FIELD NOTES FROM THE ARIZONA BUREAU OF MINES

Vol. 4 No. 4 Earth Science and Mineral Resources in Arizona *Dec. 1974*

GEOLOGY AT ARIZONA'S UNIVERSITIES

INTRODUCTION

By
Stanton B. Keith,
Geologist

Geology, or geoscience as it is also called, is the study of the planet earth from its origin to the present. The subject is part science and part history. Briefly, it involves the interpretation of the origin of the planet, the formation and structural arrangement of the rocks, the identity and fabric of the minerals, the physical forces and chemical changes that have or are taking place on or within the earth, and the record of the development of life on the planet. Of more immediate importance is the role of geology in the discovery of useful mineral materials; in engineering problems concerning the location, planning, design, and building of structures in or on the earth; in the problems of water supply and resources; and in the identification of geologic hazards to human activities and welfare from natural or man-made surface phenomena such as floods, landslides, and earthcracks or from subsurface mobile forces within the earth such as earthquakes and volcanic activity. Clearly, although we may not recognize it, geology plays an important role in our daily lives and although most geologic events and processes take place too slowly to be readily recognized, they are constantly active all around us.

The geologic record of the past and present can be read from what we can see or deduce on or in the planet itself. The earth is the primary textbook. To a large extent, the record of past geologic events can be interpreted by comparing old geologic features to similar ones currently observed or simulated. Arizona offers an excellent field laboratory for such studies. Rock exposures, the leaves of the history book, range in age from early Precambrian time (some 1.7 billion or more years ago) to the present. The Grand Canyon of the Colorado; the extensive Colorado Plateau; the volcanic structures of the Flagstaff and

Northern Arizona University

Aerial panorama, looking north, of north-central Arizona, one of the several excellent field laboratories for geologists in the State. Flagstaff, home of Northern Arizona University, is in the foreground with the cluster of San Francisco volcanic peaks behind. In the distance extends the Colorado Plateau cut by canyons such as the Grand Canyon, of which the north rim shows in the upper left hand corner. It may be possible to distinguish the dim form of Navajo Mountain on the skyline just right of the center.

White Mountain areas, the Mogollon Rim country, and the perplexing pattern of mountains and valleys of the Basin and Range Province of southern Arizona, with its numerous mineral resources, continually present challenges in geologic interpretations.

Important geologic studies have been carried out in Arizona by the U.S. Geological Survey, the Arizona Bureau of Mines, and by other organizations and individuals as evidenced by the numerous publications listed in various bibliographies, but many excellent contributions to the knowledge of the geology of the State have come from the faculty and students at Arizona's three public-supported universities: University of Arizona in Tucson, Arizona State University at Tempe, and Northern Arizona University at Flagstaff. The departments dealing with geology at these institutions have taken advantage of the superb field laboratory Arizona offers. Through classroom instruction and field training, students are prepared in many branches of geologic endeavor which, along with faculty initiative and guidance, leads to numerous research projects designed both to provide a better understanding of geologic history and processes and to prepare men and women for service to mankind in various occupations. It is an exciting challenge to students and faculty.

In order to promote a better understanding of the important role the geology departments are playing, the Arizona Bureau of Mines devotes this issue of *FIELDNOTES* to a review of the activities of those departments. To the public in general, much of the geologic terminology in the following articles may be unfamiliar but it may stimulate interest in learning more about the geology of the State. To those having geologic interests, this review will provide an insight on what investigations have been made or are in progress at Arizona's universities.

The Bureau is indebted to the chairmen and heads of the various departments at the universities for the contributions they have provided to make possible this issue of *FIELDNOTES.*

DEPARTMENT OF GEOSCIENCES COLLEGE OF EARTH SCIENCES UNIVERSITY OF ARIZONA

By
Dr. Edgar J. McCullough Jr., Head

The Department of Geosciences is one of the four units at the University of Arizona comprising the College of Earth Sciences. The Department currently has a faculty of 29 and a staff of 12. During the 1973-74 year the Department of Geosciences provided instruction to some 2610 students in 68 courses and finished the year with 323 majors: 16 B.A. candidates, 154 B.S. candidates, 101 M.S. candidates, 42 Ph.D. candidates, and 10 unclassified or international special students. Forty-seven students completed work for degrees: 24 B.S., 17 M.S., and 6 Ph.D. During this period, the faculty published 1 book, 5 chapters in books. 30 articles in referred journals, 1 map, 34 abstracts, 2 encylopedia articles, 6 reviews, and edited 5 publications. Research grants, contracts, and gifts awarded during the year totaled some $502,000. During 1973-74, faculty members presented papers at 4 international, 12 national, 15 regional, and 1 state meeting of professional and scientific organizations, as well as presenting 33 talks to local civic groups. The Department of Geosciences hosted the Joint Winter Mineralogical Meeting sponsored by the Mineralogical Society of America, Friends of Mineralogy, Mineral Museums Advisory Council, Tucson Gem and Mineral Society, and the University of Arizona.

The Department of Geosciences is organized around the disciplines of geobiology, geochemistry, geology, and geophysics. The two major areas of teaching and research, geochronology and non-renewable resources, involve all four of the disciplines. The following report on the scholarly activities of our students

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DEPARTMENT OF GEOLOGY ARIZONA STATE UNIVERSITY

By
Dr. Troy L. Péwé, Chairman

Rocks deep in the Grand Canyon, lava flows and volcanic ash deposits on the San Francisco Peaks, moon rocks, environmental geology mapping, geophysical probes of the deep water-bearing sediments near Phoenix are all part of varied teaching-research activities of the students and faculty of the Geology Department of Arizona State University. Geology was founded as a separate department at A.S.U. in 1957 and is one of the younger departments in the 89-year-old institution known as Arizona State University. The Department is now an active research-oriented department offering B.A., B.S., M.S., and Ph.D. degrees, as well as a Departmental teaching major and minor in the B.A. in the Education Degree Curriculum.

The faculty consists of 12 nationally and internationally known scholars. All of the faculty have studied widely and almost all have had valuable geologic experience in various parts of the world and are applying techniques from other countries to better understand and use the geology of Arizona.

The research-oriented teachers and visiting professors work closely with graduate and undergraduate students. In addition to faculty research in geologic problems of Arizona, most of the more than 50 graduate students on the M.S. and Ph.D. level are guided by faculty in research problems throughout the State. Funds for faculty and graduate student research are received from NSF, NASA, U.S. Army-Durham, U.S. Army-CRREL, National Academy of Sciences, National Park Service, Research Corporation, Petroleum Research Fund, U.S. Geological Survey, as well as several

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DEPARTMENT OF GEOLOGY NORTHERN ARIZONA UNIVERSITY

By
Dr. Augustus S. Cotera Jr., Chariman

Geology at Northern Arizona University consists of both teaching and research with the latter being used to supplement and compliment good teaching. Without good students to teach, Geology at N.A.U. would lose its reason for being. Programs have been formulated to prepare students, at the B.S. and M.S. levels, to enter into the mainstream of industry. We emphasize fundamentals in Geology as well as in the supporting sciences, rather than highly specialized and restricted areas of concentration. As a consequence, our staff constitutes a diverse balance of several specialities intentionally designed to overlap and support each other. The staff consists of nine full-time professors and four part-time adjunct professors from the U.S.G.S. Astrogeology Center in Flagstaff.

Foremost in 1974 was the meeting of the Rocky Mountain Section of the Geological Society of America, held in late April. By a massive joint effort with the U.S.G.S. Astrogeology Center, the Department hosted a highly successful meeting attended by 587 geological scientists. A total of 139 papers and 10 field trips provided the participants with a full and varied exposure to the geology of Northern Arizona and the surrounding area. The N.A.U. staff and students presented 21 papers and led several field trips. Especially prepared for this meeting was a first-rate publication of 821 pages: *Geology of Northern Arizona.* This 2-volume set contains 52 papers and 8 field guides edited by members of the staff of the U.S.G.S. Astrogeology Center and the Department of Geology at N.A.U. (a few copies are still available through the N.A.U. Bookstore).

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DEPARTMENT OF MINING AND GEOLOGICAL ENGINEERING COLLEGE OF MINES UNIVERSITY OF ARIZONA

By
Dr. Thomas J. O'Neil, Head

For those of us in the fields of earth science and mineral engineering education, the energy crisis provided some good news and some bad news. We need not linger on the bad news; there is nothing new to be said about long gasoline lines and skyrocketing fuel prices. However, whereas we had long been laboring in relative obscurity, last winter the fundamental impact of mineral raw material on the way we live was demonstrated with unimpeachable clarity. Even though energy was of prime concern, very little imagination was required to see analogous conditions with other mineral commodities. At the same time, environmental concern over land and water use became an important factor in both the mining and geological engineering fields. For both problems it became evident that mining engineers and geological engineers were part of the solution, not part of the problem.

The Department of Mining and Geological Engineering offers courses of study in geological engineering designed to prepare young men and women in the specialized professional application of geology in the fields of exploration for and production of mineral resources, in the engineering construction industry, and in related fields such as water-resource development, underground storage of liquified petroleum products, and urban planning. These fields of study and research deal primarily with the engineering aspects of natural forces and materials and the evaluation and correlation of geologic data concerning them. The three major divisions of study are geotechnics, dealing with fluid, soil and rock mechanics and the engineering aspects of geology, geophysics, hydrology, and other related sciences; mining geology and exploration for mineral deposits; and geomechanics, dealing with deformation phenomena in rock masses due to imposed stresses and strains. Geostatistics, the use of multivariate statistical methods as applied to sampling and analysis of geologic data, plays an important role in the training and research. Supporting courses are required or elected in allied sciences and humanities as well as from those given in the Department of Geosciences. The department offers opportunities to earn B.S., M.S., and Ph.D. degrees in Geological Engineering.

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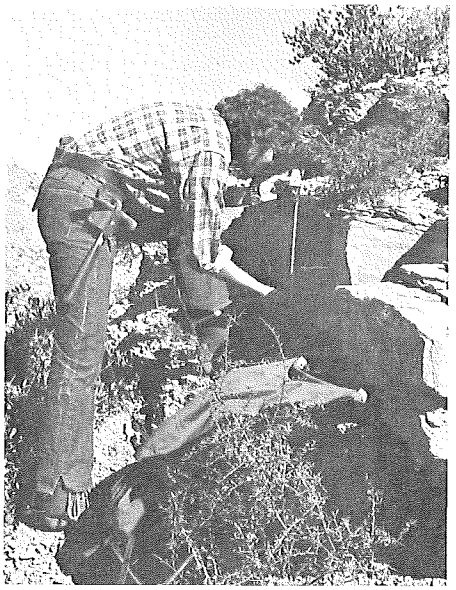
and faculty will indicate where our interests have developed in these areas.

