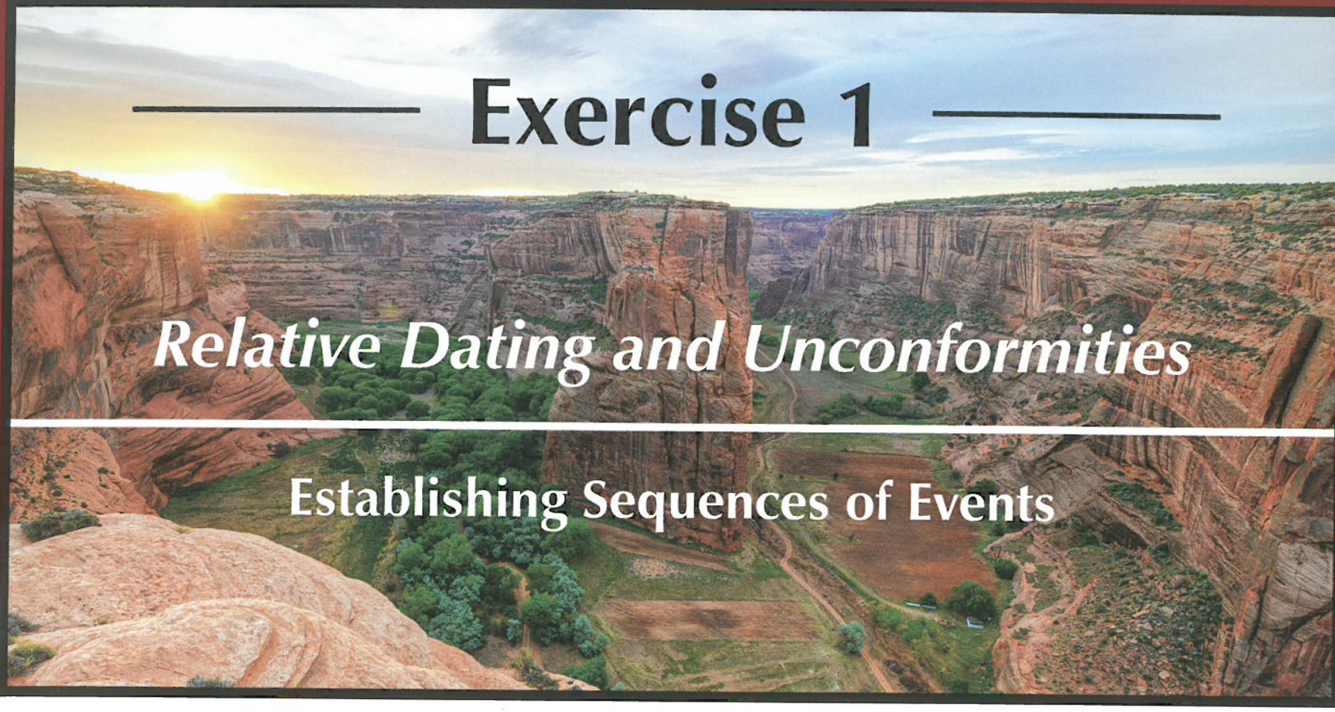


Exercise 1

Relative Dating and Unconformities

Establishing Sequences of Events

LEARNING OBJECTIVES **After completing this exercise, you will be able to:**

1. understand the differences between relative and absolute (radiometric) dating;
2. define the principles of relative dating, which include original horizontality, superposition, cross-cutting relationships, inclusions, and faunal succession;
3. establish the order of geological events that conspired to form the given relationships shown on block diagrams and images depicting geological features, as well as list the principle(s) that enabled you to establish the correct order of events;
4. recognize the four types of unconformities on block diagrams and images of actual field areas; and
5. explain the nature and relative duration of processes that create each type of unconformity.

Introduction

The discovery of "deep time" is one of geology's greatest contributions to human understanding. The conceptual foundations laid by eighteenth- and nineteenth-century geologists working in relatively small geographic areas paved the way for development of the modern high-resolution geological timescale (figure 1.1), which spans 4.6 billion years of Earth history and applies to geological features anywhere on Earth. The succession of eons, eras, and periods was constructed during the early part of the nineteenth century using the principles of relative dating that are the focus of this exercise. The absolute timescale (numerical scale) was added after the discovery of radioactivity and the development of techniques that were able to reliably measure small amounts of radiogenic isotopes in geological materials. The numerical scale, the subject of exercise 2, was developed during the latter half of the twentieth century.

Principles of Relative Dating

In this exercise, we are concerned only with a relative sequence of geological events; that is, event A preceded event B or geological feature B is younger than feature A, but older than feature C. To establish the correct order of events, geologists use five simple, but powerful, concepts. First, sedimentary rock layers are horizontal when first deposited. Any marked variation from the horizontal

