

CRATERS OF THE MOON NM

IGNIMBRITES OF THE EASTERN SNAKE RIVER PLAIN:
EVIDENCE FOR MAJOR CALDERA-FORMING ERUPTIONS

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Abstract. The eastern Snake River Plain is a predominantly rhyolitic province, analogous to the present-day Yellowstone Plateau volcanic field but older and further evolved. The widespread Quaternary basaltic lavas that now blanket the eastern Snake River Plain appear to have erupted after major rhyolitic activity ceased and represent less than 20% of the total volume of volcanic rock near the north-central margin of the plain. The rhyolites show a general age progression that becomes younger northeastward toward Yellowstone. Three major ignimbrite sheets, comparable in magnitude to those of the Yellowstone Plateau field, have been correlated on both sides of the eastern Snake River Plain from the Arco and Pocatello areas to margins of the Yellowstone Plateau. These 4.3- to 6.5-Ma-old ignimbrites are referred to herein as the Heise volcanic field. Studies of facies changes and lateral variations in the three major ignimbrites of the Heise field permit identification of related calderas that are now buried beneath the plain. Petrologic studies suggest that, although the ignimbrites overlap compositionally, each was derived from an isotopically distinct magma that contained a significant component of crustal material.

Introduction

The eastern Snake River Plain is largely blanketed by basalts and generally has been considered to be a predominantly basaltic province [Stearns et al., 1938; Hamilton, 1965; Greeley, 1982]. Rhyolitic rocks are volumetrically dominant, however, as indicated by drill hole data [Embree et al., 1978; Doherty et al., 1979; Doherty, 1979], geophysical investigations [Mabey, 1978a; Brott et al., 1981; Braile et al., 1982], and field studies along margins of the province [Mansfield and Ross, 1935; Kirkham, 1931; Mansfield, 1952; Trimble and Carr, 1976]. Furthermore, the Yellowstone Plateau volcanic field, not yet covered by basalt, appears to provide an analog for the older rhyolitic systems of the Snake River Plain [Christiansen, 1984a, b].

The complex stratigraphic relations of the

rhyolitic lavas and ignimbrites of the Snake River Plain, positions of their source vents, and their lateral extent must be better defined before details of the development of the plain can be understood. Here we focus on volcanologic, chronologic, and geochemical studies of the upper Miocene and Pliocene rhyolitic ignimbrites of the Heise volcanic field (Figures 1 and 2), emplaced approximately 6.5-4.3 Ma ago and predating eruption of the Pleistocene Yellowstone Group [Christiansen and Blank, 1972]. The Heise volcanic field contains three major ignimbrite units, the tuffs of Blacktail, Blue Creek, and Kilgore, which are intercalated with local rhyolitic pyroclastic-fall deposits, ignimbrites, rhyolitic lava flows and domes, and basalts.

Earlier studies established local stratigraphic nomenclature for these Miocene and Pliocene rhyolitic ignimbrites (Table 1) [Prostka and Embree, 1978; Skipp et al., 1978; McBroome et al., 1981; Embree et al., 1984]. The three major ignimbrites exposed on the northwestern margin of the eastern Snake River Plain are equivalent to units on the southeastern margin (Figure 2), as indicated by similarities in stratigraphic position, phenocryst composition and abundances, radiometric ages, and whole-rock trace element compositions.

Stratigraphic nomenclature of the Heise volcanic field is complex because previous investigators worked independently in different areas (Table 1) [Scholten et al., 1955; Albée et al., 1975; Prostka and Embree, 1978; Skipp et al., 1979; McBroome et al., 1981]. Brief descriptions of the major ignimbrite units of the Heise volcanics are presented in this paper; more complete descriptions are given by McBroome et al. [1981] and Embree et al. [1984].

Previous workers have suggested that a caldera complex near Rexburg [Mabey, 1978b; Prostka et al., 1979; McBroome et al., 1981] may be the source for the tuffs of Blacktail and Kilgore in addition to numerous small rhyolitic ignimbrites and lava flows in this area. We concur that some late Neogene volcanic activity was concentrated in the Rexburg area but propose that volcanism near Rexburg was part of a much larger system now buried beneath the eastern Snake River Plain.

