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How Geologists Tell Time
Part 1: Introduction and Relative Dating Techniques

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The Shroud of Turin, revered for centuries as the burial garment of Christ, retains the imprint of a man who was apparently scourged and crucified. The first recorded exhibit of the shroud was at Lirey, France in the 1350's. After passing through many hands and cities, it was ultimately enshrined in 1694 in the Royal Chapel of Turin Cathedral (Damon and others, 1989).

In the spring of 1988, as requested by the Vatican, owner of the shroud, radiocarbon laboratories in Oxford, England; Zurich, Switzerland; and Tucson, Arizona (Laboratory of Isotope Geochemistry, University of Arizona) dated the shroud by accelerator mass spectrometry. Each of the three laboratories dated four samples: one 50-milligram whole-cloth sample from the shroud and three control samples from other fabrics, the ages of which were known from previous radiocarbon measurements or from historical evidence. The age of the shroud was determined to be A.D. 1260-1390, with at least 95-percent confidence. The shroud, therefore, is medieval (Damon and others, 1989).

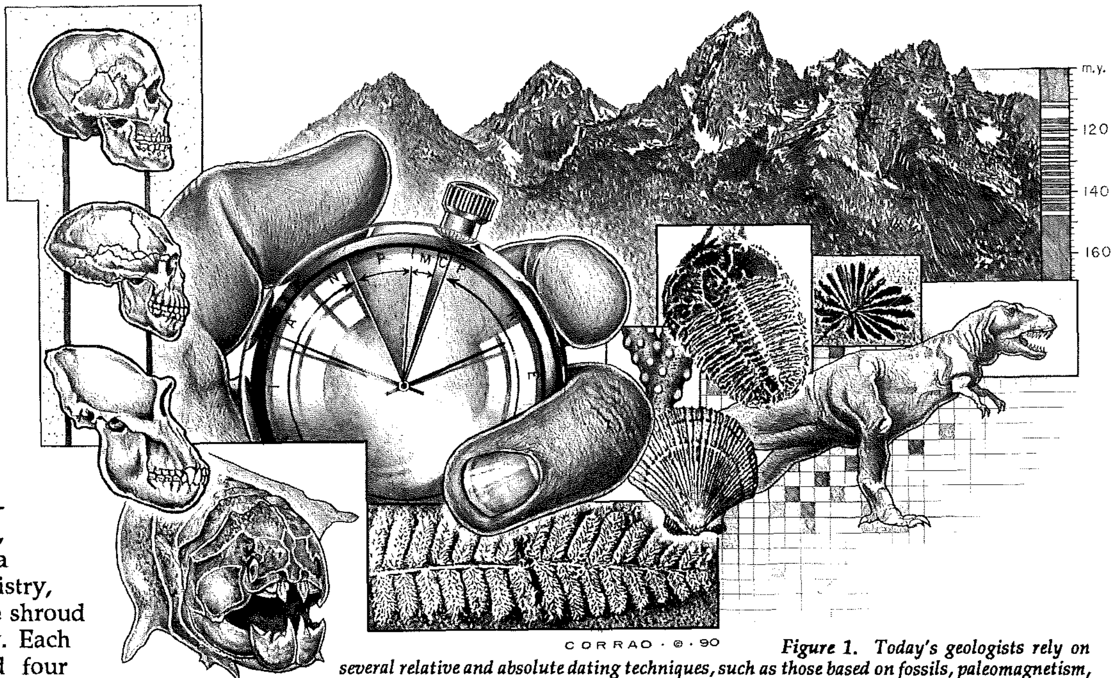

Figure 1. Today's geologists rely on several relative and absolute dating techniques, such as those based on fossils, paleomagnetism, and radioactive decay, to determine the ages of rocks and the order of geologic events.

Radiocarbon dating has been widely used to date cultural artifacts, such as the Shroud of Turin and charcoal from late Pleistocene (11,000-year-old) fires built by early hunters in southeastern Arizona (Haynes, 1987). The radiocarbon technique has also been used to date ground water in the Tucson basin to determine its recharge rate. Because it has been popularized by the media in stories of archaeological discoveries, the radiocarbon method is the most well-known dating technique. It is, however, only one of many methods that scientists use to date objects (Figure 1). Other techniques that are also based on the rates of radioactive decay allow geologists to date rocks that are millions or even billions, not just thousands, of years old.

This summary, the first section of a two-part article, gives an abbreviated history of dating rocks and minerals, describes the geologic time scale, and summarizes several relative dating techniques. Part 2 of this summary, which will be published in the next issue of *Arizona Geology*, focuses on absolute dating techniques based on tree rings, varve sequences, and radioactive decay. Used together, relative and absolute dating methods enable geologists to date fossils and rock formations and to establish a "calendar" of past geologic events.

ALSO IN THIS ISSUE

HISTORY OF DATING

One of the most important contributions to modern scientific thought is the concept of geologic time. Humans have pondered the age of the Earth and the rocks that compose it for thousands of years. Eastern and western cultures, however, have held very different concepts of time. The Hindus, for example, view time as cyclical, a continuing process of birth, life, death, and rebirth, whereas Judeo-Christian cultures generally conceptualize time as linear, with a beginning and an end. Ancient Hindu philosophers believed that one cycle of the universe equaled 1 day in the life of Brahma, the creator god, or approximately 4.3 billion years (b.y.). Hindu scriptures postulated that the Earth was almost halfway through one cycle, or 2 b.y. old (Sawkins and others, 1978). This ancient estimate is amazingly close to the actual age of the Earth.

The science of geology, however, evolved in the western world, as did the concept of geologic time. The ancient Greeks deduced that geologic processes took considerable amounts of time. Xenophanes of Colophon (570-470 B.C.) was the first of the early Greek philosophers to recognize the antiquity of both fossils and sedimentary rocks. Around 450 B.C., Herodotus, the Greek historian, concluded that the Nile delta was built from the deposits left by countless floods and thus took thousands of years to form. Other Greek and Roman philosophers, such as Aristotle, and early Christian scholars, such as St. Augustine, continued to explain natural phenomena through deductive reasoning (Press and Siever, 1982).

Despite the insight of these early thinkers, the concept of geologic time remained as constricted as the western notion of linear time for several centuries. During the late Middle Ages, theology permeated scientific thought in Europe. The age of the Earth was determined by only one "proof": the book of Genesis. In the mid-1600's, Archbishop James Ussher of Ireland and Dr. John Lightfoot, a Biblical scholar from Cambridge, England, concluded from scriptural analysis that the Earth was created at 9:00 a.m. on October 26, 4004 B.C. (Stokes, 1966; Press and Siever, 1982). Literal interpretation of the Bible was so common that many Christians, including scientists, believed this date, which was printed as an explanatory note in several editions of the Bible (Stokes, 1966). Before 1750, most scientists believed that all sedimentary rocks were deposited during the Great Flood of Noah's time. Other surface features, such as mountains, were believed to be the result of intermittent catastrophes (Faure, 1977). Until the late 18th century, most scientists didn't question the orthodox tenets advocated by religious scholars to explain the age and origin of the Earth.

During the 18th and 19th centuries, scientific observations on depositional rates of sediments and the salinity of oceans gradually increased age estimates of the Earth to 100 million years (m.y.; Stokes, 1966; Press and Siever, 1982). In 1859, Charles Darwin published his magnum opus, *On the Origin of Species by Means of Natural Selection*. As the theory of evolution became more widely accepted, fossils were used to calibrate a stratigraphic time scale. Scientists made reasonable chronological assessments based on evolutionary theory; Darwin estimated that it had taken 300 m.y. for complex life to evolve. Increasing estimates of the Earth's age, however, ousted the human species from its egocentric position in the universe. Geologists were opposed, as were astronomers and evolutionary biologists before them, by religious believers who viewed scientific theories as antithetical to Biblical teachings.

While geologists and biologists were extending estimates of the Earth's age, physicists were lowering them. In the mid-18th century, Comte de Buffon of France calculated the age of the Earth based on the assumption that the Earth was solid and had cooled from a molten state. Because he believed that the Earth's interior was iron, Buffon used his measurements on the melting and cooling rates of iron balls to calculate how long it took the molten Earth to cool to its present temperature. He estimated that the Earth was 75,000 years old (Press and Siever, 1982).

In 1854, Herman von Helmholtz, a physicist who helped to establish the science of thermodynamics, theorized about the source of the Sun's light. He believed that it was created by gravitational contraction of the Sun's mass. Particles presumably fell into the center of the Sun, releasing energy in the forms of heat and light. Helmholtz estimated that the Sun began to collapse 20 to 40 m.y. ago (Press and Siever, 1982).

Late in the 19th century, William Thompson (Lord Kelvin), the British mathematician and physicist, applied Buffon's estimates of the Earth's cooling rate to Helmholtz's theories on the Sun's luminosity. Kelvin believed that the Sun was also cooling off and that the Earth would have been too hot to support life before the Sun began to collapse (Sawkins and others, 1978; Press and Siever, 1982). His estimate of the Earth's age (20 to 40 m.y.) was reasonable based on the sources of energy known at that time. It did not, however, account for the internal heat of the Earth and Sun generated by radioactive decay. Kelvin's estimate caused a regression in scientists' understanding of geologic time. Not until the discovery of radioactivity, the energy within particles of matter, did estimates even approach the age of the Earth.

