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Field-trip guide to the geochronology of El Malpais National Monument and the Zuni—Bandera volcanic field, New Mexico

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Unpublished geochemical and geochronological data
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Preface

Much of the land that you will be crossing for the next two days is owned by the Ramah Navajo, Zuni, Laguna, and Acoma tribes, or is under the jurisdiction of the U.S. National Park Service or the Bureau of Land Management. Their permits are required for sample collection.

In this field-trip guide, two abbreviations are used that may not be familiar to the non-geologist: ka represents thousands of years and Ma represents millions of years. Both abbreviations refer to the number of years before the present, which is arbitrarily taken to be 1950 A.D.

Word processing and illustrations were done by Carol White, John Tubb, Eric Montoya, and Anthony Garcia.

Modification of basalt-flow surfaces with increasing age. In the top photograph, the ~3 ka McCartys flow shows essentially no modification, although grasses and small trees are growing on the flow in places. The center photograph shows the Zuni Canyon flow which is constrained in age between the Bandera flow (~11 ka) and the Bluewater flow (57 ka). Eolian soils are accumulating on the surface, particularly on areas of rough aa surfaces. The lower photograph shows the ~115 ka Laguna or El Calderon flow. Soil accumulations are relatively thick on this flow and in many places only the tops of pressure ridges protrude above the soil.

Introduction

This field guide grew out of the 1993 Quaternary Dating Field Conference held in Grants, New Mexico, in April 1993. The Conference, sponsored by the New Mexico Geochronology Research Laboratory and the U.S. National Park Service, was convened to consider using the Zuni—Bandera volcanic field, including El Malpais National Monument and El Malpais National Conservation Area, as a test area for evaluating, calibrating, and improving the application of Quaternary dating techniques. Improvement of the accuracy and precision of these dating techniques is one of the major goals of the New Mexico Geochronology Research Laboratory, which was established in 1992 as a collaborative effort of the New Mexico Bureau of Mines & Mineral Resources, New Mexico Institute of Mining & Technology, and Los Alamos National Laboratory.

The Zuni—Bandera volcanic field is located in west-central New Mexico south of the town of Grants (Fig. 1). It lies near the center of the Jemez zone or lineament that extends at least from central Arizona to northeastern New Mexico. The Jemez lineament is a major flaw in the Earth's crust along which volcanoes have erupted for the past 16 Ma. Approximately 100 volcanoes have been identified in the Zuni—Bandera volcanic field. The youngest volcanic activity along the lineament occurred in the area now encompassed by El Malpais National Monument, where volcanoes have erupted from about 700 to 3 ka. Because of the youthfulness of these lava flows, they are well preserved, providing the Monument visitor with spectacular views of volcanic landforms and the geologist with an ideal area for investigating volcanic processes.

One of the more important aspects of research in the Zuni—Bandera volcanic field is the geochronology of the many volcanic eruptions. Determination of the absolute ages of these basaltic volcanoes is fundamental to other geological, geochemical, and isotopic studies. Although there are several dating techniques that should be applicable to volcanic rocks of this age, their results have rarely been compared in a single area, and, where this has been attempted, they are often not in agreement. The Quaternary Dating Field Conference was convened to address this problem by assembling a group of researchers interested in applying their specific techniques to a common sequence of lava flows with the goal of improving their accuracy and precision, with the hope of improving our understanding of the significance of the results obtained by the different techniques. A secondary objective was the refinement of the geochronology of the area.

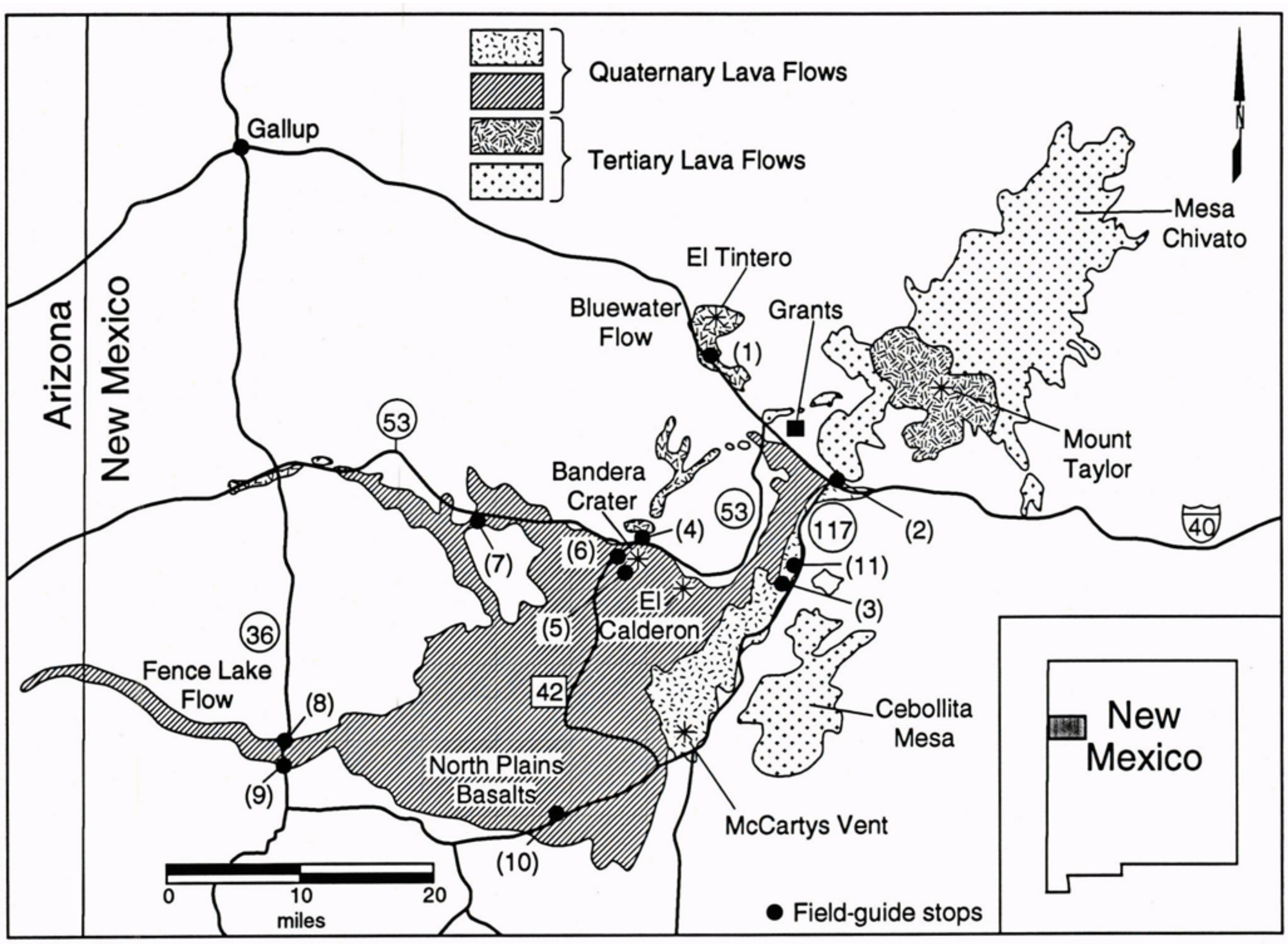

FIGURE 1—Map of Zuni–Bandera volcanic field showing field-guide stops.

FIGURE 2—El Tintero cinder cone is the source for the Bluewater flow. Cinders are being quarried at this site for use as road material. A late, stubby basalt flow from El Tintero can be seen in the foreground.

