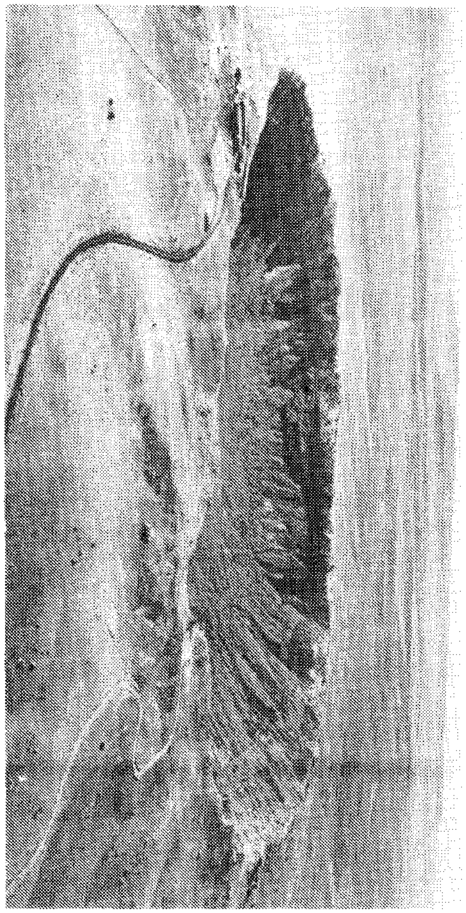
Meteor Crater

BRIEF HISTORY

About 49,500 years ago an unbroken level plain stretched where you now stand. Out of the north a bright pinpoint of light arose rapidly into a blazing sun as it approached this spot. Traveling nearly 43,000 miles per hour, with deafening sound and blinding light, a huge nickel-iron meteorite or cluster of such meteorites, weighing millions of tons, struck the solid rock of the level plain. With forces greater than any recorded nuclear explosion, the main mass was instantly converted to a gaseous state, and a huge mushroom-shaped cloud arose far into the stratosphere. From this cloud rained meteoritic droplets mixed with rock debris. For miles around, every tree was flattened and no living creature survived. Before impact, pieces of meteorite weighing up to a ton or more were stripped from the mass by friction of the lower atmosphere. Other pieces were thrown back out of the impact site. Layers of rock were flipped over, and blocks of rock—some as large as small houses—were blasted out. In all, about 300 million tons of rock were displaced, much of it forming the raised rim around the crater.

The floor of the crater is 570 feet deep — equivalent to a 60-story building — and is more than 4,100 feet across. The rim is more than 3 miles in circumference. If the Washington Monument were erected on the floor of the crater, the top would just about reach the level where you now stand. At least twenty football games could be played simultaneously on the crater floor, and the crater's sloping sides could accommodate two million spectators.

The crater was first reported by white men in 1871. It was thought to be just another extinct volcano. In 1890 nickel-iron meteorites were found on the surrounding plain. Eventually these discoveries led to the suggestion that the crater had been formed by a giant meteorite. In 1891 a leading geologist, G.K. Gilbert, dismissed that possiblility after a brief survey. In 1902 Daniel Moreau Barringer, a Philadelphia mining engineer, became convinced that the crater had been created by the impact of a large metallic object, and he assumed that the mass of the metorite was still buried. He acquired the land and formed the company to explore it. For 25 years his work and scientific research were carried on with great perseverance and much bitter disappointment.



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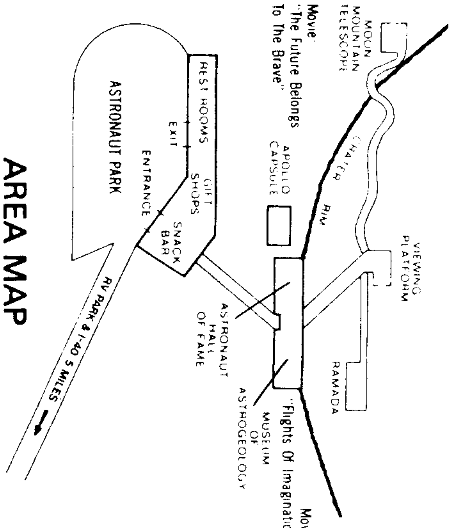
"Meteor Crater History" (length 5 min. 12 sec.)
10 minutes past the hour and 20 minutes before the hour



AREA MAP

Because the crater is roughly round, it was natural to assume that the body that created it lay beneath its center. Consequently, the first shaft was started where the low, white mounds of pulverized Coconino sandstone can still be clearly seen. A few small meteoritic fragments **were** found, but the underlying water table had combined with shattered sandstone to form a highly abrasive mixture which prevented mining to a depth where the main mass of meteorite was suspected to lie.

Later Dr. Barringer discovered that a rifle bullet fired into thick mud, even at a flat angle, would always create a round hole. This was an important clue. Looking at the far slope of the crater—its southeastern side—you will see, as Dr. Barringer did, that the rock strata arch up more than 100 feet above the levels elsewhere on the walls of the crater. This observation, coupled with the fact that most of the loose pieces of meteoritic material had been found northwest of the crater, led Dr. Barringer to conclude that the mass had come in at an angle from the north and had buried itself beneath the southeast rim of the crater. Looking again at the southeast rim, you will see a notch with a streak of red earth running from it. Drilling was started at the notch, and at a depth of a thousand feet increasing numbers of meteoritic fragments were brought up by the drill. At times, after hours without progress, the drill would gouge into something harder than itself. Then, at 1,376 feet, the drill jammed completely—apparently wedged in meteoritic debris. The drill cable broke, funds were exhausted, and the exploration had to be abandoned in 1929. By this time, however, most scientists had accepted Dr. Barringer's theory of the impact origin of the crater.

Although he died that year, Dr. Barringer had lived to see his theory accepted. Today in scientific circles the crater is called Barringer Crater in recognition of his work. His family still owns the property and regards it as a public trust. In 1968 the Department of the Interior designated the site a natural landmark.

Two later attempts were made to locate the main mass, but these efforts were also stopped by objects that could be neither penetrated nor pushed aside. Now, however, modern sophisticated testing procedures have replaced the old method of drilling a hole and examining the findings. Today testing is done by electrical and sound wave measurement, gravitational and magnetic studies, and seismographic work. Based on these procedures, scientists now believe that the major portion of the meteorite—about 80 percent—was vaporized at impact, 5 percent was physically blasted out, and 10 percent remains beneath the south rim of the crater. The remaining 5 percent had been stripped off by atmospheric friction before impact.

Dr. Eugene Shoemaker, former chief scientist of the astrogeological branch of the United States Geological Survey in Flagstaff, wrote his doctoral thesis on this crater and today is probably the best informed man on the geology of the moon. Dr. Shoemaker estimates the size of the mass that struck as 80 to 100 feet in diameter and the velocity of the mass at 43,000 miles per hour. For a mass only 80 to 100 feet in diameter to create a hole a mile wide and 60 stories deep, speed must be the governing factor.

Two new minerals—coesite and stishovite—were identified here. Both are high-pressure polymorphs of silica—SIO_2, silicon dioxide—altered to a different mineral by extreme high pressures equivalent to 20,000 times atmospheric pressure, or 300,000 pounds per square inch. Although coesite and stishovite can be produced in the laboratory, they had never before been found in nature, until identified at an impact site. Coesite has since been identified in connection with other geological features called astroblems. These features are the ancient scars of meteorite craters—some of them huge and as much as 500 million years old.

In more recent years much work has been completed here at Meteor Crater in the fields of planet comparison, astronaut training, and crater mechanics. Photographs of our moon and the other planets have shown clearly that the craters on their surfaces were caused by meteoritic impact collisions, and photographs of our earth's surface have shown that it, too, has been hit many times by large meteorites. Nearly all the craters thus formed on the land masses of the earth have been leveled by erosion. Some are known to be much larger than this crater, but this one is the **first** and the **largest** definitely identified on the basis of the meteorites found in and around it. It is also the **best preserved** crater on earth.

All the Apollo astronauts were given extensive training here at Meteor Crater. Much knowledge was gained in the fields of crater geology, crater mechanics, and meteoritic study that, coupled with their astronaut training, opened the door for a more comprehensive study of the moon. Because scientists are extremely interested in what lies beneath the surface of the moon, astronaut training, at Meteor Crater, has been particularly significant. At an impact site the blast creates an outer flap of material that actually originated far below the surface; therefore, when our astronauts went to the moon, they knew they could collect subsurface material without digging a hole or crawling into one.

Here at Meteor Crater we are attempting to illustrate the importance of meteoric phenomena. As humans continue to explore the regions of outer space in an attempt to find the origin of life, the value of studying impact sites assumes an ever-increasing role in understanding how life on earth may have begun. Meteors and comets can be likened to the space transportation system of our universe.

Our museum of astrogeology is one of the first of its kind, and we hope it will make more readily understandable the technicalities of impact cratering and how such cratering may have influenced our very existence.

Thank you.

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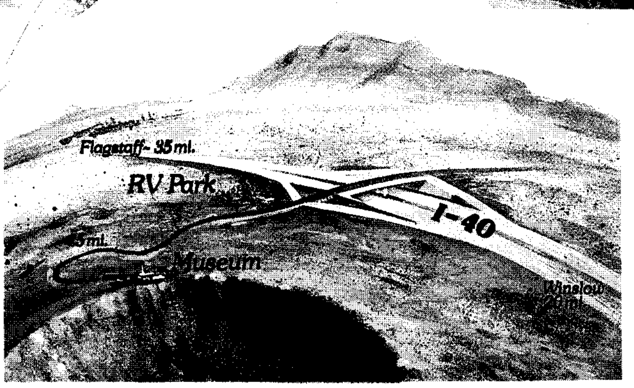

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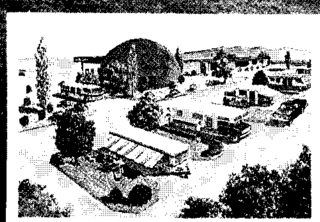

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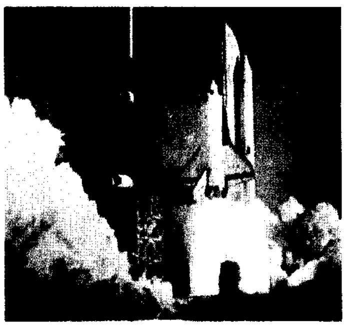
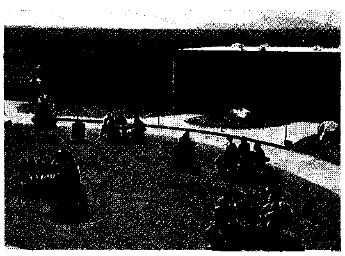


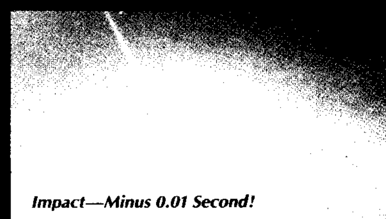


Training site for the Apollo Astronauts

The topographical terrain of Meteor Crater so closely resembles that of the Earth's Moon and other Planets, NASA designated it one of the official training sites for the Apollo Astronauts.

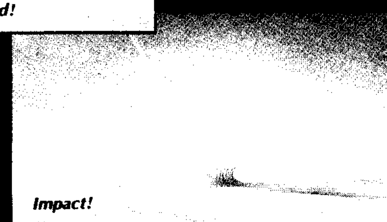
See fascinating exhibits depicting man's exploration of space in the Astronaut Hall of Fame. View an Apollo Space Capsule. Then, relax or picnic at Astronaut Park, dedicated to crew members of the Apollo I and Challenger spacecraft. The exhibits honoring our brave Americans who journeyed into space will be enjoyed by every member of your family!

A massive meteoric chasm created in less than 10 seconds!


Impact—Minus 0.01 Second!

Plummeting toward Earth at a speed of nearly 45,000 mph, the meteor begins to fragment as it enters our atmosphere, illuminating the desert sky.