In the 1890's, three physicists made discoveries that dramatically changed the way scientists viewed the natural world: Antoine Henri Becquerel discovered radioactivity in uranium, Wilhelm Roentgen discovered X-rays, and Marie Sklodowska Curie discovered the radioactive element, radium (Press and Siever, 1982). The British physicist Ernest Rutherford was the first to suggest that radioactive minerals could be used to date rocks. He, in fact, dated a uranium mineral in his laboratory in 1906. In that same year, B.B. Boltwood, an American chemist, discovered "ionium," an isotope of thorium; in 1907, he published a list of geologic ages based on radioactivity (Press and Siever, 1982; Newman, 1988). During the following decades, scientists determined the full series of decay products created by natural radioactive disintegration. Using a scientific instrument called a mass spectrometer, scientists were able to refine radiometric dating and establish that the Earth was not millions, but billions of years old. The oldest dated rocks on Earth are almost 4 b.y. old. The Earth, however, is estimated to be more than 4.5 b.y. old, based on the radiometric ages of meteorites and lunar rocks that are thought to record the age of the solar system, including the Earth (Newman, 1988). The earliest life forms preserved in the Earth's rock record (bacteria and blue-green algae) are about 3.5 b.y. old (Lambert and the Diagram Group, 1988).

GEOLOGIC TIME SCALE

Relative vs. Absolute

Geochronology, the study and measurement of time as it relates to the history of the Earth, is based on two scales, relative and absolute. **Relative time scales**, defined by sedimentary rock sequences and their included fossils, arrange events in order of occurrence. A geologic event or rock unit is identified as being relatively younger or older than other events or units. **Absolute time scales**, measured in years before the present (B.P.; "present" is defined as 1950 A.D.), give more definitive dates for events or units.* Absolute time, most commonly determined by radioactive decay of elements, is by no means "absolute": the precision and accuracy of dating techniques continue to be perfected (Duffield, 1990).

There are advantages and disadvantages to each time scale. The relative scale based on fossils, used to chronologize the last 570 m.y. of Earth history, is a powerful and accurate method for correlating sedimentary rocks, but cannot be used by itself to assign ages in years. The absolute scale based on radiometric dating can provide dates for igneous and metamorphic rocks, but the date may not represent the true age of the rock if it has a complex thermal history. The two scales are, in fact, complementary: the relative scale determines the positional relationships among rock units; the absolute scale calibrates the relative scale. Generally, fossiliferous sedimentary rocks are dated by relative methods, and nonfossiliferous igneous and metamorphic rocks are dated by absolute techniques. Most sedimentary rocks cannot be dated radiometrically because the mineral grains within the sediments have typically been derived from the weathering of much older rocks and transported to the de-

* Geologists use several abbreviations for units of geologic time. For example, "40 million years ago" might be written as "40 m.y. ago," "40 m.y. B.P.," or "40 Ma" (for "Mega-annum"). Similarly, "2 billion years ago" could be abbreviated as "2 b.y. ago," "2 b.y. B.P.," or "2 Ga" (for "Giga-annum"). Some geologists also abbreviate thousands of years as "ka" (for "kilo-annum"); e.g., "30,000 years" could be written as "30 ka."

positional site. The fossils, however, formed at about the same time as sedimentation. In 1913, the British geologist Arthur Holmes published *The Age of the Earth,* in which he plotted the ages of fossil-bearing sedimentary rocks against radiometrically dated ages of igneous rocks that crosscut them. He was the first to synchronize the relative and absolute time scales (Press and Siever, 1982).

EON	ERA	PERIOD		EPOCH	AGE (m.y. ago)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.6
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.7
			Paleogene	Oligocene	36.6
				Eocene	57.8
				Paleocene	66.4
	Mesozoic	Cretaceous		Late	
				Early	144
		Jurassic		Late	
				Middle	
				Early	208
		Triassic		Late	
				Middle	
				Early	245
	Paleozoic	Permian		Late	
				Early	286
		Carboniferous	Pennsylvanian	Late	320
			Mississippian	Early	360
		Devonian		Late	
				Middle	
				Early	408
		Silurian		Late	
				Early	438
		Ordovician		Late	
				Middle	
				Early	505
		Cambrian		Late	
				Middle	
				Early	570
Precambrian: Proterozoic	Late				900
	Middle				1600
	Early				2500
Precambrian: Archean	Late				3000
	Middle				3400
	Early				3800?
pre-Archean					4550

Figure 2. Geologic time scale. Age estimates of time boundaries are in millions of years (m.y.). Ages (subdivisions of epochs) are not shown. Sizes of time "slots" do not reflect proportionate lengths of time intervals. Rocks older than 570 m.y. are called Precambrian, a time term without specific rank. Geologic time prior to 3,800 m.y. ago is called pre-Archean, a term also without specific rank. The Mississippian and Pennsylvanian Periods, recognized in the United States, are collectively referred to as the Carboniferous Period, a term commonly used by geologists in other parts of the world. The Neogene and Paleogene are subperiods of the Tertiary Period. Modified from Palmer, 1983, p. 504.

From Eons to Ages

Geologists divide geologic time into the following main units, each of which is a smaller subdivision of time than the previous unit: eons, eras, periods, epochs, and ages (Figure 2).

Each of the three eons that encompass all of Earth history is a broad span of time distinguished by the general character of life that existed then. The Archean ("ancient") Eon, the earliest eon, is also the longest and least understood. During that time, the first microcontinents formed and primitive life forms appeared. ("Pre-Archean time" is an informal term without a specific rank that applies to the interval between the origin of the Earth and the formation of solid land masses.) The Proterozoic ("former life") Eon brought the first large continents and soft-bodied animals. These intervals, collectively known as the Precambrian, comprise more than 85 percent of geologic time and extend from the origin of the Earth more than 4.5 b.y. ago to the appearance of abundant (and well-preserved) life forms 570 m.y. ago. The Precambrian is radiometrically dated from episodes of igneous intrusion, metamorphism, and mountain building. The Phanerozoic ("visible life") Eon is the last, shortest, and best recorded eon. It is dated mainly from fossil-bearing sediments and includes the last 570 m.y. of Earth history. The Phanerozoic Eon is subdivided into the Paleozoic ("ancient life"), Mesozoic ("middle life"), and Cenozoic ("recent life") Eras (Lambert and the Diagram Group, 1988).

A period is a shorter span of time partly distinguished by evidence of major disturbances of the Earth's crust (Newman, 1988). The name of each period is derived either from the geographic locality where formations of that age were first studied or are well exposed, or from a particular characteristic of those formations. The Pennsylvanian Period, for example, is named after the State of Pennsylvania, where rocks of this age are well exposed. The Cretaceous Period, derived from the Latin word for "chalk" (*creta*), is named after the white chalk cliffs along the English Channel (Newman, 1988).

The names of epochs within the Cenozoic Era are based on the similarity of fossil molluscs to living molluscs. The Pleistocene Epoch, for example, is derived from the Greek words *pleistos* ("most") and *kainos* ("recent") and includes rocks that contain 90- to 100-percent modern mollusc species. In contrast, the Paleocene Epoch, derived from *palaios* ("ancient") and *kainos,* includes rocks that contain no modern mollusc species (Stokes, 1966). Ages within each epoch are named after geographic localities in which rocks of those ages are especially well exposed. Each unit of geologic time, from eons to ages, may also be partitioned into subunits through the use of the prefixes "early," "middle," and "late."

Scientists continue to refine the geologic time scale and revise the chronology of geologic events as more sophisticated technology provides more accurate radiometric dates for rocks and minerals (e.g., Odin, 1982; Palmer, 1983).

RELATIVE DATING TECHNIQUES

General Principles

Three fundamental laws or principles of geology form the basis for interpreting the relative sequence of geologic events in an area. The **law of uniformitarianism**, proposed by James Hutton in 1795 and popularized by John Playfair in 1802 and Charles Lyell in 1830, states that the present is the key to the past (Stokes, 1966; Poort, 1980). The physical, chemical, and biological laws of nature that govern processes today controlled identical or similar processes during the past. Interpretations of the events of geologic history, therefore, are based on analyses of modern-day analogues. Uniformitarianism, however, does not imply that the rates of these events or processes were constant over time.

The **law of original horizontality**, proffered by the Danish court physician Nicolaus Steno in 1669, states that water-laid sedimentary rocks are originally horizontal, or parallel to the Earth's surface, because the sediments that compose them were deposited in horizontal layers on the bottoms of oceans, lakes, or rivers (Press and Siever, 1982). If a sedimentary rock unit is folded or tilted, therefore, it was disturbed after it was deposited.

The **law of superposition**, also proposed by Steno in 1669 and established by Hutton about 1795, states that in any undisturbed sequence of sedimentary strata, the oldest layer is at the bottom and the youngest is at the top (Poort, 1980; Press and Siever, 1982). In other words, each layer is younger than the underlying bed on which it was deposited (Figure 3). This law assumes that the strata have not been overturned by faulting or folding.