Conodonts, which are tiny tooth- or jaw-shaped microfossils of unknown origin, are proving to be a valuable biostratigraphic tool in Arizona. Dr. Dietmar Schumacher presented evidence at the Symposium on Northern Arizona Geology concerning the age of the sequence of rocks east of the Grand Wash Cliffs that some geologists assign to the Cambrian and others assign to the Devonian. Part of this controversial sequence at localities south of Peach Springs contains Upper Devonian conodonts.



University of Arizona

Field investigations are the backbone of geologic research. Here a student measures the thickness and attitude of a rock outcrop.

Continuing research on conodonts in the Martin Formation of Devonian age indicates an age for most of the Martin as Frasnian (lower part of the Upper Devonian). A thin interval in the upper part of the Martin is Famennian (upper part of the Upper Devonian) in age and appears to be widespread in central and southeastern Arizona. Dr. Schumacher and his students are continuing to catalog Paleozoic invertebrate fossil localities in Arizona and will also check the faunal lists of these localities.

A catalog of Cenozoic vertebrate fossil localities in Arizona was published by Dr. Everett H. Lindsay, Jr. and Norman T. Tessman in the February 1974 *Journal of the Arizona Academy of Sciences* and includes faunal lists of 163 vertebrate localities. They examined and checked the identification of fossil specimens from Arizona in the collections of museums which have major collections from Arizona. New material from Cave Creek extended the Tertiary vertebrate fossil record back into the middle Oligocene. Other fossils from the Oligocene and early and middle Miocene epochs (which are middle Tertiary) include rhinoceroses, pocket mice, and camel remains. Later Tertiary fossils are more abundant with rodents, dogs, three-toes and single-toed horses, foxes, camels, llamas, mastodons, peccaries, rabbits, bears, raccoons, weasels, pronghorns, beavers, etc. The late Pliocene and Pleistocene fossils are quite abundant and include those mentioned above in addition to squirrels, woodchucks, pack rats and other rats, wolves, badgers, hyenas, shrews, bats, tortoises, gophers, ground sloths, pocket and other mice, kangaroo rats, cats, modern horses, deer, skunks, jaguars, toads and frogs, lizards and snakes, mammoths, ringtail cats, mountain goats and sheep, elk, and bison.

Dr. Lindsay is also participating in a National Science Foundation study of the paleomagnetic stratigraphy of late Cenozoic sediments in the San Pedro Valley in southeastern Arizona. Iron compounds in clay and sand line up with the magnetic poles when they settle into lakes and streams. The magnetic poles have reversed many times in the last several million years and the ages and durations of these reversals are now known back to 5 million years ago in this area. Dr. Lindsay is correlating the vertebrate faunas with the magnetic chronology. Preliminary work indicates that the St. David Formation and the Quiburis Formation, which were thought to be deposited during different intervals of time, have some overlap in their magnetic sequence.

Graduate student Louis Jacobs studied the small mammals in the Quiburis Formation near Redington and assigned a middle-to-late middle Hemphillian land mammal age based on the stage of evolution of the rodents. Potassium-argon dates for volcanic tuffs and paleomagnetic data from the Quiburis Formation indicate an age slightly older than 5 million years.

The University of Arizona Laboratory of Paleontology is also continuing its mastodon casting project under the direction of Dr. Lindsay. Graduate student J. J. Saunders and vertebrate paleontology preparator Kevin Moodie have developed several new techniques of latex molding and fiberglass casting in the process of completing these mastodon casts for display at the Osaka Museum of Natural History and Illinois State Museum.

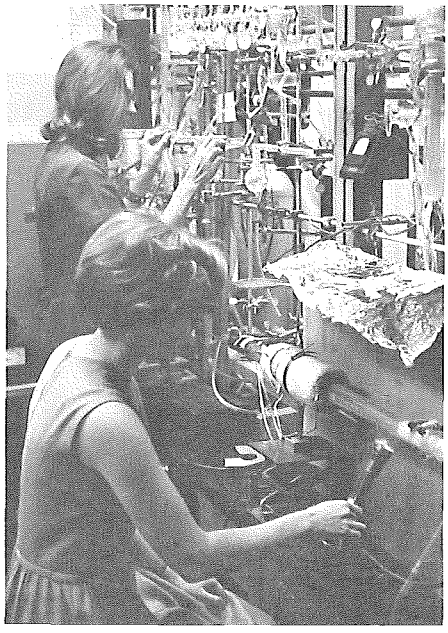
Mapping and radiocarbon dating of the layered ground sloth dung deposits in Rampart Cave and Muav Cave in the lower Grand Canyon have denoted when the ground sloth, which is extinct, lived

there. Dr. A. Long, R. M. Hansen, and Dr. P. S. Martin have published papers on the diet and the life and death of the Shasta ground sloth. The sloths were mainly browsers on vegetation that is still available in the area. Sloths used the cave before 24,000 years ago and between 14,000 to 11,000 years ago. Radiocarbon dates on ground sloth dung indicate they disappeared about 500 years later in South America than in North America. This supports Dr. Paul Martin's theory of overkill by Paleoindians 11,000 years ago. Dr. Martin is continuing to accumulate evidence for Pleistocene overkill and is currently working with Dr. James E. Mosimann on simulating overkill by Paleoindians with mathematical (computer) models.

Thomas Van Devender studied pack rat nests in the Sonoran desert for his Ph.D. dissertation and documented the change in climate and accompanying vegetation changes during the Wisconsin (latest glacial advance in North America) and post-glacial stages. The pack rat middens that yielded radiocarbon age dates between 30,000 to 11,000 years ago contained about 30% woodland plants which now occur at elevations 262-662 meters (850-2150 feet) higher than the pack rat midden collection sites. The cold-tolerant Mohave Desert plants also displaced the warmth-loving Sonoran Desert plants at least 80 km (about 50 miles) to the south. Van Devender inferred the late Wisconsin climate had 1.5-3.9° centigrade cooler annual temperature and 8.2-22.0 centimeters (about 3-9 inches) greater annual rainfall. He accounts for this by a southward shift in the winter storm tracks and concludes that the ice age affected the climate and life of southwestern Arizona only minimally and, perhaps, less than the rest of the United States.

The first Paleozoic lepospondyl amphibians discovered in Arizona have been described in a master's thesis by David Thayer. The lepospondyls are a group of amphibians to which the modern salamanders belong. Their occurrence in the Black Prince Limestone in the northern Swisshelm Mountains in Cochise County makes that the earliest North American lepospondyl amphibian site. The age of the fauna is Late Morrowan or Early Atokan (Early-early Middle Pennsylvanian).

In the area of palynology, Dr. Gerhard Kremp has begun collecting publications in the field and compiling the pertinent information for mechanized data retrieval in his PALYNO DATA project. Electron photomicrographs, which will be part of an eventual atlas of southwestern pollen grains, have been published by Dr. A. M. Solomon, Dr. P. S. Martin, Dr. J. E. King, and J. Thomas in the Arizona Academy of Science Journal. The report also includes a list of all species photographed and published to date. Dr. A. M. Solomon, J. L. Webb, and G. K. Kelso have used pollen data collected from the city of Tucson, San Xavier, and from pueblos in New Mexico to document modern and prehistoric disturbance of arid lands by humans. W. G. Spaulding examined the pollen content of mountain sheep fecal material collected from rock shelters for a master's thesis. The material was deposited only in the late spring between 7000 and 2500 years ago. Springtime occupation of the rock shelter by the sheep ended about the time that Indian occupation of a nearby rock shelter began during the spring pinyon nut season.



University of Arizona

Carbon-14, a heavy radioactive isotope of carbon, is produced in nature and breaks down at a constant rate of decay. By measuring the amount of Carbon-14 remaining in carbon-bearing material, the date of origin of the material, if formed within the last 50,000 years, can be determined within close limits. Here student assistants are working in the geochronological Carbon-14 preparation room.

Coal samples, rock and soil samples, and rain runoff samples from the Black Mesa mining area in northeastern Arizona have been analyzed for toxic trace elements. Dr. Austin Long and Pete Kresan have used atomic absorption and neutron activation techniques for these analyses which have been documented in an interim report to the U.S. Bureau of Mines.

The stable isotope content of a parcel of water can indicate much about its history. Robin White and Dr. Long are beginning analyses of rainwater, stream water, and groundwater to characterize Tucson basin water. Mr. White's master's thesis will discuss the processes that have affected the groundwater and whether the groundwater in present use is similar to the water now entering the groundwater reservoir.

In a related Ph.D. dissertation, Edward Wallick developed a chemical-isotopic equilibrium model to adjust radiocarbon ages of groundwater in the arid Tucson basin because of carbon-14 in calcite (caliche) in the soil.

Dr. D. E. Livingston is investigating the trace element geochemistry of the Precambrian rocks of the upper and lower granite gorges of the Grand Canyon. Livingston suggests in a *Geol. Soc. Am.* abstract that the rocks containing low amounts of Rubidium were differentiated before or during tectonic activity. The high Rubidium group of metamorphosed clastic sedimentary rocks and igneous rocks of the upper gorge were differentiated late in the tectonism or after the major tectonic activity. Preliminary Rubidium-Strontium age dates of the granite from Phantom Canyon and the Trinity Gneiss are 1650 million years old and 1700-1850 million years, respectively. Other material is being analyzed for additional age dates.

"Younger" Precambrian igneous rocks of central Arizona have been analyzed by Dr. Livingston for Strontium isotopic ratios and Rubidium and Strontium abundances. The diabase (a medium-grained, black, igneous rock) which intrudes both the Apache Group and the Troy Quartzite in the Sierra Ancha Mountains yields a good age date of approximately 1200 million years ago. Some diabase which intrudes the City Creek series in the Mazatzal Mountains yields a preliminary age date of 1300 million years.

Numerous Potassium-Argon age dates have been published through the continuing National Science Foundation grant to Dr. P. E. Damon and his laboratory on "The Correlation and Chronology of Ore Deposits and Volcanic Rocks."

Dr. Livingston has suggested in a paper in *Earth and Planetary Science Letters* that the ages and locations of copper porphyry deposits in the southern Basin and Range Province indicate the direction of continental drift in the area. The copper deposits were emplaced under the influence of a mantle hot spot as this part of the North American plate moved N35-40°W during the time of the Laramide orogeny 72-52 million years ago.

The age and Strontium isotope ratios of the LaCaridad, Sonora copper porphyry deposit have been published by Dr. Livingston in the *Geol. Soc. Am. Abstracts.* It is the youngest, 53 million years old, and southernmost of the Laramide deposits so far dated.

