Quaternary basalt fields of west-central New Mexico: McCartys pahoehoe flow, Zuni Canyon aa flow, Zuni Ice Cave, Bandera Crater, and Zuni Salt Lake maar

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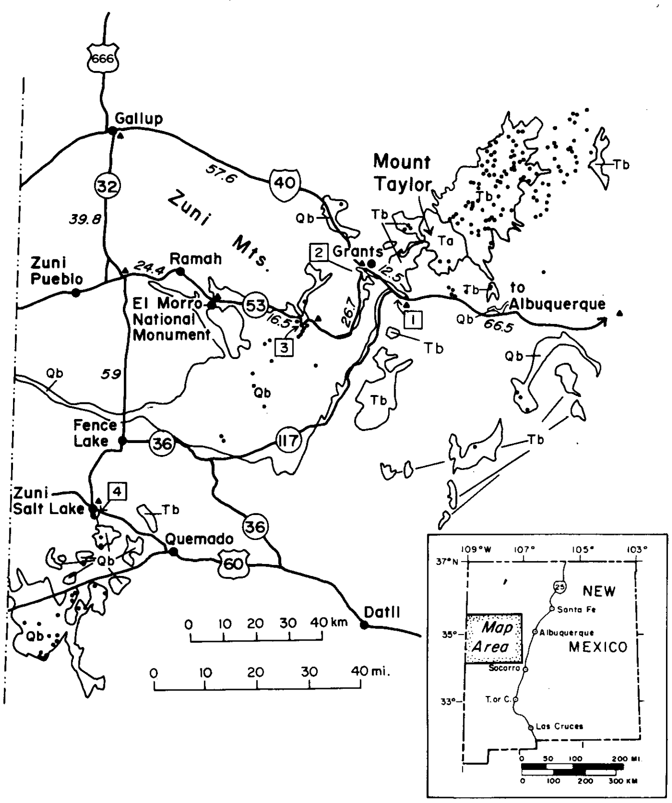

Figure 1. Mount Taylor–Zuni–Zuni Salt Lake volcanic field, west-central New Mexico. Ta, Pliocene andesite, dacite, and trachyte; Tb, Pliocene basalt; Qb, Quaternary basalt. Numbers in squares indicate sites described in this paper. 1, McCartys flow; 2, Zuni Canyon flow; 3, Zuni Ice Cave and Bandera Crater; 4, Zuni Salt Lake. Distances are in miles.

INTRODUCTION

The U.S. Geological Survey was only five years old when its director, John Wesley Powell, approved Captain Clarence Dutton's plan for one field season on Mount Taylor and the Zuni Plateau (Fig. 1). Dutton's description of west-central New Mexico, published in 1885 as part of the U.S. Geological Survey's 6th Annual Report, has become a geologic classic, not only for its lucid literary style but also because it laid the foundation of basic geologic concepts. In his account of erosion and uplift, the reader can discern the germ of ideas that would lead Dutton within four years, to the principle of isostasy. In a discussion of mountain building, he contrasted compressional fold belts, such as the Alps and Appalachians, with mountains of western interior North America, in which vertical uplift and rifting had been the principal forces. Finally, he pondered the significance of the great volcanic fields that nearly encircle the Colorado Plateau.

In the Mount Taylor–Zuni area, Dutton recorded a history of volcanism from late Tertiary to late prehistoric time. Basalt predominates; the youngest lavas issued from cones that are still well preserved, and the lava flowed down modern valleys. Older lavas cap mesas (in general, the higher the mesa, the older the cap; see Fig. 2), and many of their vents have been reduced to volcanic necks. There are dozens of small basalt volcanoes in various stages of preservation as well as one large central volcano (Mt. Taylor, elevation 11,389 ft; 3472 m) of more varied composition, including alkali basalt, andesite, dacite, trachyte, and rhyolite. Radiometric and archaeological dates now bracket volcanism between 4.4 Ma (Pliocene) and AD 700, with a probable peak between 3.0 and 2.5 Ma (Lipman and Mehnert, 1980; Nichols, 1946). All Pliocene basalts are alkalic; Quaternary basalts include both tholeiite and alkali basalt.

