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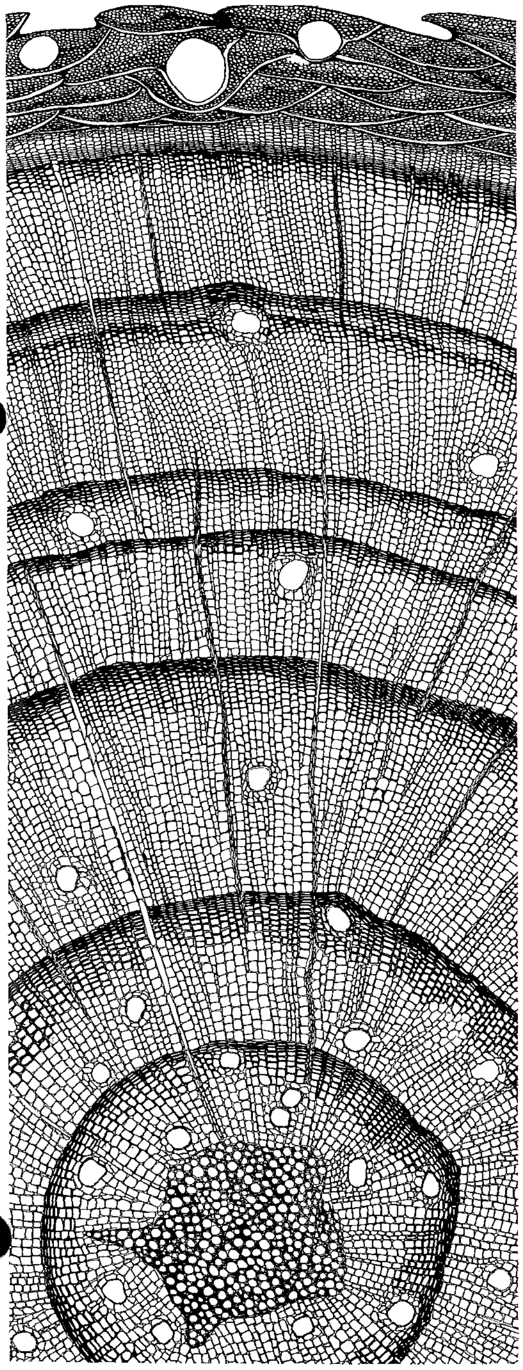
HOW GEOLOGISTS TELL TIME
PART 2: ABSOLUTE DATING TECHNIQUES



by **Evelyn M. VandenDolder**, Arizona Geological Survey

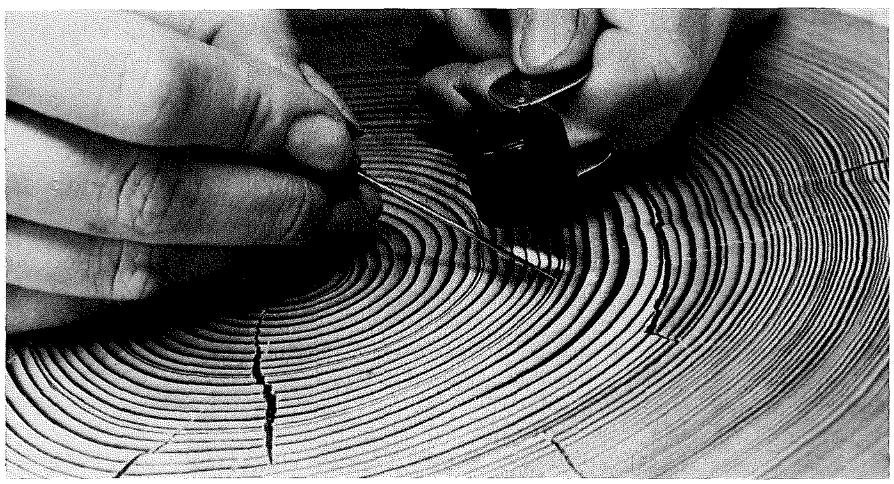
Geologic time, a revolutionary concept that has taken several centuries to develop, may be measured by both relative and absolute dating techniques. The former were discussed in Part 1 of this article, published in the previous issue of *Arizona Geology*. Nature records earthly time by two absolute methods: astronomically through tree rings, growth rings, and varve sequences, which reflect the rotation and revolution of the Earth in seasonal changes; and atomically through radioactive decay. These two standards of measurement are discussed below.

TREE RINGS

Tree rings are the most well-known seasonal records preserved in living organisms. The width and density of the rings depend on the temperature and the amount of light and moisture present when the plant cells were formed. During the spring and summer growing season, new layers of cells are produced underneath the bark of the tree. Seasonal variations are evident in early or "spring" wood, which consists of large thin-walled cells, and late or "summer" wood, which consists of smaller cells with thicker walls. One annual ring includes one layer each of spring and summer wood (Figure 1). *(continued on page 6)*

Figure 1 (left). Generalized illustration of the cross-section anatomy of conifers. Note the differences between early or "spring" wood (with large, thin, light-colored cells) and late or "summer" wood (with small, thick, dark-colored cells). New tree rings are produced by the cambium, a layer of undifferentiated plant cells directly underneath the bark. The large, open circular areas are resin ducts, which are intercellular spaces lined with thin-walled cells that secrete resin into the duct. Resin protects the plant from attack by decay-producing fungi and bark beetles. Drawing by Terah L. Smiley. Copyright © 1947 by Laboratory of Tree-Ring Research, University of Arizona. Reprinted with permission.

Figure 2 (below). Dendrochronologist examines a cross section of a Douglas fir tree from an archaeological site. Copyright © 1984 by Laboratory of Tree-Ring Research, University of Arizona. Reprinted with permission.



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S.K. Bollin*

and Larry D. Fellows, Arizona Geological Survey

Making a Profession Professional

It is almost impossible to read a newspaper, open a magazine, or watch a newscast without seeing or hearing the words "environment" or "environmental." Americans and people in other parts of the world are becoming acutely aware of the importance of taking care of our planet. Environmental concerns have spawned countless organizations, groups, projects, and causes around which the American people love to rally. And with good reason! Much stress has been placed on the land and its water, mineral, and energy resources to provide for the needs of a rapidly expanding population.

Scientists of many disciplines investigate land, water, mineral, and energy resources, all of which are required to sustain populations. They also study ways to manage these resources, with special consideration given to the environment. The scientific disciplines that address our natural heritage have earned their own designation. A new science is emerging: the science of **environology**, the study of the environment. **Environologists**, the scientists who specialize in environology, are drawn from the fields of geology, hydrology, chemistry, physics, biology, ecology, and other disciplines in which dedicated professionals are continuously advancing knowledge of the lithosphere, hydrosphere, biosphere, and atmosphere, **as well as their interrelationships**. As with all disciplines, it is the responsibility, as well as the obligation, of its professionals to inform and assist nonprofessionals in understanding and protecting our natural heritage. Use of the terms "environology" and "environologist" will clearly differentiate between professionals in this field and the concerned public.

> The scientific disciplines that address our natural heritage have earned their own designation. A new science is emerging: the science of **environology**, the study of the environment.

The need for wise stewardship of our land and natural resources increases along with the population. In order for our Nation to deal effectively with the environment, our educational system must become superior in environology. It is essential that our citizens be informed about the environment. In addition, we must provide well-qualified educators and researchers in environology. Poorly conceived scientific practices lead to unwise land- and resource-management decisions. We cannot afford to use our land, water, energy, and mineral resources unwisely, nor can we afford to pay for ill-conceived natural-resource management.

Before we can make informed decisions about the use of our land and natural resources, we must understand the character of those resources and the processes that are actively modifying them. If we understand these resources, we can make wise choices among alternatives, priorities, and expenditures for land and natural-resource management.

Many decisions that are made, actions that are taken, and structures that are built have an immediate impact on the environment; other effects may take longer to be recognized. Constructing waste-disposal facilities, shopping centers, houses, factories, highways, railroads, and airports; issuing permits to use State Trust and public lands; and controlling housing densities and growth rates directly affect the environment. Earth materials and processes can also affect decisions that are made and structures that are built. The potential for damage by floods, earthquakes, subsidence, earth fissures, problem soils, rockfalls, debris flows, and collapse must be considered during the planning, site selection, construction, and operation phases of many Arizona projects. Environologists provide the information needed to carry out such projects.

In 1990, an environmental education bill was passed by the Arizona Legislature and signed by Governor Rose Mofford. This legislation was described in the Fall 1990 issue of *Arizona Geology*. It is the legislature's intent that "the public schools, community colleges, State universities, and State agencies provide a continuing awareness of the essential mission to preserve the Earth's capacity to sustain a quality of life in the most healthful, enjoyable, and productive environment possible." Furthermore, public schools, community colleges, State universities, and State agencies are expected to "integrate environmental education throughout the educational system and public education programs so that awareness of students and the general public is thorough, continuous, and meaningful." The bill mandates that all school districts develop and implement programs that integrate environmental education into the general curriculum. It also specifies that each university under the jurisdiction of the Arizona Board of Regents shall incorporate training in environmental education into its teacher training programs.