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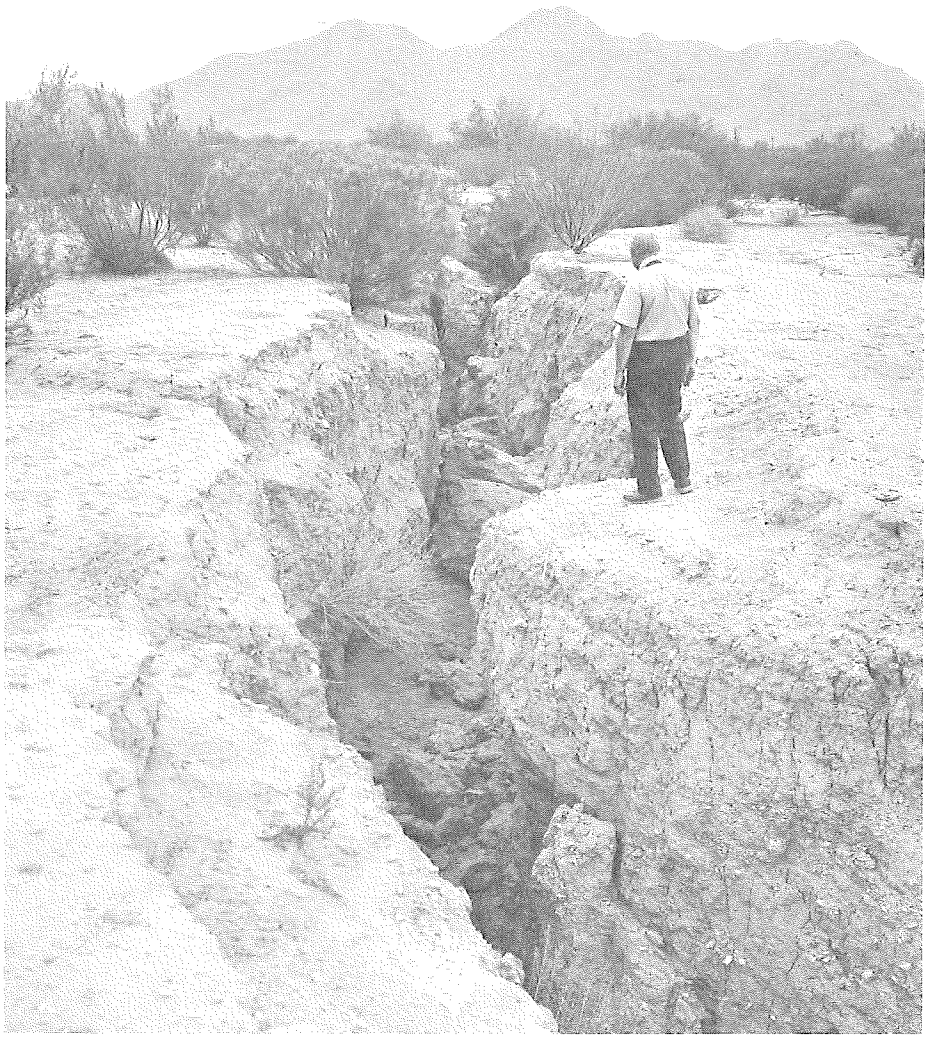
industrial companies and other organizations, including the cities of Phoenix and Scottsdale. The results of these studies are published in state, national, and international scientific journals.

A number of graduate students and faculty are involved in timely environmental geological and geochemical work, that is, the use of the principles of geology and geochemistry to provide a better understanding of man's use of and impact on the environment. Dr. William A. Sauck and a graduate student have just completed a much used, detailed, and up-to-date geophysical study of Paradise Valley near Scottsdale, which indicates a sediment-filled valley at least 9000 feet deep with ground water to satisfy Scottsdale's present demand for approximately 130 years.

Excessive ground water withdrawal in central Arizona has created a geologic hazard in the form of dangerous subsidence cracks which may be up to 50 feet deep, 6 feet wide, and hundreds of feet long. These are being studied by Drs. Sauck and Donal M. Ragan, who are currently studying the origin and distribution of these cracks. A graduate student under the direction of Dr. Ragan just completed a study to determine the factors controlling crack location and explore possible mechanisms of crack formation.

The quality and quantity of ground water is important to Arizona. Hexavalent chromium and nitrate content of ground water in parts of Paradise Valley near Scottsdale locally exceeds the limit for established health standards. Two research projects under the direction of Drs. Michael F. Sheridan and Burr A. Silver are near completion which delineate the hazardous areas and offer recommendations for future development. Dr. Carelton B. Moore and a graduate student have just completed a study of boron distribution in natural waters and sewage effluent in Arizona. Desert areas have higher boron content than the northern part of the state and locally the content is high enough to be detrimental to citrus growth. Research by Dr. Peter R. Buseck and graduate students is developing methods for the chemical analysis of particulate air pollution. Particulate air pollutants are a special problem in Arizona and current techniques are not equal to the task of determining the sources of these particulates. The primary analytical tool for this is the electron microprobe analyzer, an instrument able to do chemical analysis on particles less than 1 micron (1:25,000th of an inch) in diameter. The total investment in the laboratory facilities for this purpose approaches a quarter of a million dollars and permits a very powerful means for attacking this serious problem.



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Spectacular earthcracks in caliche-cemented alluvium occur in many valley areas of southern Arizona and are often due to land subsidence caused by ground-water withdrawal. Recognition of this hazard is important in land use planning and is the subject of geological research. Here we are looking north to the Gold Mine Mountains from the south side of Chandler Heights on Hunt Road, 1¼ miles east of Powers Road on the boundary between Maricopa and Pinal Counties. The crack is open to a depth of at least 50 feet.

Two timely projects involving three graduate students, under the direction of Dr. Troy L. Péwé, concern the environmental geological mapping of the Phoenix Mountains in Phoenix and the McDowell Mountains near the city of Scottsdale. Phoenix and Scottsdale are among the pioneers in the United States to solely fund such land use geologic studies. Similar studies by three students under the direction of Dr. Silver are under way in the Pinnacle Peak area northeast of Phoenix and the Apache Junction area near the Superstition Mountains. These geologic studies are the first to be supported by corporations and developers in the Phoenix area. From basic geologic maps it is possible to provide land use information to architects, land planners, city officials, engineers and others. These basic earth science data are presented on derivative maps in layman's language. Derivative maps include those dealing with sand and gravel resources, ground water, soil excavation and foundation problems, and geologic hazards such as flooding.

The lower Verde River Valley has been mapped geologically under the guidance of Dr. Péwé and provides information for necessary geologic background of construction sites for planned settlements as well as background for CAP reservoir studies.

Investigations of geothermal water chemistry at potential geothermal sites have been undertaken by Dr. Sheridan and a graduate student. Several areas of potentially high reservoir temperatures were determined through Na/K and SiO_2 content of thermal spring water. Dr. Sauck is continuing an evaluation of the geothermal ground noise phenomenon as an exploration tool. Most geothermal areas appear to have a characteristic low

level, nearly continuous seismic signature in the range of 1 to 20 Hz. A graduate student of Dr. Buseck's is testing mercury geochemical prospecting as a means for locating buried geothermal sources.

A seismographic station that is part of the cooperative Epicenter Program has been operating continuously since November, 1971 and reports monthly to the U.S. Geological Survey. The station consists of a long period horizontal seismograph under the supervision of Dr. Sauck.

The magnetic character of a porphyry copper deposit was investigated by a graduate student guided by Dr. Sauck. He measured the magnetic susceptibility of drill cores from the CONOCO Poston Butte deposit and correlated their magnetic response with lithology and alteration. His work matched well with a surface magnetic survey.

Two recent long-term projects give detailed information on large scale mapping of the two high peak areas of Arizona; under the direction of Dr. Péwé, the volcanic geology of the San Francisco Peaks and White Mountains, as well as the glacial deposits, are now well known. The San Francisco Peaks that are now known to have formed in about the last 2 million years are now the center of intense work because of geothermal possibilities. In addition to 150 chemical analyses used in the above mapping project, a long-term project has been under way by Drs. Moore and Holloway on the geochemistry of the San Francisco Peaks. More than 100 major element chemical analyses have been made and work is now concentrating on trace elements. The White Mountains of eastern Arizona on the Colorado Plateau are about 9 million years old and represent a dissected composite volcano built up over the years; they have been glaciated in the last 200,000 years. Basic geological information is now available for land use interpretation of both of these volcanic areas.

Arizona State University

Geophysics, a means of determining geologic features beneath the surface of the earth through measurements of natural earth currents, applied electric currents, heat flow, magnetic properties, radioactivity, seismic response, and gravity, has an important role in geologic research. The photograph shows A.S.U. students measuring seismic velocities in order to determine the thickness of overburden. The hammer produces shock waves that are recorded by the geophones spaced along the wire, and the results are read on the seismic refraction amplifier and camera console. Such portable units have many uses related to investigations of groundwater, stratigraphy, and structure.

Research projects in sedimentology and physical stratigraphy at Arizona State University range from recent marine studies in the Sea of Cortez to reconstruction of Mississippian carbonate environments of Arizona. Emphasis is placed on problems which provide additional background for understanding fossil fuel and ground water potential of Arizona host rocks and reservoirs. For example, a recently completed study on the Dakota Formation of the Black Mesa Basin guided by Dr. Silver resulted in a better understanding of the origin and distribution of coal in the formation as well as better delineation of potential ground water reservoirs. Other projects in this general area of research include stratigraphy of the Supai Formation in central Arizona, carbonate diagenesis of the Virgin Limestone, Nevada, reservoir potential of the Escabrosa Limestone, and diagenesis of sedimentary carbonates. Projects in the incipient stage by Dr. Silver and his students include depositional patterns of the Escabrosa Limestone in Arizona and northern Sonora, Mexico, and deltaic sedimentation of the Toreva Sandstone, Black Mesa Basin.

A comprehensive study of the stratigraphic and geographic distribution of conodonts in Mississippian rocks of Arizona was begun in 1969 by Dr. Robert F. Lundin and graduate students. The first studies covered southeastern and east-central Arizona. A project under way includes the Chino Valley and central Grand Canyon region. Preliminary sampling has been completed in the northwestern corner of the state.

These studies have led to correlation of the Escabrosa Limestone and Redwall Limestone (of east-central Arizona) with rocks ranging from middle Kinderhookian (Upper Choteau) to middle Meramecian (St. Louis) in age in the type area of the

Mississippian. Recognition of six conodont zones has made a refined biostratigraphic subdivision of these rocks possible. Accordingly, Mississippian history in Arizona is better known. Such basic information is important in the search for oil and gas in Arizona.

