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Chapter 1

The Grand Canyon

Reading the Rocks

LEARNING OBJECTIVES

- Recall the main subdivisions (eons, eras, and periods) of the geological timescale.
- Define the main types of metamorphic rocks, the concept of a protolith, and explain how pressure and temperature control the formation of metamorphic rocks.
- Explain how igneous rocks form and how intrusive (plutonic) and extrusive (lava) igneous rocks can be distinguished.
- Discuss how light felsic magmas and associated rocks are produced during metamorphism by partial melting.
- Define Steno's laws of original horizontality, superposition, lateral continuity, and cross-cutting relationships.
- Define the main types of unconformities (non-conformities, angular unconformities, disconformities, and paraconformities).
- Define what a fossil is and explain how fossils are useful in environmental reconstructions and determining ages of rocks.
- Define a sedimentary basin and describe the kinds of evidence that can be used to interpret the environments of deposition of the sediments that fill basins, such as the difference between proximal and distal deposits.
- Explain how structural geology and the study of deformation can be used to interpret orogenic processes, such as compressional mountain building, and extensional breakup of continents.
- Explain the difference between a fold, fracture, and fault, and the difference between ductile and brittle deformation.

Introduction

Rocks are literally underfoot and can tell marvelous stories. The authors of this book have been spellbound by rocks for most of our lives. We have been astounded at the story of how the dinosaurs were killed by an asteroid crashing into Earth from outer space, and we smile at the idea that the rocks now at the top of Mount Everest were formed beneath the surface of an ocean. We have both spent time enjoying the splendor of Grand Canyon and pondering the incredible stories recorded in the rocks that are exposed in the cliffs and along the bottom (Figure 1.1).

The tiny details as well as the broad conclusions of these and thousands of other stories of our geologic past were put together when someone looked at a rock and began wondering about its history. To most folks, a rock may be just a rock, but to a geologist, every rock is like a page in a book. The pages are sometimes hard to read and incomplete, but by paying attention to various aspects of rocks, geologists can decipher the fascinating stories locked within. These stories are told in a book that is written in the "language" of geology. Sometimes, unwrapping the mystery requires **paleontology** – the study of fossil evidence of past

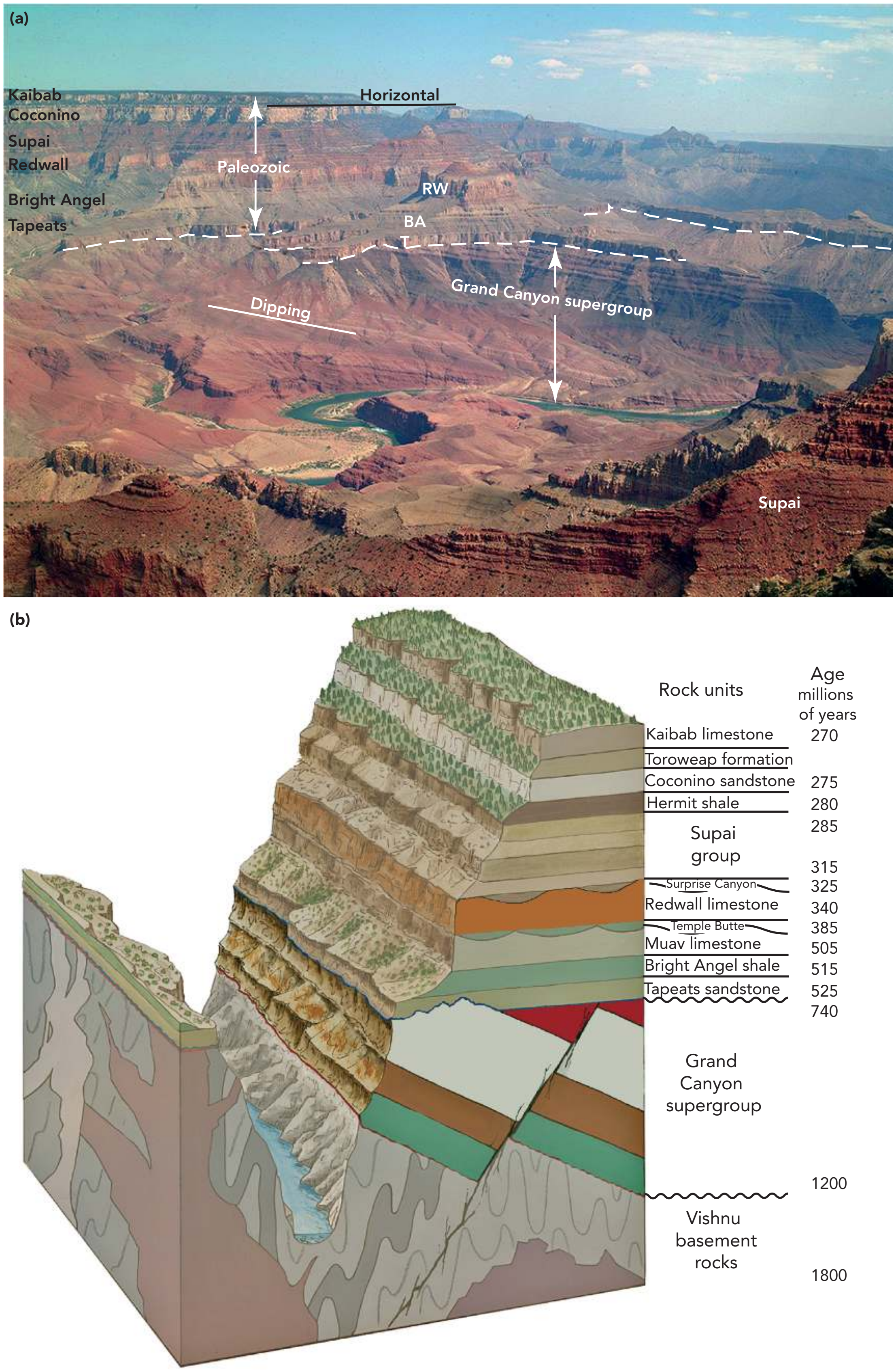

Figure 1.1 (a) Photo and (b) block diagram of the Grand Canyon. The older dipping layers of the Grand Canyon Group are separated from the younger horizontal Paleozoic layers by an unconformity surface, marked by the dashed line that separates them. The surface is actually continuous, but because it is exposed in different segments of the complex canyon, the line appears as different segments. The various formations are labeled: T – Tapeats Sandstone, BA – Bright Angel Shale, RW – Redwall Limestone. Source: (b) Karlstrom and Crossey (2019), used with permission.

life, or it could require **geochemistry** – the study of the chemical composition of rocks and minerals, or **structural geology** – the study of the deformation of rocks. In other cases, an understanding of **stratigraphy** – the study of rock layering – or Earth's geophysical properties, provide the key to unlock these stories. In this chapter we will use the example of the Grand Canyon to introduce some of fundamental concepts and terms that geologists use to read the stories that rocks tell us about how Earth and life on it have changed over its 4.5 billion years of history.