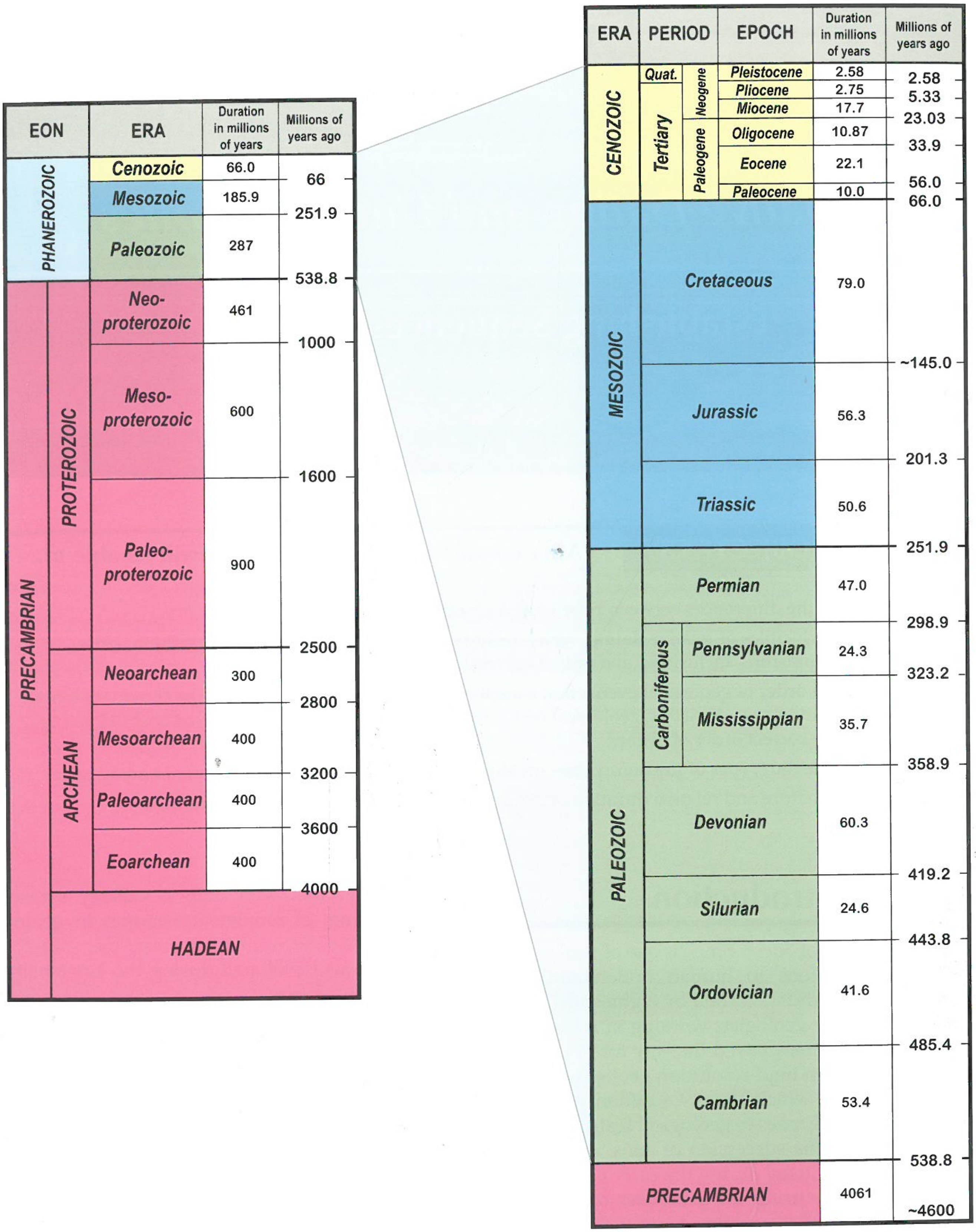


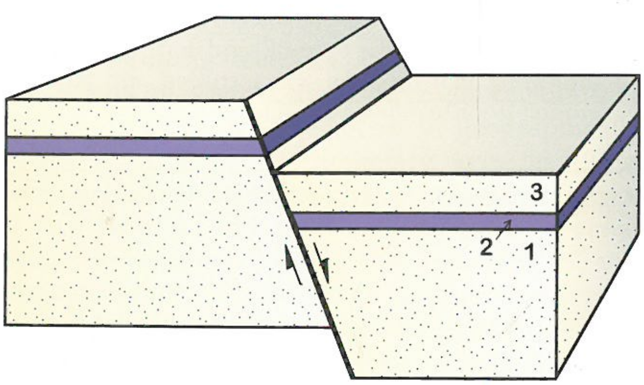
FIGURE 1.1 Modern geological timescale showing relative order and ages/durations of eons, eras, periods, and Cenozoic epochs. (Based on International Commission on Stratigraphy, International Chronostratigraphic Chart, v2022/02.)

indicates subsequent movement of the Earth's crust. This relationship is called the **principle of original horizontality**.

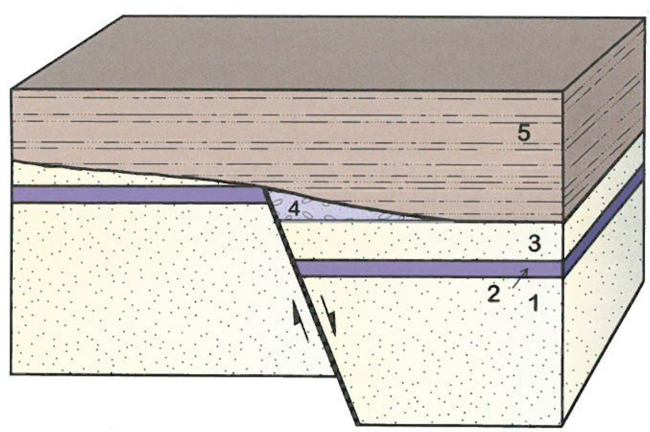
Second, those rocks that are highest in a normal, undisturbed stratigraphic succession are youngest, or, conversely, those that are lowest in the undisturbed succession were deposited first and are oldest. This major principle is known as the **principle of superposition**. For example, rocks exposed along the rim of the Grand Canyon are younger than the rocks exposed at the level of the Colorado River in the bottom of the canyon. In areas that have undergone intense folding and faulting, layers may have been overturned. In these cases, the position of a layer in a stratigraphic succession is not indicative of its relative age.

Third, geologic structures or rock bodies that cross-cut other structures or bodies are younger than the features that are cut—the **principle of cross-cutting relationships**. Geologically speaking, faults or igneous dikes that offset or cross-cut series of strata are younger than the strata that are disrupted by faulting or intrusion. If an igneous dike is offset across a fault trace, this relationship indicates that the fault became active subsequent to the dike's emplacement. Consider the timing of events in figure 1.2A. The purple bed, layer 2, was deposited as part of a single horizontal stratum. As a result of faulting, the right fault block moved down relative to the block on the left, thereby offsetting the formerly continuous layer. Since layer 2 is offset along the trace of the fault, movement of the fault occurred after deposition of layer 2. How much time passed between deposition of layer 2 and its subsequent offset by faulting is impossible to tell from figure 1.2A. The faulting could have occurred 1,000 years or 1,000,000 years after deposition of layer 2. Essentially the same relationships are shown in figure 1.2B, but here deposition was renewed after faulting. Layers 4 and 5 have not been cut by the fault and hence are younger than the most recent fault movement. Relationships in figure 1.2B permit us to conclude that deposition of layer 1 preceded deposition of layer 2 (superposition) and that layer 3 was deposited subsequent to layer 2 (superposition). However, prior to deposition of layer 4, the fault became active, thereby offsetting layers 1 through 3 (cross-cutting relationships). Layer 4 represents erosional material derived from layer 3 on the left (upthrown) side of the fault, but deposited on the down-dropped side of the fault. Since the trace of the fault does not cut across layering in layer 5, this layer must be younger than the most recent movement on the fault (cross-cutting relationships). The principles of superposition and cross-cutting relationships permit us to easily discern the proper succession of geological events portrayed by the patterns in figure 1.2.

The **principle of inclusions** is a fourth way to determine relative ages. Simply put, a rock body represented by fragments (inclusions) embedded within another rock must be older than the rock that encloses the fragments. In figure 1.3A, fragments of metamorphic rock (dark) are embedded within

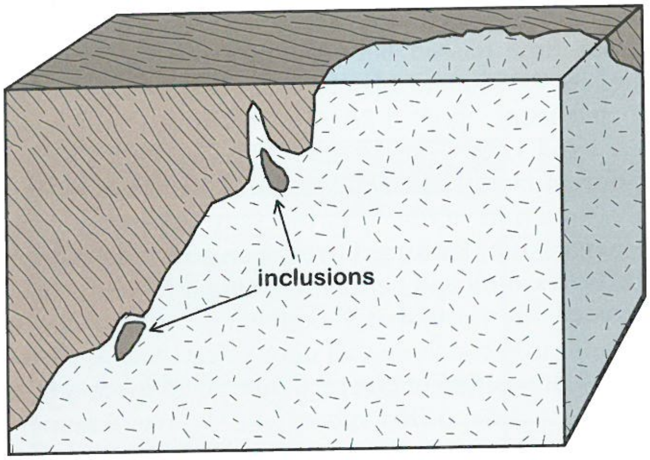


A. Relationships subsequent to faulting of units 1, 2, and 3.

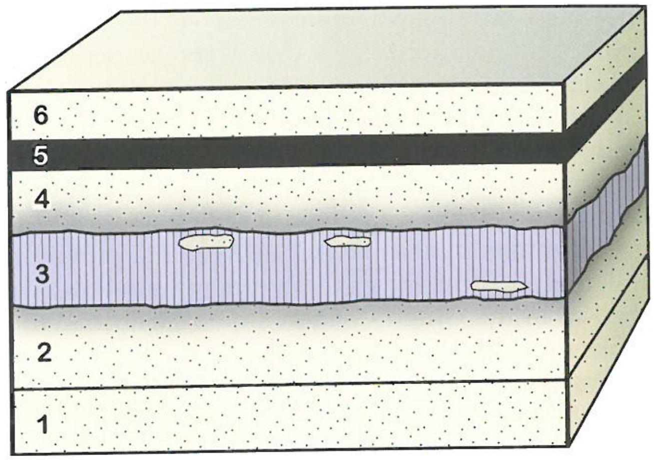


B. Relationships subsequent to erosion of the upthrown block and burial of both blocks by renewed sedimentation. Cross-cutting relations indicate that the fault has not moved subsequent to deposition of sedimentary units 4 and 5.

