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Natural history of El Malpais National Monument

Compiled by Ken Mabery
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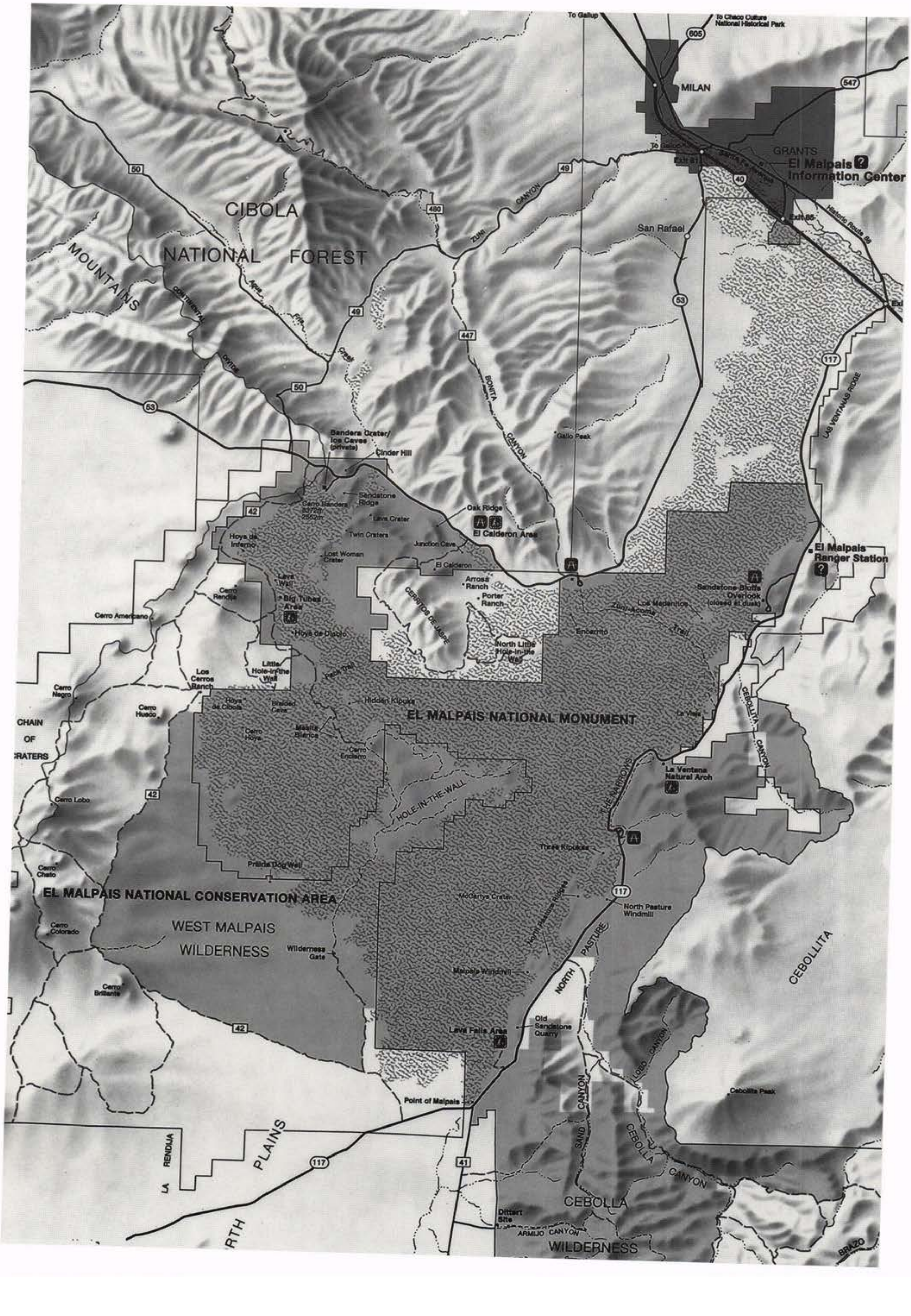

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Forward

The name "El Malpais" comes from early Spanish explorers. Literally it means "the bad country." I think this book shows quite a few good things about this country. The area now known as El Malpais National Monument has been a laboratory for natural history studies for a long time. As early as the 1930s portions of the lava flows were proposed as a National Monument to preserve their scientific value. Although the general public did not "discover" this varied volcanic landscape until the late 70s and early 80s, biologists, ecologists, and geologists were attracted to its wonders by 1938-39. R. L. Nichols and the U.S. Department of Agriculture published three separate reports in those years, one on the ice caves and two on the lava-flow features.

Alton Lindsey's pioneering ecological investigations in the middle and late 40s lead to further investigations, primarily geological, over the next 2 fi decades. As the United States pushed for landings on the moon and the possibility of developing a moon station, NASA commissioned A. W. Hatheway and A. K. Herring to study the lava tubes to see if lava caves on the moon might be adapted for human habitation. Their report was published in 1970. During the uranium bust period of the 70s and early 80s activities in the area nearly ceased. Field investigations continued primarily through the efforts of two geologists, Charles Maxwell of the U.S. Geological Survey and William Laughlin of the Los Alamos National Laboratory.

When the National Monument and Conservation Area were established in 1988, one of the National Park Service's first goals was to untangle the complex stories of El Malpais and their relationship to the global picture. Before the Park Service could develop interpretive materials, unanswered questions about unique features of the Monument needed scientific investigation. Beginning in 1989 the Park Service recruited and encouraged a broad range of scientists to delve into the secrets of this unique volcanic landscape.

What exactly makes this area unique? El Malpais is located on the southeast edge of the Colorado Plateau, most of which consists of horizontal or slightly tilted sedimentary strata. There are a few intrusives forming mountains in the central part of the plateau (La Sals, Abajos, and Henry Mountains in southern Utah) and older volcanic mountains along the southern edge of the Plateau (White Mountains in Arizona and Mount Taylor and a number of volcanic necks like Shiprock, in New Mexico). In contrast, the only volcanic fields on the Plateau are the Sunset Crater region in Arizona and El Malpais. Of the two, El Malpais has a much longer sequence of volcanic activity. In fact El Malpais contains one of the longest sequences of volcanic activity in the United States, from about 700,000 to about 3,000 years ago (see chapters by Laughlin and WoldeGabriel, Andrew, and Cascadden et al., this volume).

Having 15 or more lava flows in less than one million years contributes to other unusual features. Each flow resulted in a new land surface. From about 100,000 to 3,000 years ago, a new lava surface appeared about every 7,000-25,000 years. Immediately after the formation of these new surfaces weathering began to form primitive soils and plant invasions occurred. Caves in these flows contain important clues to the transport mechanisms of the lavas and development of minerals (see Rogers and Mosch, this volume). The El Malpais lava flows thus chronicle very recent ecological successions in an area which generally has soils and habitats dating back millions of years (see Lightfoot, Bleakly, and Northup and Welbourn, this volume).

Since many of the lava flows are very rugged and have not yet developed continuous soils, plant and animal communities have been naturally protected from logging, domestic grazing, fuelwood gathering, and other impacts of modern man. Trees that died hundreds of years ago are still laying on the rugged lava. Fragile plant communities flourish in collapse depressions in the lava and cave openings. The trees reveal an accurate record of rainfall and fire back to the time of Christ (see Grissino-Mayer et al., this volume), while the potential importance and lessons to be learned from some of the isolated vegetative communities is only just beginning to come to light (see Northup and Welbourn, this volume).

Recent scientific studies have ranged far beyond the scope of this book. It seems that every time one line of investigation was about to be concluded, a new question would arise. For example, geologic dating of the lava flows led other scientists to use non-geologic dating techniques. A team of scientists spent a couple of weeks in 1991 collecting datable materials from the Monument including tree rings, laminar ice, pack-rat middens, pollen, and archaeological remains. They concluded that each method was usable here, but more funds and time were necessary to build effective bridges between all dating methods. Some of the cave researchers discovered cultural materials associated with the caves, which led to studies by archaeologists, historians, and ethnographers.

This book, then, is a compilation of some of the more significant and basic findings of the more than 30 scientists who worked at El Malpais National Monument since its inception in 1988, the authors of the following chapters capture the most far reaching and interesting stories to be told. The research of the others is no less significant, and in some cases has contributed to the chapters that you see here. Other projects could not be completed in the time frame necessary for inclusion in this volume. Visitors are encouraged to talk with a ranger and check the displays and bulletin boards for the most current information.

What is the importance of this work? Where will it all lead? In some ways the Monument entered this next era in October 1995. The information contained here is essential to the next step. Based on the data contained in this volume, we can embark on interdisciplinary projects capable of answering more complex questions. In October 1995, researchers began looking at ecological systems that are influenced or controlled by the ages of the lava flows. We know what plants and animals live there, and now we need to find out how they have evolved in relation to the specialized habitats. Ultimately, we hope to find out how the lava environments influence the ecology of the entire area. Then we can determine which niches warrant special protection or attention, and how mankind can better relate to this part of the world. We know that permanent ice is found in many of the Monument's caves. Some of this ice was formed at least 3,000 years ago (see Dickfoss et al., this volume). The next step is to gain a better understanding of the climatic conditions and ecologic factors involved in ice formation and perpetuation at this latitude.

In 1996 El Malpais entered into a cooperative arrangement with the U.S. Geological Survey to obtain the services of a volcanologist. Richard Moore has worked in Hawaii studying active lava flow events and now brings that experience to El Malpais to examine these flows in light of recent findings in Hawaii. Building on the critical foundations that Joseph Andrew, Tracy Cascadden, Bill Laughlin, Bruce Rogers, and others have laid (see papers in this volume), Richard will have completed a comprehensive study in 1998. This interpretive history of the volcanoes and lava flows will be available to the public in a guidebook form.

All the researchers with whom we have worked since the establishment of El Malpais National Monument have made significant contributions. Volunteer or paid, all have given significant amounts of their own time to unravel El Malpais mysteries, not to mention the "donation" of materials that they probably never expected, including worn-out boots, scraped knees and elbows, and hard labor digging out of mud puddles. With well over 20,000 hours of field work, everyone is thankful for a remarkable safety record. Outside of a few minor injuries, there was one broken ankle to our research team in nine years.

The enthusiasm and dedication of this group has been nothing short of remarkable. In addition to the authors and their support teams, each of the following researchers, and their teams, is commended for contributing to our understanding of El Malpais: Craig Allen (ecology), Scott Baldridge (geology), Julio Betancourt (geology and pack-rat middens), Tom "Monty" Billings (ecology), Michael Scott Burt (zoology), Andy Campbell (geochemistry), Kent Carlton (caves), Niel Cobb (botany), Catherine Corson (ethnography), Bill Dunn (bighorn sheep), Carol Hill (mineralogy), Barbara Holmes (ethnography), Ken Hon (geology), Ken Ingham (caves), Angela Kolisnik (geology), Paul Knight (ecology), Bert Kudo (geology), Los Amigos del Malpais (volunteer group), David Love (geology), Harry Marinakis (caves), Bob Parmenter (biology), Fred Phillips (geology), Rob Ramey (big horn sheep), Jacques Renault (geology), Sandia Grotto (caves), Thomas Swetnam (dendrochronology), Lonnie Thompson (cave ice), and Cal Welbourn (cave ecology). Members of the Monument staff between 1988 and 1995 contributed greatly to this work by enthusiastically assisting, feeding, guiding, and occasionally rescuing our research teams. Special credit is due to Ken Mabery and Leslie DeLong for their efforts to see that this body of work made it into your hands. Finally, we extend our special thanks to the New Mexico Bureau of Mines & Mineral Resources for their extra efforts and working with us on this volume.

Douglas E. Eury, Superintendent
El Malpais National Monument

Introduction

Alton A. Lindsey

Department of Biological Sciences, Purdue University, West Lafayette, Indiana 49707

For this retrospective glimpse at the findings made during the 40s in the Grants malpais, I concentrate on some of its features that I think illustrate the uniqueness of the area. While in 1940 my bride Elizabeth and I were driving to a new job in southern California, we stopped to take pictures at the spot where US-66 and today's 1-40 enter the northeast tongue of lava. I hoped then that someday I might have the opportunity to do ecological investigation of this lava bed, the only North American one I had seen. Two years later we began a five-year stay in Albuquerque, and I started getting acquainted with the surrounding area.

On September 30, 1944, we drove through Grants, then through and alongside the Grants Lava Bed, now El Malpais National Monument. Of the narrow, little used dirt road, now NM-53, our diary states, "went through lots of mud holes." We stopped frequently to cope with crude barbed wire gates of ranch fences.

Lava squeeze-ups

The sole example that I have seen of one type of squeeze-up was the size and roughly the shape of a bushel basket. It was a hollow shell with walls two or three inches thick. This lava bubble was near the edge of a deep lava crevice having a pool of permanent water at its bottom. (This may explain the presence of a nearly intact Springerville Polychrome pot which had been hidden long ago through a hole broken in the bubble at ground level.)

Lava squeeze-ups add much to the interest of El Malpais geology. These features were formed when the magma was hot and viscously movable under various pressures.

Near the Ice Caves Trading Post, I found two examples of another type which apparently was hitherto unknown to geologists, so I reported it in the journal *Science*. In origin this type is related to the more common tree casts, where flowing magma surrounded the trunk bases of standing trees, producing vertical, cylindrical holes after the wood had burned or mouldered away.

I termed the more complex, newly found type a "tree-trunk squeeze-up." In this, after the surface magma surrounding a trunk had solidified, the burning away of the outer trunk layers, or perhaps shrinkage of the cooling lava, had left a space between the trunk and the solid lava around it. Pressure from below then pushed up still viscous material. This cooled and, standing a few feet above the slightly older general surface of lava, remained as a hollow cylinder above ground and a hole below, after the tree trunk decayed. So far as I know, these are still the only two specimens of their type seen anywhere.

As my research on the malpais ecology progressed, I was increasingly impressed by the number of new and unexpected things that were turning up. Most were biological items or happenings. Although by that time I had done field work on the Antarctic Continent and surrounding seas, in New Zealand and Polynesia, the Galapagos, Panama, our southwestern deserts, Mexico, Pacific Northwest, the Adirondacks and Appalachians, and many coasts, I decided that in no other place had so much of unusual interest been offered to my biological curiosity as in this malpais region.

Animal life

Once, arriving at the edge of a great tube-cavern entrance, I saw an agile bobcat bounce past me and off across the lava. It had been drinking the ice-water impounded by a mass of ice plugging the cavern farther in.

Although rattlesnakes were expected, the only snake I saw was a charming little ring-neck snake, all black except for the rosy red of its necklace and underparts. Once on lowering myself into a dry lava crevice, I came face-to-face with a canyon tree-frog, almost invisible. Its coloring and texture matched the lava surface so well that it posed motionlessly for a very close-up portrait.

Both pit-ponds and open ponds occur in the northeast tongue of the flow. This dependably high water table in a body of lava is unusual or perhaps even unique, and makes possible many of the extraordinary features found there. I will recount only a selected few of these. Strangely, I never saw a frog in these ponds or sink-hole mini-marshes.

Only one salamander was seen during the five years of study, a nine-inch adult tiger salamander which I took out of a closed-in pit-pond for taking pictures. One seven-inch chub was taken from a similar habitat. These are mentioned because the cool, dimly lit water of the closed-in ponds revealed no other individuals of any aquatic vertebrates, probably because of insufficient photosynthetic base for smaller food organisms. But even in the open, well-lighted ponds along both sides of US-66, where higher plants were conspicuous, I saw no minnows or other fish. The water was abnormally clear. Some deeper ponds supported, on their otherwise bare submerged lava-rock walls, firm calcareous crusts of blue-green algae three-eighths of an inch thick. These plant formations, which showed many clearly distinct growth layers, are unique in my experience, but I am not a limnologist.

In the mouth of a large tube cavern in high malpais country I took a microscope down 90 feet below the general surface. A pond of ice-water seven inches deep was lying over a massive plug of ice in the cavern entrance. Samples of water taken at the water-ice interface, measuring right at the freezing point, were quickly examined under the microscope. The water teemed with living diatoms and fully active animalcules, including rotifers and at least three species of protozoans swimming rapidly. (By 1981 the ice had largely thawed away, destroying the pond. Men from the Bureau of Land Management penetrated beyond where the ice plug had blocked the entrance in the 40s and found some bones. Interpreting these as human, they left them undisturbed.)

A curious case of apparent "protective coloration" was found in an animal barely visible to the unaided eye. It lives in the pond with the ooze made bright green by the crescent-shaped microscopic alga *Scenedesmus*. Great numbers of this copepod animal *(Scapholeberis)* swarm in the water over the green bottom. Taken by itself, the copepod shell is light brown, but each animal carries a dense population of a stalked, green euglenoid plant-animal attached to its shell, making the copepod bright green and blending it in with the green pond bottom and sides. The species of photosynthetic fellow-traveler had been reported very few times from North America.

The stultified forest

For the lava bed, overall, I mapped three main vegetation types. The lower elevation, warmer, drier type is dominated by the rosaceous shrub apache plume *(Fallugia)*. The type occupying intermediate elevations is ponderosa pine and associated species. The higher elevation, cool, and moist type occupies less area, mainly on the northwest lobe of lava below the Continental Divide and Bandera Cone. The tree dominant there is the Douglas-fir. Of even more interest but limited extent is a very special vegetation on highly rigorous substrates—the dwarf or pygmy forest made of either ponderosa pine or Douglas-fir.

Worldwide, the slow-growing but very long-lived trees of the pygmy forest are most prevalent in arctic or alpine tundra, and in a few other especially difficult habitats like acid bogs and very rocky or very dry substrates.

In 1944, driving south from US-66 on NM-117, I noticed that the ponderosa pines on the high sandstone country east of the road were tall, well formed, and normally fast-growing. But on the nearby lava flow, especially at a spot called "The Narrows," trees of the same species were reminiscent of Japanese bonsai trees but far larger. I found that these dwarfed and stultified but living trees had very narrow, but very many, annual layers. Another evidence of the great longevity of these distorted pines was that both recently perished individuals and reproduction-size specimens were practically lacking in the stand. At this point is the most readily accessible pygmy forest at El Ma1pais; it may be seen at close range from the visitor's car.

From my 1951 article on the Grants malpais in *Ecological Monographs,* dendrochronologists at the Tree-ring Laboratory at The University of Arizona soon learned of (and sampled at) this stand of ancient pines. One eventual outcome of their visit to The Narrows came in 1994, shortly before Christmas, when I unexpectedly received, from graduate student Henri Grissino-Mayer of that Laboratory, a fascinating, beautifully prepared cross section of a Rocky Mountain Douglas-fir, a portion of the oldest wood specimen known from Arizona and New Mexico. It started growing two centuries before Christ's birth.

In 1993, Grissino-Mayer and his team had searched the higher malpais successfully for well-preserved wood much older than any I had found at The Narrows. Their work is reported in this volume. The mounted section hanging on our living-room wall daily brings me pleasant memories of El Malpais, and especially of my having hiked just 50 years before the Laboratory team, but without cutting tools, through the exact fabulous spot which they later discovered and studied.

A sunken garden of spleenwort ferns

The last plant that I would have expected in the malpais was the delicate, moisture-loving *Asplenium trichomanes,* for this widespread plant is rarely found in dry, rocky areas. But once, when I looked down a three-foot-across hole through the surface crust, I was directly over a bright green lacework of the small fronds of this spleenwort. It was growing on the central island of a "Jacob's Well" pit-pond. The island had been formed when a large mass of rocks fell down from the roof, thinning the latter drastically but opening such a small and well-concealed hole that I may have been the only human to have peered through it. This circular cavern was about 40 feet in diameter and largely occupied by a doughnut-shaped pond that encircled the central island made up of former roofing lava. Direct sunlight seldom hit the ferns, and then only briefly.

On one of my visits to investigate this unusual geological structure, **I** lowered our three-year old son David by rope, then climbed down myself in order to photograph the pond and ferny island with a human figure for scale. The boy remained unperturbed through these unaccustomed happenings. A short article about the plant colony and its remarkable habitat was accepted by the *Fern Journal.*

Plants out of place

The place where biologists expect to see and perhaps recognize to genus some colonies of microscopic organisms with their unaided eyes is in glassware in the laboratory. But I had the rare experience of doing so in nature, in the field, and each culture involved was a colorful community at least 30 yards in diameter.

Several shallow, open ponds in sinks of that size, located near the pond with the emerald-green ooze community of one-celled algae, had their black bottom ooze concealed under a thin growth of the red sulfur bacterium *Lamprocystis roseopersicina.* The best such pond had the entire bottom colored a bright, uniformly violet-rose hue from the profuse growth of this microbe. The first green plant to invade these remarkable ponds was the alga stonewort *(Chara)*. I have not heard or read of such ponds elsewhere, though they probably occur where conditions are similar enough.

In the ice cave which is open to the public at Ice Caves Trading Post, the vertical edge of the ice mass was 14 feet high in 1926, nine feet in 1945, and only three feet when I last saw it in 1981. This ice wall received light of only one candle power, and the ice

David Lindsey sits in "Jacob's Well" next to *Asplenium trichomanes,* maidenhair spleenwort in 1945. This sinkhole was filled and paved over during the construction of I–40. Alton Lindsey Photo, El Malpais National Monument, misc. collections.

floor in front of it got only five candles; both were covered with an intensely green surface film caused by the alga *Sphaerella* and two species of *Stichococcus.* I could find no record in the literature of this species of *Sphaerella* growing on ice or snow. The genus *Stichococcus* had been found only once before growing cryoscopically, in Antarctica in 1908.

A large pit nearby harbors a crescentic pool well exposed to north light. Among the mosses on the rock wall just above the water one finds the moss *Homomallium incurvatum,* normally arctic-alpine in distribution, which has not been found growing in North America before. This was the first case known of climatic compensation furnished to an arctic-alpine plant by an ice-cave habitat or any situation other than very high altitude.

The extreme diversity of microclimates in the Grants lava and the uniqueness of some (especially the various ponded sinks) support the occurrence of a number of other plant species which have a disjunct distribution. Of the 28 moss species I collected from lava substrate, nearly all are moisture-loving and occupy protected sites of one sort or another. Only a few are drought-tolerant species from the dry Apache-plume belt. In the dim light at the bottom of the lava crevice 14 feet deep, I collected a moss species of the genus *Neckera* for the first time since its original collection from which it was described and named.

One of the most ecologically interesting ice caves had a long ramp of rocks sloping downward, supporting seven distinct belts of vegetation, to the edge of a dimly lit icewater pond. On otherwise bare soil along the water's edge, I found a totally unprecedented phenomenon (I believe) in the moss *Pohlia cruda,* a species common and widely distributed from the far north to the tropics. In the ice-cave site with a constant 34.1°F temperature, the early stage of velvety protonemal threads, normally quite temporary and seldom noted, has become the dominant stage. Very few of the "adult" or gametophyte stage were present. Overall, the plant's development had been cut short before reaching the erect reproductive stage we consider the moss. The prostrate, intertwined threads strongly resemble filamentous green algae, but are not aquatic. I have not heard before or since of this curious phenomenon.

The "Goblin Gold" reflection adaptation

This strange and beautiful behavior of light, mediated by a floating bloom of single-celled, microscopic algae, is unknown anywhere else on Earth. It is an astonishing masterpiece of Nature's adaptive evolution. Incidentally, it is the most original, though not the most practical, discovery in my long career in ecology.

Its best expression occurred in a pit-pond where the collapsed roof of lava had formed a ramp of rock, giving easy access to the dimly lit pool and a base for setting up experiments there. When I found the good-sized sink, and first looked into its recess beyond the ramp, I was startled by what appeared to be a crescent-shaped pond of bright molten gold. The color had a living quality, as though the light came through the pool from a source beneath, like a stained-glass cathedral window with sunlight coming through it. It gave the impression of transmitted rather than reflected light. And with so little light here, how could it be reflected so brightly?

When I shifted position a few feet to one side or the other, the color disappeared and only a thin film of gray tone was seen on the water surface. I recognized the effect as akin to the phenomenon I had investigated in the terrestrial species called cave moss in seaward facing caverns on the Maine coast. The country people there called it "Goblin Gold" and could not explain it. Both here and in Maine, only at a viewing angle on or close to the line of incident light could the gold color be seen.

I brought some lumber from Albuquerque and built a firm platform on the lower part of the rock ramp for use of a microscope and a camera, and to make experiments and measurements. I built also a network of two-by-fours across the cave entrance so that by shifting the dark tarpaulins it held up I could control the size and shape of the light source. Through daytime and night-time experiments, I learned how the golden effect was caused and disrupted.

In brief, the dim skylight was being reflected back from each separate, disconnected but crowded floating cell, except the wavelengths used in photosynthesis. This determined the color reflected as gold. The algal bloom consisted of *Chlorella vulgaris.* Although laboratory cultures of this plant have been much studied by plant physiologists, no reflection phenomenon occurred because the cells were cultured throughout the liquid medium, not as a thin floating layer.

Light enters the spherical cell through the curved surface which acts as a lens to concentrate, or almost focus, the light on the chloroplasts lying on the opposite side of the cell. Excess light is reflected back through the "lens", which again concentrates it like a flashlight lens and strengthens the beam as we see it.

So little light reaches the algal bloom that without

Canvas and board structure used by Alton Lindsey to discover the secret of the "Goblin Gold" on McCartys lava flow, ca 1948. Alton Lindsey Photo, El Malpais National Monument Collection, Photo no. 126, vol. 1.

this mechanism the plant could not survive there. If we disrupt, by a drop of water or small jet of air from a medicine dropper, the orientation whereby the cell aims itself at the light source, the color disappears immediately. The resulting gray bloom takes about 15 minutes to reorient the chloroplasts and restore the reflected gold color. Briefly shining a flashlight on the bloom at night produces no gold reflection, as the chloroplasts are every which way, not aimed toward our flashlight. Clearly, without being protected in the pit-ponds from wind or water currents, the reflection phenomenon would not be possible. This remarkable and efficient adaptation enables the undisturbed *Chlorella* community to utilize light of extremely low intensity. In contrast to the cave moss in its fixed position on soil, the loose-floating one-celled alga gets its needed light the hard way.

Thirty-seven years of change

During the earlier years of my work in the malpais I took, besides Kodachrome slides, many black-and-white photos of scenery, vegetation, and geological features. In the summer of 1981, with sponsorship of the Bureau of Land Management and based in a recreational campground in Grants, we repeated photography of the same sites from the same camera positions, made possible by carrying old prints and original notes into the field. This revealed changes which are ecologically significant. Sometimes the lack of change also proved of interest. For example, in 1944 I photographed timberline piñon pines high on Bandera volcano's ash cone; nearly all their branches were dead and leafless. I thought the trees would be completely dead in a few years. In 1981 I carefully compared the 37 year old prints with the trees and could detect no difference. The same few small portions persisted green and no additional twigs were noticed.

Some of the changes were brought about naturally, from plant succession. Others represent man-caused deterioration preceding the Bureau of Land Management stewardship, which in turn preceded that of the National Park Service. Some of the things I observed no longer exist.

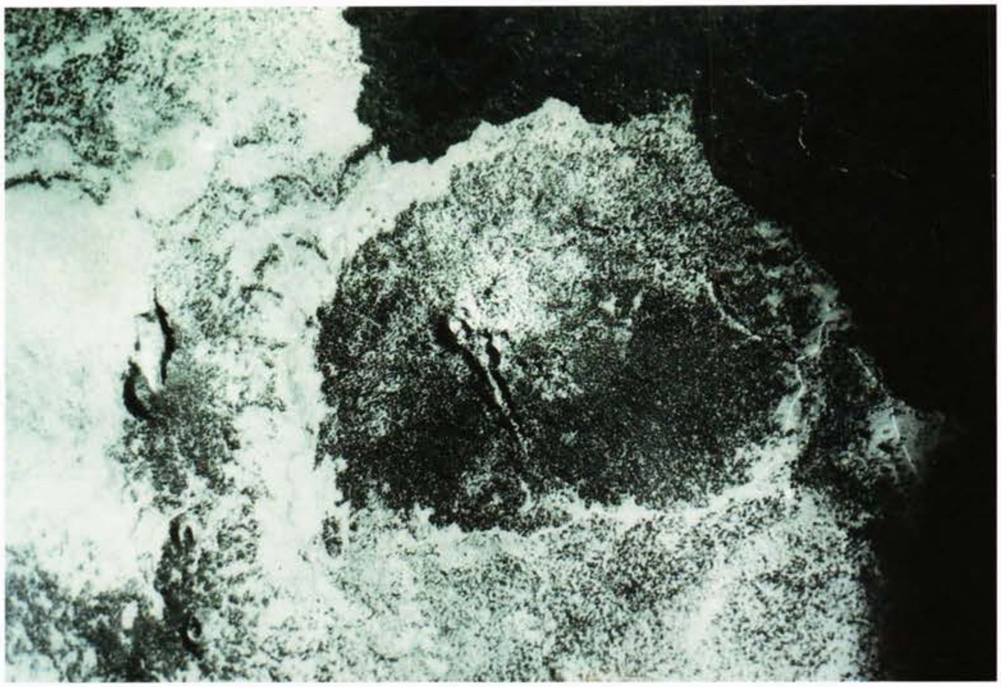
Those scientists whose work is described in the following chapters have specialized and gone deeper into many things than I, as an individual ecologist, wished or was qualified to do. I look forward with keen anticipation to reading what they learned at El Malpais National Monument and am highly gratified by their skill and energy, and the consequent accomplishments. Assuredly, this book shows that they share with an earlier persistent observer, Ponce de Leon, the essence of scientific inquiry. He consoled himself for failure to find the elusive Fountain of Youth by discovering what is better—he wrote, while in Florida, "I thank God for permitting me to see something new."

Staff House, Navajo Fluorspar Mine, Southern Zuni Mountains, 1948. The Lindsey family stayed here during the summer. Alton Lindsey Photo, El Malpais National Monument Collection, Photo no. 198, vol. 2.

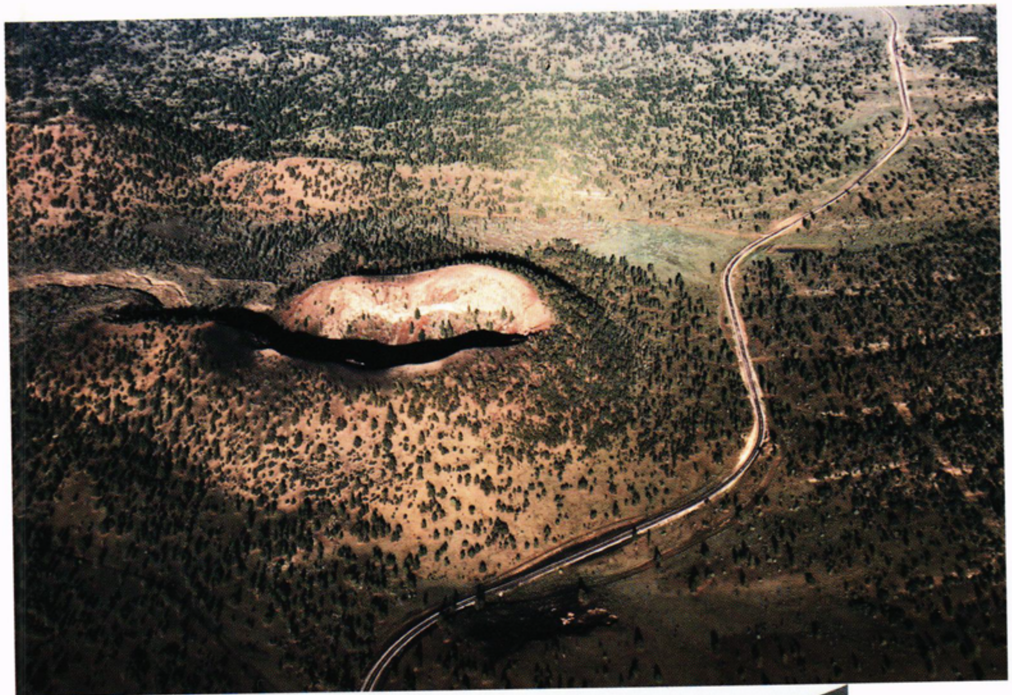
Photographic atlas of volcanic features

A. William Laughlin[1] and Frank V. Perry[2]
[1]*ICF Kaiser Engineers Inc., Los Alamos, New Mexico 87544;*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

Composite volcano is a large volcanic cone that forms over a period of hundreds of thousands to millions of years, mainly by repeated eruptions of lava. In some cases, lava flows may be interlayered with deposits of volcanic ash. Although there are no composite volcanoes within the Monument itself, Mount Taylor (above), an excellent example of a composite volcano, is a prominent feature in the region, visible from most of the Monument. Lava flows which form the cone of Mount Taylor are higher in silica and more viscous that those of the Monument, and erupted more explosively. Mount Taylor was volcanically active between 3.5 and 1.5 million years ago (Perry et al., 1990).



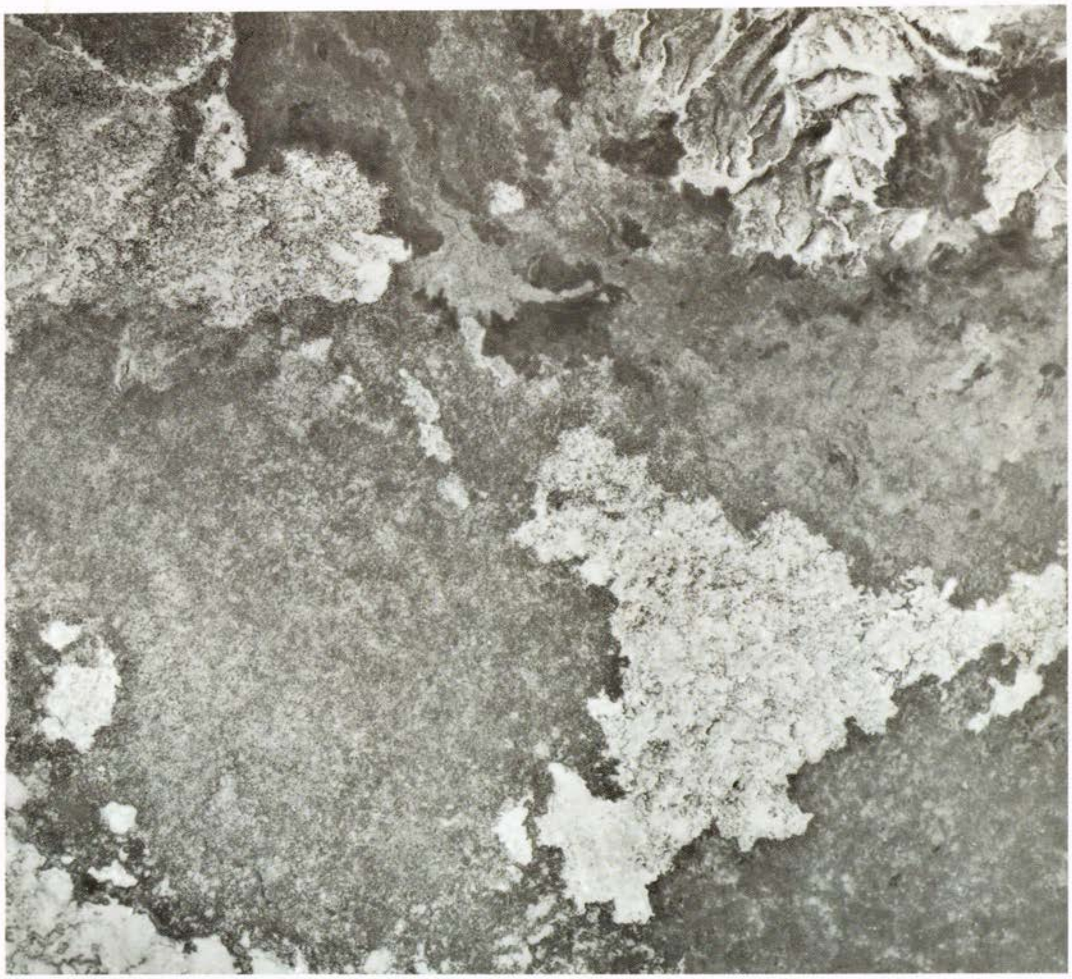
Shield volcano is a broad gently sloping volcanic cone. It is made up mainly of overlapping lava flows of relatively low viscosity, i.e. very fluid, such as those with a basaltic composition (low in silica and and rich in iron and magnesium; see Laughlin and Perry, this volume). Cerro Rendija (top), El Tintero (bottom), and the vent for McCartys flow are small shield volcanoes. Cerro Rendija is located on County Road 42, about 3 mi south of its intersection with NM–53. Two lava-tube systems are visible on the eastern and southern flanks of Cerro Rendija. The black basaltic lava to the north and east of Cerro Rendija came from the Bandera Crater. West of Grants and north of I–40 is El Tintero (arrow), a low shield volcano topped by a small cinder cone. El Tintero was the source for the Bluewater basalt flow. The lower photo illustrates the three types of volcanic vents that are present in this region, composite volcanoes (Mount Taylor, upper right) and shield volcanoes and cinder cones (El Tintero).



Cinder cone is the most common type of volcanic vent in the Zuni–Bandera volcanic field and El Malpais. It is a relatively steep cone made up of volcanic ash and/or scoria. Volcanic ash is fine-grained material less than $^1/_8$ inch in diameter, whereas scoria is more than $^1/_8$ inch in diameter. These materials were erupted explosively as solids from the vent, building up a cone. Cinder cones are often breached or broken on one side by explosion or eruption of lava which has torn away the ash and scoria accumulation. Bandera Crater, one of the most spectacular cinder cones, is shown above. It is actually a double cinder cone which erupted about 11 ka (thousand years) ago (Laughlin et al., 1994). Bandera Crater has a diameter of about 0.6 mi and is about 492 ft high. Cinder cones can be much larger than this. Like many other cinder cones of this volcanic field, Bandera Crater is breached to the southwest, probably because prevailing winds from the southwest caused thicker accumulations of cinders on the northeast sides of the cones, leaving the southwest sides weaker and more prone to breaching. Lava flows extend over 18 mi to the south from the breach in the crater wall.

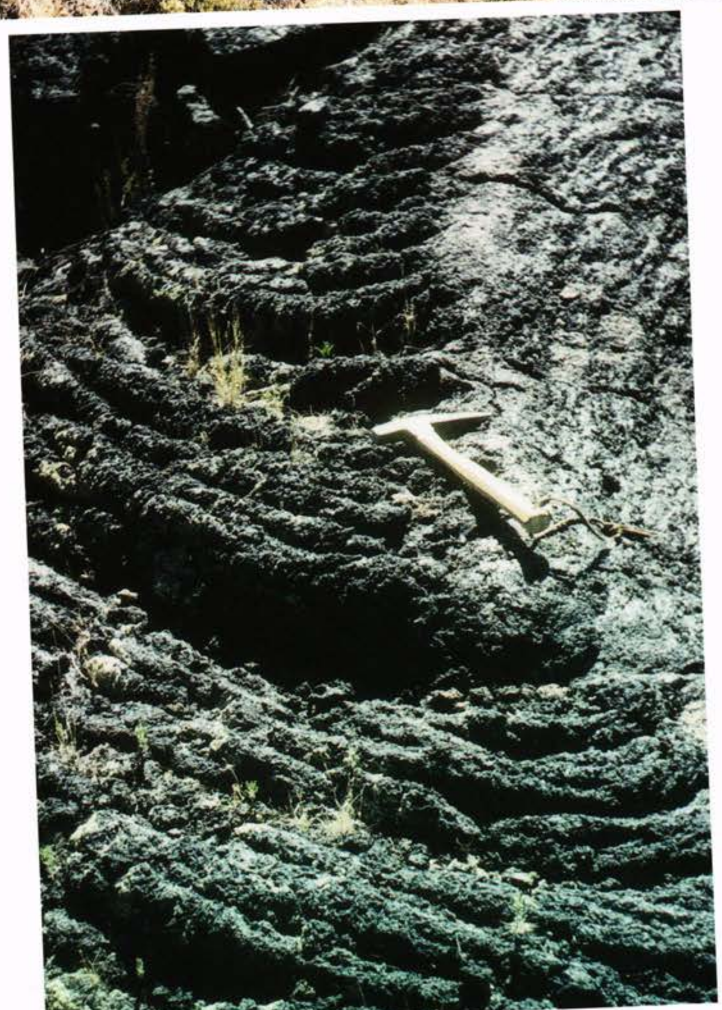
Spatter cone is formed by the ejection of dominantly plastic blobs of lava which fuse together after impact into a small edifice. It may form over a fissure or a vent or may be rootless, i.e. not over a vent. A rootless spatter cone may result from the lava flowing over wet ground where the water is vaporized by heat from the flow causing the spatter eruption. A small spatter cone along the trail to Bandera Crater is shown above.

Hornito, pronounced "or-nee'-to,"is the diminutive of the Spanish word horno or oven. Hornitos are oven-shaped mounds of spatter buildup on the pahoehoe surface of a lava flow. The spatter is ejected through a hole in the surface of the flow above a lava tube. Hornitos are rootless spatter cones. The hornito above is located near the distal (most distant from the source) end of McCartys flow about 1 mi south of where the flow is crossed by I–40. In this case, the structure is built up of "cow pie" bombs ejected from a hole in the surface of the flow.

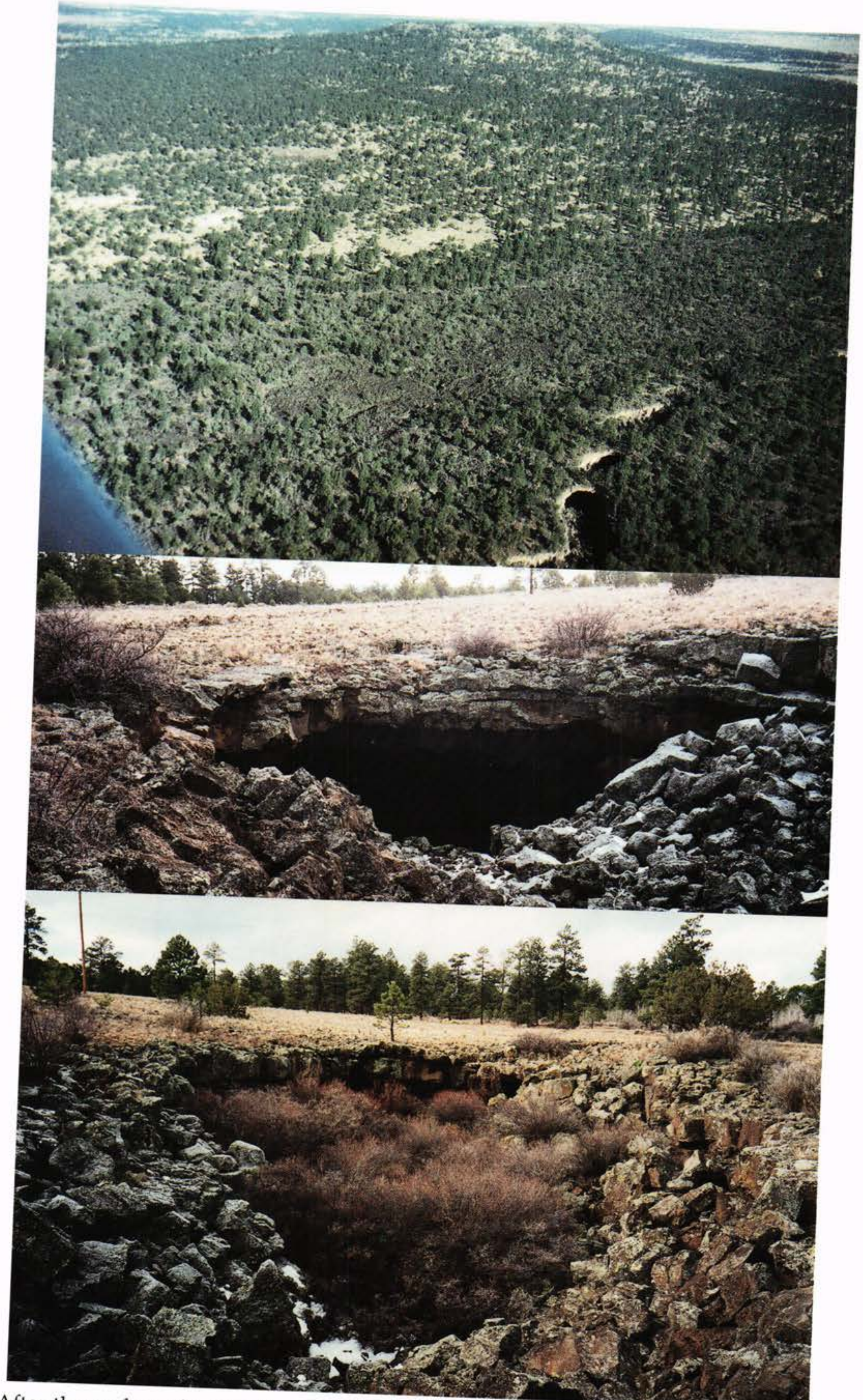


Kipuka is a Hawaiian term for an exposure of older rocks not covered by an overlying lava flow. The younger flow forms walls around the kipuka that serves as a window through which the older rocks may be seen. Above is an aerial view of the Big Hole-in-the-Wall (light gray surrounded by the black younger lava flows), a kipuka near the center of El Malpais. Several other kipukas can be seen on the west (left) side of the photograph.

Aa lava, pronounced "ah-ah," is a Hawaiian term for a lava surface characterized by a jagged, rough, or spiny texture. This type of surface is typical of lava flows with higher viscosities than those of pahoehoe lava (see below). Particularly good examples of aa lavas can be seen around Bandera Crater and in a lava pond on McCartys flow north of the intersection of I–40 and NM–117 (top) and on the south side of I–40 east of Grants (bottom).



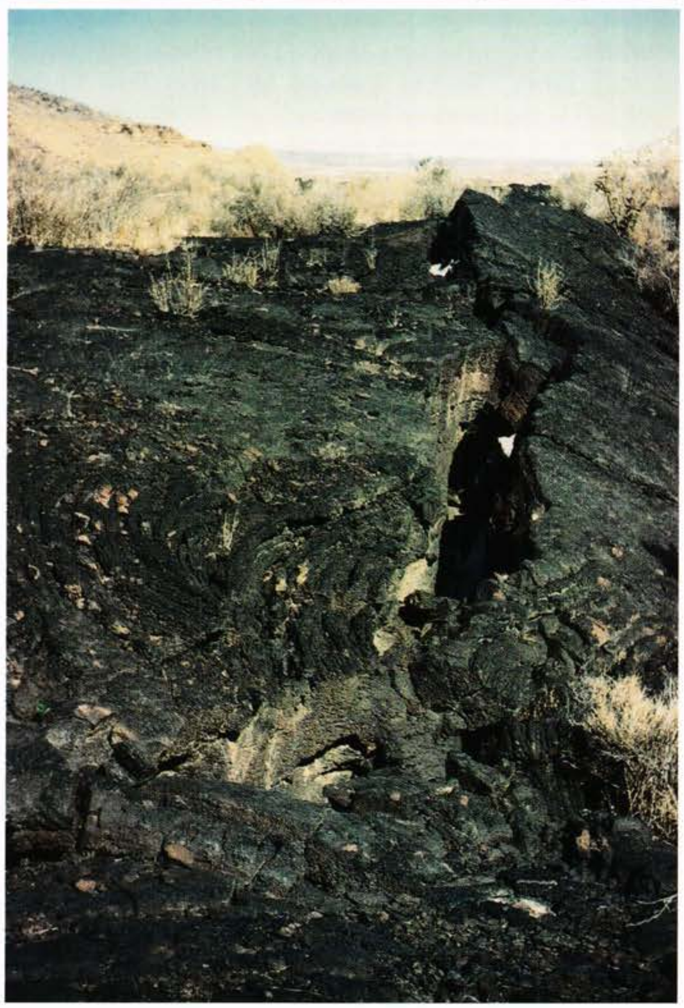
Pahoehoe lava, pronounced "pah-hoy-hoy," is a Hawaiian term for a lava surface with a characteristic ropy texture. This texture is typical of low-viscosity flows. As the flow cools and loses volatiles, the surface may change to the aa type discussed above. Pahoehoe surfaces are common throughout El Malpais and good examples can be seen around Bandera Crater and along McCartys flow (above).



Lava tube—After the surface of a lava flow has cooled and solidified, the interior of the flow may still be hot and liquid. If this channelized liquid subsequently drains out, a lava tube results. An aerial view of the main lava tube from Bandera Crater is shown in the top photo. This tube system is about 16 mi long. El Malpais is particularly well known for its many lava tubes. These tubes are discussed in detail by Rogers and Mosch (this volume). Examples of collapsed lava tubes are shown in the two lower photos.

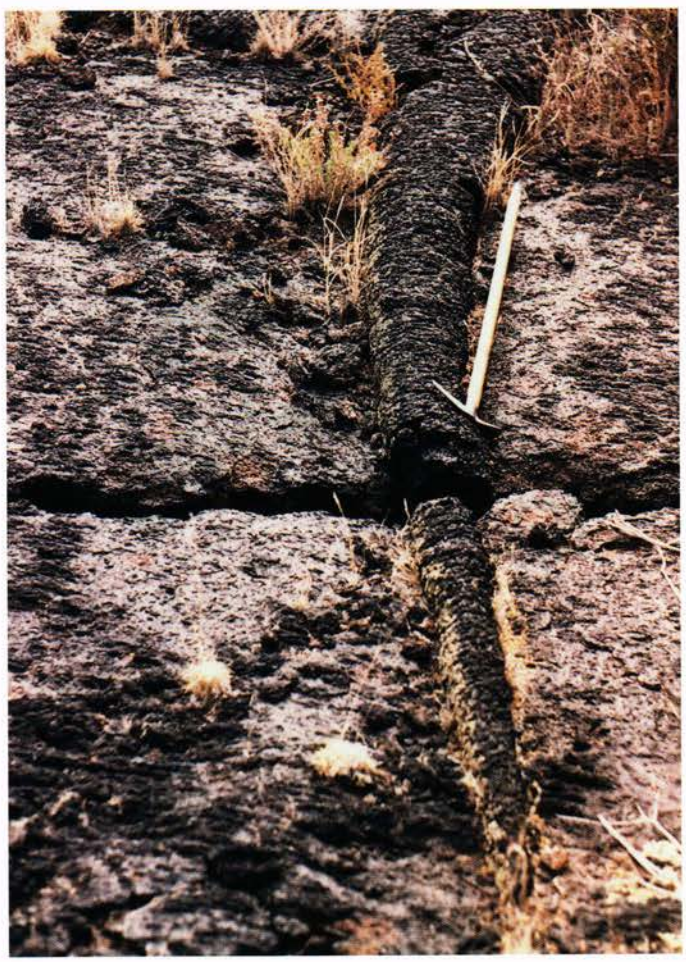
Collapse depression—If the withdrawal of the lava from a lava tube occurs while the crust is still somewhat plastic, collapse depressions may form. The last 3 mi of McCartys flow (outside of El Malpais National Monument) are marked by many of these features. Some of these are shown above.

Vesicular basalt contains a large number of vesicles, which are small cavities that formed by the expansion of gas during the solidification of the lava. Vesicles are often concentrated near the tops or bottoms of lava flows, as shown here.



Pressure ridge is produced by lateral forces pushing against the still plastic surface of a cooling lava flow. These forces cause the surface to bow upwards into an arch which is often broken by a medial crack. Note the medial cracks on these ridges near the distal end of the approximately 3 ka McCartys flow.

Tree mold—If a moving lava flow surrounds a standing tree, the molten lava will solidify around the tree, setting it on fire and burning it away. A vertical, cylindrical hole, corresponding to the trunk of the tree is left in the lava (above). Tree molds are common at El Malpais and several good examples can be seen near the Ice Cave Trading Post at Bandera Crater.



Squeeze-ups—If the brittle crust of a lava flow is broken or cracked, the still liquid lava may be forced up through the crack and form a squeeze-up such as on the McCartys flow shown.

Volcanic bombs—There are many types of volcanic bombs ejected form volcanoes. When ejected, the material may be liquid or solid. If liquid, the lava may take on a ribbon-like shape as it flies through the air, forming "ribbon" bombs. If still liquid upon impact, "cow pie" bombs may be formed. If solid, a "cored" volcanic bomb may be formed. Cored volcanic bombs were largely solid when ejected, with only a thin layer of basalt covering the solid core (above). The cores are xenoliths, "foreign rocks," i.e. fragments of older rocks that have been torn out of place by the rising lava and transported to the surface. These fragments can come from any depth down to the source region of the lava many miles below the surface. Xenoliths form Bandera Crater are samples of the source region where the lava or magma originated, and they can be very important in understanding how magma forms at depth.

Acknowledgments

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Dating the Zuni–Bandera volcanic field

A. William Laughlin[1] and Giday WoldeGabriel[2]

[1]ICF Kaiser Engineers Inc., Los Alamos, New Mexico 87544;

[2]Los Alamos National Laboratory, Los Alamos New Mexico 87545

Introduction

Because of the temporal, chemical, and mineralogical changes that can take place within a magma chamber in the Earth's interior, one of the most important first steps in interpreting the geology of a volcanic region or field is the determination of the chronology or timing of volcanic events. This chronology is particularly important when attempting to understand the changes that have occurred during the ascent and eruption of lavas that originated from many different vents as is the case in the Zuni—Bandera volcanic field, west-central New Mexico. This volcanic field is located along a major fracture in the Earth's crust called the Jemez lineament (Mayo, 1958). It is a weak zone, through which lavas were erupted beginning several million years ago.

There are two general types of volcanic chronologies, relative and absolute. Both types are necessary and important and, of course, they are complementary. A relative chronology is based primarily on the law of superposition. As applied to a volcanic field, this law requires that if one lava flow lies on top of another flow, the upper flow is younger. In large or complex volcanic fields the law of superposition may not be sufficient to establish a relative volcanic chronology. Isolated lava flows may not be in contact with other flows so that the law of superposition cannot be applied, and other geologic criteria must be used to determine relative ages. The degree of weathering or erosion exhibited by the different volcanic flows or eruptive centers such as cones will often provide clues to their relative ages. In case of very young flows such as many of those within El Malpais National Monument portion of the Zuni—Bandera volcanic field, the amount of soil cover or vegetation on the flows may be particularly useful. Maxwell (1986) has determined the relative ages of the most recent lava flows within the Zuni—Bandera volcanic field which occur in El Malpais National Monument. A simplified version of his results is presented in Table 1.

Absolute chronologies on lava flows can be obtained by the use of one or more radiometric or cosmogenic dating techniques. These techniques provide quantitative or numerical ages for some process related to the eruption of the lava flows. Relative chronologies as discussed above can be used as checks on the absolute chronologies by ensuring that the absolute ages are in the proper temporal sequence, e.g. the lava flows at the bottom of a section should give older ages that those at the top of the section, if there is a significant difference in time between eruptions of the flows.

Because of the problems associated with dating Quaternary (less than one million years old) lava flows, a Quaternary Dating Field Conference was held in Grants, New Mexico, in April 1993 to consider using the Zuni—Bandera volcanic field for testing and comparing various Quaternary dating techniques (Laughlin et al., 1993a). Different radiometric or cosmogenic dating techniques have been applied to the lava flows of the Zuni—Bandera volcanic field. Experts presented results from this area, discussed their particular method, and collected samples for additional dating. Results from dating of these additional samples were presented at the 1994 Annual Spring Meeting of the New Mexico Geological Society. These results are summarized here along with the results of earlier studies.

We give brief descriptions of the techniques that have been applied in this area and then present and discuss analytical results. The interested reader can find additional information on these and other dating techniques in Faure (1986) or Geyh and Schleicher (1990).

Radiometric or cosmogenic dating techniques

Potassium—argon (K—Ar) method

This was the first technique applied to the basalts of the Zuni—Bandera volcanic field (Laughlin et al., 1979). It is based on the fact that a radioactive isotope of potassium, ^{40}K, decays into an isotope of argon, ^{40}Ar. When the lava is hot all gases including Ar escape from the liquid system, so that as the basaltic lava cools and crystallizes (solidifies) there is theoretically no argon present in the rock. As time passes, ^{40}K decays and ^{40}Ar accumulates in the now solid basalt. Knowing the decay rate of ^{40}K to ^{40}Ar, the amounts of ^{40}K and ^{40}Ar can be measured in the laboratory by melting the samples at temperatures higher than 1200°C, and the time of eruption and crystallization of the basaltic flow can then be determined.

There are several problems related to dating very young basalts using the K—Ar method. First, when basalts are very young, e.g. less than 100 ka (thousand

TABLE 1—Relative chronology of Zuni–Bandera lava flows (modified from Maxwell, 1986).

Symbol	Description	Absolute age* ka
Qbm	McCartys flow	3.6–3.2
Qbb	Bandera flow	10.05–10.7
Qbw	Hoya de Cibola flow	50**
Qbp	Paxton Springs flow	
Qbz	Zuni flows	
Qbo	Oso Ridge flow	
Qbt	Twin Craters flows	18.4–19.1
Qbc	El Calderon flow	54
Qbu	Basalt flows (west of field)	150–200
Qb	Old basalt flows	~700
Tb	Basalt flows on Cebollita Mesa, Mesa Negra, and Horace Mesa	

* See Table 2 for all dates.

**May be too old because of excess argon.

years) old, the amounts of ^{40}Ar accumulated from decay of ^{4}0K are so small that they are difficult to measure, leading to large errors in the calculated ages Secondly, small amounts of 40Ar present in the magma when it solidified may not have escaped. This "excess" argon causes the age to be too old. This has been a major problem in the K—r dating of basalt from the Zuni—Bandera volcanic field. A third problem, inherent in all K—r dating, is that the ^{4}0K and the ^{40}Ar are measured on different portions of the sample If the sample is not homogeneous, errors may result.

Argon 40—argon 39 (^{40}Ar-^{39}Ar) method

This is an offshoot of the older K—r method, which also measures the time of crystallization of the law flow. It alleviates some of the problems discussed above because a single portion of the sample is used for both the ^{4}0K and 40Ar measurements. This is accomplished by irradiating samples in a nuclear reactor where another isotope of potassium, ^{39}K, is converted to ^{39}Ar. The amounts of both ^{39}r and ^{40}r are ther measured by melting the sample in a vacuum. The amount of ^{4}0K can then be calculated from the measured ^{39}r and, in the same fashion as with the K—r an age for the sample is calculated. This eliminates errors resulting from sample inhomogeneity. In SOME cases the presence of "excess" argon can be detected, eliminating anomalously old ages.

Carbon 14 (^{14}C) method

In some rare cases the ^{14}C or radiocarbon method can be used to date lava flows. ^{14}C is a radioactive isotope of carbon that is formed in the atmosphere by cosmic rays impacting on a nitrogen isotope, ^{14}N. This radiocarbon is subsequently incorporated into molecules of CO2 in the atmosphere and eventually is assimilated by plants, becoming part of the carbon cycle in the biosphere. As long as the plant remains alive, it is part of this carbon cycle and ^{14}C lost by radioactive decay is replaced by other ^{14}C from the atmosphere. When the plant dies, however, it is no longer part of the cycle and its ^{14}C simply decays away. The amount of radiocarbon in fossil or dead plants can be measured in several different ways and a date for the death of the plant can be determined.

The radiocarbon method can be used to date a lava flow if, in some way, the lava or the volcanic eruption caused the death of the plant. We have been able to date three volcanic events in the Zuni—Bandera volcanic field using this method (Laughlin et al., 1993a, 1994). In one case hot volcanic ash or scoria from Bandera Crater fell on top of vegetation, converting it to charcoal. In the other two cases the Lava Crater and McCartys lavas flowed over vegetation, burning and converting it to charcoal.

Helium 3 (^{3}He) method

Like ^{14}C, **^{3}He is the product of** cosmic radiation and **nuclear reactions. In this case, the ^{3}He is produced by cosmic-ray radiation of outcropping rocks instead of in the atmosphere. The interactions of** cosmic rays **with atoms in the surface of a lava flow lead to** a continual **buildup of ^{3}He over time. By knowing** the pro duction rate for this ^{3}He and measuring the amount present in a surface sample, it is possible to calculatE the length of time over which the lava flow has beer exposed to cosmic rays. Because young flows such as those found within El Malpais are not likely to have been buried by soil, the "exposure" age should closely approximate the crystallization age for a flow.

Chlorine 36 (^{36}C1) method

The radioactive isotope ^{36}C1 is also the product of the interactions of cosmic rays with atoms, primarily ^{35}C1, ^{39}K, and "Ca, in the surface of a lava flow. Because the production rate for the ^{36}C1 is known, as is the rate at which it radioactively decays, it is possible to calculate the length of time the surface of the lava flow has been exposed to cosmic rays. If the lava flow was not buried after eruption, the "exposure" age should represent the time of eruption.

Uranium series disequilibrium (U series) method

There are three naturally occurring radioactive isotopes of uranium: ^{238}U, ^{235}U, and ^{234}U. Most of the thorium in nature is the radioactive isotope ^{232}Th, although there are five other radioactive isotopes of thorium that result from the radioactive decay of ^{232}Th, ^{238}U, ^{235}U, or ^{234}U. All of these radioactive uranium and thorium isotopes eventually decay into various lead isotopes. The dating method used on Bluewater flow depends on the disequilibrium between ^{238}U and its daughter ^{23}0Th in the decay scheme where ^{238}U decays into ^{234}Th, which decays into ^{234}Pa, which in turn decays into ^{234}U. The ^{234}U decays into the isotope ^{230}Th. This technique is useful from about one thousand years to about one million years.

Discussion

The six dating methods just described have been applied to the basalt flows of the Zuni—Bandera volcanic field including the very young flows of El Malpais. In several cases, where multiple methods have been applied to the same flow, agreement between methods has been excellent; these dates are "concordant." In other cases, however, the dates do not agree, they are "discordant." Results for each flow or vent, presented in Table 2, are discussed below.

McCartys flow (Qbm of Maxwell, 1986)

Based on stratigraphic and geomorphological evidence, Maxwell (1986) concluded that the McCartys flow is the youngest basalt flow within El Malpais, supporting a similar conclusion by Nichols (1946). We have dated this flow by two methods, ^{14}C and ^{3}He, and the results are in very good agreement. The well established ^{14}C method was first applied to charcoal collected from soil beneath the eastern edge of the flow (Laughlin et al., 1993a, 1994). This charcoal resulted from burning of plant rootlets by the overlying lava flow. The ^{3}He method was applied to a surface sample of the flow immediately above the site where the ^{14}C sample was collected. The concordance or agreement at about 3 ka between the two methods is an excellent test of the ^{3}He method.

TABLE 2—Isotopic ages of basaltic flows, charcoal, and minerals from the Zuni–Bandera volcanic field, west-central New Mexico.

Volcanic vent or flow	Dating methods (ages in ka)					
	Carbon 14	Helium 3	Chlorine 36	Uranium series	K–Ar	Ar–Ar
McCartys	3.6–3.20 (1)	2.45 ± 1.2 (1)				
Bandera	10.05–10.07 (1)	11.2 ± 1.1 (1)	9.5 ± 0.9 (2)			41 ± 7 (6)
Twin Craters	18.4–19.1 (1) 16.9–17.9 (9)	17.8 ± 0.9 (2)				
Hoya de Cibola						50 ± 14 (10)
El Calderon			33.4 ± 3		54 ± 50 (3) 128 ± 33 (7)	
El Tintero (Bluewater)		57 ± 6 (1)	35.6 ± 3.4	79 + 40–3 (5)		
Laguna Pueblo					120 ± 7 (3) 110 ± 8 (3) 380 ± 250 (8)	
Flow beneath the Bandera Crater (from Cerro Bandera)					199 ± 42 (4)	
Cerrito Arizona					148 ± 87 (3)	
Black Rock					164 ± 35 (3) 70 ± 55 (4)	
El Morro					109 ± 44 (3)	
North Plains					593 ± 9 (3) 724 ± 10 (3)	

1. Laughlin et al., 1994
2. Dunbar and Phillips, 1994
3. Laughlin et al., 1993
4. Laughlin et al., 1979
5. Sims et al., 1994
6. McIntosh et al., 1994
7. Champion and Lanphere, 1988
8. Lipman and Mehnert, 1979
9. J. Quade, pers. comm. 1994
10. Laughlin and WoldeGabriel (unpublished data)

Bandera Crater flow (Qbb of Maxwell, 1986)

Four different techniques have been applied to dating of the lava flows and cinder eruption from Bandera Crater. Three techniques (^{14}C, ^{3}He, and ^{36}Cl) yield concordant ages of about 10 ka. The r—r method gave a discordant age of 41 ± 7 ka (i.e. with an error range of plus or minus 7 ka). We interpret this anomalously old age as resulting from the presence of "excess" argon in the magma at the time of eruption. This "excess" argon did not escape as the magma cooled and crystallized, leading to an age that is too high. Because of the youthfulness of the Bandera basalt flow, a very small amount of trapped argon would be enough to lead to this large error.

Agreement between the three concordant ages is remarkably good for a flow this young, especially when it is realized that two different events were measured. The ^{14}C date was obtained on charcoal from beneath basaltic cinders in a cinder pit across NM-53 from Bandera Crater (Laughlin et al., 1993a, 1994). This charcoal was formed when the very hot cinders were erupted onto a soil, burning plant roots and other organic debris as they were buried by the cinders. The two different surface dating techniques, ^{3}He (Laughlin et al., 1994) and ^{36}Cl (Dunbar and Phillips, 1994) date the time at which the Bandera flow was erupted and first exposed to cosmic radiation. Both of these surface dating techniques are in the developmental stage and it was very encouraging to obtain this agreement with the well established ^{14}C method.

Lava Crater flow (Qbt of Maxwell, 1986)

The Lava Crater basalt flow is one of a group of flows from several vents that were lumped together by Maxwell (1986) as the Twin Craters flows. Recent geologic mapping by Cascadden et al. (this volume) separated these flows and provided a relative chronology for this portion of El Malpais. Very small amounts of charcoal were found in the soil beneath the Lava Crater where it is exposed in a roadcut on NM-53. Radiocarbon dates of about 17 ka on two samples of this material are in excellent agreement with each other and with a ^{36}Cl date obtained by Dunbar and Phillips (1994). Once again this is an excellent test of the ^{36}Cl method.

Hoya de Cibola flow (Qbw of Maxwell, 1986)

Only the r—r method has been applied to dating the Hoya de Cibola flow. Our sample was collected along NM-117 on the east side of El Malpais. At this site the Hoya de Cibola flow is overlain by the younger McCartys flow. No charcoal could be found associated with the Hoya de Cibola flow, and neither the ^{3}He nor ^{36}Cl methods have yet been applied. As a result, the r—r age of 50 ka cannot be considered definite. If the relative chronology of Maxwell (1986) is correct, then this date is too old. Maxwell believed the Hoya de Cibola flow to be younger than the Lava Crater flow that we have dated at about 18 ka by multiple methods. Because these flows are not in contact, his interpretation is open to question. Eventual surface dating using the 'He or ^{36}C1 methods should settle this question.

Bluewater flow

The Bluewater flow was erupted from El Tintero, a small shield volcano west of Grants, New Mexico. The 'He and U-series methods have been applied to the dating of this flow and yielded similar ages (Table 2), whereas the ^{36}C1 date of 35.6 ka (Dunbar and Phillips, 1994) appears to be too young.

El Calderon flow (Qbc of Maxwell, 1986)

The El Calderon or Laguna flow (Laughlin et al., 1993b) has been dated by two laboratories using the K—r method. Although the error is large on one of these dates, the two results fall within experimental error of each other. The average of the two dates is 91 ka. The ^{36}o date of 33.4 ka (Dunbar and Phillips, 1994) appears to be too young. Cascadden et al. (this volume) present paleomagnetic, petrological, and geochemical data on this flow and discuss its relationship to the Grants and Laguna Pueblo flows (dated at 115 ka). The El Calderon flow does overlie the Grants flow and thus is younger.

Laguna Pueblo flow

This flow is well exposed in the Rio San Jose valley in the vicinity of Laguna Pueblo. It may be correlative with the Grants flow (Cascadden et al., this volume), which underlies the 91 ka El Calderon flow. Two laboratories have dated this flow using the K—r method; one laboratory repeated their analysis, obtaining dates of 110 and 120 ka. The second laboratory obtained an age of 280 ka. Because of the very large error on the 280 ka date (Table 2), we believe that the best estimate of the age of this flow is 115 ka (the average of 110 and 120 ka). The r—Ar or U-series method should be applied to this flow to confirm this age. The 115 ka average age appears reasonable stratigraphically, because it is older than the 91 ka date on the El Calderon flow. The El Calderon flow overlies the Grants flow, which may correlate with the Laguna Pueblo flow.

Flow beneath Bandera Crater (Qb of Maxwell, 1986)

We have one K—r date on a basalt sample, collected on the west side of County Road 42, west of Bandera Crater, which gave an age of 199 ± 42 ka. Andrew (this volume), based on his geologic mapping, believes that this flow came from Cerro Bandera.

Cerrito Arizona flow (Qb of Maxwell, 1986)

Cerrito rizona is a small, low volcanic cone south of Cerro Bandera and northwest of Cerro Rendija. We have obtained a K—r date of 148 ± 87 ka (Laughlin et al., 1993b) on a basalt sample from the wall of the lava tube east of the cone. The consistency of this date with dates on basalt flows from Cerro Bandera (above) and flows from near El Morro and at Black Rock (see below) suggest that all four dates are reasonable.

El Morro flow (Qb of Maxwell, 1986)

We have one K—r date on a basalt sample from a pressure ridge along NM-53 east of the turnoff to El Morro National Monument. This Sample gave an age of 109 ± 44 ka (Laughlin et al., 1993b). Geologic mapping by Andrew (this volume) suggests that this flow is correlative with the Choz flow from the northern Chain of Craters volcanic alignment.

Black Rock flow

We also have one K—r date on the prominent basalt flow at Black Rock on the Zuni Pueblo. This sample gave an age of 164 ± 35 ka (Laughlin et al., 1993b). Andrew (this volume) suggests that, based on his geologic mapping, this flow came from the Pig-a-ti-ana shield volcano.

North Plains basalts (Qb of Maxwell, 1986)

Three samples of the North Plains basalts have been dated by the K—r method (Laughlin et al., 1993b). These samples ranged in age from 593 ± 9 ka to 724 ± 10 ka, suggesting a long period of volcanism. Unpublished dates of Laughlin, WoldeGabriel, and McIntosh suggest that the Fence Lake flow was erupted during this period.

Basalt flows on Cebollita Mesa, Mesa Negra, and Horace Mesa (Tb of Maxwell, 1986)

These basalt flows, which are shown on the map of Maxwell (1986), are not part of the Quaternary Zuni—Bandera volcanic field. Laughlin et al. (1993b) summarized all existing geochronological data and presented several new K—r and r—r dates on these flows. These results are not included in Table 2 because they come from outside the Zuni—Bandera volcanic field, but they confirm the two periods of Tertiary basaltic volcanism recognized by Perry et al. (1990) in this area. The first of these periods [3.7-2.9 Ma (million years)] is represented by basalt flows that cap or cover the high mesas that surround Mount Taylor. Basalts at the same elevation capping Cebollita Mesa were erupted during the same period. These high mesa basalts are readily visible from much of El Malpais National Monument. A younger period of volcanism (2.6-2.4 Ma) is represented by basalt flows capping the low mesas around Mount Taylor. Again, these basalt flows are readily visible from El Malpais.

The radiometric and cosmogenic dating summarized here is in excellent agreement with the relative chronology developed by Maxwell (1986). Only the date on the Hoya de Cibola flow may be out of place, but because the Hoya de Cibola and Lava Crater flows are not in contact, we are inclined to believe the results of the absolute dating.

Conclusions

Periods of basaltic volcanism have occurred several times in west-central New Mexico during the last four million years. The first of these periods began at about 3.7 Ma north of the Zuni—Bandera volcanic field, in the area around Mount Taylor and on Cebollita Mesa. This initial volcanism continued until 2.9 Ma. After a period of quiescence, volcanism resumed at 2.6 Ma and continued until 2.4 Ma.

After a long hiatus, volcanism began in the southern part of the Zuni—Bandera volcanic field at about 0.700 Ma (700 ka). This volcanism resulted in the eruption of the North Plains basalts and the Fence Lake flow. These lavas were very fluid and covered large areas in the southern part of the volcanic field. After about a 500 ka long gap in volcanism, lava flows and cinder cones were erupted forming the Chain of Craters in the western part of the volcanic field (Andrew, this volume). This period apparently persisted from about 200 to 100 ka, although it may be continuous with the older activity within El Malpais National Monument (El Calderon, 91 ka). The youngest activity within El Malpais National Monument began at about 18 ka (Lava Crater flow) and continued until essentially the present (McCartys flow, 3 ka).

The results of radiometric and cosmogenic dating of the basalts of the Zuni—Bandera volcanic field are in excellent agreement with the relative chronology of the basalt flows of this field. Results from the relatively new cosmogenic dating techniques also are in good agreement with results from older, better established techniques.

Acknowledgments

The authors would like to thank all of the geochronologists who have worked in the Zuni—Bandera volcanic field over the past two decades: Paul Damon, Muhammad Shafiqullah, Jay Quade, Tim Jull, Bill Phillips, and Nat Lifton of The University of rizona; Jane Poths, Frank Perry, Steve Reneau, Ken Sims, and Mike Murrell of Los Alamos National Laboratory; and Bill McIntosh, Nelia Dunbar, and Matt Heizler of the New Mexico Bureau of Mines & Mineral Resources (NMBMMR). We thank Charles Chapin, Director of NMBMMR, for encouragement and help in all of our work. We also thank Doug Eury, Ken Mabery, Cindy Ott-Jones, Leslie DeLong, and Kent Carlton of the U.S. National Park Service, El Malpais National Monument, for their logistical support and encouragement. Dave and Reddy Candelaria deserve special thanks from the first author for friendship, help, good food and coffee, and access rights for more that 25 years of work in this area. Helpful reviews of this manuscript were provided by Linda Fluk and Cathy Goetz.

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Hogan on NM–117 east of lava bed, south of McCartys village, ca 1947. Alton Lindsey Photo, El Malpais National Monument Collection, photo no. 55, vol. 1.

Volcanic history of the Northern Chain of Craters

Joseph Andrew

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131

Introduction

The volcanic history of the Northern Chain of Craters is complex, with three overlapping stages of volcanic activity occurring during the last 650,000 years. The second stage of volcanism is further separated into four episodes. The chain of craters is part of the larger Zuni—Bandera volcanic field, which also contains the El Malpais National Monument and the Southern Chain of Craters (Fig. 1). There are over 50 volcanic vents and lava flows in the Northern Chain of Craters. The field relationships of these volcanic products reveal the history in this volcanic field. The following criteria characterize the three stages and

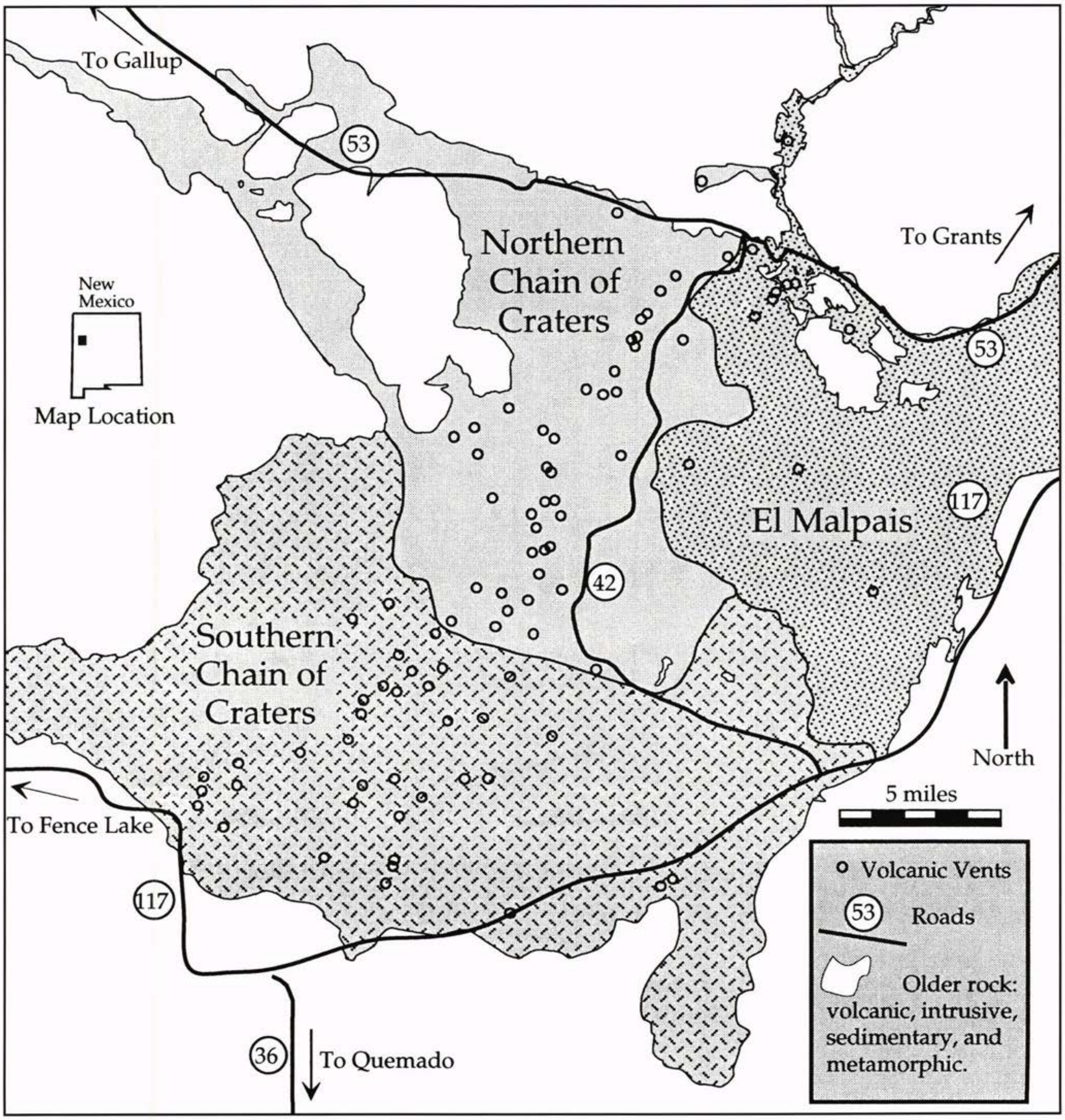

FIGURE 1—The Zuni–Bandera volcanic field, showing: area covered by basalt, volcanic vents, major roads, Northern Chain of Craters, Southern Chain of Craters, and El Malpais areas.

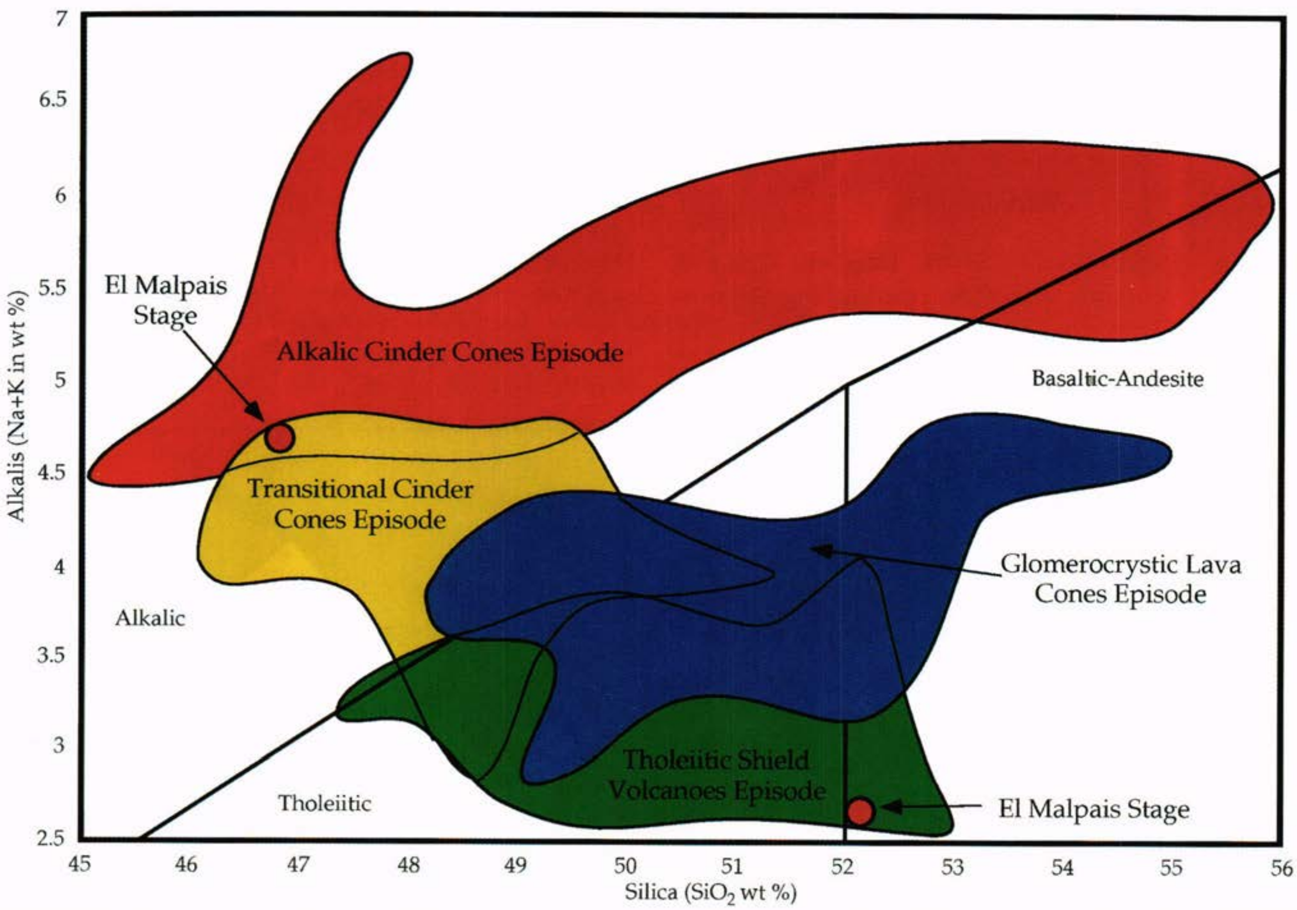

FIGURE 2—Chemical classification of Northern Chain of Craters basalts. Additional chemical data from Gawell (1975), Ander et al. (1980), Menzies et al. (1991), Laughlin et al. (1993b), and Laughlin pers. comm., (1994). Alkalic-tholeiitic line from Miyashiro (1978).

subepisodes: vent morphology (shape and texture), composition, mineralogy, relative age, and isotopic age.

The most easily observable feature of the different stages and subepisodes in the Northern Chain of Craters is the vent morphology. There are large to small cinder cones, spatter cones, and shield volcanoes. These vent morphologies correlate to the style of eruption. Cinder cones are the result of very explosive eruptions, which fragment the magma into small cinders. These fragmental pieces are usually red due to oxidation. Spatter cones are similar to cinder cones, but the pieces of lava are larger, called bombs. When these pieces hit the ground they are still hot and plastic enough to deform (colorfully called cow-pie bombs) and to weld together. Shield volcanoes repre-

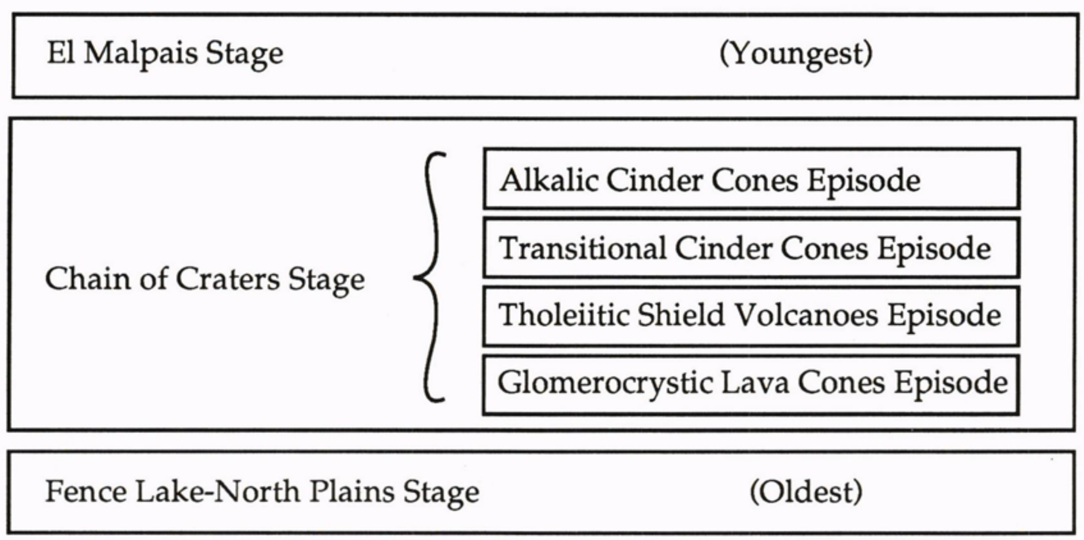

FIGURE 3—Volcanic history of the Zuni–Bandera volcanic field.

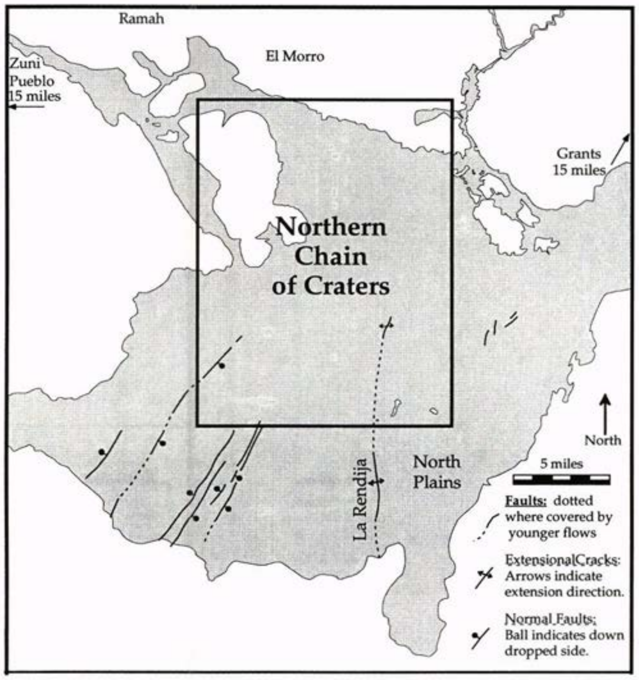

FIGURE 4—Generalized map of the Zuni–Bandera volcanic field, showing the area possibly covered by the Fence Lake–North Plains basalt flows, and also faults which cut the FLNP basalt flows. The rectangle designates the area covered by Figs. 5 through 10. The faults are from Maxwell (1987) and Baldridge et al. (1989).

sent the least explosive eruptions and the most fluid lavas, which may have oozed out of the ground with little or no explosive activity. Because of the fluidity of these lavas, the vents are low and broad, resembling shields.