First-day road log

Mileage

0.0 Best Western Motel *The Inn*, Grants, New Mexico. Turn left from the parking lot at *The Inn* and proceed west along old Highway 66 through the town of Grants. During the uranium "boom" days the Grants area was a major producer of uranium. The first discovery of uranium in this region was in 1950 in the Jurassic Todilto Formation exposed in Haystack Butte west of town. With the declining demand for uranium the economy of this region has suffered and the population of Grants has dropped. Formation of the new El Malpais National Monument is helping the local economy by drawing more tourists to the region.

0.9 Note prairie-dog town on right-hand side of the street. Residents of Grants feed them with stale vegetables from the local supermarkets.

1.6 El Malpais National Monument Tourist Center.

2.4 Grants Mining Museum on Iron Avenue. The museum provides an outstanding perspective on the history of uranium mining in the Grants area.

3.4 Proceed west on NM 122 toward Milan. Black Mesa, on the right-hand side of the road, is one of the low mesas that surround Mount Taylor. The basal flow capping the mesa has been dated at 2.57±0.13 Ma (Laughlin et al., 1993). Go through the town of Milan. Continue past the intersection of NM 605 (6.0 mileage) on NM 122. El Tintero cinder cone is at 2 o'clock. This cone is the source for the Bluewater flow. Beyond El Tintero is Haystack Butte where the first uranium discovery was made.

Mileage 13.0. STOP 1: Bluewater flow
Lat. 35° 15.80' N
Long. 107° 58.23' W

The source of the Bluewater flow is the El Tintero cinder cone (Fig. 2) about 20 km (12.4 mi) west of Grants. Except where it has been quarried for road material, the El Tintero is well preserved and maintains its original shape. Original surface features are also well preserved on the Bluewater flow except where it is covered by eolian sands and silts.

The Bluewater flow is a tholeiite, very similar in composition to the Laguna and McCartys flows (Table 1). Most samples of the flow are holocrystalline and microporphyritic with both olivine and plagioclase present as phenocryst phases. The groundmass is dominated by plagioclase and clinopyroxene with minor opaque oxides and perhaps some olivine.

Attempts to date the Bluewater flow have been made using three methods: conventional K–Ar, U-series, and the ^{3}He surface exposure dating technique. All samples used for dating were collected near Stop 1. Conventional K–Ar dates of 5.69±0.12 and 2.23±0.24 Ma were obtained on two different samples collected by Laughlin and Perry, respectively. Based on the degree of preservation of this flow and its position on the present valley floor, these apparent ages are believed to be anomalously old because of the presence of excess ^{40}Ar, i.e. ^{40}Ar incorporated into minerals from gases in the magma. Sims and Murrell (unpublished) have obtained a well defined isochron age of 79 ka using the U-series method (Fig. 3). Poths (Los Alamos National Laboratory) has also dated two samples from this outcrop using the ^{3}He surface dating method. The average for these samples was 57±6 ka (uncertainty in production rates is ±30%). During crushing of olivine, Poths has detected large amounts of excess ^{40}Ar in olivine and clinopyroxene from the Bluewater flow.

Continue west on NM 122.

13.1. Turn left on access road (NM 606) to Exit 72 on Interstate 40.

13.3 Return to Interstate 40 and proceed east.

23.8 Zuni Canyon flow is on the right. This flow, which originated from the Paxton Springs volcano, is an alkaline basalt. Based upon the degree of surface preservation, it is older than the Bandera flows and younger than both the Bluewater and Laguna flows. Although this flow has not been dated, there are several potential sites to look for charcoal beneath the flow within Zuni Canyon. The small hill on the right surrounded by lava is the Chinle Formation. It is capped and ringed by travertine deposits of Quaternary age.

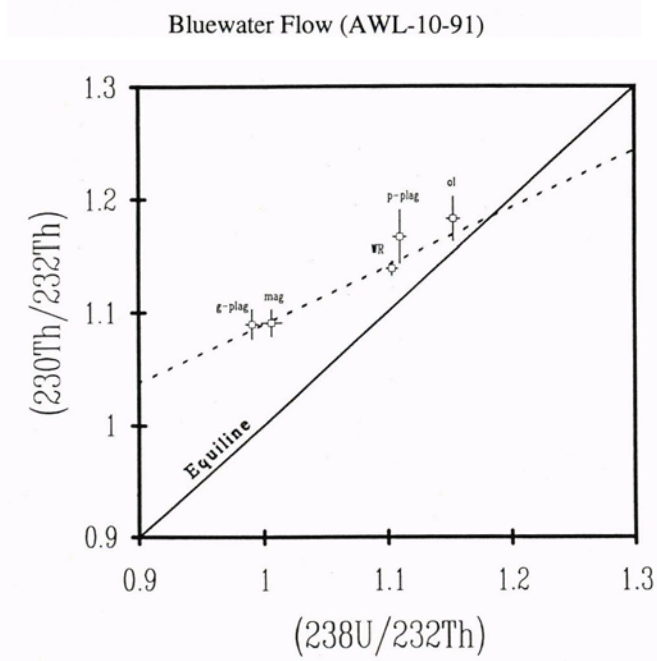

FIGURE 3—^{230}Th/^{232}Th versus ^{238}U/^{232}Th for the Bluewater flow from the Zuni–Bandera field on the Jemez lineament in New Mexico. The isochron, shown by the dashed line, gives a 2σ age of 79 ka+40 ka/–30 ka.

FIGURE 4—This photo shows the ~3 ka McCartys flow overlying the older (110–128 ka) Laguna flow near the intersection of Interstate 40 and NM 117 about 6 mi east of Grants.

TABLE 1—Representative chemical compositions of dated basalts.

	Bluewater	Laguna	McCartys	Twin Craters	Bandera	Ramah Navajo	Fence Lake	North Plains
SiO_2	51.62	50.23	51.48	48.86	44.47	50.70	50.03	52.06
TiO_2	1.25	1.53	1.41	1.44	3.04	1.17	1.38	1.45
Al_2O_3	15.13	14.50	15.18	14.84	15.22	15.05	14.92	15.72
Fe_2O_3	11.49	1.82	11.87	12.48	4.39	11.66	12.24	10.95
FeO	N.A.	9.27	N.A.	N.A.	8.42	N.A.	N.A.	N.A.
MnO	0.16	0.17	0.16	0.17	0.15	0.16	0.17	0.15
MgO	7.42	9.45	8.29	9.15	9.30	8.34	9.00	6.34
CaO	9.30	8.83	9.11	8.87	8.80	9.57	9.16	9.99
Na_2O	2.60	2.91	2.78	2.81	3.38	2.44	2.74	2.79
K_2O	0.42	0.77	0.69	0.74	1.60	0.36	0.64	0.66
P_2O_5	0.15	0.22	0.19	0.22	0.58	0.14	0.19	0.22

27.1 There are high-mesa basalts to the north on the southern flank of Mount Taylor; these range from 3.7 to 2.9 Ma (Perry et al., 1990; Laughlin et al., 1993). We are now traveling across the Laguna flow which has been dated at 110–128 ka (Laughlin et al., 1993).

30.8 Exit Interstate 40 at the NM 117 interchange toward Quemado (Exit 89), cross over the interstate and proceed east on frontage road (NM 124) to the right. McCartys flow is on the left. Geomorphic features of the McCartys flow were first described by Nichols (1946), and Carden and Laughlin (1974) described the chemical variations along the length of the flow.