KEY POINT

Geological stories are told using the language of geology including paleontology, stratigraphy, geochemistry, and structural geology.

1.1 The Grand Canyon: Overview

The Grand Canyon (Figure 1.1), in the southwestern United States, is one of the seven natural wonders of the world. It reaches a depth of 1,857 meters, is 19 kilometers across at its widest, and stretches for about 446 kilometers. The canyon was carved over many millions of years due to a combination of the erosive power of the Colorado River, and regional uplift of the Colorado Plateau in response to **plate tectonic** processes that we will cover in more detail in Chapters 5 and 14.

The first humans to inhabit the Grand Canyon area were the native American ancestors of modern Puebloans about 3,000 years ago, and the first Europeans to see the Canyon were led by Spanish conquistador García López de Cárdenas y Figueroa, led by Hopi guides in 1540. In 1869 famed American geologist and explorer John Wesley Powell, who lost an arm in the American Civil War, conducted the first major geological expedition down the Colorado River. This expedition produced the first formal geologic reports of the Grand Canyon and surrounding Colorado Plateau, and the region has been the subject of geologic investigation ever since.

1.1.1 Age of the Grand Canyon

The details of the formation of the Grand Canyon are a subject of active investigation. The modern consensus is that the modern canyon system began forming around 70 million years ago, or 70 Ma. Throughout this book we will use the standard designations Ga for Giga-annum (billion years ago), Ma for Mega-annum (million years ago), and ka for kilo-annum (thousand years ago). The main phase of uplift and erosion occurred over the past six million years. One of the first concepts that can be deduced by considering the Grand Canyon is that slow erosion can result in the formation of vast geological features when operating over long times, such that the Colorado River was able to carve the deep canyon (see Chapter 2).

In addition to the idea that it has taken millions of years for the Colorado River to carve the canyon, the rocks that are exposed along the sides and at the bottom (Figure 1.1) record an even more impressive history that tells one of the most fundamental stories about Earth: that it is old – really old. Dating of the oldest rocks in the Grand Canyon show that they were formed about 1.8 billion years ago (1.8 Ga), but that is less than half of the age of Earth, which was formed around 4.56 Ga.

Geologists have developed the Geologic Time Scale (Box 1.1, Figures 1.2 and 1.3) to keep track of where rocks fit into Earth history. Much like a year is broken up into months, weeks, days, hours, and minutes, Earth time is broken up into **eons**, **eras**, **periods**, **epochs**, and **ages** (Figure 1.3). We will tell the story of how we came to know the age of the Earth in Chapter 4, but for now the key point is that over this immense stretch of time, many things have happened. We will start our story at the bottom of the Grand Canyon.

BOX 1.1 Core Knowledge: The Geologic Time Scale

Geologic time is divided into the longest eons, which are in turn divided into eras, periods, epochs, and ages (Figure 1.3). In the Phanerozoic Eon, the most recent eon, subdivisions are primarily based on variations in fossils. In older eons, which lack diagnostic fossils, other criteria may be used. Eons older than the Phanerozoic are collectively and informally referred to as Precambrian.

1.1.1.1 The Eons

Phanerozoic (542 to 0 Ma, i.e., to the modern day): The name means "evident life"; rocks of the Phanerozoic have abundant complex fossils.

Proterozoic (2,500 to 542 Ma): The name means "earlier life"; mostly simple fossils largely from single-celled life characterize Proterozoic rocks. The Proterozoic is divided into the *Paleoproterozoic* (ancient), *Mesoproterozoic* (middle), and *Neoproterozoic* eras (new), and these eras are in turn divided into a number of periods, discussed in Chapters 3, 6, and 8.

Archean (4,100 to 2,500 Ma): The name is from the Greek for "origin"; marked by the oldest rocks on Earth. It is divided into the *Eo-*, *Paleo-*, *Meso-*, and *Neoarchean* eras.

Hadean (4,567 to 4,100 Ma): The name comes from Hades, a reflection of the hellish conditions that existed at the time of formation of the planet. The Hadean is that eon of Earth history in which no rocks presently exist (in Chapter 3 we will see that they did exist once but have been destroyed by erosion, deformation, and metamorphism). By this definition, every time we find a new record-breaking oldest rock on Earth, the Hadean becomes a little shorter.

