These pages are the first few pages of Bruce Railsback's Alpine and Glacial Geology (2nd edn) with the figures removed. They exist in this format only to provide EES 2096 students with an easily accessible set of readings for the first day of class, at which time students will receive their full copies of the book.

PREFACE II: TIROL

This book was written for use in a class taught in Innsbruck, in the Austrian state of Tirol, and the book in part focuses on the geology of Tirol. It therefore seems fitting to devote some attention to Tirol from a historical and cultural perspective, before turning to the geology of Tirol.

In a discussion of Tirol, the first issue is the name itself. Speakers of English commonly use the old spelling "Tyrol", and they commonly use the expression "the Tyrol". However, local usage in modern German almost always employs the spelling "Tirol". Some names of nations in German use a definite article, such as "die Schweiz" for Switzerland, but English speakers don't feel obligated to say "the Switzerland" when speaking of the nation to the west of Austria. The English usage most consonant with modern local usage in the German language thus seems to be "Tirol", without a "the" before it.

What is Tirol?

"Tirol" has multiple meanings. Tirol in the *historical* sense is a region extending from the northern Alps, and thus from the Karwendel mountains north of Innsbruck in today's western Austria, southward beyond Bozen (Bolzano) in northern Italy. In 1804 its borders were extended even farther south to include Trento and northern-most Lake Garda. One powerful reminder that historic Tirol extended into, and was largely in, modern Italy is the origin of the name "Tirol" itself. The name comes from Schloss Tirol, the castle above Meran (Merano) that was the seat of Tirol's rulers, the Counts of Tirol, in the Middle Ages. Dorf Tirol is the village by that now-ruined castle. Today Innsbruck is the capital of Tirol, but Tirol's first capital would have been Meran.

In the *cultural* sense, Tirol is an Alpine region inhabited by speakers of German (and Ladin, a Romance language spoken in South Tirol). Thus it is much the same region as the historical Tirol, but with its southern border defined by the transition from speakers of German to speakers of Italian. In today's northern Italy, one still commonly hears Italian spoken in the valley towns and cities, and German spoken in the uplands. The southern border of the historic Tirol was also Europe's "bread line", an important cultural division between peoples to the north who ate dark rye breads and peoples to the south who ate white wheat breads.[1]

In the modern *political* sense, Tirol is one of the nine federal states (Bundesländer) of the modern Austria. This modern political Tirol is only the northern part of the historical and cultural Tirols, and it consists of two non-contiguous regions most readily linked by travel through today's northern Italy. Innsbruck is the capital of this modern Austrian state, and Lienz (not Linz!) is the administrative center or "sub-capital" of Ost-Tirol (east Tirol).

Tirol to 1918

Tirol's most defining geographic characteristic is its spectacular mountains, and its rugged landscape means that many of its people have lived in valleys isolated from each other, and with their own dialects of Tirolean German. However, the linkages binding the historical Tirol together have been its river valleys and passes. They most notably include the Inn River, running west-to-east in a major valley in northern Tirol. If the Inn makes the top of a "T", the stem of the "T" then consists of the valley of the Sill River southward up to the Brenner Pass, and then the valley of the Eisack southward to Bozen (Bolzano). Innsbruck, Tirol's modern capital, is at the meeting of the two parts of this Tirolean "T".

Tirol's Germanic heritage dates from at least the time of the Roman Empire and its fall, when Germanic peoples moved southward. In the Middle Ages, Tirol was part of the Holy Roman Empire (das heilige Römische Reich Deutscher Nation), the loosely-defined realm of Germanic lands whose emperor was often referred to as "the German king". In 1363, Margaret of Carinthia, Tirol's last ruler descended from the lords of Schloss Tirol, was left heir-less by the death of her only son, and so she ceded Tirol to the Habsburg

[1] For more, see Chapter 3 of Ward (1993).

Duke of Austria, Rudolph IV[2]. Tirol was thereafter under the rule of the Habsburgs, and thus part of Austria, until 1918. The Habsburgs were commonly Holy Roman Emperors until Napoleon's dissolution of that institution in 1806, and thereafter they were emperors of Austria-Hungary until their abdication in 1918 and the dissolution of the Austro-Hungarian empire after World War I. Thus for most of Tirol's history, it has been part of German-speaking political realms.

One noteworthy if brief interlude in Habsburg control of Tirol took place from 1805 to 1814, when the French ruler Napoleon Bonaparte placed Tirol under Bavarian rule. The Tirolean peasantry under the leadership of Andreas Hofer, an innkeeper, revolted against the Bavarians in 1809, and Hofer's small army defeated the Bavarians multiple times. In 1810, Hofer was captured and shot on Napoleon's orders, but he remains the Tirolean national hero, with a monument in Innsbruck and an annual celebration in Meran. In 1814, during Napoleon's removal from power, Tirol from the Karwendel to Trento was reunited with Habsburg Austria.