Mileage: 32.0. Stop 2: Laguna flow

Lat. 35° 04.53' N
Long. 107° 45.22' W

The Laguna flow (*Qbc* of Maxwell, 1986) is well exposed in the Rio San Jose valley east of Grants (Fig. 4). According to Maxwell, it originated from the El Calderon volcano at the southern end of the Zuni Mountains. From its source it flowed northward around the east side of the Zuni Mountains before it turned eastward to flow down the Rio San Jose valley. Within the valley it is overlain in places by the McCartys basalt. Drake et al. (1991) concluded from water-well data that it can be traced eastward down the valley beneath alluvium to the vicinity of the Laguna Pueblo, where it is again exposed.

The Laguna flow is an olivine tholeiite (Table 1). It is typically holocrystalline, but small amounts of glass containing opaque oxides are locally present. All thin sections show olivine phenocrysts in a groundmass of plagioclase, clinopyroxene, olivine, and opaque oxides. Sample 63, collected where the flow is relatively thick, is characterized by an ophitic texture with plagioclase and clinopyroxene, as well as olivine appearing as phenocryst phases.

Several attempts have been made to date the Laguna flow by the conventional K–Ar method (Laughlin et al., 1979, 1993; Lipman and Mehnert, 1979; Champion and Lanphere, 1988) with ambiguous results. Laughlin et al. (1979) reported an apparent age of 1.57±0.26 Ma for a sample collected along Interstate 40 west of the intersection with NM 117. Because it was believed that this age was anomalously old, the flow was resampled at two new sites. Laughlin et al. (1993) report ages of 0.054±0.50, 0.110±0.076, and 0.120±0.73 Ma for these samples (sample 63 was analyzed twice) (Table 2). Lipman and Mehnert (1979) reported an apparent age of 0.28±0.25 Ma for the flow near Laguna Pueblo, and Champion and Lanphere (1988) reported an apparent age of 0.128±0.033 Ma for a sample collected by Laughlin at Stop 2.

Return to Interstate 40/NM 117 intersection and proceed south on NM 117.

43.4 Turnoff to Sandstone Bluffs overlook.

Mileage 45.8. STOP 3: McCartys flow at "Little Narrows"

Lat. 34° 56.01' N
Long. 107° 50.33' W

The McCartys flow is the youngest basalt flow in the Zuni–Bandera volcanic field. Its source is a low shield volcano located about 40 km (24.8 mi) south of the intersection of Interstate Highway 40 and NM 117. A small cinder cone about 8 m (26 ft) high sits on top of this broad shield. Although some of the lava flowed southwestward 8 to 9 km (5 to 5.6 mi), most followed the preexisting drainage and flowed northward about 40 km (24.8 mi) before turning eastward 10 km (6.2 mi)

TABLE 2—K–Ar dates on second pulse basalts in the Zuni–Bandera volcanic field.

Sample ID	Location	Material	K_2O (%)	^{40}Ar (10^{-12} m/g)	$^{40}Ar_{rd}$ (%)	Age (Ma)
B-1-74	West of Bandera Crater	Basalt	1.32	0.378	7	0.199±0.042
BR-2-74	Black Rock Zuni Pueblo	Basalt	0.48	0.483	1	0.70±0.55
153	Black Rock Zuni Pueblo	Basalt	0.59	0.139	6	0.164±0.035
AWL-2-89	Cerrito Arizona	Basalt	0.98	0.209	1	0.148±0.087
AWL-6-90	East of El Morro	Basalt	0.48	0.076	0.5	0.109±0.044
AWL-10-80	Laguna Flow	Basalt	1.13	0.088	0.2	0.054±0.050
63	Laguna Flow	Basalt	0.84	0.132	1	0.110±0.076
			0.85	0.147	1	0.120±0.073

down the Rio San Jose valley. The McCartys flow overlies older basalts of the Zuni–Bandera volcanic field and Holocene alluvium.

The McCartys flow is typically a vesicular, porphyritic basalt. Carden and Laughlin (1974) examined chemical and petrographic variations along the length of the flow and reported that within 4 km (2.5 mi) of the source the basalt is characterized by plagioclase phenocrysts 0.20 to 1.5 cm in length. At greater distances from the source, large plagioclase phenocrysts are absent and olivine phenocrysts are present. Plagioclase is the dominant mineral in samples of McCartys flow.

Prior to the work of Laughlin et al. (unpublished), the age of the McCartys flow was poorly constrained. Nichols (1946) concluded on the basis of Indian legends and archeological and faunal evidence that the McCartys eruption probably took place after 700 A.D. During the summer of 1992, two charcoal samples were collected from a baked soil beneath the flow at the "Little Narrows," including burnt roots 1–2 mm in diameter (Stop 3, Figs. 5a, b, and 6). Accelerator mass-spectrometer radiocarbon dates of 2970±60 and 3010±70 years B.P., which yielded an average, calibrated age of 3160–3200 years B.P., were obtained on these samples. Poths has analyzed three aliquots of a sample of the surface of the flow using the ^3He method. An average age of 2450 years has been obtained on these samples. An uncertainty in the production rate for ^3He of ±30% may contribute to the discrepancy with the radiocarbon dates.

Leave Stop 3 and return to *The Inn* in Grants via NM 117 and Interstate 40.

Second-day road log

Mileage

00.0 Best Western Motel *The Inn*. Turn right from the parking lot at The Inn and proceed to I-40 west.

3.6 Take Exit 81, turn left on NM Highway 53 (south).

6.4 San Rafael. The town of San Rafael was the site of the first Fort Wingate. The fort was established in 1862 and was used in the wars against the Navajos. It was abandoned in 1868 and a new Fort Wingate was built near Gallup. Fort Wingate was named after Capt. Benjamin Wingate who died from wounds inflicted by Confederate troops during the battle of Val Verde. Soldiers from Fort Wingate used to visit the Ice Cave at Bandera Crater and haul ice back to the fort.

23.9 Turnoff to El Calderon. This volcano is the source of the Laguna flow that was examined at Stop 2. Although not listed as a stop in this field guide, it is worth visiting this site to see examples of collapsed lava tubes. Precambrian granites and gneisses are exposed on the right side of the road for the next several miles. These Precambrian rocks contain numerous veins of fluorite which were extensively mined during World War II.

Mileage 26.3. STOP 4: Twin Craters flow

Lat. 34° 59.51' N
Long. 108° 02.04' W

Because of problems in separating flows from different vents, Maxwell (1986) included as one unit, *Qbt*, flows from the Twin Craters and the Lost Woman and La Tetera (Tetra) vents. He considers these flows older than the Oso Ridge flows and younger than the El Calderon flows. The Twin Craters flow at this stop is fine-grained and microporphyritic with olivine phenocrysts in a groundmass of plagioclase, clinopyroxene, olivine, and opaque oxides. It is tholeiitic in composition (Table 1).

At this stop, the Los Alamos group was able to collect charcoal from the soil beneath the flow and overlying the Precambrian gneiss. This sample yielded a radiocarbon date of 15,800±90 years B.P. No other dates are available for this flow. After looking at the charcoal in the soil, climb on top of the outcrop to look at surface features of the flow. The surface features here appear much more degraded than the ~10 ka Bandera flow (Stops 5, 6), suggesting that the 15.8 ka age may be in error (anomalously young).

29.1 Turn left on private road to the Ice Caves and Bandera Crater.

Mileage 29.8. STOP 5: Bandera Crater Trading Post
Lat. 34° 59.64' N
Long. 108° 05.22' W

The Bandera flows originated from the Bandera Crater, a double cinder cone about 150 m (492 ft) high and 1 km (0.6 mi) in diameter (Figs. 7a, b, and 8). The eruption of the Bandera Crater and its associated flows was the second youngest volcanic event in the Zuni–Bandera volcanic field. Like many other cinder cones in this field, the Bandera Crater is breached to the southwest. A large lava tube, intermittently collapsed, extends about 29 km (18 mi) south from the breach in the crater wall and a commercial ice cave is located in a collapsed portion of the tube near the Candelaria Trading Post. Causey (1971) recognized six stages in the development of the crater and its associated flows, culminating in the eruption of the black cinders that cap the cinder cone and blanket the hills to the north. Two small commercial cinder pits have been opened in the cinders covering the hills to the north of NM Highway 53 where the cinder blanket is thickest. A variety of crustal and mantle xenoliths and anorthoclase megacrysts have been found in these cinder pits (Laughlin et al., 1971, 1974; Gallagher, 1973).

