Geologic Excursions in Volcanology, GSA Guidebook – Part III

UGMS Special Studies 61, 1983

Geologic Excursions in Volcanology: Eastern Snake River Plain (Idaho) and Southwestern Utah

GUIDEBOOK – PART III

The Geological Society of America
Rocky Mountain and Cordilleran Sections Meeting
Salt Lake City, Utah
May 2 - 4, 1983

WILLIAM P. NASH
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Editor

UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
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Editor's Note: The papers contained in this Guidebook were solicited by the organizers of the GSA Rocky Mountain and Cordilleran Sections and have been edited and given a common format; however, their style and content have not been formally reviewed by the Utah Geological and Mineral Survey.

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HOLOCENE BASALTIC VOLCANISM ALONG THE GREAT RIFT, CENTRAL AND EASTERN SNAKE RIVER PLAIN, IDAHO

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Part I: Craters of the Moon lava field and the northern part of the Great Rift

Part II: Kings Bowl and Wapi lava fields and the southern part of the Great Rift

INTRODUCTION

The Snake River Plain is an arcuate topographic depression, 50 to 100 km wide, that extends from near Payette, Idaho, on the west, for about 250 km southeast to Twin Falls, and then for about 300 km northeast to near Ashton, Idaho (Figure 1). It is bounded on the north by Mesozoic and early Tertiary granitic rocks of the Idaho batholith and by basin-range, block-faulted mountains that were uplifted in Tertiary and Quaternary time. It is bounded on the southeast by basin-range, block-faulted mountains that also were uplifted in Tertiary and Quaternary time. It is bounded on the southwest by Tertiary rhyolitic and basaltic rocks of the Owyhee Plateau. Upper Tertiary and Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau are present at the northeast end of the plain. Geologists and geophysicists traditionally have divided the Snake River Plain into eastern, central, and western parts based on different geological histories and geophysical features in each part (Mabey, 1976, 1978).

The central and eastern parts of the Snake River Plain constitute a broad, flat, lava plain consisting, at the surface, of basalt lava flows of the Snake River Group and thin discontinuous interbedded loess, eolian sand, and alluvial fan deposits that together have a total thickness of about 1 to 2 km near the area described in the present report (Zohdy and Stanley, 1973; Stanley and others, 1977; Doherty and others, 1979). Flows of the central and eastern Snake River Plain were erupted from low volcanic vents that generally are aligned with, and parallel to, volcanic rift zones that trend mainly at right angles to the axis of the eastern Snake River Plain. A volcanic rift zone is a narrow belt of faults, grabens, noneruptive fissures, eruptive fissures, spatter cones, spatter ramparts, cinder cones, lava cones, pit craters, and shield volcanoes. Most vents in volcanic rift zones are elongated and overlie eruptive fissures. Well defined volcanic rift zones of the Snake River Plain are as much as 10 km wide and 120 km long. The Great Rift is the best example of a volcanic rift zone in the Snake River Plain.

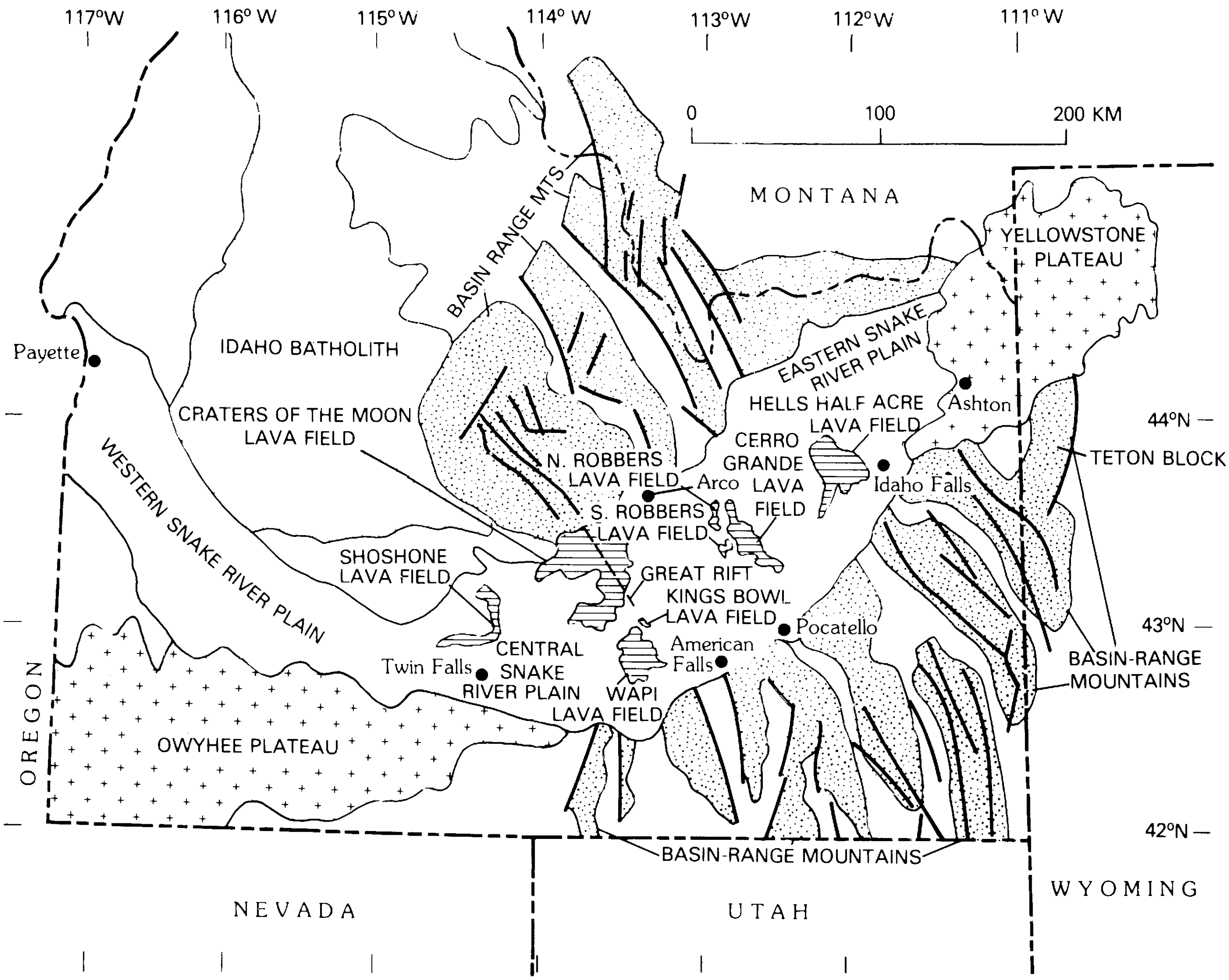


Figure 1. Index map showing generalized geology of southern Idaho and localities referred to in the text.

In the central and eastern Snake River Plain, the dominantly basaltic volcanism represents the latest phase of a complex tectonic and volcanic history characterized by an earlier phase of dominantly rhyolitic pyroclastic volcanism. Available geological, geophysical, radiometric, and drilling data suggest that the rhyolitic rocks were erupted from successive northeast-trending calderas. The earliest calderas formed about 15 m.y. ago near Twin Falls and were succeeded by progressively younger calderas northeastward to Yellowstone National Park. Models describing the formation of the belt of calderas are discussed by Armstrong and others (1975), Eaton and others (1975), Christiansen and McKee (1978), and Mabey and others (1978).

At least eight basaltic lava fields in the central and eastern Snake River Plain are known, or believed, to be less than 20,000 yrs old; they are the Shoshone, Craters of the Moon, Kings Bowl, Wapi, North Robbers, South Robbers, Cerro Grande, and Hells Half Acre lava fields (Figure 1). This two-day field trip will visit remarkable examples of Holocene to latest Pleistocene basaltic lava flows and vents in the Craters of the Moon (COM), Kings Bowl, and Wapi lava fields.

The COM lava field, located on the northern part of the Great Rift, includes more than 60 lava flows and flow units, more than 25 cinder cones, and at least eight eruptive fissures and fissure systems. The field covers an area of 1,600 km^2, contains more than 30 km^3 of lava, and is the largest basaltic lava field of dominantly Holocene age in the conterminous United States. COM lava flows were erupted during eight eruptive periods that began about 15,000 and ended about 2,100 yrs ago.

The Kings Bowl lava field is small (3.3 km^2, 0.01 km^3) and consists of flows erupted during a single fissure eruption on the southern part of the Great Rift about 2,250 yrs ago.

The Wapi lava field is a low shield volcano that covers an area of about 330 km^2 and contains about 6 km^3 of lava. It also erupted about 2,250 yrs ago on the southern part of the Great Rift.

The first day begins at Idaho Falls, Idaho, in the northeastern part of the plain, and proceeds westward, across the entire width of the eastern Snake River Plain (ESRP), to Craters of the Moon National Monument (COMNM) near Arco, Idaho. Most of the volcanic vents in the Craters of the Moon (COM) lava field are aligned along the northern part of the Great Rift and are located within the COMNM. To be examined are vents and related lava flows of the youngest (2,100 ± yrs old) eruptive period of the COM lava field. To be emphasized are dating and correlation methods used in establishing the volcanic history of the COM lava field, the volcanic and structural history of the northern part of the Great Rift, and the chemical diversity and evolution of the COM lavas. A traverse from COMNM, southeastward across the ESRP to Pocatello, Idaho, will end the first day. The second day will be spent examining volcanic features at the Kings Bowl and Wapi lava fields on the southern part of the Great Rift.

14he ideas and data to be presented on the field trip have been formulated and collected by our colleagues and ourselves during the last ten years. The work was supported by the USGS, DOE, and NASA, and is still in preliminary form and subject to further interpretation. We especially thank Elliott Spiker and Meyer Rubin of the USGS for their aid in radiocarbon dating, and Ron Greeley, Arizona State University, for his counsel in helping us reconstruct the volcanic history of the Kings Bowl and Wapi lava fields.

PART 1: CRATERS OF THE MOON LAVA FIELD AND THE NORTHERN PART OF THE GREAT RIFT

By Mel A. Kuntz, Richard H. Lefebvre, and Duane E. Champion

RADIOCARBON DATING AND EVOLUTION OF THE COM LAVA FIELD

Early studies of the COM lava field (Stearns, 1928; Murtaugh, 1961) outlined the general stratigraphic relations among lava flows. Later studies (Prinz, 1970; Valastro and others, 1972; Lefebvre, 1975; Kuntz and others, 1980; 1982a; 1982b) refined previously established stratigraphy, produced detailed geologic maps of the lava field, and attempted to date key flows by the radiocarbon method. Samples for radiocarbon studies include charcoal from tree molds and organic material in sediment buried by flows. The radiocarbon and stratigraphic data indicate that the COM lava field formed during at least eight eruptive periods (H, the oldest, through A, the youngest) that began about 15,000 and ended about 2,100 yrs ago. Each eruptive period was probably only a few tens of years or possibly a few hundred years long. Eruptive periods were separated by intervals of quiesence that lasted a few hundred to a few thousand years. Only one or a few flows in each eruptive period have been dated. Thus, the duration of each eruptive period is not established. Figure 5 shows the evolution of the COM lava field through the eight eruptive periods. Individual lava flows, their source vents, and the approximate ages of each eruptive period are listed in Table 1.

Volcanic features to be viewed on the first day of the trip are chiefly those of the youngest eruptive period (A) of the COM lava field.

PALEOMAGNETIC STUDIES

Paleomagnetic measurements have been used to correlate and approximately date lava flows and groups of flows to aid in deciphering the volcanic history of the lava fields along the Great Rift. Lava flows record the local geomagnetic field at the time of eruption and cooling. Geomagnetic field changes due to secular variation occur at a geologically rapid rate (4°/century, Champion and Shoemaker, 1977) and thus permit assignment of lava flows to groups that have similar paleomagnetic direction.

Table 1. Eruptive periods, approximate age of eruptive periods, informal names of lava flows of upper part of Snake River Group, and source vents for lava flows in the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Eruptive period	Approx. age	Informal name and lava type of major flows*	Source vents (queried where uncertain)
A	2,100 to 2,300 yrs B.P.	Broken Top (p)	Eruptive fissures, east and south flanks of Broken Top cinder cone
		Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone complex
		Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cones
		North Crater (p)	North Crater cinder cone
		Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
		Kings Bowl (p)	Fissure vents north and south of Kings Bowl
		Wapi (p)	Vents at Pillar Butte
		Serrate (a-b)	North Crater cinder cone (?)
		Devil's Orchard (a-b)	North Crater cinder cone (?)
		Highway (a-b)	North Crater cinder cone (?) or tholoid vent (?) between Grassy Cone and Sunset Cone cinder cones
B	3,500 to 4,500 yrs B.P.	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
		Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
		Devil's Cauldron (p)	Devil's Cauldron
		Minidoka (p)	Obscure vents about 5 km northeast of New Butte cinder cone
		Larkspur Park (p)	
		Rangefire (p)	Black Top Butte cinder cone (?)
C	5,800 to 6,200 yrs B.P.	Indian Wells north (a)	Big Cinder Butte cinder cone (?)
		Indian Wells south (a)	Big Cinder Butte cinder cone (?)
		Sawtooth (a)	Big Cinder Butte cinder cone (?)
		South Echo (p)	Eruptive fissures south of Echo Butte cinder cone
		Sheep Trail Butte (p-a)	Sheep Trail Butte cinder cone
		Fissure Butte (p-a)	Fissure Butte cinder cone
		Sentinel (p)	The Sentinel cinder cone
D	About 6,600 yrs B.P.	Silent Cone (a)	Silent Cone cinder cone
		Carey Kipuka (a)	Silent Cone cinder cone (?)
		Little Park (a)	Silent Cone cinder cone (?)
		Little Laidlaw Park (a)	Silent Cone cinder cone (?)
E	7,300 to 7,900 yrs B.P.	Grassy Cone (p)	Grassy Cone cinder cone
		Laidlaw Lake (p)	Grassy Cone cinder cone
		Lava Point (a)	Great Rift northwest of Echo Crater cinder cone (?)
F	10,000 to 11,000 yrs B.P.	Pronghorn (p)	Great Rift near Sheep Trail Butte cinder cone
		Bottleneck Lake (p)	Great Rift near Sheep Trail Butte cinder cone
		Heifer Reservoir (p)	Great Rift near Crescent Butte cinder cone
G	12,000 to 12,900 yrs B.P.	Sunset (p)	Sunset Cone cinder cone
		Carey (p)	Sunset Cone cinder cone
		Lava Creek (p-a)	Vents near Lava Creek
H	About 15,000 yrs B.P.	Kimama (p)	unknown
		Bear Den Lake (p)	unknown
		Baseline (p)	unknown
		Little Prairie (p)	unknown — Echo Crater and (or)
		Lost Kipuka (p)	unknown — Crescent Butte cinder cones(?)
		No Name (p)	unknown
		Brown flow (p)	unknown

*(p) Chiefly pahoehoe flows (a-b) aa' and block flows
(a) chiefly aa' flows (p-a) pahoehoe and aa' flows

Conversely, dissimilar paleomagnetic directions suggest that two lava flows do not belong to the same group.

Paleomagnetic studies have helped to solve difficult stratigraphic problems for the COM lava field. For example, we thought initially that all thick aa flows in the southern part of the COMNM were erupted in the same eruptive period from a source vent at or near Big Cinder Butte. Paleomagnetic inclination data indicate two distinct eruptions of aa lava flows from at least two source vents. Thus, we recognized groups of aa flows in eruptive periods C and D from source vents at Big Cinder Butte and Silent Cone (Table 1). Petrochemical data and radiocarbon ages led us to split one of these two aa groups into two additional groups; initially we placed the Lava Point aa flows in eruptive period D, now we place it in period E (Table 1). Because they have identical paleomagnetic field directions, we correlate the Sunset and Carey flows that moved northeast and southwest, respectively, from the northern part of the Great Rift. Without the paleomagnetic data, we had assumed originally that the Carey and Sunset flows represented separate eruptions from separate source vents.

PETROGRAPHY AND CHEMICAL COMPOSITION OF COM LAVAS

Snake River Plain basalts are texturally, mineralogically, and chemically uniform (Stone, 1967). The basalts are olivine tholeiites that consist typically of olivine (Fo_{80-50}), plagioclase (An_{70-50}), ferroaugite, titanomagnetite, ilmenite, and brown glass. An average chemical composition from 37 analyses is given in Table 2.

COM flows differ significantly from typical Snake River Plain basalt (Table 2). COM lavas contain phenocrysts of olivine (Fo_{50-10}), plagioclase (An_{60-40}), brown clinopyroxene, titanomagnetite, ilmenite, and brown glass. Some contain orthopyroxene and apatite. Evolved basalts (i.e., greater than about 52 percent SiO_2) contain xenoliths and xenocrysts of corroded anorthoclase, plagioclase (An_{55-15}), green clinopyroxene, olivine (Fo_{25-10}), and zircon. Average chemical analyses of several different types of COM flows are listed in Table 2 to illustrate the degree of chemical variability. These flows range from alkali basalt to latite in the nomenclature of Cox and others (1979). Note in Table 2 that the most primitive COM flows (columns 2, 3, 9, 12) differ from the average Snake River Plain olivine tholeiite in that they have more TiO_2, total iron, Na_2O, K_2O, and P_2O_5, and less MgO and CaO.

Evolved COM flows first were erupted about 6,600 yrs ago in eruptive period D (Figure 6) and continued to be erupted, along with more primitive flows, in eruptive periods C, B, and A.

VOLUMES OF LAVA

Stratigraphic relations, areal extent, thicknesses, and radiocarbon ages of COM lava flows, give the data plotted in Figure 7. The age and volume data reveal that volcanism along the northern part of the Great Rift is volume-predictable, i.e., the volume of each eruption is a function of the elapsed time between it and the preceding eruption. This relationship has implications to the regional stress field and the magma plumbing system.

In Figure 7, the break in slope of line 2-2′ from line 1-1′ coincides with the marked change in composition of COM lavas beginning at eruptive period D. We attribute the increased rate of volcanism since 6,600 yrs ago to the addition of supplies of evolved (SiO_2 less than 52 percent) lava to the nearly constant rate supply of non-evolved ($SiO_2 >$ 52 percent) lava over the last 15,000 yrs.

FIELD TRIP ROAD LOG: FIRST DAY

Idaho Falls to Craters of the Moon National Monument to Pocatello

STOP 1 is for an overview of the regional geography and geology of the ESRP. Older lava flows (about 12,000 yrs old) of the COM lava field, that are not well exposed within COMNM, will be viewed at STOP 2. The remaining three stops will be in COMNM. These stops are selected to study features produced during the latest (2,100 yrs old) eruptions along a 10-km segment of the Great Rift. STOPS 3, 4, and 5 require short (a few kilometers) walks over terrain that has a relief of 50 to 75 m. Despite trails, sturdy shoes or boots are recommended. A small canteen of water is recommended also but is not absolutely necessary. Hammers are unnecessary in the Monument; rock collecting is prohibited.

Mileage Incremental	Mileage Cumulative	Description
0.0	0.0	Start of road log. Junction U.S. Highway 20 and I-15 in Idaho Falls, Idaho. Proceed west on U.S. 20. Road crosses loess-

Table 2. Average chemical analyses of Snake River Plain basalts and other selected, informally named, lava flows from the Craters of the Moon lava field, Idaho (data for COM, Kings Bowl, and Wapi lava flows from Leeman and others [1976] and unpublished analyses by the U.S. Geological Survey).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SiO_2	46.59	45.32	44.27	46.87	46.02	46.20	46.32	55.84	44.55	56.29	48.76	45.84	63.25	58.22	51.00	50.37	49.08	45.85	45.98	46.77
TiO_2	2.77	3.24	3.86	3.12	3.19	3.48	3.14	1.72	3.65	1.51	2.89	3.22	0.56	1.21	2.53	2.49	2.71	2.27	2.54	3.02
Al_2O_3	14.80	14.22	13.80	13.78	13.66	13.46	12.98	13.95	13.56	14.67	13.81	14.14	14.57	14.17	13.93	13.99	13.83	14.94	15.59	14.99
Fe_2O_3	2.14	1.79	2.23	2.57	1.29	1.61	2.30	1.65	1.90	1.59	1.19	1.77	1.04	1.20	1.60	1.40	2.04	1.74	1.55	1.06
FeO	11.58	14.66	14.49	14.05	14.74	14.34	14.81	10.54	14.35	10.51	14.25	13.11	7.24	9.92	13.34	14.11	13.61	11.10	11.06	12.66
MgO	7.71	4.26	5.07	3.84	4.09	4.30	4.12	1.59	5.12	1.65	3.61	5.99	0.26	1.10	2.88	3.12	3.29	9.95	8.01	6.54
CaO	9.69	7.65	8.34	7.35	7.70	7.96	7.86	4.96	8.85	4.61	7.05	9.91	2.96	4.08	6.62	6.77	6.89	10.20	10.49	9.12
MnO	0.20	0.26	0.27	0.29	0.26.	0.24	0.27	0.20	0.25	0.21	0.24	0.24	0.19	0.19	0.28	0.29	0.26	0.19	0.18	0.20
Na_2O	2.44	3.35	3.33	3.70	3.61	3.23	3.33	3.70	3.21	4.07	3.54	2.89	4.13	4.02	3.50	3.50	3.59	2.53	2.27	2.57
K_2O	0.63	1.73	1.58	2.02	1.89	1.68	1.85	2.93	1.53	3.19	2.02	1.23	4.80	3.66	2.24	2.08	2.04	0.45	0.64	0.83
P_2O_5	0.58	2.62	2.45	2.13	2.33	2.40	2.26	0.94	2.52	0.77	2.03	2.06	0.11	0.55	1.61	1.53	1.68	0.57	0.69	0.68
CO_2	0.03	0.09	0.09	0.03	0.07	0.10	0.03	0.03	0.10	0.06	0.08	0.03	0.02	0.06	0.04	0.01	0.07	0.02	0.01	0.32
H_2O^+	0.40	0.88	0.19	0.23	0.28	0.57	0.43	0.35	0.29	0.17	0.49	0.25	0.24	0.30	0.29	0.23	0.34	0.16	0.15	0.17
Total	**99.56**	**100.07**	**99.97**	**99.98**	**99.13**	**99.57**	**99.70**	**98.40**	**99.88**	**99.30**	**99.96**	**100.68**	**99.37**	**98.68**	**99.86**	**99.89**	**99.43**	**99.97**	**99.61**	**98.93**

1. Average of 37 analyses of Snake River Plain basalts (Stone, 1967).
2. Kimama flow, eruptive period H (average of 2 analyses).
3. Lava Creek flow, eruptive period G (average of 15 analyses)
4. Sunset flow, eruptive eriod G (average of 5 analyses)
5. Pronghorn flow, eruptive period F (average of 3 analyses)
6. Lava Point flow, eruptive period E (average of 5 analyses)
7. Grassy Cone flow. eruptive period E (average of 4 analyses)
8. Silent Cone flow, eruptive period D (average of 3 analyses)
9. Sheep Trail Butte flow, eruptive period C (average of 4 analyses)
10. Sawtooth flow, eruptive period C (average of 4 analyses)
11. Minidoka flow, eruptive period B (average of 5 analyses)
12. Vermillion Chasm flow, eruptive period B (average of 2 analyses)
13. Highway flow, eruptive period A (average of 7 analyses)
14. Serrate flow, eruptive period A (average of 6 analyses)
15. Big Craters flow, eruptive period A (average of 12 analyses)
16. North Crater flow, eruptive period A (average of 3 analyses)
17. Blue Dragon flow, eruptive period A (average of 9 analyses)
18. Kings Bowl lava field (average of 3 analyses)
19. Wapi lava field (average of 3 analyses)
20. Hells Half Acre lava field (Karlo, 1977)

and alluvium-covered Snake River Plain basalt with only local exposures of the flows.