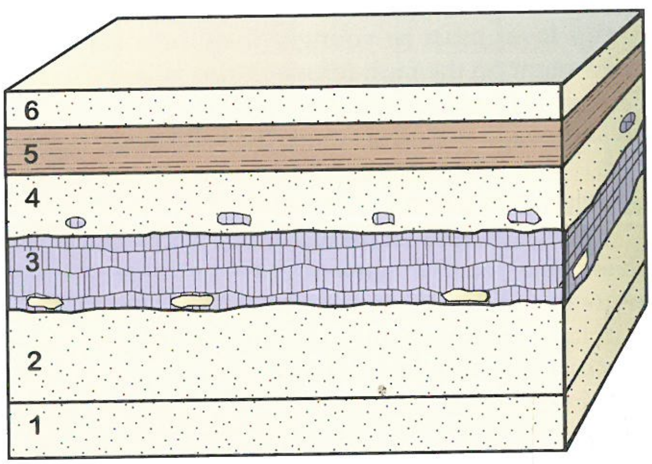
FIGURE 1.2 **Block diagrams showing relationships of normal faulting.**



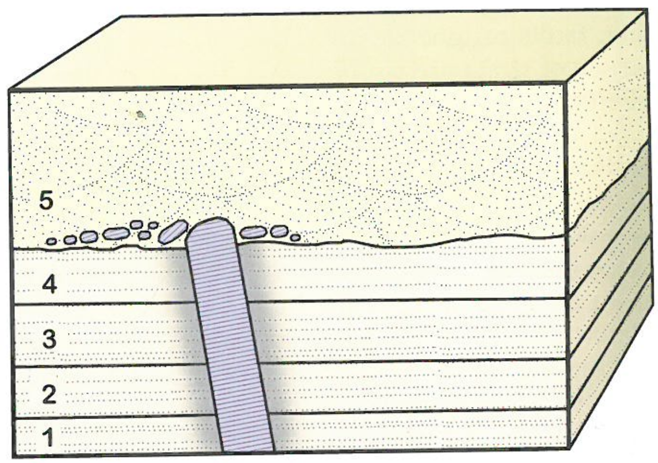
A. Inclusions of foliated metamorphic (dark) rock "floating" in the mass of granite (light) indicate that the metamorphic rock is older.



B. An igneous sill has baked both the underlying and overlying strata. Inclusions of sandstone from layers 2 and 4 indicate that igneous layer 3 post-dates both of the adjacent sandstone layers.



C. The law of inclusions indicates that igneous layer 3 was formed prior to deposition of sandstone layer 4.



D. A dike has intruded beds 1 through 4, but is overlain (cross-cut) by layer 5. Inclusions of the dike rock were incorporated into the base of sandstone layer 5, also indicating that the dike was intruded and partially eroded prior to deposition of layer 5.

FIGURE 1.3 **Block diagrams showing various relationships of igneous and sedimentary rocks that are useful in establishing the relative order of events.**

granite (light). This relationship indicates that metamorphic rocks were torn from the wall of a magma chamber and enclosed within the magma as it was emplaced. In figure 1.3B, a layer of dark igneous rock (layer 3) is located between two layers of sandstone. This relationship may have occurred in one of two ways. Either the igneous layer formed as a surface flow subsequent to deposition of layer 2, but before deposition of layer 4, or the igneous layer was intruded as an igneous sill after deposition of layers 2 and 4. A lava flow and a horizontal sill (sheet of intruded igneous material) appear similar in outcrop and on geological maps, but have quite different age relationships. The enclosure of sandstone fragments (inclusions) of layer 4 within igneous rocks of layer 3 indicates that layer 3 is an intrusive body emplaced after layer 4 was deposited. Rocks in contact with the intrusion may be baked. Baking of the top of layer 2 and the base of bed 4 (indicated by shading) provides further evidence that the igneous sheet is a sill rather than a buried basalt flow. Compare figure 1.3B with relationships shown in figure 1.3C. The inclusion of volcanic cobbles and boulders from layer 3 in the lower part of sandstone layer 4 indicates that in this case the dark igneous layer was a surface basalt flow that was extruded and crystallized before deposition of layer 4.

The fifth and final principle of relative dating is known as the **law of faunal succession**. In 1805, the British canal surveyor William "Strata" Smith noted that fossils occurred with such specificity within strata of southwestern England that he could use fossils to recognize and correlate sedimentary strata throughout all of England. Once understood, this orderly succession of fossils was used to divide geological time into the eons, eras, and periods that we know today. Time boundaries between geological periods are based upon the first appearance of fossils in strata. For example, the base of the Devonian System is defined as the first appearance of a graptolite species known as *Monograptus uniformis*. Each era, period, and epoch hosted unique species of plants and animals. Marine rocks of Paleozoic age can be recognized by the presence of trilobites. No trilobites have ever been found in Mesozoic or Cenozoic strata, neither by William Smith nor by the thousands of geologists and paleontologists that have followed him. Instead, Mesozoic rocks are characterized by the remains of organisms, such as dinosaurs, that lived during the Mesozoic Era.

The law of faunal succession is particularly useful for making long-range correlations. For example, it would be impossible to correlate sedimentary or volcanic rock layers exposed in the Grand Canyon in Arizona to age-equivalent strata in southern Russia using superposition, original horizontality, cross-cutting relations, or inclusions because these principles show the relative age relationship between rock bodies that occur in geographically contiguous areas. No sedimentary layer, lava flow, fault, or fold can be traced globally. However, if portions of Arizona and southern Russia were covered by shallow oceans during the Permian Period, and these geographically distinct basins were both populated by individuals of one or more widely dispersed species that existed only during the Permian Period, fossil remains of this species (faunal succession) could be used to establish time equivalence between sedimentary layers deposited in the two basins. It is just such paleontological relationships that permit us to recognize rocks of a particular age (Cambrian, Ordovician, etc.) on a global scale.

Unconformities in the Rock Record

The sedimentary rock record does not encode an unbroken history of deposition in any one place. A drop in sea level may cause sedimentation to cease for a period of time, or uplift and erosion may remove large volumes of rock from a given region. Surfaces between superjacent bodies of rock that reflect missing pages or chapters of Earth history are called **unconformities**. The angular unconformity at Siccar Point in southeastern Scotland (figure 1.4) is perhaps the most famous since it was discovered and described by James Hutton (the originator of uniformitarian geology) in the late 1700s.

Since Hutton's time, unconformities have been recognized and studied around the world. In some rock successions, the amount of time reflected by the unconformities is greater than the time represented by the actual rocks. The four principal types of unconformities are **angular unconformities, nonconformities, disconformities,** and **paraconformities**. Perhaps the easiest to recognize is the angular unconformity. This occurs when there is a degree of angular discordance between the layered rocks located above and below the plane of the unconformity. In figure 1.5A, horizontal rocks of Early Tertiary age straddle nearly vertical rocks of Jurassic age. Strata below the unconformity were tilted and eroded prior to deposition of the horizontal beds. Since we know that the rocks below and above the unconformity are Jurassic and Early Tertiary in age, respectively, we can determine that uplift and erosion of the Jurassic strata took place during the Cretaceous Period. A minimum of 80 million years of time (duration of the Cretaceous Period) is represented by this unconformity—far more time than it took to deposit the Jurassic and Early Tertiary rocks shown in figure 1.5A.