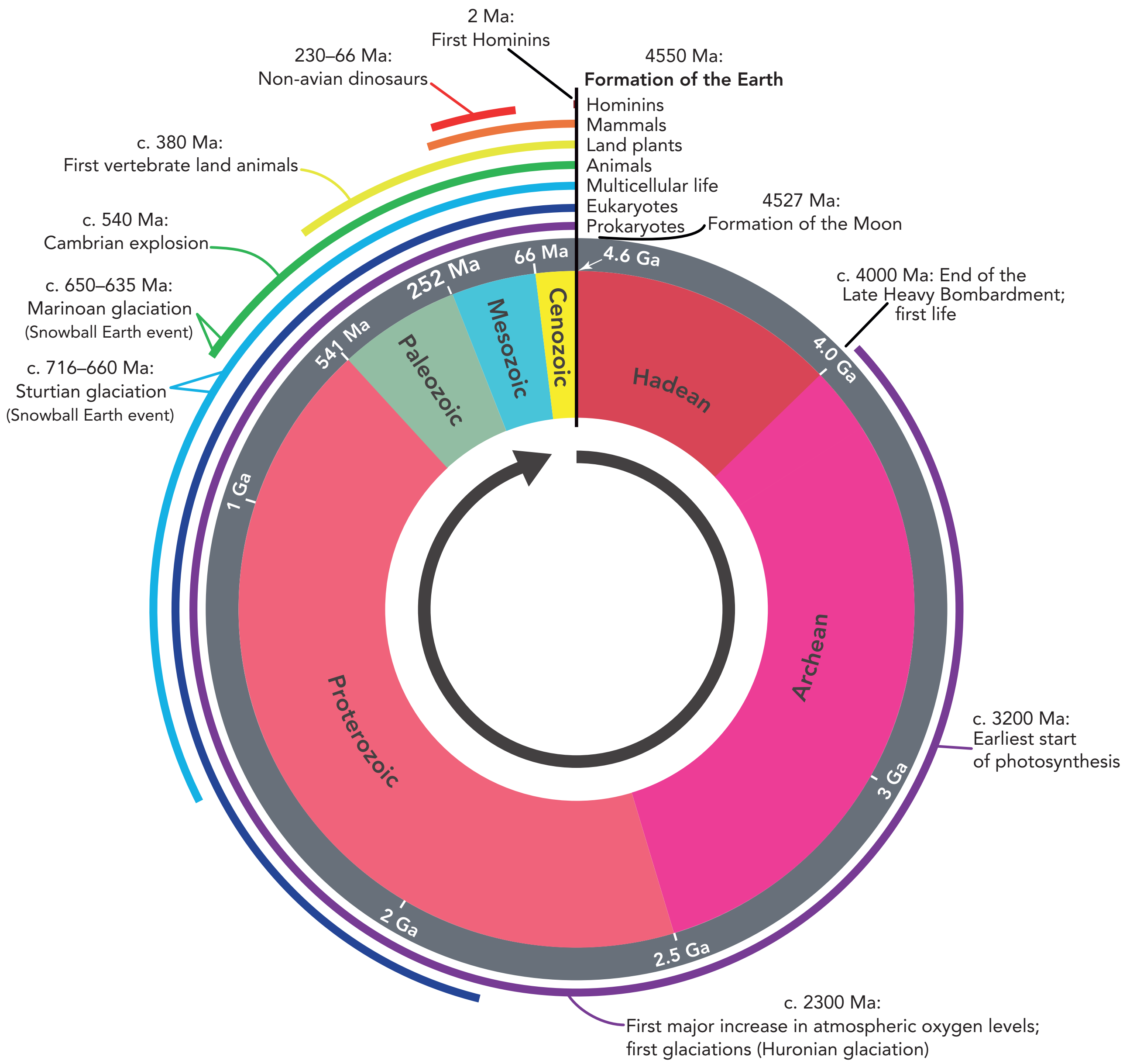

Figure 1.2 The Geologic Time Scale and key events in Earth history shown as a clock. Source: Adapted from WoudloperDerivative work: Hardwigg, Public domain, via Wikimedia Commons.

1.1.1.2 The Eras of the Phanerozoic Eon

Eras are the next level, or second-order division of geological time:

Cenozoic (65 to 0 Ma): Meaning "new life."
Mesozoic (251 to 65 Ma): Meaning "middle life."
Paleozoic (542 to 251 Ma): Meaning "old life."

1.1.1.3 The Periods of the Phanerozoic Eon

Eras are subdivided into periods, or third-order division of geological time:

Quaternary (2.6 to 0 Ma): This is the most recent period and extends to the present day. This name is a holdover from the four-fold division of rocks proposed by Alfred Werner in the late eighteenth century and discussed in Chapter 2.

Neogene (23 to 2.6 Ma): Neogene means "newborn." Fossilized organisms in this period are quite different to those from the preceding Paleogene period.

Paleogene (65 to 23 Ma): Paleogene means "ancient born" emphasizing the different nature of the fossils of this period compared to the succeeding Neogene period.

Cretaceous (145 to 65 Ma): One of the early sites of study of these rocks was southern England, where lots of the rocks are chalky limestones. The Latin word for chalk is *creta*, so these rocks were called Cretaceous.

Jurassic (199 to 145 Ma): These rocks are named from the Jura Mountains, in eastern France, where such rocks are found in abundance. This and the later Cretaceous period are famous for being the age of the dinosaurs, as discussed in Chapter 12.

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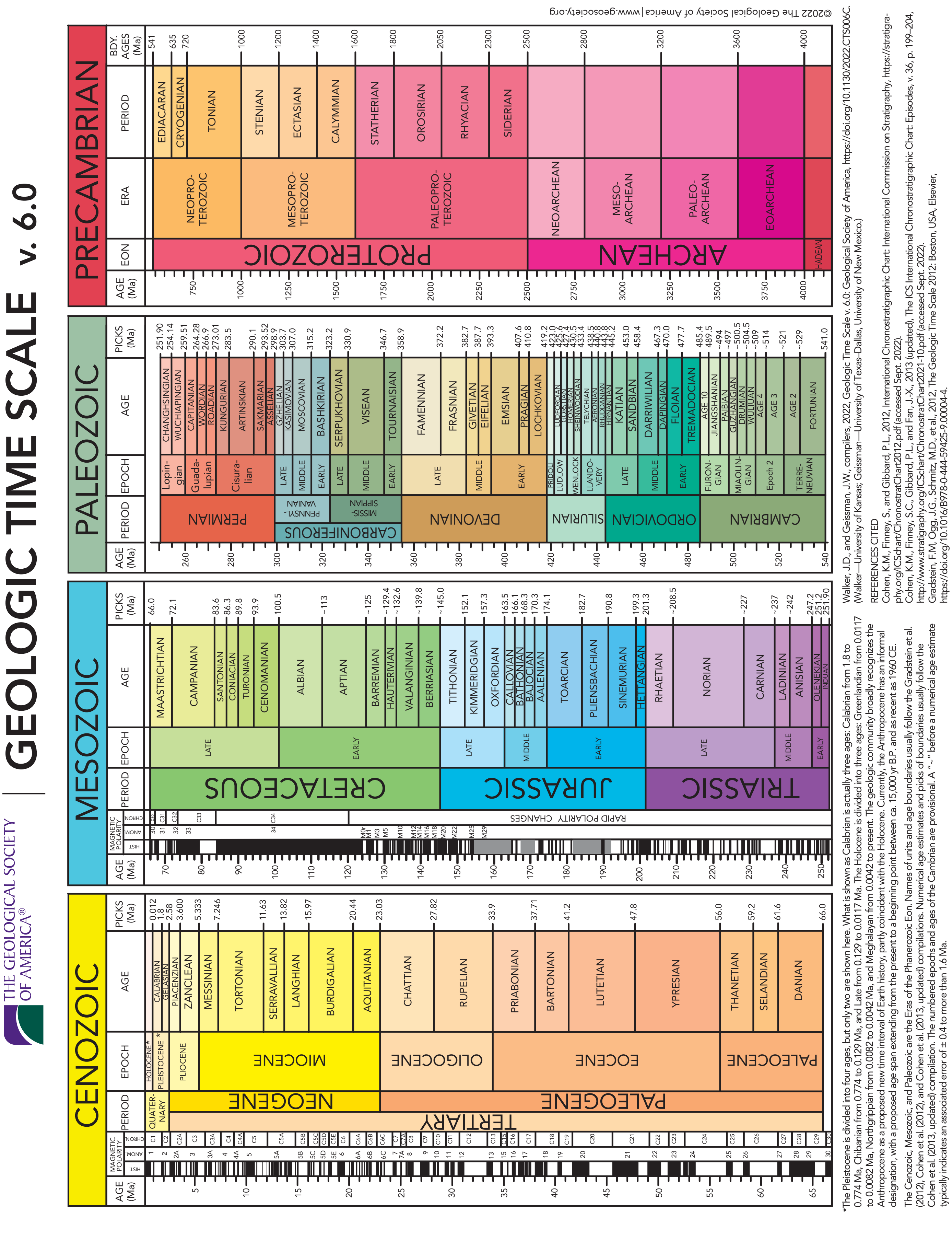

