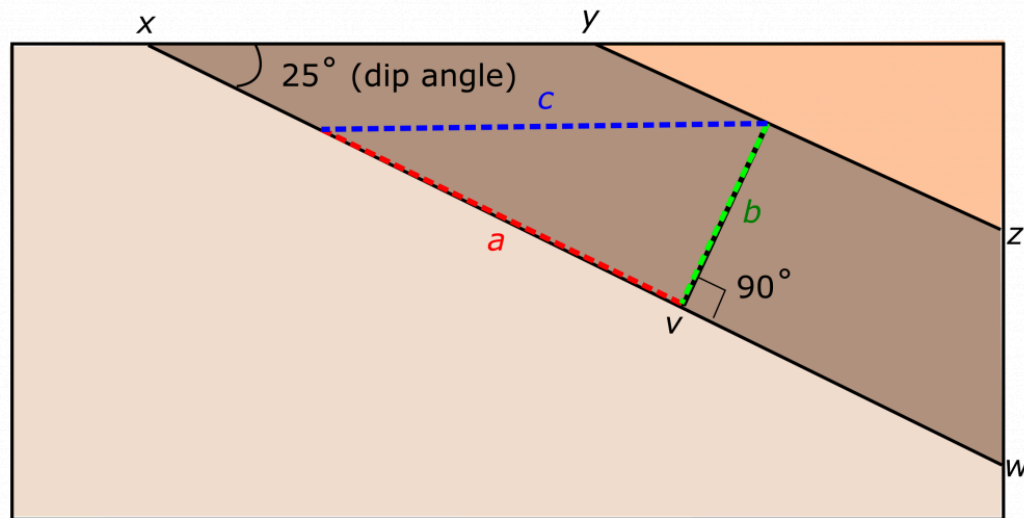
Figure 8.14 | *Apparent vs true bed thickness. The plan view map (top) shows how the cross-section is oriented perpendicular to the strike of the dipping beds along the line labelled A–A' (note strike and dip symbol and pink lines illustrating 90° angle between A–A' and the strike of the beds). The cross-section (bottom) shows how the distance between the upper and lower contacts of the brown bed (y–z and x–w respectively) are further apart at the surface (x–y, or c) than if you measure the shortest distance between the beds (b). Source: Joyce M. McBeth (2018) CC BY 4.0, original work.*

Exercises on Geological Structures Part 1: Strike, Dip, and Structural Cross-Sections

Adapted by Karla Panchuk, Joyce M. McBeth, & Lyndsay R. Hauber (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0 [View source.](#) *Last edited: 8 Jan 2020*

In Part 1 of geological structures, students will learn how to interpret strike and dip information, prepare a geological cross-section from a plan-view geologic map, and measure the thicknesses of geologic units.

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Please hand in this lab to your TAs at the end of the lab period.

This lab will take the full amount of lab time to complete. This lab and the second geological structures lab will be on the lab final and students often struggle with this material. Read the lab and overview section online in advance so you can make best use of your time in lab.

8.E1   LAB EXERCISE – STRIKE & DIP

1. *(1 pt)* For the following block diagram, determine the correct map symbol that should appear in the blue oval. *Note: the beige and red lines represent beds and the wavy blue line is a stream.*
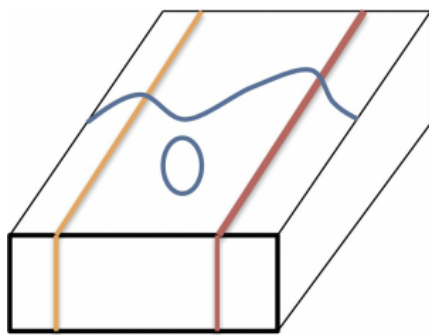
a.

b.

c.

d.

2. (1 pt) For the following map view diagram, determine the correct map symbol that should appear in the blue oval. *Note: the purple, green, and red lines represent beds, the wavy blue line is a stream, and the dotted lines are elevation contours.*
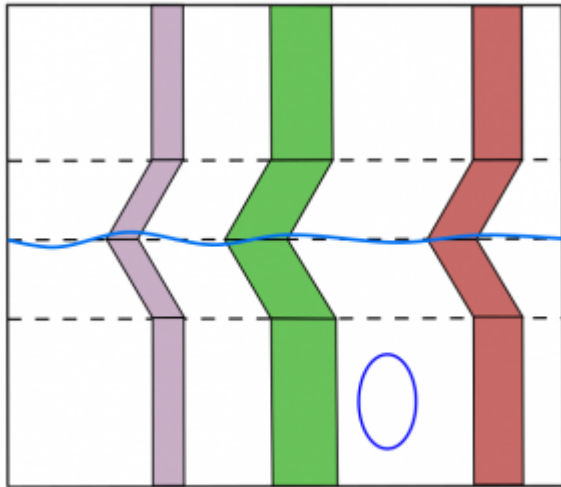
a.

b.

c.

d.

3. (1 pt) Using Google Earth or Google Maps, search for the following area in Pakistan: **27 50 35.00N 67 10 03.70E.** If you are using Google Maps through your browser, make sure satellite data is turned on. Zoom out to an eye altitude of approximately 7.9 km (about 26,000 feet; the scalebar in Google Maps will be 500 m long at this height). ***Note: double check that the position of the north arrow is pointed to the top of your screen before you answer the question!*** The layers in these folded rocks can be seen from this altitude. What evidence do you see that indicates the direction the rocks are dipping? ***Hint: If you zoom in a little bit closer on the gully that runs through the strata near the position marker you can see an example of the rule of V's in the darker-coloured strata.***

4. (1 pt) Which direction are the beds dipping?

a. Northeast (NE)

b. Southeast (SE)
c. Northwest (NW)
d. Southwest (SW)

8-E2: EXERCISES – CROSS-SECTIONS

The three geological maps on the next few pages will give you practice with constructing geological cross-sections.

Map 1: Murky Mists Mountain

1. (2 pts) Examine the map of the Murky Mists Mountain. Refer to the map legend. What kind of rocks are found in this map area: sedimentary, igneous, and/or metamorphic? How many units can you see?
2. (2 pts) Note the strike and dip symbol on the map. Presume that the units all have identical strike and dip. Which direction are the units striking and dipping?
3. (2 pts) Examine the contour lines on the map (dashed lines). Where are the highest points on the map? Where are the lowest points on the map?
4. (2 pts) Note the scale of the map. What is the distance in metres between point X and point Y? If you walk from X to Y, in what direction are you walking?
5. (15 pts) Prepare a cross-section through the map from position X to Y (X-Y) using the cross-section template we have provided. Do not forget to indicate the X and Y positions on your cross-section. Also, add a scale bar and the ratio scale, legend, and a title. To remember to add these critical components of a cross-section, remember the acronym L.O.T.S. (legend, orientation, title, scale). *Note: ensure your vertical scale and horizontal scale are the same, and order the units in your legend with the oldest at the bottom and the youngest at the top.*
6. (5 pts) Using the cross-section you have prepared and the distances between the upper and lower contacts for each unit, calculate the thickness of the limestone, sandstone, mudstone 2, chalk, and conglomerate units. Mark the location where you measured your thicknesses with a line on your cross-section. *Note: the thickness is the shortest distance between the upper and lower contact of a bed: a line that runs perpendicular to both contacts.*
7. (1 pt) Why can't you measure the thickness of the shale or mudstone 1 units?
8. (3 pts) In point form, describe the geological history of the map area. *Hint: start with the oldest event and describe events as they occurred up to the present day.*

Map 2: Delightful Dells Geological Paradise

1. (2 pts) What kind of rocks are found in this map area (sedimentary, igneous, and/or metamorphic)? How many units can you see?
2. (15 pts) Draw a geological cross-section between the points X and Y indicated on Map 2. *Note: you will have to prepare a cross-section from scratch for this exercise, but you can use the format from the Map 1 cross-section as a guide. If you are not sure where to start, use the questions from Map 1 to guide you through the process of exploring Map 2 and preparing your cross-section. Do not forget to incorporate the features described in the L.O.T.S. acronym. This is a more challenging cross-section – you will probably have to make several changes to get it right. Make sure you have an eraser with you!*
3. (2 pts) What are the thicknesses of the mudstone and sandstone layers? Indicate the locations where you

performed these measurements on your cross-section.

4. (1 pt) Why can't you measure the thickness of the conglomerate or the limestone?
5. (2 pts) In point form, describe the geological history of the map area.

Map 3: Four-River Ridge

1. (2 pts) What kind of rocks are found in this map area (sedimentary, igneous, and/or metamorphic)? How many units can you see?
2. (1 pt) Carefully study the relationship between the contour lines and the contact between the limestone and sandstone. What does this tell you about the orientation of these beds?
3. (1 pt) Examine the gabbro unit. What V pattern is formed by the four rivers that cut through this unit? What does this tell you about the orientation of this unit?
4. (2 pts) What is the strike and dip of the sedimentary units in this map area?
    strike = _ _ _ _ _ _ _ _ _ _ _ _ _   dip = _ _ _ _ _ _ _ _ _ _ _ _ _ _
5. (2 pts) What is the strike and dip of the gabbro dyke?
    strike = _ _ _ _ _ _ _ _ _ _ _ _ _   dip = _ _ _ _ _ _ _ _ _ _ _ _ _ _
6. (15 pts) Draw a cross-section through the map area along the line between points X and Y. **Hint: don't forget to incorporate L.O.T.S.!**
7. (4 pts) In point form, describe the geological history of the map area.

Maps used in these lab exercises:

- Map 1: Murky Mists Mountain
- Map 1: Cross-section template
- Map 2: Delightful Dells Geological Paradise
- Map 3: Four-River Ridge
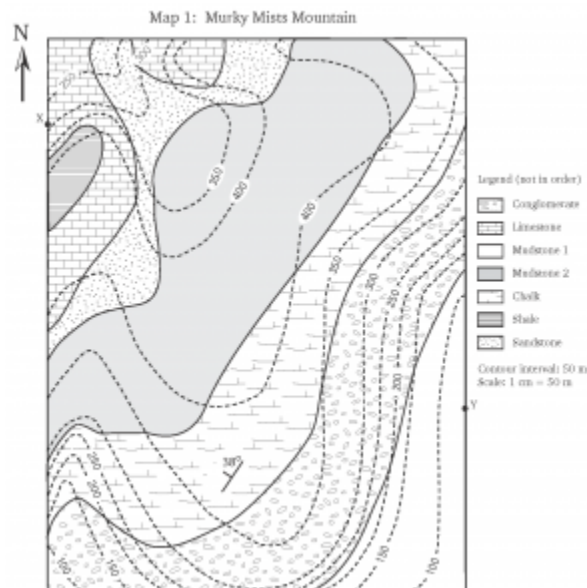
Figure 8.E3 | *Map 1: Murky Mists Mountain. Source: Karla Panchuk (2018) CC BY 4.0, original work.*

Map 1 Cross-section template

Title:

Legend

Scale:
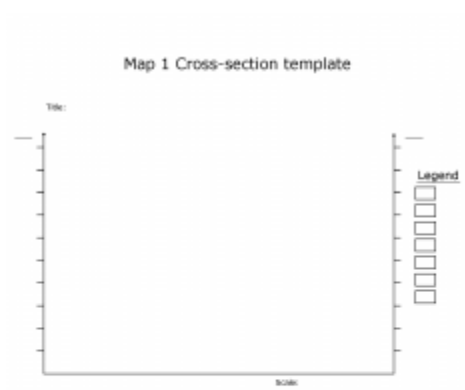
Figure 8.E4 | Map 1 Cross-section template.
Source: Lyndsay Hauber (2018) CC BY 4.0,
original work.

Map 2: Delightful Dells Geological Paradise

N

350

250

300

200

150

150

300

350

400

20°

400

450

350

Legend (not in order)

Conglomerate

Limestone

Sandstone

Mudstone

Contour interval: 50 m
Scale: 1:5000
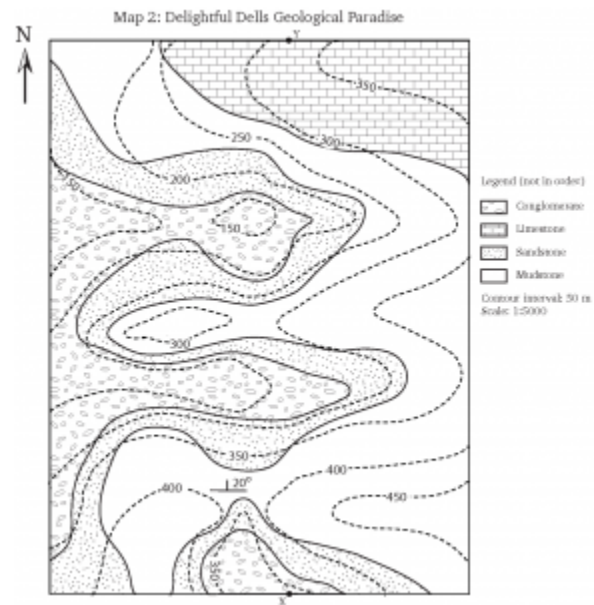
Figure 8.E4 | Map 2: Delightful Dells Geological Paradise.
Source: Karla Panchuk (2018) CC BY 4.0, original work.
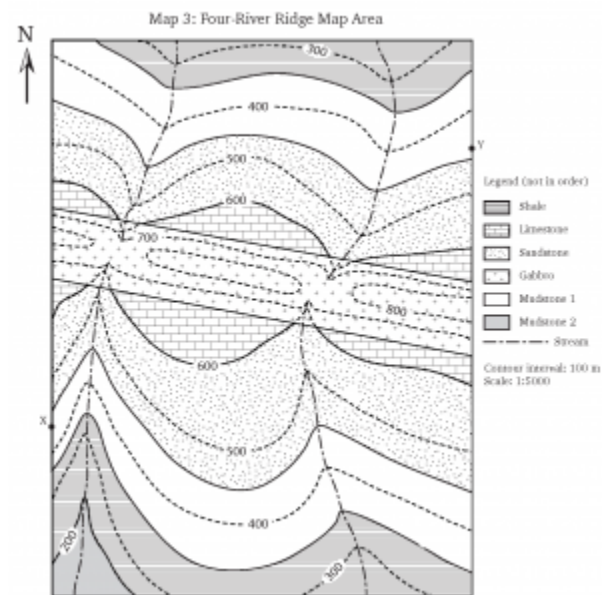
Figure 8.E5 | *Map 3: Four-River Ridge Map Area. Source: Karla Panchuk (2018) CC BY 4.0, original work.*

Overview of Geological Structures Part 2: Folds, Faults, and Unconformities

Adapted by Joyce M. McBeth, Tim C. Prokopiuk, & Lyndsay R. Hauber (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0. [View source.](#)

In Part II of geological structures, students will learn how stress and strain create more complex geological structures, and also how to interpret geological maps that display folded and faulted structures, as well as unconformities.

8.5 STRESS AND STRAIN

Rocks change as they undergo **stress.** Stress is a force applied to a given area. Since stress is a function of area, changing the area to which stress is applied will change the resulting stress. For example, imagine the stress that is created at the tip of the heel of a high heeled shoe and compare it to the bottom of an athletic shoe. In the high heeled shoe heel, the area is very small, so much stress is concentrated at that point. The stress is more spread out in an athletic shoe. If stress is not concentrated at one point in a rock, the rock is less likely to change (break or bend) because of that stress. There are three main types of stress: compression, tension, and shear. When **compressional forces** are at work, rocks are pushed together. **Tensional forces** operate when rocks pull away from each other. Simple **shear force** is created when rocks move horizontally past each other in opposite directions. Rocks can withstand much more compressional stress than tensional stress (e.g., Figure 8.15).

Figure 8.15 | The Roman Forum. Why did the Romans use so many vertical columns to hold up the one horizontal beam? If the horizontal beam spanned a long distance without support, it would buckle under its own weight. This beam is experiencing tensional stress, and rocks have very little strength when exposed to such stress. Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

Applying stress creates a deformation in the rock, known as **strain**. Initially, as rocks are subjected to increased stress which begins the process of strain, they behave in an elastic manner, meaning they return to their original shape after deformation ceases (e.g., Figure 8.16). This elastic behavior continues until the rocks reach their elastic limit (e.g., point X on Figure 8.16), at which point the rock will begin to deform plastically. **Plastic deformation** may lead to the rocks bending into folds, or if too much strain accumulates, the rocks may behave in a brittle manner and fracture. An example of **brittle behavior** is a hammer hitting glass, which of course shatters the glass. With plastic deformation, the rocks do not return to their original shape when the stress is removed. The deformation that results from applied stress depends on many factors, including the type of stress, the type of rock, pressure and temperature conditions (e.g., rocks deeper in the crust will be subject to higher pressures and temperatures), and the length of time the rock is subjected to the stress. Rocks behave very differently at depth than at the surface. Rocks tend to deform in a more plastic manner at depth, and in a more brittle manner near Earth's surface.
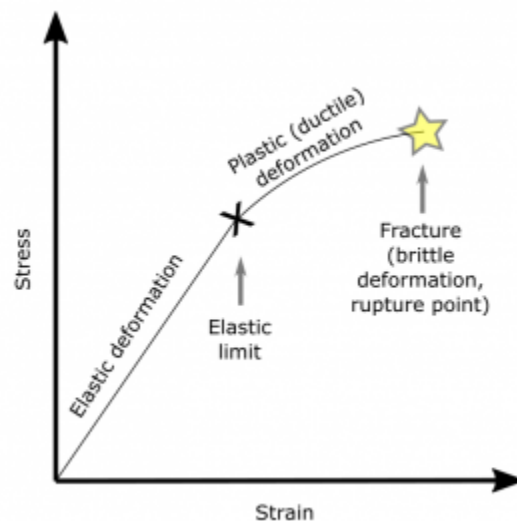
Figure 8.16 | A stress and strain diagram. As stress and strain increase, rocks first experience elastic deformation, and will return to their original shape if the stress is released. When the elastic limit is reached (point X), if stress continues to accumulate as strain, the rocks will deform plastically, and will not return to their original shape if the stress is released. If rocks are subjected to stress greater than they are able to accommodate with strain, they will fracture (brittle deformation, yellow star). Source: Joyce M. McBeth (2018) CC BY 4.0.

8.6 GEOLOGIC STRUCTURES CREATED BY PLASTIC & BRITTLE DEFORMATION

8.6.1 Folds

Folds are geologic structures created by plastic deformation of Earth's crust. To demonstrate how folds are generated, take a piece of paper and hold it up with a hand on each end. Apply compressional forces (push the ends towards each other). You have just created a fold (bent rock layers). Depending upon how your paper moved, you created one of the three main fold types (Figure 8.17).
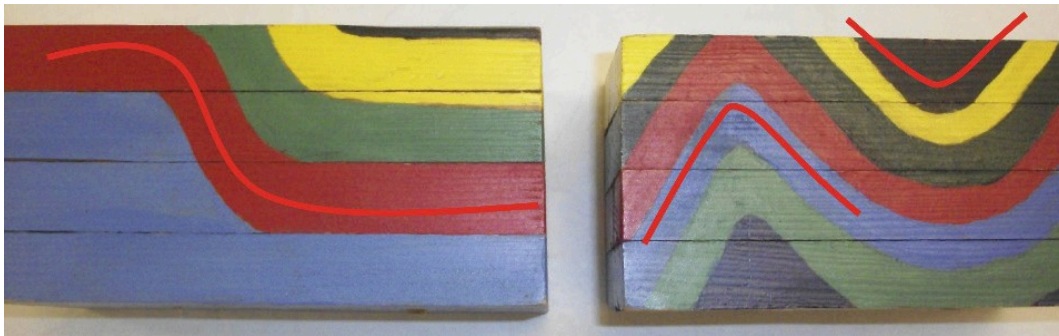
A **monocline** is a simple fold structure that consists of a bend in otherwise horizontal rock layers. Anticlines and synclines are more common than monoclines. An **anticline** fold is convex up: the layered strata dip away from the center of the fold (if you drew a line across it, the anticline would resemble a capital letter "A"). A **syncline** is a concave upward fold in which the layered strata dip towards the center of the fold (it resembles a "U"). Folds have three main parts: a fold axis (also known as the hinge line, which is the line that runs along the nose of the fold), the axial plane (an imaginary plane that contains the hinge line and generally bisects the fold), and limbs on either side of the fold axis (Figure 8.18). Note that anticlines are not always hills and synclines are not always valleys; in other words, folds are not always reflected in the current topography in a region. This is generally due to erosion wearing away the layers of rock to expose the rocks inside of the fold (Figure 8.19).
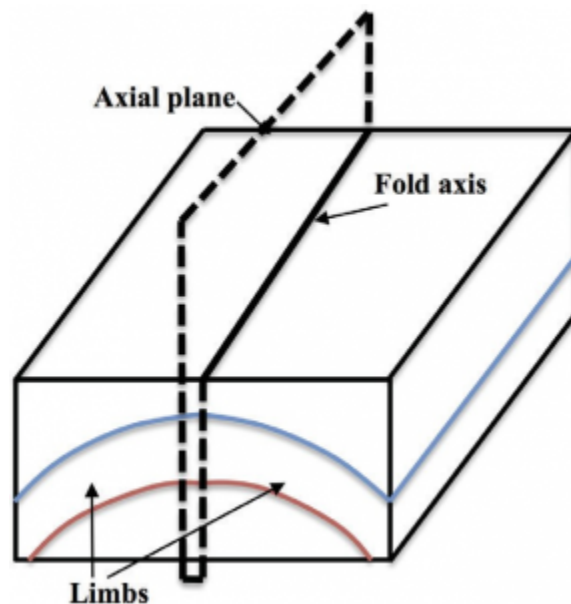
Figure 8.18 | The axial plane and fold axis, along the center of the fold, and the limbs of the fold on either side. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Figure 8.19 | This road cut shows a cross-section through a syncline ("U" shaped fold). It is located along Interstate 68 and US 40 in Maryland, USA. Source: Wikimedia User "Acroterion" (2012) CC BY-SA 3.0. View Source.

Folds observed in cross-section look much different from map view. In the map view of a flat surface, upright folds will appear as linear beds that look like Figure 8.20. To help determine what type of fold is present (monocline, syncline or an anticline), you must determine the strike and dip of each of the beds. On Figure 8.20, you can practice this: determine the strike and dip for each location marked by an oval. Check your answers using Figure 8.21.