The Bandera lavas are nepheline normative, holocrystalline, microporphyritic, and vesicular near the surface. Both aa and pahoehoe surfaces are common on the flows. The whole-rock chemistry of a representative sample of the Bandera flows is given in Table 1.

Four dating techniques have been used to date the Bandera flows or to constrain their ages: conventional K–Ar, ^{14}C, ^{3}He, and $^{40}Ar/^{39}Ar$. At the time of preparation of this road log only the ^{14}C, ^{3}He, and conventional K–Ar results were available. Two K–Ar dates (Laughlin et al., 1979, 1993) have been obtained on flows that immediately underlie flows from the Bandera Crater. These dates of 0.199 ± 0.042 and 0.148 ± 0.87 Ma (Table 2) provide maximum ages for the Bandera flows. A minimum age of 3166 ± 77 years B.P. for the Bandera activity is provided by a radiocarbon date on a twig enclosed in laminated ice from the Candelaria Ice Cave, which is located in the main lava tube extending from the Bandera Crater (Thompson et al., 1991).

In May 1992 the U.S. National Park Service provided a backhoe to excavate through the cinders on the hillside north of the Bandera Crater in an attempt to find charcoal for radiocarbon dating. In the course of two days, 10 short backhoe trenches were excavated. The first seven trenches did not penetrate the cinders and it was only when the backhoe was moved about 200 m (656 ft) to the north of the present commercial cinder pit that the trenches encountered soil below the cinders (Fig. 9). The sample site is about 1 km (0.6 mi) northeast of the crater rim in the axis of a shallow swale, with an upstream drainage area of about 0.1 km^2. The bottom of the swale is presently unchanneled, accumulating fine-textured loamy soils derived from the adjacent sandstone slopes. The scoria deposit may also have mantled a shallow valley.

The stratigraphy at the charcoal sample site consists of 0.4–1.1 m (1.3–3.6 ft) of fine-textured cumulative soil overlying 0.9–1.2 m (3–4 ft) of scoria. The scoria deposits include two distinctly different layers, a 0.55–0.75 m (1.8–2.5 ft) thick upper layer of frothy scoria and a 0.35–0.50 m (1.1–1.6 ft) thick lower layer of rounded scoria with abundant lithic fragments. Beneath the scoria deposit are sandstone boulders with intervening pockets of sandy clayey soil up to about 0.30 m (1 ft) thick. The charcoal samples were collected from these pockets of soil among the sandstone boulders. Sample Beta-53845 consisted of charcoal within patches of darker soil that possibly represented burnt roots. The charcoal was separated in the laboratory by hand-picking. Sample AA-9075 consisted of small (1–2 mm) fragments of disseminated charcoal in the soil matrix. The charcoal was hand-picked in the field. Sample Beta-53845 yielded a radiocarbon date of 9170 ± 70 years B.P. and sample AA-9075 gave an age of 9810 ± 60 years B.P. Because of the possibility of sample contamination by modern rootlets not removed during sample preparation of Beta-53845, we conclude that the date of 9810 years B.P. provides the most reliable maximum-limiting age for the eruption of the Bandera cinders. This sample yields a calibrated age of 10,990 cal. years B.P.

Two samples of the surface of the Bandera flow were collected for ^{3}He dating (Fig. 9). The first sample was collected along the west side of the trail from the Bandera Crater to the Ice Cave on the east side of the lava tube (Stop 5). The sample consisted of a slab of the pahoehoe surface of the flow. The second sample was an in-place block of aa lava from the west edge of the flow at the foot of Cerro Bandera (Stop 6). These samples yielded an average age of 10.4 ± 1.2 ka.

A sample of the Bandera flow from near the vent (Stop 6) has been collected for U-series dating and both basalt and anorthoclase megacryst samples have been collected for conventional K–Ar and $^{40}Ar/^{39}Ar$ dating. No results are available as yet for these samples.

Two stops will be made at the Bandera Crater. At Stop 5, you can park in the parking lot of Candelaria Trading Post and, after paying the admission fee, walk first to the site where a sample of the pahoehoe surface of the Bandera flow was collected for ^{3}He dating. This sample yielded an average (two aliquots) age of 10,500 years. Because the trenches through the cinders were refilled after sample collection, a stop will not be made at the cinder pit. From here proceed to the Ice Cave where the twig was collected from the laminated ice for radiocarbon dating.