Figure 1.3 The Geologic Time Scale. Source: Used with permission of the Geological Society of America.

Triassic (251 to 199 Ma): The rocks exposed in southern Germany have three distinctive layers, so these rocks were named Triassic – "tri" for three.

Permian (299 to 251 Ma): Rocks named for their prominent exposures near the city of Perm, in central Russia.

Carboniferous (359 to 299 Ma): In Europe, rocks of this age have many coal deposits in them. Coal is rich in carbon, so these rocks were named Carboniferous – literally "rich in carbon." This term is not used in North America, where rocks of this age are broken into two separate periods referred to as the:

Pennsylvanian (318 to 299 Ma) and older *Mississippian* (359 to 318 Ma), named for their prominent exposures in Pennsylvania and Mississippi respectively.

Devonian (416 to 359 Ma): Rocks named for their prominent exposures near the county of Devon, England, the largest deposits of which are the "Old Red Sandstones."

Silurian (444 to 416 Ma): These rocks were first studied in southern Wales and the time period is named after the Silures tribe, which occupied the region in Roman times.

Ordovician (488 to 444 Ma): These rocks were also first studied in Wales and named after the Ordovices tribe, which occupied the region in Roman times.

Cambrian (542 to 488 Ma): The name comes from Cambria, the Latinized version of Cymru, the name for Wales in the Welsh language.

1.2 The Basement: Metamorphic and Igneous Rocks

There are three main rock types, **igneous**, **sedimentary**, and **metamorphic**, and all of these are well represented in the Grand Canyon. The oldest rocks belong to the Vishnu basement rocks, so called because they lie at the base of the canyon and include the Granite Gorge Metamorphic Suite and the Zoroaster Plutonic Complex. Box 1.2 summarizes the minerals that make up the majority of rocks on Earth.

1.2.1 Metamorphic Rocks (Granite Gorge Metamorphic Suite)

The Granite Gorge Metamorphic Suite (Figure 1.4) consists of metamorphic rocks. These are rocks that start off as one type of rock, called the **protolith** or original rock, and are later transformed by heat and pressure into a rock with new minerals

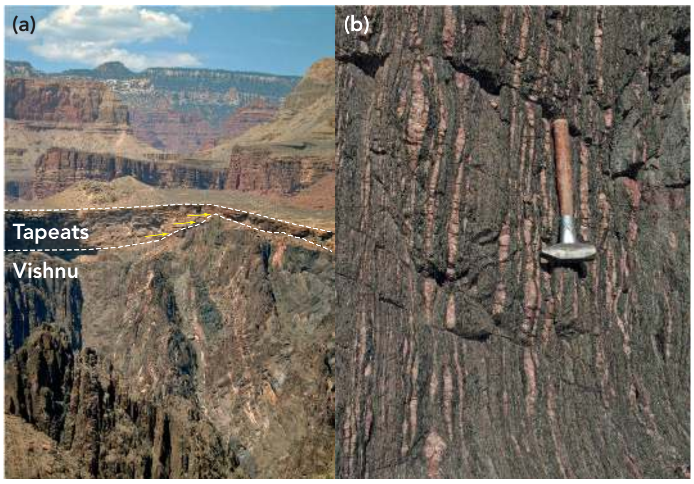

Figure 1.4 (a) The Vishnu Schist (dark) with pink granite intrusions is non-conformably overlain by the Tapeats Sandstone. Yellow arrows show onlap of Tapeats Sandstone against the Vishnu, recording deposition of shallow marine sands of the Tapeats during a time of rising sea level. The undulating top of the Vishnu would have created low and high areas that would have formed small islands as the area was flooded by the sea. (b) Banded dark schists and granite layers of the Vishnu schist.

BOX 1.2 Core Knowledge – Minerals: The Building Blocks of Rocks

Rocks mostly consist of minerals. A *mineral* is defined as a naturally occurring, inorganic solid with a regular internal structure and a narrow range of composition. Minerals are compounds made of elements. Although the periodic table includes more than 100 elements, most minerals can be described using only eight: oxygen (O), silicon (Si), aluminum (Al), calcium (Ca), sodium (Na), potassium (K), iron (Fe), and magnesium (Mg). Similarly, although more than 3,000 minerals have been identified, only about a dozen or so minerals are found in most rocks.

The crust of the Earth is about 47% oxygen and 28% silicon, so most common rock-forming minerals contain Si and O and are termed silicates. The simplest silicate is quartz, SiO_2; other common silicates include lighter-colored minerals, such as feldspars, which add potassium (K), calcium (Ca), and sodium (Na), and the so-called dark minerals, such as olivine, pyroxene, and amphibole, which are rich in iron and magnesium. Of the common rock-forming minerals, only **calcite** is not a silicate, that is, it does not contain silicon. Calcite ($CaCO_3$, where C stands for carbon) is the most important constituent of the rock limestone.