There is also an enigmatic structure with features of both cinder cones and shield volcanoes. This structure has steep slopes typical of cinder cones, but there is no observable cinder. Instead the lavas are massive, as those of shield volcanoes. These structures probably represent cinder cones mantled over by lava flows erupted out of the top of a pre-existing cinder cone.

All of these volcanic rocks are basaltic, which means they have a relatively high percentage of iron and magnesium oxides (FeO, Fe_2O_3, and MgO equal to 20-25 wt%) and relatively low silica (SiO_2 equal to 44-56 wt%). Basalts are typically dark and only a few crystals are large enough to be seen with the naked eye. Basaltic rocks break down into subcategories defined by chemical compositions. Four basaltic subcategories occur in the Northern Chain of Craters (Fig. 2): alkalic basalt, transitional basalt, tholeiitic basalt, and basaltic andesite (see Glossary). Alkalic basalts have relatively high amounts of alkalis (Na_2O and K20) and relatively low amounts of silica . Transitional basalts have alkalis and silica between alkalic and tholeiitic basalts. Tholeiitic basalts are relatively low in alkalis and high in silica. Basaltic andesites are relatively high in silica. Contamination of magmas by the rock through which they passed en-route to the surface complicates the chemical classification of basalts.

In this area there is a strong correlation between the chemical composition of the lavas and the vent morphology. Alkalic basalts produce large cinder cones, while the transitional basalts generally produce smaller cinder cones and spatter cones. The tholeiitic basalts build shield volcanoes. There is a third type of vent structure that does not correlate with chemical composition, but rather with the presence of glomerocrysts (clumps) of the minerals olivine and plagioclase.

Five minerals are easily identifiable without a microscope in the Northern Chain of Craters lavas. Olivine is the most common mineral, occurring in every flow in the Northern Chain of Craters. Plagioclase and clinopyroxene are present in some flows. Quartz and alkali-feldspar can occur in any of these lavas, because they are present in rocks that were picked up by the magmas.

The relative timing of the different episodes is shown by the overlapping of lava flows and other volcanic products. A lava flow that overlaps and covers another flow must be the younger of the two flows. Most lava flows in the Northern Chain of Craters are in contact with several other flows, allowing the determination of their chronology. Absolute dating provides a good check for the relative dating and a "true" age for the rock. Absolute dating uses unstable isotopes to obtain a date of solidification for the rock (Laughlin et al., this volume).

Northern Chain of Craters volcanism

There are three stages of volcanism in the Northern Chain of Craters (Fig. 3), in ascending order the Fence Lake—North Plains (FLNP) stage, the Chain of Craters (CC) stage, and the El Malpais (EM) stage. The FLNP stage is the simplest, having produced only

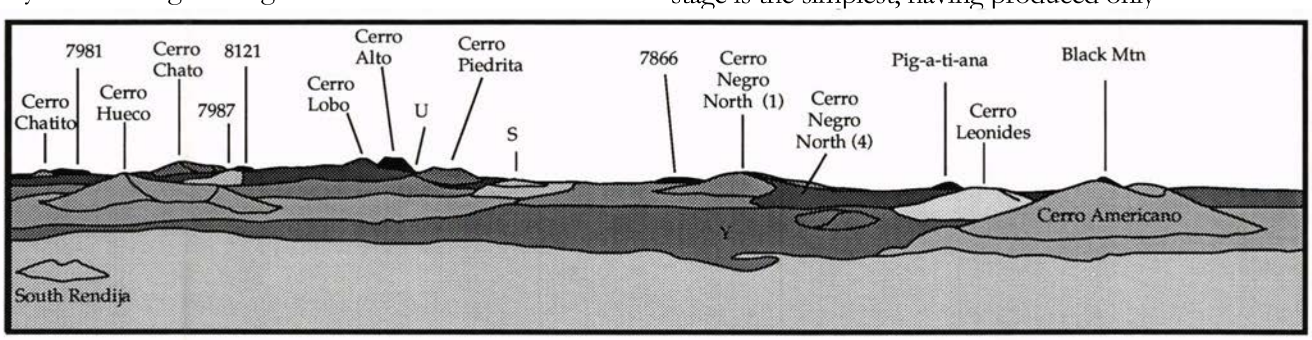

FIGURE 5—Interpreted panorama of the Northern Chain of Craters, as viewed looking southeast from the top of Cerro Rendija.

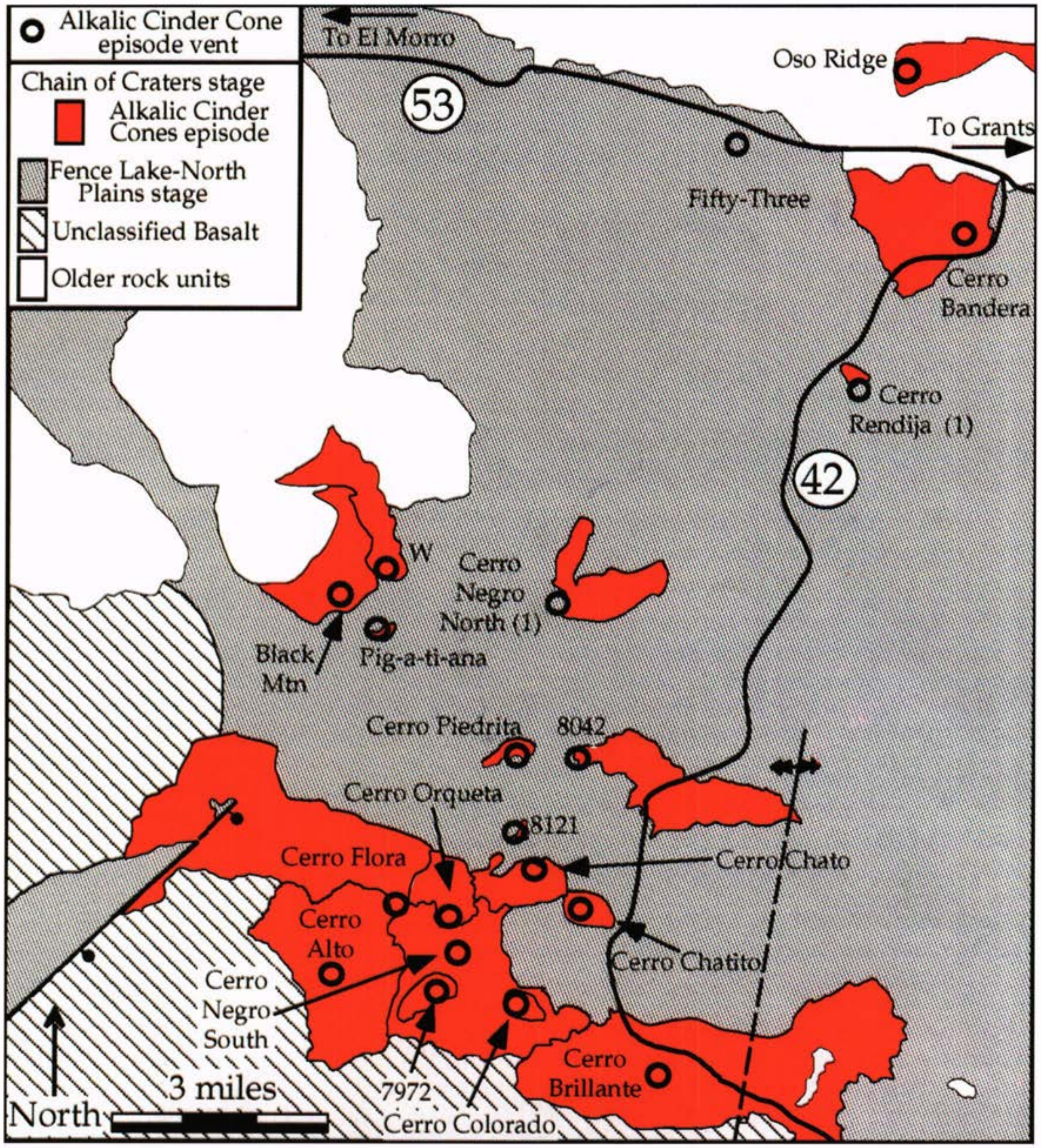

FIGURE 6—Northern Chain of Craters, showing the alkalic cinder cone episode flow coverage and vents.

tholeiitic basalts. The CC stage has four basalt types that can be divided up into four episodes of volcanism, in ascending order alkalic basalts, transitional basalts, tholeiitic basalts, and finally transitional basalts, tholeiitic basalts, and basaltic andesites together. The EM stage is similar to the CC stage in having different compositions, except that there are only three basalt types present and there is no progressive change in compositions with time. This stage has alkalic, transitional, and tholeiitic basalts that erupted almost synchronously (Laughlin et al., 1979; Jenkins et al., 1994; Cascadden et al., this volume).

Fence Lake–North Plains stage of volcanism

The first stage of volcanism occurred 650,000 ± 50,000 years ago (Laughlin et al., 1993). Because of burial by subsequent younger eruptions, only remnants of this stage are preserved. Overlapping younger volcanics buried the source areas of the FLNP flows. These flows are tholeiitic basalt. The North Plains flows cover a large area southeast of the Chain of Craters, and the Fence Lake flows extend approximately 50 miles westward into rizona. These flows may also underlie regions of the Northern Chain of Craters, as can be seen in a few "windows" through younger flows in which these first-stage basalts occur. Faults offset the flows of this stage (Fig. 4). Normal faults (Baldridge et al., 1989) and a large crack system named La Rendija cut these FLNP stage basalts (Fig. 4). These first-stage flows have a relatively thicker soil cover than the rest of the flows in this area, because they are the oldest. The soils consist mostly of wind-deposited dust, which has accumulated over time.

Chain of Craters stage of volcanism

Alkalic cinder cones—This first episode of the

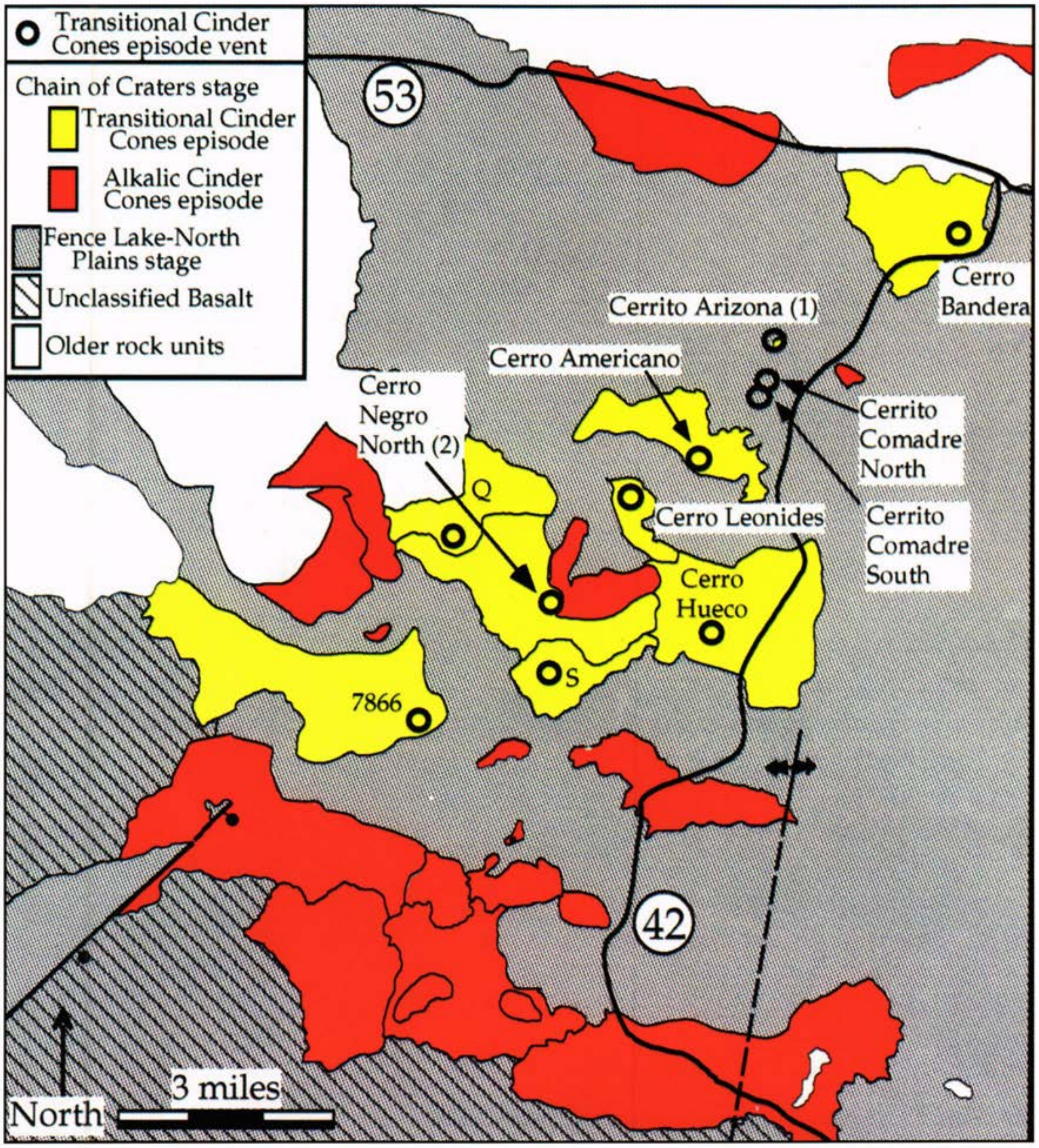

FIGURE 7—Northern Chain of Craters, showing the transitional cinder cone episode flow coverage and vents.

second stage is the most easily discernible event in the Northern Chain of Craters due to large cinder cones (Fig. 5) ranging from 100 to 900 feet tall. The cinder cones and their associated lava flows are alkalic basalts (Fig. 2). The alkalic cinder cones occur in two areas (Fig. 6), one cluster at the southern end and another smaller cluster at the northern end of the Northern Chain of Craters. At least 19 cinder cones of this episode occur in the Northern Chain of Craters; most of them are U-shaped, resembling amphitheaters. The U-shape is due to lava flows from the same vent breaking up and carrying away a section of the cinder cone in a process called breaching. Olivine is usually the only recognizable mineral, but clinopyroxene, quartz, and alkali-feldspar may also occur. None of these have been isotopically dated.

Ultramafic xenoliths (rocks foreign to the basalt) occur at Cerro Chato. These are abundant and large (up to six inches across). Ultramafic xenoliths are pieces of the mantle or lower crust of the Earth, which the host basalt carries to the surface. There are two types of xenoliths at this cinder cone: a light green rock (alters to red) and a dark green rock. The mineral olivine comprises most of the light green rock (lherzolite), and the mineral pyroxene comprises most of the dark green rock (pyroxenite).

Transitional cinder cones—This episode is similar to the previous one, but the cinder cones are generally smaller and the compositions are transitional basalts (Fig. 2). There are nine cinder cones in this episode (Fig. 7). The minerals olivine and plagioclase are usually present, with olivine dominating. Clinopyroxene, quartz, and alkali-feldspar may also occur in these flows. There is one absolute age available for this episode, from a lava flow beneath Bandera Crater that probably corresponds to the Cerro

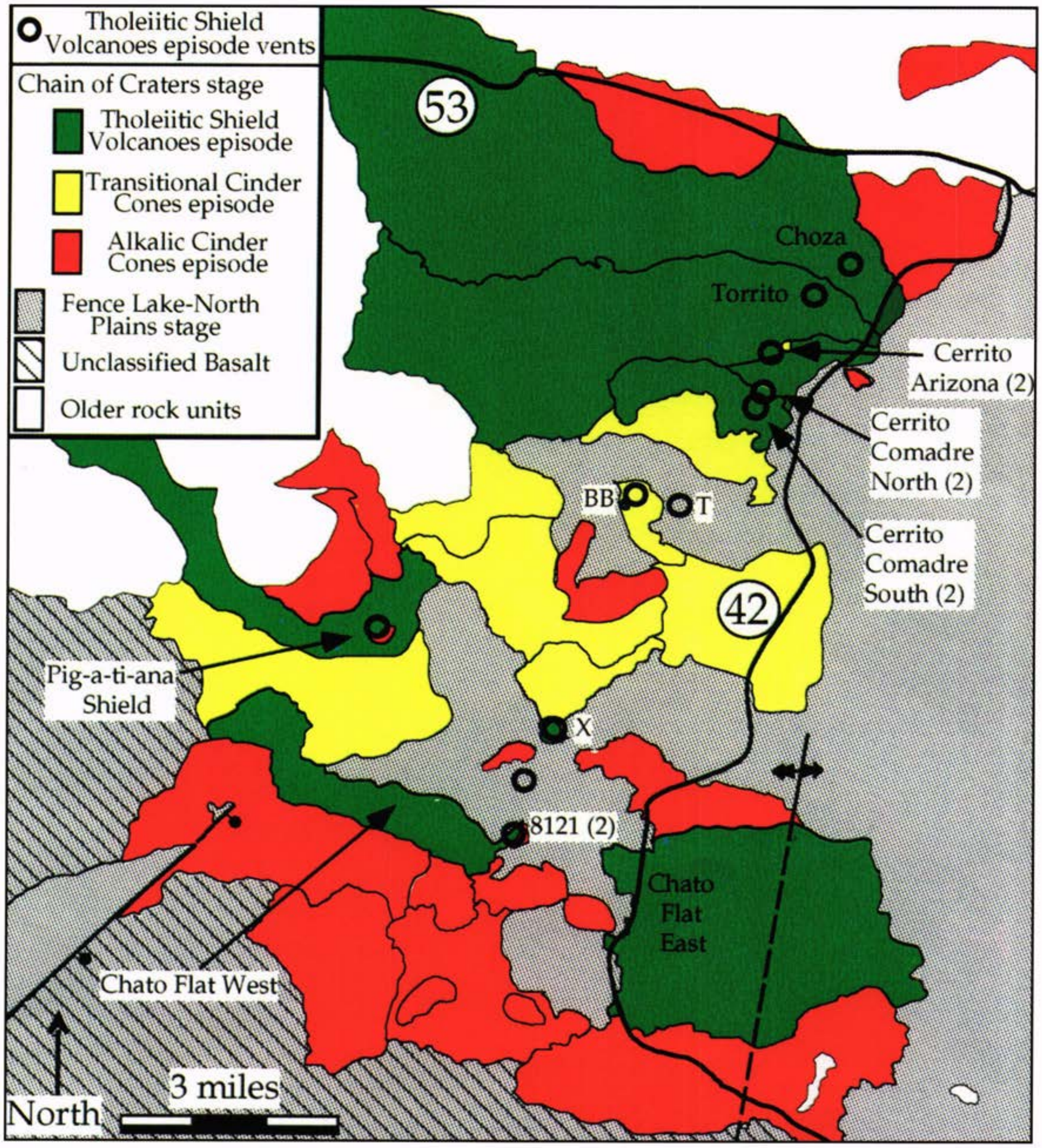

FIGURE 8—Northern Chain of Craters, showing the tholeiitic lava shield flow coverage and vents.

Bandera flow. This flow has an age of 199,000 ± 42,000 years (Laughlin et al., 1993).

The vents of this episode form a strong north-northeastward-trending lineament (Fig. 7). These vents occur north-northeast of the vent cluster of the previous episode (Fig. 6).

Tholeiitic shield volcanoes—This episode of the Chain of Craters stage reflects the changing compositions of magma in the Northern Chain of Craters. The style of eruption changes from the explosive activity of the two previous episodes to relatively fluid outpourings of lava that formed shield volcanoes. This episode has tholeiitic-basalt compositions. The change in chemistry for the first three CC episodes follows a strong trend from alkalic to tholeiitic (Fig. 2).

Olivine and plagioclase are the dominant minerals in these flows, but some flows also have quartz and alkali-feldspar. Lava tubes are present in at least two of the flows in this unit (Chato Flat East and Arizona 2).

There are 13 different flows in this unit (Fig. 8). These vents form two clusters, one in the northern part of the map area and the other in the southern part (Fig. 8). Similar to the lineament formed by the previous episode, these vents also form a strong north-northeast lineament. The northern cluster of vents seems to be a northward migration of vents from the previous episode.

Three flows of this episode have been dated. The lava flow with the oldest date is from along the Zuni River to the west of the Northern Chain of Craters; this flow probably correlates with the flow from Pig-a-tiana. The sample has a date of 163,000 ± 35,000 years ago (Laughlin et al., 1993b). The next younger absolute age is from rizona shield, which has an age of 148,000 ± 87,000 years (Laughlin et al., 1993b). The

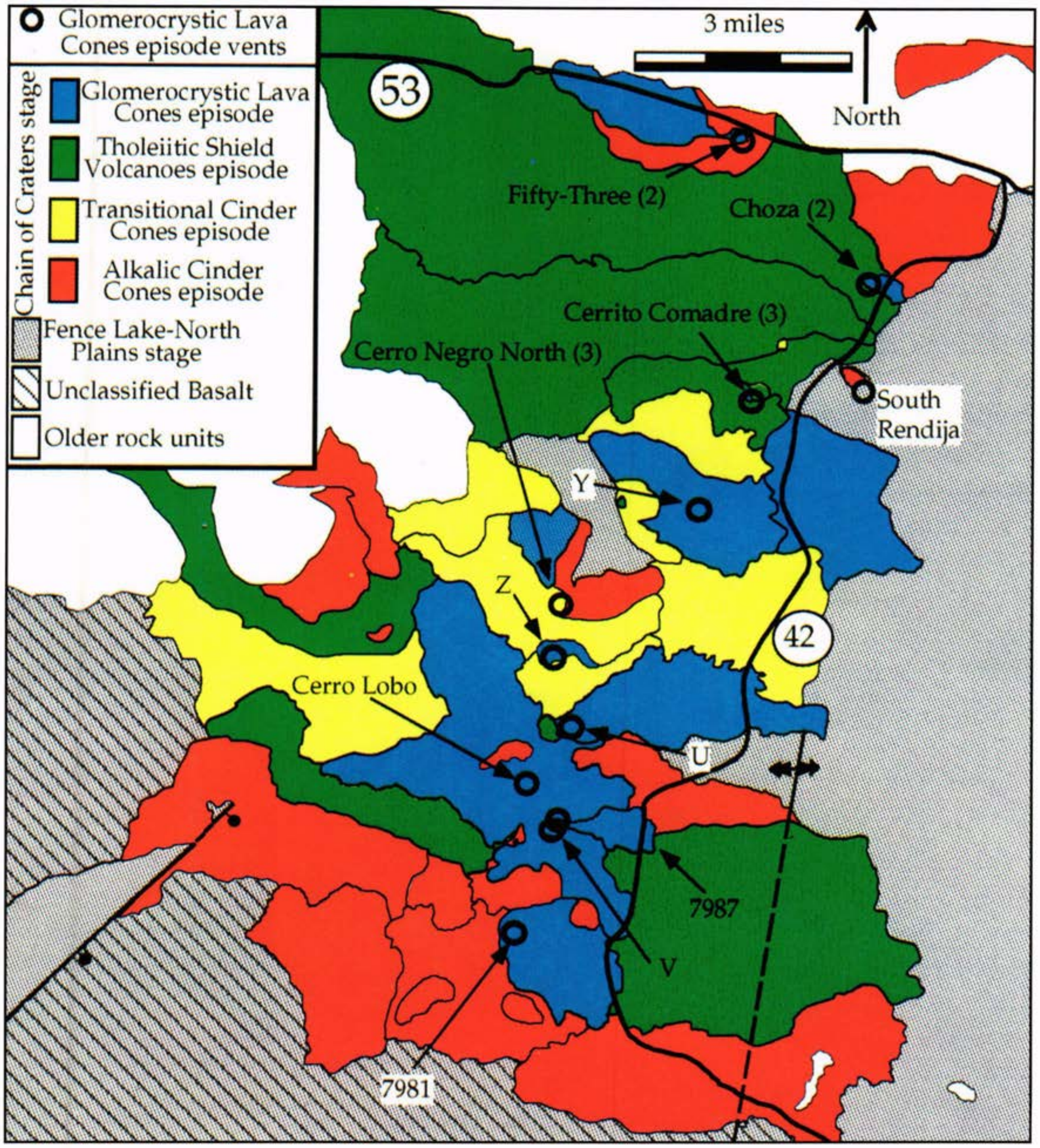

FIGURE 9—Northern Chain of Craters, showing the glomerocrystic lava cone episode flow coverage and vents.

youngest age in this episode comes from a sample collected near El Morro, west of the Northern Chain of Craters along NM-53. This flow correlates with the Choza Flow. An absolute age for the eruption of this flow is 109,000 ± 44,000 years (Laughlin et al., 1993b).

The absolute ages for this episode agree with relative dating of the lava flows, which shows an age progression from oldest in the south to the youngest in the north–northeast (Choza).

These flows are in many regards very similar to the FLNP stage lava flows. They are generally voluminous, with some that are quite large. The Pig-a-ti-ana and Choza lava flows are the most voluminous, with the Pig-a-ti-ana flow reaching the Zuni Pueblo approximately 30 miles away. The major differences between these flows and the FLNP stage flows are the greater age (greater sediment cover) and the faulting of the latter.

Glomerocrystic lava cones—The abundance of large (> fi inch) clusters (glomerocrysts) of plagioclase easily distinguishes this event from the other episodes. The plagioclase in the glomerocrysts commonly occurs as crosses or bow ties of two or more plagioclase crystals. Olivine is also present in all of these flows, and clinopyroxene is present in some. Pyroxene commonly occurs as rounded clumps of two to several dozen crystals.

There are 12 units in this episode. Most of these units erupted from or near a vent formed during a previous episode (Fig. 9). The larger glomerocrystic lava cones episode flows may cover and obscure any volcanic products from previous episodes. Several flows show evidence of lava tubes that fed an auxiliary vent away from the main vent (U and South Rendija). Some lava cones show evidence of mantling earlier cinder cones (probably from the alkalic cinder cones

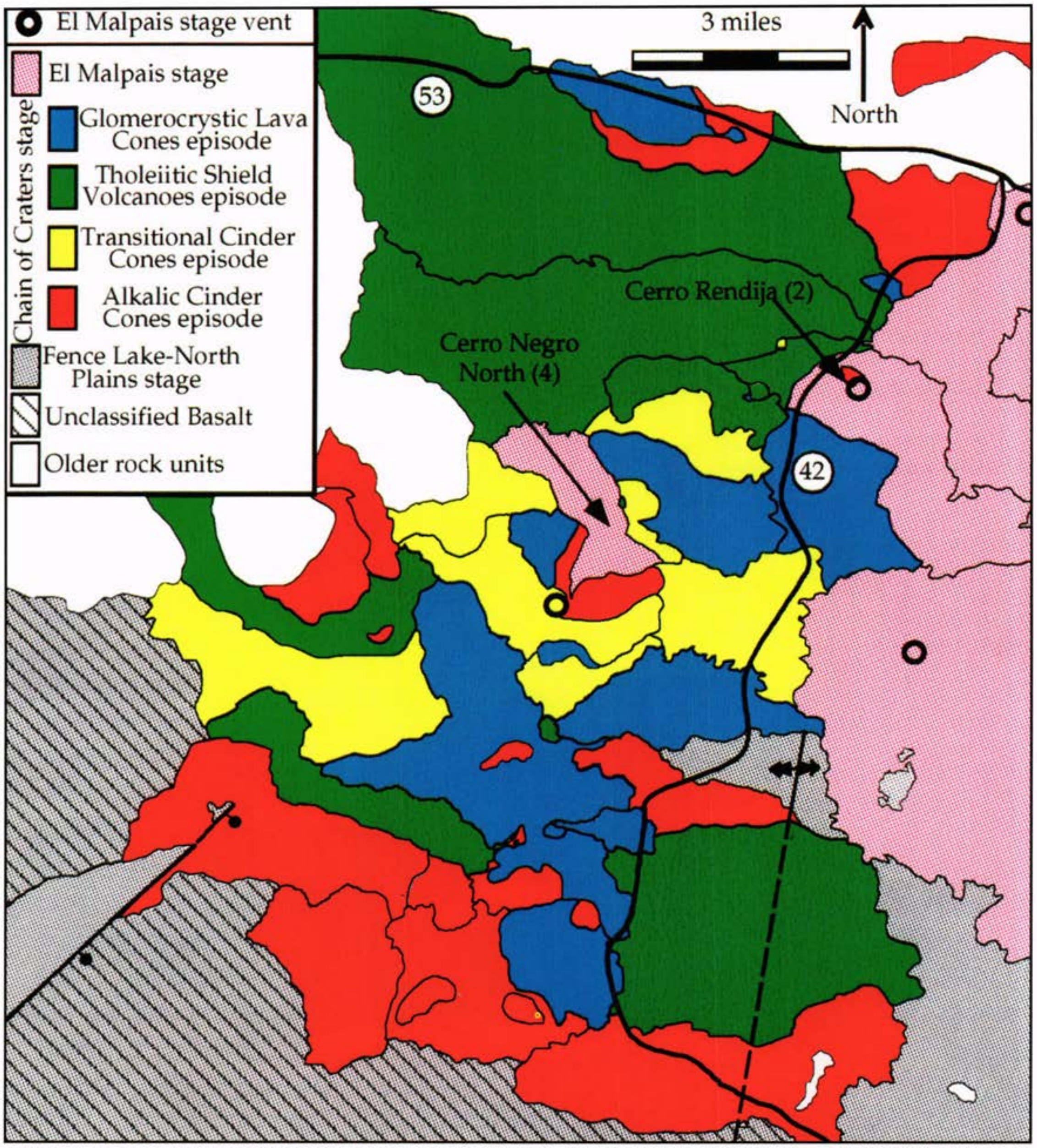

FIGURE 10—Northern Chain of Craters, showing the El Malpais stage flow coverage and vents.

episode). For instance, the great height and steep slope of Cerro Lobo may indicate a lava-covered cinder cone. Also the very irregular shape of cone 7981 may indicate a complex, breached cinder cone covered by a flow from this episode.

These flows are transitional basalt, tholeiitic basalt, and basaltic andesite that show relationship with the earlier units, especially alkalic cinder cones episode vents. The coarse size, texture, and abundance of crystals in this episode may result from some contaminant being entrained and incorporated into a batch of magma possibly related to one of the earlier-episode magmas. The composition of the crystals shows this contaminant-rock composition to be gabbroic.

El Malpais stage of volcanism

There are three types of basalts in this stage: alkalic, transitional, and tholeiitic. Unlike the previous CC stage, there is no trend in compositions with time. This stage dominates the volcanism found in the El Malpais National Monument to the east of the Northern Chain of Craters, but two of the flows occur in the Northern Chain of Craters (Fig. 10). These two flows are noticeably different from the other flows in the Northern Chain of Craters. They appear to be younger, with generally rougher surface and less soil, which makes them obvious in aerial photographs. Also, these two flows are the only ones in the Northern Chain of Craters that do not follow the order of the first two stages of volcanism, from tholeiitic to alkalic, transitional, tholeiitic, and then glomerocrystic basalts. The Cerro Negro 4 flow is alkalic, but overlaps transitional (Cerro Leonides), tholeiitic (BB and Torrito), and glomerocrystic (Cerro Negro 3 and Y) flows. The Rendija 2 flow is tholeiitic but overlaps the glomerocrystic South Rendija flow. There are no isotopic ages for these two units, but other EM stage flows in the El Malpais National Monument have ages of about 20,000 to 3,000 years (Laughlin et al., 1993a).

Summary

The Northern Chain of Craters has a sequence of six episodes of volcanism divided into three stages. The oldest activity (Fence Lake—North Plains stage) took place at about 650,000 years ago, with large-volume tholeiitic basalt flows covering most of the southern half of the Zuni—Bandera volcanic field. A hiatus in volcanic activity probably followed, during which faults offset the first stage flows. About 300,000 years ago a new and very different stage of volcanic activity began (Chain of Craters stage). The first episode of this stage was the alkalic cinder cones episode. Most of these cones are clustered at the southern end of the Northern Chain of Craters. The next episode (transitional cinder cones) occurred about 200,000 years ago. Cinder cones of this episode are generally smaller, with more spatter, and most of them are located north of the first episode cinder cones. The vents of this episode form a lineament that trends north—northeast. Following this is the tholeiitic shield volcano episode, which had some large-volume flows and an alignment of vents similar to the lineament formed by the vents of the previous episode. The basalts of this episode erupted about 160,000-100,000 years ago, with a progression of older to younger eruptions toward the north—northeast end of the lineament. Next the distinctive glomerocrystic lava cones episode formed vents which are closely linked with vents of earlier episodes. These flows are distinctive because of the abundance, size, and clusters of crystals present. Finally the El Malpais stage featured volcanic activity and basalt types similar the proceeding Chain of Craters stage, but produced no glomerocrystic basalts. The three basalt compositions of the El Malpais stage erupted without an apparent age progression.

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Jumbled lava made a haven for outlaws and spawned lurid accounts of gold buried in the malpais. Accounts of treasure have all proven false. Photo by W. Cal Brown, Museum of New Mexico, negative no. 66552.

El Calderon cinder cone and associated basalt flows

Tracy E. Cascadden[1], John W. Geissman[1], Albert M. Kudo[1], and A. William Laughlin'
'Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131;
[2]ICF Kaiser Engineers Inc., Los Alamos, New Mexico 87544

Introduction

El Calderon cinder cone is the oldest vent of the youngest stage of eruptions in the Zuni—Bandera volcanic field. Volcanic activity at El Calderon began with the eruption of scoria, forming the cinder cone. This scoria eruption varied from alkalic to transitional to tholeiitic in composition (see Glossary for definitions of compositional terms). These eruptions were followed by voluminous eruptions of subalkaline (tholeiitic) flows which breached the northeast margin of the cinder cone. The main tholeiitic flow from El Calderon is exposed discontinuously from the cinder cone vent to 1-40, east of Grants, NM, where it overlies an older flow, first named here as the Grants flow (Fig. 1). The El Calderon flow is overlain by younger flows (Lava Crater, Cerro Candelaria, and McCartys). This chapter summarizes proposed correlations of the El Calderon, Laguna Pueblo, and Grants flows, and presents geochemical and paleomagnetic evidence for the correlations (or lack thereof). Some exposures of the flows have been dated by several methods (Laughlin and WoldeGabriel, this volume).

Previous work

The El Calderon flow was correlated with a lava flow along 1-40 by earlier workers (i.e. Thaden et al., 1967), and with the Laguna Pueblo flow by Drake et al. (1991). Maxwell (1986) mapped much of the Zuni—Bandera volcanic field, following the maps of Goddard (1966) and Thaden et al. (1967). Limited chemical analyses from El Calderon, Grants, and Laguna Pueblo flows have been published (Laughlin et al., 1972,1993a, b; Lipman and Moench, 1972; Perry et al., 1987; Baldridge et al., 1991; Menzies et al., 1991) as part of broader regional studies. One paleomagnetic site near the location of our Site 1 was analyzed by Champion et al. (1988).

Basic paleomagnetic principles applied to studies in the Zuni—Bandera volcanic field

The Earth's geomagnetic field, on a time-averaged basis, approximates that of a geocentric axial dipole. In other words, the field can be approximated by a dipole magnet centered in the Earth's interior (geocentric) and aligned along its rotational axis (axial). On short time scales, however, behavior of the magnetic field differs from true axial alignment. On short time scales (in a geological sense) the dipole wobbles around the rotational axis, following a more-or-less random path through and around the rotational pole (Butler, 1992). These departures, up to 15-20° from the axial position, are termed secular variation and are

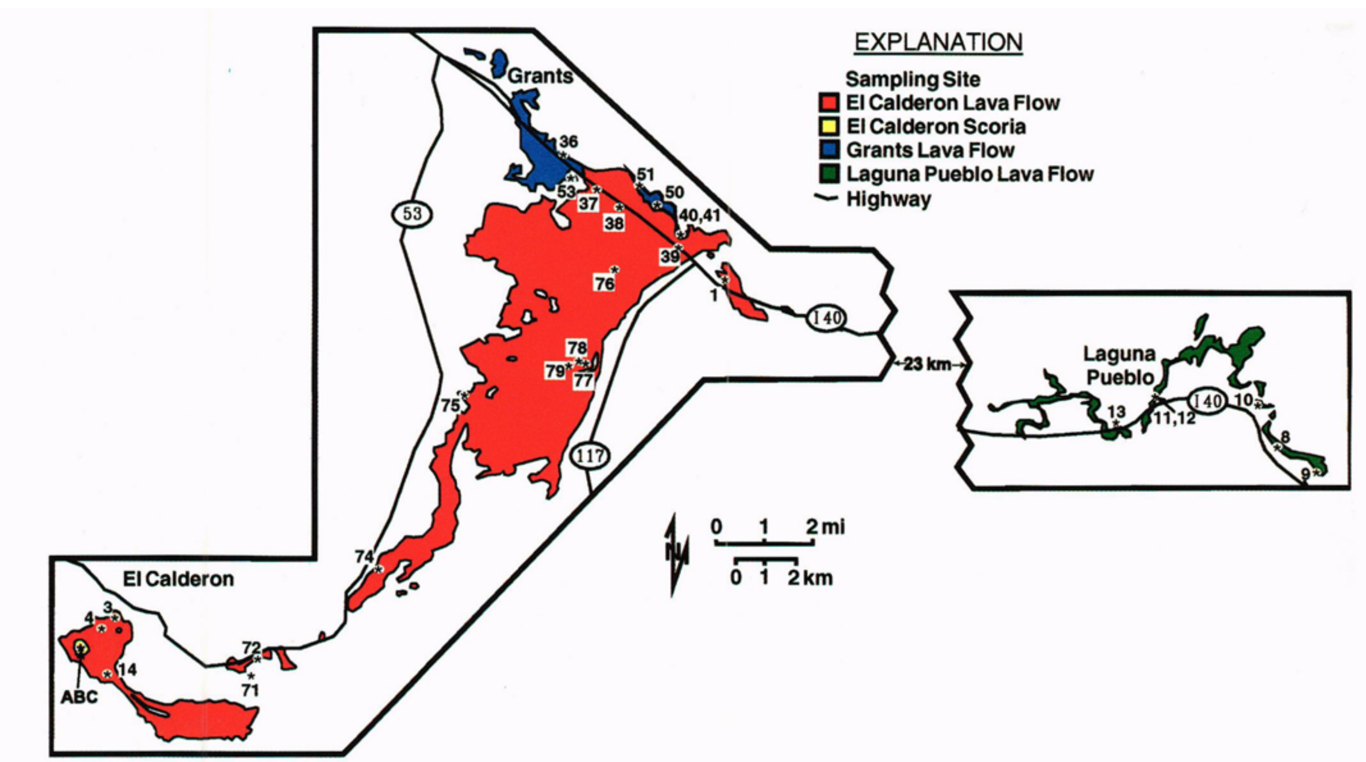

FIGURE 1—Geologic map showing distribution of El Calderon, Grants, and Laguna Pueblo flows, site locations, I–40, NM–117, exit 85, and Grants. Numbered sites are locations from which paleomagnetic, whole-rock geochemical, and microscope samples were obtained. Lettered sites are locations from which whole-rock and/or microscope samples were obtained.

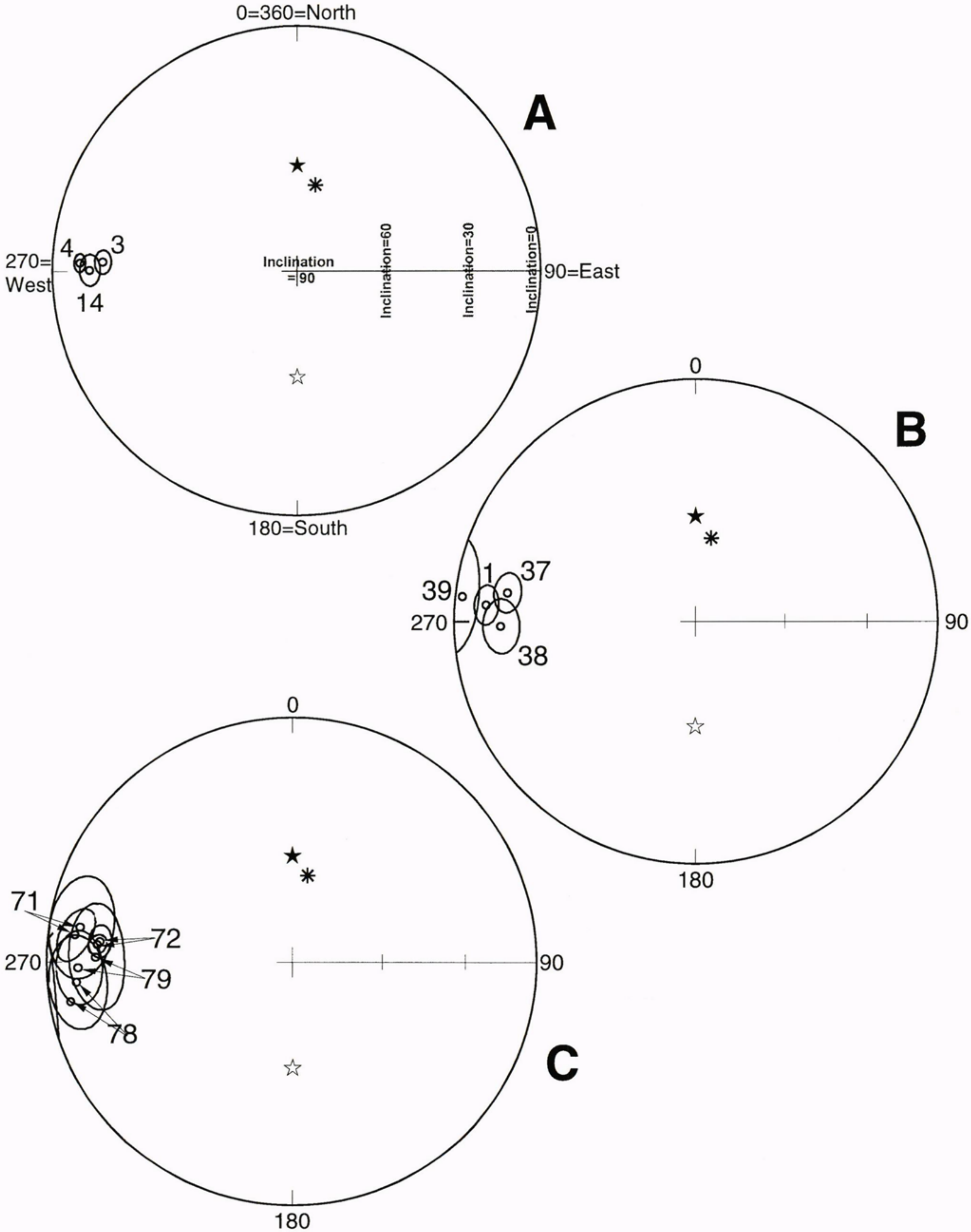

FIGURE 2—Equal-area projections of paleomagnetic data. See text for explanation of diagram. Asterisk shows direction of present-day field. Stars mark direction of normal and reverse rotation axes. **A**: Sites 3, 4, and 14, near El Calderon. **B**: Sites 1, 37, 38, and 39 along I–40. **C**: Sites 71, 72, 78, and 79 between El Calderon and I–40. In all sites the paleomagnetic direction is nearly due west, with a shallow negative inclination. This means that at the time the El Calderon flow was cooling, the Earth's geomagnetic-field vector at this locality pointed to a magnetic pole was far to the west of El Malpais, in the South Pacific Ocean.

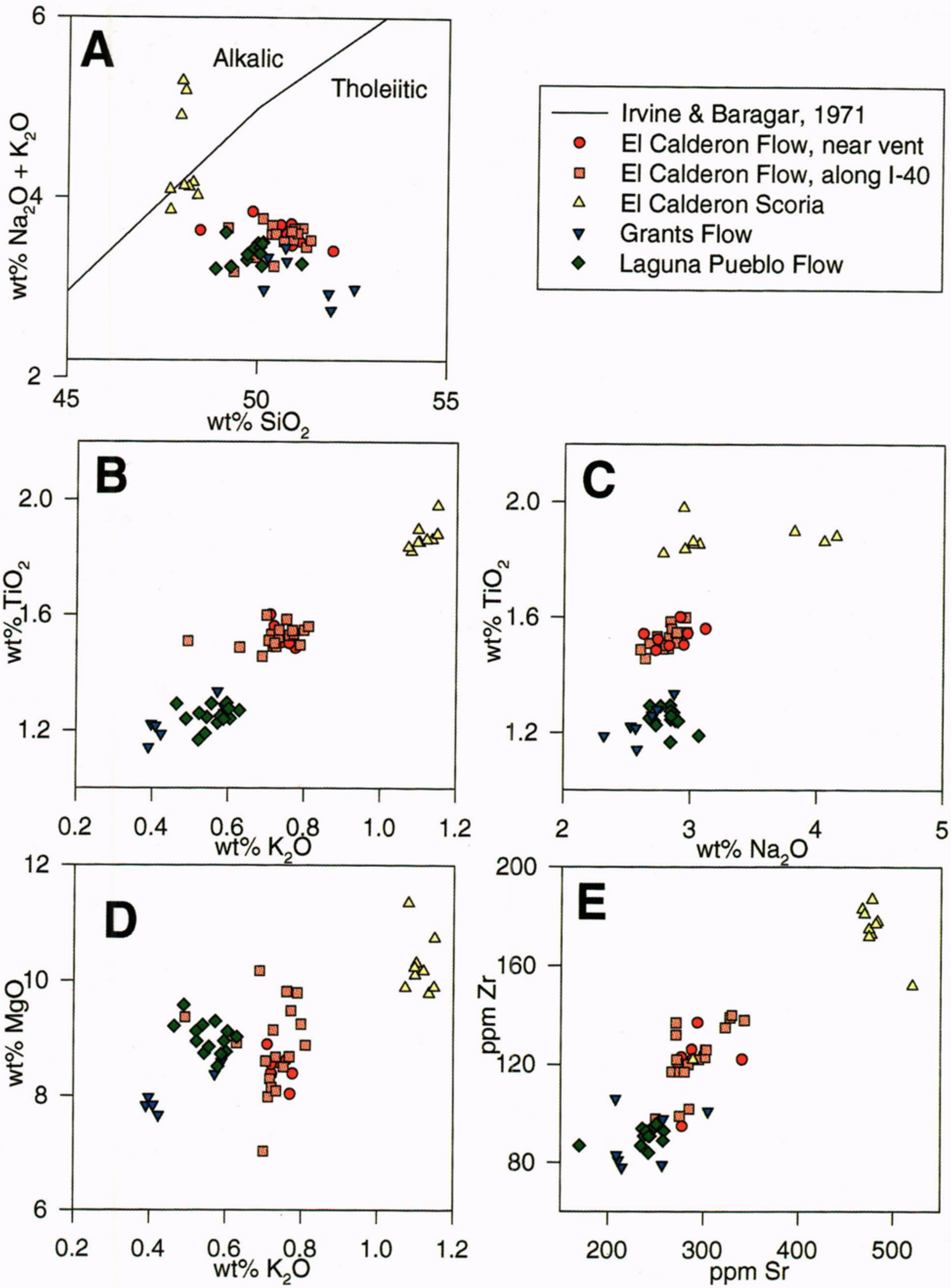

FIGURE 3—Whole-rock chemical data for El Calderon, Grants, and Laguna Pueblo flows. **A**: Alkalies vs. silica, **B**: K_2O vs. TiO_2, **C**: Na_2O vs. TiO_2, **D**: K_2O vs. MgO, **E**: Sr vs. Zr. Separation of data into three distinct groups on plots B through E demonstrates that there are three fundamental magma types: the Laguna Pueblo (green diamonds) and Grants (blue inverted triangles) flows (tholeiitic, and low in TiO_2, K_2O, MgO, Zr, and Sr); the El Calderon flow near the vent (red circles) and along I-40 (pink squares; tholeiitic, and intermediate in the above elements and oxides); and El Calderon scoria (yellow triangles; transitional to alkalic, and high in TiO_2, K_2O, MgO, Zr, and Sr).

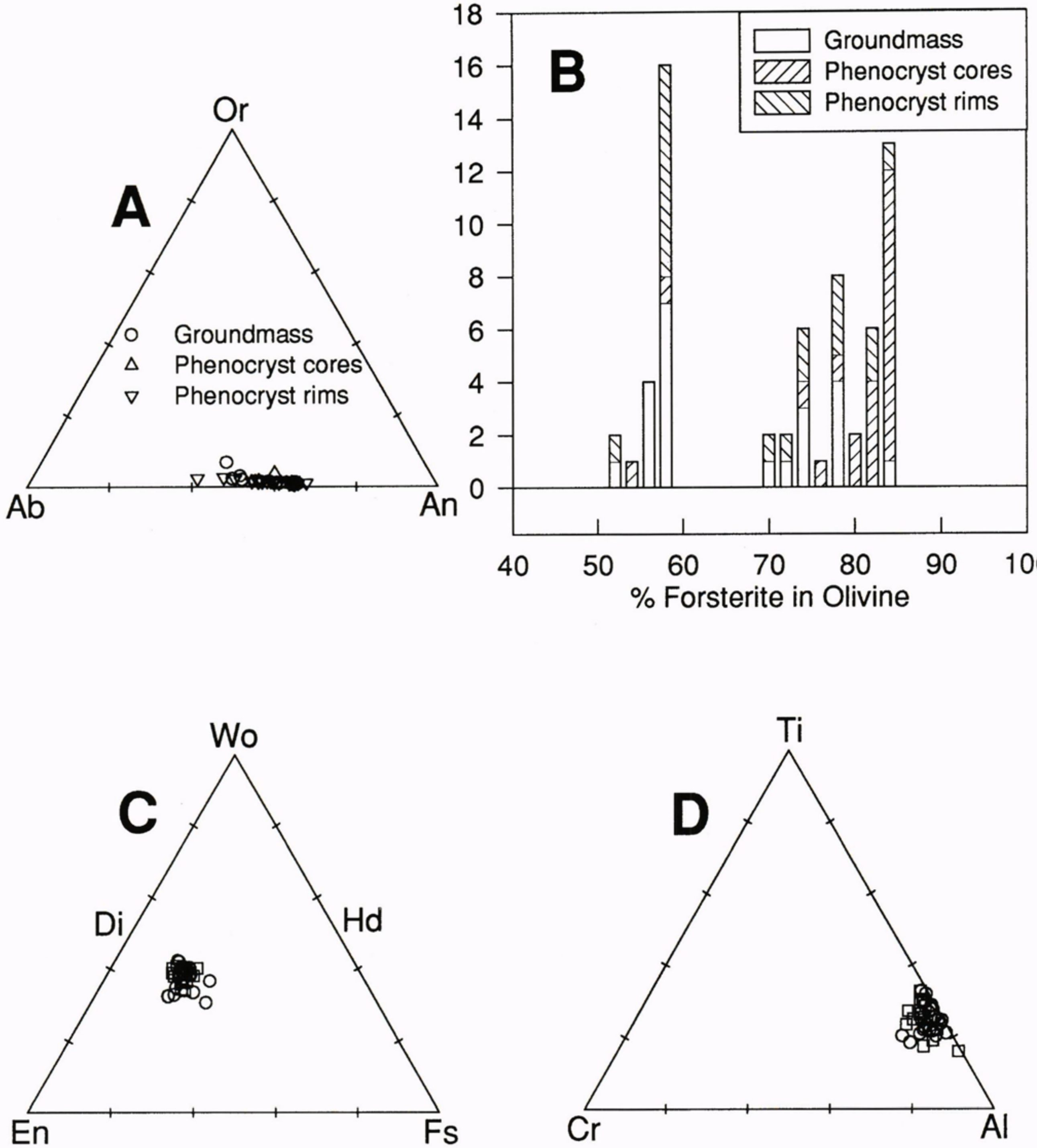

FIGURE 4—Mineral chemical data for El Calderon flow near El Calderon. **A**: plagioclase feldspar ternary plot; Ab = albite ($NaAlSi_3O_8$), An = anorthite ($CaAl_2Si_2O_8$), Or = orthoclase ($KAlSi_3O_8$). Anorthite is the most primitive plagioclase, and continuing evolution increases feldspar compositions in Na and K. **B**: Olivine histogram, vertical axis = number of analyses. Forsterite is a measure of the amount of Mg relative to the amount of Fe in olivine. Primitive olivines have high forsterite (high Mg), while more evolved olivines have lower forsterite (high Fe). **C**: Pyroxene major-element ternary plot. En = enstatite ($Mg_2Si_2O_6$), Di = diopside ($CaMgSi_2O_6$), Wo = wollastonite ($CaSiO_3$), Hd = hedenbergite ($CaFeSi_2O_6$), Fs = ferrosilite ($Fe_2Si_2O_6$). **D**: Pyroxene trace-element (Ti-Cr-Al) ternary plot. Different symbols on pyroxene plots represent analyses from different sample sites.

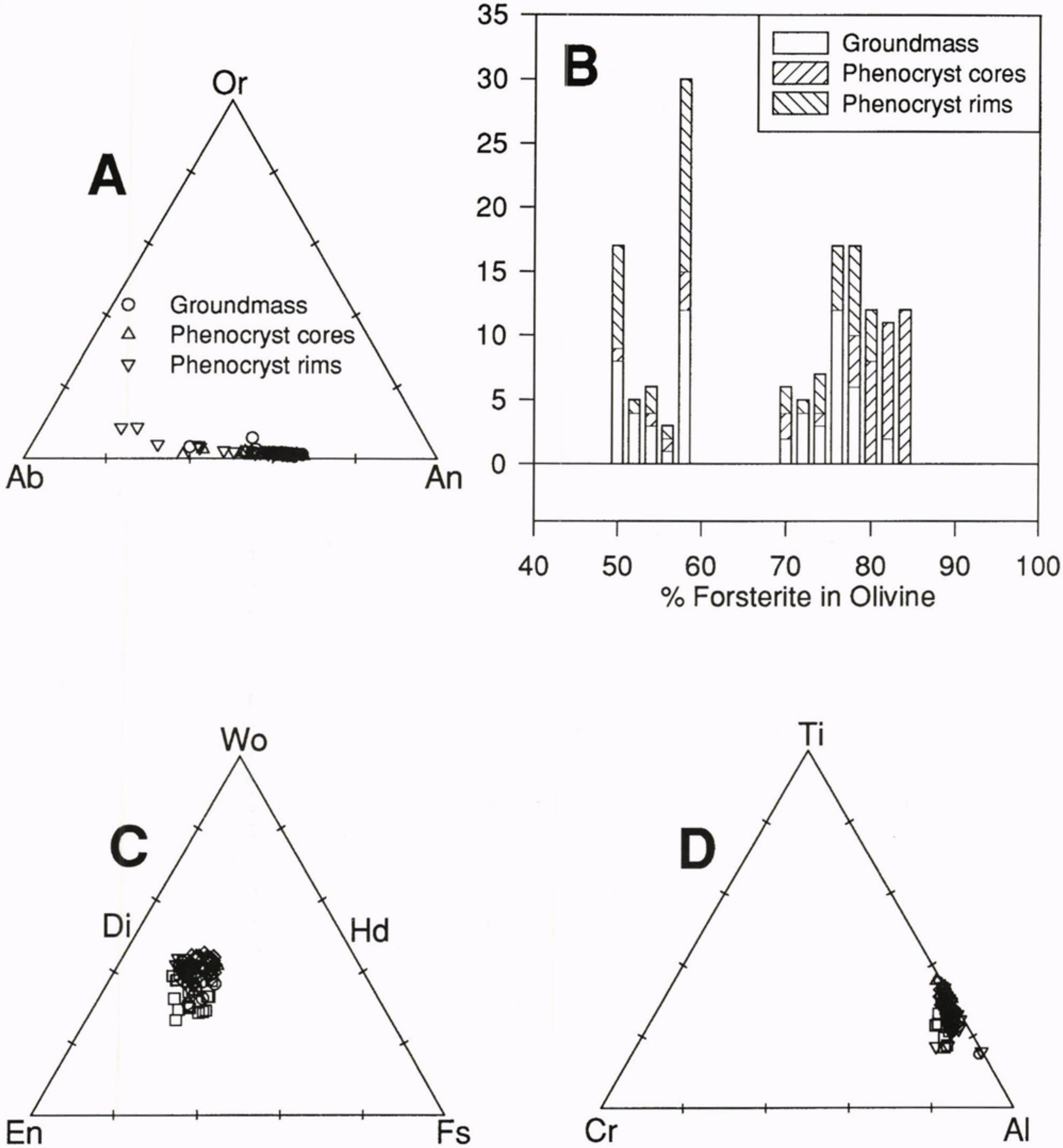

FIGURE 5—Mineral chemical data for El Calderon flow along I–40. See Fig. 4 caption for explanation. Compositions of all minerals are similar to those in Fig. 4.

recorded in rocks as paleosecular variation. Greater departures of the field from axial alignment occur during polarity reversals and geomagnetic excursions. Polarity reversals are changes of the Earth's magnetic field between normal polarity and reversed polarity. Excursions are poorly understood high-amplitude geomagnetic events which in some cases appear to represent aborted polarity reversals. The geomagnetic-field direction changes very rapidly during excursions and reversals (Verosub and Banerjee, 1977).

If a rock acquires its magnetization over a sufficiently long period of time, secular variation is averaged out and the resulting paleomagnetic direction points to the surface intersection of the Earth's rotational axis (the north or south geographic pole). This is common for sedimentary-rock sequences, which acquire their magnetization through a combination of (1) alignment of magnetic grains as they settle out of the water column, and (2) growth of new magnetic minerals during diagenesis (changes in the sedimentary material after its deposition). Voluminous intrusive igneous rocks, crystallized at great depths, also

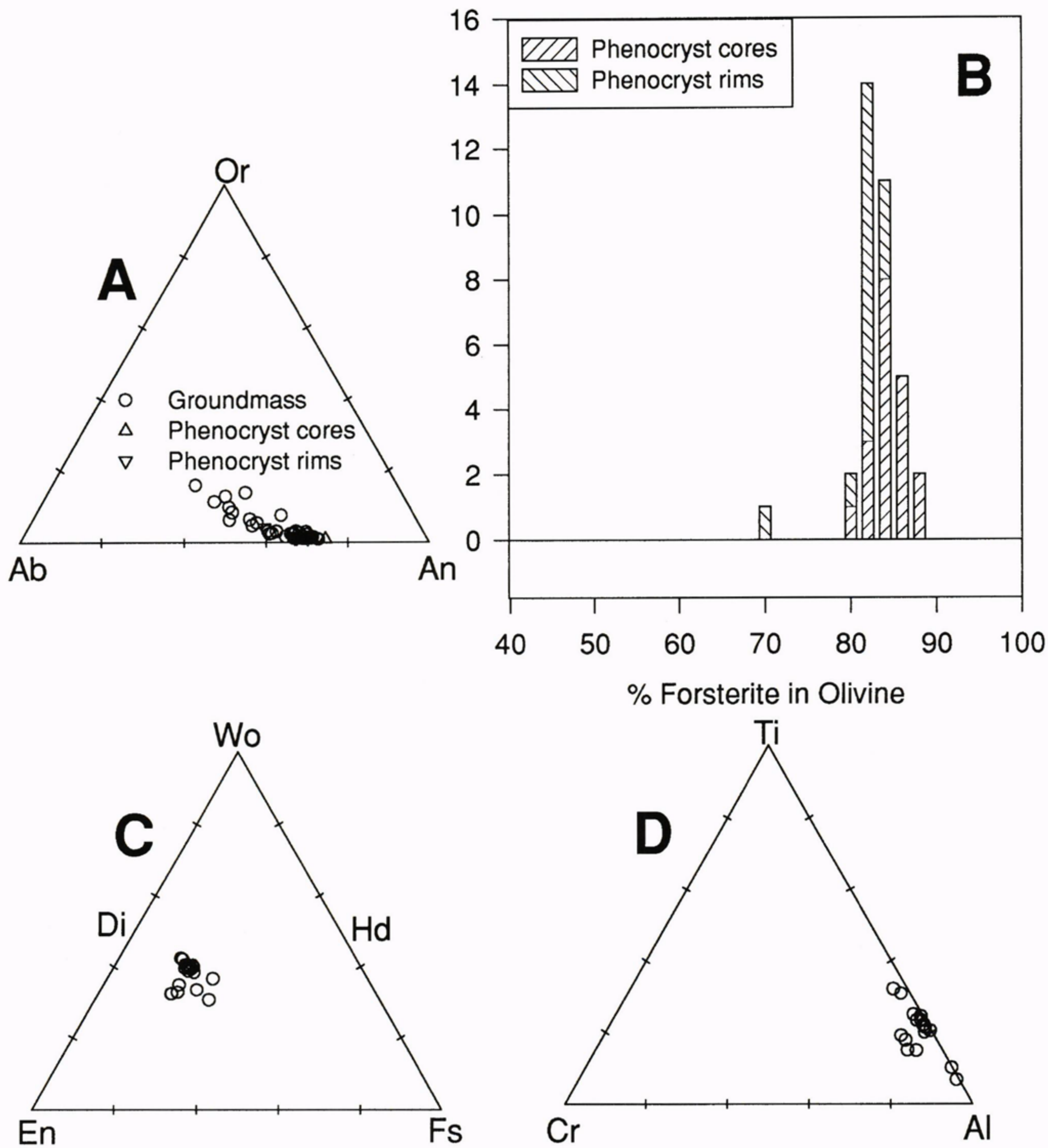

FIGURE 6—Mineral chemical data for El Calderon scoria. See Fig. 4 caption for explanation. Olivine is less evolved than olivines in Figs. 4 and 5. Plagioclase is more evolved, richer in potassium (orthoclase) than in Figs. 4 and 5.

acquire their magnetization over a long time period, as they cool slowly through their magnetization blocking temperatures.

In contrast, volcanic rocks (which cool and crystallize quickly on the surface of the Earth) acquire their magnetizations rapidly. It is thus possible for lavas to record small, short-term paleosecular variation of the Earth's geomagnetic field at great fidelity. For lavas erupted in New Mexico during the Quaternary, the field direction recorded is expected to be close to due north, with a positive (downward) inclination of about 55°. This direction is reported as Declination = 360°, Inclination = 55°. Thus, paleomagnetic data exhibiting directions near Declination = 360°, Inclination = 55° (e.g. the Grants and Laguna Pueblo flows) are of little use in correlating lava flows, except to prove lack of correlation with flows that record anomalous field directions. Anomalous field

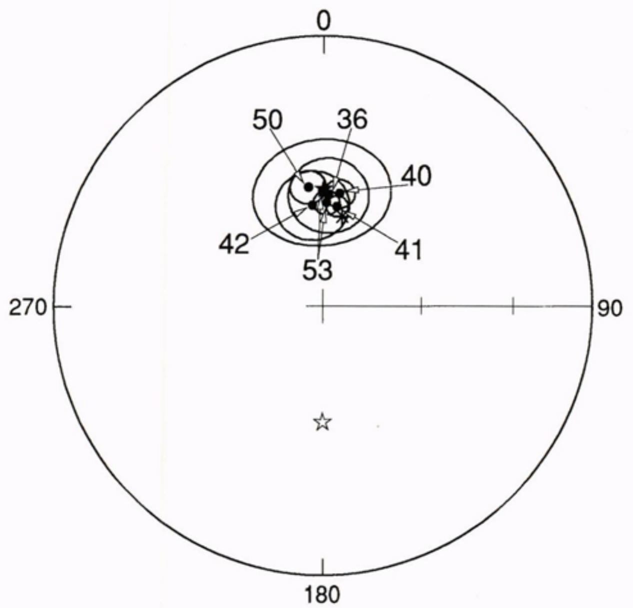

FIGURE 7—Equal-area projection of paleomagnetic data for Grants flow. At the time the Grants flow erupted, the Earth's magnetic field was aligned with the Earth's rotational axis, and the magnetic north pole coincided with the geographic north pole.

FIGURE 8—Field photographs of El Calderon and Grants flows. **Top**: El Calderon flow overlying Grants flow, south of Rio San Jose. **Center**: Broad, gently sloping Grants flow pressure ridge roadcut on I–40, 0.2 mi east of exit 85. **Bottom**: Narrow, steep-sided El Calderon flow pressure ridge roadcut on I–40, 2 mi east of exit 85.

directions are recorded if a lava is erupted and cooled during a period of moderate- to high-amplitude secular variation, an excursion (very high-amplitude departure from the geocentric axial dipole), or a polarity reversal (a "flip" in the polarity of the Earth's geomagnetic field). Because lava flows cool over a short time (geologically speaking), flows with unusual paleomagnetic directions can be considered to represent relatively unique periods of geologic time. The probability of a moderate- or higher-amplitude anomaly being repeated within the time span of the eruptions in the Zuni—Bandera volcanic field is low (Bogue and Coe, 1981). Therefore, different sites that record the same unusual paleomagnetic direction can be interpreted as having been erupted within the same "instant" of geologic time.

Paleomagnetic data

With this as a background, we sampled 30 sites in the El Calderon and associated lava flows, and 19 sites in Maxwell's (1986) Qbt map unit (products of Cerro Candelaria, Twin Craters, Lost Woman, and Lava Crater) in an attempt to correlate lava flows and to distinguish among them. One of the flows sampled for this study, the El Calderon flow, was erupted during a high-amplitude excursion. Four flows studied (the chapter on discovering relationships in a family of volcanoes, this volume), the Qbt flows, record moderate-amplitude secular variation.

Paleomagnetic directional data are obtained by progressive demagnetization of samples in a zero field. Demagnetization involves measurement of the remanent magnetization in the sample initially and after a number of increasing demagnetization steps. For this study, one specimen per sample (10-16 samples per site) was demagnetized by progressive alternating field treatment. In addition, one to three specimens from each site were demagnetized thermally, with temperatures increasing from 25 to 590°C. Three-dimensional best-fit lines have been determined for the magnetization representative of each specimen. Directions from all (or most) independent samples from a site are averaged to yield a site mean.

In this chapter three-dimensional site means are plotted on two-dimensional equal-area projections (Figs. 2, 7, 10). Declinations are measured around the perimeter of the projection, clockwise from north: north is at 0° (360°), at the top of the circle; east is at 90°, at the right of the circle; south is at 180°, at the bottom of the circle; and west is at 270°, at the left of the circle. Inclination is measured from 0° (horizontal) at the perimeter, to ± 90° (vertical down or up, respec-

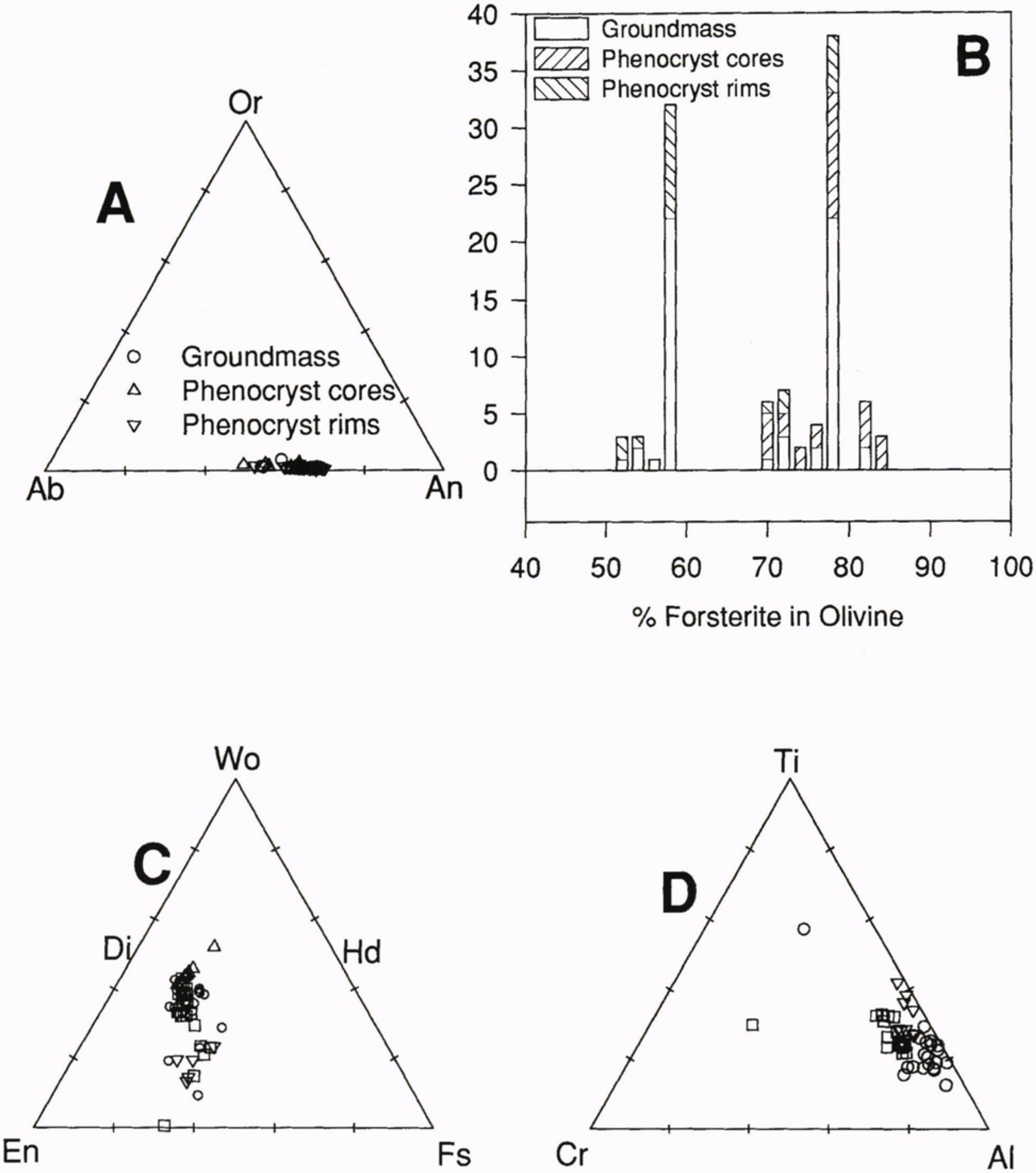

FIGURE 9—Mineral chemical data for Grants flow. See Fig. 4 caption for explanation. Pyroxenes are lower in Ca (wollastonite) and higher in Cr than are the El Calderon flow pyroxenes.

tively) at the center of the projection. By convention, positive (downward) inclinations are represented by solid symbols and negative (upward) inclinations are represented by open symbols. Ovals surrounding the site means are projected cones of 95% confidence for each mean. In a qualitative assessment, overlapping ovals suggest that at a 95% probability level the site means are two different samplings of the same data population.

Correlation of El Calderon flow with flow along Interstate 40? Yes!

Paleomagnetic data for sites near El Calderon show that a highly distinct geomagnetic field was recorded by these rocks. The average direction for three sites within 2 km of the vent (including a site drilled near the entrance to Junction Cave) is Declination = 272°, Inclination = —20°. Four sites along 1-40, 2 km or more east of exit 85, and four sites

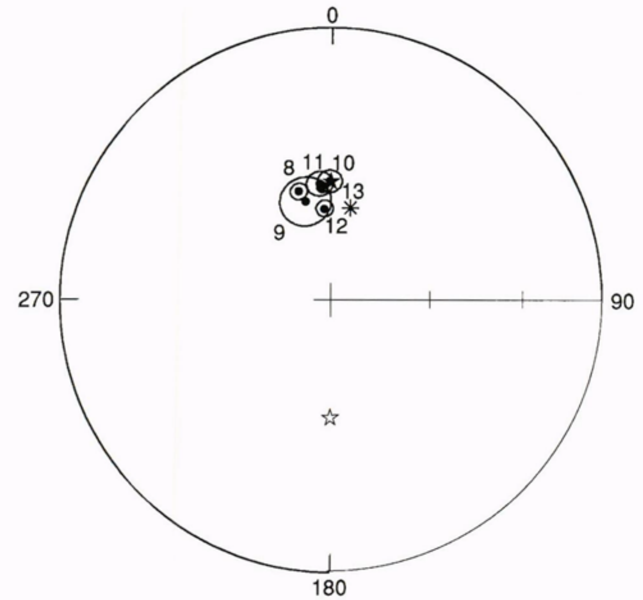

FIGURE 10—Equal-area projection of paleomagnetic data for Laguna Pueblo flow. At the time the Laguna Pueblo flow erupted, the Earth's magnetic field was nearly aligned with the Earth's rotational axis, and the magnetic north pole was very near the geographic north pole. This rules out correlation of the Laguna Pueblo flow with the El Calderon flow.

between I-40 and El Calderon, yield similar directions [Declination = 274°, Inclination = —15° (Fig. 2B), and Declination = 271°, Inclination = —16° (Fig. 2C), respectively]. This west-directed, shallow negative magnetization was first noted by Champion et al. (1988) at a single site which we reoccupied as site 1 of this study. This unusual direction is interpreted as either a high-amplitude geomagnetic excursion or part of an aborted field reversal during the latest Quaternary. As field directions may vary rapidly during excursions (Verosub and Banerjee, 1977; Herrero-Bervera et al., 1994), the same paleomagnetic direction recorded at all sites provides evidence that the sites are part of a very short-lived (probably less than 100 years) eruption sequence, and are probably in the same lava flow.

Correlation of lavas at El Calderon with those at 1-40 and between El Calderon and 1-40 is further confirmed by the nearly identical whole-rock (Fig. 3) and mineral (Figs. 4-6) chemistries for samples obtained throughout the flow. All samples are tholeiitic. No progressive trends in chemical variation are observed with distance from the vent. Early-stage scoria deposits comprising El Calderon cinder cone are more alkalic than the later tholeiitic lava that breached the vent and flowed north to 1-40 (Fig. 3). In addition, plagioclase crystals in the scoria samples have more evolved compositions (are richer in sodium and potassium) than plagioclase crystals in the El Calderon lavas. This suggests that the early stage alkalic to transitional scoria may represent early eruption of the more chemically evolved top of the magma chamber, and that lower, more primitive parts of the magma chamber were tapped later by the lava flow. In contrast, olivine crystals are more primitive (higher forsterite, more magnesium) in the scoria than in the later tholeiite. This might be explained by faster settling of denser iron-rich (low forsterite, more evolved) crystals relative to the less dense (high forsterite, less evolved) crystals. Although the magma at the top of the chamber was more evolved, settling of evolved olivine crystals resulted in the magma cap containing more primitive olivines.

Correlation of El Calderon flow with Grants flow? No!

Paleomagnetic data from six sites north and west of El Calderon flows along Interstate 40 yield a paleomagnetic direction (Declination = 360°, Inclination = 57°) that is statistically indistinguishable from that of the expected normal polarity Quaternary field (Fig. 7). These data demonstrate that the western flow (here named the Grants flow) was erupted at a different time than the El Calderon flow. On the south side of the Rio San Jose, south of NM-117, north of 1-40, the Grants flow is observed to underlie the El Calderon flow (Fig. 8, top). The Grants flow (Fig. 8, center) forms low, broad pressure ridges, while the El Calderon flow (Fig. 8, bottom.) forms steeper, narrower pressure ridges. In addition, soil cover on the Grants flow is thicker than that on the El Calderon flow. The Grants flow is overlain on its western margin by the Paxton Springs (Zuni Canyon) flow.

Whole-rock chemical and mineral chemical data reinforce the lack of correlation between the El Calderon flow and the Grants flow. Grants flow samples are lower in K20, Na2O, MgO, TiO2, Sr, and Zr than El Calderon flows (Fig. 3). Mineral compositions also differ (Fig. 9). Grants flow samples contain less K20 in plagioclase, less wollastonite in pyroxene, and have a lower overall range of forsterite in olivine than samples from Laguna Pueblo.

Correlation of Laguna Pueblo flow with El Calderon and Grants flows? No?

Six sites in the Laguna Pueblo flow (Fig. 1) yield a paleomagnetic direction (Declination = 352°, Inclination = 57.3°) near the expected normal Quaternary field (Fig. 10). This observation distinguishes the Laguna Pueblo flow from the El Calderon flow and negates the correlation of the two flows by Drake (1991). Paleomagnetic data are permissive, but not strongly supportive, of correlation of the Laguna Pueblo and Grants flows. Whole-rock compositions (Fig. 3) for the Laguna Pueblo and Grants flows are similar, although Grants flow samples are lower in MgO and Na2O than Laguna Pueblo samples. However, Grants flow pyroxenes range to lower calcium values and Laguna Pueblo plagioclase crystals range to higher Na2O, suggesting that the two flows may not correlate (Fig. 11).

Summary and conclusions

Paleomagnetic, whole-rock, and mineral chemical data conclusively rule out correlation of the El Calderon flow with the Grants and Laguna Pueblo flows. The Grants flow was emplaced prior to the El

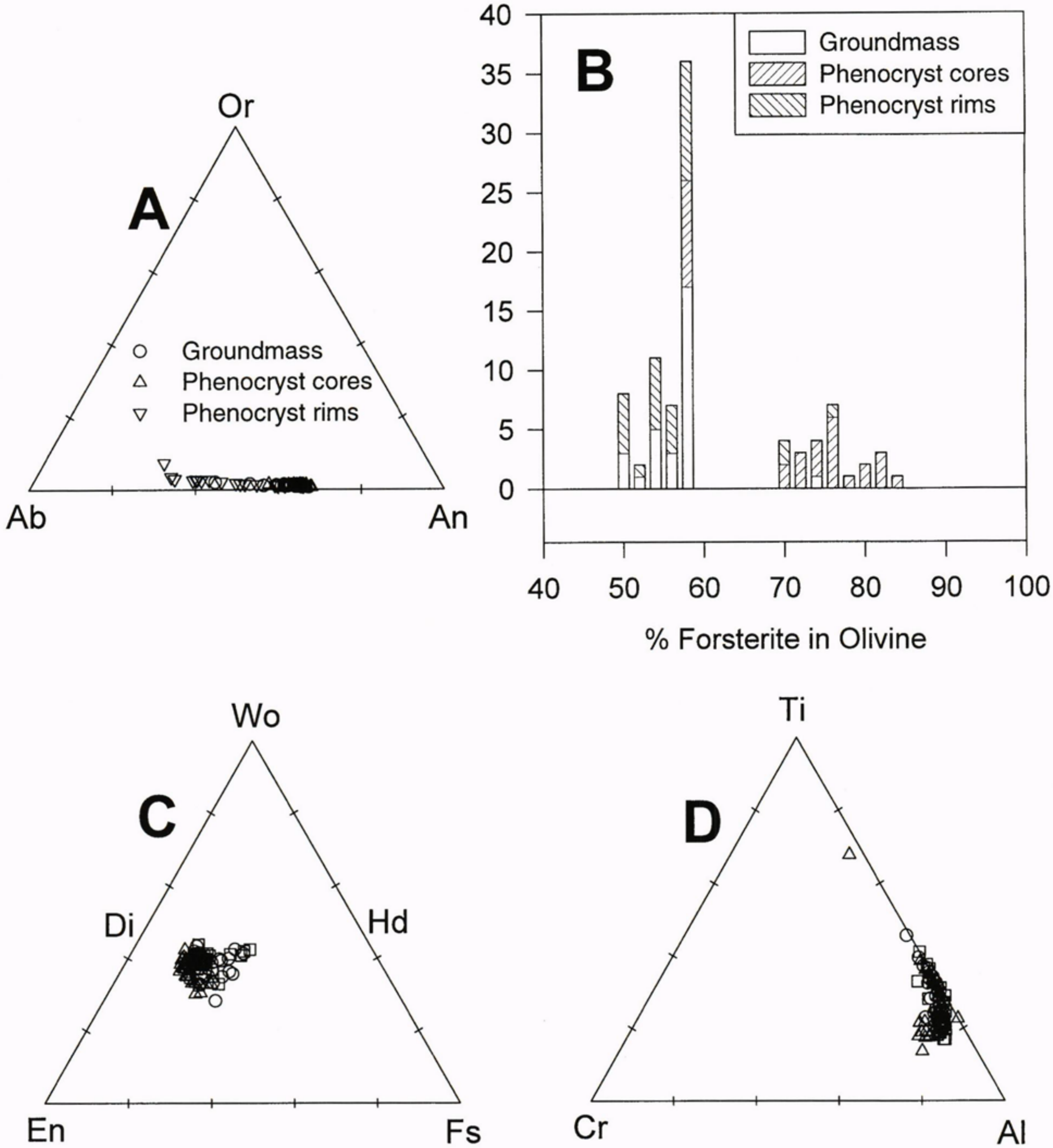

FIGURE 11—Mineral chemical data for Laguna Pueblo flow. See Fig. 4 caption for explanation. Mineral chemistries are very similar to those for the El Calderon flow (Figs. 4, 5). However, lack of low Ca (low wollastonite) or high Cr pyroxenes rules out correlation of the Laguna Pueblo flow with the Grants flow (see Fig. 9).

Calderon flow by a significant but paleomagnetically indeterminable amount of time. Whole-rock chemical differences between early alkalic to transitional scoria and the later tholeiitic flows from El Calderon may represent a significant time difference between eruption of these materials and may suggest different sources for the two magmas. Alternatively, the change in magma chemistry may represent early eruption of an alkali-enriched magma cap, followed by eruption of primitive magma from lower in the chamber. The source for the Grants flow is unknown, but if it is El Calderon (as suggested by earlier workers) then the Grants flow represents a third, earlier (possibly pre-cinder cone?) magmatic event. The source for the Laguna Pueblo flow remains unknown, although it is unlikely that the Laguna Pueblo flow correlates with the Grants flow in view of the chemical differences.

The El Calderon flow erupted during a high-amplitude excursion of the Earth's geomagnetic field. Dates (see Laughlin et al., this volume) from the El Calderon flow permit correlation of the El Calderon flow with the Blake geomagnetic polarity event (about

115,000-120,000 years ago; e.g. Tric et al., 1991) that has been observed at several localities worldwide.

Acknowledgments

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One of Alton Lindsey's 1948 research stations on the Bandera Lava flow. A minimum/maximum thermometer can be seen in the upper left and a recording thermograph is in the middle of the instrument shelter. The earliest climate records for El Malpais came from these instruments. Alton Lindsey Photo, El Malpais National Monument collection, Photo no. 196, vol. 2.

Discovering the relationships in a family of volcanoes—Cerro Candelaria, Twin Craters, Lost Woman Crater, and Lava Crater

Tracy E. Cascadden, Albert M. Kudo, and John W. Geissman
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131

Introduction

Four basaltic vents in the central Zuni—Bandera volcanic field erupted within a short span of time approximately 16,000 years ago (Laughlin and WoldeGabriel, this volume). Three of the vents, Lost Woman Crater, Twin Craters, and Lava Crater, are aligned along a N38°E trend, 2 km in length. Cerro Candelaria is 0.6 km east of Lava Crater. Previous mapping (Maxwell, 1986) grouped the products of the four vents as a single unit, differentiating pyroclastics (Qct) and lava flows (Qbt) as separate subunits. Detailed mapping and geochemical analyses have allowed distinction of lava flows from the four vents into separate map units (Fig. 1). Limited chemical analyses from Lava Crater and Cerro Candelaria flows and pyroclastic deposits have been previously published (Laughlin et al., 1972, 1993a; Perry et al., 1987; Menzies et al., 1991) as part of broader regional studies. In most cases, the locations of the samples were not reported.

Observations and data

Geomorphic and paleomagnetic distinctions

Although differences in weathering of and soil development on the lava flows produced by Cerro Candelaria, Twin Craters, Lost Woman Crater, and Lava Crater are subtle and difficult to discern, detailed mapping and aerial photographic analysis have allowed separation of the flows into four separate eruptive events. Field relations demonstrate that the Lava Crater flow is the youngest of the four and that the Lost Woman Crater flow is younger than the Twin Craters flow. The age relationship between Twin Craters and Cerro Candelaria cannot be conclusively determined on the basis of field data because these flows are not in contact. However, extremely subtle differences in weathering suggest the temporal progression may have been Cerro Candelaria followed by Twin Craters, then Lost Woman Crater, and then Lava Crater. Paleomagnetic data demonstrate that all four vents erupted within a brief span of geologic time. For a discussion of paleomagnetic principles and methods used in this study, see the chapter on El Calderon cinder cone and associated basalt flows (this volume). All 17 sites (2-6 per flow, 9-15 samples per site) yield paleomagnetic directions that are significantly distinct from the expected normal polarity Quaternary direction (Declination = 360°, Inclination = 55°). Paleo-magnetic directions derived from all sites are tightly clustered (Fig. 2) with a mean direction at Declination = 32°, Inclination = 54°. The four flows record moderate-amplitude secular variation of the geomagnetic field, and the tight clustering of data indicates that all four flows cooled within a brief span of geologic time (e.g. Bogue and Coe, 1981). Because most of the data are statistically indistinguishable at a high level of confidence, the results from Cerro Candelaria, Twin

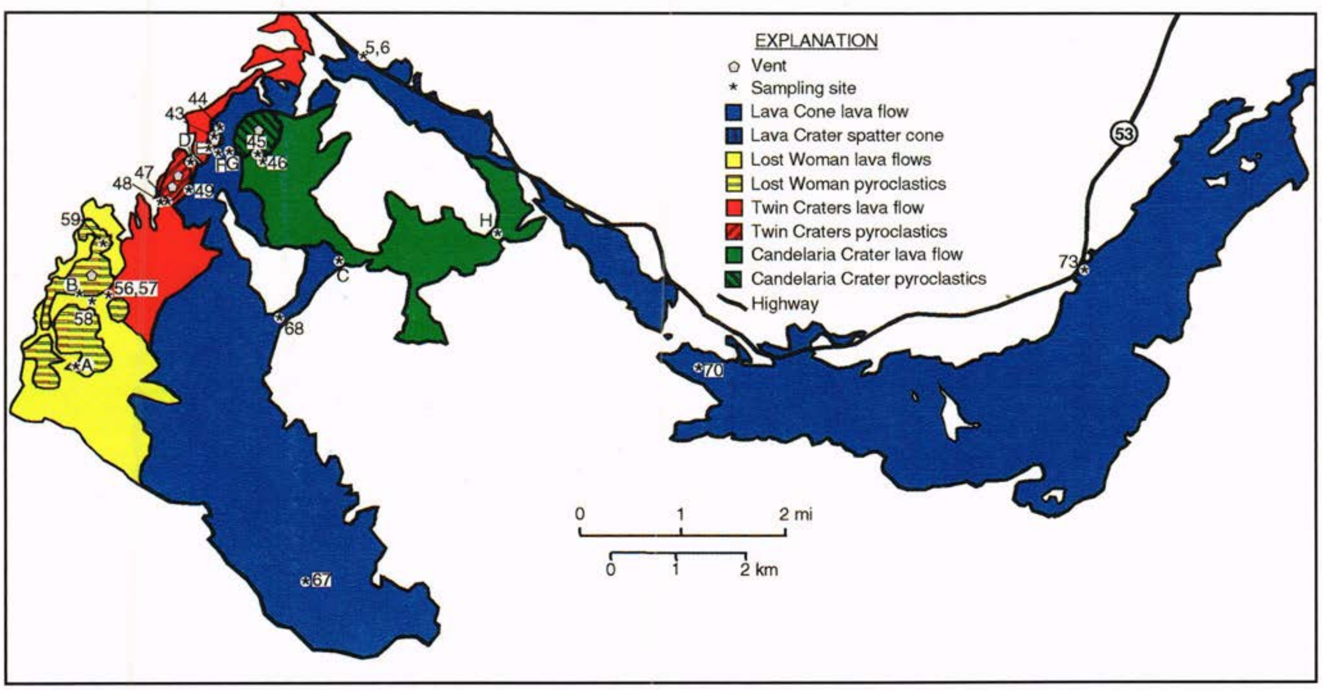

FIGURE 1—Simplified geologic map of Cerro Candelaria, Twin Craters, Lost Woman Crater, and Lava Crater. Numbered sites are locations from which paleomagnetic, whole-rock geochemical, and microscope samples were obtained. Lettered sites are locations from which whole-rock and/or microscope samples were obtained.