The meteoric mass weighing millions of tons impacts from a near-vertical descent with an explosive force equal to 15,000,000 tons of TNT.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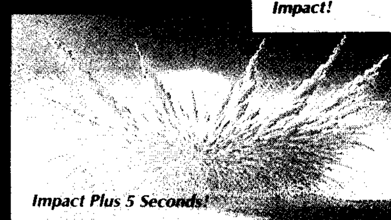
Impact Plus 5 Seconds!

Over 300,000,000 tons of rock has been displaced and the fragments begin to fall back toward Earth, the larger masses creating secondary craters.

Today, 49,000 years after the devastating impact, Meteor Crater is one of Arizona's most popular visitor attractions.


Impact Plus 49,000 Years!

The best-preserved meteorite impact site on Planet Earth!

Imagine a giant meteoric mass, more dense than any known material and weighing millions of tons, plummeting toward earth at a speed of nearly 45,000 mph. Today, 49,000 years after the devastating impact, Meteor Crater remains a gaping chasm 570 feet deep, nearly a mile across, and over 3 miles in circumference . . . Deep enough to engulf a 60-story building, and large enough at the floor of the crater to accommodate 20 football fields! You'll take an exhilirating step into space as you experience the magnitude of this awe-inspiring crater from the observation decks overhanging its depths.

Meteor Crater is the best-preserved meteorite impact site on Earth, and has been designated a Natural landmark by the United States Government. Located just minutes from Interstate 40, this highly popular attraction is visited annually by hundreds of thousands of tourists from all parts of the world. Don't miss it!

One of the World's finest Astrogeological Exhibits

Meteor Crater's Museum of Astrogeology provides visitors with a casual, self-guided tour of exhibits and video presentations vividly portraying how the meteorite impacted, the devastation that resulted, and the significant role that the Crater plays in the study of earth and space sciences. A massive 1,406-lb. meteorite, the largest ever found in the area, is on display for visitors to view and touch.

Our Gift Store and Lapidary Shop provide an excellent selection of unique and memorable gifts you'll want to take with you or have mailed to your friends. We also have a Coffee Shop for your convenience and enjoyment during your Meteor Crater Experience.

Diatremes and Uranium Deposits in the Hopi Buttes, Arizona

E. M. SHOEMAKER, C. H. ROACH, AND F. M. BYERS, JR.

U. S. Geological Survey, Menlo Park, California, and Denver, Colorado

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ABSTRACT

The Hopi Buttes diatremes erupted in a shallow lake that was filled in as volcanic activity progressed in Pliocene time. At the end of the period of volcanism the landscape included low lava domes capping some of the diatremes, a few flows, and numerous craters of the maar type, surrounded by rims of volcanic debris with gentle exterior slopes that merged with the surrounding plain. Erosion, probably chiefly during early and middle Pleistocene, has exposed the diatremes in varying stages of denudation.

The diatremes are funnel-shaped volcanic vents that range from a few hundred feet to about 2 miles across where they cut the top of the lake beds. They are filled with limburgite tuff and tuff breccia, fine-grained clastic and carbonate rocks of nonvolcanic origin, agglomerate, intrusive and extrusive monchiquite, and blocks of sedimentary rocks derived from the vent walls. In most of the vents several hundred to a few thousand feet of lacustrine and fluvial crater deposits were laid down after an initial explosive phase of volcanic activity. The structural and sedimentary evolution of many of the diatremes culminated in the quiet upwelling of lava.

The initial opening of the diatremes is attributed to the rapid unmixing of gas from magma ascending through the crust along many separate fissures. Fractures were propagated to the surface hydraulically, and decompression waves were then propagated into the ascending magma and fissure walls as the gas was drained away. Enlargement of the channels of gas flow is attributed chiefly to spalling. The funnel-shaped orifices of the diatremes, which formed the craters at the surface, were in many cases later enlarged by slumping and collapse of the crater walls during subsidence of the materials filling the vent. The most important causes of the subsidence are probably stoping and assimilation of the porous vent debris by the underlying magma and displacement of the magma.

Numerous low-grade deposits of uranium occur in carbonate rocks within the diatremes, and small deposits of higher grade occur locally in the fine-grained nonvolcanic clastic rocks, in the tuffs, and in fragments of sedimentary rocks derived from the walls of the vents and in the vent walls. Widespread radioactivity in the carbonate rocks suggests that the uranium may be at least in part syngenetic, but the highest concentrations of uranium, in the clastic rocks, are related to structures that would have influenced the flow of solutions and are probably epigenetic.

INTRODUCTION

The Hopi Buttes are a part of the Navajo and Hopi Indian reservations in northeastern Arizona (Fig. 1) characterized by scattered buttes and mesas held up by volcanic rocks. These volcanic features were first noted by Newberry (1861, p. 118), and they have since drawn the attention of numerous geologists, among

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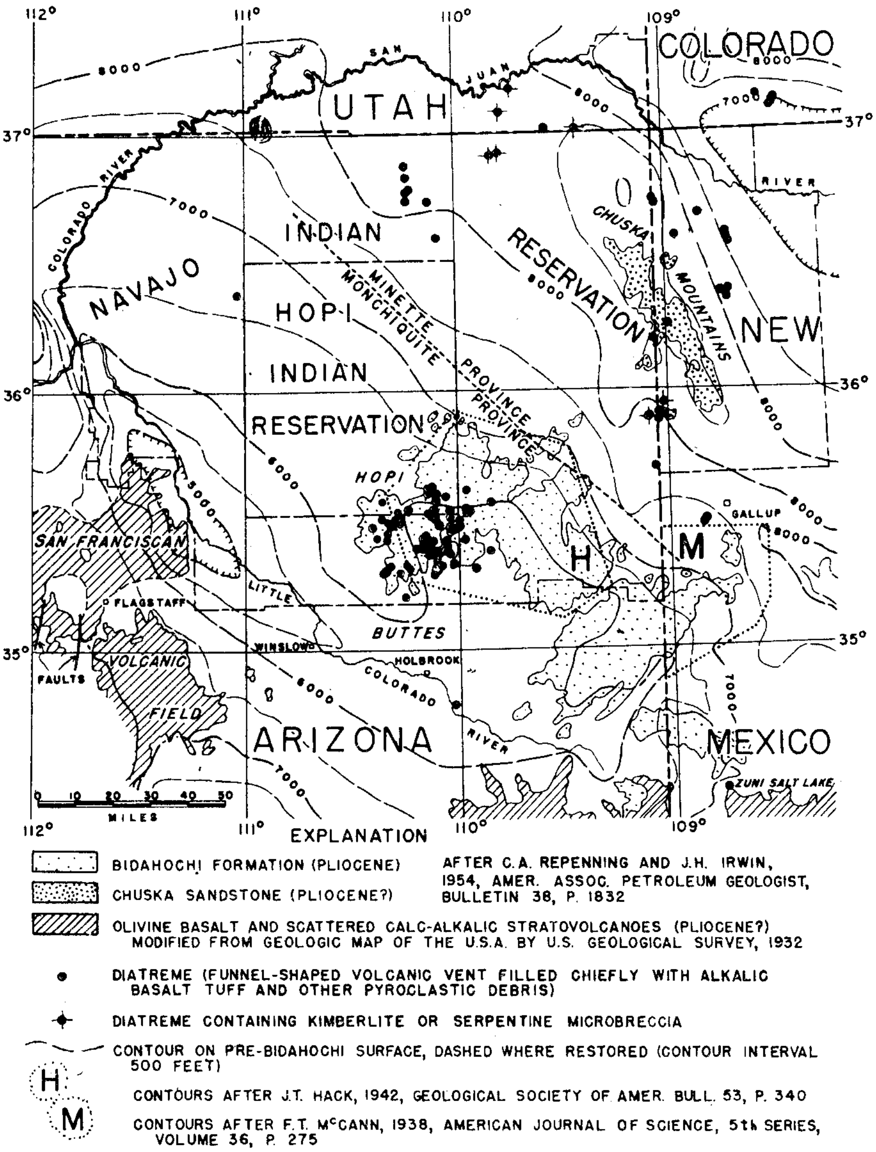

Figure 1. Index map of Navajo and Hopi reservations and vicinity showing the distribution of diatremes, sedimentary and volcanic rocks of Pliocene(?) age, and configuration of the pre-Bidahochi surface

whom Gregory (1917), Williams (1936), and Hack (1942a) have contributed most to the literature on the volcanism of this region.

Hack gave the first clear description of the principal structural type of volcanic vent represented in the Hopi Buttes, to which he gave the name diatreme, a term used previously with reference to dominantly lava-filled necks of the Hopi

Buttes by Williams (1936, p. 18). The Hopi Buttes vents exhibit many of the features found in the vents of eastern Fife, Scotland (Geikie, 1902), and to a lesser extent in the Schwabian Alb, Germany (Branco, 1894; Cloos, 1941), two of the three principal groups of volcanic structures to which Daubreé (1891) originally applied the name diatreme. The structure of the Hopi Buttes vents, where exposed at the level of the original surface of eruption, is also similar to that of the maar type of volcano of the Eifel region of Germany. (Compare with Frechen, 1956.) About 300 diatremes or volcanoes of the maar type are present in the central part of the Hopi Buttes region, more than are known in an area of comparable size in any other part of the world. Because they are exposed at varying stages of denudation, these diatremes offer an unparalleled opportunity for study of this type of volcanism.

In 1952 and 1953 many of these diatremes were found to contain low-grade deposits of uranium (Shoemaker, 1956b). Study of volcanic vents in the Navajo and Hopi Indian reservations was begun by Shoemaker in 1952. Detailed mapping in the Hopi Buttes region was undertaken in 1956 to help interpret the history and origin of the volcanic features, particularly the uranium deposits. Investigation of the geology of the diatremes and occurrence of the uranium was carried out by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. Some of the results outlined here are the product of the collective efforts of those who participated in this mapping, including, in addition to the authors, H. J. Moore II, F. S. Hensley, Jr., and R. W. Hallagan. Reconnaissance maps by C. A. Repenning, J. H. Irwin, and R. L. Jackson, of the U. S. Geological Survey, have also been utilized.

GEOLOGIC SETTING OF THE DIATREMES AND THE ORIGINAL VOLCANIC LANDSCAPE

The diatremes of the Hopi Buttes are part of a larger group scattered over the Navajo and Hopi Indian reservations and parts of adjacent areas (Fig. 1). They are all related in structural characteristics, are partly filled either with alkalic basaltic volcanic rocks or kimberlite, and are probably of about the same age. The Hopi Buttes are in a shallow Pliocene basin (Fig. 1) which was receiving sediments during diatreme activity and has been only moderately dissected subsequently; in most other places on the Navajo Reservation the diatremes have been deeply eroded. Many of the surficial volcanic deposits surrounding them at the time of volcanic activity have been preserved as part of the Pliocene sedimentary deposits.

The Navajo and Hopi reservations lie in the south-central part of the Colorado Plateau, a region underlain chiefly by gently dipping to nearly flat sedimentary beds of Paleozoic, Mesozoic, and Cenozoic age. The older exposed rocks in the Hopi Buttes include the Chinle and Wingate sandstones of Triassic age, the Moenave Formation of Triassic(?) age, the Kayenta Formation of Jurassic(?) age, the Navajo Sandstone of Jurassic(?) and Jurassic age, the Carmel Formation, Entrada Sandstone, and Cow Springs Sandstone of Jurassic age, and the Dakota Sandstone and Mancos Shale of Cretaceous age (Harshbarger and other, 1957).

In the central part of the Hopi Buttes these formations dip gently and rather uniformly to the north and are overlain unconformably by the Bidahochi Formation of late Tertiary age, a deposit composed mainly of flat-lying beds of claystone, siltstone, sandstone, and tuff with an aggregate thickness of several hundred feet. The contact of the Bidahochi on the older rocks is a remarkably smooth surface nearly horizontal in the southern part of the Hopi Buttes. The Bidahochi, in turn, is overlain unconformably by Quaternary deposits which rest on a surface with a total relief of about 900 feet. The relief on this latter surface permits a close examination of the structure of the diatremes.