This guide describes three of the youngest, best preserved, and most accessible volcanic features of the Mount Taylor–Zuni field: (1) the contrast between the Holocene Zuni Canyon aa and McCartys pahoehoe flows, (2) Bandera crater, a Holocene cinder cone of alkali basalt, with bombs cored by ultramafic nodules, and a pahoehoe flow honeycombed by lava tubes and tunnels, and (3) Zuni Salt Lake, a late Pleistocene maar crater and cinder-cone cluster flooded with salt water.

In recent decades, all three localities have been examined closely by students of comparative planetology. The late Gerard Kuiper, Chief Scientist of Ranger (the first unmanned mission to the moon), was much impressed with similarities between collapse depressions on the McCartys flow and small craters in the dark lunar maria ("seas") and between collapsed lava tunnels of the Bandera area and sinuous rilles of the moon. The Hadley Rille, a steep-sided meandering valley, was visited by Apollo 15 in 1971. Eugene M. Shoemaker, founder and first chief of the U.S. Geological Survey Branch of Astrogeologic Studies, compared lunar craters with the Zuni Salt Lake maar and Meteor Crater, Arizona.

The area holds great beauty and historical interest. Visitors driving along New Mexico 53 should leave time to see El Morro National Monument (where Spanish conquistadores and American pioneers carved their names into a great cliff of Jurassic Zuni Sandstone) and Zuni Pueblo, already ancient when first seen by Spaniards searching for the Seven Cities of Cíbola, three generations before the Pilgrims landed at Plymouth Rock.

Guidebooks 10 (1959) and 18 (1967) of the New Mexico

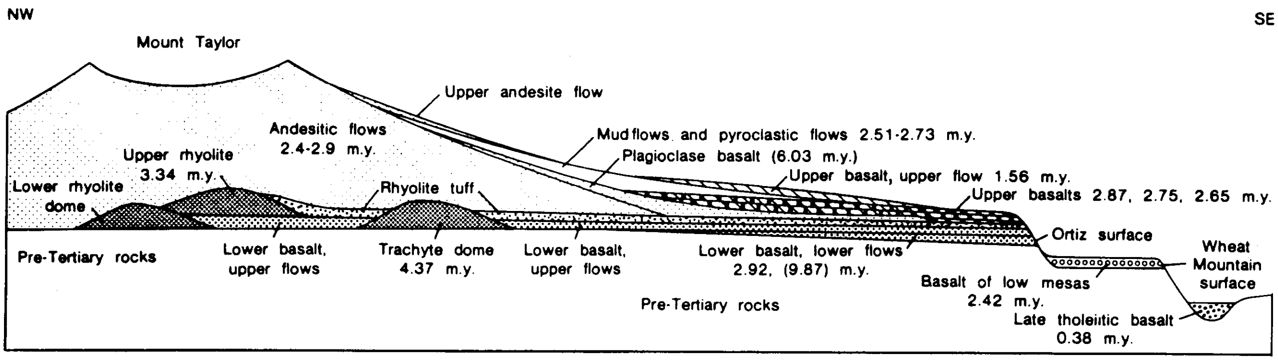

Figure 2. Diagrammatic representation of age relations between volcanic units dated by K-Ar, south side of Mount Taylor. Unreliable ages are in parentheses. From Lipman and Mehnert (1980).

Geological Society are compendia of the geology, anthropology, and history of the region; both contain detailed geologic road logs. The Society's 1:1,000,000 Highway Geologic Map (1982) provides a wealth of information. For the casual tourist, *Southern Zuni Mountains* by R. W. Foster (Scenic Trips to the Geologic Past No. 4, New Mexico Bureau of Mines and Mineral Resources, 1971) is recommended for the stretch between Grants and Gallup via New Mexico 53 and 32. These publications can be obtained from the New Mexico Bureau of Mines and Mineral Resources, Campus Station, Socorro, NM 87801, (505) 835-5410.