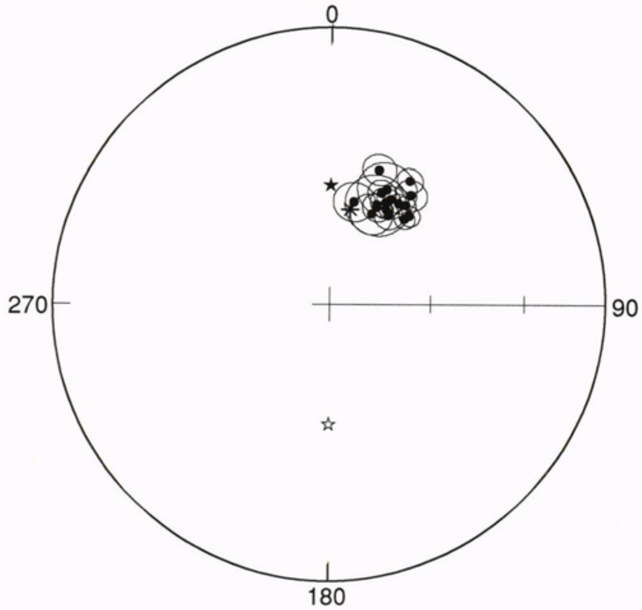

FIGURE 2—Equal-area projection of paleomagnetic data from all four vents. Asterisk shows direction of present-day field. Stars mark direction of normal and reverse rotation axes. For explanation of figure see the chapter on El Calderon cinder cone and associated basalt flows (this volume). In all sites, the paleomagnetic direction is significantly different from the expected Quaternary field direction (filled star). Tight clustering of data with a mean direction of Declination = 32°, Inclination = 54° indicates that all four flows erupted within a geologically short time span.

Craters, Lost Woman Crater, and Lava Craters are consistent with a short-lived (i.e. a few hundred years or so) time span for eruption of the four centers.

Chemical variability

Despite the close spatial (the four vents occupy an area of <5 km^2) and temporal (<1000 years) association of the four vents, their products exhibit wide chemical variability. Cerro Candelaria and Lost Woman Crater are alkalic, Twin Craters is transitional, and Lava Crater is tholeiitic (Fig. 3; see Glossary for explanation of compositional terms). Thus, if the order of eruption suggested above (Cerro Candelaria, then Twin Craters, then Lost Woman Crater, then Lava Crater) is correct, then there is no smooth progression of one magma type to another with time. The first three vents exhibit overlapping ranges of chemical content for most elements. There is a compositional gap between these three and Lava Crater.

Mineral chemical data (Figs. 4-6) show that Cerro Candelaria minerals are the most restricted and least evolved in composition. This indicates that little differentiation of the Cerro Candelaria magma took place prior to and during eruption. Twin Craters and Lost Woman Crater have the most differentiated plagioclase. Lava Crater and Twin Craters have the most differentiated olivine. Pyroxene differentiation is moderate for Lost Woman Crater, but extends toward and into pigeonitic compositions in Lava Crater samples.

Interpretation: Petrogenesis of the lavas, different sources, and different histories

The alkalic, transitional, and tholeiitic lavas can not be related by simple crystal fractionation, using observed mineral phases. Crystal fractionation is process of magmatic differentiation in which crystallization of minerals depletes the magma in the elements contained in the mineral. For example crystallization of olivine, which is rich in magnesium and iron oxides, depletes the magma in magnesium and iron, relatively enriching the magma in other elements. In basaltic magmas the fractionating minerals are usually olivine, anorthite-rich plagioclase, ilmenite (an iron—titanium oxide mineral), and sometimes pyroxene. Crystallization of these minerals from the magma causes a progressive decrease in magnesium, iron, and calcium oxides and an increase in silica and the alkalic elements sodium and potassium. On binary chemical plots (Fig. 3) crystal fractionation of a single parental magma results in linear arrays of chemical data (i.e. arrows shown for fractionation of olivine + ilmenite, and plagioclase). Preliminary results of chemical modeling tests suggest that Cerro Candelaria, Twin Craters, and Lost Woman Crater are comagmatic (they came from the same source and fractionated together in the same magma chamber) and evolved to different compositions by fractionation of olivine and ilmenite.

However, the offset of chemical trends between alkalic-to-transitional and tholeiitic vents (especially Figs. 3B, D) shows that these two fundamental magma types are not related by simple crystal fractionation. Lava Crater is genetically unrelated to the other three vents (it came from a different source and fractionated in a separate magma chamber), and chemical variation within the Lava Crater flow is due to fractionation of olivine + ilmenite + plagioclase. Variation in trace-element contents (e.g. Rb, Sr, Nb, and Zr; Figs. 3D, E) can likewise be explained by olivine and ilmenite fractionation in Cerro Candelaria—Twin Craters—Lost Woman Crater (except for one anomalous Nb value for Cerro Candelaria) and by fractionation of olivine and plagioclase in Lava Crater samples. Therefore, in this "family" of volcanoes, Cerro Candelaria, Twin Craters, and Lost Woman Crater might be considered to be close family members, siblings or cousins, while Lava Crater is not a part of the family at all, but is a neighbor with a different origin.

Isotopic evidence (Perry et al., 1987; Menzies et al., 1991) suggests an asthenospheric source for the alkalic to transitional Cerro Candelaria—Twin Craters—Lost Woman Crater magma, and a lithospheric source for the Lava Crater magma.

Summary and conclusions

Four chemically diverse volcanoes in the central Zuni—Bandera volcanic field erupted in a geologically short period of time (over a few hundred years or so) within a small area. The spatial and temporal proximity of the four vents would tend to suggest that they are genetically related in some way (i.e. that they are

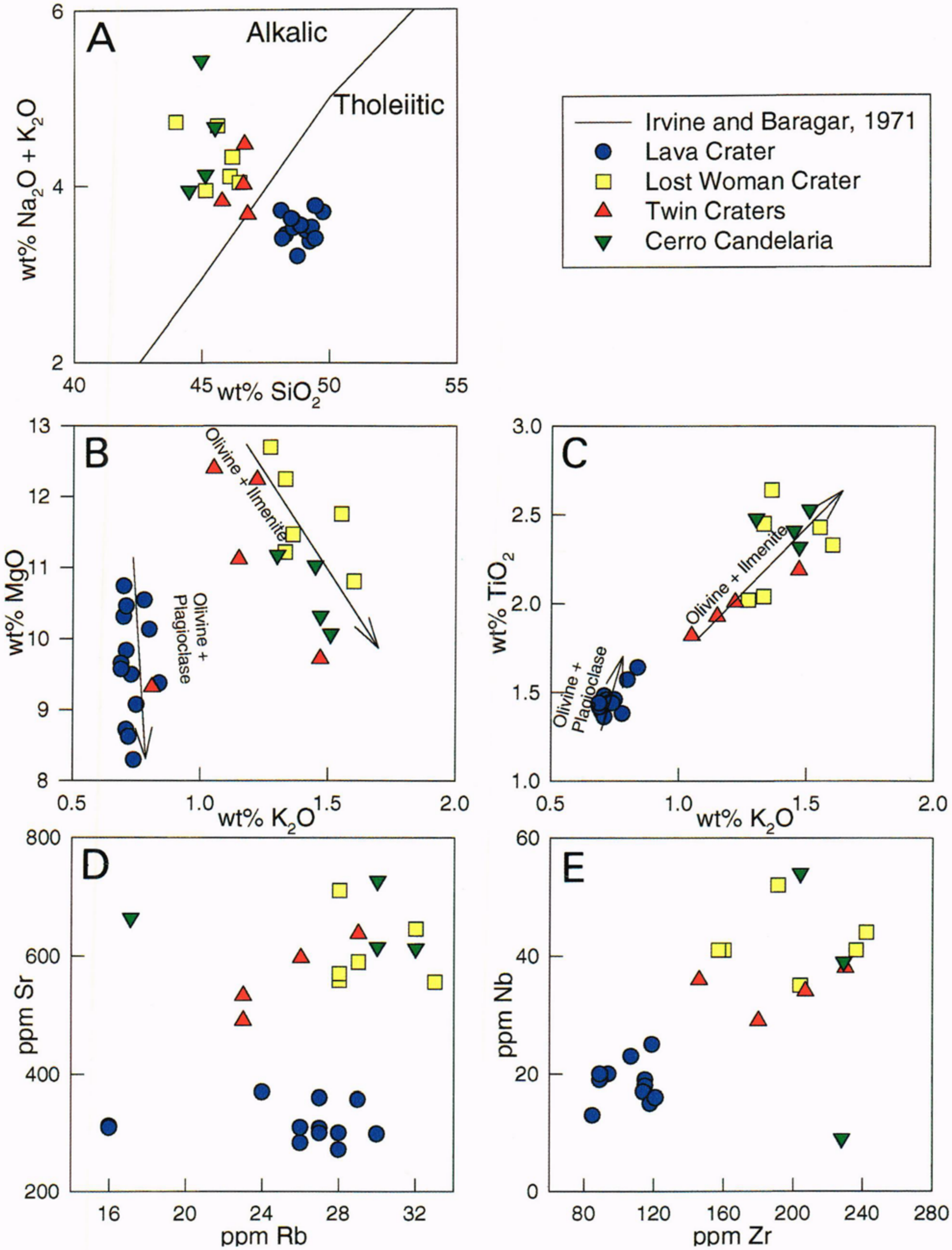

FIGURE 3—Whole-rock geochemical plots for all four vents. **A**: Alkalis vs. SiO_2, **B**: K_2O vs. MgO, **C**: K_2O vs. TiO_2, **D**: Rb vs. Sr, **E**: Zr vs. Nb. Arrows show expected trends from fractionation of olivine + ilmenite, and plagioclase. Chemical variation within Candelaria Crater (green inverted triangles), Twin Craters (red triangles), and Lost Woman Crater (yellow squares) is best explained by crystal fractionation of olivine and a small amount of ilmenite. Chemical variation within Lava Crater (blue circles) samples is best explained by removal of olivine and plagioclase. The two different magma types cannot be related by crystal fractionation.

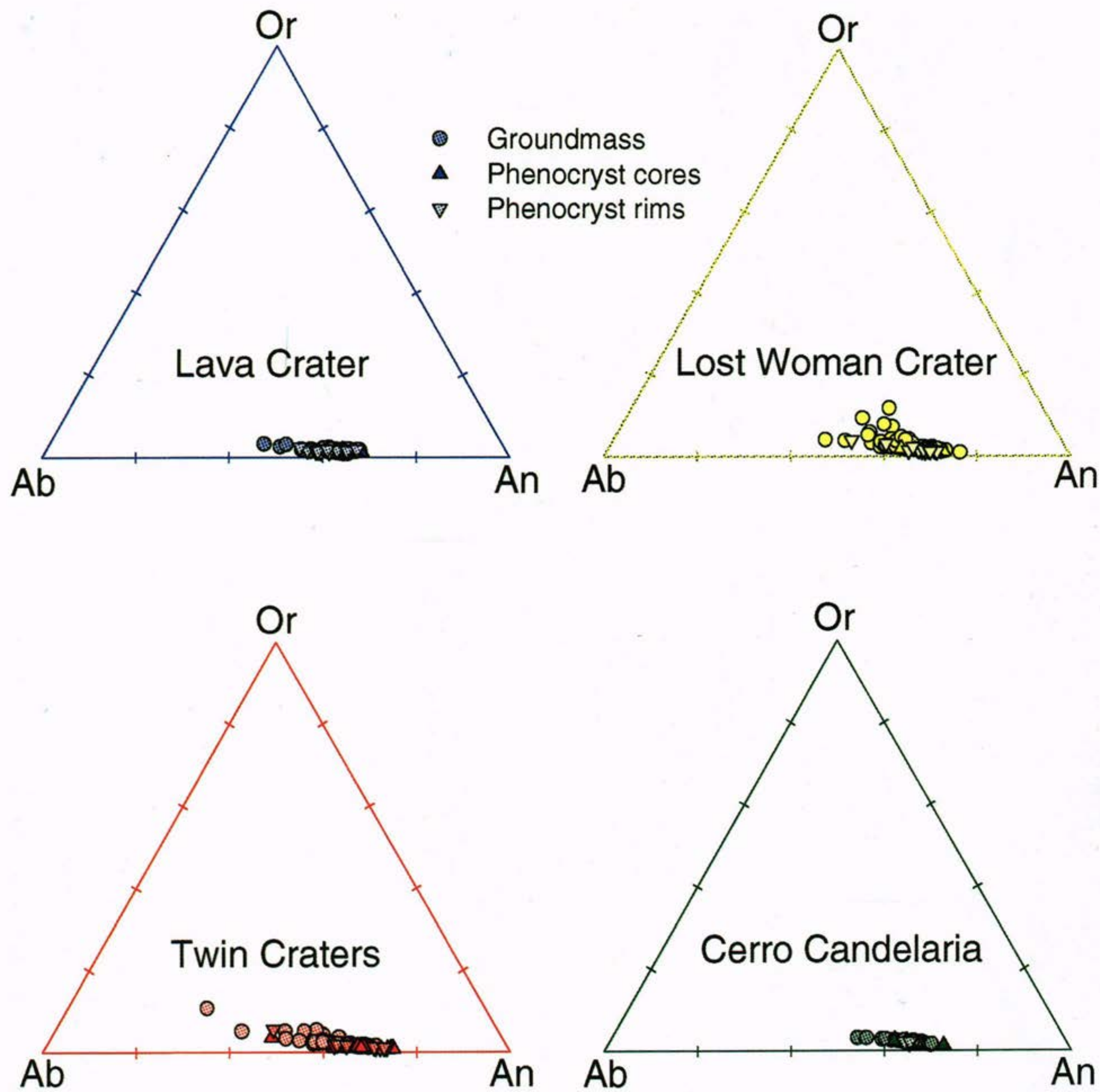

FIGURE 4—Plagioclase chemical data. Ab = albite ($NaAlSi_3O_8$), An = anorthite ($CaAl_2Si_2O_8$), Or = orthoclase ($KAlSi_3O_8$). Anorthite is the least evolved plagioclase and crystallizes first. Increased magmatic differentiation raises the plagioclase content in albite and orthoclase components. In these diagrams it is clear that Lost Woman and Twin Craters have the most evolved plagioclases, while Cerro Candelaria and Lava Crater have less evolved plagioclases.

all created by similar processes, from similar sources, and can be expected to have undergone similar histories). However, no orderly temporal or spatial progression in chemical content of the products of each vent is observed. Instead, the first eruption was alkalic and came from the northeasternmost vent (Cerro Candelaria). It was followed by eruption of transitional basalt from Twin Craters, and then by more alkalic basalt from Lost Woman Crater, the southwesternmost vent. The progression from alkalic (Cerro Candelaria) to transitional (Twin Craters) lava may represent eruption of the more differentiated top of the magma chamber first, then the eruption of less evolved magma from lower in the chamber. The return to alkalic lavas (Lost Woman Crater) may represent eruption following a period of additional fractionation in the magma chamber between the eruptions of Twin Craters and Lost Woman Crater. The source for the first three eruptions was probably the asthenosphere. The last eruption in the sequence was tholeiitic, from Lava Crater, physically situated between the first two vents to erupt (Cerro Candelaria and Twin Craters). This lava is chemically distinct from the previous lavas and is not related to them genetically. This suggests a different (probably lithospheric) source for Lava Crater.

Acknowledgments

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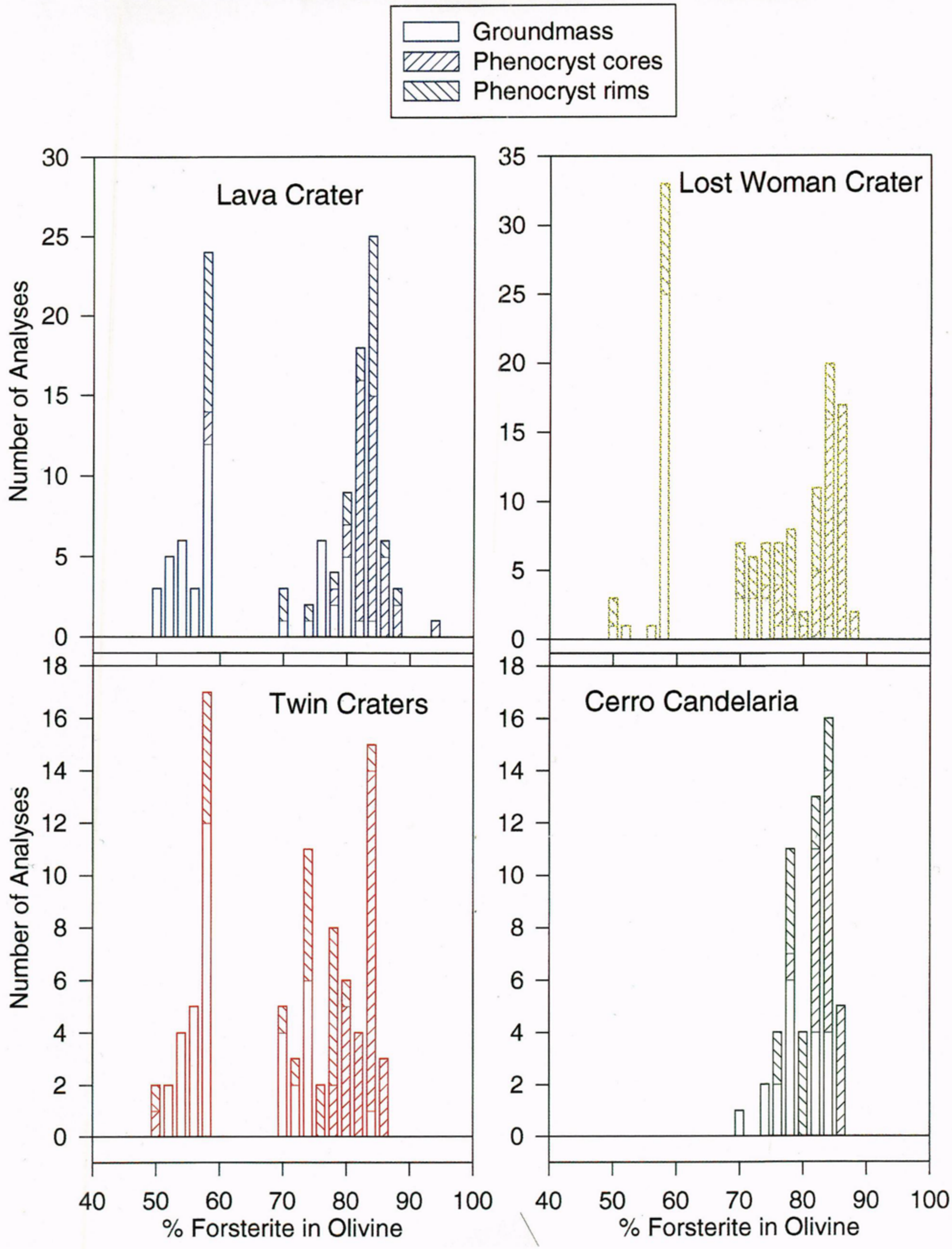

FIGURE 5—Olivine histograms, vertical axis = number of analyses. Forsterite is a measure of the amount of Mg relative to the amount of Fe in olivine. Primitive olivines have high forsterite (high Mg), while more evolved olivines have low forsterite (high Fe). Cerro Candelaria has the most primitive olivines.

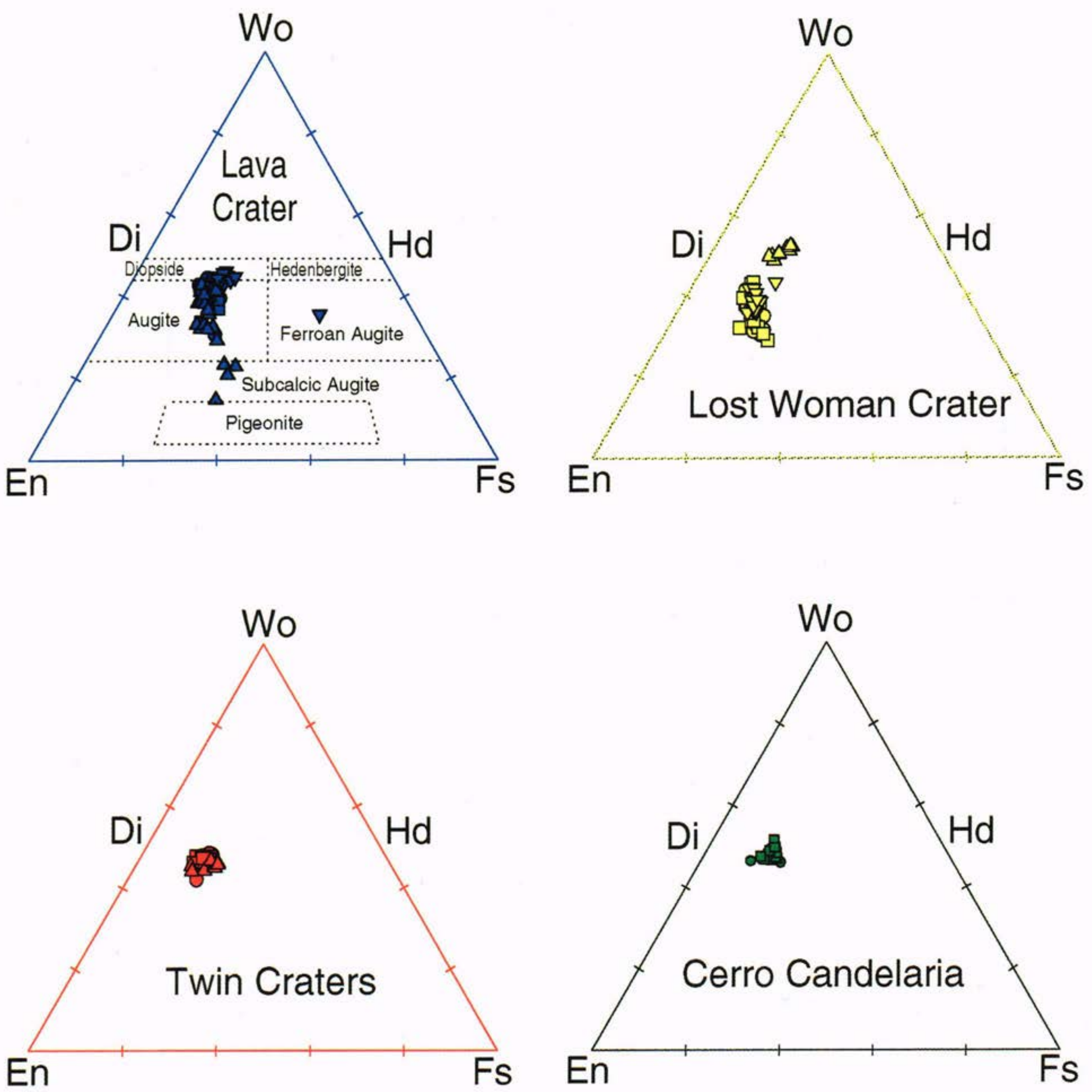

FIGURE 6—Pyroxene major-element ternary plot. En = enstatite ($Mg_2Si_2O_6$), Di = diopside ($CaMgSi_2O_6$), Wo = wollastonite ($CaSiO_3$), Hd = hedenbergite ($CaFeSi_2O_6$), Fs = ferrosilite ($Fe_2Si_2O_6$). Different symbols on pyroxene plots represent different sample sites. Cerro Candelaria and Twin Craters pyroxenes are within the more primitive diopside to augite field. Lost Woman Crater and Lava Crater pyroxenes are more evolved, lower in wollastonite, and extend into the subcalcic augite field, even into the pigeonite field for Lava Crater.

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Remains of the Earl Head homestead, constructed in 1934–38. El Malpais National Monument Resource Files, frame 7, roll #1.

In the basement—Lava-tube origins and morphology

Bruce W. Rogers[1] and Cyndi J. Mosch[2]
[1]*U.S. Geological Survey, Menlo Park, California 94025*
[2]*New Mexico State University, Las Cruces, New Mexico 88003*

Terminology

Extended discussions have been devoted to the terms lava cave, lava-tube cave, lava-tube system, or natural bridge (Halliday, 1963; Monroe, 1970; Wood, 1976; Larson, 1992). A lava cave, lava tube, or lava-tube cave is defined as a naturally occurring subterranean cavity formed by volcanic processes with some part in essentially total darkness and, usually, can be entered by humans. For our purposes in this chapter, a lava cave is any cave formed in volcanic rocks. It must be noted, however, that not all lava caves are lava tubes. Lava tubes or lava-tube caves are formed, in essence, when the central part of a lava flow is at least partly emptied, leaving a series of tubular cavities. A lava-tube system usually refers to a related, sometimes extensive, series of lava tubes which may or may not be physically connected, but which share a common origin, such as when all segments are included in one lava flow or lobe of a lava flow (Waters et al., 1990). Disagreements over terminology have resulted where collapse has broken the tube into a series of smaller separate caves (Larson, 1992). Although the merits of the International Union of Speleology's definition of a segmenting collapse being more shallow than wide have been debated both pro and con (Larson, 1992), a good rule of thumb is that if the explorer can traverse from one section of cave to the next in a rainstorm and stay dry, the feature probably can be termed a single cave and not a pair of caves.

A natural bridge can be defined as a partly collapsed section of a lava tube where the remaining roofed-tube's width is greater than the tube's length. Such a definition is needed because some tubes were originally called bridges and some bridges were called caves. Cave-naming protocol favors the first-used name, but in some cases two names of equal vintage and popularity have been applied to a cave. In these cases, such as in Acoma Trail Natural Bridge and Zuni Trail Natural Bridge, it has sometimes been advantageous to combine the two names into a single name, such as Zuni—Acoma Trail Natural Bridge.

Surface expression of lava tubes

Most lava-tube caves are generally inconspicuous elements of the Earth's geomorphology. In many places in the Malpais the only indication of a tube is a gentle linear swell meandering across the grasslands or lava fields (Causey, 1971). Two landforms, however, indicate the presence of tubes: collapse trenches and tumuli. Collapse trenches are formed by catastrophic cave-roof failure (Fig. 1). Observations in Hawaii (Peterson and Swanson, 1974) have shown that much of the collapse of lava tubes takes place either during the latter stages of tube formation or immediately after tube cooling. The trench may take on several forms depending on the plasticity of the basalt, the stresses built up in the roof part of the tube, and size and roof thickness of the tube itself (Rogers and Rice, 1992). If the lava is still relatively plastic, the roof may sag to form a shallow trough, such as over Frozen Bat and Big Skylight Caves. The height of such tube passages may be either reduced or the entire tube may be nearly squeezed shut.

If the roof totally fails, the result may either be a sharp-edged collapse trench or an alluviated trench. The sharp-edged variety has cleanly collapsed walls, in places having remnants of passage meanders or grottos preserved under overhangs, and great mounds of rubble or breakdown heaped on their floors. Most of the collapsed tubes near Candelaria Ice Cave or the Big Lava Tubes area are sharp-edged collapse trenches.

Alluviated trenches have had soil washed onto their floors either by slope wash or via a surface stream occupying the trench itself. Because the trenches are ideal tinajas or water pockets, they may subsequently become vegetated, such as the trench adjacent to Junction Cave or those near Mesita Blanca.

Tumuli, also called pressure ridges, are caused when hot, still plastic lava crust, under pressure from the still liquid lava below, bulges upwards to form an elongated mound. While many tumuli are formed randomly on a lava flow, some form over lava tubes (Hon et al., 1994). If an active lava tube became temporarily blocked downstream from a section of weak or thin roof, lava might back up beneath the still-hot crust and form a tumulus with a direct connection down to the tube. If the blockage subsequently cleared, flow would resume in the lava tube, and the lava in the tumulus would drain back down into the tube. In El Malpais, some small caves have formed under such drained tumuli.

How tubes form

Basalt, particularly the very fluid, ropy-textured pahoehoe basalt, is a heavy, dark, volcanic rock that covers a large part of El Malpais National Monument and in which the monument's caves have formed. Its origin and detailed geochemistry are covered elsewhere in this volume. Among the geochemical conditions favoring lava-tube formation are silica content and temperature.

Temperature is important because the hotter the lava, the more fluid it will be and the farther it will flow before surface cooling congeals it. Lava tubes are important because the solidified basalt roofs insulate the lava, keeping it hot and fluid, thus allowing extension of the tube-fed flows.

Several other physical factors, such as duration and rate of flow, ground gradient, and channel sinuosity, also contributed to the mode of development of the tubes in El Malpais (Hatheway and Herring, 1970; Greeley, 1971a, b; Greeley and Hyde, 1971). Obser-

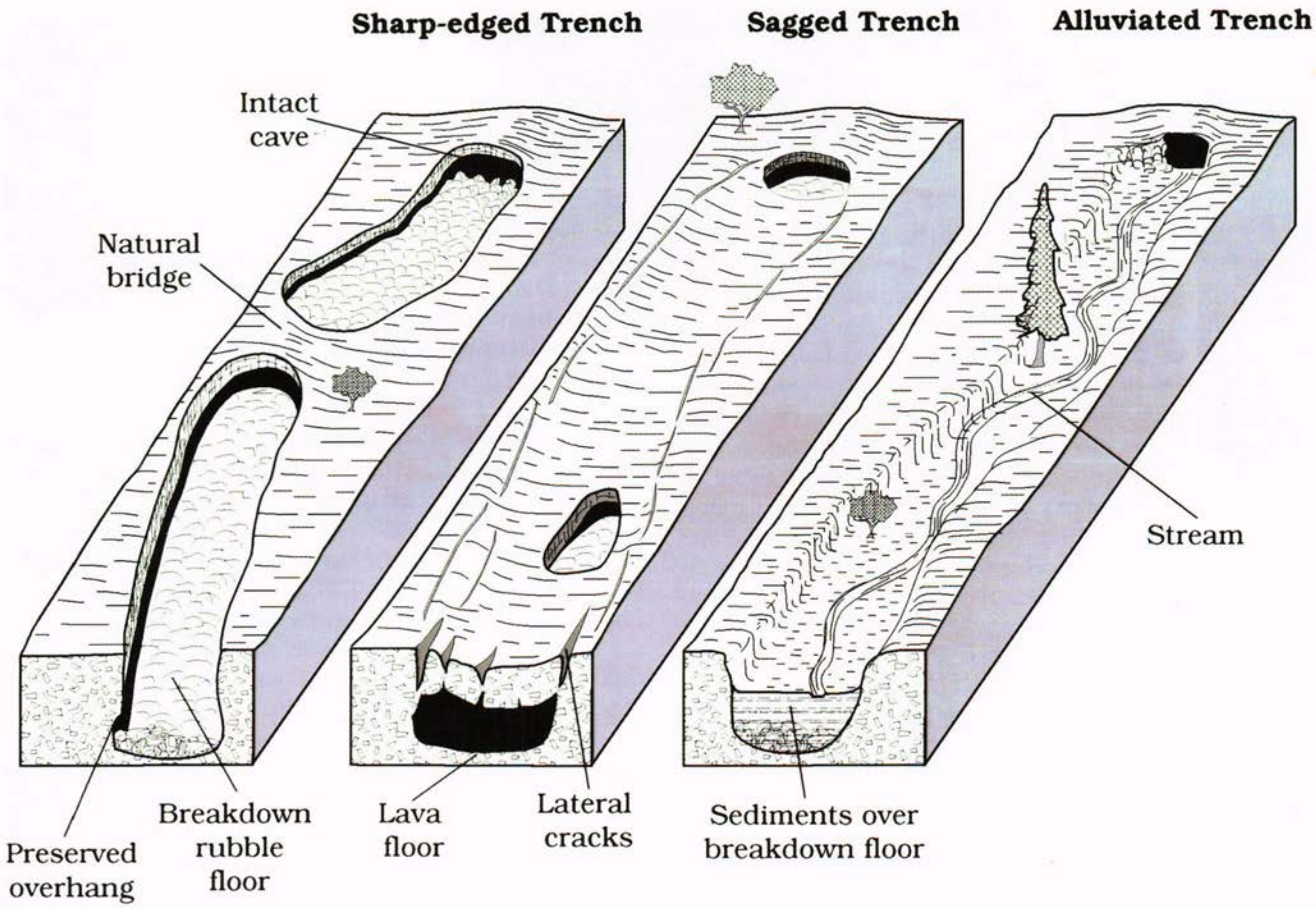

FIGURE 1—Types of collapse trenches.

vations at active volcanoes have shown that for a lava tube to form, an eruption must continue for a relatively long duration and emanate from discrete vents, not long fissures (Carr and Greeley, 1980). These conditions were met at El Malpais because the tube-containing flows all emanated from modest-size volcanoes. The rate of lava flow need not be large, and, indeed, it appears that relatively long-duration, moderate-discharge flows will produce the most lava tubes. Many initial lava flows form thin, wide sheets, but if the flow continues for even a few tens of minutes, channels begin to form within the flow (Hulme, 1974; Sparks et al., 1976). Again, the long-duration flows at El Malpais appear to have been conducive to tube formation. If the flow continues for at least several hours or days, significant lava tubes will begin to form (Peterson et al., 1994).

Many different modes of lava tube formation have been proposed during the last several decades of study (Ford, 1976; Fig. 2). The Bandera and Zuni flows of Maxwell (1986) at El Malpais have been pertinent to these studies. When studying the lava tubes of Victoria, Australia, Oilier and Brown (1965) came to the conclusion that concentric hot layers of lava sheared past each other, leaving hollow spaces that evolved into lava tubes when drained; apparently some lava tubes in Japan also have had such an origin (Ohsako, 1992). Hatheway and Herring (1970) adapted and slightly modified this mode of tube formation to account for the origin of the caves in the Bandera flows. In 1953, Wentworth and Macdonald advanced a theory that progressive roofing of channels was an important mode of tube formation. Other volcanologists, such as Greeley (1971a, b, 1987) and Peterson and Swanson (1974) observed Mauna Ulu lava tubes forming during the 1970s in Hawaii and found that many lava tubes form by the roofing over of lava channels. They recognized at least four modes of tube formation operating in concert. Three of these involve open channels: (1) roofing of channels by the accretion of nearly flat, wall-attached crusts across channeled lava streams; (2) the addition of spatter to levees resulting in arched roofs covering the channels; and (3) jammed and fused plates forming a channel roof. The fourth involves tube lengthening by progressive extension of pahoehoe "toes." Excellent, more detailed accounts are given in Peterson et al. (1994) and Hon et al. (1994). Harter (1978) also observed that in an open channel a series of linings of congealed lava may add enough material to the upper walls of the channel to eventually bridge the open surface of the channel, a process very similar to #2 above. In the above cases #1, 2, and 3 the lava was flowing over steeply to relatively gently sloping terrain in leveed channels. Greeley and Hyde (1971) and Peterson et al. (1994) also observed that the steeper-gradient lava tubes were probably roofed by over-arching, spatter-built levees from the faster flowing lavas. In case #4, that of lava

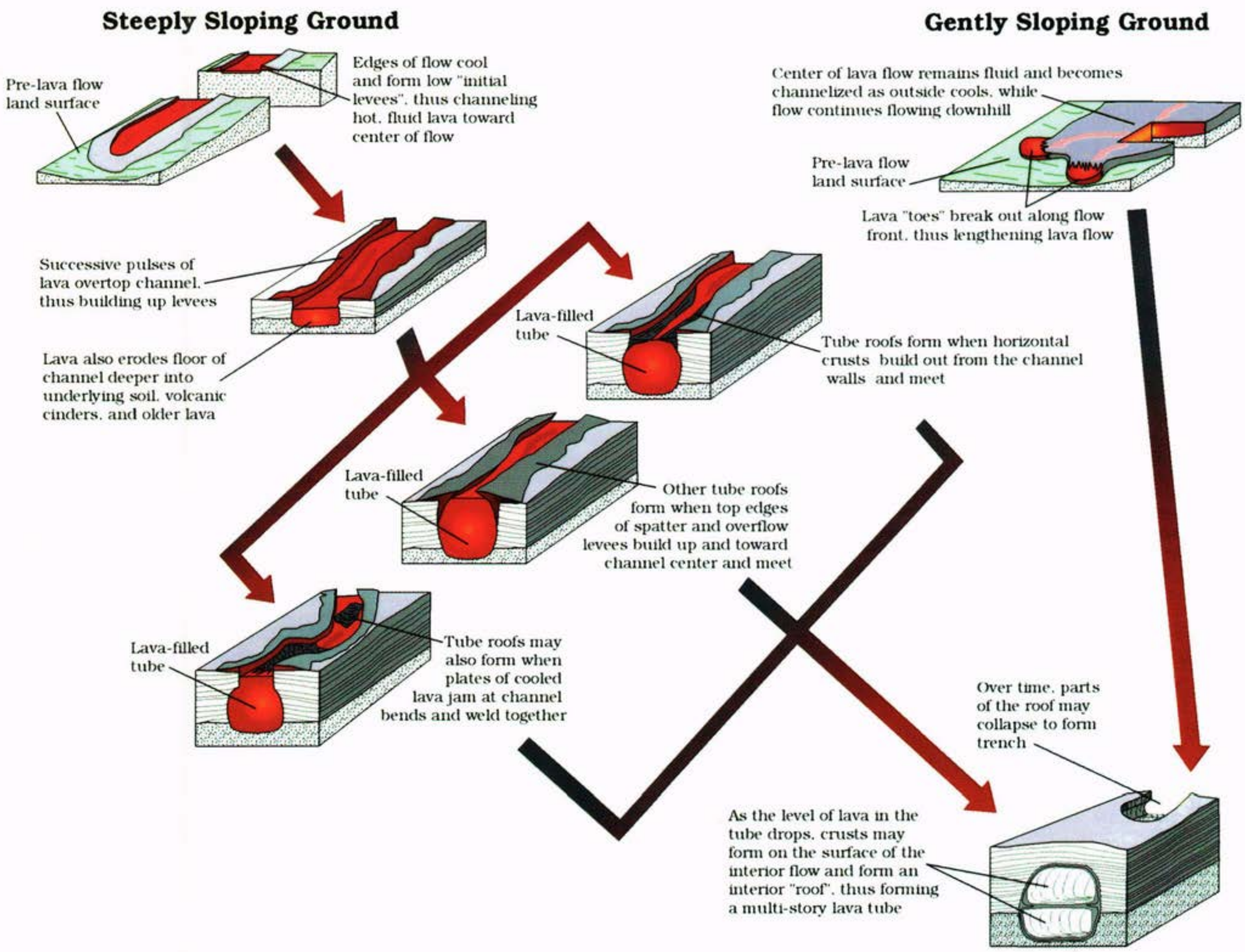

FIGURE 2—Evolution of lava tube from flow to trench. Although these drawings outline the stages of formation of a typical lava tube, the Park visitor should not expect to see caves exactly like these because lava flows and the enclosed lava tubes are typically much more complex in layout and development.

toe budding, the gradients were much lower than in the other three, thus encouraging a more random, less linear tube pattern (Hon et al., 1994). It appears that many of the larger, longer El Malpais lava tubes have been formed by processes similar to either #1, 2, or 3 above. In only one area near Mesita Blanca does process #4 appear more important.

Another aspect of lava-tube formation is the ability of hot lava streams to deepen their channels. In several El Malpais caves the lining of the tube has collapsed, allowing a view of the volcanic rocks outside the tubes, thus indicating that the lava streams were able to partly melt and erode the rocks forming their beds.

Lava tubes buried by subsequent flows may be invaded by still later flows, the invading lava entering via a collapse skylight or entrance. If the later eruption is prolonged and the lava is hot enough, the roof of the pre-existing tube may erode, breaching the roofs of underlying tubes. Once re-established inside these older or lower tubes, further down-cutting and/or lateral erosion may greatly enlarge the tubes (Peterson et al., 1994). These "stacked" tubes are moderately common in El Malpais, but their lower passages are usually filled with solidified lava, rendering the lower tubes inaccessible. Examples of these stacked tubes include Seven Bridges, Xenolith (also known as Ghost Face Cave), and Navajo Caves. In the latter there are at least three stacked tubes. The upper passage is partly preserved as short segments in the collapse trench. The middle tube is split by a lava pillar at its downstream end; both of these branches drop into lower, lava-filled passages. Benches on the walls of the middle level indicate the lava has drained back down into this lower level via several now-choked passages.

In some cases a lower tube has become filled with lava, then broken upwards into an overlying passage, resulting in a lava boil in the floor of the upper tube. At the New Mexico Junction in Four Windows Cave a lava boil is preserved in the cave's floor.

The majority of lava tubes cool when still partially filled with lava. Small, short tubes may drain suddenly, but in large tubes the withdrawal of lava is not a sudden event; rather it occurs gradually as the lava supply decreases. Eventually the lava simply stops moving and solidifies. Field reconnaissance has shown that approximately 20% of the known tubes in the monument are still intact (K. Carlton, unpubl. data

1988). This agrees well with observations that between 18 and 20% of known lava tubes have remained intact and accessible for exploration and study. Those tubes that remain open often undergo collapse during the last stages of cooling. Eventually, the roofs of the tubes will fail due to weathering and collapse, leaving only a meandering trench to mark the position of the former cave. While no studies of lava-tube longevity have been conducted, it can safely be said that lava tubes are, geologically speaking, rather short-lived features on the Earth's crust. Most known lava tubes are found in late Quaternary (including Holocene) lavas of up to several tens of thousands of years old; a few older tubes dating from the Oligocene and Miocene epochs are known, but they are rare (Kolev and Shopov, 1992; Rogers, 1992).

As more and more field observations become available, the processes that formed lava tubes such as those at El Malpais National Monument are becoming better understood. Rather than a single unified process applicable to all lava tubes, it is apparent that they form by differing processes at different points along their length and during their histories (Peterson and Swanson, 1974; Wood, 1976; Peterson et al., 1994) (Fig. 2). The internal plumbing of rivers of molten basalt is extremely complicated, involving complex, interconnected networks of both horizontal and vertical conduits.

Tube types and patterns

The major lava-tube caves in El Malpais are called master tubes, i.e. they are the primary conduits of lava along the length of the lava flow. Smaller distributary tubes diverge from the master tubes downslope from the volcano and are important in dispersing the lava along a broad front. These distributary tubes are seldom preserved in the monument, most likely due to a combination of factors such as low surface gradients, relatively short eruption lengths, and low discharge rates which have allowed their lava streams to slow and congeal within the tubes, thus blocking them.

Lava tubes may have several passage arrangements, and, indeed, a major lava tube may have differing passage patterns along its length. The passage pattern is influenced by several factors, but ground slope may be the most important. Unitary (single passage) tubes and dendritic (tree-patterned) caves are uncommon in El Malpais; braided caves with multiple, connected passages are more common. Steep ground slopes tend to favor formation of unitary tubes, while gently sloping topography with gradients between one to three degrees results in the formation of more complex caves. The formation of lengthy tubes is also favored by very shallow slopes of under one third to one fifth of a degree. Higher channel sinuosity, and hence the complexity of the tube, is favored by these gentler ground slopes where wider, lower flows can spread across the nearly flat topography, thus allowing more intricately branched tubes to form (C. Wood, 1976; Hulme, 1974). Many of the caves, however, have their side passages blocked, thus leaving only a hint of their presence; therefore, the true pattern of these caves is hard to discern. Some of the smaller caves in the monument may lack a pattern, consisting of a single, short passage or room. This is especially true of small-surface tubes that have formed under a thin roof on the ground surface from channel overflows.

The few apparently unitary tubes, such as Candelaria Ice, Big Ice, Guano, or Navajo Caves, are actually short segments of more complexly patterned caves. Abundant evidence shows that the side passages in these apparently unitary tubes have been blocked with breakdown or lava seals. Unitary tubes are usually formed near the volcanic vents where the fast-flowing lava races down channels and master tubes too fast to allow distributary tubes to form.

Junction Cave, at 581 meters long, is an example of a large but simple dendritic-patterned cave. The Right Hook Passage splays off the main passage approximately two-thirds down the tube's length. Big Skylight Cave has a pair of side passages which form a dendritic pattern; one of these passages leads to a second entrance. The large surface tubes near Mesita Blanca once formed an intricate dendritic cave, but are now largely collapsed with only a few grottos and bridges intact.

Braided Cave is perhaps the best example of a braided pattern in the monument. Its two main branches wind around several large rock pillars, creating a ladder-like pattern of passages. Such caves as Classic, Four Windows, Haltun, and Brewers Caves apparently were braided-pattern caves, but now many of the parallel passages are inaccessible due to lava seals. In both braided and dendritic-patterned caves the total cross-sectional area of the multiple passages is the same or slightly larger than the area of the upstream unitary tubes, which would have allowed discharge rates of lava to remain constant throughout the tube system.

Natural bridges are common in the monument. Natural Bridge at the Big Lava Tubes area, bridges in the Seven Bridges collapse trench, and bridges near Four Windows Cave all appear to be remnants of unitary tubes. While their original passage pattern is largely masked by piles of rubble, the tubes along which these bridges formed appear to have been unitary for a considerable length. The series of bridges adjacent to Junction Cave has formed along a largely unitary tube, as has the short bridge between Double Sinks. In contrast, Double Bridge, adjacent to Candelaria Ice Cave, appears to have formed along a segment of a partly collapsed braided cave. The remnants of a small, unitary-surface tube in the middle of the McCartys flow were utilized by Native Americans as a natural bridge on the Acoma–Zuni Trail.

Surface tubes are generally of minor interest compared with the larger master and distributary tubes found in El Malpais; however, they may be important biological refuges (see Northup, this volume). Usually short—up to tens of meters long, and of small diameter—perhaps up to a meter, these lava caves have formed over previous lava flows, often as a result of extension of bulbous pahoehoe toes (Wentworth and Macdonald, 1953; Peterson et al., 1994), leaving small tubes of limited extent. If lava had been supplied long enough, some of these caves might have evolved into larger lava tubes. The surface tubes near Mesita Blanca are unusual because of their large size in comparison with typical surface tubes and, while largely collapsed, rival in complexity and extent many of the larger lava tubes present in the monument.

Lava caves in parts of the ponded area of the McCartys flow have an origin different from typical lava tubes (Nichols, 1938). The flow spread into large lava lakes up to 30 m wide and perhaps 100 m long. After a meter-thick lake crust hardened, some of the lava drained away through marginal cracks in the levees at the lake edges, and the still-plastic crust sagged down. Parts of the more hardened crust then failed and small blocks dropped into underlying, drained cavities. These small caves typically are single chambers approximately 7-12 m in diameter and 7 m deep. Blocks, which formed the entrances, cut vertical grooves in the still-plastic lava as they slipped into the cave. Now many of these caves are nearly half-filled with in-washed sediments.

Internal features

A great variety of internal features is present in the lava tubes of El Malpais (Fig. 3). An excellent illustrated glossary of lava-tube features is in Larson (1993).

Among the common features in lava tubes are abundant piles of collapsed debris and rubble strewn about the tubes (A, Fig. 3). Blocks ranging from meters in extent to melon-sized cobbles often obscure other details about the processes that have occurred in lava tubes. Stresses from contraction brought on by initial cooling exceeded the limits of the lava's strength, causing masses of linings and debris to fall. If the extent of collapse is large, the breakdown may constrict or totally block the tube. If the collapse is vertically extensive, the surface may be breached to form a skylight. Sometimes subsequent lava flows enter the tubes through these skylights, occasionally filling them. Where the roof cools quickly, columnar joints develop along which four- to eight-sided "bricks" of lava spall off, falling into neat piles. In Haltun Cave, a series of unusual, partly hollow, approximately 2m² ceiling slabs spalled off the roof. The boulders look like hollowed limestone blocks called haltuns used by the Mayans to collect water in Yucatan caves. In the ceiling directly above each slab is the upper half of a large vesicle nearly 0.5 m in diameter. The large vesicles apparently weakened the ceiling and caused these massive slabs to fall.

Another very obvious feature of lava tubes is the shelves or benches running along the walls (B, Fig. 3). These are "high lava marks" left by the lava which coursed down through the tubes, and they mark a period of time when the discharge of lava remained constant. As the surface of the lava flow cools, bits of lava are added to the edges of these shelves, building them inward much like the initial roofing of the tubes. Generally speaking, the wider the shelves, the longer the lava flowed at that level. Often they appear to be cantilevered out into the passage with a smoothly con

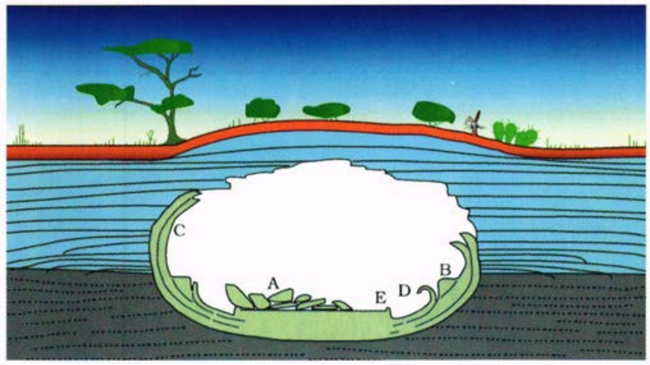

FIGURE 3—Cross section of a typical tube showing some common internal features: **A**, breakdown; **B**, benches; **C**, linings; **D**, curl-downs; **E**, gutters and levees.

cave-rounded underside because the lava, as it receded, filleted the bottoms of these shelves. Particularly wide shelves, often called benches, may make the tube's cross section look like a mushroom.

Linings, also called lava-tube glaze, are relatively thin shells of lava plastered against the inside surfaces of a tube by primary or subsequent secondary lava flows (C, Fig. 3). Where these linings fall short of the ceiling of the cave, their upper surfaces may mark the upper limits of secondary flows. In cross section, multiple linings may look like layers of a cut onion. These linings form in active tubes in one of two ways, either as an additional layer of lava or as a melted crust. In the former case the lava is added when the tube is filled with lava. In the latter case they form in the superheated vacant space over the flowing floor. Openings in the tube may allow atmospheric gases to mix with the superheated tube gases and combust. This burning of hydrogen-rich gas may heat the interior of the tube and thus assist with remelting the linings; this process, however, is poorly understood. However they form, most linings are relatively thin and very brittle, and few remain in place as the tube cools (D. Peterson, pers. comm. 1994).

In places where the entire wall has melted to a depth of a centimeter or so, a thin, plastic glaze of glassy lava, termed a sagged or slumped lining, will partially sag down the wall like a silken draped cloth. Should this sagged lining fail along a discreet crack and the lower panel sag further, the lower panel will actually stretch the lava apart, leaving a line of taffy-like strings and threads of basalt in the opening that often resembles whale baleen plates.

Gas pressure may build up occasionally behind patches of wall linings. When the pressure exceeds the strength of the still-plastic lining, a patch may literally explode from the wall. These pull-outs, or lining ruptures, have out-turned edges and are highly vesicular within.

If the level of the lava in the tube drops quickly, linings which are highly plastic may curl or roll down towards the floor like a loosely rolled parchment (D, Fig. 3). In some cases they fold back down and collapse on themselves; in Big Skylight Cave, there are excellent examples of both of these features. Near the skylight end of the tube are 10-15 cm thick, nearly one

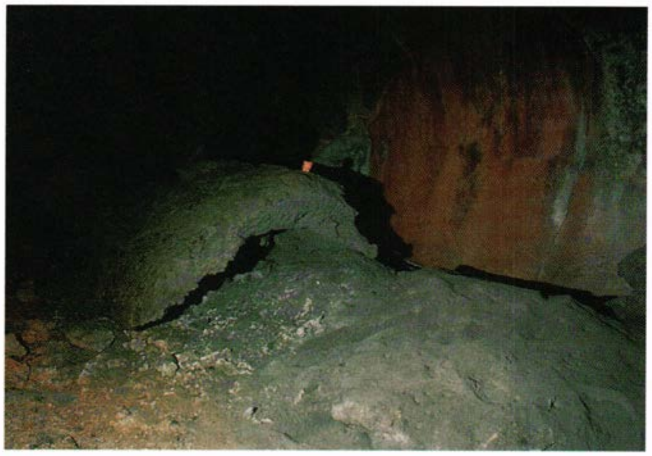

FIGURE 4—Curl-downs are sections of linings that have partly detached and curled down from lava-tube walls while still plastic, thus prompting their name. This curl-down in Braided Cave peeled from the tube wall at right. Note also the plies of black sand formed by granular disaggregation of other slabs of lava by mineral-charged, percolating ground water. (© B. W. Rogers, 1995)

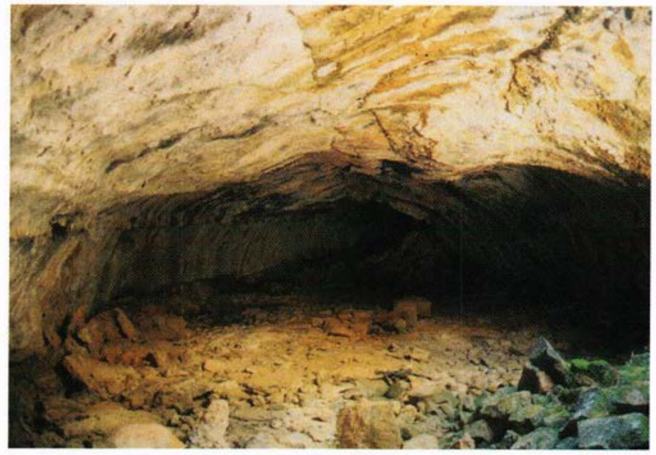

FIGURE 5—View into the entrance passage of Haltun Cave showing flat, pahoehoe-textured floor. The largely intact, smooth ceiling arches approximately 3 m above the floor. Two higher levels of lava left linings on the walls approximately 2.5 m and 1 m above the floor. The piles of angular and moss-covered breakdown in the foreground are remnants of the tube roof which collapsed to form the entrance behind the viewer. Another pile of breakdown where the tube bends to the right is composed of wall and roof collapse debris. (© B. W. Rogers, 1995)

meter high linings which have folded back down toward the tube interior and welded together. Toward the interior of the cave are lower and thinner linings (2-5 cm thick) that have bent back down toward the floor; these are called curl-downs or scrolls (Fig. 4).

Where not obscured by breakdown, the floors of lava tubes often show flow features important to deciphering the very late history of the lava tube. Most floors of El Malpais lava tubes are coarsely textured. Linear flow marks may run the length of the passage; differences in heights of the floor along these boundaries may cause the floor to resemble railroad-track beds. If these depressed linear features are lower than the general floor elevation and are adjacent to the walls, they are called gutters. The last lava flowing down a tube may be very viscous, and levees may develop along the flow margins, confining the flow to just part of the floor. As the flow declines further the levees remain, leaving a low, vertical wall beside the tube wall (E, Fig. 3).

Late in tube development, large plates of partly cooled crust may form on the surface of the flow during the decline of the lava supply. The floors in the downstream end of Big Skylight and upstream end of Four Windows Caves are comprised of buckled lava plates up to nearly a meter thick. If the lava supply subsequently increases, large "log jams" of rafted plates may pile up at constrictions in the tubes. The two large lava pillars in Navajo Cave are examples of plate jams that were over-ridden with lava and cemented to the ceiling.

The floors of most lava tubes are relatively level (Fig. 5), which is generally the result of an interruption in the supply of lava to the tube. However, some of these smooth floors result from ponding due to a constriction further downstream, forming a lava lake. Floor surface textures vary; some passage floors and ponds may be smooth like a stuccoed floor or have textures such as cauliflower pahoehoe or small-scale aa. Tongues of textured lava may remain elevated as "track beds" above the general floor level. Sometimes trapped, underlying lava boils up through the plastic floor crust and forms a lava boil; lava boils are uncommon in the tubes of El Malpais. A lava boil is well preserved in the floor in the small alcove at the New Mexico Junction in Four Windows Cave.

Blocks broken from the ceiling or walls of the tube may be carried along with the moving flow. They may be partly melted and moved either by rafting on the top of or rolling within the flow. If the blocks are too large to melt, the tremendous viscous drag of the lava stream will drag and roll the blocks along with the stream. As they become rounded because of partial melting and abrasion, and sometimes coated with lava, they become lava balls (D. Peterson, written comm. 1995). Junction, Braided, and Haltun Caves have excellent examples of large lava balls (Fig. 6). In several caves, such as Xenolith and Junction Caves, blocks became jammed between the floor and ceiling and cemented in place by the still-flowing lava, nearly closing off the lava-tube passage.

A great variety of floor textures occurs in response to changes in viscosity and differential shear strain in the flow. Variables affecting the viscosity and/or rate of shear strain were identified by Peterson and Tilling (1980) to include lava temperature, gas content, flow velocity and duration, channel configuration, lava vesicularity and crystallinity, and ground slope. If all the lava flowing inside the tubes merely stopped moving and quickly cooled, the floors would be relatively smoothly paved with ropy pahoehoe textures. However, changes in viscosity and rate of shear strain can cause tube floor textures to change from smooth pahoehoe to aa with its loose, clinkery fragments. It is common to see the centers of floors textured with ropy

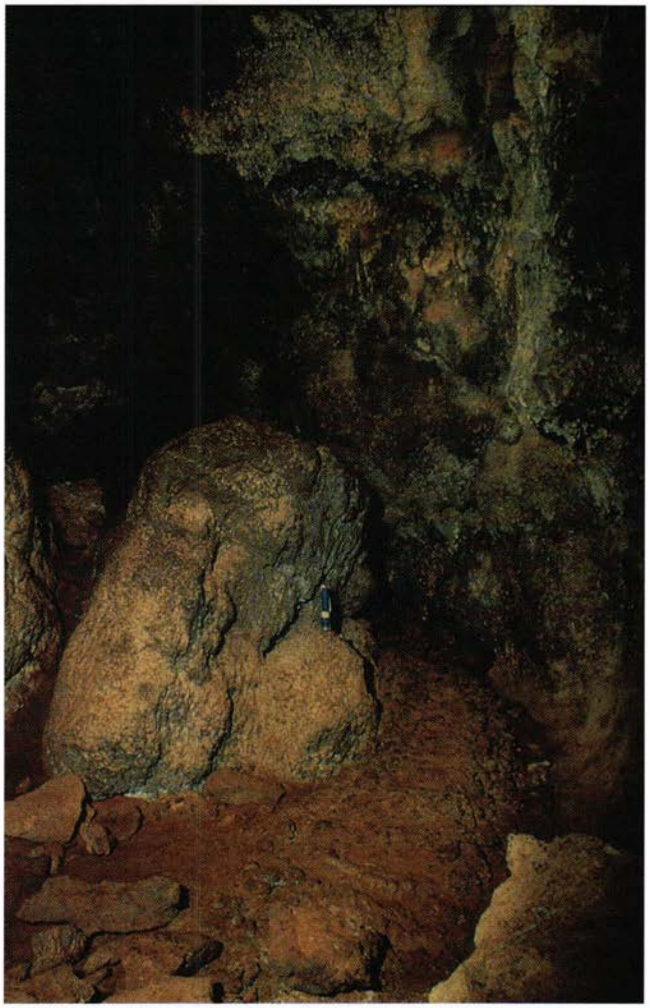

FIGURE 6—A rafted block of lava nearly blocks the Right Hook Passage in Junction Cave. Note the irregular but smooth lava coating of the block as contrasted with the angular pieces of breakdown on the passage floor in the foreground. Note also low lava falls where lava coursed around the block once it was wedged into place. Flashlight is approximately 16 cm high. (© B. W. Rogers, 1995)

coils of pahoehoe, while the edges of the flow are aa-textured. Gradations between these extremes, including cauliflower lava, are usually well displayed wherever the floors are preserved and are not covered with breakdown.

Ceiling collapses called skylights often form during tube formation. These are important because they allow atmospheric gases to mix with the superheated tube gases and combust. This burning of hydrogen-rich gas may heat the interior of the tube and thus assist with remelting the linings; however, this process is poorly understood. The forms caused by this process can be easily removed by the enormous drag of flowing lava streams, but they may be just as easily re-deposited after the flows subside.

Cultural uses and modifications

Although an exhaustive listing of human activity in El Malpais lava tubes is beyond the scope of this chapter, some brief comments are appropriate. Approximately 12,000 years of Native American history is recorded in the archaeological deposits in and around the monument (A. Ireland, unpubl. data, 1988). Among the most obvious records of human visitation is the Acoma—Zuni/Zuni—Acoma Trail which crosses the McCartys flow. As previously mentioned, part of the trail extends over a natural bridge, the remnants of a collapsed lava tube. Throughout the lava tubes are found scattered cultural remains; apparently most of the cultural material dates from the Ancestral Pueblo and later peoples.

The lava tubes were also physically modified at scattered locations throughout the monument. In at least two caves, Navajo and Candelaria Ice Caves, Native Americans made several modifications to cave features. In Navajo Cave, basalt floor plates each ca $1 m^2$ in area were moved to form several wells to collect drip water from seasonal melting of cave ice. Large amounts of charcoal, ash, and wood approximately 1200 years old (J. Bradford, unpubl. data, 1993) are found adjacent to the wells in the outer parts of the cave, presumably left from fires used to melt the ice. The constructors of these wells were apparently Ancestral Pueblo.

In Candelaria Ice Cave, ice was quarried for refrigeration of food stuffs (K. Mabery, oral comm. 1990; see also Dickfoss, Mangum, this volume). Reportedly, both the U.S. Army headquartered at nearby Fort Wingate and local ranchers and settlers removed enough ice to lower the main cave floor by nearly 1.4 m despite naturally occurring ice restoration each winter.

Several caves, such as Junction and Frozen Bat Caves, were modified as dwellings for both Native American peoples and settlers in the area. Breakdown on the floors was re-arranged, and fireplaces, rings, and rock walls were constructed to make the caves habitable. Frozen Bat Cave also had the luxury of an ice-floored "deep freeze" room adjacent to the living part of the cave, which provided both food storage and a water supply.

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Most of all, we appreciate the timely and detailed reviews by Julie Donnelly-Nolan, Don Peterson, and Ron LeCompte of the U.S. Geological Survey that have much improved this and the lava-tube morphology chapters. We would also like to thank the following Cave Research Foundation personnel for their unflagging enthusiasm while tramping through the lava fields of El Malpais, be the weather fair or foul: Mike Goar, Patricia Helton, Ken Ingham, Dale and Jill DesJardins, Dennis McKeon, Diana Northup, and Cal Welborn; they were most supportive. We greatly appreciate the laboratory assistance of Paul Russell and V. Polyak in identifying some of the more intractable minerals. Finally, we thank the staff of El Malpais National Monument and the Western Regional Geology Branch of the USGS for their support and for giving this study their blessing.

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Life in the twilight zone—Lava-tube ecology

Diana E. Northup[1] and W. Calvin Welbourn[2]

[1]Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131;
[2]Division of Plant Industry, Florida Department of Agriculture and Consumer Services, Gainesville, Florida 32614

Introduction

Walking through one of the lava tubes in El Malpais National Monument, you might notice faint signs of life, a dry owl pellet on the floor, spider webs between rocks, or plants in the entrance. If you examined the walls very carefully, you might spot a harvestman on the wall, a camel cricket in an alcove, or a spider deep in a crack. Unlike the animals found in areas on the surface above the lava tubes, life in the lava tubes is hidden. How those animals make the lava tubes their home is the subject of this chapter. We examine factors that control distribution of organisms in the lava-tube environment, food resources, the effect of climatic factors on life in lava tubes, and the results of our studies in selected lava tubes at El Malpais National Monument.

Major biotic inventories are available for lava tubes in Hawaii (Barnard, 1977; Bellinger and Christiansen, 1974; Brindle, 1980; Bousfield and Howarth, 1976; Fennah, 1973; Gagne and Howarth, 1975a, b; Gertsch, 1973; Gurney and Rentz, 1978; Howarth, 1972, 1973, 1991; Liebherr and Samuelson, 1992; Muchmore, 1979; Schultz, 1973; Wirth and Howarth, 1982; Zacharda, 1982). Another geographic area whose lava tubes have received much attention is Japan, particularly Mt. Fuji (Habu, 1971; Imamura, 1971; Inoue, 1972; Ishikawa, 1972; Mack-Fira and Kawakatsu, 1972; Shiba, 1971b; Shinohara, 1973; Suzuki, 1972; Uéno, M.; 1971b; Uéno, S. I., 1971b, c; Yaginuma, 1972; Yamamoto and Aoki, 1971) and western Japan (Kawakatsu and Mack-Fira, 1975; Morimoto, 1970; Murakami, 1971; Shiba, 1971a; Uéno, M., 1971a; Uéno, S. **I.,** 1971a; Yaginuma, 1970; Yamaguchi and Yaginuma, 1971; Saito, 1977).

In the Western Hemisphere, several studies have been published on the fauna of lava tubes in the Azores (Ashmole et al., 1992; Borges and Oromi, 1991; Eason and Ashmole, 1992; Gama, 1988; Morell and Subias, 1991; Oromi et al., 1990), and the Canary Islands (Ashmole and Ashmole, 1988; Huys, 1988; Martin and Oromi, 1984, 1986, 1988; Remane and Hoch, 1988). Oromi et al. (1990) found a great diversity in the Canary Islands, with more than 50 species of troglobites in about 30 genera.

The Galapagos Islands were studied by Peck and Shear (1987a, b). In the continental United States, studies include Benedict (1979), Briggs (1974), Genter (1986), Peck (1973, 1982), and Senger and Crawford (1984).

Lava-tube habitats and food resources

The volcanic area of the El Malpais National Monument consists of at least eight major flows, El Calderon, Twin Craters, Bandera, Hoya, and McCartys, ranging in age from 100,000 to about 3,000 years (see Cascadden et al., this volume; Laughlin and WoldeGabriel, this volume). In these flows, there is a number of lava tubes, some of which were identified by Maxwell (1986).

The authors undertook a study of six lava tubes (Bat, Braided, Four Windows, Junction, Big Skylight, and Navajo Caves) in the Monument to provide baseline inventory and seasonal data for the National Park Service. These six tubes vary in terms of size, energy sources, number of entrances, presence or absence of ice, and amount of human visitation. These baseline data help with the protection and management of lave-tube biota.

One of the lava tubes included in this study, Bat Cave, is an important roost for the Mexican freetail bat *(Tadarida brasiliensis).* The proximity of this lava tube to Junction, a much visited lava tube, and the importance of the bat population make it one of the most significant lava tubes in the Monument. The other five lava tubes are receiving increasing visitation as the Monument becomes better known. Navajo Cave is the only examined lava tube with permanent ice. Big Skylight, Four Windows, and Braided Caves contain significant moss gardens (Fig. 1). The former two have at least two entrances and skylights.

Like limestone caves, lava tubes have distinct zones: entrance, twilight, and deep. Howarth (1973) designated an additional region, the transition zone, a dark zone that is not stable due to the size of the tube, the existence of multiple entrances, or the location of the tube on a steep slope. Some lava tubes may never develop a true, stable, deep zone suitable for a community of troglobites.

Within the different zones, food resources vary in their nature and distribution. Thus, to an organism seeking to colonize a lave tube, the terrain appears patchy, with some areas being much more habitable. Energy sources in lava tubes include plant materials (especially roots in Hawaii), cave oozes composed of

FIGURE 1—Moss garden in Four Windows Cave. Note the luxurious growth of moss that covers the rocks and wood that has fallen in through the skylight. (© K. Ingham, 1995)

FIGURE 2—Spider inhabiting the moss garden in Big Skylight Cave. Many invertebrates utilize this protected microclimate. (© K. Ingham, 1995)

organic and mineral colloids, minerals and organic matter in ground water that percolates into the lava tubes, and accidentals from the surface (Ahearn and Howarth, 1982; Howarth, 1982). It may also take the form of detritus from the surface (twigs, leaves, etc.), fecal material (bat, bird, and cricket guano, scat of larger mammals, and rodent droppings), or in some cases material brought in inadvertently by humans (skin, hair, pieces of clothing, urine, feces, food, or building materials). Major accumulations of organic matter occur under the skylights and, to a lesser extent, under bird nests and bat roosts. The distribution of organic matter is an important determinant of the distribution of organisms.

A greater number of species and individuals are often found near the entrance of lava tubes due to the sheltered and more equable environment as compared to the surface (Jefferson, 1983), in addition to the accumulation of organic matter there. However, the shortness of many of the tube sections and the presence of at least two openings in many of the tubes leads to a less sheltered entrance area during much of the year due to the increased air flow and its drying-out effect.

Leaving the entrance and twilight zones, we enter the dark zone where no light enters and niches of high relative humidity are present. The dark zone repre

FIGURE 3—This velvet mite was found under a rock in the entrance collapse of Junction Cave. (© K. Ingham, 1995)

sents a rigorous environment for most invertebrates. Cave-adapted invertebrates are found where moisture is available, in cracks and crevices, under rocks, on or in guano or other organic matter, and on surfaces of pools.

El Malpais lava tubes contain similar habitats and organic-matter inputs as other lava tubes, but some of their features are unique. In contrast to lava tubes in Hawaii and some other areas, El Malpais lava tubes do not develop significant food resources from plant roots hanging down into the tubes. The dryness of the epigean terrain in El Malpais National Monument makes water an important limiting factor for El Malpais lava-tube fauna and flora. The rainy season in July and August may create small pools in the dark zones of Braided, Four Windows, Big Skylight, and Junction Caves that may last into the fall. During most of the year invertebrates must retreat into the cracks and crevices for moisture.

Mammals and birds provide organic matter in the form of their droppings in lava tubes. Dry owl pellets can be observed in several of the tube segments of Braided Cave. Bat Cave has extensive deposits of guano and fur from Mexican freetail bats. Several other lava tubes contain scattered droppings from colonies of long-ear bats *(Plecotus)*.

The mosses and lichens in the entrances of most lava tubes represent unique and very delicate habitats. Moss in lava tubes is an excellent habitat for invertebrates, providing protection, camouflage, advantageous microclimates, and food. Richardson's (1981) review of the literature revealed that moss invertebrates include mites, water bears (tardigrades), rotifers, roundworms (nematodes), amoebae, scorpion flies, aphids, fly larvae, caterpillars of small moths, small grasshoppers, and most snails (gastropods). Studies of moss invertebrates in caves are scarce, but include the finding of a relict new pseudoscorpion inhabiting the bottom of a lava-tube sink (Benedict, 1979).

The moss gardens at the entrances of many El Malpais lava tubes and in deep cracks in lava flows are excellent habitats for invertebrates (Fig. 2). In addition to the entrances, several of the skylights have significant moss gardens below them. The moss in the entrances and under skylights are refugia (Lightfoot and Bleakly, pers. comm. 1993; Lightfoot et al,. 1994) for many alpine species that cannot survive anywhere else in the Monument, and a source for fauna colonizing the dark zones of lava tubes. Examination suggests the dominant taxa in the moss are springtails and mites. Both these groups are also abundant in the entrance collapse areas, where they are found amongst the plant detritus, under rocks, and deep in protected cracks (Fig. 3).

Junction Cave has more cave-adapted species than any of the other caves (tubes) examined. The depth (stable temperature) and wet conditions in the lower levels make this lava tube a good habitat for cave fauna. The very back of Junction is an area of permanent mud (Mud Room). Depressions in the passage near and in the Mud Room often fill with water and the surfaces of these pools usually have mites and springtails. Organic matter washes into the lava tube during heavy rains, and spring snow melt accumulates in the Mud Room.

Animals in lava-tubes

The animals found in lava tubes may be either accidentals from the surface, or organisms exhibiting a range of adaptations that help them utilize this environment effectively. Often they have retreated into lava tubes to escape harsh or changing conditions on the surface. Some organisms were not escaping, but were seeking out an environment that offered them conditions to which they were already adapted. Scientists use lava tubes to study how animals adapt to the conditions of total darkness, air that is highly saturated with water, a relatively constant temperature, and limited food resources. These studies have spanned the globe and include the volcanic regions of Hawaii, Japan, the continental United States, the Canary and Azores Islands in the Atlantic Ocean, and the Galapagos Islands. Many of the studies of lava-tube fauna are faunal lists or descriptions of new species. Spiders and beetles are the groups of biota most often reported from lava tubes. Martin and Oromi (1986) found that springtails and booklice were the most abundant biota near entrances of lava tubes in the Canary Islands.

Lava tubes were considered to be very depauperate in species until Howarth (1972) reported on the cavernicolous fauna in the Hawaiian lava tubes. His studies disclosed approximately 45 species of cave-adapted animals (Howarth, 1982, 1987b). Oromi et al. (1990) contrasted the more than 50 species of troglobites in about 30 genera found in lava tubes on four of the seven Canary Islands with the much more sparse fauna (12 cave-dwelling species) from lava tubes on the Azores, which are much more isolated from the mainland. Thus, faunal diversity in lava tubes varies depending on a number of factors.

Although some of the El Malpais lava tubes have been known for many years, little is known about their invertebrate fauna. Peck's (1982) preliminary examination of some lava tubes in the mid- and late 1970s resulted in a list of 10 species from the area now occupied by El Malpais National Monument. Species found included mites, pseudoscorpions, entomobryidid collembolans, campodeidid diplurans, rhaphidophorid camel crickets, staphylinid beetles, fleas, and sphaerocerid and ephydrid flies. Peck (1982) felt that the "fauna was exceedingly impoverished and contained solely species that have peripheral ecological associations with caves." However, Pecks work was limited to one time visits of selected caves during the summer. Peck (1982) attributed the lack of species to the "absence of a suitable ancestral litter fauna." His survey of nearby Mount Taylor found it to be somewhat impoverished compared to montane regions to the north. He hypothesized that barriers existed between it and the more northerly montane areas that would have been sources of flightless litter arthropods.

To find the invertebrates inhabiting the lava tubes, we studied each lava tube during spring, summer, and fall. We used visual inspection, pitfall trapping, and extraction from substrates to sample the invertebrates in different zones of the lava tubes. Using a magnifier, we closely inspected a variety of habitats to locate and sample invertebrate fauna. The habitats included organic material in the lava tubes (leaf litter, wood, guano, feces, roots, etc.) as well as different substrates (soil, under rocks, cracks, crevices, surfaces of pools). The moss gardens and algae-covered walls were examined with particular care. Pitfall traps constructed from small plastic cups (16 and 10 oz) with funnel shaped inserts (used only in 16 oz cups) and buried in the substrate up to the rim were set unbaited in Bat Cave. Finally, we collected several small samples of soil and organic matter from which we extracted the invertebrates using a heptane flotation method described by Walter et al. (1987).

Biota

A variety of cave-adapted and noncave-adapted invertebrates were found in the lava tubes examined (Fig. 4) at El Malpais National Monument. A listing of invertebrates found through 1995 is provided in Table 1, and we highlight the more interesting findings here. Many of the species collected are still under study by specialists around the United States. We found four possible troglobites: a mite (Acari), two species of springtails (Collembola), and a dipluran. In addition, two spiders (one from Big Skylight Cave and another from Braided and Four Windows Caves) were pale and probably troglophilic.

The two apparently troglobitic springtails were found only in the dark zone and usually on the surface of small pools. One springtail, a tiny white sminthurid (Sminthuridae), was relatively common on the small pools in Braided, Four Windows, and Junction Caves. These lava tubes have the most extensive dark zone and are also the wettest lava tubes examined. The other springtail was a tiny, white, eyeless, elongate onychiurid (Onychiuridae) that was usually found on or around pools in the same lava tubes. This springtail appears to be a species new to science, and is currently being studied by an expert. Springtails feed on microflora. The pools in these caves are probably rich in fungi and bacteria that grow on the arthropods, usually flies, that get trapped in the water.

Several species of eyed and pigmented springtails are common in the moss gardens and algae at the entrance and skylight areas of most lava tubes. The springtails serve as prey for the predacious rhagidiid mites that also live in the dark zone of these lava tubes.

The dipluran is currently known only from two specimens in Junction Cave (Fig. 5). Diplurans are relatively common detritivores in limestone caves, but this is the first record from lava tubes in New Mexico.

Mites (Acari) are the most common invertebrates in the El Malpais lava tubes, being represented by beetle mites (oribatids), whirligig mites (anystids), snout mites (bdellids), eupodids, nanorchestids, pentalodids, and rhagidiids (Table 1). Other lava-tube studies have also reported mites. Morell and Subias (1991) found almost two dozen families of beetle mites

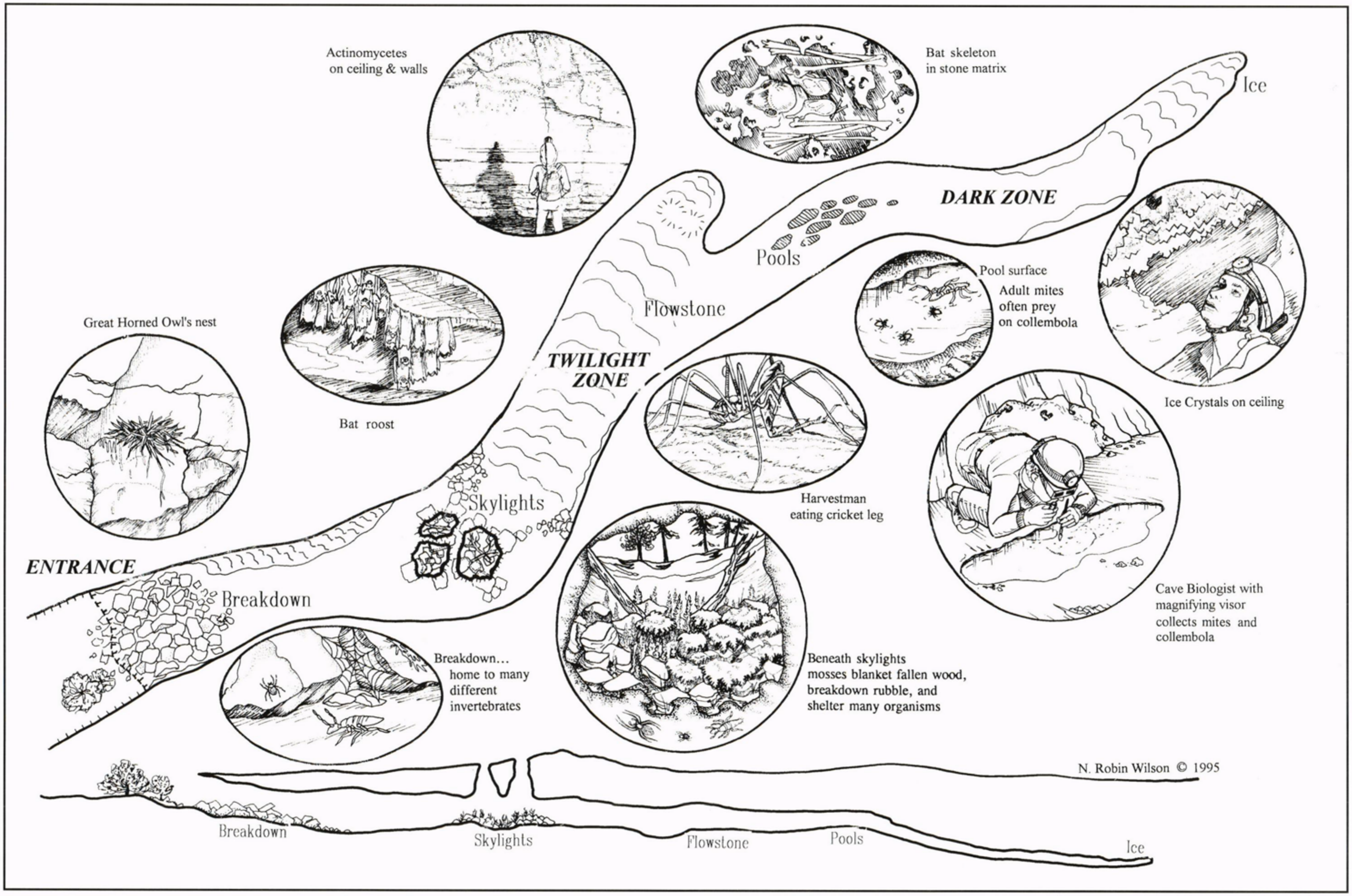

FIGURE 4—The entrance, twilight, and dark zones of the lava tube harbor a variety of accidental and cave-adapted invertebrates in diverse habitats that include the underside of rocks, moss and algae, surfaces of pools, and deep cracks in the lava. (© N. Robin Wilson, 1995)

TABLE 1—List of vertebrates and invertebrates from six caves in El Malpais National Monument. The 62 species identified from field collections in 1993–1995 included 41 accidentals, 2 trogloxenes, 10 troglophiles, 6 troglobites, and 2 guanophiles. BA = Bat Cave; BS = Big Skylight Cave; BR = Braided Cave; FW = Four Windows Cave; J = Junction Cave; and N = Navajo Cave.

Taxa	**Caves**						**Classification (Habitat)**
VERTEBRATA							
Hylidae (tree frogs)							
Hyla exemia (mountain tree frog)	–	BS	–	–	–	–	Accidental (moss/rocks)
ANNELIDA (segmented worms, earthworms)							
Enchytraeidae							
undetermined species	BA	–	–	FW	J	–	Accidental (soil)
MOLLUSCA							
Gastropoda							
undetermined species	BA	BS	–	FW	–	–	Accidental (moss)
ARTHROPODA							
Myriapoda							
Diplopoda (millipedes)							
Parajulidae							
Apacheius guadalupensis Loomis	BA	BS	BR	FW	J	N	Accidental (moss)
Chilopoda (centipedes)							
Lithobiomorpha							
undetermined species	BA	BS	–	–	–	–	Trogloxene (moss)
Scolopendromorpha							
Scolopendra sp.	BA	–	–	–	–	N	Accidental (moss/under rocks)
Insecta (insects)							
Collembola (springtails)							
Entomobryiidae							
Entomobrya sp.	BA	BS	BR	FW	J	N	Accidental (moss)
Onychiuridae							
Onychiurus sp.	BA	–	BR	FW	J	–	Troglobite (dark zone, pool surface)
Sminthuridae A							
undetermined species	–	–	BR	FW	J	–	Troglobite (dark zone, pool surface)
Sminthuridae B							
Sminthurus sp.	–	BS	BR	FW	J	–	Accidental (moss)
Coleoptera (beetles)							
Carabidae (ground beetles)							
Rhadine sp.	BA	–	BR	–	–	–	Troglophile (twilight/under rocks)
Dermestidae (dermestid beetles)							
undetermined species	BA	–	–	–	–	–	Guanophile (guano)
Scarabaeoidea (scarab beetles)							
undetermined species	BA	–	–	–	–	–	Accidental (entrance)
Staphylinidae (rove beetles)							
undetermined species	BA	BS	BR	FW	–	N	Accidental (entrance)
Tenebrionidae (darkling beetles)							
Eleodes sp.	BA	–	BR	–	–	–	
Diplura (diplurans)							
Campodeidae (campodeids)							
undetermined species	–	–	–	–	J	–	Troglobite (mud, moist rocks)
Diptera (flies)							
Bombyliidae (bee flies)							
undetermined species	BA	–	–	–	–	–	Accidental (entrance)
Chironomidae							
undetermined species	–	–	BR	FW	J	–	Accidental (moss, algae)
Phoridae							
undetermined species	BA	BS	BR	FW	J	N	Accidental (moss)
Tipulidae							
Empedomorpha empedoides (Alexander)	–	–	BR	–	–	–	Accidental (alcove)
Hemiptera (true bugs)							
Cydnidae							
Pangaeus sp.	–	BS	BR	FW	–	–	Accidental (entrance)
Homoptera							
Aphididae (aphids)							
undetermined species	BA	–	–	BR	–	N	Accidental (entrance)

Table 1, con't

Taxa	Caves						Classification (Habitat)
Hymenoptera (wasps/bees/ants)							
Formicidae							
undetermined species	BA	–	BR	–	J	–	Accidental (entrance)
Lepidoptera (butterflies/moths)							
undetermined species	BA	BS	BR	FW	–	–	Accidental (entrance)
Microcoryphia (jumping bristletails)							
Machilinus sp.	–	–	BR	–	–	–	Accidental (entrance)
Orthoptera (grasshoppers & crickets)							
Rhaphidophoridae							
Ceuthophilus (cf.) *utahensis*	BA	BS	BR	FW	J	–	Trogloxene (passage)
Psocoptera (barklice/booklice)							
Psyllipsocidae							
Psyllipsocus sp.	–	–	BR	–	–	–	Troglophile (entrance/under rocks)
Siphonaptera (fleas)							
Ischnopsyllidae							
undetermined species	BA	–	–	–	–	–	Accidental (guano)
Thysanoptera (thrips)							
undetermined species	–	–	BR	–	–	–	Accidental (entrance)
Arachnida (arachnids)							
Acari (mites)							
Alicorhigidiidae							
Alicorhigia sp.	–	–	BR	FW	–	–	Troglobite? (dark zone, on surface of pools)
Anystidae (whirligig mites)							
Anystis sp.	–	BS	BR	FW	–	–	Accidental (moss)
Chausseria new species	–	–	BR	–	–	–	Accidental (soil surface/under rocks)
Bdellidae (snout mites)							
Bdella sp.	–	BS	BR	FW	–	–	Troglophile (moss, dark zone,walls, rocks)
Caeculidae							
Caeculus sp.	–	BS	–	–	–	–	Accidental (entrance)
Eupodidae							
Eupodes sp.	BA	BS	BR	FW	–	N	Troglophile (moss)
Linapodes sp.	BA	BS	–	–	–	–	Troglophile (moss)
Erythraeidae							
Abrolophus new species	–	–	BR	–	–	–	Accidental (entrance)
Leptus sp.	–	–	BR	–	–	–	Accidental (entrance, parasite of harvestmen)
Erythraeus new species	BA	–	–	–	–	–	Accidental (entrance)
Labidostommatidae							
Nocolettiella sp.	–	BS	–	–	–	–	Accidental (moss)
Laelapidae							
Geolaelops sp.	BA	–	BR	–	–	–	Accidental (moss)
Lordalychidae							
Lordalychus sp.	–	–	–	FW	–	–	Accidental (moss)
Macronyssidae							
Macronyssus sp.	–	–	BR	–	–	–	Accidental (parasite of bats)
Microtrombiidae (velvet mites)							
new genus and species	BA	BS	–	–	–	–	Accidental (entrance)
Nanorchestidae							
Nanorchestes sp.	–	BS	–	FW	–	–	Troglophile (algae, moss)
Neothrombiidae (velvet mites)							
Ceuthothrombium new species	BA	BS	–	–	–	–	Troglobite (larva parasitic on crickets)
Oribatida (3–4 species)							
undetermined species	BA	BS	BR	FW	J	N	Accidental (algae, moss)
Parasitidae							
Parasitus sp.	BA	–	–	–	–	–	Accidental (moss)
Penthalodidae							
Penthalodes sp.	–	BS	–	FW	–	–	Accidental (moss)
Rhagidiidae							
Poecilophysis, probably two new species	BA	BS	BR	FW	J	N	Troglobite and troglophile (dark zone, mud, pools, moss)
Rosensteineidae							
Nycteriglyphus sp.	BA	–	–	–	–	–	Guanophile (guano)

Table 1, con't.