Faunal Succession

The British geologist William "Strata" Smith (1769-1839) determined that each layer of fossil-bearing strata within a sedimentary sequence could be distinguished from the others by the fossils contained within it (Poort, 1980). Smith proposed the **law of faunal succession,** which states that assemblages of fossil organisms (both plants and animals) preserved in rock strata succeed one another in a definite and recognizable order. Evolutionary changes and changes in fossil assemblages are preserved in successive layers of sediments. In general, the older the rock is, the greater are the differences between fossil species within the rock and living species. The fossil content of rocks may, therefore, be used to determine the relative ages of sedimentary strata and to correlate them with rock formations in other geographic areas.

Index fossils are especially useful in correlating strata. An **index fossil** is a fossil from an organism that had a distinctive appearance, was widely distributed, and lived during a relatively short interval, such as an epoch or less. Trilobites and ammonites, for example, may be used as index fossils. Other fossils, such as shark teeth, are not very useful in dating rocks because the species lived during too long an interval of geologic time. Correlating **fossil assemblages,** or groups of distinctive fossils, is the best way to date rocks because the sediments must have been deposited when all the fossil species existed.

Many species, however, have left no record because their remains have not been preserved in rock. This nonfossilization may be due to the species' lack of hardened skeletons, destruction of their hard parts by predators or waves, erosion or metamorphism of the fossilized rocks, or other factors. Scientists estimate that less than 1 percent of all species that ever lived have been identified (Sawkins and others, 1978).

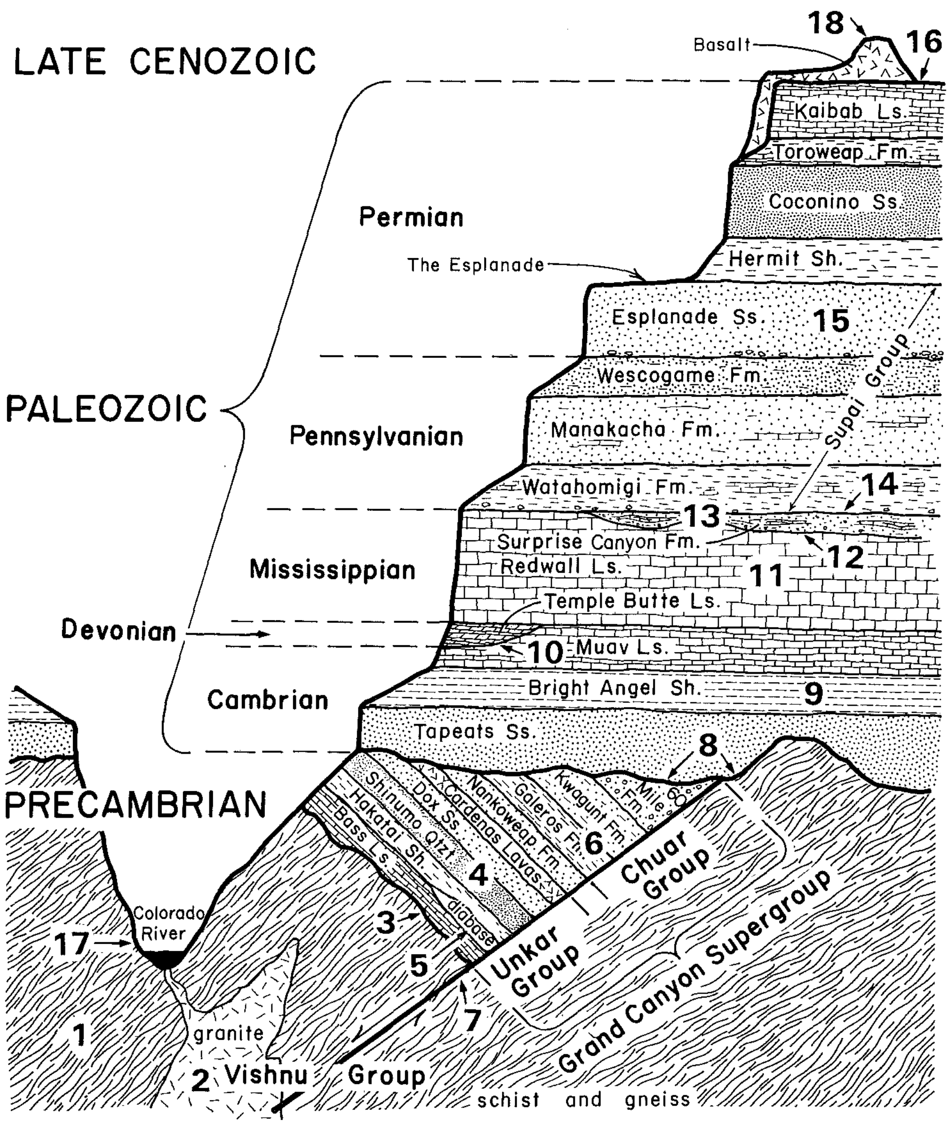

Figure 3. Generalized stratigraphic section of rock units in the Grand Canyon, illustrating superpositional, crosscutting, and unconformable relationships. All unconformities have not been identified. The order of major geologic events and ages of rock units, from oldest to youngest, are as follows: (1) formation and metamorphism of Vishnu Group (schist and gneiss); (2) granitic intrusion; (3) erosion and formation of nonconformity (about 450 m.y. missing); (4) deposition of Bass Limestone, Hakatai Shale, Shinumo Quartzite, and Dox Sandstone; (5) intrusion of diabase sill; (6) deposition of rest of Grand Canyon Supergroup; (7) faulting and tilting of Grand Canyon Supergroup; (8) uplift and extensive erosion; formation of angular unconformity between Grand Canyon Supergroup and Tapeats Sandstone (at least 300 m.y. missing); formation of nonconformity between Vishnu Group and Tapeats Sandstone ("The Great Unconformity"; more than 1 b.y. missing); (9) deposition of Tapeats Sandstone, Bright Angel Shale, and Muav Limestone; (10) erosion and formation of disconformity (about 135 m.y. missing); (11) deposition of Temple Butte Limestone (in channels) and Redwall Limestone; (12) erosion and formation of disconformity (a few million years missing); (13) deposition of Surprise Canyon Formation in estuaries, caves, and collapsed depressions; (14) erosion and formation of disconformity (about 15 m.y. missing); (15) deposition of Supai Group, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone; (16) Uplift and extensive erosion; all Mesozoic and nearly all Cenozoic sedimentary rocks stripped away or never deposited (about 243 m.y. missing); (17) cutting of Grand Canyon (starting about 5 m.y. ago); and (18) volcanic eruptions. Modified from Potochnik and Reynolds, 1986, p. 2.

Crosscutting Relationships and Included Fragments

Any rock unit or fault that cuts across other rock units is younger than the units it cuts (Figure 3). Crosscutting units include igneous intrusions of solidified magma. Simply stated, crosscutting relationships indicate that a disrupted pattern (a rock sequence) is older than the cause of the disruption (an igneous intrusion). Although a rock unit may not be intersected by an intrusion, it could still be identified as younger than the intrusion if the unit is metamorphosed near the intrusion (i.e., if it was altered by the intrusion's heat). If fragments of one rock formation are contained within another, the former rock formation is older than the latter.

Unconformities

An **unconformity** is a surface that represents a break or gap in the geologic record due to erosion or nondeposition. These gaps are recognized by abrupt and striking changes in the composition or orientation of the rocks and by a marked age difference between the rocks above and below the unconformity. Unconformities are commonly caused by uplift of an area, which induces erosion and removal of previously formed rock units.

Geologists classify unconformities into three types: nonconformities, angular unconformities, and disconformities. A **nonconformity** is a break between eroded igneous or metamorphic rocks and younger sedimentary strata (Figure 3). A nonconformity may be identified by the presence of an erosional surface composed of broken fragments of the underlying rock unit or by a lack of metamorphism in the strata overlying an igneous or metamorphic formation. Because igneous and metamorphic rocks form deep below the Earth's crust, a nonconformity generally indicates that deep or long-lasting erosion occurred before additional sediments were deposited (Poort, 1980).

An **angular unconformity** is an erosional surface between tilted or folded older sedimentary rocks and younger sedimentary strata that are oriented differently (Figure 3). This type of unconformity indicates that the underlying rocks were deposited, folded or tilted, uplifted, and eroded before the overlying rocks were deposited.

A **disconformity** is a surface that represents a gap between essentially parallel sedimentary strata (Figure 3). Because the strata have the same orientation and an erosional surface may not be apparent, a disconformity is the most difficult unconformity to detect. It is commonly identified by studying the fossils within the rock units and recognizing a substantial gap in the faunal succession. A disconformity implies that the area was uplifted, but not severely deformed or metamorphosed (Poort, 1980).

Because several geologic events could have taken place during these missing intervals, unconformities must be included in the reconstruction of an area's geologic history. Unconformities help geologists to determine the relative sequence, duration, and intensity of geologic processes within a particular region.