AA AND PAHOEHOE: ZUNI CANYON AND McCARTYS BASALT FLOWS

Clarence Dutton, who had studied volcanoes of the Cascade Range and Hawaii before coming to New Mexico, found Mount Taylor uninteresting; a modern geologist might wonder how so large a volume of intermediate-composition magma originated 600 mi (1,000 km) from a plate margin and 28 m.y. after subduction had ceased. Dutton was more impressed with the similarities between the basalt flows of New Mexico and Hawaii. The McCartys flow, 12 mi (20 km) east of Grants, New Mexico, is typical *pahoehoe* (a term coined by Dutton); its ropy surface formed as slowly moving viscous lava congealed. A typical *aa* flow can be seen at San Rafael, along New Mexico 53, 1.2 mi (2 km) south of Grants, where the Zuni Canyon alkali basalt flow debouched from a narrow canyon. Its rubbly top formed when the crust of the rapidly moving flow broke up. In Zuni Canyon, most of the flow is covered, but remnants can be seen as a "bath-tub ring" on the canyon walls.

The primary features of the McCartys pahoehoe flow can be seen in rest areas on both sides of I-40, about 66.5 mi (107 km) west of the intersection of I-40 and I-25 in Albuquerque (Fig. 1). The rest areas are in the terminal segment of the flow, an olivine tholeiite that flowed from a small cone about 25 mi (40 km) south of I-40. The main part of the flow can be seen along New Mexico 117. Just south of I-40, a tongue flowed through a narrow constriction and then turned sharply east for its last 6 mi (10 km), following the valley of the Rio San José. The river was partly dammed and the area is swampy, even though precipitation is only 10 in. (25 cm) per year. Indian potsherds of Pueblo I period, AD 700–900, have been found buried beneath 4 ft (1.2 m) of the youngest valley fill, 17 mi (27 km) east of the terminus of the McCartys flow. Nichols (1946) correlated this valley fill with material beneath the McCartys flow.

The primary features of the McCartys flow were described in numerous publications by R. C. Nichols, especially Nichols (1946). In addition to the ropy surfaces characteristic of pahoehoe lavas, the flow is characterized by pressure ridges, collapse depressions, and minor features such as spatter cones, squeeze-ups, cavities, grooved lava, tree molds, cracks, and banded lava. Longitudinal and transverse pressure ridges abound in the last mile (1.6 km) above the terminus, which includes the rest areas. They surround a general collapse area (Fig. 3) formerly a dome 27 ft (8 m) high (Nichols, 1946). After a crust 6–9 ft (2–3 m) thick had formed, lava drained from the dome, and pressure ridges formed by lateral compression, sliding, and hydrostatic pressure. The next 2 mi (3.2 km) above the terminus are characterized by numerous collapse depressions, formed when liquid lava drained out from lava tubes beneath a solidified crust. The

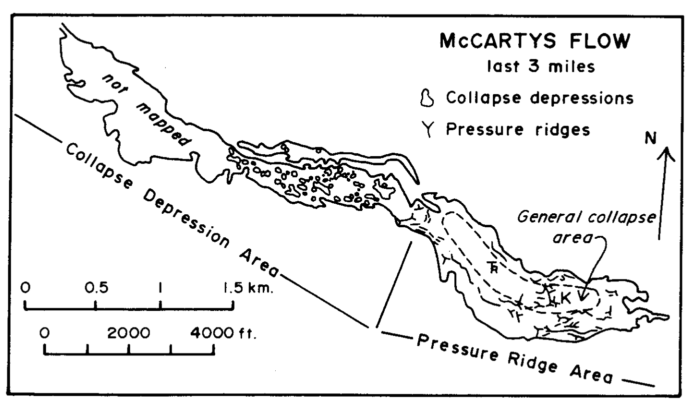

Figure 3. Distribution of collapse depressions and pressure ridges, terminus of McCartys flow. From Nichols (1946).