Taxa	Caves						Classification (Habitat)
Smarididae							
Fessonia sp. (probably new species)	BA	–	–	FW	–	–	Accidental (entrance)
Trombidiidae (velvet mites)							
new genus and species	–	BS	–	–	J	–	Accidental (entrance)
Araneae (spiders)							
Linyphiidae (sheetweb weavers)							
Lepthyphantes sp.	BA	–	–	–	–	–	Troglophile (entrance, rocks, passage)
undetermined	BA	–	BR	–	–	–	
Pholcidae (cellar spiders)							
Pholocphora sp.	BA	BS	BR	FW	–	–	Troglophile (entrance, rocks, passage)
Salticidae (jumping spiders)							
Habronattus sp.	BA	BS	–	–	–	–	Accidental (moss, entrance)
Theridiidae (combfooted weavers)							
Steatoda sp.	BA	BS	–	FW	–	–	Accidental (moss, entrance)
Opiliones (harvestmen, daddy longlegs)							
Phalangiidae							
Leiobunum townsendi Weed	BA	BS	BR	FW	–	–	Trogloxene (passage)
Pseudoscorpionida (false scorpions)							
undetermined species	BA	–	BR	–	–	–	Accidental, troglophile (entrance, under rocks, guano)
Scorpiones							
Vaejovidae							
Vaejovis sp.	BA	–	–	–	–	–	Accidental (entrance, under rocks)

(Oribatida) in cave soils. Zacharda (1982) reported mites of the families Rhagidiidae and Eupodidae from lava tubes on Hawaii and Molokai. Elliott (1976) reported a troglobitic rhagidiid genus *Flabellorhagidia* from lava tubes in Idaho and Washington. Another rhagidiid genus, *Elliotta,* was reported from lava tubes in Idaho (Zacharda, 1982). Peck (1973) noted the presence of *Rhagidia* sp. (Rhagidiidae) in western North American caves. One of the most common mites in the dark zone of the wetter lava tubes and at the moss gardens at El Malpais is the rhagidiid *Poecilophysis* sp. This genus is common in limestone caves, but the species that inhabits El Malpais lava tubes may be new. These fast moving, white, eyeless predators have massive chelicerae that are used to catch springtails and other small arthropods.

The rhagidiid from the moss gardens and dark zone appear to be the same species, but detailed comparative studies are needed to determine the relationships between the deep-cave and the moss specimens. This rhagidiid is at least troglophilic. It is frequently encountered on the surface of small pools in the dark zone of Braided, Four Windows, and Junction Caves and under rocks and logs in the moss gardens. The other mite, an alicorhigid, appears to be a troglobite; it is tiny, white, eyeless, and is known from only a few specimens collected on pools in Braided and Four Windows Caves. Other alicorhigid species are known from the soil and additional study is needed to determine the relationships of this mite to other species in the family. Of the other mites, most were found in the moss gardens at the entrances and under skylights of all lava tubes. Beetle mites (oribatids) were common in the moss gardens; three or possibly four species were found. Only a few beetle mites and a snout (bdellid) mite, *Bdella* sp., were occasionally found in the dark zone of the lava tubes where they are probably accidentals strayed from their primary moss-garden habitat. Beetle mites feed on microflora and dead organic material, while the snout mite is an aggressive predator.

Specialized habitats of the lava tubes in El Malpais National Monument support unique communities. One such habitat is the algal gardens found on the walls and sometimes the floor of most lava tubes. Microscopic examination of algae from several sites revealed mites, springtails, and occasional fly larvae living in this habitat. The algophagous mite *Nanorchestes* sp. was the most numerous invertebrate in the algae and was found concentrated in small pockets on the wall. *Nanorchestes* are common in soil where they feed on the algae. The concentrated patches of algae make an excellent habitat. No predators were observed, but rhagidiid and bdellid mites probably forage in the algal gardens looking for springtails and nanorchestids. As we continue to study the algae, we hope to observe additional invertebrates and to learn more about the relationships among the residents and visitors to this habitat.

Accumulations of bat guano provide a habitat with rich and abundant food resources for invertebrates. Our examination of the guano habitat in Bat Cave revealed a population of guanophiles which include mites, a pseudoscorpion (Fig. 6), and a dermestid beetle. The mite genus *Nycteriglyphus* sp. (Rosensteinidae) feeds in Mexican freetail bat *(Tadarida braziliensis)* guano and is common in other Mexican freetail caves, such as Carlsbad Cavern, New Mexico. Due to the multiple entrances, Bat Cave is very dry. To survive in this environment, the mite populations reach their peak while the bats are present and moisture is the highest. The mite population rapidly

FIGURE 5—Dipluran found on the mud at the back of Junction Cave. These troglobitic detritivores require high humidity. (© K. Ingham, 1995)

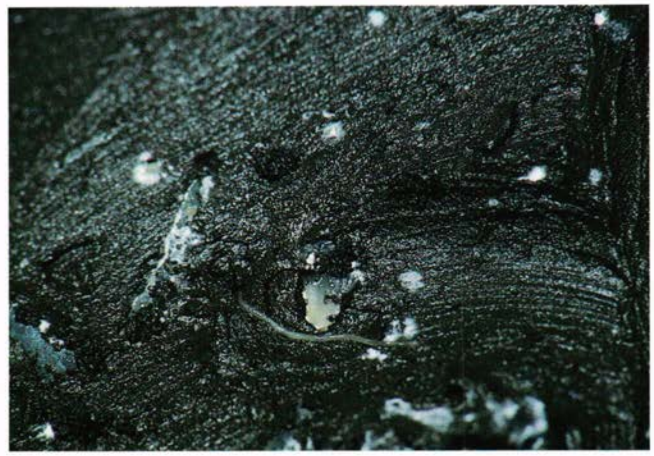

FIGURE 7—Moderate numbers of these enchytraeid worms are found at the back of Junction Cave on the mud and under candle wax left by visitors. (© K. Ingham, 1995)

declines when the bats migrate south in the fall. Some parasitic mites from the bats were found in the guano, but they apparently had fallen from the bat roost in the ceiling. The other invertebrates were a pseudoscorpion, which feeds on the mites, and a dermestid beetle that feeds on the guano. There were small guano accumulations from the long-eared bat *(Plecotus townsendii)* in Braided Cave, but not extensive enough accumulation to support guanophiles.

Runoff accumulates moisture and sediment which result in a mud habitat. Junction Cave has a mud habitat in its terminal room, the Mud Room, which has accumulated dirt and silt from spring runoff and heavy rains for many years. Due to the depth of the lava tube, the accumulation remains wet throughout the year. During floods, enchytraeid earth worms were sometimes washed into the bottom of the cave (Fig. 7). Because of the organic material and constant moisture, these worms have been able to survive between periods of flooding. As we continue to study these enchytraeid worms, we will determine if they are different from surface forms.

Interactions with surface groups

El Malpais lava tubes are used as temporary refuges by a wide variety of surface invertebrates,

FIGURE 6—Pseudoscorpion, a common inhabitant of the guano in Bat Cave. (© K. Ingham, 1995)

especially insects, during hot and dry periods. The tubes offer protection and increased moisture in comparison to surface conditions. Such accidentals are found in protected areas in the entrance and twilight zones. In October, numerous flies (dipterans) and wasps (hymenopterans) were found in and around the skylights in Braided Cave, suggesting they were using the cave as a temporary shelter and source of moisture. The whirligig (anystid) mite *Chausseria* sp. is common in open sunny areas, but for some reason a small population had become established in the flat entrance area of one of Braided Cave's skylights in 1993; it was not found in 1995, however.

The moss gardens and their inhabitants are generally relicts from wetter times in El Malpais. The moss gardens may serve as a reservoir of species that colonize deep areas of the lava tubes. Over time, such species become even more adapted to the cave environment. Accidentals from the surface interact with the moss garden inhabitants to a limited extent, and not at all with the more cave-adapted lava-tube fauna.

Lava-wall slime

A curious and intriguing phenomenon in lava tubes is the presence of slimes. At certain times of the year, these slimes give the lava-tube walls a silverish appearance. Besides being pleasing visually, it is also interesting from a scientific standpoint. Howarth (1981) found extensive patches of white slime (and some patches of brown) that were primarily inorganic and probably created by percolating water. The deposits do contain fungi and aerobic bacteria and serve as a habitat for arthropods that feed on nutrients captured in the slimes, e.g. springtails, mites, fly larvae, earthworms (oligochaetes), a water treader, and carabid beetles (Howarth, 1973, 1981). Howarth (1981) hypothesized that the slimes are important sites of nutrient recycling (especially nitrogen) and that they represent areas of soil formation.

Slimes have also been reported by Ashmole et al. (1992), who found them present in humid caves in the Canary and Azore Islands, but never in dry caves. Washington lava-tube slimes consist of different species of bacteria, including Actinomycetes of the genus *Streptomyces* (Staley and Crawford, 1975), and include two main types: a white slime that is hydrophobic and occurs in warmer areas (>6°C), and an orange slime which underlies the white slime in colder areas (see also Senger and Crawford, 1984). Associated with the slime, Staley and Crawford (1975) found fly larvae (Mycetophilidae), overwintering harvestmen, a troglobitic harvestman *(Speleonychia),* and a millipede (Polyzoniidae).

Actinomycetes are a highly varied group of bacteria with the unusual characteristics of filamentous growth and exospore production, which resemble fungi, yet they are definitely bacteria. They may make 10-33% of total soil microbes, with *Streptomyces* and *Norcardia* as the most abundant genera. They are relatively resistant to desiccation and prefer alkaline or neutral pH environments. Metabolically, their main role in nature is the decomposition of organic matter. Many Actinomycetes are known to fix atmospheric nitrogen either in association with some plant roots or as free-living cells. The organic nitrogen produced may represent a significant amount of soil nitrogen, particularly in extreme environments. The role of Actinomycetes in nitrogen fixation in caves has not been explored (Lavoie, pers. comm. 1993).

We have found extensive deposits of white slime in Four Windows Cave (Fig. 8) and less extensive deposits in Braided and Navajo Caves. The distribution of slime (Fig. 9) is patchy and appears to be most dense in areas of lower light and where moisture enters the lava tube through cracks. Cover ranges from solitary colonies to dense mats several millimeters thick. The visible color of both individual and massed colonies is predominately whitish tan, but a few gold-colored colonies were observed. Observation shows that colonies are hydrophobic, with water or secreted fluids beading up on the surface. This water often reflects back cavers' lights. Senger and Crawford (1984) associated the hydrophobic reaction with the presence of spores produced by the bacteria. Examination by Scanning Electron Microscopy revealed a dense mat of bacteria which were tentatively identified as Actinomycetes (Lavoie, pers. comm. 1993). No invertebrates have yet been observed on the slime at El Malpais.

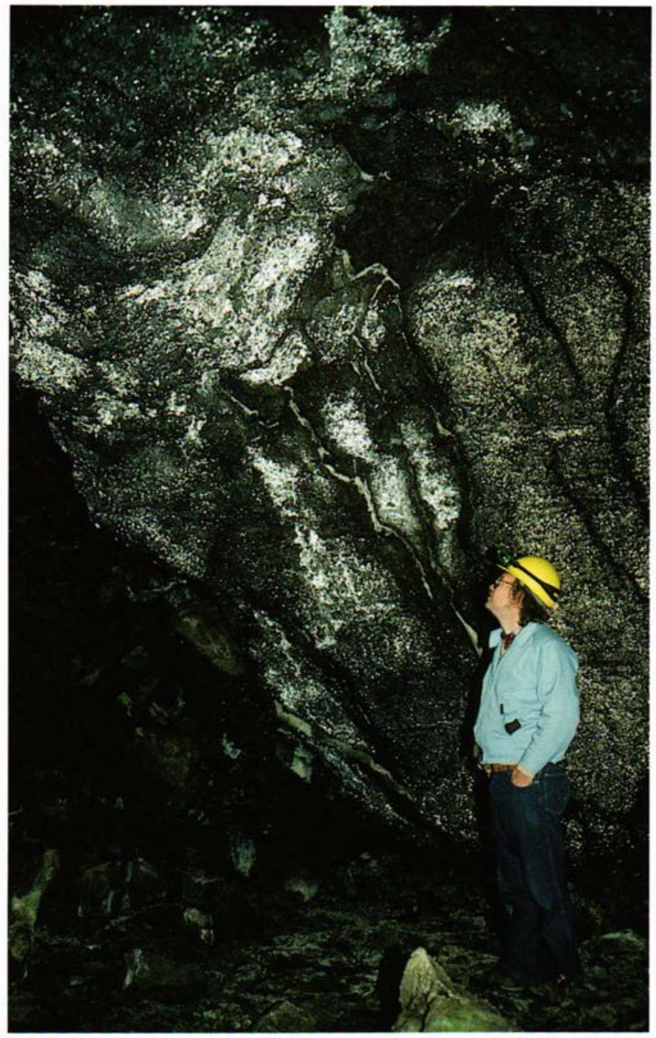

FIGURE 8—Actinomycetes covering a portion of the wall in Four Windows Cave. Water beading on their surface gives the silvered appearance. (© K. Ingham, 1995)

Climate in the lava tubes

Climatic factors strongly influence the makeup of the biotic community in lava tubes. In the Canary Islands, Martin and Oromi (1986) found that tubes with several entrances had increased airflow which resulted in a community of trogloxenes and a few troglophiles with low abundance. On the other hand, blind tubes exhibited stable temperatures, high humidity, and developed a community of troglobites. Hoch and Howarth (1989) agree that the most cave-adapted species will be found in the deepest lava-tube passages with high humidity. In fact, Howarth called the troglobites "freshwater aquatic animals living in an aerial environment" (Howarth, 1987a), because they require relative humidities above 99%.

Howarth (1982, 1991) believes that the key environmental factor that determines the distribution of troglobites is the degree to which the atmosphere approaches saturation. Evaporation decreases deeper into the lava tube (provided there are no additional entrances). Howarth (1987a) found that the rate of potential evaporation in the deep cave zone was only 8% of that of the twilight zone, and hypothesized that the rate in the mesocaverns was much lower still. Cave organisms further take advantage of areas with low evaporation by moving into the small voids, which are often sites of accumulation of organic matter (Howarth, 1982).

The degree of air humidity in lava tubes is dependent on several surface factors and is a dynamic phenomenon. Climate on the surface influences the movement of air in lava tubes. When the temperature is lower outside than inside, as often happens at night in the winter, the vapor pressure of water is higher inside the cave than outside, causing moist air to diffuse out of the cave. If the daytime water-vapor pressure is still less than that in the cave, the water vapor will continue to diffuse out of the cave in the daytime, resulting in a winter drying of the tube known as the "wintering effect" (Howarth, 1980, 1982). When conditions reverse, the cave gains moisture from the surface air.

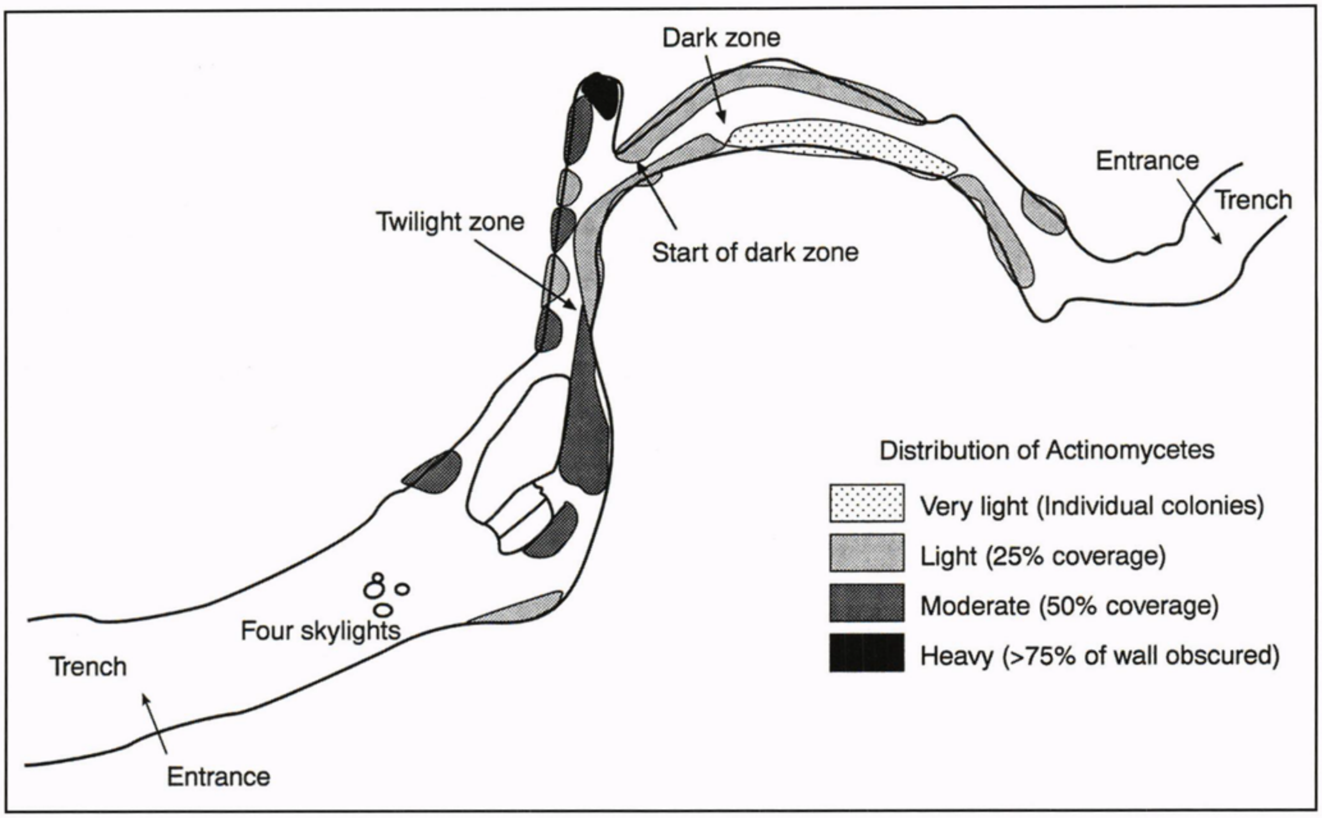

FIGURE 9—Distribution of Actinomycetes in the lava tube Four Windows Cave, El Malpais National Monument, New Mexico. Map adapted, with permission, from the map of Four Windows (© B. W. Rogers, 1989). Heavy distributions occurred in alcoves in the twilight–dark zone interface; moderate distributions occurred in the twilight zone; light distributions were found mainly in the dark zone, and occasionally in the twilight zone.

The "wintering effect" does not seem to apply to the blind tubes at El Malpais. Frequent snowpacks that remain for days or weeks provide moisture for the caves both in the form of atmospheric moisture and as melting water percolating through cracks. Ice in the lava tubes accumulates over winter, reaching a peak in early spring.

The deeper into the cave one goes, the longer the lag between changes in the surface conditions and the corresponding changes in the cave environment. The amount of change becomes less with increasing distance from the entrance (Howarth, 1982).

The lava-tube caves at El Malpais are similar to those elsewhere in the world. Caves with multiple entrances are drier and more closely follow the surface temperature and humidity. Bat Cave is an example of this type. It has several entrances, allowing air to circulate through and dry out the tube.

Caves with only one entrance become more thermally stable and moister with depth. Examples of this type include Navajo Cave (with its perpetual ice and nearly constant 32°F temperature), Junction Cave (with the Mud Room at the end where humidity is quite high and the temperature remains around 40°F all year), and Braided Cave (which also becomes cooler and more humid as you go deeper). The true troglobitic community occurs in the deep zone that has blind sections or other areas with restricted air flow to the surface. These are the only areas that develop a high enough degree of saturation of the air by water. Temporary pools that form during the rainy season are an important resource to the cave-adapted species. The moss gardens also are important areas of protected microclimate with abundant organic resources.

Conservation and management

As the number of visitors to El Malpais National Monument increases, greater impact on the lava-tube inhabitants will occur. The nature of this impact is well documented by studies on limestone caves. This information, our own observations concerning the effects of human visitation, and solutions used to protect cave biota in limestone caves form a basis of our recommendations for protecting and managing the El Malpais lava-tube inhabitants.

Threats to biota and their habitats

There are many threats to cave biota in general. Stitt (1977) and Poulson and Kane (1977) listed some of these threats. Perhaps the most publicized threat to cave organisms in recent years has been pollution. Surface runoff of pesticides, nitrates, and herbicides from agricultural land and petrochemicals from roads pose major problems for karst waters and cave biota. Contamination of cave waters by gasoline and septic leakage can kill aquatic species. Surface modification, such as the construction of parking lots and campgrounds, alters the input of organic matter and water from the surface and may even introduce further pollutants. The lava tubes in El Malpais are not yet impacted by these common threats. The Monument status and remote location help to protect the lava tubes.

Additional potential impacts include the dumping of garbage in sinkholes, which leads to the entry of harmful substances into the cave environment. On a lesser scale, visitors to the lava tubes occasionally leave their trash behind. Chapman (1993) noted that the composition of cave fauna changed in an area containing food trash from cavers. We have found food trash in Bat Cave and Four Windows (Fig. 10), as well as human feces in Big Skylight. The dumping of carbide (Lavoie, 1980; Peck, 1969) which is toxic to invertebrates, and cigarette smoking (nicotine is an insecticide) in the cave could be harmful to organisms (Howarth, 1982). The former is less of a problem today as many cavers switch to electric systems.

Physical actions of humans in caves may be detrimental to cave biota. Physical trampling by cave visitors can kill invertebrates which are either not noticed or are hiding under the rocks on which the visitors walk. Entrances may be especially vulnerable to physical disturbance by humans visiting the cave due to the greater species diversity and amount of activity that often occurs in the entrance. Just the act of visiting caves may affect biota. The impact of visitation on bats is well known (Mohr, 1976; Chapman, 1993), but the impact on invertebrates has received little or no attention. Northup et al. (1992) found evidence that large expeditions in Lechuguilla Cave in Carlsbad Caverns National Park reduce numbers of invertebrates caught in pitfall traps.

Introduction of organic matter into the cave ecosystem affects both invertebrates and microorganisms. Early studies in Lechuguilla Cave by Northup et al. (1992) showed mainly fungal spores present, but little in the way of fungal growth. Over time, in areas of heavy use (i.e. main trails and camping sites) fungal mycelia began appearing on the soil, food particles, and human hair. This may seem of little consequence, but the problem lies in the buildup of organic matter and the eventual impact on native species. It is important to preserve native microorganisms which may be consequential to the cave ecosystem and which may produce as yet undiscovered compounds beneficial to human welfare.

One source of new organic matter in the lava tubes has been wood brought in for camp fires. This is a problem because the fire itself can be damaging or fatal to bats and invertebrates. Secondly, the wood adds to the ecosystem organic matter which would not normally be there. Often it will remain dry and uncolonized, but during rainy season it may become damp enough for colonization. We feel that wood that has been newly introduced by humans should be removed, while historic wood that has developed an ecosystem should be left in place. Over time it will decompose, allowing the community of organisms time to adjust to changing levels of resources.

At El Malpais National Monument we have observed wood brought into the tubes for camp fires. Also, wax from candles left by groups visiting the Mud Room in Junction Cave is a concern. In the interest of preserving the current ecosystem, new organic matter should not be introduced into the caves.

FIGURE 10—Visitors to the lava tubes often leave trash and food remains. A fungus has begun the process of decomposing this jellybean. (© K. Ingham, 1995)

Strategies for conservation of biota

Protecting the moss and lichen habitats around cave entrances by concentrating human traffic in specific areas is of critical importance to protecting the biota that use this habitat. The Monument staff are taking steps to implement this protection by installing educational signs about the importance of these habitats. Roping off moss gardens and building limited rock-wall marked trails will direct traffic away from the algal and moss gardens.

Acknowledgments

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Tourist camp east of Cerro Bandera in the 1920's. Visitors to the area (in gentlemen's clothes, left of the tents and behind the smoke plume) may have been visiting the Candelaria Ice Cave, other area caves, El Morro National Monument, or all three. A pack horse can be seen behind and to the left of the tents. Photo taken by W. T. Lee, U.S. Geological Survey, Denver Colorado. El Malpais National Monument Collections, misc. collections.

Snowballs in the underground—Lava-tube deposits and morphology

Bruce W. Rogers[1] and Cyndi J. Mosch[2]
[1]*U.S. Geological Survey, Menlo Park, California 94025*
[2]*New Mexico State University, Las Cruces, New Mexico 88003*

Introduction

Organic sedimentary deposits are small in volume but widely scattered in El Malpais caves. Bat guano is common throughout the caves. Although 17 species of bats are known from the monument, most of the cave guano is from Mexican freetail *(Tadaria brasilensis)* or western big-eared bats *(Plecotus townsendii)*. Early this century, relatively large amounts of *Tadaria* guano were collected from Bat Cave (also known as Truckitts Bat Cave or Truckitts Cave) for agricultural use. Unusual gray and black layers were found near the base of a sediment deposit in Bat Cave. We found these to be an upper, 1 cm thick gray ash layer and a lower, 3 cm thick layer of carbonized insect parts. Evidently sometime in the past the guano spontaneously corn-busted, burned, and then smoldered, turning the upper layer into ash and the lower layer rich in insect parts into "coke."

The lack of large amounts of guano under the large *Plecotus* bat colony in Guano Cave suggests that minor-scale guano collection took place in this cave as well.

Throughout the monument's caves are pack-rat middens composed of vegetation, droppings, and "amberat," dehydrated pack-rat *(Neotoma* sp.) urine. It cements great masses of pack-rat droppings and preserves them in the dry desert air. These deposits are significant because pack rats forage for vegetation only in the immediate vicinity of their nests and generations of rats may use the same nest for thousands of years. When analyzed and carbon 14-dated, the organic material cemented by the amberat provides a precise history of vegetation succession, and thus climatic conditions, for the area.

Fragmentary bone deposits, mostly of insectivorous bats and bighorn sheep but also including some deer, are sparsely but widely distributed in the caves of the monument. Often the bighorn bones are mixed with bighorn droppings in the twilight zones of the caves, sometimes forming deposits nearly a half-meter deep. In several locations, notably in Braided and Haltun Caves, the bighorn and deer bones are being slowly destroyed by secondary minerals. These minerals crystallize in the pores and cracks of the bones, and the minute crystals splinter the bones apart much like hoar frost wedging soil particles apart.

Another unusual organic sedimentary deposit is found in the ice caves of the monument. As well as using the liquid water collected naturally in tinjanas or pockets inside the Malpais caves, Native Americans apparently also built fires of juniper and pine on the ice to melt it in order to obtain water. In some of the ice caves layered deposits of ash and charred wood are nearly one-third of a meter deep, and ash and soot deposits several millimeters thick coat the walls and ceilings.

Cave sediments

A great variety of inorganic and organic deposits can be found in nearly every lava tube at El Malpais. The inorganic sediments are derived from the lava tube itself or from weathering debris carried into the tubes by invading agents such as surface streams, wind, or percolating water. These sediments have an unusual size distribution. Coarse (blocks and boulders) and fine (sand, silt, and clay) sizes are prevail, whereas medium-sized fragments are uncommon. Most of the organic sediments are derived from external sources and are brought into the caves by animals using the tubes as shelters.

One of the most prominent products of sedimentation in lava tubes is "breakdown," piles of coarse rubble derived from partial collapse of the roof or unraveling of wall linings. At the end of tube flow activity, stresses developed during cooling may exceed the strength of the roof and cause collapse. Likewise, after cooling, residual stresses often cause wall linings to crack and fall like layers peeling off an onion. The size range of this type of debris is large; fallen blocks may reach several meters in diameter. Some of these match cavities in the ceiling, a disconcerting observation by those standing beneath similar loosely attached blocks. Moderate-size breakdown in the 0.2-1.0 m diameter range makes up the great bulk of the rubble heaped on the floors of lava tubes. This breakdown may be piled as high as several meters above the floor, indicating extensive collapse of the tube lining.

Fine-grained sediments such as sand, silt, and clay are found in nearly every cave in the monument. Most of these deposits have been transported into the tubes by surface streams, but some have been wind-borne (Fig. 1).

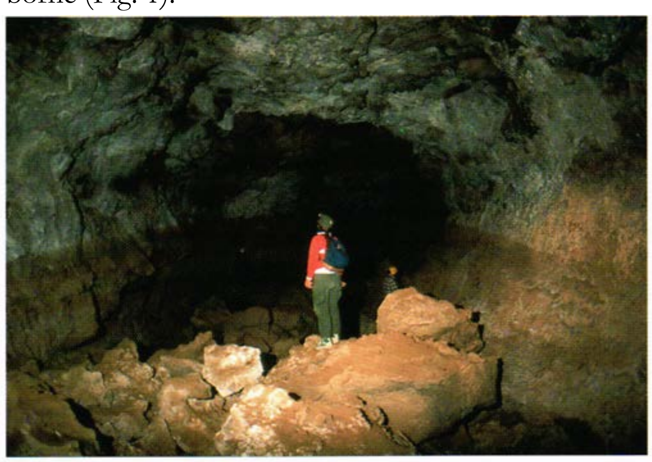

FIGURE 1—The lower section of Junction Cave has a "bath-tub ring" of silty deposits apparently settled out of massive flood waters. Here three cavers study both the bath-tub ring and additional silty sediments up to 6 cm thick on the floor. (© B. W. Rogers, 1995)

Two unusual sedimentary deposits occur sparingly throughout the lava tubes of El Malpais. Under benches and along walls of Four Windows, Big Skylight, and Braided Caves are piles of dark-gray to black sand. When we analyzed the black sand, it proved to be a mixture of fine-grained albite (plagioclase feldspar), blackish-green hedenbergite (pyroxene), and basaltic glass. In Braided Cave we found similar small deposits of ashy-white dust banked along the walls of the passage to be a mixture of albite and hedenbergite with enough admixed clear basaltic glass and calcite to color it white. We speculate that ground water charged with dissolved salts precipitated in the tiny cracks and vesicles in the basalt and, when crystallizing, mechanically wedged the grains of the basalt apart. The traces of gypsum and calcite in the black sand and the calcite in the white dust are probably the remnants of the salts that wedged the basalt apart. These salts were later flushed out of the sand by percolating water lacking dissolved salts in any amount.

Cave decorations

Secondary features in the caves may include cave decorations similar in form to stalactites and stalagmites in limestone caves. Considerable debate continues about whether these forms should be considered primary features, such as linings or benches (Larson, 1992). Some argue that remelting of the tube's interior by combustion of gases takes place as one of the last phases of tube formation, making the lava forms. In either case, the lava tube must already exist and be partly drained of lava before the lava forms can develop. Thus, these lava forms are considered as equivalents to speleothems (secondary mineral deposits formed from water in caves) in this chapter. Despite years of study, we still do not have a clear picture of the processes that form lava speleothems.

The current suite of minerals in the lava tubes apparently is much different from those that formed when the tubes first cooled. When the magma reached the surface and began to flow down lava tubes, gases rich in water vapor, hydrogen, carbon, oxygen, sulfur, fluorine, and chlorine exsolved into the tube atmosphere (Ford et al., 1976; Neal et al., 1988; Rogers and Rice, 1992). As the tubes cooled, these residual gases sublimated onto the walls of the still-hot passages as a suite of minerals that were stable only within the hot environment of the newly formed tube. Because of the instability of these initial minerals, few of them appear to have survived the subsequent phases of the tube's development and have either altered to other more stable compounds or simply eroded away (Hill and Forti, 1986; K. Hon, oral comm. 1995). Possibly some of the calcite, mirabilite, and thenardite may represent remnants of these primary minerals.

Sixteen rocks, minerals, and mineraloids have been identified as speleothems in the monument's caves, and more probably exist (Table 1). Most of these minerals and rocks were identified by X-ray diffraction; a few were identified by optical properties observed under the microscope. Basalt, ice, calcite, gypsum, mirabilite, thenardite, opal-A, cristobalite, amberat, trona, burkeite, amorphous silica, malachite, opal-CT, glaserite(?), and epsomite(?), roughly in that order of abundance, have been reported.

Basaltic lava is by far the most common decorative material in the caves. As the tubes form, the temperatures of gasses inside them often approach yellow to white heat, hotter than the lava coursing over the floor or forming the walls; temperatures measured in tubes in Hawaii have registered 1,150-1,155°C (Swanson, 1973). Melting of interior surfaces takes place, resulting in lava forms similar to common limestone-cave decorations. Field observations suggest that the higher the temperature of the gasses melting/remelting the surface, the more developed the forms will be and the smoother and more glazed the surface finish will

TABLE 1—Rocks, minerals, and mineraloids from El Malpais lava tubes.

Name	Chemical name	Chemical formula
Amberat	Dehydrated pack-rat urine	
Amorphous silica	Silicon dioxide	SiO_2
Basalt	Mixture of feldspar, pyroxene, olivine, and glass	
Burkeite	Sodium carbonate sulfate	$Na_6(CO_3)(SO_4)_2$
Calcite	Calcium carbonate	$CaCO_3$
α-Cristobalite	Silicon dioxide	SiO_2
Epsomite (Epsom salt)	Hydrous magnesium sulfate	$MgSO_4 \cdot 7\ H_2O$
Glaserite	Potassium and sodium sulfate	$(K, Na)Na(SO_4)_2$
Gypsum	Hydrous calcium sulfate	$CaSO_4 \cdot 2\ H_2O$
Ice	Hydrogen oxide	H_2O
Malachite	Basic copper carbonate	$Cu_2(CO_3)(OH)_2$
Mirabilite (Glauber's salt)	Hydrous sodium sulfate	$Na_2SO_4 \cdot 10\ H_2O$
Opal-A	Hydrous silicon dioxide	$SiO_2 \cdot n\ H_2O$
Opal-CT	Hydrous silicon dioxide	$SiO_2 \cdot n\ H_2O$
Thenardite	Sodium sulfate	Na_2SO
Trona	Acid hydrous sodium carbonate	$Na_3(CO_3)(HCO_3) \cdot 2\ H_2O$

be. However, widespread ceiling and wall collapse in the caves of El Malpais has limited the preservation of these features.

Lava stalactites include "sharks' teeth," flattened forms similar to shark teeth; soda straws, hollow tubes mimicking soda straws; globular lavacicles which look like columns of small grapes, and lavacicles which resemble golf tees in shape, are found throughout the monument. The more viscous lava tends to form more massive stalactites (Knox and Gale, 1959), such as shark-tooth stalactites, whereas highly fluid lava tends to form the more delicate lavacicles. Where the Right Hook Passage in Junction Cave joins the much larger main passage, partial wall and roof melting has resulted in granular-textured, poorly formed lavacicles. However, lavacicles further back in the Right Hook Passage are well developed. Gas temperatures in the Right Hook Passage apparently were higher than those in the main passage and, because they lost part of their heat to the somewhat cooler gases in the larger main passage, the gases lost their ability to thoroughly melt the ceiling and walls of the Right Hook Passage adjacent to the main passage.

Thin lava draperies and ribs that developed where trails of lava slowly trickled down the walls are fairly common in the lava tubes of El Malpais. Often these have white or ochre-colored coatings of other minerals precipitated much later in the history of the caves.

Masses of frozen lava flowstone or cascades, mimicking calcite speleothems found in limestone caves, are also common.

Lava helictites are sparingly found in many caves with intact ceilings or wall linings (Fig. 2). Usually having stems 0.2-0.5 cm in diameter, the helictites twist and turn in gravity-defying contortions; some have beaded surfaces and may be partially hollow near their tips. Other helictites are relatively straight, thin tubes growing at an acute angle to the wall, ceiling, or soda-straw lavacicles. Some of these helictites appear to have been bent downstream by the entrained gases flowing above the moving lava floor. It is theorized that degassing from a near-surface vesicle may trigger helictite formation. The subsequent drop of pressure adjacent to the vesicle promotes further melting of the adjacent lava and supplies the helictite with more lava with which to grow (K. Howard, oral comm. 1991); however, the mode of formation has yet to be confirmed.

Lava stalagmites form where spots on the ceiling melt and dribble blobs and clots of lava to the floor. They are often much less numerous than the lavacicles above them, a result of having been incorporated into the fluid floor or having been swept away from their point of origin by floor movement. Most of the stalagmites in El Malpais look like small-diameter columns of small grapes. These stalagmites are commonly found along the edges of passages below cracks in the linings, at the join between the wall and the roof. At other places, however, lava dripped through a central crack to spawn a series of stalagmites in the center of the passage. If only a single lavacicle supplied the lava and the floor was crusted and moving relatively slowly, trails of small stalagmites may have formed along the floor.

FIGURE 2—This lava helictite is nearly 20 cm long and about as thick as a pencil. The tip of the helictite is covered with a thin film of calcite deposited by seeping ground water. (© C. J. Mosch, 1995)

Basalt bubbles or blisters of various sizes, up to ca 2 cm in diameter, can be found on the walls and floors of some of the lava tubes. Most of these are attached to the walls or floors, but some, such as those in Braided Cave, are simply found loose on the floor. The smaller bubbles often have walls so thin that they are a translucent gold in color, whereas the thicker-walled bubbles are shiny black. Apparently entrained gas escaping from the still-plastic basalt formed the bubbles and blisters.

Most of the lava decorations in the Malpais caves are some shade of black. Shades range from nearly pearlescent gray to dull black and appear to be the result of the texture of the form's surface.

Ice is the second most common mineral in El Malpais caves. Large amounts of ice accumulate seasonally in the lava tubes, beginning in the spring and persisting into the early to middle summer. The ice forms when percolating spring rain and melting snow enter the freezing zone of the caves. Most of the ice melts by late summer. Little ice forms during the early winter because lowered temperatures freeze the ground water and the winter air contains very little moisture (M. Sims and D. Denbo, oral comm. 1989). Icicles, stalagmites, draperies, flowstone, hexagonal crystals up to 7 cm in diameter, 3 cm long ice needles, and curved "angel hair" crystals have been reported from the caves. Although almost all the ice observed in El Malpais lava tubes is clear to white depending on its crystallinity, part of the ice floor in Candelaria Ice Cave is stained pale green. Apparently algae flourish in the part of the ice floor directly swept by the sun. The lower parts of the ice floor can be seen at the back of the cave, in a small grotto formed by melting of the ice floor. Layers of clear ice up to 15 cm thick are delineated by horizons of frost-wedged rock debris (see Dickfoss, this volume).

Ice persists throughout the year in at least 20 caves in the monument. Most of the ice is in the form of massive floor or wall slabs. Much of this massive ice flow-

FIGURE 3—When ground water entered Haltun Cave along cracks in the lava-tube lining, it carried a host of dissolved minerals and compounds, including white calcite, orange humic and fluvic acids, and extremely fine particles of reddish soil. When the water evaporated, the minerals were deposited as delicate traceries along the walls. These colorful crusts now nearly obliterate the original velvety black color of the pahoehoe lava walls of this 3 m high passage. (© B. W. Rogers, 1995)

FIGURE 4—These button-like coralloids of calcite moonmilk have been deposited on the walls of Brewers Cave. The two isolated, mushroom-shaped coralloids at left center are approximately 1.5 cm in diameter; a 25-cent piece is partly hidden by the moonmilk coralloids at right center. (© C. J. Mosch, 1995)

stone is coarsely crystalline and may reflect relative antiquity, similar to glacial ice which becomes more and more granular over time.

Calcite (calcium carbonate) is the third most common mineral in the caves of the monument. It is very pure, generally with less than 2% magnesium impurities, the most common minor element found in calcite. We speculate that while some of the calcium making up the calcite may have been leached from the basalt itself, most of it appears to have been derived either from the underlying Mesozoic sedimentary rocks or from sublimates deposited during cooling of volcanic gasses contained within the Tertiary volcanic rocks. The calcium may have been leached from these older rocks by ground water, re-precipitated as calcite in deposits above the tubes, and then finally carried in solution into the caves. Here, as the carbonic acid degassed, much like escaping carbon dioxide from an opened bottle of soda, the calcite dropped out of solution, crystallizing and painting the cave's walls; evaporation played a very minor role in this process.

Pure calcite is clear or white, but commonly is colored various shades of cream, ochre, brown, and orange, especially in Braided Cave and adjacent tubes (Fig. 3). These earthy colors are not simply due to incorporated iron oxides as formerly thought, but appear to be caused by interactions between a host of compounds and/or microorganisms. Minute amounts of fluvic and humic soil acids, iron oxides, staining by thin films of soil itself, various metal salts, and minute organisms such as the iron bacteria *Lepthothrix* all have been found to color speleothems (White et al., 1994). Although it seems that the richest colors are caused by a complex or chelate of both iron and humic substances (Sevenair, 1983), clearly much more investigation is needed to explain the rich colors so admired in many of the monument's caves.

Also among the calcite speleothems found in the lava tubes are thin crusts and sheets of flowstone which plaster large areas of walls or hang from the ceilings like miniature draperies.

Coralloids, which look like popcorn or spindly ocean corals, are found throughout the lava tubes. Seeping water deposits small calcite nubbins, often along sharp-edged wall cracks. The internal structure of these coralloids consists of concentric, differently colored mineral bands. Analysis reveals that their chemical make-up is predominantly calcite interlayered with small amounts of the silica minerals opal-A and cristobalite. The later two may have been deposited in discrete layers during drier periods, while the calcite layers probably reflect wetter periods.

A white-cream, cheese-like deposit called moonmilk is found in a few El Malpais caves. This uncommon speleothem consists of felted masses of extremely small, equant to lath-shaped calcite crystals which crystallized out along filaments of actinomycete bacteria. These same rod bacteria contribute to the smell of "damp earth" in caves (Lavoie and Northup, 1994). In Brewers Cave, which is cold (5°C) and wet, calcite moonmilk occurs on walls near the Root Room as blebs less than 2 cm in diameter on lava coralloids, and as larger, up to 2 cm thick crusts (Fig. 4). The moonmilk ranges in luster from pearlescent to satiny to chalky and in color from white to pale blue, lavender, peach, and yellow. Texture ranges from cottage cheese-like through tufted and fibrous. On the floor in Braided Cave, near white calcite-covered walls, moonmilk is present as soft white, often button-like encrustations sometimes covered with fluffy white coating of gypsum "angel hair."

Calcite also forms in caves with permanent ice deposits. Coatings of powdery white calcite are often found on the rocks adjacent to ice deposits, and appear to be the residue from pools of melted and evaporated ice water. Another unusual calcite deposit is found under the ice floor of Candelaria Ice Cave. Long, curving fractures in the ice have acted as small faults, allowing some movement of the ice floor. The resulting movements along these paper-thin channels have allowed some of the ice to melt, de-gas, and deposit its dissolved mineral load as thin fins of white calcite. Pressure from the plastically deforming ice also may have assisted in the extrusion of the calcite fins several millimeters out from the ice fractures themselves.

Gypsum (hydrous calcium sulfate) is another common mineral found in the lava tubes of El Malpais. The gypsum scavenged its calcium from the same sources as the calcite, while the sulfur was derived from either sublimated volcanic gases or liberated by weathering of sulfide minerals, such as pyrite, in the older sedimentary rocks exposed within or near the monument. Although much of the gypsum has a pale-orange surface tinge, probably due to wind-blown dust having been sprinkled on its surface, the interiors of the sugary-textured gypsum speleothems are sparkling white.

Most of the gypsum present in the lava tubes is in the form of crusts on the walls and ceilings that are commonly weathered and partly dissolved. Piles of these broken crusts may be found on tube floors below ceiling and higher wall crusts. These crust fragments are pitted and have embayed edges, features more associated with crust dissolution than with mere shedding of loosely attached growing crusts. This may indicate that the gypsum was deposited in conditions different from those now present in the caves.

Although limited in extent, other varieties of gypsum have formed in the lava tubes. Small gypsum stalactites, stalagmites, columns, and flowstone have been found in several caves, such as Big Ice Cave. Gypsum "angel hair," nearly 1 cm long, seasonally forms in Junction Cave on both lava balls and walls. In Four Windows Cave a small, pale-orange, consolidated, linear mound of gypsum ca. 20 cm high and 2 m long is located under a bench. Water dripping from the bench above the dune has dissolved sloping, parallel grooves, called rillen karren, into its surface (Fig. 5). Gypsum powder is commonly found on benches and floors of the dry passages throughout the monument's caves. This powder may be residue from long-ago evaporated pools or the last traces of disintegrating fallen crusts.

Gypsum is suspected to be the operating agent in the formation of black-sand deposits found sparingly in the tubes in the monument, such as Four Windows, Braided, and Big Skylight Caves. Apparently gypsum-charged ground water percolated through the basalt and evaporated, the gypsum crystallizing in the pores of the basalt and wedging the mineral grains apart. Later flushing by fresh water removed the highly soluble gypsum, leaving the resulting banks and miniature sand dunes of jet-black sand scattered throughout the tubes.

Another common mineral found in the lava tubes of El Malpais is opal-A, a hydrous silicate mineral with the same basic formula as quartz (silicon dioxide) but with a different crystal structure that incorporates varying amounts of water. The opal found in the caves of El Malpais ranges from white or cream to many shades of brown and ochre. Opal-A is usually found as spiky cave coral growing from the walls or floors of the monument's lava tubes. Close inspection of broken pieces of these coralloids shows concentric bands of varying color similar to a calcite stalactite. Since banding is thought to represent changes in steady-state growth conditions, these bands probably correspond to long-term climatic cycles rather than annual wet and dry cycles (G. Moore, oral comm. 1988). The source of the silica in this uncommon mineral is probably solution of the unstable volcanic glass which originally carpeted the volcanic terrain of El Malpais.

FIGURE 5—Near the back of Four Windows Cave is a low bank of gypsum. The gypsum was initially deposited as powder and flakes of crust which then slowly spalled off the overhanging wall. Subsequently, gypsum-saturated water compacted and cemented the loose material into a low berm. Currently dripping water has dissolved rills in the surface. A white, 14 cm long pen is located in a crack at the center of the berm. (© B. W. Rogers, 1995)

Also found in the lava tubes of El Malpais is another silicon-dioxide mineral, a-cristobalite. This mineral normally forms at elevated temperatures of slightly over 1700°C, but two unstable, low-temperature forms, a- and ß-cristobalite, can form at normal temperatures and pressures (Deer et. al., 1963). Like opal-A, a-cristobalite forms ochre-colored layers in coralloids, along with white calcite. Its origin probably closely parallels that of opal-A.

Mirabilite (hydrous sodium sulfate) is sparingly found in the lava tubes of El Malpais. Although it forms in the cave environment (Hill and Forti, 1986), it readily alters to thenardite with the loss of the loosely attached water molecules. The exact details of mirabilite's stability fields and mode of deposition in cave environments are still poorly understood. In Braided Cave and other caves it forms angel hair, masses of silky-white, hair-like curved crystals (Fig. 6). The angel hair in most caves is usually seasonal. In the wet season it dissolves and the mineral is drawn back into pore spaces in the basalt walls and ceilings. When dry weather returns, the pore water is drawn out of the basalt and evaporates, depositing mirabilite.

White, chalky coralloids in Braided Cave were found to be a mixture of mirabilite and calcite, with the thread-like crystals of mirabilite coating the button-like calcite coralloids.

Thenardite (sodium sulfate without water) is also

FIGURE 6—In a ceiling crack near the downstream end of Braided Cave is an area of delicate mirabilite encrustation. In the late winter and spring the mirabilite dissolves because of increased rain-water infiltration. As the climate dries throughout the summer and fall, capillary action draws the mirabilite-bearing solutions back out to the surface of the cave walls and floor; the mirabilite then re-crystallizes out as delicate, white "angel hair" crystals. The scale object is 6 cm long. (© B. W. Rogers, 1995)

FIGURE 7—Unstable in most cave climates, these thenardite snowballs in Braided Cave started out being deposited under more humid conditions as mirabilite. As the climate of the cave dried, the mirabilite crystals lost their weakly bonded water molecules, dehydrating to thenardite. Scale object, toy microbus, is 5 cm long. (© B. W. Rogers, 1995)

sparingly found throughout the lava tubes of El Malpais. It is probable that the deposits of thenardite were initially deposited as mirabilite, then dehydrated, changing to thenardite. The thenardite in the caves usually looks like small (ca 3-5 cm diameter) dull white snowballs (Fig. 7), but is also found as floor and lower-wall crusts or as white powder on benches. It is also a minor constituent of gypsum coralloids and stalagmites in Big Ice Cave.

Amberat is an organic deposit which "looks like amber and smells like rats," as described by Phil Orr of the Santa Barbara County Museum from a Great Basin cave (A. McLane, written comm. 1972). The amber-like material is actually dehydrated pack-rat (*Neotoma* sp.) urine. Amberat has a vitreous to dull luster and may be colored amber, black, brown, orange, yellow, deep red, or dark green. In addition to the mass of vegetable and fecal debris included in amberat, the main constituents are dehydrated urine and bile secretions (Loew, 1875; Berger et al., 1965).

Amorphous silica glass has formed on the exposed surfaces of some of the sandstone xenoliths in Xenolith Cave. It appears that the sandstone xenoliths exposed in the tube walls have been heated to the melting point of the quartz, then quenched to form a bubbly, clear-green glass. Although known only from Xenolith Cave, similar deposits of glass are probably to be found in other caves of El Malpais containing sandstone xenoliths.

We have identified opal-CT from the same location as the amorphous silica glass described above. The opal-CT forms glassy, amber-colored, rounded crystals at the edges of the green-glass selvages developed on the xenoliths. As with the glass, the opal-CT appears to have formed as a result of heating of the xenolith faces exposed in the tube walls, possibly by the combustion of gases in the partly open tube.

Malachite (basic copper carbonate) is found in a very few lava tubes. The faint- to intense-green stains of malachite are seen in the sandstone xenoliths in several caves. The copper in the malachite was probably derived from very small blebs of chalcopyrite, a copper-bearing sulfide ore mineral, which formed when the sandstone was first laid down in the Mesozoic seas. Occasionally, blocks of sandstone were carried along by the basalt as xenoliths. We speculate that where exposed in the lava-tube walls, the chalcopyrite in the xenoliths oxidized, liberating the copper which then reacted to form the malachite (Rogers and Williams, 1982). The colors are pastel shades of green, because only tiny amounts of copper (in the order of 100 to 500 parts per million) are necessary to strongly stain light-colored rocks (White and Van Gundy, 1974; Rogers and Williams, 1982).

Trona (hydrous sodium carbonate) has thus far been found at El Malpais only in Outlaw Cave, where it occurs as thin, silky-white crusts (K. Mabery, written comm. 1988). Some investigators ascribe the origin of the trona to elements derived from the vapors of waning volcanism or from solution of the basalt itself, but it is possible that the elements required for the mineral to form were derived from other sources (Rogers, 1990, 1992). We speculate that the sodium has more likely been derived from weathering products of the underlying sandstones, dissolved by percolating ground water, deposited in nearby saline marshes, and then wind-transported to the soils above the lava tubes. The sodium was then carried into the lava tubes and finally combined with soil carbon dioxide and water to form the trona deposits. As a speleothem, trona is known from only a handful of other arid-land lava-tube caves in the Mojave Desert (R. Harter, oral comm. 1990).

Burkeite (sodium carbonate sulfate) also occurs in the same cave as the trona (K. Mabery, written comm. 1988) and is a rare mineral usually found in saline-lake deposits. Apparently, this mineral has not been previously identified from any cave in the world. Its origin is probably similar to that of trona, except that a little sulfate was added to the elemental brew by ground water.

We have identified glaserite (potassium sodium sulfate) from Braided Cave. It appears to be a minor constituent of thenardite and mirabilite snowballs on the floor of a dry part of the cave. Because of the extremely small amount of material, it is not possible to speculate on its origin. As with burkeite, it appears that this occurrence marks the first time this mineral has been found in a cave anywhere in the world.

We have tentatively (not verified by X-ray diffraction) identified epsomite—natural Epsom salt (hydrous magnesium sulfate) in two caves in El Malpais by its bitter-salty taste. In Brewers Cave the epsomite occurs as an efflorescent floor deposit of "angel hair." In Braided Cave it occurs as felted masses of nearly transparent, silky crystals approximately 1 cm long, covering large lava balls and rafted blocks. The origin of epsomite is probably very similar to glaserite, trona, and burkeite.

FIGURE 8—This 20 cm long xenolith in the wall of Xenolith Cave was torn from the underlying Mesozoic sandstone surrounding the throat of the volcano and transported down-flow by the lava. The sandstone has been bleached white and slightly melted, resulting in a smooth, slightly bubbly surface texture. Scale object, "Mr. Bill," is approximately 6 cm long. (© B. W. Rogers, 1995)

Petromorphs

Petromorphs are features in the bedrock exposed during cave formation. In limestone caves petromorphic features such as pre-existing crystal pockets, mountain leather, boxwork, and ore-bearing vugs are uncommon but widespread. In the lava tubes of El Malpais the only common petromorphs seem to be xenoliths and some very small vugs.

In many of the caves, small fragments of the underlying Mesozoic sandstone have been torn from the throat of the volcano and carried up to the surface by the basalt flows (Fig. 8). Most of the sandstone xenoliths (from the Greek word for "stranger") have been bleached white, but still retain traces of their original bedding. Along cracks and fractures in the white sandstone of a few caves are faint- to intense-green stains. Most of these stains are malachite (hydrous copper carbonate) derived from oxidation of copper-sulfide minerals in the quartz sandstone itself. In some locations, however, where the xenoliths are bathed in sunlight for part of the day, the green coloration appears to be due to algae living just beneath the surface of the xenolith in a sort of a micro-greenhouse.

In a few cases, such as in Xenolith Cave, the smaller xenolith fragments have scattered millimeter-sized pockets containing matted filaments of what appears to be amber-colored volcanic glass; this may be included Pele's Hair, but further study is required to clarify its exact nature and origin. The size of the xenoliths varies, but generally ranges from 3 to 15 cm in diameter; in Yeso Chio Cave, however, angular blocks of bleached white sandstone approach 0.75 m in length.

In the breakdown at the entrance to both Xenolith and Bat Caves are vugs (mineral-filled vesicles) ca 3-10 mm in diameter, which have been filled with mixtures of extremely fine-grained amorphous silica or opal-A, calcite, and gypsum, probably deposited in that order.

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History of ice at Candelaria Ice Cave, New Mexico

Paul V. Dickfoss[1], Julio L. Betancourt[2], Lonnie G. Thompson[1], Raymond M. Turner[3], and Steve Tharnstrom[4]

[1]*Byrd Polar Research Center, Ohio State University, 1090 Carmack Rd., Columbus, Ohio 43210*
[2]*Desert Laboratory, U.S. Geological Research, 1675 W. Anklam Rd., Tucson, Arizona 85745*
[3]*Dept. of Geosciences, The University of Arizona, Tucson, Arizona 85721*
[4]*Defense Nuclear Agency, Field Command, 1680 Texas St. S.E., Kirtland Air Force Base, Albuquerque, New Mexico 87117*

Introduction

Unlike deep cores from continental (Dansgaard et al., 1993) and mountain ice sheets (Thompson et al., 1995), which have yielded a spectacular history of global climate variations during the last few hundred thousand years, cave ice has been virtually ignored as a climate proxy. This is in spite of the fact that cave ice has a global distribution, primarily in high-elevation or high-latitude lava tubes (Henderson, 1933), and tends to be layered, suggesting annual resolution. Ice caves are restricted to areas that have sub-zero winter temperatures, but not necessarily a mean annual temperature below zero (Henderson, 1933; Blach, 1970). Conceivably, some of these caves could contain Pleistocene ice; cave ice was dated to 3000 yrs B.P. (years Before Present) in Romania's Ghetarul de la Scarisvara (Bogli, 1980, p. 227).

There has been little quantitative research to explain the physics of ice formation and accumulation in caves, which probably varies with cave morphology and degree of air circulation (Kovarick, 1898; Wigley and Brown, 1971, 1976, pp. 340-343). Wigley and Brown (1971, 1976) derived a model based on Equations of Continuity to define distributions of temperature and humidity throughout a cave. In general, perpetual ice develops because cold, dense winter air sinks into the cave and density stratification between this cool air and lighter summer air keeps the warmer air from entering the cave (Martin and Quinn, 1990). The cold, winter air freezes any existing water and cools the surrounding rock. The latent heat released by freezing the ice warms the cave, which strengthens the exchange (Ohata et al., 1994a). Cooling also may be enhanced by evaporation of surface water and removal of the latent heat by slight turbulence (Harrington, 1934). However, there are disagreements about the importance of evaporation and turbulence in maintaining ice in caves with limited air circulation (Harrington, 1934 vs. Halliday, 1954). Also, little is known about the surface conditions that control rates of ice accumulation and ablation. In northern California lava tubes, perennial ice may have a negative balance during prolonged surface drought conditions (Swartzlow, 1935). In Fuji Ice Cave, Japan, Ohata et al. (1994a, 1994b) found alternating periods of positive and negative ice accumulation. The net accumulation of a given year was highly correlated with deviations from average winter air temperature during the previous four years. This indicates that such cave systems have a high heat capacity, and that the ice bodies they harbor may be highly sensitive to long-term temperature trends at the surface.

As a pilot project to explore the paleoclimatic potential of cave ice in North America, we have been studying Candelaria Ice Cave, west-central New Mexico, a tourist attraction and one of the better-known ice caves in North America. The paleoclimatic potential of layered ice at Candelaria Ice Cave was first indicated by Willis T. Lee (1926, p. 59), a U.S. Geological Survey geologist, who noted, "Each layer may represent a year's accumulation or it may represent a climatic cycle... It is not impossible that the climatic changes recorded in the ice might supplement the chronology obtained by studying the growth of trees." This chapter reconstructs the history of cave ice at Candelaria Ice Cave based on rephotography of images taken by Lee et al. during this century. A paper in progress uses this "chronology" to interpret variations in physical and chemical attributes of ice cores taken on the ice cliff (pre-1900) and ice pond (post-1900).

In June 1990 three ice cores were drilled at Candelaria Ice Cave using an ice-core hand auger. These cores are currently being analyzed for microparticle concentrations, oxygen and hydrogen isotopes, and anion chemistry at the Byrd Polar Research Center, Ohio State University. To obtain the age of the oldest ice exposed in the very back of the cave, we sampled ice, plant, feathers, and insect fragments embedded in the ice and submitted these samples for Tandem Mass Accelerator (TAMS) dating. An attempt was also made to directly date the CO2 in the older ice using a sublimation procedure and TAMS dating. In June 1996 we mapped the ice body at Candelaria Ice Cave with an Electronic Distance Meter (EDM) Total Station. We also measured temperature and humidity every 6 seconds for 41 hours on June 11, 12, and 13, using a Cole Parmer, Smart Reader, continuous-data logger. The resolution is 0.6°C for the internal thermistor and 0.4% for the relative humidity sensor. The logger was suspended 1.5 m above the ice-pond surface. Ablation and accumulation observations have never been conducted for Candelaria Ice Cave, so we were forced to rely on core measurements and historical photographs. Photographs dating from the 1920s to the 1970s were matched from the same vantage point in May 1991 and June 1996. Photographs were scanned into a Power Macintosh G100 / 60AV using Ofoto (Version 2) and a Macintosh Color OneScanner. Adobe Photoshop version 2.5 for Macintosh was used to crop and adjust contrast and brightness of the images. The TIFF files were then imported into CorelDRAW! version 3.0 and adjusted to equal scale.

Physical setting

Candelaria Ice Cave (34°59'30" N, 108°05'00" W, 2393 m elevation) is part of a collapsed lava tube at the base of Bandera Crater, directly east of the Zuni Mountains and approximately 25 km southwest of

Grants, Cibola County, New Mexico. The Zuni-Bandera field (also referred to here as El Malpais) resulted from extensive basaltic volcanism during the last million years along the central portion of the Jemez lineament in west-central New Mexico (Maxwell, 1986; Laughlin et al., 1993a). The Bandera flow formed 10,000 yrs B.P., according to radiocarbon dating of charcoal in buried soil and cosmogenic dating (Laughlin et al., 1993b, 1994, this volume). This places an early Holocene upper-age limit to Candelaria Ice Cave and other ice bodies in the Bandera flow. It also indicates that disjunct distributions of arthropods, algae, and cryptogams in the lava-tube caves of the Bandera flow, thought to be Pleistocene relicts (Peck, 1982; Lindsey, 1951), actually represent Holocene dispersals from older flows nearby.

The relatively open woodland in the immediate area of the cave is dominated by ponderosa pine *(Pinus ponderosa),* Douglas-fir *(Pseudotsuga menziesii),* Colorado piñon *(Pinus edulis),* Rocky Mountain juniper *(Juniperus scopulorum),* quaking aspen *(Populus tremuloides),* and Gambel oak *(Quercus gambelii)* (Lindsey, 1951). Shallow soils and relatively slow growth rates have produced ideal conditions for development of millennia-long climate reconstructions from tree rings in conifers growing on the Bandera flow and other local basalts (Grissino-Mayer, 1995, 1996, this volume). These tree-ring reconstructions serve as a control for interpreting climatic effects on the history of the ice body at Candelaria Ice Cave.

Based on the period 1948-1994, mean annual temperature at El Mono National Monument, 30 km west of Candelaria Ice Cave, is 8.8°C, and mean annual precipitation is 347 mm, with 33% occurring as monsoonal rains in July and August. Interannual and interdecadal variability in regional precipitation is modulated in part by the Southern Oscillation, the flip flop in sea surface pressure patterns across the equatorial Pacific that marks alternation between El Niño (warm Pacific) and La Nina (cold Pacific) states. In the region of Candelaria Ice Cave, El Niño conditions are associated with stormier winters and springs (Andrade and Sellers, 1988) and its drier summers (Harrington et al., 1992); the opposite is considered true for La Niña years. Twentieth-century climatic trends stemming from interdecadal behavior of the tropical Pacific include wet winters in the early part of the century, a mid-century dry period, and wet winters and erratic summers since 1976. The late 1940s and 1950s constitute the most extreme event of recurrent widespread drought in the southwestern U.S. during the past 300 years (Meko et al., 1993; Betancourt et al., 1993; Grissino-Meyer, 1995, 1996). Ice accumulation at Candelaria Ice Cave should be related positively with low average winter air temperatures and increased annual precipitation. Ablation should be correlated with high summer temperatures and prolonged drought.

Candelaria Ice Cave is one of 100 lava caves and crevices containing perennial ice in the El Malpais, including Navajo, Brewers, La Marchantia, and Lichen Caves (Goar and Mosch, 1994; Hatheway, 1971; Lindsey, 1951). Candelaria Cave is located at kilometer 1.7 along a 26 km long lava-tube system emanating from Bandera Crater.

Candelaria Ice Cave is made up of an upper chamber and a lower chamber (Fig. 1). The upper chamber is approximately 15 m below the surface of the lava and contains perennial ice (Figs. 2-4). The lower chamber is dry and devoid of ice. The ice is composed of two distinct ice accumulations. The first part was deposited as flat layers filling the cave to probably more than 4.5 m above the floor. The front of this older ice body has retreated as a vertical wall through ablation, leaving a vertical to overhanging, semicircular ice "cliff." In its place a new ice body has accumulated as an ice "pond" dammed at the entrance by the steep rock talus and at the back by the ice cliff. The vertical bank has distinctive layering reminiscent of more imposing ice cliffs at the receding edge of ice caps in the Andes and Himalayas. At Candelaria Ice Cave, clear ice alternates with thinner layers of white porous ice; blue—green algae *(Stichococcus subtilis* and *S. bacillaris)* tend to cover the ice more thickly on the latter, imparting a distinct, banded arrangement to the ice. During summer the ice pond becomes slushy or covered by a thin layer of water, and is colonized by the rare green cryoscopic alga *Sphaerella lacustris* (Lindsey, 1951). Unlike ice sheets, the layers in cave ice do not always represent annual increments. It is possible that some layers are semiannual while others are biennial. Along the back of the ice cliff, we counted approximately 85 layers from top to bottom. If the layers are annual or even biennial, then the 4.5 m deep ice cliff should represent no more than 170 years.

The general air circulation in the cave is different in summer and winter as seen in Figure 5 (Harrington, 1934; Blach, 1970; Denbo, 1981). In winter, cold, dense air displaces warmer, lighter air, thus freezing all surface water. This process is referred to as "passive settling of heavier cold air" by Harrington (1934). The latent heat released by the freezing of water, and thus warming the air, is replaced by cold air from outside the cave. This continues until all water is frozen and the surrounding rock is cooled to below freezing. A computer model by Denbo (1981) has shown that in summer warm air can only penetrate a cave as deep as the entrance is wide. Subtle changes in circulation may be caused by sunlight entering the cave, but these changes are negligible. Heat losses are not compensated for during summer and thus ice accumulates. In June 11-13 temperature remained constant between —1.8 and —2.7°C and relative humidity stayed at 100%. This demonstrates that there is no daily cycle in the cave, and it rules out the exchange of outside air during summer. Most of the water in Candelaria Ice Cave probably collects as runoff from the bowl created by collapse of the lava tube, with minor contributions by infiltration and seepage from above the cave. Ablation of the ice cliff probably is an additional internal source of water for current accumulation in the ice pond. This latter process recycles and mixes waters of different isotopic, chemical and microparticle composition, clouding paleoclimatic inferences. Hypothetically, discharge from the basin immediately above Candelaria

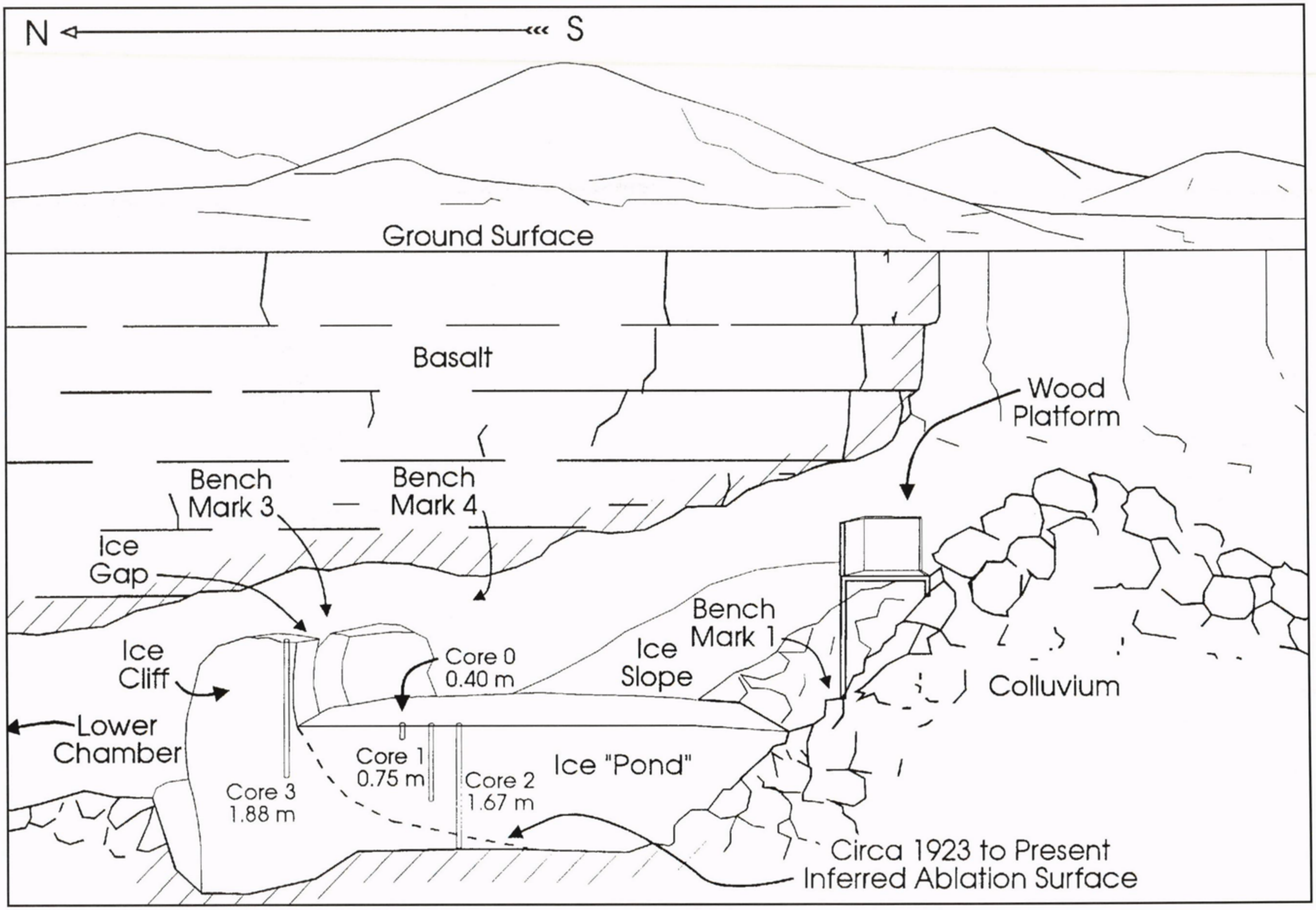

FIGURE 1—Schematic cross section of the upper chamber of Candelaria Ice Cave.

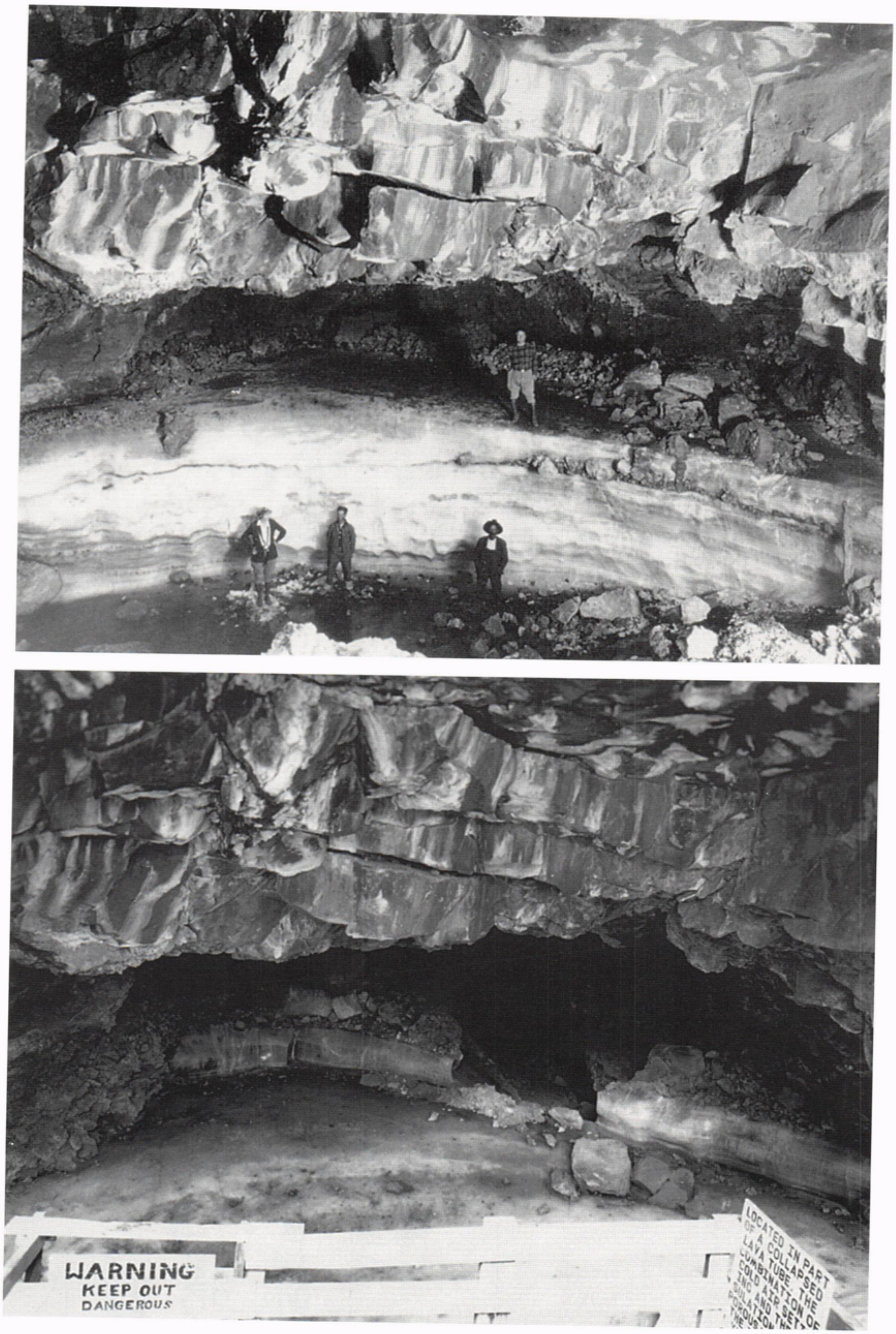

FIGURE 2—Matched views of Candelaria Ice Cave in (top) 1924 (Willis T. Lee Collection, U.S. Geological Survey Photo Library, Denver, Lee #2662) and (bottom) May 15, 1991 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1548). In the top photo, Lee is standing on top of the cliff (Layer 1). Layer 1 appears to make contact along the back wall of the cave, though Vogt (1924) indicated some separation at that time. Note roof fall to the right of Lee, and rocky layer (Layer 2) below Lee and roof fall. Layer 2 represents about 1.3 m of vertical erosion by ablation between 1924 and 1991. Also note that the ice pond where the two men and a woman are standing at the base of the ice cliff had risen 2 m by 1991.

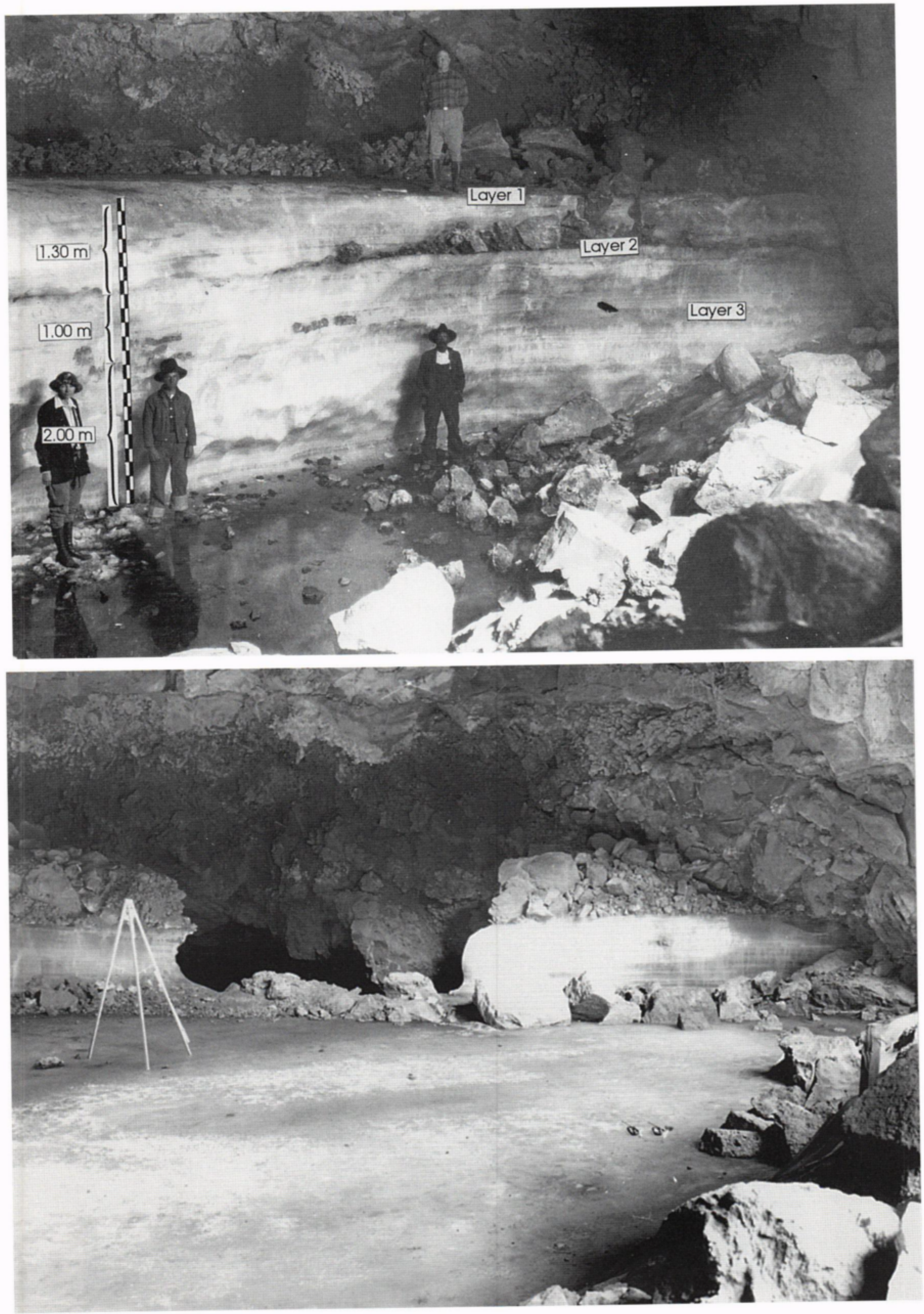

FIGURE 3 —Matched views of Candelaria Ice Cave in (top) 1924 (Willis T. Lee Collection, U.S. Geological Survey Photo Library, Denver, Lee #2663), and (bottom) June 12, 1996 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1546). A scale was developed using Lee's estimate of 4.3 m height of the ice cliff (Lee, 1926).

FIGURE 4—Matched views of Candelaria Ice Cave in (top) 1924 (Willis T. Lee Collection, U.S. Geological Survey Photo Library, Denver, Lee #2664), (center) May 15, 1991 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1547), and (bottom) June 12, 1996 (U.S. Geological Survey, Desert Laboratory Collection, Stake 1547). Note standing water in the top photo, indicating that Lee photograph was taken in late summer or early fall. In the center photo a field assistant is standing at the base of slight incline in the ice pond that probably represents ablation in the very dry and warm period of 1988–1990, which included the extreme 1989 La Niña event. In the bottom photo the ice-pond surface has been lowered about 0.13 m (new layers emerge at base of ice cliff), the ice cliff has evidently retreated (new rocky debris at base of cliff), and the gap in the ice cliff has widened. The dynamic changes that occurred between 1991 and 1996 point out how gaps and discontinuities in accumulation and layering may be the rule rather than the exception.

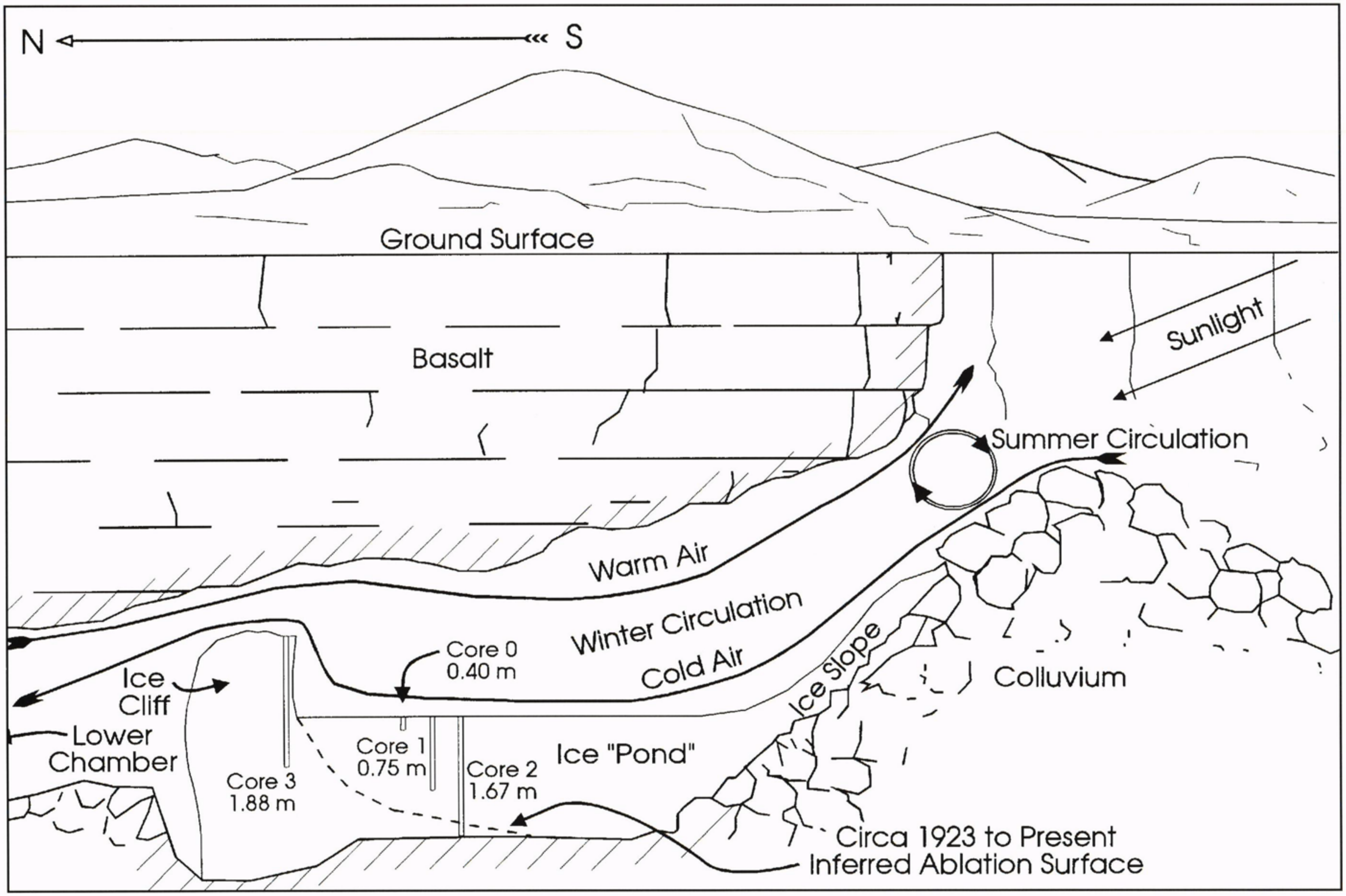

FIGURE 5 —Schematic cross section indicating circulation of air in summer vs. winter.

Ice Cave has to exceed losses from summer ablation to yield ice accumulation in any given year.

Cultural setting

Little is known about Native American use of Candelaria Ice Cave prior to European settlement. Soldiers from nearby Fort Wingate often entered the lava flows near Candelaria Ice Cave (Meketa, 1986). Hearsay has it that soldiers may have mined the ice in the late 1800s. In the 1880s Benito Baca homesteaded land 3 km from the cave (Mangum, 1990) and also may have mined the ice. Sylvestre Mirabal purchased the land containing the ice cave in 1920. In the early 1900s a wooden stairway was built to provide access from the edge of the collapsed lava tube down to the cave's entrance. This stairway was struck by lightning and burned in the 1920s (David Candelaria, pers. comm.). In the 1920s the cave became known to locals as the Perpetual Ice Cave (Vogt, 1924). In the 1930s, a marked trail from the State Highway (present NM-53) led to the cave; still, access was limited and two women lost their way to the cave and were not found for three days. This near-tragedy prompted locals to improve access and take measures to protect the ice cave from vandals (Magnum, 1990). In 1938 Sylvestre Mirabal arranged a lease agreement with Cecil Moore, a local homesteader, to oversee the property. Moore built a saloon and dance hall using the ice from the cave as a means of keeping the beer cold. This establishment served the local homesteaders, lumberjacks, and miners. Cecil also showed the cave and improved the trail and stairway. During this period ice mining slowed but continued until 1946, when Prudencia Mirabal Caldelaria inherited the property and her son David took over management. Dave Candelaria closed the saloon and concentrated on promoting tourism, establishing the Ice Caves Trading Post (Alford, pers. comm.). Candelaria's business picked up with the addition of electricity in 1955 and paving of NM-53 from Grants to the Ice Cave in 1966; improvements were made to the stairway in 1963 (Mangum, 1990). During its early development as a New Mexico tourist stop, Candelaria Ice Cave also attracted considerable scientific interest (Vogt, 1924; Lee, 1926; Yeo, 1930; Harrington, 1934; Lindsey, 1951).

Results

Tandem Mass Accelerator radiocarbon ^{14}C dates were obtained from a moth, two twigs, one feather, and CO2 gas from four ice samples summarized in Tables 1 and 2. The material was taken from different depths along the back wall of the ice cliff, on both sides of a large gap that first opened in 1976 (depths are from the top surface of the ice cliff, referred to here as layer 2; east and west segments refer to direction from the gap). CO_2 gas from ice samples was extracted by placing the sample of ice core in a glass vacuum system, where it is allowed to sublime at low temperature. The water vapor, CO2, and other gases produced in the sublimation process are collected in appropriate cold traps, and the CO2 gas can be dated directly using accelerator mass spectrometry. Though we report these dates in Table 2, all of the CO2 gas dates from the Candelaria Ice Cave ice samples can be challenged on the basis of carbon isotope ratios ranging from —17.2 to —38 per mil. Carbon isotopic values in the CO2 gas from the ice should be from —6.5 per mil in preindustrial times to —8.0 per mil in modern samples, or the same isotopic composition as atmospheric CO2. Fractionation of from —10.7 to —31.5 per mil for the prehistoric dates and —14 per mil for modern samples suggest contamination by diffusion or some other process. Here we rely only on the dates from organic remains. Note, however, that such organic remains have long residence times and can recirculate in caves such as Candelaria Ice Cave.

The radiocarbon dates suggest that the bottom one meter of the ice cliff (3.4-4.5 m) could be as old as

TABLE 1—Tandem Mass Accelerator ^{14}C dates in Candelaria Ice Cave.

Sample description	Sample material	Sample number	δ^{13}C ‰	Radiocarbon age, years B.P.
Core 3, 1.5 m depth in west segment	Moth	AA-20595	1.0	243 ± 55
2.5 m depth in west segment	Feather	AA-6022		27 ± 73
3.4 m depth in back of west segment	Unidentified twig	GX-15920	–24.6	3,116 ± 77
4.0 m depth in back of east segments	Unidentified twig	GX-15919	–20.3	1,810 ± 100

TABLE 2—Tandem Mass Accelerator ^{14}C dates on CO_2 gas from ice samples in Candelaria Ice Cave.

Sample description	Sample material	Sample number	δ^{13}C ‰	Radiocarbon age, years B.P.
0.30 m depth in west segment	Ice sample B	AA-6024	Too small	24 ± 94
2.5 m depth in west segment	Ice sample D	AA-6022	–22.0	55 ± 60
4.3 m depth in east segment	Ice sample A	AA-6021	–17.2	1,857 ± 56
4.5 m depth in east segment	Ice sample E	AA-4915	–38	1,780 ± 60

1800-3000 yr B.P., and that there is a 1500-2000 yr hiatus between this older ice and the upper 3 m of ice, which yielded modern to historic dates. This apparent hiatus may have resulted from similar catastrophic loss of ice that happened in the 20th century. The upper 3 m of the ice cliff probably represent no more than 250-300 years before about A.D. 1850-1880, when the ice cliff apparently formed at the front of the cave and began to retreat. If the 85 layers in the 4.5 m tall ice cliff are annual or even biennial, they did not accumulate continuously. Erosion of layers through ablation probably has happened as frequently as accumulation. This is particularly evident in the discontinuities and unconformities observed in the layering in the bottom part of the ice cliff.