Field relations suggest that later calderas of the Heise volcanic field are nested within or overlap the initial caldera that formed 6.5 Ma ago. The locations of these calderas are inferred from stratigraphic and facies relationships in the ignimbrites, distributions of

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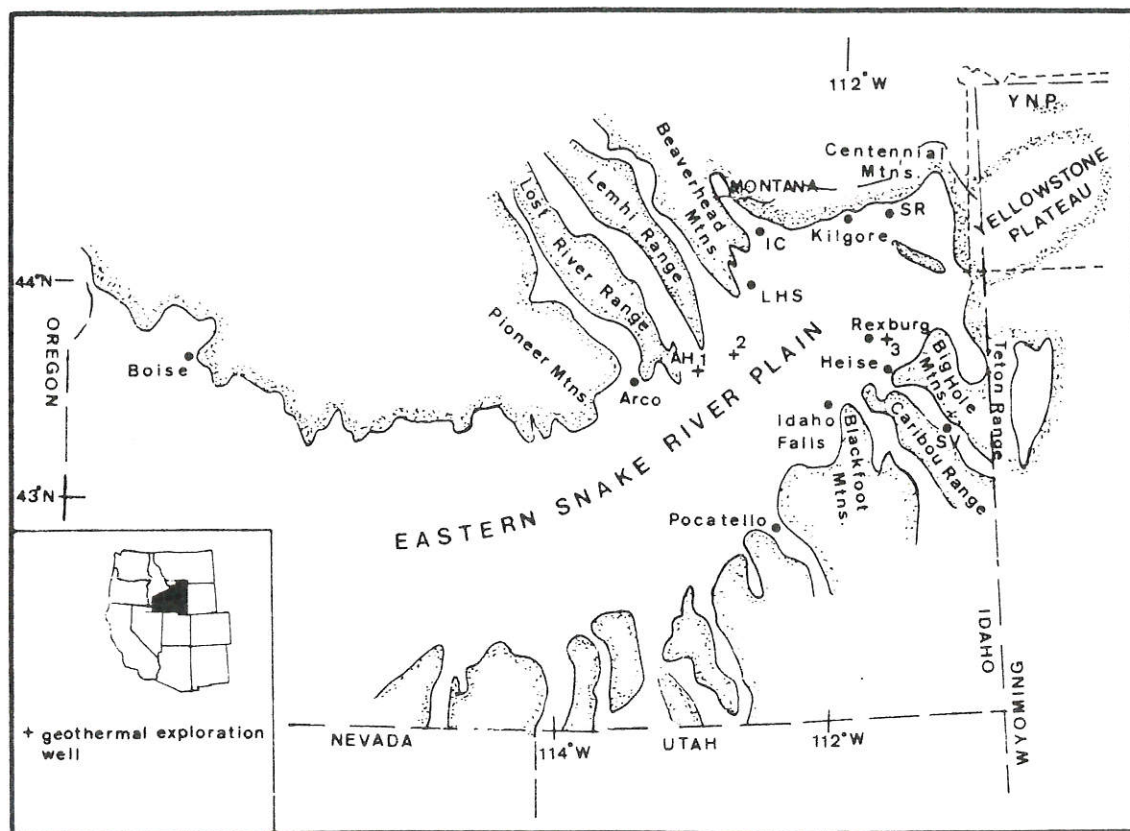


Fig. 1. Index map of the Snake River Plain area. Localities discussed in text include AH, Arco Hills; IC, Indian Creek; LHS, Lidy Hot Springs; SR, Sheridan Reservoir; SV, Swan Valley; YNP, Yellowstone National Park; 1, INEL-1, Idaho National Engineering Laboratory geothermal exploration well 1; 2, geothermal exploration well 2-2A; 3, Sugar City geothermal exploration well 3.

associated deposits, volcanic structures, and geophysical anomalies.