Environology and environologists play a critical role in land and natural-resource management. Environology must be taught throughout the educational system and reach as many students as possible to ensure that future citizens understand its basic concepts. Some students must attain advanced degrees and teach or conduct research in environology to continue the cycle for future generations.

The Arizona Geological Survey is deeply committed to environology through its programs of investigation and information dissemination. The establishment of a publication series, *Down to Earth*, is its newest effort. This series will feature nontechnical books and maps for the general public. The first publication will be released soon. Watch for it!

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*S.K. Bollin earned a bachelor of science degree in geology at the University of Arizona. She devoted much of the early part of her career to earth science education as a teacher at the secondary level, science department chair, and author of geology publications for children and adults. She also has more than 25 years of experience in the business and financial management of technical firms. Ms. Bollin is now directing her attention to environmental geology. She is a member of the Earth Science Education Advisory Committee to the Arizona Geological Survey.

On Mineral Resource Activities

by the
**Mineral Resources Advisory Committee
to the Arizona Geological Survey***

Figure 1. Advisory committee members discuss recommendations on mineral resource activities. Seated (left to right): J.N. Mayor, T.H. Eyde, D.M. Aiken, W.E. Heinrichs, J.D. Sell, and R.A. Metz; standing (left to right): J.A. Briscoe, C.P. Miller, R.M. Corn, J.D. Loghry, and J.D. Forrester.

The Arizona Geological Survey (AZGS) was established by the State legislature to investigate, describe, and interpret Arizona's geologic setting, including its natural hazards and limitations, its natural attributes, and its **mineral resources.** To receive guidance from the private sector for planning mineral-resource-related projects and activities, Larry D. Fellows, director of the AZGS, established the Mineral Resources Advisory Committee. The committee is composed of 13 senior geologists employed by major mineral exploration and mining companies or as consultants, with a combined total of more than 400 years of experience in mineral exploration.

In January 1991, the committee reviewed and considered the types of investigations and information activities conducted by the AZGS that are most useful to mineral explorationists (Figure 1). Development of mineral-exploration programs is based on knowledge of the regional geologic setting, including the age, origin, occurrence, and character of the contained mineral deposits. Mineral exploration begins with review of all available geologic information and then proceeds with field investigations to identify exploration targets. With this in mind, we recommend that high priority be given by the AZGS to the following projects and activities, listed in order of priority.

1. Preparation of regional and detailed geologic maps. The preferred mapping scale is 1:24,000, but larger scales are recommended in areas that are more complex or mineralized. The maps should be accompanied by reports that focus on regional synthesis of the geologic framework of Arizona. Mapping emphasis should be given, in general, to areas that are favorable and available for mineral exploration. To characterize alteration, the AZGS should include results of laboratory studies of selected samples in its reports. Individual maps should be released to the AZGS open-file system as soon as possible. Interpretive reports, which may include the results of different types of geologic investigations, should be completed later, if appropriate.

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2. Maintenance of a computerized geologic database and a comprehensive library. All citations pertaining to geologic data, maps, and reports on Arizona geology should be entered into a computer database. All pertinent geologic maps, reports, and theses should be available in the AZGS library. Indexes and bibliographies of geologic maps and reports, air photos, and geophysical and geochemical data should be compiled. Solicitations should be made to the public, industry, and government agencies to donate additional geologic information.

3. Other activities and projects, listed below:

a. Urban-area and remote-subdivision studies and mapping. Known and potential mineral deposits in areas with the highest potential for urban development should be identified. Population growth dictates increased demand for the raw materials needed for construction. These materials include limestone, clay, shale, and gypsum, which are required for the production of cement, as well as sand, gravel, and other aggregate to mix with the cement to make concrete. Because transportation is the largest single cost component of concrete aggregates, their availability from nearby sources is important. Consumers ultimately pay for the added cost of transporting aggregate materials from greater distances. A database that includes information about the location and character of these important resources is needed.

b. Earth science education. Programs of outreach to the general public, including earth science teachers, teacher groups, and students, should be expanded. A volunteer or docent program that also involves the participation of professional societies should be considered to assist in attaining these objectives. Recommended activities include a speakers' bureau, field trips, and nontechnical publications.

c. Mineral-district studies. Investigations of selected mineral districts, including field studies and compilation of existing data, should be conducted. Such studies will provide a better understanding of the origin, character, and relationships of known mineral districts and will help assess mineral potential within those districts and other areas.

d. Repository for rock cores and cuttings. The AZGS has a statutory requirement to maintain a repository for rock cores and cuttings from oil and gas test holes, mineral exploration holes, and water wells. Because the storage facilities are inadequate, however, the agency has been unable to accept these materials. These rock cores and well cuttings, which are costly to obtain and are donated by industry, are invaluable sources of information on the geology and resource potential of the subsurface. Drill cores and cuttings from areas with concealed bedrock should be given priority. These materials should be made available to the public. Graduate students, among others, should be encouraged to study them.

Conclusion. The AZGS has done a commendable job, with limited resources, in acquiring and making available information to assist in the development of Arizona's mineral resources. Arizona mine production led the Nation at $3.1 billion in 1990, yet State support for the AZGS is among the lowest for all the State geological surveys in the Nation. An expanded level of effort is needed to cover the entire State adequately. Detailed investigations and mapping should focus on areas where improved understanding will lead to the greatest advances in our knowledge of the geologic framework of Arizona and the regional distribution and controls of mineralization. Reexamination of areas mapped in the past, which now require reinterpretation based on new concepts, is also needed. The AZGS should solicit contributions from industry for geochemical, geophysical, core, and drill-hole information for incorporation in final reports.

Use of computers for data storage and retrieval is essential because of the large amount of geologic information that is available and that continues to be generated. Basic information, such as bibliographies and indexes, is needed by the mineral industry, land-management agencies, and the general public. Although the AZGS has made significant progress in this direction, much more work is needed.

Arizona's rapid population growth has resulted in competition for available land and resources. Industrial and urban development require metallic and nonmetallic mineral resources, energy resources, water, and waste repositories. The AZGS has statutory responsibility to provide the basic geologic reports, maps, information, and assistance to aid in the wise stewardship of all of Arizona's resources. To fulfill these responsibilities and, thus, ensure that mineral resources will be available to sustain Arizona's dynamic growth, the AZGS will require more funding.

Resource Materials for Earth Science Teachers

Slides, videotapes, computer software, books, pamphlets, and other educational materials for earth science teachers are available from numerous scientific organizations. A small number of these are listed below.

American Association for the Advancement of Science Books, P.O. Box 753, Waldorf, MD 20604. Publishes *Sourcebook for Science, Mathematics, and Technology Education, 1990-1991,* which includes the names, addresses, and telephone numbers of administrators and policymakers in associations, government agencies, educational research centers, scientific academies, and museums. Also lists programs and activities for students, teachers, and parents.

American Geological Institute, 4220 King St., Alexandria, VA 22302-1507; tel: (703) 379-2480. Publishes pamphlets, classroom activity exercises, nontechnical magazines, textbooks, posters, and other educational materials. *Earth Science Investigations,* a laboratory book for high school students, includes 27 exercises that teachers can integrate with any earth science text or program. Each activity has been tested with students and reviewed for scientific accuracy. This 232-page book includes maps and diagrams, as well as exercises on beach erosion, seismic waves, rock and mineral analyses, ground-water contamination, solar eclipses, and other topics in the earth sciences.

American Ground Water Trust, 6375 Riverside Dr., Dublin, OH 43017; tel: (614) 761-2215. Compiles *Ground Water Education in America's Schools,* a catalog of educational materials published by various organizations on ground-water resources and related environmental concepts.

Arizona Geological Survey, 845 N. Park Ave., Suite 100, Tucson, AZ 85719; tel: (602) 882-4795. Publishes geologic maps of Arizona (with explanatory text) and *Arizona Geology,* a quarterly newsletter that includes articles on the geology of the State and information for earth science teachers. Also conducts field trips and workshops for teachers and provides lists of other sources of information.

Geological Society of America, P.O. Box 9140, Boulder, CO 80301; tel: (303) 447-2020. Sells the film, "The Earth *Has* a History," which explains the concept of geologic time and demonstrates how a student can decipher the major events in the geologic history of an area by examining its surface features. Available on VHS video or 16-mm film.

National Center for Earthquake Engineering Research, State University of New York at Buffalo, Red Jacket Quadrangle, Buffalo, NY 14261. Publishes *NCEER Bibliography of Earthquake Education Materials,* which lists resource materials on earthquakes, volcanoes, tsunamis, and plate tectonics for grades K-9. Teachers may obtain a free copy by writing on school letterhead.

National Geophysical Data Center, 325 Broadway, E/GC4, Dept. 839, Boulder, CO 80303; tel: (303) 497-6277. Sells slide sets depicting geologic hazards throughout the world, including earthquakes, faults, tsunamis, landslides, and volcanoes. Sets include descriptive information and teaching aids, if requested.