Figure 8.20 | *A block diagram of an anticline and syncline. The top of the block represents map view and the side of the block is a cross-section view. Determine the strike and dip symbols that should appear in the ovals. Source: Randa Harris (2015) CC BY-SA 3.0. [view source](#).*
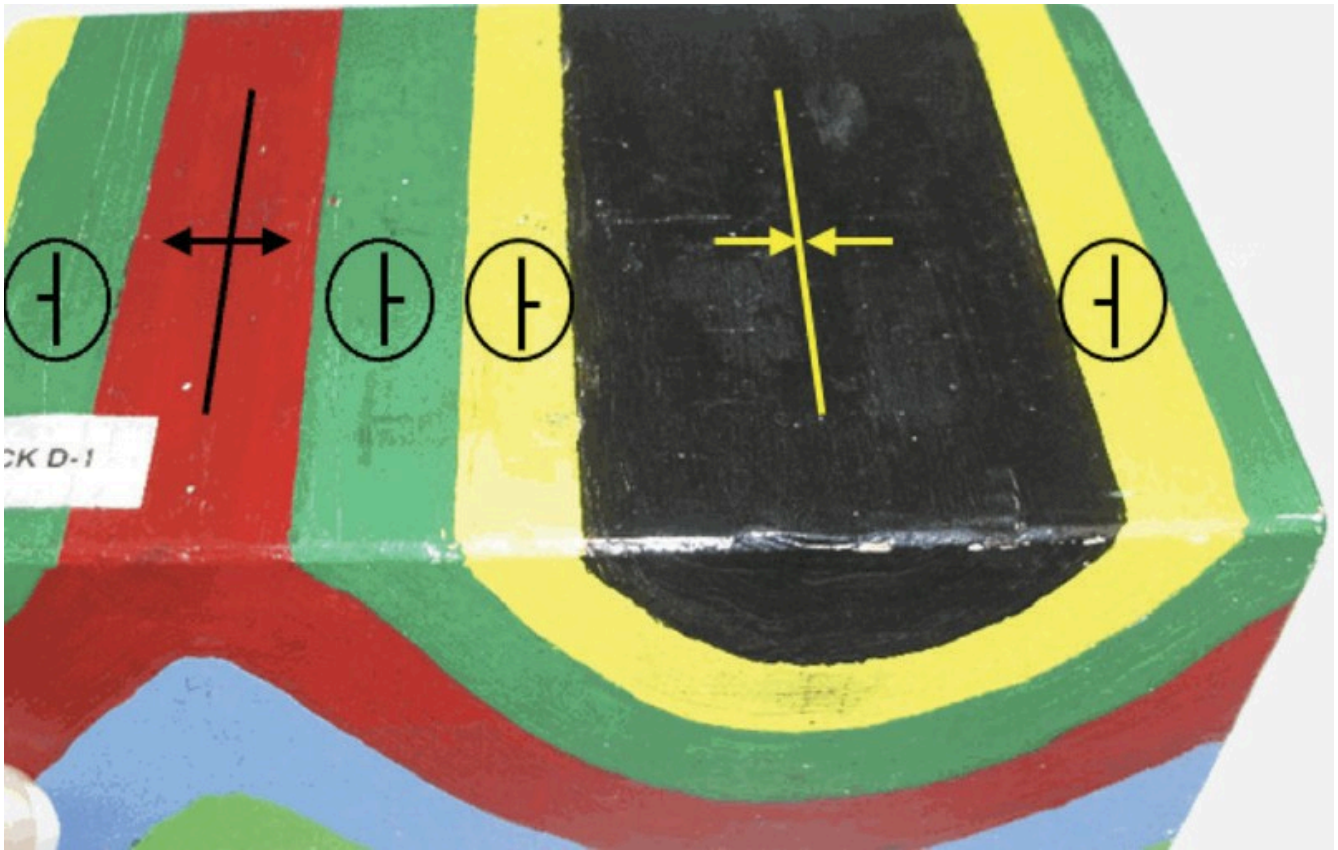
Figure 8.21 | *This block includes the strike and dip symbols and symbols for the anticline and syncline. Note that on the anticline, the beds dip AWAY from the fold axis, and the anticline symbol is drawn along the fold axis, with arrows pointing away from each other, indicating the dip direction of the limbs of the fold. In the syncline, the beds dip TOWARDS each other. Hence, for the syncline symbol, the arrows point inwards. Source: Randa Harris (2015) CC BY-SA 3.0. view source.*

Once rocks are folded and exposed at Earth's surface, they are subjected to erosion, creating certain patterns. The erosion exposes the interiors of the folds, and parallel bands of dipping strata can be observed along the fold axis. In an anticline, the oldest rocks are exposed along the fold axis, or core of the fold. In a syncline, the youngest rocks exposed at the fold axis, or core of the fold (Figure 8.22, Table 8.1).

Figure 8.22 | The top block (A) shows a typical anticline and syncline. Look at the center of the folds. Are the beds that you see in the center of the anticline older or younger than the beds on either side of it? What about for the syncline? In the lower block (B) the top portion of the block has been removed to simulate erosion of rock layers. Note the pale blue bed now lies in the center of the anticline. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Table 8.1

Fold Type	Direction of dip of beds	Age of beds in core
Anticline	Away from fold axis	Oldest
Syncline	Towards fold axis	Youngest

So far, we've studied folds that contain a horizontal fold axis. These folds are shaped like ripples in water, with the axes of the folds lying in the tops and bottoms of the ripples. Some folds have a fold axis that plunges downwards, and these are called plunging folds. Let's explore what beds might look like for a plunging fold. Take a piece of paper and create a fold by compressing the paper from either side. Tip the piece of paper along the fold axis so that the axis is no longer horizontal, and instead plunges in one direction. You have now created a plunging fold. Plunging folds create a V-shaped pattern when they intersect a horizontal surface (Figures 8.23, 8.24, and 8.25). In an anticline, the oldest strata can be found at the center of the V, and the V points in the direction of the plunge of the fold axis. In a syncline, the youngest strata are found at the center of the V, and the V points in the opposite direction of the plunge of the fold axis.

Figure 8.23 | Both blocks are plunging folds. Note the V shape created in map view in a plunging fold. Based on our view of the cross section at the end of the left block, it is a plunging anticline. The fold on the right block is a plunging syncline. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Figure 8.24 | The side of this block shows a cross-section view of a plunging anticline. It illustrates how the rock layers plunge into Earth. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Figure 8.25 | *These blocks show examples of map views for both plunging (top) and non-plunging (bottom) folds. Note the characteristic V-shape of the map view for the plunging fold (top). Note the linear intersection of each bed with the surface for the map view of the non-plunging folds (bottom).*
Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Domes and basins are somewhat similar to anticlines and synclines; they are basically the circular (or elliptical) equivalent of these folds. A **dome** is an upwarping of Earth's crust, which is similar to an anticline in terms of the age relationships of the rocks, and a **basin** is an area where the rocks have been warped downwards towards the center, with age relationships being similar to a syncline (Figure 8.26). The key to identifying these structures is similar to identifying folds. In a dome, the oldest rocks are exposed at the center, and rocks dip away from this central point. In a basin, the youngest rocks are in the center, and the rocks dip inward towards the center.
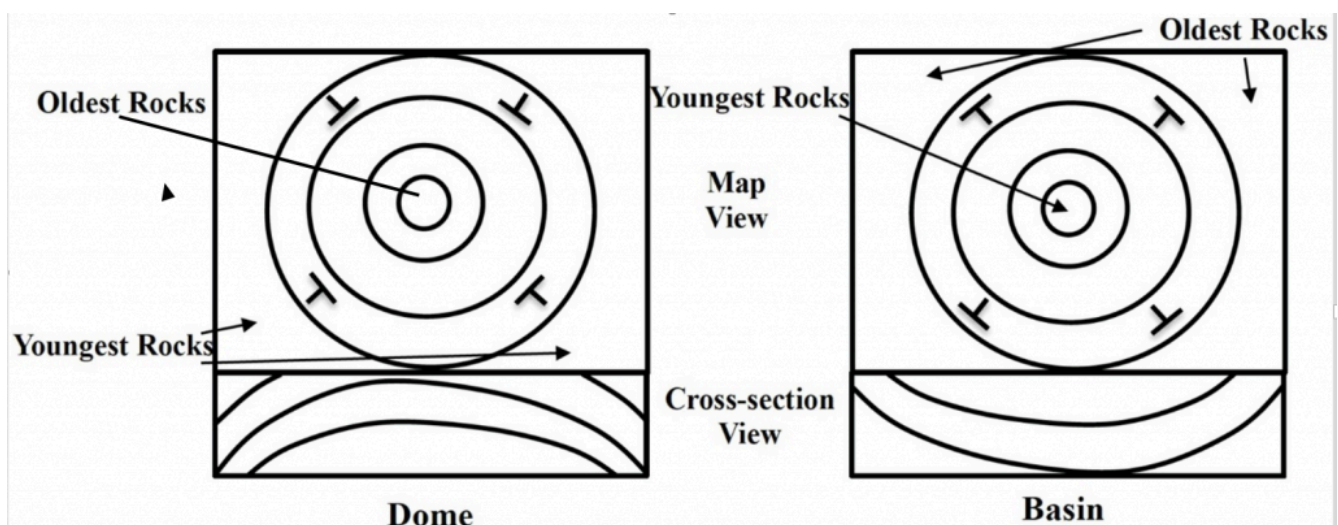
Figure 8.26 | *A dome (left) has older rocks in the center, with rocks dipping away from this point, while a basin (right) has rocks dipping inwards and the youngest rocks in the center. Source: Randa Harris (2015) CC BY-SA 3.0. view source.*

Here are some helpful hints to remember when constructing a cross-section for an area that includes folded strata:

1. Anticlines – these folds have the oldest beds in the middle, with beds dipping away from the fold axis. Plunging anticlines plunge towards the closed end of the V.
2. Synclines – these folds have the youngest beds in the middle, with beds dipping towards the fold axis. Plunging synclines plunge towards the open end of the V.

8.6.2 Faults

As rocks undergo brittle deformation, they may fracture. If no appreciable lateral displacement has occurred along fractures, they are called **joints**. If lateral displacement occurs, these fractures are referred to as **faults**. In **dip-slip faults**, the movement along the fault is either up or down. The two masses of rock that are cut by a fault are termed the fault blocks (Figure 8.27). The type of fault is determined by the relative direction that the fault blocks have moved.

Figure 8.27 | Two fault blocks. The fault is the break in the block that separates the two fault blocks. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

Fault block movement is described based on the relative movement of the **hanging wall**, the block located above the fault plane, and the **foot wall**, the block located beneath the fault plane. The term hanging wall comes from the idea that if a miner was climbing along the fault plane, they would be able to hang their lantern above their head from the hanging wall. For beginners, it is often useful to draw a stick figure straight up and down across a cross-section of the fault plane to help identify which wall is the hanging wall. The head of the stick figure will be on the hanging wall and the feet of the stick figure will be on the foot wall (Figure 8.28).
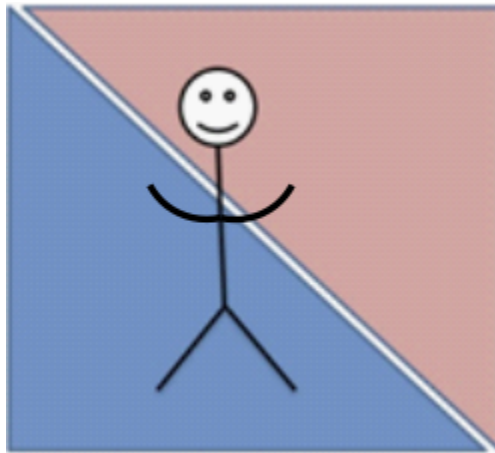
Figure 8.28 | In this image, the head of the stick figure is on the hanging wall (in mauve) and the feet of the stick figure are on the foot wall (in blue). Source: Joyce M. McBeth (2018) CC BY-SA 4.0, after Randa Harris (2015) CC BY-SA 3.0. view source.

When extensional forces are applied to the fault blocks (e.g., in tectonic environments where tectonic plates are pulling apart, such as along the Mid-Atlantic Ridge), the hanging wall block will move down with respect to the foot wall block. This creates a **normal fault.** An easy way to remember that the hanging wall drops in a normal fault is to use the mnemonic "It's normal to fall down". As this happens, the crust is lengthened (stretched apart) and thinned (Figure 8.29).
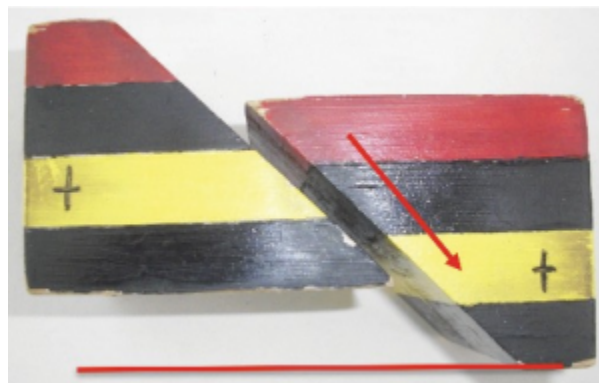
Figure 8.29 | The hanging wall block, on the right, has moved down relative to the foot wall block, on the left, resulting in a normal fault. Notice how close together the cross symbols were in Figure 8.27, compared to this figure, which is evidence for the lengthening of the crust, due to extension. Also note that the crust has thinned in the region of the fault. Source: Randa Harris (2015) CC BY-SA 3.0. view source.

When compressional forces are applied to the fault blocks (such as in a convergent plate boundary tectonic setting), the hanging wall block will move up relative to the foot wall block, creating a **reverse fault**. This causes the crust to shorten laterally but thicken vertically (e.g., Figure 8.30). A special type of reverse fault is a **thrust fault**. A thrust fault is a low angle reverse fault (the dip angle is less than 30o). Table 8.2 summarizes the characteristics of normal and reverse faults.
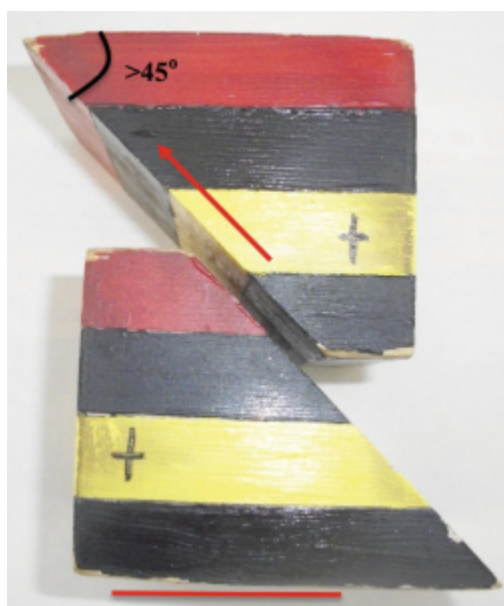
Figure 8.30 | The hanging wall block, at the top, has moved up relative to the foot wall block, at the bottom, resulting in a reverse fault. Note how much closer the cross symbols have become as compared to figure 8.27, evidence for the shortening of the block, due to compression. Also note that the crust has thickened in the region of the fault. Source: Randa Harris (2015) CC BY-SA 3.0. [view source.](#)

Table 8.2

Fault type	Type of force	Direction*	Length of block	Crustal thickening or thinning
Normal	Extensional	Down	Lengthened	thinning
Reverse	Compressional	Up	Shortened	thickening

* hanging wall block movement relative to foot wall block

Tensional forces acting over a region can produce normal faults that result in landforms known as horst and graben structures. In **horst and graben topography**, the graben is the crustal block that drops down relative to the crust around it. The graben is surrounded by two horsts; these are relatively uplifted crustal blocks (Figure 8.31). This terrain is typical of the Basin and Range province in the western United States.
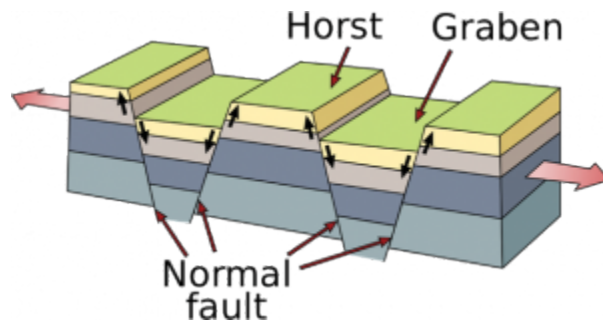
Figure 8.31 | This figure depicts an area that has been stretched by tensional forces, resulting in numerous normal faults and horst and graben landforms. Source: Wikimedia User "Gregors" (2011) modified from USGS, Public Domain. View source.

In dip-slip faults (normal and reverse faults), the fault movement has occurred parallel to the fault's dip, and the movement is characterized by both a vertical and horizontal change in position of the hanging wall relative to the foot wall. In a **strike-slip fault**, the movement is only horizontal along the fault plane in the direction of strike (hence the name), the fault blocks do not move vertically relative to one another. Also, faults that behave as purely strike-slip faults are usually vertical in their orientation. The blocks on opposite sides of a strike-slip fault slide past each other, and the movement is driven by shear forces acting on the fault blocks on either side of the fault. The classic example of a strike-slip fault is the San Andreas Fault in California, USA (Figure 8.32). Strike-slip faults can be furthered classified as right-lateral or left-lateral strike-slip faults. To determine whether a fault is left- or right-lateral, use the following test. Imagine an observer standing on one side of the fault looking across at the opposite fault block. If the fault block on the opposite side of the fault appears to have moved right relative to the observer, it is right-lateral; if it appears to have moved left, it is left-lateral.

Figure 8.33 provides examples of all three fault types for your review.
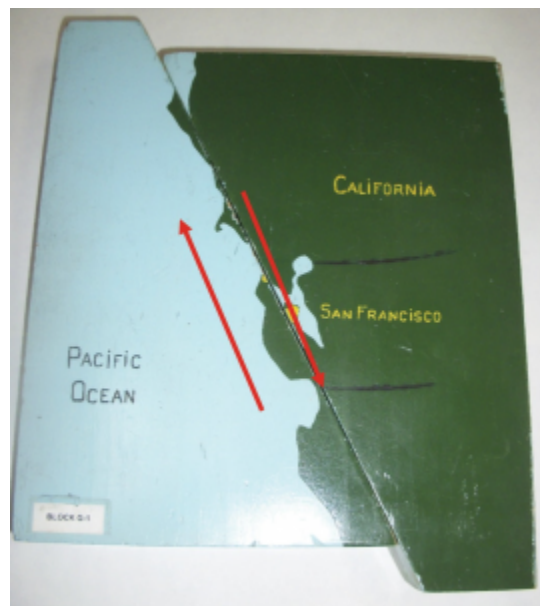

Figure 8.32 | A block diagram of the San Andreas Fault, a right-lateral strike-slip fault. Note that the positions of the blocks do not represent the current position of the crust on each side of the fault. Source: Randa Harris (2015) CC BY-SA 3.0. view source.
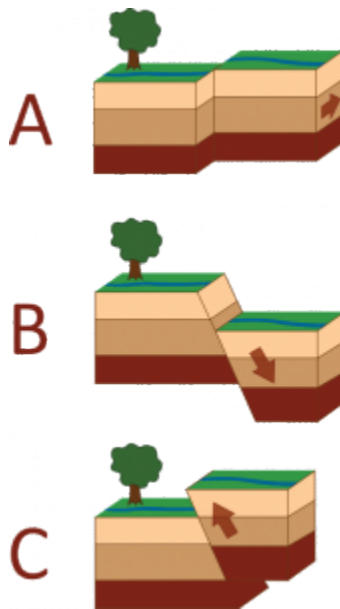
Figure 8.33 | The three types of faults discussed in this lab: A) strike-slip fault, B) normal fault, and C) reverse fault. Source: Wikimedia User "Karta24" (2008) after USGS, Public Domain. [View Source.](#)

8.7 Unconformities on Geological Maps

Unconformities have been discussed in a previous section of this lab manual. Recall the definition of an unconformity: a gap in the geological record where a rock unit is overlain by another rock unit which was deposited substantially later in time. The unconformity is the gap in time between the rocks above and below. Also recall the different types of unconformities: (1) disconformity: a gap in time between parallel sedimentary rocks caused by either erosion or nondeposition during the time period; (2) nonconformity: a gap in time between crystalline (i.e. igneous and metamorphic) basement rock and the sedimentary rocks located immediately upon the basement rock. Nonconformities commonly span vast amounts of time, up to billions of years; and (3) angular unconformity: a gap in time in which a sequence of sedimentary rocks lies upon an older sequence of sedimentary rocks, but these older rocks were tilted so lie in a different orientation than the rocks above.

Identifying unconformities on geological maps can be difficult. Disconformities are almost impossible to locate, unless you are told the ages of the different layers of rocks. In that case, look for the gaps in time and you will locate any disconformities.

Nonconformities can also be tricky, as intrusive contacts can be mistaken for them. But if you locate sedimentary rocks that are located next to large swaths of igneous and metamorphic rocks, you have likely located a nonconformity. Figure 8.34 show examples of nonconformities: the sedimentary rocks of the Athabasca Basin, and the sedimentary rocks of the western Canadian Sedimentary Basin and Williston Basin all rest nonconformably on the metamorphic basement rocks of the Canadian Shield, with gaps in the rock record ranging from 1 – 2.7 Ga.

Angular unconformities can be very simple to locate on geological maps. Since overlying sedimentary rocks were deposited upon lower tilted units, these overlying rocks will drape on top of the lower units. If you follow along the

contacts of the lower units, you will find that they all truncate against the angular unconformity. The boundary between the sedimentary rocks of the Western Canadian Sedimentary Basin and the Williston Basin are an example of an angular unconformity (Figure 8.34) that represents a gap in the rock record of 300 Ma.
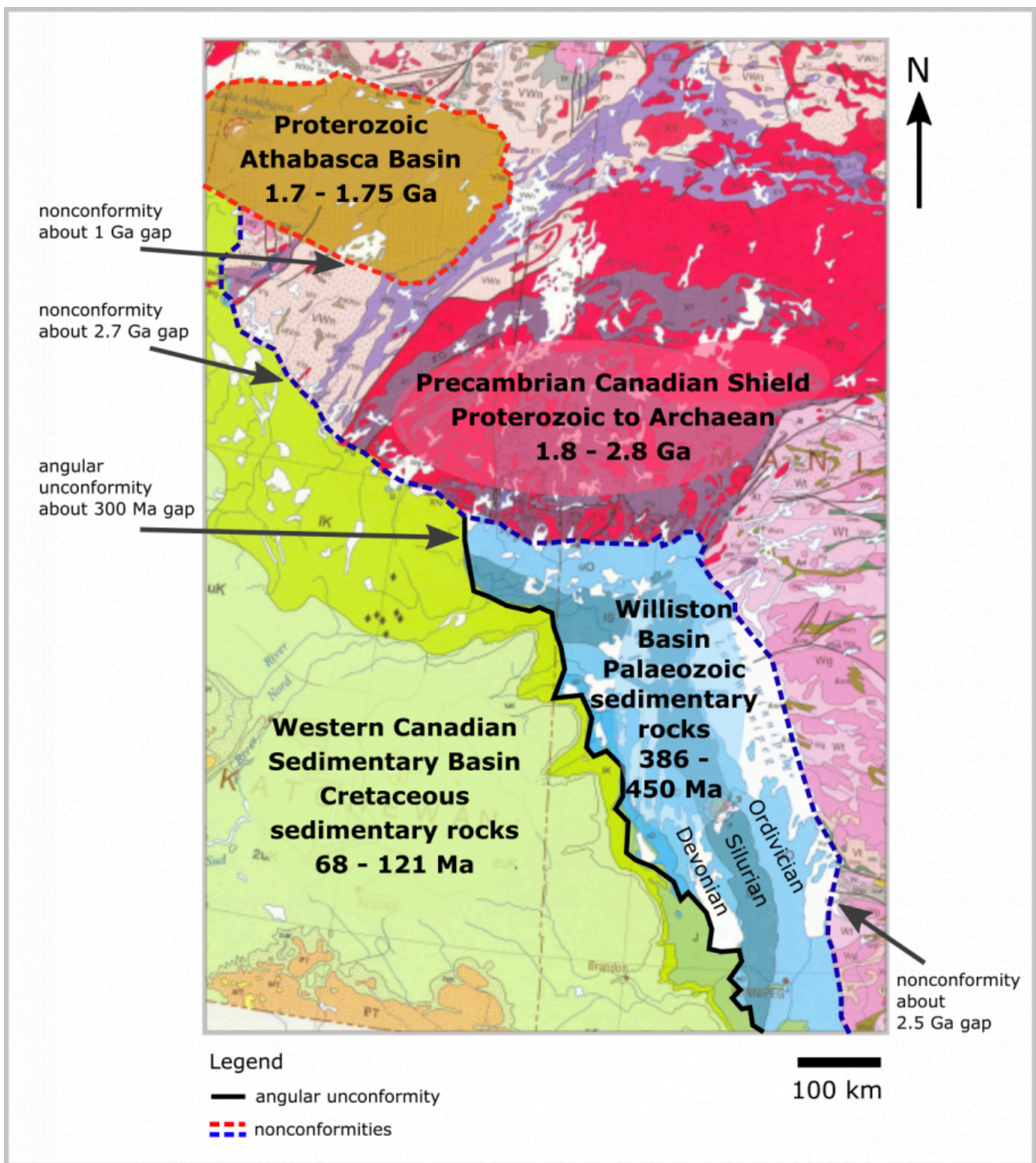
Figure 8.34 | Map of three examples of unconformities. The map area shows the bedrock over part of Saskatchewan and Manitoba. The units in green are Cretaceous sedimentary rocks. At the north end of these units, they overlay Precambrian basement rocks of the Canadian Shield nonconformably (the dashed blue line represents an approximately 2.5 – 2.7 Ga gap in time). To the west, the Cretaceous units are deposited on tilted Palaeozoic sedimentary units along an angular unconformity (the black line represents an approximately 300 Ma gap in time). A second nonconformity is highlighted at the NW corner of the map area. The Proterozoic sedimentary rocks of the Athabasca Basin were deposited on top of older Proterozoic and Archaean basement rocks (the dashed red line represents and approximately 1 Ga gap in time). Source: Joyce M. McBeth & Tim C. Prokopiuk (2018) CC BY-SA, original work. Map source: National Resources Canada (1996) Contains information licensed under the [Open Government Licence – Canada 2.0](). Geoscan ID 208175. [view source]()

Exercises on Geological Structures Part 2: Folds, Faults, and Unconformities

Adapted by Karla Panchuk, Joyce M. McBeth, & Lyndsay R. Hauber (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0. View source. Last edited: 18 Oct 2020

In Part 2 of geological structures, students will learn how to interpret more complex geological structures generated by folding and faulting.