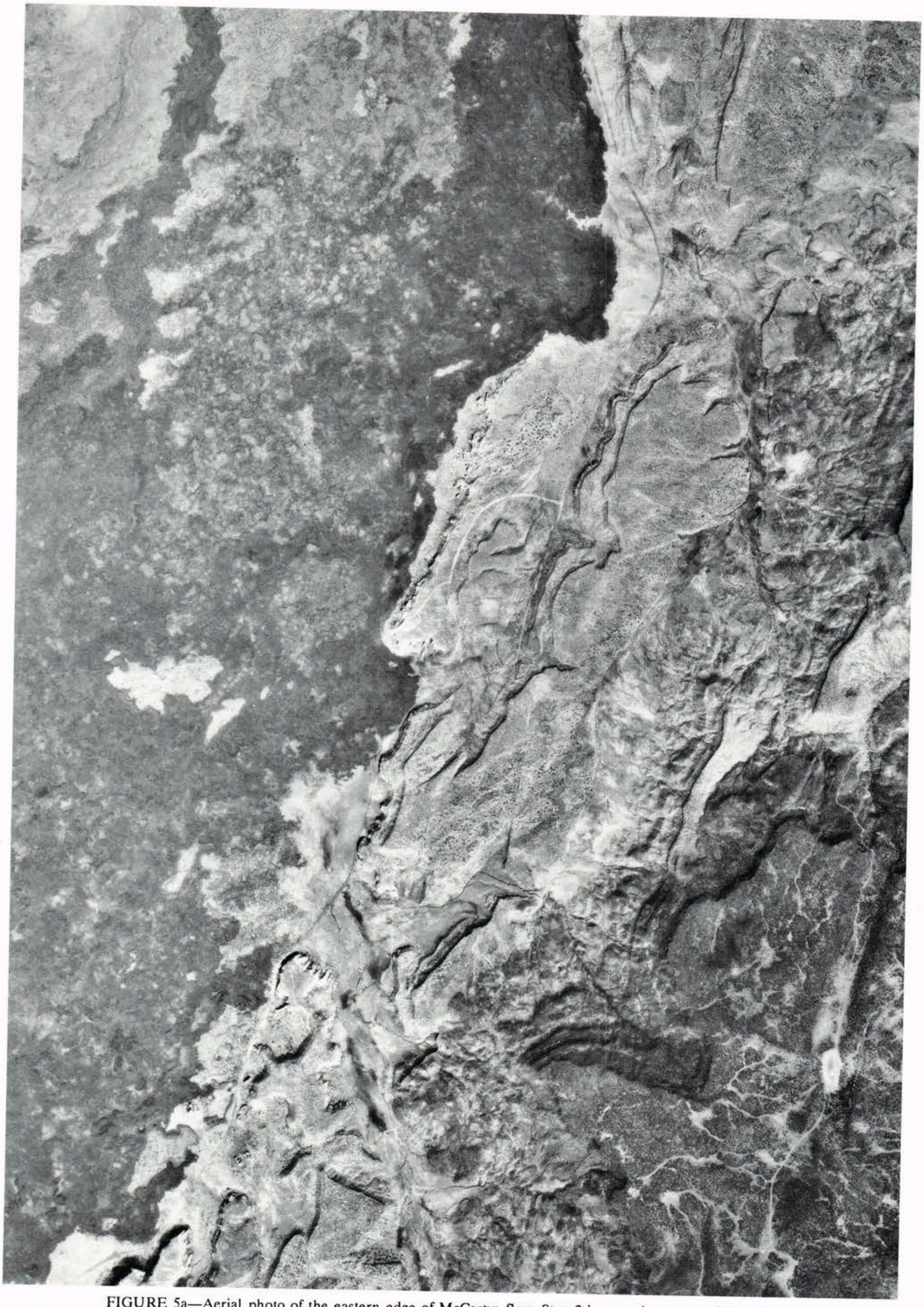

FIGURE 5a—Aerial photo of the eastern edge of McCartys flow. Stop 3 is near the center of the photo.

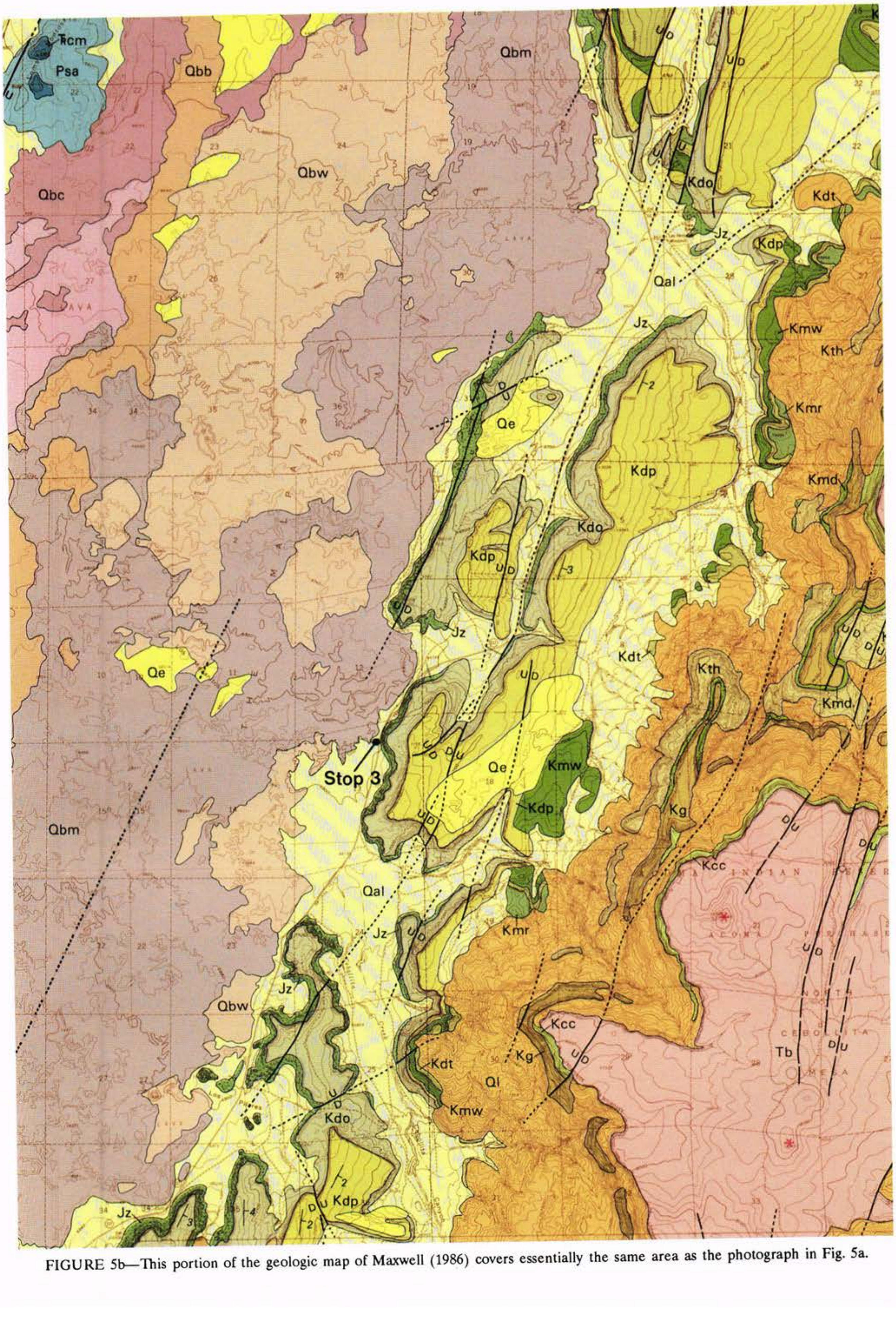

FIGURE 5b—This portion of the geologic map of Maxwell (1986) covers essentially the same area as the photograph in Fig. 5a.

FIGURE 6—Geologist Steven Reneau of the Los Alamos National Laboratory is collecting charcoal for ^{14}C dating from the baked soil beneath McCartys flow.

30.4 Turn left onto NM 53.

31.0 Continental Divide, elevation 2403 m (7882 ft).

31.6 Turn left onto County Road 42. Laughlin et al. (1979) reported a conventional K–Ar date of 0.199 ± 0.042 Ma on basalt (Table 2) of the west side of County Road 42 at approximately this spot. This flow is from the second pulse of volcanic activity recognized in the Zuni–Bandera volcanic field (Laughlin, et al., 1993).

Mileage 32.6. STOP 6: West side of Bandera flow
Lat. 34° 59.57' N
Long. 108° 05.48' W

Stop 6 is on the west side of the Bandera flow, at the base of Cerro Bandera (Figs. 8 and 9). At this site, Poths collected her second sample for ^{3}He dating (12,500 years). A short walk across the aa surface of the flow will take you to the main lava tube from the Bandera Crater. Samples have been collected here for conventional K–Ar and $^{40}Ar/^{39}Ar$ dating. Results are not yet available for these samples.

Laughlin et al. (1993) report a conventional K–Ar date of 0.148 ± 0.087 Ma on a basalt flow from Cerrito Arizona collected about 4 km (2.5 mi) southwest of this stop (Table 2). This flow is also from the second pulse of volcanic activity recognized in the Zuni–Bandera volcanic field.

Approximately 8 km (5 mi) south of this stop a plagioclase phyric basalt, "the Big Plag Basalt," is exposed south of Cerro Rendija. Stratigraphic relations suggest that eruption of this basalt should fall within the second phase (about 0.150 Ma) of volcanic activity. Conventional K–Ar dating, however, yields results of 3.7 ± 0.4 Ma and 5.92 ± 0.14 Ma. A very pure plagioclase separate, enriched in the phenocryst plagioclase component, was prepared to emphasize the effect of excess ^{40}Ar. This sample gave an apparent K–Ar age of 19.5 ± 2.2 Ma (WoldeGabriel and Laughlin, unpublished data), suggesting a large amount of excess ^{40}Ar was incorporated in the phenocrysts during crystallization.

33.7 Return to NM 53 and continue west.

34.6 Forest Road 50 on the right provides access to the Oso Ridge and Paxton Springs volcanoes which erupted alkali basalts.