Stratigraphy

The three ignimbrites of the Heise volcanic field form a coherent stratigraphic package in most areas along both margins of the plain

(Figures 2 and 3). On the northwest margin they extend from the Pioneer Mountains (Figure 1) northeastward to the western margin of the Yellowstone Plateau; along the southeast margin they extend from Pocatello northeastward to the western edge of Yellowstone. The total volume of the three ignimbrites exceeds 2000 km³, based on their exposed and inferred areal distributions and estimated average thicknesses.

TABLE 1. Stratigraphic Nomenclature of the Heise Volcanic Field

Previous Nomenclature for Units on the North Margin of the Plain	Stratigraphic Nomenclature of This Paper	Previous Nomenclature for Units on the South Margin of the Plain
Tuff of Spencer ^a	Tuff of Kilgore	Tuff of Heise ^{c,d,f}
Tuff of Blue Creek ^{a,b,f}	Tuff of Blue Creek	Tuff of Heise ^{c,d}
Tuff of Edie School ^a	Tuff of Blacktail	Tuff of Elkhorn Spring ^{c,f}
Tuff of Edie Ranch ^{b,f}		Tuff of Heise B ^d
Edie School Rhyolite ^e		Tuff of Spring Creek ^{c,f}
Tuff of Howe Peak ^f		Tuff of Heise A ^d

^aSkipp et al. [1979].

^bMcBroome [1981].

^cProstka and Embree [1978].

^dAlbee et al. [1975].

^eScholten et al. [1955].

^fMcBroome et al. [1981].

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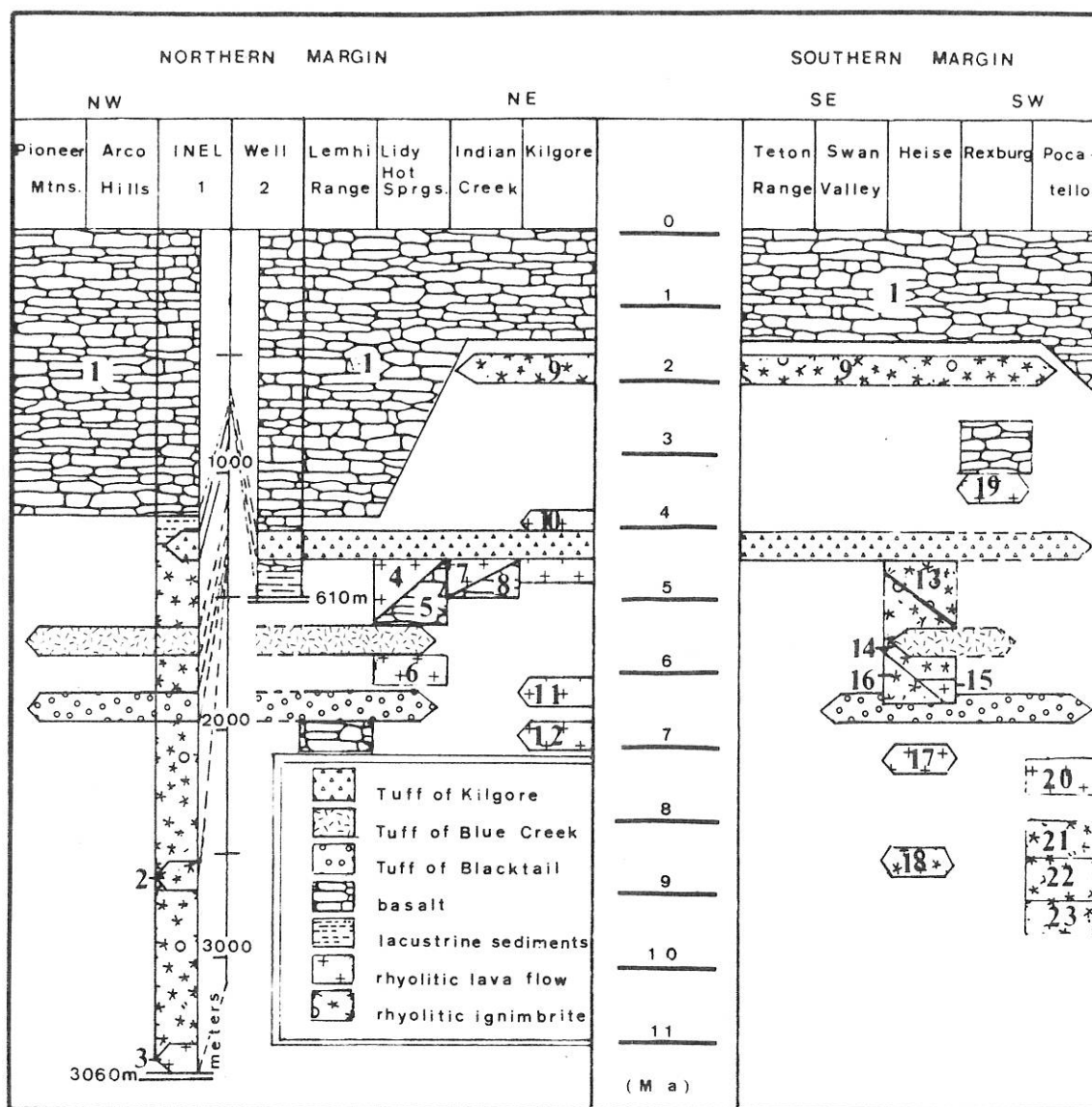