Paleomagnetic Properties

The Earth is surrounded by a magnetic field believed to originate in the fluid part of its iron core. Heat generated by radioactivity in the Earth's core stirs the fluid into convective motion. A weak magnetic field interacting with the moving iron fluid generates electric currents, creating a stronger magnetic field and a self-sustaining magnetic system (Press and Siever, 1982).

The Earth's magnetic field, like a bar magnet, has a specific direction that is defined by the magnetic north and south poles. Geomagnetic north, the direction to which a compass needle points, is not the same as geographic, or true north. True north coincides with the Earth's axis of rotation; geomagnetic north is presently inclined about 11° from true north. The direction of the geomagnetic field at any point on the Earth's surface includes its **declination** (its angle east or west of true north) and its **inclination** (its angle with respect to the Earth's surface). Declination varies with both latitude and longitude. In Flagstaff, Arizona, for example, the geomagnetic north pole is 13.5° east of true north, whereas in Tucson it is 12.5° east. Inclination varies primarily with latitude. At the magnetic poles, the inclination is vertical; near the magnetic Equator, it is horizontal. The intensity of the geomagnetic field also varies with latitude; it is strong at the poles, but relatively weak at the Equator. Both the intensity and direction of the geomagnetic field vary gradually with time, a phenomenon called **secular variation**. Despite this deviation, the average position of the magnetic pole over millions of years has centered on the Earth's rotational (geographic) pole (Press and Siever, 1982).

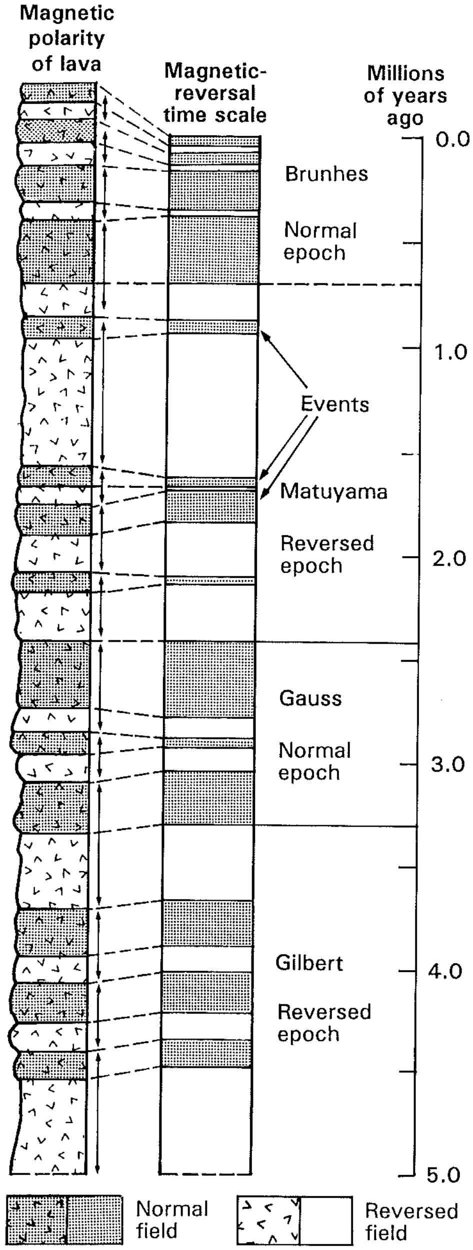

Figure 4. Time scale of magnetic reversals based on magnetic polarities of lava flows on land. The entire sequence is not present in any one area; the time scale is pieced together from the ages and polarities of lava beds around the world. Normal and reverse magnetic epochs are named after scientists who made major contributions to the study of geomagnetism. This time scale based on lava flows has recently been extended to 7 m.y. ago. The time scale based on magnetic anomalies on the sea floor extends to the Jurassic Period, 162 m.y. ago. From Press and Siever, 1982, p. 427. Copyright © 1974, 1978, 1982 by W.H. Freeman and Company. Reprinted with permission.

Rocks may contain a magnetic signature that reflects the orientation of the Earth's magnetic field when the rocks were formed. This signature is recorded when iron-rich minerals crystallize from a molten state, are deposited in calm bodies of water, such as an ocean, or crystallize within a rock during metamorphism or diagenesis (the processes that compact and harden sediments and turn them into rock). When molten materials cool and harden and when sediments lithify, the magnetic iron minerals are "frozen" in place, essentially pointing to the Earth's magnetic pole like a compass needle. This **remanent magnetization** has a fixed direction that is independent of the current magnetic field of the Earth. Remanent magnetization in rocks leaves a record of the Earth's ancient magnetic field, just as a fossil leaves a record of ancient life.

Paleomagnetism, the study of the Earth's magnetic field during the geologic past, involves measuring both the direction and intensity of remanent magnetization in rocks. By comparing the paleomagnetic properties of rocks of similar age on different continents, scientists discovered during the 1950's and 1960's that the positions of the magnetic poles inscribed in the rocks did not agree. If, however, the continents were reassembled on the globe by matching the shapes of their edges like the pieces of a puzzle, the directions of the paleomagnetic poles also coincided. Paleomagnetism thus provided evidence of continental drift. To reconstruct the positions of the continents during the geologic past, scientists had to determine the average position of the geomagnetic pole from numerous sample sets, each of which included rocks dated within a few million years of each other. If the average geomagnetic pole and the geographic pole did not match, scientists conceptually moved the continents on the globe until the poles coincided and the previous geographic positions were established.

Paleomagnetic studies of layered sequences of lava flows on land revealed that the geomagnetic field has reversed itself every few hundred thousand years, taking a few thousand years or so to change its direction (Press and Siever, 1982). The history of magnetic reversals over the past 7 m.y. has been constructed by piecing together the ages and polarities of lava beds around the world. Based on this restoration of geomagnetic history, scientists compiled a time scale of magnetic reversals consisting of normal and reverse magnetic epochs (Figure 4). Each epoch lasted a few hundred thousand years or more, but included short-lived reversals, called **magnetic events**, that lasted from several thousand to 200,000 years (Press and Siever, 1982). The cause of geomagnetic reversals, however, is unclear.

Highly sensitive magnetometers developed during World War II to detect enemy submarines were later adapted by oceanographers to study the sea floor. These scientists discovered bands of magnetic anomalies that parallel the mid-oceanic ridges. The bands are almost perfectly symmetrical with respect to the ridge axes. In other words, bands of normal and reversed magnetism (known as positive and negative magnetic anomalies, respectively) in the rocks on one side of a ridge are mirrored in the rocks on the opposite side. In the 1960's, scientists suggested that these duplicate patterns were evidence for the theory of sea-floor spreading. This theory proposes that new oceanic crust solidifies from magma forced upward into the mid-oceanic ridges and spreads outward as it is pushed aside by new upwellings of magma. By comparing the magnetic anomalies on the sea floor with the magnetic reversals in lava flows on land, scientists were able to determine sea-floor spreading rates. Because the geomagnetic record is longer and more complete on the ocean floor than on land, scientists used these spreading rates to extend the time scale of geomagnetic reversals back to the Jurassic Period, 162 m.y. ago (Press and Siever, 1982).

Paleomagnetism has provided not only a method to correlate rock formations, but also evidence of continental drift and sea-floor spreading, two aspects of the unifying geologic theory of plate tectonics. One drawback of this method, however, is that magnetism in rocks is destroyed if they are heated above a certain temperature, called the Curie point. For most magnetic rocks and minerals, the Curie point is about 500°C (Press and Siever, 1982). If a rock has been reheated, its paleomagnetic properties reflect the Earth's magnetic field at the time the rock cooled below its Curie point, not necessarily the geomagnetic field at the time the rock was formed.

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New Publications on Arizona Geology

Geological Highway Map Provides Guide to the Four Corners States. Few places on Earth match the southern Rockies in their dramatic display of geologic history. From Colorado's Rocky Mountain National Park to Arizona's Grand Canyon to New Mexico's Carlsbad Caverns to Utah's Canyonlands National Park – the Four Corners States record entire chapters of geologic history, from Precambrian to Cenozoic time. *Geological Highway Map, Southern Rocky Mountain Region: Utah, Colorado, New Mexico, Arizona,* published by the American Association of Petroleum Geologists (AAPG), includes information about places of geologic interest and fossil, mineral, and gemstone localities, as well as geologic, tectonic, and physiographic maps. Arizona Geological Survey geologists T.G. McGarvin and S.J. Reynolds provided information for the section on Arizona geology. This 1:1,622,000-scale map may be purchased from AAPG, P.O. Box 979, Tulsa, OK 74101; single copies are $9.90 for AAPG members and $13.90 for nonmembers.

Definitive Book on Grand Canyon Geology. The Grand Canyon has captivated the curiosity of geologists since John Wesley Powell's journey down the Colorado River in 1869 and 1871. The geologic history preserved in the canyon walls includes most of the last 2 billion years, almost half of the life span of this planet. Although the Grand Canyon is neither the deepest nor the longest canyon in the world, it is one of the few places on Earth where so many chapters of geologic history are legible.