Society of Economic Paleontologists and Mineralogists, P.O. Box 4756, Tulsa, OK 74159-0756; tel: (918) 743-9765. Publishes *A Sedimentary Geologists' Guide to Helping K-12 Earth Science Teachers: Hints, Ideas, Activities, and Resources.* This 91-page guide is divided into four sections to help both earth science teachers and scientists who want to become involved in their local schools: (1) hints for successful class visits; (2) activities for teachers; (3) field trips; and (4) list of resources.

U.S. Department of Energy, Office of Communications, Office of Fossil Energy, 1000 Independence Ave., S.W., Washington, DC 20585. Publishes *Dinosaurs and Power Plants,* a 16-page illustrated brochure designed for students in grades 5 through 8, which relates the story of mining and drilling for coal, oil, and gas, including environmental concerns and modes of transportation. This free brochure also contains puzzles, maps, and a glossary.

U.S. Geological Survey, Book and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Publishes nontechnical pamphlets on geology, hydrology, maps, and related subjects. Single copies are free; bulk copies for classroom use are also available. Write for free catalog, *General Interest Publications of the U.S. Geological Survey.*

AGS Spring Field Trip

The spring field trip of the Arizona Geological Society will be held on April 13 and 14 in Prescott. Stops will include the Iron King mine, Huron-Victor-Swindler prospect, Bluebell mine, Texas Gulch Formation, Gold Belt mine, Crazy Basin pluton, and Moore Gulch shear zone. The cost will be $20. For reservations, call the Arizona Geological Survey at (602) 882-4795.

The Arizona Desert Wilderness Act of 1990

by **Larry Bauer**
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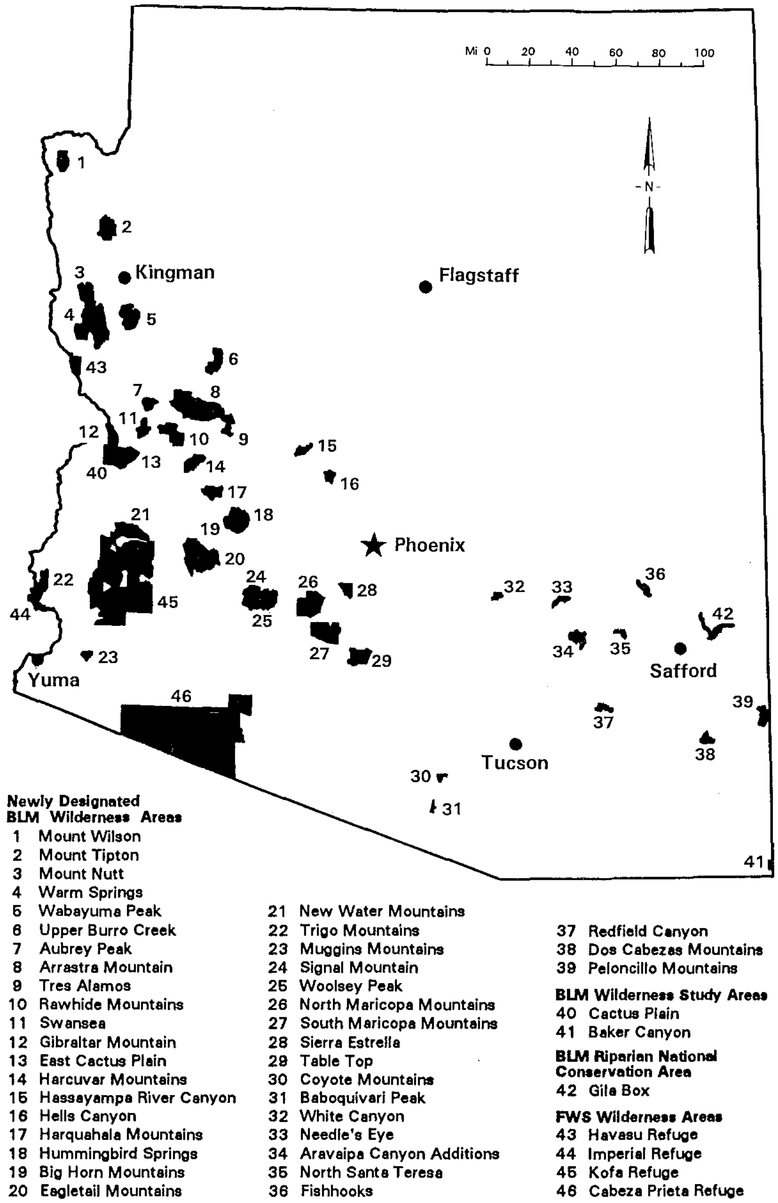
Until recently, the U.S. Bureau of Land Management (BLM) in Arizona managed 272,569 acres, or 75 percent of the Nation's designated wilderness on BLM lands. With the enactment of the *Arizona Desert Wilderness Act of 1990* on November 28, the acreage in Arizona skyrocketed to 1,362,539, or well over 90 percent of the Nation's BLM wilderness. The new law enlarged 1 area and added 38 others, bringing the total to 47 BLM wilderness areas in Arizona. The law also created the Gila Box Riparian National Conservation Area and designated four new wilderness areas on lands that are managed by the U.S. Fish and Wildlife Service as wildlife refuges. Two BLM Wilderness Study Areas are still under review (see figure).

Arizonans and visitors to the State can enjoy a wide variety of wilderness experiences in the newly designated areas. These lands boast a rich diversity of plant life representing the great southwestern deserts: Sonoran, Mohave, and Chihuahuan. They are virtually unchanged since the earliest hunters roamed the areas in search of game. Time and climatic forces have shaped them into geologic wonderlands, where hikers can squeeze through narrow canyons, climb rugged peaks, and discover cultural landmarks or artifacts hidden in side canyons or caves. These areas also contain a host of wildlife, including bighorn sheep, peregrine falcons, Gila monsters, coatimundi, javelina, and desert tortoises.

The new wilderness areas lie in the Basin and Range physiographic province. The areas are structurally complex and lithologically diverse. For the most part, they consist of fault-bounded mountain blocks, but many areas extend onto the intervening basins. Many of the wilderness areas encompass sites of historic mineral production. During the process that led to passage of the act, mineral-potential considerations resulted in boundary adjustments and the establishment of "cherry-stem" areas to provide access to existing operations or patented claims.



Although some 3,100 mining claims are currently within these wilderness areas, no new claims may be staked. For extant claims, the rules have changed. Each claimant was notified of the new operating requirements. Before a claimant may start or continue mining operations, the BLM must determine if the claim was valid (i.e., economically viable) when the area was designated as wilderness. Validity is based on the discovery of a valuable mineral and on the reasonable expectation of developing a profitable mine. BLM geologists determine validity by conducting a mineral examination of the claim area. The BLM will approve operational plans for valid claims if they meet certain requirements to prevent unnecessary or undue degradation and to preserve the wilderness character of the land. Claims that the BLM deems invalid will undergo contest proceedings to determine their validity conclusively. These determinations are also subject to administrative appeal. If the final administrative decision rules that the claim is invalid and if the BLM requires it, a claimant must restore the land affected by mining.

The BLM has begun mineral examinations of two mining operations in the Muggins Mountains Wilderness Area. BLM geologists used pack horses or nonmechanized equipment to transport 250-pound placer samples to the wilderness boundary. Because of the large number of new wilderness areas, the BLM expects to examine several operations each year for the next 5 years.

The BLM will prepare a Wilderness Management Plan for each area. These plans detail how the wilderness will be managed and how the area may be used. While the plans are being prepared, public input will be actively sought. Until the plans are completed, only the State director may authorize certain activities, such as the use of mechanized equipment, in a wilderness area. After the plans are approved, the district manager may be delegated to authorize uses as prescribed by the plan. Administrative and other actions that must be taken within the wilderness areas before the plans are completed will be considered under interim management plans or on a case-by-case basis.

The addition of these wilderness areas provides an opportunity for both current and future generations to experience what Arizona was like when the West was "wild." The widespread distribution of these areas makes a wilderness adventure a possibility for almost every Arizonan.

(continued from page 1)

Dendrochronology, the study of tree rings, has been used to date archaeological sites, especially in the arid Southwest, where wooden beams that supported ancient dwellings are well preserved (Figure 2). In living trees, the outer ring was formed during the current year. By counting the total number of rings, scientists can establish an age for the living tree. Because living trees in the same area share a common environment, their rings exhibit a similar pattern of wide and narrow bands, which usually reflect when rainfall was plentiful and scarce, respectively. If the inner-ring pattern of a living tree matches the outer-ring pattern of an ancient tree (e.g., a structural beam of an old building) that grew in the same area, the rings were formed during the same time, and thus, are the same age. Through such cross-dating, dendrochronologists can determine when the ancient tree was cut and the edifice built.

In the Southwest, the continuous tree-ring chronology extends back to 322 B.C. (Arizona State Museum, Tucson). By piecing together tree-ring data from various parts of the world, scientists have extended the continuous chronology even further to 7938 B.C. (Stuiver, 1990). Bristlecone pines in the western United States and oaks in Irish peat bogs are among the trees used to establish this chronology.