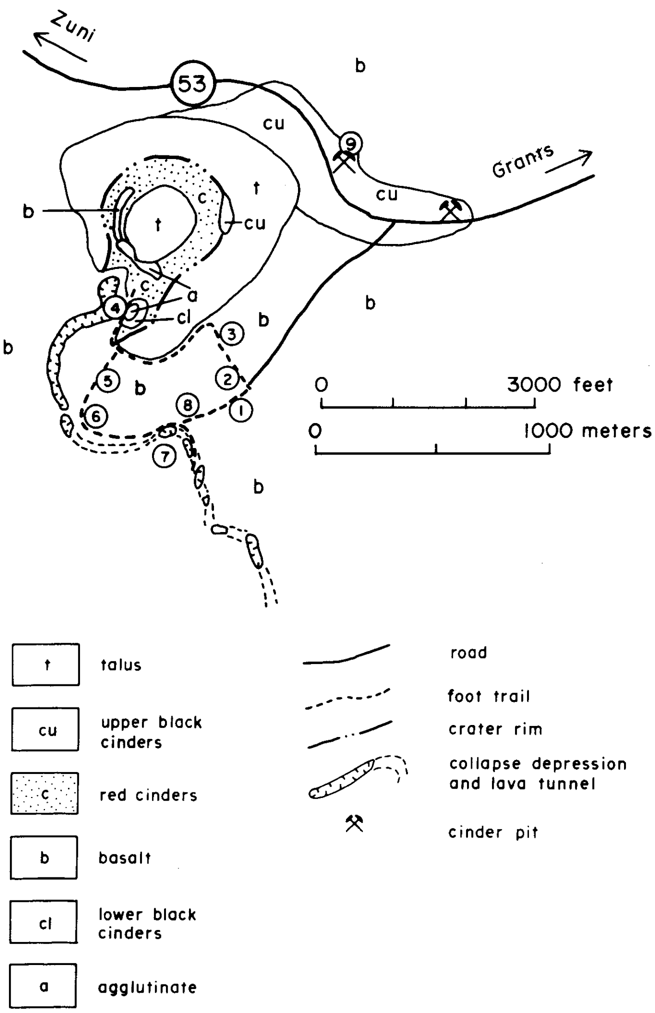

Figure 4. Geologic sketch map of Bandera Crater and Zuni Ice Cave, adapted from J. D. Causey, unpublished M.S. thesis, University of New Mexico (1971). 1, parking area; 2, tree molds; 3, hornito; 4, (heading into the crater breach) spatter (agglutinate) rampart on right, drained lava lake and head of channel-tunnel system on left; 5, aa; 6, pahoehoe with ropy surface, pressure ridges, lava tubes, collapse depressions; 7, ice cave.

surface of the flow is highly irregular; ridges and valleys tend to be parallel to flow direction.

The McCartys flow is an olivine tholeiite (XRF analysis, in weight percent, by J. Renault, New Mexico Bureau of Mines and Mineral Resources: SiO_2 = 49.93, TiO_2 = 1.38, Al_2O_3 = 16.62, Fe_2O_3 = 1.54, FeO = 9.25, MnO = 0.17, MgO = 8.45, CaO = 8.90, Na_2O = 2.89, K_2O = 0.75, P_2O_5 = 0.25). It has phenocrysts of olivine and ophitic clinopyroxene to 2 mm and plagioclase to 1 mm in a matrix of clinopyroxene, plagioclase, and opaque oxides. Embayed quartz grains may be xenocrysts.