46.5 A sample of basalt was collected from the pressure ridge at this site. Conventional K–Ar dating gave an age of 0.109 ± 0.044 Ma (Table 2), suggesting that it is correlative with the basalts beneath the Bandera Crater and the basalt at Black Rock on the Zuni Pueblo approximately 50 km (31 mi) to the west (Laughlin et al., 1993).

48.7 Entrance to El Morro National Monument. Inscription Rock is to the left. From the days of the Spanish explorer Don Juan de Oñate, in 1605, travelers have carved their names on Inscription Rock as they passed through this area. A pool of water at the base of the rock provided relief to the travelers in this typically dry region. This was also a stop on the Indian trail between Zuni and Acoma Pueblos.

52.1 Turn left on Navajo Highway 125.

Mileage 54.1. STOP 7: Ramah Navajo flow
Lat. 35° 01.58' N
Long. 108° 24.51' W

This is a very brief stop to look at a basalt flow that has given an extremely anomalous apparent age of 7.65±0.08 Ma. It is a tholeiitic flow (Table 1), holocrystalline and equigranular. It consists of plagioclase, olivine, clinopyroxene, and opaque oxides. About two feet of eolian sands and silts cover the flow and only the tops of pressure ridges are exposed above the alluvial surface. This flow is probably coeval with the approximately 0.700 Ma flows of the North Plains (Stop 10) and the Fence Lake flow (Stops 8 and 9). Return to NM 53.

56.2 Continue west on NM 53. For the next hour, until you reach Stop 8, you will be passing intermittently through both Ramah Navajo and Zuni Indian lands. Vegetation along the highway is dominantly piñon and juniper.

63.2 Timberlake Road on right. About one-half mile up this road, cliff dwellings can be seen on your left.

64.3 Town of Ramah. This is a Mormon farming town established in the late 1800s. There are no basalts around Ramah. The lavas flowed west down the valley beyond the hills south of NM 53 and thence into the Rio Pescado and eventually the Zuni River valleys.

76.4 Turn left on NM 36. If you continue west on NM 53 for about 10 km (6.2 mi), you would reach the Zuni Pueblo and the Black Rock basalt outcrop dated by Laughlin et al. (1993) at 0.164±0.035 Ma.

Mileage 103.2. STOP 8: North edge of Fence Lake flow
Lat. 34° 44.37 N'
Long. 108° 40.60'

The Fence Lake flow is one of the oldest and probably the largest basalt flow in the Zuni–Bandera volcanic field. Its vent, which cannot be identified, was probably located somewhere along the present Continental Divide where it is now covered by the Chain of Craters or flows from them. From this general area, lava flowed both to the north and to the west for distances of up to about 100 km (62 mi). North of the present town of Fence Lake, the lava was apparently confined by a preexisting drainage to a width of 2–3 km (1.2–1.9 mi).

TABLE 3—Conventional K–Ar and $^{40}Ar/^{39}Ar$ dates for the Fence Lake flow and North Plains basalts.

Sample ID	Location	Material	Mesh size	K_2O (wt%)	$^{40}Ar^*$ (10^{-12} m/g)	$^{40}Ar^*$ (%)	Age (Ma)†
AWL-5-89	North Plains	Basalt		0.64	0.674	6	0.69±0.13
AWL-1-90	North Plains	Basalt		0.52	0.656	8	0.72±0.10
AWL-3-90	North Plains	Basalt		0.51	0.519	4	0.59±0.09
FL-3-74	Fence Lake	Basalt		0.46	0.9250	6	1.41±0.29
AWL-4-90#	Fence Lake	Basalt		0.65	0.2060	1	0.18±0.04
AWL-4-90	Fence Lake	Basalt	-28+40	0.77	0.5044	2	0.46±0.04
AWL-4-90	Fence Lake	Basalt	-100+140	0.83	0.6925	2	0.58±0.04
AWL-4-90	Fence Lake	Basalt	-100+140	0.83	0.8226	3	0.69±0.07
AWL-14-91	Fence Lake	Basalt	-28+40	0.47	0.3357	3	0.53±0.03
AWL-14-91	Fence Lake	Basalt	-100+140	0.54	0.2507	2	0.23±0.03

Sample ID	Location	Material	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$ (%)	$^{40}Ar^*$ (m.y.)	J	Age‡
AWL-4-90	Fence Lake	Basalt	4.07806	0.10856	33.28092	4	0.000277	0.6±0.09
AWL-14-91	Fence Lake	Basalt	8.52051	0.05782	19.11986	11	0.000278	0.67±0.30

* Radiogenic argon; † Determined from decay constants and isotopic abundance of Steiger and Jager (1977); # Data from the University of Arizona (sample UAKA 90 051); ‡ McIntosh and Laughlin (unpublished data).

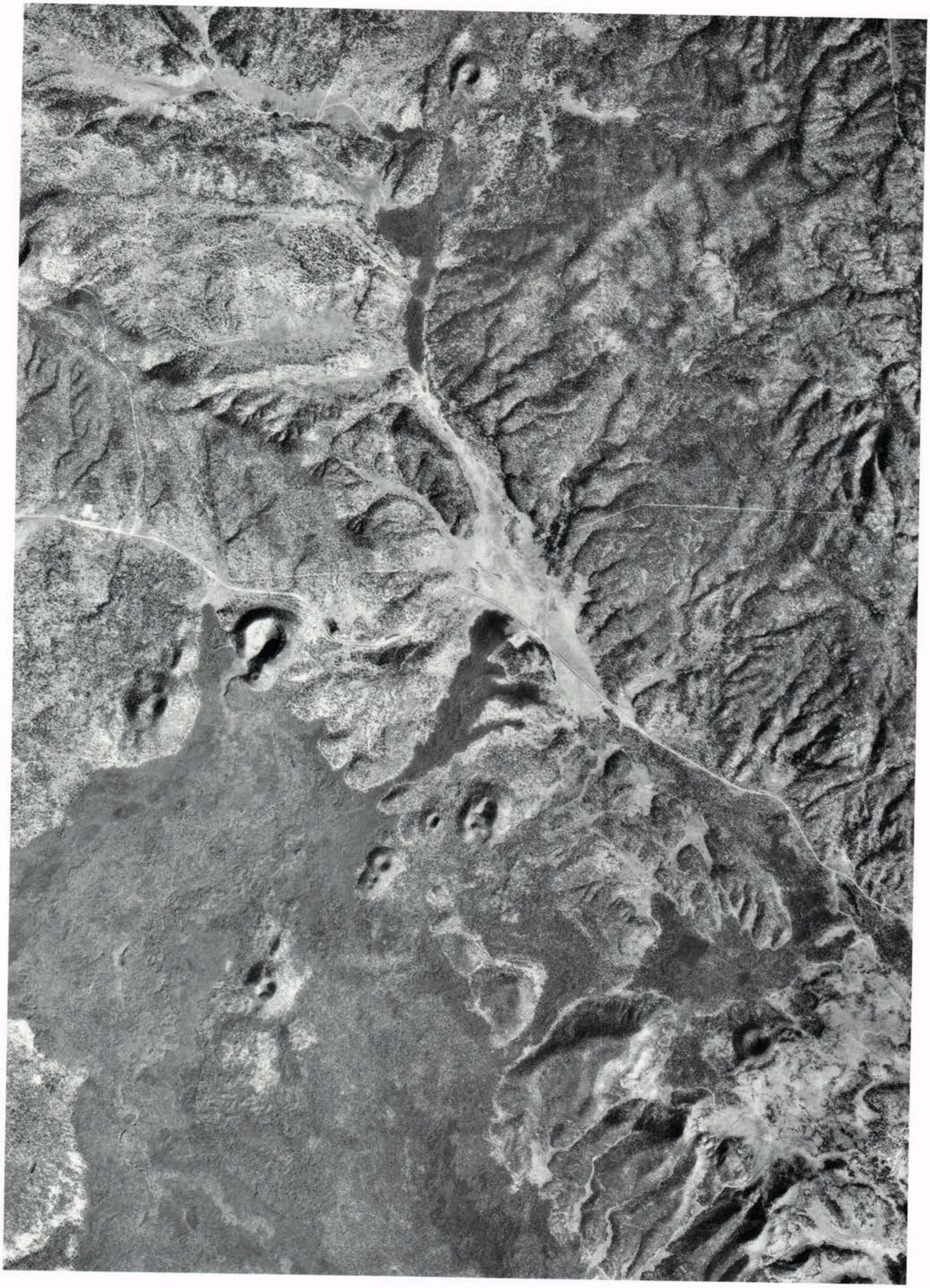

FIGURE 7a—Aerial photo showing the numerous volcanic vents near Bandera Crater.