A new book, published by the Oxford University Press and Museum of Northern Arizona Press, details the geology of rock formations in the Grand Canyon. *Grand Canyon Geology,* edited by Stanley S. Beus and Michael Morales, incorporates the most recent discoveries and interpretations of the origin and history of the canyon. The contributing authors are experts in their respective fields. One chapter on the geology of side canyons, coauthored by Arizona Geological Survey geologist S.J. Reynolds, was originally published (in an abbreviated form) in *Fieldnotes*, the predecessor of *Arizona Geology.* This 518-page book, intended for geologists as well as general readers with some geological sophistication, may be purchased from the Museum of Northern Arizona Bookstore, Rt. 4, Box 720, Flagstaff, AZ 86001. Paperback copies are $23.45 each, and hardback copies are $36.50 each, including shipping charges.

A Citizen's Guide to Radon. The U.S. Environmental Protection Agency (EPA) and Surgeon General have determined that radon is the second leading cause of lung cancer in the Nation and the leading cause among nonsmokers. Public concern about the health effects of radon exposure has increased the demand for accurate information. In response, the Arizona Radiation Regulatory Agency (ARRA) has published a guide to help readers understand this problem. *A Citizen's Guide to Radon: What It Is and What to Do About It* explains how radon causes lung cancer, accumulates in buildings, and is detected, and what actions should be taken to reduce radon levels in the home. The results of a recent ARRA survey indicate that 7 percent of single-family homes in Arizona may have radon levels that exceed the EPA recommended action level. Although measured radon levels in Arizona are among the lowest in the Nation, ARRA and EPA recommend that every house be tested for radon. Copies of the free booklet and additional information may be obtained from the Arizona Radiation Regulatory Agency, 4814 S. 40th St., Phoenix, AZ 85040; tel: (602) 255-4845.

Mineral Resources in Two Wilderness Study Areas. The Federal Land Policy and Management Act requires the U.S. Geological Survey (USGS) and U.S. Bureau of Mines (BOM) to conduct mineral surveys on certain areas to determine what mineral values, if any, may be present. USGS Bulletin 1704 presents the results of a mineral survey of parts of the Gibraltar Mountain and Planet Peak Wilderness Study Areas (WSA's). Geologists from the USGS, BOM, and Arizona Geological Survey (AZGS) appraised the known mineral resources and assessed the potential for undiscovered resources in 35,237 acres. This area lies within a region containing detachment faults, including the Buckskin-Rawhide detachment fault, which has been extensively studied by AZGS geologists. Outside the study area, economic deposits of copper and gold are associated with this fault. The mineral potential in both WSA's is high for copper, iron, and gold. *Mineral Resources of the Gibraltar Mountain and Planet Peak Wilderness Study Areas, La Paz County, Arizona,* coauthored by AZGS geologists J.E. Spencer, S.J. Reynolds, and M.J. Grubensky, as well as USGS and BOM geologists, may be purchased from USGS Books and Open-File Reports, Federal Center, Box 25425, Denver, CO 80225; tel: (303) 236-7476.

TONTO NATURAL BRIDGE
ARIZONA'S NEWEST STATE PARK

A 33-YEAR EFFORT

by Cheryl A. Steenerson

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On Friday, October 12, 1990, the privately owned Tonto Natural Bridge became Arizona's 26th State park (Figure 1). The State Parks Board listed its acquisition as one of its highest priorities back in 1957. Legislation was introduced in the 1960's to acquire the bridge, but the appropriation caused the bill continual problems. In 1969, a bill finally passed with an appropriation of $55,000, only 31 percent of the original request of $175,000. Although the board matched the appropriation with Federal Land and Water Conservation funds and worked closely with The Nature Conservancy to acquire funds from additional sources, it was not able to secure enough money to buy the bridge. The board's interest continued through the 1970's and 1980's. The lack of funding and a clouded title, however, precluded attempts to purchase the bridge by acquisition or land exchange through the State Land Department.

In 1989, the Wolfswinkel family began discussions with Arizona State Parks director Ken Travous to determine if the board was still interested in purchasing the property. During a presentation of Arizona State Parks' 5-year plan to the Senate Natural Resources Committee in January 1990, Senator Leo Corbet asked, "When are you going to get Tonto Natural Bridge as a State park?" Capitalizing on his and other senators' interest and on discussions with legislators in the House, Arizona State Parks staff members, with board concurrence, initiated the process by which the bridge could become a State park. This led to an amendment to Senate bill 1030, which was introduced in the Senate Appropriations Committee under the leadership of Senator Pat Wright on March 9, 1990. Governor Rose Mofford signed the bill on April 12. On October 12, escrow closed, making the Tonto Natural Bridge a State park. It is a site well worth the 33-year effort.

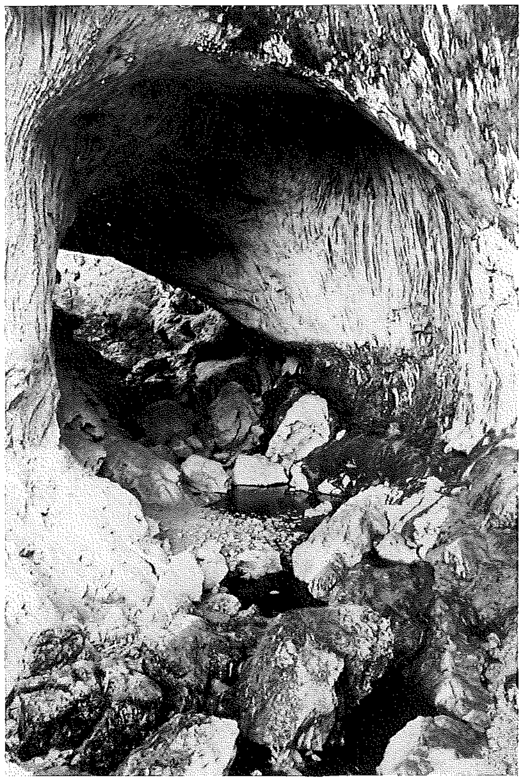


Figure 1. Tonto Natural Bridge, as viewed toward the north. The large travertine blocks in the creek fell from the bridge walls and ceiling.

Figure 2. The 1927 lodge, with its antiques and heirlooms, serves as both museum and inn.

Tonto Natural Bridge is believed to be the largest natural travertine bridge in the world. The span is 183 feet high over a 400-foot-long tunnel that measures 150 feet at its widest point. The park totals 160 acres and encompasses not only the bridge, but also several buildings and a beautifully restored lodge built in 1927 (Figure 2).

The discovery of this small but beautiful valley between Pine and Payson was documented in 1877 by David Gowan, a prospector who stumbled across the bridge while being chased by Apaches. Gowan hid for two nights and three days in one of several caves that dot the inside of the bridge (Figure 3). On the third day, he left the cave to explore the tunnel and the green valley surrounding it. Gowan claimed squatter's rights. In 1898, he persuaded his nephew, David Gowan Goodfellow, to bring his family from Scotland and settle the land permanently. After a week of difficult travel from Flagstaff, the Goodfellows arrived at the edge of the mountain and lowered their possessions down the 500-foot slopes by ropes and burros into the valley.

During the early 1900's, guest ranching grew into an Arizona industry. Between 1901 and 1908, David Goodfellow and his sons built a road and lodge at the site. The new facilities were promoted in newspapers and magazines, along with the benefits of Arizona's healthful climate and exotic scenery. Soon easterners traveling the West and Arizonans wanting to escape the heat of the Phoenix Valley began visiting Tonto Natural Bridge. As business rapidly grew, a new "modern" lodge was built in 1927. The Goodfellows sold the property in 1948. Over the years, it fell into disuse and decay.

In 1958, Clifford Wolfswinkel took his family to the site and promptly fell in love with the place. It was a memorable experience for the Wolfswinkel family. As they hiked down the trail to the bridge, 5-year-old Kathy slipped, hit her head, and was rushed to the hospital. Despite the accident, Clifford worked for 14 years to gain ownership of the property that mixed one of Arizona's most beautiful natural wonders with a historic landmark. Under the management of Wolfswinkel's Southwest Properties, it again became a well-known tourist attraction.

In 1987, at a cost of $360,000, the Wolfswinkel family renovated the lodge and refinished the interior with period wallpaper and beautiful woodwork. The lodge is filled with a variety of antiques and Gowan-Goodfellow family heirlooms. Ten bedrooms, six with adjoining porches and two with adjoining baths, are named after colorful characters from Arizona's frontier days. The bathrooms come complete with claw-footed tubs and pine washstands.

Since David Gowan's discovery 113 years ago, Tonto Natural Bridge had been privately owned. Sometimes it was closed to the public. At least once, it was almost lost forever to business interests in a foreign country. Today, for the first time in its history, it is publicly owned and managed by the Arizona State Parks Board. Arizonans, their children, and their children's children, as well as visitors to the State, can now be certain that the world's largest natural travertine bridge and the historic Tonto Lodge will always be protected and preserved.

The making of a State park is a time-consuming effort. Tonto Natural Bridge State Park is currently closed to the public while water and septic systems are replaced and facilities are built. The park's grand opening will come this spring. More than 70,000 persons are expected to visit the park in 1991 alone.