A second type of unconformity is called a **nonconformity**. In this case, layered sedimentary rocks overlie an erosion surface developed on metamorphic and igneous rocks. Because the crystalline rocks that underlie nonconformities form deep in the crust where magmatism and regional metamorphism occur, the nonconformity reflects a period of tectonic mountain building followed by a prolonged period of regional erosion.

To understand the complexity and meaning of nonconformities, let's consider the surface between the Precambrian Vishnu Schist and Cambrian Tapeats Sandstone exposed in the Grand Canyon (figure 1.5B). The Vishnu Schist (dark rocks in the lower

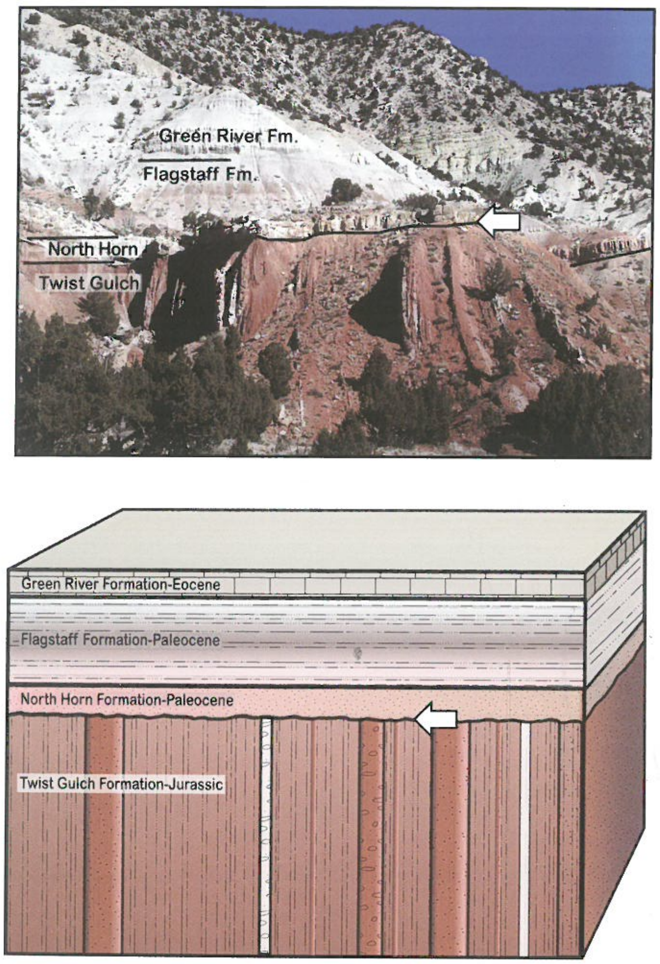
FIGURE 1.4 Historically significant angular unconformity exposed as Siccar Point in southeastern Scotland. The angular discordance between Silurian (below) and Devonian (above) strata shown here corroborated James Hutton's inference that the Earth was old and that its formative processes were cyclical.

part of figure 1.5B) began as a succession of marine shale and siltstone deposited in a Precambrian sea that occupied the Grand Canyon area over 1.8 billion years ago. The area was subjected to mountain building from 1.8 to 1.7 billion years ago (radiometric ages), at which time the fine-grained sediments were altered to schist and intruded by veins of granitic magma. During the ensuing 1.27 billion years, the tectonic highlands were taken down to their metamorphic-igneous roots by weathering and erosion, resulting in production of a relatively flat surface underlain by deeply weathered schist and granite. Approximately 530 million years ago, Cambrian seas spread across this surface, reworking unconsolidated materials into a basal conglomerate (basal Tapeats Sandstone) that was covered by subsequent layers of sand (Tapeats Sandstone), clay (Bright Angel Shale), and limestone (Muav Limestone). Radiometric dating of key beds indicates that the nonconformity between the Vishnu Schist and basal Tapeats Sandstone represents approximately 1.27 billion years of "missing" time. Compare the duration of this nonconformity with that of the angular unconformity shown in figure 1.5A.

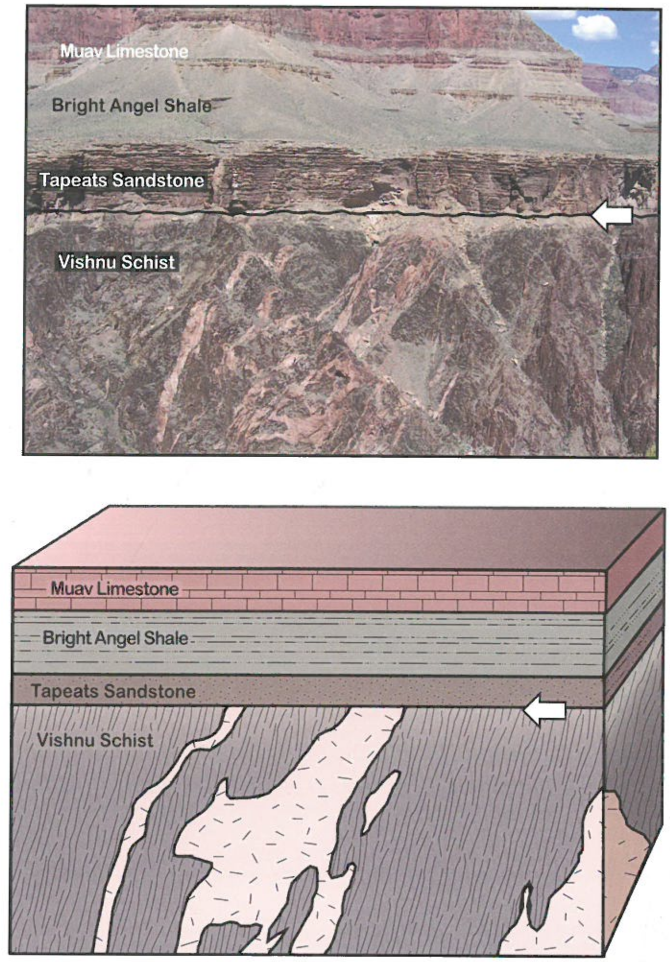
Disconformities comprise a third type of unconformity. These are more difficult to recognize than the preceding two types of unconformities because the sedimentary strata above and below the disconformity are parallel to one another. By definition, a disconformity is a surface of buried erosional relief between parallel layers of sedimentary rock. This means that the surface underlying the disconformity was carved by shallow to deep stream channels prior to deposition of the overlying strata. Figure 1.5C shows a disconformity developed within the Paleogene Colton Formation of central Utah. It is not possible to tell how much time is represented by this disconformity, but it certainly reflects less time than either of the two unconformities described above.

Finally, an unconformity between sets of parallel sedimentary strata that shows no evidence of erosional relief is defined as a **paraconformity**. The suspected paraconformity surface may be overlain by a pebble conglomerate or by a concentration of insoluble minerals such as phosphates and sulfides. In some cases the paraconformity is physically indistinguishable from a simple bedding plane. The most certain evidence of a paraconformable relationship is juxtaposition of fossils of distinctly different ages above and below the unconformable surface. Figure 1.5D shows paraconformable strata exposed in a road cut in southwestern Missouri. The recess in the cliff (white arrow) indicates the position of the paraconformity between the Early Ordovician Cotter Dolomite and Early Mississippian strata (Bachelor Formation and Compton Limestone). Ages of these formations are determined by fossil content. Hence this seemingly simple bedding plane represents a hiatus that encompasses part of the Ordovician and the entirety of the Silurian and Devonian Periods. Without the aid of fossils, the significance of this surface could be easily overlooked.