2.5 2.5 Osgood Road intersection; continue on U.S. 20.

1.0 3.5 Shelley-New Sweden Road intersection. Continue on U.S. 20 over irregular topography of hummocky flow surfaces mantled by loess.

2.7 6.2 Skyline Gun Club on right. Road begins ascent of Rifle Range Butte flows.

2.0 8.2 One of several vents in the Rifle Range Butte vent complex on right.

1.7 9.9 Highway leaves surface of Rifle Range Butte flows and continues west onto the older Butterfly Butte flows (drainage follows contact). More subdued topography of Butterfly Butte flows is due, in part, to thicker loess rather than for younger Rifle Range Butte flows.

3.2 13.1 Brunt Road intersection; continue on U.S. 20. At 4:00 is North Butte, a low shield volcano.

2.0 15.1 Intersection with unnamed road just over crest of hill. Features to be viewed at this locality, in a counterclockwise direction, include: 2:00 Kettle Butte, a low shield volcano; 1:30 south end of the Lemhi Range in far distance; 12:30 Lost River Range in far distance; 11:00 East Butte, a rhyolite dome; 10:30 Big Southern Butte, a rhyolite dome; 10:00 highest point marks an extremely broad, low shield volcano that constitutes the Hells Half Acre lava field. The lava field is the dark sage- and cedar-covered area on the horizon south of the highway.

		The knobs to the south of the apex of the shield are spatter cones along the Hells Half Acre eruptive fissure system. This fissure system is represented by a set of open cracks that extends northwest from the northwest edge of the lava field (see Figure 3).
0.6	15.7	Road to left leads to Seventeenmile Cave, an opening (skylight) in a lava tube in Butterfly Butte flow. Just beyond road to cave, highway crosses contact onto flows from vent at Kettle Butte.
3.5	19.2	Mile marker 288. Road to right leads to a skylight entrance, about 4 mi north of highway, in a lava tube in Kettle Butte flow. The area is known as "Owl Cave," or the Wasden archeological site. Faunal materials include bison, mammoth, camel, pronghorn, grizzly bear, wolf, and other animals. Fluted points and bone tools suggest that the rock shelter was used by bison and mammoth hunters as long ago as 12,500 yrs B.P. (S. J. Miller, written communication, 1975).
1.1	20.3	Twentymile Rock is 1/8 mi off road to left. This northernmost exposure of the Hells Half Acre field is now a National Historic Site and was a landmark to early settlers as they crossed the eastern Snake River Plain.
0.9	21.2	Highest point on skyline to left (south) is the vent area for the Hells Half Acre lava field (see Figure 2).
1.6	22.8	Small lava cone at 3:00.
5.0	27.8	Road to right leads to crest of Microwave Butte. Microwave Butte is at the intersection of the axis of the ESRP and the Lava Ridge-Hells Half Acre volcanic rift zone (see Figure 2). At 10:00 to 11:00 are East Butte, Middle Butte, and Big Southern Butte rhyolite domes that project above surrounding basalt lava flows. The three rhyolite domes are discussed in more detail at STOP 1.
2.4	30.2	Road to left leads to television transmitters atop East Butte.
0.1	30.3	Boundary of Idaho National Engineering Laboratory (INEL). INEL, formerly called the National Reactor Testing Station, was established in 1949, so that the U.S. Atomic Energy Commission (AEC), later the Energy Research and Development Administration (ERDA) and now the Department of Energy (DOE), could build, operate, and test various types of nuclear reactors. More than 50 reactors have been built to date. INEL occupies 894 mi^2 (2320 km^2).
0.7	31.0	Road to right leads to Argonne National Laboratory reactor and related facilites (see Figure 2, "ANL").
0.5	31.5	Small tree-covered hill on horizon, to right of East Butte (9:00), marks top of unnamed, low rhyolite dome that is mostly covered by basalt lava flows. Basalt flows that dip south cap Middle Butte.
5.8	37.3	Small unnamed lava cone at 3:00.
0.4	37.7	Cedar Butte at 10:30, left of Big Southern Butte.
2.3	40.0	Road to right leads to Auxiliary Reactor area.

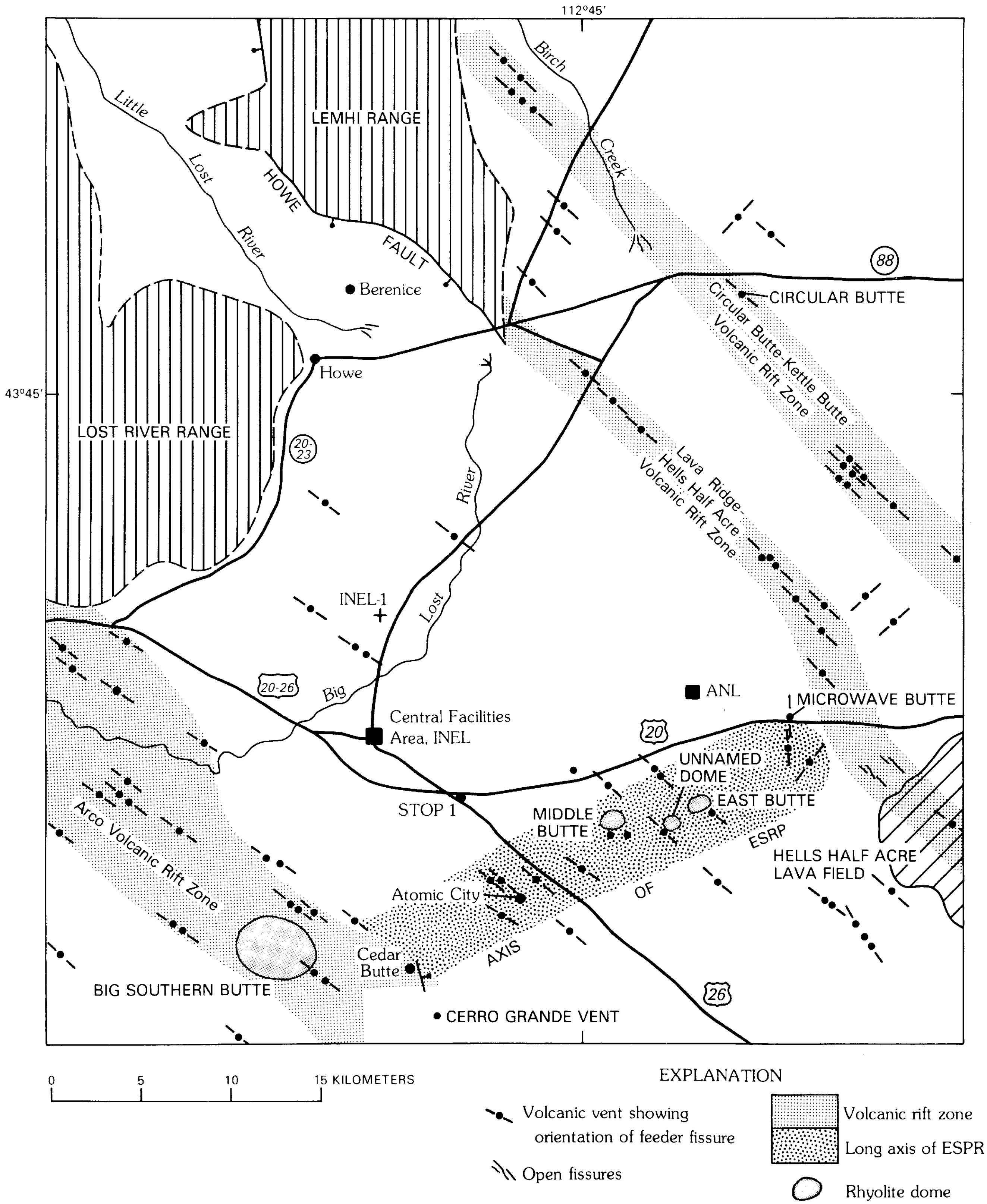


Figure 2. Map showing volcanic and structural features in the central part of the eastern Snake River Plain, Idaho (modified from Kuntz and Dalrymple, 1979).

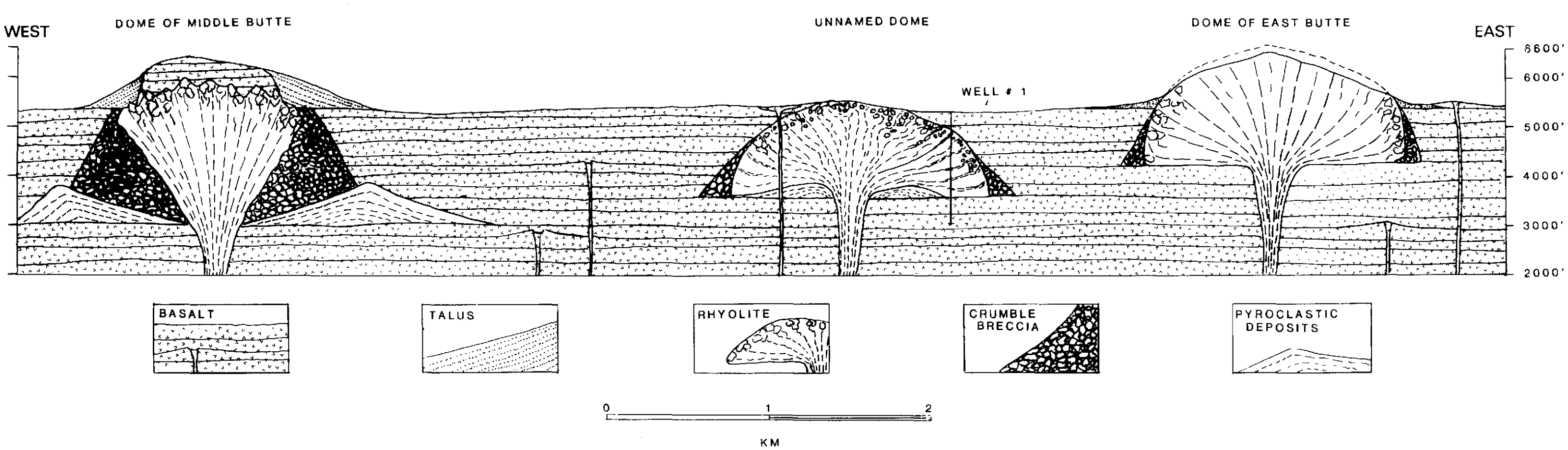


Figure 3. East-west cross section through rhyolite domes at East and Middle Buttes, Idaho (from Kuntz and Dalrymple, 1979)

2.1 42.1 Highway descends onto Rye Grass Flat.

1.2 43.3 **STOP 1.** Turn left and park in lot next to piles of gravel. This stop is designed to review the origin and volcanic history of the ESRP, as outlined in the Introduction. The local geology, including East, Middle, and Big Southern Buttes, will be pointed out and related to the regional geologic framework. Climb to the top of the pile of road metal, face south, and note the following landmarks: 9:00 East and Middle Buttes are the two steep-sided hills that rise as much as 350 m above the surrounding basalt-lava-covered terrane. An unnamed hill, about 1 km southwest of East Butte, represents the apex of another rhyolite dome (see Figures 2 and 3). Rhyolite lava flows and breccias are exposed at East Butte and at the unnamed hill, but not at Middle Butte. The steep sides of Middle Butte are covered by thick accumulations of talus composed of blocks that have been dislodged from the approximately 75-m-thick layer of basalt lava flows that cap the butte. However, magnetic and gravity data suggest that the core of Middle Butte consists of rock that is less dense and less magnetic than basalt, and is probably rhyolite (Don Mabey, USGS, oral communication, 1978). These factors and the structural data described below all indicate that the three hills are the upper parts of rhyolite domes. Figure 2 is an east-west cross section through Middle and East Buttes that is based on mapping, a drill core (see Figure 3, well no. 1), and interpretation of geophysical data. K-Ar ages for the rhyolite domes are given in Table 3.

The internal structure of East Butte is known from study of the orientation of the flow layering in its rhyolite lava flows. The flow banding generally defines inward- dipping, concentric layers similar to those of a short, stubby carrot or the lower half of an elongated onion. Flow layering parallel to an original upper surface occurs in many rhyolite domes but only locally at East Butte. The orientation of flow layering suggests that East Butte is a protrusion of lava that was too viscous to flow, and that the magma rose as inclined concentric sheets (Kuntz and Dalrymple, 1979).

12:00 Cedar Butte (Spear, 1979) is a unique volcanic complex on the ESRP. The vent area consists of a circular pyroclastic cone more than 100 m high and 1.2 km in diameter and an elongated arcuate vent, 1 km long and 30 to 60 m high. The arcuate vent extends north-northwest from the base of the pyroclastic cone. Field and petrographic data show that the two vents were active at different times; the pyroclastic cone is younger. Lava flows at Cedar Butte have a range in SiO_2 content from 54 to 67 percent; thus they are compositionally similar to flows of the COM lava field. A K-Ar age on a flow from Cedar Butte is 400,000 yrs (Kuntz, 1978).

1:30 Big Southern Butte (Spear, 1979) is the most prominent landmark in the ESRP; it rises 760 m above the surrounding lava plain. The butte is oval in plan, about 6.5 km in longest dimension, and elongated in a northwest-southeast direction. Big South-

Table 3. Potassium-argon ages of rhyolite domes in eastern Snake River Plain, Idaho (from Kuntz and Dalrymple, 1979).

Rhyolite dome	Age	Reference
East Butte	0.58 ± 0.09 m.y.	Armstrong and others (1975)
Middle Butte	Rhyolite not exposed; basalt flow capping butte is 1.9 $^{+}$ 1.2 m.y.	Armstrong and others (1975)
Unnamed dome between Middle Butte and East Butte	1.42 ± 0.02 m.y.	Kuntz and Dalrymple, (1979)

ern Butte is a volcanic dome complex that consists of two coalesced cumulo-domes. A 350-m-thick section of basaltic lava flows is exposed on the north flank of the butte. The basalt section was uplifted and tilted by the rise of the volcanic dome. Three K-Ar ages and one fission-track age show that Big Southern Butte is about 300,000 yrs old (Kuntz, 1978).

Faults, grabens, Big Southern Butte, Cedar Butte, and the vent for the Cerro Grande lava field are structural and volcanic features that define the Arco volcanic rift zone (Figure 2). A electrical sounding profile across the ESRP from Blackfoot to Arco (Zohdy and Stanley, 1973) suggests an upper crustal structure in this area that consists of an upper layer, 1.5 to 5 km thick, of basaltic rocks, and a lower layer of sedimentary and rhyolitic rocks of unknown thickness. A 3,160-m-deep exploratory geothermal test well (INEL-1, see Figure 2) was drilled at INEL in 1978 (Doherty and others, 1979). More than 2,400 m of rhyolite ash flow tuffs, rhyolite lava flows, and interbedded air-fall ash material are present in the lower part of the well. Less than 1 km of basaltic lava flows and interbedded continental sediments overlie the rhyolite section. Doherty and others (1979) concluded that the well penetrated caldera fill material. The geographic relations of the Arco volcanic rift zone, the axis of the ESRP, the Lava Ridge-Hells Half Acre volcanic rift zone, and other localities near this stop, that are referred to in the text, are shown in Figure 3.

0.1	43.4	Return to highway and head west (left). Junction U.S. Highways 20 and 26. Continue west on combined Highways 20-26 toward Arco. Highway 26 to left leads to Blackfoot.
4.3	47.7	Highway now on alluvium of Big Lost River.
1.1	48.8	Road to left leads to EBR-1 (Experimental Breeder Reactor-1), the first reactor built at INEL. Construction of EBR-1 was begun in 1949 to test a plutonium-fueled reactor for electrical power generation. The reactor was decommissioned in 1964, and in 1966 the facility was designated a Registered National Historic Landmark open to the public.
0.5	49.3	Borrow pit to left in alluvial gravels of Big Lost River.
1.0	50.3	Big Lost River Rest Area on left. Highway leaves Big Lost

		River flood plain west of rest area.
3.3	53.6	Crater Butte at 11:00.
4.5	58.1	Road to left leads to spectacular crater vent in Crater Butte.
0.6	58.7	Tumuli in flows from Crater Butte to right.
0.5	59.2	Leaving INEL.
0.2	59.4	Junction with Idaho State Highways 22 and 23. Continue on Highways 20-26.
1.7	61.1	Six Mile Butte, a broad shield volcano, at 9:00. Note profile of cinder cones along the Great Rift in Craters of the Moon National Monument at 10:00 (the largest cone is Big Cinder Butte). Pioneer Mountains, north of the COMNM, at 11:00-1:00. The Pioneer Mountains immediately north of COMNM consist chiefly of Eocene extrusive and intrusive rocks and Paleozoic, including Carboniferous sedimentary rocks (Skipp and Hait, 1977). For next several miles on right, note large, eastward verging folds in Carboniferous and Permian carbonate rocks in south-facing slopes of the Arco Hills (Skipp and Hait, 1977).
1.5	62.6	Highway now on alluvial fan formed by streams emerging from Arco Hills to right.
0.7	63.3	Butte City.
1.0	64.3	Railroad tracks.
2.1	66.4	Enter Arco.
0.5	66.9	Junction U.S. Highway 93. Turn left on main street of Arco.
1.7	68.6	Highway crosses the Big Lost River.
0.6	69.2	Highway rises up onto higher alluvial terrace along Big Lost River.
0.4	69.6	Arco Airport. Vent area for the Lost River Butte flows is at 2:30. The flow margin is north of the highway and continues for about 1 mi (1.6 km) past the airport. The Lost River Butte flows rests on gravel-size alluvium of the Big Lost River.
5.3	74.9	The low rounded flow front on the left is that of the Sunset flow of the COM lava field. The 12,000-yr-old Sunset pahoehoe flows traveled more than 17.5 km from a source vent at Sunset Cone in COMNM to this site. The Sunset flow margin is subparallel to the highway all the way to STOP 2.
1.2	76.1	Tongue of Sunset flow crosses highway.
1.5	77.6	Another tongue of Sunset flow crosses highway.
1.6	79.2	Outliers of Ordovician-Kinnikinic Quartzite at top of hill at 3:00.
0.4	79.6	Sign for "Rough Road."
0.2	79.8	Highway rises onto Lava Creek flow of the COM lava field.
0.3	80.1	Highway rises onto overlying Sunset flow, where it is in contact with the Lava Creek flow.
0.1	80.2	**STOP 2.** Turn off onto wide shoulder on right. Walk east

back to the contact of the Sunset and Lava Creek flows. At this, the first of four stops in the COM lava field, we will see the two oldest flows (of eruptive period G; see Table 1 and Figure 5) at the north end of the field and their source vents. Flows about 15,000 yrs old lie at the nearly inaccessible south end of the COM lava field. The Lava Creek flow was erupted about 12,600 yrs ago from the southernmost Lava Creek vent along the Great Rift within the Pioneer Mountains. The flow cascaded about 500 m in about one mile to the level of the Snake River Plain at the site of the old town of Martin. It then traveled as an aa flow past the site of STOP 2 until it reached a point about 19 km from its source.

The Sunset flow is approximately 12,010 yrs old. It erupted from Sunset Cone at the north end of the Craters of the Moon National Monument. The Sunset flow consists of pahoehoe and its surface is hummocky with pressure ridges and plateaus (look south of highway), collapse depressions, ropes, and squeeze-ups. The Sunset flow is progressively more ash covered toward COMNM because dominant westerly winds blew tephra onto it during succeeding eruptions from Sunset Cone.

Walk on the Sunset flow about 50 ft in from highway to observe the surface of this 12,000-yr-old pahoehoe flow. Blue glassy crust that is common on younger pahoehoe flows of the COM lava field is present here, but most has been obliterated by weathering, vegetation, and sediment cover.

The Lava Creek alkali basalt flow is hypocrystalline and ranges from microporphyritic to porphyritic. Phenocrysts are mainly olivine and plagioclase; the latter are common near the south vent. The Sunset flow is hypocrystalline and microporphyritic with microphenocrysts of olivine and plagioclase. Both the Sunset and Lava Creek flows represent the "primitive" eruptive products that are common in the early history of the COM lava field (Table 2).

1.4	81.6	Mile Post 234.
2.0	83.6	Mile Post 232. Junction with road to Blizzard Mountain to right. Flow with serrated profile on left is the Serrate flow. The jagged profile is due to cinder cone monoliths that the Serrate flow transported to the east when North Crater (in COMNM) was partially destroyed (to be discussed at STOP 3).
0.7	84.3	Boundary of Craters of the Moon National Monument.
0.7	85.0	On right and left sides of road are downwind cinder accumulations from Sunset Cone.
1.1	86.1	Entrance to Craters of the Moon National Monument, Visitors Center on left. Stop for snack and rest stop at Visitors Center, then follow the loop road into the Monument.
0.4	86.5	Entrance to campground. The cinder-covered latite block flow in the campground is one of the most felsic flows of the COM lava field, and it is con-

sidered to be part of the undated Highway flow (to be discussed at STOP 3).

0.1 86.6 Tongue of blue-crusted North Crater flow on left. This flow is one of several 2,100-yr-old basalt-hawaiite pahoehoe flows common along the loop road. We will visit the source of this flow in North Crater at STOP 3.

0.2 86.8 Turnout on right for North Crater flow trail. Continue on loop road, which crosses North Crater flow.

0.1 86.9 Turnout on right is at the east flank of North Crater. This is one of the trailheads to the North Crater-Spatter Cones trail. Continue on loop road.

0.4 87.3 Big Craters flow on right mantles the western flank of Paisley Cone. We will see the fissure vents for this pahoehoe and aa basalt-hawaiite flow at STOP 3. For the next 1.3 mi, the loop road follows the north, east, and south flanks of Paisley Cone.

0.2 87.5 Devils Orchard flow on left. This heavily cinder-covered latite block flow was thought by early workers to be quite old. We correlate it with the Highway and Serrate flows of eruptive period A (Table 1). The Serrate, Devils Orchard, and Highway flows are considered to be quite young on the basis of stratigraphic and paleomagnetic data, which will be discussed in more detail at STOP 3.

0.4 87.9 Entrance to Devils Orchard Nature Trail on left; continue on loop road.

0.1 88.0 Intersection with one-way loop drive; bear right.

0.2 88.2 Tongue of Big Crater flow on left in valley between Paisley Cone on right and Inferno Cone on left. The vents for this flow will be seen at STOP 3. Inferno Cone at 9:00, Big Craters cinder cone complex at 12:00, North Crater at 2:00.