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____   _____

Please hand in this lab to your TAs at the end of the lab period.

This lab will take the full amount of lab time to complete. This lab and the second geological structures lab will be on the lab final and students often struggle with this material. Read the lab and overview section online in advance so you can make best use of your time in lab.

8-E3 EXERCISE – GOOGLE EARTH

This exercise is part of your grade for this lab. Open Google Earth or Google Maps and navigate to the location 75°50′18.91″N 101°18′55.83″W. This is a view of part of Bathurst Island, Nunavut, Canada. If you are using Google Maps ensure you have satellite data turned on. Zoom out to about 75 km altitude (45 miles). Note that the landscape is fairly flat in this region, there is only about 400 m of relief (elevations are between 0 m and 400 m). Refer to the figure below (Figure 8-E7) along with Google Earth or Google Maps to answer the following questions.
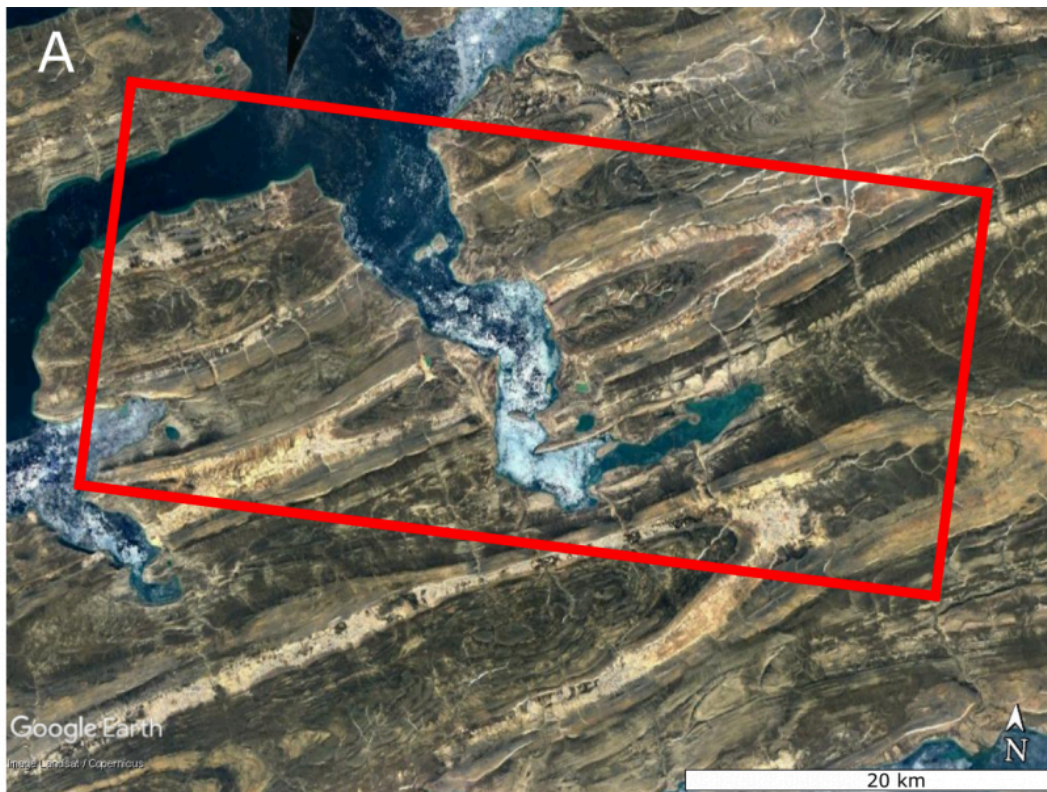
Figure 8-E7 | *Satellite image (A) and partial geologic map (B) of rocks at Bathurst Island, Nunavut. The red box in the satellite image is the region detailed in the lower box of the figure. The ages of the rocks from oldest to youngest: (1) blue, (2) green, (3) yellow, (4) pink. Source: Joyce M. McBeth (2018) CC BY 4.0, Satellite image from © 2018 Google Earth, Data: Landsat/Copernicus. Geologic map prepared by J. M. McBeth based on information from Harrison et al (2014) Canadian Geoscience Map 32 (preliminary), Geological Survey of Canada, view source.*
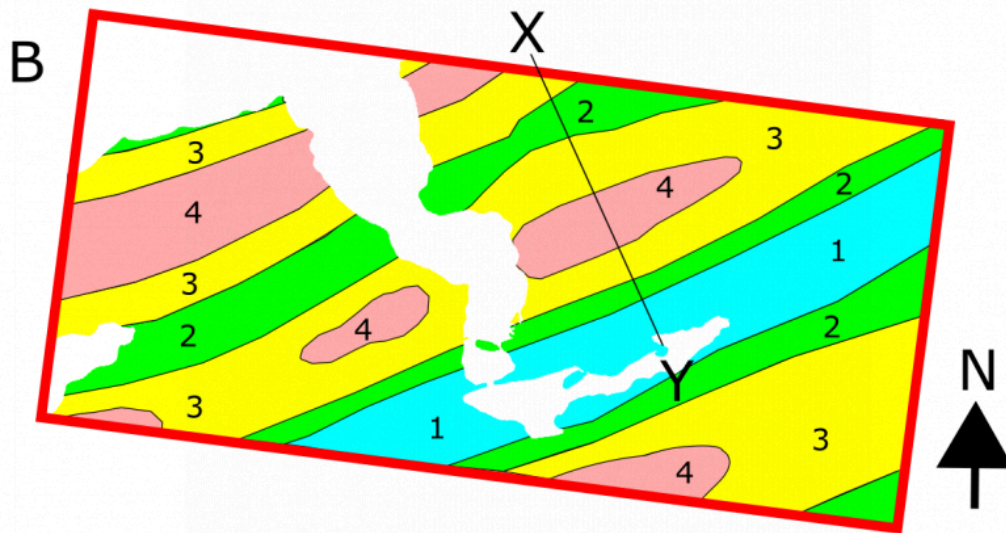
1. (2 pts) Describe the patterns formed by the layers of rock exposed in this image. What do these patterns tell you about the geologic structure(s) formed by the rocks in this area?
2. (1 pt) Note the relative ages of the rocks presented in Figure 8-E7. Given this information, what kind of structure do you think is found in the red boxed area of the satellite image?
3. (2 pts) Sketch a rough cross-section of your interpretation of the geology in Figure 8-E7, between points X and Y (X-Y).
4. (1 pt) Is there data missing from the map that would help you improve the accuracy of your interpretation? If so, what data would help you to understand the geology better?

8-E4 EXERCISES – BLOCK DIAGRAMS

Practice exercises: your TA will walk you through this exercise to help you learn how to interpret block diagrams. Fill in the missing information on the block diagrams below. A key is provided at the end of this lab document for you to check your work. For each diagram, draw in the geological contacts on each side of the block. Add strike and dip symbols, and other symbols to document geologic features (like direction of movement on faults). Also write the name of the geological feature next to each diagram. Presume that the geologic units have not been overturned (i.e., they are not flipped upside down). Note: *the blue lines at the top of block #3 represent a road. Blocks #4 and #5 have more than one correct answer – can you see both possibilities?*

1.

2.

3.

4.

5.
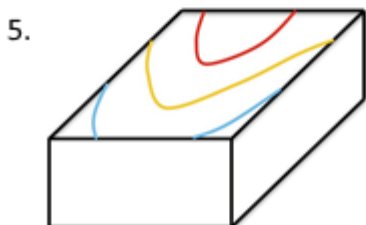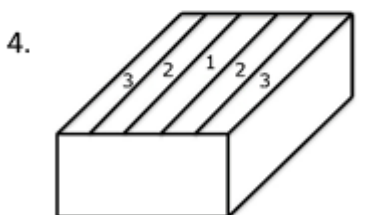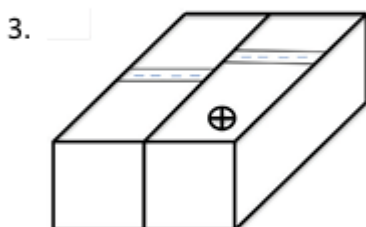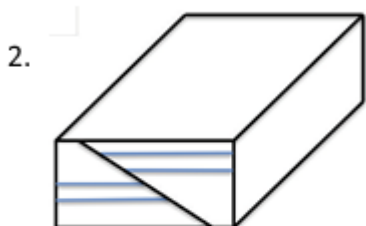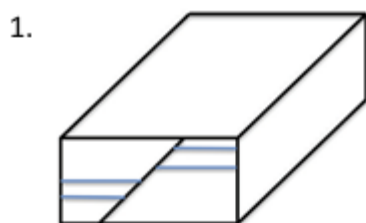
The rest of the exercises in this lab will be part of your grade for this lab.

1. (4 pts each, 24 pts total) Please complete the following block diagrams. For each block diagram:

- Complete the diagram drawing in the geological contacts on each side of the block
- Add symbols indicating the strike and dip of each geological layer as well as symbols documenting any other geological features (include the direction of movement for any faults)
- In the space provided under the block diagram write the specific name of the geological feature
- Please note that relative ages of the layers are provided for diagrams 4 and 5 (1 is the oldest, 6 is the youngest)
- Presume that the geologic units have not been overturned for any of the exercises in this lab (i.e., they are not flipped upside down).
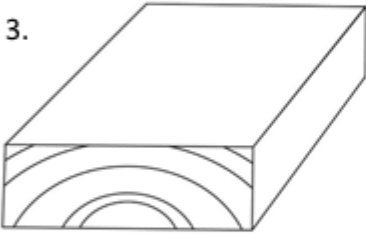- The black line at the top of block #2 is a fault line
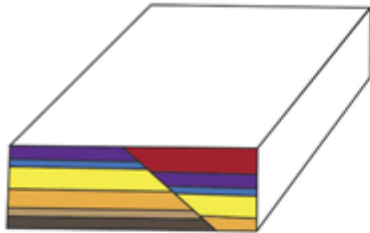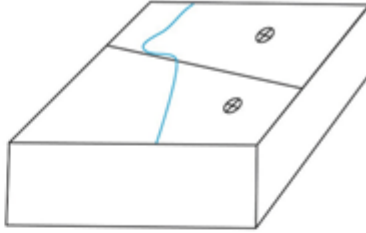
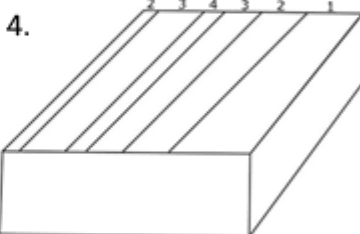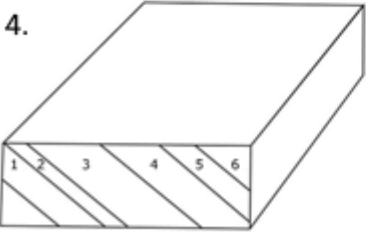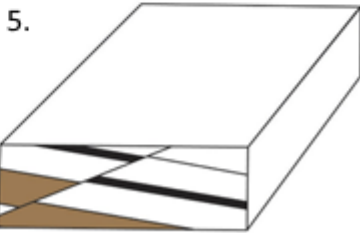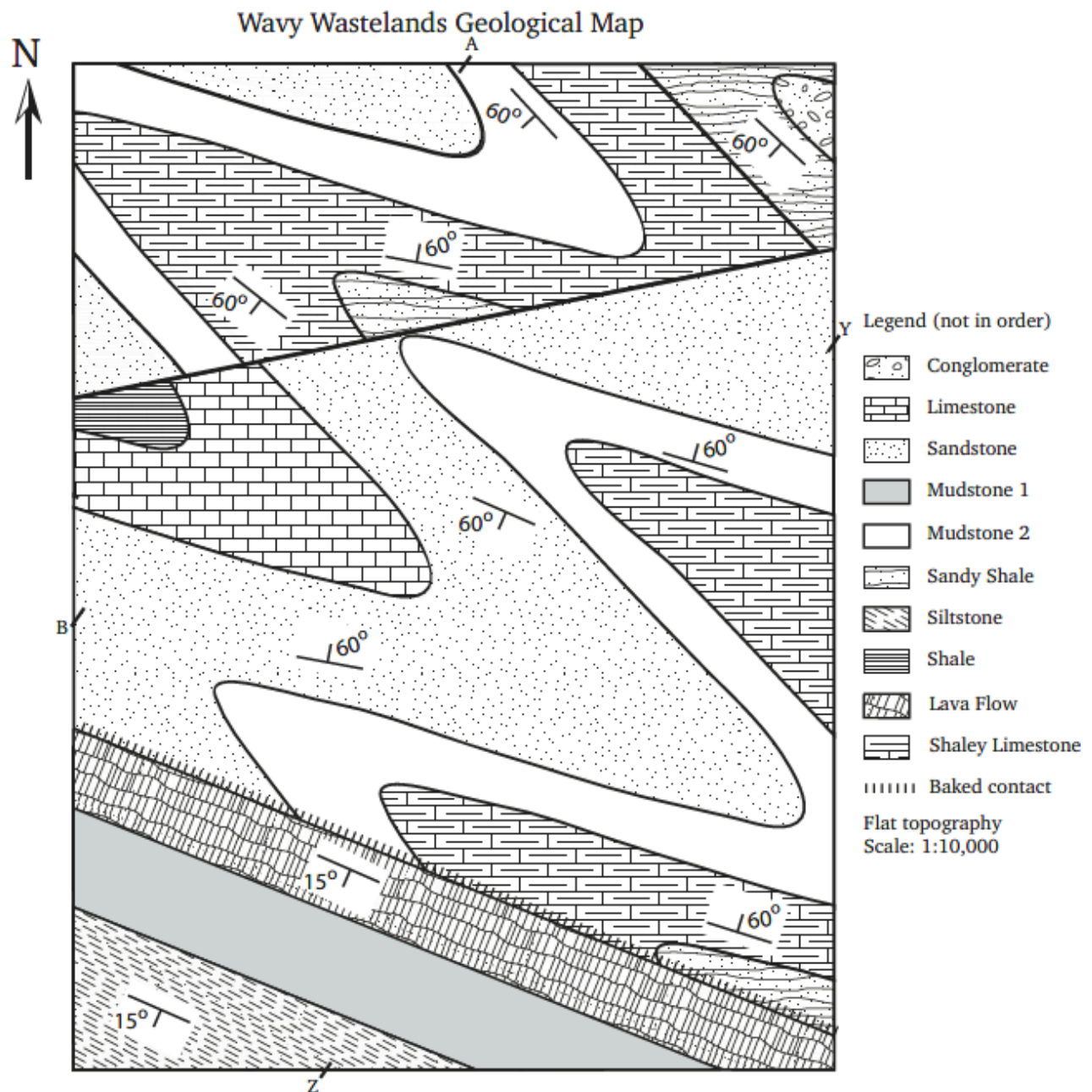# 8-E5 EXERCISES – COMPLEX GEOLOGICAL MAPS & CROSS-SECTIONS

The following geological map exercise will give you practice with constructing geological cross-sections for more complex mapping areas. The mapping area in this exercise is flat; there is no topography (and thus no contour lines). *Note: you will need to hand in your map along with the cross-sections you prepare in this exercise.*
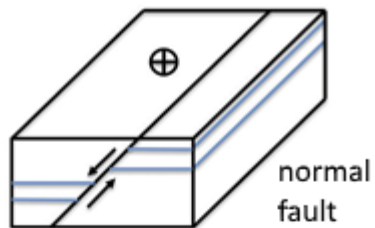
Map: Wavy Wastelands

1. (2 pts) Examine the map of the Wavy Wastelands. Refer to the map legend. Note that the rock types are not presented in order of age in the legend – this is one of the things you will determine in this lab. What kind of rocks are found in this map area: sedimentary, igneous, and/or metamorphic? How many units can you see?
2. (2 pts) Note the strike and dip symbol on the map. Which direction are the units striking and dipping? Do the strike and dip of the beds change at all as you move across the map area?
3. (2 pts) There is a major unconformity in the map area: what kind of unconformity is it? Outline the trace of the unconformity in red on your map.
4. (12 pts) Draw fold axial traces on the map for the folds in the map area (there should be six). Indicate whether the folds are anticlines or synclines by putting the appropriate symbols on the map for each fold. Note that all the folds are plunging in the same direction.
5. (7 pts) Make a list of formations from oldest to youngest. Which geologic laws/principles did you use to prepare your list?
6. (1 pt) There is a fault in the map area. Which side of the fault is upthrown relative to the other side? Mark this on your map.
7. (1 pt) The fault plane for this normal fault dips in which direction? _____
8. (2 pts) Note the scale of the map. What is the distance in metres between point Y and point Z? What is the distance in metres between point A and point B?
9. (15 pts) Prepare a cross-section through the map from position Y to Z (Y-Z).
10. (15 pts) Prepare a cross-section through the map from position A to B (A-B).
11. (7 pts) In point form, describe the geological history of the map area.

Maps used in these Exercises:

Wavy Wastelands Geological Map

Legend (not in order)

- Conglomerate
- Limestone
- Sandstone
- Mudstone 1
- Mudstone 2
- Sandy Shale
- Siltstone
- Shale
- Lava Flow
- Shaley Limestone
- Baked contact

Flat topography
Scale: 1:10,000

Answers to exercises – practice with block diagrams

1.

normal
fault

2.

reverse
fault
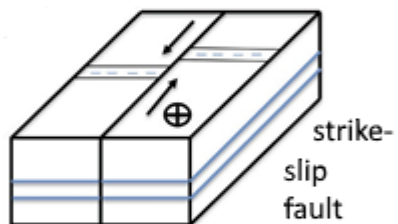
HW
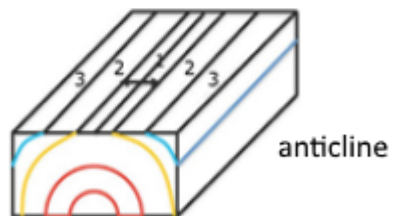FW
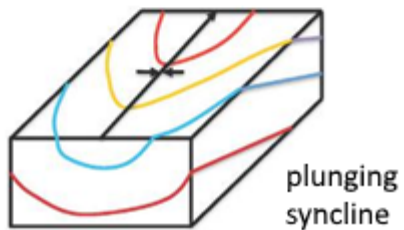
3.

strike-
slip
fault

4.

anticline

5.

plunging
syncline
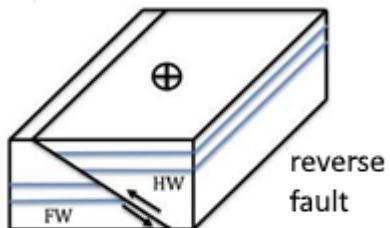
6. Practice Questions on Geological Structures

Adapted by Joyce M. McBeth, Karla Panchuk, & Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 12 "Crustal Deformation" by Randa Harris and Bradley Deline, CC BY-SA 4.0. View source. Last edited: 8 Jan 2020

Block Diagrams:

PDF copy of Block Figure 8-E11a. Source: Joyce McBeth (2018) CC BY-SA 4.0 after Randa Harris (2015) CC BY-SA 3.0 view source

PDF copy of Block Figure 8-E11b. Source: Joyce McBeth (2018) CC BY-SA 4.0 after Randa Harris (2015) CC BY-SA 3.0 view source

8-E6. Practice Exercise – Practice with Block Diagrams

There are two full-page block diagrams (links above) that you will use in this exercise, and the diagrams are replicated below in a flat version that you can complete and use for review after you complete the exercise. Using the full-page versions of the block diagrams, cut along the dashed lines and fold along the solid lines to examine the block in three dimensions. For each of the block diagrams complete the following:

- Complete the diagram drawing in geological contacts on each side of the block
- Add symbols indicating the strike and dip of each geological layer as well as symbols documenting any other geological features
- Identify the geologic structure presented on the block and write the name of this feature on the top surface of the block
- Transfer the information you have drawn on the 3-D block diagrams onto the flat versions below.