The Bidahochi Formation, named by Reagan (1924), underlies about half the Hopi Buttes region and extends 50–70 miles to the east and southeast in Arizona and into adjacent parts of New Mexico (Repenning and Irwin, 1954, Fig. 1; Repenning and others, 1958, Fig. 3). The lower parts are of particular interest in connection with the diatremes. To elucidate the structure and history of the diatremes we divided the Bidahochi Formation into six members for mapping (Shoemaker, Hensley, and Hallagan, 1957; Shoemaker, Byers, and Roach, 1958). Four of the members predate diatreme activity, and one member is contemporaneous with the main period of volcanism.

The lower four members constitute a conformable sequence of claystone and siltstone or very fine-grained sandstone that corresponds approximately to the lower member of Repenning and Irwin (1954, p. 1822–1824). In ascending order these are: (1) a unit of reddish-brown claystone with subordinate siltstone and sandstone, (2) a unit of greenish- and yellowish-gray claystone with subordinate pink siltstone or very fine-grained sandstone, (3) a unit of pink to buff siltstone and very fine-grained sandstone with subordinate greenish-gray claystone, and (4) a variegated to reddish-brown claystone member that locally contains sandstone and conglomerate. In these members, individual beds of siltstone or claystone, 1–4 feet thick, can be traced and correlated over several square miles. The siltstone beds appear almost perfectly massive; cross-bedding was noted only in a few thin sandstone beds of the lowest or No. 1 member.

Twelve individual thin beds of white, medium- to very fine-grained, waterlaid tuff, chiefly rhyolitic, occur interbedded in the claystone, siltstone, and sandstone sequence represented by members 1 to 4. Some of these tuffs are nearly 100 per cent glass, but most show varying degrees of devitrification, although shard structure is commonly preserved. They are all referred to as vitric tuffs to distinguish them from the coarse basaltic tuff derived locally from the diatremes. Their source probably lies in the Verde Valley about 100 miles southwest of the Hopi Buttes region (Sabels, 1960). Many vitric tuffs are continuous for many miles, despite the fact that some of them rarely exceed 0.1 foot in thickness, and a few are traceable over the known extent of the containing members. This regional uniformity of the stratigraphy, coupled with rarity of cross-stratification, supports the interpretation suggested by Repenning and Irwin (1954, p. 1823) of a lacustrine origin for the lower part of the Bidahochi Formation. We have adopted the name Hopi Lake, proposed by Williams (1936, p. 117), for the body of water in which these sediments were laid down.

The only fossils found to date in any of the lower four members are fragmentary remains of fresh-water mollusks, and several species of ostracods in the No. 4 member. A mammalian fauna discovered by Paul W. Howell near Sanders, Arizona (Lance, 1954), occurs in beds that are probably equivalent in age to one of the lower four members. According to Lance (1954) a Clarendonian (early Pliocene) or Barstovian (late Miocene) age is suggested by the fauna, which contains *Merycodus, ?Gomphotherium*, a large and a small camelid, and a fox (Repenning and others, 1958).

The fifth member of the Bidahochi Formation consists mainly of gray claystone and limburgite tuff, minor amounts of nonvolcanic sandstone, and, in the vicinity of some diatremes, limburgite flows. For mapping in the area of the diatremes, the base of the member has been placed at the lowest occurrence of limburgite detritus. This member includes the major part of the section measured at White Cone by Gregory (1917, p. 82), which was designated the White Cone Series by Reagan (1932, p. 255–256). It includes beds designated as the volcanic member as well as beds included in the lower part of the upper member of Repenning and Irwin (1954).

In general, the fifth member—referred to in this report as the "White Cone" member (an informal field designation)—has at its base about 5–10 feet of claystone with sparse grains of limburgite. Near the diatremes this claystone is succeeded by coarse gray limburgite tuff or limburgite flows. The basal tuffaceous claystone beds of the "White Cone" member lie conformably on the underlying claystones and siltstones. The contact is gradational and is marked only by a few scattered grains of limburgite.

In contrast to the underlying members, the "White Cone" member exhibits abrupt local changes of facies related to the distribution of the diatremes. Away from the diatremes the "White Cone" member generally consists mainly of claystone, minor sandstone, and vitric tuff, with only thin beds of limburgite tuff or tuffaceous claystone; near the diatremes the "White Cone" is made up predominantly of limburgite tuff with some interstratified lava flows. The limburgite detritus is clearly derived from the diatremes. In an area of closely spaced diatremes west of Indian Wells, the tuff may reach a total thickness of 200–300 feet.

In many places adjacent to diatremes, where the "White Cone" member has been partly preserved from erosion, the member, or part of the member, rims each vent with stratified tuff ranging from a few tens of feet to as much as 100 feet in thickness. These tuff deposits thin gradually away from the diatremes, commonly to a thickness of only a few feet over distances ranging from a fraction of a mile to several miles. The landscape at the time of diatreme eruption included numerous craters surrounded by ridges of volcanic debris with gentle exterior slopes that merged with the surrounding plain. The countryside must have appeared similar to the maars of the Lower Chindwin Valley of Burma (Oldham, 1906; Burri and Huber, 1932), or the Xalapazcos and Valle de Santiago regions of Mexico (Ordoñez, 1905; 1906). Maars and craters of the maar type of comparatively recent origin in the United States, with which the Pliocene craters of the Hopi Buttes may be compared, include the Afton Craters (Lee, 1907; Reiche, 1940) and Zuñi Salt Lake (Darton, 1905), all in New Mexico, and the Soda Lake maars of Nevada (Russell, 1885, p. 73–76). The beds of the tuff rims in the Hopi Buttes probably originated in part by fallout of ejected volcanic ash, as is the case of modern maars (Shoemaker, 1957), and perhaps in small part by fluvial and eolian reworking of the fallout deposits.

The "White Cone" member at White Cone contains abundant fossils. The fauna includes nine species of fresh-water invertebrates (Gregory, 1917; Reagan, 1932; and Taylor, 1957), fish, amphibians, reptiles, and water-loving and burrowing mammals (Stirton, 1936; Lance, 1954). Some sandstone beds interbedded with the claystone are cross-stratified and locally fill small channels cut into underlying beds. Both the fossil fauna and the sedimentary structures support the interpretation, first advanced by Hack (1942a, p. 344) for the entire Bidahochi Formation, of a stream and swamp environment of deposition for part of the "White Cone" member. The environment of deposition of the lower part of the "White Cone" may have been transitional between lacustrine and fluvial. Maar rims of the earliest diatremes probably rose as islands from a shoaling Hopi Lake. A Hemphillian (middle Pliocene) age is indicated for the "White Cone" member by the mammalian remains (Stirton, 1936; Lance, 1954).

The sixth, and uppermost, member of the Bidahochi Formation in the Hopi Buttes area is composed of both horizontal and cross-stratified sandstone with minor interbedded claystone. This member is not preserved over most of the area around the Hopi Buttes diatremes but forms the principal part of the Bidahochi Formation north and east of the Hopi Buttes. The original thickness of this member is not known, but locally about 600 feet is preserved (Kiersch and Keller, 1955, p. 476). Grains of limburgite and augite, fairly abundant in the sandstones of the No. 6 member north and northeast of the Hopi Buttes diatremes, probably were derived from ash showers produced by diatreme eruptions in the upwind Hopi Buttes area. Such showers may have occurred during deposition of part of the No. 6 member or prior to deposition of the beds in which the volcanic material is now found.

Camel and beaver remains have been found in the No. 6 member where it overlies the "White Cone" member at White Cone (Lance, oral communication). Probably other camel material and camel tracks mentioned by Williams (1936, p. 130) and by Hack (1942a, p. 344) were obtained from the No. 6 member. Both the fauna and the cross-stratification support a fluvial origin for most of the sandstone of this member. The highest known fossils are late Hemphillian, and several hundred feet of beds is preserved above the highest known fossil mammal zone. The only definite upper limit that may be placed on its age is afforded by the oldest formations of known Quaternary age that rest unconformably upon it.

Quaternary formations described by Hack (1942b, p. 48–54) in the Jeddito Valley along the northern margin of the Hopi Buttes are widely distributed over the Hopi Buttes region. In ascending stratigraphic order the Quaternary units recognized by Hack are the Jeddito Formation, a deposit of alluvium and loess of Pleistocene age; a loess, not previously described; the Tsegi Formation, an alluvial deposit of Recent age; the Naha Formation, an alluvial deposit of Recent age; dune sand that rests on the Tsegi and Naha; and the modern alluvium. The Quaternary deposits have only moderate thickness but mantle at least three-fourths of the Hopi Buttes region.

The oldest of these units, the Jeddito Formation, rests upon an erosion surface quite similar to the present topography. Proboscidian and horse bones establish the age of the Jeddito as Pleistocene. It has generally been correlated with very late Pleistocene formations of other areas (compare with Leopold and Miller, 1954, p. 57–60); the topographic relief of the Hopi Buttes region at the present time was developed largely between deposition of the Bidahochi and Jeddito formations. This interval probably includes part of early Pleistocene and perhaps middle Pleistocene time.

The age of the upper part of the Tsegi Formation in the Hopi Buttes has been established as Recent by radiocarbon methods (Rubin and Alexander, 1960, p. 154–155).

COMPOSITION AND STRUCTURE OF THE DIATREMES

The diatremes of the Hopi Buttes region are funnel-shaped volcanic vents filled with limburgite tuff and tuff breccia, fine-grained clastic and carbonate rocks of dominantly nonvolcanic origin, agglomerate, intrusive and extrusive monchiquite, and blocks of sedimentary rocks derived from the vent walls. In general, the walls of the diatremes dip inward 45°–90° where they cut Mesozoic rocks and more gently where they cut the lower members of the Bidahochi Formation. At the base of the "White Cone" member the diatremes range from a few hundred feet to about 2 miles across. The small diatremes tend to be filled mainly with agglomerate and intrusive monchiquite; the large ones are filled at the level of exposure mainly either with agglomerate and monchiquite or with tuff and nonvolcanic sediments, depending in part on the level at which they are exposed.

During deposition of the "White Cone" member most large diatremes, at one time or another, were expressed topographically as craters and were filled partly with fluvial and lacustrine sediments. Each crater was a local basin of deposition, commonly separated from the surrounding area by a low encircling ridge of ash. The vent sediments have been mapped separately from the "White Cone" member, with which they are, in general, probably contemporaneous but with which they only rarely have physical continuity. Great thicknesses of sediments have accumulated in some of the diatremes as a result either of great initial depth of the crater or of repeated subsidence within the vent during deposition, or in some cases perhaps both. All variations have been found between beds gently depressed toward the center of the vent and beds steeply inclined on all sides and displaced along numerous small reverse faults dipping outward toward the vent wall.