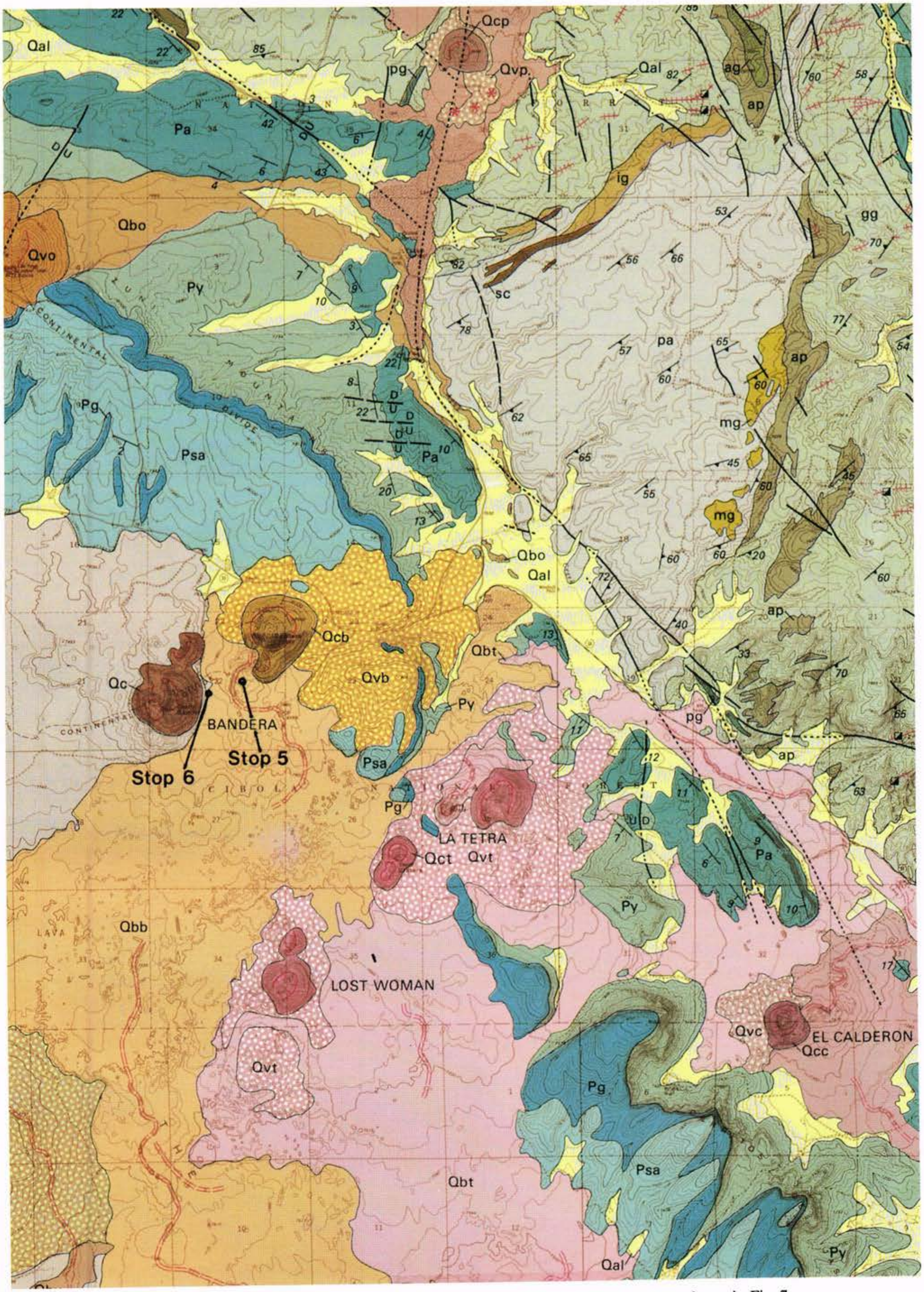

FIGURE 7b—This portion of the geologic map of Maxwell (1986) covers the area shown in Fig. 7a.

TABLE 4—Summary of Zuni–Bandera volcanic field stratigraphy.

	Method	Apparent age (ka)
Qbm–McCartys flow	^{14}C (cal.) ^{3}He	3.160-3.200 2.450±1.20
Qbb–Bandera flows	^{14}C (cal.) ^{3}He	10.99 10.40
Qbw–Hoya del Cibola flows		
Qbp–Paxton Springs flows		
Qbo–Oso Ridge flow		
Qbt–Twin Craters, Lost Woman, Cerro Candelaria, Lava Crater flows		
Bluewater flow (not shown on Maxwell's map)	U-series ^{3}He	79+40/-30 57.0±6.0
Qbc–El Calderon = Lava flow	K–Ar	115
Qbu–Basalts in west		
Qb–Old basalts	K–Ar, 40/39	150 (Pulse 2) 600–700 (Pulse 1)
Tb–Cebollita, Black, and Horace Mesas	K–Ar, 40/39	4000 to 2900 2600 to 2400

Stratigraphy from Maxwell (1986). Unpublished ages by William Laughlin, Jane Poths, Giday WoldeGabriel, Frank Perry, Steve Reneau, Michael Murrell, and Ken Sims of Los Alamos National Laboratory, and William McIntosh and Matthew Heizler of the New Mexico Bureau of Mines & Mineral Resources.

Twenty to 30 m (66 to 98 ft) of post-flow erosion has left the flow remaining as a prominent ridge. Further west, the lava turned and flowed southwestward into the valley of the Zuni River.

The Fence Lake flow is tholeiitic (Table 1) and is chemically very similar to basalts of the North Plains. Because of differences in flow thickness, there is considerable variability in the petrography of samples from this flow. Most samples are relatively coarse-grained, however, with phenocrysts of olivine, plagioclase, and, in some cases, clinopyroxene in a groundmass of plagioclase, clinopyroxene, and opaque oxides. Where the flow is thick, the texture is commonly subophitic to ophitic.

The Fence Lake flow has been dated by both the conventional K–Ar and $^{40}Ar/^{39}Ar$ methods with mixed results (Table 3). Laughlin et al. (1979) reported a K–Ar date of 1.41±0.29 Ma for a sample collected from the north side of the flow (sample FL-3-74, Stop 8). This date was believed to be anomalously old and another sample was collected from the south side of the flow (AWL-4-90, Stop 9). A date of 0.184±0.036 Ma was obtained on this sample (Laughlin, Perry, Damon, and Shafiqullah, unpublished data). Because of the discrepancy between these two apparent ages, additional material was collected from the north side of the flow (sample AWL-14-91) and both conventional K–Ar and $^{40}Ar/^{39}Ar$ dates were run on both this sample and on sample AWL-4-90 from the south side of the flow. Results of these analyses are given in Table 3. We conclude that the age of the Fence Lake flow falls between 0.6 and 0.7 Ma.