The economic impact of a State park in rural communities is enormous. The 160-acre property that encompasses the bridge has been taken off the tax rolls. A total of $12,434 in taxes was paid in 1988. Anticipated expenditures by visitors within 50 miles of the park, however, will reach $4 million per year. The protection of such a significant Arizona resource has been a long time in coming. Then again, it was a long time in the making.

THE FIRST 1.7 BILLION YEARS

by Larry D. Fellows

Arizona Geological Survey

That's right, **billion**, with a "b"! When many people think about the history of an area, they think of its most recent settlement and development. In Arizona, that means the last 300 years or so. If artifacts from the Anasazi, Hohokam, Mogollon, Sinagua, and Clovis cultures are considered, the historic record in the State may be extended back 11,000 years. In other parts of the world, scientists have discovered evidence of human activity from 40,000 years ago. By interpreting the rock record, however, one may study geologic events that occurred more than 3 billion years (b.y.) ago. Geologic events in Tonto Natural Bridge State Park extend

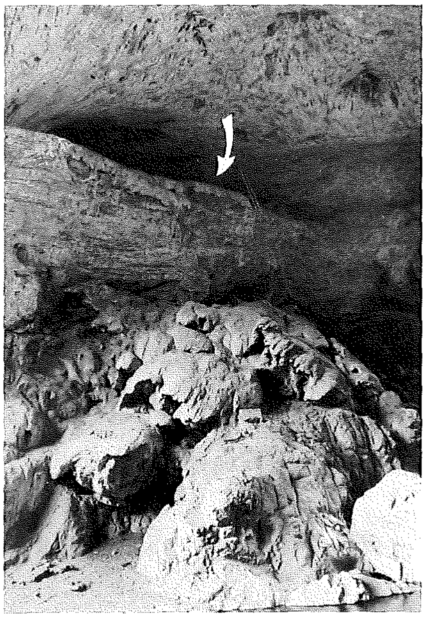


Figure 3. One of several caves (arrow) that pockmark the inside walls of Tonto Natural Bridge. The mound in the foreground is travertine deposited from water that flowed from the cave.

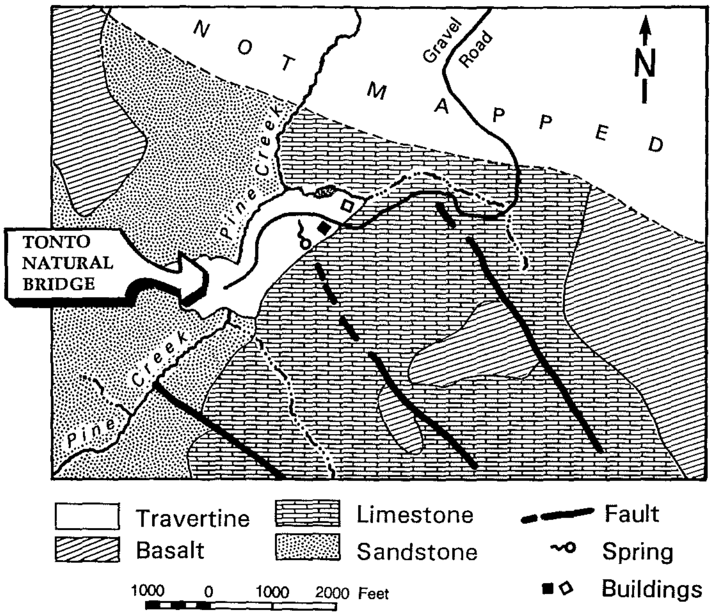


Figure 4 (above). Highly generalized geologic map of the Tonto Natural Bridge area, showing predominant rock types. Note the positions of the spring and middle fault. The natural bridge extends from north to south across the white (travertine) area. Modified from Wrucke and Conway, 1987.

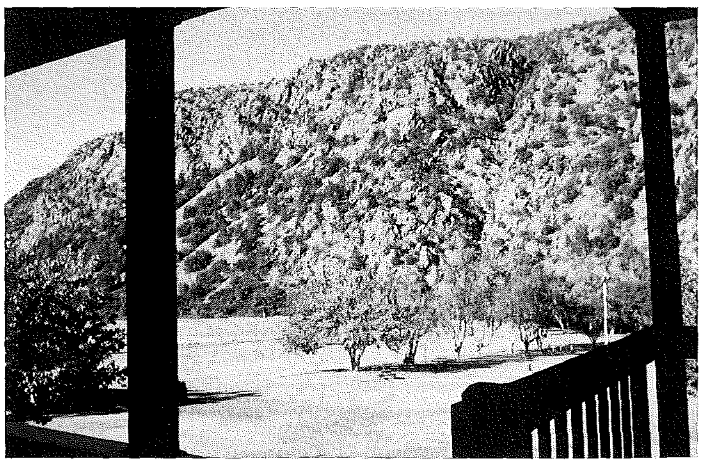
Figure 5 (right). Hillside west of Pine Creek, as viewed from the lodge. Pine Creek is at the base of the hill. The flat valley floor is the top of the travertine deposit.

back 1.7 b.y. The geologic history, which is both fascinating and varied, could easily be included in interpretive programs for park visitors. Some knowledge of the geologic setting of the area (Figure 4) is also needed to manage the park prudently.

The Tonto Natural Bridge area was created somewhat like a building–from the foundation upward. Periods of construction were interrupted by times of destruction and modification. Major phases in the development of the area as it exists today include the following: (1) formation of an ancient ridge, (2) submergence of the ridge and burial by sediment deposited on a sea floor, (3) burial of the sedimentary rocks by lava flows, (4) cutting of Pine Creek Valley, (5) build-up of spring deposits, and (6) formation of the natural bridge. These developmental phases are summarized in general terms below. Most details are omitted in this discussion, but are included in the technical reports and maps listed under "References." Much can be determined about the age relationships of strata and the timing of geologic events in the park area by studying rocks in adjacent areas. This summary, however, focuses on geologic features that are visible within the park.

Ancient Ridge

The hillside on the west bank of Pine Creek (Figure 5) was also a hillside before 500 million years (m.y.) ago. It was formed in several phases. Rocks exposed at creek level at the south end of the natural bridge, the oldest rocks in the park, were determined by radiometric dating methods to be 1.7 b.y. old. They are red, coarse-textured volcanic rocks (rhyolite), which cooled and solidified from a molten condition. The landscape over which the molten material flowed is not exposed in the park. A thick sequence of reddish-purple quartz sand, derived from weathering and erosion of older rocks, including the underlying rhyolite, was deposited in nearly horizontal layers on top of the rhyolite. All strata were then lithified, tilted, faulted, and deeply eroded. The hard sandstones resisted erosion and formed a ridge, the development of which is shown in Figures 6A and 6B.



Submerged Ridge

Beginning about 500 m.y. ago, the surrounding area was gradually submerged by a sea. The park area, however, was not covered