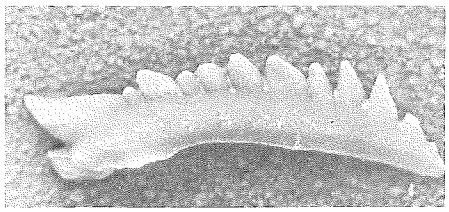
Work is proceeding on a reconnaissance survey of the Precambrian metamorphic rocks present in the several mountain blocks which surround the Valley of the Sun. Under the general direction of Dr. Ragan, some of the mapping has been done in conjunction with other studies, including Mummy Mountain pegmatites and the environmental studies listed above. Altogether, several hundred square miles have been briefly surveyed, and several smaller areas chosen for more detailed work. As this work progresses, the results promise to be an important contribution to the understanding of the Precambrian history in central Arizona.

Dr. Sheridan has been studying textures of primary volcanic deposits in the circum-Pacific area and Arizona to develop a model of pyroclastic transport. A general model of eruption is an initial fluidized system above the vent that deflates as it moves laterally by wind shearing or by ground-hugging surges. A facies classification of primary textures will lead to a better understanding of the nature of the eruption and emplacement conditions of volcanic clouds in Arizona and elsewhere.

Using in part rock units found in the Superstition Mountains and adjacent volcanic areas. Drs. Sheridan and Ragan have started an attack on the fundamental mechanical processes involved in the eruption, transport, and compaction of ash from tuffs and related products. It has been found possible to decipher much of the post-eruptive history by studying the grain structure of noncompacted ash deposits, and by measuring the strain history in compacted or welded units.

Culmination of a long-term project with several students is the detailed study and interpretation of volcanic geology of the Superstition Mountains, Goldfield Mountains, and other volcanic mountains along the Salt River east of Phoenix. Several huge calderas have been discovered and work by several graduate students under the guidance of Dr. Sheridan has provided modern interpretation of the type and origin of rocks and perhaps associated mineralization in similar caldera environments.

Dr. Buseck and students working on ore deposits are concerned with geochemical prospecting for buried ore deposits, the development of supergene minerals, and their use for searching for ore. They have developed a new, highly sensitive, field portable instrument for detecting mercury at the part-per-billion level. The instrument is the size of a shoebox, is easy to operate and transport into the field, and is both less expensive and more sensitive than existing instruments. It is used to detect mercury concentrations at the surface from deposits that are buried by hundreds of feet of alluvium, glacial debris, or perhaps even volcanic rocks. They also are studying the mineralogy of the weathered zone of porphyry copper deposits as an aid to prospecting for buried copper deposits.



Arizona State University

What is it? These small, tooth- or plate-like fossils, called conodonts, are a mystery as to their origin and biologic function but have become very useful in identifying and correlating rock units on the basis of the fossil contents. They are found in rocks ranging in age from Middle Cambrian to Upper Triassic. Pictured here is a new conodont, approximately 2 mm long, from the Redwall Limestone of Mississippian age.

In the field of solid state geochemistry, Dr. Buseck has been studying the structure of minerals using high resolution electron microscopy. By using the transmission electron microscope, he and his students are able to increase the volumetric resolution by 15 orders of magnitude (10^{15}) and consequently see for the first time a great deal of fine-structure previously unsuspected. They study and photograph individual clusters and rows of atoms both in ore minerals and in silicates. The techniques which are being pioneered by Dr. Buseck and his students here will eventually find themselves used in most if not all of the larger geology departments around the country – within 5 or 10 years every department that now has an x-ray diffractometer will find it advantageous to also have a high resolution electron microscope.

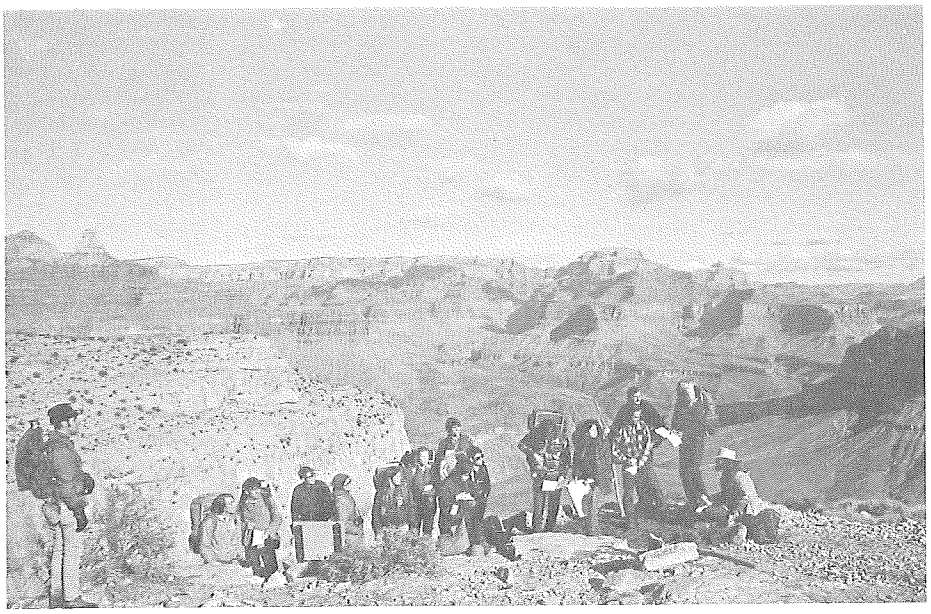
Meteorites are of particular interest because they are samples from the outer regions of the solar system and thus provide us information from areas that are otherwise inaccessible. The Center for Meteorite Studies at Arizona State University, under the directorship of Dr. Moore, houses a collection of now more than 1000 different meteorite specimens from different localities, making it one of the four or five largest collections in the world. The Center has a publication series and research program. Major research efforts by Drs. Moore, Buseck, Larimer, and graduate students include the characterization and description of new meteorites using atomic absorption, scanning electron microscope, transmission electron microscope, electron microprobe, and combustion analysis techniques, as well as the more classical methods. A major program for the analysis of amino acids and other organic compounds in carbonaceous chondrites has been initiated in conjunction with the ASU Department of Chemistry and the NASA Ames Research Center. Also, studies of the metallic fragments in the vicinity of Barringer Meteorite Crater near Winslow are under way by Dr. Moore.

The geochemistry of the volatile elements carbon, sulfur, and nitrogen in igneous rocks and lunar samples is being studied by Dr. Moore and a graduate student. The moon samples are depleted in carbon and nitrogen as compared to the earth but appear similar in total sulfur content. Studies of sulfur in basalts from northern Arizona may shed light on sources of sulfates in the soils of the upper Verde Valley and the Painted Desert areas.

Dr. John W. Larimer is continuing studies aimed at understanding the chemical and physical processes that were operative in the primitive solar nebula during the time the planets and other objects were forming. This research involves extensive calculation to predict the condensation temperatures of various key elements and stability fields of key minerals in a cooling gas of solar composition. The predictions are then compared to the composition and mineralogy of meteorites primarily, but also to terrestrial and lunar rocks. For example, the deficiency of elements such as Pb, Bi, In and Tl in meteorites, coupled with the presence of FeS and lack of Fe_3O_4 points to a formation temperature of 400 to 500°K. These studies are now being extended to the rare, highly reduced meteorites which appear to have evolved in a carbon-rich region of the nebula. Another current study is aimed at predicting the history of metallic trace elements. These results will be useful in testing the competing hypotheses of whether the earth accreted heterogeneously, in a layer -cake fashion from the core outward, or homogeneously, in which the metal initially was distributed uniformly but later segregated to form the core.

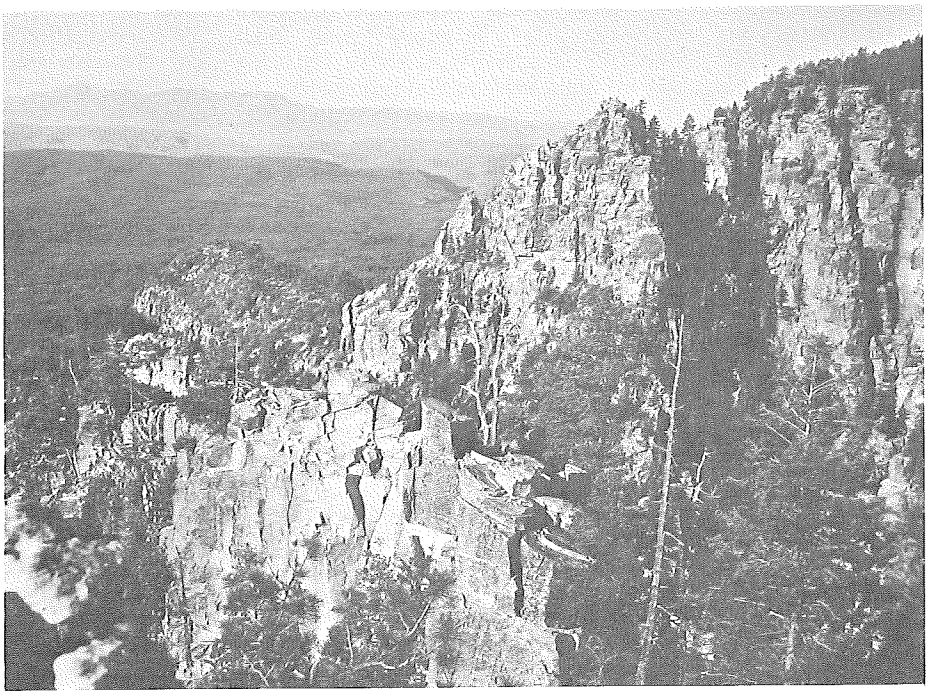
Peridot Mesa on the San Carlos Indian Reservation has been a world-famous source of the semiprecious gem peridot for many years. The peridot crystals and the basaltic lava flow in which they occur are also of great scientific interest because they appear to have originated at great depth (about 15-20 miles) below the earth's surface, that is, near the

Continued page 10



Northern Arizona University

The deep gorge of the Colorado River exposes geologic formations dating back to older Precambrian time (some 1.7 billion years) which record the geologic history of the area. Note how the various fromations have characteristic physiographic exposures such as cliffs, slopes, or benches depending on their physical and chemical character. Here Dr. Dale Nations and students at N.A.U., on a field trip, are on a bench formed on the Redwall Limestone of Mississippian age (some 345-320 million years ago).