The crystalline structure of minerals reflects the geometry of the molecules that they are constructed from (Figure 1.5). Although only a few elements make up the majority of most minerals, trace amounts of different elements can be found in many minerals, which leads to a wide range of different varieties. For example, emerald is the gem variety of beryl, which includes trace amounts of chromium (Cr), giving it its characteristic green color. As another example, zircon can include trace amounts of radioactive uranium (U), which decays over time to lead (Pb). As we will discuss in Chapter 4, the ratio of parent uranium versus daughter lead can be used to date zircons and the rocks that contain them.

(Figure 1.5) and new textures. The Vishnu Schist, found at the base of the Grand Canyon, started as sediments formed as muds and sands deposited in an ocean along the flanks of a chain of volcanic islands around 2.5 Ga. These muds and sands were buried to become **shales** (clay-rich sedimentary rock) and **sandstones** (sand-rich sedimentary rock) and later, around 1.7 Ga, they were buried further as a consequence of plate tectonics, which is the idea that the Earth's surface consists of a series of rigid plates that split, slide, and collide relative to each other to produce all the major and most of the minor features of the planet, such as mountains and oceans. The sedimentary rocks were squeezed and heated because of plate collision to form metamorphic rocks, including **schists** and **gneisses** (Figure 1.6). **Slates**, schists, and gneisses are common metamorphic rocks distinguished by the size and composition of crystals as well as the types of minerals they contain (Figure 1.6). Metamorphic rocks are reflective of the temperature and pressure of formation, or metamorphic grade. Low-grade metamorphosis of shales produces slate, at higher grades schists, and at even higher grades gneisses (Figures 1.6 and 1.8).

The protolith of a metamorphic rock can be deduced by the mineral composition. Quartz and mica-rich schists usually have

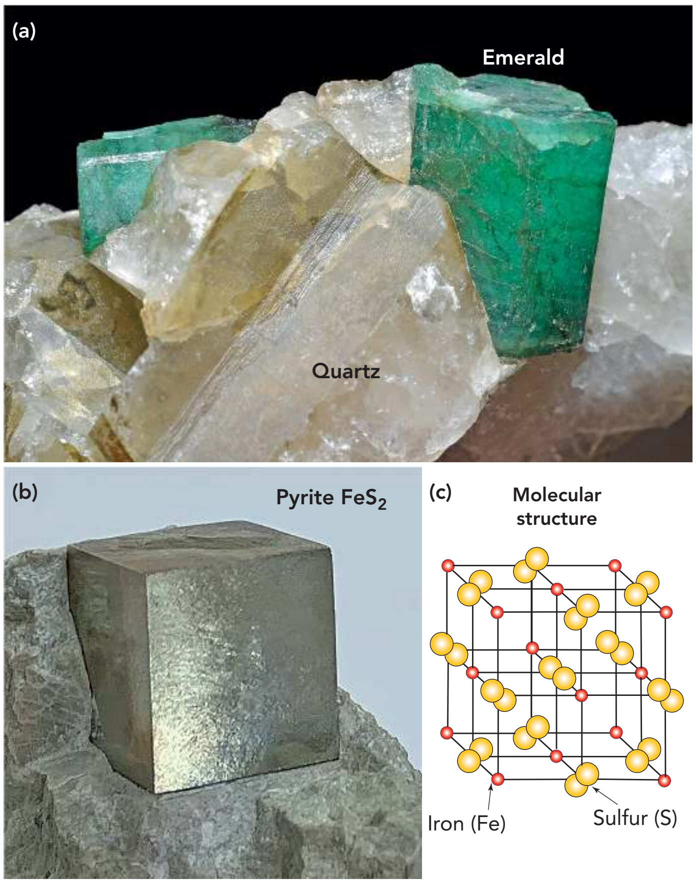

Figure 1.5 Examples of minerals. (a) White quartz and green emeralds. (b) Pyrite cube made of iron sulfide (FeS_2). (c) Inset shows that the molecular structure mimics the larger crystal shape. Source: (a) From Parent Géry, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons.