BANDERA CRATER AND ZUNI ICE CAVE

Travelers crossing western New Mexico on a hot summer day might be surprised to learn that billboards advertising a perpetual ice cave refer to a real geologic phenomenon, not a tourist trap. Zuni Ice Cave is the most accessible of numerous lava tunnels in the Zuni volcanic field; several of them are partly filled with ice. Alkali basalt lava that once flowed through the tunnel originated at Bandera Crater, one of the youngest cinder cones in the southwestern United States (Fig. 4). The rim of Bandera Crater stands 430 ft (130 m) above the surrounding country; the central crater is 650 ft (200 m) deep. Bandera Crater and Zuni Ice Cave have long been owned and maintained by the David Candelaria family (phone 505/783-4303) and are open daily from 8:00 a.m. to one-half hour before sunset. They can be reached via a short (0.6 mi or 1.0 km) side road off the south side of New Mexico 53, 25.2 mi (40.3 km) from its intersection with I-40 in Grants (Fig. 1). In 1985, admission was $3.50 for adults and $1.75 for children aged 5 to 11 years. Bandera Crater straddles the Continental Divide and is surrounded by ponderosa forests at an elevation of 7,900 ft (2400 m). In winter, cold weather and snow are common. Trails rise about 120 ft (35 m) over 0.5 mi (0.8 km) between the Candelaria trading post and a breach on the southwest side of the crater; after that, they are downhill or level.

There are 74 vents in the Zuni volcanic field, most of them aligned along NE structural trend, parallel to a positive gravity anomaly. The field has erupted between 15 and 30 mi^3 (64 and 123 km^3) of basalt (Ander et al., 1981). Bandera Crater is superimposed on an earlier and smaller crater on its south side. According to an unpublished study by J. D. Causey (University of New Mexico), it probably formed by the following sequence of events: (1) tephra eruption from the small crater; (2) agglutinate eruption from the small crater; (3) major tephra eruption from Bandera Crater; (4) lava eruption in Bandera Crater; (5) eruption of red cinders to form the present cone, cinders have partly fused inclusions of Permian sedimentary rocks; (6) quiescence; and (7) explosive eruption to form a deep crater, ejection of black cinders and alkali basalt bombs with ultramafic inclusions. The general sequence of tephra-lava-tephra is common to many cones in the field. The lava flow that developed during stage 4 breached the cone and covered about 40 mi^2 (100 km^2). Lava ponded just outside the breach and drained through a lava tunnel, 17.9 mi (28.6 km) long. As the tunnel has partly collapsed, much of its course is now marked by depressions and short channels. Ice accumulated in part of the tunnel where air circulated in winter but was stagnant in the summer, because of differences in the angle of incident sunlight (Fig. 5). The ice is layered and colored green by algae. Ice caves exist only in cool climates; at Bluewater, New Mexico (the weather station nearest the Zuni Ice Cave), the mean annual temperature is 47.6°F (8.7°C). The temperature in the ice cave is 31°F (–0.5°C) throughout the year.

The lava flow of stage 4 is an alkali basalt with phenocrysts of olivine (to 3 mm) and plagioclase laths (1 mm). From the degree of weathering, an age of about 10,000 years can be estimated. Along its axis it is typical pahoehoe with the same primary features as the McCartys flow, but it turns into aa along its flanks and blocky lava near its terminus. The black cinders from stage 8

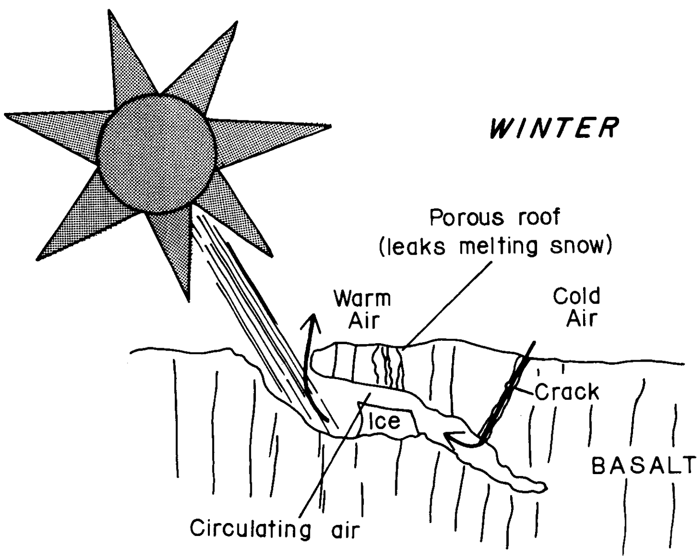

Figure 5. Winter air circulation in Zuni Ice Cave. In summer, the sun's rays are steeper and do not reach the bottom of the cave, where cold air stagnates. Air circulation was determined through smoke experiments by Harrington (1940).