South Tirol

The historic Tirol was split asunder in 1919 in the redefinition of European geography following World War I, and in the dismemberment of the German and Austro-Hungarian empires. Early in World War I, Italy had remained neutral, but the secret 1915 Treaty of London promised Italy Tirol up to the Brenner Pass, if Italy would enter the war on the Allied side. Italy did so, and southern Tirol was the site of harsh fighting between Italian and Austro-Hungarian troops. In 1919, after the war, international diplomacy gave Italy its promised reward for supporting the victorious Allies.

With this partitioning of Tirol, the southern part became the "South Tirol" of today, although to Italians it is known as "Alto Adige", the high (alto) watershed of the Adige (or Etsch), the river that flows through Meran, Bozen, Trient, and Verona. Teaching of the German language to children was forbidden, except for private religious schooling, and expressions of Tirolean nationalism, such as displays of red and white in clothing, were commonly suppressed by the Italian government. Migration of Italians northward into the towns of South Tirol was encouraged. Unhappiness among Germanic people in South Tirol was sufficiently great that, when fascist Italy and Nazi Germany held a plebiscite in 1939, a majority of the Germanic population voted to leave their ancestral farms and move northward across the Brenner Pass. Negotiations between Italy and Austria over conditions in South Tirol went on until the 1960s but stalled in response to terrorism by Tirolean separatists, who carried out more than 300 attacks between 1956 and 1988. In Innsbruck, squares and streets named Bozner Platz, Sud Tiroler Platz, Meraner Straße, Salurner Straße, Brixner Straße, Brunecker Staße, and Sterzinger Straße are public indications of the memory of South Tirol[3], and in the 1990s graffiti on the Inn floodwalls still demanded "Free South Tirol". A 2006 survey found that 54% of German speakers in South Tirol still favored reunification with Austria.

(North) Tirol

The partitioning of Tirol in 1919 left North Tirol, previously part of the large and powerful Austro-Hungarian empire, as part of the much reduced and less powerful new nation of Austria. Unimpressed with the new "rump" Austria and instead seeing the power and cultural similarity of Germany, Tiroleans voted overwhelmingly (>98%) in 1921 that their land should be united with post-war democratic Germany (much as Austria's westernmost state, Vorarlberg, had voted by more than 80% in 1919 to join Switzerland). The border gates between Tirol and Germany at Kufstein and Scharnitz were almost immediately torn down. France and her allies, however, were intent on breaking up Germany rather than seeing it grow, and so northern Tirol remained part of the new Austria[4].

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[2] Margaret was also known as Margaret Maultasch. Her other lasting legacy to Tirol was to introduce a symbol still commonly seen today, the Tirolean eagle. It's a red eagle facing left, with a green laurel crown. It was actually the heraldic eagle of the family of her second husband Ludwig, the margrave of Brandenburg.

[3] The places commemorated are Bolzano, South Tirol, Merano, Salorno, Bressanone, Brunico, and Vipiteno. Note that Innsbruck has no Landecker, Imster, Telfser, Seefelder, Jenbacher, Wörgler, Kufsteiner, or Lienzer Straße – all the streets and squares named after Tirolean towns are named after South Tirolean towns.

[4] In fact, the entire new Austrian nation had sought inclusion in the German republic, declaring in its constitution of November 1918 that "German-Austria

Tirol, along with the rest of Austria, was incorporated into Hitler's Third Reich with the Anschluss, or annexation of Austria into Germany, in 1938.[5] Tirol was thus a part of the Third Reich in World War II, as its cemeteries and soldiers' monuments attest. Because the railroad yards in Innsbruck are the take-off point of the tracks up the Brenner Pass and Italy, Allied bombing focused on Innsbruck, and bombs fell not only on the railroad yards but across much of the city. Brixlegg, a town down the Inn, was the site of copper mines and thus a had a factory making shell casings, and it was bombed just a few days before the war ended.

With the end of World War II in 1945, Tirol and the rest of Austria were extracted from Germany and re-established as a nation, necessarily and deliberately neutral between NATO and the Soviet-dominated Eastern Bloc. In 1995, after great debate, Austria voted to enter the European Union, despite grave concerns about unification's implications for Austria's economy and especially for its farmers. In 2002 Austria adopted the euro and gave up its national currency, the schilling, which had been a source of national pride because the schilling had not been allowed to inflate nearly so much as some other European national currencies. In Tirol, signs on barns still (as of 2007) condemned entry into the European Union, and in 2006 much dismay arose as new health regulations imposed by the EU forced the closing of many alpine hüttes, the tiny inns feeding and sheltering hikers high in the mountains.