Igneous rocks in the Hopi Buttes are almost entirely dark basaltic rocks of monchiquitic affinity. In their intrusive phase they would be classed as mon-

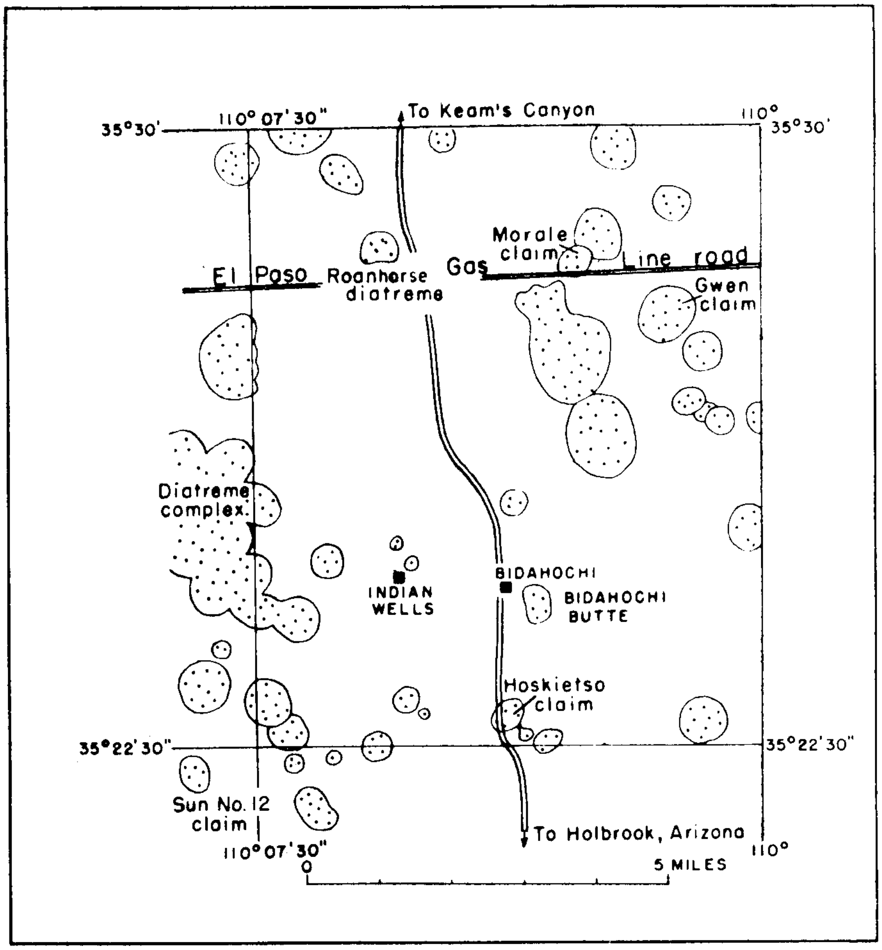

Figure 2. Index map showing location of diatremes in central part of Hopi Buttes region, Navajo County, Arizona

chiquite. In their extrusive phase the groundmass is either glass or crystalline analcite. The glassy rocks may be properly referred to as limburgite. We have applied the term limburgite as a general field term to the tuffs, agglomerates, and flows. Chemically, the rocks are markedly undersaturated in silica (Williams, 1936, p. 166) and are characterized by a greater abundance of several minor elements, including uranium and thorium, than is usually found in basalts (Shoemaker, 1955 and 1955b). In two diatremes thick sills of monchiquite contain dikes and pods of syenite, presumably derived by differentiation of the monchiquite magma in place (Shoemaker, Byers, and Roach, 1958).

Diatremes along the Holbrook-Keams Canyon highway in the vicinity of Indian Wells (Fig. 2) illustrate some of the structural variations. The diatreme at the Hoskietso claim is crossed by the highway southeast of Indian Wells (Fig. 3). Rocks in the diatreme crop out as low hills rising 50–80 feet above the floor

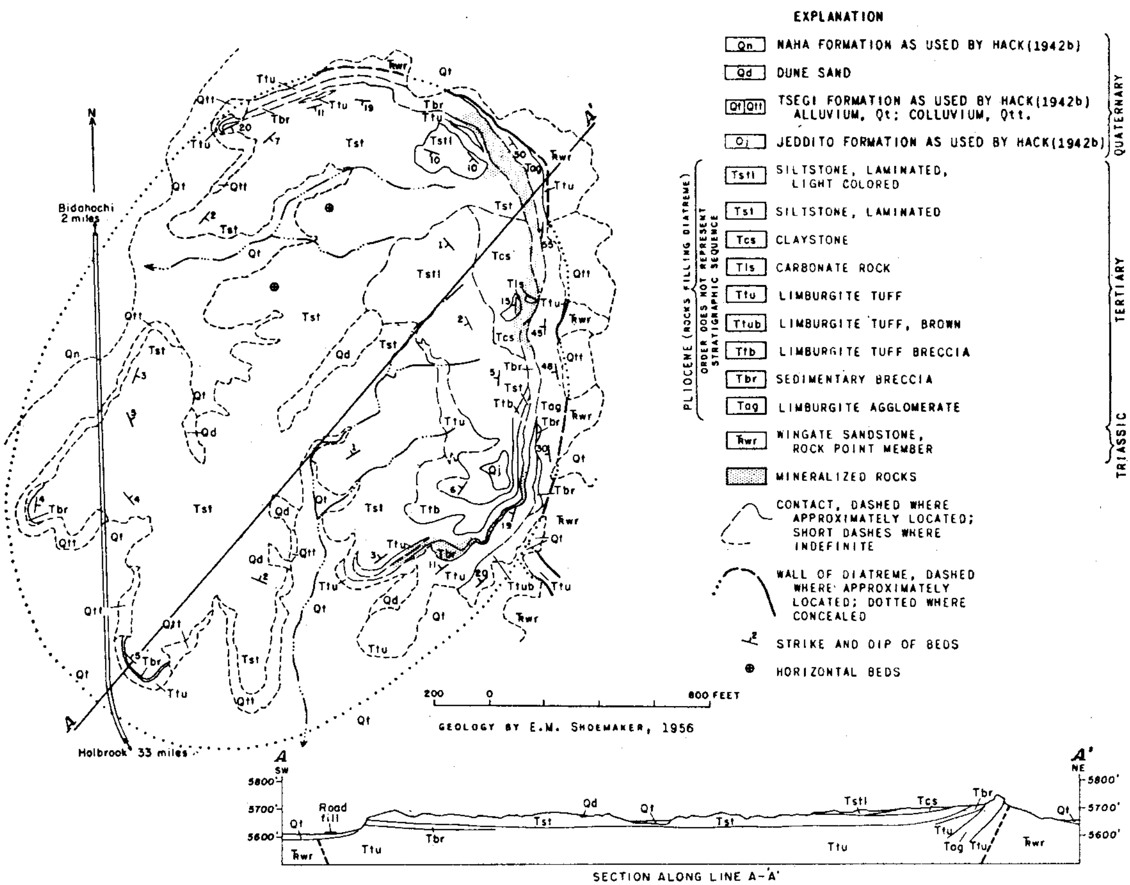

Figure 3. Geologic map and section of the diatreme at the Hoskietso claim showing distribution of mineralized rocks

of Teshbito Valley. The vent units dip gently through the central part of the diatreme, and the bulk of the rocks exposed is laminated siltstones that constitute a relatively thin unit within the vent. The exposed sequence turned up on the east side of the diatreme includes, from base to top, limburgite tuff of unknown thickness, agglomerate ranging from a feather edge to more than 50 feet thick, more limburgite tuff with local breccia lenses as much as 70 feet thick, a persistent unit of breccia about 30 feet thick, and about 50 feet of water-laid laminated siltstone that interfingers with tuff, tuff-breccia, claystone, and some carbonate rock toward the east side of the vent. Younger beds successively overlap older beds toward the east wall of the vent. The level at which the diatreme is exposed is about 600 feet below the base of the "White Cone" member, and the wall of the vent is against the Rock Point Member of the Wingate Sandstone of Triassic age.

Features of particular interest at the Hoskietso claim are the persistent sedimentary breccia unit around the edge, the laminated siltstones, and a tuff-breccia tongue in the siltstones. The sedimentary breccia unit is composed of angular blocks of the Rock Point Member of the Wingate Sandstone and subordinate blocks of limburgite in a tuff matrix. Some blocks are as much as 6 or 7 feet across. Thin lenses of platy siltstone are locally interlayered in the breccia. The Wingate blocks must either have been derived from the walls of the diatreme when it formed a crater open to the depth of the Rock Point Member or have been carried up from depth during the explosive phase of activity of one of the diatremes, and then have fallen or been washed back in. The intermixture of large limburgite blocks suggests that the blocks were blown out of this or an adjacent vent. Lamination in the overlying siltstone, composed largely of nonvolcanic detritus, shows that subsequent sedimentation proceeded slowly and and rather uniformly. If the laminae are varves, which they closely resemble, then several thousand years may be represented by the 50 or 60 feet of siltstone. The silt may have been transported into the crater by wind and deposited on the floor of a small lake that occupied the crater during this part of its history.

The tuff-breccia tongue projecting into the siltstone from the southeast shows a pronounced facies change from a coarse tuff-breccia to a fine-grained tuff from the side of the vent toward the center. It probably indicates an explosive outburst in the immediately adjacent vent on the southeast.

The vent that adjoins the diatreme at the Hoskietso claim on the southeast (Fig. 4) is representative of a slightly different type. It is only about 800 feet in diameter, as contrasted with 2500 feet for the Hoskietso claim diatreme, and underlies a butte that rises about 500 feet from the valley floor. It is filled mainly with rudely bedded coarse tuff and agglomerate intruded by irregular dikes and sills of monchiquite. The walls of the vent cut the Rock Point Member of the Wingate Sandstone and are exceptionally well exposed on the south side, where they are nearly vertical or dip 70°–90° inward. Bedding in the tuff dips 20°–35° from all sides toward the center of the vent. A few immense blocks of lower members of the Bidahochi Formation are enclosed in the tuff and are partly hornfelsed where they are intruded by dikes of monchiquite on the north side of the vent.

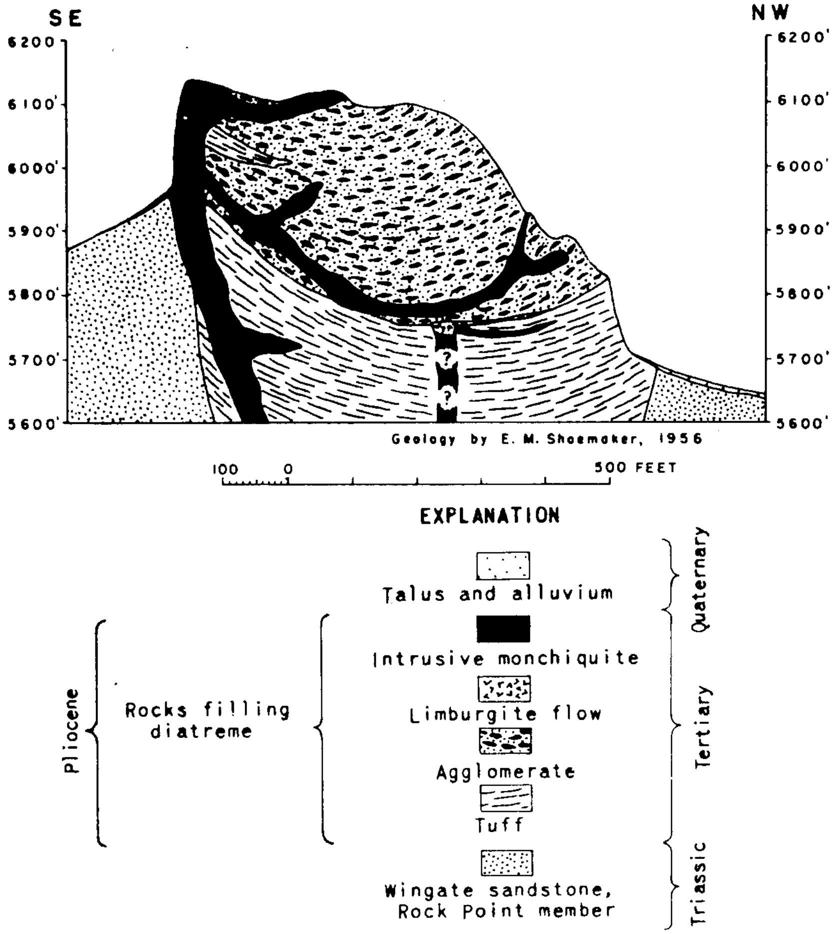

Figure 4. Cross section of diatreme southeast of Hoskietso claim

Bidahochi Butte (Fig. 5), east of Indian Wells, is an example of a vent filled largely with agglomerate and intrusive monchiquite, although some bedded tuff is present in the vent filling. The wall of the vent is well exposed only on the east side, where it cuts lower beds of the Bidahochi Formation at about 45°. One sill crosses the vent wall on the north side of the butte and is intruded near the contact of the No. 3 (siltstone) and "White Cone" members. Further out from the diatreme it may once have emerged as a flow. A higher sill forms part of the cap of the butte underlain by the diatreme; its feeder is well exposed on the east face of the butte. A pod and dikes of syenite occur in the thick part of the sill over the feeder. Angular unconformities in the tuff-agglomerate sequence indicate a complex history of eruptive activity and vent filling.