The relationships shown in figure 1.5D suggest that the shallow oceans that covered southwestern Missouri during deposition of the Cotter Dolomite withdrew from the area, probably owing to regional uplift. By Early Mississippian time, the area subsided below sea level once again and sedimentation resumed. The parallel arrangement of strata above and below the paraconformity indicates that strata below the paraconformity in this area were not



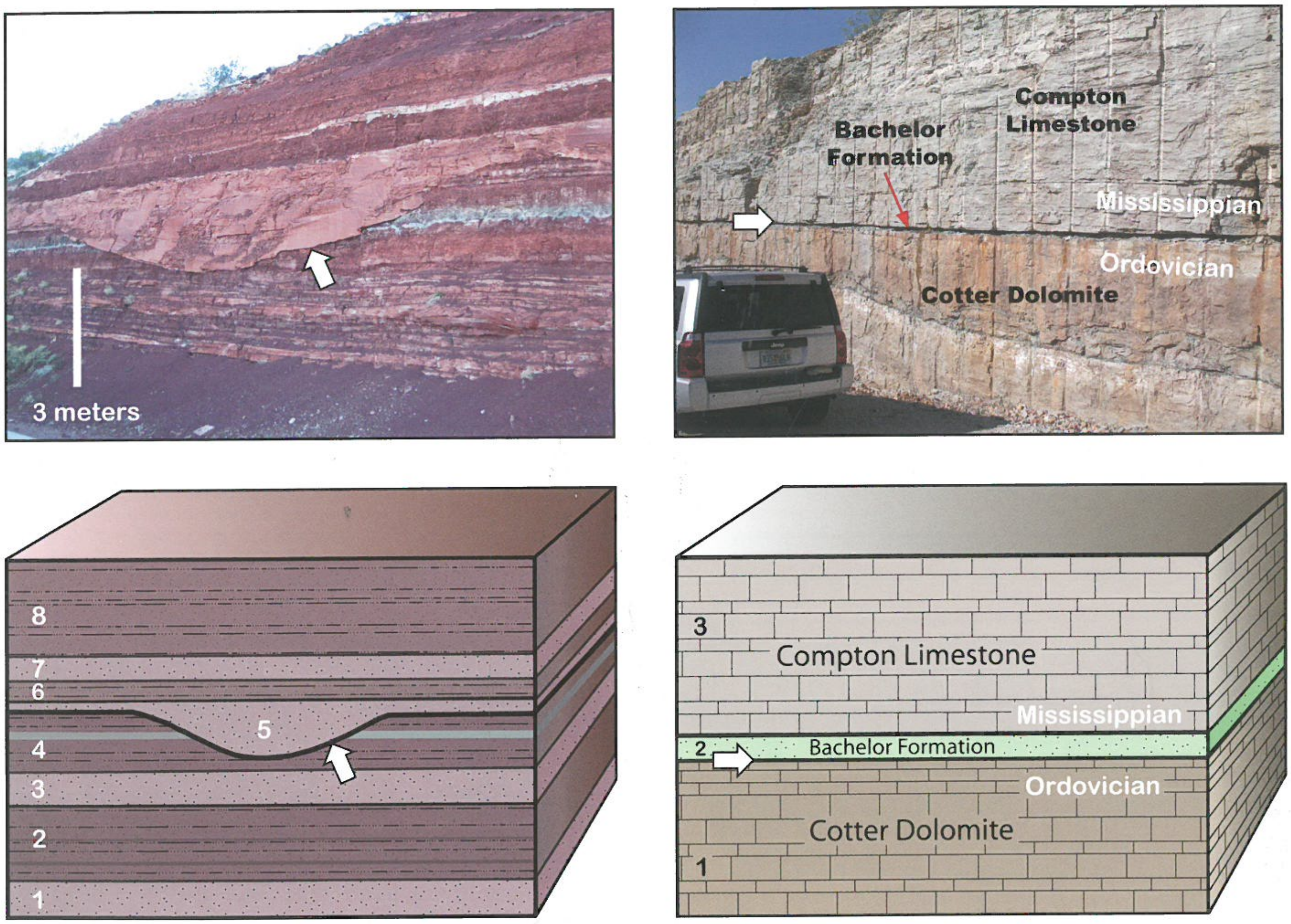
A. Angular unconformity between Jurassic and Early Tertiary strata exposed in Salina Canyon, central Utah.



B. Nonconformity between Precambrian crystalline rocks (foliated schist and granite veins) and horizontally bedded deposits of the Cambrian Tapeats Sandstone located in the lower part of the Grand Canyon of northern Arizona.

FIGURE 1.5 **Types of unconformities.** *(continued)* tilted or folded during the period of non-deposition (Ordovician through Early Mississippian time). The duration of the paraconformity shown in figure 1.5D may be unusually long for this type of unconformity. Paraconformities typically represent hiatuses of much shorter duration, perhaps on the order of thousands to tens of thousands of years.

Deformation (folding, faulting), metamorphism, igneous activity, and regional thinning of strata in conjunction with unconformities are evidence for major periods of mountain building that have affected the continental borders of North America during the geological past. The nature of the sediments related to erosional surfaces and to fault scarps, or other features of relief, may also aid in defining the relative time of formation of particular features. For example, the clastic wedges of the Devonian Catskill delta and the major Cretaceous belts of coarse conglomerates, coal-bearing sandstone, and shale in western North America effectively date the time of major uplift of the Acadian Mountains in the east and Sevier Highlands of the west, respectively. Associated igneous and metamorphic rock bodies permit radiometric dating of these orogenic (mountain building) events.



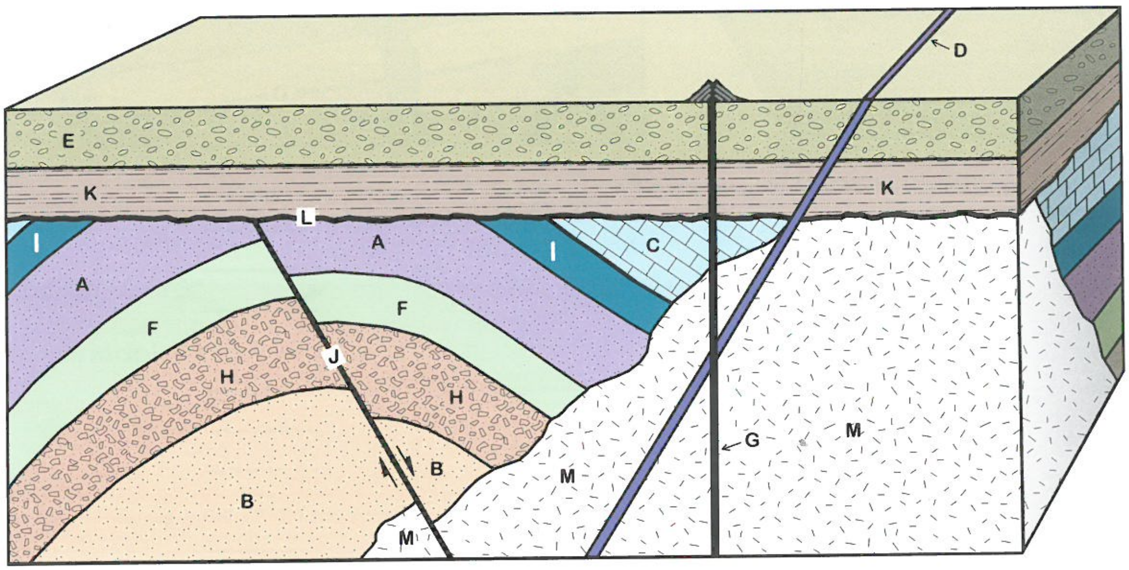
C. Disconformity (white arrow) in the Paleogene Colton Formation, central Utah. The sand lens in the upper part of the outcrop photo is over 2 m thick and fills relief scoured into underlying siltstone and shale.