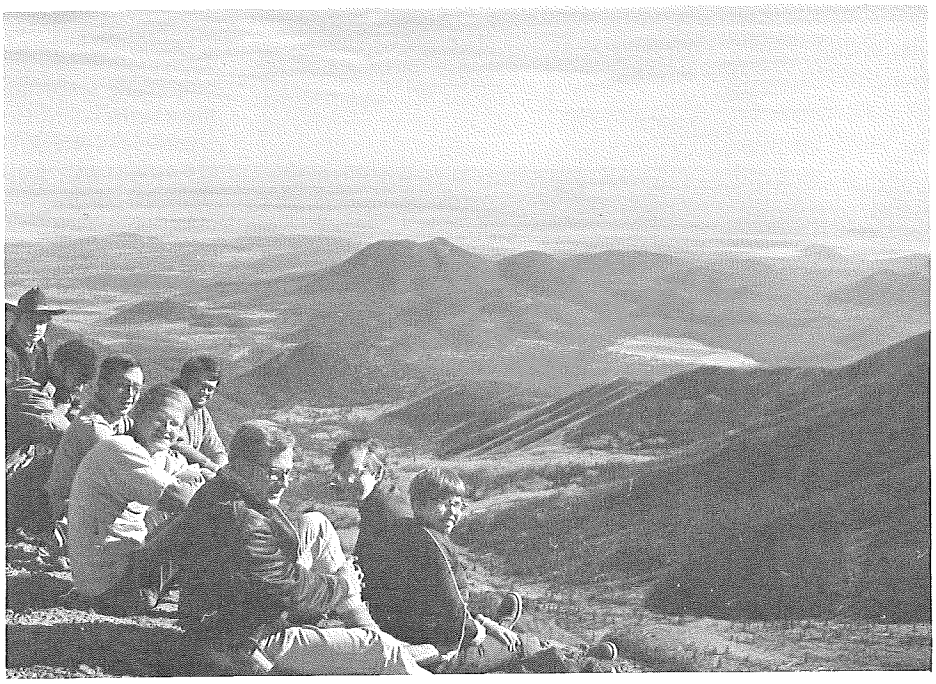


Arizona Bureau of Mines

The Mogollon Rim is a striking physiographic feature in central Arizona, forming a break between the relatively flat Colorado Plateau to the north and the rough, mountainous transition zone and the Basin and Range Province to the south. The view is to the southwest from the Rim east of Payson with the Coconino Sandstone of Permian age (some 280-225 million years ago) in the foreground, and Precambrian rocks and the Mazatzal Mountains beyond. The complex formational and structural relationships of the Rim country offers a challenge to geological research.

Arizona Bureau of Mines

Complex block-faulted mountain ranges with intervening alluvium-filled valleys are the main features of southern Arizona. Many such ranges are the sites of important mineral deposits and both mountains and valleys offer students and faculty many research problems in numerous fields of geology. Here we are looking east across the Santa Cruz Valley to the Santa Rita Mountains, south of Tucson.



Arizona State University

Geology students from A.S.U. on a field trip to the San Francisco Peaks near Flagstaff. Research projects on the glacial deposits, volcanic rocks, and physiographic features of this area have been carried out for many years by faculty and graduate students of A.S.U., N.A.U., and U.of A. The view is to the east down the interior valley, exposing the glacial deposits. The main peaks are about 2 million years old. Sugarloaf Mountain at the mouth of the valley, in the middle, is 250,000 years old and was emplaced following an explosive ash surge. Sunset Crater, in the far middle right, is 900 years old.

ASU *Continued*

crust-mantle boundary. In addition to the peridot (which is a variety of the mineral olivine), many other interesting minerals occur in the lava flow. Dr. John R. Holloway and graduate students are studying the chemical properties of these minerals and rock in several of these lava flows in the San Carlos area, to determine the pressure, temperature and chemical conditions existing near the crust-mantle boundary beneath Arizona. Such information is of great value in the understanding of the origin of volcanoes and ore deposits. To aid in that determination, they use in the laboratory a special pressure apparatus in which they can simulate the very high pressure and temperature found at great depth below the earth's surface. The results of these experiments are minaturized lavas which closely resemble those found at San Carlos.

In addition to teaching and research with undergraduate and graduate students, the Department long has been associated with Earth Science education for High School teachers. Dr. Paul T. Miller has directed and taught in many National Science Foundation supported Summer Institutes and Academic Year Institutes for Earth Science teachers and Secondary School Science teachers at ASU. Geology (Earth Science) as a subject taught in High Schools has had a phenomenal growth in Arizona since the early 1960s. In Maricopa County alone it has increased from a few classes in one school to several classes in most of the schools. It is conservatively estimated that in Maricopa County there are more than 8000 students enrolled in Earth Science classes at present. It is in part from this growing group that future geology students will be derived for the three State Universities and, therefore, later for service as teachers and researchers in geology in Arizona.

At present, Dr. Miller is conducting a pilot program for the Earth Science teachers of Maricopa County for the Southwest Section of the National Association of Geology Teachers to foster a closer relationship and exchange of information among High School Earth Science teachers.

The faculty of the Geology Department of Arizona State University are training students for various levels of teaching as well as for geological research in Arizona and throughout the country. Some graduates occupy positions in the mining industry in the State, and others are employed by petroleum companies in the western United States. Geologists serve with State and Federal Geological Surveys and with many of the State organizations dealing with oil, gas, water, and mining. Other graduates are concerned with land planning and utilization, pollution control, and are associated with various consulting firms locally and in the Southwest.

The Department of Geology at ASU is growing rapidly, and nearing completion is a 6-story Geology-Physics building generously funded by the taxpayers of Arizona. The geological and geochemical research conducted by the faculty and students is contantly solving problems vital to further growth and development of Arizona, from finding better methods for outlining ground water supplies, potential petroleum fields, or new mineral deposits, to better use of the environment through wise application of the principles of earth science.

NAU *Continued*

In the 1974 academic year, enrollments in geology courses broke all records. Although the number of majors was held steady (130 undergrad and 35 graduate students), the large number of non-majors taking Geology resulted in an increase in enrollment of 21% over last year. For geology graduates, the employment prospects were and continue to be excellent. Many students received several job offers and every graduate is currently professionally employed. Eighteen major petroleum and mining companies, technical consultants, and the U.S.G.S. hired our students, with many companies interviewing on campus. The prospects for June 1975 look even brighter as demand for geologists continues to increase as mineral and energy resources become increasingly critical.

Finally a large number of less spectacular but significant accomplishments were made, chief of which was approval of a new seismic observatory, and an agreement with the Grand Canyon National Park for supplying staff and students in the visitor program. In the latter area, the staff will teach courses in geology to Park personnel and graduate students will explain geology and conduct field trips for visitors to the Park.

The research investigations of the staff and students continue to diversify and intensify in an attempt to comprehend the geology of northern Arizona and to apply this new knowledge to the betterment of society. Our research efforts have been grouped into five categories and hopefully will provide some insight into our activities, interests, and accomplishments.

Dr. David S. Brumbaugh has been involved in geophysical studies focused chiefly on structural problems. The Gray Mountain Monocline, north of Flagstaff, has been studied using both gravity and magnetic mapping programs and computer modelling. Other monoclines in the transitional zone near Paulden, Arizona are also currently being investigated using these tools. The Anderson Mesa fault zone near Lake Mary was studied by Dr. Errol L. Montgomery using magnetic and gravity profiling and modelling in order to delineate structural controls.

Using geophysics, Dr. Montgomery also is cooperating with the City of Flagstaff for continued exploitation of groundwater resources. Because volcanic and structural features are chief controls for the occurrence and circulation of groundwater in the Flagstaff area, geophysical methods are quite useful in groundwater studies. Reports giving results of these studies are available for the Wood Mountain, Lake Mary, and San Francisco Mountain Inner Basin well field areas.

A magnetic map of western Flagstaff is now available together with engineering geology data of the entire Flagstaff area. Geologic mapping for these and other projects was compiled and is now available. Further mapping, including land capability studies for Flagstaff, will be available in the near future.

Research in structural geology by Dr. Charles W. Barnes, Dr. Brumbaugh, and seven graduate students has been concentrated in two somewhat diverse areas: understanding the evolution of monoclines such as that at Gray Mountain, and Precambrian polyphase deformation and metamorphism.

Recent research includes mapping in the southeastern intersection areas of the Grandview, Black Point, and East Kaibab monoclines northwest of Wupatki National Monument and northwestward into the eastern Grand Canyon.

Precambrian research has included work on the Vishnu structure in the Bright Angel area of the Grand Canyon, a lit-par-lit terrane near Skull Valley, southwest of Prescott, and the Matzatzal Quartzite near Del Rio, north of Prescott. Further, a detailed structural study in the Big Chief Mine area, east of Jerome, includes not only some interesting new data on the time evolution of the Mingus Mountain frontal fault system, but also a reinterpretation of some of the volcanogenic sulfide deposits in the area.

Research in igneous petrology under Drs. Richard F. Holm, Raymond L. Eastwood, and Edward W. Wolfe, Adjunct Professor from the U.S.G.S. Astrogeology Center, is centered in the San Franciso Volcanic Field. Several long-term projects, in the initial stages, are determining the field relationships of the various volcanic units and interpreting these data in terms of the volcanological and structural development of the San Francisco Volcanic Field.

A major current project involves a

detailed structural, stratigraphic, and petrological study of the San Francisco Peaks Volcano north of Flagstaff. This project is designed to provide a better understanding of the geological and petrochemical evolution of the volcano and its role in the development of the San Francisco Volcanic Field.