The Roanhorse diatreme (Fig. 6) is filled with sedimentary rocks that project as arcuate ridges above the alluvial floor of Teshbito Valley just west of the highway about 5 miles north of Indian Wells. The ridges are hogbacks upheld by thin discontinuous carbonate beds dipping 15°–55° toward the center of the vent.

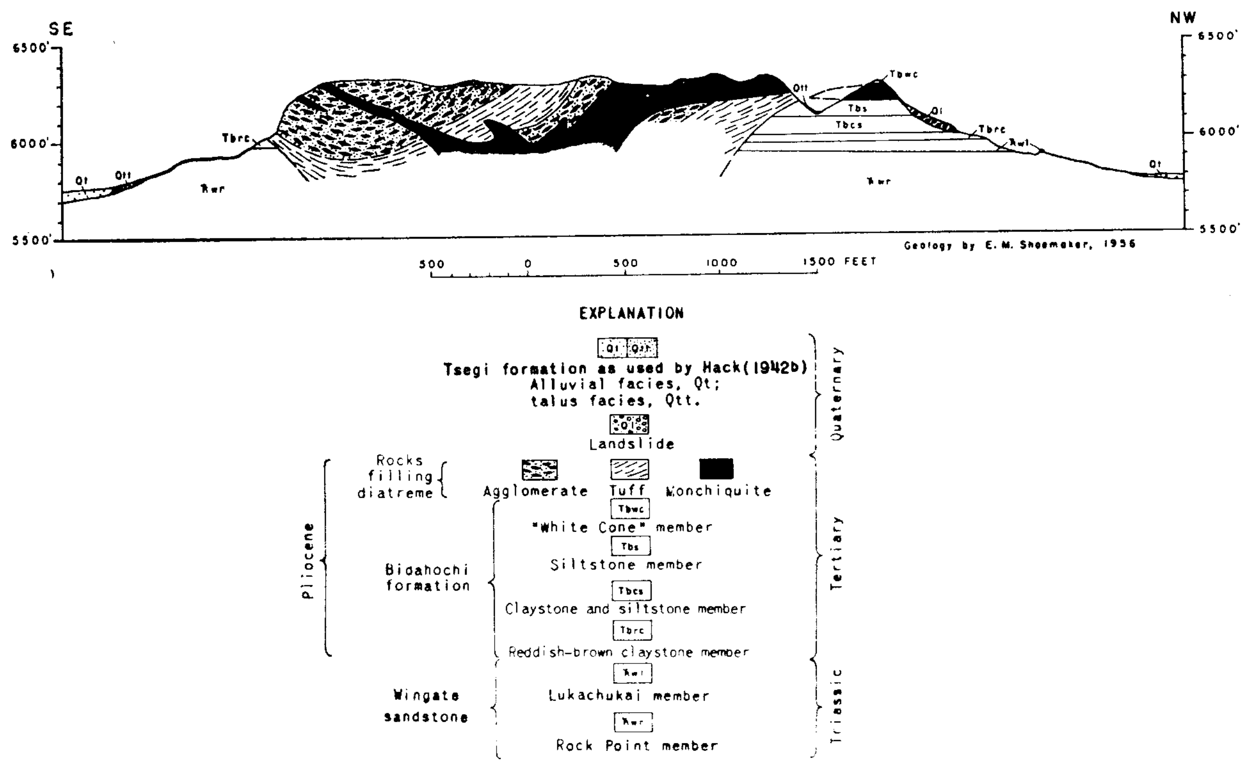

Figure 5. Cross section of Bidahochi Butte

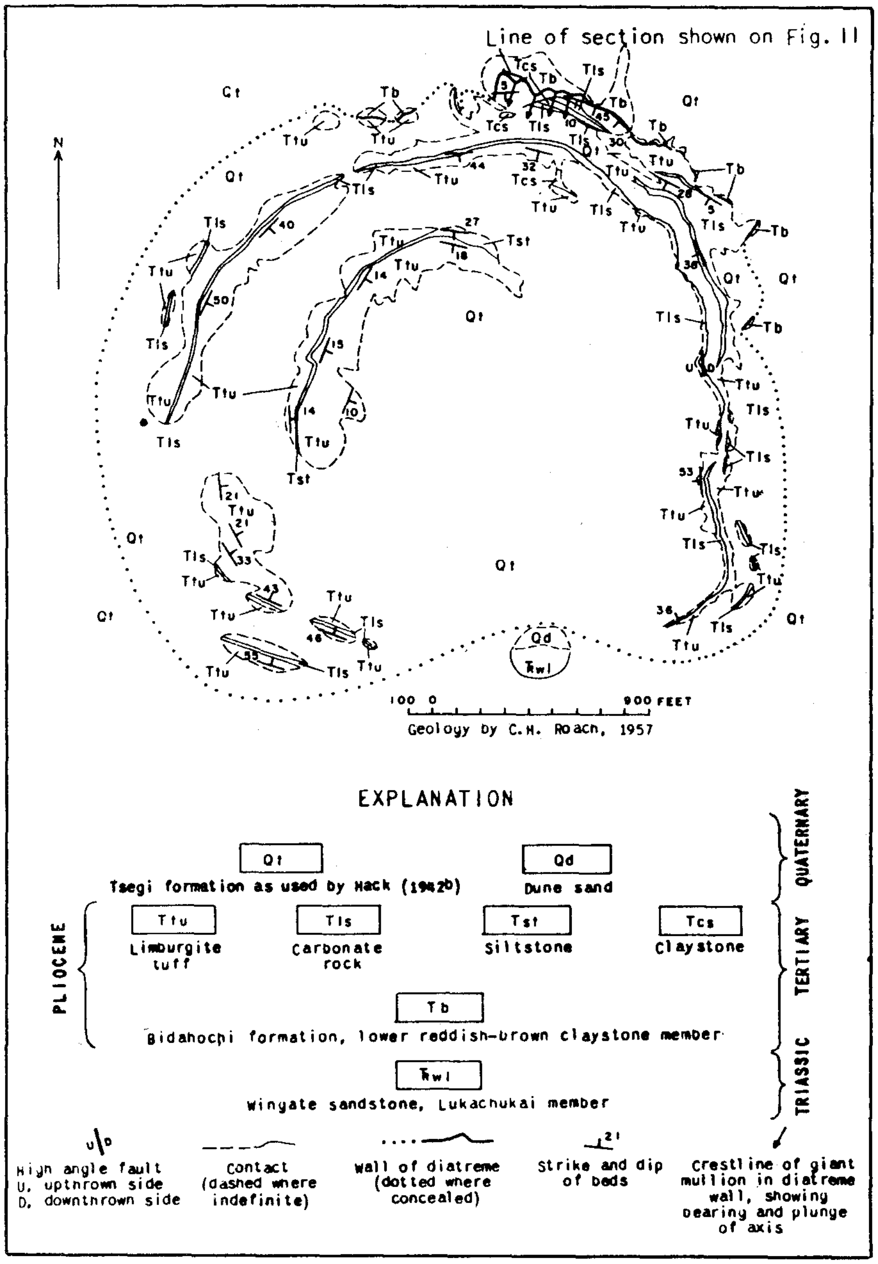

Figure 6. Geologic map of Roanhorse diatreme

These beds are enclosed in bedded limburgite tuff, which also contains minor interbeds of siltstone and claystone. The wall of the vent is exposed only on the north side where it cuts the lower reddish-brown claystone member (No. 1 member) of the Bidahochi Formation. In ground plan the wall is highly irregular

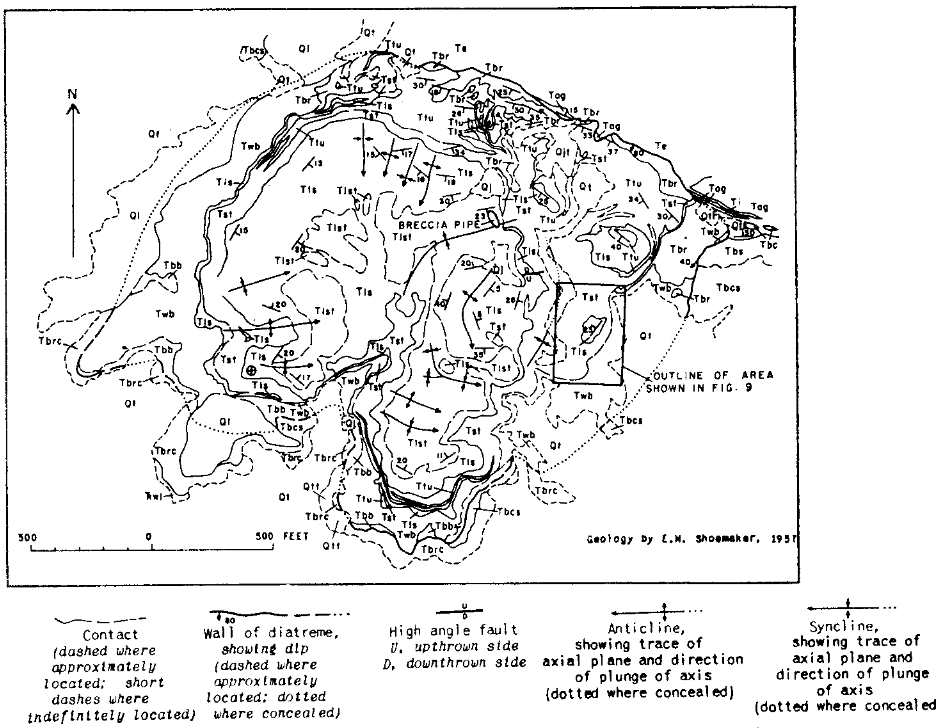

Figure 7. Geologic map of the diatreme at the Morale claim

because it is crenulated in large mullionlike structures 70–80 feet across that plunge toward the vent center (Fig. 11).

A well-exposed diatreme at the Morale claim (Fig. 7) about 2 miles east of the Roanhorse diatreme is accessible by a road following the El Paso Gas Company pipe line. The lower exposed part is filled with a chaotic assemblage of blocks and finer debris derived from prevolcanic members of the Bidahochi Formation and the volcanic "White Cone" member, which range from detrital particles of the original sediments to large masses a few hundred feet long emplaced by inward slumping of the walls of the vent. Two units may be mapped in the slump debris, a lower unit composed mainly of material from pre-"White Cone" members of the Bidahochi, and an upper unit made up of blocks of the "White Cone", which represent parts of the initial maar rim engulfed by the slumping. Resting unconformably on the chaotic slump debris is a sequence of laminated to massive siltstone, limy siltstone, and carbonate rock, which interfingers toward the walls of the vent with tuff and coarse volcanic breccia.