D. Paraconformity between parallel beds of the Ordovician Cotter Dolomite and the Mississippian Bachelor–Compton Formations.

FIGURE 1.5 **Types of unconformities.**

PROCEDURE PART A

Using the dating techniques discussed above, determine the sequence of geologic events represented in each of the block diagrams in figure 1.6.



A

youngest

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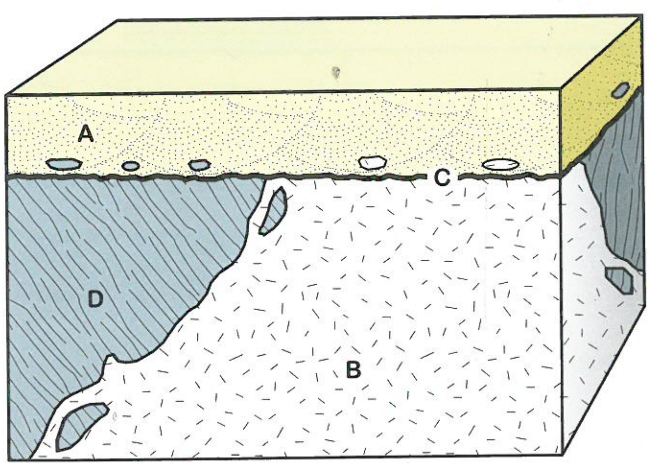
oldest



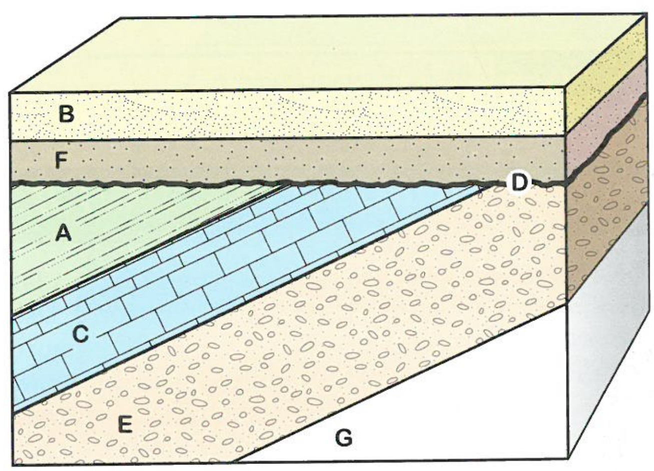
B

youngest ________

____

____

oldest ________



C

youngest ________

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____

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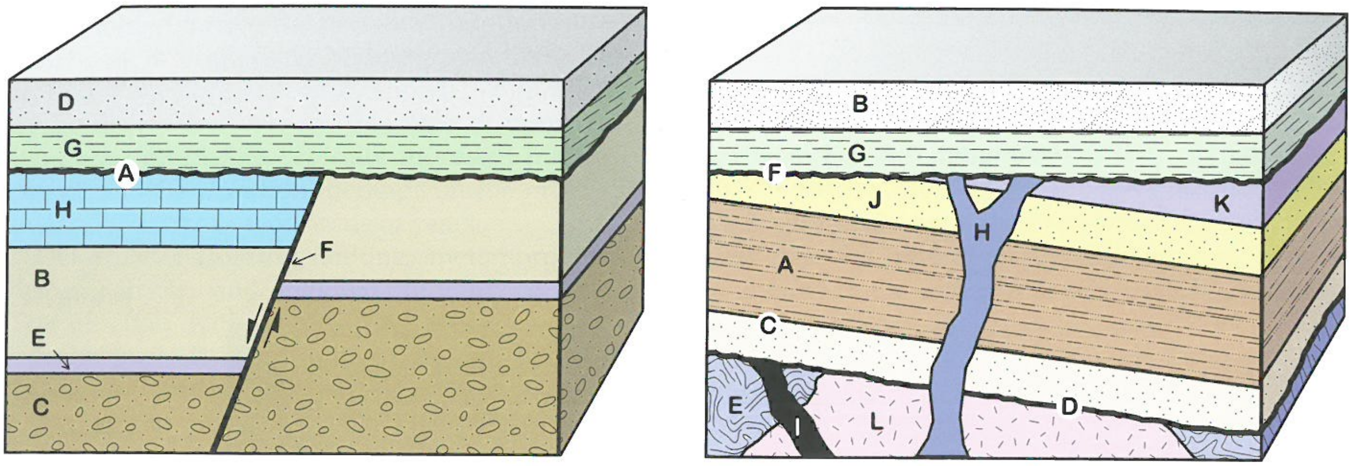
oldest ________

FIGURE 1.6 **Block diagram exercise.** *(continued)*



D

youngest

oldest

E

youngest

oldest

FIGURE 1.6 Block diagram exercise.

PROCEDURE PART B

The Grand Canyon is one of the most spectacular laboratories of historical geology in the world. Use the cross section of the eastern Grand Canyon (figure 1.7) to answer the following questions. For questions 1 through 5, indicate which principle(s) of relative dating guided you in arriving at your answers.

1. What is the oldest body of rock in the Grand Canyon?

Principle(s)

2. What is the oldest sedimentary layer in the Grand Canyon?

Principle(s)

3. What is the youngest Precambrian formation in the canyon?

Principle(s)

4. What is the oldest Paleozoic formation exposed in the canyon?

Principle(s)

5. What is the name and lithology of the youngest formation?

Principle(s)

6. What formations comprise the Cambrian System in this area?

7. Visually trace the unconformity at the base of the Tapeats Sandstone from left (west) to right (east) across the diagram. How does the nature of the unconformity change from west to east?