0.6 88.8 Turnout to Inferno Cone parking lot.

0.2 89.0 Turn right on road to Spatter Cones parking lot.

0.1 89.1 **STOP 3.** Park in lot (vans return to Visitors Center). A 3.6-km walk to the Visitors Center will constitute STOP 3. The hike is designed to view eruptive features and vent areas along a part of the Great Rift that was active about 2,100 yrs ago. A segment of the Great Rift 10 km long, that extends from North Crater southeast to the Watchman cinder cone (Figure 4), was active at various times during the latest eruptive period (A) of the COM lava field. The hike begins at the Spatter Cones, traverses the west side of the Big Craters cinder cone complex, crosses into North Crater, extends along the North Crater flow, and ends at the highway fault near the Visitors Center. The vents to be seen on the walking tour produced about 3.5 km^3 of lava that now cover about 20 percent of the COM lava field. At about the same time as this activity, a rift segment of comparable length was active also and formed the Kings Bowl and Wapi lava fields to the south of the COM lava field (Figure 4). The Kings Bowl-Wapi area will be visited on the

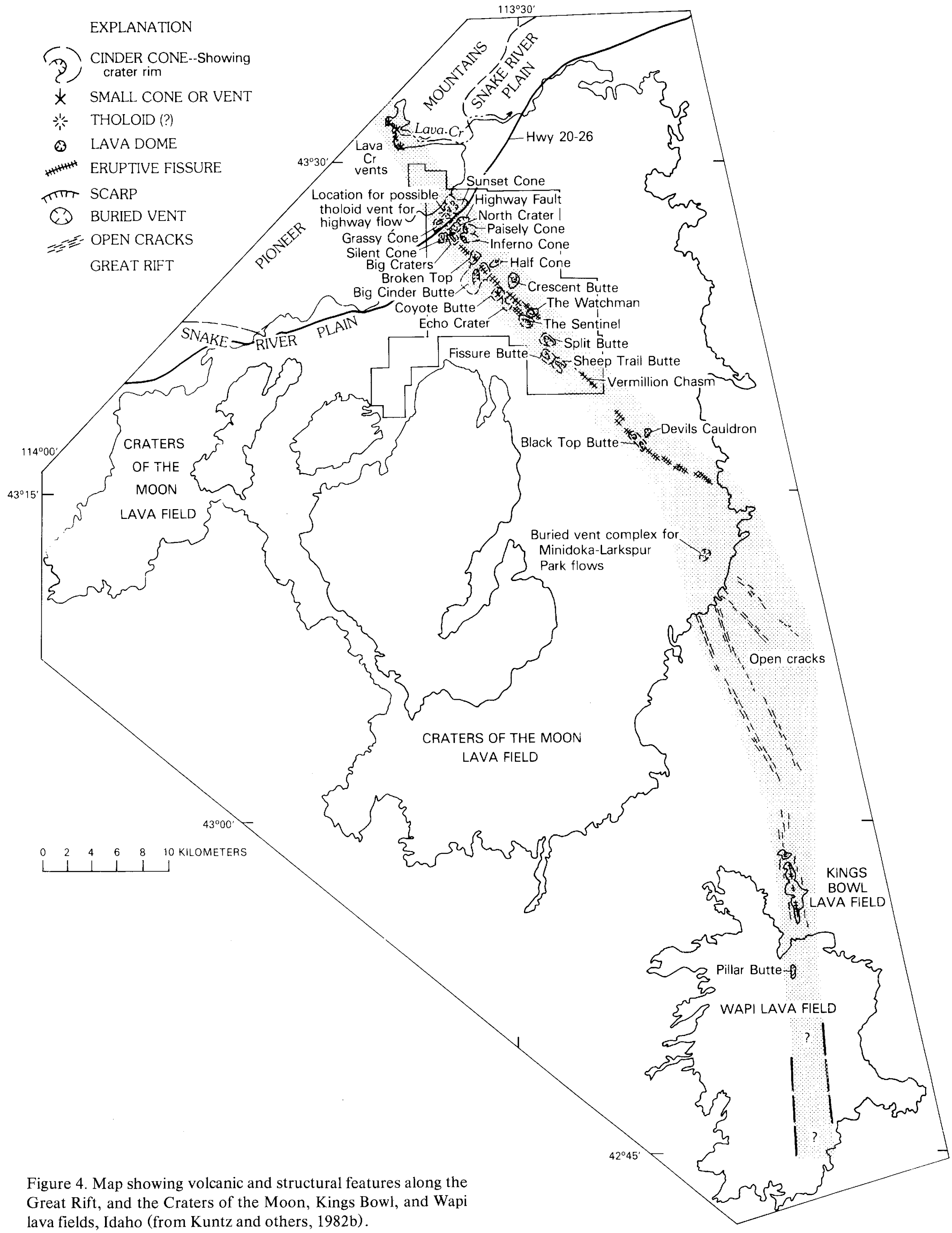


Figure 4. Map showing volcanic and structural features along the Great Rift, and the Craters of the Moon, Kings Bowl, and Wapi lava fields, Idaho (from Kuntz and others, 1982b).

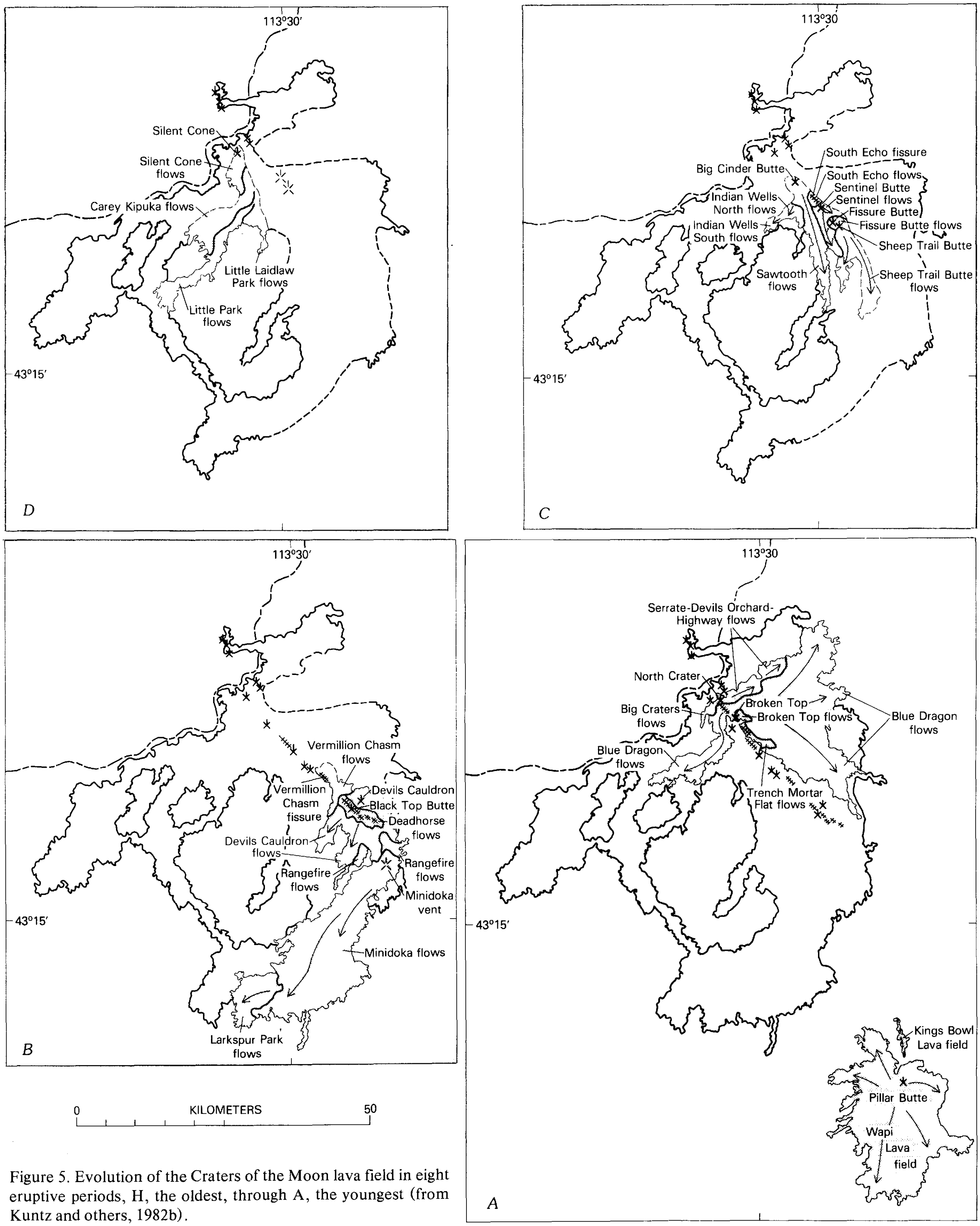
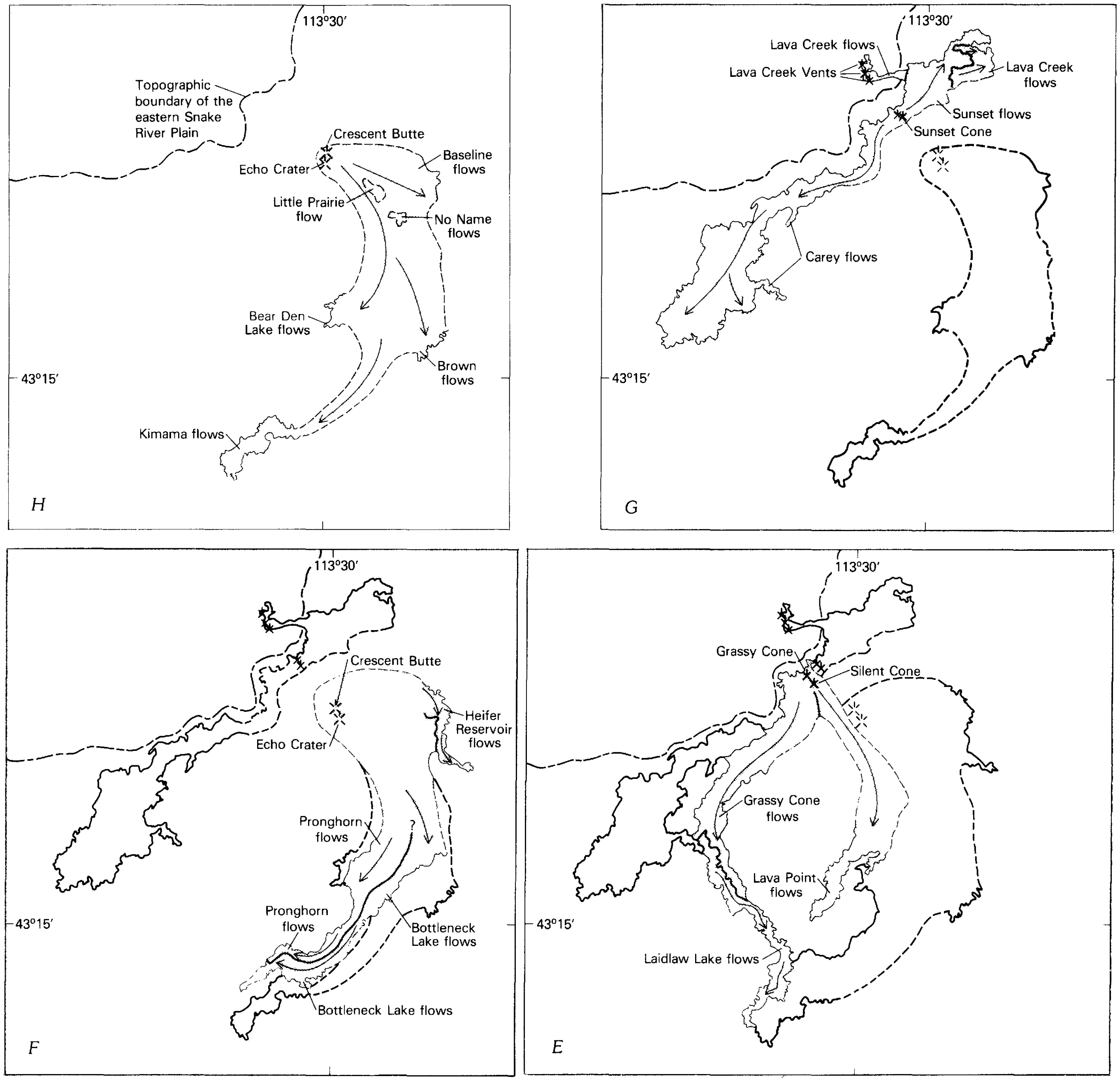


Figure 5. Evolution of the Craters of the Moon lava field in eight eruptive periods, H, the oldest, through A, the youngest (from Kuntz and others, 1982b).



second day of the field trip.

The Spatter Cones formed in the waning activity along a short (1-km-long) eruptive fissure that extends southeast of the south end of Big Craters cinder cone. Most of the lava that forms the extensive Blue Dragon flow was erupted from the Great Rift in the Spatter Cones area. After viewing one spatter cone, take trail to west that ascends to south end of the Big Craters cinder cone complex.

Big Craters is a cinder cone complex that contains at least nine nested cones. On the southwest rim, agglutinated spatter mantles the inner wall

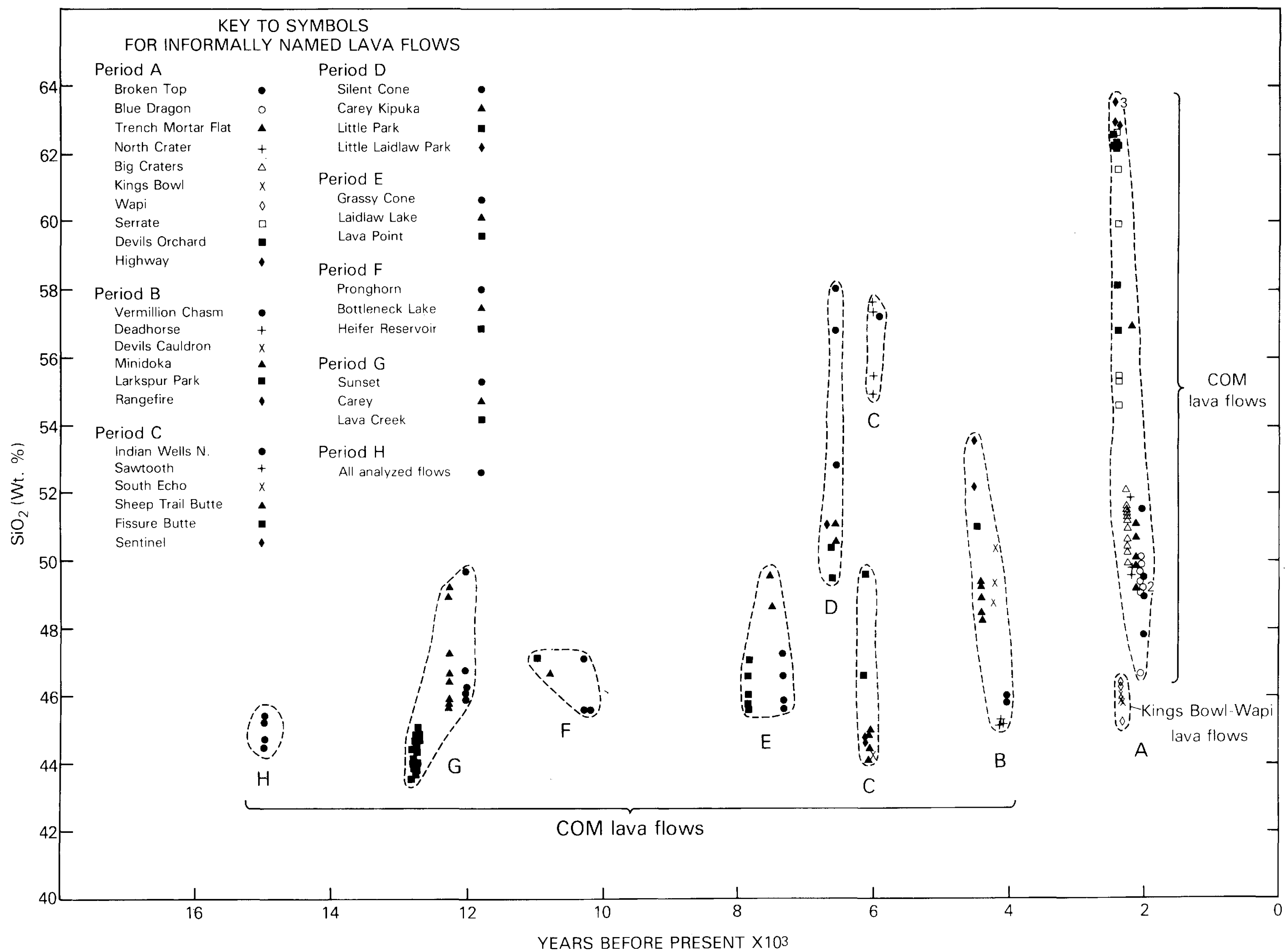


Figure 6. SiO_2 (weight percent) versus age of eruption for analysed rocks of the Craters of the Moon, Kings Bowl, and Wapi lava fields, Idaho.

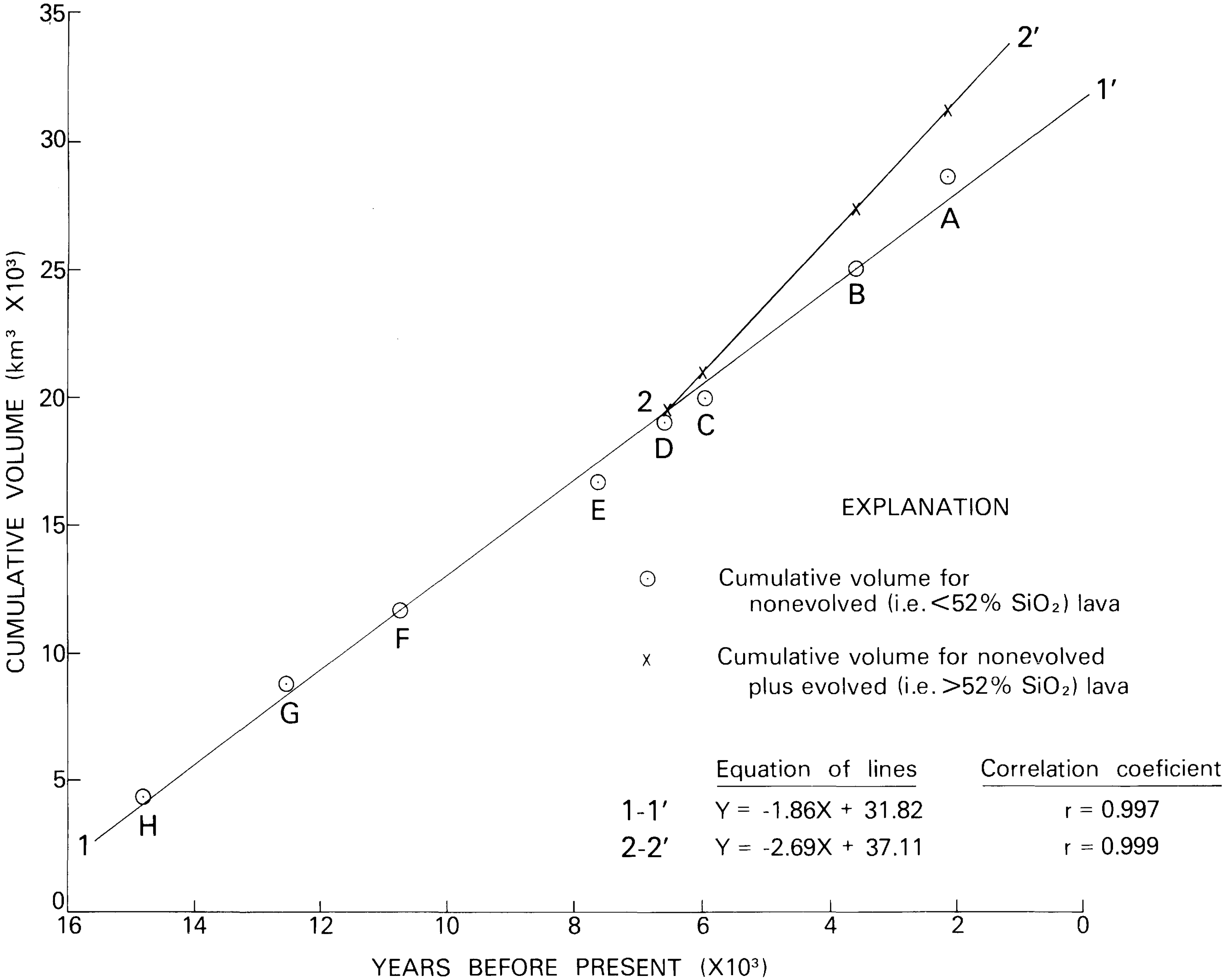


Figure 7. Relation of cumulative volume of erupted lava to ages of lava for the Craters of the Moon lava field, Idaho. A-H are eruptive periods, youngest to oldest.

of the south and southeast parts of the complex. The mantle drapes over the rim of the complex and covers the outer wall (visible from STOP 4). About 100 m north along the trail, remnants of a lava lake lie along the north wall of the inner crater. Just south of the lava lake remnant, the crest of a small cinder cone has a red streak aligned parallel to the eruptive fissure. Late-stage corrosive steam from the fissure oxidized the black cinders. Lava issued from several satellite vents at the base of Big Craters cinder cone complex along its western (left) flank and travelled to the southwest. Additional nested craters are viewed in the Big Craters complex along the trail. As the trail descends the west slope of Big Craters, it passes near small craters on the west flank of the complex. Where the trail flattens out, it passes near a few small eruptive fissures to the left of the trail. The trail crosses eruptive fissures, source vents for the Big Craters flows, in the area between the Big Craters cinder cone complex and the southwest flank of North Crater. Big Craters flows travelled both east and northwest from this area. This lava has an olive-green to greenish-brown crust, which is useful in distinguishing Big Craters flows in areas where they abut younger and older flows.

The trail continues north to the west rim of North Crater cinder cone, which has had a complex history. Clearly, North Crater cinder cone was larger than it is at present. We believe that much of the northwest, north, and northeast flanks of North Crater was broken by slumping during a relatively explosive eruption of the Highway-Devils Orchard-Serrate group of flows, and crater-wall remnants were rafted away on flows from vents in and near North Crater. Some of these crater-wall remnants now appear as monoliths in the Serrate and Devils Orchard flows and as kipukas surrounded by the North Crater flow. From the crest of the trail on the west side of North Crater, slumped blocks and slump scarps can be observed on the northwest and northeast flanks of North Crater cinder cone. The trail descends into the vent area at North Crater. An entrance through a skylight into a lava tube is along the trail near the contact of the North Crater pahoehoe flow and the southwest part of the inner wall of North Crater. Farther east along the trail, near the vent for the North Crater flow, is a large block of agglutinated cinders that contains a granulitic xenolith. Such xenoliths, as well as xenoliths of pumiceous glass, are common in cinders in the walls of North Crater. Leave the trail and walk north-northwest across the surface of the North Crater pahoehoe flow toward the highway. Ropes, hummocky surfaces, small monoliths, and the blue crust color of the North Crater flow are well displayed. Contacts between green-crusted Big Craters flows and blue-crusted North Crater flows can be observed near the steep scarp (called the "highway fault") parallel to and several hundred yards south of the highway. We believe this fault formed during collapse of the north flank of North Crater and the related eruption of the Highway-Devils Orchard-Serrate group of flows.