Fig. 2. Schematic stratigraphic relations among the three major ignimbrites of the Heise volcanic field and associated volcanic deposits. Localities are given in Figure 1 and radiometric ages in Table 2. (1) Basalts of the Snake River Group; (2) 8.8-Ma rhyolitic ignimbrite, INEL-1, 1482 m; (3) 11.3-Ma quartz latite flow, INEL-1, 3060 m; (4) rhyolite of Lidy Hot Springs; (5) basalt of Rattlesnake Point; (6) rhyolite of Reno Gulch; (7) rhyolite of Indian Creek Butte; (8) basalt of Indian Creek; (9) Huckleberry Ridge Tuff; (10) rhyolite of Sheridan Reservoir; (11) rhyolite of Ching Creek; (12) rhyolite of Opal Mountain; (13) tuff of Willow Creek; (14) tuff of Wolverine Creek; (15) rhyolite of Kelly Mountain; (16) tuff of Dora Springs; (17) rhyolite of Hawley Spring; (18) tuff of Newby Ranch; (19) rhyolite of Long Hollow; (20) rhyolite of Carlton Creek; (21) Walcott Formation; (22) Neeley Formation; (23) Starlight Formation. Stratigraphic units with pointed sides are units for which radiometric ages are approximate; those with flat sides are units of uncertain radiometric age but known stratigraphic sequence.

Tuff of Blacktail

The most extensive ($>12,000 \text{ km}^2$) and voluminous ($>1500 \text{ km}^3$) ignimbrite in the Heise volcanic field is the tuff of Blacktail. This unit is exposed along the northern margin of the eastern Snake River Plain from the Pioneer Mountains to the Centennial Mountains and along the southeastern margin of the plain from the Blackfoot Mountains to the Big Hole Mountains

(Figure 3). Its distribution and thickness indicate that topographic relief was moderate during the time of its emplacement; the thickness averages 75 m but ranges from 2–3 m near Kilgore to 100 m in the southern Beaverhead Mountains. On the southern margin of the plain, the tuff of Blacktail is greater than 200 m thick in some exposures.