Block Figure 8-E11a

Block Figure 8-E11b

Note: ages of beds labelled
from 1 (oldest) to 5
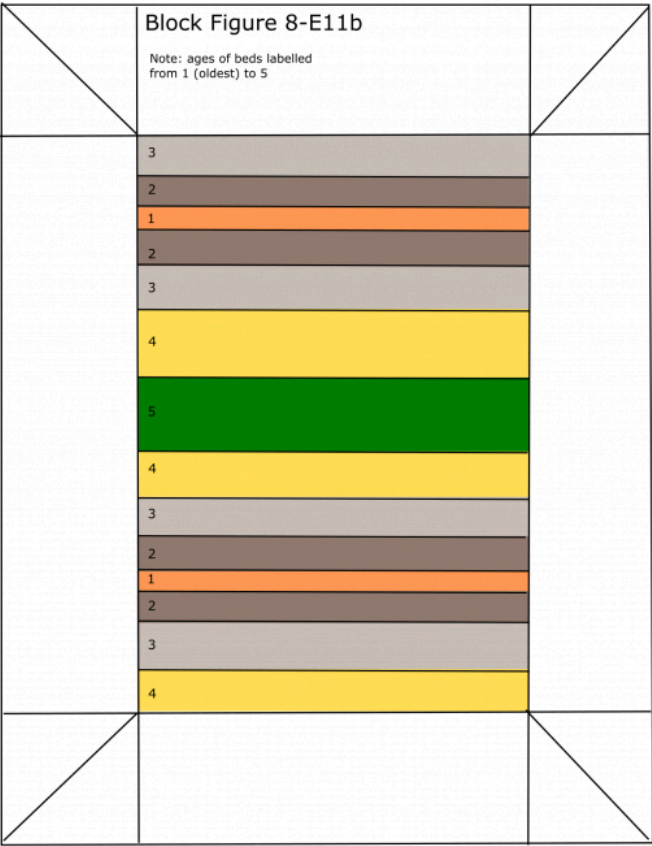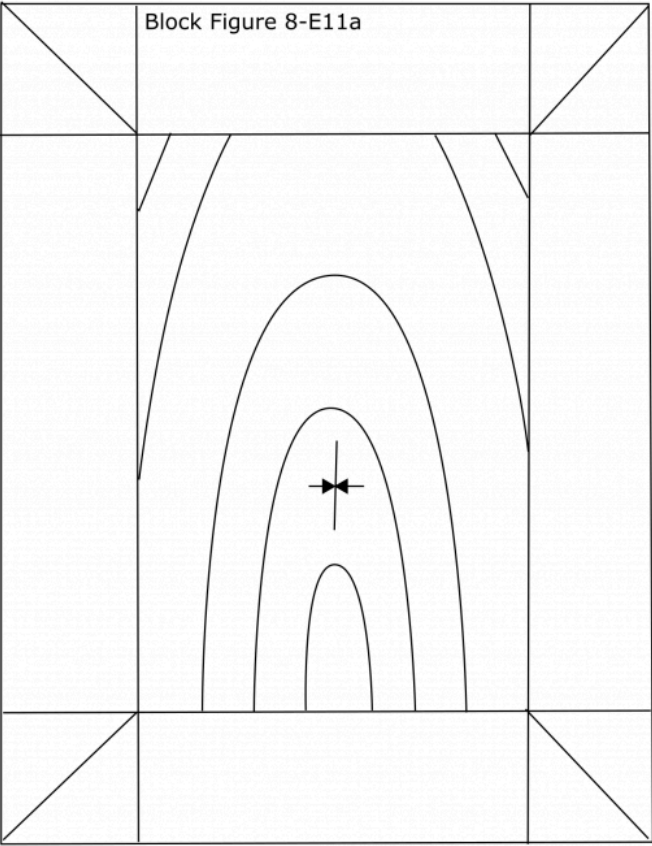
CHAPTER 9. EARTHQUAKES

Adapted by Sean W. Lacey & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 13 "Earthquakes" by Randa Harris, CC BY-SA 4.0. [View Source](). Last edited: 8 Jan 2020

9.1 INTRODUCTION

It was the deadliest day in the history of Mt Everest. On April 25, 2015, a 7.8 magnitude earthquake hit Nepal. This triggered an avalanche that killed 19 climbers on Mt Everest. In Nepal, over 8,800 people died, and many more were injured and made homeless. Hundreds of aftershocks (smaller earthquakes that follow a larger earthquake) have occurred since the initial earthquake (Figure 9.1). Earthquakes are not new to the region where Mt Everest resides. A similar death toll was experienced in a 1934 earthquake, and many other smaller earthquakes have occurred within historical times.
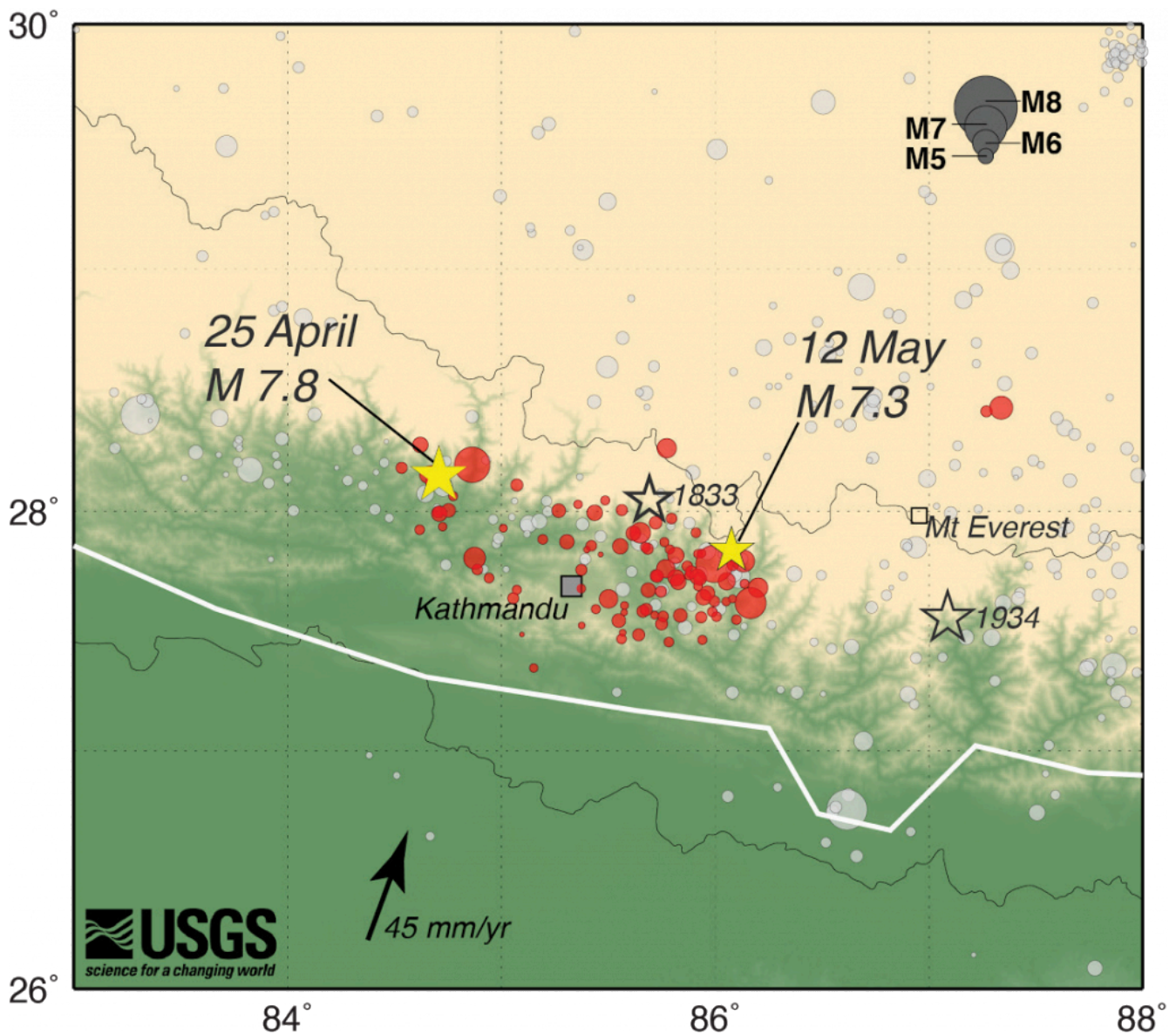
Figure 9.1 | *A map of the main earthquake to hit Nepal on April 25, 2015, along with a major aftershock on May 12, and numerous (>100) other aftershocks (in red – note the magnitude scale in the upper right).*
Source: Harris (2015), map originally from USGS Public Domain view source

An 1833 earthquake of similar magnitude in the same region resulted in less than 500 deaths. In this case, there were two very large foreshocks (smaller earthquakes that precede the main earthquake) that sent most residents out of doors in alarm. Fewer people were indoors for the main earthquake and were thus spared injury and death when the earthquake hit. Worldwide, there have been much deadlier and stronger earthquakes in this century. For example, in 2010 the earthquake that hit Haiti killed an estimated 316,000 people, and the 2004 Sumatra earthquake killed approximately 227,000 people. The deaths in these earthquakes were related to ground shaking and the other hazards that were created by the earthquake.

While earthquakes can be highly destructive, they can also give geologists valuable information about the Earth. They can tell us about the structures in the interior of the Earth, and about conditions at the Earth's surface.

9.1.1 Learning Outcomes

After completing this chapter, you should be able to:
• Compare and contrast the different types of seismic waves generated by earthquakes
• Understand the different scales used to measure earthquakes
• Understand how different geologic materials behave during an earthquake, and how these differences can impact structures during an earthquake
• Explain how to locate an earthquake epicenter on a map
• Explore the relationship between the oil and gas exploration and seismicity

9.1.2 Key Terms

• Benioff Zone
• Body waves
• Epicenter
• Focus
• Induced seismicity
• Intensity
• Liquefaction
• Love waves
• Magnitude
• P Waves
• Rayleigh waves
• S Waves
• Seismogram
• Seismograph
• Seismology
• Surface waves
• Wadati Benioff Zone

Overview of Earthquakes

Adapted by Sean W. Lacey & Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 13 "Earthquakes" by Randa Harris, CC BY-SA 4.0. [View Source](). Last edited: 8 Jan 2020

9.2 THE EPICENTER, FOCUS, AND WAVES

An earthquake is a like a telegram from the Earth. It sends a message about conditions beneath the Earth's surface. The shaking or trembling experienced during an earthquake is the result of a rapid release of energy within the Earth, usually as a result of movement along geologic faults (weak planes in the Earth's crust). In the chapter on geologic structures, we introduced you to faults. In a strike-slip fault like the San Andreas fault in California, USA, rocks on either side of the fault slide past each other. As they move in opposite directions, the rocks become deformed, bend slightly, and build up pressure. Eventually they will reach a breaking point. Once the strength of the rock has been exceeded, the rocks will snap back to their normal shape, releasing the stored energy as an earthquake. The more energy that has been stored, the larger the earthquake. In the chapter on geologic structures we also introduced you to a diagram illustrating the relationship between stress and strain. When rocks are under too great of a stress, the strength of the rock is exceeded, and the rocks undergo brittle failure (the earthquake).
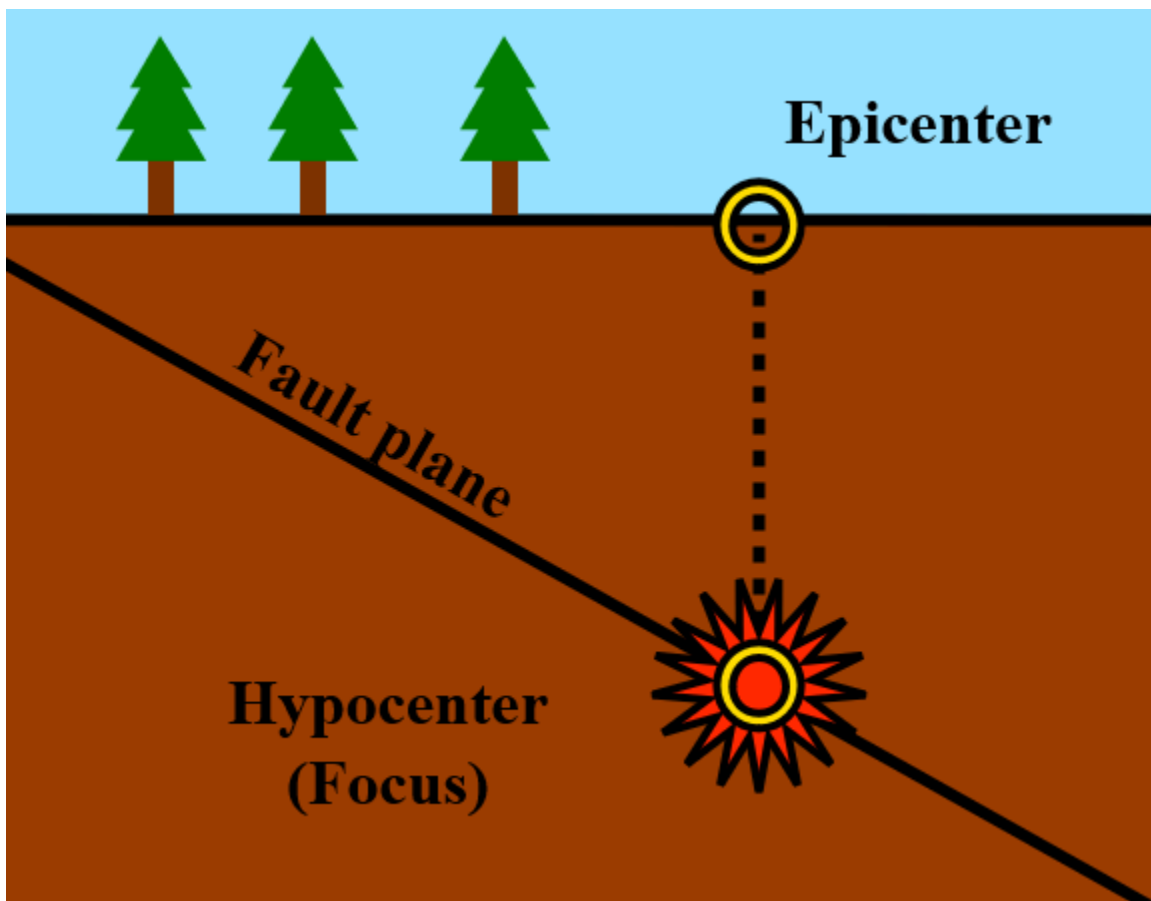
Figure 9.2 | *An illustration depicting the focus (where the earthquake originates) and the epicenter (the point on the ground's surface directly above the focus).*
Source: Wikimedia user Sam Hocevar (2014) CC BY-SA 1.0 *view source*

Earthquakes originate at a point called the **focus** (plural **foci**). From this point, energy travels outward in different types of waves. The place on the Earth's surface directly above the focus is called the epicenter (Figure 9.2). Earthquake foci may be shallow (less than 70 km from Earth's surface) to deep (greater than 300 km deep), though shallow to intermediate depths are much more common. Earthquakes are more frequent along active tectonic plate boundaries (95 % of all earthquakes occur along plate boundaries), and their depth is related to the type of plate boundary. Shallow focus earthquakes tending to occur at divergent and transform plate boundaries. Convergent plate boundaries have a range of earthquake depths, with the earthquakes moving from shallow to intermediate to deep focus as the subducting plate moves deeper under the overriding plate. The earthquakes associated with convergent boundaries occur along the **Wadati-Benioff zone** (or Benioff zone) an area of dipping seismicity along the subducting plate (Figure 9.3).
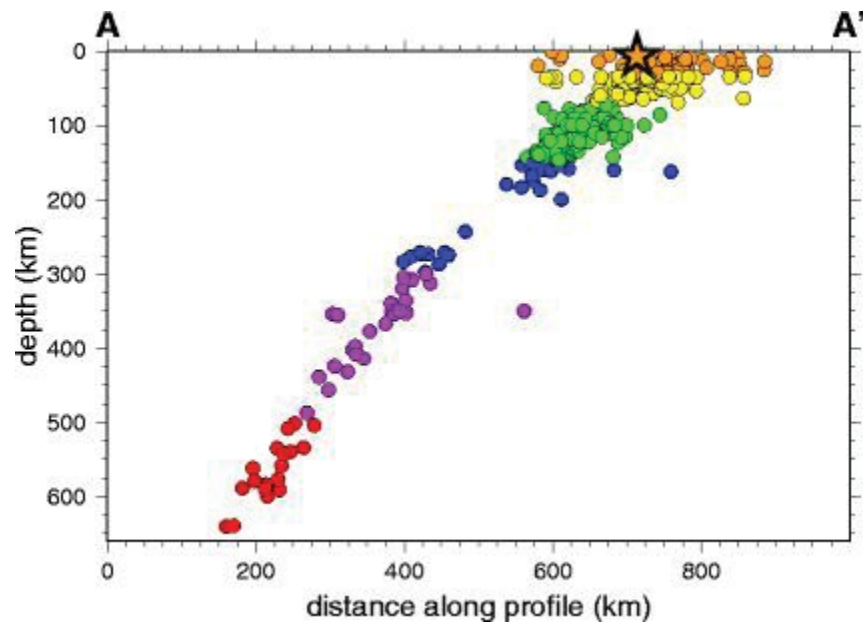
Figure 9.3 | This is a seismicity cross-section, taken along the subducting plate in an ocean-ocean convergent boundary at the Kuril Islands, located just northeast of Japan. Foci are located in the descending slab. Only brittle substances (like the lithosphere) can generate earthquakes, so this must be the subducting slab. The star represents the location of an 8.3 magnitude earthquake that occurred on 11/15/06.
Source: USGS (2006) public domain [view source](#)

As an earthquake occurs, two different types of waves are produced; **body waves**, so termed because they travel through the body of the Earth, and **surface waves** that travel along the Earth's surface (Figure 9.4). There are two types of body waves. **P-waves**, or primary waves, are compressional waves that move back and forth, similar to the action of an accordion or a slinky. As the P waves pass through the Earth's crust, the rock is compressed and stretched. Movement is compressional parallel to the direction of wave propagation, and because of this P-waves the fastest of the seismic waves. In other words, if you are standing some distance away from the source of an earthquake, the P waves will reach you before the other kinds of seismic waves produced by the earthquake. The P waves can travel through solids, liquids, and gases, because all materials can be compressed to some degree. **S-waves**, or secondary waves, are shear waves that move material in a direction perpendicular to the direction of travel. S-waves can only travel through solids, and are slower than P-waves. A similar motion to S-wave motion can be created by two people holding a rope, with one snapping the rope quickly. Alternately, you can also think of this wave movement similar to the wave created by fans in a stadium that stand up and sit down. Body waves are responsible for the jolting and motions felt during an earthquake.

Surface waves are slower than body waves. If you are in an earthquake, the surface waves will be more like being in a boat on the sea, a rolling sensation. Because surface waves are located at the ground's surface where humans (and their structures) are located, and because they move so slowly, which bunches them up and increases their amplitude, they can do a great deal of damage. **Love waves** are the faster surface waves, and they move material back and forth in a horizontal plane that is perpendicular to the direction of wave travel (see Figure 9.4). Buildings do not handle this type of movement well, and Love waves can also be responsible for considerable damage to structures. **Rayleigh waves** make the Earth's surface move in an elliptical motion, similar to the movement in a sea wave. This results in ground movement that is up and down and side-to-side.
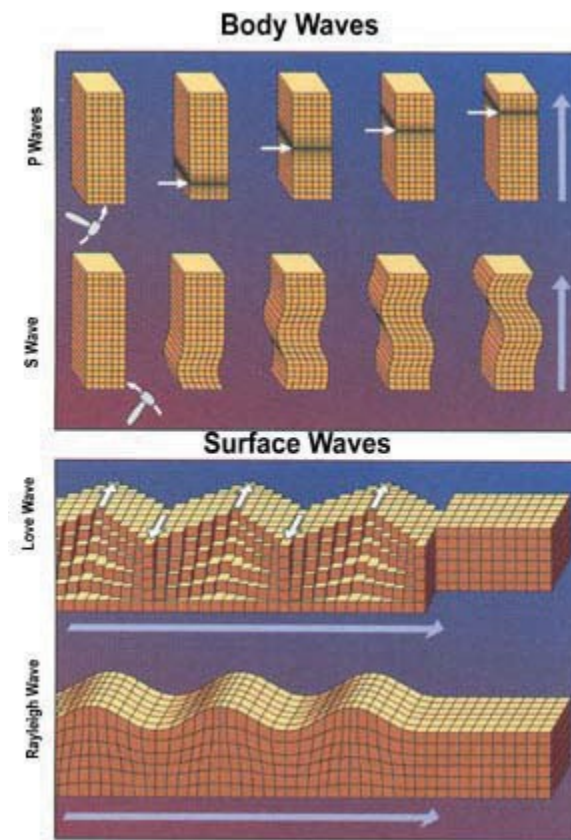
Figure 9.4 | *The different types of seismic waves. Body waves, in the upper portion of the figure, consist of P-waves and S-waves. The P-wave motion is compressional. In this example, when the rock is struck with a hammer (left side of the diagram) this starts the wave moving. The arrow on the right shows the general direction of the wave. In the S-wave, the motion is undulating. Surface waves are depicted in the lower portion of the chart. Love waves move similarly to S-waves, resulting in horizontal shifting of the Earth's surface. Rayleigh waves are surface waves that travel much like a wave along the surface of water.*
Source: USGS (2004) public domain view source

9.3 SEISMOLOGY

Humans have experienced earthquakes as long as we have existed as a species. Many cultures developed legends to explain them, including envisioning large creatures within the Earth that were moving to create the earthquake. The study of earthquakes, called **seismology**, began to take off with the development of instruments that can detect earthquakes. A **seismograph** is an instrument used to measure vibrations moving through the Earth (Figure 9.5). A typical seismograph consists of a mass suspended on a string from a frame that moves as the Earth's surface moves. A rotating drum is attached to the frame, and a pen attached to the mass, so that the relative motion is recorded in a **seismogram**. It is the frame (attached to the ground) that moves during an earthquake. The suspended mass generally stays still due to inertia (the tendency of a body to stay at rest and resist movement).

9.3.1 How Are Earthquakes Measured?

The consequences of earthquakes can be quantified in death tolls and damage to structures, and also in terms of the force and amount of ground shaking. These types of measurements are divided into two types of measurements. Qualitative measures of the damage inflicted by an earthquake (measures that depend upon factors such as the local geology and population density) are referred to as **intensity** measures. Quantitative measures of the energy released by an earthquake are termed **magnitude** measures. Both measures provide meaningful data for interpreting the relative importance of an earthquake.
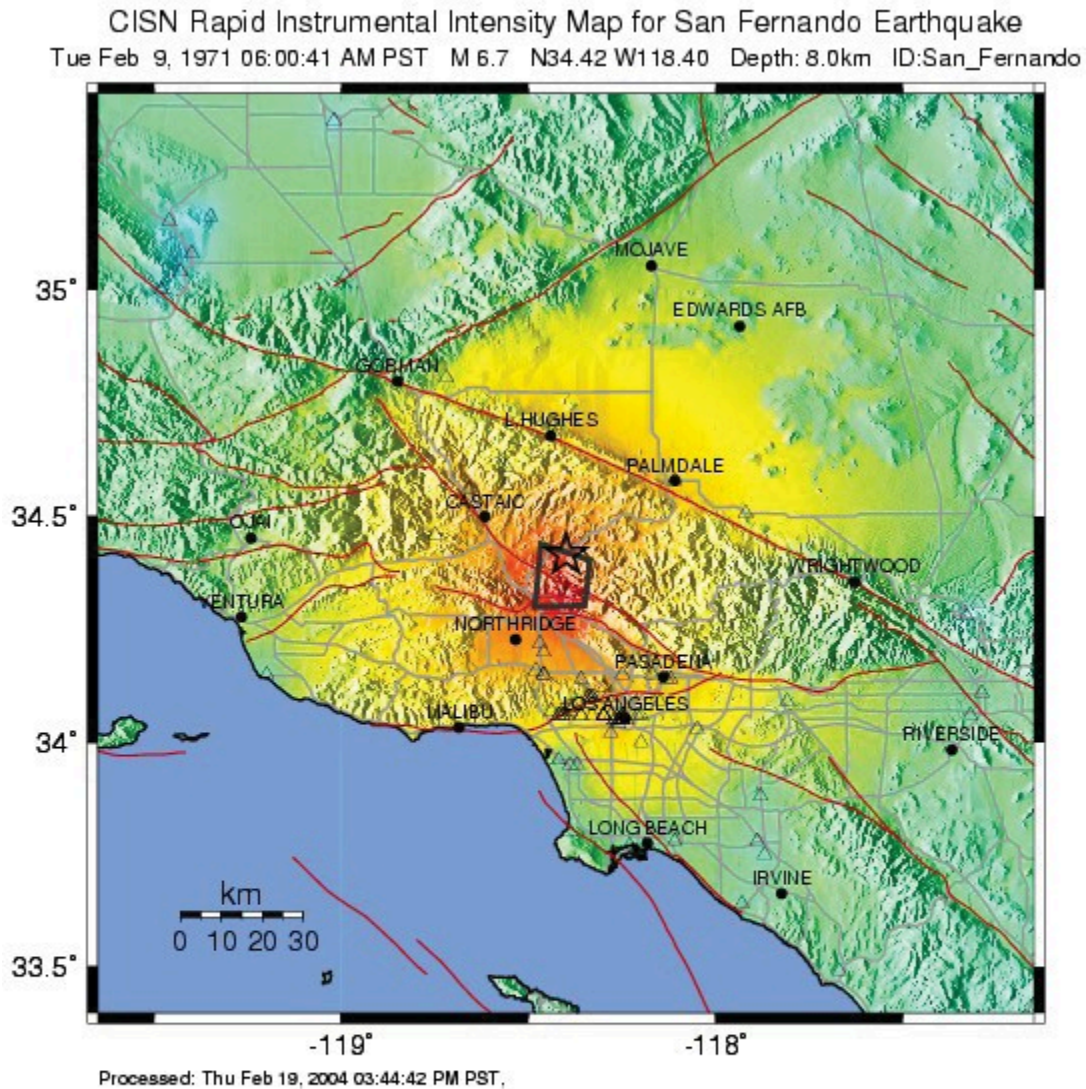
9.3.2 Earthquake Intensity

Intensity measurements take into account both the damage incurred due to the earth quake and the way that people respond to it. The Modified Mercalli Intensity Scale (Figure 9.6) is the most widely used scale to measure earthquake intensities. This scale has values that range from Roman numerals I to XII which characterize the damage observed and people's reactions to it. Data for this scale is often collected right after an earthquake by having the local population answer questions about the damage they see and what happened during the quake. This information can then be pooled to create an intensity map, which creates colored zones based on the information collected (Figure 9.7). These maps are frequently used by the insurance industry, since the relative amount of damage experienced by infrastructure in a region is included in the characteristics used in the scale.