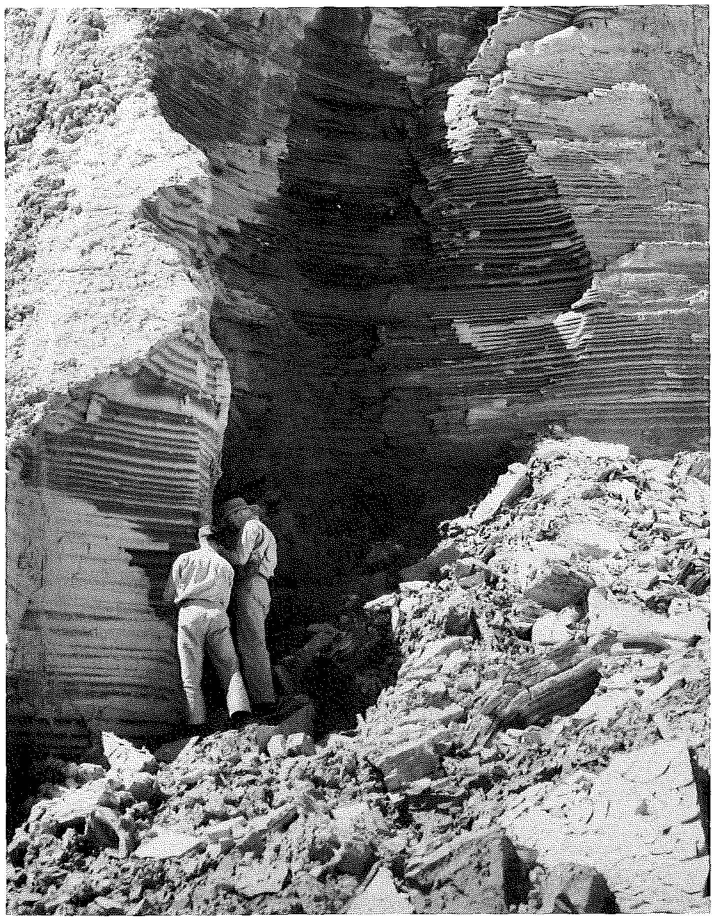


Figure 3. Pleistocene varves formed of alternating silt and clay near mouth of Sherman Creek, Ferry County, Washington. Photo by F.O. Jones (no. 119), U.S. Geological Survey Photographic Library.

GROWTH RINGS

Some aquatic organisms also record seasonal variations in temperature and food supply, especially those that live in lakes in the Temperate Zone where temperature fluctuations are extreme. Fresh-water clams typically grow annual bands that resemble tree rings. Dark narrow bands indicate colder weather, when scarce food restricted shell growth. Lighter and wider bands indicate a warmer season and more abundant food supply (Stokes, 1966). These rings are also evident in fossil shells.

Fish scales, both modern and fossilized, show tiny, annual growth rings, called "annuli." Corals, on the other hand, record daily growth rings. By studying the rings of fossil corals from the Devonian Period (about 375 million years [m.y.] ago), geologists concluded that there were 400 days in a year and inferred that days were shorter during this time (Stokes, 1966).

VARVE SEQUENCES

Seasonal changes are also reflected in the sedimentary record. Precipitational variations during wet and dry seasons locally affect erosion, transportation, and deposition of sediments. Wet seasons with high stream flow cause rapid deposition of sediments, whereas dry seasons with low flows cause little or no deposition.

A **varve** is a sedimentary layer deposited in a body of still water, such as a lake, within a single year. The term "varve" specifically refers to an annual layer deposited in a glacial lake by meltwater streams. A glacial varve includes two layers: a lower "summer" layer composed of coarse-grained light-colored sediments, such as sand or silt, formed by rapid melting of ice and vigorous runoff during the warmer months; and an upper, thinner "winter" layer composed of very fine grained, often organic, darker clay sediments, produced when suspended particles were slowly deposited while the streams were ice bound and the lake was quiet. Glacial varves range from less than an inch to several inches in thickness (Figure 3; Stokes, 1966).

Hundreds of years have been recorded within the varves of a single lake or pond (Stokes, 1966). Variations in the size of varves, due to differences in the length and warmth of seasons, allow geologists to correlate varve sequences. The oldest preserved sequence associated with a particular glacier generally lies adjacent to the area where that glacier reached its maximum extent. The youngest sequence is nearest the glacier's edge (if the glacier still exists) or lies where an "extinct" glacier retreated and melted away. Geologists have counted and correlated varves to determine the ages of Pleistocene glacial deposits and the time when the last ice sheets retreated from Europe and North America.

RADIOACTIVE DECAY

The nucleus of an atom contains two kinds of particles, each with a mass of 1 (in atomic mass units): **neutrons**, which are electrically neutral, and **protons**, each of which has an electrical charge of +1. The atomic number is equal to the number of protons, which uniquely defines an element and establishes its place among the 103 known elements on the Periodic Table of the Chemical Elements. The number of protons is also equal to the number of electrons that surround the nucleus in nonionized atoms. An **electron** has an electrical charge of -1. Because the mass of an electron is negligible, an element's atomic weight essentially equals the total number of protons and neutrons in its nucleus.

Each element consists of several **isotopes**. Derived from a Greek term meaning "same place" (Faure, 1977), isotopes have the same number of protons (and thus, occupy the "same place" on the Periodic Table), but different numbers of neutrons (and thus, different atomic masses and weights).

Some isotopes of every chemical element are unstable and spontaneously disintegrate to form atoms of different elements, releasing energy in the process. Isotopes radioactively decay through one of three nuclear processes: by emitting **alpha particles**, which are essentially helium nuclei composed of two protons and two neutrons; by emitting **beta particles**, or high-energy electrons; or by capturing electrons. An element that emits an alpha particle becomes another element because it loses two protons. The electrons that are beta particles are not released from the electron cloud surrounding the nucleus, but from the nucleus itself. A neutron breaks up, emits an electron, and becomes a proton, thus creating a new element with one more proton and one less neutron than the previous element. In **electron capture**, a proton in the nucleus picks up an orbital electron and turns into a neutron, thus creating a new element with one less proton and one more neutron (Faure, 1977).

The initial atoms of a radioactive isotope are called **parents;** the new atoms produced after a decay are called **daughters.** One daughter atom is produced by the decay of one parent atom; thus, the number of daughter atoms in a rock or mineral is equal to the number of parent atoms that decayed, as long as no daughter atoms leaked from the sample. Radiometric dating based on the disintegration of parent atoms into daughter atoms may be roughly compared to an hourglass, which tells time by the amount of sand that flows from one chamber to another. By determining the ratio of daughter atoms to parent atoms still in a sample, scientists can determine the original amount of parent atoms in the rock or mineral. Knowing the rate of decay, they can determine the time when no daughters, only parents, were present. For some isotopes, this date is considered to be the age of crystallization of the rock or mineral. For other isotopes, this date represents the time when a mineral cooled to its **blocking temperature.** When the temperature of a mineral is above its blocking temperature, parent or daughter atoms can leak from the sample, thus resetting the radiometric clock or preventing it from even starting. The blocking temperature is specific to the type of mineral. Some geologists study the cooling histories of rocks by determining the radiometric ages of various minerals for which the blocking temperatures are known. This type of research is called **thermochronology.**

The nuclear reactions within radioactive isotopes (also called **radioisotopes)** occur almost instantaneously. Although it is impossible to predict when atoms will disintegrate, scientists have determined how long it takes for a specific quantity of atoms to decay. This rate of decay is determined by the number of atoms (n) that disintegrate in a specific period of time, usually per second or per year, relative to the total number of atoms (N) of that isotope in any given amount of material. The ratio n/N, called the **decay or disintegration constant,** is invariable no matter what N is (Press and Siever, 1982). In other words, the rate of decay is fixed for a given isotope.

Rates of decay, which have been experimentally determined for most radioisotopes, are defined in terms of half-lives. The **half-life** of an isotope is the time required for half of the original number of atoms (parents) to decay. The remaining parent atoms disintegrate at the same rate, being diminished by half during each half-life period until their number approaches zero (Figure 4). Half-lives range from a fraction of a second in some isotopes to billions of years in others. ^{14}C (pronounced "carbon 14"), a radioisotope of carbon, for example, has a half-life of 5,730 years, whereas ^{87}Rb, a radioisotope of rubidium, has a half-life of 50 billion years (b.y.). The half-life of a radioisotope determines the number of years, and thus the types of rocks or minerals, that it may effectively date. A sophisticated ^{14}C counting instrument at the University of Arizona in Tucson uses this radioisotope to date objects up to 60,000 years old, or about 10.5 half-lives, at which point only $^{1}/_{1,448}$ of the original amount of ^{14}C remains in the sample (P.E. Damon, oral commun., 1991). ^{87}Rb, in contrast, may be used to date the oldest rocks on Earth, which are almost 4 b.y. old.