The 6.5-Ma-old tuff of Blacktail (Table 2) is petrographically distinct from the other two

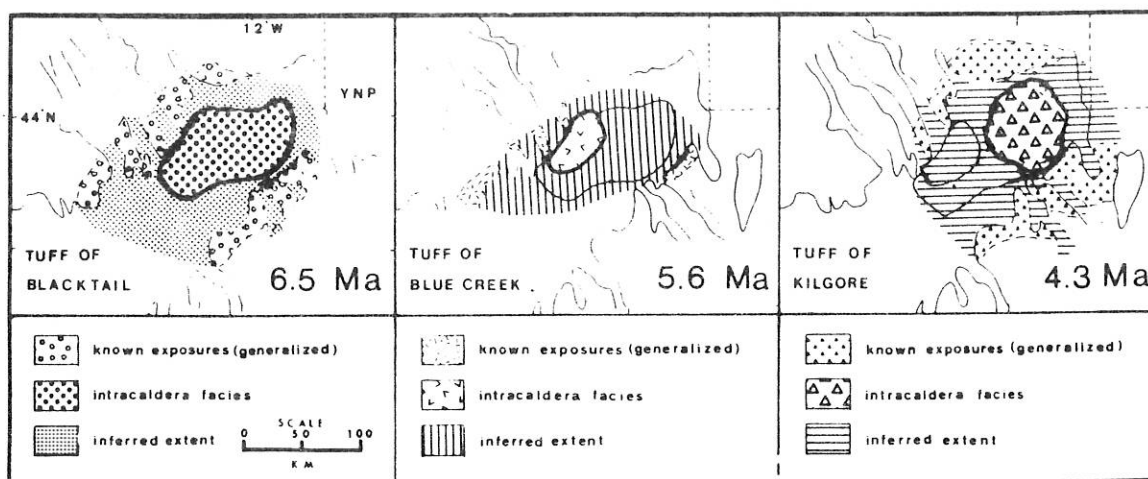


Fig. 3. Map showing the proposed locations for the Blacktail, Blue Creek, and Kilgore calderas and schematically depicting the sequence of development of major calderas of the Heise volcanic field. Locations of the calderas are inferred from near-vent volcanic facies and structures exposed along the margin of the plain, borehole data, seismic refraction, and Bouguer gravity. A generalized distribution of each of the three major ignimbrites from these inferred calderas shows the large areal extent of each unit. Exposures of the outflow facies of the ignimbrites are discontinuous in foothills along the margins of the eastern Snake River Plain. Ignimbrites of the Heise volcanics have been identified in the subsurface of the plain in geothermal exploration wells 2-2A and INEL-1. Subsurface distribution from stratigraphic data obtained from these boreholes and from correlative units exposed on opposite margins of the plain.

ignimbrites in the Heise volcanic field (Table 3), and its paleomagnetic polarity is normal [McBroome, 1981]. Prostka et al. [1979] suggested that it was erupted from a caldera complex near Rexburg; however, thickness, distribution, and textural features of this ignimbrite suggest that ring fracture vents from which the tuff of Blacktail erupted were present near the northern as well as the southern margin of the plain, as will be discussed later.

Tuff of Blue Creek

The tuff of Blue Creek forms a widespread sheet exposed along the northern margin of the plain from the Pioneer Mountains to the Beaverhead Mountains; thickness ranges from 0 to 100 m, averaging 75 m. Along the southern margin of the plain, outcrop of this unit is limited to the northern Big Hole Mountains, where it ponded in topographic depressions to thicknesses of greater than 70 m; this ponded facies is excellently exposed in cliffs above the town of Heise (Figures 1 and 2). The area covered by this unit is about 10,000 km²; its total volume is estimated to be 500 km³. The tuff of Blue Creek is a simple cooling unit [cf. Smith, 1960] along both margins of the plain.

The tuff of Blue Creek has a distinctly lower phenocryst content (<2%) than the other two major ignimbrites (Table 3). A fission-track age of 5.6 Ma has been determined for this tuff (Table 2), and it has normal paleomagnetic polarity [McBroome, 1981]. Eruption of this ignimbrite resulted in a caldera whose margin is well exposed near the north-central margin of the plain, especially in the southern Lemhi Range (Figure 3).