Mileage 106.1. STOP 9: South side of Fence Lake flow

New exposures have been cut by the Highway Department while widening the road.

109.3 Turn left on NM 36/117.

127.8 Turn left on NM 117. Now crossing the North Plains. These plains are covered by 0.6 to 0.7 Ma basalts, which in turn are covered by eolian soils. Much of the land in this area is part of the old York Ranch owned by New Mexico Governor Bruce King and his family.

Mileage 136.9. Stop 10: South of Cerros de los Gatos

Lat. 34° 37.22 N
Long. 108° 14.72 W

These plugs may have served as vents for some of the North Plains basalts which are tholeiitic and generally similar to the Fence Lake flow in composition (Table 1). These flows have not been adequately mapped and, because of eolian sand cover, it is difficult to determine how many flows are present in the area.

FIGURE 8—Aerial photo looking south toward Bandera Crater. Cerro Rendija is the low shield volcano in the background.

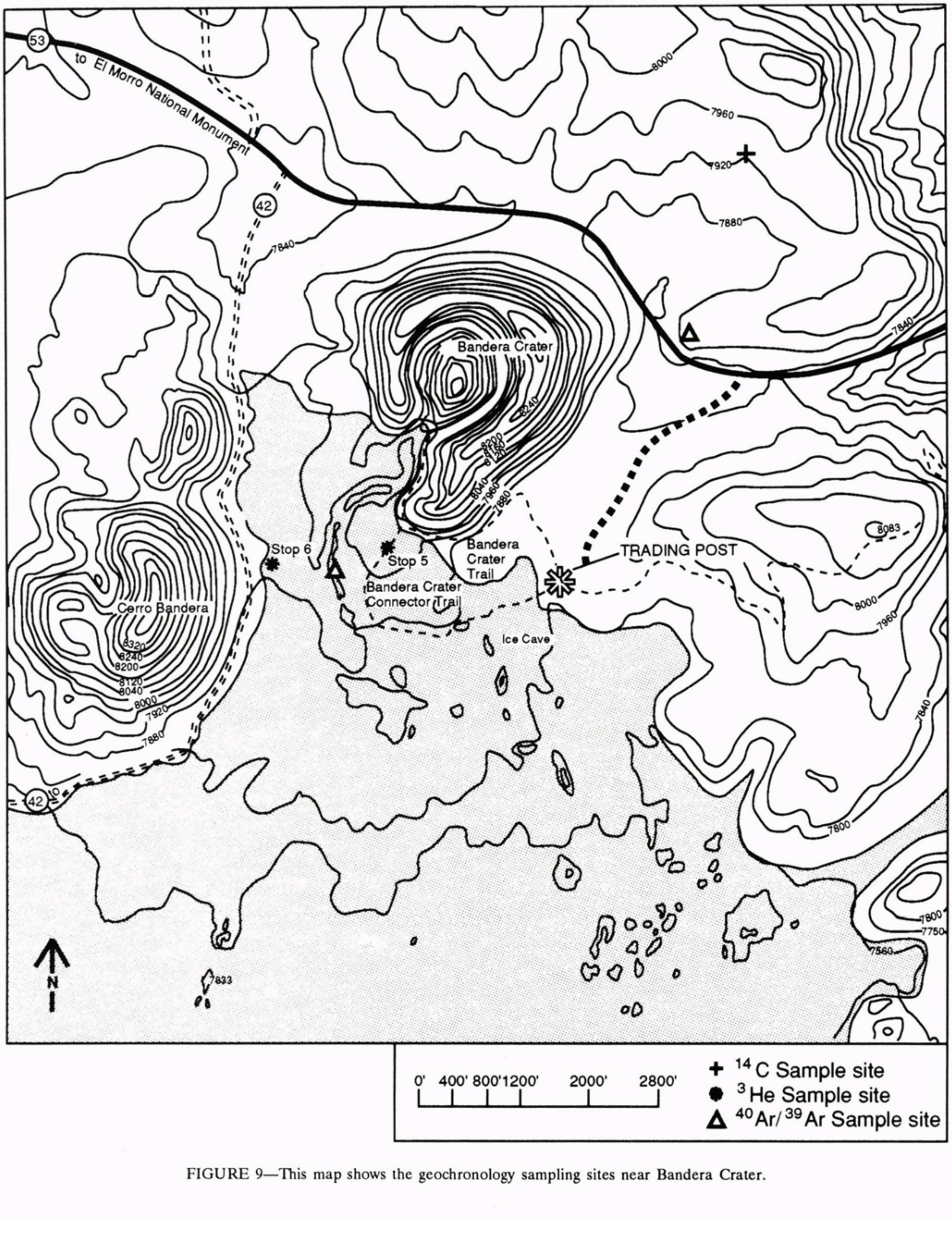

FIGURE 9—This map shows the geochronology sampling sites near Bandera Crater.

They comprise the southern part of the Zuni–Bandera volcanic field and are overlain in the north by the Hoya de Cibola flows and the McCartys flow. Their source vent or vents cannot be located because of probable burial by younger flows from the Chain of Craters and associated cinder cones. In many places these flows are covered by eolian sands and silts, and only the tops of pressure ridges protrude above the alluvium.

The North Plains basalts typically are relatively coarse-grained and porphyritic, with phenocrysts of both plagioclase and olivine. Groundmass constituents include plagioclase, clinopyroxene, opaque oxides and, in some cases, minor glass and olivine.

Several attempts to date these flows have been made using the conventional K–Ar method (Table 3). Ander et al. (1981) reported an age of 3.8 Ma for one of the North Plains basalts, but this date appears to be anomalously old. More recent dates fall between 0.593 and 0.724 Ma (Laughlin et al., 1993), suggesting that these flows are coeval with the Fence Lake flow.

152.4 Gus Rainey's ranch house is on the left. Gus was a local folk hero often accused of murder, and died in his 90s in the Grants jail while awaiting trial for a double murder. The southern end of McCartys flow is on the left. Cebollita Mesa is the high north–south trending mesa at 12 o'clock. This mesa is about the same elevation as the high mesas around Mount Taylor. It is capped by 4.0 Ma basalt approximately 20 m (66 ft) thick and the surface is dotted by many maars and at least three shield volcanoes, one of which has been dated at 3.4 Ma (Laughlin et al., 1993). Cebollita Peak at the south end of the mesa is composed of relatively evolved alkaline basalt (Laughlin et al., 1993). Our brief reconnaissance in 1992 is the only geologic work done on the mesa.

167.5 La Ventana Natural Arch straight ahead.

Mileage 175.3. STOP 11: Sandstone Bluffs Overlook
Lat. 34° 58.53' N
Long. 107° 49.03' W

This stop provides an excellent overview of the younger basalts of the El Malpais National Monument. From this point you can see the McCartys flow in the foreground and, in the background to the west, older flows from the Hoya de Cibola, Bandera Crater, and El Calderon. A summary of the volcanic stratigraphy of the Zuni–Bandera volcanic field is presented in Table 4.

This is the last stop. From here you may proceed north on NM 117 to Interstate 40 and then east to Albuquerque. As you drive east on the interstate, note basalts in the valley east of Laguna Pueblo. These flows are generally believed to be the distal end of the Laguna flow that were examined at Stop 2 and that originated from El Calderon. Detailed geochemical/geochronological/paleomagnetic investigations by the University of New Mexico/Los Alamos National Laboratory staff have been started to test the El Calderon/Laguna flow/Laguna Pueblo flow correlation.

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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}
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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