If you ever experience an earthquake, you can report your experience on the USGS "Did you feel it?" website. Your data will be added to that submitted by other people, and once there is enough data the USGS will plot the Modified Mercalli Intensities across the region affected by the earthquake.

Intensity	Characteristics
I	Shaking not felt under normal circumstances.
II	Shaking felt only by those at rest, mostly along upper floors in buildings.
III	Weak shaking felt noticeably by people indoors. Many do not recognize this as an earthquake. Vibrations similar to a large vehicle passing by.
IV	Light shaking felt indoors by many, outside by few. At night, some were awakened. Dishes, doors, and windows disturbed; walls cracked. Sensation like heavy truck hitting a building. Cars rock noticeably.
V	Moderate shaking felt by most; many awakened. Some dishes and windows broken. Unstable objects overturned.
VI	Strong shaking felt by all, with many frightened. Heavy furniture may move, and plaster breaks. Damage is slight.
VII	Very strong shaking sends all outdoors. Well-designed buildings sustain minimal damage; slight-moderate damage in ordinary buildings; considerable damage in poorly built structures.
VIII	Severe shaking. Well-designed buildings sustain slight damage; considerable damage in ordinary buildings; great damage in poorly built structures.
IX	Violent shaking. Well-designed buildings sustain considerable damage; buildings are shifted off foundations, with some partial collapse. Underground pipes are broken.
X	Extreme shaking. Some well-built wooden structures are destroyed; most masonry and frame structures are destroyed. Landslides considerable.
XI	Few structures are left standing. Bridges are destroyed, and large cracks open in the ground.
XII	Total damage. Objects thrown upward in the air.

Figure 9.6 | *An abbreviated table of the Modified Mercalli Intensity Scale. Intensity for a particular earthquake is determined by the maximum damage incurred.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

CISN Rapid Instrumental Intensity Map for San Fernando Earthquake
Tue Feb 9, 1971 06:00:41 AM PST   M 6.7   N34.42 W118.40   Depth: 8.0km   ID:San_Fernando

Processed: Thu Feb 19, 2004 03:44:42 PM PST,

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 9.7 | An intensity map for the San Fernando earthquake in southern California on 2/9/76. Notice that near the epicenter (marked by a star), the intensity was extreme.
Source: USGS (2013) Public Domain [view source](#)

9.3.3 Earthquake Magnitude

Another way to classify an earthquake is by the amount of energy released during the earthquake event; this is referred to as the magnitude of the earthquake. Magnitude has been measured using the **Richter scale** in the past. News media still often report earthquake magnitudes "on the Richter scale" but these numbers are actually magnitudes on a new

scale that is more commonly used for describing earthquake magnitudes. As the frequency of earthquake measurements around the world increased, it was realized that the Richter magnitude scale was not valid for all earthquakes, because it is not accurate for large magnitude earthquakes. The new scale is called the **Moment Magnitud**e scale. The Moment Magnitude scale is very similar to the Richter scale, and for small earthquakes the numbers are virtually identical. In contrast with the Richter scale, the Moment Magnitude scale estimates the total energy released by an earthquake and can be used to describe the magnitude of any size of earthquake including very large earthquakes. The magnitude is based on the seismic moment (estimated based on ground motions recorded on a seismogram), which is a product of the distance a fault moved and the force required to move it. The abbreviation used to indicate that an earthquake magnitude is on the moment magnitude scale is M or M_w (e.g., a magnitude 4 earthquake is an M 4 or M_w 4 earthquake).

Both the Richter and Moment Magnitude scales are logarithmic scales, which means for each whole number that you increase on the scale the energy released increases by a factor of 10. Each unit on the Moment Magnitude scale represents an increase in energy release of $10^{1.5}$ (about 32 times the energy). So a magnitude 3 earthquake has 32 times the energy release of a magnitude 2 earthquake. A magnitude 4 earthquake releases 10^3 or 1000 times as much energy as a magnitude 2 earthquake.

Why is it necessary to have more than one type of scale? The magnitude scale allows for worldwide characterization and comparison of any earthquake event, while the intensity scale does not. With an intensity scale, a IV in one location could be ranked a II or III in another location, based off of building construction (e.g., poorly constructed buildings will suffer more damage in the same magnitude earthquake as those built with stronger construction). Figure 9.8 shows a rough comparison of magnitude scale to intensity.

Magnitude	Typical Maximum Modified Mercalli Intensity
1.0 – 2.9	I
3.0 – 3.9	II – III
4.0 – 4.9	IV – V
5.0 – 5.9	VI – VII
6.0 – 6.9	VII – IX
7.0 and above	VIII or above

Figure 9.8 | *A comparison of magnitude versus intensity scales for earthquakes.*
Source: Randa Harris (2015) CC BY-SA 3.0 *view source*

9.4 LOCATING AN EARTHQUAKE EPICENTER

During an earthquake, seismic waves travel all over the globe. Though they may weaken with distance, seismographs are sensitive enough to still detect these waves. The seismogram data from seismographs can give us information including the distance between the earthquake and the seismograph station. Figure 9.9 shows an example of a seismogram from a station where a small earthquake has occurred, and Figure 9.10 shows a set of seismograms from a station recording a single earthquake event.
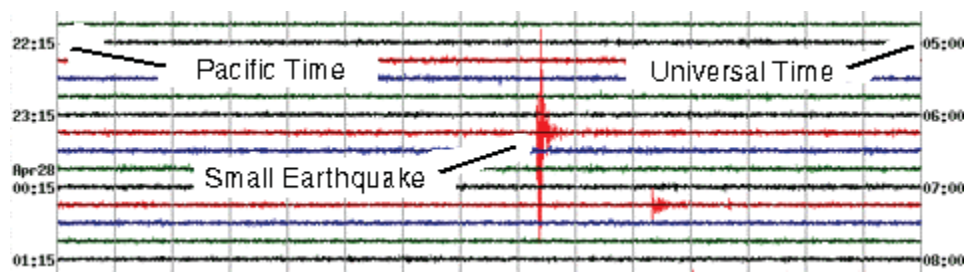
Figure 9.9 | *This seismogram is read from left to right and top to bottom. Note the small earthquake that is marked, and the resulting change in wave amplitude at that point.*
Source: USGS Public Domain View source

Seismologists use characteristics of the wave recorded on the seismogram to calculate the times when the P- and S-waves arrived at the seismograph station. This data can be used to calculate the distance from a seismograph station to the earthquake epicentre. Let's walk through the process of identifying P- and S-wave arrival times at a seismograph station using the seismograms in Figure 9.10. First, identify the positions of the P- and S-wave arrivals, reading from left to right on the seismogram. The arrival of seismic waves will be recognized by an increase in amplitude – look for a pattern change as lines get taller and more closely spaced. By The P-wave arrival is easy to identify, it is the first point where the amplitude of the line (also known as the trace) on the seismogram moves above the flat line. Read the arrival time (usually in seconds) for the P-wave on the x-axis beneath the point where the P-wave arrive (note that there aren't numbers on the x-axis of Figure 9.10 so for the purposes of this example let's call the timepoint "0"). The S-wave arrival is a bit trickier to identify, here, it is an increase in the amplitude of the trace that occurs after the P-wave amplitudes start to decrease. All three traces in Figure 9.10 are from the same seismograph station. Note that the arrival times of the P- and S-waves are virtually identical for all three traces but there are some differences in the wave amplitudes depending on the direction of shaking recorded in the trace.
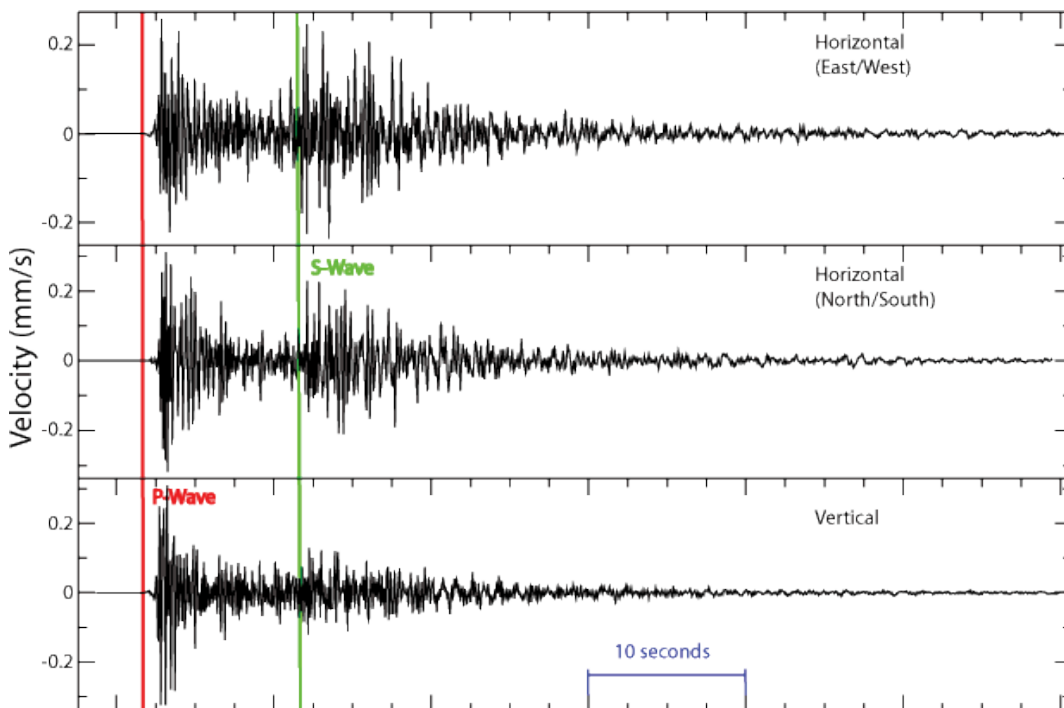

Figure 9.10 | *An example seismogram with the arrival of P and S waves included (red and green lines on the seismogram, respectively). The x-axis is time and is read from left to right, and the z-axis is the velocity, or shaking that causes the needle on the seismograph to deviate either up or down from the zero line. Note how the arrival of waves is marked by a change in the wave height (amplitude) and by more tightly packed waves. The three traces in this figure are from the same seismograph station and are separate measurements of shaking in three directions: horizontal East-West, horizontal North-South, and vertical. Source: Pekachu (2006) view source*

The next step of determining how far the earthquake occurred from the seismograph is to calculate the time interval between the arrival of the P-wave and the arrival of the S-wave. In the example in Figure 9.10, the time between the P- and S-wave arrival times is about 10 s. We can then use a travel-time curve, which is a graph of P- and S-wave arrival times, to determine the distance of the earthquake from the seismograph station (see Figure 9.11). In the example from Figure 9.10, if the P-S arrival difference is 10 s, the earthquake occurred approximately 100 km from the seismograph. A longer time interval between the P- and S-wave indicates the earthquake is a longer distance from the station.

Though distance to the earthquake epicentre can be determined using a travel-time graph, this single seismogram cannot tell us exactly where the earthquake occurred. The earthquake could lie anywhere along a circle with a radius equal to the calculated distance to the earthquake from the seismograph station; we can plot this circle on a map of the region. With additional seismograph data from other stations and corresponding circles on the map we could identify the spot where the circles intersect to narrow down the possible earthquake epicentre locations. Data from at least three seismographs locations are needed to pinpoint the earthquake epicentre (Figure 9.12). Sometimes it takes more than three seismograms to pinpoint the epicentre, depending on the geometry of the station locations. Ideally the stations are located in a triangle around the earthquake epicentre (Figure 9.12) but this is not always the case.
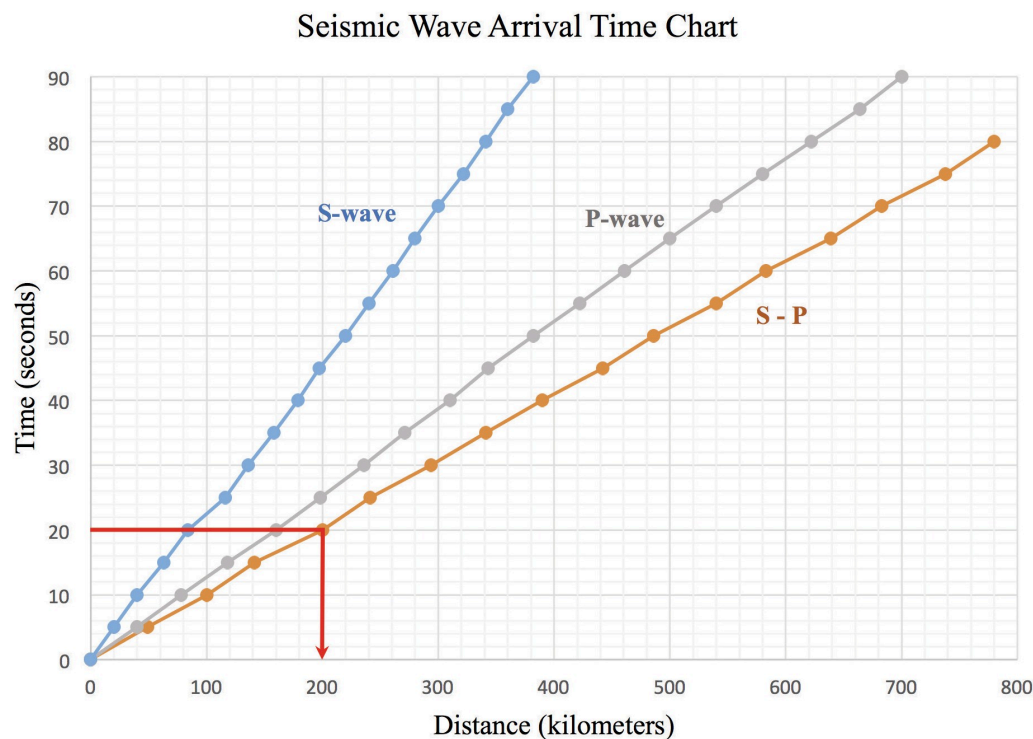

Figure 9.11 | A travel-time graph that includes the arrival of P-waves and S-waves. Note that these curves plot distance versus time and take into consideration that the Earth is spherical. Curves vary with the depth of earthquake because waves behave differently (i.e. their velocities change) with depth and changes in the material properties of the Earth. This curve is used for shallow earthquakes (<20 km deep) with stations within 800 km of the earthquake epicentre. The S-P curve refers to the difference in time between the arrival of the P-wave and S-wave. If you noted on your seismogram that the P-wave arrived at 10 seconds, and the S-wave arrived at 30 seconds, the difference between arrival times would be 20 seconds. You would read the 20 seconds off the y-axis above to the S-P line, then drop down to determine the distance to the epicenter. In this case, it would be approximately 200 kilometers.
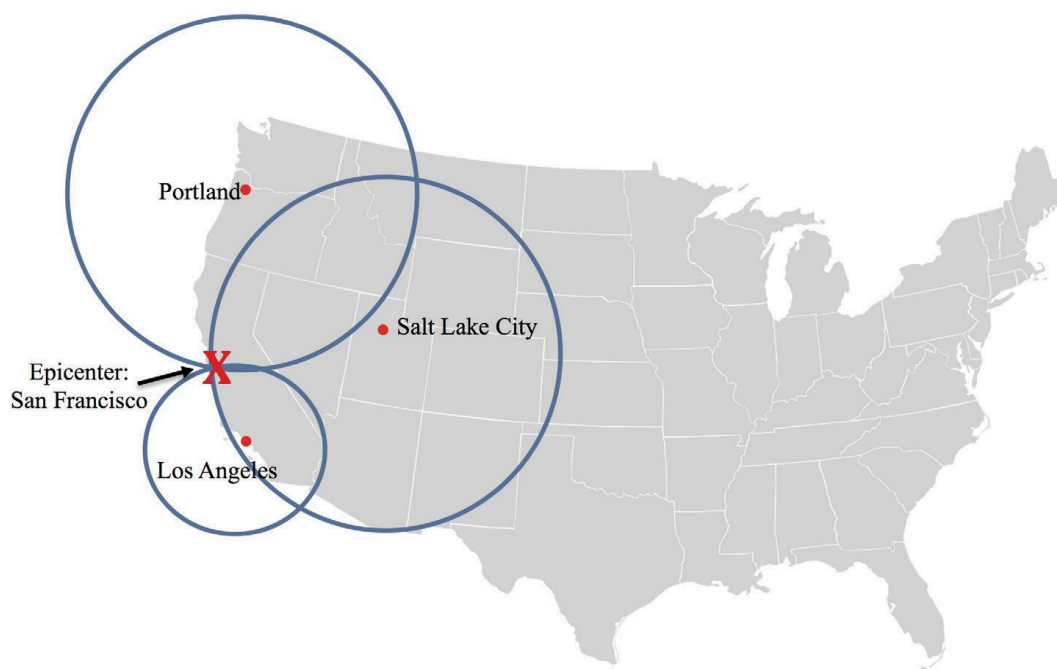Source: Randa Harris (2015) CC BY-SA 3.0 <u>view source</u>

9.5 HAZARDS FROM EARTHQUAKES

Earthquakes are among nature's most destructive phenomena, and there are numerous hazards associated with them. Ground shaking can lead to collapse of structures and falling debris; this is most dangerous hazard in urban areas and for people indoors at the time of an earthquake. The intensity of ground shaking depends on several factors, including the size of the earthquake, the duration of shaking, the distance from the epicentre, and the geology and material properties of the ground. Solid bedrock will not shake much during an earthquake, rendering it safer than other ground materials. Artificial fill refers to areas that have been filled in for construction and/or waste disposal (think of a hill that gets cleared for a shopping mall – the soil that was removed is dumped somewhere else as artificial fill). Sediment is not always well compacted in areas where people have filled in natural landscapes (e.g., in developments in coastal regions where developers have reclaimed marshes to build houses); compaction will occur during the shaking of an earthquake, and this can lead to structure collapse. Artificial fill sediments behave similarly to water-saturated sediments. As saturated sediments are shaken, they may experience **liquefaction**, a process where saturated sediments behave like a fluid. Normally, friction between grains prevents sediments from flowing. When an earthquake occurs, water surrounds every grain, eliminating the friction between the grains, and decreasing their strength and allowing them to flow (Figure 9.13). Liquifaction can be very destructive if there are buildings on top of these deposits when it occurs; they can sink into the ground. Another hazard associated with liquefaction is that seismic waves will amplify as they come in contact with the weaker saturated sediment materials, leading to even more damage.
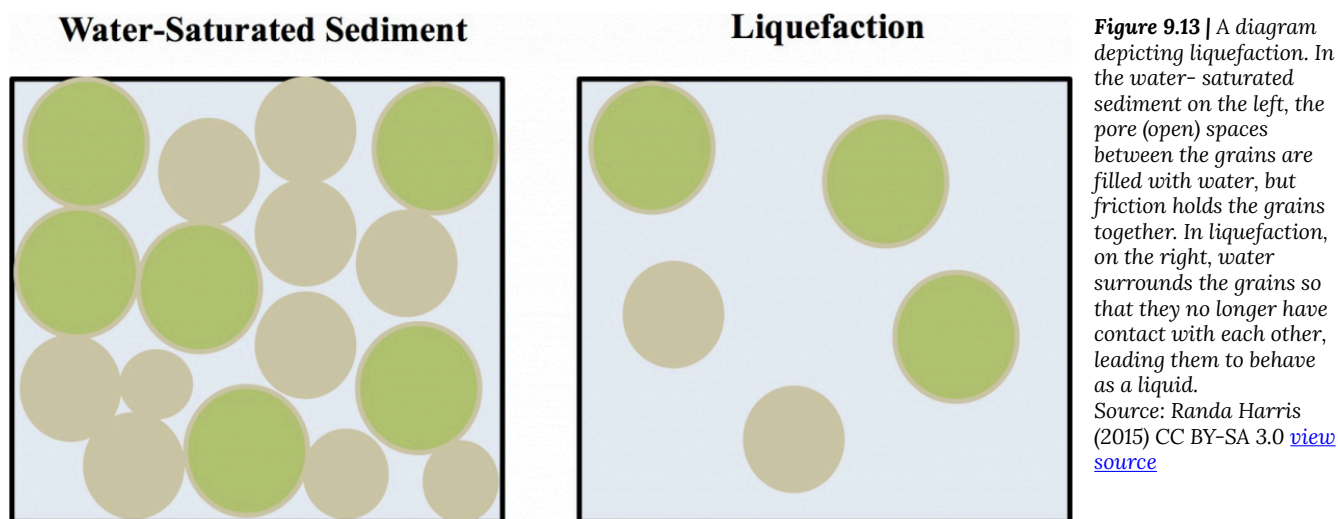
Another hazard associated with earthquakes is fires that can occur when gas lines rupture. These fires can be difficult to combat as water lines may also be ruptured and damage and debris may make it difficult for fire crews to reach the fire. The vast majority of damage during the 1906 San Francisco earthquake was due to fire. Earthquakes can also trigger tsunamis, large sea waves created by the displacement of a large volume of water vertically during fault movement under the ocean. The Sumatra-Andaman earthquake in 2004 triggered a tsunami in the Indian Ocean that resulted in approximately 230,000 deaths. Earthquakes can trigger landslides in mountainous areas, and initiate secondary hazards such as fires, dam breaks, and chemical spills.

Governments in earthquake-prone areas can take steps to minimize destruction, such as: implementing stronger building codes and retrofitting older buildings to strengthen them; educating the public to prepare for earthquake hazards; using the global tsunami warning system to prepare for tsunami events and evacuate citizens if necessary; addressing poverty and social vulnerability in earthquake-prone areas to decrease risk for affected citizens; and limiting development in hazardous zones.

9.6 INDUCED SEISMICITY

The number of notable earthquakes within the central and eastern United States has climbed sharply in recent years. During the thirty-six year period between 1973 and 2008, only 21 earthquakes with a magnitude of 3.0 or greater occurred. During the 5 year period of 2009-2013, 99 earthquakes of that size occurred within the same area, with 659 earthquakes in 2014 alone. There were well over 800 earthquakes in 2015 in Oklahoma (see the blue and red line on the graph in Figure 9.14).

Human intervention is apparently the cause of this increase in earthquake frequency. The term we used to describe this increase is **induced seismicity** (earthquakes caused by human activities). There has been much research into the potential causes for the recent induced seismicity; evidence points to several contributing factors, all related to types of fluid injection used by the oil industry. **Hydraulic fracturing,** also referred to as **fracking**, has been used for decades by oil and gas companies to improve well production. Fracking fluid contains water and additives (e.g., compounds to kill bacteria and decrease friction as the fluid is delivered into the reservoir rocks) as well as propping agents (e.g., sand) to hold fractures open in the reservoir rock. This fluid is injected at high pressure into low-permeability rocks in an effort to fracture the rock and increase the permeability. As more fractures open up within the rock, fluids such as oil or gas can move more easily through the reservoir rock, increasing well production.

With the recent advent of horizontal drilling technology, the fracking industry has increased dramatically since this technology offers opportunities to access previously inaccessible oil and gas resources. Drillers can now access thin horizontal oil and gas reservoirs over long distances, highly increasing well production in rocks that formerly were not exploited. While there have been many reports in the public that blame fracking for increased seismicity rates, this is not the whole story. Fracking mainly produces very minor earthquakes (less than magnitude 3), though it has been shown to produce significant earthquakes on occasion. The majority of induced earthquakes are caused by injection of wastewater deep underground. This wastewater is the byproduct of fracking, so ultimately the source of the induced seismicity is still primarily the oil and gas industry.