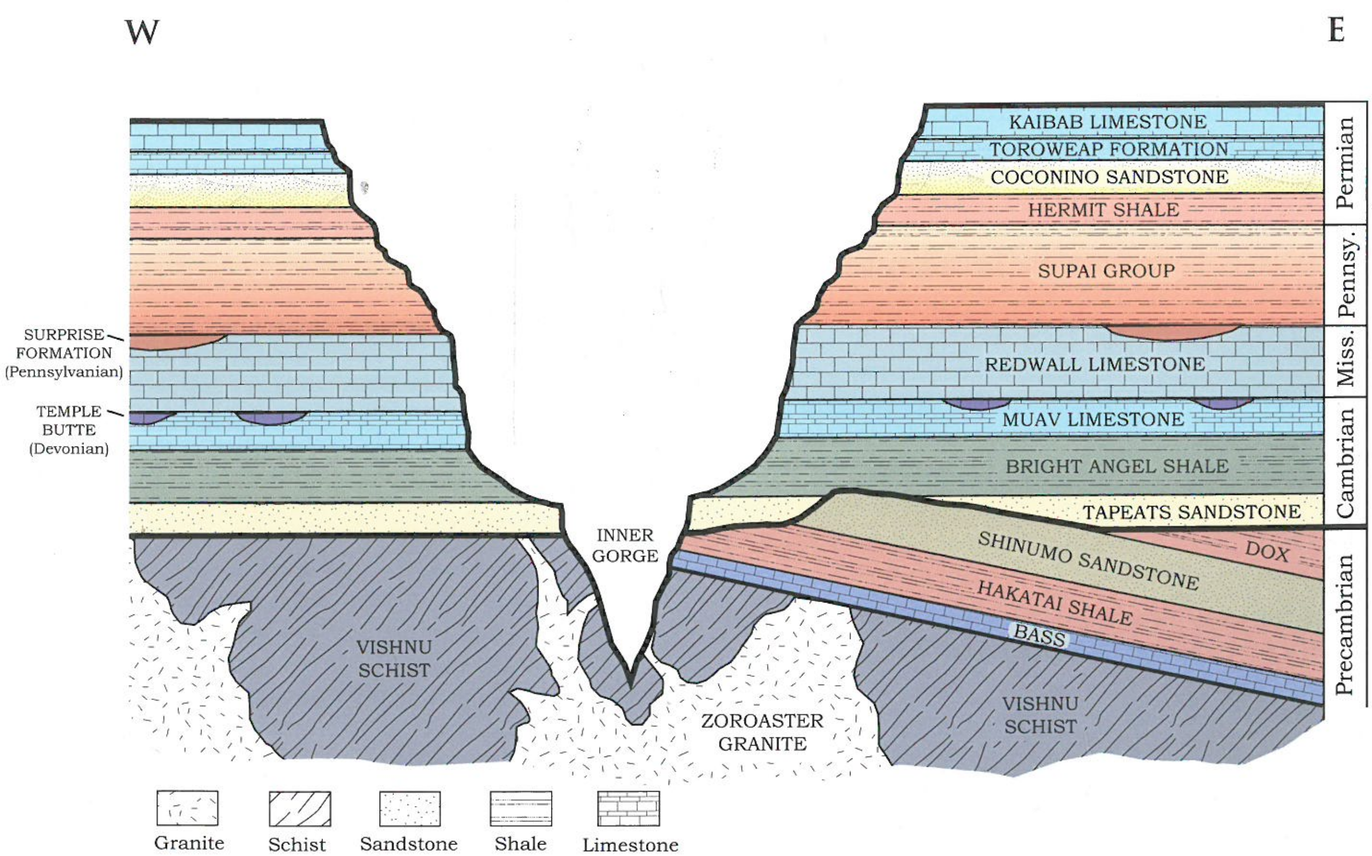


FIGURE 1.7 Geological relationships in the eastern portion of the Grand Canyon, Arizona.

8. What Paleozoic Systems are not represented in the Grand Canyon?

9. Briefly discuss the nature of the Devonian System in this region in terms of its regional extent, lithology, and history.

10. What was occurring in this area during the Mississippian Period?

11. What is the nature of the boundary between the Redwall Limestone and the Supai Group?

12. What was happening geologically in the Grand Canyon during the Ordovician Period?

13. Briefly outline the geological history of the Grand Canyon from Precambrian time until now based upon the patterns revealed in figure 1.7.

14. Which unconformity depicted in figure 1.7 represents the greatest hiatus (most complex and prolonged sequence of geological processes) in the Grand Canyon? Explain your answer in terms of the processes involved with the production of these types of unconformities.

PROCEDURE PART C

One of the best-kept secrets of the US Park Service is Grand Canyon National Monument. Located approximately 170 km downstream from Grand Canyon National Park, the monument area displays a dramatic close-up view of the Grand Canyon, several episodes of faulting, and a spectacular display of recent as well as ancient volcanic activity, including a lava cascade that spilled into the Grand Canyon adjacent to Vulcan's Throne and is preserved now as a frozen lava fall.

At this location, it is possible to apply the rules of relative dating to reconstruct the local geologic history with great clarity. Superposition and crosscutting relations are clearly illustrated by the geologic relationships that can be observed in the rocks of the monument area.

Figure 1.8 illustrates, in (A) photo, (B) sketch, and (C) cross section, the rocks in the immediate vicinity of Vulcan's Throne at Grand Canyon National Monument. Study the photograph and the two line drawings of the area and answer the following questions.

1. Using superposition and cross-cutting relations, establish the proper chronologic sequence for the following list of topographic/geologic features seen in this area:

_____ Erosion of Grand Canyon

_____ Erosion of ancient Toroweap Valley

_____ Basalt cascades

_____ Deposition of Supai Formation

_____ Deposition of Muav Limestone

_____ Deposition of Redwall Limestone

_____ Deposition of Temple Butte Formation

_____ Most recent eruption of Vulcan's Throne

_____ Early displacement of Toroweap Fault

_____ Late displacement of Toroweap Fault

_____ Deposition of Bright Angel Shale

_____ Basalt filling ancient Toroweap Valley

_____ Lava dams (remnants of which are preserved against the lower walls of canyon, labeled intracanyon lava flows on the cross section)

2. The elevation of the Colorado River below Vulcan's Throne is 1,675 ft. How deep was the lake behind the highest lava dam adjacent to Vulcan's Throne? Assume the lava dam was level with its remnant on the canyon wall below Vulcan's Throne.

3. What is the total displacement of the Toroweap Fault in this area?

4. What is the thickness of the lavas that have filled ancient Toroweap Valley (see figure 1.8C)?

5. If the basalt at the top of ancient Toroweap Valley yields a radiometric date (K/Ar) of 15,000 years, and the lowermost flows in the same valley yield an age of 1.2 million years, calculate the rate of basalt filling in the valley (ft/my).