The Tirol(s) of today

In the early 21st century, Tirol tries to balance its past and its future, its extent as the larger cultural region and the smaller Austrian state, its Tirolean sense of independence and its EU membership. Tirol's defining characteristics, the Alps and Tirolean culture, provide a magnet drawing tourist dollars and euros that fuel the Tirolean economy. Tirol's T intersection of the Inn Valley and the route through the Brenner Pass assure that trains, tourists, and trade will pass through Tirol. However, the Autobahn superhighways and the many ski lifts mar the alpine landscape, and the influx of tourists inevitably intrudes upon and changes the native Tirolean culture. It's hard to teach your children the Tirolean ways and the dialect of the valley in which your family has lived for centuries, when you spend all day speaking English to the carloads and busloads of tourists who come up the new highway to your once-remote village. For visitors who would never think of leaving trash on the splendid Alpine landscape, it may also be important to not bring foreign cultural expectations when coming to see Tirolean culture. Saying "Gruss Gott" in greeting rather than "Hello" or "Guten Tag"[6], obeying a "don't walk" signal,

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[the new post-war Austria] is a component part of the German Republic". However, France made clear that Germany's reparations for World War I would be much greater if Anschluss with Austria took place, and Germany did not pursue the matter further.

[5] The story of the Tirolean vote in 1919 casts a different light on the welcome given German troops in Tirol in 1938 during the Anschluss or annexation of Austria into Germany. To modern American eyes, the Anschluss was a welcoming capitulation to Nazism. From the Tirolean post-World-War-I perspective, on the other hand, unification with Germany could be seen as a reunification of Germanic peoples of the Holy Roman Empire that had been sought since 1918, well before the rise of the Nazis. Thus the Anschluss might have looked, to Tiroleans in 1938, like something akin to the 1990 reunification of East Germany and West Germany after the fall of the Berlin Wall, likewise the termination of an artificial political division imposed by foreign powers at the end of a world war. None of this, however, provides any excuse for the mistreatment, expulsion, and murder of the Jewish people that came with Nazi rule and the Holocaust, and Innsbruck's memorial in Eduard Wallnöfer Platz on Salurner Straße is a reminder of the persecution that took place in the Tirolean capital.

[6] Some bits of Tirolerisch (for each, the first is the most common and standard):

Saying "Hello"

Grüss Gott ("let God greet you" - probably used more among older or more traditional people, but common throughout)

Grüss Di ("greetings to you" - perhaps used by younger or more secular people)

Servus (used more by men or to men, especially younger ones)

More follows on next page

keeping quiet in a church, and other ways of blending in, rather than standing out, are small but significant ways of helping preserve the cultural landscape, as well as the physical landscape, that we've come to enjoy in Tirol.

Sources:

Encyclopedia Britannica (1968) entries on Tirol and Margaret of Carinthia.

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Stodddard, F. Walcott. 1914, *Tramps Through Tirol:* New York, James Pott & Co., 299 p.

Ward, M.C., 1993, *The Hidden Life of Tirol:* Prospect Heights, Illinois, Waveland Press, 222 p.

Wikipedia entries on Andreas Hofer, South Tyrol, Trentino-South Tyrol, and Sterzing.

Further browsing:

The Tirol Atlas produced by the Department of Geography of the University of Innsbruck (http://tirolatlas.uibk.ac.at/content.html.en)

Saying "Thanks"
Danke Schön ("Thanks nicely" - the universal Bavarian-Tirolean thank you)
Danke Dir ("Thanks (to) you" with the informal you - used more by and/or to women)
Gelts Gott ("May God repay you" - a peculiarly Tirolean expression rarely heard on the street)

Saying "Good-bye"
Wiedersehn (just a shorter form of the standard German expression "Auf Wiedersehen")
Wiederschauen (the short version of the southern German "Auf Wiederschauen" for good-bye)
Tschüss (a casual good-bye more common among younger people)

Add two critical words universally used in German:
Bitte ("please")
Entschuldigung ("Excuse me")

Part I. Fundamentals of Geology

CHAPTER 1: GEOLOGIC CONCEPTS

Geologists, and persons with some education in geology, take a somewhat different view of the world than do people who have never considered geology before. This chapter introduces a few ideas that may help newcomers get into the flow of geologic thinking.

The size of the Earth

From a human perspective, the Earth is large, and probably larger than our casual thoughts would suggest. Our deepest mines impress us with the temperatures at which miners work, and the long trips in and out that miners must make each day impress us with regard to depth. However, these mines only penetrate a small part of Earth's crust (Fig. 1-1). Our deepest wells and boreholes go deeper, to about 10 kilometers or 6 miles, but they similarly don't get far into the continental crust. With that said, the crust is only a very thin film compared to the entire volume of the Earth, and to the thickness of the underlying mantle.

Another way to consider the size of the Earth is to look at its most prominent features. Earth's highest mountains and deepest seafloor are barely perceptible as blemishes on the smooth sphere of the entire planet (Fig. 1-1). Also consider the international space station, the laboratory we have boldly constructed in outer space. We envision the space station as something far above the Earth. In fact, compared to the size of the Earth, our far-away space station is barely above our planet's surface (Fig. 1-1).