Climb the scarp and walk to the Visitors Center for lunch.

3.8 92.9 Depart Visitors Center and then travel 2.7 mi along loop road to parking lot at Inferno Cone.

2.7 95.6 **STOP 4.** Inferno Cone parking lot on left. Climb path up side of Inferno Cone. At top of cone, facing north, geographic features to be noted, in a clockwise direction, are: 9:30 to 10:00 Big Craters cinder cone complex; 10:30 Grassy Cone cinder cone; 11:00 North Crater cinder cone; 12:00 Sunset Cone directly behind Visitors Center with Pioneer Mountains in far background; 1:00 Paisley Cone. The profile against the mountains of the vegetated surface of the Sunset flow is visible beyond Paisley Cone. On the near side of the Sunset flow is the Serrate flow that extends to the east (right) as far as Round Knoll (2:30). Round Knoll is a grass-covered kipuka of older Snake River Plain flows and cinders.

At the "Snake River Plateau" display sign on the east rim of the summit of Inferno Cone, note Big Southern Butte and the surrounding terrane. To the left of Big Southern Butte are East (left) and Middle (right) Buttes that appear to be one butte. Low shield volcanoes are clearly visible to the left and right of Big Southern Butte. The eastern part of the vast Blue Dragon flow is in the foreground.

At the "Great Rift" display sign on the south rim of the summit of Inferno Cone, facing southwest toward Big Cinder Butte, note the following: 11:00 the two easternmost cinder cones in this direction are Half Cone in the foreground and Crescent Butte, with its distinctive crescent shape, in the background; 11:10 in this direction, the dark saddle shaped cone is Blacktop Butte, the most southerly cone along the northern part of the Great Rift, and 12 mi distant. Many of the more than 25 cinder cones in the COM lava field can be seen from this vantage point, but they are too numerous and closely spaced to differentiate them.

From the southwest rim of the crest of Inferno cone (no sign), one may observe the "plumbing system" that was responsible for the eruption of the vast eastern lobe of the Blue Dragon flow, the largest of all the 2,100-yr-old flows. The plumbing system consists of, from the northwest to southeast, 1) an eruptive fissure, located in the southern part of Big Craters cinder cone complex and beneath the area of the spatter cones; 2) pit craters, such as Crystal Pit, that overlie the southern end of the eruptive fissures; 3) perched lava ponds, such as Big Sink waterhole, that are located on the upper part of a lava tube system that extends east and south of the eruptive fissure, and 4) a lava tube system that contains numerous skylight entrances into tubes (cave area along the Caves trail). Farther east are rootless vents, where lava moving through the tube system was extruded through openings in tube ceilings. Also visible, directly south beyond Big Sink waterhole and the Lava Cascades, is Broken Top cinder cone and the area to be visited at STOP 5. Two 2,100-yr-old fissures slice across the northeast and southwest sides of Broken Top cinder cone. Source vents for the youngest flow in the COM lava field, the Broken Top flow, are on the eruptive fissure on the east and northeast flanks of Broken Top.

Return to parking lot. Turn left (one way) and proceed past entrance to Spatter Cones parking lot.

0.2 95.8 Entrance to Spatter Cones parking lot, bear left.

0.2 96.0 Big Cinder Butte on horizon. Continue straight ahead. Blue Dragon slab pahoehoe lies to the right between the road and the spatter cones. West flank of Inferno Cone to left.

0.5 96.5 Turn right on road to parking lot for Tree Molds and Wilderness Trails.

0.3 96.8 Turnout on right for viewing Lava Cascades. Here Blue Dragon lava flowed in a radial pattern from a lava lake in Big Sink waterhole, a perched lava pond. The eastern rim of Big Sink waterhole lies several hundred feet west of the Lava Cascades parking area.

0.3 97.1 On left is a slab of Blue Dragon flow that mantles the north side of Broken Top. Either the flow was considerably inflated as it passed this site or the lava "sloshed" up onto the side of the cone as it changed direction from south to east. There are several other "slosh slabs" present in the Monument, some of which do not seem to be explained by either of the two above mechanisms.

0.5 97.6 Road crosses Blue Dragon slab pahoehoe.

0.1 97.7 **STOP 5.** A short walk (about 1.5 km) will constitute STOP 5. Park in Tree Molds and Wilderness Trails parking lot. Walk back on road east to Buffalo Caves trailhead on southwest side of Broken Top near 2,100-yr-old fissure. Turn right (southwest) onto trail; do not take trail to left, which ascends Broken Top. The trail to Buffalo Caves drops down into a fissure on the west side of Broken Top, which has been filled by a tongue of Blue Dragon lava. Follow cairns on trail to southeast and walk on the surface of the Blue Dragon flow. To the left, the southwest-facing wall of the fissure has been mantled with spatter and bombs erupted from the fissure. Many faults that trend parallel to the Great Rift cut the west side of Broken Top. Walk along trail to contact of Broken Top flow with Blue Dragon flow. Pahoehoe toes of Broken Top flow lie on top of Blue Dragon flow. The Broken Top flow, though not dated numerically, is stratigraphically younger than the 2,076-yr-old Blue Dragon flow and therefore the youngest flow in the COM lava field. The Broken Top flow is mainly a lava lake in this area; large slabs of the crust of the lake occur on the right side of the trail. The Broken Top flow is also blue-crusted, especially in squeeze-ups that rise through cracks in the crust of the lava lake. The squeeze-ups appear to be from a younger flow. The surface of the Broken Top flow has a relatively light color due, in part, to the weathering of its highly vesicular crust and to relatively greater amounts of vegetative cover than nearby flows. Continue on trail (follow cairns) to Buffalo Cave.

Buffalo Cave, in the Broken Top flow, shows several interesting features: lava stalactites, curbing (showing successive flow levels on the cave walls), ropes (showing flow direction), and floors formed by incomplete crusts of several levels of the lava stream. What was the direction of movement of lava in the tube system? Where was the source vent(s)?

Follow southwest flank of Broken Top cinder cone east to cinder path (the old Wilderness Trail). Turn left and take path up southeast side of Broken Top. The Broken Top flows came from vents to the right of this path. At a very small borrow pit on the right side of the trail (on the north flank of Broken Top), turn left off path and climb to the top of the cinder cone. (Spread out and walk amidst the sage and bitterbrush when making this ascent so as not to form foot paths on the side of the cone). The top of the cone is strewn with cinders and large (1 m) bombs erupted from the fissure on the west flank of Broken Top. Here we will have a last overview of the Monument and review observations, data, and concepts. Return northwest (toward Big Craters) to cinder path and descend to roadway and walk to parking lot. The bus will return to the Visitors Center for a **short** restroom stop. Leave Tree Molds-Wilderness parking lot.

1.3	99.0	Turn right on loop road.
0.6	99.6	Road to Caves parking lot on right; continue straight on loop road.
0.2	99.8	Devil's Orchard block flow on right.
0.3	100.1	Intersection; turn right.
0.1	100.2	Entrance to Devil's Orchard parking lot on right; continue straight ahead.
1.7	101.9	Visitors Center. Park for quick rest stop. Leave COMNM, turn right (east) on Highway 20-26, pass through Arco, turn right on Highway 20-26 in Arco, and return to intersection of U.S. Highways 20 and 26 at location of STOP 1.
42.7	144.6	Intersection of U.S. Highways 20 and 26. Turn right on Highway 26 toward Blackfoot.
0.3	144.9	Highway crosses Rye Grass Flat, a grass-covered kipuka between Snake River Plain lava flows.
0.8	145.7	Distal flow fronts of Cerro Grande lava field on right. The Cerro Grande lava field is about 10,000 yrs old and was fed from a vent at the base of the southeast flank of Cedar Butte, the prominent butte immediately southeast of Big Southern Butte (see Figure 2).
3.6	149.3	Bingham County line. To right is the town of Atomic City.
1.6	150.9	Sign: "Leaving INEL."
0.6	151.5	Intersection, Atomic City to right; continue straight ahead.
0.9	152.4	Table Legs Butte to right. This shield volcano has a high-crowned vent due to lava lake

activity. Middle and East Buttes to left.

1.1	153.5	Low hills on right represent rootless vents on tube system in flow that traveled east from Table Legs Butte.
0.3	153.8	Borrow pit on right shows accumulation of at least 1 m of loess on Snake River Plain flow.
3.2	157.0	Kipuka filled with loess on left.
1.7	158.7	Ascend Taber Butte, a low shield volcano whose crest is at 11:30.
2.2	160.9	Low shield vent area of Taber Butte, at 9:00. Portneuf Range at 1:00.
11.6	172.5	Highway crosses distal tongues of the Hells Half Acre lava field. Pressure ridges and pressure plateaus are common morphologic features of this 4,000- to 6,000-yr-old pahoehoe flow. The Hells Half Acre lava field (Karlo, 1977) covers an area of about 430 km^2, and contains about 3 km^3 of lava. The lava field probably formed during a single eruptive event that lasted perhaps several months or a few years. The flow units that make up the lava field all flowed from a central vent complex about 1,000 m long and 300 m wide. The vent complex consists of an elongated crater that contains remnants of lava lakes. A few small cinder cones, aligned parallel to an eruptive fissure system lie in the crater and beyond its edges. An extensive lava tube system reaches south and east of the vent area. Lava flows of the Hells Half Acre lava field consist of olivine tholeiite; a representative chemical analysis is given in Table 2.
0.9	173.4	Highway drops off Hells Half Acre flows.
0.1	173.5	Highway crosses Peoples Canal. Gravel-size alluvium from former courses of the Snake River is common along the sides of irrigation canals. This area was inundated by the 1976 flood caused by the failure of Teton Dam.
5.1	178.6	Highway crosses Snake River.
0.1	178.7	Intersection of U.S. 26 and I-15. Turn right on entrance ramp to I-15. Head south on I-15 toward Pocatello. Blackfoot on left after turning on interstate highway.
4.5	183.2	Overpass, Willie Road. On left is Blueberry Hill. This broad, round hill (diameter of 9 km) probably overlies a rhyolite dome, but no rhyolite is exposed. Basalt flows dip outward on its north, west and south flanks.
1.1	184.3	The broad, low shield volcano on right is Ferry Butte, a landmark for early travelers on the Oregon Trail. This was one of the few safe places to ford the Snake River.
6.8	191.1	Fort Hall and Fort Hall Indian Reservation to right. Continue on I-15. In the early 1800's, Fort Hall was a trading post in this part of Idaho.
3.9	195.0	Pocatello Range on left, Michaud Flats on right. Pocatello Range consists chiefly of a basement complex of Precambrian quartzite, sandstone, argillite, and metavolcanic rocks. Several thrust sheets

have been recognized. The Precambrian rocks are overlapped by Miocene rhyolite tuffs of the Starlight Formation. Michaud Flats is a fan-delta that consists of boulders, sand, gravel, deposited by Bonneville flood upon its emergence onto the Snake River Plain (Trimble, 1976).

3.7 198.7 Junction of I-15 and I-86.

END OF FIRST DAY OF FIELD TRIP.

PART 2: KINGS BOWL AND WAPI LAVA FIELD AND THE SOUTHERN PART OF THE GREAT RIFT

By Duane E. Champion, John S. King, and Harry R. Covington

The Kings Bowl and the Wapi lava fields are shown in generalized form in Figure 4. The volcanic features to be observed on the second day of the field trip contrast with the features observed on the first day. The Kings Bowl and Wapi lava fields are relatively simple, the products of single eruptive bursts. They are not compound lava fields that record multiple eruptions such as the COM lava field. However, there are also marked contrasts between the Kings Bowl and Wapi fields that reflect different styles of eruption for each field. The Kings Bowl lava field is small and accumulated adjacent to a 7-km-long eruptive fissure segment of the Great Rift. The Wapi lava field is larger and probably began initially as a fissure eruption and, with more prolonged activity, progressed to a sustained eruption from a central vent complex.

The compositions of both Kings Bowl and Wapi lava flows resemble the average olivine tholeiite of the Snake River Plain (Table 2), in contrast to the evolved COM lava flows from the northern part of the Great Rift.

KINGS BOWL LAVA FIELD

The Kings Bowl lava field consists of about 0.005 km^3 of pahoehoe lava flows that cover an area of about 3.3 km^2 along the southern part of the Great Rift, 12 km southeast of the Craters of the Moon lava field (Figures 4 and 8). The lavas were erupted about 2,220 $\pm$ 100 yrs ago from a 7-km-long central fissure of the Kings Bowl rift set (King, 1977). The set consists of a central eruptive fissure that trends N. 10° W., flanked by two subparallel, noneruptive sets of cracks that are from 600 to as much as 1,100 m from the main fissure (see Figure 8 of this report and Covington, 1977). Flanking cracks are older than the central fissure, and typically are less than 1 m wide. The central eruptive fissure consists of discontinuous, linear, en echelon cracks, 2 to 3 m wide, that locally are filled with breccia and feeder dikes.

The Kings Bowl lava field is characterized by thin (typically < 0.2 m), fissure-fed pahoehoe lava flows, lava lakes, low natural levees, spatter ramparts, spatter cones, and explosion pits. Large spatter cones and spatter ramparts adjoin explosion pits at South Grotto and Creons Cave, and light-colored blankets of lapilli tephra spread eastward from the explosion pits (Figure 8). The largest explosion pit on the Kings Bowl rift is Kings Bowl, 85 m long, 30 m across, and 30 m deep. A lava lake surrounded Kings Bowl before the explosive eruption. Prominent basalt mounds, believed to be the remnants of levees, define the limits of the lava lake. Blocks as large as 10 cm in diameter were hurled explosively westward as far as 245 m. The lapilli-ash tephra resulting from the explosion was carried eastward by the prevailing winds; tephra about 1 mm in diameter occurs as far as 1.2 km east of Kings Bowl (see Figure 8). The tephra blankets an area of 0.15 km^2 (King, 1977). As the larger blocks that resulted from the explosion fell on the west side of Kings Bowl, many broke through the crust of the lava lake and through squeeze-ups. At some localities, the impacting projectile can be found in place beneath the crust. Calculations by King (1977) show that the volume of the ejected material falls far short of that needed to refill the cavity of Kings Bowl, indicating collapse in the vent area subsequent to the explosive vent.

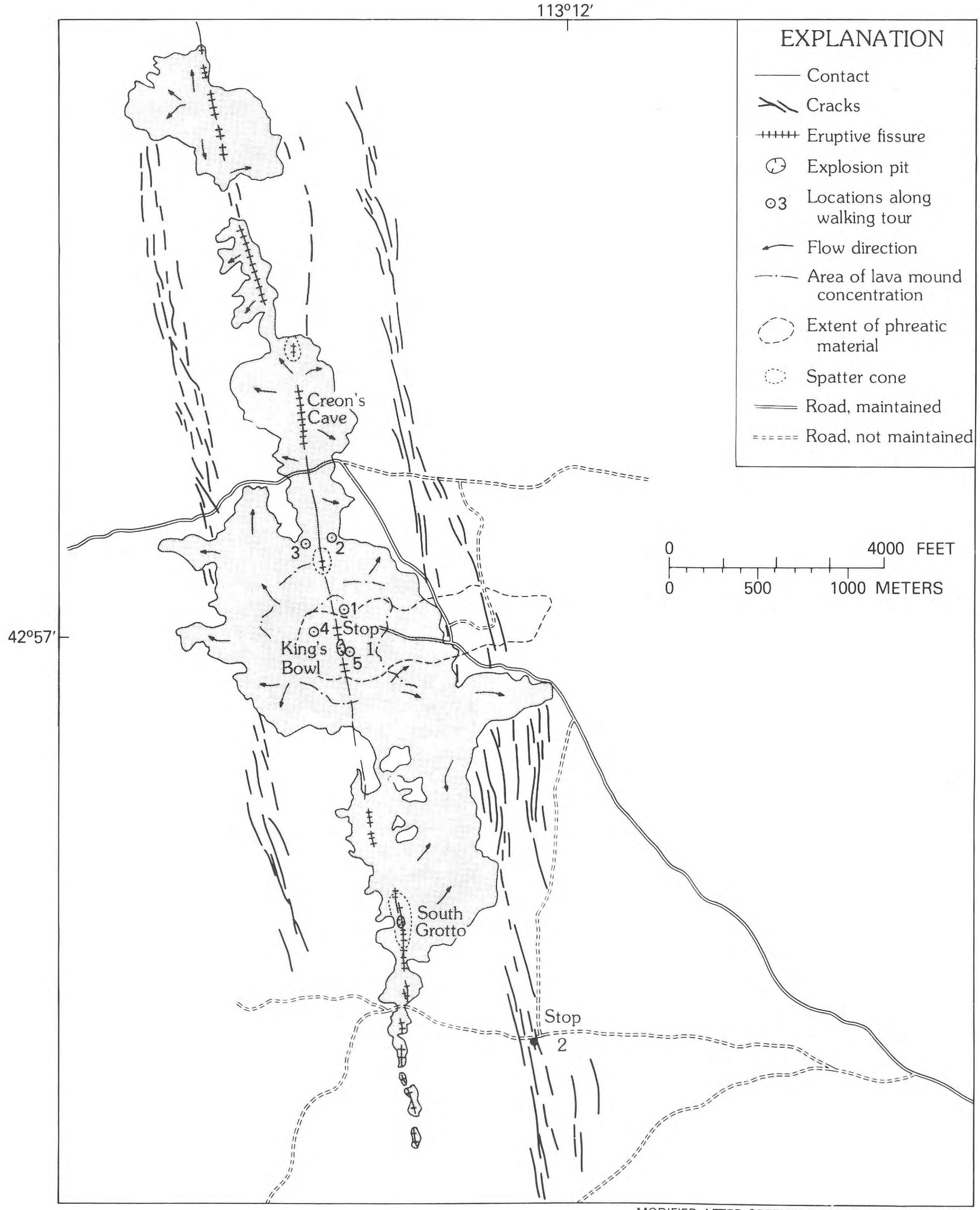


Figure 8. Generalized geologic map of the Kings Bowl lava field, Idaho, showing features discussed in text. Circled numbers refer to localities on walking tour for STOP 1, Day 2. Map modified from Greeley and others (1977).

WAPI LAVA FIELD

Unlike the COM lava field, the Wapi lava field is a monogenetic volcano and typical of many of the low shield volcanoes that make up most of the present surface of the central and eastern Snake River Plain. Thus, study of the Wapi low shield is important in understanding the processes involved in the formation of this type of volcano.

The Wapi field covers a 326-km^2 area that is elongated north-south along the Great Rift. The margin of the field is smooth on the north and east sides, where it ponded against the regional slope of the Snake River Plain. On the south and west sides, the margin is formed of long, lingular flows where they filled drainages of small intermittent streams.

The slope of the Wapi lava field over distances of 10-20 km is less than one degree. The flat slope is a consequence of 1) the very fluid pahoehoe flows, 2) the relatively high rates of lava effusion, and 3) the original flat slopes over which the flows moved. The only area of the lava field that has a steeper slope is near the vent area of Pillar Butte, where the slopes range from 5° to 7° (Champion and Greeley, 1977).

The Wapi field is composed of numerous flow units of pahoehoe lava that are piled side by side and atop one another; this forms a type of lava flow described by Walker (1972) as "compound." Exposures in many kipukas along the south and west sides of the lava field suggest that the flows there are about 5-10 m thick. Thicknesses of the Wapi flows are 15-25 m, except at Pillar Butte, where the total thickness may be 100 m (Champion, 1973). Near the margins of the field, the flow units are larger and tend to have a greater local relief (as much as 10 m) and are characterized by large pressure plateaus, flow ridges, and "collapse depressions." The transition in the size of the flows from the periphery to the interior of the field is apparently a function of proximity to the vent area; thus, closer to the vent, many small pahoehoe flows have filled depressions in earlier flow units and generally leveled the local relief.

The numerical age of the Wapi lava field was unknown until recently. Wapi lava flows overlie and flowed into open cracks of the King's Bowl rift set, which in turn produced the Kings Bowl lava field. The weighted average of three radiocarbon ages on charred sagebrush found under the Kings Bowl lavas is 2,220 ± 100 yrs B.P. (King, 1977). In 1977, a sample of charred root material was obtained, by Ronald Greeley and Ronald Papson of Arizona State University, from an excavation under the Wapi lavas at the east edge of Wapi Park. A radiocarbon age on this sample was 2,270 ± 50 yrs B.P. (S. Robinson, USGS, personal communication 1978). Thus the Wapi and Kings Bowl lava fields formed simultaneously.

The contemporaneity of the Wapi and Kings Bowl lava flows is supported by paleomagnetic data (Figure 9). Precise directions of ramanent magnetization obtained from two separate outcrops (17 km apart) within the Wapi field agree closely with each other and with the direction of magnetization of lavas from the Kings Bowl field. In addition, the paleomagnetic data suggest that the Wapi field took a short time to form, probably several months to a few years, despite the large volume (approximately 6.5 km^3) of basalt erupted.

Ramanent magnetization directions of lava flows near Pillar Butte differ from those from lava flows of the Wapi lava field. The difference can be attributed to rotation associated with summit deflation near Pillar Butte at the close of the eruption, or to a younger age of lava flows near Pillar Butte than the age of the main part of the Wapi field. The latter possibility seems unlikely in that flows near Pillar Butte both underlie and overlie flows of the rest of the Wapi field.

Surface morphologies of the Wapi lava field are readily observable and are characteristic of low shield volcanoes of the Snake River Plain. Near Pillar Butte, thin flows were fed on the surface from the vent complex; leveed-channel aa′ flows, shelly pahoehoe rootless flows, and pahoehoe flows composed of toes are common. Other lava flows of the Wapi field are pahoehoe in surface texture and were fed by tubes. Ubiquitous features are "pressure ridges" and "collapse depressions." Unfortunately, both features are incorrectly named with respect to their mechanisms of formation. True pressure ridges in lava flows are analogous to pressure ridges of sea ice that form from wind pressure pushing up ridges transverse to the direction of the wind. The lava ridges of the Wapi lava field are parallel to the direction of lava flow (Champion, 1973). Thus, the term "flow ridge" is used here in contrast to "pressure ridge." Pressure ridges have been observed to form on the surface of a lava lake in Mauna Loa (Champion, 1973). Nichols (1946), in a paper describing the ridges on the McCartys lava field in New Mexico, recognized flow ridges and attributed them to collapse of the inflated crust over a lava flow.