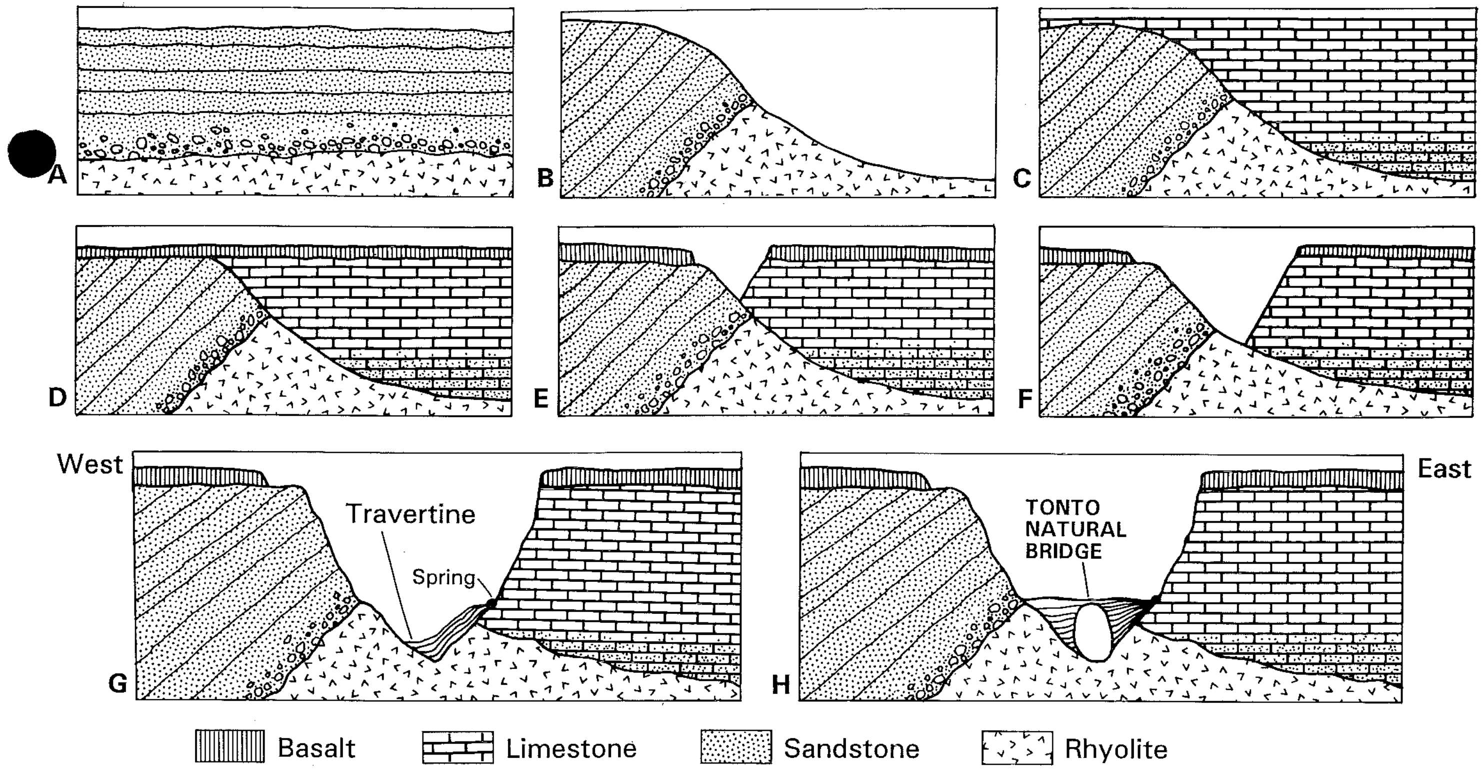


Figure 6. Highly generalized cross sections, showing the major geologic events that occurred from 1.7 b.y. ago to the present in the area surrounding Tonto Natural Bridge. Figures G and H are modified from Darton, 1925, p. 251.

by marine sediment (mainly sand and lime mud) until about 380 m.y. ago. The ridge itself was not completely buried until about 300 m.y. ago. In the park area, therefore, submergence and burial of the ancient ridge took nearly 80 m.y. (Figure 6C). These marine sedimentary rocks are exposed in road cuts within a mile of the lodge on the east side of Pine Creek.

Rocks that were deposited in the park area from 1.3 b.y. ago to 380 m.y. ago have been eroded away. This represents a gap in the rock record of almost 1 b.y.! Events that occurred during that interval have been determined by studying rocks in adjacent areas.

Lava Flows

The sedimentary layers that ultimately covered the ancient ridge were subsequently eroded and partially removed during uplift of the region, especially from about 80 to 30 m.y. ago. A new landscape developed. Volcanic eruptions began about 13 to 10 m.y. ago and completely covered the park and adjacent areas with lava that solidified into a black rock called basalt (Figure 6D).

Basalt forms the upland surface that the park road crosses between Highway 87 and Pine Creek Valley. The best exposures are in the road cuts where the road begins to descend into the valley.

Pine Creek Valley

During the last 10 m.y., the basalt has eroded and been displaced by faults. Pine Creek has incised a narrow canyon into the underlying strata, approximately following the contact between the marine-deposited limestone and the ancient ridge (Figure 7). As a result, the east side of the ridge has been exhumed, forming the cliffs on the west side of Pine Creek. Because basalt is present on both sides of the valley at nearly the same elevation, it is known that the valley was cut after the basaltic lava flows covered the area. Figures 6E and 6F illustrate the development of Pine Creek Valley.

Spring Deposits and Tonto Natural Bridge

During the last several million years, precipitation from the uplands on the east side of Pine Creek Valley seeped underground through fractures and bedding planes in the rock and partially dissolved the limestone. Some of the water emerged as a spring (or possibly a series of springs). This spring is probably related to a fault that cuts the limestone strata; the fault zone may have provided an easy path for the water to follow.

The dissolved limestone (calcium carbonate) in the spring water was redeposited as **travertine** at the mouth of the spring, partially filling Pine Creek Valley. The travertine deposits eventually pushed Pine Creek to the western edge of the valley and may have even dammed the creek. Travertine forms the flat floor of the valley (Figures 5 and 6G).

Water from the creek began to seep underneath a portion of the travertine where it is in contact with the underlying rhyolite. While the creek carved a "tube" through the basal travertine, additional travertine was deposited on top, eventually forming the natural bridge (Figure 6H). Portions of both the north and south ends of the natural bridge have recently fallen, as indicated by the large travertine blocks in and along Pine Creek (Figure 1).

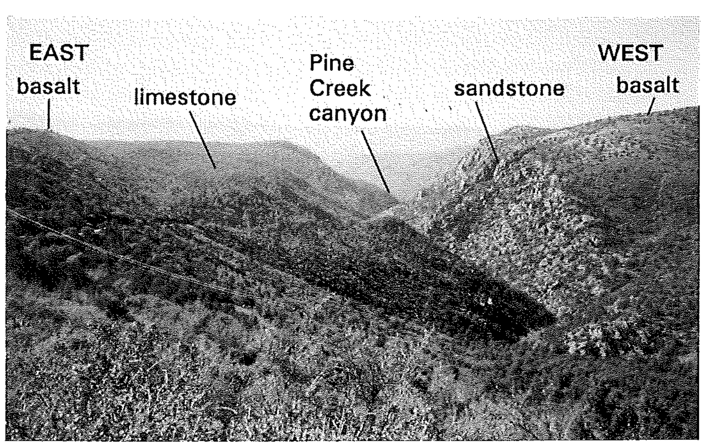


Figure 7. Pine Creek canyon, as viewed toward the south.

Practical Applications of Geologic Knowledge

The geologic history of Tonto Natural Bridge State Park includes several episodes. During the last 1.7 b.y., the area has been buried at least twice by lava and materials spewed from erupting volcanoes, tilted, faulted, submerged by seas, covered by marine sediment, deeply eroded several times, incised by Pine Creek, and filled with travertine spring deposits that were later carved out to form the natural bridge. These processes could easily be explained and their evidence noted as part of an interpretive park program.

Several aspects of park management require an understanding of the geologic setting of the area. Because precipitation that falls on the upland surface seeps underground, contaminants discharged there could easily enter the spring system below. The uplands, fortunately, are managed by the U.S. Forest Service. Caution must be used, however, by those who site waste-disposal facilities. Effluent will move quickly and easily through the travertine and underlying limestone into the spring and possibly the water-supply system.

Adequate water supply could also be a matter for concern if yields from the shallow limestone beneath the area are insufficient to meet the needs of the public. Deeper wells will likely encounter rhyolite, similar to that exposed at the south end of the natural bridge. Rhyolite is not considered to be an effective aquifer, unless it is highly fractured.

The park staff and visitors must be aware of the potential for flash flooding, especially where Pine Creek flows through the natural bridge. Persons hiking along the creek or beneath the natural bridge would be especially susceptible.

Those who plan structures or activities near active rockfall areas must also be cautious. Huge travertine blocks have periodically fallen from the south side of the natural bridge on the west side of the creek, and others will no doubt fall in the future.

Location

To visit Tonto Natural Bridge State Park, drive 13 miles north of Payson on Highway 87 to the park sign, turn left (west) onto a gravel road, and drive for 3 miles. The park is in section 5 of township 11 north, range 9 east (T. 11 N., R. 9 E., sec. 5) on the Buckhead Mesa topographic quadrangle (7.5-minute series, scale 1:24,000). The park is closed until late spring.

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New AZGS Publications

The following publications may be purchased from the Arizona Geological Survey (AZGS), 845 N. Park Ave., #100, Tucson, AZ 85719. Orders are shipped by UPS; a street address is required for delivery. All orders must be prepaid by check or money order payable in U.S. dollars to the Arizona Geological Survey. Add shipping and handling charges, listed below, to your total order:

In the United States:	20.01 - 30.00, add 5.50	50.01 - 100.00, add 10.00
$1.01 - $5.00, add $1.75	30.01 - 40.00, add 6.25	Over 100.00, add 10%
5.01 - 10.00, add 2.25	40.01 - 50.00, add 7.75	Other countries: Request price quotation.
10.01 - 20.00, add 4.25		

Wohl, E.E., and Pearthree, P.A., 1990, Controls on the origin and recurrence of debris flows in the Huachuca Mountains, southeastern Arizona: Open-File Report 90-6, 48 p. $7.25

During the summer rainy season of 1988, debris flows occurred in the Huachuca Mountains in areas that were scorched by fire earlier that summer. One flow damaged residential property. Debris flows also occurred in 1977 after a major fire, which suggests a causative link between fires and flows. Fires destroy vegetation, destabilize slopes, enhance surface runoff, and increase erosion. Debris flows are then triggered by intense rainfall. Abundant evidence of older flows preserved in channels and alluvial fans indicates that repeated flows have occurred in this area during the last 10,000 years. In individual drainage basins, recurrence intervals between flows are on the order of 1,000 years. This report describes the debris-flow deposits and identifies the geomorphic role that flows have played in the evolution of the Huachuca Mountains.