The age of the Earth

According to modern widespread consensus among scientists, the Earth is 4.6 billion years old. We know that age because we have measured the age of Earth's oldest rocks and minerals to be more than 4.0 billion years old, and we recognize that those rocks and minerals formed *after* the origin of the Earth, so that they only provide a minimum age. Furthermore, we know the age of the Earth because we can use the composition of Earth's lead, the product of radioactive decay, to determine Earth's age. Those calculations yield an age of 4.6 billion years. In addition, we have determined the age of the oldest rocks on Earth's moon, a body that we think formed at the same time as the Earth. We find an age of 4.6 billion years there too. We have also determined the age of meteorites that we think formed when the solar system condensed to form the planets, including Earth. Again we find an age of 4.6 billion years. In addition, we can deduce from the time required for many processes on Earth (cooling and exposure of rocks formed from molten mineral material, thicknesses and rates of deposition of sediments, accumulation of salts in the sea, etc.) that the Earth must be very old, and not merely thousands or even a few million years old.

The age of the Earth is important in geologic thinking for at least three reasons. First, it explains how slow processes can nonetheless cause major changes. Erosion of mountains, deposition of deep-sea sediments, and movements of continents seem like incredibly slow processes at human time scales. However, if a process acts for millions of years, the results are impressive. If something accumulates at the rate of an inch per year, 1026 miles of it will have accumulated since the last dinosaur died 65 million years ago.

Secondly, the duration of geologic time makes rare events common. If we estimate, for example, that a meteorite of a certain size hits the Earth once every 100,000 years, we can dismiss meteorite impacts of that size as events that are unlikely to happen in our lifetimes. However, such impacts will have happened 46,000 times in the time allowed by the age of the Earth. To summarize, extension of processes to geologic time scales makes the slow very effective and makes the rare common.

A third implication of the immensity of geologic time is that we see the Earth at just a moment in its history. This means that geologists look at the Earth, and especially its landscapes, and envision what those mountains were previously and what they may become. For example, a casual visitor to Stone Mountain, a large hill of granite east of Atlanta, sees a sizeable bump on the landscape. Someone acquainted with geology,

however, will realize that the granite formed deep beneath Earth's surface and is exposed only because kilometers of overlying rock have been removed by erosion. Thus the geologically aware will think a bit about the landscape of the past. Someone acquainted with geology will also realize that someday erosion will have removed Stone Mountain and perhaps leave only its underlying root. Thinking like this makes one realize that other analogs of Stone Mountain may have existed in the past but have been lost to erosion by now, and other bodies of granite deeper in the Piedmont may be waiting to be exhumed and then to stand as high above the landscape as Stone Mountain does today. Thus an appreciation of geologic time makes on realize that present landscapes are just one snapshot in a very long series, and likewise that the present configuration of continents and ocean basins is just the one step that we happen to see in the progression from the various geographies of the past to those of the future.

Describing this expanse of geologic time requires a vocabulary that is collectively the geologic time scale. Just as one might divide 19th-century American history into an Early Republic, Ante-Bellum, Civil War, and Reconstruction period, geologists use terms for periods with distinctive characteristics, usually characteristics of the fossils of those times. Just as a scholar of American History might subdivide one of the broad periods above - the Civil War might be divided Bull Run to Antietam, Antietam to Gettysburg, etc. - geologists break down their broadest time intervals into shorter subdivisions. The result is the hierarchical scheme shown in Figure 1-2.

Rock, bedrock, and the water within

The Earth surface on which we walk does not typically consist of solid rock. We commonly walk, garden, and farm on soil, a loose material resulting from action of organisms and weather on the land surface. We may also walk on sediments, especially if we walk or wade on sands at the shore or in a river, or if we track through muds of floodplains and marshes. We may also come across larger chunks of mineral material that we call rocks, but they are commonly just large chunks that sit on or amidst the soil or sediment.

Beneath the soil or sediment, and sometimes at the land surface, there is bedrock (Fig. 1-1). Bedrock is solid rock that has not moved, at least relative to its tectonic plate, in thousands if not millions of years, and below which there is only more rock. This bedrock may have cracks in it, but they decrease in abundance and width downward. Bedrock is commonly visible at the land surface in mountains, in canyons, and in soil-free patches called barrens or balds. It is commonly a few feet to a few tens of feet below the surface of soils. In river valleys it may be tens to a few hundred feet below the surfaces of floodplains, and in glaciated landscapes it may be similar distances below the surfaces of glacial tills. On coastal plains, it may be hundreds to thousands of feet below the surface of the loose sediments making those landscapes. However, whether it begins a few inches or a few thousand feet below the land surface, bedrock is the solid thing that makes up the rest of the 1800 miles (2900 kilometers) of crust and mantle beneath our feet.

The other thing beneath our feet is water (Fig. 1-1). Dig a well into any soil or sediment, or drill a well into any bedrock, and you will encounter water, commonly within a few tens of feet and certainly within a thousand feet or so. This water fills the pore space, or inter-particle space, in soils and sediments, and it fills the cracks or fractures in bedrock. The water table is surface below which water, rather than air, fills those pores and fractures. The significance of this water is at least twofold. First, it means that we should not think of air as filling the deep spaces within the Earth - in fact, groundwater commonly precludes the resupply of atmospheric oxygen into the subsurface. Secondly, it means that movement of solutes through or with water will explain many subsurface processes, such as chemical precipitation of minerals like ore deposits. It also means that we all walk on water.