Collapse depressions have been thought to form by collapse of the roofs of lava tubes. In a study of 100 collapse depressions (Champion, 1973), none

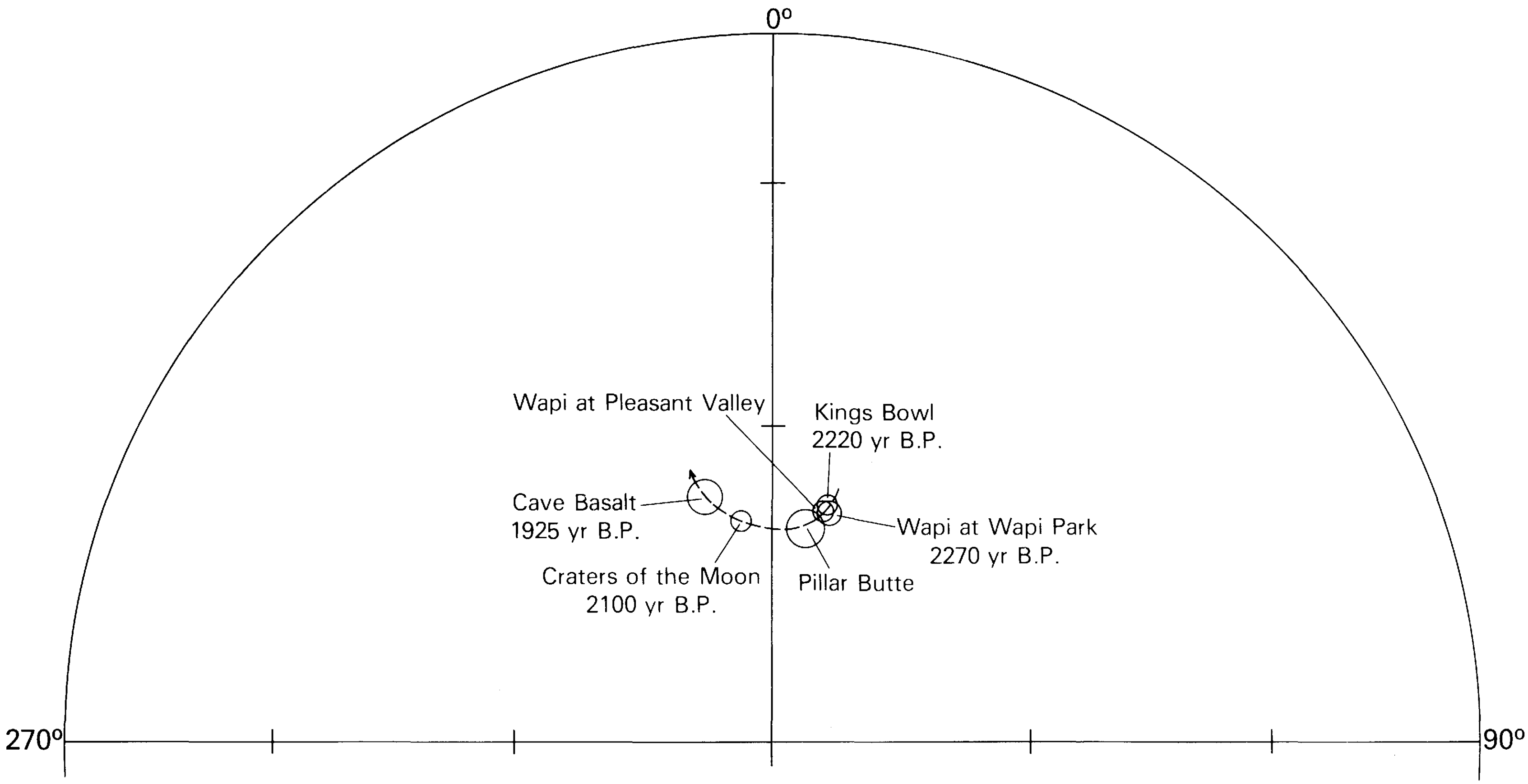


Figure 9. Equal-area diagram of directions of remanent magnetization, with circles of 95 percent confidence, obtained from lava flows of the Wapi and Kings Bowl lava fields and other ^{14}C dated lava flows of the Pacific Northwest. Arrow shows the trend in field direction due to secular variation of the geomagnetic field during the time interval between 2,300 and 1,900 yrs B.P.

were found to be related to an uncollapsed lava tube system. From their shapes and positions, it is apparent that the collapse depressions of the Wapi field are instead related to an internal flow system. The gentle slopes of the Wapi field make it seem unlikely that a hydrostatic head could exist to drain tube systems. Observations of the pattern of flow, preserved in surface textures around collapse depressions, the morphology of the depressions, and the striations on inward-facing scarps of depressions, suggest that depressions form early in the cooling of the flow, and not from collapse; rather, they can be thought of as localities where the lava crust never was inflated.

FIELD TRIP ROAD LOG: SECOND DAY

American Falls to Kings Bowl and Wapi lava fields and return

Mileage		Description
Incremental	Cumulative	
0.0	0.0	Start log at traffic light at junction of Business I-86 and Idaho Rt. 39 in American Falls. Proceed west on Idaho Rt. 39 across the American Falls Dam toward Aberdeen, following signs to Crystal Ice Cave.
6.3	6.3	Road junction. Turn left on North Pleasant Valley Road.
8.4	14.7	Road junction. Turn right; cemetery on right.
1.0	15.7	Road bears left.
1.9	17.6	Pillar Butte in view ahead on horizon. Pillar Butte marks summit of the lava cone of the Wapi lava field.
0.4	18.0	Road junction. Turn right.
1.5	19.5	Pillar Butte and part of Wapi lava field in view to left. The rounded hill in the middle ground is a kipuka vent surrounded by lava flows of the Wapi field.
1.1	20.6	Cattle guard and road junction. Take left fork.
4.6	25.2	Kings Bowl lava field in view ahead. Pillar Butte and part of Wapi lava field in view to left.
0.6	25.8	Queens Bowl crater to the right. This explosion crater is located on a north-trending rift system that is older, but similar in appearance, to the Kings Bowl rift set.
1.1	26.9	Flows of the Kings Bowl lava field to the left.
0.3	27.4	**STOP 1.** Crystal Ice Cave parking area. At this stop we will examine the Kings Bowl lava field (Figure 8) and we will discuss its eruptive history and relationship to the Great Rift. Features to be observed while walking include the main eruptive fissure, spatter cones spatter ramparts, lava lakes, lava levees, basalt mounds, the Kings Bowl explosion pit, and effects of the explosive event at Kings Bowl.

Walk to top of lookout directly west of Cyrstal Ice Cave parking area (locality 1, Figure 8). The view to the west and southwest is of a former lava lake surface. North and west of the lava lake are several basalt mounds, believed to be remnants of levees that contained lava lakes.

Proceed northward from the lookout, along the main eruptive fissure, to an area where age relationships of Kings Bowl lava flows and noneruptive fissures of the Great Rift are apparent (locality 2, Figure 8). Cracks cut the older flow, but are overlapped by the younger flow.

Proceed west across the main eruptive fissure to an area of levees that contained a lava lake (locality 3, Figure 8). Lava tubes and lava channels that resulted in overflow of the levee system also can be observed here.

Proceed southward along the main eruptive fissure to an area with squeeze-ups, ejecta blocks, basalt mounds, and surface of the lava lake (locality 4, Figure 8). "Flow-out" features can be seen between the basalt mounds. The lava lake is flat at this locality and it is broken into large plates as a result of subsidence of the lake. Bulbous squeeze-ups resulting from lava oozing through cracks between plates on the lava lake surface are abundant. Lithic blocks thrown out by the explosive event at Kings Bowl litter the surface; impact craters in the lava lake surface from such blocks can be observed.

Proceed eastward across the main eruptive fissure to locality at the north end of the Kings Bowl crater, near the tourist wall, where a feeder dike intrudes the main eruptive fissure (locality 5, Figure 8). Follow the trail southward around the east side of Kings Bowl crater to the crater entrance. Here, the surface east of the main eruptive fissure has been blanketed by fine tephra erupted during the phreatic explosions at Kings Bowl. At the crater entrance, the upper flows display a swirling pattern described by Swanson (1973) as a flow variety characteristic of near-vent activity. Farther down the trail, a soil horizon separates the young Kings Bowl lava flows from older massive flows in the crater wall. Continue down the trail to the north end of the Kings Bowl crater where a feeder dike is exposed in the central eruptive fissure. Walk north into the fissure to observe the grooved walls resulting from phreatic eruptions. Retrace trail out of the crater, turn north and return along trail to parking area.

Leave Crystal Ice Cave parking lot on same gravel road traveled from American Falls, traveling to the southeast. Parts of the next segment of the field trip require a high-centered or 4-wheel drive vehicle, particularly in wet weather.

2.2	29.6	Turn sharply right onto dirt road. Proceed first west, then curve south.
0.3	29.9	Turn right onto dirt road and proceed nearly due west. In near distance are spatter vents and near-vent flows of the southern part of the Kings Bowl lava field.
0.8	30.7	Continue west past road on right.
0.1	30.8	**STOP 2.** This area constitutes an optional stop (time permitting) to observe fissures of the Kings Bowl segment of the Great Rift. Extensional deformation produced fissures as much as 0.5 m across at this locality. These fissures belong to the eastern set of three parallel fissure sets. The eastern set of fissures is separated from fissures of the central set by about 0.7 km. Systems of nearly parallel fissures also characterize the area immediately southeast of the COM lava field (Figure 4). Although the Kings Bowl fissure system trends N. 10° W., the individual fissures trend N. 22° W. in an en echelon manner (Champion, 1973). This trend suggests a component of left

		shear in this area of the Great rift.
0.2	31.0	Proceed west past left turn.
0.2	31.2	Cross the Great Rift and eruptive fissures that produced the Kings Bowl lava field. Spatter cones occur both north and south of the road at this point.
0.1	31.3	Turn left and proceed south on dirt road. Road traverses the length of Wapi Park, a vent complex that trends southwesterly, and is older than the nearby Wapi and Kings Bowl lava fields.
1.5	32.8	Turn right and proceed south-southwest between the edge of the Wapi lava field and the old vents of Wapi Park.
0.1	32.9	Proceed south-southwest past left turn.
0.4	33.9	A hand-dug tunnel here yielded charred sagebrush beneath lava flows of the Wapi field, whose radiocarbon age is 2,270 ± 50 yrs B.P.
0.8	34.1	One of the paleomagnetic sites for the Wapi lava field is located on the inflated pressure plateau to the west of the road; data are the same for the Pleasant Valley arm of the Wapi field, which projects from the eastern margin of the field, 20 km to the south (see Figure 9).
0.3	34.4	**STOP 3.** End of the dirt road at the southern end of Wapi Park. A walk that does NOT follow a trail to and from the Pillar Butte vent complex constitutes STOP 3 and begins and ends at this locality (STOP 3, Figure 10). The traverse is about 5 km long and requires about 4 hours. Water should be carried on this traverse, particularly in the hot summer months. Descriptions of localities on this traverse were provided, in large part, by Champion and Greeley (1977).

Walk about half way from STOP 3 to the north end of the Pillar Butte vent complex (locality 1, Figure 10). As a landmark during the traverse, walk toward the left of Pillar Butte. The hummocky relief of the lava surface is characterized by pressure ridges and local collapse depressions. Local relief changes from low over the pressure plateau areas to fairly high (10 m) near flow ridges. This form of topography is characteristic of the margins of the Wapi field, but quite different from that of the Pillar Butte vent complex.

Continue south-southeast for about one mile to the contact between lavas of the main Wapi lava field and tube- and surface-fed flows of the Pillar Butte vent complex (locality 2, Figure 10). The Pillar Butte flows at this locality emanated from the northwest side of the Pillar Butte area. Observable here are tubes and channels in the flows and small pit craters.

Proceed southeast to the north flank of the summit area of Pillar Butte (locality 3, Figure 10). This area is a complex of several pit craters and vents that fed flows to the northern part of the lava field. Lava flows of the summit area consist chiefly of shelly pahoehoe that contains numerous channels that slope to the north. Shelly pahoehoe forms near vent areas from gas-charged fluid lavas (Swanson, 1973).

Traverse south, along the eastern margin of the summit

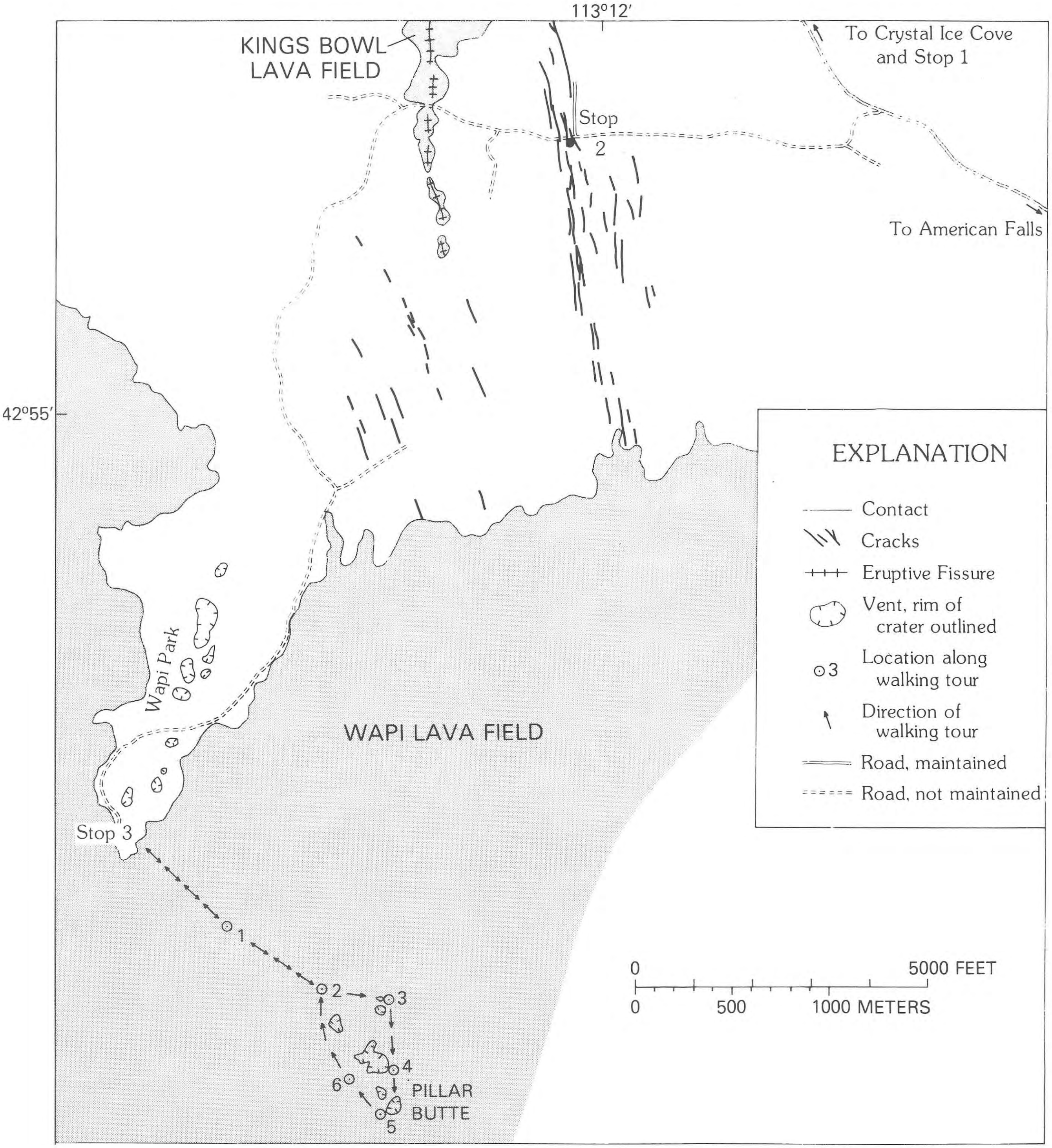


Figure 10. Generalized geologic map of the Pillar Butte area of the Wapi lava field, Idaho, showing features discussed in text. Circled numbers refer to localities on walking tour for STOP 3, Day 2. Map modified from Champion and Greeley (1977).

region, and note more shelly pahoehoe and slab lava. Proceed to the eastern edge of the major pit crater complex of the Pillar Butte vent area (locality 4, Figure 10). The western wall of the vent area displays layered rootless flows of the summit region in cross section. In the pit craters, observe ledges of lava lakes that filled the pit craters and then subsided. Thin deposits of lapilli, generated by vigorous fountaining, occur along the east margin of the vent area.

Continue south to Pillar Butte, an excellent vantage point (locality 5, Figure 10) for the general aspects of the Wapi lava field as well as the topography and features of the eastern Snake River Plain. The origin of Pillar Butte is unclear; its relief is due either to deflation of the area around it or to inflation directly beneath it.

Proceed northwest to an area containing well-exposed, east-facing, subsidence faults that have truncated flow channels and tubes (locality 6, Figure 10). The orientation of these faults is parallel to fissures of the Kings Bowl Rift system. From this locality, continue northwest to locality 2, and then west-northwest back to STOP 3, where the vehicles are parked (Figure 9).

Retrace route north out of Wapi Park, east across the southern edge of the Kings Bowl field, and along to the main gravel road back to American Falls.

END OF ROAD LOG.

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MID-TERTIARY HISTORY OF THE CENTRAL PIOCHE-MARYSVALE IGNEOUS BELT, SOUTHWESTERN UTAH

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INTRODUCTION

This paper deals with the character of Cenozoic magmatism in the central part of the Pioche-Marysvale igneous belt in the Needle Range and southern Wah Wah Mountains of southwestern Utah (Figure 1). This belt is one of several that trend east-west across Nevada and western Utah (Stewart and others, 1977; Rowley and others, 1978). Following a long period of erosion that had reduced the terrain to a subdued relief of generally less than 100 m, magmatic activity began in the mid-Oligocene and continued, with few interuptions, into the Miocene until about 18 m.y. ago. After a hiatus of about 5 m.y., activity resumed again, but only for a brief period of about one million years. There has been no magmatism manifest since.

Oligocene magmatic rocks are generally of intermediate calc-alkaline composition and include voluminous, regionally extensive ash-flow tuffs and minor local lava flows. Large caldera complexes formed as the result of catastrophic explosive expulsion of thousands of cubic kilometers of ejecta. In contrast, the two episodes of Miocene magmatism, from 23 to 18 and 13 to 12 m.y. ago, produced bimodal mafic-silicic assemblages, chiefly rhyolite lava flows, tuffs, minor shallow intrusions, and local mafic lava flows that were erupted from many local centers. No calderas developed during the Miocene, although major extensional block faulting along a northeast trend occurred during the early Miocene magmatic pulse. These faults localized some of the hydrothermal activity that accompanied emplacement of Miocene silicic magmas.

OLIGOCENE VOLCANISM

The lowest part of the volcanic sequence (Figure 2) consists of rhyolitic ash-flow tuffs, thick rhyolite and pyroxene andesite flows, and local volcanic sandstones belonging to the Sawtooth Peak Formation and the overlying Escalante Desert Formation (Grant, 1978; Campbell, 1978). The Lamerdorf ash-flow tuff near the top of the latter has a K-Ar age on biotite of 32.3 ± 1.1 m.y. (Best and others, 1983). These units are thickest in paleovalleys that commonly trend more or less east-west. It was not until deposition of the voluminous tuffs of the Needles Range Group 30 to 28 m.y. ago that most of the remaining hills of Paleozoic sedimentary rocks were covered. By the time of deposition of the densely welded andesitic tuffs of the latest Oligocene Isom Formation 25 m.y. ago, topographic relief in southwestern Utah was nil because this formation is on the order of a few tens of meters thick almost everywhere in the central part of the Pioche-Marysvale belt. The near uniformity of its thickness also implies absence of any tectonic disturbance causing differential uplift during the late Oligocene.

Needles Range Group

Since the pioneering efforts of J. H. Mackin and his students in the 1950s and early 1960s (Mackin, 1960; Cook, 1965), the crystal-rich dacitic tuffs of the Needles Range Group have been recognized as a lithologically distinctive and remarkably widespread time marker in the succession of mid-Tertiary ash-flow tuffs in the eastern Great Basin and high plateaus of south-central Utah. Mapping at a scale

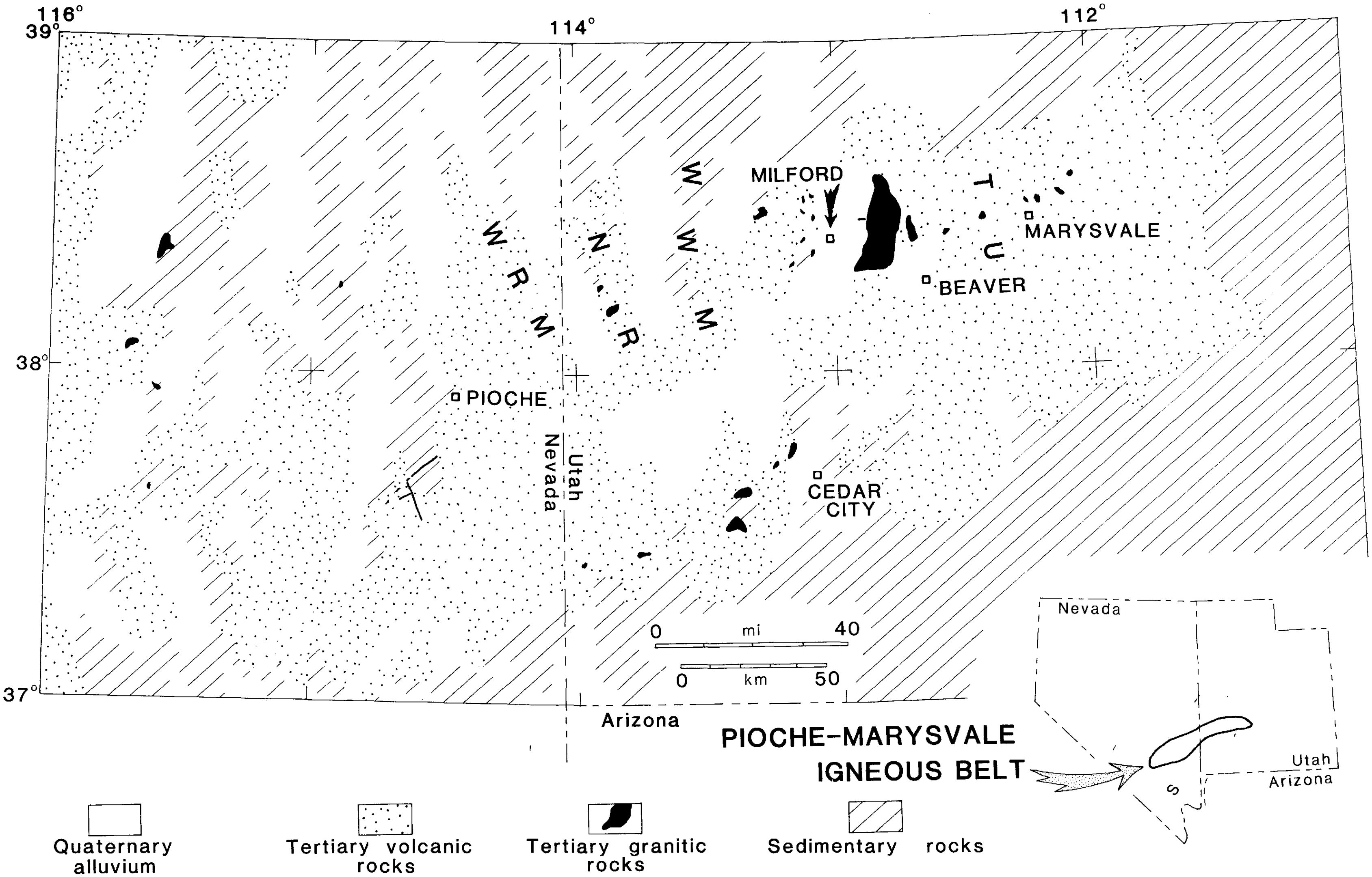

Figure 1. Tertiary volcanic (stipled) and intrusive igneous (black) rocks of the Pioche-Marysvale igneous belt in southern Utah and eastern Nevada. Quaternary alluvium is blank. NR, Needle Range; WWM, Wah Wah Mountains; TU, Tushar Mountains; WRM, White Rock Mountains.