Because Candelaria Cave is accessible and easily photographed from a well-lit overlook, it has a rich photographic history dating back to the 1920s. The earliest photographs were taken by Willis T. Lee of the U. S. Geological Survey, most likely in 1924 (Figs. 2-4; Lee, 1926). The Lee images are undated, but the lady in the three photographs appears in a 1925 Lee photograph of Mammoth Caves, Kentucky; she appears to be wearing the same hat. Also, another Lee photo of nearby Inscription Rock (El Morro National Monument) has a 1920s roadster in the foreground. Alton A. Lindsey photographed the cave in 1947 and again in 1981 (Lindsey, pers. comm.). Another series of photographs, mostly from Dave Candelaria's files, date from the late 1930s/early 1940s to the 1980s. The latest photographs were taken in May 1991 and June 1996 from the same vantage point as earlier photographs to measure rates of ice-cliff retreat and accumulation in the ice pond.

The most distinctive feature of Candelaria Ice Cave is the photogenic ice cliff at the back of the cave (Figs. 2-4, 6-15). Lee (1926) estimated the ice cliff at 4.3 m high in 1924, compared to Yeo's (1930) estimate of 2.3 m. The latter number is probably an eyeball estimate and in gross error; Lindsey (unpublished notes) estimated a height of 2.7 m for the ice cliff in 1947. Lee (1926) stated that the upper surface of the ice cliff was level for about 9 m from the face, gradually sloping towards the back of the cave. Evon Vogt, superintendent of nearby El Morro National Monument, accompanied Lee's party in their visit to Candelaria Ice Cave (Vogt, 1924). In 1924 the ice had separated from the back wall: "With a miner's lamp or trustworthy flash light, one may descend into this hole which opens into a tunnel. It winds below and around a part of the ice..." (Vogt, 1924, p. 38).

Distinctive layers (1-3) in the semicircular ice cliff in the back of the cave can be identified across most of the photographs (Figs. 2-4) and are labeled in Figure 3. We developed a scale from Lee's photo in 1924 (Figs. 2-4) by using Lee's estimate of 4.3 m for the ice cliff. This allowed us to measure the depth between layers 1-3. The same scale was exported to other photographs, which were reduced or enlarged to equalize the depth between layers 1 and 3. Our estimate of 2.70 m in 1947 agrees with Lindsey's measurement. The uppermost Layer 1 was recognized in all the pre-1950 images. Layer 1 is missing in the more recent photographs, indicating ablation at the top of the ice cliff down to the level of Layer 2 between 1924 and the early 1950s. Layer 3 is a dark layer in between a thick upper and a thin lower white layers ca 0.85 m below Layer 2.

Poor dating of the photographs probably yields the largest error in ablation and accumulation. Few of the photographs are dated to the year. We made estimates based on the current ages of individuals in the photographs, styles of clothing worn, and the height of the ice cliff relative to those photographs for which we knew the exact date. Error bars were assigned to each image based on the earliest and latest possible dates. To minimize this error, only the images with the most precise dates were used. We further reduced the effect of poor dating by estimating ablation and accumulation over the longest time intervals possible.

Vertical ablation (from the top down) is evident throughout the photographic record. This ablation has been countered by accumulation of the ice pond at the base of the ice cliff, giving the illusion of more vertical ablation than actually occurred. The ice appears to have ablated vertically from Layer 1 to Layer 2 from 1924 to the early 1950s (Figs. 6-13). Between these layers the ice first ablated down to Layer 2 along the east wall and later ablated on the west side. Layer 2 is a very dirty layer, representing a prolonged lull in ice growth and accumulation of roof fall on the ice surface, and/or concentration of debris from several layers of ablated ice. No measurable vertical mass loss occurred after 1950. Today, remnants of layered ice up to 0.23 m thick, representing the interval between Layer 1 and 2, are patchy across the top surface of the ice cliff. In the debris on top of Layer 2, small amounts of unlayered ice may be seen as high as 0.62 m in the interstices between the rocks.

Horizontal ablation (recession of the ice cliff from the front to the back of the cave) is more difficult to reconstruct from photography. The ice contact with the west wall is only seen in Figures 4, 6, and 13 Top where the ice retreated over 4.5 m since 1924. The retreat along the east wall was less dramatic (Fig. 3), with only about 2 m of ice loss. Between these points, it appears the ice curves gently back. As the ice cliff ablated horizontally, debris sloughed off the top of the ice cliff to the ice pond, continuously changing basin topography (Figs. 6-16). We estimated ice-cliff retreat and measured the area lost using the 1996 survey (Fig. 17, Table 3).

Table 4 summarizes ice-pond accumulation and ice cliff height reconstructed from the photographic record. In 1924 the ice cliff was approximately 2.7 m in front of its current position, and there appeared to be little to no ice in the pond in front of it (Fig. 5). In 1990 an ice core drilled from the ice pond "bottomed-out" at 1.67 m depth, in rocky debris assumed to be debris sloughed off the ice cliff as it retreated past that point. A piece of dimensional lumber encountered at 1.67 m depth could help constrain rates of ice accumulation in the ice pond. This lumber could represent scrap from stairway construction and repairs done in 1963, indicating that the ice-pond core represents the period 1963-1991. Figures 9-15 confirms this conclusion. We

FIGURE 6 —Photograph of Candelaria Ice Cave probably taken between 1933 and 1940. Note series of layers between two dark bands at head level.

FIGURE 7—Ice cliff between 1947 and 1950. Note abundant debris at base of cliff, suggesting rapid ablation of the ice cliff during the mid 1940s.

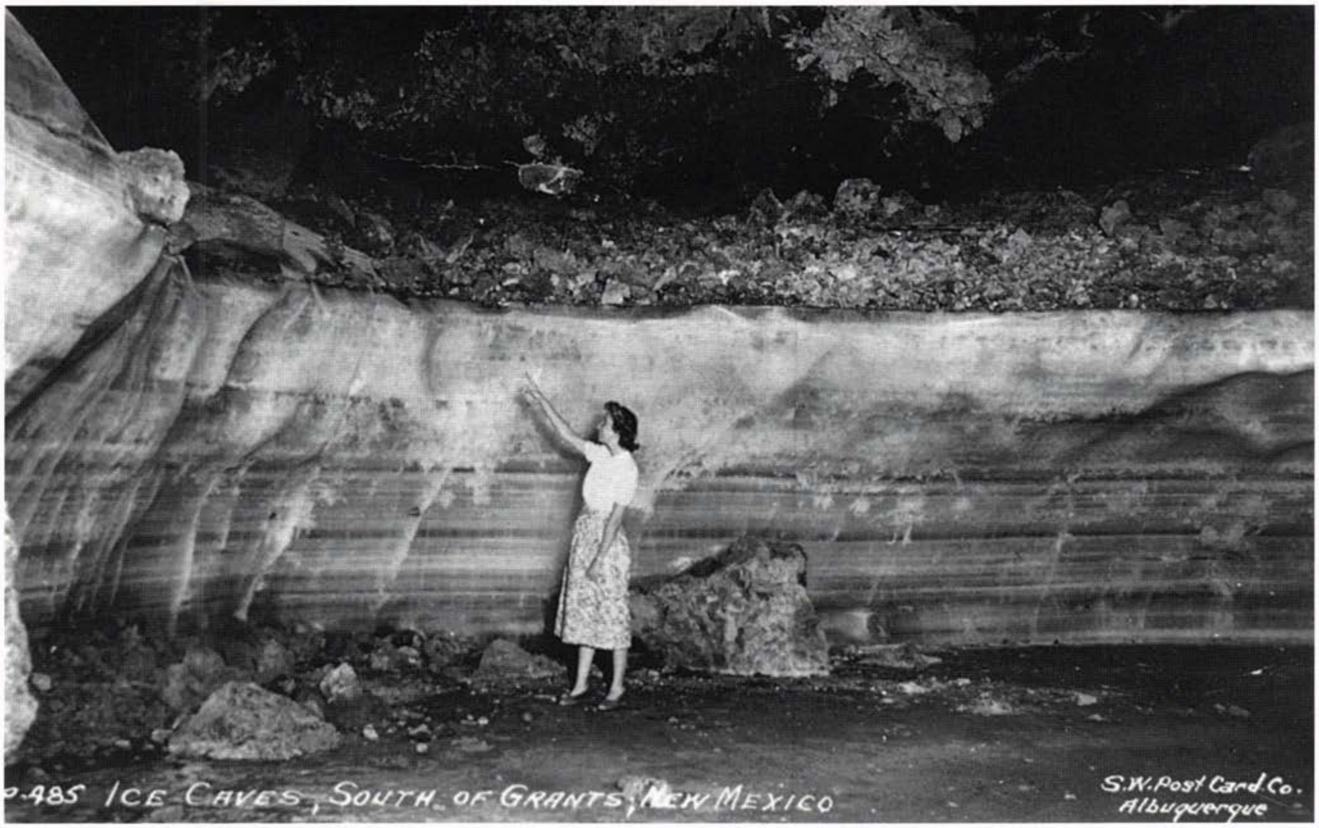

FIGURE 8 —Woman posing in front of the ice cliff between 1950 and 1955. Note that ice between Layers 1 and 2 has completely ablated.

relied primarily on the photographic record to estimate interdecadal variation in rates of accumulation. We did not take into account the fact that basin size has gradually changed with retreat of the ice cliff since 1924.

The average yearly accumulation in the ice pond is summarized in Table 5. Accumulation was moderate from the late 1920s to ca 1936. The ice rapidly decreased from ca 1936 to 1947. The ice resumed moderate accumulation until 1956-1976, when ice accumulation slowed. Ice-accumulation rates began to increase from the early 1970s to 1981 and reached the highest rates from 1981 to 1991, when the ice pond attained its current height. Photographs in 1996 show ca 0.13 m of ablation since 1991 (Fig. 4). In 1976 a hole developed in the middle of the ice cliff (Dave Candelaria, oral comm.), leaving a bridge of ice approximately 0.70 m deep (Fig. 14). By 1981 the hole had grown to about four times its size in 1976 (Fig. 15, top). By ca 1985 the ice bridge collapsed under the weight of the overlying debris (Fig. 15, bottom). Today all remnants of the fallen ice are buried beneath the ice pond and the ice cliff continues to recede gradually toward the back of the cave.

Discussion

Radiocarbon dates from different depths in the 4.5 m tall ice cliff at Candelaria Ice Cave indicate that the bottom ice could be as old as 1800-3000 yrs, but the upper 2.5-3 m probably encompass some portion of the period between A.D. 1650-1850. Admittedly, there are large uncertainties in these age estimates. However, the lack of ice older than 3000 yrs B.P., as well as the apparent discontinuities in ice buildup, suggest that ice bodies in Candelaria Ice Cave have accumulated and ablated several times during the Holocene, most likely tracking century to decadal and century-scale variability in climate.

The ice cliff at Candelaria Ice Cave could have been initiated several different ways. All explanations assume that the top of the ice cliff in 1924 represents the level to which ice filled the cave, and that ablation began vertically at the entrance and progressed towards the back. The ice cliff could have been initiated by seepage of runoff and/or meltwater along the contact between the ice and the talus that slopes down into the cave (Yeo, 1930). This assumes that seepage can travel below the ice without freezing, which is unlikely in this setting. A second explanation is analogous to the way moats form around the contact of a nunatak, an island of rock surrounded by glacier ice. During an extended warm and dry period, ice at the front of the cave begins to retreat from the rocks near the entrance. Once a "nickpoint" forms, the lack of runoff and warm surface temperatures could accelerate recession though horizontal ablation. Yet another explanation involves collapse of a key overhang exposing the front of the ice body to direct sunlight (Yeo, 1930). The most likely cause of "nickpoint" initiation is extraction of ice by Ft. Wingate soldiers and nearby settlers in the late 1800s. Yeo (1930, p. 22) observed that, "On the day of the examination some

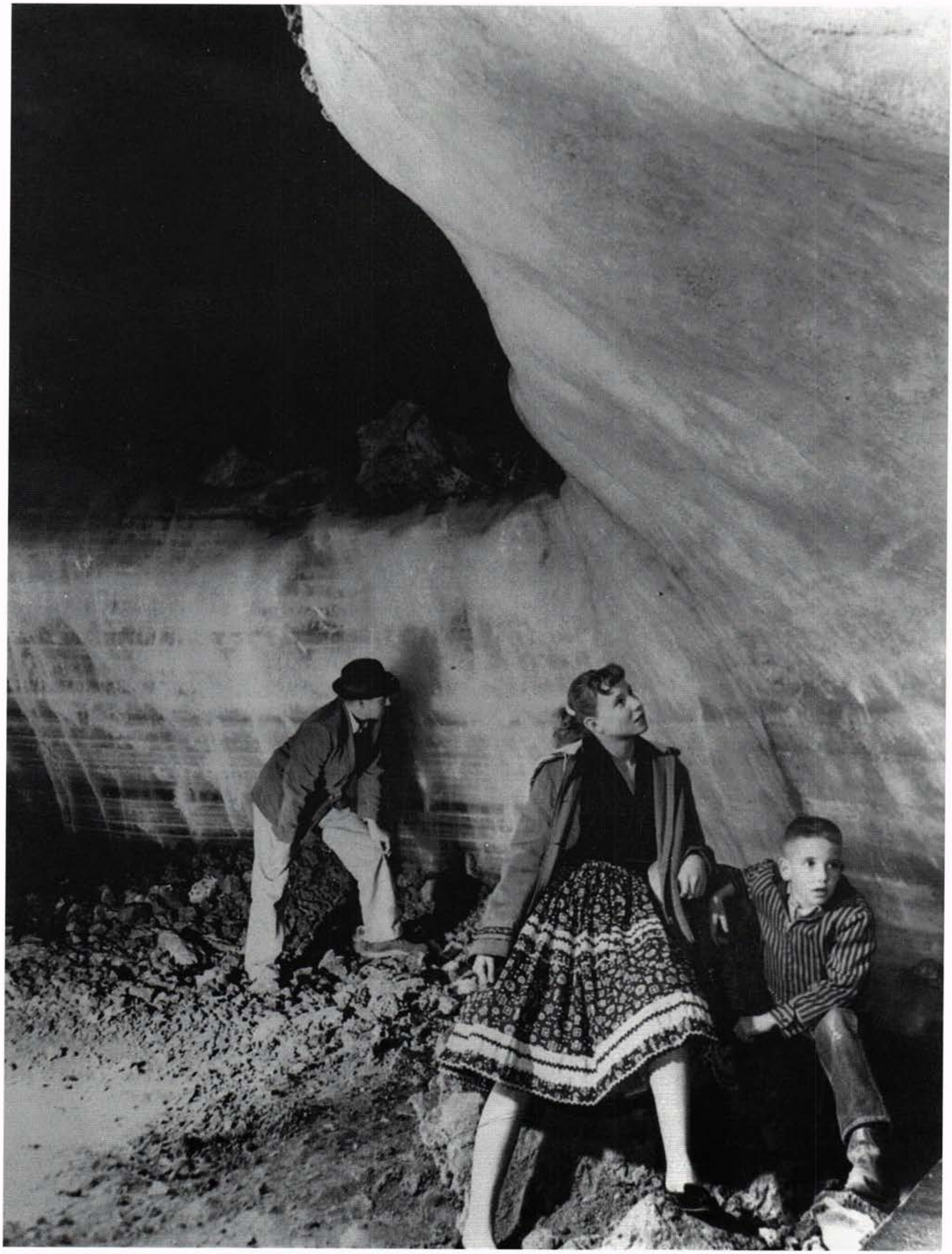

FIGURE 9—Dave Candelaria and his children in front of the ice cliff in 1956.

vandal had taken an axe with a large blade and loosened about a half bushel of ice from the main face, and it was lying at the bottom of the cave. When any warm air or summer comes in contact with this it will melt readily." It is not inconceivable that large volumes of ice were removed from Candelaria Ice Cave, and that ablation of the exposed vertical faces of the excavated pits outpaced refilling of the pits with ice. In 1934 Evon Vogt, the superintendent of nearby El Morro National Monument, wrote a letter to the director of the National Park Service expressing concern over the summertime extraction of hundreds of pounds of ice by nearby homesteaders (Mangum, 1990, p. 81). The mining of ice probably decreased when Cecil Moore began to develop Candelaria Ice Cave as a tourist attraction in 1938, and soon after mining of ice probably ceased. Finally, we cannot rule out possible negative effects that excessive runoff might have on ice accumulation, specifically late in the warm season. In September 1996, heavy rains flooded the pond and the ice floor buckled and cracked towards the front of the cave. The same heavy summer and fall rains that might have been responsible for arroyo-cutting in New Mexico during the 1880s (Leopold, 1951; Tuan, 1966) could have accelerated the erosion initiated by mining of the ice at about the same time.

With few exceptions, accumulation rates in the ice pond that formed in front of the ice cliff generally covary with precipitation and temperature trends in the twentieth century. Climate and tree-ring records (Grissino-Meyer, 1995, 1996, this volume), the latter being most sensitive to cool-season precipitation, indicate that a significant drought with warm summers in 1895-1904 was succeeded by highly variable but generally wet conditions between 1905 and 1943, with particularly wet years in 1905, 1907, 1914-1916, 1919, 1931, and 1941 (Fig. 18). The slow accumulation in the ice pond during at least the early part of this period could be due to ice removal exceeding the rate of accumulation. Also, we know that the cave floor was exposed in the 1920s, which may have enhanced seepage and retarded ponding for an undetermined period of time. Little ice is evident in the pond during the late 1940s and 1950s. This period corresponds with one of the worst droughts in the last 2,219 years (GrissinoMayer 1995, 1996). Most of the ice in the present pond accumulated since the early 1960s, a period that was consistently wetter than any other time during the last 100 years (Fig. 18). Although the period from 1960 to 1975 was cooler than normal, the period since 1975 has been warmer during both seasons. Apparently net accumulation was negative from 1968 to 1977, and again in 1980-1981. Note the extreme rainfall in late summer and early fall of 1972 (Fig. 18), which could have had a negative effect similar to fall of 1996. The greatest accumulation rates, between 1981 and 1991, coincide with above-normal winter rainfall and temperatures. The greatest accumulation rates, between 1986 and 1991, coincide with the greatest rainfall reconstructed from the 2000 yr tree ring record. Photographs indicate some ablation between 1991 and 1996. This period is marked by drought during a strong La Nina event.

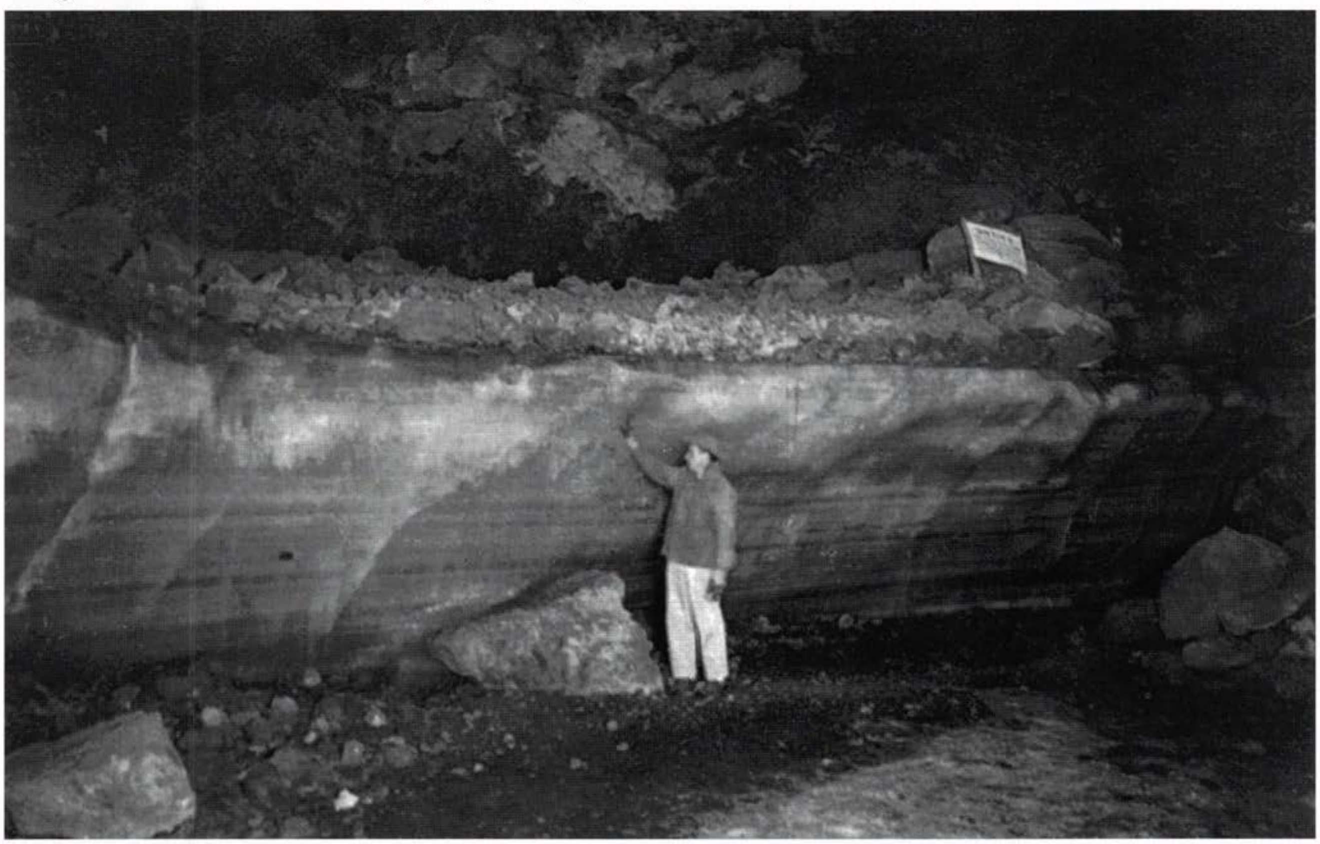

FIGURE 10—Man posing in front of the ice cliff between 1950 and 1970.

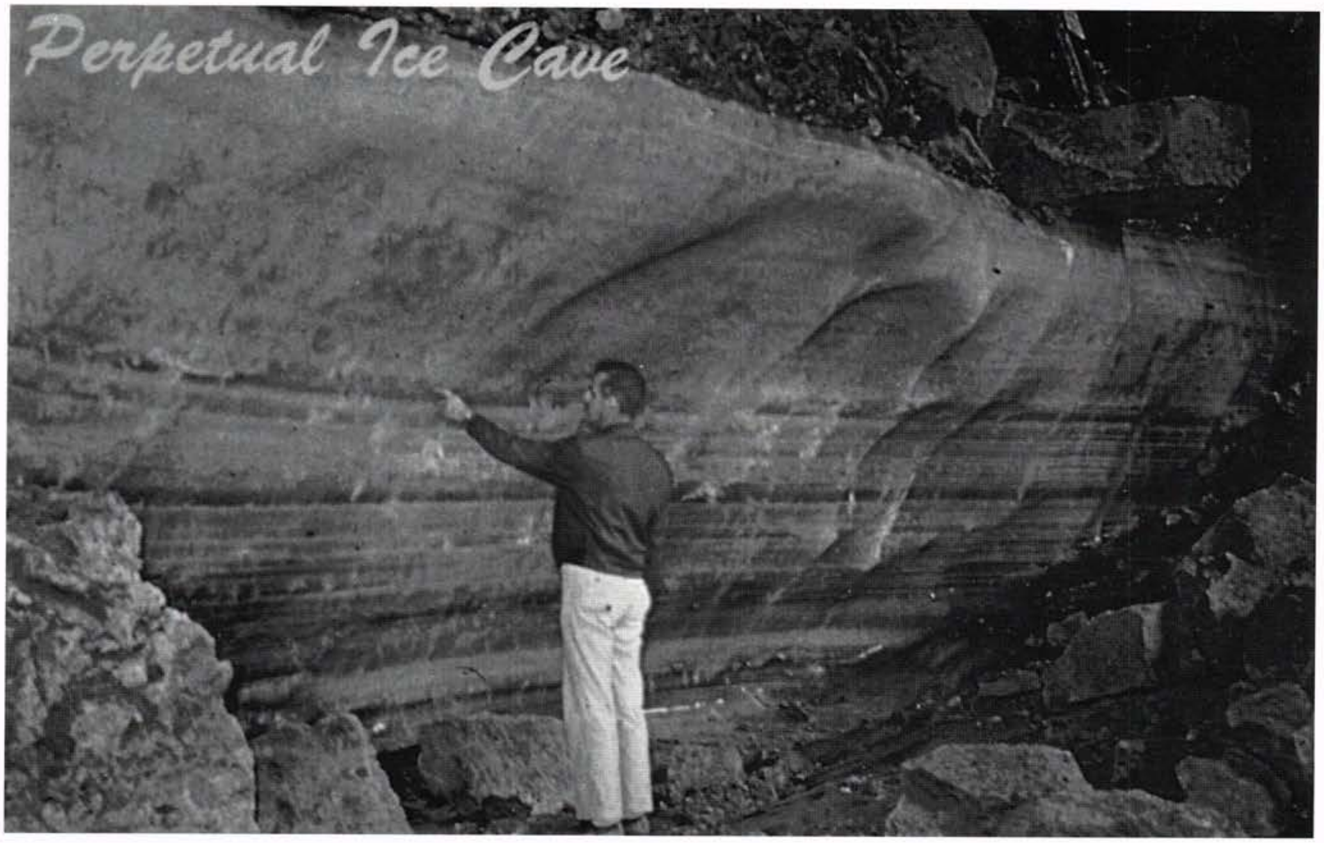

FIGURE 11—Ice cliff between 1950 and 1970. Man is standing at base of ice slope. Large rock in lower left corner of photograph is the same as in center of Figs. 9, 10.

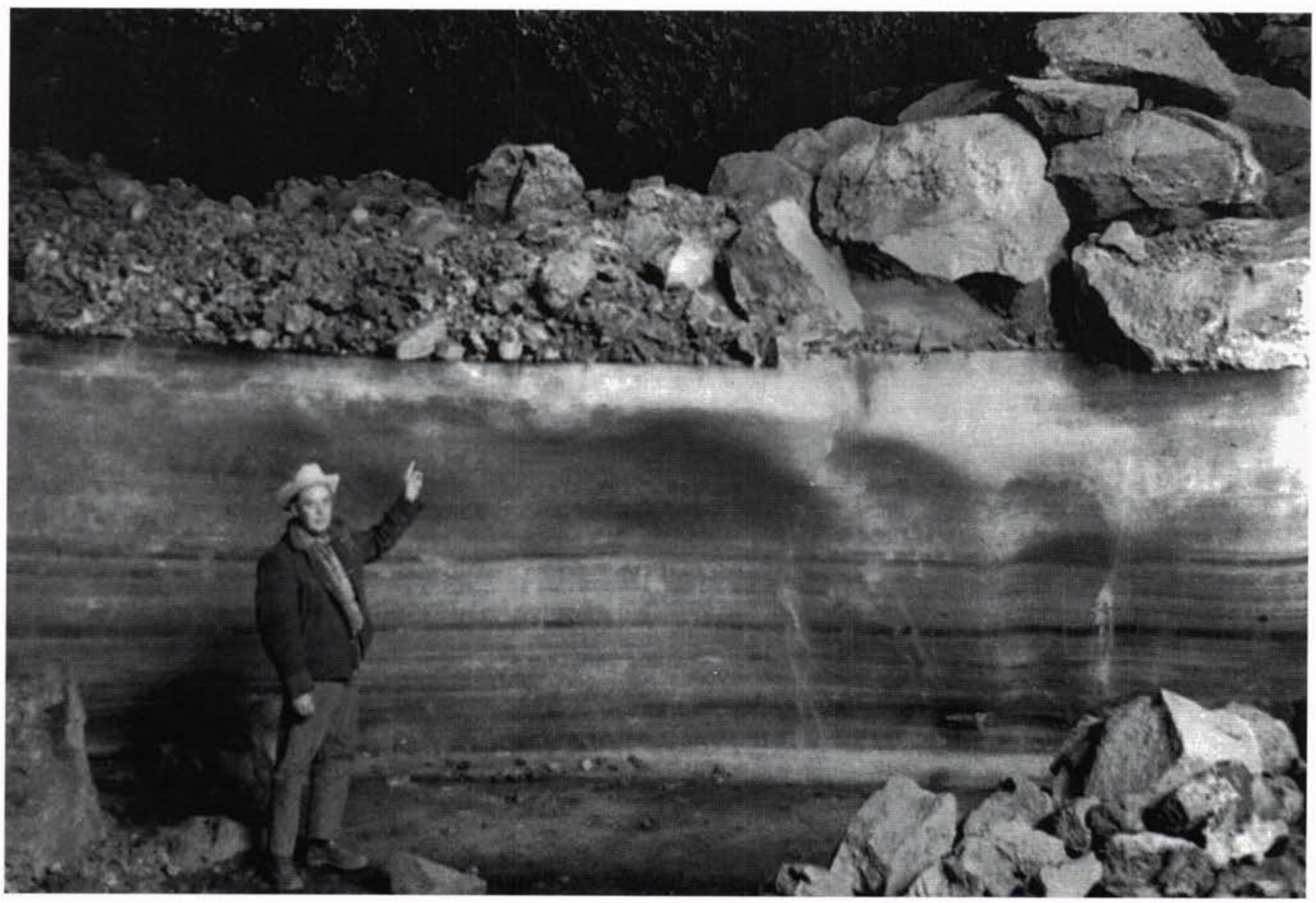

FIGURE 12—Dave Candelaria at base of ice cliff between 1950 and 1970. Compare overhanging rock on top of ice cliff at right-center of photograph with Fig. 11.

FIGURE 13—Candelaria Ice Cave between 1950 and 1970 (top) and May 1991 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1550). Note overhanging rock on top of ice cliff at right of the top photo. In the bottom photo the ice cliff has retreated considerably and the overhanging rock now rests on the pond surface at the base of the cliff; most of the ice cliff has completely separated from the back wall; and ablation from both the front and the back has breached the ice cliff. Also, the ice pond "rose" approximately 1.30 m between 1970 and 1991.

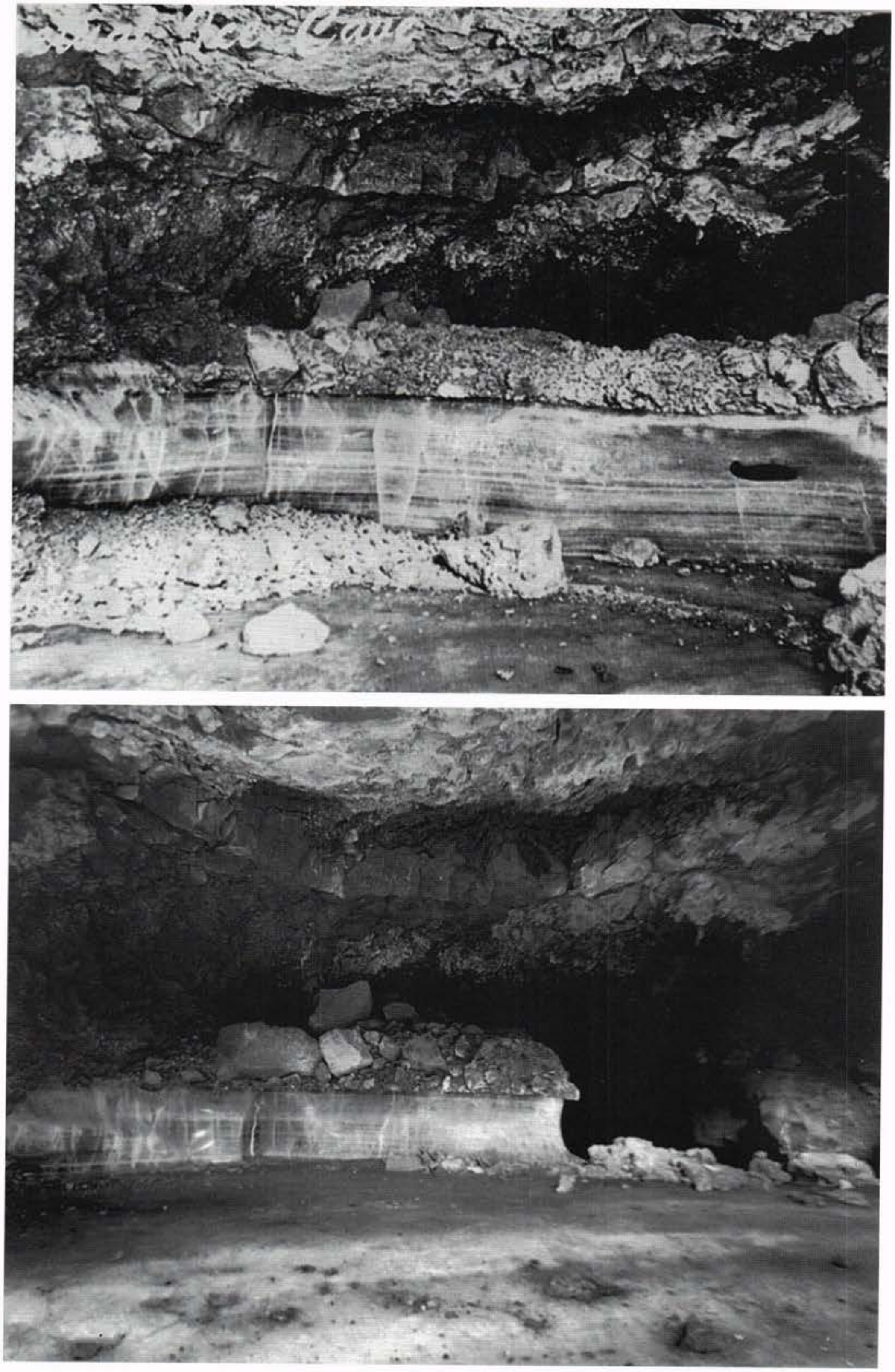

FIGURE 14—Candelaria Ice Cave in 1976 (top), when a hole developed through ablation from the back and front of the ice cliff and May 1991 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1549), showing eventual collapse and development of the gap in the ice cliff.

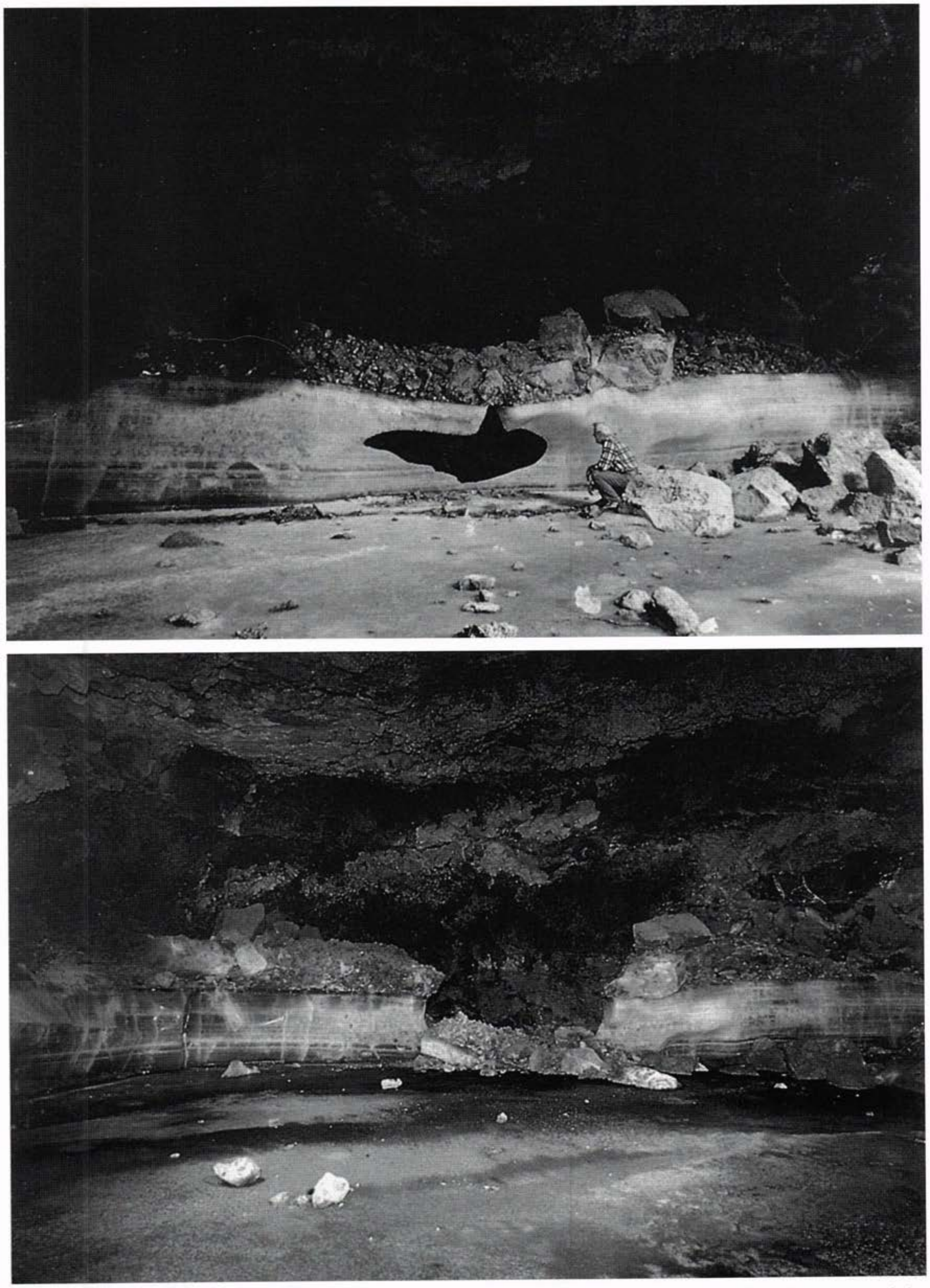

FIGURE 15—Candelaria Ice Cave in 1981 (top) showing widening of hole in ice cliff and collapse of the resulting bridge in 1991 (bottom).

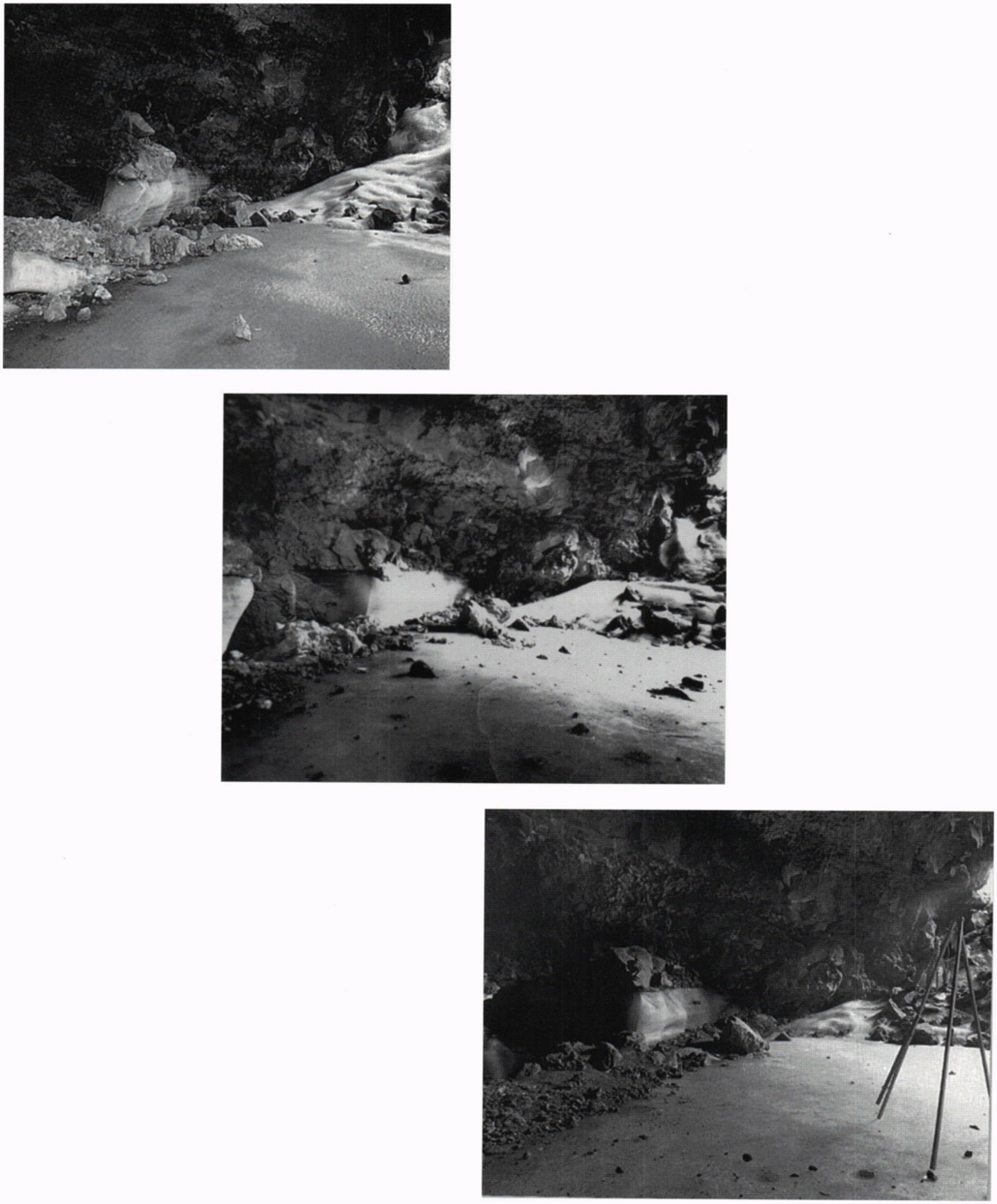

FIGURE 16—Candelaria Ice Cave, showing ice slope from runoff into the cave in 1980s (top), May 1991 (center) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1551), and June 1996 (bottom) (U.S. Geological Survey, Desert Laboratory Collection, Stake 1551). Note sequential emergence of rocks in ice slope from 1980s to 1996.

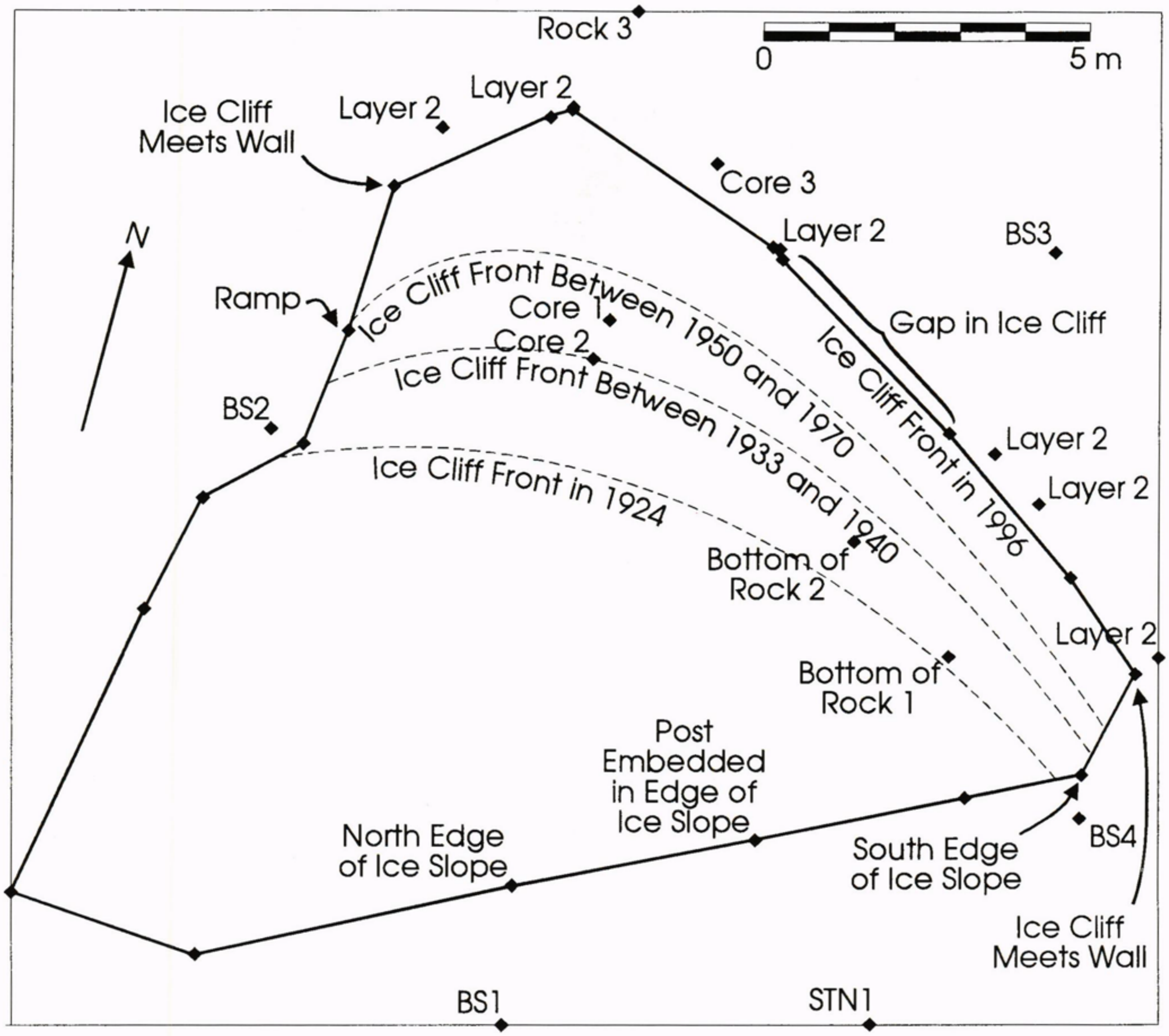

FIGURE 17—Survey of Candelaria Ice Cave showing important features in the cave, the area of the ice pond, and estimated position of the ice-cliff front in 1924, between 1933 and 1940, and between 1950 and 1970.

Conclusions

Cave ice has a global distribution and may have utility as a proxy for past climates. The reconstructed history of cave ice at Candelaria Ice Cave suggests that, in some cave systems, this application may be hindered by frequent discontinuities in ice accumulation and large uncertainties in age estimates. Candelaria Ice Cave may be less than ideal as a paleoclimate proxy because it is hypersensitive to climate variability—prolonged conditions unfavorable for ice accumulation encourage ablation and loss of the ice record. Human impact in this easily accessible cave also confounds attempts to calibrate climate and ice accumulation during the period of instrumental record (the last hundred years or so). Conditions that may be ideal for developing paleoclimate proxies from cave ice include inaccessibility to humans, larger basins for ice accumulation, protected and shaded entrances due to intact lava-tube roofs (Martin and Quinn, 1990), and dominance of inflow from slow infiltration/seepage during snowmelt versus direct runoff. Such ideal conditions may be met elsewhere at El Malpais National Monument and other large basalt flows at higher latitudes and/or altitudes in North America (e.g. the Snake River Plains in Idaho).

Acknowledgments

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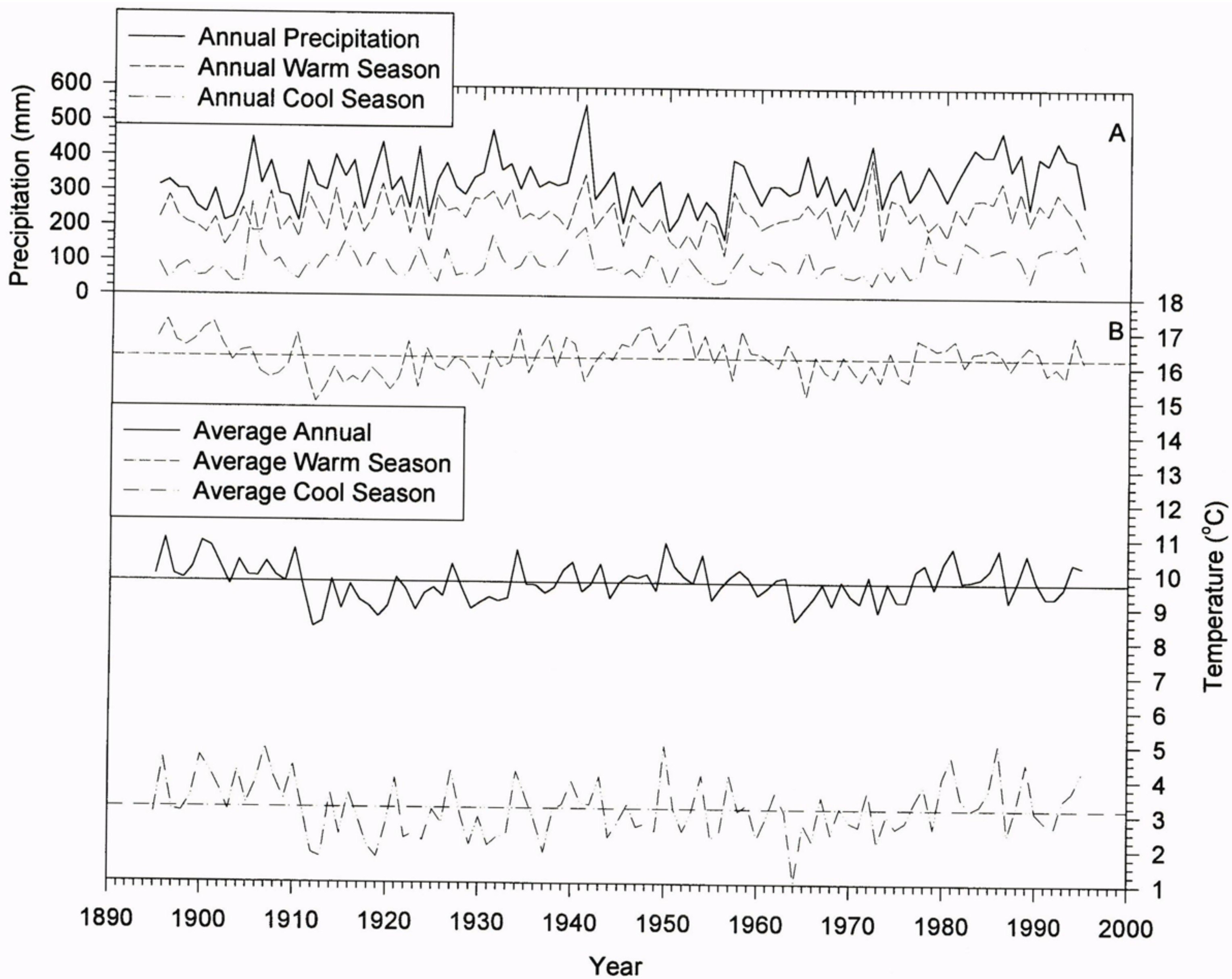

FIGURE 18 —Yearly warm and cool season averages for both temperature (A) and precipitation (B) for NOAA Climate Subdivision Four, South-Central Mountains. Note that annual precipitation is the total of the monthly averages and average temperature is derived from the monthly averages for all the sites in this subdivision.

TABLE 3—Ice cliff ablation history in Candelaria Ice Cave.

Date	Vertical ablation of the ice cliff	Dimensions of ice gap	Horizontal ablation of the ice cliff
1924		—	
1933–1940	–0.95 ± 0.20 m	—	13 ± 3 m²
June 20, 1947	Most ice has ablated down to Layer 2, 1.30 ± 0.35 m on east side of ice cliff	—	
1947–1953	At least 0.80 ± 0.40 m of ice remains above Layer 2 on west side of ice cliff	—	
1950–1955	Most ice has ablated to Layer 2 along the hole length of the ice cliff	—	
1956		—	
1976		A hole opens in the ice cliff to the back of the cave 0.70 ± 0.10 m below the debris 0.22 ± 0.05 m tall and 0.95 ± 0.23 m long	
May 26, 1981		The ice hole has opened through to the overlying debris 2.80 ± 0.75 m long	
1983–1988		The ice hole collapses and is 3.21 ± 0.75 m long	
May 15, 1991		3.30 ± 0.70 m long	32 ± 3 m² since 1933–1940
June 12, 1996		4.10 ± 0.05 m long	

TABLE 4—Estimated ice-pond accumulation and ice-cliff height history in Candelaria Ice Cave.

Date	Total ice-pond accumulation (m)	Ice cliff, total height above ice pond (m)
1924	Little to no ice	4.30 ± 0.80
1933–1940	0.60 ± 0.12	3.35 ± 0.70
June 20, 1947	0.30 ± 0.04	2.70 ± 0.50
1947–1953	1.10 ± 0.25	2.60 ± 0.80
1950–1955	0.50 ± 0.12	2.05 ± 0.50
1956	0.70 ± 0.24	2.30 ± 0.80
1976	0.90 ± 0.21	2.10 ± 0.50
May 26, 1981	1.25 ± 0.25	1.75 ± 0.35
1983–1988	1.60 ± 0.35	1.40 ± 0.30
May 15, 1991	2.00 ± 0.40	1.00 ± 0.20
June 12, 1996	1.87 ± 0.05	1.13 ± 0.05

TABLE 5—Average yearly accumulation in the ice pond of Candelaria Ice Cave for the available time intervals.

Years	Interval (yrs)	Average yearly accumulation (m/yr)
1924–1947	23	0.008 ± 0.005
1924–1936 ± 4	12 ± 4	0.050 ± 0.040
1936±4–1947	11 ± 4	-0.036 ± 0.024
1947–1950 ± 3	3 ± 3	0.300 ± 0.300
1950 ± 3–1956	3 ± 3	0.067 ± 0.067
1947–1956	9	0.050 ± 0.0301
1956–1968	12	0.058 ± 0.020
1968–1977	9	-0.044 ± 0.014
1977–1980	3	0.167 ± 0.047
1980–1981	1	-0.250 ± 0.078
1981–1986	5	0.060 ± 0.012
1986–1991	5	0.090 ± 0.019
1991–1996	5	-0.026 ± 0.005

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Plantlif e on the lava—The vegetation and flora of El Malpais

David L. Bleakly
Bleakly Botanical & Biological, 3813 Monroe NE, Albuquerque, New Mexico 87110

In contrast to the barren volcanic waste that the word "malpais" implies, the plantlife of El Malpais National Monument is well-developed and diverse. The youngest lava flows (El Calderon, Twin Craters, Hoya, Bandera, and McCartys) that cover most of the monument proper comprise a "mesic island"—an area that is moister than the land around it—surrounded on all but the northwest side by drier habitats. The northwestern part is the highest in the monument (up to about 2438 m [8000 ft]) and is contiguous with the Zuni Mountains which are densely covered with conifers. Mixed-conifer woodlands, composed primarily of ponderosa pine *(Pinus ponderosa)* with lesser numbers of Douglas-fir *(Pseudotsuga menziesii),* Rocky Mountain juniper *(Juniperus scopulorum),* and piñon pine *(Pinus edulis),* blanket most of the four older of these lava flows and adjacent areas to the northwest. The fifth and youngest flow, the McCartys, is barren or sparsely vegetated with shrubs, grasses, and stunted conifers. Grasslands surround the flows on the east and south. Lava-capped mesas, sedimentary outcrops, and the Chain of Craters, all located within or near the monument, support piñon/juniper woodlands often mixed with ponderosa pine.

The fact that most of the lava flows are covered with trees is remarkable and unexpected in itself. However, there are other notable features of the vegetation at El Malpais. Some plants, such as Douglas-fir, Mogollon geranium *(Geranium lentum),* blackspined hedgehog cactus *(Echinocereus coccineus),* and most ferns, found during a recent study (Lightfoot et al., 1994), apparently grow only on the lava. These plants also occur on other substrates and/or moister areas elsewhere. For example, Douglas-fir grows in the nearby moist Zuni Mountains but not off the lava in the lower and drier monument. Four hundred and forty-one plant species have been found in the monument, several of which are rare, uncommon, localized, or near the extremes of their distributions. Unique features of the monument include "ice caves" with associated flora, rare plants, and lava-flow-associated vegetation.

This paper is divided into two sections, the first discussing the monument's vegetation and plant communities and the second introducing the flora, including information about common and rare plants. Two appendices list the plant species by scientific name in plant families (Appendix A) and by common name (Appendix B).

Physiography and plant communities

El Malpais is located near the southeastern edge of the Colorado Plateau Physiographic Province in the Datil Section (Fenneman and Johnson, 1946; Fig. 1). This section is characterized by extensive volcanic deposits (Hunt, 1974), such as those found at the monument. The plants at El Malpais may be fit into at least two vegetational or floristic schemes. At the simplest level is Brown and Lowe's (1980) map of biotic communities of the Southwest, which is based on observational evidence. Using Brown and Lowe's map, three communities are present in the monument area: (1) Rocky Mountain (Petran) and Madrean Montane Conifer Forest is found in the Zuni Mountains and the highest, northwestern part of the monument; (2) Plains and Great Basin Grasslands are found primarily around and off the youngest lava flows; and (3) Great Basin Conifer (piñon /juniper) Woodland. According to these two authors, the last is the "matrix" in which the other two community types are "embedded." Great Basin Conifer Woodland is the typical plant community of much of the Colorado Plateau, although it is not found in abundance within the monument. At El Malpais it is best developed on sedimentary outcrops and cinder fields. Because of the scale of the map, this system is most useful in the broad view.

An innovative and scientifically rigorous study of the flora of the western United States was performed by McLaughlin (1989, 1992), who statistically analyzed the distributions of native flowering plants to derive a series of maps indicating floristic affinities. These groupings correspond, in most cases, to those obtained empirically. For example, his Colorado Plateau Floristic Area aligns well with the Colorado Plateau Physiographic Province except in part of northwestern New Mexico where the monument is located (Fig. 1). According to McLaughlin's maps, El Malpais is located in the Southern Rocky Mountain-Mogollon Floristic Area. As explained in this chapter, in most respects the plantlife of the monument actually is more similar to that found in regional mountain ranges than to that in the Colorado Plateau. Other McLaughlin's floristic areas that contribute to the floral diversity of the monument include the Colorado Plateau, Apachean, Chihuahuan, and Great Plains. See the Flora section below for details about specific plants whose distributions are centered in the surrounding floristic areas.

Recent work by Carroll and Morain (1992) has revealed four plant communities at El Malpais: (1) mixed-conifer woodland, (2) shrub /conifer, (3) grass or grass/shrub, and (4) barren to sparse grass/shrub. The first and last are found on the lava flows and the other two are located off them. The vegetation map (Fig. 2) was created by simplifying, modifying, and adding to Carroll and Morain's (1992) map as the result of extensive field experience by the author and others.

The mixed-conifer-woodland community is found on the four older of the five lava flows and is therefore the most widespread and common community within the monument (Fig. 3). It is also present in higher areas off the lava flows. There is much bare rock on the flows, so plant density is relatively low. Nevertheless, it is likely that all possible growth sites are utilized and plant density is probably near its maximum.

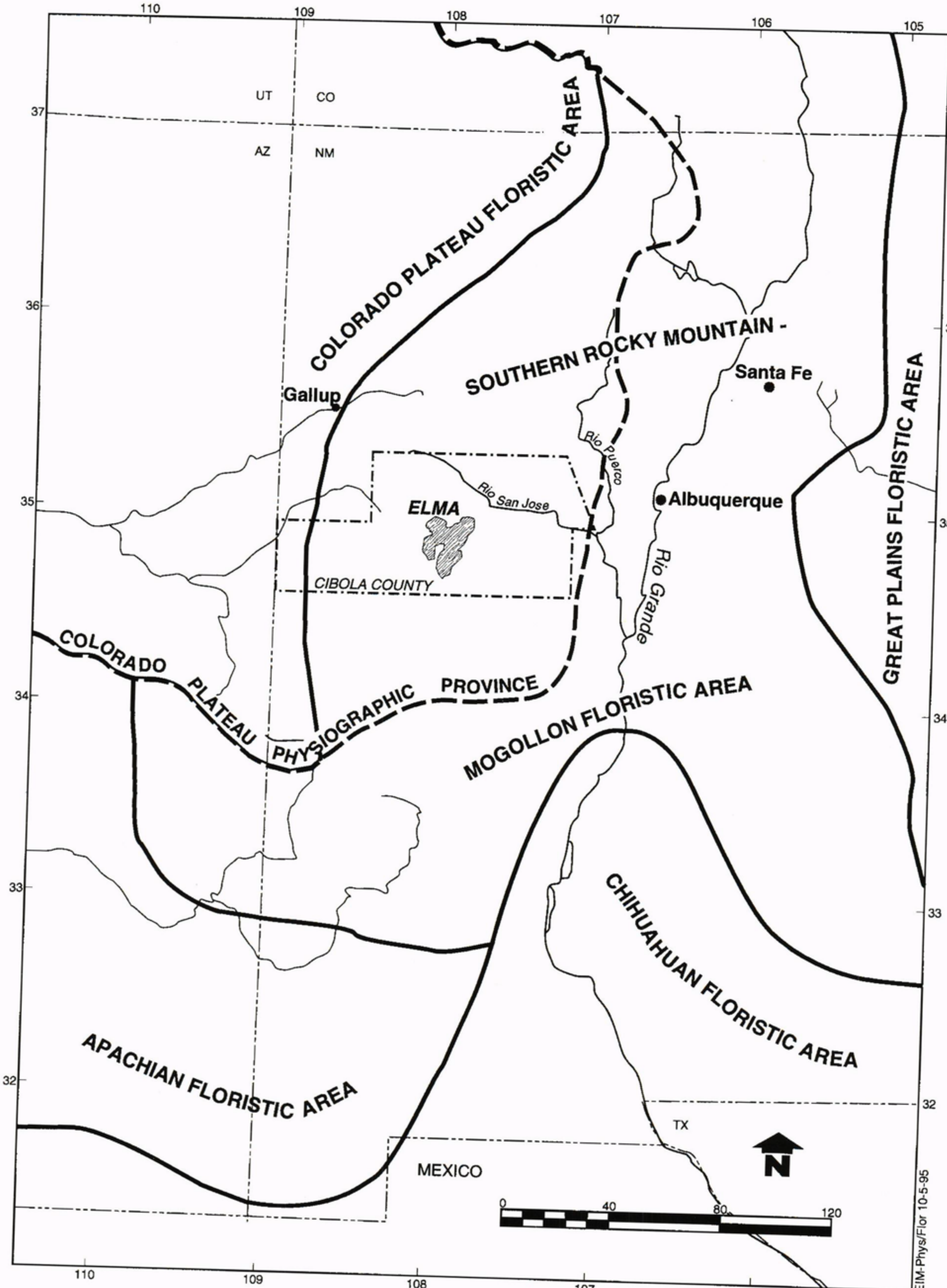

FIGURE 1—El Malpais in physiographic and floristic area context. **ELMA** = El Malpais National Monument. (© David L. Bleakly, 1995)

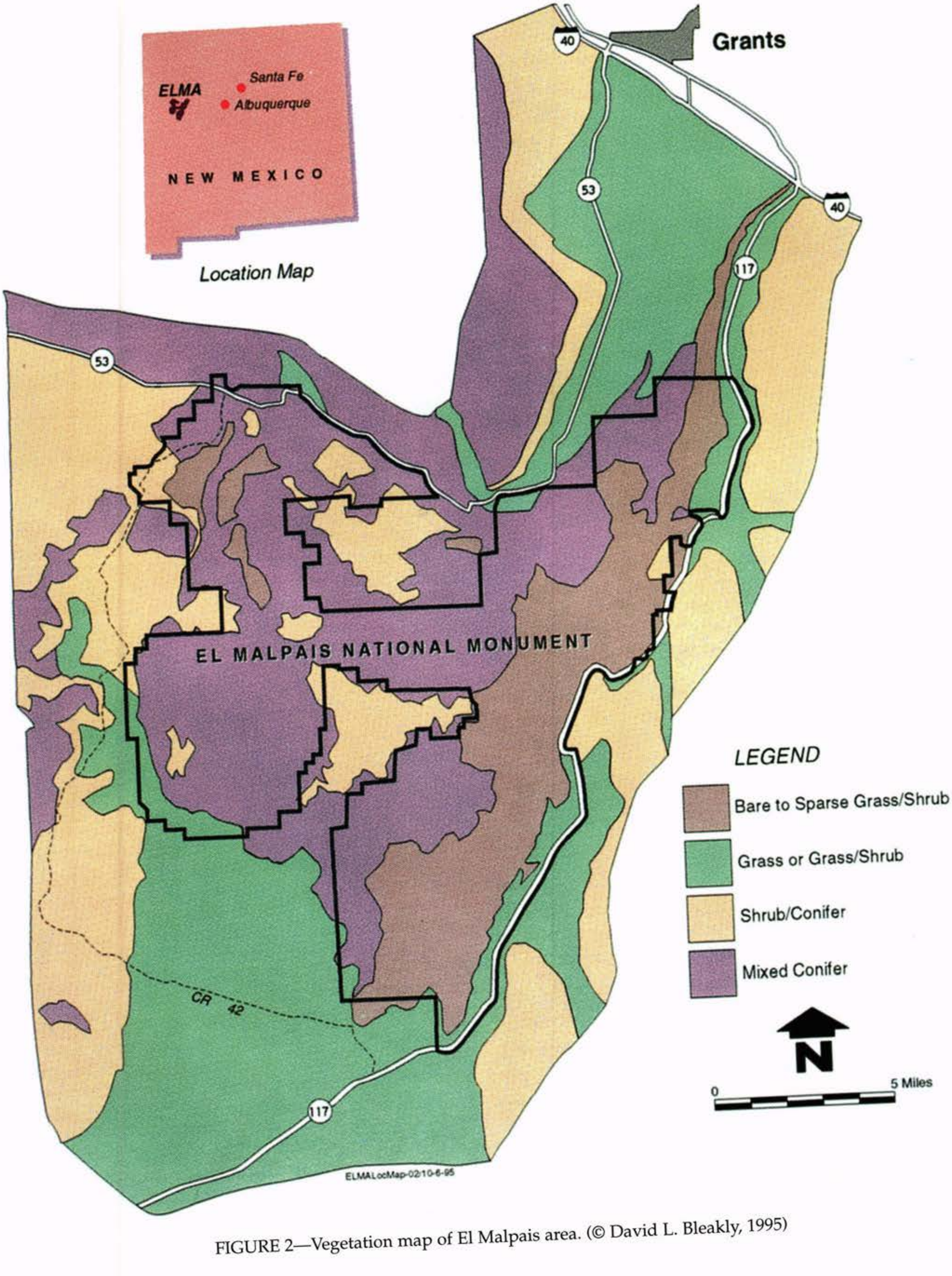

FIGURE 2—Vegetation map of El Malpais area. (© David L. Bleakly, 1995)

FIGURE 3—View approximately north from Lost Woman Crater. The vegetation, dominated by ponderosa pine, on the upper Bandera flow is fairly dense. Just to the right of the tree is Cerro Bandera, in the center is Bandera Crater, and Oso Ridge of the Zuni is barely visible beyond. (© David L. Bleakly, 1995)

FIGURE 5—Rockspirea (*Holodiscus dumosus*) is found most frequently in the moister collapse structures. (© David L. Bleakly, 1995)

Long-rooted conifers grow mostly in cracks and low spots on the rock surface where there is some soil accumulation and extra moisture. Ponderosa pine dominates and piñon is common at most locations on the lava. In addition, higher elevations support Douglas-fir and Rocky Mountain juniper, while lower areas support one-seed juniper. Many shrubs, herbs, and grasses occur within the mixed conifer community. Common ones include wax currant *(Ribes cereum),* Apache plume *(Fallugia paradoxa),* skunkbush *(Rhus trilobata,* Fig. 4), rockspirea *(Holodiscus dumosus,* Fig. 5), James wild buckwheat *(Eriogonum jamesii),* skyrocket *(Ipomopsis aggregata),* running fleabane *(Erigeron flagellaris),* Wright deervetch *(Lotus wrigthii),* King lupine *(Lupinus kingii),* mullein *(Verbascum thapsus),* mountain muhly *(Muhlenbergia montana),* and blue grama *(Bouteloua gracilis).*

Typically, the mixed-conifer woodland that grows on the flows ends abruptly near the flows' edges. Lindsey (1951) pointed out that Douglas-fir and ponderosa pine grow at lower elevations on the lava flows than they do off them. Conifers require more water

FIGURE 4—Skunkbush (*Rhus trilobata*) with ripe fruits, a very common plant at El Malpais. (© David L. Bleakly, 1995)

than grasses, which suggests that the basalt flows are more moist than the surrounding grasslands, and thus more like mountains. The observation that lava flows are "mesic islands" was also noted on the Carrizozo lava flow in south-central New Mexico (Shields and Crispin, 1956). Lava is not absorbent, so runoff moves down through the heavily fractured surface into areas of high moisture, low evaporation, and cool temperatures. These are suitable growth conditions for deep-rooted plants such as conifers, but not for shallow-rooted plants such as grasses and annuals.

The oldest known living inland Douglas-firs in the country grow on the Bandera flow at El Malpais (Grissino-Mayer et al., this volume). The oldest has a pith date of 718 A.D. In addition, a complete tree-ring record, compiled from living and dead trees and from log remnants, has been established to 136 B.C. Tree-ring data allow for interpretation of aspects of past climate in the area. Trees have grown and dead wood has survived on the lava flows for several reasons: (1) relatively favorable growth conditions; (2) infrequent and cool wildfires (about every 10 years; GrissinoMayer, this volume); little undergrowth or fine fuels and widely scattered trees do not support hot fires; and (3) low decomposition rates because of the dry climate.

The shrub /conifer community, which contains piñon/juniper woodlands, is not common within the monument and grows here mostly on sedimentary substrates (Fig. 6) or cinders. Piñon/juniper woodlands are found on Sandstone Bluffs, in the Cerritos de Jaspe area, near the Chain of Craters, and in Little and Big Holes-in-the-Wall. In its purest form, dominated by piñon and juniper, this community is best developed on sedimentary substrates in the monument. Ponderosa pines are commonly present, especially on cinders.

Several sedimentary kipukas, such as Mesita Blanca, Hidden Kipuka, and Encerrito, as well as Sandstone Bluffs and other sedimentary outcrops and kipukas near NM-117, support many plants found nowhere else within the monument boundaries. Such plants include dwarf blue-eyed grass *(Sisyrinchium*

FIGURE 6—Piñon/juniper woodland on a sedimentary kipuka, Encerrito, near the beginning of the Zuni–Acoma trail. This community type is found only on sandstone, limestone, or cinders in the National Monument. (© David L. Bleakly, 1995)

FIGURE 7—Birdbill dayflower (*Commelina dianthifolia* var. *longispatha*) is fairly common at Sandstone Bluffs. (© David L. Bleakly, 1995)

demissum), showy fameflower *(Talinum pulchellum),* cream pincushion cactus *(Mammillaria heyderi meiacantha,* so named because it is one of the very few cacti with milky sap), painted milkvetch *(Astragalus ceramicus),* alderleaf mountain mahogany *(Cercocarpus montanus),* spike dropseed *(Sporobolus contractus),* and sandhill muhly *(Muhlenbergia pungens)* among others. Sedimentary and alluvial areas are much more easily grazed than the lava flows (although some of these were previously grazed also), so they were not incorporated into El Malpais and thus are rare within its boundaries. Common plants include Colorado piñon *(Pinus edulis),* one-seed juniper *(Juniperus monosperma),* ponderosa pine *(Pinus ponderosa),* sand sage *(Artemisia filifolia),* fourwing saltbush *(Atriplex canescens),* fragrant sand verbena *(Abronia fragrans),* Colorado four-o'clock *(Mirabilis multiflora),* birdbill dayflower *(Commelina dianthifolia longispatha,* Fig. 7), whiteflower ipomopsis *(Ipomopsis longiflora),* spectaclepod *(Dimorphocarpa wislizenii),* tuber-root flatsedge *(Cyperus fendlerianus),* sandhill muhly *(Muhlenbergia pungens),* Indian ricegrass *(Oryzopsis hymenoides),* sand dropseed *(Sporobolus cryptandrus),* and needle-andthread grass *(Stipa comata).*

Grasslands and grass/shrublands dominate the landscape surrounding the youngest flows at El Malpais (Fig. 8). Grasslands are more common on the east and south in North Pasture and the North Plains, while grass/shrublands are better developed in the west along the middle part of County Road 42. Extensive expanses of the Old Basalt occupy much of the region south and west of the monument; it is old and eroded enough to have fairly well-developed eolian (wind-deposited) soils. Alluvium has been deposited adjacent to most of the flows and is particularly visible on the east side; these deposits, too, are grassy and have deep soils. Runoff sometimes forms temporary lakes next to the flows. Typical grasses include the gramas, little bluestem *(Schizachyrium scoparium),* three-awns *(Aristida* sp.), squirreltail *(Elymus longifolius),* junegrass *(Koeleria macrantha),* and ring muhly *(Muhlenbergia torreyi).* Common shrubs are rubber rabbitbrush *(Ericameria nauseosus),* gray horsebrush *(Tetradymia canescens),* sages *(Artemisia* sp.), and broom snakeweed *(Gutierrezia sarothrae).* One-seed junipers *(Juniperus monosperma)* are seen occasionally especially on outcrops. All of this community around the monument has been heavily grazed for more than 100 years.

The barren to sparse grass /shrub community, which also includes stunted conifers, also occurs on the lava flows. It is found almost exclusively on the McCartys, the youngest of all the flows in the monument, and on as lava of the upper Bandera flow (Fig. 9). These areas are too young to have enough soil or too unstable due to loose lava rock to be able to support much vegetation. Shrubs such as Apache plume *(Fallugia paradoxa),* New Mexico olive *(Forestiera pubescens),* and fragrant ash *(Fraxinus cuspidata)* are common, as are a variety of grasses such as blue grama *(Bouteloua gracilis)* and sideoats grama *(Bouteloua curtipendula).* Normally shaped but dwarfed ponderosa and piñon pines are sometimes found in open "bonsai" or "pygmy" forests that are visible from parts of

FIGURE 8—Grassland with scattered one-seed juniper (*Juniperus monosperma*) on the Old Basalt along lower Cibola County Road 42. The cattle are in a natural playa-like depression. The Chain of Craters is visible in the distance. (© David L. Bleakly, 1995)

FIGURE 9—Aa lava in the upper Bandera flow. This material is too unstable to support plant growth. (© David L. Bleakly, 1995)

NM-117. Many very distorted, twisted conifers (Fig. 10) are also found on the McCartys flow and sometimes on the Bandera flow, usually on pahoehoe lava.

Cinders compose an unusual, loose substrate whose vegetation resembles in some ways that on sedimentary soils. As stated above, piñon /juniper woodland is found on cinders as well as in the sandy soil of sedimentary outcrops. Although untested, it is possible that since cinders have often collected in deep banks or around cinder cones, water may be more abundant than it seems below the surface of such areas, as it is in sand dunes. This may explain the presence of alligator juniper *(Juniperus deppeana),* a species that requires more water than other junipers (Dick-Peddie, 1993), only on cinders in the monument area. Cinders appear to be quite different than sediments as a plant substrate because of the different plants that grow on them. For example, Cinders phacelia *(Phacelia serrata)* is a rare plant that is restricted to cinders. Its sole known occurrence in New Mexico is in the Bandera Crater area. Until 1993 it was known only from the San Francisco volcanic field in northern Arizona. Also some other plants are found

FIGURE 10—A twisted ponderosa pine near the edge of a lava tube on the Bandera flow. Note the normally shaped trees beyond. It is not known how or why such trees grow this way. (© David L. Bleakly, 1995)

FIGURE 11—Quaking aspens (*Populus tremuloides*) between the Bandera and Twin Craters flows near Twin Craters cinder cone. In the monument, these trees grow mostly between or at the edges of flows. Extra moisture in these areas promotes denser plant growth to cause an "edge effect". (© David L. Bleakly, 1995)

only on cinder cones within the monument, e.g. limber pine *(Pinus flexilis)* and bracken fern *(Pteridium aquilinum).*

An interesting phenomenon is the "edge effect.' The boundaries between the lava flows and betweer lava flows and the surrounding grass /shrublands are obvious not only topographically and geologically but also vegetationally. The denser vegetation usually found in these areas is apparently caused by collection of runoff from the non-lava substrates and from the lava itself at the outside edges. Aspens are found only at lava-flow boundaries (Fig. 11) or occasionally in small collapses within the flows.

Ice-cave communities are unique and fascinating features of El Malpais. They are located in certain deep lava tubes, particularly in the Bandera flow, and contain often massive deposits of ice year-round, usually near their entrances. Access to the caves is via collapsed sections of the tube. Important ice caves include the commercial Ice Caves (also called Candelaria Ice Cave), Marchantia, and Navajo Caves. Strong gradients of temperature, moisture, and light near their entrances have allowed the establishment of rare and unusual communities. The collapses are colder, wetter, and darker at the bottom but become progressively warmer, drier, and brighter toward the top. In each ice cave, a consistent sequence of bands of different lichen species is found at different levels within the collapses (Fig. 12). Liverworts such as *Marchantia polymorpha* also grow here and are very unusual occurrences at this elevation and under these circumstances. Dense mounds of mosses grow in many ice-cave entrances. A type of gooseberry, *Ribes inerme,* apparently occurs exclusively in ice-cave collapses.

Flora

While the vegetation of El Malpais is interesting in itself, the individual plant species that compose it are equally so. Something could be written about each species, but this section will concentrate on only a few.

The plants discussed below are endemics (restricted to the locale), or rare, or localized, or uncommon; others grow only on the lava in the area; and still others are near the edges of their distributions in the monument.

The 441 plant species known to occur in El Malpais National Monument are listed in Appendices A and B. No such compilation is ever complete, as undocumented plants are almost always found when additional effort is made to look for them. Such plants may already be present but remain unnoticed for a number of reasons, e.g. they may be rare (few in number), bloom or grow early or late in the season, very small or cryptic (difficult to detect), grow only in special or inaccessible habitats, or be annuals that grow only in years with ideal conditions. In addition, some plants may be expanding into the survey area from the surroundings or may be artificially introduced. Twenty-nine plants (6.6% of the total) are introduced from regions outside of North America. The Asteraceae (Sunflower family) contains the largest number of genera (52) and species (92). Other families represented by more than 10 species, in descending order, followed by genera and species in parenthesis, are Poaceae (Grass family, 29, 65), Fabaceae (Pea family, 13, 27), Brassicaceae (Mustard family, 13, 19), Scrophulariaceae (Figwort family, 8, 12), Chenopodiaceae (Goosefoot family, 7, 12), Cyperaceae (Sedge family, 5, 11), Rosaceae (Rose family, 7, 10), Cactaceae (Cactus family, 4, 10), and Polygonaceae (Knotweed family, 3, 10). The largest genera (with more than 5 species) are *Muhlenbergia* (Poaceae, 11 species), *Astragalus* (Fabaceae, 9 species), *Ericameria* (formerly *Chrysothamnus,* 8 species), *Erigeron* (Asteraceae, 7 species), *Aristida* (Poaceae, 6 species), *Artemisia* (Asteraceae, 6 species), and *Mirabilis* (Nyctaginaceae, 6 species).

Cinders phacelia, mentioned earlier, is known only from the Bandera Crater area and from the San Francisco volcanic field in northern Arizona. This plant was discovered in New Mexico by Paul Knight, former New Mexico state botanist, in 1993 during a road survey. It is common on the black cindery road-cut that crosses the hill east of the turnoff to Candelaria Ice Cave (Fig. 13). It is listed in New Mexico as rare and sensitive and by the U.S. Fish and Wildlife Service as C2 (needs additional information to support a proposal to list as threatened or endangered; Sivinski and Lightfoot, 1994).

Two milkvetches found in the monument, *Astragalus egglestonii* and *Astragalus mollissimus matthewsii,* are endemic to the area. The former is found only in west-central New Mexico and adjacent Arizona and the latter only in west-central and northwestern New Mexico. They are uncommon in the monument and like many other milkvetches may be difficult to identify in the field. The milkvetches comprise arguably the largest genus of plants in the world with about 2000 species. Their greatest abundance is in the western United States where there are hundreds of species and scores of endemics. Nine astragali in all have been found in the monument.

There are a few other seldom seen plants at El Malpais that grow only in Arizona and New Mexico. Navajo cinquefoil *(Potentilla subviscosa)* is an early blooming, small plant that grows only at higher elevations in the two states. Another mountainous plant in this category is upright blue beardtongue *(Penstemon virgatus).* Others are slimleaf bean *(Phaseolus angustissimus),* an inconspicuous, trailing relative of the garden bean, and Chihuahuan yellowcress *(Rorippa microtitis).*

FIGURE 12—Lichen Ice Cave near Candelaria Ice Cave showing bands of lichens and mosses. Ice caves in El Malpais almost always support the same sequence of cryptogams within them. (© David L. Bleakly, 1995)

Many people may be surprised to learn that nine ferns have been found on the lava flows and cinder cones at El Malpais. Four of these, two lipferns *(Cheilanthes* sp.), smooth cliffbrake *(Pellaea glabella),* and Plummer cliff fern (*Woodsia plummerae),* are small, xerically adapted (evolved to live in dry habitats), and often grow on other substrates elsewhere in the Southwest. All four grow in small cracks with shady exposures. Plummer cliff fern is the most frequently encountered fern in the monument (Fig. 14). Bracken *(Pteridium aquilinum),* male fern *(Dryopteris filix-mas),* and two *Asplenium* species (grass fern and maidenhair spleenwort) are typically found in mesic (moist) habitats, so their presence in El Malpais gives more support to the concept that lava flows are mesic islands

FIGURE 13—Cinders phacelia (*Phacelia serrata*) grows only on cinders and is known only from the Bandera Crater area of El Malpais and the San Francisco volcanic field in northern Arizona. This plant is protected by state law. (© David L. Bleakly, 1995)

FIGURE 14—Plummer woodsia (*Woodsia plummerae*) is the most common and widespread fern in El Malpais. It grows in partially shaded cracks usually in vertical faces on all the lava flows. (© David L. Bleakly, 1995)

FIGURE 15—Grass fern (*Asplenium septentrionale*) is an inconspicuous, grasslike fern often found in small cracks on the sides of north–south oriented pressure ridges in the McCartys flow. (© David L. Bleakly, 1995)

(or mountainlike). Bracken is a large colonial plant and covers much of the upper slopes of Bandera Crater. It is the most widespread vascular plant in the world. Male fern is also large but uncommon, and typically is found in collapse structures and a few other moist, shady habitats. Maidenhair spleenwort *(Asplenium trichomanes)* is a medium-size fern, rare in the monument, which was originally found in a collapse structure in the McCartys flow that was destroyed during the construction of 1-40 (Lindsey, 1945). Grass fern *(Asplenium septentrionale)* is an interesting occurrence. It is found most commonly on the McCartys flow where it typically grows on the sides of north—south oriented cracks (Fig. 15). This inconspicuous, grasslike, and uncommon plant grows mostly in the central Rocky Mountains at widely scattered, more mesic localities. Water-clover *(Marsilea mollis)* is another unexpected occurrence, since it grows in standing water or mud which is rare at El Malpais. It was found in a natural playa-like depression southwest of Holein-the-Wall in 1991, but not in 1992 or 1993. It was probably brought in by migrating waterfowl but did not become established.

A few plants grow only on lava in the monument area, but elsewhere they are usually or typically found on other substrates. Such plants include Douglas-fir, taperleaf *(Pericome caudata),* Mogollon geranium *(Geranium lentum),* blackspine hedgehog cactus, and all the ferns except bracken. Bracken, cinders phacelia, and limber pine were found only on cinders in the monument. Most of these plants grow on lava or cinders in El Malpais probably because of the increased moisture availability. Douglas-fir is, of course, widespread in the western United States, including the Zuni Mountains, but it is rare at the relatively low elevations of the lava flows. However, it is fairly common on the upper Bandera flow near Candelaria Ice Cave. As stated above, some of these trees are the oldest Douglas-firs in North America. Taperleaf is an easily recognized shrub in the Sunflower family with bright green, triangular, long-pointed leaves. Mogollon geranium (Fig. 16) is much more common south of El Malpais. It is often seen growing on the lava to the very edge, but never on the adjacent alluvium. This plant is widespread in the monument; many may be seen near the Narrows picnic area. Blackspined hedge-

FIGURE 16—In El Malpais, Mogollon geranium (*Geranium lentum*) grows only on the lava flows, where it is quite common. (© David L. Bleakly, 1995)

FIGURE 17—Huge clumps of blackspined hedgehog cacti (*Echinocereus coccineus*) are found on the summit of Lost Woman Crater. (© David L. Bleakly, 1995)

FIGURE 18—Mexican campion (*Silene laciniata*) is occasionally found on sedimentary substrates. (© David L. Bleakly, 1995)

FIGURE 19—Showy fameflower (*Talinum pulchellum*) is found only in limy soil at El Malpais. (© David L. Bleakly, 1995)

hog cactus is the most frequently seen ball-type cactus in the monument. Small clusters of it are abundant in cracks in pahoehoe lava on all the flows. Gigantic mounds of the cactus, the largest the author has ever seen, grow on the summit of Lost Woman Crater (Fig. 17). Increased supply water as well as warmer temperatures may explain the commonness of this cactus on the lava.

Several plants are near the edges of their distributions in El Malpais area. Such species help to characterize the floristic affinities of the monument better than wide-ranging species like fourwing saltbush *(Atriplex canescens),* yarrow *(Achillea millefolium),* or prairie sunflower *(Helianthus petiolaris).* Blue pygmyflower *(Monnina wrightii),* Chihuahuan prairieclover *(Dalea exigua),* Huachuca Mountain morning glory *(Ipomoea plummerae),* Mexican campion *(Silene laciniata,* Fig. 18), showy fameflower *(Talinum pulchellum,* Fig. 19), harlequin spiralseed *(Schistophragma intermedia),* waterclover *(Marsilea mollis),* Torrey craglily *(Echeandia flavescens),* mountain gromwell *(Lithospermum cobrense),* and cream pincushion cactus *(Mammillaria heyderi meiacantha)* all are primarily Mexican plants near the northern edges of their distributions. Piñon groundsmoke *(Gayophytum ramosissimum),* Nuttall larkspur *(Delphinium nuttallianum),* woolly cinquefoil *(Potentilla hippiana),* Drummond willow *(Salix drummondiana),* and cutleaf nightshade *(Solanum triflorum)* all are northern (mostly Rocky Mountain) in distribution. These two components helped McLaughlin (1989, 1992) place El Malpais in the Southern Rocky Mountain—Mogollon Floristic Region, as discussed above. Other floristic areas have contributed to the monument's diversity as well. Cane cholla *(Opuntia imbricata),* spotted beebalm *(Monarda punctata),* annual wild buckwheat *(Eriogonum annum),* and plains coreopsis *(Coreopsis tinctoria)* are near the western edges of their distributions and constitute a Great Plains element. Organ Mountain larkspur *(Delphinium wootonii)* grows from southeastern Colorado and southeastern Arizona to west Texas and is at its northwestern boundary in the monument area. Dwarf rabbitbrush *(Ericameria depressus)* is centered in the Intermountain region (Great Basin) to the northwest. Horseshoe mousetail *(Myosurus cupulatus)* is found most commonly west of El Malpais, in southern Arizona and northwestern Mexico.