When dating rocks and minerals by radiometric methods, geologists make three major assumptions. First, the rate of decay is accurately known and constant, i.e., it doesn't vary with changes in temperature or pressure. Once a quantity of a radioisotope is formed in any part of the universe, it begins releasing atoms at a definite rate. Evidence that decay rates are constant is derived from interpretations of the light spectra of stars, some of which are older than the Earth. Second, the daughter atoms are solely the product of radioactive decay of the parent. No daughter atoms were present in the rock or mineral specimen before the radiometric clock began ticking. Third, the rock or mineral being dated has remained a "closed" system. No changes have occurred, such as reheating, that have allowed daughter atoms to leak out or parent atoms to be added. Such changes would reset the radiometric clock, as would a cracked hourglass that allowed sand grains to escape. Radiometric dating actually determines the time that has elapsed since sand grains escaped from the hourglass, i.e., since the last time that the mineral within a rock sample was at a temperature above its blocking temperature (Faure, 1977).

To count the atoms of a radioisotope, scientists use a **mass spectrometer,** a machine that was developed during the 1920's and 1930's. A mass spectrometer produces a beam of electrically charged atoms from a rock or mineral sample. This beam is then deflected by electrical and magnetic fields. The atoms that compose the beam are proportionately deflected according to their atomic masses, and thus may be separated and counted. During World War II, dating techniques were developed and refined as part of the Manhattan Project, the U.S. government's effort to develop the atomic bomb (Press and Siever, 1982). The mass spectrometer has since evolved into a tool that is used to research problems in geology, chemistry, and biology, as well as physics. Scientists continue to improve the sensitivity and precision of this instrument.

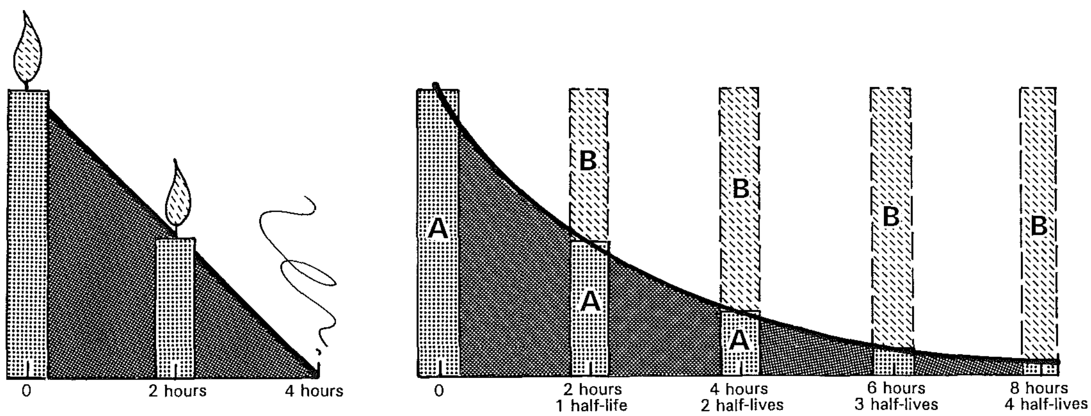


Figure 4. *Linear vs. exponential decay. A candle (left) with a "life expectancy" of 4 hours, gives off heat, light, and gases at a linear rate. After 4 hours, the candle has burned down to nothing. Radioactive decay (right), in contrast, occurs at an exponential rate. The unstable parent isotope A decays to the daughter product B. After one half-life (2 hours), one-half of the parent isotope A remains; after two half-lives (4 hours), one-fourth remains. From Sawkins and others (1978, p. 103). Reprinted with permission.*

Several radiometric dating techniques are used today. The most common are the K-Ar, Ar-Ar, U-Pb, Th-Pb, Rb-Sr, ^{14}C, and fission-track methods.

K-Ar and Ar-Ar Methods

Potassium (K) is one of the eight most abundant elements in the Earth's crust and a major constituent of many rock-forming minerals (Faure, 1977). Because of potassium's abundance and isotopic character, the most commonly used radiometric technique is based on the decay of radioactive potassium (^{40}K).

^{40}K decays via one of two paths: About 89 percent of ^{40}K atoms disintegrates by beta decay to stable calcium (^{40}Ca); the remaining 11 percent disintegrates by electron capture to stable argon (^{40}Ar; Faure, 1977). The quantity of the latter is used to determine the age of the mineral because ^{40}Ar can be distinguished from atmospheric argon, whereas ^{40}Ca cannot be separated from ordinary calcium. In addition, argon can be completely liberated simply by melting the rock or mineral. The K-Ar technique, discovered in 1948 (Stokes, 1966), is used to date potassium-bearing minerals and rocks that retain radiogenic argon at low temperatures. These include biotite and muscovite (both micas) and hornblende in plutonic and metamorphic rocks, as well as feldspar in volcanic rocks. Because they are very common in igneous and metamorphic rocks, micas are the best minerals to date by this technique. The K-Ar method cannot, however, be used to date sedimentary rocks. Minerals that were transported and deposited are generally older than the sedimentary rocks that contain them, and minerals that did form at the same time as the rocks are commonly affected by **diagenesis** (the chemical, physical, and biological processes that turn sediments into rock). The half-life of ^{40}K is 1.31 b.y. Rocks from 10,000 years old to the oldest rocks on Earth may be dated by the K-Ar method (Table 1; Jones, undated).

When using this method to determine the age of crystallization, geologists assume that no argon was present in the mineral when it formed and that it has retained argon since it cooled through its argon blocking temperature (Faure, 1977). ^{40}Ar, however, is the only isotope commonly used in dating that is a gas; thus, it may easily escape from a mineral, especially at temperatures exceeding several hundred degrees centigrade (Dalrymple and Lanphere, 1969). The K-Ar date is the time at which the mineral cooled enough to prevent ^{40}Ar from escaping. This blocking or closure temperature differs with each mineral. For hornblende, for example, the ^{40}Ar blocking temperature ranges between 480°C and 570°C, depending on whether the rock cooled slowly (5°C/m.y.) or quickly (1,000°C/m.y.). For the feldspar microcline, however, the ^{40}Ar blocking temperature ranges from 120°C to 180°C (McDougall and Harrison, 1988). Though perceived as a disadvantage by some scientists, the potential for argon loss is actually considered an advantage by others because K-Ar dates are useful in determining the cooling histories of plutonic and metamorphic rocks.

A variation of the K-Ar technique has been used to overcome some of its limitations. In the Ar-Ar method, the isotopic ratios of ^{40}Ar and ^{39}Ar in the sample are determined. ^{39}Ar is produced from ^{39}K through a reaction induced by neutron irradiation of the sample in an atomic reactor. Because absolute measurements of potassium and argon concentrations are unnecessary, the Ar-Ar method is used to date very small or valuable samples, such as lunar rocks or meteorites. This technique, unlike the K-Ar method, can commonly determine if argon has been added or lost since the time of crystallization (Faure, 1977).

U-Pb and Th-Pb Methods

Uranium (U) and thorium (Th) radioactivity, discovered at the turn of the century, was the first to be used in dating rocks and minerals (Faure, 1977). Because they have similar electron configurations, these two elements also have similar chemical properties and decay schemes. Two radioisotopes of uranium (^{235}U and ^{238}U) and one of thorium (^{232}Th) disintegrate to lead (Pb) through alpha and beta decay. The reactions include chains of radioactive intermediate daughters, but the parents and stable daughters are as follows: $^{235}U \rightarrow {}^{207}Pb$; $^{238}U \rightarrow {}^{206}Pb$; and $^{232}Th \rightarrow {}^{208}Pb$ (Faure, 1977).

Ordinary lead consists of four naturally occurring isotopes: ^{208}Pb, ^{207}Pb, ^{206}Pb, and ^{204}Pb. The first three are radioactive-decay products; ^{204}Pb is nonradiogenic. Any lead that was incorporated into a mineral at the time of crystallization consists of all four isotopes. Scientists assume that the total amount of ^{204}Pb has remained constant since the Earth was formed, whereas the amounts of ^{206}Pb, ^{207}Pb, and ^{208}Pb have steadily increased because of radioactive decay (Faure, 1977). The amount of ^{204}Pb is therefore used as a stable reference isotope to determine the ratios of the other lead isotopes.

Table 1. Common radiometric dating methods. Compiled from Wyllie (1971), Faure (1977), and Jones (undated).