Perspectives on the Earth

Geologists try to think in terms of three-dimensional images of Earth's interior. Sometimes they draw those, as in block diagrams (Fig. 1-3). However, they more commonly draw in terms of two-dimensional vertical or horizontal slices or surfaces. Images of vertical slices are cross-sections. Images of horizontal slices or semi-planar surfaces are maps. Whenever you're completely at a loss about a diagram, the first question to ask may be "Is this a cross-section or a map?", and the second question is either "From

where to where does this cross-section extend?" or "Of what surface, or at what depth, is this map drawn?". Another good question will be "What is the scale?". A good diagram answers these questions on its own, but a student should never be afraid to ask these questions if the diagram doesn't provide the answers.

CHAPTER 2: MINERALS

Minerals are defined as naturally occurring inorganic crystalline solids with set chemical composition and characteristic physical properties. That's quite a long definition and deserves some explanation. "Naturally occurring" means we're only interested in the solids found in nature, which means that we can ignore all the solid substances synthesized by chemists but not found in natural settings. "Inorganic" means that we can likewise ignore organic chemicals (things with carbon-carbon bonds, which in nature would include the constituents of coal and natural asphalt). "Crystalline" means that the atoms of minerals are arranged in some regular order, rather than being an amorphous jumble (Fig. 2-1). "Set chemical composition" means that we can write a chemical formula for every mineral (for example, SiO_2 for quartz and $CaCO_3$ for calcite), even though many minerals include minor or trace elements (for example, Mg^{2+} and Fe^{2+} can substitute for some of the Ca^{2+} in the $CaCO_3$ of calcite). That leaves us with "characteristic physical properties", which deserve a section of their own below.

Minerals are the fundamental building blocks of geology. Minerals consist of atoms, and a mineralogist or geochemist would take interest in those atoms. However, for a geologist, minerals are the smallest units of matter observed, and so they are the building blocks of which all larger geological entities consist (see the table below). That's why we need to develop a rudimentary understanding of minerals in this chapter, before proceeding to the larger-scale topics of this book.

Scales of observation in Geology, from smallest to largest:

Atoms
Minerals
Rocks
Rock Layers & Structures
Geologic Provinces
Tectonic Plates
Core, Mantle, & Crust
Planets

Physical properties of minerals

Geologists working in the field identify minerals by the physical properties of those minerals – the physical characteristics that have been found to be typical and hopefully diagnostic of each mineral. Most geologists can identify several dozen and perhaps more than a hundred minerals, but even a beginning student can soon identify the twenty or thirty common minerals by recognizing the properties of those minerals.

One category of physical properties is shape, and the shape of a mineral can be the result of at least three factors. One is the **growth shape** of the mineral, the configuration of crystal faces or facets that form as the mineral forms. Another is **cleavage**, the sets of planes along which a mineral breaks. Thirdly there is **fracture**, the irregular rather than planar surfaces to which a mineral may break, rather than cleaving. For example, fluorite grows in cubes but breaks to yield an octahedral shape, and so it does not fracture. Quartz can grow with six parallel sides that are capped by inclined crystal faces that come to a point, but it does not cleave and instead breaks to give a conchoidal fracture (a fracture of curved or scalloped surfaces). Calcite, on the other hand, often grows to form steep three-sided pyramids, but when broken cleaves to give rhombs. Halite, by comparison, is simple: it grows to form three mutually perpendicular surfaces and cleaves to form three mutually perpendicular surfaces. These four different minerals thus have very different shapes, both in terms of how they grow and how they break.

Another category of physical properties has to do with how minerals reflect light. Seemingly the simplest of these is **color**. Some minerals have characteristic colors; for example, chlorite is always green (and thus gets its name for the Greek word for "green"). Many minerals have typical colors, such as the light green of olivine. However, color can be a fickle trait. For example, olivine can range from white to black, and its usual light green only results from the chemistry of its most common composition. Quartz is commonly colorless, but trace elements in quartz can give us rose quartz (a pink variety), smoky quartz (which can be almost black) and amethyst (the purple semi-precious gemstone).

More trustworthy than color, for some minerals, is **streak**. Streak is the color of a particular mineral when powdered, and the common way to generate that powder is to grind the mineral on a streak plate, a piece of unglazed porcelain. The most common and useful appli-

cation of this property is to hematite (Fe_2O_3), a mineral that can look black, or metallic and shiny, or red and dull, depending on the size of its crystals and how they are configured. However, the streak of hematite is always red, because the powdered form consistently reflects red light and absorbs other wavelengths.