Despite its forbidding appearance and rough topography, El Malpais National Monument supports fascinating vegetation and a variety of plants that are still only partially known. An appreciation of the unusual habitats and associated plantlife in El Malpais can provide a lifetime of enjoyment for those willing to explore the lava flows with open eyes and minds.

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Appendix A
Vascular plants from El Malpais National Monument area

List of all vascular plants identified from 1991–1996 mostly from El Malpais National Monument proper, but also from the Candelaria property (near the Ice Caves and Bandera Crater) which is not currently part of the monument, and the roadsides of NM–117, NM–53 (including the Gallo Spring area), and Cibola County Road 42. Arranged by groups (ferns and allies, gymnosperms, dicots, and monocots) and, within groups, alphabetically by family, genus, and species. The number of families and genera in parentheses follows each group heading. Family names according to Kartesz (1994). The number of genera and taxa (species, subspecies, and varieties) in parentheses after the family names. The ***correct nomenclature*** (in this document) in ***bold italics***. Names of ferns and allies and gymnosperms according to Flora of North America, Vol. 2 (1993), Brassicaceae according to Rollins (1993), Poaceae according to Allred (1993), and most other plants according to Kartesz (1994); some exceptions according to more recent literature. An "at" sign (@) means plant is introduced (adventive; 29 total). *Synonyms* in *italics* for some names (A = according to Allred; K = Kartesz; R = Rollins). COMMON NAMES in CAPITAL LETTERS, from various sources. This list contains 441 plants (including subspecific taxa) in 70 families.

LARGEST FAMILIES (# of genera / # of taxa): Asteraceae (52 / 92), Poaceae (29 / 65), Fabaceae (13 / 27), Brassicaceae (13 / 19), Chenopodiaceae (7 / 12), Scrophulariaceae (8 / 12), Cyperaceae (5 / 11), Cactaceae (4 / 10), Polygonaceae (3 / 10), Rosaceae (7 / 10), Euphorbiaceae (4 / 9), Lamiaceae (6 / 9), Nyctaginaceae (2 / 8), Onagraceae (3 / 8), Boraginaceae (3 / 7), Solanaceae (4 / 6).
LARGEST GENERA (# of taxa): *Muhlenbergia* (11), *Astragalus* (9), *Ericameria* (*Chrysothamnus*; 8), *Erigeron* (7), *Aristida* (6), *Artemisia* (6), *Mirabilis* (6), *Chenopodium* (5), *Dalea* (5), *Elymus* (5), *Eriogonum* (5), *Penstemon* (5).

FERNS AND ALLIES (nomenclature according to Flora of North America, Vol. 2; 6 / 10)

ASPLENIACEAE Spleenwort family (1 / 2)
Asplenium septentrionale (L.) Hoffman GRASS FERN
Asplenium trichomanes L. ssp. ***trichomanes*** MAIDENHAIR SPLEENWORT

DENNSTAEDTIACEAE Bracken family (1 / 1)
Pteridium aquilinum (L.) Kuhn var. ***pubescens*** Underw. WESTERN BRACKEN

DRYOPTERIDACEAE Wood Fern family (2 / 2)
Dryopteris filix-mas (L.) Schott MALE FERN
Woodsia plummerae Lemmon PLUMMER CLIFF FERN

MARSILEACEAE Pepperwort family (1 / 1)
Marsilea mollis B.L. Robins. & Fern. WATER CLOVER

PTERIDACEAE Maidenhair Fern family (2 / 3)
Cheilanthes feei T. Moore SLENDER LIPFERN
Cheilanthes fendleri Hook. FENDLER LIPFERN
Pellaea glabella Mett. *ex* Kuhn ssp. ***simplex*** (Butters) A. & D. Löve SMOOTH CLIFFBRAKE

SELAGINELLACEAE Spikemoss family (1 / 1)
Selaginella densa Rydb. ROCKY MOUNTAIN SPIKEMOSS

GYMNOSPERMS (nomenclature according to Flora of North America, Vol. 2; 2 / 7)

CUPRESSACEAE Cypress family (1 / 3)
Juniperus deppeana Steud. ALLIGATOR JUNIPER
Juniperus monosperma (Engelm.) Sarg. ONESEED JUNIPER
Juniperus scopulorum Sarg. ROCKY MOUNTAIN JUNIPER

PINACEAE Pine family (2 / 4)
Pinus edulis Engelm. COLORADO PINYON
Pinus flexilis James LIMBER PINE
Pinus ponderosa Dougl. *ex* Lawson & C. Lawson var. ***scopulorum*** MOUNTAIN PONDEROSA PINE
Pseudotsuga menziesii (Mirbel) Franco var. ***menziesii*** DOUGLAS-FIR

DICOTS (nomenclature according to Kartesz (1994), except where noted; 55 / 338)

AMARANTHACEAE Pigweed family (1 / 3)
@ ***Amaranthus albus*** L. PALE PIGWEED
@ ***Amaranthus blitoides*** S. Wats. PROSTRATE PIGWEED
@ ***Amaranthus retroflexus*** L. REDROOT or ROUGH PIGWEED

ANACARDIACEAE Sumac family (1 / 2)
Rhus glabra L. SMOOTH SUMAC
Rhus trilobata Nutt. var. ***trilobata*** SKUNKBUSH

APIACEAE (*UMBELLIFERAE*) Parsley family (2 / 3)
Cymopterus acaulis (Pursh) Raf. var. ***fendleri*** (Gray) Goodrich FENDLER SPRINGPARSLEY
Cymopterus purpurascens (Gray) M.E. Jones WIDEWING SPRINGPARSELY
Pseudocymopterus montanus (Gray) Coult. & Rose MOUNTAIN PARSLEY

APOCYNACEAE Dogbane family (1 / 1)
Apocynum sp. DOGBANE

ASCLEPIADACEAE Milkweed family (1 / 3)
Asclepias asperula (Dcne.) Woods. ssp. ***asperula*** SPIDER MILKWEED
Asclepias subverticillata (Gray) Vail WHORLED MILKWEED
Asclepias tuberosa L. ssp. ***interior*** Woods. ORANGE MILKWEED

ASTERACEAE (*COMPOSITAE*) Sunflower family (52 / 92)
Achillea millefolium L. var. ***occidentalis*** DC. YARROW
@ ***Acroptilon repens*** (L.) DC. (*Centaurea repens* L.) RUSSIAN KNAPWEED

Ageratina herbacea (Gray) King & H.E. Robins. (*Eupatorium herbaceum* (Gray) Greene WHITE THOROUGHWORT
Ambrosia artemisiifolia L. COMMON RAGWEED
Ambrosia tomentosa Nutt. SKELETONLEAF BURR RAGWEED
Anaphalis margaritacea (L.) Benth. & Hook. f. PEARLY EVERLASTING
Antennaria parvifolia Nutt. PUSSYTOES
Artemisia campestris L. ssp. ***pacifica*** (Nutt.) Hall & Clements WESTERN SAGEWORT
Artemisia carruthii Wood *ex* Carruth. CARRUTH WORMWOOD
Artemisia dracunculus L. SILKY WORMWOOD, TARRAGON
Artemisia filifolia Torr. SAND SAGEBRUSH
Artemisia frigida Willd. FRINGED SAGEBRUSH
Artemisia ludoviciana Nutt. LOUISIANA WORMWOOD
Aster falcatus see Symphyotrichum falcatum
Bahia dissecta (Gray) Britt. CUTLEAF
Brickellia brachyphylla (Gray) Gray PLUME BRICKELLBUSH
Brickellia eupatorioides (L.) Shinners var. ***chlorolepis*** (Woot. & Standl.) B.L. Turner SOUTHWEST KUHNIA
Brickellia grandiflora (Hook.) Nutt. TASSELFLOWER
Centaurea repens see Acroptilon repens
Chaetopappa ericoides (Torr.) Nesom (*Leucelene ericoides* (Torr.) Greene) WHITE ASTER
Chrysothamnus sp see Ericameria sp.
Cirsium neomexicanum Gray NEW MEXICO THISTLE
Cirsium ochrocentrum Gray YELLOWSPINE THISTLE
@ ***Cirsium vulgare*** (Savi) Ten. BULL THISTLE
Cirsium wheeleri (Gray) Petrak WHEELER THISTLE
Conyza canadensis (L.) Cronq. HORSEWEED
Coreopsis tinctoria Nutt. var. ***tinctoria*** PLAINS COREOPSIS
Cosmos parviflorus (Jacq.) Pers. SOUTHWEST COSMOS
Dyssodia papposa (Vent.) A.S. Hitchc. (*Tagetes papposa* Vent.) FETID MARIGOLD, MAYWEED
Ericameria depressa (Nutt.) L.C. Anders. (K = *Chrysothamnus depressus* Nutt.) DWARF RABBITBRUSH (Anderson 1995)
Ericameria filifolia (Rydb.) L.C. Anders. (K = *Chrysothamnus greenei* (Gray) Greene) GREENE RABBITBRUSH (Anderson 1995)
Ericameria nauseosa (Pallas *ex* Pursh) Nesom & Baird ssp. ***consimilis*** (Greene) Nesom & Baird var. ***arta*** (A. Nels.) Nesom & Baird (K = *Chrysothamnus nauseosus* ssp. *consimilis* (Greene) Hall & Clements) RUBBER RABBITBRUSH (Nesom & Baird 1993)
Ericameria nauseosa (Pallas *ex* Pursh) Nesom & Baird ssp. ***nauseosa*** var. ***bigelovii*** (Gray) Nesom & Baird (K = *Chrysothamnus nauseosus* (Pallas *ex* Pursh) Britt. ssp. *bigelovii* (Gray) Hall & Clements) BIGELOW RUBBER RABBITBRUSH (Nesom & Baird 1993)
Ericameria nauseosa (Pallas *ex* Pursh) Nesom & Baird ssp. ***nauseosa*** var. ***nauseosa*** (K = *Chrysothamnus nauseosus* ssp. *nauseosus* RUBBER RABBITBRUSH (Nesom & Baird 1993)
Ericameria parryi (Gray) Nesom & Baird var. ***attenuata*** (M.E. Jones) Nesom & Baird (K = *Chrysothamnus parryi* (Gray) Greene ssp. *attenuatus* (M.E. Jones) Hall & Clements PARRY RABBITBRUSH (Nesom & Baird 1993)
Ericameria viscidiflora (Hook.) L.C. Anders. ssp. ***lanceolata*** (Nutt.) L.C. Anders. (K = *Chrysothamnus viscidiflorus* (Hook.) Nutt. ssp. *lanceolatus* (Nutt.) Hall & Clements LANCELEAF RABBITBRUSH (Anderson 1995)
Ericameris viscidiflora (Hook.) L.C. Anders. ssp. ***viscidiflora*** var. ***stenophylla*** (Gray) L.C. Anders. (K = *Chrysothamnus viscidiflorus* ssp *viscidiflorus* var. *stenophyllus* (Gray) Hall VISCID RABBITBRUSH (Anderson 1995)
Erigeron canus Gray HOARY FLEABANE
Erigeron colomexicanus A. Nels. RUNNNING FLEABANE
Erigeron divergens Torr. & Gray SPREADING FLEABANE
Erigeron flagellaris Gray TRAILING FLEABANE
Erigeron formosissimus Greene var. ***formosissimus*** BEAUTIFUL FLEABANE
Erigeron speciosus (Lindl.) DC. ASPEN FLEABANE
Erigeron vetensis Rydb. LA VETA FLEABANE
Eupatorium herbaceum see Ageratina herbacea
Gaillardia pinnatifida Torr. HOPI BLANKET FLOWER
Grindelia nuda Wood var. ***aphanactis*** (Rydb.) Nesom MOUNTAIN GUMWEED
Gutierrezia sarothrae (Pursh.) Britt. & Rusby BROOM SNAKEWEED
Helianthella quinquenervis (Hook.) Gray FALSE SUNFLOWER
Helianthus annuus L. COMMON SUNFLOWER
Helianthus ciliaris DC. BLUEWEED
Helianthus petiolaris Nutt. PRAIRIE or PLAINS SUNFLOWER
Heliomeris multiflora Nutt. var. ***nevadensis*** (A. Nels.) Yates (*Viguiera multiflora* (Nutt.) Blake) SHOWY GOLDENEYE
Heterosperma pinnatum Cav. FINELEAF HETEROSPERMA
Heterotheca villosa (Pursh) Shinners var. ***villosa*** HAIRY GOLDEN-ASTER
Hieracium fendleri Schultz-Bip. var. ***fendleri*** FENDLER HAWKWEED
Hymenopappus filifolius Hook. var. ***cinereus*** (Rydb.) I.M. Johnston HYALINE HERB, WOOLLYWHITE
Hymenopappus flavescens Gray var. ***canotomentosus*** Gray YELLOW WOOLLYWHITE
Hymenopappus flavescens Gray var. ***flavescens*** YELLOW WOOLLYWHITE
Hymenoxys argentea see Tetraneuris argentea
Hymenoxys bigelovii (Gray) Parker BITTERWEED
Hymenoxys richardsonii (Hook.) Cockerell PINGUE, COLORADO RUBBERWEED
@ ***Lactuca serriola*** L. PRICKLY LETTUCE
Machaeranthera canescens (Pursh) Gray ssp. **glabra** (Gray) B.L. Turner var. **glabra** Gray (*Machaeranthera linearis* Greene) HOARY TANSYASTER
Machaeranthera gracilis (Nutt.) Shinners GOLDENWEED
Machaeranthera pinnatifida (Hook.) Shinners ssp. ***pinnatifida*** var. ***pinnatifida*** (*Haplopappus spinulosus* (Pursh) DC.; *Machaeranthera australis* (Greene) Shinners) GOLDENWEED
Machaeranthera tanacetifolia (Kunth) Nees TANSYLEAF ASTER
Malacothrix fendleri Gray FENDLER DESERT DANDELION

Pericome caudata Gray TAPERLEAF
Picradeniopsis woodhousei (Gray) Rydb. WOODHOUSE BAHIA
Psilostrophe tagetina (Nutt.) Greene WOOLLY PAPERFLOWER
Ratibida columnifera (Nutt.) Woot. & Standl. PRAIRIE CONEFLOWER
Sanvitalia abertii Gray ALBERT CREEPING ZINNIA
Schkuhria multiflora Hook. & Arn. THREADLEAF
Senecio flaccidus Less. var. ***flaccidus*** (*Senecio douglasii* DC. var. *longilobus* (Benth.) L. Benson) DOUGLAS GROUNDSEL
Senecio multicapitatus Greenm. *ex* Rydb. RAGWORT GROUNDSEL
Senecio multilobatus Torr. & Gray *ex* Gray UINTA GROUNDSEL
Senecio neomexicanus Gray var. ***mutabilis*** (Greene) T.M. Barkl. NEW MEXICO GROUNDSEL
Solidago velutina DC. THREE-NERVE GROUNDSEL
Solidago wrightii Gray var. ***adenophora*** Blake WRIGHT GOLDENROD
@ ***Sonchus asper*** (L.) Hill SPINY SOW THISTLE
Stephanomeria pauciflora (Torr.) A. Nels. FEWFLOWER WIRELETTUCE
Stephanomeria tenuifolia (Raf.) Hall SLENDER WIRELETTUCE
Symphyotrichum falcatum (Lindl.) Nesom var. ***commutatum*** (Torr. & Gray) Nesom (K = *Aster falcatus* Lindl. ssp. *commutatus* (Torr. & Gray) A.G. Jones) CLUSTERED ASTER (Nesom 1994)
Tagetes micrantha Cav. LICORICE MARIGOLD
Tagetes papposa see Dyssodia papposa
@ ***Taraxacum officinale*** G.H. Weber *ex* Wiggers COMMON DANDELION
Tetradymia canescens DC. GREY HORSEBRUSH
Tetraneuris argentea (Gray) Greene (*Hymenoxys argentea* (Gray) Parker) BITTERWEED
Thelesperma megapotamicum (Spreng.) Kuntze GREENTHREAD, HOPI TEA
Townsendia exscapa (Richards.) Porter EASTER DAISY
Townsendia incana Nutt. HOARY TOWNSENDIA
@ ***Tragopogon dubius*** Scop. WESTERN SALSIFY
@ ***Tragopogon pratensis*** L. MEADOW SALSIFY
Verbesina encelioides (Cav.) Benth. & Hook. f. *ex* Gray ssp. ***encelioides*** GOLDEN CROWNBEARD
Verbesina encelioides (Cav.) Benth. & Hook. f. *ex* Gray ssp. ***exauriculata*** (Robins. & Greenm.) J.R. Coleman GOLDEN CROWNBEARD
Viguiera see Heliomeris
Xanthium strumarium L. var. ***canadense*** (P. Mill.) Torr. & Gray COCKLEBUR
Zinnia grandiflora Nutt. ROCKY MOUNTAIN ZINNIA

BERBERIDACEAE Barberry family (2 / 3)
Berberis fendleri Gray FENDLER BARBERRY
Mahonia haematocarpa (Woot.) Fedde RED BARBERRY
Mahonia repens (Lindl.) G. Don CREEPING MAHONIA

BORAGINACEAE Borage family (3 / 7)
Cryptantha cinerea (Greene) Cronq. (*Cryptantha jamesii* (Torr.) Payson) JAMES HIDDENFLOWER
Cryptantha crassisepala (Torr. & Gray) Greene PLAINS CRYPTANTHA
Cryptantha fendleri (Gray) Greene FENDLER CRYPTANTHA
Lappula occidentalis (S. Wats.) Greene (Lappula redowskii *auct. non* (Hornem.) Greene STICKSEED
Lithospermum cobrense Greene MOUNTAIN GROMWELL
Lithospermum incisum Lehm. NARROWLEAF PUCCOON, SHOWY STONESEED
Lithospermum multiflorum Torr. *ex* Gray MANYFLOWER PUCCOON

BRASSICACEAE (*CRUCIFERAE*) Mustard family (nomenclature according to Rollins 1993; 13 / 19)
Arabis fendleri (S. Wats.) Greene var. ***fendleri*** FENDLER ROCKCRESS
Arabis fendleri (S. Wats.) Greene var. ***spatifolia*** (Rydb.) Rollins FENDLER ROCKCRESS
Arabis perennans S. Wats. COMMON ROCKCRESS
Descurainia incisa (Engelm. *ex* Gray) Britt. ssp. ***incisa*** (K = *D. incana* (Bernh. *ex* Fisch. & C.A. Mey.) Dorn ssp. *incisa* (Engelm. *ex* Gray) Kartesz & Gandhi) MOUNTAIN TANSY MUSTARD
Descurainia obtusa (Greene) O.E. Schulz ssp. ***obtusa*** (K = *D. obtusa* ssp. *brevisiliqua* Detling) DESERT TANSY MUSTARD
Descurainia pinnata (Walt.) Britt. ssp. ***halictorum*** (Cockerell) Detling PINNATE or WESTERN TANSY MUSTARD
Dimorphocarpa wislizenii (Engelm.) Rollins SPECTACLEPOD
Draba cuneifolia Nutt. *ex* Torr. & Gray WEDGELEAF WHITLOW GRASS
Erysimum capitatum (Dougl. *ex* Hook.) Greene PLAINS or WESTERN WALLFLOWER
Lepidium densiflorum Schrad. PRAIRIE PEPPERWEED or PEPPERGRASS, DENSECRESS
Lepidium ramosissimum A. Nels. BUSHY PEPPERGRASS
Lesquerella rectipes Woot. & Standl. COLORADO BLADDERPOD
Pennellia micrantha (Gray) Nieuwl. MOUNTAIN MOCK THELYPODY
Rorippa microtitis (B.L. Robins.) Rollins CHIHUAHUAN YELLOWCRESS
Rorippa sinuata (Nutt. *ex* Torr. & Gray) A.S. Hitchc. SPREADING YELLOWCRESS
Schoenocrambe linearifolia (Gray) Rollins (*Thelypodiopsis linearifolia* (Gray) Al-Shehbaz) SLIMLEAF PLAINSMUSTARD
@ ***Sisymbrium altissimum*** L. TALL TUMBLEMUSTARD
Thelypodium wrightii Gray WRIGHT TELYPODY
Thlaspi montanum L. var. ***fendleri*** (Gray) P. Holmgren ALPINE PENNYCRESS

CACTACEAE Cactus family(4 / 10)
Echinocereus coccineus Engelm. (*Echinocereus triglochidiatus* Engelm. var. *melanacanthus* (Engelm.) L. Benson) BLACKSPINED HEDGEHOG CACTUS
Echinocereus fendleri (Engelm.) F. Seitz FENDLER HEDGEHOG
Echinocereus triglochidiatus Engelm. var. ***triglochidiatus*** CLARET CUP CACTUS
Escobaria vivipara (Nutt.) Buxbaum var. ***arizonica*** (Englem.) D.R. Hunt (*Coryphantha vivipara* (Nutt.) Britt. & Rose) SPINYSTAR, ARIZONA BEEHIVE CACTUS
Mammillaria heyderi Muehlenpfordt var. ***meiacantha*** (Engelm.) L. Benson CREAM PINCUSHION CAC-

TUS

Mammillaria wrightii Engelm. var. ***wrightii*** WRIGHT NIPPLE CACTUS
Opuntia imbricata (Haw.) DC. WALKINGSTICK CHOLLA
Opuntia macrorhiza Engelm. LOW PRICKLY PEAR
Opuntia phaeacantha Engelm. BROWNSPINE PRICKLY PEAR
Opuntia polyacantha Haw. PLAINS PRICKLY PEAR

CAPPARACEAE Caper family (1 / 1)
Cleome serrulata Pursh ROCKY MOUNTAIN BEE--PLANT

CARYOPHYLLACEAE Pink family (3 / 5)
Arenaria fendleri Gray var. ***fendleri*** FENDLER SANDWORT
Arenaria lanuginosa (Michx.) Rohrb. ssp. ***saxosa*** (Gray) Maguire SPREADING SANDWORT
Drymaria glandulosa K. Presl FENDLER DRYMARY
Silene laciniata Cav. MEXICAN CAMPION or CATCHFLY
Silene scouleri Hook. ssp. ***scouleri*** SCOULER CATCHFLY

CHENOPODIACEAE Goosefoot family (7 / 12)
Atriplex canescens (Pursh) Nutt. FOURWING SALTBUSH
Ceratoides see Krascheninnikovia
Chenopodium capitatum (L.) Aschers. STRAWBERRY BLITE or SPINACH
Chenopodium dessicatum A. Nels. DESERT GOOSEFOOT
Chenopodium fremontii S. Wats. FREMONT GOOSEFOOT
Chenopodium graveolens Willd. RAGLEAF GOOSEFOOT
Chenopodium leptophyllum (Moq.) Nutt. *ex* S.Wats. NARROWLEAF GOOSEFOOT
@ ***Kochia scoparia*** (L.) Schrad. FIREWEED, SUMMER or MOCK CYPRESS
Krascheninnikovia lanata (Pursh) Guldenstaedt (*Ceratoides lanata* (Pursh) J.T. Howell; *Eurotia lanata* (Pursh) Moq.) WINTERFAT
Monolepis nuttalliana (J.A. Schultes) Greene NUTTALL POVERTYWEED
@ ***Salsola kali*** L. RUSSIAN THISTLE
@ ***Salsola paulsenii*** Litv. BARBWIRE RUSSIAN THISTLE
Suckleya suckleyana (Torr.) Rydb. POISON SUCKLEYA

CONVOLVULACEAE Morningglory family (3 / 6)
@ ***Convolvulus arvensis*** L. FIELD BINDWEED
Convolvulus equitans Benth. GREY BINDWEED
Evolovulus nuttallianus Roemer & J.A. Schultes SHAGGY DWARF MORNING GLORY
Ipomoea costellata Torr. CRESTRIB MORNING GLORY
Ipomoea cristulata Hallier f. TRANSPECOS MORNING GLORY
Ipomoea plummerae Gray HUACHUCA MOUNTAIN MORNING GLORY

CUSCUTACEAE Dodder family (1 / 1)
Cuscusta umbellata Kunth FLATGLOBE DODDER

EUPHORBIACEAE Spruge family (4 / 9)
Acalypha neomexicana Muell.-Arg. NEW MEXICO COPPERLEAF or THREE-SEEDED MERCURY
Chamaesyce fendleri (Torr. & Gray) Small var. ***fendleri*** FENDLER SPURGE
Chamaesyce fendleri (Torr. & Gray) Small var. ***chaetocalyx*** (Boiss.) Shinners FENDLER SPURGE
Chamaesyce revoluta (Engelm.) Small THREADSTEM SPURGE
Chamaesyce serpyllifolia (Pers.) Small THYMELEAF SPURGE
Euphorbia bilobata Engelm. BLACKSEED EUPHORBIA
Euphorbia exstipulata Engelm. SQUARESEED SPURGE
Euphorbia lurida Engelm. SHORTHORNED SPURGE
Tragia ramosa Torr. CATNIP NOSEBURN

FABACEAE (*LEGUMINOSAE*) Pea family (13 / 27)
Astragalus brandegei Porter BRANDEGEE MILKVETCH
Astragalus calycosus Torr. *ex* S. Wats. var. ***scaposus*** (Gray) M.E. Jones TORREY MILKVETCH
Astragalus ceramicus Sheldon var. ***ceramicus*** PAINTED MILKVETCH
Astragalus egglestonii (Rydb.) Kearney & Peebles EGGLESTON MILKVETCH
Astragalus humistratus Gray var. ***humistratus*** GROUNDCOVER MILKVETCH
Astragalus humistratus Gray var. ***humivagans*** (Rydb.) Barneby GROUNDCOVER MILKVETCH
Astragalus mollissimus Torr. var. ***matthewsii*** (S. Wats.) Barneby MOGOLLON WOOLLY MILKVETCH
Astragalus praelongus Sheldon var. ***praelongus*** STINKING MILKVETCH
Astragalus wootonii Sheldon WOOTON MILKVETCH
Calliandra humilis Benth. DWARF STICKPEA
Dalea candida Willd. var. ***oligophylla*** (Torr.) Shinners SLENDER WHITE PRAIRIECLOVER
Dalea compacta Spreng. COMPACT PRAIRIECLOVER
Dalea exigua Barneby CHIHUAHUAN PRAIRIECLOVER
Dalea leporina (Ait.) Bullock FOXTAIL PRAIRIECLOVER
Dalea polygonoides Gray SIXWEEKS PRAIRIECLOVER
Lotus wrightii (Gray) Greene WRIGHT DEERVETCH
Lupinus argenteus Pursh ssp. ***argenteus*** var. ***argenteus*** SILVERY LUPINE
Lupinus kingii S. Wats. var. ***kingii*** KING LUPINE
@ ***Medicago lupulina*** L. BLACK MEDICK
@ ***Melilotus officinalis*** (L.) Lam. (includes *Medicago alba* Medic.) YELLOW SWEETCLOVER
Peteria scoparia Gray RUSH PETERIA, CAMOTE DEL MONTE
Phaseolus angustissimus Gray SLIMLEAF BEAN
Psoralidium lanceolatum (Pursh) Rydb. LEMON SCURFPEA
Psoralidium tenuiflorum (Pursh) Rydb. SLIMFLOWER SCURFPEA
Sophora nuttalliana B.L. Turner SILKY SOPHORA
Thermopsis rhombifolia (Nutt. *ex* Pursh) Nutt. *ex* Richards. var. ***montana*** (Nutt.) Isely MOUNTAIN GOLDENPEA
Vicia americana Muhl. *ex* Willd. ssp. ***minor*** (Hook.) C.R. Gunn AMERICAN VETCH

FAGACEAE Beech family (1 / 3)
Quercus gambelii Nutt. GAMBEL OAK

Quercus grisea Liebm. GREY OAK
Quercus x pauciloba Rydb. (pro. sp.) WAVYLEAF OAK

FUMARIACEAE Fumitory family (1 / 1)
Corydalis aurea Willd. GOLDENSMOKE, SCRAMBLED EGGS

GENTIANACEAE Gentian family (1 / 1)
Frasera speciosa Dougl. *ex* Griseb. ELKWEED

GERANIACEAE Geranium family (2 / 3)
@ ***Erodium cicutarium*** (L.) L'Hér. *ex* Ait. REDSTEM STORK'S BILL, FILARIA
Geranium caespitosum James TUFTED GERANIUM
Geranium lentum Woot. & Standl. MOGOLLON GERANIUM

GROSSULARIACEAE Gooseberry family (1 / 2)
Ribes cereum Dougl. (includes *R. inebrians* Lindl.) WAX CURRANT
Ribes inerme Rydb. WHITESTEM GOOSEBERRY

HYDROPHYLLACEAE Waterleaf family (2 / 3)
Nama dichotomum (Ruiz & Pavón) Choisy WISHBONE FIDDLELEAF
Phacelia alba Rydb. WHITE SCORPIONWEED
Phacelia serrata J. Voss CINDERS PHACELIA

LAMIACEAE (*LABIATAE*) Mint family (6 / 9)
Agastache pallidiflora (Heller) Rydb. ssp. ***pallidiflora*** var. ***gilensis*** R.W. Sanders x var. ***greenei*** (Briquet) R.W. Sanders NEW MEXICO GIANT HYSSOP
Hedeoma drummondii Benth. DRUMMOND FALSE-PENNYROYAL
Hedeoma nana (Torr.) Briq. LOW FALSE PENNYROYAL
@ ***Marrubium vulgare*** L. HOREHOUND
Monarda pectinata Nutt. PLAINS BEEBALM, HORSEMINT
Monarda punctata L. ssp. ***punctata*** var. ***lasiodonta*** Gray SPOTTED BEEBALM
Salvia reflexa Hornem. LANCELEAF SAGE
Salvia subincisa Benth. SAWTOOTH SAGE
Stachys rothrockii Gray ROTHROCK HEDGENETTLE

LINACEAE Flax family (1 / 3)
Linum aristatum Engelm. BRISTLE or AWNED FLAX
Linum lewisii Pursh PRAIRIE FLAX
Linum neomexicanum Greene NEW MEXICO YELLOW FLAX

LOASACEAE Loasa family (1 / 3)
Mentzelia albicaulis (Dougl. *ex* Hook.) Dougl. *ex* Torr. & Gray WHITESTEM BLAZINGSTAR
Mentzelia multiflora (Nutt.) Gray DESERT BLAZINGSTAR
Mentzelia pumila Nutt. *ex* Torr. & Gray DWARF MENTZELIA

MALVACEAE Mallow family (1 / 3)
Sphaeralcea coccinea (Nutt.) Rydb. SCARLET GLOBEMALLOW
Sphaeralcea digitata (Greene) Rydb. ssp. ***digitata*** JUNIPER GLOBEMALLOW
Sphaeralcea fendleri Gray FENDLER GLOBEMALLOW

MOLLUGINACEAE Carpetweed family (1 / 1)
Mollugo cerviana (L.) Ser. THREADSTEM CARPETWEED

MONOTROPACEAE Indian Pipe family (1 / 1)
Pterospora andromedea Nutt. WOODLAND PINEDROPS

NYCTAGINACEAE Four o'clock family (2 / 8)
Abronia elliptica A. Nels. FRAGRANT WHITE SAND VERBENA
Abronia fragrans Nutt. *ex* Hook. SNOWBALL SAND VERBENA
Mirabilis diffusa (Heller) C.F. Reed RIBBED SPREADING FOUR O'CLOCK
Mirabilis glabra (S. Wats.) Standl. SMOOTH FOUR O'CLOCK
Mirabilis linearis (Pursh) Heimerl NARROWLEAF FOUR O'CLOCK
Mirabilis multiflora (Torr.) Gray COLORADO FOUR O'CLOCK
Mirabilis oxybaphoides (Gray) Gray SMOOTH SPREADING FOUR O'CLOCK
Mirabilis pumila (Standl.) Standl. DWARF FOUR O'CLOCK

OLEACEAE Olive family (3 / 3)
Forestiera pubescens Nutt. var. ***pubescens*** (*Forestiera neomexicana* Gray)NEW MEXICO OLIVE
Fraxinus cuspidata Torr. FRAGRANT ASH
Menodora scabra Gray ROUGH MENODORA

ONAGRACEAE Evening Primrose family (3 / 8)
Gaura coccinea Nutt *ex* Pursh SCARLET BEEBLOSSOM
Gaura hexandra Ortega ssp. ***gracilis*** (Woot. & Standl.) Raven & Gregory HARLEQUINBUSH
Gaura parvifolia Dougl. *ex* Lehm. VELVETWEED
Gayophytum ramosissimum Torr. & Gray PINYON GROUNDSMOKE
Oenothera albicaulis Pursh WHITESTEM EVENING PRIMROSE
Oenothera caespitosa Nutt. ssp. ***marginata*** (Nutt. *ex* Hook. & Arn.) Munz TUFTED EVENING PRIMROSE
Oenothera coronopifolia Torr. & Gray CROWNLEAF EVENING PRIMROSE
Oenothera laciniata Hill CUTLEAF EVENING PRIMROSE

OROBANCHACEAE Broomrape family (1 / 2)
Orbanche ludoviciana Nutt. ssp. ***multiflora*** (Nutt.) Collins *comb. nov. ined.* MANYFLOWERED BROOMRAPE
Orobanche uniflora L. ONEFLOWERED BROOMRAPE

OXALIDACEAE Oxalis family (1 / 1)
@ ***Oxalis corniculata*** L. CREEPING WOODSORREL

PLANTAGINACEAE Plantain family (1 / 2)
Plantago argyrea Morris SILVERY PLANTAIN
Plantago patagonica Jacq. (*Plantago purhsii* Roemer & Schultes) WOOLLY PLANTAIN

POLEMONIACEAE Phlox family (3 / 6)
Gilia pinnatifida Nutt. *ex* Gray STICKY GILIA
Gilia sinuata Dougl. *ex* Benth. ROSY GILIA
Ipomopsis aggregata (Pursh) V. Grant ssp. ***formosissima*** (Greene) Wherry SCARLET SKYROCKET
Ipomopsis longiflora (Torr.) V. Grant WHITEFLOWER IPOMOPSIS
Ipomopsis multiflora (Nutt.) V. Grant MANYFLOWERED IPOMOPSIS
Phlox gracilis (Hook.) Greene SLENDER PHLOX

POLYGALACEAE Milkwort family (2 / 2)
Monnina wrightii Gray BLUE PYGMYFLOWER
Polygala alba Nutt. WHITE MILKWORT

POLYGONACEAE Knotweed family (3 / 10)
Eriogonum alatum Torr. WINGED WILD BUCKWHEAT
Eriogonum annuum Nutt. ANNUAL WILD BUCKWHEAT
Eriogonum cernuum Nutt. NODDING WILD BUCKWHEAT
Eriogonum jamesii Benth. var. ***jamesii*** JAMES WILD BUCKWHEAT
Eriogonum racemosum Nutt. REDROOT WILD BUCKWHEAT
Polygonum aviculare L. PROSTRATE KNOTWEED
Polygonum erectum L. ERECT KNOTWEED
Polygonum ramosissimum Michx. BUSHY KNOTWEED
@ ***Rumex crispus*** L. CURLY DOCK
Rumex salicifolius Weinm. var. ***mexicanus*** (Meisn.) C.L. Hitchc. (*Rumex triangulivalvis* (Danser) Rech. f.) MEXICAN DOCK

PORTULACACEAE (2 / 4)
Portulaca halimoides L. SILKCOTTON PURSLANE
@ **Portulaca oleracea** L. COMMON PURSLANE
Talinum confertiflorum Greene NEW MEXICO FAMEFLOWER
Talinum pulchellum Woot. & Standl. SHOWY FAMEFLOWER

PRIMULACEAE Primrose family (1 / 1)
Androsace septentrionalis L. ssp. ***glandulosa*** (Woot. & Standl.) G.T. Robbins NORTHERN ROCK JASMINE

RANUNCULACEAE Buttercup family (4 / 6)
Clematis ligusticifolia Nutt. WESTERN WHITE CLEMATIS or VIRGIN'S BOWER
Delphinium nuttallianum Pritz. *ex* Walp. var. ***nuttallianum*** NUTTALL or NELSON LARKSPUR
Delphinium wootonii Rydb. ORGAN MOUNTAIN LARKSPUR
Myosurus cupulatus S. Wats. HORSESHOE MOUSETAIL
Myosurus minimus L. TINY MOUSETAIL
Thalictrum fendleri Engelm. *ex* Gray FENDLER MEADOWRUE

RHAMNACEAE Buckthorn family (1 / 1)
Ceanothus fendleri Gray FENDLER MOUNTAIN LILAC, DEERBRIAR, or BUCKBRUSH

ROSACEAE Rose family (7 / 10)
Cercocarpus montanus Raf. var. ***montanus*** ALDERLEAF MOUNTAIN MAHOGANY
Fallugia paradoxa (D. Don) Endl. *ex* Torr. APACHE PLUME
Holodiscus dumosus (Nutt. *ex* Hook.) Heller ROCKSPIREA, MOUNTAIN SPRAY
Potentilla crinita Gray BEARDED CINQUEFOIL
Potentilla hippiana Lehm. var. ***hippiana*** WOOLLY CINQUEFOIL
Potentilla pensylvanica L. PENNSYLVANIA CINQUEFOIL
Potentilla subviscosa Greene NAVAJO CINQUEFOIL
Prunus virginiana L. var. ***melanocarpa*** (A. Nels.) Sarg. CHOKECHERRY
Rosa sp. ROSE
Rubus idaeus L. ssp. ***strigosus*** (Michx.) Focke RED RASPBERRY

RUBIACEAE Madder family (1 / 1)
Houstonia wrightii Gray PYGMY BLUET

SALICACEAE Willow family (2 / 3)
Populus deltoides Bartr. *ex* Marsh. ssp. ***wislizenii*** (S. Wats.) Eckenwelder RIO GRANDE COTTONWOOD
Populus tremuloides Michx. QUAKING ASPEN
Salix drummondiana Barratt *ex* Hook. DRUMMOND WILLOW

SANTALACEAE Sandalwood family (1 / 1)
Comandra umbellata (L.) Nutt. ssp. ***pallida*** (DC.) Piehl PALE BASTARD TOADFLAX

SAXIFRAGACEAE Saxifrage family (1 / 1)
Heuchera parvifolia Nutt. *ex* Torr. & Gray LITTLELEAF ALUMROOT

SCOPHULARIACEAE Figwort family (8 / 12)
Castilleja integra Gray WHOLELEAF INDIAN PAINTBRUSH
Cordylanthus wrightii Gray WRIGHT BIRD'S BEAK
Mimulus floribundus Lindl. MANYFLOWERED MONKEYFLOWER
Orthocarpus purpureoalbus Gray *ex* S. Wats. PURPLE-WHITE OWLCLOVER
Penstemon ambiguus Torr. var. ***laevissimus*** (Keck) N. Holmgren GILIA BEARDTONGUE
Penstemon barbatus (Cav.) Roth ssp. ***torreyi*** (Benth.) Keck SCARLET PENSTEMON
Penstemon linarioides Gray ssp. ***coloradoensis*** (A. Nels.) Keck COLORADO PENSTEMON
Penstemon ophianthus Pennell COILED ANTHER PENSTEMON
Penstemon virgatus Gray UPRIGHT BLUE BEARDTONGUE
Schistophragma intermedia (Gray) Pennell HARLEQUIN SPIRALSEED
@ ***Verbascum thapsus*** L. WOOLLY MULLEIN
Veronica peregrina L. NECKWEED or SPEEDWELL

SOLANACEAE Nightshade family (4 / 6)
Chamaesaracha coronopus (Dunal) Gray GREENLEAF FALSE NIGHTSHADE
Lycium pallidum Miers PALE WOLFBERRY
Physalis hederifolia Gray var. ***fendleri*** (Gray) Cronq. IVYLEAF GROUNDCHERRY
Solanum elaeagnifolium Cav. SILVERLEAF NIGHTSHADE
Solanum jamesii Torr. WILD POTATO
Solanum triflorum Nutt. CUTLEAF NIGHTSHADE

TAMARICACEAE Tamarisk family (1 / 1)
@ ***Tamarix chinensis*** Lour. FIVESTAMEN SALTCEDAR

ULMACEAE Elm family (2 / 2)
Celtis laevigata Willd. var. ***reticulata*** (Torr.) L. Benson NETLEAF HACKBERRY
@ ***Ulmus pumila*** L. SIBERIAN ELM

VERBENACEAE Vervain family (3 / 4)
Glandularia wrightii (Gray) Umber DAVIS MOUNTAIN MOCK VERVAIN, WRIGHT or DESERT VERVAIN
Phyla cuneifolia (Torr.) Greene WEDGELEAF FOGFRUIT

Verbena bracteata Lag. & Rodr. BIGBRACT or PROSTRATE VERBENA
Verbana macdougalii Heller MACDOUGAL VERVAIN

VISCACEAE Mistletoe family (2 / 2)
Arceuthobium vaginatum (Willd.) J. Presl ssp. ***cryptopodum*** (Engelm.) Hawksworth & Wiens SOUTHWESTERN DWARF MISTLETOE
Phoradendron juniperinum Engelm. JUNIPER MISTLETOE

VITACEAE Grape family (2/2)
Parthenocissus quinquefloa (L.) Planch. var. ***quinquefolia*** (*Parthenocissus inserta* (Kerner) Fritsch) VIRGINIA or THICKET CREEPER, WOODBINE
Vitis arizonica Engelm. ARIZONA GRAPE

ZYGOPHYLLACEAE Caltrop family (2 / 2)
Kallstroemia parviflora J.B.S. Norton WARTY CALTROP
Tribulus terrestris L. GOATHEAD, PUNCTURE VINE

MONOCOTS (nomenclature according to Kartesz (1994), except where noted; 7 / 86)

AGAVACEAE Agave family (1 / 2)
Yucca baccata Torr. var. ***baccata*** BANANA YUCCA, DATIL
Yucca baileyi Woot. & Standl. x ***Y. glauca*** Nutt. *ex* Fraser NARROWLEAF YUCCA

COMMELINACEAE Spiderwort family (2 / 3)
Commelina dianthifolia Delile var. ***longispatha*** (Torr.) Brashier BIRDBILL DAYFLOWER
Commelina erecta L. var. ***angustifolia*** (Michx.) Fern. NARROWLEAF DAYFLOWER
Tradescantia occidentalis (Britt.) Smyth var. ***scopulorum*** (Rose) E.S. Anderson & Woods. PRAIRIE SPIDERWORT

CYPERACEAE Sedge family (5 / 11)
Bulbostylis capillaris (L.) Kunth *ex* C.B. Clarke HAIRSEDGE
Carex filifolia Nutt. THREADLEAF SEDGE
Carex geophila Mackenzie WHITE MOUNTAIN SEDGE
Carex occidentalis Bailey WESTERN SEDGE
Carex vallicola Dewey VALLEY SEDGE
Cyperus fendlerianus Boeckl. FENDLER FLATSEDGE
Cyperus squarrosus L. BEARDED FLATSEDGE
Eleocharis acicularis (L.) Roemer & J.A. Schultes NEEDLE SPIKERUSH
Eleocharis palustris (L.) Roemer & J.A. Schultes COMMON SPIKERUSH
Scirpus americanus Pers. AMERICAN BULRUSH
Scirpus pungens Vahl THREESQUARE BULRUSH

IRIDACEAE Iris family (2 / 2)
Iris missouriensis Nutt. ROCKY MOUNTAIN IRIS
Sisyrinchium demissum Greene DWARF BLUE-EYED GRASS

LILIACEAE Lily family (2 / 2)
Allium cernuum Roth NODDING ONION
Echeandia flavescens (J.A. & J.H. Schultes) Cruden (*Anthericum torreyi* Baker *p.p.*) TORREY CRAGLILY

POACEAE (*GRAMINAE*) Grass family (nomenclature according to Allred 1993; K = according to Kartesz (1994); 29 / 65)
Agrostis scabra Willd. ROUGH BENTGRASS
Andropogon gerardii Vitman var. ***gerardii*** (K = *A. gerardii* Vitman) BIG BLUESTEM
Andropogon gerardii Vitman var. ***paucipilus*** (Nash) Fern. (K = *Andropogon hallii* Hack.) SAND BLUESTEM
Aristida adscensionis L. SIXWEEKS THREEAWN
Aristida arizonica Vasey ARIZONA THREEAWN
Aristida havardii Vasey HAVARD THREEAWN
Aristida purpurea Nutt. var. ***fendleriana*** (Steud.) Vasey FENDLER THREEAWN
Aristida purpurea Nutt. var. ***longiseta*** (Steud.) Vasey RED THREEAWN
Aristida purpurea Nutt. var. ***purpurea*** PURPLE THREEAWN
Blepharoneuron tricholepis (Torr.) Nash PINE or HAIRY DROPSEED
Bothriochloa laguroides (DC.) Herter ssp. **torreyana** (Steud.) Allred & Gould SILVER BLUESTEM
Bouteloua curtipendula (Michx.) Torr. SIDEOATS GRAMA
Bouteloua gracilis (Willd. *ex* Kunth) Lag. *ex* Griffiths BLUE GRAMA
Bouteloua hirsuta Lag. HAIRY GRAMA
Bouteloua simplex Lag. MAT GRAMA
Bromus anomalus Rupr. *ex* Fourn. NODDING BROME
Bromus lanatipes (Shear) Rydb. WOOLLY BROME
Bromus porteri (Coulter) Nash PORTER BROME
@ ***Bromus tectorum*** L. CHEATGRASS, DOWNY BROME
Chloris verticillata Nutt. TUMBLE WINDMILL GRASS
Echinochloa muricata (Beauv.) Fern. var. ***microstachya*** Wieg. ROUGH BARNYARDGRASS, COCKSPUR
Elymus canadensis L. CANADA WILDRYE
Elymus longifolius (J.G. Smith) Gould (K = *Elymus elymoides* (Raf.) Swezey) BOTTLEBRUSH SQUIRRELTAIL
Elymus smithii (Rydb.) Gould (K = *Pascopyrum smithii* (Rydb) A. Löve) WESTERN WHEATGRASS
Elymus trachycaulus (Link) Shinners SLENDER WHEATGRASS
Elymus trachycaulus x ***smithii*** ?
@ ***Eragrostis curvula*** (Schrad.) Nees WEEPING LOVEGRASS
@ ***Eragrostis lehmanniana*** Nees LEHMANN LOVEGRASS
Eragrostis pectinacea (Michx.) Nees CAROLINA LOVEGRASS
Festuca arizonica Vasey ARIZONA FESCUE
Hordeum jubatum L. FOXTAIL BARLEY
Koeleria macrantha (Ledeb.) J.A. Schultes JUNEGRASS
Lycurus setosus (Nutt.) C.G. Reeder WOLFTAIL
Muhlenbergia brevis C.O. Goodding SHORT MUHLY
Muhlenbergia depauperata Scribn. SIXWEEKS MUHLY
Muhlenbergia dubia Fourn. PINE MUHLY
Muhlenbergia fragilis Swallen DELICATE MUHLY
Muhlenbergia minutissima (Steud.) Swallen LEAST MUHLY
Muhlenbergia montana (Nutt.) A.S. Hitchc. MOUNTAIN MUHLY
Muhlenbergia pauciflora Buckl. NEW MEXICO MUHLY
Muhlenbergia pungens Thurb. SANDHILL MUHLY

Muhlenbergia repens (J. Presl) A.S. Hitchc. CREEPING MUHLY

Muhlenbergia torreyi (Kunth) A.S. Hitchc. *ex* Bush RING MUHLY

Muhlenbergia wrightii Vasey *ex* Coult. SPIKE MUHLY

Munroa squarrosa (Nutt.) Torr. (K = *Monroa squarrosa* (Nutt.) Torr.) FALSE BUFFALOGRASS

Oryzopsis hymenoides (Roemer & J.A. Schultes) Ricker *ex* Piper INDIAN RICEGRASS

Oryzopsis micrantha (Trin. & Rupr.) Thurb. LITTLE-SEED RICEGRASS

Panicum bulbosum Kunth BULB PANICGRASS

Panicum capillare L. var. ***brevifolium*** Rydb. & Shear WITCHGRASS

Panicum hirticaule J. Presl MEXICAN PANICGRASS

Phragmites australis (Cav.) Trin. *ex* Steud. REED

Pleuraphis jamesii Torr. (K = *Hilaria jamesii* (Torr.) Benth.) GALLETA

Poa bigelovii Vasey & Scribner BIGELOW BLUEGRASS

Poa fendleriana (Steud.) Vasey MUTTONGRASS

Schedonnardus paniculatus (Nutt.) Trel. TUMBLE-GRASS

Schizachyrium scoparium (Michx.) Nash var. ***scoparium*** LITTLE BLUESTEM

Setaria grisebachii Fourn. GRISEBACH BRISTLE-GRASS

@ ***Setaria viridis*** (L.) Beauv. GREEN BRISTLEGRASS

Sorghastrum nutans (L.) Nash INDIANGRASS

Sporobolus contractus A.S.Hitchc. SPIKE DROPSEED

Sporobolus cryptandrus (Torr.) Gray SAND DROPSEED

Stipa comata Trin. & Rupr. NEEDLE-AND-THREAD

Stipa neomexicana (Thurb. *ex* Coult.) Scribn. NEW MEXICO NEEDLEGRASS or FEATHERGRASS

Stipa scribneri Vasey SCRIBNER NEEDLEGRASS

Vulpia octoflora (Walt.) Rydb. SIXWEEKS FESCUE

TYPHACEAE Cattail (1 / 1)

Typha latifolia L. BROADLEAF CATTAIL

Appendix B
Common names of plants from El Malpais National Monument area

Alphabetical by common name; see Appendix A for more information concerning these plants.

Common name	Scientific name	Plant family
alumroot, littleleaf	*Heuchera parvifolia*	Saxifragaceae
Apache plume	*Fallugia paradoxa*	Rosaceae
ash, fragrant	*Fraxinus cuspidata*	Oleaceae
aspen, quaking	*Populus tremuloides*	Salicaceae
aster, clustered	*Aster falcatus commutatus*	Asteraceae
aster, tansyleaf	*Macheranthera tanacetifolia*	Asteraceae
aster, white	*Chaetopappa ericoides*	Asteraceae
bahia, Woodhouse	*Picradeniopsis woodhousei*	Asteraceae
barnyardgrass, rough	*Echinochloa muricata microstachya*	Poaceae
barberry, Fendler	*Berberis fendleri*	Berberidaceae
barberry, red	*Mahonia haematocarpa*	Berberidaceae
barley, foxtail	*Hordeum jubatum*	Poaceae
bean, slimleaf	*Phaseolus angustissimus*	Fabaceae
beardtongue, gilia	*Penstemon ambiguus laevissimus*	Scrophulariaceae
beardtongue, upright blue	*Penstemon virgatus*	Scrophulariaceae
beebalm, spotted	*Monarda punctata*	Lamiaceae
beebalm, plains	*Monarda pectinata*	Lamiaceae
beeblossom, scarlet	*Gaura coccinea*	Onagraceae
beehive cactus, Arizona	*Escobaria vivipara arizonica*	Cactaceae
beeplant, Rocky Mountain	*Cleome serrulata*	Capparaceae
bentgrass, rough	*Agrostis scabra*	Poaceae
bindweed, field	*Convolvulus arvensis*	Convolvulaceae
bindweed, grey	*Convolvulus equitans*	Convolvulaceae
bird's beak, Wright's	*Cordylanthus wrightii*	Scrophulariaceae
bitterweed	*Tetraneuris argentea*	Asteraceae
bitterweed	*Hymenoxys bigelovii*	Asteraceae
bladderpod, Colorado	*Lesquerella rectipes*	Brassicaceae
blanket flower, Hopi	*Gaillardia pinnatifida*	Asteraceae
blazingstar, desert	*Mentzelia multiflora*	Loasaceae
blazingstar, whitestem	*Mentzelia ablicaulis*	Loasaceae
blite, strawberry	*Chenopodium capitatum*	Chenopodiaceae
bluegrass, Bigelow	*Poa bigelovii*	Poaceae
bluestem, big	*Andropogon gerardii gerardii*	Poaceae
bluestem, little	*Schizachyrium scoparium*	Poaceae
bluestem, sand	*Andropogon gerardii paucipilus*	Poaceae
bluestem, silver	*Bothriochloa laguroides torreyana*	Poaceae
bluet, pygmy	*Houstonia wrightii*	Rubiaceae
blueweed	*Helianthus ciliaris*	Asteraceae
blue-eyed grass, dwarf	*Sisyrinchium demissum*	Iridaceae
bracken, western	*Pteridium aquilinum pubescens*	Dennstaediaceae
brickellbush, plume	*Brickellia brachyphylla*	Asteraceae
bristlegrass, green	*Setaria viridis*	Poaceae
bristlegrass, Grisebach	*Setaria grisebachii*	Poaceae
brome, downy	*Bromus tectorum*	Poaceae
brome, nodding	*Bromus anomalus*	Poaceae
brome, Porter	*Bromus porteri*	Poaceae
brome, woolly	*Bromus lanatipes*	Poaceae
broomrape, manyflowered	*Orobanche ludoviciana multiflora*	Orobanchaceae
broomrape, oneflowered	*Orobanche uniflora*	Orobanchaceae
buckbrush, Fendler	*Ceanothus fendleri*	Rhamnaceae
buffalograss, false	*Munroa squarrosa*	Poaceae
bullrush, American	*Scirpus americanus*	Cyperaceae
bullrush, threesquare	*Scirpus pungens*	Cyperaceae
caltrop, warty	*Kallstroemia parviflora*	Zygophyllaceae
campion, Mexican	*Silene lacinata*	Caryophyllaceae
carpetweed, threadstem	*Mollugo cerviana*	Molluginaceae
catchfly, Mexican	*Silene lacinata*	Caryophyllaceae
catchfly, Scouler	*Silene scouleri scouleri*	Caryophyllaceae

cattail, broadleaf	*Typha latifolia*	Typhaceae
cheatgrass	*Bromus tectorum*	Poaceae
chokecherry	*Prunus virginiana melanocarpa*	Rosaceae
cholla, walkingstick	*Opuntia imbricata*	Cactaceae
cinquefoil, bearded	*Potentilla crinita*	Rosaceae
cinquefoil, Navajo	*Potentilla subviscosa*	Rosaceae
cinquefoil, Pennsylvania	*Potentilla pensylvanica*	Rosaceae
cinquefoil, woolly	*Potentilla hippiana*	Rosaceae
claret cup cactus	*Echinocereus triglochidiatus*	Cactaceae
clematis, western white	*Clematis ligusticifolia*	Ranunculaceae
cliffbrake, slender	*Pellaea glabella simplex*	Pteridaceae
cliff fern, Plummer	*Woodsia plummerae*	Dryopteridaceae
cocklebur	*Xanthium strumarium canadense*	Asteraceae
coneflower, prairie	*Ratibida columnifera*	Asteraceae
copperleaf, New Mexico	*Acalypha neomexicana*	Euphorbiaceae
coreopsis, plains	*Coreopsis tinctoria tinctoria*	Asteraceae
cosmos, Southwest	*Cosmos parviflorus*	Asteraceae
cottonwood, Rio Grande	*Populus deltoides wislizenii*	Salicaceae
craglily, Torrey	*Echeandia flavescens*	Liliaceae
crownbeard, golden	*Verbesina encelioides encelioides*	Asteraceae
crownbeard, golden	*Verbesina encelioides exauriculata*	Asteraceae
cryptantha, Fendler	*Cryptantha fendleri*	Boraginaceae
cryptantha, plains	*Cryptantha crassisepala*	Boraginaceae
currant, wax	*Ribes cerium*	Grossulariaceae
cutleaf	*Bahia dissecta*	Asteraceae
cypress, summer or mock	*Kochia scoparia*	Chenopodiaceae
daisy, Easter	*Townsendia exscapa*	Asteraceae
dandelion, common	*Taraxacum officinale*	Asteraceae
datil	*Yucca baccata*	Agavaceae
dayflower, birdbill	*Commelina dianthifolia longispatha*	Commelinaceae
dayflower, narrowleaf	*Commelina erecta angustifolia*	Commelinaceae
deerbriar, Fendler	*Ceanothus fendleri*	Rhamnaceae
deervetch, Wright	*Lotus wrightii*	Fabaceae
densecress	*Lepidium densiflorum*	Brassicaceae
desert dandelion, Fendler	*Malacothrix fendleri*	Asteraceae
dock, curly	*Rumex crispus*	Polygonaceae
dock, Mexican	*Rumex salicifolius mexicanus*	Polygonaceae
dodder, flatglobe	*Cuscuta umbellata*	Cuscutaceae
dogbane	*Apocynum* sp.	Apocynaceae
Douglas-fir, inland	*Pseudotsuga menziesii menziesii*	Pinaceae
dropseed, pine or hairy	*Blepharoneuron tricholepis*	Poaceae
dropseed, sand	*Sporobolus cryptandrus*	Poaceae
dropseed, spike	*Sporobolus contractus*	Poaceae
dwarf morning glory, shaggy	*Evolvulus nuttallianus*	Convolvulaceae
dwarf mistletoe, southwestern	*Arceuthobium vaginatum crytopodum*	Viscaceae
elkweed	*Frasera speciosa*	Gentianaceae
elm, Siberian	*Ulmus pumila*	Ulmaceae
euphorbia, blackseed	*Euphorbia bilobata*	Euphorbiaceae
evening primrose, crownleaf	*Oenothera coronopifolia*	Onagraceae
evening primrose, cutleaf	*Oenothera laciniata*	Onagraceae
evening primrose, tufted	*Oenothera caespitosa marginata*	Onagraceae
evening primrose, whitestem	*Oenothera albicaulis*	Onagraceae
everlasting, pearly	*Anaphalis margaritacea*	Asteraceae
false nightshade, greenleaf	*Chamaesaracha coronopus*	Solanaceae
false pennyroyal, Drummond	*Hedeoma drummondii*	Lamiaceae
false pennyroyal, low	*Hedeoma nana*	Lamiaceae
fameflower, New Mexico	*Talinum confertiflorum*	Portulacaceae
fameflower, showy	*Talinum pulchellum*	Portulacaceae
feathergrass, New Mexico	*Stipa neomexicana*	Poaceae
fescue, Arizona	*Festuca arizonica*	Poaceae
fescue, sixweeks	*Vulpia octoflora*	Poaceae
fiddleleaf, wishbone	*Nama dichotomum*	Hydrophyllaceae
filaria	*Erodium cicutarium*	Geraniaceae

fireweed	*Kochia scoparia*	Chenopodiaceae
flatsedge, bearded	*Cyperus squarrosus*	Cyperaceae
flatsedge, Fendler	*Cyperus fendlerianus*	Cyperaceae
flax, awned or bristle	*Linum aristatum*	Linaceae
flax, New Mexico yellow	*Linum neomexicanum*	Linaceae
flax, prairie	*Linum lewisii*	Linaceae
fleabane, aspen	*Erigeron speciosus*	Asteraceae
fleabane, beautiful	*Erigeron formosissimus*	Asteraceae
fleabane, hoary	*Erigeron canus*	Asteraceae
fleabane, La Veta	*Erigeron vetensis*	Asteraceae
fleabane, running	*Erigeron colomexicanus*	Asteraceae
fleabane, spreading	*Erigeron divergens*	Asteraceae
fleabane, trailing	*Erigeron flagellaris*	Asteraceae
fogfruit, wedgeleaf	*Phyla cuneifolia*	Verbenaceae
four o'clock, Colorado	*Mirabilis multiflora*	Nyctaginaceae
four o'clock, dwarf	*Mirabilis pumila*	Nyctaginaceae
four o'clock, narrowleaf	*Mirabilis linearis*	Nyctaginaceae
four o'clock, ribbed spreading	*Mirabilis diffusa*	Nyctaginaceae
four o'clock, smooth	*Mirabilis glabra*	Nyctaginaceae
four o'clock, smooth spreading	*Mirabilis oxybaphoides*	Nyctaginaceae
galleta	*Pleuraphis jamesii*	Poaceae
geranium, Mogollon	*Geranium lentum*	Geranaceae
geranium, tufted	*Geranium caespitosum*	Geranaceae
giant hyssop, New Mexico	*Agastache pallidiflora* hybrid	Lamiaceae
gilia, rosy	*Gilia sinuata*	Polemoniaceae
gilia, sticky	*Gilia pinnatifida*	Polemoniaceae
globemallow, Fendler	*Spheralcea fendleri*	Malvaceae
globemallow, juniper	*Spheralcea digitata digitata*	Malvaceae
globemallow, scarlet	*Spheralcea coccinea*	Malvaceae
goathead	*Tribulus terrestris*	Zygophyllaceae
golden aster, hairy	*Heterotheca villosa villosa*	Asteraceae
goldeneye, showy	*Heliomeris multiflora nevadensis*	Asteraceae
goldenpea, mountain	*Thermopsis rhombifolia montana*	Fabaceae
goldenrod, Wright	*Solidago wrightii adenophora*	Asteraceae
goldensmoke	*Corydalis aurea*	Fumariaceae
goldenweed	*Machaeranthera gracilis*	Asteraceae
goldenweed	*Machaeranthera pinnatifida pinnatifida*	Asteraceae
gooseberry, whitestem	*Ribes inerme*	Grossulariaceae
goosefoot, desert	*Chenopodium dessicatum*	Chenopodiaceae
goosefoot, Fremont	*Chenopodium fremontii*	Chenopodiaceae
goosefoot, narrowleaf	*Chenopodium leptophyllum*	Chenopodiaceae
goosefoot, ragleaf	*Chenopodium graveolens*	Chenopodiaceae
grama, blue	*Bouteloua gracilis*	Poaceae
grama, hairy	*Bouteloua hirsuta*	Poaceae
grama, mat	*Bouteloua simplex*	Poaceae
grama, sideoats	*Bouteloua curtipendula*	Poaceae
grape, Arizona	*Vitis arizonica*	Vitaceae
grass fern	*Asplenium septentrionale*	Aspleniaceae
greenthread	*Thelesperma megapotamicum*	Asteraceae
gromwell, mountain	*Lithospermum cobrense*	Boraginaceae
groundcherry, ivyleaf	*Physalis hederaefolia cordifolia*	Solanaceae
groundsel, Douglas	*Senecio flaccidus douglasii*	Asteraceae
groundsel, New Mexico	*Senecio neomexicanus mutabilis*	Asteraceae
groundsel, ragwort	*Senecio multicapitatus*	Asteraceae
groundsel, three-nerved	*Solidago velutina*	Asteraceae
groundsel, Uinta	*Senecio multilobatus*	Asteraceae
groundsmoke, pinyon	*Gayophytum ramosissimum*	Onagraceae
gumweed, mountain	*Grindelia nuda aphanactis*	Asteraceae
hackberry, netleaf	*Celtis laevigata reticulata*	Ulmaceae
hairsedge	*Bulbostylis capillaris*	Cyperaceae
harlequinbush	*Gaura hexandra gracilis*	Onagraceae
hawkweed, Fendler	*Hieracium fendleri fendleri*	Asteraceae
hedgehog cactus, blackspined	*Echinocereus coccineus*	Cactaceae

hedgehog cactus, Fendler	*Echinocereus fendleri*	Cactaceae
hedgenettle, Rothrock	*Stachys rothrockii*	Lamiaceae
heterosperma, fineleaf	*Heterosperma pinnatum*	Asteraceae
hiddenflower, James	*Cryptantha cinerea*	Boraginaceae
Hopi tea	*Thelesperma megapotamicum*	Asteraceae
horehound	*Marrubium vulgare*	Lamiaceae
horsebrush, grey	*Tetradymia canescens*	Asteraceae
horsemint	*Monarda pectinata*	Lamiaceae
horseweed	*Conyza canadensis*	Asteraceae
hyalineherb	*Hymenopappus filifolius cinereus*	Asteraceae
Indiangrass	*Sorghastrum nutans*	Poaceae
Indian paintbrush, wholeleaf	*Castilleja integra*	Scrophulariaceae
ipomopsis, manyflowered	*Ipomopsis multiflora*	Polemoniaceae
ipomopsis, whiteflower	*Ipomopsis longiflora*	Polemoniaceae
iris, Rocky Mountain	*Iris missouriensis*	Iridaceae
junegrass	*Koeleria macrantha*	Poaceae
juniper, alligator	*Juniperus deppeana*	Cupressaceae
juniper, one seed	*Juniperus monosperma*	Cupressaceae
juniper, Rocky Mountain	*Juniperus scopulorum*	Cupressaceae
khunia, southwest	*Brickellia eupatorioides chlorolepis*	Asteraceae
knapweed, Russian	*Acroptilon repens*	Asteraceae
knotweed, bushy	*Polygonum ramosissimum*	Polygonaceae
knotweed, erect	*Polygonum erectum*	Polygonaceae
knotweed, prostrate	*Polygonum aviculare*	Polygonaceae
larkspur, Nelson or Nuttall	*Delphinium nuttallianum*	Ranunculaceae
larkspur, Organ Mountain	*Delphinium wootonii*	Ranunculaceae
lipfern, Fendler	*Cheilanthes fendleri*	Adiantiaceae
lipfern, slender	*Cheilanthes feei*	Adiantiaceae
lovegrass, Carolina	*Eragrostis pectinacea*	Poaceae
lovegrass, Lehmann	*Eragrostis lehmanniana*	Poaceae
lovegrass, weeping	*Eragrostis curvula*	Poaceae
lupine, King	*Lupinus kingii kingii*	Fabaceae
lupine, silvery	*Lupinus argenteus argenteus*	Fabaceae
mahonia, creeping	*Mahonia repens*	Berberidaceae
male fern	*Dryopteris felix-mas*	Dryopteridaceae
marigold, fetid	*Dyssodia papposa*	Asteraceae
marigold, licorice	*Tagetes micrantha*	Asteraceae
mayweed	*Dyssodia papposa*	Asteraceae
meadowrue, Fendler	*Thalictrum fendleri*	Ranunculaceae
medick, black	*Medicago lupulina*	Fabaceae
menodora, rough	*Menodora scabra*	Oleaceae
mentzelia, swarf	*Mentzelia pumila*	Loasaceae
milkvetch, Brandegee	*Astragalus brandegei*	Fabaceae
milkvetch, Eggleston	*Astragalus egglestonii*	Fabaceae
milkvetch, groundcover	*Astragalus humistratus humistratus*	Fabaceae
milkvetch, groundcover	*Astragalus humistratus humivagans*	Fabaceae
milkvetch, Mogollon woolly	*Astragalus mollissimus matthewsii*	Fabaceae
milkvetch, painted	*Astragalus ceramicus*	Fabaceae
milkvetch, stinking	*Astragalus praelongus*	Fabaceae
milkvetch, Torrey	*Astragalus calycosus scaposus*	Fabaceae
milkvetch, Wooton	*Astragalus wootonii*	Fabaceae
milkweed, orange	*Asclepias tuberosa interior*	Asclepiadaceae
milkweed, spider	*Asclepias asperula asperula*	Asclepiadaceae
milkweed, whorled	*Asclepias subverticillata*	Asclepiadaceae
milkwort, white	*Polygala alba*	Polygalaceae
mistletoe, juniper	*Phoradendron juniperinum*	Viscaceae
mock thelypody, mountain	*Pennellia micrantha*	Brassicaceae
mock vervain, David Mountain	*Glandularia wrightii*	Verbenaceae
monkeyflower, manyflowered	*Mimulus floribundus*	Scrophulariaceae
morning glory, crestrib	*Ipomoea costellata*	Convolvulaceae
morning glory, Huachuca Mt.	*Ipomoea plummerae*	Convolvulaceae
morning glory, transpecos	*Ipomoea cristulata*	Convolvulaceae
mountain lilac, Fendler	*Ceanothus fendleri*	Rhamnaceae

mountain mahogany	*Cercocarpus montanus montanus*	Rosaceae
mountain spray	*Holodiscus dumosus*	Rosaceae
mousetail, horseshoe	*Myosurus cupulatus*	Ranunculaceae
mousetail, tiny	*Myosurus minimus*	Ranunculaceae
muhly, creeping	*Muhlenbergia repens*	Poaceae
muhly, delicate	*Muhlenbergia fragilis*	Poaceae
muhly, least	*Muhlenbergia minutissima*	Poaceae
muhly, mountain	*Muhlenbergia montana*	Poaceae
muhly, New Mexico	*Muhlenbergia pauciflora*	Poaceae
muhly, pine	*Muhlenbergia dubia*	Poaceae
muhly, ring	*Muhlenbergia torreyi*	Poaceae
muhly, sandhill	*Muhlenbergia pungens*	Poaceae
muhly, short	*Muhlenbergia brevis*	Poaceae
muhly, sixweeks	*Muhlenbergia deparuperata*	Poaceae
muhly, spike	*Muhlenbergia wrightii*	Poaceae
mullein, woolly	*Verbascum thapsus*	Scrophulariaceae
muttongrass	*Poa fendleriana*	Poaceae
neckweed	*Veronica peregrina*	Scrophulariaceae
needle-and-thread	*Stipa comata*	Poaceae
needlegrass, New Mexico	*Stipa neomexicana*	Poaceae
needlegrass, Scribner	*Stipa scribneri*	Poaceae
nightshade, cutleaf	*Solanum triflorum*	Solanaceae
nightshade, silverleaf	*Solanum elaeagnifolium*	Solanaceae
nipple cactus, Wright	*Mammillaria wrightii wrightii*	Cactaceae
noseburn, catnip	*Tragia ramosa*	Euphorbiaceae
oak, Gambel	*Quercus gambelii*	Fagaceae
oak, grey	*Quercus grisea*	Fagaceae
oak, wavyleaf	*Quercus X pauciloba*	Fagaceae
olive, New Mexico	*Forestiera pubescens*	Oleaceae
onion, nodding	*Allium cernuum*	Liliaceae
owl clover, purplewhite	*Orthocarpus purpureo-albus*	Scrophulariaceae
panicgrass, bulb	*Panicum bulbosum*	Poaceae
panicgrass, Mexican	*Panicum hirticaule*	Poaceae
paperflower, woolly	*Psilostrophe tagetina*	Asteraceae
parsley, mountain	*Pseudocymopterus montanus*	Apiaceae
pennycress, alpine	*Thlaspi montanum fendleri*	Brassicaceae
penstemon, coiled anther	*Penstemon ophianthus*	Scrophulariaceae
penstemon, Colorado	*Penstemon linaroides coloradoensis*	Scrophulariaceae
penstemon, scarlet	*Penstemon barbatus torreyi*	Scrophulariaceae
peppergrass, bushy	*Lepidium ramosissimum*	Brassicaceae
peppergrass, prairie	*Lepidium densiflorum*	Brassicaceae
peteria, rush	*Peteria scoparia*	Fabaceae
phacelia, cinders	*Phacelia serrata*	Hydrophyllaceae
phlox, slender	*Phlox gracilis*	Polemoniaceae
pigweed, pale	*Amaranthus albus*	Amaranthaceae
pigweed, prostrate	*Amaranthus blitoides*	Amaranthaceae
pigweed, redroot or rough	*Amaranthus retroflexus*	Amaranthaceae
pincushion cactus, cream	*Mammillaria heyderi meiacantha*	Cactaceae
pinedrops, woodland	*Pterospera andromedea*	Monotropaceae
pine, limber	*Pinus flexilis*	Pinaceae
pine, ponderosa	*Pinus ponderosa*	Pinaceae
pingue	*Hymenoxys richardsonii*	Asteraceae
piñon, Colorado	*Pinus edulis*	Pinaceae
plainsmustard, flaxleaf	*Schoenocrambe linearifolia*	Brassicaceae
plantain, silvery	*Plantago argyrea*	Plantaginaceae
plantain, woolly	*Plantago patagonica*	Plantaginaceae
povertyweed, Nuttall	*Monolepis nuttalliana*	Chenopodiaceae
prairieclover, Chihuahuan	*Dalea exigua*	Fabaceae
prairieclover, compact	*Dalea compacta*	Fabaceae
prairieclover, foxtail	*Dalea leporina*	Fabaceae
prairieclover, sixweeks	*Dalea polygonoides*	Fabaceae
prairieclover, slender white	*Dalea candida oligophylla*	Fabaceae
prickly lettuce	*Lactuca serriola*	Asteraceae

prickly pear, brownspine	*Opuntia phaeacantha*	Cactaceae
prickly pear, low	*Opuntia macrorhiza*	Cactaceae
prickly pear, plains	*Opuntia polyacantha*	Cactaceae
puccoon, manyflower	*Lithospermum multiflorum*	Boraginaceae
puccoon, narrowleaf	*Lithospermum incisum*	Boraginaceae
puncture vine	*Tribulus terrestris*	Zygophyllaceae
purslane, common	*Portulaca oleracea*	Portulacaceae
purslane, silkcotton	*Portulaca halimoides*	Portulacaceae
pussytoes	*Antennaria parvifolia*	Asteraceae
pygmyflower, blue	*Monnina wrightii*	Polygalaceae
rabbitbrush, Bigelow rubber	*Ericameria nauseosa nauseosa bigelovii*	Asteraceae
rabbitbrush, dwarf	*Ericameria depressa*	Asteraceae
rabbitbrush, Greene	*Ericameria filifolia*	Asteraceae
rabbitbrush, lanceleaf viscid	*Ericameria viscidiflora lanceolata*	Asteraceae
rabbitbrush, Parry	*Ericameria parryi attenuata*	Asteraceae
rabbitbrush, rubber	*Ericameria nauseosa consimilis arta*	Asteraceae
rabbitbrush, rubber	*Ericameria nauseosa nauseosa nauseosa*	Asteraceae
rabbitbrush, viscid	*Ericameria viscidiflroa viscidiflora stenophylla*	Asteraceae
ragweed, common	*Ambrosia artemisiifolia*	Asteraceae
ragweed. skeletonleaf burr	*Ambrosia tomentosa*	Asteraceae
raspberry, red	*Rubus idaeus strigosus*	Rosaceae
reed	*Phragmites australis*	Poaceae
ricegrass, Indian	*Oryzopsis hymenoides*	Poaceae
ricegrass, littleseed	*Oryzopsis micrantha*	Poaceae
rockcress, common	*Arabis perennans*	Brassicaceae
rockcress, Fendler	*Arabis fendleri spatifolia*	Brassicaceae
rockcress, Fendler	*Arabis fendleri fendleri*	Brassicaceae
rock jasmine, northern	*Androsace septentrionalis glandulosa*	Primulaceae
rockspirea	*Holodiscus dumosus*	Rosaceae
rose	*Rosa* sp.	Rosaceae
rubberweed, Colorado	*Hymenoxys richardsonii*	Asteraceae
sage, lanceleaf	*Salvia reflexa*	Lamiaceae
sage, sawtooth	*Salvia subincisa*	Lamiaceae
sagebrush, fringed	*Artemisia frigida*	Asteraceae
sagebrush, sand	*Artemisia filifolia*	Asteraceae
sagewort, western	*Artemisia campestris pacifica*	Asteraceae
salsify, meadow	*Tragopogon pratensis*	Asteraceae
salsify, western	*Tragopogon dubius*	Asteraceae
saltbush, fourwing	*Atriplex canescens*	Chenopodiaceae
saltcedar, fivestamen	*Tamarix chinensis*	Tamaricaceae
sand verbena, fragrant white	*Abronia elliptica*	Nyctaginaceae
sand verbena, sweet	*Abronia fragrans*	Nyctaginaceae
sandwort, Fendler	*Arenaria fendleri fendleri*	Caryophyllaceae
sandwort, spreading	*Arenaria lanuginosa saxosa*	Caryophyllaceae
scorpionweed, white	*Phacelia alba*	Hydrophyllaceae
scrambled eggs	*Corydalis aurea*	Fumariaceae
scurfpea, lemon	*Psoralidium lanceolata*	Fabaceae
scurfpea, slimfllower	*Psoralidium tenuiflorum*	Fabaceae
sedge, threadleaf	*Carex filifolia*	Cyperaceae
sedge, valley	*Carex vallicola*	Cyperaceae
sedge, western	*Carex occidentalis*	Cyperaceae
sedge, White Mountain	*Carex geophila*	Cyperaceae
skunkbush	*Rhus trilobata trilobata*	Anacardiaceae
skyrocket, scarlet	*Ipomopsis aggregata formosissima*	Polemoniaceae
snakeweed, broom	*Gutierrezia sarothrae*	Asteraceae
sophora, silky	*Sophora nuttalliana*	Fabaceae
sow thistle, spiny	*Sonchus asper*	Asteraceae
spectaclepod	*Dimorphocarpa wislizenii*	Brassicaceae
speedwell	*Veronica peregrina*	Scrophulariaceae
spiderwort, prairie	*Tradescantia occidentalis*	Commelinaceae
spikemoss, lesser	*Selaginella densa*	Selaginellaceae
spikerush, common	*Eleocharis palustris*	Cyperaceae
spikerush, needle	*Eleocharis acicularis*	Cyperaceae

spinach, strawberry	*Chenopodium capitatum*	Chenopodiaceae
spinystar	*Escobaria vivipara arizonica*	Cactaceae
spiralseed, harlequin	*Schistophragma intermedia*	Scrophulariaceae
spleenwort, maidenhair	*Asplenium trichomanes*	Aspleniaceae
springparsley, Fendler	*Cymopterus acaulis fendleri*	Apiaceae
springparsley, widewing	*Cymopterus purpurascens*	Apiaceae
spurge, Fendler	*Chamaesyce fendleri fendleri*	Euphorbiaceae
spurge, Fendler	*Chamaesyce fendleri chaetocalyx*	Euphorbiaceae
spurge, shorthorned	*Euphorbia lurida*	Euphorbiaceae
spurge, threadstem	*Chamaesyce revoluta*	Euphorbiaceae
spurge, thymeleaf	*Chamaesyce serpyllifolia*	Euphorbiaceae
squirreltail, bottlebrush	*Elymus longifolius*	Poaceae
stickpea, dwarf	*Calliandra humilis*	Fabaceae
stickseed	*Lappula occidentalis*	Boraginaceae
stoneseed, showy	*Lithospermum incisum*	Boraginaceae
stork's bill, redstem	*Erodium cicutarium*	Geraniaceae
suckleya, poison	*Suckleya suckleyana*	Chenopodiaceae
sumac, smooth	*Rhus glabra*	Anacardiaceae
sunflower, common	*Helianthus annuus*	Asteraceae
sunflower, false	*Helianthella quinquenervis*	Asteraceae
sunflower, prairie or plains	*Helianthus petiolaris*	Asteraceae
sweet clover, yellow	*Medicago officinalis*	Fabaceae
tansyaster, hoary	*Macheranthera canescens glabra*	Asteraceae
tansy mustard, desert	*Descurainia obtusa obtusa*	Brassicaceae
tansy mustard, mountain	*Descurainia incisa incisa*	Brassicaceae
tansy mustard, pinnate	*Descurainia pinnata halictorum*	Brassicaceae
taperleaf	*Pericome caudata*	Asteraceae
tarragon	*Artemisia dracunculus*	Asteraceae
tasselflower	*Brickellia grandiflora*	Asteraceae
telypody, Wright	*Thelpyodium wrightii*	Brassicaceae
thicket creeper	*Parthenocissus quinquefolia quinquefolia*	Vitaceae
thistle, barbwire Russian	*Salsola paulsenii*	Chenopodiaceae
thistle, bull	*Cirsium vulgare*	Asteraceae
thistle, New Mexico	*Cirsium neomexicanum*	Asteraceae
thistle, Russian	*Salsola kali*	Chenopodiaceae
thistle, Wheeler	*Cirsium wheeleri*	Asteraceae
thistle, yellowspine	*Cirsium ochrocentrum*	Asteraceae
thoroughwort, white	*Ageratina herbaceum*	Asteraceae
threadleaf	*Schkuhria multiflora*	Asteraceae
threeawn, Arizona	*Aristida arizonica*	Poaceae
threeawn, Fendler	*Aristida purpurea fendleriana*	Poaceae
threeawn, Havard	*Aristida havardii*	Poaceae
threeawn, purple	*Aristida purpurea purpurea*	Poaceae
threeawn, red	*Aristida purpurea longiseta*	Poaceae
threeawn, sixweeks	*Aristida adscensionis*	Poaceae
three-seeded mercury, New Mexico	*Acalypha neomexicana*	Euphorbiaceae
toadflax, pale bastard	*Comandra umbellata pallida*	Santalaceae
townsendia, hoary	*Townsendia incana*	Asteraceae
tumblegrass	*Schedonnardus paniculatus*	Poaceae
tumblemustard, tall	*Sisymbrium altissimum*	Brassicaceae
tumble–windmill grass	*Chloris verticillata*	Poaceae
velvetweed	*Gaura parvifolia*	Onagraceae
verbena, prostrate or bigbract	*Verbena bracteata*	Verbenaceae
vervain, MacDougal	*Verbena macdougalii*	Verbenaceae
vervain, Wright or desert	*Glandularia wrightii*	Verbenaceae
vetch, American	*Vicia americana minor*	Fabaceae
Virginia creeper	*Parthenocissus inserta*	Vitaceae
virgin's bower, western white	*Clematis ligusticifolia*	Ranunculaceae
wallflower, western or plains	*Erysimum capitatum*	Brassicaceae
water clover	*Marsilea mollis*	Marsileaceae
wheatgrass, slender	*Elymus trachycaulus*	Poaceae
wheatgrass, western	*Elymus smithii*	Poaceae

whitlow grass, wedgeleaf	*Draba cuneifolia*	Brassicaceae
wild buckwheat, annual	*Eriogonum annuum*	Polygonaceae
wild buckwheat, James	*Eriogonum jamesii jamesii*	Polygonaceae
wild buckwheat, nodding	*Eriogonum cernuum*	Polygonaceae
wild buckwheat, redroot	*Eriogonum racemosum*	Polygonaceae
wild buckwheat, winged	*Eriogonum alatum*	Polygonaceae
wild potato	*Solanum jamesii*	Solanaceae
wildrye, Canada	*Elymus canadensis*	Poaceae
willow, Drummond	*Salix drummondiana*	Salicaceae
winterfat	*Krascheninnikovia lanata*	Chenopodiaceae
wirelettuce, fewflower	*Stephanomeria pauciflora*	Asteraceae
wirelettuce, slender	*Stephanomeria tenuifolia*	Asteraceae
witchgrass	*Panicum capillare brevifolium*	Poaceae
wolfberry, pale	*Lycium pallidum*	Solanaceae
wolftail	*Lycurus setosus*	Poaceae
woodbine	*Parthenocissus quinquefolia quinquefolia*	Vitaceae
woodsorrel, creeping	*Oxalis corniculata*	Oxalidaceae
woolywhite	*Hymenopappus filifolius cinereus*	Asteraceae
woollywhite, yellow	*Hymenopappus flavescens*	Asteraceae
wormwood, Carruth	*Artemisia carruthii*	Asteraceae
wormwood, Louisiana	*Artemisia ludoviciana*	Asteraceae
wormwood, silky	*Artemisia dracunculus*	Asteraceae
yarrow	*Achillea millefolium occidentalis*	Asteraceae
yellowcress, Chihuanhuan	*Rorippa microtites*	Brassicaceae
yellowcress, spreading	*Rorippa sinuata*	Brassicaceae
yucca, banana	*Yucca baccata*	Agavaceae
yucca, narrowleaf	*Yucca baileyi* X *Y. glauca*	Agavaceae
zinnia, Albert creeping	*Sanvitalia abertii*	Asteraceae
zinnia, Rocky Mountain	*Zinnia grandiflora*	Asteracea

The fauna of El Malpais National Monument

David C. Lightfoot

Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131

Introduction

El Malpais National Monument (El Malpais) provides animals with a wide variety of habitats including lava flows, lava tube caves, sandstone outcrops, sandy areas, a variety of woodlands and savannas, and even temporary ponds and small lakes. Given the variety of habitats, it is not surprising that El Malpais supports a large number of animal species. The lava flows and cinder cones are distinctive geological features of El Malpais and provide special habitats for some animal species that are not found on the surrounding landscapes. Recent faunal studies have revealed many undescribed species of arthropods that are endemic to El Malpais, indicating a unique fauna that we are just beginning to understand.

History of animal research at El Malpais

The most extensive animal surveys done in the El Malpais area were studies of mammals by Hooper (1941), reptiles and amphibians by Gehlbach (1965), and an inventory of all animals and plants (Lightfoot et al., 1994). Stoltz (1986a, b) produced unpublished lists of amphibians, reptiles, and mammals from nearby El Morro National Monument. The birds of El Malpais have not been studied to any extent. The most extensive records of bird species occurring in the El Malpais area are those of Lightfoot et al. (1994) and records from the New Mexico Department of Game and Fish (Klingel, 1992) for Cibola County. Painter (New Mexico Department of Game and Fish, pers. comm. 1993) provides additional records of reptiles and amphibians from Cibola County. Peck (1982) conducted a survey of El Malpais lava-tube caves for invertebrates in 1975-1979 in an attempt to find cave-specialized species. The most extensive survey of arthropods at El Malpais was that by Lightfoot et al. (1994).

Zoogeography and habitat associations

The fauna of El Malpais is typical for the Colorado Plateau/southern Rocky Mountain region (Brown, 1982). Some animal species that occur in the El Malpais area have geographic distributions that extend from the Great Basin, while others extend from the Chihuahuan Desert, Great Plains, or Rocky Mountains.

Different animal species tend to occur in certain habitats because of preferences for particular types of soils or substrates, or because of relationships with certain species of plants or types of vegetation structure. Some species are more specific to certain habitat requirements than other species that may occur in a variety of habitats (Parmenter et al., 1995). Geological features and vegetation types probably best describe the animal habitats. Habitats are not discrete units, but tend to intergrade with each other and form intermixed patch mosaics with other habitats. Topographic and vegetation landscape patterns provide us with useful ways of assessing animal distributions. The following major vegetation formations provide large scale habitats to animals at El Malpais, and are similar to vegetation communities of Brown (1982) and DickPeddie (1993).

Ponderosa pine/Douglas-fir forests (mostly above 2,300 m elevation but lower on north slopes and moist/cool areas) are composed of large trees with dense canopy foliage and poorly developed understory vegetation (Fig. 1). These forests occur mostly in the Twin Craters—Lost Woman area and in the adjacent Zuni Mountains. Mid-low elevation ponderosa pine woodland (mostly below 2,300 m elevation, but higher on south slopes) are open ponderosa pine parklands with well developed grass understories. This habitat occurs on and off lava flows and on cinder cones.

Dense to open piñon /juniper woodlands are found at all elevations in El Malpais. The understory vegetation is well developed and consists largely of blue grama grassland, snakeweed, and rabbitbrush (Fig. 2). This habitat is found primarily off the lava flows, but also occurs on lava flows as well as sandstone slopes and cinder cones. Juniper savanna is represented by open blue grama grassland with widely scattered piñon or juniper trees and common snakeweed and rabbitbrush (Fig. 3). Dominant grasses include blue grama, wolf-tail, and three-awn. This habitat is found almost entirely off lava flows, on fine loam or silty soils.

Sand dunes and sandy areas (Fig. 4) are common on the east side of El Malpais. Sand habitats are best developed between the McCartys lava flow and the bases of sandstone bluffs from Sandstone Bluffs Overlook to North Pasture.