As wells are developed (made to produce more oil or gas) by fracking or other processes, large amounts of waste fluid are created. These fluids may contain potentially hazardous chemicals. When the fluids cannot be recycled or stored in retention ponds above ground, they are injected deep underground, to a depth that theoretically is deep enough to not come into contact with oil reservoirs or water supplies. These wastewater wells are quite common and are considered a safe option for wastewater disposal based on models for water flow in the subsurface. If water is injected in areas that contain faults, however, the stress conditions on the faults may change as the friction is reduced by the fluids. This can result in movement along faults and earthquakes.
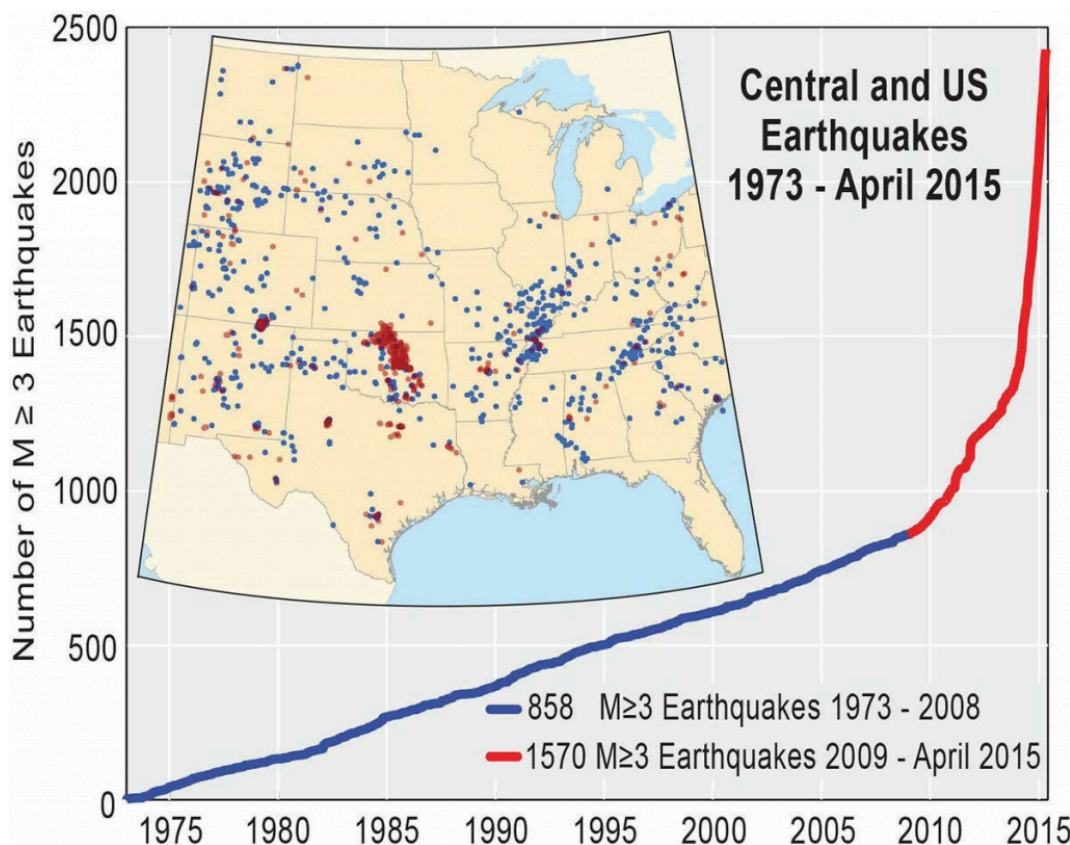

Figure 9.14 | *Chart of increased seismicity of magnitude 3 or greater earthquakes within the central and eastern U.S. from 1973-2015. The spatial distribution of the earthquakes is shown on the map, with blue dots representing quakes from 1973-2008, and red dots representing quakes from 2009-2015. Source: USGS (2016) Public Domain* [view source](#)

In the lab exercises for this chapter, we will explore data from induced seismicity in the state of Oklahoma. Figure 9.14 shows the distribution of earthquakes through the central USA between 1973 and 2015. Note the high density of red spots in the centre of the map, these are earthquakes in the years 2009-2015 and are mostly in the state of Oklahoma (Figure 9.15). Research by the USGS has determined that source of this seismic hazard is the disposal of wastewater from the oil and gas industry by deep injection, though some smaller quakes (magnitude 0.6 to 2.9) have been shown to correlate directly to fracking. A 50% increase in earthquake rate has occurred within Oklahoma since 2013. One large

earthquake of 5.7 magnitude struck in November, 2011, and has been linked to an active wastewater injection site about 200 meters away.
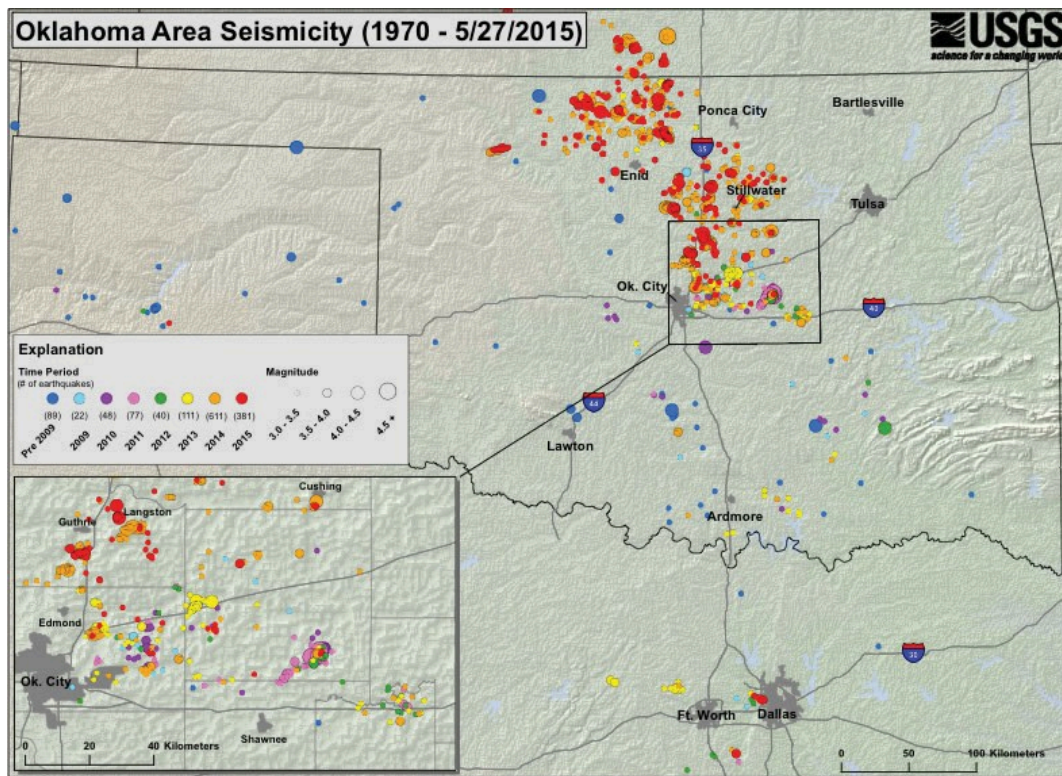

Figure **9.15** | *Earthquakes that occurred within Oklahoma from 1970 – 5/27/15 are depicted above. Please note that the colors indicate year and the size indicates magnitude (see legend on image). The inset image is a close-up view of the outlined box.*
Source: USGS Public Domain [view source](#)

Exercises on Earthquakes

Adapted by Joyce M. McBeth, Sean W. Lacey, Tim C. Prokopiuk (2018) University of Saskatchewan from Deline B, Harris R, & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 13 "Earthquakes" by Randa Harris, CC BY-SA 4.0. [View Source](). *Last edited: 23 Mar 2020*

Name: _____

NSID and student number: _____

Date and lab section time: _____

TAs' names: _____

Please hand in this lab to your TAs at the end of the lab period.

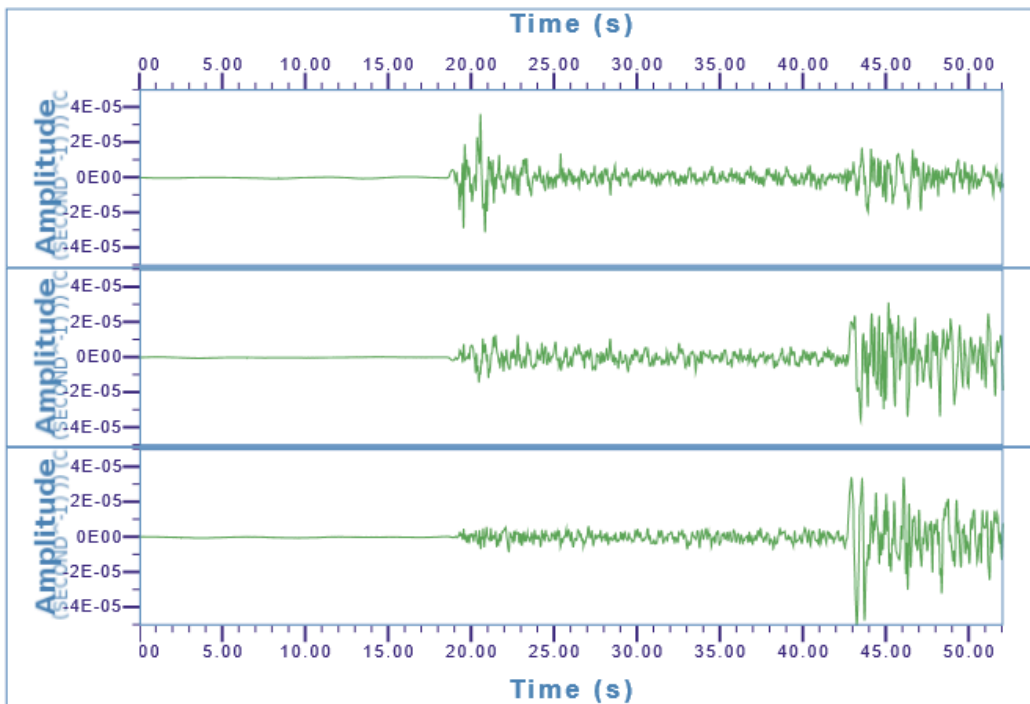## 9-E1 LAB EXERCISE – LOCATING AN EPICENTER

You will determine the location of an earthquake epicenter using seismograms from Carrier, Oklahoma, Smith Ranch in Marlow, Oklahoma, and Bolivar, Missouri. These are actual seismograms that you will be reading, from an actual earthquake event. For each seismogram, three different readouts are given, because the seismograph measured movement along three different axes simultaneously. You can use any of the three readouts for each station in your calculations, because each of the readouts will have the same arrival time for the different components of each wave.

First, determine the time when the P and S waves first arrived for each station. To identify the P and S waves, refer to the illustrations in the overview section of this chapter. Look for a pattern change as the amplitude of the lines gets bigger; this indicates the arrival of each of the waves. Mark both the arrival of the P-wave and S-wave on the seismogram, then using the time scale in seconds, determine the time difference between the P and S wave first arrivals. Write these times in Table 9.1 below for each of the three seismograms. (12 pts).

Table 9.1

Station	P-wave arrival time (s)	S-wave arrival time (s)	Difference between P- and S-wave arrival times (s)	Distance to epicentre from station (km)
Carrier, OK				
Smith Ranch, Marlow, OK				
Bolivar, MO				

Figure 9-E1 |
Seismogram readings from Smith Ranch, Marlow, Oklahoma. Source: USGS (2015) public domain, source webpage: https://earthquake.usgs. gov/

Figure 9-E2 |
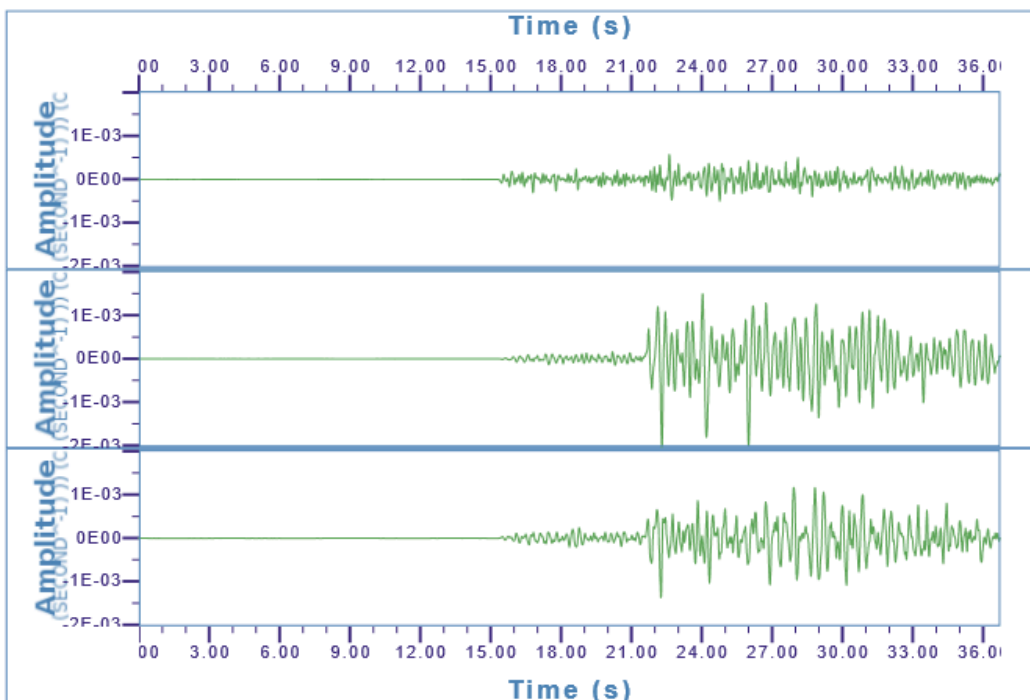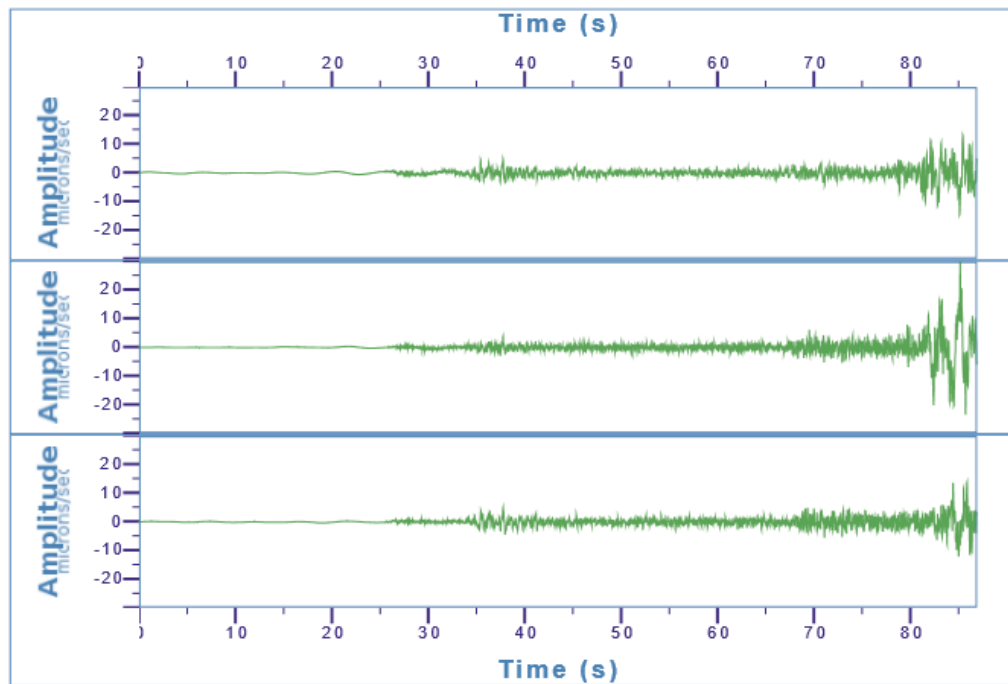*Seismogram readings from Carrier, Oklahoma. Source: USGS (2015) public domain, source webpage: https://earthquake.usgs. gov/*

Seismogram Begin Time: 2015-06-14 18:17:41 GMT
Station: S39B - Bolivar, MO, USA
Station Location: Latitude 37.69 N, Longitude 93.32 W

Data retrieved from the United States Geologic Survey.

Figure 9-E3 |
Seismogram readings from Bolivar, Missouri. Source: USGS (2015) public domain, source webpage: https://earthquake.usgs.gov/

The difference between the P and S wave first arrivals will be used to determine the distances to the epicenter from each station in Figure 9-E4. Use Figure 9.11 from the overview section of this lab (replicated below) to determine the distance of the epicenter from each station. Make sure that you use the curve for the difference between the S and P wave first arrival times (S-P). Find the difference between the S and P first arrival times in seconds on the y-axis, draw a line over to the S-P curve at the same time, then draw a line down to the x- axis to determine the distance. Add the values to Table 9.1 above.
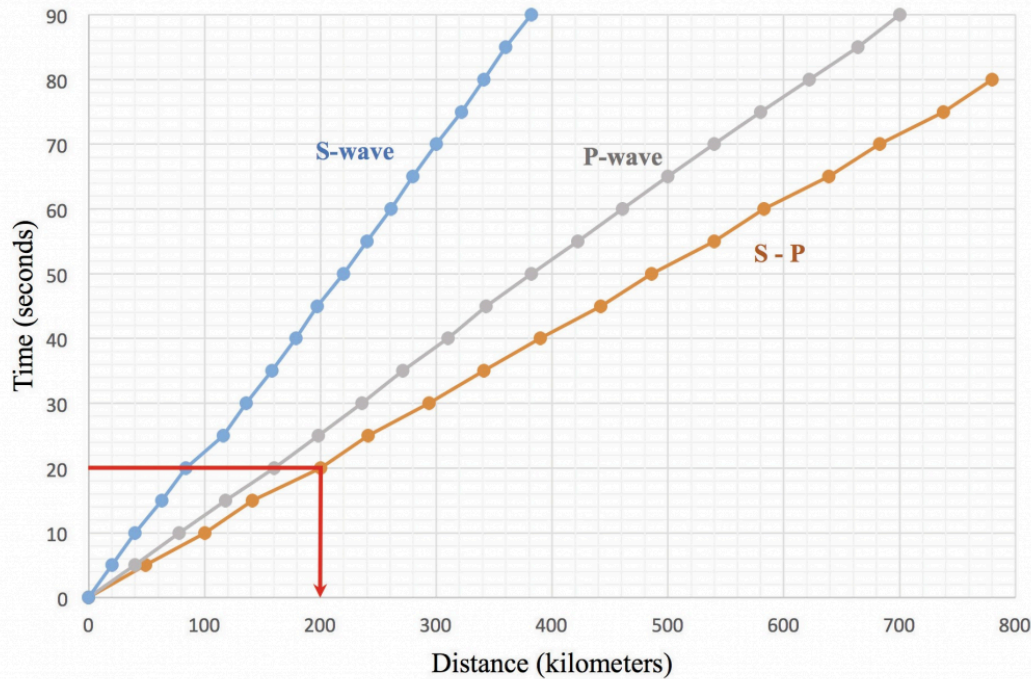
Seismic Wave Arrival Time Chart

Figure 9.11 | *A travel-time graph that includes the arrival of P-waves and S-waves. Note that these curves plot distance versus time, and are calculated based on the fact that the Earth is a sphere. Curves vary with the depth of earthquake because waves behave differently (i.e. their velocities change) with depth and change in material. This particular curve is used for shallow earthquakes (<20 km deep) with stations within 800 km. The S-P curve refers to the difference in time between the arrival of the P-wave and S-wave. If you noted on your seismogram that the P-wave arrived at 10 seconds, and the S-wave arrived at 30 seconds, the difference between arrival times would be 20 seconds. You would read the 20 seconds off the y-axis above to the S-P line, then drop down to determine the distance to the epicenter. In this case, it would be approximately 200 kilometers. Source: Randa Harris (2015) CC BY-SA 3.0 view source*

Figure 9-E4 is a map showing the three stations on it. Next, you will draw circles on this map to represent the distance of the earthquake epicenter from each station. Use a drafting compass to draw the circles. This map includes a legend in kilometers. For each station, note the distance to the epicenter. Measure the scale on the map in Figure 9-E4 in centimeters and convert your distances in kilometers to centimeters (e.g., if the map's scale of 100 km = 2.1 cm on your ruler, and you had a measured distance from one station of 400 km, that would equal 8.4 cm on your ruler). For this fictional example, you would use a drafting compass to make a circle around the station that is 8.4 cm in radius (from the centre to the edge). Create a circle for each of the three stations, using their different distances to the epicenter. They should overlap (or nearly overlap) in one location. The location where they overlap is the approximate epicenter of the earthquake. (7 pts total: 2 points for each circle and 1 pt for location of epicentre)
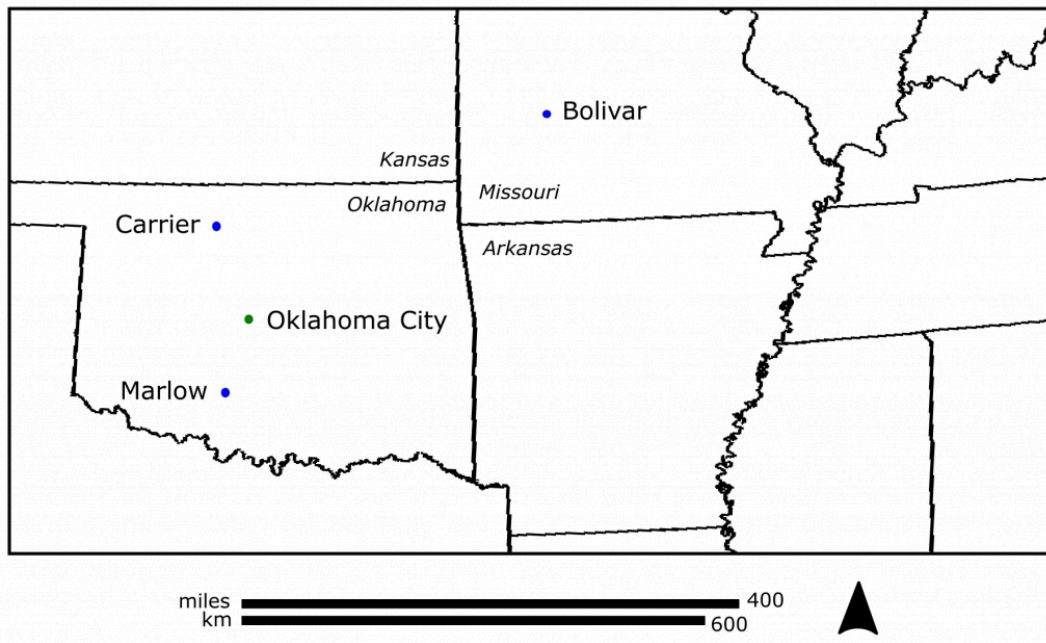
Figure 9-E4 | *Map depicting three seismograph stations (Carrier, Smith Ranch, and Bolivar) located in Oklahoma and Missouri, USA. Source: Joyce McBeth (2018) CC BY 4.0, after Randa Harris (2015)* view source

1. (1 pt) For Carrier, Oklahoma, what is the approximate time of the arrival of the first P-wave?

a. 10 seconds

b. 15 seconds

c. 21 seconds

d. 30 seconds

2. (1 pt) For Smith Ranch, Marlow, Oklahoma, what is the approximate time of the arrival of the first S-wave?

a. 19 seconds

b. 22 seconds

c. 35 seconds

d. 42 seconds

3. (1 pt) For Bolivar, Missouri, what is the difference between the P and S wave arrival times?

a. 10 seconds

b. 20 seconds

c. 40 seconds

d. 55 seconds

4. (1 pt) What is the approximate distance to the epicenter from Carrier, Oklahoma?

a. 70 km

b. 130 km

c. 240 km

d. 390 km

5. (1 pt) What is the approximate distance to the epicenter from Smith Ranch, Marlow, Oklahoma?

a. 70 km

b. 130 km

c. 240 km

d. 390 km

6. (1 pt) What is the approximate distance to the epicenter from Bolivar, Missouri?

a. 70 km

b. 130 km

c. 240 km

d. 390 km

7. (1 pt) Look at the location that you determined was the earthquake epicenter. Compare its location to Oklahoma City. Which direction is the epicenter located from Oklahoma City?
a. southeast

b. northwest

c. northeast

d. southwest

9-E2 LAB EXERCISE – INDUCED SEISMICITY

The table below contains data showing the number of fracking wells in the state of Oklahoma and the number of significant earthquakes (magnitude 3 or greater) that have occurred between 2000 and 2015. Before answering the questions for this lab exercise, plot the information in the table below on the graph that is provided. Note the graph has two y-axes, one for the number of fracking wells and the other for the number of earthquakes. Plot a line for each set of data on the graph, using the appropriate y axis for each set of data.