Parent	Daughter	Half-Life (Years)	Effective Dating Range	Some Materials That May Be Dated
^{40}K	^{40}Ar	1.31×10^9	10^4 years to Earth formation	micas, hornblende, feldspar
^{235}U	^{207}Pb	7.13×10^8	10^7 years to Earth formation	zircon, uraninite, allanite, monazite, sphene, apatite, epidote, thorite
^{238}U	^{206}Pb	4.51×10^9	10^7 years to Earth formation	same as ^{235}U
^{232}Th	^{208}Pb	1.39×10^{10}	10^7 years to Earth formation	same as ^{235}U
^{87}Rb	^{87}Sr	5.0×10^{10}	10^7 years to Earth formation	potassium feldspar, micas, clay minerals
^{14}C	^{14}N	5.73×10^3	0 to 6×10^4 years	wood, fabric, paper, rope, seeds, bone, pottery
Fission tracks from U decay			0 years to Earth formation	apatite, micas, sphene, epidote, garnet, zircon, tektites, glass

Separate age calculations using the different uranium isotopes are commonly made for a single sample. Coinciding values, called **concordant ages**, represent the time of crystallization. Values that disagree, called **discordant ages**, indicate that parent or daughter atoms, most commonly lead, were gained or lost through thermal metamorphism (heating) or other processes. By examining the results of these analyses, researchers may be able to obtain both the crystallization and metamorphic ages of the mineral.

The half-lives of ^{235}U, ^{238}U, and ^{232}Th are 713 m.y., 4.5 b.y., and 13.9 b.y., respectively. Rocks from approximately 10 m.y. old to the oldest rocks on Earth may be effectively dated by these methods (Table 1). Intermediate parent-daughter sequences of the ^{235}U and ^{238}U decay series have also been used to date minerals between 50,000 and 300,000 years old (Sawkins and others, 1978). One intermediate sequence, the decay of ^{238}U to ^{234}U and ^{230}Th (the half-life of which is 75,000 years) is used to calibrate radiocarbon dates. (See section titled "^{14}C Method.")

As molten magma cools and crystallizes, uranium and thorium become concentrated in the more silica-rich components. Granitic igneous rocks thus contain more uranium and thorium than does basalt (Faure, 1977). Uranium and thorium are contained in many minerals, but minerals that are rich in these elements are rare. Only minerals that retain uranium, thorium, their intermediate daughters, and lead may be effectively dated by the U-Pb and Th-Pb methods. Zircon is the best choice for these techniques; other useful minerals are uraninite (pitchblende), allanite, monazite, sphene, apatite, epidote, and thorite. Because these minerals, as well as uranium and thorium, are commonly present in more silicic rocks, this technique is commonly used to date rocks with a high SiO_2 content (Faure, 1977; Jones, undated).

CORRECTION

In Part 1 of this article, included in the last issue of *Arizona Geology*, two errors were printed on page 4. In the section titled "Crosscutting Relationships and Included Fragments," the fourth sentence should read "Although a rock unit may not be intersected by an intrusion, it could still be identified as **older** [not younger] than the intrusion if the unit is metamorphosed near the intrusion...." In the second paragraph of the section titled "Unconformities," the fourth sentence should read "Because **intrusive** igneous and metamorphic rocks form deep below the Earth's crust...." [Extrusive igneous rocks, such as basalt, form at or near the Earth's surface.]

Rb-Sr Method

Radioactive rubidium (^{87}Rb), through release of a beta particle, disintegrates to strontium (^{87}Sr). Because the half-life of ^{87}Rb is so long (about 50 b.y.), its accuracy is somewhat uncertain. For this reason, the Rb-Sr method cannot be used to date young rocks.

The Rb-Sr technique is used to date rubidium-bearing minerals, such as micas, potassium feldspar, and clay minerals, in igneous and metamorphic rocks (Table 1). Thermal metamorphism may release daughter atoms and reset the radiometric clock in rubidium-bearing minerals. Whole-rock samples the size of hand specimens, however, may remain closed systems even if metamorphism has occurred (Faure, 1977). Rubidium and strontium may migrate from one mineral to another, but remain within the rock. The Rb-Sr technique, therefore, may be used to establish the time of crystallization through whole-rock analysis, as well as the time of metamorphism through separate mineral analyses. It may be the most valuable method for dating metamorphic rocks.

^{14}C Method

Radioactive carbon (^{14}C) is naturally created in the atmosphere when cosmic-ray-produced neutrons interact with stable nitrogen (^{14}N) atoms, causing each atom to lose one proton. The ^{14}C atoms are quickly oxidized to CO_2. When a plant is alive, it "breathes" in CO_2 and incorporates into its cell structure carbon molecules from the CO_2 through the process of photosynthesis. Carbon from the atmosphere includes both radioactive ^{14}C and the more abundant stable isotope, ^{12}C. When a plant dies, photosynthesis and CO_2 intake both cease. As the age of the dead organic material increases, the amount of ^{14}C in that material decreases due to beta decay to ^{14}N, whereas the amount of ^{12}C does not. The $^{14}C/^{12}C$ ratio in the plant material provides a measure of the time that has elapsed since the organism died (Faure, 1977).

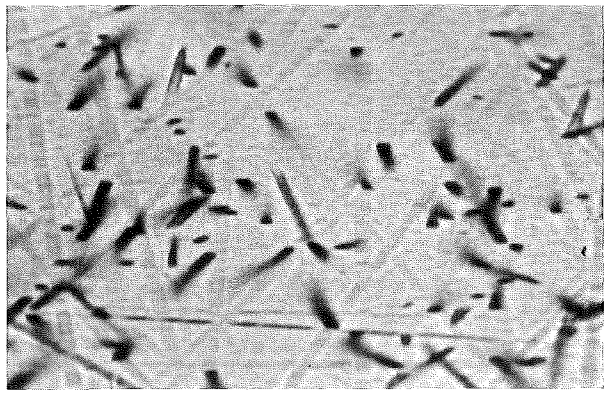


Figure 5. Spontaneous fission tracks in apatite mineral grain, as viewed through a petrographic microscope at a magnification of 1,000X. These natural tracks (short dark lines) were produced by the spontaneous fission of ^{238}U atoms. The very long, light-colored lines are merely scratches on the surface of the grain. This apatite is from a granodiorite from the Dry Valleys of Antarctica. The apatite fission-track age of this particular sample (58 $\pm$ 4 m.y.) reflects the early Cenozoic uplift of the Transantarctic Mountains. Photo by Paul Fitzgerald, Dept. of Geology, Arizona State University.

Unlike other radioisotopes, ^{14}C does not have to be measured by use of a mass spectrometer. Instead, the amount of ^{14}C in the sample may be indirectly determined by counting the number of beta particles emitted, which is proportional to the number of ^{14}C atoms present. This total is compared to the ^{14}C radioactivity in living plant tissues. In preparation for ^{14}C dating, the sample is treated to remove impurities and burned with oxygen or treated with acid to release CO_2 gas. This gas is also treated to remove impurities and compressed within a copper tube. ^{14}C emissions are then counted for 12 hours or more, depending on the sample's age (Faure, 1977).

During the past decade, mass spectrometry has been increasingly used instead of radioactive-decay counting to measure minute amounts of ^{14}C. This method allows researchers to count all the ^{14}C atoms in a sample (or at least those that the detector collects), not only those that decay during the counting period (Levi, 1990).

The ^{14}C method is used to date charcoal, wood, fabric, seeds, nutshells, paper, hide, rope, bone, ivory, and pottery, especially for archaeological purposes. The half-life of ^{14}C is about 5,730 years. The most sophisticated mass spectrometers can use ^{14}C to date small samples up to 45,000 years old. The most sophisticated counting instruments can date larger samples up to 60,000 years old (P.E. Damon, oral commun., 1991; Table 1).

The ^{14}C dating technique is based on two assumptions: (1) the level of ^{14}C activity is constant in both the atmosphere and biosphere; it does not vary with time, latitude, or species; and (2) the sample is a closed system; no ^{14}C was incorporated into tissues after the organism's death, and radioactivity is the sole cause of ^{14}C depletion. Researchers have shown, however, that the ^{14}C content of the atmosphere varies with the level of cosmic-ray activity, which in turn depends on latitude, solar activity, and the Earth's magnetic field. About 20,000 years ago, the ^{14}C content of the atmosphere was 40 percent higher than it is today (Levi, 1990). This variation is mainly due to changes in the Earth's magnetic dipole, which 30,000 years ago, was only about half its current strength (Levi, 1990). The weaker field allowed more cosmic rays to penetrate the atmosphere at the midlatitudes and thus, generate more ^{14}C.

Variations in atmospheric ^{14}C levels due to human activities have also been noted. ^{14}C levels decreased from the 19th to the 20th century, possibly because of the combustion of fossil fuels during the Industrial Revolution, which added "dead" ^{14}C-depleted CO_2 to the atmosphere. They have risen, however, since 1945 because of the development of the atomic bomb, nuclear reactors, and particle accelerators (Faure, 1977). In addition to fluctuating levels of atmospheric ^{14}C, ^{14}C from surrounding water, soil, rock, or vegetation may contaminate a sample.

Because these variations may affect the accuracy of radiocarbon dates, studies of tree rings and varve sequences are commonly used to check and correct ^{14}C dates of sample materials. By measuring the ^{14}C content of annual rings in bristlecone pines and other trees and of varved sediments that contain organic matter, researchers can determine the ^{14}C content of the atmosphere at the time the rings and varves were formed. Radiocarbon dates that are cross-checked with dates from tree rings or varve sequences are exceptionally accurate. These calibrations, however, cover only about the last 9,000 years of Earth history (Levi, 1990).