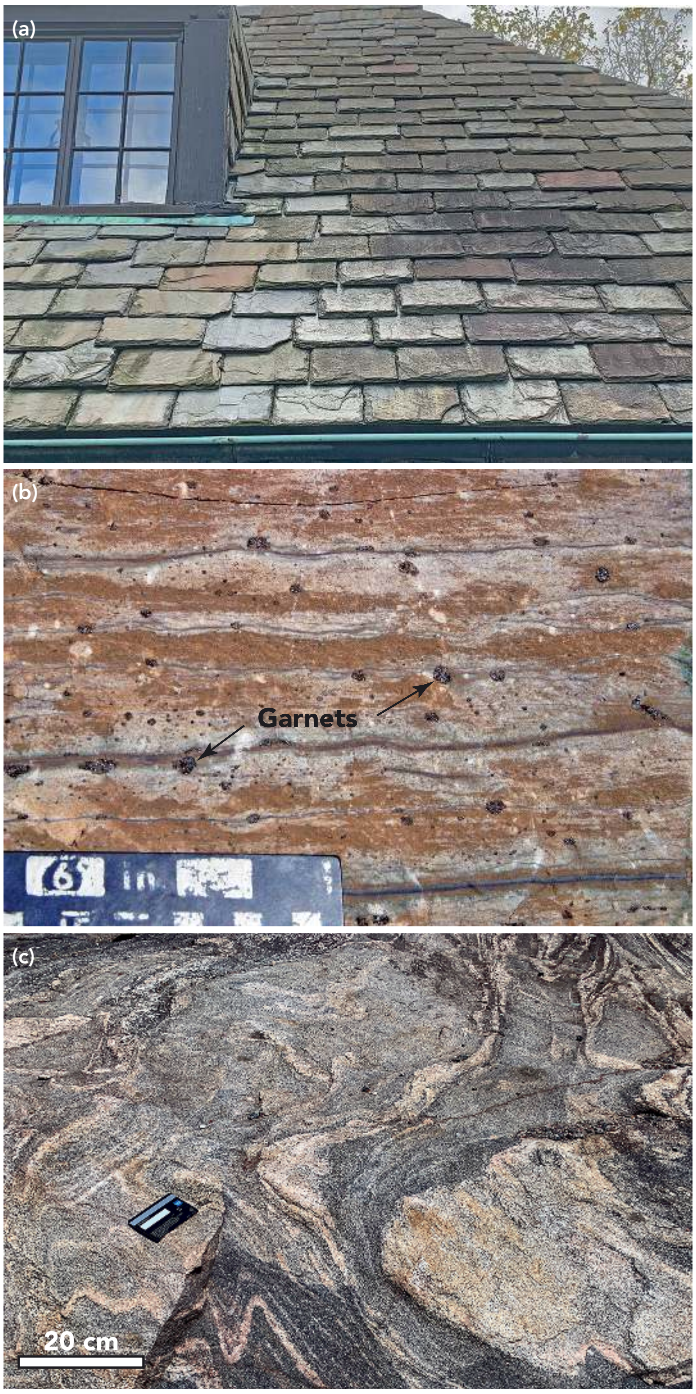

Figure 1.6 Common metamorphic rocks: (a) slate roof shingles; (b) garnet schist, Franklin Mountains Texas; and (c) gneiss with folds, Ontario, Canada.

a sedimentary origin, and original sedimentary features may sometimes be observed (Figure 1.7). The forces required to heat and deform these basement rocks in the Grand Canyon are understood to have been created when several volcanic island chains called **island arcs**, such as seen in the modern-day Aleutian Islands between Alaska and Siberia, collided with the North American craton (Figure 1.9). The Brahma Schist consists of metavolcanics, the metamorphosed remnants of the island

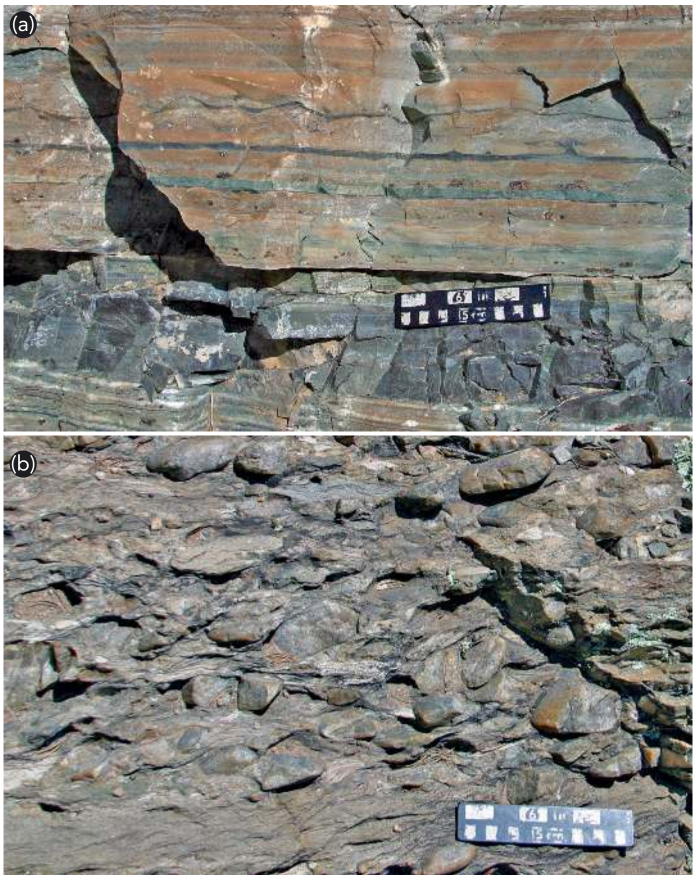

Figure 1.7 Metasediments. (a) This schist shows alternating lighter and darker layers representing the original sand and mud interbedding. Undulating tops of red beds are interpreted as preserved ripple marks. (b) This metaconglomerate, technically a schist, shows well-rounded pebbles indicative of an origin as a gravel that are now aligned and flattened as a result of later metamorphism.

arcs around which the sediments of the Vishnu Schist were originally deposited.

Cratons are large areas of stable crystalline basement rocks that form the central parts of continents. In the North American continent, the craton is exposed in the **Canadian Shield**, an area covering most of Canada east of the Rockies (Figure 1.10). The North American craton extends farther south, but except for parts of Minnesota and Wyoming it is not well exposed in the United States because it is covered by younger sedimentary rocks.

As with most cratons, the North America craton is surrounded by mountain belts (Figure 1.10), the **Cordillera** to the west, which is active today and which we will discuss in Chapter 14, and the **Appalachians** on the eastern side, which were formed between 450 to around 300 million years ago, the story of which we will tell in Chapter 10. We commonly use the term **Laurentia** to refer to the older continent of North America, which formed long before the Appalachians and Rockies were attached to its margins. Like most continents, Laurentia was surrounded by oceans that opened and closed, because of plate tectonic processes that we will introduce in Chapter 5. As the oceans surrounding Laurentia closed, volcanic island arcs (Figure 1.9) were accreted to its margins, increasing its size. Geologists like to give names to periods of mountain building, technically termed **orogeny**, and the one associated with the formation of the mountains associated with the formation of the Vishnu Schist, referred to as the Vishnu Mountains, which lie at the bottom of the Grand Canyon, is referred to as the **Yavapai Orogeny**.

Metamorphism (the transformation of one or a group of minerals into a new mineral assemblage) occurs entirely in the solid state, whereas igneous minerals that make up igneous rocks (described in a later section), form by crystallization from a liquid melt. Metamorphism happens because, given enough time, minerals subjected to temperatures or pressures different to those under which they formed change (often due to tectonic processes) because they are no longer stable under new combinations of temperature and pressure. Laboratory experiments can calibrate the pressures (P) and temperatures (T) at which diagnostic metamorphic minerals form, and observations of these minerals in metamorphic rocks can therefore be used to infer the conditions of formation (Figure 1.8). This can be used to build up a pressure–temperature (P–T) history, or "path" of a sequence of rocks, which can then be used to infer the sequence of burial, metamorphosis, and later uplift and erosion that they experienced, which in the case of the Vishnu basement rocks of the Grand Canyon record the formation and ultimate erosion of the ancient Vishnu mountain belt (Figure 1.9).