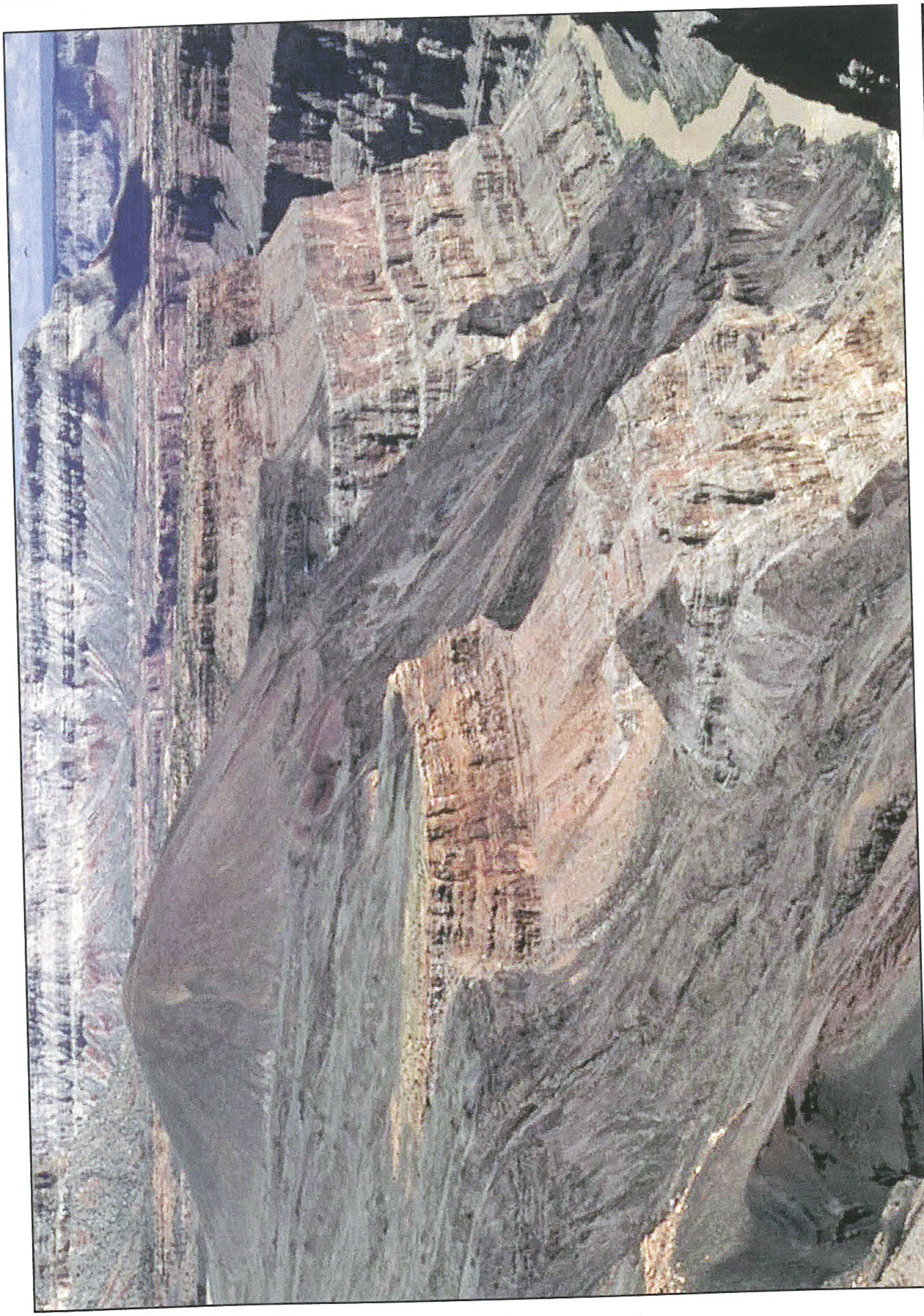


FIGURE 1.8A Photograph of Vulcan's Throne and immediate area looking northeast. The difference in elevation from the Colorado River to the top of Vulcan's Throne is 3,422 ft.

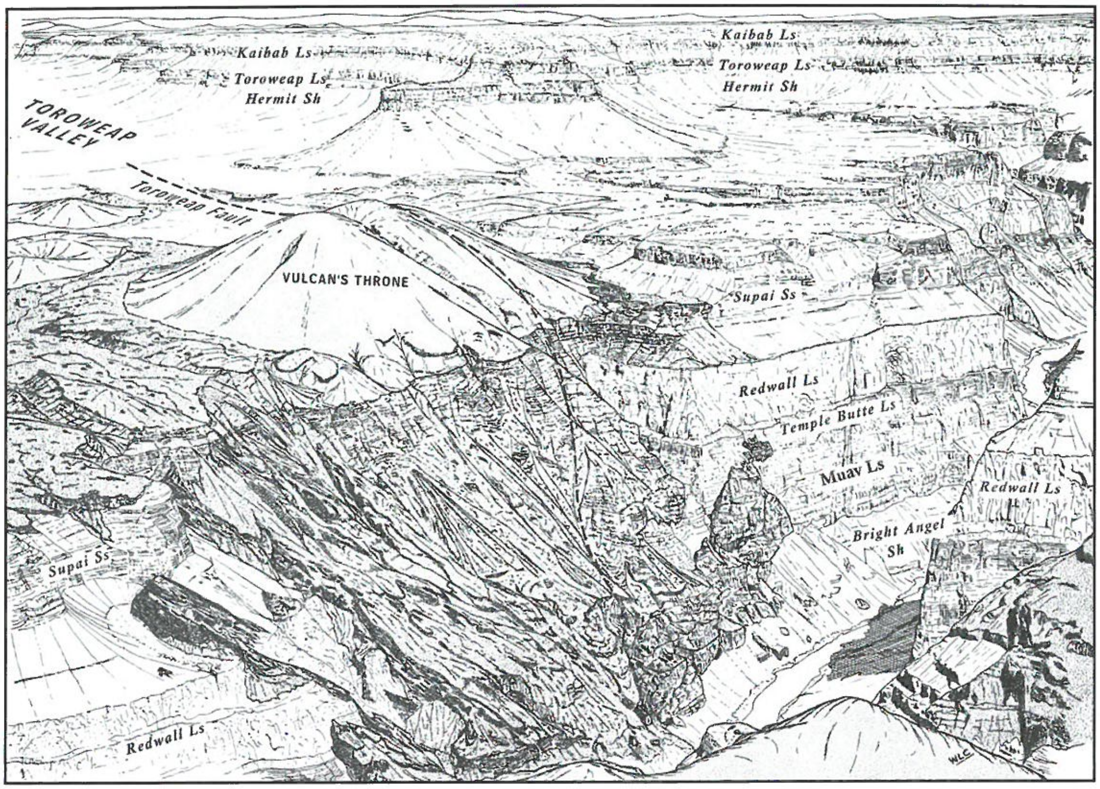


FIGURE 1.8B Sketch of the area included in figure 1.8A. (Courtesy of W. K. Hamblin.)

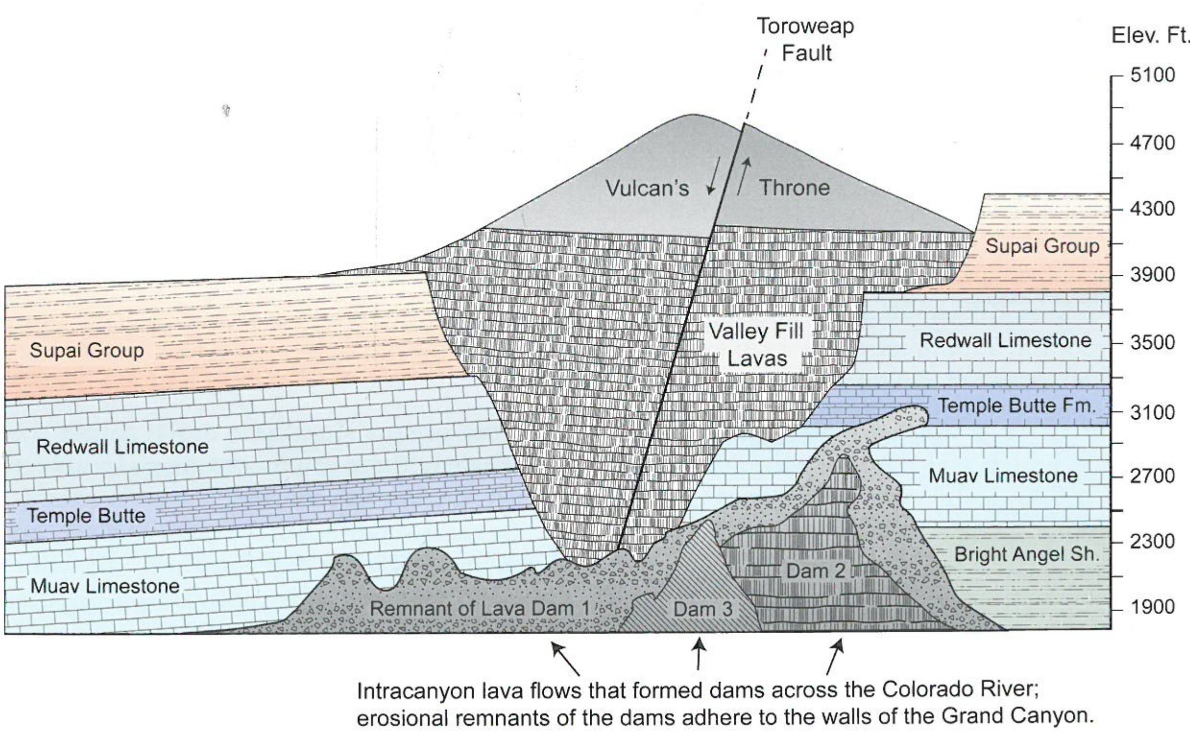


FIGURE 1.8C Line drawing of the wall of Grand Canyon below Vulcan's Throne. The basalt cascade shown in these illustrations is derived from a volcano located between 4 and 5 miles north–northwest of Vulcan's Throne. This view is looking to the north.