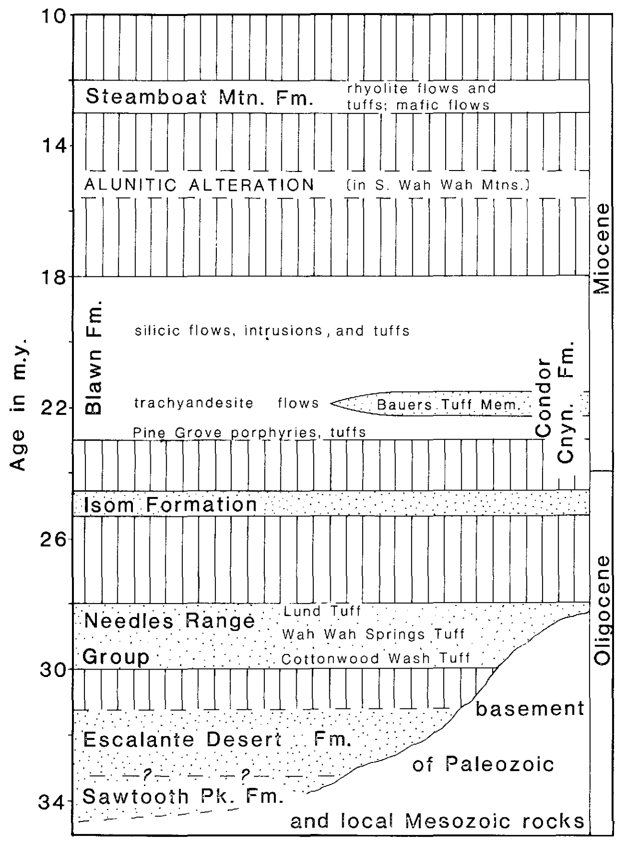

Figure 2. Stratigraphic relations of volcanic units in the Wah Wah Mountains and Needle Range. Regional ash-flow sheets are stippled.

of 1:24,000 by the U.S. Geological Survey combined with paleomagnetic investigations (Shuey and others, 1976) have defined the areal extent and regional stratigraphic correlation of the tuffs in Utah (Figures 3 and 4). Less is known of the Needles Range tuffs in eastern Nevada as little has been done there since the reconnaissance work of Cook (1965) and Gromme' and others (1972).

Although originally defined as a formation, with the individual tuff sheets comprising members, it is now apparent that the tuff sheets constitute a stratigraphic group of formations, each formation being a genetic entity manifesting a period of catastrophic explosive eruption and caldera collapse. Four tuff formations have been recognized in southwestern Utah; in ascending stratigraphic order they are the Cottonwood Wash, Wah Wah Springs, Lund, and Wallaces Peak (Best and others, 1973). All are crystal-rich, lapilli ash-flow tuffs with plagioclase comprising about half of the phenocrysts, and combinations of biotite, hornblende, and quartz the remaining half.

The Cottonwood Wash Tuff is thickest in the northern Needle Range and in easternmost Nevada where its source caldera is perhaps largely, if not entirely, concealed beneath younger deposits, especially alluvial valley fill (Figure 3).

The Wah Wah Springs Formation includes densely to weakly welded lapilli ash-flow tuffs compositionally distinct from other Needles Range tuffs in that hornblende phenocrysts are more abundant than biotite, and quartz phenocrysts are generally small (2 mm) and constitute no more than 2 to 3 percent of the tuff. The unit is especially unique in terms of its reversed magnetic polarity (Gromme' and others, 1972; Shuey and others, 1976); other Needles Range tuffs have normal magnetic polarity. In westernmost Utah the Wah Wah Springs Formation appears to be a single cooling unit in sections as much as 500 m thick. In the Richfield area of Utah it is a multiple ash-flow compound cooling unit with local intercalated mudflows.

The areal extent of the Wah Wah Springs Formation is much broader than that of the other Needles Range tuffs and is surely one of the most voluminous ash-flow sheets known anywhere (Figures 3 and 4). It crops out over an area of almost 25,000 km^2 — chiefly west, north, and east of the source caldera (see below). To the south, the sheet is covered by a thick, widespread sequence of Miocene rocks (Williams, 1967; Stewart and others, 1977) but appears to be thin because of a regional highland that existed during deposition. The average thickness of the tuff outside the caldera, from data shown on Figure 4, is 0.2 km. The total volume of 5,000 km^3 calculated from these area and thickness values must surely be subject to unknown amounts of adjustment because of the effects of predeposition topography, variable compaction and porosity, uncertainties in the original extent of the deposit (particularly to the south of the caldera), in the area of the caldera, the thickness of caldera-filling tuff (locally at least 2km), and the amount of east-west crustal extension in the Great Basin since the Miocene.

The possibility that the enormous volume of the Wah Wah Springs Formation originated from more than one magma-caldera source cannot totally be discounted. However, the unique and uniform magnetic polarity of the tuff, the absence of any other candidate source, and the large size of the Indian Peak caldera (at least 60 km x 20 km, uncorrected for east-west post-Oligocene crustal extension) favor a single source.

The Indian Peak caldera that collapsed during

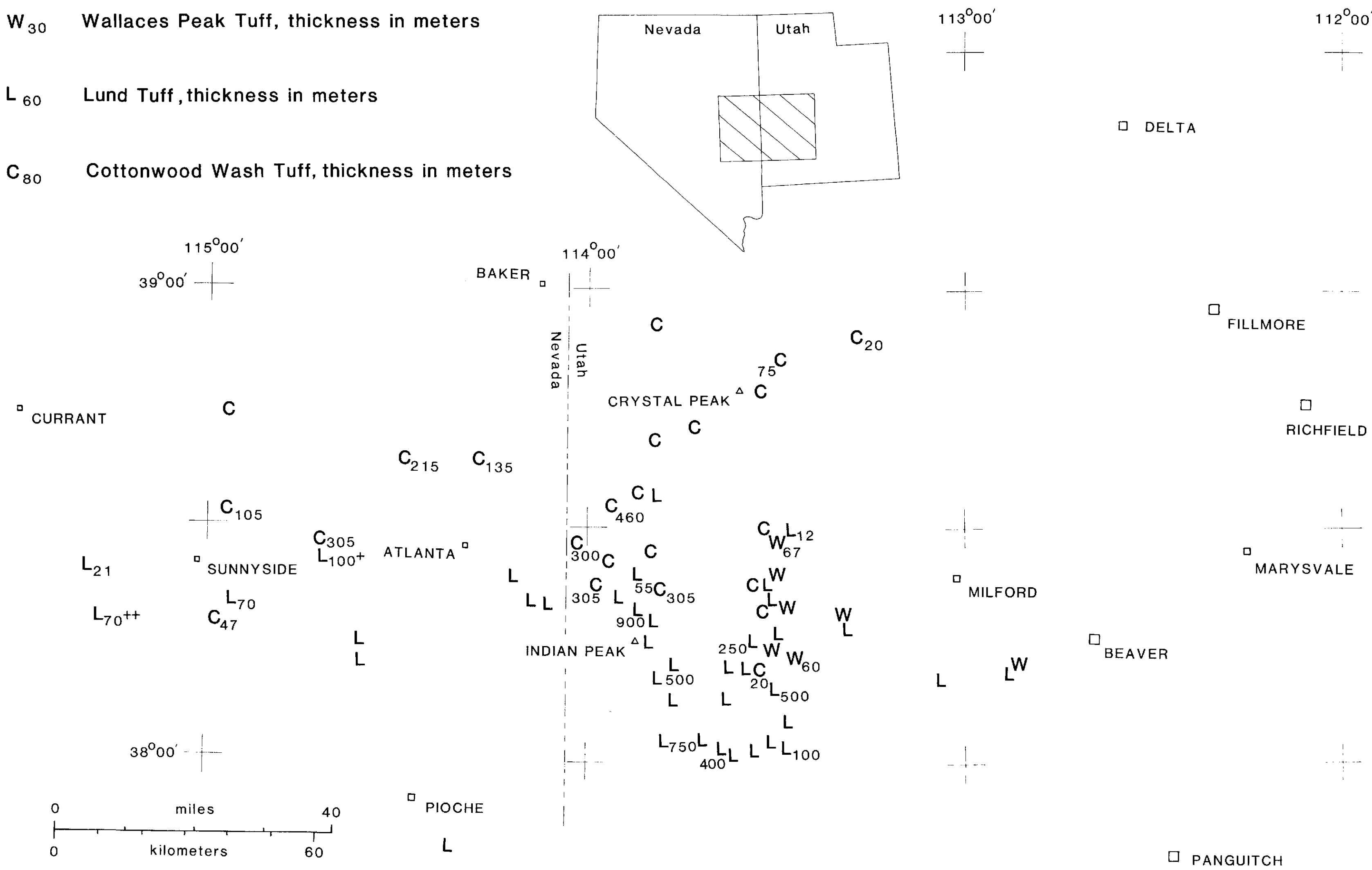

Figure 3. Distribution and thickness of known exposures of the Cottonwood Wash, Lund, and Wallaces Peak tuffs in southwestern Utah and southeastern Nevada. Data in Nevada from Cook (1965) and in Utah from numerous published maps.

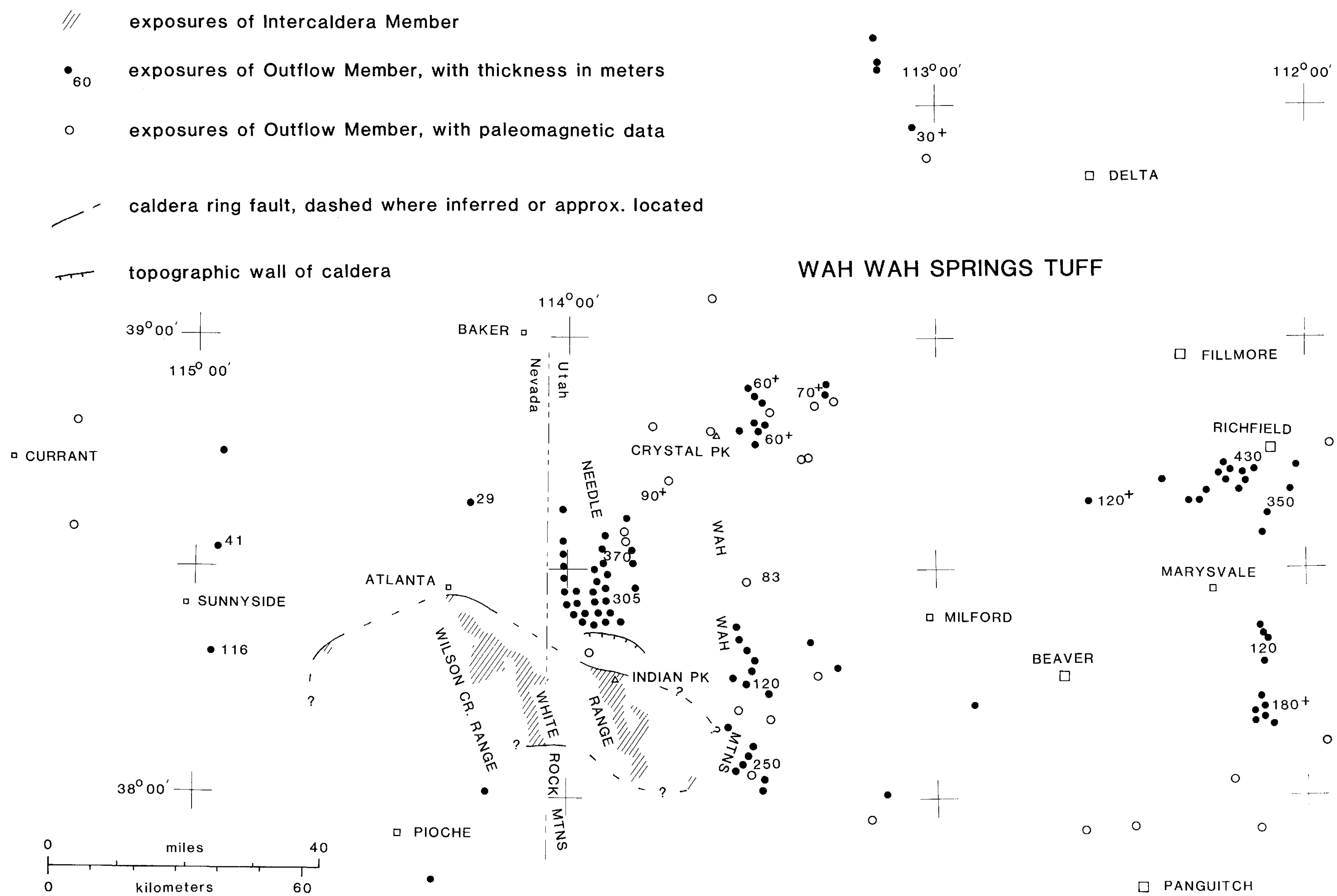

Figure 4. Distribution and thickness of known exposures of the Wah Wah Springs in southwestern Utah and southeastern Nevada. Data in Nevada from Cook (1965), and Gromme' and others (1972); in Utah from Shuey and others (1976), and numerous published maps.

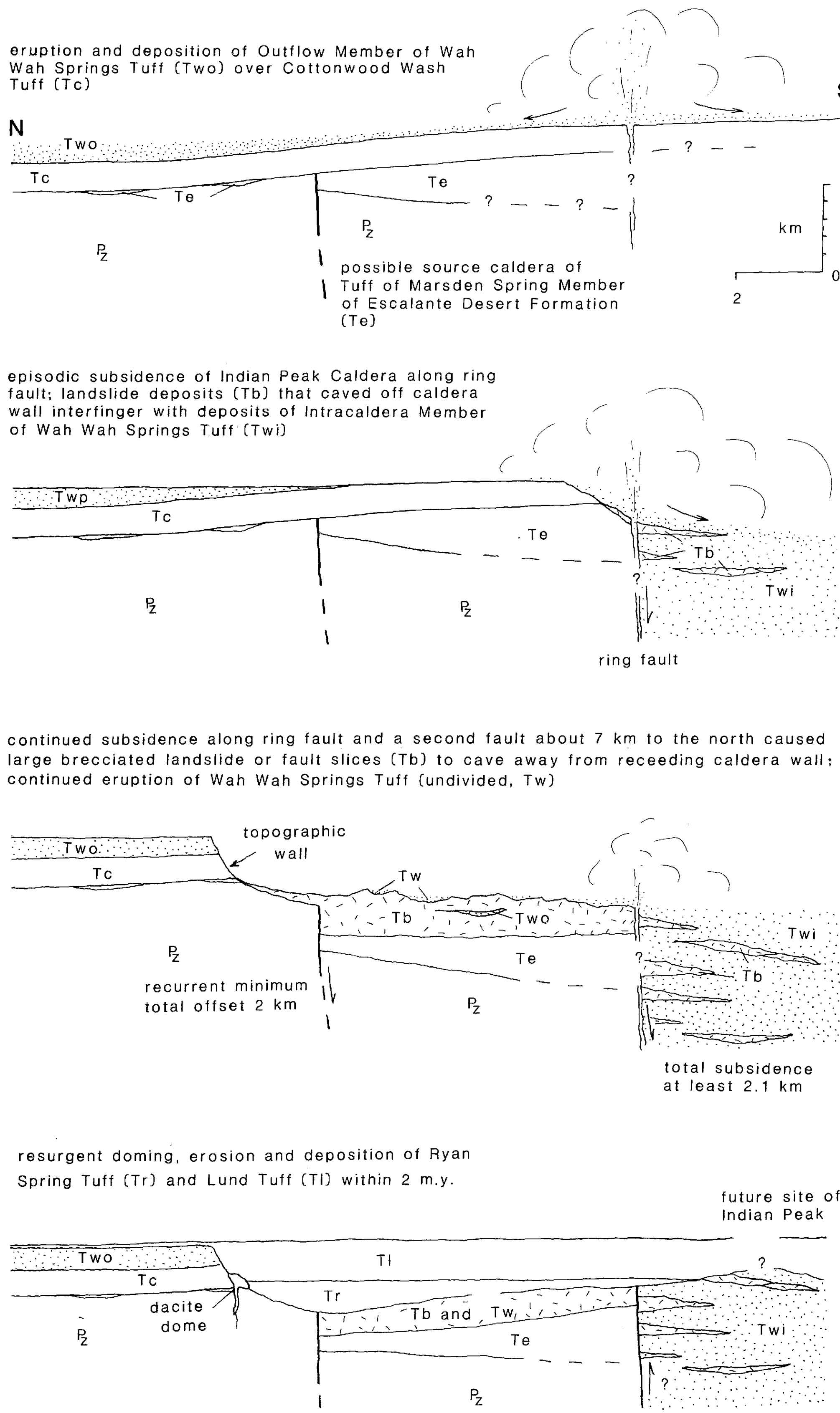

Figure 5. Idealized and schematic north-south cross sections through the central Needle Range showing the evolution of the northeastern segment of the Indian Peak Caldera.

catastrophic eruption of the Wah Wah Springs Formation is a gourd-shaped structural depression that straddles the Utah-Nevada border. The northern and western extent of the caldera in Nevada is known only imperfectly from reconnaissance investigations; the eastern segment appears to be buried beneath Pine Valley between the Needle Range and the Wah Wah Mountains and Miocene and younger deposits conceal its southern extremities. However, its northeastern segment is well exposed in the east-tilted Needle Range just north of Indian Peak. Subsidence began along the ring fault, exposed 1.5 km north of the peak, after much of the Outflow Member of the Wah Wah Springs Formation was extruded (Figure 5). Episodic caving of older volcanic rocks from the unstable caldera wall into the deepening depression created tongues of landslide breccia that interfinger with caldera-filling tuff. There are conspicuous lateral variations in the appearance of the Intracaldera Member of the Wah Wah Springs Formation within the caldera that probably represent different batches of magma from an inhomogeneous chamber; these variations in space and probably in time have yet to be investigated. Recurrent subsidence along the northeast segment of the ring fault and along a parallel fault to the north created such instability that massive gravity-driven fault slides moved southward toward and into the deepening depression; remnants of these slides are now found as cataclastic (not mylonitic) and chiefly monolithologic volcanic breccias north of the ring fault. Wedges of Wah Wah Springs tuff lie within this sequence of breccias that is as much as 800 m thick. Some of these wedges are internally sheared whereas others several meters thick are only of densely welded vitrophyre. The topographic wall of the caldera receded 10 km north of the ring fault as a consequence of the caving and faulting (Figures 5, 8, and 9).

Overlying the fault-landslide breccias in the Needle Range are the lithic rhyolite ash-flow tuffs of the Ryan Spring Tuff that contain sparse phenocrysts of plagioclase and biotite. Although absent beyond the topographic wall of the caldera, this unit is as much as 560 m thick inside the depression. Additional caldera fill is represented in the overlying 28 m.y. old Lund Tuff, a compound cooling unit that is up to 600 m and possibly 1,000 m thick within the topographic depression of the caldera and less than 55 m outside it just to the north.

Six kilometers southeast of Indian Peak the Ryan Spring Tuff pinches out and 500 m of Lund Tuff lies directly on the Intracaldera Wah Wah Springs Tuff Member. However, 10 km farther southeast the Ryan Spring Tuff reappears, but is never more than 500 m thick, and the Lund Tuff is still as much as 750 m. These relations suggest resurgent doming of the eastern part of the Indian Peak caldera before deposition of the Ryan Spring Tuff.

The source calderas of the Ryan Spring and Lund Tuffs have not been located but the distribution and great thickness of the tuffs suggest they are probably nested within the topographically enlarged basin of the Indian Peak caldera.

Only minor shows of Cu-Fe-skarn mineralization appear along the ring fault of the Indian Peak caldera about 6 km northwest of Indian Peak where a porphyry intrusion, compositionally similar to the Wah Wah Springs tuffs, intruded Paleozoic carbonate rocks that are now marbles.

Isom Formation

The last regionally extensive intermediate-composition ash-flow tuffs to be deposited in the Oligocene, about 25 m.y. ago (Fleck and others, 1975), were those comprising the Isom Formation. These lapilli tuffs with sparse phenocrysts of plagioclase and pyroxene occur widely over much of southwestern Utah and adjacent Nevada and constitute excellent stratigraphic markers, in part because of their densely welded character and the thinness of the sheets (generally less than 10 m). The location of the source caldera is unknown, but unusually thick sections occur locally in the southern Needle Range and central White Rock Mountains in Nevada.

MIOCENE MAGMATISM

Two episodes of Miocene magmatic activity, 23 to 18 and 13 to 12 m.y. ago, produced similar bimodal assemblages of mafic and silicic rocks in the central part of the Pioche-Marysvale belt. Magmas invaded the uppermost crust and erupted onto the surface at numerous places without the formation of calderas. The earlier of these episodes more or less overlaps the period of extrusion of the ash-flow sheets of the Quichipa Group 24 to 21 m.y. ago from caldera sources south of Pioche, Nevada (Williams, 1967). Only one of these sheets, the Bauers Tuff Member of the Condor Canyon Formation with an age of 22 m.y. (Fleck and others, 1975), is present in the Needle Range and Wah Wah Mountains; it is generally less than 20 m thick and densely welded.

Blawn Formation

Rocks of the early Miocene bimodal magmatic association comprise the Blawn Formation (Best and others, 1983). The base of the unit is a sequence of rhyolitic pyroclastic rocks, chiefly crystal-poor, weakly welded lapilli ash-flow tuffs.

Overlying these tuffs are K-rich mafic flows that are most extensively exposed on the east flank of the Wah Wah Mountains. SiO_2 (weight percent) ranges from 54 to 62 and K_2O from 2.2 to 4.0, so that they may be classed as trachyandesite to latite — not basalt.

Overlying the mafic flows are more rhyolitic tuffs similar to those beneath. These are in turn capped by, or locally interfinger with, rhyolite lava-flows that range from virtually aphyric to crystal-rich with phenocrysts of quartz and sanidine several millimeters across in addition to plagioclase, biotite and rare hornblende.