By comparing ^{14}C and $^{230}Th/^{234}U$ ages of submerged Barbados corals, researchers have recently shown that radiocarbon dates of 20,000 years could be as much as 3,800 years too young (Bard and others, 1990; Stuiver, 1990). Because the $^{230}Th/^{234}U$ dates were determined by a high-precision mass-spectrometry technique, the researchers were able to calibrate ^{14}C dates up to 40,000 years ago (Levi, 1990). The adjusted ^{14}C timescale recalibrates the dates of global glacial periods, as well as the ages of some archaeological artifacts. Scientists will continue to refine radiocarbon dating techniques and use other methods to cross-check ^{14}C dates.

Fission-Track Method

Uranium isotopes generally disintegrate by emitting an alpha particle, but sometimes undergo an alternate mode of decay: spontaneous nuclear fission. The nucleus spontaneously breaks into two charged particles that travel in opposite directions, leaving trails of molecular destruction as their energy is transferred to the atoms of the mineral. If the mineral is etched with acid, the more soluble damaged areas become enlarged and are visible as tracks under an optical microscope (Figure 5). These tubular **fission tracks**, which are mostly created by the spontaneous fission of ^{238}U atoms, are 2 to 3 microns wide and 10 to 20 microns long (Gleadow and others, 1983). Scientists estimate that for every 2 million ^{238}U atoms that decay by alpha emission, only 1 will fission (Jones, undated).

The density of fission tracks in a mineral increases with time and uranium concentration, but the tracks disappear if the mineral is heated above a specific temperature, known as the **annealing temperature**. Tracks in different minerals have different annealing temperatures. The fission-track method can thus provide information about the thermal histories of rocks. A fission-track date is the cooling age, not necessarily the crystallization age, of the mineral.

If the mineral cooled rapidly and was not reheated, the date is the actual age of the mineral. The fission-track method is used to date apatite, micas, sphene, epidote, garnet, zircon, tektites, volcanic glass, and synthetic glass, including some archaeological objects (Faure, 1977). Samples from one decade old to the oldest rocks on Earth may be dated by this technique (Table 1; Jones, undated).

To date a mineral by the fission-track method, a researcher must determine both the density of fission tracks and the uranium concentration within the specimen. A fresh unweathered surface of the mineral is cut, polished, and etched with acid. The specimen is then placed under a petrographic microscope, and the fission tracks are counted within a known area. To determine the uranium concentration of the sample, the researcher may prepare the sample in one of two ways. For minerals, such as apatite, in which the uranium content is homogeneous, i.e., the same in each grain, the spontaneous fission tracks are annealed, or destroyed by heating, after they are counted. The researcher then cuts, polishes, and etches a new surface of the mineral. To date minerals with nonhomogeneous uranium, such as zircon and sphene, the researcher does not heat or etch the mineral. Muscovite containing very little uranium is attached to the sample to serve as a track detector (Faure, 1977; Jones, undated). After preparing the sample by either method, the researcher irradiates it with thermal neutrons in a nuclear reactor to induce fission of ^{235}U atoms and counts the density of induced fission tracks. Because the ratio of ^{238}U to ^{235}U atoms is constant in nature (137.8:1; Faure, 1977), the density of induced ^{235}U fission tracks may be compared with that of spontaneous ^{238}U fission tracks to determine the number of parent atoms that were originally in the sample.

Fission-track dating has several advantages. This analysis does not require the use of a mass spectrometer and is relatively easy to perform. It may be used to date materials, such as highly weathered rocks and minerals, that cannot be dated by other means. Disadvantages of this method, however, are that the track density of the sample must exceed 10 tracks per square centimeter and the sample must be relatively free of inclusions and defects to permit counting (Faure, 1977).

Alpha particles emitted by radioisotopes do not release enough energy to produce fission tracks. They may, however, produce **pleochroic haloes**, minute dark or colored concentric rings surrounding inclusions of radioactive minerals. The intensity of the ring color depends on the number of alpha emissions. Coloration increases to a maximum intensity as the number of emissions and the age of the mineral increase, but then decreases as radiation damage becomes extreme. Pleochroic haloes have been extensively studied in biotite because this mineral has perfect cleavage and the haloes are readily visible. The accuracy of the pleochroic-halo dating method, however, remains controversial (Faure, 1977).

Other Methods

Several other techniques have been used to date certain rocks and minerals that cannot be dated by the conventional methods described above. The most promising methods are based on beta decay of the naturally occurring radioisotopes of rhenium (^{187}Re) and lutetium (^{176}Lu) to osmium (^{187}Os) and halfnium (^{176}Hf), respectively. The Re-Os method is used to date iron meteorites, molybdenite-bearing vein deposits, and rhenium-bearing copper-sulfide ores. The Lu-Hf method is used to date apatite, garnet, and monazite in igneous rocks. The naturally occurring radioisotopes of some rare-earth elements, most notably samarium (^{147}Sm) and lanthanum (^{138}La), have also been used to make age determinations (Faure, 1977). The alpha decay of samarium (^{147}Sm) to neodymium (^{143}Nd) has been used to date Precambrian rocks, but is more commonly used as an isotopic tracer to study the genesis and history of the Earth's crust.

Although the radioactive decay of ^{40}K to ^{40}Ar, described above, is more widely used as a dating technique, the decay of ^{40}K to ^{40}Ca may be used to date minerals that are greatly enriched in potassium and depleted in calcium, such as micas in pegmatite and sylvite in evaporite rocks (Faure, 1977). The high natural abundance of ^{40}Ca, however, does pose problems with this method.

Tritium (^{3}H), a radioisotope of hydrogen, is created in the atmosphere from ^{14}N in a way similar to ^{14}C production, but in smaller amounts. It is also produced by manmade nuclear explosions. Tritium, which decays to stable helium (^{3}He), has a short half-life of about 12.5 years (Stokes, 1966; Faure, 1977). It is therefore not used to date geologic events, but may be used to determine the flow rate of ground water and the circulation rate of deep ocean currents.

THE IMPORTANCE OF DATING ROCKS AND MINERALS

By dating rocks and minerals, geologists can clarify the chronology of geologic events, relationships between rock units, sources of rock materials, and timing of metamorphic and mineralizing events. Age determinations are so important to geologists deciphering the geologic history of Arizona that more than 1,600 radiometric dates had been determined for rocks in the State by 1986 (Reynolds and others, 1986). Because this history is extremely complex, geologists continue to generate dozens of new radiometric dates each year. Relative dating methods, such as those based on sedimentary sequences, fossils, and cross-cutting relationships, as well as other absolute dating methods, such as those based on tree rings, are no less valuable to geologists. These techniques provide geologic information and insights that radiometric dates cannot offer. They are also crucial to understanding the relationship between radiometric dates and the geologic history of an area. Some examples of the knowledge gained by geochronologic studies in Arizona are given below.

Such studies in western Arizona have helped in understanding the geologic history of the Gulf of California region. The Bouse Formation along the Colorado River consists of estuarine deposits, or sediments deposited in the brackish water of an **estuary**, an arm of the sea at the lower end of a river. Fossils and volcanic tuffs associated with this formation indicate that it is early Pliocene to late Miocene. This age and the composition of the formation suggest that the Gulf of California and the Salton Trough were connected 3 to 11 m.y. ago (Schmidt, 1990).

By dating minerals within a mountain range, geologists can determine not only when the rocks were formed and uplifted, but also the rate of the orogenic (mountain-building) process. Rocks in the forerange of the Santa Catalina Mountains near Tucson and in the South Mountains near Phoenix were once thought to be Precambrian, or approximately 1.6 b.y. old. Because of new age determinations, it is now known that the rocks were formed during the Tertiary Period. Uplift of these mountains, which was relatively fast (in geologic terms), largely occurred between 30 and 15 m.y. ago.

The mountains in the Basin and Range Province of Arizona are mostly composed of igneous and metamorphic rocks. Many of the granites in these ranges are very similar in appearance and could not be distinguished from each other without knowledge of their ages. By using radioisotopes, geologists can link ore deposits with specific intrusive episodes and formations. Except in the Bisbee area, all porphyry copper deposits in Arizona are associated with granites of a specific age (early Tertiary to Late Cretaceous, or 55 to 75 m.y. old). Some minerals, such as micas, were formed by the mineralizing process, and therefore, may be used to date the deposits. By dating micas at the Vulture mine, geologists from the Arizona Geological Survey (AZGS) and U.S. Geological Survey (USGS) have determined that this deposit is Cretaceous, not Precambrian, as was previously thought (Spencer and others, 1989). Knowing the age of a mineral deposit is important to explorationists who are searching for more deposits of the same type.