Slaff, Steven, 1990, Bibliography on Arizona earth fissures and related subsidence, with selected references for other areas: Open-File Report 90-7, 28 p. Hard copy, $4.75; 3.5" or 5.25" high-density floppy disk, $15.00

Land subsidence and earth fissures due to ground-water withdrawal have developed in many areas of the world, including Arizona, where they have affected more than 3,000 mi^2 and caused considerable damage. This bibliography is divided into two sections: a comprehensive list of published works on subsidence and earth fissures in Arizona and a selected list of references for areas outside of the State. To make it more useful to investigators, the AZGS is offering this bibliography as a printed document and on floppy disk as a DOS text file, Word Perfect 4.2 file, and dBase IV file.

Demsey, K.A., 1990, Geologic map of Quaternary and upper Tertiary alluvium in the Little Horn Mountains 30' x 60' quadrangle, Arizona: Open-File Report 90-8, scale 1:100,000. $3.00

This map depicts the alluvial and eolian deposits that compose the piedmonts (gently sloping valley sides) and basins (valley floors) in this area of southwestern Arizona. The deposits are classified according to age, inferred from changes in surface morphology caused by erosion and soil formation. This map is based on interpretation of aerial photographs, supplemented by reconnaissance field investigations. The project was supported by the Cooperative Geologic Mapping Program (COGEOMAP) between the AZGS and U.S. Geological Survey.

Spencer, J.E., and Reynolds, S.J., 1990, Geology and mineral resources of the Bouse Hills, west-central Arizona: Open-File Report 90-9, 21 p., scale 1:24,000. $6.00

This report includes a detailed geologic map of the Bouse Hills and text that describes map units and mineral deposits. The Bouse Hills consist of Proterozoic crystalline rocks that are intruded by a Miocene pluton and overlain by a sequence of Oligocene(?) to Miocene sedimentary and volcanic rocks. Numerous manganese deposits in the western Bouse Hills were derived from low- to moderate-salinity aqueous fluids; however, barite veins in the northwestern Bouse Hills were apparently derived from high-salinity fluids.

Duncan, J.T., 1990, The geology and mineral deposits of the northern Plomosa mineral district, La Paz County, Arizona: Open-File Report 90-10, 55 p., scale 1:9,318. $11.00.

The northern Plomosa Mountains largely consist of Tertiary sedimentary and volcanic rocks and underlying Proterozoic crystalline rocks. Numerous Tertiary normal faults within the upper plate of the Plomosa detachment fault are common sites of copper and gold mineralization or served as conduits for high-salinity mineralizing fluids that caused replacement mineralization in adjacent Tertiary limestone. Primary ore minerals are native gold, chrysocolla, and malachite; common gangue minerals are specular and earthy hematite, quartz, barite, fluorite, calcite, and manganese oxides. This report describes the mineral deposits and their host rocks and includes a geologic map.

R·E·C·O·M·M·E·N·D·A·T·I·O·N·S

on Environmental and Engineering Geology Activities

by the

Environmental and Engineering Geology Advisory Committee to the Arizona Geological Survey*

In 1985 Larry D. Fellows, director of the Arizona Geological Survey (AZGS), asked Ralph E. Weeks, president of the Arizona Section of the American Institute of Professional Geologists (AIPG), to appoint and chair a special committee to review the performance of the AZGS relative to its statutory mandate. The AZGS' enabling legislation had been substantially modified in 1977, and a sunset review is scheduled for 1992. Members of Weeks' committee, who represented a broad spectrum of geologic activities, including mineral exploration, hydrogeology, environmental and engineering geology, and education, conducted a review and submitted a report. The report contained recommendations about functions and activities to which the AZGS should give priority to meet its statutory mandate more fully.

In 1988 Fellows established three separate advisory committees to focus on environmental and engineering geology (geotechnical), mineral and energy resources, and earth science education. Each group meets twice per year. Members serve on their own time and at their own expense.

In November 1990, the Environmental and Engineering Geology Advisory Committee (Figure 1) met to review and update the 1985 AIPG report on AZGS performance. The committee was asked to identify statutory responsibilities that require priority. Committee recommendations are identified and discussed below.

1 Current AZGS activities encompass the statutory mandate and are generally responsive to the objectives of the enabling legislation. These ongoing programs include geologic mapping and related field investigations, maintenance of a geoscience database, preparation and distribution of publications, library services, educational activities, operation of a repository for geologic samples, and response to public inquiries.

Figure 1. Advisory committee members review recommendations. From left to right: R. Bruce Mack and Barbara H. Murphy (seated); Frank S. Turek and William G. Wellendorf (standing).

Because of a substantial population increase and related development in Arizona since 1950, geologically related problems are increasingly being encountered in the State. Such problems, which commonly require costly repairs or mitigation procedures, fall within the broad spectrum of "natural hazards and limitations" specified in the AZGS' enabling legislation. **Investigating problems that have the greatest potential to impact the health, safety, and quality of life of Arizona's residents and that would require costly mitigation should be a primary AZGS objective.**

2 The AZGS should accelerate the assessment of Arizona's natural hazards and the development of strategies to mitigate their potential impact on land and resource management and on the State's inhabitants.

The common natural and induced hazards that require investigation include land subsidence and earth fissures, earthquakes, flooding and related problems, expanding and collapsing soils, landslides, and the geologic environs that influence groundwater quality.

To provide this much needed assessment of Arizona's potential natural hazards, the AZGS should engage in several investigative activities:

- Provide a statewide, regional characterization of potential hazards, including location, type, risk, and mitigation approaches;
- Conduct areal field investigations and geologic mapping of specific localities where existing or planned development necessitates avoidance or mitigation of known or potential geologic hazards;
- Prepare maps, bulletins, circulars, interpretative reports, and other supporting documents for release to the public; and
- Assist land-management agencies and provide pertinent data to the private sector.

3 The AZGS should implement an earth science education program for elementary and secondary school teachers and for public groups.

4 The AZGS should expand and enhance its comprehensive computerized database on Arizona geology. This activity should include soliciting nonproprietary geologic information from the geologic community, including government agencies, the private sector, and academia. The AZGS should publish a bibliography of geologic literature, maps, and graduate theses on Arizona geology as soon as possible and update it every 2 years. The AZGS should also implement a geographic information system (GIS) for geologic data.

5 The AZGS should secure adequate storage space for drill cores, well cuttings, and related subsurface information and provide a usable system of sample cataloging and retrieval.

Conclusions. Recognition and pursuit of the objectives discussed above will ensure that the AZGS continues to be responsive to the needs of Arizonans. As practiced by the AZGS in the past, every effort should be made to make the public aware of available resources and the value of characterizing Arizona's geologic framework. We, as members of the geologic profession, have found the products and services provided by the AZGS to be invaluable to the understanding and application of our science. We fully support any effort to improve and strengthen the AZGS and its capability to address those aspects of the geologic framework that have the greatest influence on the health, safety, welfare, and quality of life of Arizona's citizens.

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PROFESSIONAL MEETINGS

Tucson Gem & Mineral Show. Annual exhibit, Feb. 13-17, Tucson, Ariz. Contact Gem & Mineral Show Committee, P.O. Box 42543, Tucson, AZ 85733; tel: (602) 322-5773.

Geological Society of America, Cordilleran Section. Annual meeting, March 25-27, San Francisco, Calif. Contact Raymond Sullivan, Dept. of Geosciences, San Francisco State University, San Francisco, CA 94132; tel: (415) 338-7730.

Arizona-Nevada Academy of Science. Annual meeting, April 20, Flagstaff, Ariz. Contact Betsy Cooper, Dept. of Biology, Glendale Community College, 6000 W. Olive Ave., Glendale, AZ 85302; tel: (602) 435-3613.

Geological Society of America, Rocky Mountain–South-Central Section. Annual meeting, April 22-24, Albuquerque, N. Mex. Contact John Geissman, Dept. of Geology, University of New Mexico, Albuquerque, NM 87131; tel: (505) 277-4204.

Arizona Geology

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State of Arizona: Governor Rose Mofford

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Editor: Evelyn M. VandenDolder
Editorial Assistant: Nancy Schmidt
Illustrators: Peter F. Corrao, Sherry F. Garner

AGS Digests Available at AZGS Office

All digests published by the Arizona Geological Society (AGS) may be purchased over the counter at the Arizona Geological Survey (AZGS) office at 845 N. Park Ave., Suite 100, in Tucson. Although these two organizations are separate (the AGS is a professional society; the AZGS is a State agency), the AZGS has agreed to sell AGS publications, as well as its own, as a public service. Only over-the-counter sales of AGS digests may be made through the AZGS office. Mail orders must be sent to the Arizona Geological Society, P.O. Box 40952, Tucson, AZ 85717.

Bibliography on the Grand Canyon

The most comprehensive bibliography on the Grand Canyon has just been released by the Grand Canyon Natural History Association as Monograph 8. *Bibliography of the Grand Canyon and the Lower Colorado River, From 1540*, compiled by E.E. Spamer, cites publications on the human history of the canyon, as well as its geologic and natural history. As an aid to those with specialized interests, the volume is divided into 12 categories, such as geology, Native Americans, and works for young people. It is an indispensable research tool for historians, librarians, and anyone fascinated with the grandest of canyons. It is available both in hard copy and on computer disk from the Grand Canyon Natural History Association, P.O. Box 399, Grand Canyon, AZ 86023.

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