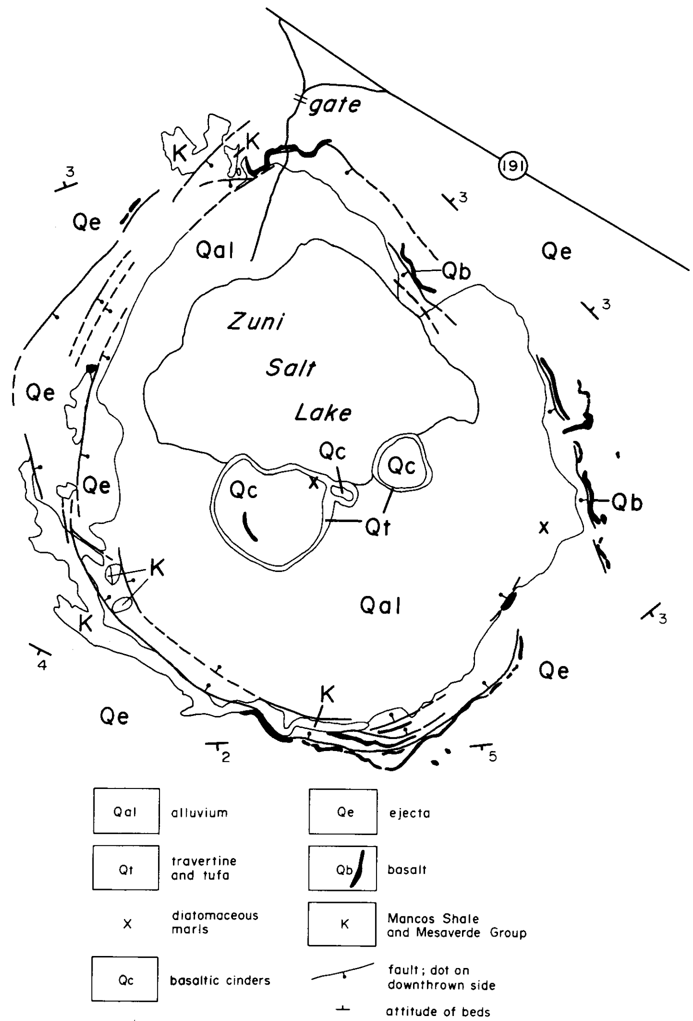

Figure 6. Geologic map of Zuni Salt Lake, from Bradbury (1967) and Cummings (1968).

could be much younger. A Pueblo I stone axe (AD 700–900) was found in a cinder pit by a bulldozer operator, who thought he had uncovered it from beneath the cinders. The possibility that it had fallen to the floor of the pit from above the cinders cannot be ruled out. The state of erosion of Bandera Crater is about the same as at Sunset Crater, Arizona, dated at AD 1065 by the tree-ring method. Bombs found in cinder pits along NM Highway 53 are cored by inclusions of olivine-red spinel lherzolite and pyroxene-green spinel lherzolite, as well as sandstone, shale, anorthoclase crystals, and jasper (Laughlin et al., 1971). The rim around a lherzolite inclusion is a nepheline-normative alkali basalt (analysis by K. Aoki in weight percent: SiO_2 = 44.47, TiO_2 = 3.04, Al_2O_3 = 15.22, Fe_2O_3 = 4.39, FeO = 8.42, Mn = 0.42, MgO = 9.30, CaO = 8.80, Na_2O = 3.38, K_2O = 1.60, H_2O+ = 0.28, H_2O^- = 0.08, P_2O_5 = 0.58). Although the last-stage eruption of Bandera Crater may be close in age to the McCartys flow, the products are chemically quite different.