Table 9.2

Year	# of Fracking Wells in Oklahoma	# of Earthquakes greater than M 3
2000	0	0
2001	0	0
2002	0	3
2003	0	0
2004	0	2
2005	0	1
2006	0	2
2007	0	1
2008	1	2
2009	4	20
2010	1	43
2011	637	63
2012	1,568	34
2013	1,939	109
2014	3,296	585
2015	1,749	850

(From: http://www.oudaily.com/news/oklahoma-reports-surge-in-earthquakes-during/article_79a364da-a1d4-11e5-894a-5ba84c8399c1.html)

Note: *Information on number of fracked wells was obtained by SkyTruth through accessing FracFocus. Oklahomans are required to report all fracked wells, but the site was only created in 2011, so some wells may have not been retroactively added pre-2011. Seismic data was obtained from the USGS.*

Your graph plot is worth 6 pts.

Seismicity vs Fracked Wells in Oklahoma
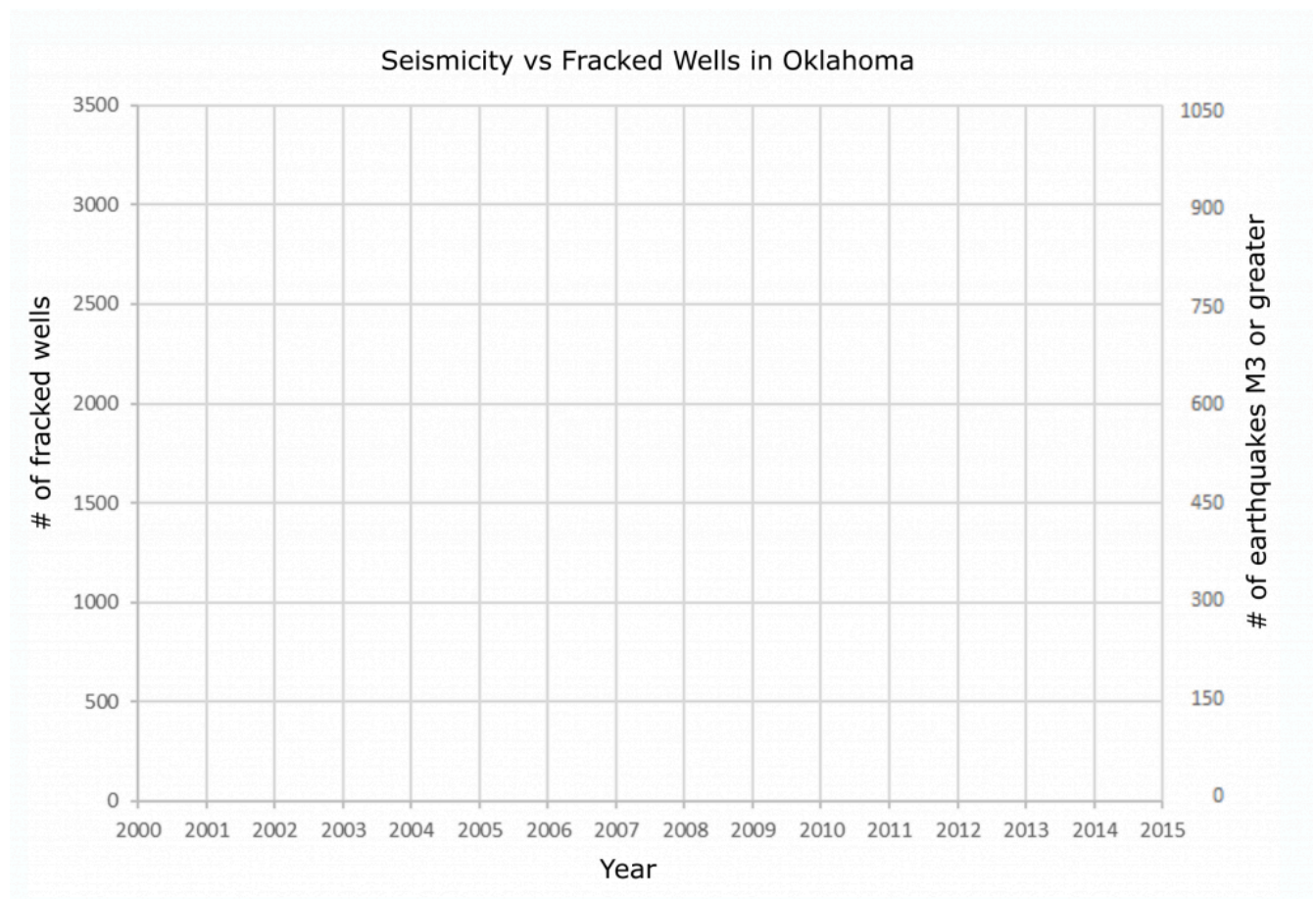
8. (1 pt) Referring to the graph, what year does the number of magnitude 3 or greater earthquakes begin to rise significantly?

a. 2007

b. 2009

c. 2010

d. 2015

9. (1 pt) What year does the number of fracking wells rise significantly?

a. 2007

b. 2009

c. 2010

d. 2015

10. (1 pt) Based on the graph that you constructed, do significant earthquakes and the number of fracking wells appear to be related?

a. Yes

b. No

9-E3 LAB EXERCISE – HISTORICAL EARTHQUAKE

The exercises that follow use Google Earth to explore a historical earthquake. The San Andreas Fault is ~1300 km long and it is located in California. In 1906, a major earthquake occurred along a portion of the fault.

Let's start by examining the 1906 earthquake that hit Northern California using the [USGS virtual tour of the 1906 earthquake website](). Spend some time familiarizing yourself with the site. Scroll down to the section entitled "The Northern California Earthquake, April 18, 1906" and open the link. Scroll down and check out the Rupture Length and Slip.

11. (1 pt) How long was the rupture length (the length of the fault that was affected)?

a. 25 km

b. 194 km

c. 298 km

d. 477 km

e. 542 km

Horizontal slip, or relative movement along the fault, ranged from 0.5 to 9.7 meters. To envision this, imagine that you are facing an object directly across the fault from you. Suddenly, it moves up to 9.7 meters to your right! To visualize horizontal slip, geologists can plot the slip along the rupture as a histogram (a graph with distance on the x axis and the amount of slip on the y axis; higher bars in the plot represent regions with more slip). Check out the histogram of slip measurements along the fault by clicking the link Rupture Length and Slip; this will open a Google Earth file. If you do not have a computer with Google Earth available to you in the lab, your TA can open the file in Google Earth on the lab computer.

12. (1 pt) Locate the epicenter of the 1906 quake. Does the amount of horizontal slip decrease faster along the northern end or the southern end of the rupture?
a. northern end of the rupture

b. southern end of the rupture

Go back to the "The Northern California Earthquake, April 18, 1906" page in your browser and scroll down to check out the section on Shaking Intensity. Click on the link to the Shaking Intensity file to open it in Google Earth. If your map is difficult to read, remember that by clicking on a checked box in the Places folder in Google Earth, you can select the data you want to look at (and deselect data you do not want to look at). Use the search box to display the desired location for the questions below.

13. (1 pt) What was the shaking intensity like in Sacramento?

a. light

b. strong

c. severe

d. violent

e. extreme

14. (1 pt) What was the shaking intensity like in Sebastopol?

a. light

b. strong

c. severe

d. violent

e. extreme

Return to your browser window and navigate back to the main page of "The Northern California Earthquake, April 18, 1906". Select "Earthquake Hazards of the Bay Area Today." Check out the Earthquake Probabilities for the Bay Area.

15. (1 pt) Based on the map, would you be more likely to experience an earthquake of magnitude >6.7 by 2031 if living in the northwest Bay Area or southeast Bay Area?
a. northwest

b. southeast

Go back to the "Earthquake Hazards of the Bay Area Today" page and open the file "Liquefaction Susceptibility in San Francisco". The red areas on the map are the areas in danger of liquifaction. Look at the overall trend in the areas affected by liquefaction.

16. (1 pt) Based on the liquefaction map, are areas more dangerous inland or along the coast?
a. inland

b. along the coast

CHAPTER 10. WATER

Adapted by Joyce M. McBeth (2018) University of Saskatchewan from Deline B, Harris R & Tefend K. (2015) "Laboratory Manual for Introductory Geology". First Edition. Chapter 5 "Water" by Randa Harris, CC BY-SA 4.0. [View source.](#)

10.1 INTRODUCTION

Think how many times a day you take water for granted – you assume the tap will be flowing when you turn on your faucet, you expect rainfall to water your lawn, and you may count on water for your recreation. Not only is water necessary for many of life's functions, it is also an important geologic agent. Water can sculpt the landscape dramatically over time both by carving canyons as well as depositing thick layers of sediment. Some of these processes are slow and result in landscapes worn down over time. Others, such as floods, can be dramatic and dangerous.

What happens to water during a rainstorm? Imagine that you are outside in a parking lot with grassy areas nearby. Where does the water from the parking lot go? Much of it will run off as sheet flow and eventually join a stream. What happens to the rain in the grassy area? Much of it will infiltrate, or soak into the ground. We will deal with both surface and ground water in this lab. Both are integral parts of the water cycle, in which water gets continually recycled through the atmosphere, to the land, and back to the oceans. This cycle, powered by the sun, operates easily since water can change form from liquid to gas (or water vapour) quickly under surface conditions.

Both surface and ground water are beneficial for drinking water, industry, agriculture, recreation, and commerce. Demand for water will only increase as population increases, making it vital to protect water sources both above and below ground.

10.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Understand how streams erode, transport, and deposit sediment
- Know the different stream drainage patterns and understand what they indicate about the underlying rock
- Explain the changes that happen from the head to the mouth of a stream
- Understand the human hazards associated with floods
- Know the properties of groundwater and aquifers
- Understand the distribution of groundwater, including the water table
- Learn the main features associated with karst topography
- Understand the challenges posed by karst topography

10.1.2 Key Terms

- Aquifer
- Discharge

- Drainage Basin
- Drainage Divide
- Drainage Pattern
- Floodplain

Overview of Water

10.2 STREAMFLOW AND PARTS OF A STREAM

The running water in a stream will **erode** (wear away) and move material within its channel, including dissolved substances (materials taken into solution during chemical weathering). The solid sediments may range in size from tiny clay and silt particles too small for the naked eye to view up to sand and gravel sized sediments. Even boulders have been carried by large flows. The smaller particles kept in suspension by the water's flow are called **suspended load**. The dissolved substances in the water are called **dissolved load**. Larger particles typically travel as **bed load**. The bed load rolls, slides, and salts (hops) along the stream bed (Figure 10.1). While the dissolved, suspended, and bed loads may travel long distances (e.g., from the headwaters of the Bow River in the Rocky Mountains to the mouth of the Saskatchewan River where it discharges into Lake Winnipeg), they will eventually settle out, or deposit. These stream deposited sediments, called **alluvium**, can be deposited at any time, but most often occur during flood events. To more effectively transport sediment, a stream needs energy. This energy is mostly a function of the amount of water and its **velocity** (speed), as more (and larger) sediment can be carried by a fast-moving stream. As a stream loses its energy and slows down, material will be deposited.
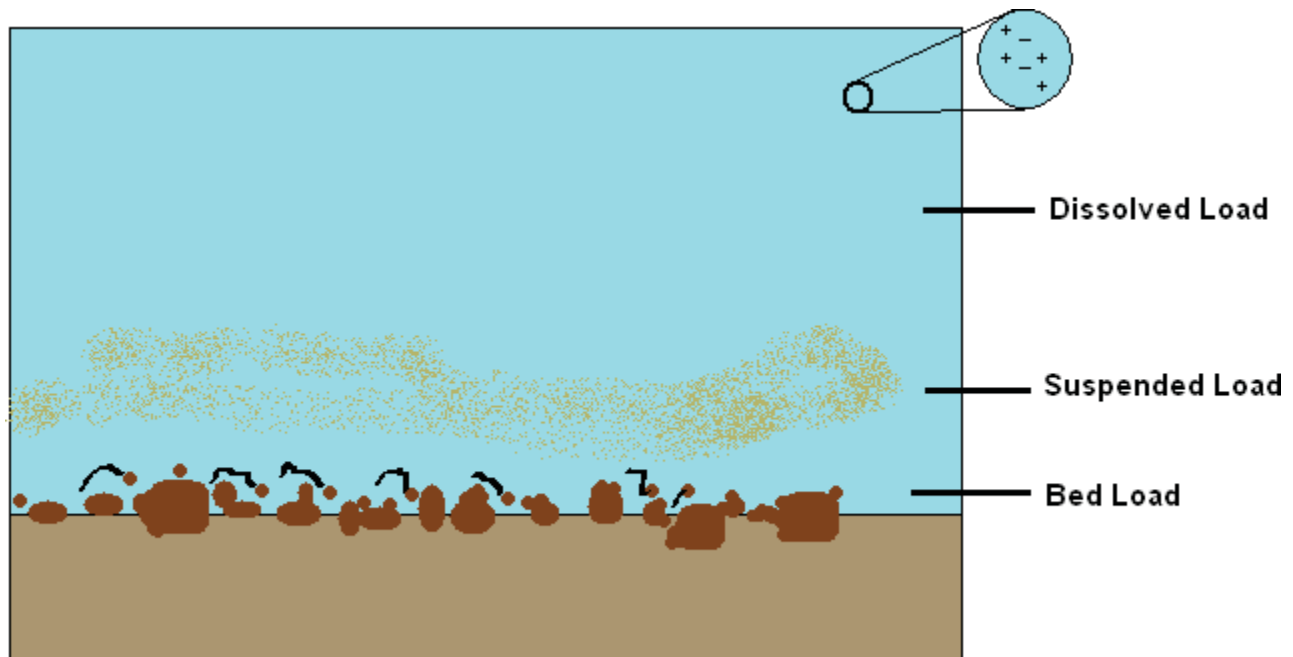

Figure 10.1 | *An illustration depicting dissolved, suspended, and bed load.*
Source: PSUEnviroDan (2008) public domain [view source]()

Under normal conditions, water will remain in a stream channel. When the amount of water in a stream exceeds its

banks, the water that spills over the edges of the channel decreases in velocity rapidly. As the water velocity drops, the water will also drop the larger sandy material it is carrying right along the channel margins, resulting in ridges of sandy alluvium called **natural levees** (Figure 10.2). As numerous flooding events occur, these ridges build up under repeated deposition. These levees are part of a larger landform known as a **floodplain**. A floodplain is the relatively flat land adjacent to the stream that is subject to flooding during times of high discharge.
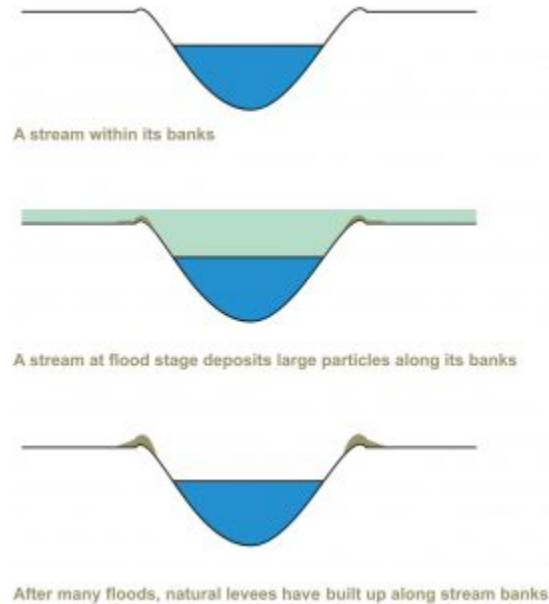

A stream within its banks

A stream at flood stage deposits large particles along its banks

After many floods, natural levees have built up along stream banks

Figure 10.2 | After many floods, natural levees built up along stream banks.
Source: Julie Sandeen (2009) CC BY-SA 3.0 view source

10.2.1 Stream Drainage Basins and Patterns

The **drainage basin** (also known as **watershed**, **catchment area**, or **river basin**) of a stream includes all the land that is drained by the stream and all of its **tributaries** (the smaller streams that feed into the main stream). Small drainage basins are part of larger drainage basins (e.g., the drainage basin for a small mountain stream will be part of the drainage basin for the river it flows into). You are in a drainage basin right now. Do you know which one? Search for images of "drainage basin" or "watershed" and your province on the internet to find information on your local watersheds. For example, if you live in Saskatchewan you can refer to the Saskatchewan Water Security Agency's map of watersheds in Saskatchewan.

At the continental scale, ocean watersheds drain the runoff from large regions of the continents into oceans. There are five ocean watersheds in Canada: the Arctic Ocean watershed, the Pacific Ocean watershed, the Hudson Bay watershed, the Atlantic Ocean watershed, and a small part of southern Alberta and Saskatchewan drains into the Gulf of Mexico watershed.

The higher areas that separate drainage basins are called **drainage divides.** Drainage divides can be very high topographically (e.g.; the Great Divide in the Rockies which separates drainage to the Pacific Ocean in the west from drainage to the Arctic Ocean, Hudson Bay, the Atlantic Ocean, and the Gulf of Mexico) or lower (e.g., the Arctic Divide that runs through Alberta, Saskatchewan, the NWT, and Nunavut, dividing drainage to the Arctic Ocean from drainage to Hudson Bay).

Water erodes softer rocks more easily than it erodes hard, resistant rock. This can result in characteristic patterns of drainage. Some of the more common **drainage patterns** include:

- **Dendritic** – this drainage pattern indicates uniformly resistant bedrock that often includes horizontal rocks. Since all the rock is uniform, the water does not erode any area preferentially; thus, the channels form a branching pattern similar to the branches of a tree.
- **Trellis** – this drainage pattern indicates alternating resistant and non-resistant bedrock that has been deformed (folded) into parallel ridges and valleys. The water erodes the softer rock, and the channels that develop from erosion appear much like a rose climbing on a trellis in a garden.
- **Radial** – this drainage pattern forms as streams flow away from a central high point, such as a volcano, and the pattern resembles the spokes in a wheel.
- **Rectangular** – this drainage pattern forms in areas in which rock has been fractured or faulted which created weakened rock. Streams erode the less resistant rock and create a network of channels that make right-angle bends as they intersect these breaking points. This pattern will often look like rectangles or squares.
- **Deranged** – this drainage pattern does not follow any of the patterns above, it is a random pattern of irregular stream channels. Deranged drainage patterns are found where drainage developed recently and has not yet had time to form one of the other drainage patterns.
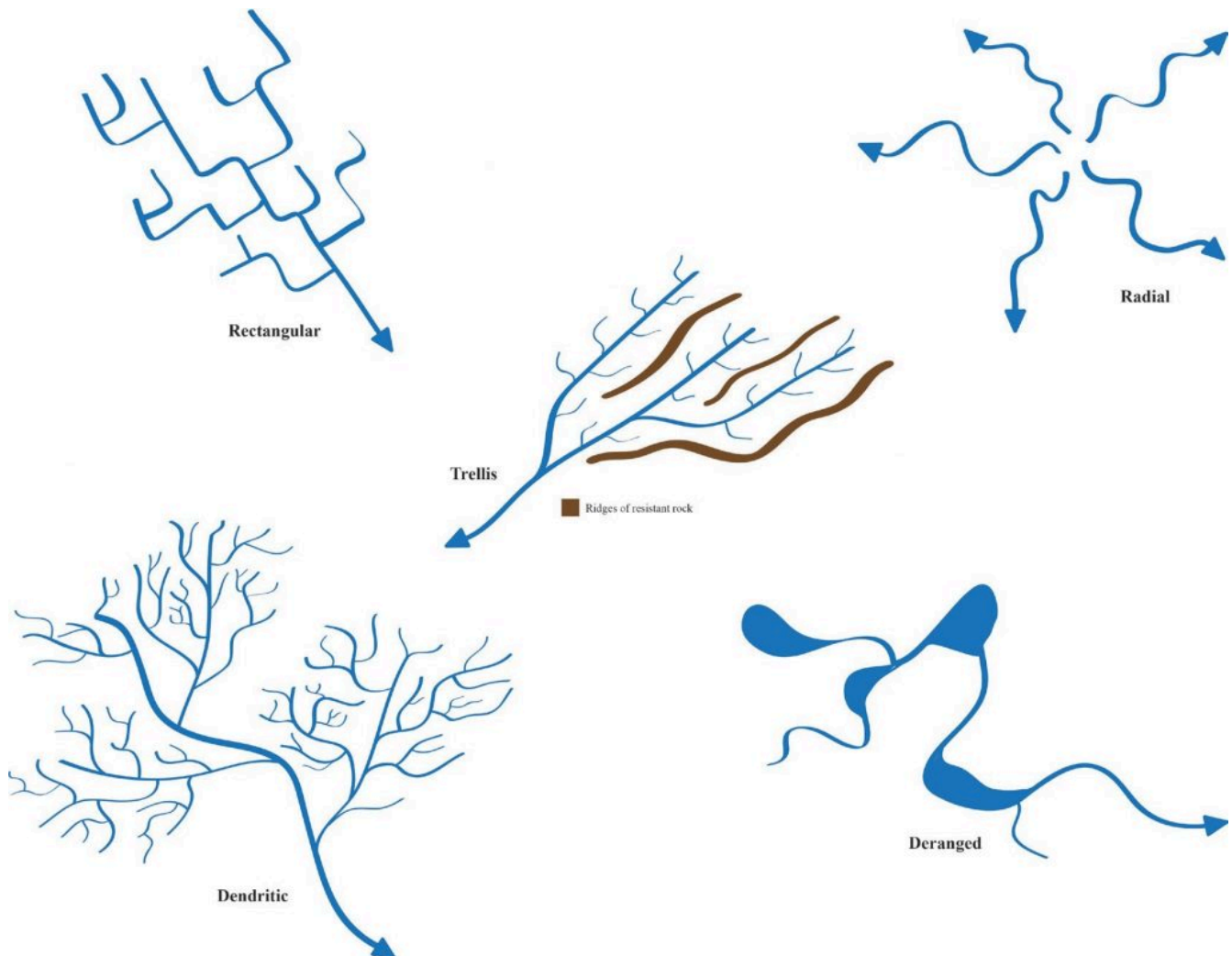

Figure 10.3 | Drainage patterns.
Source: Corey Parson (2015) CC BY-SA 3.0 view source

10.3 STREAM GRADIENT AND THE CYCLE OF STREAM EROSION

Stream gradient refers to the slope of the stream's channel. It is the vertical drop of the stream over a horizontal distance (the rise and run, respectively). You have dealt with gradient before in Topographic Maps. The gradient can be calculated using the following equation:

Gradient = (change in elevation) / distance

Let's calculate the gradient from A to B in Figure 10.4 below. The elevation of the stream at A is 980 m, and the elevation of the stream at B is 920 m. Using the scale bar on the figure, we calculate the distance from A to B is 2 km. Gradient = (980 m – 920 m) / 2 km, or 30 m/km.
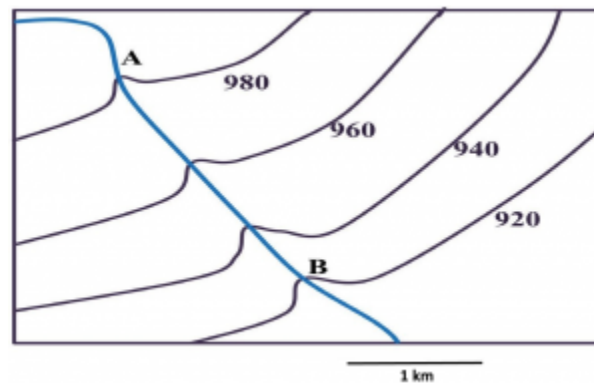

Figure 10.4 | *Gradient calculation.*
Source: Joyce McBeth (2018) CC BY–SA 4.0, after Randa Harris
(2015) CC BY–SA 3.0 *view source*

Stream gradients tend to be higher in a stream's **headwaters** (where it originates), and lower at the stream's **mouth** (where it discharges into another body of water such as the ocean). **Discharge** measures stream flow at a given time and location; it is a measure of the volume of water passing a particular point in a given period of time. It is found by multiplying the area (width multiplied by depth) of the stream channel by the velocity of the water, and is often in units of cubic meters per second. Discharge increases downstream in most rivers, as tributaries join the main channel and add water.