Lava-flow landscapes consist mostly of bare lava with very little soil development (Fig. 5). Bandera, Hoya, Twin Craters, and McCartys lava flows are the principal geological features defining this habitat. The lava-flow habitat varies across an elevation gradient.

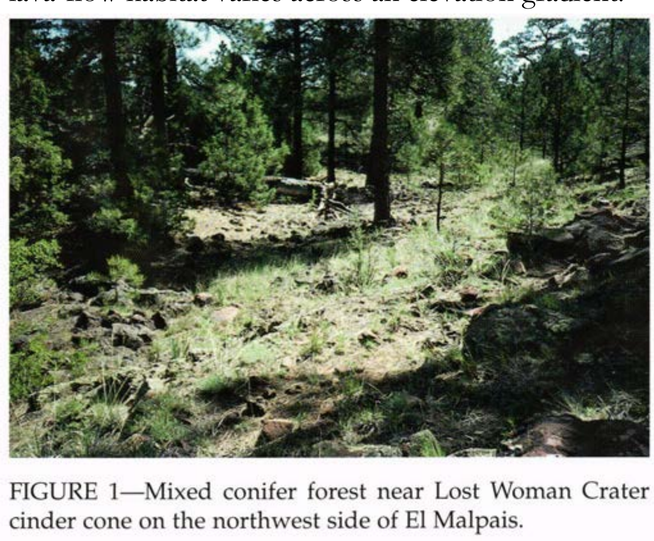

FIGURE 1—Mixed conifer forest near Lost Woman Crater cinder cone on the northwest side of El Malpais.

FIGURE 2—Piñon–juniper woodland on the North Kipuka of the Three Kipukas, on the easd side of El Malpais near The Narrows.

At higher elevations in the Bandera Crater area, lichen cover is much higher on the lava than at lower elevations on the McCartys flow. Temperature and moisture conditions vary across this gradient from cooler and higher on the upper elevation flows to warmer and drier on the lower elevation flows.

Cinder cones and sandstone and limestone ridges consist of rocky slopes, and often rock cliffs and bluffs, with or without vegetation. Steepsided cinder cones (Fig. 6) are common in the western portion of El Malpais, and sandstone and limestone escarpments (Fig. 7) are found in the north central area (Cerritos de Jaspe, Oak Ridge) and along the east side (sandstone bluffs).

Lava-tube caves, including ice caves (Fig. 8), dry caves (Fig. 9), and lava-tube collapse structures (Fig. 10), provide unique and important habitats for many animal species. The dark, cool, moist environments of the the lava tubes are very different from the surrounding open lava-flow habitats. The edges of lava flows appear to provide an environment where water availability is greater than in surrounding areas. The presence of Douglas-fir and aspen and high densities and sizes of other trees and shrubs along upper-elevation lava-flow edges indicate greater moisture availability.

FIGURE 3—Juniper savanna near Prarie Dog Well on the south side of El Malpais.

Small ephemeral lakes or playas and associated livestock ponds (Fig. 11) are present in the southern portion of El Malpais. These playas provide important habitat to many species when water is present, such as aquatic insects, crustaceans, amphibians, and water birds. Most of the records of aquatic animals from El Malpais are from these small ponds and lakes. When the ponds and lakes dry out or are partially dry, the mud-flats provide important habitats for many insects and shorebirds. These playas are situated primarily within grassland habitats. Small temporary pools of water called tinajas in sandstone depressions (Fig. 12) provide additional habitats for some aquatic invertebrates and breeding pools for amphibians. Tinajas are common in the sandstone bluffs on the east side, at Hidden Kipuka, and at Cerro de Jaspe and Oak Ridge.

Human disturbances such as roadsides, trails, and structures are generally occupied by colonizer or pioneer species. The vegetation of these areas is often very different from the surrounding undisturbed habitats, and thus the habitat structure and food resources are different for animals. Animals use such disturbed habitats primarily for foraging. Such animals include scavengers and predators that feed on road-killed animals or garbage, and granivores and herbivores that feed on the abundance of foliage and seeds produced by weedy plants.

The animals of El Malpais

Mammals

Seventy-one species of mammals are known to occur in the El Malpais area, including 18 species of bats, 4 species of rabbits, 31 species of rodents, along with coyotes, foxes, bears, raccoons, weasels, skunks, mountain lions, bobcats, deer, elk, and pronghorn antelope (Appendix 1).

Rodents and shrews—The most abundant mammals at El Malpais are rodents, including chipmunks and squirrels, pocket gophers, mice and rats, and porcupines. Chipmunks are commonly seen running up and down trees and across the lava flows. The Colorado chipmunks tend to be associated with mixed-conifer and ponderosa pine forests and woodlands at higher elevations in and near the Zuni Mountains. These chipmunks rely to a large extent on the cones of conifer trees for food. The cliff chipmunks are associated with lava flows and sedimentary-rock outcrops. Cliff chipmunks occur throughout the lava field of El Malpais, usually in association with ponderosa pine.

Gray rock squirrels occur throughout El Malpais, and like the cliff chipmunks, are usually found associated with lava or sedimentary rock outcrops. The impressive-looking tassel-eared or Abert's squirrels are less common than the larger grey rock squirrels. Tassel-eared squirrels are named for the large tufts of hair at the tips of the ears, similar to that of bobcats. Tassel-eared squirrels are associated with ponderosa pine forests, and are found mostly at higher elevations at El Malpais, near the Zuni Mountains.

The largest squirrels of El Malpais are the whitetail or Gunnison's prairie dogs. They are large, gregarious ground squirrels that live in colonies of around half a dozen to over 100 individuals in open grassland habitats at El Malpais where they feed on grasses and fortis. They dig extensive burrow systems and build large mounds of soil around the entrances. Groups of these large earth mounds are easily observed where colonies live. When the animals are active, individuals may be observed foraging and interacting with each other in the areas surrounding their burrows. When alarmed by human observers or predators, individuals stand on their soil mounds and whistle loud warning calls. At El Malpais the whitetail prairie dog colonies are scattered in open grassland habitats with fine loamy soils along the eastern boundary of the monument near the McCartys lava flow and NM-117, and along the western border of the monument south and west of the Hoya lava flow.

Other squirrels found in the area include the spotted ground squirrel, whitetail antelope squirrel, and the red squirrel. Spotted ground squirrels and antelope squirrels live in open grassland or shrubland areas with fine-grained soils, such as the San Jose River valley near Grants. Red squirrels or Chickarres live in mixed conifer forests of the Zuni Mountains.

Botta's pocket gophers are common at El Malpais where soil is well developed. They live underground feeding on plant roots, and frequently push up small mounds of soil. Pocket gophers are rarely seen above ground, but their soil mounds are commonly observed on the alluvial and eolian soils and cinder cones of El Malpais.

Eleven species of native mice and rats occur at El Malpais, and a number of additional species are known from the surrounding areas (Lightfoot et al., 1994). The deer mouse and piñon mouse are the most common mice of El Malpais, and both species are found in practically all habitats throughout the monument. Deer mice are most abundant in the ponderosa pine forests at higher elevations on the west side of El Malpais. Piñon mice occur throughout El Malpais, but tend to be the dominant species on the lava flows and piñon—juniper woodlands on the east side of El Malpais.

The rock mouse is relatively common but restricted to lava flows and sedimentary rock outcrops of El Malpais. The brush mouse is even less common and tends to be associated with oak thickets on sedimentary outcrops. The white-footed mouse occurs in a variety of habitats, usually associated with open woodlands where herbaceous vegetation is well developed.

Wood rats or pack rats are large relatives of the deer mouse that construct nests composed of materials gathered from surrounding areas. Pack rat nests at El Malpais usually consist of piles of sticks, pine cones, and prickly pear cactus pads situated in rock crevices, on ledges under overhangs, and around the bases of trees or large shrubs. The Mexican woodrat and white-throated woodrat are both common at El Malpais. Both species are usually associated with lava flows and construct their nests in crevices and lava tube cave entrances.

FIGURE 4—Sandy area near Prarie Dog Well on the south side of El Malpais.

Other mice include the western harvest mouse which is small, looks similar to the house mouse, and occurs in grassy areas at El Malpais. The northern grasshopper mouse is a largely carnivorous mouse known from areas surrounding El Malpais, and likely occurs within the monument in open grassy areas. Several species of voles or meadow mice are known from the surrounding areas, and at least one species, the Mexican vole, probably lives in dense grassy meadows at higher elevations at El Malpais.

Pocket mice and kangaroo rats are less abundant at El Malpais than the deer mouse and its relatives. The silky pocket mouse, Ord's kangaroo rat, and bannertail kangaroo rat all occur in the juniper savanna areas on the north, east, and south sides of the El Malpais lava fields. These animals all live where the soil is well developed and grass and forb cover is relatively high. The large soil mounds of the bannertail kangaroo rat occur in the southern portions of El Malpais, and from a distance may be mistaken for whitetail prairie dog mounds. Bannertail kangaroo rat mounds have multiple small entrances rather the one large entrance of the prairie dog mounds.

Shrews are insectivores that are more closely related to bats than mice and rats. One species, the dwarf shrew, has been found at several locations throughout

FIGURE 5—McCartys lava flow near The Narrows on the east side of El Malpais.

FIGURE 6—Bandera Crater cinder cone in the foreground, and Lost woman Crater cinder cone in the distance, both on the northwest side of El Malpais.

El Malpais. Two other species, the dusky shrew and the desert shrew, are also known from the surrounding areas.

Rabbits and hares—Rabbits are frequently observed at El Malpais, but rarely on the lava flows. The most common rabbit is the desert cottontail. Two other species, the eastern and mountain cottontails, occur in the area. The three species of cottontails are very difficult to separate when observed in the field. The best way to tentatively identify them is by habitat association. Desert cottontails occur in dry, open, lower-elevation habitats such as juniper savanna, piñon-juniper, and ponderosa pine woodlands. Eastern cottontails generally prefer moist places with dense vegetation, usually at lower elevations. Mountain cottontails occur in conifer forests at relatively high elevations.

Black-tailed jackrabbits are large hares with relatively longer legs and ears than cottontails. Jackrabbits are associated with the open juniper savannas and piñon-juniper woodlands at lower elevations.

Porcupines are large rodents with the characteristic large quills. They are relatively common at El Malpais, feeding on the living bark (cambium) of trees and shrubs. Scars are evident on the pine trees at El Malpais where porcupines had been feeding.

Carnivores—The coyote is the most abundant and widespread of large, carnivorous animals at El Malpais. Coyotes are often heard calling and often seen crossing roads. Gray fox appears to be less common and usually occurs in the juniper savannas and piñon-juniper woodlands on the south and east sides of El Malpais. The small kit fox has been reported from El Morro National Monument. At El Malpais, kit fox would most likely occur in the open juniper savannas. The black bear is the largest animal known from El Malpais. Bears occur in the Zuni Mountains, and mostly in the northwest portion of El Malpais.

Raccoons and ringtails are known from the areas surrounding El Malpais and probably occur at the Monument. Raccoons are usually found near permanent water, whereas ringtails generally prefer forest or woodland in hills and canyons.

Badgers, several species of skunks (hognose, spotted, and striped), and both long and short-tailed weasels are reported from the areas surrounding El Malpais. Several sightings of animals looking much like the endangered black-footed ferret have been reported from a whitetail prairie dog colony along NM-117 at the mouth of Cebollita Creek canyon. The animals sighted were probably long-tailed weasels, which in the Southwest have black facial markings similar to those of the larger black-footed ferret. The black-footed ferret is currently not recognized as present in the El Malpais area.

Mountain lions and bobcats are secretive animals seldom seen by humans. However, mountain lion sightings are not uncommon at El Malpais, nor are observations of their tracks. Most of the sightings are on the northwest side of the monument in areas of sandstone and limestone ridges and ponderosa pine forests. These large cats probably prey mostly on mule deer which tend to be fairly common in these areas. Bobcats have not been observed at El Malpais, but are known from surrounding areas.

Hoofed animals—Large hoofed animals of El Malpais include mule deer, elk, and pronghorn antelope. Elk from the nearby Zuni Mountains occasionally move into the northwest portion of El Malpais, especially during the winter. Mule deer are common throughout El Malpais, but most abundant in the ponderosa woodlands of the northwest portion. Pronghorn occur in the open grasslands and juniper savannas in the southwest portion of El Malpais. Rocky Mountain bighorn sheep occurred at El Malpais as recently as 50-100 years ago (Carleton, 1993). Remains of bighorn are found in many lava-tube caves, especially in the Big Tubes area.

Bats—The numerous lava-tube caves of El Malpais provide habitats for many species of bats. All of the bat species that occur at El Malpais feed on flying insects, and most of the species require caves or crevices to roost. A large colony of the Mexican freetail bat, sometimes also called the Brazilian freetail bat, lives in Bat Cave lava tube near El Calderon. Smaller colonies of Mexican freetail bat live in other lava-tube caves such as Braided Cave. The Mexican freetail bat lives in the caves during the summer months, and most migrate south to Mexico during the winter.

The big brown bat, which is one of the most common bat species at El Malpais, roosts in caves, rock crevices, and hollow trees. Big brown bats begin their evening flights earlier than other bats, and are often seen flying in the evening before dusk.

Five species of little brown bats belonging to the genus *Myotis* occur at El Malpais. These bats prefer caves and rock crevices for roosting. Little brown bats along with free tail bats appear to comprise most of the roosting bat colonies found in lava-tube caves at El Malpais.

Silver-haired and western big-eared bats are also known from El Malpais. The silver-haired bat generally roosts in trees, and the western big-eared bat roosts in caves. Unlike most other bat species, the western big-eared bat uses its roost year round, hibernating during the winter.

Birds

One hundred and nine species of birds occur at El Malpais, and 30 more species are known from the surrounding areas (Appendix 2). The most widespread and frequently encountered birds include the western bluebird, violet-green swallow, dark-eyed junco, piñon jay, common nighthawk, and common raven. Because so many bird species occur at El Malpais, a mention of common and distinctive species by the main habitat types is probably the most efficient way to introduce readers to the birds of El Malpais.

Ponderosa pine/mixed conifer woodlands—Many bird species frequent the ponderosa pine woodlands of El Malpais, including the dark-eyed junco, western wood peewee, common flicker, common nighthawk, red-tailed hawk, ash-throated flycatcher, violet-green swallow, common raven, black-capped chickadee, white-breasted nuthatch, rufous-sided towhee, and chipping sparrow. Some birds that are uncommon and largely restricted to the ponderosa pine woodlands at El Malpais include the sharp-shinned hawk, downy, hairy, and Lewis's woodpeckers, yellow-bellied sapsucker, dusky flycatcher, purple martin, tree swallow, Clark's nutcracker, Steller's jay, brown creeper, pygmy nuthatch, black-headed grosbeak, hepatic tanager, western tanager, pine siskin, and red crossbill. Most of the above birds prefer the tall stature of the ponderosa pine trees as habitat, and some require the pine cones and seeds as food.

Piñon-juniper woodlands—Many of the birds abundant in ponderosa pine woodlands are also common in the piñon-juniper woodlands. However, some species, such as the piñon jay, western bluebird, Townsend's solitaire, and cedar waxwing, prefer the Piñ^{o}n-juniper woodlands over other habitats. These birds feed on juniper berries or piñon seeds.

Juniper savanna—The open grassy juniper savannas of El Malpais provide a habitat that is quite different from the ponderosa pine and piñ^{o}n-juniper woodlands. Common birds of the juniper savannas include the American kestrel, northern harrier, mourning dove, common nighthawk, Cassin's kingbird, western kingbird, horned lark, common raven, western bluebird, mountain bluebird, Cassin's sparrow, chipping sparrow, savannah sparrow, and vesper sparrow. Birds that are largely restricted to the juniper savanna habitats include the American kestrel, northern harrier, horned lark, scaled quail, greater roadrunner, burrowing owl, Say's phoebe, Cassin's kingbird, western kingbird, sage thrasher, loggerhead shrike, blue grosbeak, Brewer's sparrow, Cassin's sparrow, lark sparrow, savannah sparrow, and vesper sparrow.

Lava flows and sandstone—Some birds are associated specifically with rock habitats of the lava flows and sandstone, regardless of surrounding vegetation. Such species include the band-tailed pigeon, rock dove, white-throated swift, cordilleran flycatcher (formerly Rocky Mountain race of the western flycatcher), cliff swallow, rock wren, and canyon wren. Of these, only the cordilleran flycatcher is largely associated with the lava flows, and only the cliff swallows are largely associated with sandstone. The other birds are found on both lava and sandstone.

FIGURE 7—Limestone bluffs on the North Kipuka of the Three Kipukas near The Narrows on the east side of El Malpais.

Though cordilleran flycatcher is generally uncommon throughout its range and displays no preference for rock type, at El Malpais it is abundant and mostly restricted to the steep sides and cave entrances of lava-tube collapse structures. Many of the lava-tube collapse structures at El Malpais support nesting pairs of the cordilleran flycatcher. The distinctive call of these small birds is so often heard around the lava-tube cave entrances that some frequent visitors to El Malpais call these flycatchers "ice cave birds."

Ephemeral ponds—Temporary natural ponds or small lakes are found in the juniper savanna areas along the west and southeast sides of El Malpais. Examples include Laguna Americana and small ponds at North Pasture. Cattle ponds or tanks have been constructed at most of these. The temporary waters and mud-flats provide habitat to several species of aquatic birds and shorebirds that would not otherwise occur at El Malpais, such as great blue and green-backed herons, white-faced ibis, green-winged teal and northern pintail ducks, and killdeer and mountain plovers. It is unlikely that any of the above birds, perhaps with the exception of killdeer, breed in these habitats. Most are migrants that stop to forage on their way to or from breeding grounds.

FIGURE 8—Marchantia Cave on the northwest side of El Malpais.

Amphibians and reptiles

Nine species of amphibians and 27 species of reptiles are known from El Malpais and the surrounding area (Appendix 3).

Frogs and toads—The canyon treefrog is widespread at El Malpais. These small frogs are associated with the lava flows and sandstone outcrops. They are heard calling and observed occasionally at lava-tube collapse structures in the upper Bandera lava flow. These frogs require standing pools of water to breed, and probably utilize small pools found in some collapse structures. Their small dark tadpoles occur in large pools of water or tinajas found in sandstone formations on the east side of El Malpais.

The New Mexico spadefoot toad occurs on the east side of El Malpais. Adult toads may be heard calling loudly from ephemeral pools of water following summer rains, and may be observed on NM-117 at night during the rainy season. The large gray tadpoles occur in pools of water at the base of the sandstone escapements, in roadside ditches, and in stock tanks. Two additional species of spadefoot toads, the plains spadefoot toad and Couch's spadefoot toad, are also known from nearby locations.

The red-spotted toad and Woodhouse's toad are known from the Zuni Mountains and probably occur

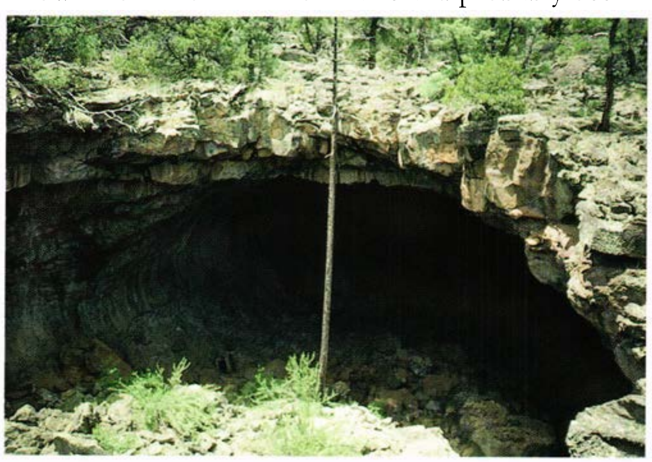

FIGURE 9—Tree Pole collapse structure in the Big Tubes area near the center of El Malpais.

in woodland areas in the northwest part of El Malpais. The northern leopard frog and chorus frog are also known from the Zuni Mountains, but are not likely to occur at El Malpais because they need permanent waters.

Slamanders—The tiger salamander occurs in stock tanks and temporary ponds along the west and east sides of El Malpais, but is rarely seen. It is a distinctly colored dark brown to black salamander with light yellow bands.

Lizards—Many species of lizards are abundant at El Malpais. The most widespread and frequently observed is the eastern fence lizard, which is common on the lava flows and on non-lava substrates throughout El Malpais. The coloration of this lizard is variable at El Malpais. Most individuals from lava flows are dark gray, while those on sandstone are light gray to brownish. The tree lizard is almost always found only on the lava at El Malpais. On the lava at El Malpais they are typically dark gray to blackish, whereas elsewhere they are lighter gray.

The Great Plains skink and the variable skink prefer grassy habitats with soil near the lava flows. Collared lizards are rare at El Malpais and tend to perch on large rocks in open areas at lower elevations, generally in juniper savanna habitats. The plateau and the Chihuahuan whiptail lizards and the lesser earless lizards all prefer open grassy habitats with sandy soil on the east side of El Malpais. All of these lizards are fast runners difficult to approach.

The short-horned lizards or "horned toads" are found on open sandy soils surrounding the lava flows in the juniper savannas and piñon-juniper woodlands. These short, robust, spiny lizards are beautifully colored to match the variably colored soil surfaces.

Several other lizard species are known from the Zuni Mountains and surrounding areas and may occur at El Malpais. These include the northern sagebrush lizard, side-blotched lizard, and the New Mexico and little striped whiptail lizards.

Snakes—The most frequently observed snakes at El Malpais include the western or prairie rattlesnake and the gopher snake. Both are widespread and occur in all habitats. The large western diamondback rattlesnake occurs at low elevations on the east side of El Malpais in the sandstone bluffs area. The wandering garter snake is frequent along roadsides, especially where water collects in roadside ditches. The large and fast striped whipsnake is uncommon in the juniper savanna areas on the east side of El Malpais.

Several other snakes including the black-necked gartersnake, coachwhip, milk snake, night snake, mountain patch-nosed snake, and ringneck snake inhabit the area, but have not yet been found at El Malpais. The black-tailed rattlesnake had been found in the Grants area and may also occur in the northern part of El Malpais.

Invertebrates

By far the largest number of animal species at El Malpais are invertebrates, mostly arthropods along with a couple of species of mollusks and at least one species of leech. The most extensive inventory of invertebrates at El Malpais to date was done by Lightfoot et al. (1994), resulting in the discovery of at least 17 new species and one new genus of arthropods. The large number of new arthropod species demonstrates that the invertebrate fauna of El Malpais was previously poorly known. Most of the new species appear to be endemic, which indicates that El Malpais provides a diversity of unique habitats. For example, some of the new endemic species were found only on lava flows or in the entrances of lava tube caves, habitats that are regionally unique.

In addition to the endemic species of arthropods, El Malpais supports many species of invertebrates that typically occur throughout the piñon—juniper and ponderosa pine woodlands of central New Mexico. Frequently observed arthropods include millipedes, centipedes, scorpions, spiders, crickets, grasshoppers, beetles, flies, butterflies and moths, bees, wasps, and ants. Crustaceans such as tadpole shrimp, fairy shrimp, and clam shrimp occur in ephemeral pools of water, including tinajas. Leeches are found occasionally in stock tanks, and one species of land snail and one species of pond snail are known from El Malpais.

It is not possible to discuss the many species of invertebrates that occur at El Malpais in this chapter. An account of invertebrates of El Malpais can be found in Lightfoot et al. (1994) and in subsequent update reports to the National Park Service.

Animals of the volcanic landscapes at El Malpais

Volcanic landscapes support animals with adaptations to live on barren lava fields (Best and James, 1984; Howarth, 1983) and unique species associated mostly with lava-tube caves (Peck, 1973; Howarth, 1972). Some animals adapt to life on lava habitats by darkening their body, presumably to be camouflaged from predators on the dark lava. This darkening is called melanism and is genetically based. Melanism has been found in a number of species of rodents (Dice, 1929; Benson, 1932; Blossom, 1933) and reptiles (Lewis, 1949, 1951; Prieto and Jacobson, 1968; Best and James, 1984) living on lava in southern and central New Mexico. Some melanistic rodent populations are considered to be distinct subspecies (Weckerly and Best, 1985).

Lava-tube caves are unique features of lava fields throughout the world. They form extensive subsurface habitats that are typically cooler, moister, and darker than the surrounding areas (Howarth, 1983). The stable isolated environments of caves provide situations where populations may become adapted to the local environment and evolve into new species (Barr, 1968; Howarth, 1983).

Most of the vertebrate animals of El Malpais that occur on lava fields are geographically widespread species that prefer rock habitats. The rock wren, tree lizard, eastern fence lizard, rock mouse, and rock squirrel are typical of the open lava habitats at El Malpais. The vertebrate animals of El Malpais exhibit little evidence of specialization specifically to lava habitats and occur on sandstone and limestone as well. Only animals found in lava-tube caves, such as

FIGURE 10—Massive collapse structure in the Big Tubes area near the center of El Malpais.

bats and some birds, are largely restricted to those habitats at El Malpais.

In contrast to vertebrates, several species of invertebrates at El Malpais do appear to be restricted to lava habitats. Two species of crickets are restricted to open habitats on the McCartys lava flow on the east side of El Malpais. A new species of camel cricket, a rare stone centipede, several new species of springtail insects, and several species of spiders are only known from the entrances of lava tube caves at El Malpais. The specialization of certain arthropod species to lava habitats at El Malpais is consistent with the findings of other studies demonstrating unique invertebrate faunas associated with basalt fields (Peck, 1973; Ashmole et al., 1992; Howarth, 1979; Ashmole and Ashmole, 1987). In contrast, Horning and Barr (1970) did not report any insects specialized to lava-field habitats in Idaho.

Melanism at El Malpais

Hooper (1941) conducted a survey of the melanism in mammals of the El Malpais lava fields and did not find any clear examples. He reported that some individuals of the rock mouse, white-throated woodrat, and Mexican woodrat were darker than

FIGURE 11—Small livestock pond at the south end of North Pasture on the east side of El Malpais.

FIGURE 12—Tinajas on top of sandstone bluffs and Sandstone Bluffs Overlook on the east side of El Malpais.

usual. However, he found dark animals both on and off the lava flows, and no melanistic populations restricted to the lava flows. Lightfoot et al. (1994) supported Hooper's findings. Some rock mice *(Peromyscus difficilis)* on El Malpais lava tended to be slightly darker than rock mice caught on sandstone or limestone, but the distinctions were not clear. Several melanistic subspecies of the rock pocket mouse *(Chaetodipus intermedius)* are known from different lava fields in southern New Mexico and Arizona (Weckerly and Best, 1985).

Tree lizards *(Urosaurus ornatus)* occur mostly on lava substrates at El Malpais (despite the common name, tree lizards typically occur on rocks) and are darker than tree lizards off lava flows in the area. Since the tree lizards are consistently dark, one may assume that those of El Malpais are melanistic. Lewis (1951) found melanistic tree lizards on lava flows in southern New Mexico. Dark short-horned lizards *(Phrynosoma douglassi)* have also been observed on lava at El Malpais. Horned lizards typically match the color of the substrate on which they live, and the dark lizards at El Malpais may be an example of melanism. The eastern fence lizard is the most common lizard species on and off lava substrates at El Malpais, yet there are no observations of melanism in individuals on the lava flows. These lizards are lighter in color than tree lizards at the same locations on the Bandera lava flow.

Other species of lizards known to be melanistic in New Mexico include the side-blotched lizard, desert spiny lizard, and collared lizard (Lewis, 1951). Lizards found on lava that are not melanistic include the leopard lizard and desert whiptail lizard. The western diamondback rattlesnake and black-tailed rattlesnake are commonly melanistic on lava, but the western rattlesnake is not (Best and James, 1984). Western rattlesnakes are commonly observed near and on lava at El Malpais, and they are characteristically light-colored, showing no evidence of melanism.

Two species of ground-dwelling grasshoppers at El Malpais are melanistic on lava. *Trimerotropis cyaneipennis* and *Phrynotettix tshivavensis* both typically occur on rocky substrates. At El Malpais both species are found on lava and sandstone substrates. Individuals from lava flows are much darker than those living on sandstone (Lightfoot et al., 1994). Substrate color matching is common in ground-dwelling grasshoppers, and may be induced either genetically or environmentally (Uvarov, 1977).

Hooper (1941) concluded that melanism does not occur in mammals at El Malpais probably because the lava habitats are less isolated from other rocky habitats (e.g. sandstone) than the lava fields in south-central New Mexico. He suggested that the lack of habitat isolation may allow enough gene flow between lava and non-lava populations to prevent the evolution of lava-colored populations. The lava fields in south-central New Mexico are isolated from adjacent rocky habitats and do harbor populations of melanistic mammals.

Another possible reason for low frequency of melanism among animals at El Malpais relative to animals at other lava fields in New Mexico may be that the lava surfaces at El Malpais have enough light-colored lichen cover to mask much of the darker color of the lava. The link between lichens on lava at El Malpais and virtual lack of melanism in animals may be analogous to the reverse of industrial melanism as demonstrated by Kettlewell (1961) in the peppered moth. Kettlewell (1961) found that when lichens were killed by pollution, the frequency of a dark or melanistic form of the moth became dominant over the previously light-colored form that was cryptic on lichens. The lack of light-colored lichens on the trees favored dark morphs of the moths, which were better camouflaged from bird predators.

The Carrizozo or Tularosa and other lava fields in south-central New Mexico that do have melanistic forms of rodents and reptiles are only about 1,000-10,000 years old (Shields and Crispin, 1956) and, perhaps because they occur at elevations lower than the El Malpais flows, support very little lichen. These lava flows tend to be black. Large portions of the McCartys lava flow at El Malpais are also black and barren, however we did not find any obvious examples of melanism in animals living there, perhaps for the reason suggested by Hooper (1941).

Lava-tube caves at El Malpais

Bats are the most obvious animals associated with caves at El Malpais. The large colony of Mexican free-tail bat at Bat Cave is the best example, yet the lava-tube caves of El Malpais provide important habitat for many other species of bats as well. Lightfoot et al. (1994) observed bats in a number of lava-tube caves and found that most bats were in the drier and warmer caves rather than in ice caves. The many skeletons of the southwestern cave myotis bats *(Myotis velifer),* other *Myotis* species, and the big brown bats *(Eptesicus fuscus)* found in Four Windows Cave indicate that many bats utilized that cave at some time in the past.

Colonies of bats in caves also create habitats for many invertebrate species. Guano accumulations are rich in nutrients and are usually occupied by many species of micro-arthropods including mites, pseudoscorpions, diplurans, and collembolans (see Northup, this volume).

The historic use of lava-tube caves by bighorn sheep is another ecologically unusual feature of El Malpais. Remains of bighorn sheep have been found in many of the lava-tube caves, particularly in the Big Tubes area of the Bandera lava tube (Carlton, 1993).

The use of lava-tube collapse structures and caves by the cordilleran flycatcher is one of the most distinctive associations between birds and lava tubes at El Malpais. The cordilleran flycatcher uses rock overhangs in cave entrances for nesting sites. Most of the lava-tube cave entrances on the upper Bandera lava tube and along the Lava Crater lava tube are utilized by nesting pairs of the cordilleran flycatcher. This association is one of the biologically unique features of El Malpais. The cordilleran flycatcher is generally uncommon in any given area and utilizes steep rocky cliffs, such as those of canyons, for breeding habitat.

Peck's (1982) survey of the El Malpais lava tubes revealed no troglobites nor any other distinctive species. He concluded that the most likely reason for absence of troglobites was the lack of a suitable ancestral soil-litter fauna in the area. Peck stated that the Zuni Mountains and surrounding areas supported a impoverished fauna of ground-dwelling and subterranean arthropods from which lava-tube troglobites at El Malpais might evolve. The discovery by Lightfoot et al. (1994) of many species of ground-dwelling arthropods, including camel crickets, harvestmen, and spiders, does not support Peck's hypothesis.

The cool moist conditions in the entrances of ice caves do support unique species of arthropods. Sheet-web spiders such as *Lepthyphantes turbatrix* are found associated with the ice-cave moss communities. These spiders typically occur in more northern latitudes where similar habitats are more common, and probably are Pleistocene relics of geographically more extensive populations. The new species of springtails, chloropid flies, and a camel cricket found in ice-cave entrances (Lightfoot et al., 1994) may also be new species derived from Pleistocene relics. These arthropods demonstrate that the ice-cave entrances provide habitats for populations of unique arthropods, further demonstrating the biological importance of ice-cave moss communities at El Malpais.

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Appendix 1—Mammals of the El Malpais National Monument area

Information sources: Numbers to left correspond to Source column in table below. Readers may refer to source references for more detailed information on distribution records.

1 = Hooper (1949); El Malpais region
2 = Stoltz (1986b); El Morro National Monument
3 = Lightfoot et al. (1994); El Malpais National Monument
4 = Klingel (1992); Cibola County

COMMON NAME	SCIENTIFIC NAME	SOURCE
BATS	Order Chiroptera	
Evening Bats	Family Vespertilionidae	
Big Brown Bat	*Eptesicus fuscus*	1,2,3,4
California Myotis	*Myotis californicus*	3,4
Cave Myotis	*Myotis velifer*	3
Fringed Myotis	*Myotis thysanodes*	1,2,3,4
Hoary Bat	*Lasiurus cinereus*	1,2,4
Little Brown Myotis	*Myotis lucifugus*	4
Long-eared Myotis	*Myotis evotis*	1,3,4
Long-legged Myotis	*Myotis volans*	1,2,4
Pallid Bat	*Antrozous pallidus*	4
Silver-haired Bat	*Lasconycteris noctivagans*	1,2,3,4
Small-footed Myotis	*Myotis subulatus*	1,2,3,4
Spotted Bat	*Euderma maculatum*	
Western Big-eared Bat	*Plecotis townsendi*	3
Western Pipistrelle Bat	*Pipistrellus hesperus*	4
Yuma Myotis	*Myotis yumanensis*	4
Freetail Bats	Family Molossidae	
Big Freetail Bat	*Tadarida macrotis*	
Mexican Freetail Bat	*Tadarida brasiliensis*	3,4
INSECT EATERS	Order Insectivora	
Shrews	Family Soricidae	
Desert Shrew	*Notiosorex crawfordi*	4
Dusky Shrew	*Sorex monticolus*	4
Dwarf Shrew	*Sorex nanus*	3,4
RABBITS and HARES	Order Lagomorpha	
	Family Leporidae	
Black-tailed Jackrabbit	*Lepus californicus*	1,2,3,4
Desert Cottontail	*Sylvilagus auduboni*	1,2,3,4
Eastern Cottontail	*Sylvilagus floridanus*	4
Mountain Cottontail	*Sylvilagus nuttallii*	1
RODENTS	Order Rodentia	
Squirrels	Family Sciuridae	
Cliff Chipmunk	*Eutamias dorsalis*	1,2,3,4
Colorado Chipmunk	*Eutamias quadrivittatus*	1,3,4
Red Squirrel	*Tamiasciurus hudsonicus*	4
Rock Squirrel	*Spermophilus variegatus*	1,2,3,4
Spotted Ground Squirrel	*Spermophilus spilosoma*	1,2
Tassel-eared Squirrel	*Sciurus aberti*	2,3,4
Whitetail Prairie Dog	*Cynomys gunnisoni*	1,2,3,4
Whitetail Antelope Squirrel	*Ammospermophilus leucurus*	4
Pocket Gophers	Family Geomyidae	
Botta's Pocket Gopher	*Thomomys bottae*	1,2,3,4
Northern Pocket Gopher	*Thomomys talpoides*	4
Pocket Mice and Kangaroo Rats	Family Heteromyidae	
Apache Pocket Mouse	*Perognathus apache*	1
Bannertail Kangaroo Rat	*Dipodomys spectabilis*	1,3,4
Ord's Kangaroo Rat	*Dipodomys ordii*	1,2,3,4
Plains Pocket Mouse	*Perognathus flavescens*	2,4
Rock Pocket Mouse	*Perognathus intermedius*	4
Silky Pocket Mouse	*Perognathus flavus*	1,3,4
New World Mice and Rats	Family Cricetidae	
Brush Mouse	*Peromyscus boylei*	1,2,3,4
Deer Mouse	*Peromyscus maniculatus*	1,2,3,4
Long-tailed Vole	*Microtus longicaudus*	4
Meadow Vole	*Microtus pennsylvanicus*	4
Mexican Vole	*Microtus mexicanus*	4

Appendix 1, cont.

New World Mice and Rats, cont.		
Mexican Woodrat	*Neotoma mexicana*	1,2,3,4
Northern Grasshopper Mouse	*Onychomys leucogaster*	1,2,4
Piñon Mouse	*Peromyscus truei*	1,2,3,4
Rock Mouse	*Peromyscus difficilis*	1,2,3,4
Southern Plains Woodrat	*Neotoma micropus*	4
Stephen's Woodrat	*Neotoma stephensi*	4
Western Harvest Mouse	*Reithrodontomys megalotis*	1,3,4
White-footed Mouse	*Peromyscus leucopus*	3,4
White-throated Woodrat	*Neotoma albigula*	1,2,3,4
Porcupines	Family Erethizontidae	
Porcupine	*Erethizon dorsatum*	1,2,3,4
CARNIVORES	Order Carnivora	
Dogs	Family Canidae	
Coyote	*Canis latrans*	1,2,3,4
Gray Fox	*Urocyon cinereoargenteus*	1,3,4
Kit Fox	*Vulpes macrotis*	2
Bears	Family Ursidae	
Black Bear	*Ursus americanus*	1,3,4
Raccoons	Family Procyonidae	
Raccoon	*Procyon lotor*	1,2,4
Ringtail	*Bassariscus astutus*	1,4
Weasels and Skunks	Family Mustelidae	
Badger	*Taxidea taxus*	1,2
Hognose Skunk	*Conepatus leuconotus*	1,4
Long-tailed Weasel	*Mustela frenata*	1,4
Short-tailed Weasel	*Mustela erminea*	2
Spotted Skunk	*Spilogale putorius*	2
Striped Skunk	*Mephitis mephitis*	1,2,4
Cats	Family Felidae	
Bobcat	*Lynx rufus*	1,2,4
Mountain Lion	*Felis concolor*	1,2,3,4
HOOFED MAMMALS	Order Artiodactyla	
Deer	Family Cervidae	
Elk	*Cervus canadensis*	2,4
Mule Deer	*Odocoileus hemionus*	1,2,3,4
Pronghorns	Family Antilocapridae	
Pronghorn	*Antilocapra americana*	3,4

Appendix 2—Birds of El Malpais National Monument area

Information sources: Numbers to left correspond to Source column in table below. Readers may refer to source references for more detailed information on distribution records.

1: Lightfoot et al., (1994); El Malpais National Monument

2: Klingel (1992); Cibola County

COMMON NAME	FAMILY/ SCIENTIFIC NAME	SOURCE
HERONS	ARDEIDAE	
Great Blue Heron	*Ardea herodias*	1
Green-backed Heron	*Butorides striatus*	1
IBISES	THRESKIORNITHIDAE	
White-faced Ibis	*Plegadis chihi*	1
DUCKS	ANATIDAE	
Green-winged Teal	*Anas crecca*	1
Northern Pintail	*Anas acuta*	1
PLOVERS	CHARADRIIDAE	
Killdeer	*Charadrius vociferus*	1
Mountain Plover	*Charadrius montanus*	1,2
VULTURES	CATHARTIDAE	
Turkey Vulture	*Cathartes aura*	1,2
EAGLES and HAWKS	ACCIPITRIDAE	
Bald Eagle	*Haliaeetus leucocephalus*	2
Cooper's Hawk	*Accipiter cooperii*	1,2
Golden Eagle	*Aquila chrysaetos*	1
Northern Goshawk	*Accipiter gentilis*	1,2
Northern Harrier	*Circus cyaneus*	1
Red-tailed Hawk	*Buteo jamaicensis*	1
Sharp-shinned Hawk	*Accipiter striatus*	1,2
Swainson's Hawk	*Buteo swainsoni*	
FALCONS	FALCONIDAE	
American Kestrel	*Alco sparverius*	1
American Perigren Falcon	*Falco peregrinus anatum*	2
QUAIL	PHASIANIDAE	
Blue Grouse	*Dendragapus obscurus*	2
Scaled Quail	*Callipepla squamata*	1
Wild Turkey	*Meleagris gallopavo*	1
PIGEONS	COLUMBIDAE	
Band-tailed Pigeon	*Columba fasciata*	1
Mourning Dove	*Zenaida macroura*	1
Rock Dove	*Columba livia*	1
CUCKOOS	CUCULIDAE	
Greater Roadrunner	*Geococcyx californianus*	1,2
OWLS	STRIGIDAE	
Barn Owl	*Tyto alba*	1
Burrowing Owl	*Athene cunicularia*	1
Flammulated Owl	*Otus flammeolus*	2
Great Horned Owl	*Bubo virginianus*	1
Long-eared Owl	*Asio otus*	1,2
Mexican Spotted Owl	*Strix occidentalis lucida*	2
Northern Saw-whet Owl	*Aegolius acadicus*	2
GOATSUCKERS	CAPRIMULGIDAE	
Common Nighthawk	*Chordeiles minor*	1
Common Poorwill	*Phalaenoptilus nuttallii*	1
SWIFTS	APODIDAE	
White-throated Swift	*Aeronautes saxatalis*	1
HUMMINGBIRDS	TROCHILIDAE	
Black-chinned Hummingbird	*Archilochus alexandri*	1
Broad-tailed Hummingbird	*Selasphorus platycercus*	1
Rufous Hummingbird	*Selasphorus rufus*	1
WOODPECKERS	PICIDAE	
Acorn Woodpecker	*Melanerpes formicivorus*	1
Common Flicker	*Colaptes auratus*	1
Downy Woodpecker	*Picoides pubescens*	1
Hairy Woodpecker	*Picoides villosus*	1
Lewis' Woodpecker	*Melanerpes lewis*	1

Appendix 2, cont.

COMMON NAME	FAMILY/ SCIENTIFIC NAME	SOURCE
WOODPECKERS, cont.		
Three-toed Woodpecker	*Picoides tridactylus*	2
Williamson's Sapsucker	*Sphyrapicus thyroideus*	2
Yellow-bellied Sapsucker	*Sphyrapicus varius*	1
FLYCATCHERS	TYRANNIDAE	
Ash-throated Flycatcher	*Myiarchus cinerascens*	1
Cassin's Kingbird	*Tyrannus vociferans*	1
Cordilleran Flycatcher	*Empidonax occidentalis*	1
Dusky Flycatcher	*Empidonax oberholseri*	1
Olive-sided Flycatcher	*Contopus borealis*	2
Say's Phoebe	*Sayornis saya*	1, 2
Willow Flycatcher	*Empidonax traillii extimus*	2
Western Kingbird	*Tyrannus verticalis*	1
Western Wood-Peewee	*Contopus sordidulus*	1
LARKS	ALAUDIDAE	
Horned Lark	*Eremophila alpestris*	1
SWALLOWS	HIRUNDIDIDAE	
Bank Swallow	*Riparia riparia*	2
Cliff Swallow	*Hirundo pyrrhonota*	1
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	1
Purple Martin	*Progne subis*	1,2
Tree Swallow	*Tachycineta bicolor*	1
Violet-green Swallow	*Tachycineta thalassina*	1
JAYS	CORVIDAE	
American Crow	*Corvus brachyrhynchos*	1,2
Clark's Nutcracker	*Nucifraga columbiana*	1
Common Raven	*Corvus corax*	1
Piñon Jay	*Gymnorhinus cyanocephalus*	1
Scrub Jay	*Aphelocoma coerulescens*	1
Steller's Jay	*Cyanocitta stelleri*	1
CHICKADEES	PARIDAE	
Black-capped Chickadee	*Parus atricapillus*	1,2
Bridled Titmouse	*Parus wollweberi phillipsi*	2
Mountain Chickadee	*Parus gambeli*	1
Plain Titmouse	*Parus inornatus*	1
BUSHTITS	AEGITHALIDAE	
Bushtit	*Psaltriparus minimus*	1,2
CREEPERS	CERTHIIDAE	
Brown Creeper	*Certhia americana*	1,2
NUTHATCHES	SITTIDAE	
Pygmy Nuthatch	*Sitta pygmaea*	1,2
Red-breasted Nuthatch	*Sitta canadensis*	1,2
White-breasted Nuthatch	*Sitta carolinensis*	1,2
WRENS	TROGLODYTIDAE	
Bewick's Wren	*Thryomanes bewickii*	1
Canyon Wren	*Catherpes mexicanus*	1
House Wren	*Troglodytes aedon parkmanii*	2
Rock Wren	*Salpinctes obsoletus*	1
THRUSHES	MUSCICAPIDAE	
American Robin	*Turdus migratorius*	1
Golden-crowned Kinglet	*Regulus satrapa*	2
Hermit Thrush	*Catharus guttatus*	2
Mountain Bluebird	*Sialia currucoides*	1,2
Ruby Crowned Kinglet	*Regulus calendula*	1
Townsend's Solitaire	*Myadestes townsendi*	1,2
Western Bluebird	*Sialia mexicana*	1,2
MIMIC THRUSHES	MIMIDAE	
Brown Thrasher	*Toxostoma rufum longicauda*	2
Gray Catbird	*Dumetella carolinensis*	2
Northern Mockingbird	*Mimus polyglottos*	1
Sage Thrasher	*Oreoscoptes montanus*	1,2
WAXWINGS	BOMBYCILLIDAE	
Cedar Waxwing	*Bombycilla garrulus*	1
SHRIKES	LANIIDAE	

Appendix 2, cont.

COMMON NAME	FAMILY/ SCIENTIFIC NAME	SOURCE
Loggerhead Shrike	*Lanius ludovicianus*	1
SHRIKES, cont.		
Northern Shrike	*Lanius excubitor invictus*	2
VIREOS	VIREONIDAE	
Gray Vireo	*Vireo vicinior*	2
Solitary Vireo	*Vireo solitarius*	1
Warbling Vireo	*Vireo gilvus*	2
WARBLERS and SPARROWS	EMBERIZIDAE	
Black-and-white Warbler	*Mniotilta varia*	2
Black-headed Grosbeak	*Pheucticus melanocephalus*	1,2
Black-throated Gray Warbler	*Dendroica nigrescens*	1,2
Blue Grosbeak	*Guiraca coerulea*	1
Brewer's Blackbird	*Euphagus cyanocephalus*	1
Brewer's Sparrow	*Spizella breweri*	1,2
Brown Towhee	*Pipilo fuscus*	1
Brown-headed Cowbird	*Molothrus ater*	1
Canyon Towhee	*Pipilo fuscus*	2
Cassin's Sparrow	*Aimophila cassinii*	1
Chestnut-sided Warbler	*Dendroica pennsylvanica*	2
Chipping Sparrow	*Spizella passerina*	1
Common Yellowthroat	*Geothlypes trichas*	2
Dark-eyed Junco	*Junco hyemalis*	1
Eastern Meadowlark	*Sturnella magna lilianae*	2
Evening Grosbeak	*Coccothraustes vespertinus*	2
Grace's Warbler	*Dendroica graciae*	1
Hepatic Tanager	*Piranga flava*	1
Hooded Warbler	*Wilsonia citrina*	2
Lark Bunting	*Calamospiza melanocorys*	2
Lark Sparrow	*Chondestes grammacus*	1
Mcgillivray's Warbler	*Oporornis tolmiei*	2
Northern Oriole	*Icterus galbula*	1
Olive Warbler	*Peucedramus taeniatus*	2
Orange-crowned Warbler	*Vermivora celata*	2
Painted Redstart	*Myioborus pictus*	2
Pine Grosbeak	*Pinicoloa enucleator montana*	2
Rufous-sided Towhee	*Pipilo erythrophthalmus*	1,2
Sage Sparrow	*Amphispiza belli*	1
Savannah Sparrow	*Passerculus sandwichensis*	1
Scott's Oriole	*Icterus parisorum*	1
Vesper Sparrow	*Pooecetes gramineus*	1
Virginia's Warbler	*Vermivora virginiae*	1,2
Western Meadowlark	*Sternella neglecta*	1,2
Western Tanager	*Piranga ludoviciana*	1
White-crowned Sparrow	*Zonotrichia leucophrys*	1,2
Wilson's Warbler	*Wilsonia pusilla*	1
Yellow Warbler	*Dendroica petechia*	1
Yellow-rumped Warbler	*Dendroica coronata*	1,2
FINCHES	FRINGILLIDAE	
Cassin's Finch	*Carpodacus cassinii*	1,2
House Finch	*Carpodacus mexicanus*	1
Lesser Goldfinch	*Carduelis psaltria*	1,2
Pine Siskin	*Carduelis pinus*	1
Red Crossbill	*Loxia curvirostra*	1

Appendix 3—Amphibians and reptiles of El Malpais National Monument area

Information sources: Numbers to left correspond to Source column in table below. Readers may refer to source references for more detailed information on distribution records.

1 = Gehlbach (1965); Zuni Mountains
2 = Stoltz (1986a); El Morro National Monument
3 = Lightfoot et al. (1994); El Malpais National Monument
4 = C. Painter, NM Game and Fish (pers. comm. 1993); Cibola County

COMMON NAME	SCIENTIFIC NAME	SOURCE
AMPHIBIANS	Class Amphibia	
Salamanders	Order Caudata	
Mole Salamanders	Family Ambystomatidae	
Tiger Salamander	*Ambystoma tigrinum*	1,2,3,4
Frogs and Toads	Order Anura	
Spadefoot Toads	Family Pelobatidae	
Couch's Spadefoot Toad	*Scaphiopus couchii*	4
Plains Spadefoot Toad	*Spea bombifrons*	1,2,4
New Mexico Spadefoot Toad	*Scaphiopus multiplicatus*	1,2,3,4
True Toads	Family Bufonidae	
Red-spotted Toad	*Bufo punctatus*	1,2,4
Woodhouse's Toad	*Bufo woodhousii*	1,2,4
Treefrogs	Family Hylidae	
Canyon Treefrog	*Hyla arenicolor*	1,3,4
Chorus Frog	*Pseudacris triseriata*	1,4
True Frogs	Family Ranidae	
Northern Leopard Frog	*Rana pipiens*	1,4
REPTILES	Class Reptilia	
Lizards	Suborder Lacertilia	
Iquanids	Family Phrynosomatidae	
Collared Lizard	*Crotaphytus collaris*	1,3,4
Eastern Fence Lizard	*Sceloporus undulatus*	1,2,3,4
Lesser Earless Lizard	*Holbrookia maculata*	1,2,3,4
Northern Sagebrush Lizard	*Sceloporus graciosus*	1,2,4
Roundtail Horned Lizard	*Phrynosoma modestum*	4
Short-horned Lizard	*Phrynosoma douglasii*	1,2,3,4
Side-blotched Lizard	*Uta stansburiana*	1,2,4
Tree Lizard	*Urosaurus ornatus*	1,2,3,4
Whiptail Lizards	Family Teiidae	
Checkered Whiptail	*Cnemidophorus grahami*	4
Chihuahuan Whiptail	*Cnemidophorus exsanguis*	3,4
Little Striped Whiptail	*Cnemidophorus inornatus*	4
New Mexico Whiptail	*Cnemidophorus neomexicanus*	4
Plateau Striped Whiptail	*Cnemidophorus velox*	1,2,3,4
Skinks	Family Scincidae	
Great Plains Skink	*Eumeces obsoletus*	1,3,4
Variable Skink	*Eumeces multivirgatus*	1,2,3,4
Snakes	Suborder Ophidia	
Colubrid Snakes	Family Colubridae	
Black-necked Garter Snake	*Thamnophis cyrtopsis*	1,2,4
Coachwhip	*Masticophis flagellum*	1,4
Gopher Snake	*Pituophis melanoleucus*	1,2,3,4
Milk Snake	*Lampropeltis triangulum*	2
Night Snake	*Hysiglena torquata*	1
Mountain Patcnosed Snake	*Salvadora grahamiae*	1,4
Ringneck Snake	*Diadophis punctatus*	1,2,4
Striped Whipsnake	*Masticophis taeniatus*	1,2,3,4
Wandering Garter Snake	*Thamnophis elegans*	1,2,3,4
Vipers	Family Viperidae	
Black-tailed Rattlesnake	*Crotalus molossus*	1,4
Western Diamondback	*Crotalus atrox*	1,3,4
Western Rattlesnake	*Crotalus viridis*	1,2,3,4

Introduction

In the mid-1940s ecologist Alton Lindsey began a systematic floristic study of the area later to become El Malpais National Monument. This research, subsequently published in the journal *Ecological Monographs* (Lindsey, 1951), was the first comprehensive survey of the flora of the malpais in relation to the unique habitats found on the lava flows. The monograph particularly emphasized the unique nature of various species of trees, shrubs, mosses, and algae. Lindsey discovered entire stands of Douglas-fir *(Pseudotsuga menziesii)*, ponderosa pine *(Pinus ponderosa)*, *piñon (Pinus edulis)*, and various species of juniper *(Juniperus* spp.) trees existing in areas with little soil throughout the malpais. In his many excursions onto the lava flows, Lindsey also discovered that both Douglas-fir and ponderosa pine trees growing on the malpais lava reached great ages. He cored numerous trees to investigate the relationship between tree growth and substrate material.

More than 40 years later, we sampled in the same areas and confirmed that these trees hold great potential for revealing past climatic trends over the last 1,000-2,000 years. Using dendrochronology, the science of tree-ring dating, researchers can absolutely date to the exact year of formation each tree ring formed by the malpais trees over their respective lifespans. Because tree growth is strongly associated with regional climate (Fritts et al., 1965; Fritts, 1976), dendroclimatologists (scientists who use tree rings to study past climate) can measure the width of each individual tree ring and determine the rainfall in any given year long before climate records were kept. Furthermore, by reconstructing climate from tree rings, dendroclimatologists can learn about past *long-term* trends in climate and determine whether extended periods existed in the past when climate was particularly favorable or unfavorable for human and plant populations when compared to modern climate records. We can then relate these long-term climate trends to our knowledge about the behavior of the Ancestral Puebloan culture of the Four Corners area of the Southwest. This leads to an intriguing question asked by many archaeologists and visitors to the abandoned ruins of the Southwest: Could climate have been partially responsible for the abandonment and migratory behavior of these ancient inhabitants? Perhaps the old-aged conifers of the malpais can provide some answers to this long-perplexing question.

How trees can grow on the lava surfaces

The presence of trees on the lava flows at first appears paradoxical: How is it possible for such humid-site trees like Douglas-fir and ponderosa pine to exist on the seemingly harsh lava surfaces with little soil and an apparent lack of water? Our field reconnaissance essentially supported the observation first made by Lindsey (1951) that the lava flows support a more mesophytic vegetation type (i.e. plants that grow in more humid conditions) than areas off the lava flows. This observation suggests that the lava substrate somehow alters environmental conditions to allow certain species to exist in areas that would otherwise be considered inhospitable. This further suggests that the ability of the lava substrate to retain moisture is important in determining the distribution of plants throughout the malpais (Lindsey, 1951). We hypothesize, as did Lindsey, that the porous nature of the lava acts as a reservoir that traps and holds moisture from winter snowmelt and summer monsoonal rainfall. Ice caves that occur throughout the malpais provide evidence that the lava may act as a special type of aquifer. The lava therefore retains water necessary for Douglas-fir and ponderosa pine establishment and continued propagation.

Sampling the living malpais trees

Following our initial sampling efforts in 1990, we began an extensive systematic sampling during the next four years, specifically targeting long-lived Douglas-fir and ponderosa pine trees found growing at two locations on the surface of the Bandera lava flow (Fig. 1): (1) along the perimeter of the lava tube just south and west of Bandera Crater, and (2) northeast of Cerro Rendija, a site now known as the Lindsey Site. We confirmed what Lindsey (1951) had previously described regarding the unusual growth forms of individual trees. Most Douglas-fir trees are short, seldom more than eight meters in height, very wide at the base, and often exhibit a near-horizontal spiral grain (Figs. 2, 3). These traits are usually indicative of great age in conifers (Schulman, 1937). We found ponderosa pine trees to be similarly influenced by the lava substrate. On the McCartys lava flow, west of The Narrows and surrounding McCartys Crater, the forest consists of stunted pine trees that rarely reach three meters in height (Fig. 4). However, the pines can reach great heights in well-watered areas off the lava flow, such as near Three Kipukas and Cerro Bandera.

To obtain tree-ring samples from living trees, we used increment borers (a hollow metal tube screwed into the tree) to extract pencil-thin cores of wood from the old-aged conifers. The coring process removes very little living wood tissue, and the sampled tree seals the small wound in a few weeks.

Sampling the remnant wood in the malpais

Initially, we concentrated on the living old-aged conifers, but soon discovered numerous samples of old wood lying on the lava surface that appeared to be well-preserved (Figs. 5, 6). To extend the tree-ring calendar back in time, dendrochronologists often sample

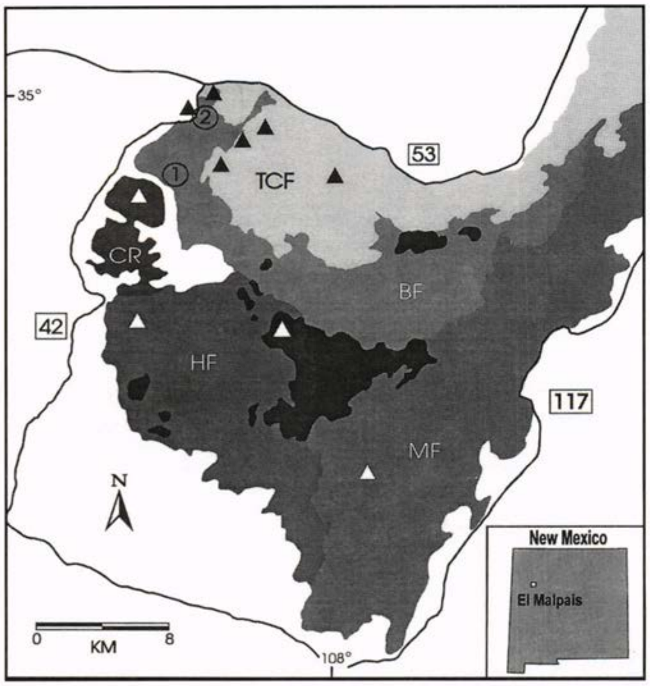

FIGURE 1—El Malpais National Monument, showing locations of the Cerro Rendija East (or Lindsey) site (1) and the Bandera Ice Cave site (2) in the Bandera lava flow (BF). Other lava flows include Twin Craters (TCF), McCartys (MF), Hoya (HF), and Cerro Rendija (CR). Triangles denote prominent volcanic vents.

FIGURE 2—A living Douglas-fir tree, CRE-37, showing the typical growth form found on the lava flows. CRE-37 dates to A.D. 1062.

dead wood, then match the outer pattern of wide and narrow tree rings from this dead wood with the identical pattern from the living trees. Matching the unique patterns of rings to date samples of unknown age is a technique known as crossdating, which uses both graphical and statistical methods to ensure exact year assignment to each individual tree ring (Stokes and Smiley, 1968; Holmes, 1983). The malpais contained abundant remnant wood that we knew could be used to extend our climate reconstruction even further back in time.

Using an increment borer on the remnant wood was not feasible, because the brittle wood repeatedly breaks inside the borer. Therefore, we used a chainsaw to remove complete and partial cross sections from Douglas-fir and ponderosa pine logs and smaller pieces of remnant wood.

Ages of the malpais trees

Once all samples had been mounted and sanded, we used a microscope to view the tree rings and graphically crossdate all tree rings from all cores and cross sections. We learned that El Malpais National Monument contained some of the oldest living trees, as well as the oldest sections of remnant wood, ever dated in the greater American Southwest. The two oldest living Douglas-fir trees, samples BIC-63 (inside ring date of A.D. 719) and CRE-37 (inside ring date of A.D. 1062), are the oldest confirmed, crossdated individuals for this species yet discovered in North America (Table 1). We found numerous Douglas-fir trees growing on the Bandera lava flow with ages in excess of 600 years. Given the very small area sampled, we believe that the malpais likely contains several individual Douglas-fir trees more than 1,000 years old. The living trees gave us a continuous, well-replicated tree-ring chronology back to A.D. 719, but the number of trees in our sample with rings prior to A.D. 1000 was low. A climate reconstruction based solely on living trees would not have been reliable prior to A.D. 1000.

The remnant wood solved this problem. The first remnant specimen collected was sample CRE-46, a section from the base of a ponderosa pine tree that once grew in the malpais (Fig. 6). Neither modern collection chronologies nor archaeological reference dating chronologies from New Mexico sites could date this sample. We had to turn to longer and older archeological tree-ring chronologies from outside the state, specifically those from Canyon de Chelly (Arizona) and Durango (Colorado). This decision was both crucial and fortunate, because eventually we were able to date this tree back to the year A.D. 111 using the Durango reference tree-ring chronology. We had, with this one high-quality, well-preserved specimen, a sample of a tree older than any other yet collected in New Mexico.

The effort to extend the malpais tree-ring chronology back in time continued as sample after sample of remnant wood dated prior to A.D. 1000, very effec-

FIGURE 3—A living Douglas-fir tree, BIC-63, showing an atypical growth form in which the main stem has died, yet the root system remains intact and supports a lateral branch regrowth. This tree has an inside-ring date of A.D. 719 and is currently the oldest known living Rocky Mountain Douglas-fir tree in North America.

FIGURE 4—A living ponderosa pine tree on the McCartys lava flow, showing the stunted and contorted growth form typical of pine trees growing on this lava flow.

tively linking the living-tree chronology with the remnant-wood chronology. Eventually, we collected sections from 28 trees that had tree-ring sequences extending prior to A.D. 1000 (Table 2), more than any other site, archaeological or modern, studied in the

TABLE 1—Inner- and outer-ring dates (yrs A.D.) of 10 oldest living trees sampled in the malpais. All samples are from Douglas-fir trees.

Number	Sample ID	Inner ring	Outer ring	Length
1	BIC 63	719	1992	1274 yrs
2	CRE 37	1062	1990	929
3	CRE 121	1147	1992	846
4	BCS 06	1235	1991	757
5	BCS 09	1256	1990	735
6	BIC 30	1288	1989	702
7	BFL 01	1293	1990	698
8	BIC 06	1294	1989	696
9	CRE 59	1298	1991	694
10	CRE 29	1316	1990	675

FIGURE 5—A remnant of a Douglas-fir tree, sample CRE-51, found lying on the surface of the Bandera lava flow. This sample has an inside-ring date of A.D. 706.

FIGURE 6—Remnant of a ponderosa pine tree, sample CRE-46, found lying on the surface of the Bandera lava flow. This sample has an inside-ring date of A.D. 111.

Southwest. The most remarkable remnant sample collected was CRE-148, a section from a Douglas-fir log found at the Lindsey site on July 25, 1993. This tree, now known as the Bannister Tree in honor of the eminent dendrochronologist Dr. Bryant Bannister, had an inside tree ring crossdated to 200 B.C. and an outer ring dated to A.D. 550, making this currently the oldest dated wood in either Arizona or New Mexico. Unfortunately, we could not include the innermost 64 rings from this sample in the final chronology because they were too compressed for accurate ring measurement.

We made another breakthrough during that same field trip in the summer of 1993. We had previously concentrated our sampling to only Douglas-fir and ponderosa pine trees because wood from these two species was by far the easiest to crossdate. We collected a cross section from a remnant Rocky Mountain juniper *(Juniperus scopulorum)* tree found near the lava tube just south of Bandera Crater, and were surprised at the ease with which this sample dated. This tree also provided us with a continuous tree-ring sequence

TABLE 2—Inner- and outer-ring dates of 10 oldest sections of remnant Douglas-fir (DF) and ponderosa pine (PP) wood that extend prior to A.D. 1000.

Number	Sample ID	Inner ring	Outer ring	Length	Species
1	CRE 148	200 B.C.	A.D. 550	751 yrs	DF
2	CRE 184	A.D. 103	A.D. 216	114	PP
3	CRE 46	A.D. 111	A.D. 456	346	PP
4	CRE 117	A.D. 118	A.D. 734	617	DF
5	CRE 110	A.D. 128	A.D. 525	398	PP
6	CRE 186	A.D. 502	A.D. 610	109	PP
7	CRE 109	A.D. 567	A.D. 874	308	PP
8	BIC 74	A.D. 589	A.D. 1089	501	DF
9	CRE 45	A.D. 599	A.D. 1349	751	DF
10	CRE 174	A.D. 664	A.D. 1164	501	DF

FIGURE 7—Cross section of a remnant Rocky Mountain juniper, sample CRE-175. This juniper germinated in approximately 29 B.C. and died in A.D. 1859, making this the oldest known tree to have lived in the American Southwest.

extending from A.D. 318 to A.D. 1459. A cross section cut later from another Rocky Mountain juniper log, sample CRE-175, showed this tree had germinated on the Bandera lava flow in the year 29 B.C. This tree then lived for 1,888 years until the year A.D. 1859 when it died, making this the oldest known tree to have lived in the American Southwest (Fig. 7). We are confident that the malpais contains 2,000 year-old living juniper trees, and perhaps even older ones as well. We hope to eventually collect additional juniper specimens from the malpais to complete a well-replicated juniper tree-ring chronology.

After several years of continuous tree-ring dating, we eventually dated 248 Douglas-fir and ponderosa pine tree-ring series. We averaged together annual indices of tree growth derived from the raw measurements, a process known in dendrochronology as chronology building (Fritts, 1976), to develop a 2,129 year-long tree-ring chronology back to 136 B.C. The malpais tree-ring chronology is currently the longest single-site chronology in the greater American Southwest.

Developing the climate reconstruction

Before we could reconstruct climate, we first had to determine to which climatic variables the trees were responding. Using correlation and response function analyses, statistical techniques commonly used by dendroclimatologists (Fritts, 1976), we found the strongest relationship between tree growth and total precipitation extending from July of the previous

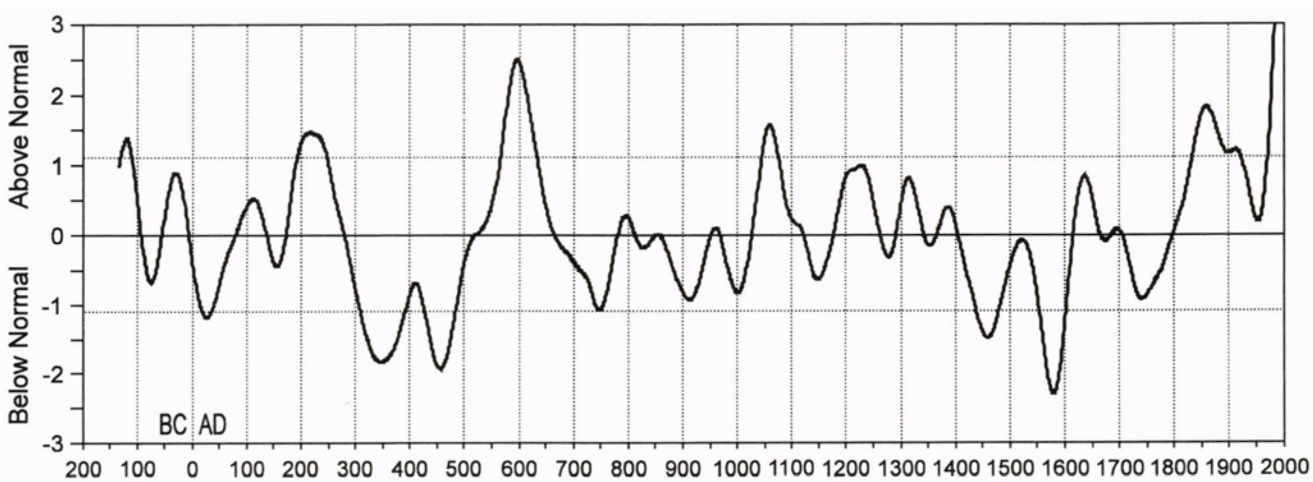

FIGURE 8—The final reconstruction of total annual (July–July) precipitation for the period 136 B.C.–A.D. 1992 based on the malpais trees and presented as a smooth curve fit through the actual yearly reconstructed values. The curve accentuates long-term (more than 100 years) trends in past climate. Sections on the curve above or below the 1.1 level (dashed lines) are considered very wet or very dry climate periods.

year to July of the current year, a period commonly termed in hydrology a "water year" as opposed to a calendar year. This relationship indicates the malpais trees are responding more to hydrological than to direct climatic factors because the lava flows tend to retain water year-round. This long response was fortunate because it allowed us to reconstruct annual total precipitation rather than rainfall for only one season, such as winter or spring.

The reconstruction was carried out by first calibrating widths of tree rings with annual (July-July) precipitation for the malpais area over the historic period when weather records were kept (1895-1992). The calibration was conducted using an ordinary least-squares regression to develop a linear equation that predicted annual rainfall for any particular year from the tree-ring width for the same year. Essentially, the statistical calibration allows us to say that a tree-ring width of so many millimeters resulted from annual precipitation totaling a specific amount. Once the calibration was completed, we were able to reconstruct annual rainfall for the malpais area spanning the entire length of the tree-ring chronology, back to 136 B.C.

The climate of the malpais area over the past 2,100 years

A smooth-curve fit through the climate reconstruction revealed that climate in northwestern New Mexico between 136 B.C. and A.D. 1992 was dominated by seven alternating, long-term periods of above normal and below-normal rainfall (Fig. 8, Table 3), which correlate very well with long-term fluctuations reconstructed from other paleoenvironmental reconstructions (Euler et a1.,1979). These long-term periods also provide additional information on past environmental changes that may have affected behavioral characteristics of the populations that lived in northwestern New Mexico during the last 2,100 years. Our results also provide an opportunity to independently compare the malpais tree-ring reconstruction with paleoenvironmental reconstructions for the Four Corners area developed using other techniques based on geomorphic, archaeological, and stratigraphic evidence of past environmental change (Euler et al., 1979).

A period of above-normal rainfall between A.D. 81 and 257 correlates very well with a fluvial maximum that occurred in the Four Corners area of the Southwest prior to A.D. 230 (Euler et al., 1979). In some portions of the Four Corners area, such as southeastern Utah and southwestern Colorado, local populations increased during this period (Dean et al., 1994). However, this favorable period was followed by the most severe long-term drought period (A.D. 258-520) in the last 2,129 years. Tree growth was noticeably reduced during this period, especially beginning near A.D. 350. Euler et al. (1979) and Dean et al. (1985) reported that a prolonged hydrologic minimum occurred between A.D. 250-450, which correlates very well with this prolonged drought. Interestingly, the differentiation of the three major Southwestern cultures, Hohokam, Mogollon, and Ancestral Puebloan, accelerated during this unfavorable period (Gumerman and Gell-Mann, 1994), suggesting that differentiation, migration, and other changes in behavioral patterns may have occurred as a means to cope with changing environmental conditions.

Between A.D. 100 and 550 the human population of the entire greater Southwest experienced little change, which was followed by a dramatic increase, especially in the Colorado Plateau area (Dean et al., 1994). The malpais climate reconstruction shows that a major climatic change began occurring around A.D. 550, with annual rainfall increasing to extremely high levels between A.D. 521 and 660. During this favorable period Basketmaker populations increased throughout the Four Corners region, especially in southwestern Colorado and southeastern Utah, the Kayenta area, and the San Juan Basin (Dean et al., 1994). This very favorable period was followed by a long period of below-normal rainfall between A.D. 661 and 1023. Interestingly, the Ancestral Puebloan population continued to increase during this unfavorable period, indicating that long-term, low-frequency fluctuations in climate had little influence on regional populations (Dean et al., 1985). Other studies (Schoenwetter, 1970; Eddy, 1974; Euler et al., 1979) also confirm that a hydrologic minimum occurred between A.D. 661 and 1023.

Favorable climate conditions returned between A.D. 1024 and 1398, a period that correlates very well with above-normal hydrologic conditions reconstructed by Euler et al. (1979). However, two major short-term droughts occurred during this period that doubtless had prolonged effects on the Ancestral Puebloan population. A secondary hydrologic minimum and its corresponding drought are clearly reconstructed near A.D. 1150. Dean et al. (1985) observed that this drought played an important role in Ancestral Puebloan population shifts and abandonment. Cultural centers at the Virgin Branch area, Grand Canyon, northern Black Mesa, Red Rock Valley, and Chaco Canyon were all depopulated around A.D. 1150.

Following this drought, favorable conditions returned to the Four Corners area for the next 100 years, during which time the Ancestral Puebloan people made important cultural advances and achievements. Population densities, based on the number of sites, habitation units, or artifacts within the ruins, peaked in nearly all areas around A.D. 1250. However,

TABLE 3—Long-term periods of above-normal (AN) and below-normal (BN) rainfall since A.D. 100 in northwestern New Mexico based on the malpais reconstruction.

Period	Duration	Length	Sample depth[1]
AN-1	A.D. 81–257	177 yrs	6–14
BN-2	A.D. 258–520	263	5–12
AN-2	A.D. 521–660	140	5–12
BN-3	A.D. 661–1023	363	11–38
AN-3	A.D. 1024–1398	375	38–85
BN-4	A.D. 1399–1790	392	85–122
AN-4	A.D. 1791–1992	202	18–114

[1]Minimum and maximum number of measured series.

a second major short-term drought, also known as the "Great Drought," occurred between A.D. 1271 and 1296 (Douglass, 1931; Baldwin, 1935). This period ".. undoubtedly contributed substantially to the wide-spread abandonment and population redistributions of the late thirteenth century" (Dean et al., 1985). During the previous 100 years Ancestral Pueblo populations peaked and agriculture intensified, further reinforcing a settled lifestyle. Once the climate deteriorated, rainfall became less reliable to a culture more than ever dependent on it. This may have contributed to the overall depopulation of major Ancestral Pueblo areas that occurred around A.D. 1300.

After A.D. 1400, below-normal rainfall set in and lasted until approximately A.D. 1800, forming the longest of the seven long-term periods. However, rainfall began declining as early as in the late 1200s (the "Great Drought"), and widespread abandonment of Ancestral Pueblo areas occurred, perhaps in response to these unfavorable environmental conditions. Interestingly, large settlements became established in areas with more reliable water supplies, such as the Mogollon Highlands area, the Hopi Mesas, the Zuni area, and the Rio Grande area, perhaps as a means for large populations to cope with these unfavorable climatic conditions. This aggregation of local populations was fortunate, because the worst and most severe of any of the short-term (less than 50 years long) droughts occurred between A.D. 1566 and 1608 (D'Arrigo and Jacoby, 1991).

The last of the seven long-term periods, one of very high rainfall, began around A.D. 1800 and still persists. This current period is the wettest since the A.D. 521-660 period, which is illustrated by the fact that the 1800s have the distinction of being the only century without a severe short-term drought. Below-normal rainfall did occur during certain years, such as 1806, 1819, 1822, 1847, 1851, and 1880, but these were very short-lived droughts. A major short-term drought did not occur until between A.D. 1950 to 1964, and it was one of the worst droughts in the last 2,129 years. However, rainfall following this severe drought has been unprecedented in the last 2,000 years, and researchers believe a dramatic shift in oceanic—atmospheric circulation patterns may be responsible for this increased rainfall (Miller et al., 1994). More rainfall occurred between 1978 and 1992 than in any other 15-year period during the last 2,129 years.

Conclusions and recommendations

The malpais trees reveal several long-term periods of above-normal and below-normal rainfall over the last 2,100 years. These climatic changes must have had some impact on behavioral characteristics of the populations that lived in the Four Corners area of the Southwest during the last 2,100 years. The worst long-term drought occurred between A.D. 258 and 520, and may have accelerated the differentiation of populations into the three major cultures. The change to the settled lifestyle during the Basketmaker **III** stage occurred during a period of highly favorable climate between A.D. 521 and 660, but populations continued to increase even during the unfavorable climate between AD. 661 and 1023.

The worst short-term droughts during periods of population increase occurred in A.D. 1133-1161 and A.D. 1271-1296, the latter being the "Great Drought." Both droughts occurred during a long-term period of generally abundant rainfall, between A.D. 1024 and 1398. This suggests that favorable environmental conditions aided the technological advances made during that period and caused an unprecedented increase in Ancestral Puebloan populations. These large populations could not be supported during the mid-12th century and late 13th century droughts. The worst short-term drought overall occurred between A.D. 1566 and 1608, but major population centers had become established near more reliable water sources and were better able to cope with this severe drought.

The paleoclimate history revealed by the malpais trees, and the unique environment in which they live, make these old-aged conifers a natural resource unlike any other in the National Park system of the United States. Their longevity shows that the seemingly "stressful" environment offered by the malpais is perhaps not so "stressful" as it is protective. Obviously, the Douglas-fir and ponderosa pine trees find the lava flows quite hospitable. They have been able to establish, mature, and propagate on the lava flows for at least 2,000 years and perhaps much longer. The lava flows, especially the Bandera flow, afford a very protective environment, because lack of soil development and subsequent grass cover inhibit fire occurrence. Erosion processes are retarded because water rapidly seeps into the porous lava. Wild and domestic grazing animals (with the exception of the bighorn sheep) do not venture into the interior of these lava flows, and humans tend to collect wood only near the edges of the rugged lava surface.

Because the malpais region has been incorporated into the National Park system, these living trees and the remnant wood lying on the lava surfaces are guaranteed continued protection. Precautionary measures should be taken to ensure the trees of the malpais are not destroyed during activities such as road or highway clearing, building construction, or cutting for fence posts. The abundant remnant-wood samples should be protected from being collected for fuel, cut for fence posts, and being consumed in future prescribed burns. We all should treat the living trees and remnant pieces of wood found lying on the lava surface with respect and consideration deserving of extremely rare natural resources found in national parks. Additionally, there is a need for public education on the uniqueness and scientific value of the dead and living trees in the malpais to ensure their continued protection.

In the future, we would like to collect additional remnant-wood samples to eventually extend the malpais tree-ring chronology farther back into the pre-Christian Period and beyond. The possibility exists that we can eventually develop a 3,000 year long tree-ring chronology (back to 1000 B.C.) and learn more about past short-term and long-term climate fluctuations that may have affected the local populations. The possibility of developing a tree-ring chronology of such length currently does not exist elsewhere in the greater Southwest. In the future, we would like to specifically target remnants of Rocky Mountain junipers, because these trees are highly resistant to decay, are abundant throughout the malpais, and are extremely long-lived. We believe the junipers of the malpais hold the key to extending our knowledge of the climate of the Southwest over the past 3,000 years.

Acknowledgments

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Until the paving of Route 66 in the 1930s, travel in El Malpais country could be an adventure. Pot holes, stray livestock, and axle-deep mud were common encounters. Photograph taken by W. T. Lee about 1920 near Laguna, New Mexico, courtesy of U.S. Geological Survey, Photographic Library, Denver Colorado.

Multi-century history of wildfire in the ponderosa pine forests of El Malpais National Monument

Henri D. Grissino-Mayer and Thomas W. Swetnam
Laboratory of Tree-Ring Research, The University of Arizona, Tucson, Arizona 85721

Introduction

In recent years, an important land-management concept has evolved based on principles formulated in conservation biology and landscape ecology. *Ecosystem management* seeks to sustain the viability of ecological systems by maintaining or restoring past processes that created and shaped these ecosystems over long periods (Kaufmann et al., 1994). To do so requires knowledge of (1) the ecological processes that were historically important, (2) the temporal and spatial scales on which these processes operated, and (3) the natural range of variability (i.e. the upper and lower limits) of these processes (Allen, 1994; Morgan et al., 1994). In many areas of the western U.S. humans have so greatly altered ecosystems that many ecological processes (e.g. wildfires, erosion, and insect outbreaks) currently operate outside of their historic range of variability (i.e. outside the physical capability of the ecosystem). Therefore, ecosystem management emphasizes the restoration of more stable and sustainable environmental conditions and processes, especially in "...pieces of the landscape made uncommon by human activities" (Kaufmann et al., 1994).

Wildfire in particular is a process that currently functions outside of its normal range. Over the millennia fires co-evolved with ecosystems and became an integral process in the maintenance of the mosaic pattern of open meadows, grasslands, woodlands, and forests we see today. However, human-related activities such as livestock grazing and fire suppression have so impacted western forests that catastrophic, stand-replacing fires are much more likely than the low-intensity surface fires that once characterized many western forests (Swetnam, 1990; USDA Forest Service, 1993). To better understand impacts due to wildfire and other ecological processes upon present and future environmental conditions, reference "templates" should be established based on the role of ecological processes prior to Euro-American settlement (approximately 1880) (Allen, 1994; Kaufmann et al., 1994). A key recommendation of federal agencies is additional research on the history of fire to learn about its role in shaping western forest landscapes (USDA and USDI, 1989; Kaufmann et al., 1994; Swanson et al., 1994), in order to place the present-day wildfire situation in better perspective for those charged with managing public lands. In this sense, *the past is the key to the future.*

Restoring fire as a vital ecosystem process requires reassessments of past fire-management policies: Should all wildfires continue to be suppressed, or should wildfires be allowed to burn under certain environmental conditions (i.e. a "prescription" for fire)? Should fuel loadings in western forests be allowed to increase, or should agencies use management-ignited prescribed fires to reduce high fuel loadings? If agencies do use prescribed fires as a tool to preempt wildfires, what knowledge and justification is necessary to implement such a policy? To what degree have we changed the landscape of western forests, and what do these changes imply about future wildfire occurrences? At El Malpais National Monument, past policies were incompatible with the fundamental objective "... to restore the natural function of fire within the ecosystems of the park to the greatest extent possible" (USDI National Park Service, 1992). However, restoration of fire within the monument is challenging because of the lack of information on the range within which past fire functioned. Management of fire is further complicated by the complex geology, diverse landscape, and various human-related factors (e.g. grazing, logging, and fire suppression) that have influenced the malpais landscape.

Our research sought to establish reference conditions within which fire functioned as an ecosystem process at El Malpais National Monument prior to Euro-American settlement (approximately 1880). We had four objectives. (1) Because of the complexity of the malpais landscape, it was imperative to compare past fire histories in various habitat types within and adjacent to the monument. (2) We wished to establish the upper and lower limits, as well as the average conditions, within which fire functioned. (3) We wished to investigate any changes in past fire over both time and space, and propose possible explanations for these changes. (4) Using these results, we wished to make preliminary recommendations for managing fire that would take into consideration the complexity of the malpais landscape and the historical perspective of human land-use patterns.

Habitat types and sites selected for fire history

El Malpais contains numerous lava flows of varying sizes and ages (Fig. 1) that create vegetative associations in various successional stages. This landscape heterogeneity suggests that the probability of fire ignition and spread is highly variable, depending on the physical and vegetative characteristics of the individual habitat (Touchan and Swetnam, 1995). Hence, no single fire regime (i.e. fire frequency, size, and severity) is likely to characterize the fire history of all habitats within the monument. We therefore sampled several representative habitat types.

Cinder cones and shield volcanoes

To characterize the fire history in ponderosa pine forests on cinder cones and shield volcanoes (Fig. 2), we collected samples at: (1) Cerro Rendija, an eroded, low-lying shield volcano in the western portion of the malpais; (2) the eastern flank of Cerro Bandera, a slightly eroded cinder cone in the northwest corner of the malpais; and, (3) Lost Woman, a cinder cone also in the northwest portion of the malpais, but separated

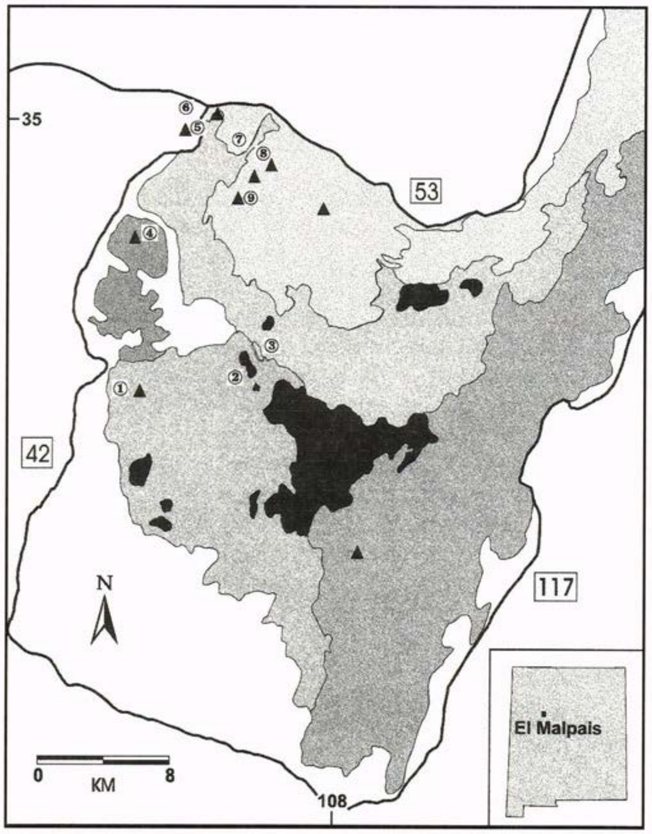

FIGURE 1—El Malpais National Monument, showing boundaries of major lava flows and locations of the nine sites sampled: (1) Hoya de Cibola, (2) Mesita Blanca, (3) Hidden Kipuka, (4) Cerro Rendija, (5) Cerro Bandera East, (6) Cerro Bandera North, (7) Candelaria, (8) La Marchanita, and (9) Lost Woman. Triangles denote major cinder cones and shield volcanoes.

from the other two sites by the Bandera lava flow. All three sites are adjacent to surrounding grasslands with a long history of grazing (Mangum, 1990). The forests in these areas were logged of many of their larger trees, and the numerous stumps contained well-preserved fire-scarred specimens. Occasional dense ("doghair") thickets of young ponderosa pines occur on the slopes of these landforms, most likely because

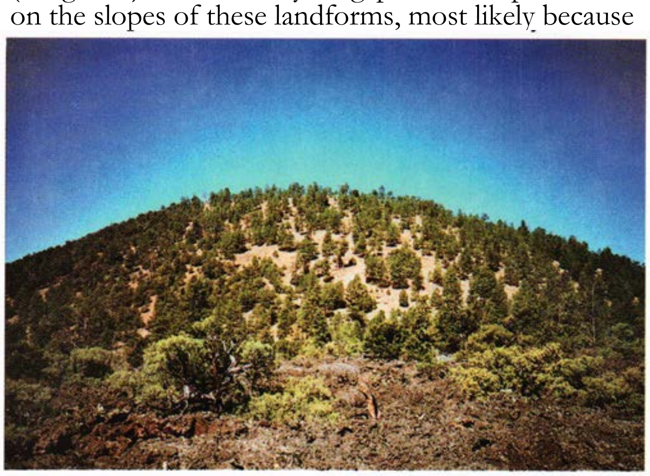

FIGURE 2—Cerro Bandera cinder cone viewed from the east on the Bandera lava flow, showing the open ponderosa pine forests on its east flank.

FIGURE 3—Overlooking the La Marchanita site from the Candelaria cinder cone, with the Bandera lava flow in the background. The La Marchanita site is representative of the ponderosa pine forests on older, highly eroded lava flows.

of fire suppression. Under presettlement conditions, these thickets would have been reduced in size and density by episodic, low-intensity surface fires.