Tuff of Kilgore

The 4.3-Ma tuff of Kilgore (Table 2) covers an area of >11,000 km² and has a minimum estimated volume of 800 km³. It is well exposed in the Rexburg area and surrounding foothills south of the plain. It is also exposed along the northern margin of the plain from the southern Lemhi Range to the Centennial Mountains and is present in the subsurface in geothermal exploration boreholes INEL-1 and well 2-2A (Figures 1 and 2). In most exposures, multiple vitrophyres, accompanied by lithophysal and devitrified zones, define as many as four reversals of cooling zonation. Thus the tuff of Kilgore is a compound cooling unit [cf. Smith, 1960]. Maroon, and locally gray, pumice is characteristic of this ignimbrite.

The tuff of Kilgore varies in thickness from approximately 150 m near Kilgore to less than 4 m in the southern Lemhi Range. It is at least 40 m thick in the Snake River graben near Swan Valley (Figures 2 and 3), and where irregular paleotopography existed near the present-day site of Rexburg, the thickness of the unit ranges from 1 to 120 m [Troshinets, 1982]. The tuff of Kilgore is mineralogically similar to the other ignimbrites of the Heise volcanic field but commonly has an intermediate phenocryst content (2-7%), relative to the crystal-poor tuff of Blue Creek (<2% total phenocrysts) and the relatively crystal-rich (5-15% total phenocrysts) tuff of Blacktail (Table 3).

Prostka et al. [1979] proposed that the source for this ignimbrite was also a caldera complex near Rexburg. Distribution and zonal characteristics of the tuff of Kilgore suggest, however, that its source caldera spans the width of the plain and has buried ring fracture vents

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TABLE 2. Radiometric Ages of Minerals and Whole Rock Samples From the Heise Volcanic Field

Unit	Sample	Method	Age, m.y.	Reference	Location
Rhy. of July Ck.	F-5458	F	2.1+0.2	1	Kilgore
Rhy. of Long Hollow	R-102-78	Z	3.5+0.4	2	Rexburg
Rhyolite (229 m)	BB3-750	Z	3.5+0.3	2	borehole 3
Rhy. of Sheridan Reservoir	F-5454	F	4.0+0.4	1	Sheridan Reservoir
Tuff of Kilgore	69-9	WR	4.1+0.1	5	Ammon
Tuff of Kilgore	2512	Z	4.2+0.3	3	INEL-1
Tuff of Kilgore	H794C-78	Z	4.4+0.4	2	Heise
Tuff of Kilgore	80-183	Z	4.1+0.6	3	Howe Point
Tuff of Kilgore	76-16	F	4.3+0.3	2	Kilgore
Tuff of Kilgore	H794D78	Z	4.4+0.6	2	Heise
Tuff of Kilgore	F5453	F	4.8+0.3	1	Kilgore
Basalt of Indian Creek	76G016	WR	5.2+0.2	4	Indian Creek
Rhy. of Lidy Springs	76G017	WR	5.4+0.1	4	Lidy Hot Springs
Tuff of Blue Creek	80-13	Z	5.6+0.6	3	Howe Point
Rhy. of Kelly Mountain	76G009	WR	5.7+0.1	4	Heise
Rhy. of Willow Creek	87-9	WR	5.9+0.1	1	Kilgore
Rhy. of Spring Creek	87-5	WR	5.9+0.3	1	Kilgore
Tuff of Blacktail	D2671B	Z	6.5+0.3	2	Heise
Tuff of Blacktail	80-34	Z	6.6+0.7	3	Arco Hills
Rhy. of Reno Gulch	80-264	Z	6.2+0.5	3	Reno Gulch
Rhy. of Ching Creek	F5452	F	6.3+0.3	1	Ching Creek
Rhy. of Opal Mtn.	81-6	F	6.9+0.7	1	Spencer
Rhy. of Hawley Spring	76G008	F	7.2+0.1	4	Heise
Rhy. of Newby Ranch	H79-198	Z	8.6+0.5	2	Heise

F, K-Ar determinations of feldspar phenocrysts; WR, K-Ar determinations of whole rock samples; Z, fission-track determinations of zircon microphenocrysts; Rhy., rhyolite.

References: (1) Samples submitted by Doherty while at the Geothermal Division, Chevron Resources Company, San Francisco, and analyzed at Geochron Laboratories; (2) D. J. Doherty (unpublished data, 1981); (3) McBroom [1981]; (4) B. Dalrymple (written communication, 1979), and (5) Armstrong et al. [1975].

near Kilgore on the northern margin of the plain and near Idaho Falls on the southern margin.