Sediment load (the amount of sediment carried by the stream) also changes from the stream's headwaters to its mouth. At the headwaters, tributaries quickly carry their load downstream, combining with loads from other tributaries. The main river then eventually deposits that sediment load when it reaches **base level** (the point where the stream is at the same elevation as a lake or ocean that it discharges into).

Sometimes in this process of carrying material downstream, the sediment load is large enough that the water cannot support it, so deposition occurs. If a stream becomes overloaded with sediment, braided streams may develop, with a network of intersecting channels that resembles braided hair. Sand and gravel bars are typical in these **braided streams**. Braided streams are common in regions with abundant sediments and variable discharge, for example in streams that discharge from glaciers.

Straight streams are less common; these stream channels remain nearly straight due to a linear zone of weakness in the underlying rock (e.g., a fault). They are common near the headwaters of streams in mountainous regions, where the stream flows in a generally straight line through steep-sided canyons. Straight channels can also be man-made, to help with flood control.

Meandering streams have broadly looping curves that resemble an "S"-shape. These are known as **meanders** (Figure

10.5). The water traveling in a meandering stream moves fastest on the outside bends of the stream. This greater velocity and turbulence from the faster flow lead to more erosion on these outside bends, forming a featured called a **cut bank** (a bank with a steep slope). Erosion on this bank is offset by deposition on the opposite bank of the stream, where slower moving water allows sediment to settle out. These deposits are called point bars.
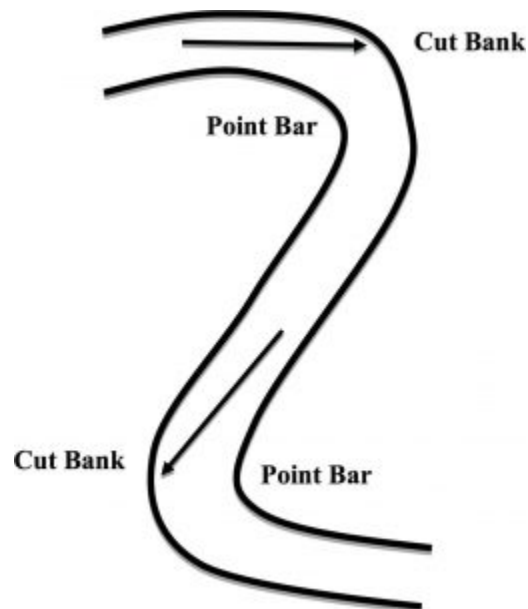
Figure 10.5 | Parts of a meandering stream. The S-curves are meanders. The arrows within the stream depict where the fastest water flows. That water erodes the outside bank, creating a steep bank called the cut bank. The slowest water flows on the inside of the meander, slow enough to deposit sediment and create the point bar.
Source: Randa Harris (2015) CC BY-SA 3.0 [view source](#)

As meanders become more complicated, or sinuous, they may cut off another meander in the stream. When this happens, the cut off meander becomes a crescent-shaped oxbow lake (Figure 10.6).

Figure 10.6 | Formation of an oxbow lake. A meander begins to form and is cut off, forming the oxbow. Source: User Maksim on Wikimedia Commons (2005) CC BY-SA 2.5 view source

Even though streams are not living, they do go through characteristic changes over time as they change the landscape. Ultimately, streams will reach **base level.** This is the low elevation at which the stream can no longer erode its channel – often a lake or other stream. The ultimate base level is the ocean. Over a stream's evolution, it will experience a cycle of stream erosion, which consists of these stages (Figure 10.7):

- **Youthful (early) stage** – these streams are downcutting their channels (vertically eroding), picking up sediment from the bottom of their channels and decreasing their elevation. The land surface will be above sea level, and these streams form deep V-shaped channels.
- **Mature (middle) stage** – these streams experience both vertical (downcutting) and lateral (meandering) erosion. The land surface is sloped, and streams begin to form **floodplains** (the flat land around streams that are subject to flooding).
- **Old age (late) stage** – these streams erode laterally rather than vertically (i.e., they move by meandering across the landscape) and have very complicated meanders and oxbow lakes. The land surface is near base level.
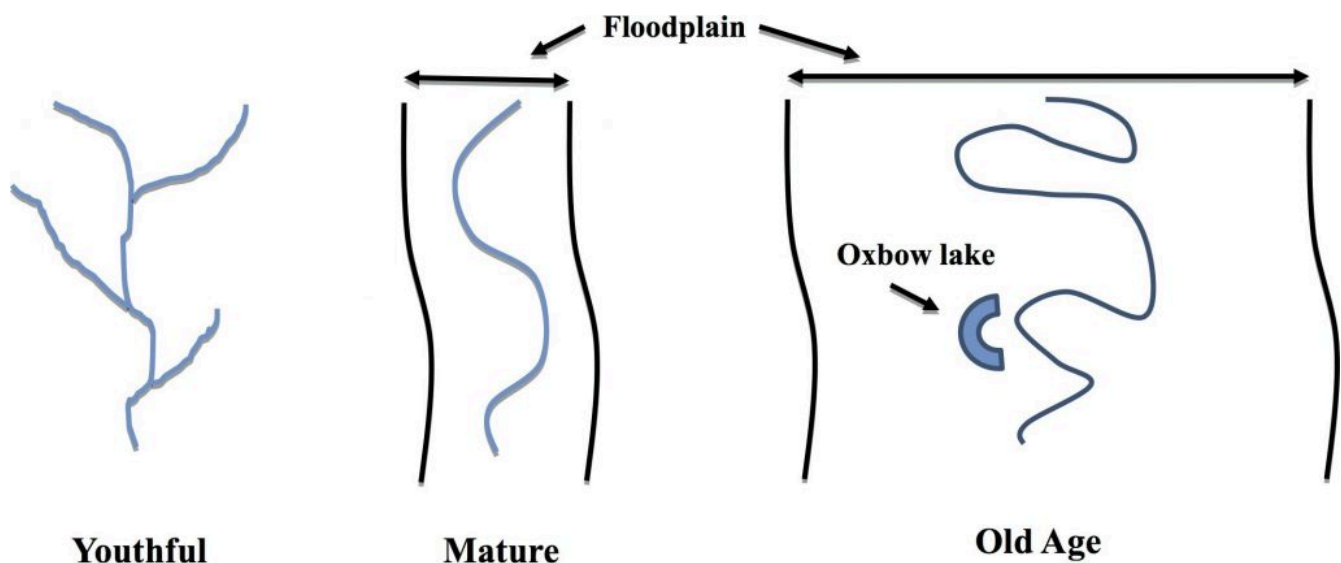
Figure 10.7 | *Streams displaying the youthful, mature, and old age stages within the cycle of stream erosion. Note that the youthful stream does not have a floodplain.*
Source: Randa Harris (2015) CC BY-SA 3.0 view source

An interruption may occur in this cycle. If the base level drops (e.g., due to a drop in sea level) the stream will begin to downcut again. This can also occur if the area around it was uplifted (think building mountains). If the stream was in the old age stage when this change in base level or uplift occurred, it will begin to form a deep V-shaped channel within that complicated meandering pattern that it has. This creates a neat geologic feature called an entrenched meander (Figure 10.8).

Figure 10.8 | *Entrenched meanders along the San Juan River, Goosenecks State Park, Utah.*
Source: User "Finetooth" (2010) CC BY-SA 3.0 view source

10.4 FLOODING

Flooding is a common and serious problem globally. Flood stage is reached when the water level in a stream overflows its banks. Floodplains are evidence for past flooding of a stream. Floodplains are also popular sites for development: they have nice water views and are flat and composed of sediments that are easy to landscape. Perhaps these areas are best left for playgrounds and golf courses if you consider the potential damage that a flood might do to buildings and property.

When we describe flood risk, we often describe the risk frequency in terms such as "1 in 100 year flood". How often do you think a 1 in 100 year flood will occur? Does it mean that a flood of similar magnitude will occur every 100 years? Not necessarily! It means that – on average – we can expect a flood of this size or greater to occur within a 100 year period. One cannot predict that it will occur in a particular year, only that each year has a 1 in 100 chance of having a flood of that magnitude. It also does not mean that only one flood of that size can occur within 100 years. The "1 in 100 year flood" is based on previous historical and geological records, so if the climate of a region is experiencing change over time (e.g., if there is more rainfall in a mountainous region over a period of several years where in previous decades it was arid) the flooding frequency may be higher than that predicted using the historical data.

In order to better understand stream behavior, Environment Canada has installed thousands of stream gauges across the country to record water level and stream discharge. Data from these stations can be used to make flood frequency curves, which are useful in making flood control decisions.

A major flood event on the Bow and Elbow rivers that run through Calgary, Alberta occurred in June 2013 (Figure 10.9). The flood resulted in an estimated $5 billion in property damage, one of the most costly natural disasters in Canadian history. In the days before the flood, the region west of Calgary received rainfall far above seasonal averages. Over 100,000 people were evacuated due to the flooding and five people died. While this was a catastrophic event, it is important to note that there are numerous dams upstream of Calgary that normally regulate the flow of water and prevent major flooding events. Historically, major floods were more common in Calgary than they are today. Other major floods in Canada include the Red River flood in Manitoba in 1997, and the Fraser River flood in B.C. in 1894.

Figure 10.9 | *Flooding in Downtown Calgary, AB, 2013.*
Source: Flickr user Ryan Quan (2013) CC BY-SA-NC view source

10.5 GROUNDWATER

It is best not to envision groundwater as underground lakes and streams (which only occasionally exist in caves). Instead, think of groundwater as water slowly seeping from one miniscule pore in the rock to another, or along fractures in the rock. Have you ever been to the beach and dug a hole, only to have it fill with water from the base? If so, you were looking at the **water table**, the boundary between the **unsaturated** and **saturated zones** in the beach sediments (Figure 10.10). Rocks and soil just beneath the land's surface (and above the water table) are part of the unsaturated zone, and the pore spaces in these rocks are filled with air. Once the water table is reached, then rocks and soil pore spaces are filled with water; this is the saturated zone.
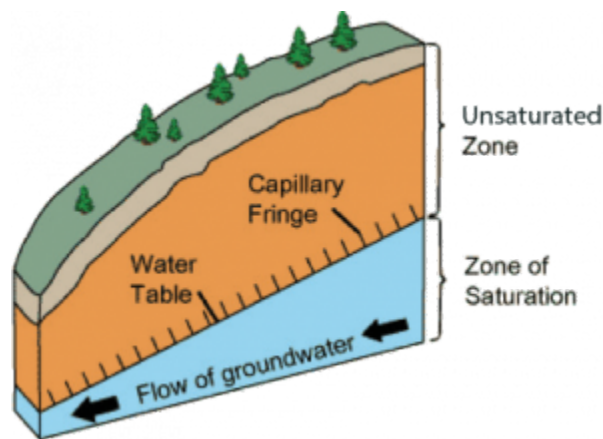
Figure 10.10 | The water table is the boundary between the unsaturated zone and saturated zone.
Source: USGS (2011) Public Domain view source

The water table is said to mimic topography, in that it generally lies near the surface of the ground. It is often within a few metres below the surface, though this can vary greatly with location depending on factors such as the rock type and the amount of regional precipitation. The water table rises with hills and sinks with valleys, often intersecting with the surface to discharge into streams. It receives additional inputs as rainfall infiltrates into the ground, called **recharge**. Its position is dynamic – during **droughts** (periods of low rainfall) the water table will lower and when it is rainier it will rise.

Two important properties of aquifers that influence groundwater availability and movement are porosity and permeability. **Porosity** refers to the open or void space within the aquifer rock or sediments. Porosity is the percentage of the total rock volume composed of open spaces. Porosity will vary with rock type. Many rocks with tight interlocking crystals (such as igneous and metamorphic rocks) generally have low porosity since they lack open spaces between the mineral crystals. Sedimentary rocks composed of well sorted sediment tend to have high porosity because of the abundant spaces between the grains that make them up. If these spaces are filled with cement sedimentary rocks may have low porosity.

To visualize porosity, envision a room filled from floor to ceiling with basketballs (this is analogous to a rock composed completely of sand grains). Now add water to the room. The room will be able to hold a good deal of water, since the basketballs don't pack tightly due to their shape. That would be an example of high porosity.

Permeability refers to the ability of a geologic material to transport fluids. It depends upon the porosity within the rock, but also on the size of the open space and how interconnected those open spaces are. Even though a material is porous, if the open spaces aren't connected, water won't flow through it. Rocks that are permeable make good **aquifers**, geologic units that are able to yield significant water. Sedimentary rocks such as sandstone and limestone are generally good aquifers. Rocks that are impermeable make confining layers and prevent the flow of water. Examples of confining layers would be sedimentary rocks like shale (made from tiny clay and silt grains) or unfractured igneous or metamorphic rock. In an unconfined aquifer, where there is no confining geological layer above the aquifer, the top of the aquifer is the water table.

Groundwater generally flows from areas of higher elevation to lower elevation in the shallow subsurface (Figure 10.11). About 30% of the population of Canada uses groundwater as their source of drinking water. Groundwater can be contaminated which is a threat to this resource. Common sources of contamination include sewage, landfills, industry, and agriculture. The movement of groundwater helps spread the pollutants, making containment a challenge.
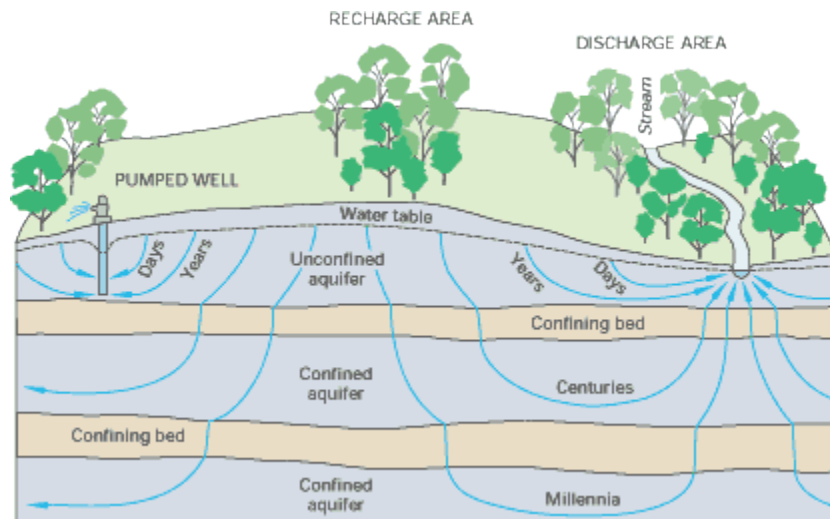
Figure 10.11 | *Groundwater flow in confined and unconfined aquifers. Source: USGS (2005) Public Domain* [view source](#)

10.6 KARST TOPOGRAPHY

The sedimentary rock limestone is composed of the mineral calcite, which is water soluble, meaning it will dissolve in water that is weakly acidic. In humid areas where limestone is found, water dissolves the rock, forming large cavities and depressions which vary in size and shape. As more dissolution occurs, the caves become unstable and collapse, creating sinkholes. These broad, crater-like depressions are typical of **karst topography** (Figure 10.12), named after the Karst region in Slovenia. Karst topography is characterized by sinkholes, sink lakes (sinkholes filled with water), caves, and disappearing streams (surface streams that disappear into a sinkhole).
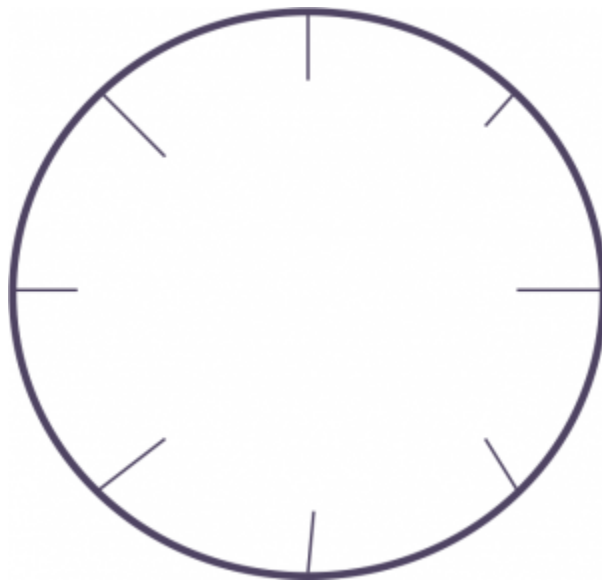

Figure 10.12 | *Appearance of a sinkhole on a topographic map. Source: Randa Harris (2015) CC BY-SA 3.0* [view source](#)

Living in karst topography poses challenges for building infrastructure; sinkholes can appear rather rapidly and cause great damage to any structures above them. In Canada, there are examples of karst across the country aside from on the Canadian Shield. For example, there is karst topography in Wood Buffalo National Park and near Norman Wells, NWT (Figure 10.13) and in southern Ontario.

Figure 10.13 | *Sinkhole near Norman Wells, NWT.*
Source: Dennis McBeth (1994) CC BY–SA 4.0.

USASK GEOL 121 QUIZ & LAB EXAM

This section contains resources to help USask Geology 121 prepare for the lab rock and mineral quiz and lab final exam.

7. USask GEOL 121 Rock & Mineral Quiz Information

The rock and mineral quiz tests students on their ability to identify the rocks and minerals covered in the first few labs of the course. It is worth 10 % of your final grade for the course.

The format for the rock and mineral quiz:

- Bring a printout of the rock and mineral quiz sheet, your mineral identification kit and pen or pencils.
- The Rock and Mineral quiz takes place in your regular lab section. Other lab sections cannot accommodate additional students due to fire regulations and limited resources so it is critical that students take the quiz in the section where they are registered.
- It is a closed-book quiz. You are not allowed use your lab books or keys in the quiz.
- Students must work independently during the quiz; cheating will not be tolerated. Please familiarize yourself with the USask academic integrity policy.
- You will be required to name a total of 34 rock and mineral specimens. Some rocks or minerals could appear more than one time. The specimens will be similar to the ones you saw in your labs. They will NOT be numbered with the same numbers they were marked with in your labs.
- You will have 90 seconds to identify and name each specimen. After this time, you will get a new specimen for 90 seconds, and so on, until you have seen each of the 34 specimens. You will only have one chance to look at each specimen.
- You will fill in each rock and mineral specimen on your answer key beside the number corresponding to the number on the specimen. Only one student will begin with specimen #1, so make sure you are putting the answers in the correct place in on your quiz paper.
- There is only one correct answer per question – if you put down more than one answer your TA will mark the question incorrect.
- You can ask your TA if a specimen would react to dilute HCl acid, or if it would taste salty.
- AES students: contact the lab coordinator (Michael Cuggy, michael.cuggy at usask.ca) (not your TA!) at the start of the semester or as soon as possible to arrange to write the rock and mineral quiz at a different time.

How to succeed on the rock and mineral quiz:

- To succeed on the rock and mineral quiz it is critical that students attend and participate in the labs. There is no substitute for working through the rock and mineral identification methods we teach you in the labs. It takes practice to learn how to accurately identify rocks and minerals. Ask your TA lots of questions if you are struggling!
- As you study, try to write down as much information as you can about each specimen (not just the name – even if you are sure you know what it is!). What characteristics can you use to help identify the mineral? Write down details such as cleavage, lustre, streak, hardness, crystal habit, colour, and foliation.
- On your quiz you can also note characteristics of your mineral or rock. This is very useful if you are unable to identify the rock or mineral when you are looking at it, but then remember what the sample is later in the quiz.
- Test yourself – as you get more confident with rock and mineral identification, get your lab partner to test you with the specimens provided in the lab. This is an effective way to review and will help you build confidence before the quiz.

Good luck!

University of Saskatchewan Geology 121.3 Rock and Mineral Quiz

Name _____   Student Number _____

1. _____   18. _____

2. _____   19. _____

3. _____   20. _____

4. _____   21. _____

5. _____   22. _____

6. _____   23. _____

7. _____   24. _____

8. _____   25. _____

9. _____   26. _____

10. _____   27. _____

11. _____   28. _____

12. _____   29. _____

13. _____   30. _____

14. _____   31. _____

15. _____   32. _____

16. _____   33. _____

17. _____   34. _____

8. USask GEOL 121 Lab Final Exam Overview

The lab final exam is comprehensive; it covers material from all the labs. It is worth 10 % of your grade for the course.
General information about the lab final exam:

1. The lab final exam is three hours long and is a closed-book exam (i.e., notes are NOT permitted during the exam). You will be required to do exercises similar to those you did in the lab.
2. Students must each bring all of the materials that they will need for the exam. Coloured pencils, pens, pencils with erasers, ruler, compass and a protractor are recommended. Blank paper will be provided for the structure cross-sections. Calculators are permitted.
3. Cheating will not be tolerated. Collaboration is NOT permitted on the final. Please familiarize yourself with the USask academic integrity policy.
4. Students are **strongly** encouraged to check their work when they finish their exam! If you have extra time at the end of the exam, take time to check you have answered all questions. Check your answers for accuracy and completeness.
5. AES students: arrange with AES to write the lab final exam. Their standard rules and deadlines apply for writing the lab final exam as for midterms or final exams arranged through AES. If you do not arrange in advance with them we will not be able to accommodate your request for accommodation.

Content covered on the exam:

a. Introduction to Canadian Geology: review Saskatchewan and Canadian mineral and energy resources and know approximate locations of several major resources in Saskatchewan and Canada (e.g., nickel is a resource found in Ontario).
b. Rocks and minerals will be covered on the lab final exam but there will be no actual specimens to examine during the exam. Students must know the basic properties of the rocks and minerals, including things such as what metals are found in the economic minerals, number of cleavage planes where relevant, and rock classifications. These questions will probably be fill-in-the-blank or multiple-choice style questions.
c. Relative and absolute dating: students will be provided with a cross-section diagram and they must be prepared to correctly order the strata using the principles of stratigraphy and to provide a geological history in point form based on this analysis.
d. Students are responsible for understanding the principles of topographic maps (scale, elevations, topographic profile, vertical exaggeration).
e. Earthquakes (if this lab was covered this semester): know definitions, be able to locate the epicentre of an earthquake.
f. Structural Geology – the exam will contain questions where students will be tested on their knowledge of:

   ▪ Preparing structural sections (L.O.T.S.)

   ▪ Calculating true thickness

   ▪ Geological history

   ▪ Folds – relative ages, using symbols to label fold axes and dip directions on geological maps, how to draw folds in a cross-section

   ▪ Faults – types of faults and features of faults (hanging wall, foot wall), determining and labelling relative direction of movement, how to draw faults in cross-sections and how to indicate on geological maps

- Unconformities – how to indicate on cross-sections and on geological maps

- Strike and Dip – definitions, labelling correctly on maps and how to use to construct cross-sections

- Horizontal and vertical beds and rules of Vs – recognizing features on geological maps

Good luck!

Appendix

Contents

1. Canadian geology [map](#)
2. SK geology [map](#)
3. SK mineral resource [map](#)
4. BC topographic map [Two Rivers](#)
5. BC topographic map [Garibaldi](#)
6. SK topographic map [Saskatoon area](#)

For Chapter 10 exercises on water (not used in Winter Term 2 2018-2019 at USask):

1. BC topographic map Monkman Park