Geothermal energy (useful energy that can be harnessed from naturally occurring steam and hot water, such as hot springs, fumaroles, and geysers) is associated with areas of Quaternary volcanic activity. Volcanic rocks in western Arizona were once thought to be Quaternary (less than 1.6 m.y. old) or Cretaceous (66 to 144 m.y. old). If they had been Quaternary, they would have been prime sites for geothermal energy, and thus, were the subject of several geothermal studies. If they had been Cretaceous, they would have been prime sites for porphyry copper deposits. Because of recent geologic mapping and age determinations by geologists from the AZGS, USGS, and University of Arizona, it is now known that these rocks are middle Tertiary (20 to 40 m.y. old). Geologists can now link these rocks with other mid-Tertiary volcanic rocks (and hence, other episodes of volcanism) in southern Arizona, such as those in the Chiricahua and Superstition Mountains.

By dating Quaternary materials, such as terrace (flood-plain) deposits and sediments that are cut by or overlap faults, geologists can determine the potential for flooding, earthquakes, and other geologic hazards in an area. AZGS geologists have determined that some faults north of the San Francisco Mountains are Quaternary because they crosscut older basalt flows and are overlain by younger flows. These faults are young; i.e., movement along them has recently occurred. It is not surprising that this area is also one of high seismicity. AZGS geologists have also dated terrace deposits and studied the pattern of erosion along stream channels in the Tucson area. They have established when the last flood occurred and estimated the potential for future floods in the metropolitan area.

As the population of Arizona continues to grow, along with the demand for mineral resources and responsible city planning, the need for reliable geologic mapping, including accurate age determinations of rock units, will become increasingly important.

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NEWS NOTES

Recent Report Addresses Mineral Potential in South-Central Arizona

The Tucson and Nogales 1° by 2° quadrangles in south-central Arizona have made important economic contributions to a mineral-rich State. The area's 1985 mineral production represented 77 percent of molybdenum, 42 percent of boron, 29 percent of zinc, 27 percent of silver, 22 percent of copper, and 10 percent of gold production in Arizona; most of this came from porphyry copper systems. The known and possible deposit types in the study area include 22 metallic and 9 nonmetallic minerals.

A recent report by the U.S. Geological Survey (USGS), which was coauthored by Arizona Geological Survey geologist S.J. Reynolds, inventories available data and literature pertinent to a mineral-resource assessment of this area. It does not address the part of the Nogales quadrangle in Mexico. The 129-page report, titled *Preliminary Mineral Resource Assessment of the Tucson and Nogales 1° by 2° quadrangles, Arizona,* was released as USGS Open-File Report 90-276 and contains 24 1:250,000-scale maps. A paper copy may be purchased for $97.00 (microfiche copy, $22.00) from the USGS Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225; tel: (303) 236-7476.

Turek Appointed to AIPG National Executive Committee

Frank S. Turek, vice president of A-N West, Inc. in Phoenix, has been appointed to the National Executive Committee of the American Institute of Professional Geologists (AIPG) for 1991. Mr. Turek was also selected by the AIPG's president to serve on the National Geology Test Committee. He is a member of the Advisory Committee on Engineering and Environmental Geology for the Arizona Geological Survey.

Minerals Information Office Relocated

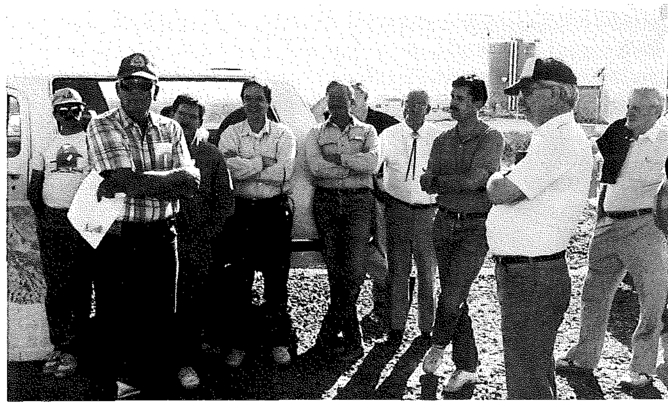
The Tucson branch of the Minerals Information Office (MIO) has been relocated. Formerly housed within the offices of the Arizona Geological Survey at 845 N. Park Ave., the MIO was moved to the U.S. Geological Survey offices in the Corbett Building, 340 N. 6th Ave., Tucson, AZ 85705. Karen Bolm, Minerals Information Specialist, may be reached by calling (602) 670-5544. The MIO provides access to an extensive computerized database containing information on more than 80,000 mineralized sites, statistics on mineral commodities, bibliographies of current references on mineral deposits, and other mineral-related data. Because of its cooperative relationship with the Center for Interamerican Mineral Resource Investigations (CIMRI), the Tucson MIO can also provide information on mineral deposits in Latin America.

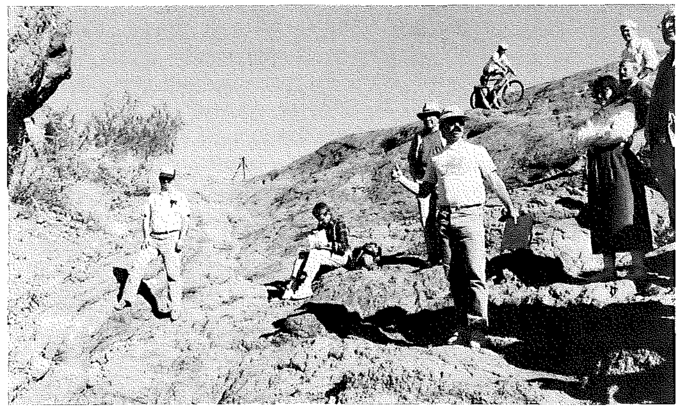
New AEG Southwestern Section

In June 1990, the Association of Engineering Geologists (AEG) established a Southwestern Section, which includes Arizona and Nevada. AEG is an international organization of professional geologists and engineers who conduct engineering-geology, groundwater, and environmental studies and investigations. Recent meetings have focused on geologic hazards associated with rapid urbanization, such as flooding, landslides, and earth fissures. Geoscientists and the general public interested in geology and its applications are invited to attend AEG meetings. Information, including meeting dates, speakers, and topics, may be obtained from Richard Brose, Interim Section Chairperson, c/o Malcolm Pirnie, Inc., 4636 E. University Dr., Suite 150, Phoenix, AZ 85034; tel: (602) 241-1770.

IOCC Members Examine the Geology of the Phoenix Area

The annual meeting of the Interstate Oil Compact Commission (IOCC) was held in Phoenix, Arizona in December 1990. The meeting was hosted by Governor Rose Mofford, with the assistance of the Arizona Oil and Gas Conservation Commission (OGCC). A premeeting field trip, organized by Dr. J. Dale Nations, OGCC Chairman, and the OGCC staff, provided an opportunity for participants to examine the geology of the South Mountains, Papago Park, and the Luke salt deposit west of Phoenix. The field-trip leaders were Drs. Stephen J. Reynolds, H. Wesley Peirce (retired), and Larry D. Fellows of the Arizona Geological Survey and Dr. Daniel J. Brennan and Mr. Steven L. Rauzi of the OGCC.





H.W. Peirce (top, second from left) explains the discovery of the Luke salt deposit. In 1968, Peirce stimulated the interest of Jerry Grott in developing a salt industry at this site. The facility is now operated by the Morton Salt Division of Morton Thiokol, Inc.

S.J. Reynolds (bottom, right center foreground) explains the local geology at Papago Park. Spanning eons of geologic time, Dr. Charles J. Mankin, director of the Oklahoma Geological Survey (at left), places his left foot on eroded Precambrian granite (1.7 billion years old) and his right foot on mid-Tertiary sedimentary rocks (25 million years old).

STAFF NOTES

Tom McGarvin co-led a workshop, titled "Geo-Literacy -- Understanding Earth's Secrets," for the annual conference of the Arizona Association for Learning in and about the Environment (AALE), which was held in Prescott in September 1990. Some 40 teachers participated in the session, which focused on methods for identifying and classifying rocks. In October, he conducted a workshop with JoAnne Wolf, Science Resource Specialist in the Mesa School District, for the annual convention of the Arizona Science Teachers Association (ASTA), held in Phoenix. The workshop, "Our Movin' Groovin' Earth," presented activities from a new curriculum unit that Ms. Wolf developed on basic concepts in geology, such as plate tectonics, earthquakes, and volcanoes. Approximately 75 teachers attended the workshop. On October 27 and November 3, McGarvin conducted field trips for local teachers on the geology of the Tucson area. A total of 23 teachers participated in both field trips.

Phil Pearthree has been appointed to the Advisory Committee of the Pima County Flood Control District, which advises county staff and the Board of Supervisors on flood-control and floodplain-management issues. He is also a member of the subcommittee that reviews technical issues of floodplain management for the Arizona Floodplain Management Association. On November 1, he and **Steve Reynolds** toured Kartchner Caverns to provide geologic expertise, at the request of Arizona Conservation Projects, Inc., a nonprofit organization devoted to conservation and education activities related to the cave.

Steve Reynolds also led a field trip on November 14 for Chevron geologists to view the structural geology of the Rincon Mountains near Tucson. On December 8 and 9, he led the fall field trip for the Arizona Geological Society, which focused on the geology and mineral deposits of the Lake Pleasant, Congress, and Wickenburg areas.

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