Ancient eroded basalt flows

We analyzed the fire history of ponderosa pine forests on ancient, highly eroded basalt flows by collecting fire-scarred samples from: (1) the low-lying open ponderosa forests north of Cerro Bandera; (2) the woodland savanna surrounding La Marchanita Cave; and, (3) a site north of the Bandera lava flow on the Candelaria property (Fig. 3). Soils at these sites are highly developed and deeper than soils on younger basalt flows, and support abundant grasses and woodland savannas that grade into open ponderosa pine forests. Extensive logging, grazing, and fire suppression have occurred in these areas, because they are relatively accessible to springs, major roadways, trails, and rail systems (Mangum, 1990).

Younger basalt flows

We collected one site, on the Hoya de Cibola lava flow (Fig. 4), a young, moderately eroded lava flow characterized by pahoehoe lava that creates a broken topography with numerous fissures. Forest litter accumulates in the fissures. Aerial photographs of the 1989 Hoya Fire Complex showed surface fires spreading across large areas by means of the litter that accumulated in these fissures. The lava flow supports an open ponderosa pine forest on shallow soils with patchy grass cover. This site is immediately adjacent to grasslands with a long history of grazing. The broken topography and rough terrain would inhibit grazing directly on the lava flow, but the ability of fire to spread to the lava flow may have been reduced due to grazing. Fires have been suppressed in this area up to the present, but we found no evidence of logging.

Isolated kipukas

This was the fourth and final habitat type we sampled (Fig. 5). Kipukas are "islands" of original substrate material (such as sandstone, limestone, or older

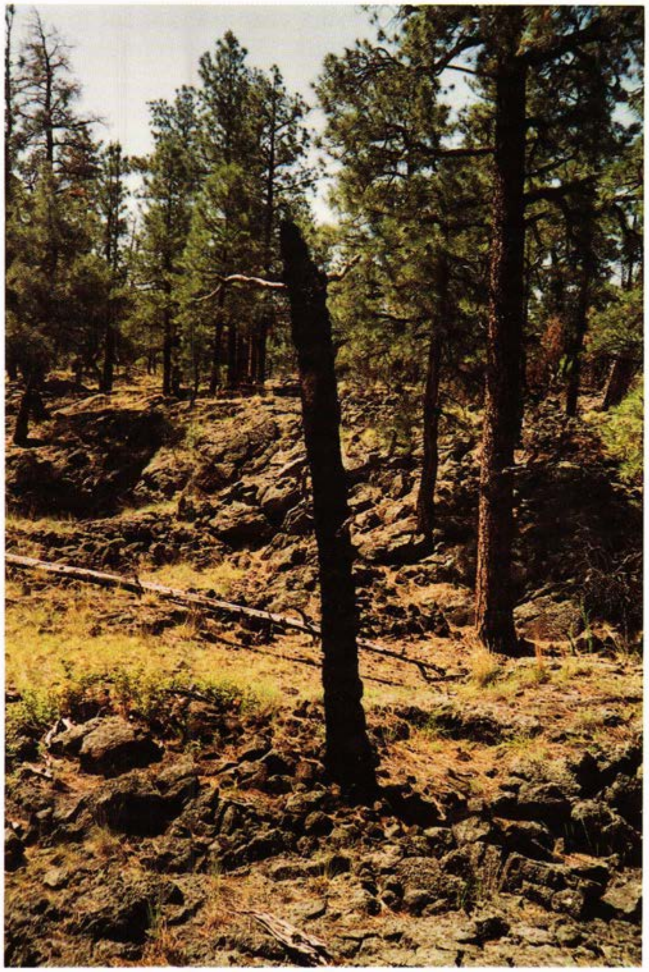

FIGURE 4—The Hoya de Cibola lava flow site, representative of the younger, moderately eroded lava-flow habitat. This photograph was taken in 1992 within the periphery of the 1989 Hoya Complex fires. Other than isolated charred logs (note fire-charred tree in foreground), there is little evidence of this fire today.

lava) surrounded by younger lava flows (Lindsey, 1951). We collected samples at: (1) Mesita Blanca, a kipuka surrounded by the Hoya de Cibola lava flow; and (2) Hidden Kipuka, located approximately 1 km

FIGURE 5—The interface between the Hoya de Cibola lava flow (at right) and the grasslands, ponderosa, and piñon–juniper forests (at left) at Hidden Kipuka.

FIGURE 6—An old ponderosa-pine log at the La Marchanita Cave site, showing the characteristic basal wound caused by fire. By using such well-preserved fire-scarred samples, we crossdated fire scars back to the 1300s, currently the longest continuous fire history in the Southwest.

FIGURE 7—A stump located on the Cerro Bandera cinder cone east slope, with a very large fire-scarred area on its uphill side. Left from previous logging earlier this century, this sample contained a record of 23 fire scars dating back to A.D. 1640.

to the northeast of Mesita Blanca and bounded by the Hoya de Cibola lava flow to the west and by the Bandera lava flow to the east. These kipukas support both ponderosa pine forests and piñon-juniper woodlands, and have well developed grass cover. Because of their isolation, these sites were not logged. Fire-suppression effects are probably minimal. The surrounding rough terrain, lack of water source, and limited forage prevented extensive grazing on these kipukas.

Methods of reconstructing fire history

Wildfire patterns prior to Euro-American settlement were analyzed to establish reference conditions of wildfire as an ecosystem process. Most western forests preserve such records in the growth rings of conifer species such as the ponderosa pine (Figs. 6, 7). Before the Euro-American settlement, low-intensity surface fires were characteristic of western pine forests. These fires sometimes wound the lower portion of the stem by killing the outer layer of living

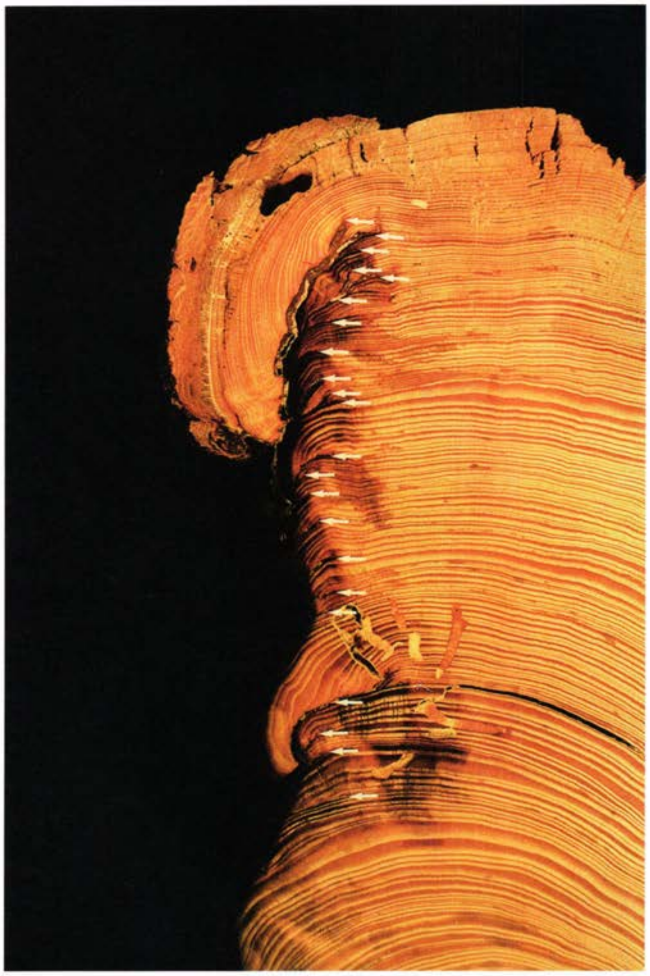

FIGURE 8—Portion of a fire-scarred cross section showing a record of numerous fire scars (arrows) from the low-intensity, frequent surface fires characteristic of the malpais area prior to 1880. This one tree contained a record of 30 fires dating to the late 1500s.

cells, usually on the uphill side of the tree where fuels collect. In subsequent years, the tree will form successive growth layers (tree rings) over the old wound. Usually another surface fire occurs later on to once again kill the outer layer of cells before the tree has completely overgrown the old wound. The probability of subsequent fires scarring the tree is increased, because flammable resins in the initial wound increase the likelihood of fire re-igniting on the old wound. Hence, once scarred by fire, ponderosa pines tend to be good "recorders" of frequent, low-intensity surface fires (Fig. 8).

At each site, we collected cross sections from stumps, logs, and snags that showed evidence of repeated scarring by fire. Small wedges were also cut from a few fire-scarred living trees to obtain dates of the most recent fires (Arno and Sneck, 1977). In the laboratory, all cross sections were sanded with progressively finer sandpaper until the cellular structure of each tree ring was visible under magnification. We then crossdated all tree rings and fire scars to their exact year of formation. Crossdating is the cornerstone of dendrochronology, using both graphical and statis tical methods to ensure exact year assignment to each individual tree ring (Fritts, 1976; Holmes, 1983; Swetnam et al., 1985).

All fire-history information was entered into databases and analyzed using software developed specifically for this project (Grissino-Mayer, 1995). For each site, we first constructed master fire charts that displayed the spatial and temporal patterns in past fire regimes as recorded by sampled fire-scarred trees (Dieterich, 1980). Using these charts, we noted any changes in widespread fires (defined as those fires recorded by the majority of trees sampled within the study areas) within and between sites.

To establish the historical range of variability of past fires, we statistically assessed patterns of fires during the presettlement period (defined as pre-1880) across the four habitat types sampled by calculating the minimum and maximum fire intervals, as well as the Weibull Median Probability Interval (WMPI). WMPI is the fire interval associated with the 50% probability level (i.e. half of all fire intervals will be above and half below this interval) derived from the Weibull distribution, a flexible distribution able to model highly skewed fire-interval data (Johnson and Van Wagner, 1985; Baker, 1992; Grissino-Mayer et al., 1995). Finally, we propose possible explanations for any observed changes in past fire based on habitat characteristics (i.e. substrate, fuel types and amounts, local topography, and land-use history).

The fire history of El Malpais

We dated nearly 3,000 fire scars recorded on over 700 specimens from 217 trees at nine sites within and adjacent to the monument. Fires occurred in 245 of the 660 years between A.D. 1333 and 1993. However, the number of samples extending prior to A.D. 1500 is low because older, well-preserved samples are rare. The master fire charts constructed for the nine sites clearly show that wildfires were a recurrent process of the malpais landscape for many centuries. The oldest dated fire events occurred in 1367 and 1382 at both the Hoya de Cibola and La Marchanita sites, making these sites the longest continuous fire histories yet developed in the Southwest. The most recent fire event dated was the series of scars caused by the 1989 Hoya Complex fires.

Spatial patterns of fires within and between sites

The master fire chart for the Cerro Bandera cinder cone (Fig. 9) shows the synchroneity of fires recorded among the sampled trees. At this site, we collected 19 samples at the highest elevations and 13 samples at lower elevations to determine whether differences in fire patterns existed at such small spatial scales. Both subsites were equal in area, approximately 10 hectares, separated by an equivalent-size area. Nearly all fire years were synchronous between the upper and lower areas, suggesting these fires were widespread within the site. Two asynchronous fire years occurred, however. The 1841 and 1923 fires affected primarily the upper areas of the cinder cone, while the 1843 and 1925 fires were confined to the lower slopes.

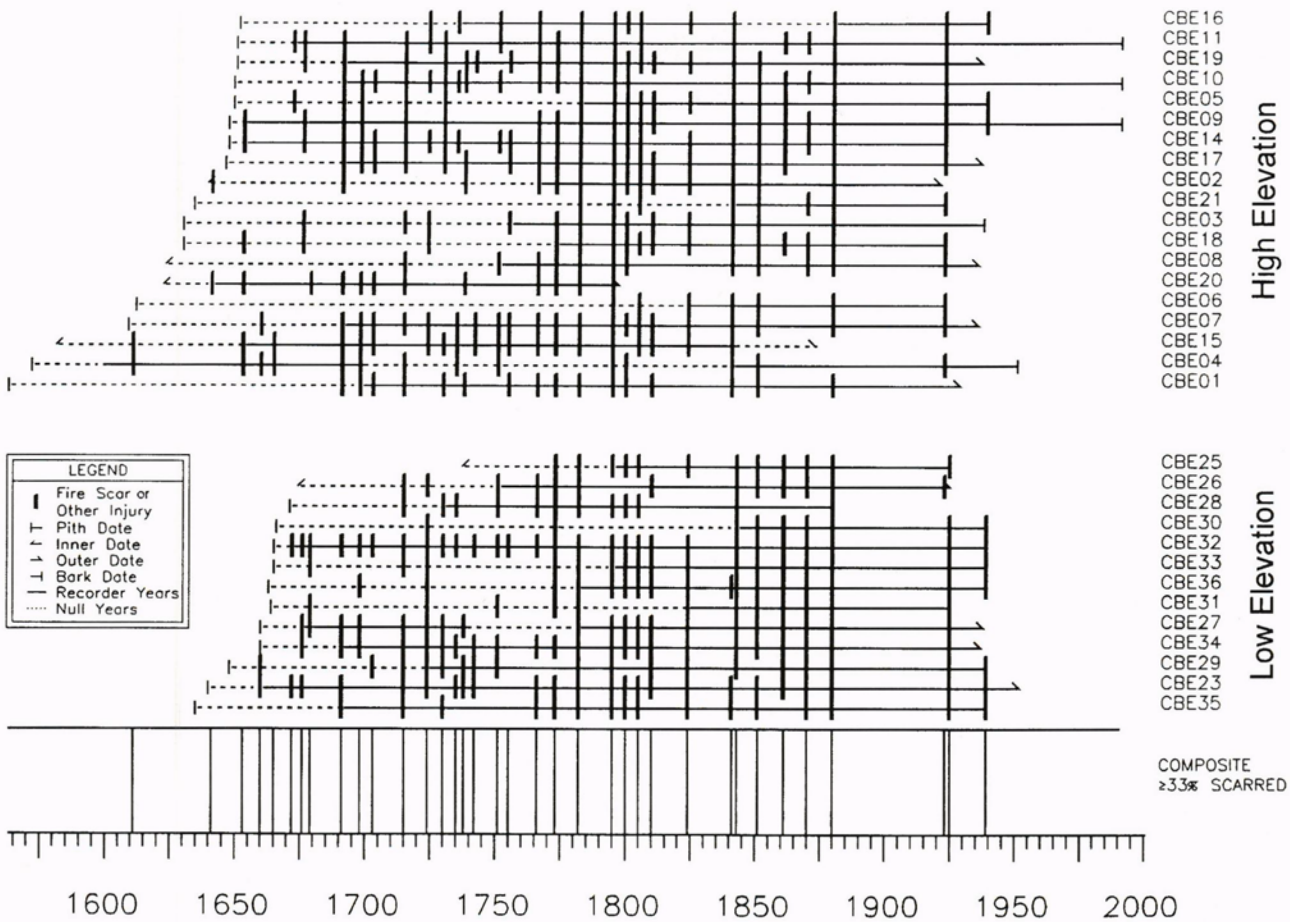

FIGURE 9—The master fire-history chart for the eastern slopes of the Cerro Bandera cinder cone, divided into upper and lower slope samples. The fire history is filtered to show only more widespread fires. Each sampled tree is plotted as a horizontal line. Symbols along this line denote fire years.

Prior to 1880, fires were synchronous between sites as well, suggesting that presettlement fires spread over extensive areas (Fig. 10). Between 1650 and 1880, at least 13 fires occurred at four or more of the sampled sites. Three fires (1824, 1841, and 1861) occurred at six sites, extending over much of the western and northwestern sides of the monument. This synchroneity occurs across habitat types. For example, the 1841 and 1861 fires occurred in all four habitat types. A record of the 1824 fire, on the other hand, was absent from the kipukas. At the Candelaria and La Marchanita sites, fires were mostly synchronous despite extensive as lava separating these sites (Fig. 1). Because fire spread across this lava is unlikely due to lack of fuels, fire must have spread from outlying areas, or multiple ignitions may have occurred at the two sites.

Temporal changes in fire patterns

Disruption in episodic fires started occurring approximately at 1880 (Figs. 9, 10). Wildfires that were common before 1880 suddenly ceased. Wildfires did not occur again until 1923 at Cerro Bandera, until 1932 at Cerro Rendija, until 1916 at Candelaria, until 1925 at Cerro Bandera North, and until 1915 at the Hoya de Cibola site. No widespread fire has occurred at the La Marchanita site since 1900. Although smaller fires (i.e. fires that scarred a small percentage of trees) did occur during this 40 year period, some factor prevented them from spreading within each site, in contrast to pre-1880.

Another temporal change in fire patterns occurred beginning approximately at 1940 (Figs. 9, 10). Regardless of extent, fires ceased abruptly at all sites except the two kipukas. For example, at the Cerro Bandera site fire-scarred samples were collected from three living trees, CBE09, CBE10, and CBE11. These trees recorded fires continuously since the early 1600s, yet showed no fires between 1940 and 1992. Similar long fire-free periods occurred at other sites as well: 1916 to the present at the Candelaria site; 1909 to 1976 at the Lost Woman cinder cone; and 1933 to 1989 at the Hoya de Cibola site. These long 20th century fire-free periods were unprecedented in the malpais region for the last 600 years.

Fire regimes in different habitat types

Statistics of fire in the different habitats of the malpais region over the period 1700-1880 revealed differences as well as similarities among the habitat types

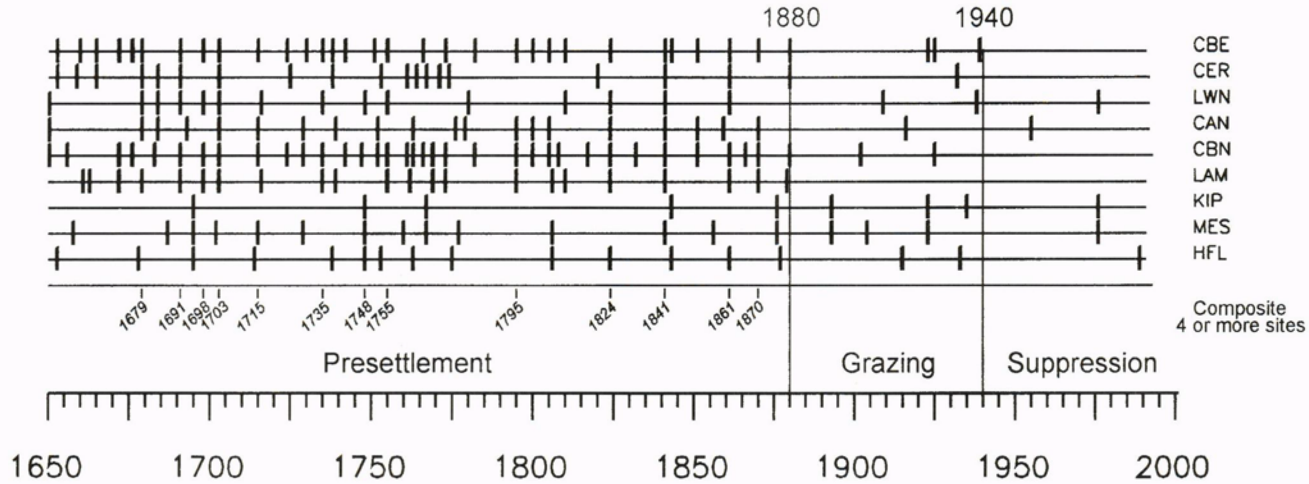

FIGURE 10—Fire history for El Malpais National Monument, filtered to show the most widespread fires at each site. CBE, CER, and LWN represent cinder-cone/shield-volcano habitats, CAN, CBN, and LAM represent ancient basalt-flow habitats, KIP and MES are the two kipuka sites, and HFL represents the younger basalt flows.

(Table 1). At the three cinder-cone/shield-volcano sites, fires occurred approximately once every five to eight years. This frequency is similar to the five to seven years for the three sites sampled on the ancient basalt flows that surround the malpais. When the composite fire information for each of the three sites on these two habitat types is combined, we find that fire occurred in both habitat types approximately once every three years. This contrasts the frequency of one fire every seven years for the combined kipuka sites, and once every 11 years for the Hoya de Cibola site. In general, fires during the presettlement period were much more frequent in the ponderosa pine forests and grasslands on cinder cones, shield volcanoes, and outlying pine savannas than on the kipukas and younger basalt flows.

Combining all nine sites to provide an overall assessment of presettlement fires in the malpais area, fire occurred at our sites at least once every two years during the period 1700 to 1880. Analyzing only those fires that affected at least 25% of all trees within each study area (i.e. widespread fires that were perhaps more ecologically important), we found fires occurred on average in the sampled areas about once every 2 fi half years.

Conclusions

The fact that fires occurred frequently at El Malpais National Monument for hundreds of years is an important finding. If the National Park Service is to restore natural processes of El Malpais in order to more closely approximate presettlement conditions, then surface fires must be re-introduced. Presettlement fires were usually low-intensity surface burns that crept through grassy understories of ponderosa pine and mixed-conifer forests, consuming fuels that accumulated since the last fire. These fires maintained forests in open, park-like conditions observed by the many pioneers that first entered the Southwest (Cooper, 1960; Savage, 1991; Covington and Moore, 1994). An excellent modern-day analog to these park-like conditions can be seen on the northern and northeastern slopes of the Lost Woman cinder cone, where the 1976 fire removed dense fuels, shrubs, and most understory trees.

The malpais fire histories revealed two major changes in fire frequency, the first around 1880 and the second around 1940. After 1880 fire frequency decreased at most sites, resulting in the longest fire-free intervals in the past 600 years. This decrease was coincident with the onset of widespread livestock grazing in the malpais area in the early 1880s following the subjugation of the Navajos and the arrival of railroads in 1881. By 1885 the nearby community of San Rafael became the center of sheepherding with tens of thousands of sheep grazing within and adjacent to the monument (Bailey, 1980; Mangum, 1990, this volume). Grazing reduced grasses and herbaceous cover required for spreading of surface fires (Cooper, 1960; Wright and Bailey, 1982; Savage and Swetnam, 1990; Touchan et al., 1995), thus lowering both frequency and areal extent following 1880.

The change in fire frequency around 1940 was most likely due to an increase in the efficiency of fire suppression. After 1945, aerial handling of wildfires using modified surplus warplanes became common, smoke jumping was perfected, fire-detection methods became more advanced, and the number of roads and trails increased to allow quicker access. Following these improvements, numerous pine thickets became established throughout the monument, especially on the western side. Tree-ring dating of these young ponderosa pines on the eastern slopes of Cerro Bandera confirmed that these dense "doghair" thickets appeared immediately after the 1939 fire.

Different fire histories of the various sites correspond with the heterogeneity of the landscape. Before

TABLE 1—Fire-history information for the nine sites collected for this study over the period 1700–1880.

Habitat type/ site name	Number of samples	Minimum interval (years)	Maximum interval (years)	WMPI[1] (years)	Fire[2] freq.
Cinder cones and volcanoes					
Cerro Bandera East	32	1	12	5.2	0.192
Cerro Rendija	11	1	25	7.8	0.128
Lost Woman	20	2	30	7.7	0.130
Composite	63	1	10	3.2	0.317
Ancient basalt flows					
La Marchanita	37	2	21	6.8	0.147
Candelaria	20	2	17	6.9	0.144
Cerro Bandera North	35	1	13	4.9	0.202
Composite	92	1	13	3.1	0.324
Kipukas					
Mesita Blanca	26	2	22	8.6	0.116
Hidden Kipuka	13	3	55	13.3	0.075
Composite	39	2	22	6.8	0.147
Younger basalt flow					
Hoya de Cibola flow	23	2	31	10.8	0.092
El Malpais National Monument					
Composite, all fires	217	1	8	2.1	0.489
Composite, 25% scarred	217	1	13	2.6	0.391

[1]Weibull Median Probability Interval, see text for definition.
[2]Fire frequency (x 100) is the probability (in %) of fire occurring in any given year.

1880 fire was a common phenomenon on the highly weathered basalt flows, cinder cones, and shield volcanoes, occurring approximately once every five to eight years. However, at the two kipuka sites fires occurred in 9-13 year intervals. Because both the kipuka sites are small, fires most likely spread to them from the surrounding forests on the Hoya de Cibola lava flow, where they occurred approximately once every 11 years. These results confirm that El Malpais forests have different regimes that the Park Service should consider when developing a fire management plan.

Recommendations

In some areas the fuel structure of malpais forests should be restored before processes such as fire can be expected to behave naturally (i.e. within the range of historic natural variability). Large fuels, such as logs and snags, are abundant because extensive logging occurred in some parts of the monument early in this century, namely around El Calderon and the Lava Wall northeast of Cerro Rendija. Fire suppression has further altered fuel loadings primarily by allowing dense "doghair" thickets of young ponderosa pines to get established, creating ladder fuels that increase the probability of crown fires. Specific recommendations include: (1) using management-ignited prescribed burns to reduce high fuel loadings; (2) allowing natural, lightning-caused wildfires to burn as long as they occur within prescribed conditions and do not threaten developed areas, structures, or human lives; (3) thinning thickets of "doghair" ponderosa pines using either manual techniques (i.e. chainsaws) or carefully managed controlled burns; and (4) reducing or eliminating domestic grazing. Once the fire regime has been restored, management plans must consider the complexity of the malpais landscape which results in diverse conditions. Our knowledge of how to restore natural structures and processes is very limited. Reintroduced fire may not produce the desired presettlement conditions because ecosystems may be pervasively altered due to human factors (Allen, 1994).

We believe the malpais kipukas are extremely important for understanding the dynamics of ecological processes, especially fire. Kaufmann et al. (1994) stated "... we would like to have undisturbed ecosystems available for direct evaluation of natural ecosystem structure, composition, and function." The two kipukas sampled in this study revealed fire histories that were essentially uninterrupted (Fig. 11), indicating that human disturbances had little or no effect on fire regimes at these sites. Such sites are extremely rare in the western U.S. The kipukas are therefore suited to serve as control sites for (1) establishing the role of ecological processes that functioned during the presettlement period, and (2) establishing reference conditions to evaluate changes in fire over both time and space, especially those changes attributed to human disturbances. El Malpais National Monument has many kipukas with varied histories of land use, and these areas should be targeted for future fire-history and ecological research.

The fire histories show that fires were widespread throughout much of the malpais during certain years, e.g. in 1824 when fire was recorded as far south as the Hoya de Cibola site and as far north as the Paxton Springs cinder cone in the Zuni Mountains (H. D. Grissino-Mayer and C. H. Baisan, unpublished data). Such fires were probably tens of thousands or even

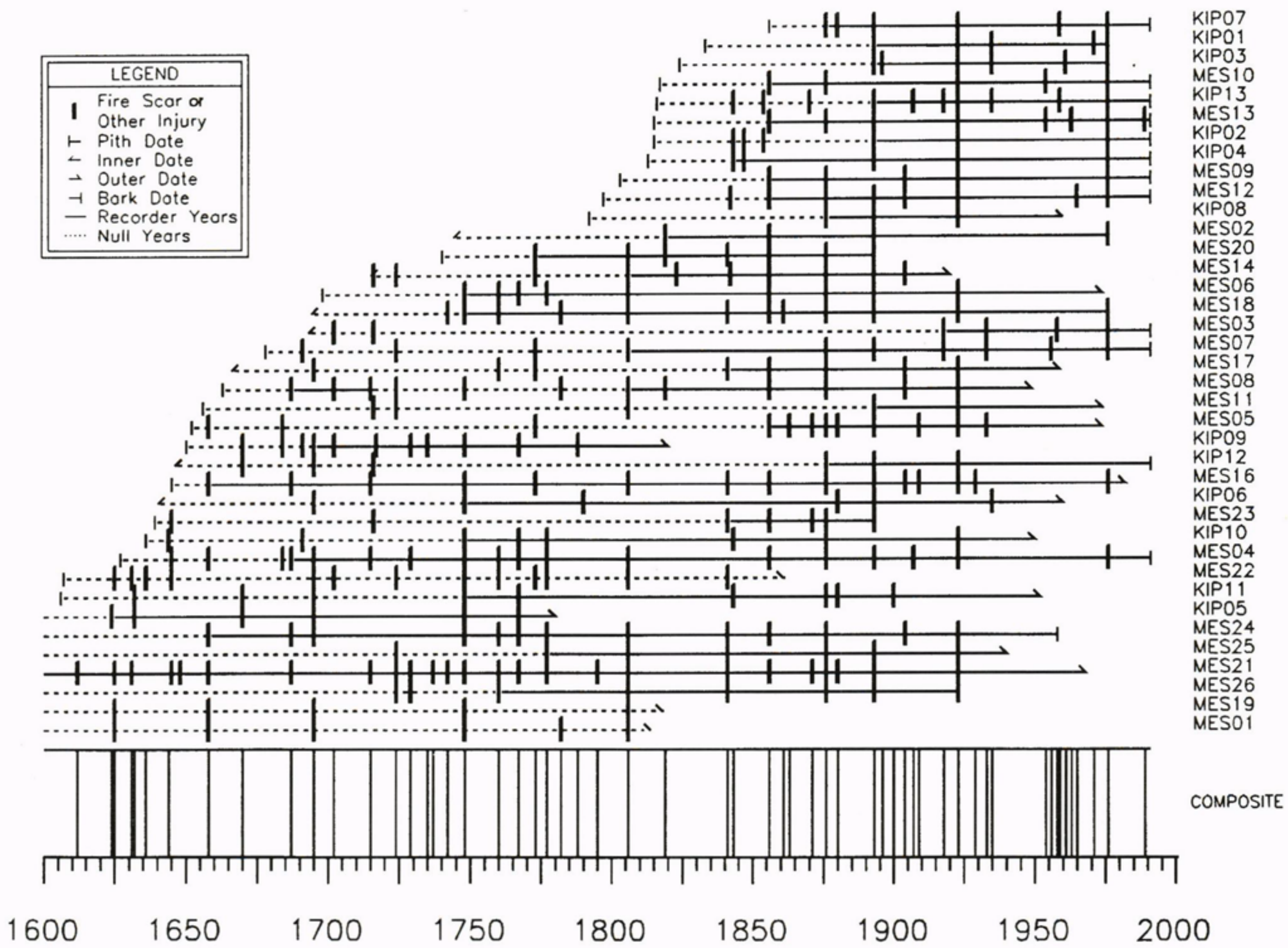

FIGURE 11—Combined fire history for the two kipuka sites, Mesita Blanca and Hidden Kipuka, illustrating uninterrupted fire occurrence into the 20th century. All other sites in the malpais showed changes in the temporal pattern of fires beginning approximately at 1880.

hundreds of thousands of hectares in size. These regional-scale fire years were a natural and recurrent phenomenon over much of the Southwest for many centuries (Swetnam and Baisan, 1996). In the 20th century, however, such regional-scale fire years are almost uniformly high-intensity, destructive burns in forest types where such fires did not previously occur. Such catastrophic fires could alter the successional pathways for malpais habitats (Connell and Slatyer, 1977). The question is not *if* such a fire occurs, but *when.* Effects of such fires on the environment will be more beneficial if fuel loadings and vegetative characteristics are restored to levels that existed prior to 1880.

Acknowledgments

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Remains of the Robert Garrett homestead, constructed 1935–37. El Malpais National Monument Resource files, frame 15, roll # 2.

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In the land of frozen fires—History of human occupation in El Malpais country

By Neil C. Mangum
Intermountain Field Area, U.S. National Park Service, Santa Fe, New Mexico 87504

Evidence of early human activity in El Malpais, "the badlands" in Spanish, is everywhere. From archeological records the region's first dwellers appeared in the area during the Paleo-Indian Period (10,000-5,500 B.C.). These earliest inhabitants subsisted chiefly by hunting game. About all that remains of their occupation are the stone and bone tools they left behind. During the Archaic Period (5,500 B.C.-400 A.D.), El Malpais' residents exhibited a growing dependence on agriculture. Indians began to utilize the surrounding mesa tops and valleys.

The Anasazi Period (A.D. 400-1600) represents the transformation of Indians from hunter-gatherers to a Pueblo people who were mostly farmers. The Anasazi created stationary villages and established permanent architecture. Cave shelters were replaced by jacal and pithouses beginning about 800 A.D. During the Cebollita Phase (950-1000 A.D.), Indian presence intensified above canyon mouths and declined on mesa tops. The Kowina Phase (A.D. 1200-1400) was a period of significant cultural modification. Population shifted from numerous small units to centralized locations. Indians returned to the mesa tops.

Toward the end of the thirteenth century, widespread drought affected the inhabitants living on the mesas. Archaeological data point to the abandonment of the mesa tops in favor of living along the valleys, such as the Rio San Jose to the north and Rio Puerco and Rio Grande to the east. By the 1400s the Kowina Phase ended, and Indians lived in fewer towns with larger populations. Acoma Pueblo is typical of this process.

When Francisco Vasquez de Coronado's expedition entered the present area of the United States in 1540, it constituted the first intensive exploration of what is now the Southwest United States. Captain-General Coronado departed with a crew of 300 Spaniards and 800 Indian allies from Culican on Mexico's west coast in April 1540. Coronado advanced northward into present-day Arizona. On July 7 he reached Cibola, probably the Zuni village of Hawikuh.

Indians shot arrows and hurled rocks at their adversary but to little avail. Coronado drove the Zunis inside their walled fort. Wasting little time, the Spaniards catapulted over the walls, drove the Indians from their shelters, and took possession of Cibola (or Hawikuh). The victory was barren. Cibola represented no Incan Empire. No gold-filled rooms or pendants studded with silver greeted the conquerors. Instead, the Spaniards discovered adobe and stone structures reminiscent of the small villages in Mexico.

After pausing at Hawikuh, Coronado continued east. Captain of Artillery, Hernan de Alvarado, assumed the advance. Although there is no mention of it, Alvarado's party constituted the first non-Indians to cast eyes on the malpais country. In April 1542 Coronado passed the lava flows again on his return trip to Culican. He was not the same haughty, energetic Spaniard who had marched triumphantly through the region two years before. The fire of conquest and vision of riches had vanished from his eyes. Two years of wandering over the Southwest and portions of the Midwest had sapped his ardor; his failure to discover precious metals stamped him a failure by his peers.

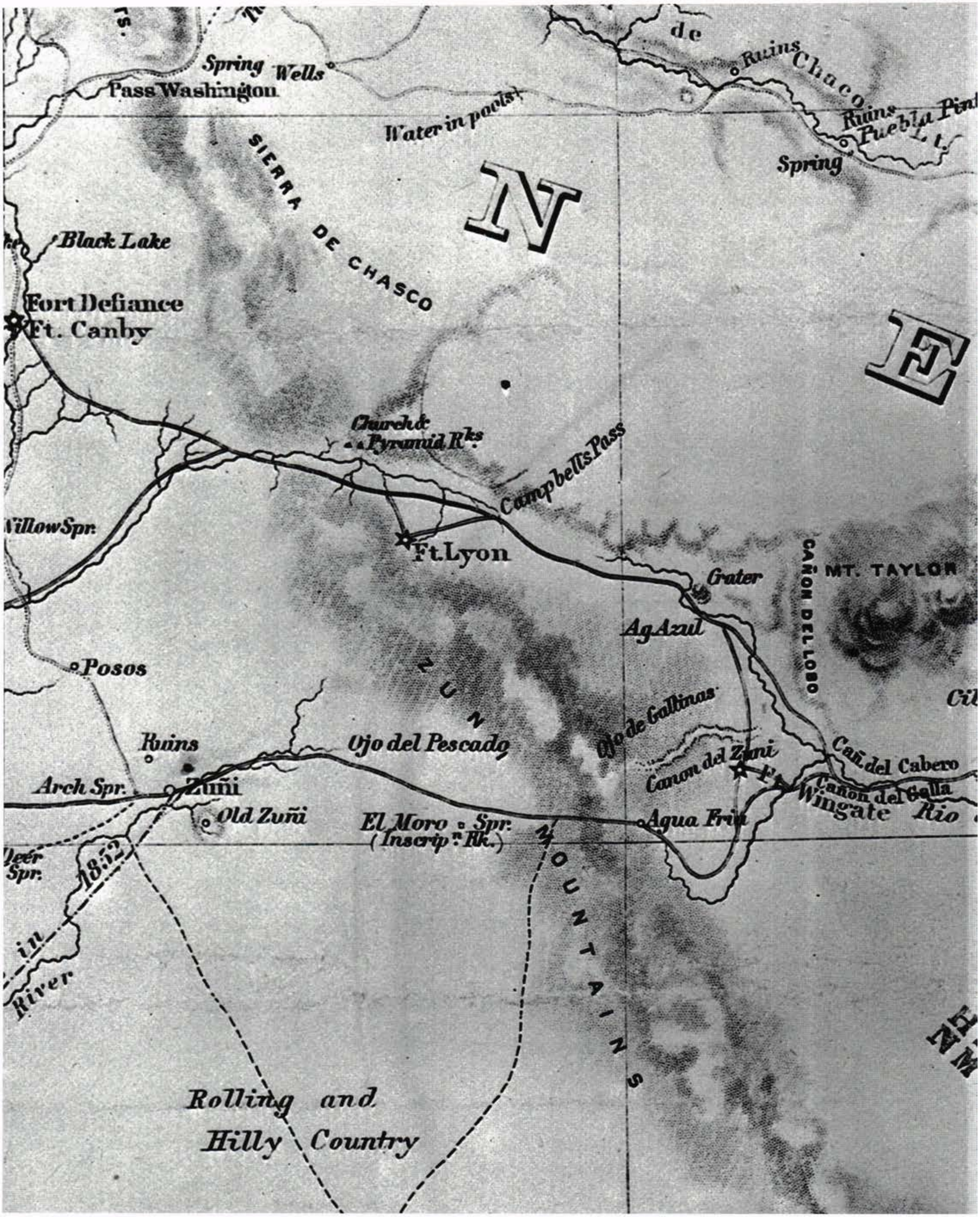
It would be 40 years before Spain again attempted to explore New Mexico. In 1581 Frayles Agustin Rodriguez headed an expedition from Chihuahua that ultimately sliced through the malpais region and to the pueblos of Jemez, Acoma, and Zuni. The exploration of Rodriguez was followed up by another under Antonio de Espejo. One explorer with Espejo, Perez de Luxan, recorded the first official penetration of El Malpais. Luxan recorded in his journal: "March 7, to Acomita; March 8, another four leagues past a marsh (probably near present-day McCartys); March 9, another 4 leagues in waterless malpais; March 10, 7 leagues, pine forest waterless mountain; March 11, three leagues, stopped at a water hole at the foot of a rock" (El Morro).

The explorations of Rodriguez and Espejo reawakened Spain's interest in New Mexico. Don Juan de Oñate gained permission from Spain for a permanent settlement in New Mexico and established his colony at San Juan Pueblo (present-day Chamita). Oñate explored his vast domain. In October 1598 he visited Acoma as part of a goodwill tour. He was planning to explore to the Pacific Ocean when the Acomas killed his nephew. In January 1599 Oñate, leading a punitive expedition, approached the base of Acoma's Sky City. After several days of maneuvering and scaling the precipitous cliff, Oñate reached the top where he systematically destroyed Acoma resistance. Approximately 600 Acomas surrendered while another 5,000 perished.

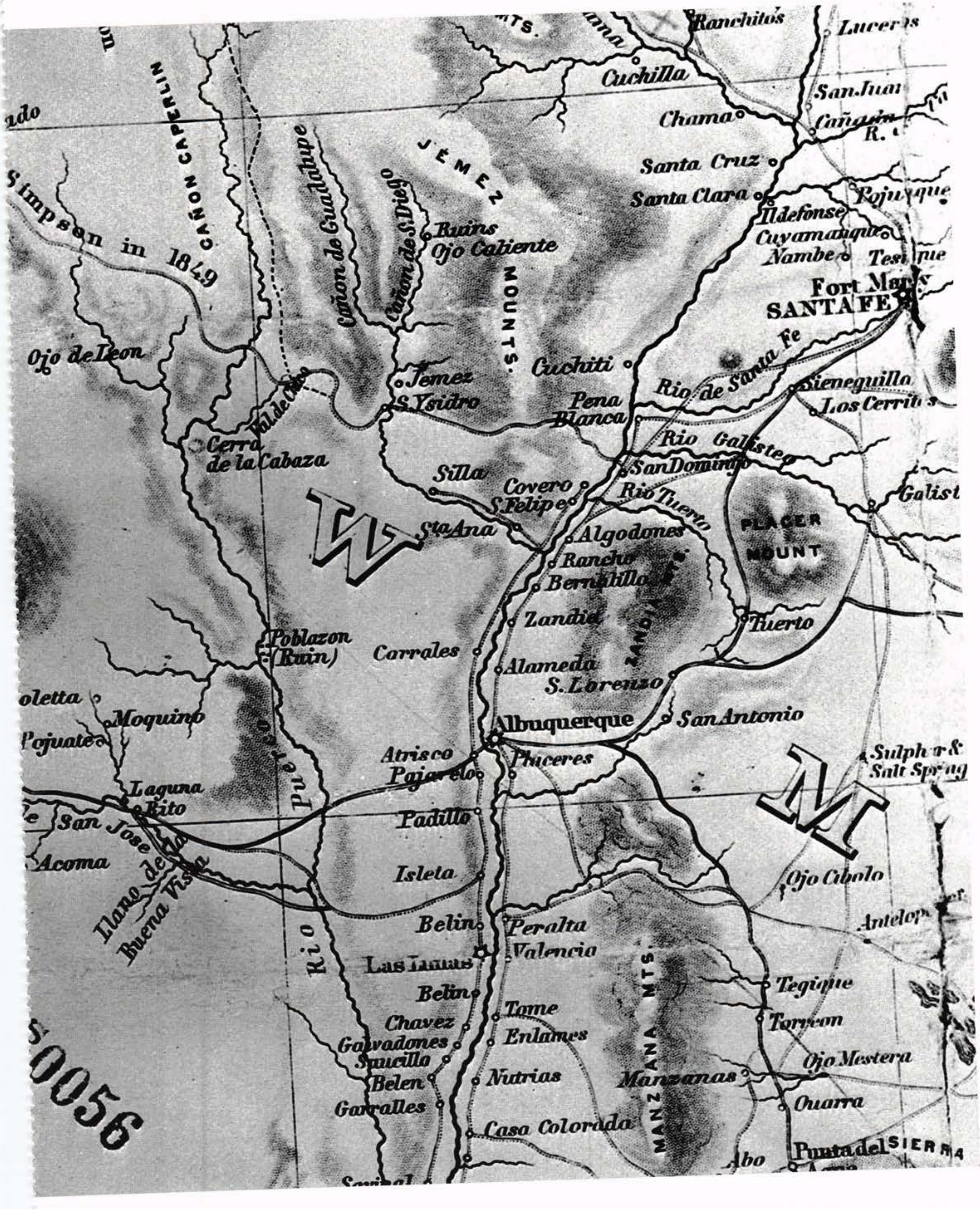
Oñate achieved his dream of reaching the Sea of Cortez (Pacific Ocean). On his return, Oñate paused at El Morro and carved his name in the rock marking the earliest known inscription. He wrote: "Passed by here the Adelantado Don Juan de Oñate, from the discovery of the Sea of the South, the 16th of April of 1605."

New Mexico's early pioneers diverted their attention from seeking mineral wealth to domestic activities. Farming and livestock assumed high priority. Missionaries established a foothold in the pueblos and began in earnest the tedious task of winning converts. To the east the Salinas pueblos of "Los Humanus," Abo and Quarei, were established. At Acoma, priests arrived to assist in the rebuilding of the mesa-top pueblo. The primary settling force on the Acomas came from Fray Juan Ramirez, who arrived in 1629. Fray Ramirez initiated construction of San Estevan del Ray Mission, which is still in use today.

Pueblo Indians, however, resented the foreign intruders into their homelands. Pent-up frustrations exploded in 1680. Rising in revolt, the Indians threw off the mantle of oppression and struck viciously at



Ft. Wingate environs, taken from territorial map of New Mexico, 1967. Courtesy Museum of New Mexico, Neg. No. 142599.


Ranchitos
Cuchilla
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Santa Cruz
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JEMEZ
Ruins
Ojo Caliente
MOUNTS.
CAÑON CAPERLIN
Cañon de Guadalupe
Cañon de S. Diego
Simpson in 1849
Ojo de Leon
Jemez
S. Ysidro
Val de Chio
Cerra de la Cabaza
Cuchiti
Pena Blanca
Rio de Santa Fe
Fort Marcy
SANTA FE
Sieneguilla
Los Cerritos
Rio Galisteo
San Domingo
Rio Tuerto
PLACER MOUNT
Ildefonso
Cuyamanque
Nambe
San Juan
Silla
Covero
S. Felipe
Sta Ana
Algodones
Rancho
Bernalillo
Zandia
Tuerto
Poblazon (Ruin)
Corrales
Alameda
S. Lorenzo
San Antonio
Moquino
Pojuate
Albuquerque
Atrisco
Pajarelo
Placeres
Sulphur & Salt Springs
Laguna
Rito
San Jose
Acoma
Llano de la Buena Vista
Rio Puerco
Padillo
Isleta
Ojo Cibolo
Belin
Peralta
Valencia
Las Lunas
Tome
Chavez
Galvadones
Saucillo
Belen
Garralles
Enlames
Nutrias
MANZANA MTS.
Manzanas
Tegique
Torreon
Ojo Mestera
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their conquerors. At Acoma's San Estevan del Ray Mission, Fray Lucas Maldonado was killed. For the next 12 years New Mexico belonged to the Indians.

The man selected to reconquer New Mexico for Spain was Don Diego de Vargas. In August 1692 De Vargas and a minuscule band of Spaniards and friendly Indians returned to New Mexico. De Vargas toured New Mexico following the customary route through the malpais en route to Zuni and Hopi. He camped at El Morro where he carved into the soft sandstone: "Here was the General Don Diego de Vargas who conquered for our Holy Faith, and for the Royal Crown, all of New Mexico at his own expense, year of 1692."

The Spanish influenced the people of the region, and in turn they were influenced by the country's dominant geographical feature—the malpais. Strategically situated, the malpais lay astride the Spanish travel route linking the Rio Grande Pueblos with the western outposts of the Zunis and Hopis. Despite the indomitable features of the lava beds, the malpais were a veritable oasis. Refreshing waters were trapped in the lava, and thick stands of trees offered relief to the weary travelers. The malpais became a favorite resting place for Spanish wayfarers. Springs and caves also attracted local Indians. Other Indians, such as Navajos and Apaches, who like the Spanish were interlopers, utilized the malpais resources for their advantage. They also collided, sometimes violently, with the Spaniards and the Rio Grande pueblos.

Spanish exploration in the eighteenth century decreased due to unrelenting battles with recalcitrant tribes and the perennial flare-ups at pueblos that kept Santa Fe officials in a constant state of flux. Internal bickering between the Church and Santa Fe extracted a toll on human and financial resources. Nonetheless, there was one major expedition in the last quarter of the eighteenth century that involved El Malpais. Concurrent with Spain's desire to boost its presence in New Mexico was the buildup of California. In between the two territories lay lands that had not been sufficiently explored.

The 1776 reconnaissance fell to two Franciscan friars, Francisco Atanasio Dominguez and Silvestre Velez de Escalante. Known as the Dominguez-Escalante expedition, it penetrated the interior of the Great American West traversing more than 2,000 miles. In their travels they made a wide arc journeying through northwestern New Mexico, western Colorado, and central Utah before turning southward and entering Arizona. On December 14 the explorers camped for the evening at Ojo del Gallo (present-day San Rafael). Although the Franciscans failed to discover a suitable east-west road linking California to New Mexico, they were more than compensated with extensive knowledge concerning the geography of the country and establishing new contacts with Native Americans.

Spain remained master of this empire for another 50 years. Political upheaval in the New World and Europe brought to an end 300 years of Spanish rule in America. Discord and revolution in Mexico and South America brewed a boiling caldron that Spain no longer could control. On September 27, 1821, Mexico declared its independence from Spain. New Mexico formed part of Mexico. The open-door trade policy with the United States became the single most important event of the Mexican period.

Hispanic settlements continued to grow during Mexico's rule, but at a snail's pace. Most immigrants tended to gravitate in the direction of the Rio Grande valley. Movement towards the malpais was nil; however, by the 1830s Hispanic communities at Cubero east of El Malpais and San Mateo north of El Malpais, took root.

New Mexico under Mexico's flag was short-lived. Like Spain, Mexico exhibited a generally apathetic attitude to her northern territory. Economic and military support remained weak. When war with Mexico erupted in 1846, the United States targeted New Mexico for annexation. Mexico offered little resistance when Brigadier General Stephen Watts Kearny captured Santa Fe in August 1846. El Malpais witnessed dramatic changes too, for it would no longer be just a highway passing through or around "bad country"

Following the Mexican-American War, the United States Army engaged in a host of scientific explorations. In 1849 Lt. James H. Simpson of the Topographical Engineers attached himself to a punitive force against the Navajo. The column proceeded west roughly coinciding with the 36th parallel. The expedition stumbled onto the extensive ruins of Chaco Canyon. Through the descriptive pen of Simpson the ruins and their condition were described.

The command marched undisturbed into the very abyss of Navajo strongholds—Canyon de Chelly. While the Navajos sued for immediate peace, Simpson and his crew of scientists duplicated their accomplishment at Chaco Canyon by recording Navajo hogans and customs for posterity. Continuing south, the column reached the pueblo of Zuni then veered east to camp at El Morro. His team copied, to the delight of future historians, every legible inscription found on the rock. Simpson left his own inscription, the first in English: "Lt. J. H. Simpson USA & R. H. Kern Artist, visited and copied these inscriptions, September 17th 18th 1849."

After ascending the Zuni Mountains, Simpson glimpsed El Malpais. Unlike early explorers who casually referenced the malpais, Simpson recorded every minute detail of their wonder. He referred to them as "Some unseemly piles of blackened scoriaceous volcanic rocks." The party camped in the fertile valley of Ojo del Gallo at modern-day San Rafael. The journey from Ojo del Gallo took the travelers to the Rio San Jose valley east of present-day Grants. On traversing the malpais, Simpson noted that with benefit of a few picks and shovels the valley could be negotiated by wagons. That visionary idea would be planted in the heads of his superiors.

Just two years after Simpson's report, Capt. Lorenzo Sitgreaves scoured the territory west of Zuni for the purpose of finding a suitable wagon road. Sitgreaves' expedition proved significant for it supplied missing pieces to the landscape features of Arizona. His route from Zuni to the Colorado River confirmed that portions of the territory were suitable for wagon traffic. Three decades later the Santa Fe

Railway benefited from Sitgreaves' work.

Following Sitgreaves' expedition, the United States government embarked on an ambitious plan to extensively survey the American West and to map suitable transcontinental railroad routes. One of the areas under consideration followed the 35th parallel. Lieutenant Amiel W. Whipple spearheaded the 35th parallel survey. Whipple's party proceeded west following much of the current 1-40 corridor. Whipple, like Simpson, discovered the lush meadows around Ojo del Gallo ideal for a camp, which he dubbed "Hay Camp." From Hay Camp, Whipple divided his force to survey three diverging routes. One column followed Simpson's path from Zuni; another traveled the military road west to Ft. Defiance. Whipple accompanied the third contingent, which headed south, utilizing portions of the Zuni-Acoma Trail. Whipple's report spoke favorably of a transcontinental railroad, but Congressional support wavered in the face of staggering cost figures.

In 1857 Lt. Edward F. Beale, formerly of the United States Navy, conducted the last of the military surveys through El Malpais. Congress appropriated more than half a million dollars to construct wagon roads to the Pacific coast, with $50,000 earmarked for the wagon road along the 35th parallel. What separated Beale's 1857 expedition from earlier surveys was his means of transportation. A herd of 76 camels accompanied Beale's party. Herded by Turks, Greeks, and Armenians, the United States Government purchased the dromedaries in an experiment to test their practicability and adaptability to the Southwest environs.

Beale started from San Antonio in June. Plodding west he reached El Paso and the Rio Grande. He continued north to Albuquerque before turning west to camp near Ojo del Gallo. Beale eventually reached Los Angeles, proving the practicability of an east-west wagon road. In 1859 Beale and his camel corps again trudged through El Malpais, this time with Congressional funding, to develop the highway and bridges west of the Rio Grande. The camel experiment championed by Beale failed to impress some observers. And when its most ardent supporter, Secretary of War Jefferson Davis, left office, the entire experiment crashed.

The military probes escalated contacts with Native Americans, particularly the Navajos and Apaches. Relations with the tribes continued to deteriorate even as the new American government in New Mexico sought to preserve and secure a fragile peace between the Hispanics and the native tribes. Navajos and Apaches pursued their raids on the Rio Grande settlements. New Mexicans countered with punitive expeditions of their own. To deal with the problem, the government built new forts in the region, including Ft. Defiance situated north of present-day Gallup at Canon Bonito.

Colonel Edwin V. Sumner launched a summer campaign in 1851, but the elusive Navajos managed to avoid clashes with Sumner's superior force and the army returned to Santa Fe with negligible results. To counter Navajo depredations in the region, the military established Ft. Fauntleroy in 1860—a garrison located approximately 50 miles southeast of Ft. Defiance and about 35 miles west of the malpais. On ration day, September 22, 1861, Navajos assembled at Ft. Fauntleroy to receive their monthly food allowance, an inducement designed to reduce Navajo raids. Fighting erupted following a horse race between a Navajo and U.S. soldier. When the dust cleared, 12 Navajos lay dead and another 40 suffered wounds. The incident fueled the flames of aggression. To the Navajos, the death of their kinfolk served to strengthen their perceptions of New Mexicans as deceitful and treacherous.

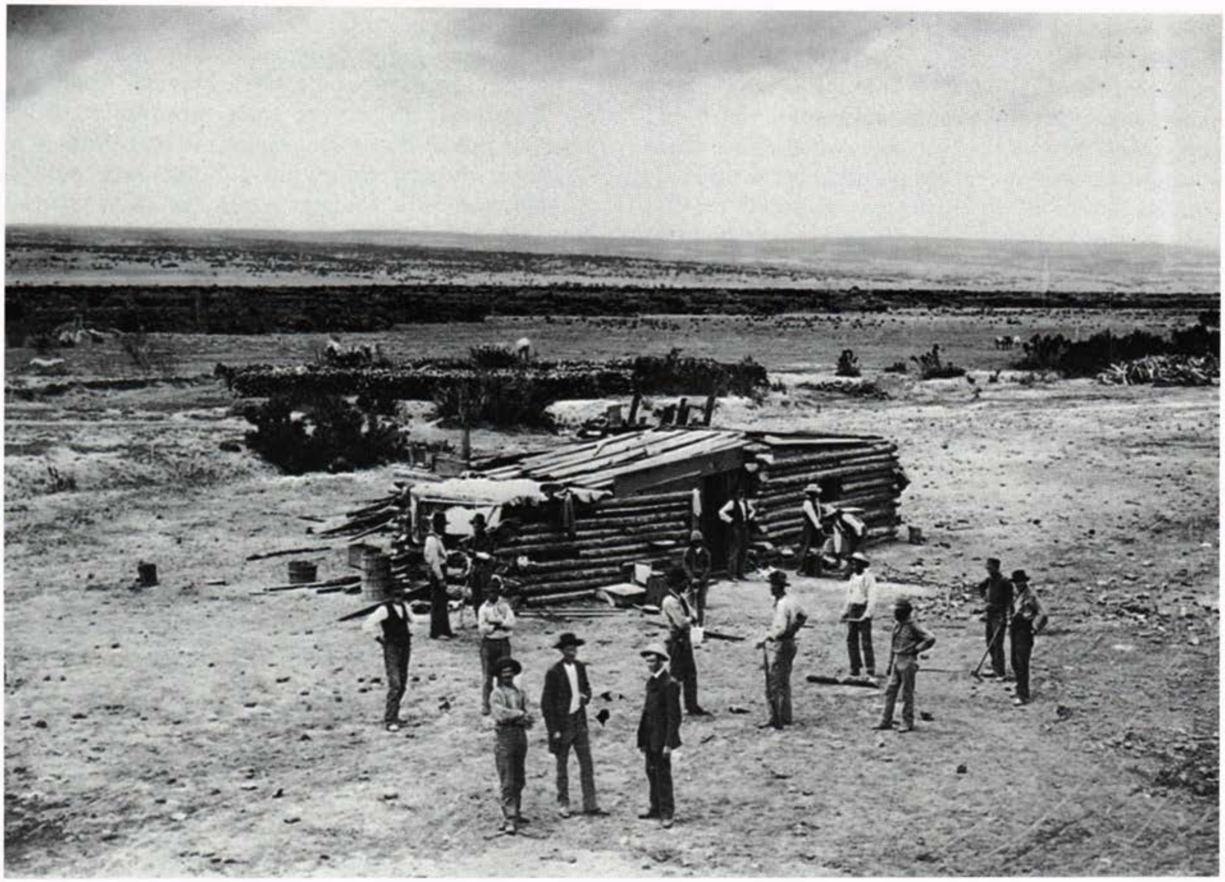
The timing of the Ft. Fauntleroy debacle could not have been worse for U.S. troops stationed in the region. The Civil War necessitated the withdrawal of most of the regular soldiers for campaigns in the east. Both Fts. Defiance and Fauntleroy were abandoned, which the Navajo perceived as an omen of having sapped the fighting spirit of the military. Coinciding with the receding blue troops came the resumption of Indian strikes on villages, ranches, and mines. Colonel Edward R. S. Canby, now commanding all troops in New Mexico, was powerless to halt the new round of Navajo raids. Defending New Mexico from Confederate invasion preoccupied all of Canby's time. Defense of New Mexico's frontier fell to local militia units. Not until after Confederate defeat at Glorieta Pass in March 1862 did Canby redirect his efforts to blunting Indian attacks permeating the state at every corner.

After the expulsion of the Confederates from New Mexico in May 1862, Canby redirected his defenses to cover the entire territory. In August he formalized a strategy to both protect and punish the Navajos. New forts would be constructed in Navajo country to supplant the defunct posts. Canby outlined a stratagem for Indian self-preservation. He perceived a reservation system far removed from population centers of the territory as the only viable means of preventing the extermination of the native tribes.

But Canby never implemented his Navajo removal policy; he was transferred east. Canby's replacement was Brig. Gen. James H. Carleton, commander of the California volunteers. Carleton adhered to much of his predecessor's philosophy for dealing with the Navajos. Whereas Canby formulated the fate of the Navajos, Carleton enforced the plan with devastating consequences for the Navajos.

Carleton pursued Canby's plan for building a new military post at Ojo del Gallo, Ft. Wingate. Two prime considerations favored the malpais' location. The Ojo del Gallo valley afforded excellent pasturage. In addition, its position astride an intersection that blanketed the approaches of two major highways, the old military roads to Ft. Defiance and the Spanish highway to Zuni Pueblo, provided control and access in which to block or pursue the Navajos.

U.S. regulars manned the post but were quickly replaced in October 1862 by four companies of the 1st New Mexico Volunteers under command of Lt. Col. Jose Francisco Chavez. Despite its strategic position, the post suffered from a poor site location—on top of a swampy plain with ground water only two feet



Section house, Grant Station, New Mexico, July 1881. Photo by Ben Wittick, Museum of New Mexico.

below the surface. Built of adobe and a wooden stockade around the perimeter, Ft. Wingate nevertheless played a pivotal role in the Navajo wars.

In 1863 Ft. Wingate served as a major supply depot for Colonel Christopher "Kit" Carson's summer campaign to break Navajo resistance once and for all. But Wingate's biggest role followed Carson's January 1864 destruction of Canyon de Chelly. By early 1864 stunned Navajos faced starvation or acceptance of Carleton's plan to relocate them in eastern New Mexico at Bosque Redondo. Navajos by the hundreds began to funnel into Wingate, which served as a temporary detention center. Over the next three years thousands of Navajos were channeled through Wingate. In 1868 General William T. Sherman saw that the Bosque Redondo experiment was a failure, commenting "that the Navajos had sunk into a condition of absolute poverty and despair." The Navajos were allowed to return to their homeland and rebuild a new life from the ashes of Bosque Redondo. The return of the Navajos also signaled the end of Ft. Wingate at Ojo del Gallo. The post was in decay and considered too costly to rebuild and too far removed from the Navajo reservation. A new Ft. Wingate was constructed 15 miles east of Gallup.

During the dismantling of Wingate in 1869, ex-soldiers and citizens built a cluster of homes within a mile of the old post. They called their new settlement San Rafael. The industrious settlers adapted the military's irrigation ditch for use in supplying water to their homes and crops. The village grew rapidly. In just one year its population exploded to 678, surpassing the older and more established communities of Cubero (population 581) and Cebollita (population 630). Settlers developed an economic base centered around livestock, principally sheep, the economic standard-bearer of frontier New Mexico.

As San Rafael prospered, expansion began beyond the bulging limits of the community. Five miles north Don Jesus Blea homesteaded on the Rio San Jose. Other small communities emerged along the western flank of the malpais. The village of Tinaja, three miles north of El Morro, blossomed in the late 1860s. The Navajo community of Ramah became a target for a new wave of missionary activities initiated by the Mormon Church in the late 1870s. The Mormon knowledge of controlling water supplies in New Mexico's arid climate and their affinity for communal living attracted modest converts among the Navajos.

Despite the emergence of villages around the malpais, growth remained agonizingly slow until the coming of the railroad. In January 1881 steel rails invaded the malpais along the Rio San Jose valley to a point four miles north of the village of San Rafael near the site of Don Jesus Blea's homestead. The railroad selected Blea's homestead as a railroad stop, naming the site Grant after the three Grant brothers who were contractors building the Atlantic and Pacific Railroad. A closer inspection reveals that Grant probably owed its existence to neighboring San Rafael. This thriving agri-

Sheep camp at Cerro de la Bandera about 1920. Sheep remained kingpin in El Malpais economics until supplanted by cattle. Photograph by W. T. Lee, courtesy U.S. Geological Survey Photographic Library, Denver, Colorado.

cultural and livestock community offered economic potential that railroad executives coveted.

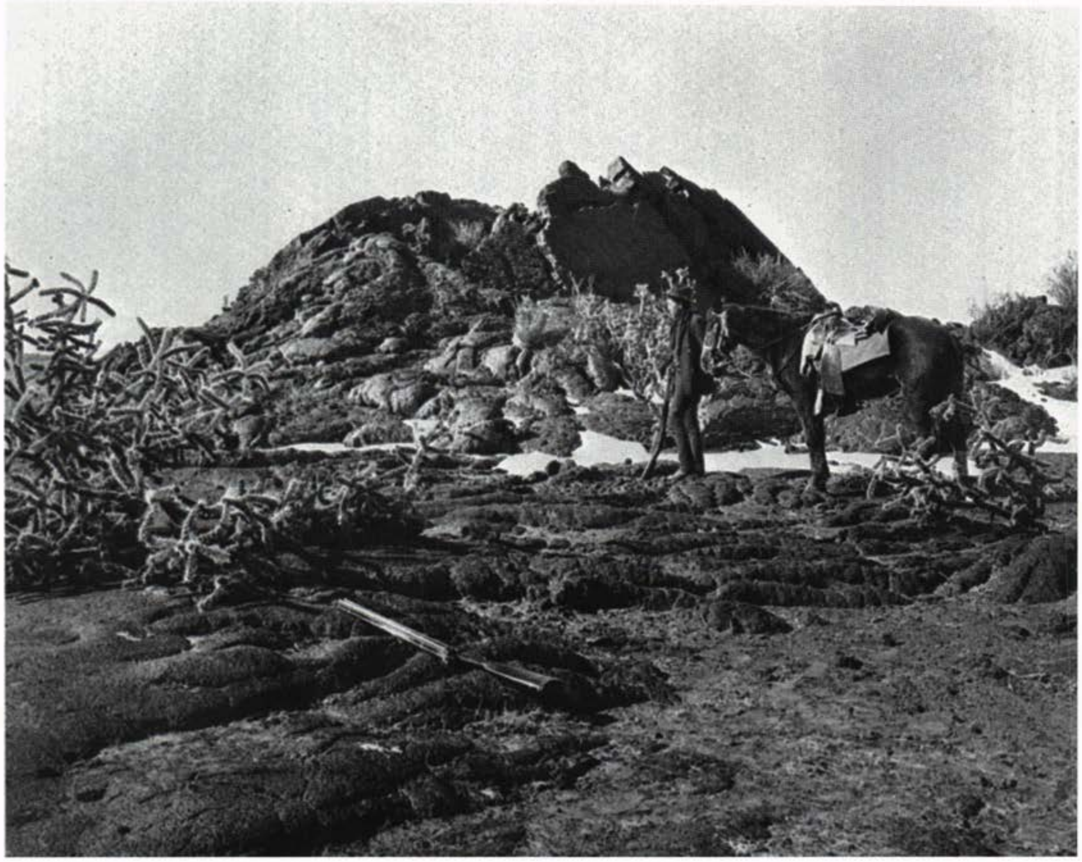
San Rafael rapidly became the center for sheep raising. Sheep ranchers acquired or controlled vast grazing empires blanketing an area south of the Chain of Craters and continuing eastward to the Acoma Reservation. From San Rafael Monico Mirabal and his son, Don Mirabal, purchased or leased more than 250,000 acres of land extending south of Bandera Crater. By 1885 more than 3.9 million sheep were being raised in New Mexico with several San Rafael residents owning more than 10,000 head each.

Coinciding with the development of sheep ranching around the malpais, the cattle industry took root. For ethnic and economic reasons its growth lagged far behind the more established sheep business. By the late 1880s cattle companies began to make inroads into the region. The Arizona Cattle Company purchased thousands of acres south and west of the malpais. Another outfit, the Cebola Cattle Company, acquired more than 40,000 acres east of the malpais, while near Grant the Acoma Land & Cattle Company incorporated even more land. Ten miles west of Grant, at the new Mormon village of Bluewater, the Zuni Mountains Cattle Company started operations in 1892.

The timber industry struck an economic cord in the malpais in the 1880s and 1890s. In 1890 William and Austin Mitchell of Cadillac, Michigan, purchased more than 300,000 acres of forested land in the Zuni Mountains. A new townsite named Mitchell, located 30 miles west of Grant Station, was founded in 1892. A narrow-gauge railroad, the Zuni Mountain Railway, was constructed; however, timber operations ceased due to the Panic of 1893. Mitchell became a ghost town but was repopulated a few years later under the name Thoreau, named after the poet-philosopher Henry David Thoreau.

At the turn of the century the malpais region still reflected some of the charm and the reputation as a holdover of the Wild West. Railroad workers, cowboys, sheep ranchers, sodbusters, and lumberjacks formed an unlikely melting pot. Fisticuffs, stabbings, shootings, drunken rowdies, and train robberies occurred frequently. At the closing of the century, the malpais region showed remarkable economic and sociological adjustments. The Navajos no longer held dominion over the country. Taking their place were sheepmen and cattle ranchers. Along the ridges and valleys of the Zuni Mountains, timbermen arrived and tapped into an unlimited resource, or so it seemed to them.

Resurrection of the timber industry around Thoreau occurred in 1903 when the American Lumber Company acquired the Mitchell Brothers' vast acreage. Forming a business partnership with the Atchison, Topeka, and Santa Fe Railway, the American Lumber Company thrived for a decade. At its peak about 1910 the firm sawed 60 million board feet of timber. More



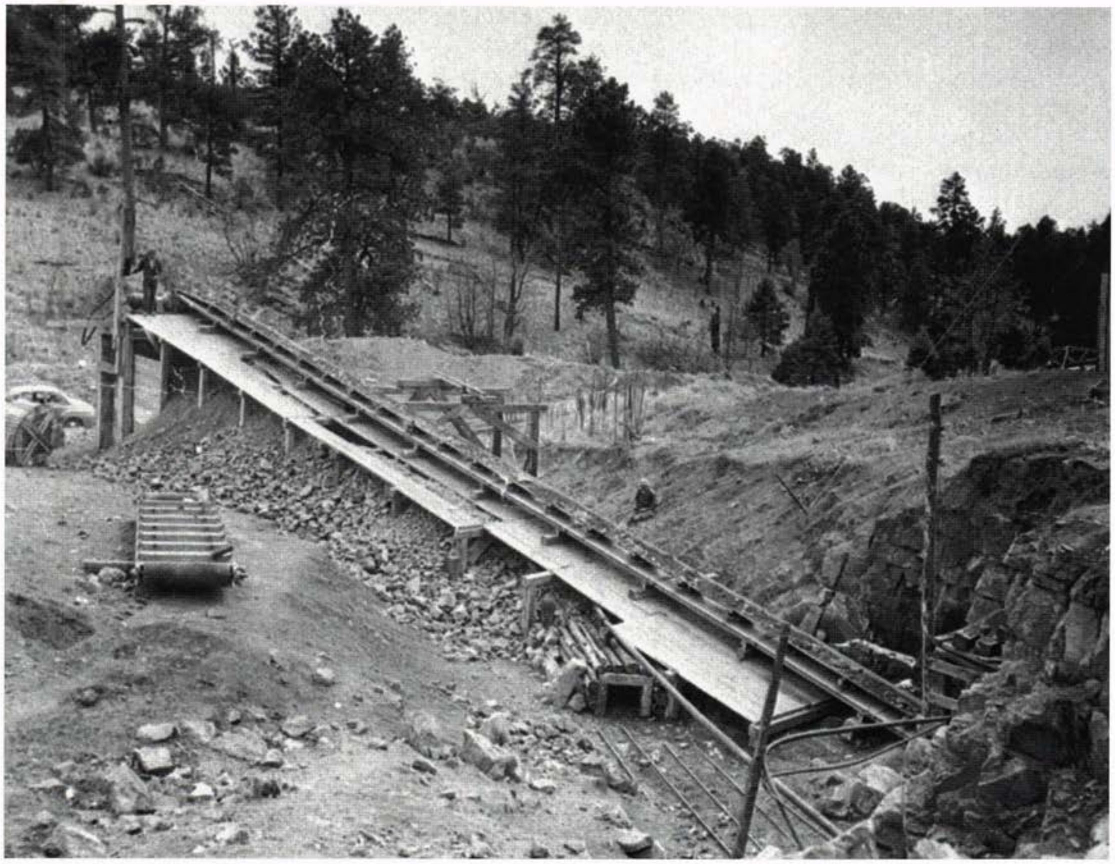
In the lava beds near McCartys, circa 1885. Photo by Ben Wittick, Courtesy School of American Research Collections, Museum of New Mexico, Neg. No. 16475.

than 1,500 persons were on its payroll, 700 of them employed as cutters in the Zuni Mountains. An average of 100 cars of timber rumbled eastward from Thoreau to Albuquerque daily. The American Lumber Company remained active until 1913, when it suddenly halted all operations after defaulting on its mortgage bonds.

In 1916 Congress passed the "Stock Raising Homestead Act," which permitted homesteaders to homestead the public domain. The east side of the malpais became dotted with new settlers. Most immigrants originated from Texas and Oklahoma, and nearly all were poor. A hardscrabble existence marked the life of the homesteader. Lack of water defeated most attempts to make a living from dry-land farming, as did lack of amenities such as schools, churches, and electricity—the latter a creature comfort unavailable in the rural malpais until the 1950s. Beans, corn, and vegetables together with chickens, hogs, and beef were the normal fare. Yet, the homesteaders were not self-sufficient. Often they worked for the large ranches, timber companies, sold firewood, or sought seasonal employment to make ends meet. Most homesteaders did not last the three years required to satisfy the requirements of the 1916 Homestead Act. Primitive living conditions, low wages, and the Great Depression of the 1930s forced many to abandon their dreams and follow the road to better paying jobs. They left behind their cabins—poignant reminders that life can be bitter and the malpais landscape unrelenting and unforgiving.

Not since the railroad had one single event that so significantly altered the fortunes of El Malpais as the emergence of timber mogul George E. Breece, who acquired the McKinley Land and Lumber Company and renamed the company after himself, George E. Breece Lumber Company. Because 25 years of timber cutting on the western half of the Zuni Mountains had depleted timber reserves, Breece shifted timber operations from Thoreau to the untapped forest belts south of Grant. He constructed a roundhouse in Grant where the Diamond G Hardware is now located. Breece laid tracks from his roundhouse southwest to Zuni Canyon, which continued to Malpais Springs, Paxton Springs, and Agua Fria Springs—a distance of 20 miles. The development of the thriving timber industry around Grant increased the number of homesteads on the malpais perimeter.

Economic prosperity hit Grant. Schools, churches, and community buildings sprang up. Grant's population exploded by more than 4,000. In 1929 Grant boasted a high school, one of the few in the huge expanse of western Valencia County. *The Grant Review,* a weekly newspaper published in Gallup and bused to Grant, provided local news and commentary. Running water and electric lights came to Grant, catapulting the booming settlement into mainstream America. In 1935 Grant was renamed Grants.



Fluorspar mines were active in the Zunis until the 1950s when cheap imports undercut domestic prices. Shown here is Fluorspar Mine Number 21, photograph taken about 1948, from the collection of Mrs. Dovey Bright.

Sheepmen and cattle ranchers who escaped the financial debacle of the Panic of 1893 rode the crest of prosperity into the twentieth century. Demand for wool and beef increased through the end of World War I, but post-war stock prices plummeted and drought reappeared. To make matters worse for the cattlemen, an epidemic of scabies hit the cattle herds. Sheep ranchers fared even worse. At the beginning of the Depression, market prices plunged due to a declining demand for sheep, while expenses of feeding the animals skyrocketed. Most of the smaller sheepmen went out of business.

Timber, a source of erratic employment in the region for 40 years, fell on hard times during the Depression; even the crafty Breece felt the sting of the Depression. In 1932 he leased timber operations to Grant businessmen, M. R. Prestige and Carl Seligman, co-owners of the Bernalillo Mercantile Company. They maintained operations in the Zuni Mountains, modernized Breece's rolling stock, and continued timber harvests until 1942. In 1946 the Prestridge Brothers contracted with the New Mexico Timber Company to haul timber from Mt. Taylor. The Prestridges remained in business for about four more years, and then large commercial timber operations ceased.

With timber and sheep hit hard, malpais residents turned toward agriculture and mining as a means of economic support. Prior to the late 1930s, mining activities were marginal in the malpais. With the advent of World War II, fluorspar and pumice mines developed near Grants. The Navajo Fluorspar Company, flanking the west side of the malpais near the commercially operated Ice Caves, operated three mines. Much of the mineral extraction was for national defense. Fluorspar was utilized in the manufacture and hardening of steel, in paints, and in acids. The fluorspar mines remained active until 1952, when foreign competition drove down the price.

Whereas pumice and fluorspar assisted the war effort, the lava beds aided the nation's war effort in a different manner. The United States Army at Kirtland Air Force Base in Albuquerque used nine square miles of rugged lava terrain in El Malpais as a bombing range. Large-scale farming developed in the 1940s and 1950s with carrots as the primary cash crop. The carrot industry flourished until the late 1950s, when cheap California produce put growers out of business.

The malpais region experienced its greatest cycle of boom with the discovery of uranium north of Grants in 1950. Grants' population escalated to more than 10,000 in 1960, reaching its zenith of more than 11,000 in 1980. West of Grants, the town of Milan supplied a supporting population of 2,700. With an increase in population, western Valencia County was severed from Valencia County creating the new county of Cibola. Grants became the county seat.

Unfortunately the decade of the 1980s witnessed the return of the bust cycle of El Malpais economics.

Demand for uranium dropped. Businesses folded and Grants went into a decline. The 1990s have seen a slow but steady growth in the region, mainly in tourism. Officials in Grants perceive El Malpais National Monument as the cornerstone in the area's attempt to adapt to ever-changing economic patterns, this time based on a growing tourism industry. As the region enters the twenty-first century, the communities are embarking on an ambitious plan to lure motorists off busy 1-40 with its nearby attractions such as the Acoma Pueblo at Sky City, El Malpais National Monument, Bluewater State Park, and the new visitor center complexes in Grants and near 1-40. Only time will tell whether tourism is a panacea or merely the latest phase in the perpetual up-and-down economic cycle that has been a benchmark of the history of El Malpais.

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GLOSSARY

Aa—Lava with a rough, jagged, clinkery surface. Molten lava that moves more slowly than pahoehoe owing to a cooler temperature and less gas content. Lava tubes usually do not form in as lava flows. Hawaiian term; *see* Photographic atlas, p. 18.

Ablation—All processes by which ice (or snow) mass is lost, including evaporation, melting, and mass wasting.

Accidental-1) Biology: organisms that wander into the cave but cannot survive there. 2) Geology: *see* Xenolith.

Algophagous—organisms that feed primarily or exclusively on algae.

Alkalic basalt/cinder cone—Basalt (or cinder cone) that is higher in light-colored elements (primarily sodium and potassium) than is average for all basalts (or cinders); *see* Basalt.

Angiosperm—Flowering plants. Plants that produce seeds and pollens, and are fruit bearing.

Basalt—A fine-grained, dark- or medium-colored, generally extrusive mafic igneous rock composed of calcium plagioclase feldspar and pyroxene (± olivine). Basalt is the most abundant extrusive igneous rock and is common along rifts in the Earth's lithosphere. Most of the bedrock beneath our oceans is basalt.

Basaltic andesite—Basalt that is relatively high in silica.

Cave—A naturally occurring subterranean cavity with a length greater than the diameter of the opening. Usually consists of an entrance, twilight zone and a dark zone. May have more than one entrance. Lava caves almost always are part of a larger lava-tube system (see entry below). At El Malpais all caves are in the lava and **are** sometimes referred to as lava-tube caves.

Clinopyroxene—A dark-green mineral that breaks along smooth planes. A pyroxene mineral that either contains more calcium than normal or lacks aluminum and alkalis. Pyroxene minerals form a series of different minerals including augite and jadeite.

Cinder cone—A conical hill formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition; *see* Photographic atlas, p. 15.

Collapse, Collapse structure, or Collapse trench— Depressions in the lava surface that are filled with loose rock. Formed when a hardened or partially hardened lava surface falls into a void left by a gas bubble or lava tube. Collapses may be circular, oval or elongated. Collapses usually occur during or shortly after the cooling **process;** *see* Photographic atlas, p. 21.

Composite volcano—A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills. Viscous, acidic Tava may flow from fissures radiating from a central vent, from which pyroclastics are ejected. Also called a Stratovolcano; *see* Photographic atlas, p. 13.

Cosmogenic dating—Geologic or archaeologic dating using cosmogenic nuclides , e.g. nuclides such as ^{14}C or ^{36}Cl produced by cosmic radiation.

Cryptogam—Plant that reproduces by means of spores rather than seed, e.g. ferns, mosses, algae, or fungi.

Dark zones—Transition plus deep zones of caves..

Deep zone—An area of total darkness and high humidity (often approaching 100%), with relatively stable temperature in caves.

Diagenesis—Changes undergone by sediments between deposition and becoming sedimentary rock, including compaction, cementation, and replacement.

Dendritic—Branching pattern like the limbs of a tree.

Dendrochronology—The study of annual tree-ring patterns to establish a chronology or time scale.

Dendroclimatology—The study of past climates using tree ring data.

Distal end—Farthest end from the entrance of a cave, or farthest end from the origin of a lava flow.

Ecotone—Where two or more ecological communities or habitats come together and overlap. A boundary between habitats. Often several hundred feet wide, the ecotones at El Malpais often are more compressed, influenced by lava margins.

Endemic—Found only in one area.

Entrance zone—Entrance of a cave; while subject to greater environmental extremes than deeper areas of the cave, the entrance area often has a richer accumulation of surface detritus.

Feldspar—A group of abundant rock-forming minerals containing potassium, sodium, or calcium. They are the most common minerals, being found in all kinds of rocks and constituting 60% of the Earth's crust. *Plagioclase* is a sodium- and/or calcium-bearing feldspar. *Orthoclase* in a potassium feldspar. *Anorthoclase* in a sodium-rich feldspar.

Flow (Lava flow)—Lava that came from an identifiable vent (volcano), fissure or fault line, of the same or similar mineral composition and within an identifiable time frame. A flow contains one or more "flow units."

Flow unit—The most specific, identifiable unit of a lava flow. Distinguished by mineral composition and a separation in time. Generally the time separation between successive flow units is relatively short—often a matter of weeks or years; not hundreds of years.

Geomorphology—The study, classification, and description of the Earth's land forms.

Guanophile—organisms that are associated with bat guano.

Gymnosperm—Plants whose seeds are encased in cones, such as pine trees.

Holocene—see Quaternary.

Hydrophobic—water repelling or repelled by water.

Hypogean—beneath the surface of the earth.

Kipuka—An island of older rocks, soils, and vegetation surrounded by younger lava flow(s). Hawaiian term. These isolated areas often contain important clues to conditions off the lava prior to the advent of European settlement, since few have been impacted by settlement, grazing, timbering or other ground disturbing activity; *see* Photographic atlas, p. 17.

Igneous—Literally means "of fire" (Latin). Rocks that form from molten material called magma. Also applies to the processes related to the formation of such **rocks.**

Jemez lineament—An alignment of volcanic fields extending from west-central Arizona to the extreme southeastern corner of Colorado, including the White Mountains, El Malpais, Mount Taylor, Jemez Mountains, and Capulin Volcano.

Lava cave—A cave formed in lava; *see* Cave.

Lava channel—An open channel that contained a molten river of lava; not unlike a stream or river channel. Often leaves banks or levees.

Lava *flow—see* Flow and Flow **unit.**

Lava tube (system)—Subterranean cavity formed by the flow of molten lava which later drained, leaving a series of caves and collapse depressions. The structure formed by a river of molten lava; as the surface cooled, the hotter molten material underneath flowed out, leaving a long, linear void. Later, collapses occur along the tube system, opening access to portions of the system, or caves; *see* **Photographic atlas, p. 20.**

Lavicoles—Organisms that are adapted to taking advantage of temporary habitats in the lava created by wind-borne materials.

Mesic island—A area that is moister than the land around it.

Macrocaverns—Cave habitats exceeding 200 mm in diameter.

Mesocaverns—Cave habitats 1-200 mm in diameter. Microcaverns—Cave habitats less than 1 mm in diameter.

Microflora—Bacteria and fungi.

Mineraloid—A mineral that lacks crystal form, e.g. **opal.**

Modal—The actual composition of a rock, usually given in percent of weights of volumes of different oxides as opposed to the theoretical norm of a rock.

Morphology-1) The shape of the Earth. 2) The study of the form and structure of animals and plants or their fossil remains. 3) The study of distribution patterns in soil horizons and soil properties.

Natural bridge—In volcanic landscapes, a bridge-like remnant of a lava tube where the width of the bridge is less than the **length.**

Olivine—A green or brow glassy mineral composed of silica, iron, and magnesium oxides. Commonly found in basalt, gabbro, and other dark colored igneous rocks.

Pahoehoe—Basalt that has a ropy surface texture. Formed from a hot (1200+°C) gaseous fluid lava. "Ropes" were formed where the crust was wrinkled as it was pulled by the continuing flow. All of the lava tubes at El Malpais were formed in pahoehoe lava. Hawaiian term; *see* Photographic atlas, p. 19.

Paleomagnetic—Iron-bearing minerals align with the magnetic poles as the rocks are formed. Since the magnetic poles have wandered over time and this wandering has been mapped, science can date the age of a rock by analyzing the magnetic orientation of iron particles. Lavas are particularly good to sample since the magnetic particles align themselves with the magnetic field before the rest of the lava solidifies.

Paleosecular—Measurement of past systematic changes in the Earth's magnetic field as recorded by magnetic minerals.

Petrogenesis—Branch of petrology (study of rocks) that deals with the origin and formation of rocks; especially igneous rocks.

Petrography—The study of the origin, mineral composition, and classification of rocks, especially with the aid of a microscope.

Pilotaxitic—Irregular, unoriented microscopic crystals in a groundmass of igneous rock.

Phenocryst—a relatively large crystal in a ground mass of micro- or crypto-crystalline rock.

Playa—A natural depression in the landscape that occasionally holds water from snow melt and rain and dries up at other times. Often has a white crusty ring at the dry shoreline, from the concentration of minerals as the water evaporates.

Plagioclase—see Feldspar.

Pyroxene—A group of common rock-forming minerals; typically dark and usually abundant in igneous rocks.

Quaternary—The most recent period of geologic time up to the present. Includes Pleistocene *(majority + recent—most* modern species are present) and Holocene *(entire + recent—all* modern species are present).

Radiometric dating—Calculating an age in years for geologic materials by measuring the presence of a short-life radioactive element, e.g. potassium-40, or by measuring the presence of a long-life radioactive element plus its decay product, e.g. argon-40/argon-39.

Relict species—organisms belonging to groups whose distribution was once greater than at present.

Saturation zone-1) Biology: A dark zone of a cave that exchanges air with the surface only slowly. 2) Geology: The zone of the Earth's crust below the water table.

Secular variation—Wobble of the Earth's magnetic field.

Scoria—Although "cinder" is used somewhat interchangeably, scoria is usually considered to be larger than cinders.

Shield volcano—A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. *(see* Photographic atlas, p. **14.)**

Stratigraphy—The study of rock strata; the sequential layers of rock and all their characteristics. The arrangement of strata.

Subalkaline basalt—Basalts that contain no alkaline (light colored) minerals other than feldspars.

Subophitic—Said of the texture of an igneous rock in which the feldspar crystals are approximately the same size as the pyroxene.

Stygobionts—organisms inhabiting underground waters.

Tholeiitic basalt—A silica-oversaturated basalt characterized by the presence of low-calcium pyroxenes in addition to clinopyroxene and calcic **plagioclase.**

Tinaja—Water hole; Spanish.

Transitional basalt—Basalt having alkali and silica composition between that of alkaline basalt and tholeiitic basalt.

Transition zone—In caves, a dark zone that is not stable due to the large size of the tube, the existence of multiple entrances, or the location of the tube on a steep slope.

Troglobites—Organisms that depend on the cave for their survival. Most troglobites are pale (depigmented), blind (often eyeless, or with reduced eyes), and have attenuated appendages.

Troglophiles—Organisms that complete their life cycle within the cave, but can exist in similar epigean (surface) environments.

Trogloxenes—Organisms that use caves as refuges but return to the surface regularly to feed.

Tumuli—Dome and elongated dome shaped features on lava flows. Sometimes called "pressure ridges" because they result from a buckling of the lava crust aided by pressure from the underlying liquid lava. Typically in pahoehoe lava flows. Singular is tumu-

lus.

Twilight zone—An area of decreasing light before the dark zones.

Ultramafic—Ultrabasic; volcanic rocks that contain almost exclusively dark colored minerals.

Viscosity—How fluid a substance is. High viscosity is very thick like cold molasses; low viscosity is very runny like water.

Volatiles—Gasses and vapors included in molten lava. These boil away or escape when the lava comes to the surface and begins cooling.

Xenolith—A foreign inclusion (usually bedrock) incased in lava. At El Malpais the inclusion usually is altered sandstone or limestone; occasionally it is granite; *see* Photographic atlas, p. **24.**

Xeric—Dry climate environment.

Zuni-Bandera volcanic field—Term applied to the lava flows that occurred between ca 300,000 and 3,000 years ago along the southern edge of the Zuni Mountains. Includes all of the lava flows in the National Monument, National Conservation Area (including the Chain of Craters), and the Zuni Mountains. Does not include Mount Taylor and related basalts, which are much older *(see* cover photo).

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, μm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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