A third term expressing how a mineral reflects light is **luster**. Luster expresses the extent to which a mineral reflects light, absorbs light, or transmits light. Kinds of luster thus include metallic (reflects light a lot), glassy (reflects some but transmits some), earthy (absorbs much light and so is not shiny), and waxy (reflects at the surface and within).

Hardness expresses whether an individual crystal of a mineral (not a mass of crystals) can scratch another surface, or is scratched by other surfaces. It is thus a relative property that is expressed in terms of the Mohs scale of hardness, which establishes certain minerals, and other materials, as benchmarks on a scale of 1 to 10. A mineral with a greater hardness can scratch any mineral of lesser hardness.

Mohs hardness	*Benchmark mineral*	*Other benchmark material*
1	Talc	
2	Gypsum	Finger nail ~2.2
3	Calcite	Copper coin = 3
4	Fluorite	
5	Apatite	Pocket knife = ~5.2
6	K-Feldspar	Window glass = 5.5
7	Quartz	Steel file = 6.5
8	Topaz	
9	Corundum	
10	Diamond	

A property quantifiable for all minerals and striking for some is **specific gravity**, or (less technically) density. Density is weight per unit volume and so expresses the heft of a chunk of mineral when lifted – does it feel exceptionally heavy or exceptionally light? A good example is galena (PbS), which is very dense because of the lead in it.

Other properties are significant for one mineral or group of minerals. Magnetism is an example, in that magnetite (Fe_3O_4) is magnetic, whereas almost no other minerals are. Reaction with dilute acid is another, in that calcite reacts with dilute acid, a characteristic it shares to varying degrees with other carbonate minerals. For those persons willing to put minerals in their mouths, two more properties emerge, in that kaolinite consists of such a mass of tiny platelets that it adsorbs water sufficiently to stick to one's tongue, and halite (NaCl) tastes salty because it is the stuff of table salt.

Identification of minerals

Geologists in the field, collectors, and students all commonly identify minerals by the physical properties above. In the laboratory, however, at least two other major methods are used. One involves examining rocks and their constituent minerals when cut and polished in thin sections that are by convention 30 microns (0.03 mm) thick. These thin sections are examined under a microscope in transmitted polarized light, and the interaction of light with each mineral is sufficiently distinctive that almost all minerals can be identified, even when individual crystals are less than a millimeter across. This method, called "**optical mineralogy**", is of great use because it allows examination of minerals in their native context, in rocks where they are interlocked with other minerals, rather than after some mechanical extraction that removes them from their immediate geological context in a rock.

The second major method of mineral identification is to pass monochromatic X-rays (X-rays of just one wavelength) through a mineral and to measure the angles at which the X-rays are coherently diffracted, rather than scattered and dissipated. The magnitude of these angles in **X-ray diffraction** depends on the spacing of atomic planes in a crystal (Fig. 2-1), and the number of angles at which diffraction occurs depends on the symmetry of the crystal. This method thus identifies minerals by the spacing of their atomic planes, rather than by their chemical composition. The various configurations and spacings of atomic planes are sufficiently unique for each mineral that X-ray diffraction is considered the fool-proof scientific identifier of minerals, or the "gold standard" of mineral identification among professional geologists and mineralogists.

How minerals form

We said above that "minerals grow", but clearly crystals of minerals form and become larger by very different processes that those of living things. One major way that minerals form and

enlarge is by crystallization from molten rock material, which is called magma. The details of that process will be a major topic of Chapter 3, which deals with igneous rocks. The other major way that minerals form and grow is by chemical precipitation from solution (for example, from seawater or groundwater). Every mineral has a fixed limit of concentration, or limiting solubility, in water, and water containing a concentration beyond that equilibrium limit will precipitate the mineral in question. One familiar non-natural example is precipitation of "lime" (really $CaCO_3$) in pipes, and one spectacular natural example is the precipitation of crystals from groundwater in geodes. Of greater significance in geology is precipitation of minerals from groundwater in the intergranular spaces of sediments, in the interparticle spaces of soils, and in fractures in rocks.

Categorization of minerals

Mineralogists have identified about 5,000 minerals, so clearly we need some capability to categorize among this remarkable diversity. We commonly distinguish groups of minerals on the basis of their chemical compositions (Fig. 2-2). These groups include **oxides**, where a cation, a positively charged atom, combines in more-or-less equal proportion with O^{2-}, as for example in hematite (where Fe^{3+} combines with O^{2-} to form Fe_2O_3). Similarly, cations can combine with negatively charged sulfur to make **sulfides**, as for example with galena (where Pb^{2+} combines with S^{2-} to form PbS). Cations can also combine with anions with –1 charge to form **halides**, as for example with halite, where Na^{1+} combines with Cl^{1-} to form NaCl. Ca^{2+} likewise combines with F^{1-} to make the halide mineral fluorite, CaF_2.