Many of the diatremes in the general vicinity of the Morale claim are similarly filled partly with Bidahochi debris derived by slumping or collapse of the vent wall. On the east side of the nearby Gwen claim (Fig. 8), individual blocks or slides are large enough to be mapped. The vent wall cuts across the lower members of the Bidahochi Formation at about 20°. Individual slices or slides, generally including part of the maar rim and part of the underlying No. 4 mem-

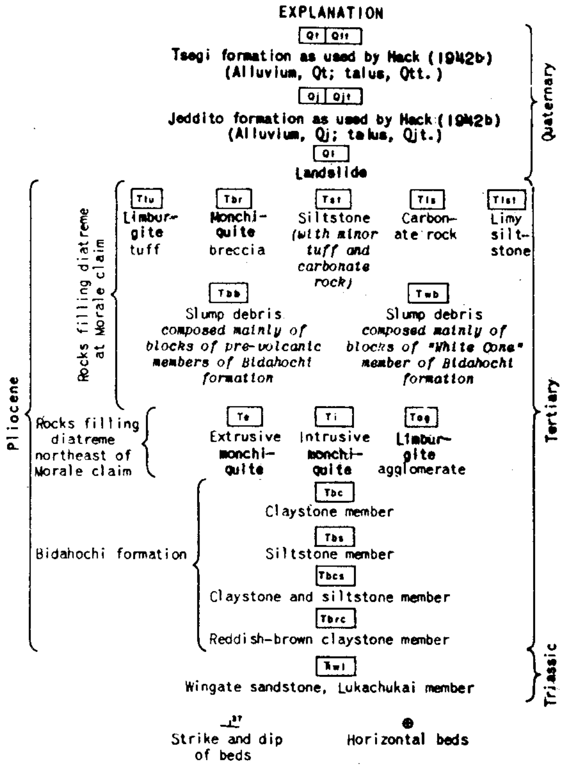

Figure 7—Explanation

ber, have descended along the wall and overridden one another like a series of small thrust sheets. Five superposed sheets have been mapped in which the stratigraphy is partly or entirely duplicated (Fig. 8).

MECHANICS OF DIATREME DEVELOPMENT

The history of structural development of some of the larger diatremes includes three periods: (1) explosive activity and "gas coring" of the vent; (2) subsidence, collapse of the walls, and sedimentary infilling of the crater; (3) quiet upwelling of lava.

To reconstruct the early history and mechanism of diatremes in the Hopi Buttes it is necessary to consider evidence from the other diatremes widely scattered on the Navajo Reservation (Williams, 1936; Shoemaker, 1956b). These include vents filled with minette and minette tuff-breccia and some filled with kimberlite (serpentine microbreccia) (Fig. 1). Some of the kimberlite vents in the northern part of the Navajo Reservation, in particular, show most clearly the initial stages of opening of the diatremes. At the deep level at which some of these vents are exposed (Shoemaker, 1956b, p. 180–182), the structure does not involve beds deposited at the surface, and is not appreciably complicated by subsidence of the vent filling and collapse of the walls (Shoemaker and Moore, 1956).

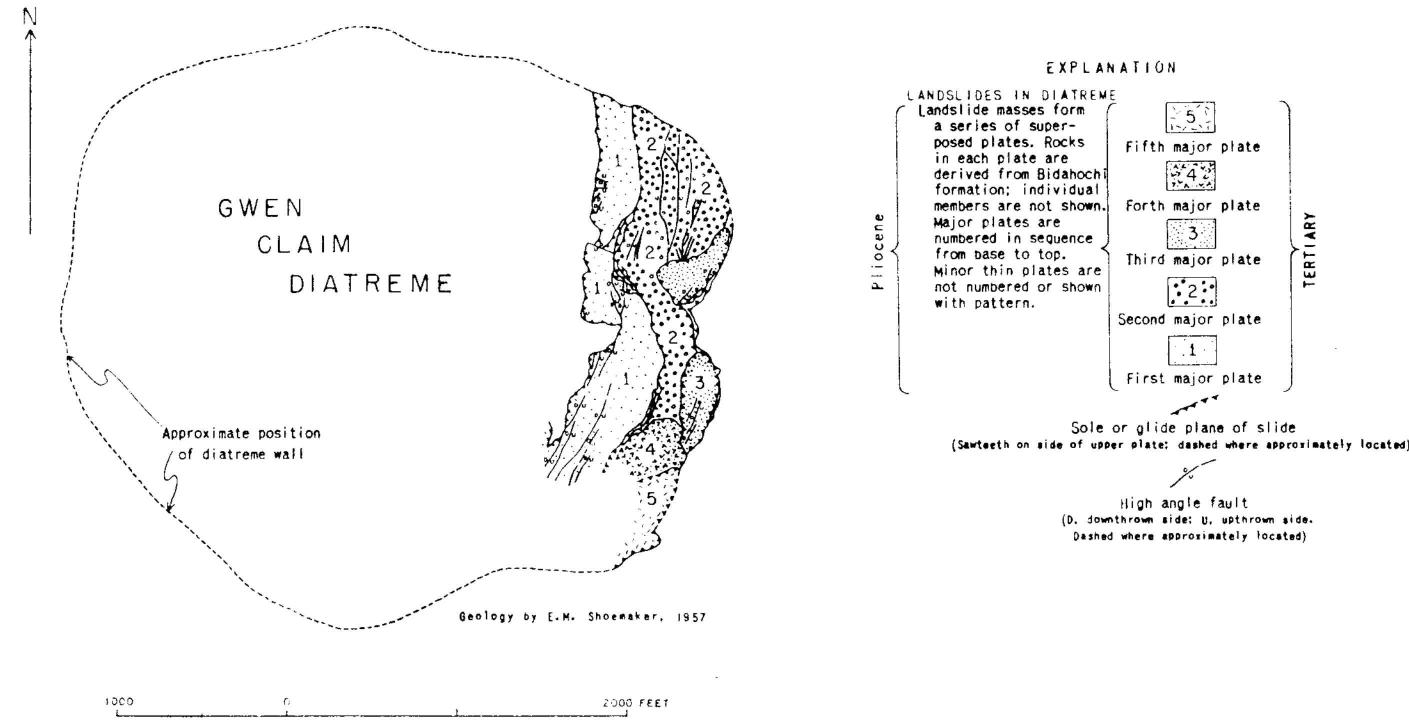

Figure 8. Geologic map of part of the diatreme at the Gwen claim

One of the few maars observed in eruption is the Nilahue maar, opened in the Riñinahue volcanic field of southern Chile during the summer of 1955 (Müller and Veyl, 1957). The entire eruptive history at Nilahue spanned about 3½ months. The initial volcanic activity consisted of violent gaseous discharges for about 20–30 minutes interrupted by periods of quiescence. The periods of gas discharges and intervening quiescent intervals gradually became longer. Ejecta, mainly new lava and subordinate pieces of older rock, were carried to heights of about 5–8 km by the gas discharges and showered down over an area extending more than 200 km from the volcano. The stratigraphic relations of the ejecta from the Hopi Buttes diatremes suggest that most of them were similarly short-lived.

Steam clearly plays an important role in the formation of some maars, but the source of the water and the steps in its transformation to the gas phase are not evident in every case. Some volcanologists (Stearns and Vaksvik, 1935, p. 15–16) have emphasized the importance of ground water in maar formation. There seem to be strong reasons to believe that ground water has played the key role in rare "explosive" eruptions at Kilauea, Hawaii (Jagger and Finch, 1924; Stearns, 1925), and possibly in the formation of Hawaiian maars or tuff rings and in other unusual eruptions as at Tarawera, New Zealand, in 1886 (Smith, 1887; Thomas, 1888). On the other hand many maars, such as those of the Hopi Buttes and the Eifel and the classical diatremes of Fife and the Schwabian Alb, are associated with alkalic basalts characteristically rich in water and other volatile rock constituents. The monchiquite, minette, and kimberlite associated with the diatremes of the Navajo Reservation generally contain more than ordinary amounts of water as compared with common basaltic rocks (Williams, 1936, p. 166; Allen and Balk, 1954, p. 102–103). The gas phase may have been derived chiefly, if not entirely, from the basaltic magma. The distribution of crystalline rock fragments among the different diatremes of the Navajo Reservation can be readily explained if the gases given off are assumed to be juvenile constituents of the magmas.

The initial stages of opening of a diatreme of the Hopi Buttes type can only be inferred. Suppose that a magma rich in dissolved volatile constituents is ascending through the earth's crust along pre-existing fractures or along new fractures propagated by the intruding magma. Events will be controlled by the vertical pressure gradient in the crust, which in turn is a direct function of the superincumbent load of rocks. For simplicity of discussion the rock pressure will be taken to be hydrostatic. The ascending magma ultimately reaches a level where the rock pressure is equal to the partial vapor pressure of the magma. Unmixing or boiling of gas should begin in the magma intruded above this level.

One of the mechanical properties of rocks important to the next stage of the opening of the diatreme is very low tensile strength. Tensile fractures may be propagated in rocks by fluids moving along them under pressures only slightly exceeding, or in some cases even less than, the lithostatic or overburden pressure (Odé, 1956; Hubbert and Willis, 1957). This fact is well known from the practice of hydraulic fracturing to increase oil recovery in certain oil-well operations. Depending on the supply and viscosity of the fluid, the fractures may be propagated very rapidly. If sufficient gas were evolved from a boiling magma to transmit pressure from the magma to the overlying regions of lower rock pressure, a fracture could be propagated up the lithostatic pressure gradient to the surface. Through this fracture the gas could then escape. During initial propagation there is a slight overpressure on the walls which forces them apart, but once the fracture is opened to the point where the gas begins to move along it at appreciable velocity, there will be a drop of pressure from the rock in the wall to the moving fluid.

If the gas is drained rapidly away up the fracture, the pressure on the upper surface of the magma, or at the level where froth or bubbles are beginning to form, will drop. A decompressional wave will therefore be propagated down the column of magma which will permit boiling in a lower level in the magma column. If the gas unmixes sufficiently rapidly so that the formation of bubbles keeps pace with the wave front, the conditions of wave propagation would be somewhat analogous to those for deflagration waves in burning gases. Material would be accelerated upward in the direction opposite the propagation direction of the decompressional wave at a velocity governed by the pressure difference across the wave front. Boiling could descend to the depth where the pressure on the low-pressure side of the wave front just equals the vapor pressure of the magma. The physical condition of the material on the low-pressure side of the wave front would be complex and probably would change rapidly as it moves up the vent. The bubbles would expand as the froth moves into regions of ever-decreasing pressure, ultimately coalescing to form a gaseous continuum with entrained bits of partly degassed magma (Verhoogen, 1951).

Decompressional waves would also be propagated into the walls of the fracture and the walls of the boiling part of the magma column, permitting rock to spall and become entrained in the moving gas-liquid system. As pointed out by Reynolds (1954), the entire gas-liquid-solid melange can be described as a complex fluidized system (Matheson and others, 1949). Intricate mixing, rounding, and polishing of debris derived from depth, particularly in some of the kimberlite-filled diatremes in the northern part of the Navajo Reservation (Malde, 1954; Shoemaker and Moore, 1956), suggest fluidization. Depending on the velocity and density of the system, individual particles and fragments may rise, sink, or maintain their level in the vent. Some initial widening of the vent probably takes place by simple abrasion of the walls by the entrained debris, but spalling (plucking) is probably the main process that opens the fracture along a channel which soon localizes most of the flow. At great depth the spalling may be sudden and violent, as in the case of rock bursts in deep mines, but near the surface it may be a more gentle slumping. Along the length of the channel the pressure drop across the walls tends to be greatest where the channel is narrowest (Venturi effect). By these processes the vent is cored out, perhaps in a fashion similar to the gas coring observed by Perret (1924, p. 62–69) in the 1906 eruption of Vesuvius.

Periodicity in gas discharge, such as was observed at Nilahue, could be due to a number of causes. In the simplest case, a periodic discharge would occur if there were a continuous slow upwelling of magma uniformly charged with dissolved volatiles. Each time the top of the fresh magma reached a certain critical level boiling would begin. The upper part of the column would be removed as a fluidized system, after which the vent would be choked with the unexpelled debris.