ZUNI SALT LAKE

In 1598 Don Juan Oñate came to Cibola in search of gold but settled for "unas salinas famosas mejores que Christianos han discobierto" (one of the most noted and best salt pans which Christians have discovered). During hot and dry weather, salt precipitates from Zuni Salt Lake (mean depth 2.8 ft—70 cm), which occupies the northern half of a maar crater, about 1.0 mi (1.6 km) in diameter (Fig. 6). Its maximum salinity reaches 35% by weight, about ten times that of sea water. Actually, there are two salt lakes; a second small saline pool occupies the crater of the largest of three cinder cones that rise from the center of the maar. The archeology, ethnology, limnology, biology, volcanology, and economic geology of Zuni Salt Lake were described by Bradbury (1967); a 1:6,000 geologic map was published by Cummings (1968).

Zuni Salt Lake occupies the best preserved and northernmost member of a NNE-trending belt of maars and cinder cones, about 35 mi (60 km) long and probably controlled by a fracture zone. Elevation of the lake is about 6,215 ft (1895 m). In the surrounding country, outcrops of shale and sandstone of the Upper Cretaceous Mancos and Mesaverde Groups are covered by sparse vegetation.

In general, maar craters form by phreatomagmatic or Surtseyan processes, i.e., repeated steam explosions resulting from interactions between ascending magma and surface water or shallow groundwater. Zuni Salt Lake documents a history of decreasing magma-water interactions. An early Surtseyan stage of nearly continuous phreatomagmatic surges gave way to a Strombolian stage of intermittent explosions (Fig. 7) and a final stage of cinder eruptions, to form the central cones. The particles of Surtseyan

ZUNI SALT LAKE

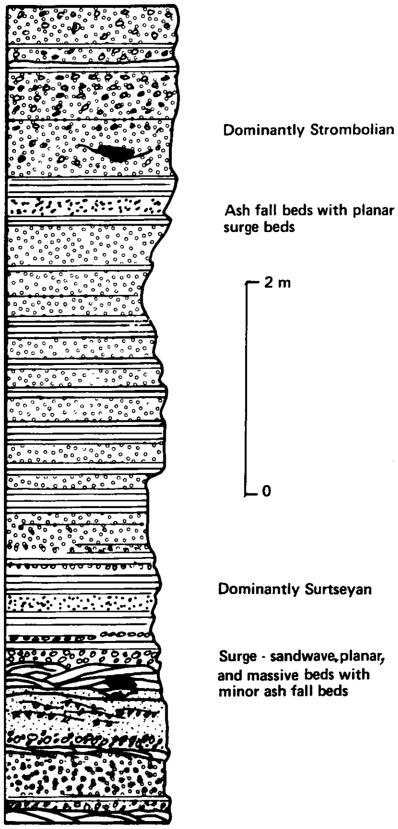

Figure 7. Stratigraphic column of upper third of crater-rim beds of Zuni Salt Lake maar, showing transition from dominantly Surtseyan (phreatomagmatic) eruptions of ash, emplaced in pyroclastic surges, to Strombolian eruptions of ash, lapilli, and scoria falls.

surge deposits were propelled and rapidly transported along the ground in a cushion of turbulent steam. Consequently, they are abraded, fine-grained, and moderately to poorly sorted. During the early high-energy Surtseyan stage, sand-wave and massive surge beds built up a tuff ring. The ash particles are strongly altered to palagonite; accretionary lapilli and armored mudballs are common. During transition to the Strombolian stage, weakening surges deposited their load in planar beds; coarser ash-and-lapilli fall deposits became abundant and mantled the earlier tuff ring. In contrast to the abraded and altered particles of surge deposits, the coarser particles of Strombolian fall deposits are better sorted, angular, glassy (sideromelane), and vesicular. Fine ash was deposited downwind as much as 5 mi (8 km) from Zuni Salt Lake. Large (to 12 in—30 cm) clasts of basalt and pre-volcanic sedimentary rocks were ejected ballistically all during the eruption.