In several categories of minerals, O^{2-} anions cluster around a central atom to make a radical group or complex ion. For example, O^{2-} clusters in threes around carbon to make the CO_3^{2-} group that is then the building bock of the **carbonate** minerals like calcite and aragonite, which both have the formula $CaCO_3$ (Figs. 2-2 and 2-3). The same applies when O^{2-} clusters in fours around sulfur to make the SO_4^{2-} group that is then the building bock of the **sulfate** minerals like gypsum, with the formula $CaSO_4 \bullet 2H_2O$, and anhydrite, with the formula $CaSO_4$. There are many other analogous "-ate" groups of minerals, such as nitrates, phosphates, tungstates, arsenates, and selenates. However, because silicon is second only to oxygen in abundance in Earth's crust (Fig. 2-4), by far the largest such group is the silicates, which deserve a section of their own (Fig. 2-5).

Silicate minerals

All silicate minerals contain a fundamental building block consisting of four O^{2-} anions clustered around a Si^{4+} cation (Fig. 2-3). The four O^{2-} anions collectively form a tetrahedron, a three-sided pyramid that, along with its base, has four identical triangular sides. This configuration of silicon and oxygen is called the silicate tetrahedron. The arrangement of these tetrahedra in silicate minerals turns out to have major implications for the structure of the Earth and especially its volcanic mountains.

Silicate tetrahedra are linked in various ways to make different kinds of silicate minerals. **Nesosilicates**, for example, consist of isolated silicate tetrahedra whose O^{2-} anions bond to cations like Mg^{2+}, Fe^{2+}, and Ca^{2+} that lie between the tetrahedral (Fig. 2-3). The mineral olivine, with the formula $(Mg,Fe)_2SiO_4$, is a good example. In **sorosilicates**, on the other hand, every two silicate tetrahedra share one oxygen atom, so that pairs of silicate tetrahedra form dumbbell-like assemblages from which again bonds extend to interspersed cations (Fig. 2-3). An example is the mineral hemimorphite with the chemical formula $Zn_4Si_2O_7(OH)_2 \bullet H_2O$. The main thing to note in this chemical formula is that the ratio of Si to O is now 2 to 7, rather than the 2 to 8 to nesosilicates, because the sharing of one O^{2-} anion in the each pair of tetrahedra lessens the total number of oxygens.

This trend continues with chain silicates, or **inosilicates**, where tetrahedra share O^{2-} anions to form long chains of silicate tetrahedra.[7] In **pyroxenes**, silicate tetrahedra are arranged in lines wherein each silicate tetrahedron shares one O^{2-} with the silicon to one side and another O^{2-} with the silicon to the other side (Fig. 2-3). Each silicon is thus surrounded by two entire oxygens and effectively the halves of two others, giving a Si-to-O ratio of 1to 3, or 2 to 6. This is reflected in the

[7] This discussion of silicates has completely skipped cyclosilicates because they are not essential to understanding the progression of structures covered here and because their most common examples are beryl and tourmaline, neither of which is a common mineral.

chemical formulas of pyroxene minerals like diopside ($CaMgSi_2O_6$) and enstatite ($MgSiO_3$). The chain-like structure of pyroxenes is reflected in elongate crystals with growth faces and cleavages that meet at roughly right angles.

Pyroxenes form single chains, but another category of inosilicate minerals called **amphiboles** forms double or linked chains. Here, two pyroxene-like chains are linked, because every other silicate tetrahedron not only shares two of its O^{2-} anions with its neighbors in its own chain but also shares an O^{2-} with a tetrahedron of matching chain. Thus half of the tetrahedra have a Si-to-O ratio of 2 to 6, and half have a ratio of 2 to 5, yielding an average ratio of 4 to 11 and thus chemical formulas like that of grunerite, with the chemical formula $Fe_7Si_8O_{22}(OH)_2$. The chain-like structure of these minerals is also reflected in elongate crystals, but the double-chains cause growth faces and cleavages to meet at 60° and 120° angles, rather than the ~90° characteristic of pyroxenes.[8]

The next stage in this progression of structures is for every pyramidal tetrahedron to share its three basal O^{2-} anions with neighboring tetrahedra. The linked silicate tetrahredra thus form layers or sheets, and so they are called "**phyllosilicates**" ("leaf-silicates"). Each tetrahedron shares three of its four O^{2-} anions, so that the Si-to-O ratio is 1 to 2 1/2 or 2 to 5, yielding chemical formulae like that of kaolinite ($Al_2Si_2O_5(OH)_4$) and talc ($Mg_3Si_2O_5(OH)_4$). Al^{3+} can substitute for some of the Si^{4+} in the tetrahedra, leading to chemical formulas like that of the mica phlogopite ($KMg_3(AlSi_3O_{10})(OH)_2$). The sheet structure of phyllosilicates leads to strikingly planar growth shapes and cleavages best exemplified by the micas, of which muscovite and biotite are the most common. In fact, muscovite (the clear mica) cleaves in such planar sheets that it was used for window panes in the Middle Ages, when it was called "Muscovy glass" because it was mined near Moscow.