Depths from which fragments are derived from the vent walls may be indicative of the depth at which boiling occurred or to which it ultimately descended and, in the general situation where the wall-rock pressure is primarily a function of depth, may be indices of the vapor pressure of the magma. The deepest source of debris in diatremes appears to be correlated with the principal type of eruptive rocks they contain. The kimberlite-bearing diatremes contain a great variety of crystalline rocks from the Precambrian basement complex ranging from granites to highly mafic rock types, but the greatest proportion of the crystalline material consists of mafic rocks, including abundant talc-chlorite schists. In nearby minette-bearing diatremes the principal crystalline rock fragments are granites, also found in the kimberlite. It must be supposed either that the Precambrian at the localities of the kimberlite-bearing diatremes is significantly different from the Precambrian at the localities of the minette-bearing diatremes or that a greater thickness of Precambrian rocks is represented in the debris of the kimberlite vents. As the kimberlite- and minette-bearing diatremes are geographically interspersed over a large part of the Navajo Reservation and, in one area, clustered together with only 2 or 3 miles' separation, the conclusion that the kimberlite contains debris from a greater vertical range seems most probable.

If the serpentine component of the kimberlite has been derived from the mantle, the great variety of crystalline rocks in the kimberlite may represent essentially mixed "cuttings" or samples of the entire crust, estimated to be about 20 miles thick under the Colorado Plateau by the seismic-refraction method (Tatel and Tuve, 1955) and about 30 miles thick from the phase velocity of Rayleigh waves (Ewing and Press, 1959, p. 238). In the minette-bearing vents, boiling apparently descended at least to the level of Precambrian rocks, generally more than a mile deep, and in many places may have descended several miles into the crust.

In the monchiquite-bearing Hopi Buttes diatremes, few Precambrian fragments are found in the pyroclastic ejecta of the diatremes, and only a few rock types, principally a red miarolitic granophyric granite, are represented. The depth to the top of the Precambrian is about a mile; the red granite has been encountered in drilling directly beneath Paleozoic sedimentary rocks. The vapor pressure of the monchiquitic magma is inferred to have been generally less, perhaps much less than that of the minette magmas and the kimberlite.

As noted by Williams (1936, p. 118) and by Hack (1942a, p. 367) the Hopi Buttes diatremes tend to be arranged in northwest-southeast lines. In many places narrow dikes are associated with the diatremes, and they almost invariably exhibit this same alignment, which presumably reflects the position and trend of fractures in the Precambrian basement along which the monchiquite magma ascended from greater depth. The alignment is also the prevailing trend of groups of diatremes and associated dikes elsewhere on the Navajo Reservation. Other structures observable in the pre-volcanic rocks of the region are generally diversely oriented. It therefore seems more likely that the trend of the fractures may have been governed primarily by regional tectonic stresses at the time of intrusion over a large segment of the Colorado Plateau, rather than by local pre-existing structures in the Precambrian rocks. In this case, most of the fractures may have been propagated by the intruding magma.

The deposits filling a great majority of diatremes in the Hopi Buttes show evidence of subsidence, a feature first noted by Williams (1936, p. 120–121), who referred to a diatreme southwest of Indian Wells as a cauldron subsidence. Hack (1942a, p. 351–365, 367–369) called attention to the widespread evidence of subsidence, evidence which led Hager (1948, p. 17–18) to interpret some of the structures entirely in terms of subsidence and sink holes. A very steep inward dip of thick sections of tuff filling some vents indicates subsidence or withdrawal measurable in hundreds, and in some cases perhaps thousands, of feet. The upper widely flaring part of the funnel of the Hopi Buttes diatremes can be shown in many places to have developed by inward sliding of the vent walls. Commonly the original ashy maar rim was almost or entirely engulfed by collapse of the walls. Not only are beds deposited both in and out of the vents involved but also great slabs of the country rock.

Undoubtedly some subsidence or collapse could and probably did occur during and perhaps immediately following explosive drilling of the vent, as described by Perret (1924, p. 66, 113–118) for the 1906 eruption of Vesuvius. The demonstrable subsidence in most of the diatremes, however, occurred some time after the explosive activity and, in many cases, took place more or less synchronously with the sedimentary filling of the vent. Collapse of the walls and engulfment of the maar rim, which seemingly postdates the eruptive activity, also occurred at the modern maar-type craters of Kilborne Hole and Zuñi Salt Lake in New Mexico (Reiche, 1940).

Explanations advanced for the subsidence in the diatremes of the Navajo Reservation include (1) withdrawal or contraction of molten material at depth (Williams, 1936, p. 121; Hack, 1942a, p. 369) because of transfer of gas or magma to another diatreme or another fracture, or possibly because of cooling; (2) solution of underlying limestone (Hager, 1948, p. 17); and (3) compaction of an originally gas-charged ash (Allen and Balk, 1954, p. 110–111). As subsidence is such a prevalent feature of the diatremes, not only in the Hopi Buttes, but elsewhere on the Navajo Reservation (Shoemaker, 1953; 1956b, p. 182), the cause or causes of subsidence are probably inherent in the general volcanic process.

The most likely general cause of subsidence would seem to be the foundering of the surficial filling of the vents into underlying columns of still liquid magma. Stoping and assimilation of the near-surface pyroclastic debris by the underlying magma colum may have been facilitated by convection in the magma column

(McBirney, 1959). Impregnation and digestion of the porous pyroclastic material by the magma would result in a net volume decrease of the total mass of material filling the vent, and, in some places where the lava later welled out on the surface, the underlying magma may simply have been displaced upward.

In many diatremes the structural and sedimentary evolution of the vent culminated in the relatively quiescent extrusion of lava that formed a broad dome capping the diatreme and that in some places flowed out onto the surrounding plain. Some of the flows emerged from the diatremes as sills that cut across the diatreme wall into the surrounding pre-"White Cone" or "White Cone" strata and gradually rose through the stratigraphic section until they emerged at the pre-flow surface. Such flows tended to float large blocks of Bidahoci rocks that are now found embedded in the flows far from their original position. In other vents the lava simply welled up in the crater and spilled over the maar rim. Where the maar rim was not engulfed by subsidence, a layer of agglomerate is commonly observed that rises up the steep inner slope of the tuff rim and may be traced over the top and down the gentle exterior slope. In many vents a great thickness of agglomerate accumulated within the crater and was later injected by the upwelling lava.

The agglomerate is interpreted as the product of fire fountaining of the lava as it reached the surface. Locally, spindle-shaped bombs are well preserved, but more commonly the bombs are drawn out or have merged with one another on compaction and welding of the agglomerate. As the bombs are generally slightly to moderately vesicular, the lava must have been slightly charged with gas, but it was not explosive in the sense that it disintegrated, as did the magma that formed most of the tuffs. Probably either part of the lava column under the vents became degassed during the explosive phase of activity, and perhaps partly during subsequent collapse and sedimentation, or only the upper parts of the column were originally saturated with volatiles, a condition of magma chambers that has been pointed out by Kennedy (1955), among others. In the latter case, the lava that ultimately reached the surface would represent the lower part of the magma filling of deep-seated fractures or perhaps new magma from a still deeper reservoir.

Diatremes apparently fed by the same fissure may show diverse histories and can be shown to have reached different stages of development at the same time. The diatreme at the Hoskietso claim, for example, had reached a stage of slow sedimentary infilling, perhaps preceded or accompanied by considerable subsidence, at the same time that the adjacent vent was still in a mildly explosive stage. Indeed, the adjacent vent on the southeast side (Fig. 4) appears never to have progressed beyond this stage. It may be a representative example of a "gas-cored" tuff-filled pipe relatively unmodified by later collapse and infilling or major upwelling of lava. The history of development of paired diatremes, such as at the Hoskietso claim, poses limitations on how much of the sequence of diatreme evolution can be ascribed to changing conditions of the magma at depth.

URANIUM DEPOSITS

Many diatremes in the Hopi Buttes area contain low-grade deposits of uranium, and the known occurrences of rocks mineralized with uranium are restricted to the diatremes (Shoemaker, 1956b). Uranium is further restricted chiefly to the diatremes that contain bedded carbonate rocks; no deposits have been found in diatremes that are filled only with agglomerate and intrusive or extrusive monchiquite. Uranium is widespread in the carbonate rocks and occurs locally in the fine-grained nonvolcanic clastic rocks, in the tuffs, and in fragments of sedimentary rocks derived from the walls of the vents or in the walls.

Most beds of carbonate rocks exposed in the diatremes are slightly radioactive, either locally or throughout most of their outcrop, but no ore-grade deposits of uranium have been found in a carbonate host. Generally, the carbonate rocks contain only a few thousandths of a per cent uranium.

The carbonate rocks contain variable proportions of calcium and magnesium as well as insoluble clastic fractions, chiefly quartz and subordinate amounts of volcanic debris. Compared with Paleozoic and Mesozoic limestones of the Colorado Plateau, which are chiefly of marine origin, the carbonate rocks deposited in the Hopi Buttes diatremes are strikingly richer in sodium and tend to have higher concentrations of strontium, vanadium, copper, nickel, and cobalt, as well as of uranium and molybdenum (Shoemaker, 1956a, p. 81–84). In addition, the carbonate rocks of the diatremes contain, on the average, about five times as much phosphorus as the average limestone and significantly more arsenic and selenium. Part of these differences may be due to contamination of the carbonate rocks of the diatremes by limburgite detritus, but vanadium, copper, nickel, and cobalt are independent of the insoluble detrital fraction in their distribution and are largely soluble with a hot citric acid leach. Only molybdenum has been found to have a definite correlation with uranium (Shoemaker, 1956a, p. 81, 84).

It is suspected that most of the carbonate rocks have been derived in part by evaporation of thermal solutions, in which case some of them may be referred to as travertine. No structures indicative of terrace-forming travertine have been observed, however, perhaps partly because of post-depositional deformation that could have obscured delicate structural features. Algal structures are found in some carbonate beds, and, in one locality, a thin carbonate bed contains well-preserved fossil fish. Most of the elements studied that are present in unusual concentrations in the carbonate rocks are also relatively abundant in the monchiquite and limburgite (Shoemaker, 1955), p. 83–85; 1956b, p. 183). A genetic relation between the solutions from which the carbonate rocks were formed and the igneous rocks seems likely. The solutions might have been derived from the magma degassing at depth or during crystallization of the magma or perhaps by deuteric alteration of the crystallized rock.

About one-third of the diatremes in the central part of the Hopi Buttes contain exposed carbonate rocks and probably more than half the vents contain carbonate rocks either exposed or at depth. The presence of carbonate rock in a vent can probably be considered only a very broad guide to uranium deposits.

The highest concentrations of uranium discovered to date are found mainly in fine-grained clastic sedimentary rocks and lapilli tuff in three general types of structural setting: (1) at unconformities within the diatremes, (2) at the vent walls of the diatremes, and (3) enclosing beds of coarse breccia.

A good example of uranium localized at an unconformity is found at the Morale claim. A cavernous carbonate bed that caps a butte underlain by the diatreme is slightly uraniferous in most places (Lowell, 1956), but mineralized rock of ore grade appears to be restricted to the first three beds above the unconformity between sediments laid down in the vent and slumped debris from the maar rim. Where mined, the first three beds above the unconformity include, in ascending order, a laminated siltstone, a lapilli tuff, and a second laminated siltstone. The radioactivity decreases progressively upward in this sequence. Within a few feet of the contact, blocks of tuff from the maar rim or "White Cone" member in the chaotic debris beneath the unconformity are also mineralized.

Ore-grade rock occurs where the beds above the unconformity are sharply flexed (Fig. 9). In detail, the most radioactive rocks are on the crests and flanks of small anticlinal folds generally localized over large blocks in the underlying slump debris that project above the general surface of the unconformity. The ore-bearing beds not only are folded over these projecting blocks but also thin or pinch out against the blocks (Fig. 10). In general it is at the points of greatest thinning that the beds are most radioactive. At least a part of the pinching of the beds is post-depositional and is apparently due to renewed movement in the slump debris and jostling of the blocks, some of which protruded into the overlying sedimentary rocks. Production records of the U. S. Atomic Energy Commission, Grand Junction, Colorado, show that the tenor of the material mined ranges from 0.10 per cent U_3O_8 to 0.18 per cent U_3O_8 in truckload lots and averages 0.15 per cent for 186 tons. Selected grab samples taken from the thinnest parts of the host beds contain as much as 0.40 to 0.50 per cent U_3O_8. The mineralogy of the uranium has not yet been determined.