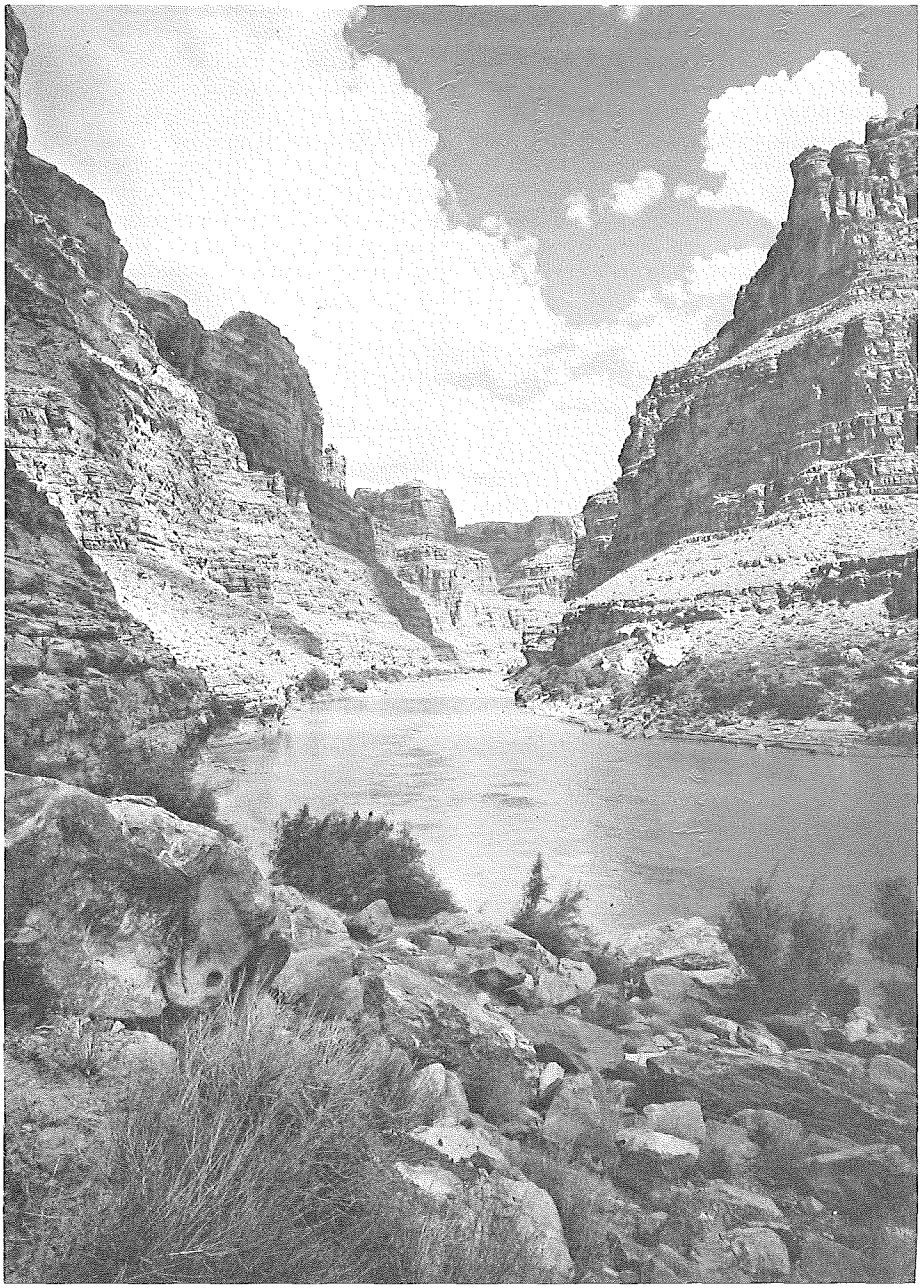
A second project consists of studies to better understand the geological and petrological evolution of smaller silicic centers of the volcanic field. Two recent graduate theses have made major contributions to this project. One, by Charles Kluth, describes the volcanological and structural development of Elden Mountain, on the northern outskirts of Flagstaff. The second, by Kent Murray, is a study of Williams Mountain, a complex of silicic domes, east of Flagstaff.

A third long-term project is designed to better understand the structural, volcanological, and petrochemical evolution of a part of the San Francisco Volcanic Field between the San Francisco Peaks and the Mogollon Rim. This project has involved studies of detailed relationships between volcanism and faulting, including the Oak Creek Fault, in the Woody Mountain area southwest of Flagstaff and of Shadow Mountain, the northernmost vent of the San Francisco Field. Finally, a reconnaissance geologic map of part of the Coconino National Forest is being prepared in cooperation with the U.S. Forest Service that involves detailed structural, volcanological, and petrographic studies of the area between Anderson Mesa on the east and Sycamore Canyon on the west.

In other areas of Arizona, graduate theses related to igneous petrology have been completed or are in progress and include a detailed study of the younger Precambrian basaltic rocks of the Grand Canyon by John Hendrix; a massive calcite body (a possible carbonatite) near Wickenburg by David Sanders; an emplacement of Precambrian granite near Payson by Rondi Martinsen; and a field study of Older Precambrian metamorphic and plutonic igneous rocks at Weble Mountain, southwest of Buckeye, Arizona, by Carl Smith.

A major project involving the Biostratigraphy of the Devonian system in northern Arizona is being done by Dr. Stanley S. Beus and two graduate students. One major paper on the general stratigraphy has been published and work is continuing on the Paleontology and Paleoecology of the system, particularly in northwestern Arizona. Also in this area, a thesis project by John Matthews has been initiated on the general Paleozoic stratigraphy in the Wheeler Ridge area.

Paleontological studies of the Pennsylvanian system, especially the Naco Formation in Central Arizona, is proceeding satisfactorily and one paper has already been submitted for publication.



Northern Arizona University

The Grand Canyon of the Colorado River has been the subject of geologic study and research since the time of John Wesley Powell's historic pioneer river trip through the canyon, over a century ago. It continues to present intriguing geological problems to university faculty and students. The view is one looking downstream in upper Marble Gorge.

Considerable work is in progress by Drs. J. Dale Nations and Thor N. V. Karlstom, Adjunct Professor from the U.S.G.S. Astrogeology Center, in the Mesozoic and Cenozoic in the general area of northeastern Arizona. The paleontology and paleoecology of the Cretaceous Fruitland Formation in northwestern New Mexico, the Triassic Moenkopi near Meteor Crater, the Cretaceous Mancos Shale in Black Mesa, the Holocene Naha Formation in Tsegi Canyon are all being investigated. In addition, one major paper has been published on the biostratigraphy of the Pliocene-Pleistocene Verde Formation and research is continuing on the paleontology and paleoecology of this unit.

The sedimentary rocks in northern Arizona have been investigated by several staff members and graduate students. Research by Dr. Augustus S. Cotera Jr. is almost complete in two Precambrian sandstones, the Shinumo and Hakatai Formation in the inner gorge of the Grand Canyon. Together with completed studies of the other units in the Unkar

Group of the younger Precambrian, this research will be submitted as a special publication to the GSA and will provide a complete summary of the petrology, sedimentary structures and paleogeographic interpretation of the Unkar Group. In addition, work has been initiated on the stratigraphy and sedimentology of the Nankoweap Formation, which overlies the Unkar Group in the inner gorge of the Grand Canyon.

A second research area has been focused on facies analysis of several carbonate units in the Paleozoic rocks of northern Arizona. Studies are complete and published on the marine facies of the Toroweap Formation, and further studies are being extended into Utah and Nevada. Analysis of the non-marine facies in the Toroweap has also been completed and published. Further carbonate research in various units of the Mississippian, Devonian, and Permian systems in northern Arizona are in progress with the petrographic facies analysis of the Redwall Limestone in Chino-Verde Valley virtually complete.

Dr. John D. Strobell, Adjunct Professor from the U.S.G.S. Astrogeology Center, in Stratigraphy and Economic Geology, is continuing his research on the oil and gas possibilities of the Colorado Plateau. Dr. John F. McCauley, Adjunct Professor of Lunar and Space Geology from the U.S.G.S. Astrogeology Center, is cooperating with Dr. Cotera on the sand dune landscape project on the Navajo Reservation.

From the above summary of research in Geology at Northern Arizona University, it is evident that we do a lot of field work. In northern Arizona, we have an excellent field laboratory and it is our firm contention that our students learn geological principles best in the field, where geology is. We should like to extend a sincere invitation to you, the reader, to come up into the high country and visit with us. We will delight in sharing this magnificent country with you at any time.

U of A *Continued*

Molybdenum mineralization appears to be about 4 million years younger than the main phase of copper mineralization.

The Potassium-Argon dates, patterns of eruption, and periods of mineralization of the Tertiary volcanic rocks of the Mogollon-Datil Province of New Mexico and surrounding regions were published in the *Geol. Soc. Am. Bull.* by W. E. Elston, P. E. Damon, P. J. Coney, R. C. Rhodes, E. I. Smith, and M. Bikerman. They found three major volcanic cycles 28-23 m.y. and 23-30 m.y., each of which consists first of andesite to rhyloite lava flows, then ash-flow-tuffs, and ends with basaltic andesite lava flows. Alkali basalt and tholeiite (basalt poor in olivine) became the most common types of volcanic rocks after 20 million years ago.

Dr. P. E. Damon, M. Shafiqullah, and D. J. Lynch have determined Potassium-Argon age dates of 12 to 17 million years on volcanic rocks associated with Miocene sediments which have a profound angular unconformity. This unconformity is the result of faulting, tilting, and erosion, after which other sediments were deposited on the angular surface. After 12 million years ago, the basins have been subsiding relative to the ranges with only minor tilting of the strata. Several basins contain salt or anhydrite, which indicates extreme evaporite conditions during late Miocene and Pliocene time.

Potassium-Argon age dates of over 30 volcanic rocks in the San Francisco Volcanic Field have been used by Dr. Damon, Dr. Shafiqullah, and J. S. Leventhal to calculate the rate of erosion of the Little Colorado River. During the last 2.4 million years, the average rate of downcutting has been 315 feet per million years. Most of the erosion of the Little Colorado River occurred during the Hemphillian, before the Bidahochi lake beds were deposited. Their chronology is consistent with M. E. Cooley's (1962) geomorphologic classification of volcanic stages.

A Potassium-Argon date of 6.7 million years has been published by R. E. Scarborough, P. E. Damon, and M. Shafiqullah for a basalt of the middle volcanic member of the Bidahochi Formation about 2 miles northwest of White Cone on the Navajo Reservation. This lava flow occurred after the lake deposits of Pliocene aged Hopi Lake and before the Pliocene stream deposits in the same area.

A reliable conversion table from radiocarbon years to tree ring years has been published by Dr. Damon, Dr. Long, and Dr. E. I. Wallick. The conversion chart covers the last 7355 years before present (before 1950 A.D.), although the radiocarbon time scale is more precisely defined from 500 through 2200 years B.C.

Dr. Spencer Titley has published several articles concerning the tectonic framework of southeastern Arizona porphyry copper deposits and criteria applicable to the search for them. Dr. Titley is also the author of an article in *Fieldnotes* on "Copper Mining and Land Use Planning."

Dr. Denis Norton is studying the heat and mass transfer in and around igenous bodies. The cooling process is relevant to metamorphism and to hydrothermal processes which are very important in forming ore deposits. In a related research project, Dr. Norton is using the theory of chemical mass transfer to interpret data on characteristic mineral zones in porphyry copper deposits. Dr. Norton is also applying mathematical modeling and field investigations to a feasibility study for evaluating geothermal water resources in Arizona.