The last stage in this progression is to have each silicate tetrahedron share all four of its O^{2-} anions, so that the silicate tetrahedra form a three-dimensional framework (rather than the two-dimensional sheets in phyllosilicates or one-dimensional chains in inosilicates). These minerals with three-dimensional silicate frameworks are called "**tectosilicates**"[9]. Because each Si^{4+} shares all four of its O^{2-} anions with its neighbors, the Si-to-O ratio in tectosilicates is 1 to (4 x 1/2) or 1 to 2. This is seen in the chemical formula of the very common mineral quartz, SiO_2.

As in phyllosilicates, Al^{3+} can substitute for Si^{4+} in the tetrahedral sites of tectosilicates. This leads to the **feldspar** minerals. Orthoclase, the most common K-feldspar mineral, thus has the chemical formula $KAlSi_3O_8$, and its Na-bearing analog albite has the formula $NaAlSi_3O_8$. In those cases, one of every four tetrahedra is occupied by Al^{3+}. If two of every four tetrahedra are occupied by Al^{3+}, minerals like the feldspar anorthite ($CaAl_2Si_2O_8$) form. In fact, a whole range of compositions of feldspar exists between albite and anorthite, and those minerals are collectively called plagioclase feldspars.

Trends among the silicate minerals

The progression of silicate mineral structures discussed above dictates trends in the properties of these minerals that have great implications for geological processes (Fig. 2-6). One aspect of the progression above is that of chemical composition. For example, Fe^{2+} and Mg^{2+} are abundant in nesosilicate and inosilicate minerals, but they progress to absence in the common tectosilicates. On the other hand, Al^{3+} and Si^{4+} progress from less abundant in nesosilicates and inosilicates to more abundant in phyllosilicates and tectosilicates. We therefore speak of the minerals at the nesosilicate end of this progression as "mafic", for "magnesium-and-iron rich", and the minerals at the phyllosilicate and tectosilicate end as "sialic", for "silicon-and-aluminum rich".[10] "Mafic" and "sialic" are also used to characterize entire rocks, and in fact entire parts of Earth's crust, and even the magmas (molten mineral material) from which these minerals and rocks can form.

The progression from mafic to sialic silicate minerals is a progression from less linkage

[8] Pyroxenes and amphiboles are collectively "inosilicates" in the progression from neso- to soro- to cyclo- to ino- to phyllo- to tecto-silicates.

[9] Persons already familiar with the geological use of the word "tectonics" as the study of large-scale three-dimensional geological structures should see in "tecto-silicate" the corresponding reference to microscopic three-dimensional mineralogical structures.

[10] A word essentially synonymous with "sialic" is "felsic", which originated as "feldspar-like".

of silicate tetrahedra to more linkage. The same is true in silicate magmas, where (despite the molten state of matter) Si^{4+} still forms tetrahedra that share O^{2-} anions and that thus link themselves together. These linkages control the magma's viscosity, or its resistance to flow, so that more sialic magmas are more viscous and more mafic magmas are less viscous. This has major implications for the formation of volcanoes, where the tendency of mafic magma to flow and sialic magma to congeal determines both the form and behavior of the volcano.

The progression from mafic to sialic silicate minerals is also one from minerals with higher melting temperatures (or temperatures of crystallization from magma) to minerals with lower melting temperatures (or temperatures of crystallization) (Fig. 2-6). Thus, as a magma cools, more mafic minerals tend to form first, and more sialic minerals tend to form later.[11] The melting of more sialic minerals at lower temperatures in the Earth allows more sialic magmas to form from mafic rocks in the mantle and crust, so that magmas rising to form Earth's crust are more sialic than the underlying mantle.

The progression from mafic to sialic silicate minerals is also one from more dense minerals (largely because of the presence of Fe) to less dense minerals. Where sialic magmas have risen and joined with other sialic rocks at Earth's surface, they have collectively formed the continental crust. By contrast, the oceanic crust, while still more sialic than the mantle, is nonetheless more mafic than the continental crust. The lesser density of the continental crust is what lets it sit higher across Earth's surface than the more dense oceanic crust of the sea floor. The difference in density between sialic and mafic minerals is thus why we have an Earth with continents rising above sea level and ocean basins below sea level. The difference in density between sialic and mafic crust is thus the reason for the global geography that we take for granted as land-dwelling animals perched on our concentrates of sialic rock.

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[11] This temporal progression from crystallization of mafic to crystallization of felsic minerals is called "Bowen's Reaction Series" after American petrologist N.L. Bowen. The word "reaction" denotes Bowen's observation that the early-formed more mafic minerals do not sit unchanged in the magma that has become progressively more sialic as mafic minerals form. Instead, these early-formed minerals commonly react with the magma and commonly break down, at least in part, to form more sialic minerals. Thus olivine and pyroxene crystals formed early from magmas commonly have outer rims of pyroxene or amphibole, respectively. The same is true among plagioclase feldspars, where anorthite forms at higher temperatures than albite but may then react to form a more albitic plagioclase feldspar or at least to have rims of more albitic plagioclase.