The cause for the decrease in water-magma interaction may have been a basalt ring dike that was emplaced during the eruption. In places, it penetrated to the surface to form spatter and short flows. The ring dike may have progressively sealed rising magma from contact with groundwater.

Subsidence of the Zuni Salt Lake maar occurred during the eruption, as is shown by numerous small faults. At the end of the eruption, the rim of the maar crater stood at an elevation of about 6,500 ft (2,000 m), 100 ft (30 m) above the surrounding country. Its floor was about 400 ft (120 m) below the rim. According to Bradbury (1967), the climate was more humid than at present, and the crater filled to the 6,270-ft (1,910-m) contour with a brackish lake in which diatoms, ostracodes, gastropods, and algae lived. P. E. Damon (University of Arizona) dated ^{14}C from the charophyte *Chara* at 22,900 ±1400 years. The basin partly filled with tufa, marl, sand, gravel, and, as the climate became drier, salt and gypsum. The lake shrank to one-third of its former size, and its brines now only support bacteria, algae, the brine shrimp *Artemia salina,* and the shore fly *Hydropyrus hians.* Salinity varies with evaporation and influx of fresh water; an analysis made in 1935 reported (in ppm) Ca = 345, Mg = 2255, Na = 75,000, K = 498, $CO_3^{=}$ = 46, $(HCO_3)^-$ = 235, $SO_4^{=}$ = 14,650, Cl^- = 113,100, Br^- = 35, total dissolved solids 206,306, specific gravity at 20°C = 1.158. In the small pool in the cinder cone, total dissolved solids were 99,935 ppm (ocean water contains about 35,000 ppm, dissolved solids and the Great Salt Lake 263,000 ppm). All investigators have concluded that Permian evaporite deposits are the source of salt. The fault that controls the Zuni Salt Lake maar may have acted as a conduit for brines.

Indians have obtained salt from Zuni Salt Lake for at least 1000 years. In modern times salt was harvested for cattle feed, water softeners, ice cream makers, metallurgical processes, and highway salting. At present the plant is abandoned. The road leading from the crater rim to the lake is barred for vehicles, but visitors can go on foot. At times of low water, salt-encrusted tumbleweeds, grasshoppers, etc., can be collected along the lakeshore.

REFERENCES CITED

Ander, M. E., Heiken, G., Eichelberger, J., Laughlin, A. W., and Huestis, S., 1981, Geologic and geophysical investigations of the Zuni-Bandera volcanic field, New Mexico: Los Alamos National Laboratory Report LA-8827-MS, 39 p.

Bradbury, J. P., 1967, Origin, paleolimnology and limnology of Zuni Salt Lake maar, west-central New Mexico [Ph.D. thesis]: Albuquerque, University of New Mexico, 247 p.

Cummings, D., 1968, Geologic map of the Zuni Salt Lake volcanic crater, Catron County, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-544, scale 1:6,000.

Harrington, E. R., 1940, Desert ice box: New Mexico Magazine, July 1940, p. 14–15, 45.

Laughlin, A. W., Brookins, D. G., Kudo, A. M., and Causey, J. D., 1971, Chemical and strontium isotopic investigations of ultramafic inclusions and basalt, Bandera Crater, New Mexico: Geochimica et Cosmochimica Acta, v. 35, p. 107–113.

Lipman, P. W., and Mehnert, H. H., 1980, Potassium-argon ages from the Mount Taylor volcanic field, New Mexico: U.S. Geological Survey Professional Paper 1124-B, p. B1–B8.

Nichols, R. C., 1946, McCartys basalt flow, Valencia County, New Mexico: Geological Society of America Bulletin, v. 57, p. 1049–1086.

ACKNOWLEDGMENT

Elston's work was funded by NASA grant NGR 32-004-062.