Analysis of key minerals show that the Granite Gorge Metamorphic Suite experienced maximum temperatures of 800 °C and pressures of 8 kilobars (8,000 times atmospheric pressure), indicating they formed at a depth of about 25 kilometers below the surface in the deep roots of the Vishnu Mountains (Figure 1.8). At these temperatures, in addition to metamorphism, some of the rocks also experienced partial melting, forming igneous rocks, discussed next.

KEY POINT

The oldest rocks in the Grand Canyon are metamorphic and igneous, formed 1.8 Ga during the Yavapai Orogeny at a depth of 25 km in the roots of the Vishnu Mountains.

1.2.2 Igneous Rocks: The Zoroaster Plutonic Complex

The compression and heating associated with the Yavapai Orogeny also caused some rocks to melt, which resulted in the formation of the rocks of the Zoroaster Plutonic Complex, although as we will explain below, the melting was not complete.

The term *igneous* literally means "fire-rock," from the root *ignis* from which we obtain the English word ignite. All igneous rocks start off as a liquid **magma**, which is called **lava** when it

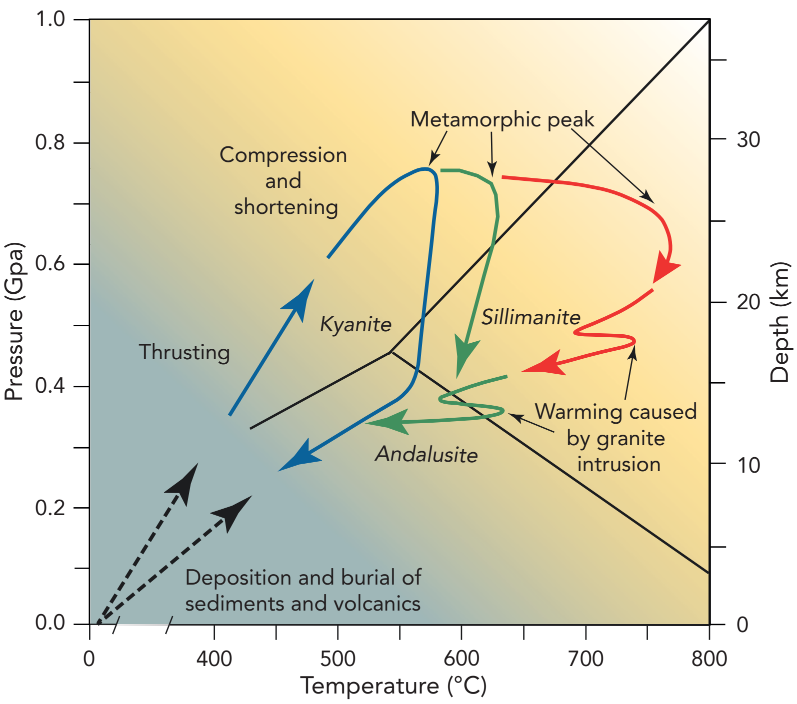

Figure 1.8 Pressure/temperature paths of different geological blocks, shown with different colored lines, of the Vishnu basement rocks, Grand Canyon. Different blocks experience different levels of metamorphism. Andalusite, Kyanite, and Sillimanite, as well as other mineral assemblages (not shown), are used to plot the PT pathways. Source: Modified from figure 10 in Karlstrom et al., in Timmons and Karlstrom (2012). Used with permission of the Geological Society of America.

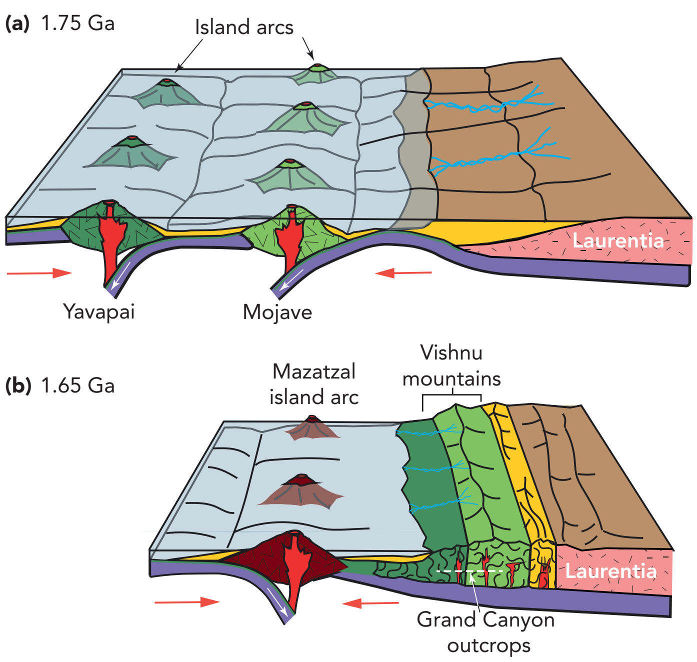

Figure 1.9 The Yavapai and Mojave volcanic island arc systems (a) eventually collided with Laurentia during the Yavapai Orogeny and built the Vishnu Mountains (b). The Vishnu basement rocks formed at a depth of about 25 kilometers below the surface in the mountain roots. Source: Modified from figure 6 in Karlstrom et al., in Timmons and Karlstrom (2012). Used with permission of the Geological Society of America.

flows at the surface. Igneous rocks that cool and solidify beneath the surface are called **plutonic** or **intrusive**, and when solidification happens on or above the surface, we call the resulting igneous rocks **volcanic** or **extrusive**.

Igneous rocks mostly contain minerals in the form of crystals (Figure 1.5). Crystal size primarily relates to how quickly a magma cools. The ability of magma or lava to flow means it behaves like a liquid. When lava is extruded at the surface, or underwater, it cools very quickly, and the liquid freezes without forming crystals, making volcanic glass (Figure 1.11a). Volcanic glass is therefore characteristic of extrusive rocks. Conversely, plutonic magmas that cool slowly below the surface allow more time for larger crystals to grow, eventually turning all that was once liquid into crystals (Figure 1.11c and d). Large crystals are therefore characteristic of plutonic rocks.