An example of uranium localized at a vent wall may be found at the Roanhorse diatreme. Most of the carbonate rock exposed in the vent is radioactive. Beds of limburgite tuff in the vent are truncated against the ridges of huge mullion-like structures in the vent wall. Uranium occurs along the wall of the vent in beds both inside and outside of the vent. The most radioactive rocks occur near the crests of the mullion-like ridges where beds inside the vent are pinched or truncated by the vent wall (Fig. 11). In some of these places uranium is dispersed in small amounts for a few feet outward into rocks outside the vent.

At the Hoskietso claim (Fig. 3), the mineralized rocks are in or closely associated with the persistent bed of sedimentary breccia. Both the tuff matrix of the breccia and parts of the blocks of Wingate Sandstone are weakly mineralized. Laminated siltstone immediately overlying the breccia is also locally mineral-

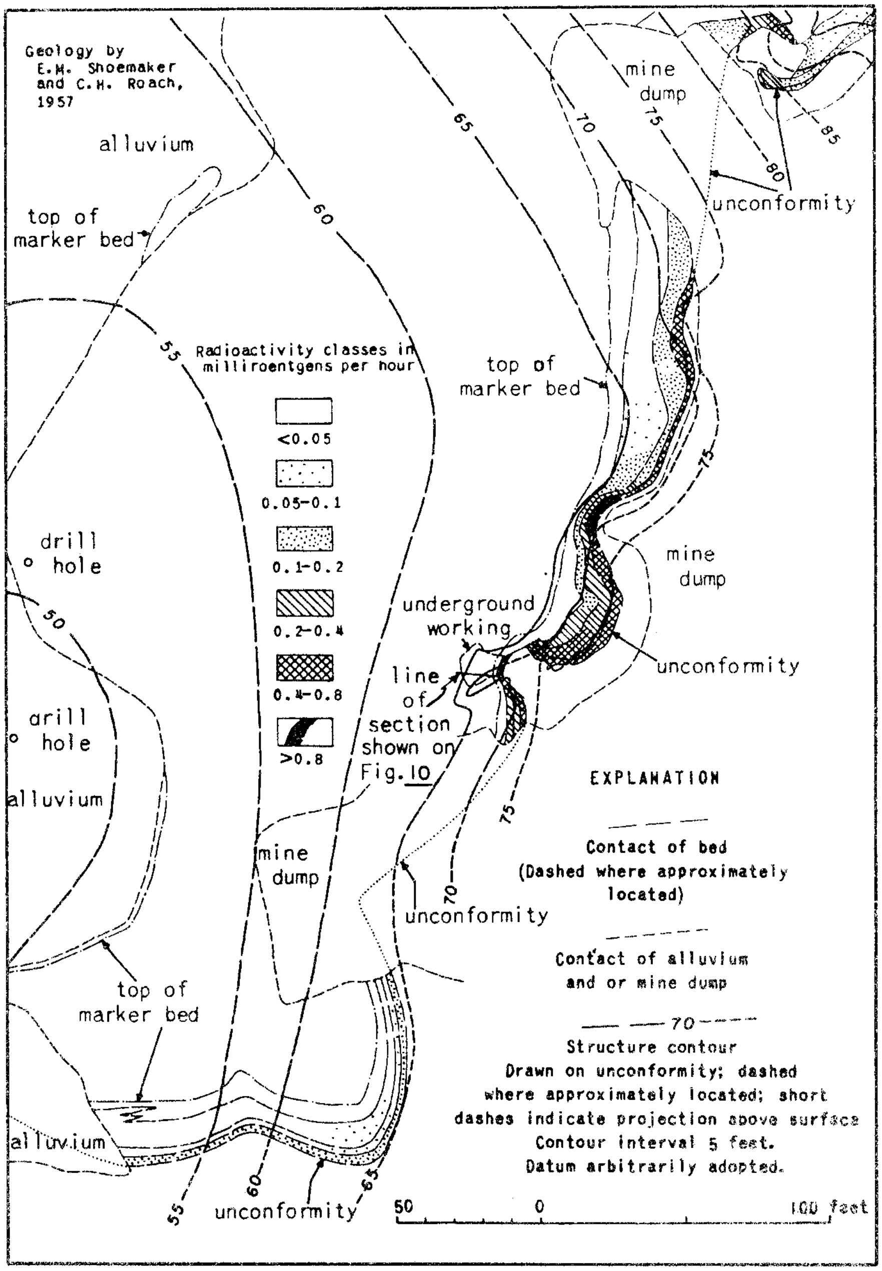

Figure 9. Map of part of Morale claim showing configuration of unconformity and radioactivity of first three beds above unconformity

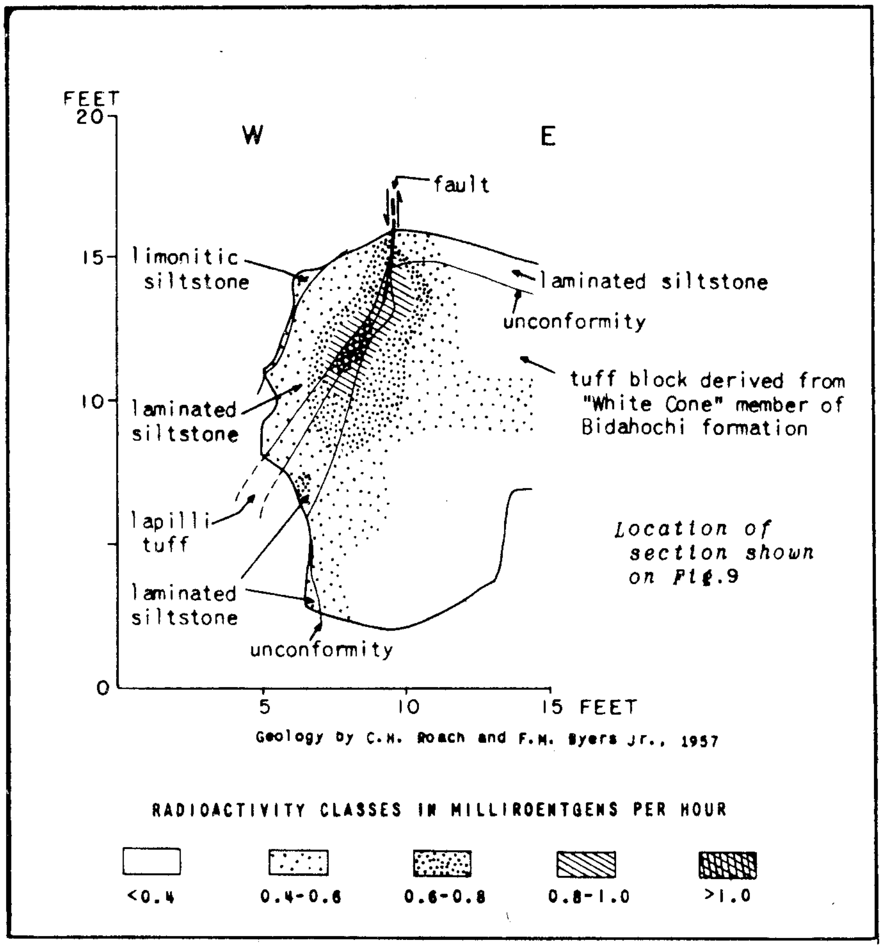

Figure 10. Long wall section in mine at Morale claim showing distribution of radioactivity

ized, and a claystone lens is weakly mineralized where it overlaps the breccia toward the east margin of the vent. As in most diatremes, the uranium-bearing rock is generally low grade, and uranium minerals, with one exception, are not visible. Some schroeckingerite was observed in a small prospect pit near the northern edge of the mineralized area.

The widespread radioactivity in the carbonate rocks of the Hopi Buttes diatremes suggests that the uranium may be at least in part syngenetic, possibly precipitated with the carbonate material as a result of evaporation of carbonated water that emerged at the surface or along the floors of the crater lakes as hot springs in the vents. The highest concentrations of uranium, on the other hand, occur in the clastic rocks in the diatremes where the distribution of uranium is related to structures that would have influenced the flow of solutions. Emplacement of uranium in these clastic rocks is probably largely epigenetic,

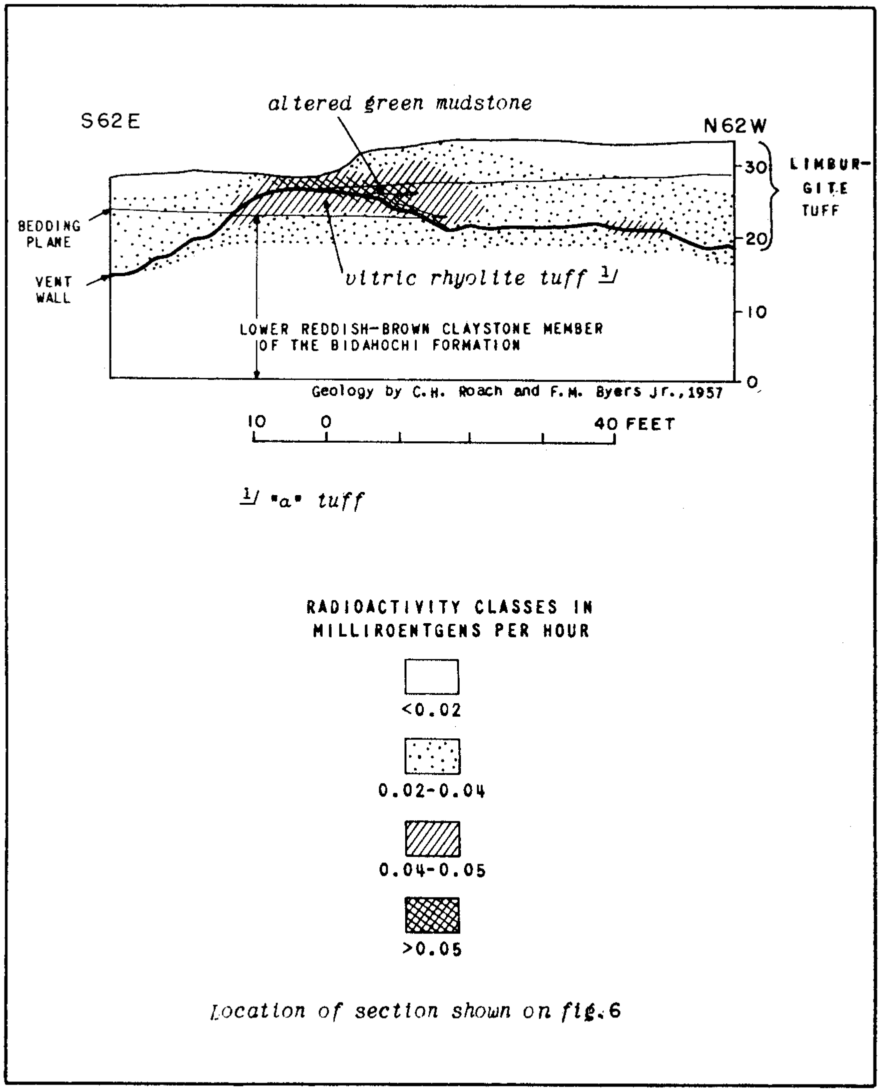

Figure 11. Cross section of part of vent wall of Roanhorse diatreme, showing distribution of radioactivity projected from outcrop

because many of the structures associated with the highest concentrations of uranium are at least partly post-depositional in origin. Structures that involve the lateral or up-dip thinning or truncation of beds appear to be among those especially favorable for the location of rocks containing most uranium.

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