Dr. J. M. Guilbert and J. D. Lowell have published information on variations in zoning patterns in porphyry ore deposits in the *Bull. Can. Inst. Min.* A talk to the Min. Society of America on hypogene mineralogy of porphyry base metal deposits is also an outgrowth of Dr. Guilbert's continuing research on he chemistry, mineralogy, and environment of porphyry copper deposits. Dr. Guilbert is directing numerous graduate student investigations in this project. Some of these include Verl Smith on Alteration at Esperanza and Hypogene and Supergene Alteration, John Mohon on Sodium/Potassium ratios in micas, Darrell Dean on Alteration at El Alacran, Clancy Wendt on Alteration at Batamote, and Roger Laine on Geochemistry of Alteration. Jerry Davis has investigated the alteration, fluid inclusion geothermometry, and trace elements geochemistry of drill core samples from San Manuel-Kalamazoo for his Ph.D. dissertation, which will be published in *Economic Geology* when it is completed. Dr. Guilbert has also given several talks on natural resource consumptions, shortfalls, and planning.

David Spatz has completed a master's thesis on the geology and alteration-mineralization zoning of the Pine Flat prophyry copper occurrence in Yavapai County. He concluded that mineralization is probably time-correlative with alteration since copper recurs with main-stage alteration and lead and zinc with late-stage alteration. Current erosional truncation has exposed a shallow level of the original intrusive complex and the techniques used in the thesis offer useful guides to exploration.

Although much of Dr. W. B. Bull's published research uses examples from California, the processes are applicable for Arizona as well. His article in the *Geol. Soc. Amer.* on geologic factors affecting compaction of deposits in a land subsidence area is applicable to southern Arizona valleys such as the Picacho-Eloy area.

The impact of mining gravel from urban streambeds in the southwestern United States was pointed out in an article in *Geology* by Dr. W. B. Bull and K. M. Scott. Digging gravel pits in the stream bottom lowers the local base level which causes erosion of the stream bottom upstream from the pit and endangers bridge piers. The stream banks also become more susceptible to erosion.

Ground water recharge is also reduced when clay is deposited in the bottom of abandoned pits from the muddy pools left after rains. Because inactive channels can easily become active, gravel mining in inactive channels poses the same major threat to upstream bridges and housing developments.

Dr. W. B. Bull has also developed equations to analyze the landforms near the mountain to basin boundary and predict present stability. Dr. Bull has also investigated the playa (dry lake) processes in the volcanic craters of the Sierra Pinacate, Sonora, Mexico. Dr. Bull is presently researching the Quaternary alluvium and terraces of the Lower Colorado River. The terrace profiles suggest that they were deposited as a braided river and that there has been no vertical uplift since the terraces were formed in the Holocene.

A comprehensive catalog of mineral occurrences in Arizona has been prepared by Dr. J. W. Anthony, Dr. S. A. Williams, and R. A. Bideaux. The book, which will be published by the University of Arizona Press, recognizes about 585 mineral species. It is arranged by county and mining district and includes descriptions of the most interesting mineral occurrences. The book will be illustrated with line drawings and color plates.

Dr. Anthony and Dr. W. J. McLean have also described a new mineral, jurbanite, a hydrous aluminum sulfate, from the 2700-foot level of the San Manuel mine north of Tucson.

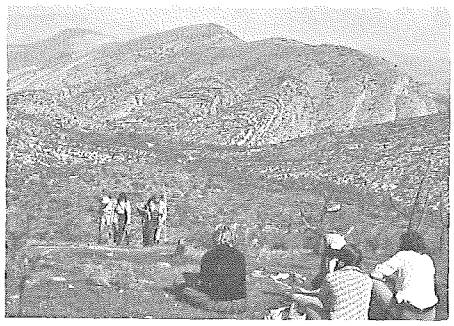
Dr. Richard F. Wilson has written a summary of the Mesozoic stratigraphy of northeastern Arizona for the 1974 Flagstaff meeting of the Geological Society of America. Dr. Wilson is also currently collecting data for a stratigraphic atlas of Paleozoic and Mesozoic formations of Arizona and adjacent regions.

Dr. J. F. Schreiber, Jr. and his graduate students are continuing research on coastal geology studies near Puerto Penasco, Sonora, Mexico. A sedimentation survey of Rose Canyon Lake, Santa Catalina Mountains is also in progress.

A master's thesis by William Jones has unraveled the general geology of the northern portion of the Ajo Range in Pima County. The Ajo Range is principally composed of mid-Tertiary volcanic rocks and has been tilted eastward approximately 25 degrees along north-northwest trending normal faults.

Constance N. Dodge has analyzed and compared the pebbles from the Chinle and Morrison formations in Arizona and New Mexico for a master's thesis. The place the distinctive pebbles (such as fossiliferous, volcanic, and white chert pebbles) came from was probably moved by strike-slip faulting (with horizontal movement of adjacent masses) between the Late Triassic of the Chinle Formation and the Late Jurassic of the Morrison Formation.

Dr. G. H. Davis and his students have written several papers about the mid-Tertiary gravity-glide folding off the Rincon Mountains near Tucson. The main mountain mass, which is composed of Catalina Gneiss, was uplifted relative to the basin between 20 and 24 million years ago. The Paleozoic and Mesozoic sedimentary rocks, which were above the gneiss, "slid off the hill" and were intricately folded. Davis presents evidence in favor of gravity-gliding from the mountain rather than overthrusting from the basin. Dr. Davis is also using ERTS photos in a photogeologic and field analysis of macroscopic folds in the Colorado tectonic province of Arizona. Tom Heidrick gave several talks on fracturing and diking in Laramide plutons, work which will add significantly to our understanding of southwestern tectonics.



University of Arizona

Excellent exposures, such as shown here in the Mescal Mountains, offer an ideal field laboratory for geologic studies and research by faculty and students. Note how the erosion of the steeply dipping formations give a false impression of folding.

In his master's thesis, Joe Wilkins has used induced-polarization (IP) and resistivity methods to locate the zone of meteorite particles at Meteor Crater at the base of the impact breccia.

An aeromagnetic study of the Colorado River delta area, Mexico by M. De la Fuente Duch has detected a spreading center which should be investigated for possible geothermal resources.

The Second Annual Geoscience Daze Student Colloquium was held April 10-11, 1974 with participation by approximately one-fourth of the graduate students. Over half the papers presented covered some aspect of the geology of Arizona.

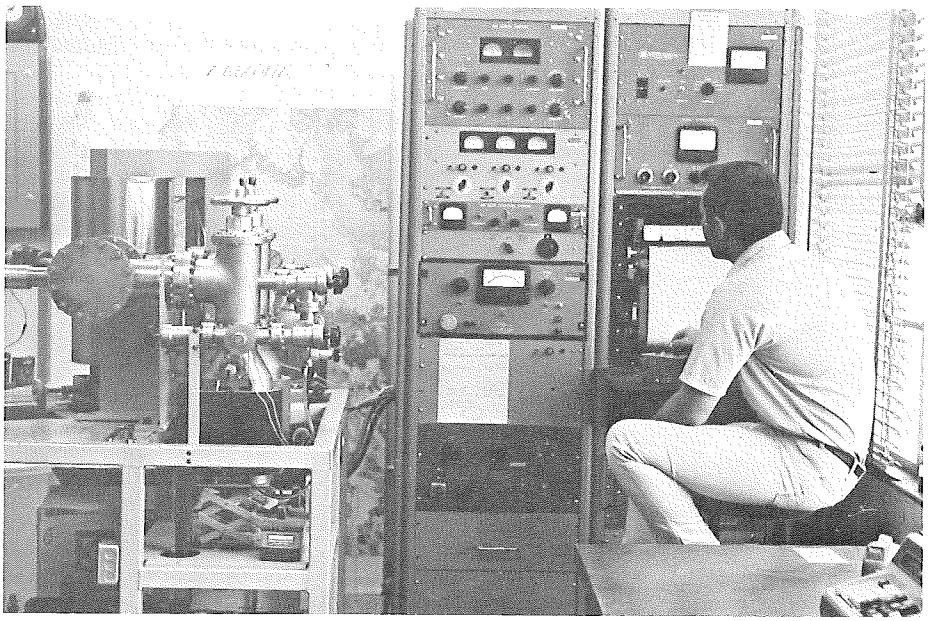
Talks on the mineralogy or petrology of certain rocks in Arizona included the O'Leary Porphyry, the Red Cloud Mine, tuff rings, and the Monte Cristo Pegmatite. Katherine Bladh studied the O'Leary Peak volcanic dome of northern Arizona and did some experimental work on rapakivi texture (oligoclase rimming sanidine). Gary M. Edson studied the mineralogy of the Red Cloud Mine, Yuma County with particular emphasis on the distinctive, red-orange mulfenite crystals.

Daniel J. Lynch explained the origin of tuff rings in multi-vent basaltic volcanic fields. John P. Mohon applied the geothermometer, which is based on Sodium substitution for Potassium in muscovite, to the Monte Cristo Pegmatite in Yavapai County.

Talks on structural geology included gravity gliding, isostatic rebound, and the Texas lineament. Eric G. Frost, John P. Schloderer, and Dr. George H. Davis scrutinized folded gravity-glide sheets in Saguaro National Monument east of Tucson. R. Brett Liming analyzed the deformation in the Martinez Ranch area on the southeastern margin of the Rincon Mountains near Tucson. He questions Drewes' (1973) interpretation that Laramide thrust faulting moved the Paleozoic "block" 10 to 20 miles northeast and suggests that the "block" moved south-southwest off the high Rincon Mountains. John P. Schloderer also questions previous thrust faulting interpretations for the presence of sedimentary and metasedimentary rocks in the Redington Pass area east of Tucson and suggests folding resulted from gravity sliding along bedding planes. Monte M. Swan examined the Stockton Pass Fault which truncates the south end of the Pinaleno Mountain Precambrian Gneiss complex in Graham County. He concluded that the Stockton Pass Fault, which is expressed as a N. 70° W. shear zone, is an element of the Texas Lineament and that it demonstrates major Precambrian left-lateral wrench faulting as the origin of the Lineament.

Geophysical investigations in the Basin and Range Province of Arizona are discussed by Carlos Aiken and Dr. John Sumner. They have correlated the Bouguer Gravity Anomaly Map of Arizona (West and Sumner, 1973) with the Residual Aeromagnetic Map of Arizona (Sauck and Sumner, 1970).

A geochronological study is being conducted by Robert B. Scarborough on the vitric air-fall volcanic ashes which are found in Pliocene valley fill sediments in southern Arizona. Thus far, he has recognized two volcanic episodes. One episode between 5 and 6 million years ago produced at least 7 ash falls in the lower San Pedro Valley, Verde Valley, and lower Colorado River. A younger episode between 2 and 3 million years ago produced at least 4 thin ash falls in the upper San Pedro Valley and Sulfur Springs Valley. Chemical studies suggest that no more than 2 major source volcanoes were responsible for all these deposits.