Many crystal-rich rhyolite dikes and other shallow intrusions of early Miocene age occur in both the Wah Wah Mountains and Needle Range. In the former, several intrusions are exposed from south of The Tetons northward to Pine Grove — where an intrusive-vent complex is host to disseminated Mo and W at depth (Keith, 1982). In the Needle Range, two swarms of dikes are exposed in an upthrown horst that forms the backbone of the range. There is no recognizable difference in the radiometric age between the northern swarm that trends east-northeast and the southern that trends northeast — both are 22 to 19 m.y. old. Rhyolite lava flows that were undoubtedly fed from the same dike swarms occur in adjacent grabens.

Steamboat Mountain Formation

Mafic and silicic rocks extruded during the mid-Miocene episode 13 to 12 m.y. ago comprise the Steamboat Mountain Formation. Many centers of activity developed, as in the early Miocene episode, but the silicic ones lie in a northeast trending band parallel to and just to the south of the Blawn centers (Figure 6). Steamboat Mountain silicic activity also began with the explosive eruption of gas-charged magma, forming pyroclastic deposits around vents. Mostly capping but locally interfingering with these sequences are extrusions of flow-layered rhyolite.

Rhyolite tuffs of the Steamboat Mountain Formation are petrographically indistinguishable from those of the Blawn Formation. However, lava flows tend to be less phenocrystic and are uniformly more enriched in Si and F and have less Ti, Fe, Mg, and Ca than Blawn rhyolites. Only some of the younger Blawn rhyolite lava flows, and the 18 m.y. old Staats rhyolite intrusion, contain a little topaz whereas in Steamboat Mountain flows topaz is a virtually ubiquitous vapor-phase crystal in lithophysal cavities.

Mid-Miocene mafic flows are more restricted in area extent than those of the Blawn Formation. They have less Si and K and, therefore, are of a more basaltic composition.

Thus, the bimodal association of the mid-Miocene Steamboat Mountain Formation comprises high-silica topaz-bearing rhyolite and basaltic lavas in contrast to the early Miocene Blawn Formation that comprises rhyolites generally not so enriched in Si and F and mafic lavas with intermediate amounts of Si and high K.

Two younger episodes of bimodal rhyolite-basalt magmatism — 8 to 6 m.y. and less than 3 m.y. old — are manifest farther northeast in the Pioche-Marysvale igneous belt, chiefly in the Mineral Mountain area, and west of Fillmore in the Black Rock Desert (Best and others, 1980; Rowley and others, 1978).

EARLY MIOCENE TECTONISM

The tectonic pattern of the central part of the Pioche-Marysvale belt is a composite of north and northeasterly trending features (Figure 1). Fault-bounded northerly-aligned mountain ranges are truncated at their southern ends by the northeast-trending northern margin of the Escalante Valley. The southern termini of these ranges are linked by a prominent zone of northeast-striking high-angle faults that coincides with belts of early and middle Miocene silicic magmatic activity (Figure 6). Data show that the northeast-striking faults were chiefly early Miocene and possibly related to a left-lateral, almost east-west shear couple. Development of the northerly trending more conspicuous basins and ranges typical of this part of the Basin and Range province apparently followed the early Miocene event.

The pattern of northeast-striking faults of early Miocene age is displayed in Figure 6. The virtually unfaulted segment of the Wah Wah Mountains north of Pine Grove Canyon where few Tertiary volcanic rocks are exposed contrasts sharply with the segment to the south where numerous subvertical, northeast-striking faults continue southwestward into the southernmost Needle Range and into the southern White Rock Mountains in Nevada; however, our mapping there is incomplete.

These northeast-striking faults, as well as the one northwest-striking fault zone extending from Blue Mountain to Blawn Mountain in the Wah Wah Mountains, have vertical displacements as great as 1 km. The northeast-striking faults are slightly ob-

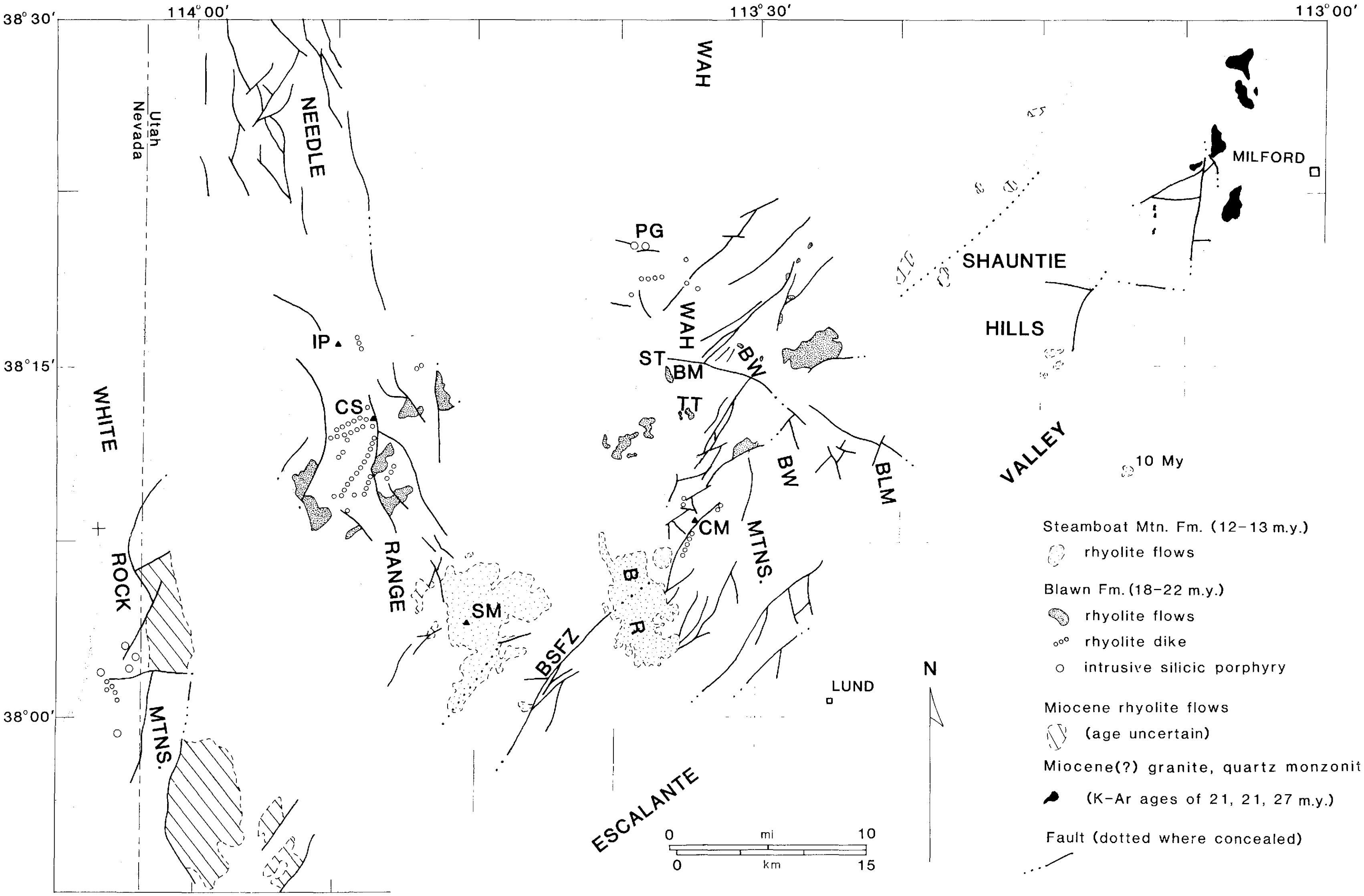

Figure 6. Generalized distribution of faults and Miocene igneous rocks in the central part of the Pioche-Marysvale igneous belt. IP, Indian Peak; CS, Cougar Spar mine; SM, Steamboat Mountain; PG, Pine Grove; ST, Staats mine; BM, Blawn Mountain; BW, Blawn Wash; BLM, Blue Mountain; CM, Cima mine; BR, Broken Ridge; BSFZ, Bible Spring fault zone; TT, The Tetons.

lique to the overall trend of the Pioche-Marysvale belt because of a more northerly strike (Figure 1). A crude en echelon pattern is apparent. Although no unequivocal strike-slip displacement of map units has been found, several well-exposed subvertical fault surfaces have strongly developed subhorizontal slickensides. These are common along the Bible Spring fault zone in the low hills linking the southern termini of the Needle Range and Wah Wah Mountains. The emplacement of the northeast-striking early Miocene rhyolite dikes around the Cinna mine in the Wah Wah Mountains and the two swarms near the Cougar Spar mine in the Needle Range indicates a northwest-southeast direction of extension.

The age of the northeast faulting is well-constrained. Oligocene volcanic rocks and overlying older members of the Blawn Formation are cut and tilted whereas 13 to 12 m.y. old rhyolites of the Steamboat Mountain Formation are generally not faulted and lie unconformably on top of the older rocks. At The Tetons the constraints are even tighter because unfaulted 18 m.y. old Blawn rhyolite rests unconformably on tilted and eroded Oligocene units; older Blawn units as well as the 22 m.y. old Bauers Tuff are tilted in fault slices 4 km to the southeast (Figure 1).

Additional evidence for early Miocene block faulting are deposits of chaotic megabreccia and associated coarse alluvial deposits that occur along the northeast striking Bible Spring fault zone and contain abundant clasts of 22 m.y. old Bauers Tuff. These deposits, whose total area of exposure is about 4 km^2, appear to represent landslide debris that sloughed off uplifted fault blocks. The deposits underlie virtually unfaulted, subhorizontal, 13 to 12 m.y. old rhyolite lava flows of the Steamboat Mountain Formation. Locally, as at the northeast end of the Bible Spring fault zone, altered Steamboat Mountain rhyolite flows are cut by faults that might be reactivated early Miocene fractures.

FIELD TRIP ROAD LOG: FIRST DAY

Stops will be made in the Needle Range to examine Oligocene volcanic rocks, chiefly regional ash-flow tuffs. Log begins in Milford at the junction of State Highways 257 and 21. Proceed west on Highway 21.

Mileage		**Description**
Incremental	**Cumulative**	
0.0	0.0	Milford. Head west on Highway 21.
32.0	32.0	Junction of gravel road to Lund. **STOP 1.** Overview of Needle Range (also referred to as the Mountain Home Range at its northern end and the Indian Peak Range farther south). The rocks comprise a complexly faulted but generally east-tilted sequence of Oligocene ash-flow tuffs and Paleozoic sedimentary rocks. Continue south and west on gravel road toward Lund.
4.6	40.2	Intersection. Continue southwesterly toward Sawtooth Peak, **not** south down Pine Valley.
11.2	51.3	Intersection southeast of Sawtooth Peak; continue west.
2.7	54.0	Vance Spring. Take second road (the one just past corral) heading northwest and then north.
2.6	56.6	Intersection. **STOP 2.** Walk about 230 m northeast along road and then view outcrops along low hill just south of and paralleling road back toward intersection. First exposures are in the upper part of the Cottonwood Wash Tuff, the basal formation of the Needles Range Group (Figure 7). This lapilli ash-flow tuff is usually red-brown to pink except for a local gray vitrophyre near the base of the sheet. Here, however, the upper part of the deposit is gray, probably because of slight hydrothermal activity along nearby faults. Nonetheless, the crystal-rich character of the Needles Range tuffs is obvious; about one-half of the phenocrysts are plagioclase. In the Cottonwood Wash Tuff large euhedral books of biotite several millimeters across are abundant. A few per-

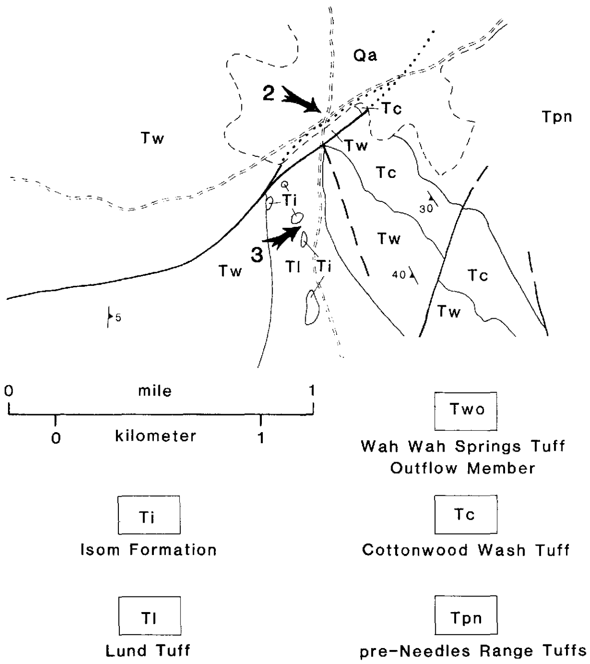

Figure 7. Geologic map of area around STOPS 2 and 3, Secs. 4 and 5, R. 18 W., T. 28 S. (Best, 1976; Best and Hintze, 1980).

cent of large, embayed, and broken quartz phenocrysts are obvious. Much smaller hornblendes are generally visible only in thin sections and green augite occurs in trace amounts. The first conspicuous exposure of the overlying Wah Wah Springs Formation of the Needles Range Group is a black to dark gray vitrophyre a few meters thick produced by intense welding near the base of the ash-flow deposit. In this area, which is about 12 km north of its source caldera, the Wah Wah Springs tuff is 300 to 500 m thick. In the overlying red-brown and slightly devitrified tuff the characteristic phenocryst assemblage is easily seen. Plagioclase, hornblende, and biotite occur in order of decreasing abundance. Augite and quartz phenocrysts less than a millimeter across are minor. Upwards in the section toward the southwest the intensity of welding diminishes until just south of the road intersection the tuff is only moderately welded and rather porous; light-colored devitrified pumice lapilli and biotite phenocrysts are conspicuous.

Turn around and drive south back towards Vance Spring.

0.5 57.1 **STOP 3.** Along roadside are exposures of gray Lund Tuff, the upper-most of the three principal sheets of the Needles Range Group (Figure 7). Here, outside the Indian Peak caldera, the Lund is only about 30 m thick and is weakly welded. In addition to the dominant plagioclase, other phenocrysts include pale amethyst quartz and biotite. Hornblende is less abundant. Brown sphene occurs in trace amounts. A short distance to the west, dark-colored rubble is all that remains of a thin ash-flow sheet of the 25 m.y. old Isom Formation.

Continue south on road toward Vance Spring.

2.1 59.2 Intersection at Vance Spring.

Depending upon road conditions and snow cover, proceed either to stops 4 and 5 or to alternate stop A4.

To reach stop 4, turn south at intersection and proceed toward Ryan Spring.

2.7 61.9 Intersection; continue straight (west).

1.9 63.8 Ryan Spring. **STOP 4.** Exposed here is a thick section, totaling some 1200 m, of ash-flow tuffs that were deposited within the Indian Peak caldera after its collapse during catastrophic expulsion of the Wah Wah Springs Formation (Figure 8).

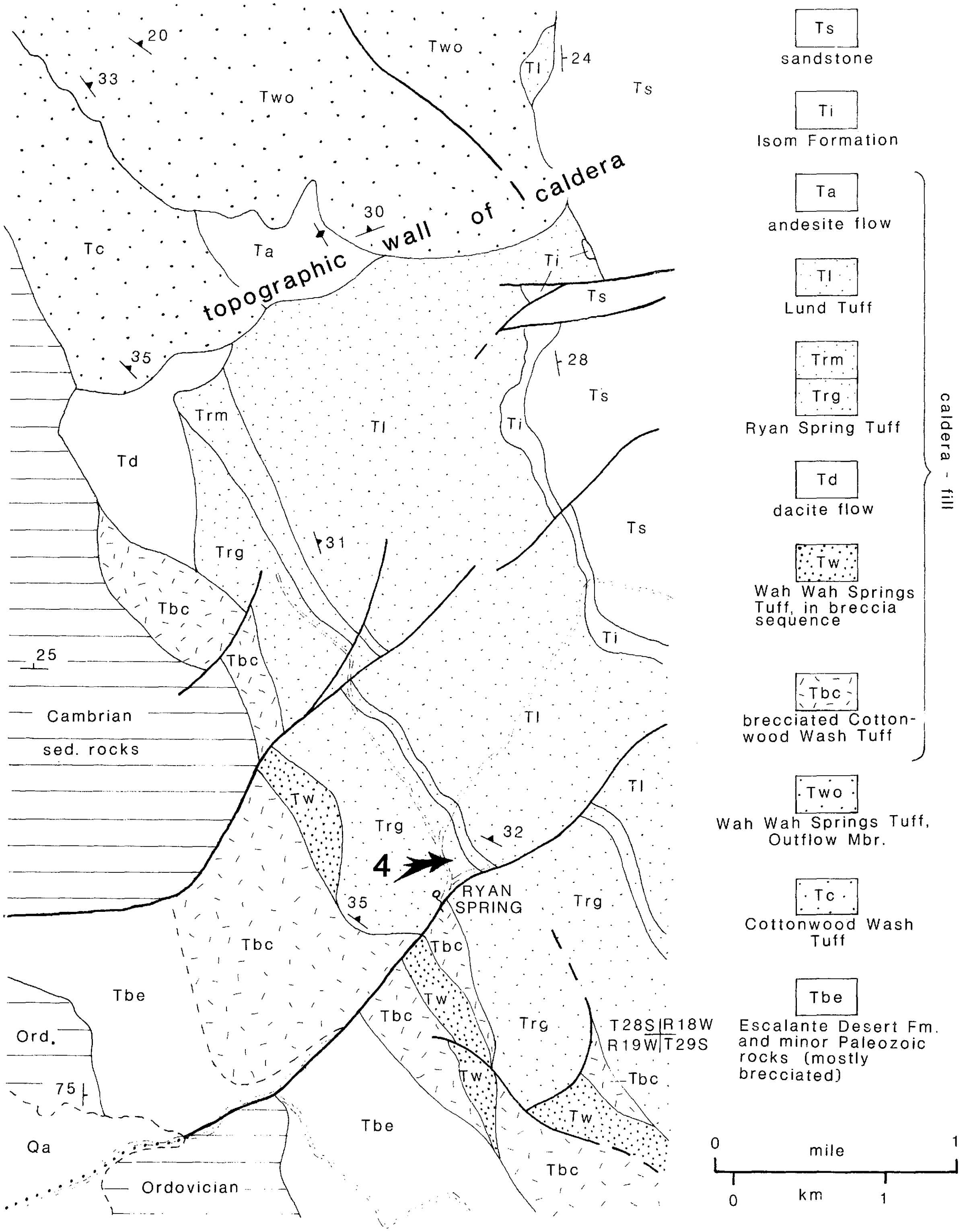

Figure 8. Geologic map around Ryan Spring STOP 4 showing the topographic wall of the Indian Peak caldera and 1200 m thick caldera-fill sequence (Best, 1976; Best, Grant, and Holmes, 1979).

This section lies on a complex sequence, as much as 800 m thick, of cataclastic and chiefly monolithologic breccias of pre-Wah Wah Springs volcanic rocks with intercalated wedges of Wah Wah Springs tuff.

During catastrophic eruption of thousands of cubic kilometers of Wah Wah Springs tuffs, subsidence occurred along the ring fault of the caldera 4 km south of Ryan Spring. Apparently, subsidence was so great (> 3 km) that gravity-driven fault slices (or large landslides) caved into the deepening depression from the unstable caldera wall, extending the topographic rim of the caldera 10 km northward from the initial scarp of the ring fault (Figure 5). Discontinuous wedges of Wah Wah Springs tuffs, some similar to that occurring as the Outflow Member to the north, lying within the sequence of breccias suggest continued eruption during subsidence.

The Ryan Spring Tuff overlying the sequence of breccias includes crystal-poor and locally lithic, rhyolitic ash-flow tuffs with minor volcanic sandstones and debris flow deposits. Plagioclase phenocrysts comprise 2 to 15 percent and biotite 1 to -2 percent of the tuffs. The lower tuff member has conspicuous light-colored haloes surrounding voids in the matrix.

The overlying 28 m.y. old Lund Tuff is a compound cooling unit that is 600 m thick here, compared to only 30 m at Stop 3 just north of the topographic rim of the caldera. Because of this much greater thickness there is a well-developed basal vitrophyre several meters thick and the overlying red-brown divitrified tuff is densely welded for hundreds of meters.

Continue down road (southwest) through the wet spring area.

1.1	64.9	Turn left (southeast) at intersection.
1.4	66.3	Fork in road; continue straight (east).
1.5	67.8	**STOP 5.** Cataclastic, variably altered, monolithologic breccias of the Cottonwood Wash Tuff along the road are overlain by several meters of Wah Wah Springs tuff vitrophyre, then by more Cottonwood Wash breccia and finally by the basal member of the Ryan Spring Tuff (Figure 9). The thick Wah Wah Springs vitrophyre here is either 1) a fault slice derived from a thick section to the north and transported here, or 2) a remnant of a much thicker *in situ* deposit that was welded, compacted, and then decapitated by subsequent faulting/landsliding, or 3) an *in situ* thin deposit that was welded and compacted by immediate burial beneath the overlying Cottonwood Wash breccia deposit. In any case, there is evidence here for transport of fault/landslide masses. To the southeast about 900 m is a spectacular exposure of brecciated pre-Wah Wah Springs volcanic rocks with a subhorizontal slickensided surface above cataclastic layering. Continue on road.
0.2	68.0	Intersection; turn right (south).
0.9	68.7	Intersection; turn left (east).
0.6	69.3	Road forks; continue up ridge.