The Zoroaster Plutonic Complex includes a variety of igneous rock types, including **granites** (Figure 1.12), which have a distinctive pink color reflective of the dominance of the felsic minerals, potassium feldspar and quartz, and which show relatively large crystals, indicating that the magma cooled slowly, underground. It also includes darker-colored mafic **gabbros**, which have darker minerals, such as **pyroxene**, that are richer in magnesium (Mg) and iron (Fe). These different rock types record cooling of magmas that had different chemical compositions. Granites are formed from **felsic** magmas, rich in **feldspar** (fel) and silica (Si). Gabbros crystallize from **mafic** magmas, rich in magnesium (Mg) and iron (Fe).

But wait a minute, you might say, if plutonic igneous rocks form by cooling of magma, how do you get rocks with different composition? Isn't magma all one thing? The answer to this question is no. Magmas have variable compositions that relate to how magmas are produced in the first place. Most magma is produced by **partial melting** of older rocks. Compared to most people's everyday experience, the temperature needed to melt

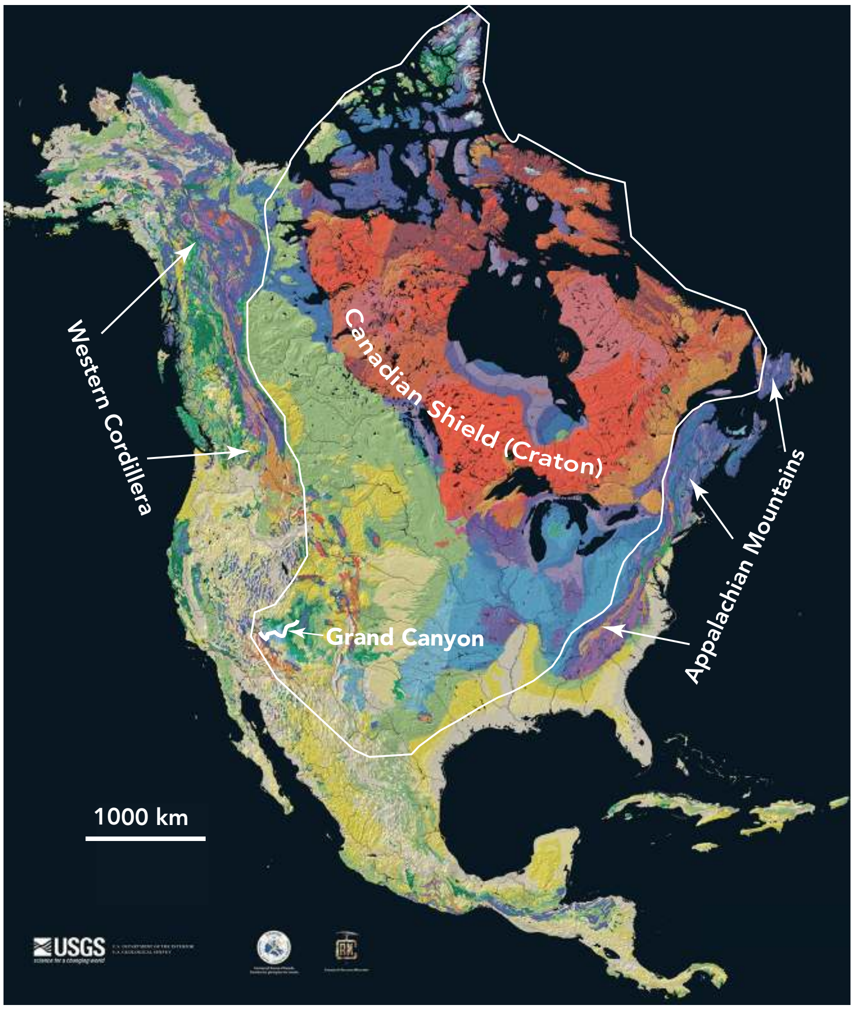

Figure 1.10 North American map showing Laurentian Craton and fold and thrust belts. Source: Original map from US Geological Society.

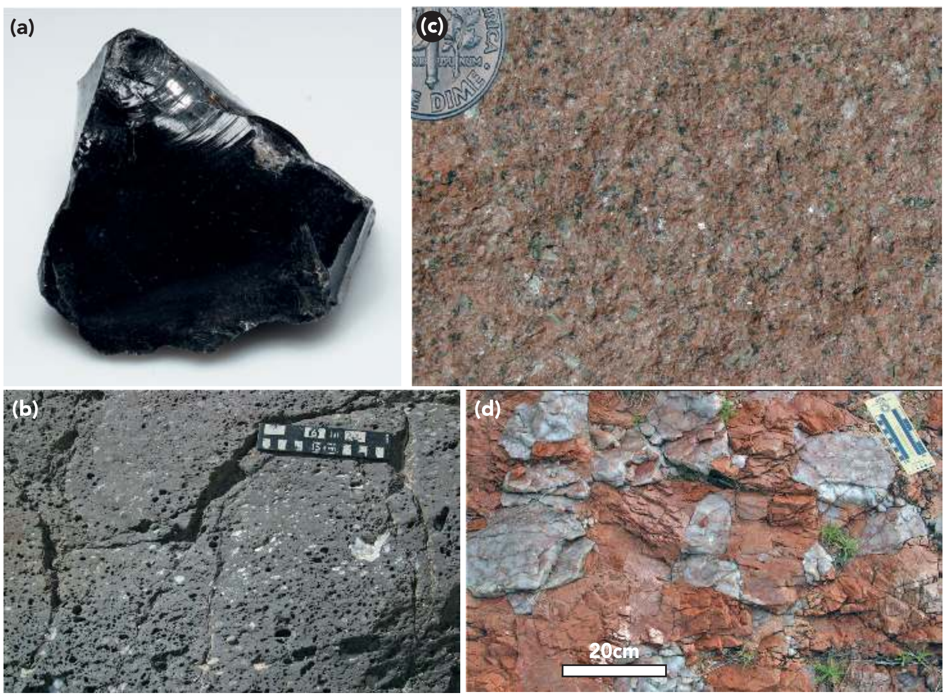

Figure 1.11 Examples of common igneous rocks: (a) obsidian (volcanic glass); (b) basalt with gas holes (vugs), some are filled with white calcite that formed after the rock cooled; (c) granite; and (d) pegmatite. In (c) and (d) the pink mineral is potassium feldspar and white crystals are quartz. Source: (a) Credit: V&G Studio via iStock / Getty Images Plus.