University of Arizona

The age of rocks older than a few million years can be determined by measuring the radioactive rate of decay of the isotope rubidium-87 to strontium-87. The rubidium-strontium ratio method is used for such problems as the age of porphyry copper deposits or of the ancient Precambrian rocks of the Grand Canyon. The picture shows the electronic equipment in the geochronological laboratory which is used in conjunction with a mass spectrometer to make such age determinations.

Economic geology was represented by papers on alteration at the San Manuel ore body by Jerry D. Davis and the secondary dispersion of tungsten by Richard Frederickson, which have been discussed above. Other papers include the alteration assemblage at Esperanza by Verl L. Smith and strata-form sulfides at the Copper Queen Mine by Ken Brook. Both the wall rock and the layered sulfide ore at the Copper Queen Mine near Mayer, Yavapai County have undergone similar deformation. Therefore, Ken Brook concludes that the sulfide bands were present in the rock before the deformation occurred.

George Eliopulos examined the geology of the Mineral Mountain area, Washington County, Utah near the eastern margin of the Basin and Range Province just north of Arizona. Tom Andrews summarized the structural and igenous geology of the Troy mining district in the central Dripping Spring Mountains southeast of Ray, Arizona.

Jeffrey A. Boyer investigated the hydrogeology of the Carefree Ranch area north of Scottsdale to determine the groundwater availability. Frank A. Packard discussed some discontinuous streams near Tucson and proposed a theoretical model for their formation.

M&G-ENG *Continued*

Undergraduate enrollments in geological engineering have increased recently in the Department and job opportunities and starting salaries for graduates are excellent. Even though this growth cannot be attributed entirely to the energy crisis, that phenomenon focused attention on the importance and challenges of applying geology in the mineral and construction industries as well as in environmental and urban problems – a key element when a young man or woman is choosing a career.

Spurred on by larger enrollments and expanded research and teaching programs, the Department has embarked on a number of new activities. Simulation of actual problems and field characterisitics has played a large role in the teaching methods as indicated in the following selected sketches, illustrating how students may learn to adapt themselves to real-life situations that they may meet in their later professional years.

Exploration is the first step in finding new mineral resources. With the rapid depletion of known mineral reserves and the increasing difficulties and costs of discovery of new sources, the geological engineer needs all the scientific training, imagination, logic, and experience he can muster.

Dr. W. C. Peters offers the following example of a problem in the search for ore and the design of an exploration program.

The Casi Cuatrocientos mountain range rises in rugged isolation above the desert alluvium in Geronimo County: 6000 square miles of relatively unmapped and unexplored Mesozoic rocks with reported occurrences of lead-zinc districts in similar geologic terrain.

Can a group of students with the background provided by the University of Arizona's courses in geoscience, exploration, and mining find a hidden orebody in the Casi Cuatrocientos Mountains? A course in the department of mining and geological engineering, using a simulation gaming technique adopted from management training, lets them try. It provides students with a learning experience to bridge the gap between textbooks and the "real world." Real world exploration conditions are simulated: budgets, costs, time schedules, decisions, unforeseen developments, and competition between groups of students trying to find the same orebody.

The model for the Casi Cuatrocientos Mountains is real, but it exists half-way around the earth from Arizona. None of the students have had the prior advantage of seeing it, so all begin on an equal footing.

In order to give one of the recent simulation games a southwestern flavor and to hide the identity of the model until the final "moment of truth," two mining districts, Touissit-Bou Beker and Aouli in Morocco, became the Tarantula-Big Bug and Anteater districts, Arizona. The towns of Matarka, Tissaf, and Mahirisa became Mad Dog, Two Guns, and Mesa Ridge on the borders of the Casi Cuatrocientos Mountains. Nothing else was changed; the terrain, its geological, geophysical, and geochemical characteristics, and its Arizona-like climate remained as in Morocco.

Exploration teams, each with two or three students, submit weekly exploration plans, with each week representing two months in the field. The results of exploration – field geologic maps, geochemical data, geophysical profiles, and drillhole logs – are furnished by the professor so that each team can argue and anguish over them as a basis for the next plan.

Interest and competition mount with each step as the budgeted funds for exploration shrink and the unexplored area is reduced to anomalies and targets.

A stream sediment sampling program may disclose a minor drainage area with higher lead content than elsewhere, but subsequent rock sampling shows no specific anomalies. Another look at the reconnaissance geologic map and the pattern suggests a broad, anticlinal structure. Look once more at the aeromagnetic map and a basement uplift is indicated. Now try ground magnetics for stronger indications. Induced polarization is tried; it gives a significant response, but not where expected. Try changing the assumptions (the tentative exploration model). Back to more detailed geologic mapping, and the limestone plotted on reconnaissance maps is now seen to contain a reef member.

Meanwhile, where are the other competing teams working? Is there time for a drillhole? What will the budget permit?

One team may have decided that they will drill some holes for stratigraphic information. Suppose that some of the holes encounter no bedrock and one hole encounters unexpected mineralization. Shall we deepen some of the holes, drill additional holes, or continue with the original schedule? The clock is ticking, the budgeted funds are shrinking. This is as close to the "real world" as a student can get while still in the college laboratory.

Meanwhile, back at the source of original data, the professor doles out the information as it is "bought" from budget funds on a realistic cost basis. Nothing more is supplied until the next-to-final course meeting when the orebody is unveiled. Then, winners and losers exchange congratulations and commiserations.

At the final meeting in the course there is a critique, and a comparison between each team's approach and the program used in the discovery from which the original information was gathered. The students now have an inkling of how they will be called upon to make professional decisions. This time it was a simulation, the next time will be "for real" in a world pressed by mineral shortage.

A part of the answer to problems of mineral shortage lies with exploration; exploration based on science, stimulated by imagination, guided by logic, and made practical by experience. The geological engineering course at the University of Arizona in "simulation gaming in exploration" should help students become tomorrow's engineers who will have to find the answer.

Another important aspect of mining geology is mineral economics. In order to greatly expand our capabilities in the latter field, we are fortunate to have Dr. DeVerle Harris join our faculty to continue his research and teaching in mineral economics, especially quantitative exploration models and statistical methods for mineral resource appraisal.

Most civil engineering projects require the acquisition, interpretation, and use of geological knowledge concerning the materials in the Earth's crust. This branch of geology is called geotechnics. For students oriented more towards geotechnics than mineral exploration, simulation problems, similar to the following, are given by Dr. Charles Glass. Dr. Glass' main fields of teaching and research are earthquake engineering, engineering geology, and photogeology.

The Pima Gas and Electric Company has contacted the firm of Glass-Peters and Associates to make a feasibility study for twin pressure tunnels to be constructed in an area of northern Arizona. A preliminary outcrop geologic map is available from the client which show a predominant conglomerate-sandstone-shale facies with rather peculiar topographic relief. Can a group of students design an exploration program to locate the geologic hazards in the area and based on their conclusions make recommendations regarding design? Can they do it within a fixed budget? Vertical and angled boreholes and open and closed trenching will be the exploration tools, and a computer will provide the cold, impartial means by which they get their results. A deep hole in the hard conglomerate may deplete three-quarters of one student's budget. Another student spends $18,000 of his allotted $20,000 in a shotgun pattern and misses the numerous wide fault zones slicing through the area. Planning, careful plotting, and geologic and engineering skill pay off when the students arrive at their final tunnel alignment and preliminary design factors. Not only is the student harried by the whims of the geologic environment and the pressure of a tight deadline and budget, but before he can spend the money he must present orally the logic behind his exploration program. After his geologic map and cross-sections are complete, he must make an oral presentation of his report and recommendations to a sometimes skeptical group of professors and students representing the interests of the client.

Yes, in the "Geotechnical Investigations" course at the University of Arizona, students make mistakes, squander clients' money, and learn how hard and embarrassing it is to try to explain a poor exploration program orally in front of a group of professionals. Brutal? Perhaps. But, better here than later in their professional career.

Geomechanics is another subject taught in the Department and one in which active research is being carried forward. This branch of geology deals with the structural response of natural materials to deformation or changes due to the application of stress or strain. Teaching in this field are Dr. R. D. Call, a part-time lecturer specializing in slope stability, and graduate student D. Nichols, covering underground openings.

A great deal of research effort in the Department has been directed toward the planning and development of open-pit mines. Dr. Young Kim, specializing in geostatistics and computer applications, is involved in two interesting projects related to the evaluation of surface mining ventures. One project is directed toward verifying Matheron geostatistical concepts (a specialized statistical interpretation) on a large Arizona porphyry copper deposit. Graduate student Pete Knudsen is completing his master's degree on this project.

The second study by Dr. Kim is a part of a major project, funded by the Canadian government, concerned with producing a Pit Slope Design Manual. Our contribution to this effort is to develop a generalized model for the financial evaluation of altering the pit slope angle in a surface mining operation. The incentive for mining at a steeper slope is obvious – less waste or unprofitable material needs to be mined to extract the ore. For large, deep open-pit copper mines, an increase of a few degrees in the slope angle can literally mean the saving of millions of dollars.

However, steeper slopes mean that a failure, such as a slide, is more likely to occur with the resulting expense of cleanup or perhaps even suspended ore production and equipment damage. Thus, there are clearly costs as well as benefits associated with steeper pit slopes. Our objective is to find the slope angle which will produce the highest expected net results.

First, there is the problem of defining the cost of a failure. Cleanup costs may be straightforward, but what about the costs of lost production or lost ore? Secondly, slope failures clearly are not dependent solely on the slope angle. A large number of other parameters, largely geologic such as the characteristics of the rock or alluvium, moisture content, and local structure and slope heights, also are relevant. One slope may stand very well at 60 degrees while another will fail at 35 degrees.

The first problem of cost of failure has been attacked by defining a number of failure models from which the program user may select the likely failure modes for his mine. Alternatively, he can specify a unique failure model with associated costs if he wishes to do so. The second problem of other factors has been overcome by adopting the "probability of failure" concept. Here, the geomechanics specialist will estimate the likelihood of failure under varying conditions for each slope as a function of slope angle and slope height. Then by using Monte Carlo sampling methods, a procedure in which random figures are used to approximate the solution to an intractable problem, we can simulate the mining of the deposit many times to find a probability distribution of possible net benefits.

The value of the study is the methodology involved rather than any specific results. Although slope angle is a critical variable in the financial analysis of surface mining ventures, there are many divergent operating philosophies regarding slope angles. Our work attempts to provide a method for analyzing the elements pertinent to that decision.

FIELD NOTES
Volume 4 No. 4 *Dec. 1974*
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