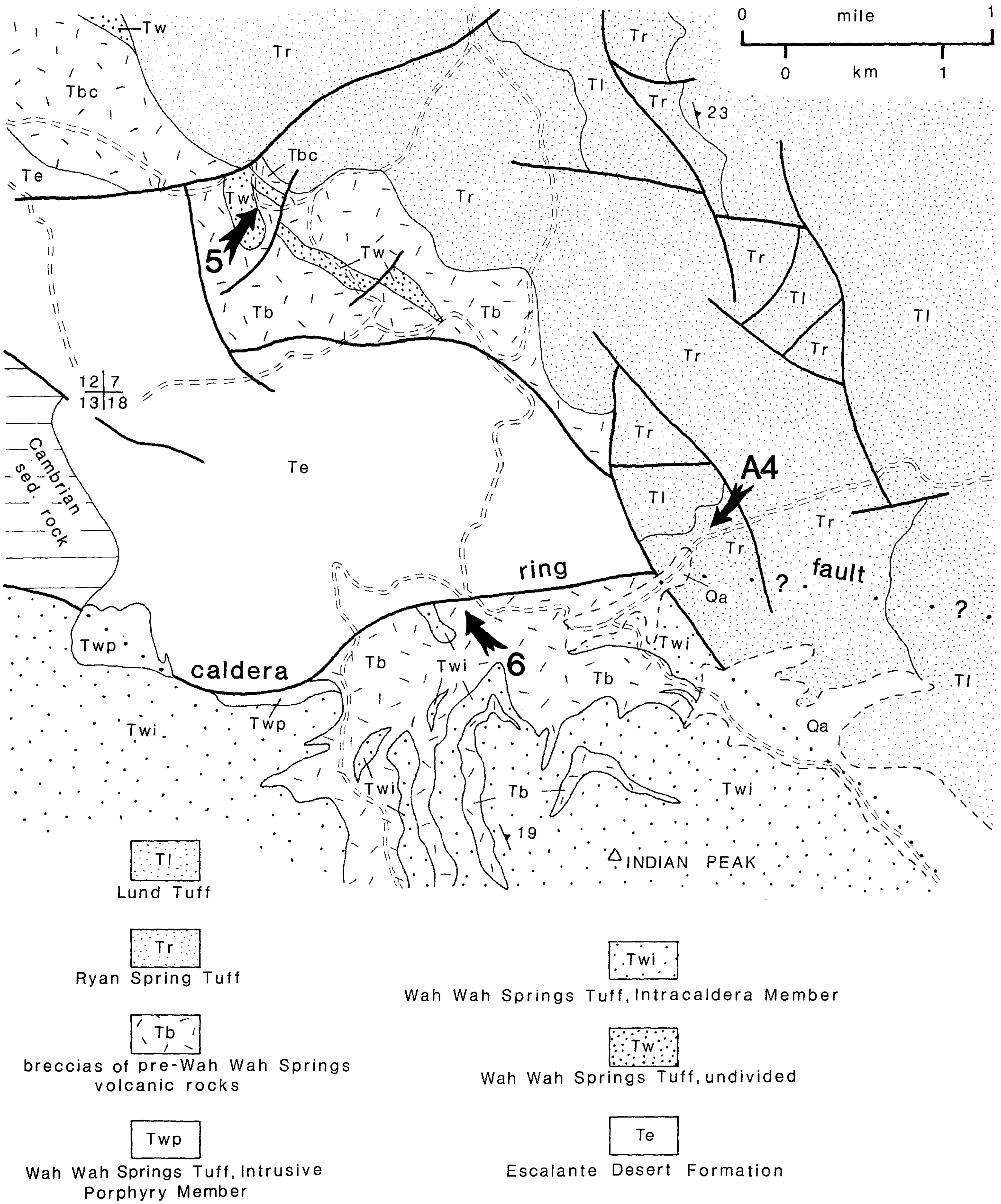

Figure 9. Geologic map of ring fault of the Indian Peak caldera STOPS 4A, 5 and 6 (Best, Grant, and Holmes, 1979). Northwest corner of map joins with southeast corner in Figure 8 map.

1.4 70.7 Intersection in saddle. **STOP 6.** Ring fault of Indian Peak caldera (Figure 9). Pre-Wah Wah Springs tuffs to the north are juxtaposed against caldera-fill rocks on the south. The caldera-fill sequence exposed here comprises southward thinning wedges of non-cataclastic volcanic breccias that interfinger with tuffs of the Intracaldera Member of the Wah Wah Springs Formation. The wedges of breccia are essentially monolithologic accumulations of Cottonwood Wash Tuff and some other familiar pre-Wah Wah Springs volcanic rocks that originated as landslide masses caving from the unstable wall of the caldera. These breccias are not cataclastic as are those north of the ring fault. The Intracaldera Member of the Wah Wah Springs Formation is a compound cooling unit in which zones of black vitrophyre alternate with orange-brown to gray-green devitrified but still densely welded tuff. The Intracaldera Member varies petrographically within the exposed area of the caldera. In places, it has a higher concentration of quartz phenocrysts than the Outflow Member. Generally, it contains lapilli-size lithic fragments and locally these are cognate clasts of texturally different Wah Wah Springs rock. Locally, near the ring fault some accidental clasts of older rock are several meters across and comprise most of an outcrop.

Shows of Cu-mineralization occur along the ring fault 4 km to the west where dikes of an intrusive porphyry compositionally similar to the Wah Wah Springs tuffs have invaded Paleozoic carbonate rocks along the caldera wall.

Return to Highway 21 and Milford.

To reach alternate Stop A4 from Vance Spring, continue on road going east that passes just south of Sawtooth Peak.

2.7 73.4 Intersection southeast of Sawtooth Peak overlooking Pine Valley. Turn right (south).

0.6 74.0 Road divides; continue southeast.

0.4 74.4 Intersection; continue straight (east).

0.3 74.7 Road divides; turn right (south).

0.5 75.2 Road comes in from right (west); continue straight ahead (southeast).

4.5 79.7 Major intersection; turn right (west).

4.0 83.7 Road divides; turn right (west).

3.6 87.3 **ALTERNATE STOP A4.** View of Lund and Ryan Spring Tuffs that filled the topographically enlarged caldera depression (Figure 9). The road for the past several miles has passed through the Lund Tuff. The exact thickness of this compound cooling unit here is indeterminate because of faulting but is probably on the order of 700 m. Beneath the Lund Tuff are two members of the Ryan Spring Tuff.

Continue on road to west.

0.6 87.9 Intersection; proceed right (west) through gate to top of ridge.

0.7 88.6 Intersection. **STOP 6.** See mile 70.7

FIELD TRIP ROAD LOG: SECOND DAY

Stops will be made in the southern Wah Wah

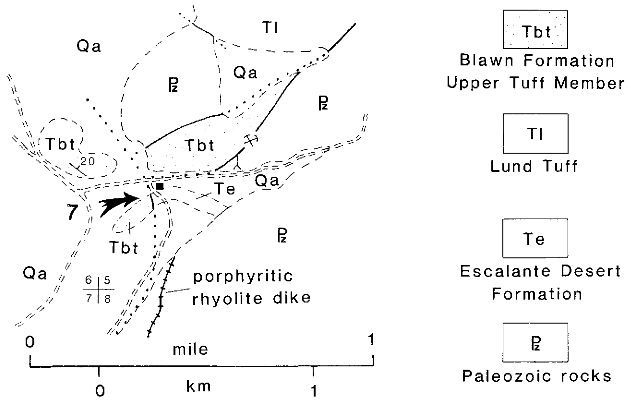

Figure 10. Geologic map of area around the Cinna mine STOP 7, mostly in Sec. 5, R. 15 W., T. 31 S. (Morris and others, 1982).

Mountains to examine bimodal associations of silicic and mafic igneous rocks of early and middle Miocene age. Log begins just north of Minersville at the junction of Highways 21 and 130.

Mileage		Discription
Incremental	Cumulative	
0.0	0.0	Head south on Highway 130.
0.2	0.2	Intersection with first road south of Beaver River. Turn right (west).
0.4	0.6	Intersection; turn right (north) and drive around corner past Minersville Cow Palace Association heading west.
1.3	1.9	Main road veers right (northwest); continue straight (west).
11.2	13.1	Union Pacific railroad tracks.
3.2	16.3	Road joins in from right; proceed left (southwest).
1.5	17.8	Intersection. Turn right (northwest).
13.7	31.5	Road joins in from left (southeast); head right (northwest).
5.9	37.4	Intersection with minor road; turn left (south) across cattle guard.
0.9	38.3	Intersection; continue straight (southwest).
0.9	39.2	Intersection; continue straight (south).
0.2	39.4	Road divides; turn left (southeast).
0.9	41.5	Road divides; turn left (east).
0.2	41.7	Old building. **STOP 7.** Walk down dry wash to south to view a section through the 23 to 18 m.y. old tuff member of the Blawn Formation (Figure 10). The exact source of the pyroclastic material exposed here is uncertain as several vent areas existed in the southern Wah Wah Mountains during the early Miocene. At the top of the section at the northeast end of the wash are ash-flow lapilli tuffs with intervening thin layers of reversely graded air-fall or surge material. The pyroclastic material is chiefly vitric with only minor amounts of quartz, biotite, and sanidine phenocrysts; xenoliths of Lund Tuff and flow-layered rhyolite are rare. Lapilli of green perlite in the uppermost part of the section suggest it may be as young as 12 m.y. because the only other green perlite occurrences in the region lie a few kilometers to the southwest in Broken Ridge where such K-Ar ages have been determined. Farther down the wash and down section, following an interval of no exposure, is a meter-thick air-fall layer of pumice lapilli that has a subtle normal gradation in clast size. At the bottom of the section is another vitric ash-flow tuff. Return to old building and

then proceed east along road past old mercury retorts to Cinna mine. Brown, iron-stained jasperoid north of the road is silicified lapilli tuff of the Blawn Formation. A major high-angle fault separates these rocks from Paleozoic carbonate rocks to the south and east. Shallow-seated hydrothermal activity probably manifest as hot springs at the surface was localized along this fault. Veins of gypsum carry disseminated native sulfur, cinnabar (gray-black on weathered surfaces) and jarosite. The age of high-angle northeast-striking block faulting is bracketed between 22 and 12 m.y., and at least locally between 22 and 18 m.y. To the southwest of here, the Bible Spring fault zone of tilted horst and graben slices underlies undeformed 12 m.y. rhyolite of the Steamboat Mountain Formation. The faulted rocks include the 22 m.y. old Bauers Tuff. North of here, The Tetons are remnants of 18 m.y. rhyolite lying uncomformably on tilted Oligocene rocks (see Stop 8 and Figure 11). The time of hydrothermal activity here at the Cinna mine could be about 20 ± m.y. with a 12 m.y. overprint, but no radiometric data are available.

4.3 46.0 Retrace route back to main gravel road; turn left (west).

3.0 49.0 Intersection with jeep trail; turn right (northeast).

2.1 51.1 End of road between The Tetons. **STOP 8.** Rhyolite tuff and capping rhyolite lava flow with a K-Ar age of 18.3 ± 0.7 unconformably overlie tilted Oligocene volcanic rocks (Figure 11). Four kilometers to the southeast at the top of this faulted and tilted section is the 22 m.y. old Bauers Tuff. The age of faulting, therefore, lies between 22 and 18 m.y.

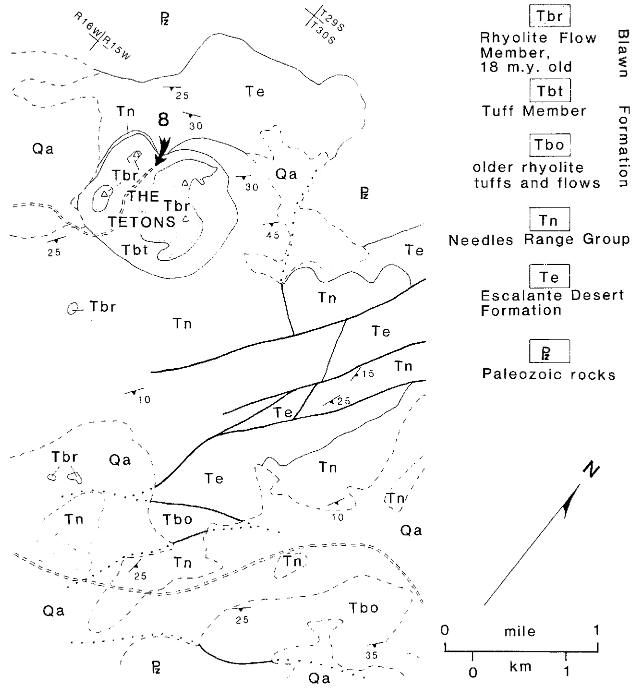

Figure 11. Geologic map of The Tetons area STOP 8 (Morris and others, 1982).

The vitric tuff in the saddle between The Tetons contains minor feldspar crystals and abundant clasts up to a meter in diameter of the underlying Lund Tuff. This is not a welded ash-flow or air-fall tuff as the vitric particles are neither pumice nore curved sliver-like shards of discintegrated pumice. The nonvesicular character of the vitric clasts possibly indicates derivation by explosive decrepitation of a glassy dome that encountered water near the surface.

Upper parts of the tuff, as on the flank of the hill to the west, are argillized. The overlying flow-layered rhyolite is virtually aphyric with only sparse small phenocrysts of quartz and sanidine. Topaz and fluor-

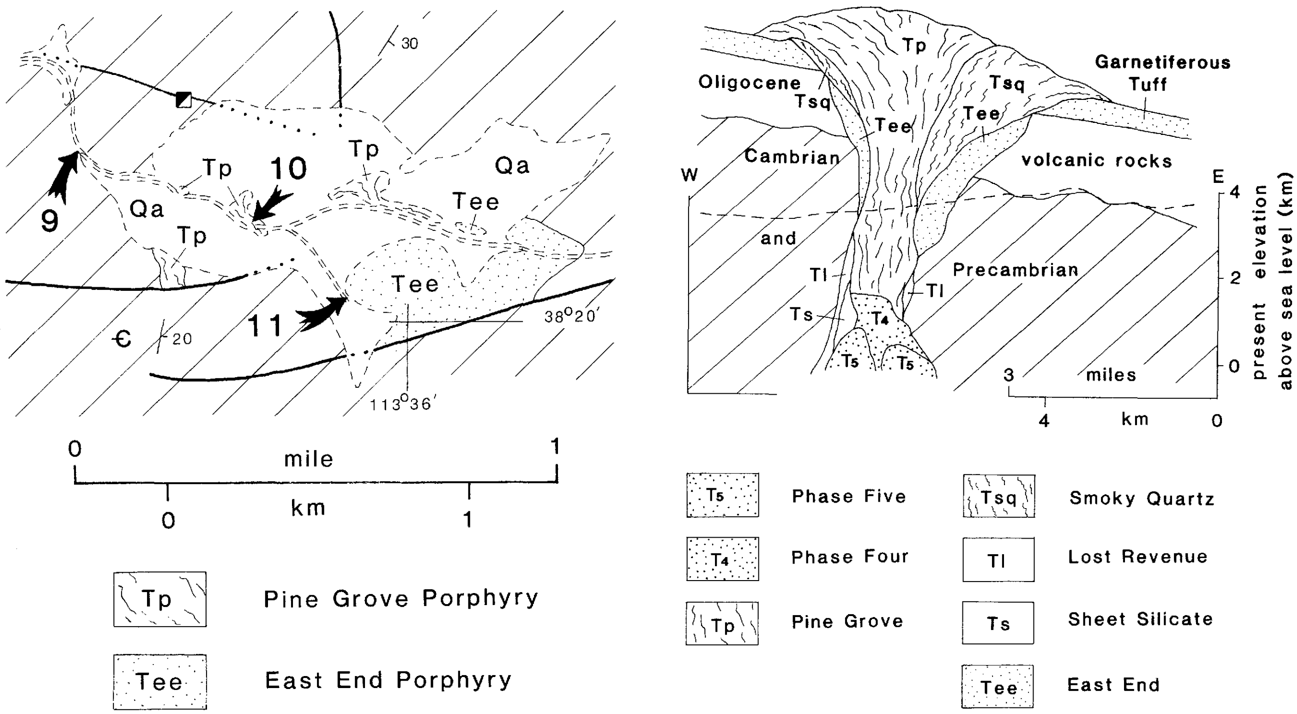

Figure 12. Geologic map and schematic east-west cross section of the Pine Grove volcanic center STOPS 9, 10, and 11 (Abbott and others, 1981; Keith, 1982).

		ite are very rare vapor-phase crystals in vugs.
2.1	53.2	Return to main gravel road and turn right (north); continue into Pine Valley.
6.0	59.2	Intersection with main valley road; turn right (north).
12.2	71.4	Intersection on east side of wash; continue east toward Wah Wah Mountains.
1.5	72.9	Road joins in from left; turn right (southeast).
5.0	77.9	**STOP 9.** A small porphyry sill about 1 m thick was intruded into the uppermost part of the Cambrian Prospect Mountain Quartzite (Figure 12).
0.4	78.3	**STOP 10.** Principal exposures of the largely concealed Pine Grove Porphyry body (Figure 12). The rock here is moderately to highly altered to an assemblage of quartz and sericite with locally abundant kaolinite, montmorillonite, and carbonate minerals. Relict phenocrysts of quartz, alkali feldspar, plagioclase, biotite, and garnet lie in a felsic matrix. Nine hundred to more than 2,000 m below the surface lies a disseminated Mo-W ore deposit explored and evaluated by Pine Grove Associates, a joint venture of Phelps-Dodge Corporation and Getty Oil Company.

The Pine Grove Porphyry is but one of the seven silicic porphyry bodies in the Pine Grove volcanic center (Figure 12). Though mostly concealed and strongly altered at the surface, these bodies have been encountered in over 30 km of drill core and can be distinguished on the basis of contrasting textures and modal and bulk chemical compositions (Keith, 1982). The East End Porphyry is a vent-facies deposit formed by early ash-flow eruptions (see Stop 12). Subsequently, two dome-forming bodies, the Pine Grove and Smoky Quartz Porphyries, were intruded. Shortly after formation of this composite dome, cobbles of rhyolite porphyry were eroded and are now found exposed in a thin conglomerate layer in Blawn Wash about 14 km to the southeast.

Two intrusive bodies that produced Mo-mineralization, Phase Four and Phase Five Porphryies (Figure 12), differ in several important aspects. Phase Four Porphyry has a transitional upper contact with Pine Grove Porphyry, euhedral quartz phenocrysts, a low alkali feldspar/plagioclase ratio, a relatively coarse matrix, and weak mineralization. Phase Five Porphyry exhibits broken quartz phenocrysts, a high alkali feldspar/plagioclase ratio, a fine-grained matrix, and much stronger mineralization.

Contemporaneous emplacement of rhyolite and dacite porphyry occurred during eruption of the ash-flow tuff sequence and also between intrusion of Phase Four and Phase Five Porphyries. The rhyolitic phase of the mixed intrusitons is designated Lost Revenue Porphyry and the dacitic phase is Sheet Silicate Porphyry. Mixtures of these two units are common. Both units exhibit moderately broken quartz phenocrysts and have similar matrix crystal sizes. Textural evidence suggests that the second episode of emplacement of Lost Revenue and Sheet Silicate Porphyry probably occurred coincident with increased convection and volatile exsolution rates immediately prior to emplacement of Phase Five Porphyry and the dominant episode of mineralization.

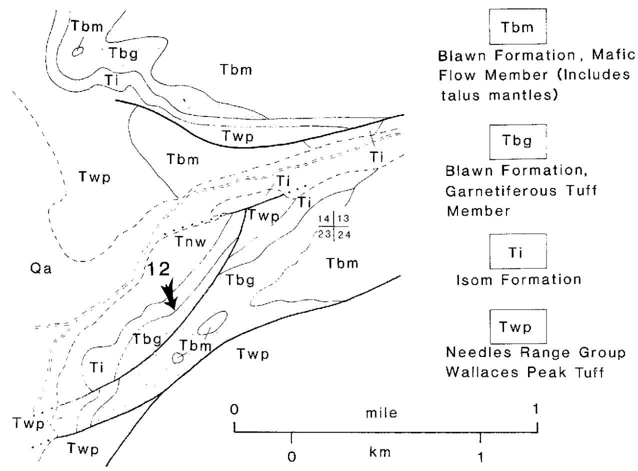

Figure 13. Geologic map of a part of the east flank of the Wah Wah Mountains around STOP 12 (Abbott and others, 1981).

Post-mineralization events include intrusion of a few narrow trachyandesite(?) dikes and eruption of trachyandesite (K-rich mafic) lavas of the Blawn Formation across the region (unit Tbm, Figure 13). A few post mineralization rhyolite dikes cross-cut Pine Grove and are probably an unrelated younger event.

0.1 78.4 Take right fork (southeast).

0.2 78.6 **STOP 11.** East End Porphyry. This rock contains phenocrysts of quartz, sanidine, plagioclase and very minor amounts of biotite, hornblende, and garnet in an altered felsic matrix. Lithic fragments include quartzite, shale, and limestone.

That this rock body is the pyroclastic filling of a volcanic vent, rather than an intrusion, is indicated by the presence of locally significant amounts of moderately flattened pumice lapilli that are now altered to clay minerals (Keith, 1982); very rarely the body is still glassy and spherulitic. Drill-hole information indicate the body is rootless, resting on the flared, funnel-shaped sides of the vent and cut off by the dome-forming porphyries (Figure 12).

The East End body also contains fragments of rhyolite and dacite porphyry — probably pieces of the Lost Revenue and Sheet Silicate units. A few fragments appear to have been quite ductile when incorporated, suggesting they might represent bits of magma spatter ejected along with the East End pyroclasts.

0.2 78.8 Return to main Pine Grove road and turn right (east). Continue over divide to east flank of range.

7.0 85.8 **STOP 12.** Garnet-bearing Tuff Member of Blawn Formation (Figure 13). Ascending the hill to the south of the road the section begins in the Wallaces Peak Tuff, a local ash-flow sheet in the Needles Range Group that lies above the Lund Tuff. It is overlain by the 25 m.y. old Isom Formation which here comprises three cooling units; this tuff is a crystal-poor vitric tuff with less than 10 percent phenocyrsts of plagioclase and minor augite. Overlying the Isom Formation is the garnet-bearing Blawn tuff upon which lies the K-rich-Mafic Flow Member of the Blawn Formation. In these lavas, phenocrysts of augite, hypersthene, plagioclase, and minor altered olivine lie in a black glassy matrix. A sample from across the canyon north of here gave a whole-rock K-Ar age of 23.2 ± 1 m.y. (Best and others, 1980). Chemical analysis of the same sample yielded (in weight percent) SiO_2 60.5, TiO_2 1.0, Al_2O_3 15.9, Fe_2O_3 (total Fe) 7.4, MgO 3.9, CaO 6.0, Na_2O 2.9, K_2O 3.3, P_2O_5 0.3. Other samples have SiO_2 as low as 57 and K_2O up to 4.0.

Initial plinian eruptions from the Pine Grove magma system deposited up to 4 m of poorly sorted and non-welded air-fall ash, lapilli, and lithic blocks. In addition to glass shards and pumice there are crystals of quartz, sandine, and plagioclase with minor to trace amounts of biotite, garnet, titanomagnetite, zircon, monazite, and xenotime. Overlying these deposits are lapilli ash-flow tuffs of similar composition that are locally over 150 m thick. Lithic fragments include Isom and Needles Range tuffs, phyllitic shale, quartzite, and limestone. In these tuffs, the proportions of biotite and garnet vary and near the middle of the sequence there are trace amounts of hornblende, augite, apatite, and ilmenite.

Despite the fact that the Pine Grove intrusions (Stops 9-11) have eroded approximately 1.7 km from the early Miocene paleo-surface (Figure 12) correlation with the pyroclastic deposits exposed at this stop is made possible by the presence of unique accessory garnet in all rhyolitic intrusive and extrusive units (Keith, 1982). Microprobe analysis of garnets from ash-flow and intrusive units demonstrates that both are yttrium-rich almandine-spessartine garnets of identical chemical composition. In addition, included within garnets from both units are titanomagnetite grains of identical composition. Contained within the garnet and titanomagnetite are small crystals of U-Th-bearing monazite, zircon, and xenotime. This sequence of successively included mineral phases of identical composition seems to be conclusive evidence of comagmatic origin for the ash-flow tuffs and Pine Grove intrusive units. Microprobe analyses of other minerals and whole-rock major and trace element analyses of both intrusive and extrusive units also substantiate this correlation.

In addition, the pyroclastic deposits have a distribution and thickness that is compatible with venting of the Pine Grove magma system. The tuff rests on 25 m.y. old Isom Formation and is capped by trachyandesite flows with an age of 23 m.y. (Best and others, 1980). The age of the tuff bracketed by these two units agrees with the K-Ar age of 24 m.y. from Pine Grove Porphyry (Abbott and others, 1981).

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