Petrologic Characteristics as Related to Stratigraphic Correlation

Correlations of the major ignimbrites of the Heise volcanic field based on stratigraphic position, petrographic characteristics, and geochronology have been evaluated using trace element and isotopic geochemistry (Tables 4 and 5). The ignimbrites are peraluminous rhyolites to high-silica rhyolites and are similar in major element composition (Table 4).

The tuffs of Blacktail and Kilgore both show vertical zonation in phenocryst content and compositions (Table 2). The tuff of Blacktail ranges from approximately 15% (predominantly plagioclase, quartz, and sanidine) at the base to about 5% near the top, where pyroxene phenocrysts

are present in addition to plagioclase, quartz, and sanidine phenocrysts. An upward trend toward more mafic compositions, indicated by the increase in pyroxene phenocrysts, is reflected also in the anorthite content of the plagioclase phenocrysts, which range from An^{27} near the base to An^{35} at the top of the unit. Similarly, the tuff of Kilgore contains approximately 7% phenocrysts at the base and only 2% near the top, but it retains the same assemblage of plagioclase, sanidine, quartz, and pyroxene throughout the section. The plagioclase phenocrysts in this ignimbrite range from An^{10} near the base to An^{35} at the top. In contrast, the tuff of Blue Creek exhibits no distinct vertical phenocryst zonation, probably because it is so crystal-poor. Detailed geochemical studies are in progress to examine further the compositional zonations within these units.

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TABLE 3. Petrography of Major Ignimbrites of the Heise Volcanic Field

	Tuff of Blacktail	Tuff of Blue Creek	Tuff of Kilgore
Phenocryst content, %	5-16	0.4-2.5	2-7
Major phenocryst relative abundances	P>>Q>S>M>>A>O	P>>M>Q>S>>A	P>>S>M>Q>A
Plagioclase			
top of unit	An ₄₅	An ₃₅	An ₃₅
bottom of unit	An ₂₇	An ₃₀	An ₁₀
Accessory phenocrysts	Z, Ap, B	Z	Z, B

P, plagioclase; Q, quartz; S, sanidine; M, iron-titanium oxides; A, augite; O, orthopyroxene; Z, zircon; Ap, apatite; B, biotite.

element) abundances, all the ignimbrites of the Heise volcanic field show light REE enrichment and moderate negative Eu anomalies (Figure 4a). The REE abundance patterns are similar for each ignimbrite but appear somewhat different from at least one other ignimbrite exposed elsewhere on the margins of the Snake River Plain (Figure 4b). Concentrations of some trace elements are distinct for each ignimbrite. Relative concentrations of Sr, Zr, and Rb define separate fields for each ignimbrite of the Heise volcanic field (Figure 5a). These units are also readily distinguishable on this plot from other, older ignimbrites, such as the 9.9- and 12.3-Ma-old rhyolitic ignimbrites present in the southern

Lemhi Range and the Eocene Challis volcanics exposed along the periphery of the eastern Snake River Plain [McBroome, 1981]. In plots of other trace elements, the units also appear compositionally distinctive (Figures 5b and 5c), although there is slight overlap for the tuffs of Kilgore and Blacktail.

Strontium isotopic determinations (Table 5, Figure 6) further demonstrate the petrologic individuality of the major ignimbrites of the Heise volcanic field. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of samples from individual ignimbrite units from both the northern and southern margins of the plain are consistent within analytical precision (± 0.0002). The relatively high values of the

TABLE 4. Representative Chemical Analyses of the Major Ignimbrites of the Heise Volcanic Field

	Tuff of Blacktail	Tuff of Blue Creek	Tuff of Kilgore			
	Selected Whole-Rock Major Element Analyses*					
SiO ₂	74.75	76.24	74.17	76.52	73.88	75.00
TiO ₂	0.22	0.23	0.27	0.11	0.20	0.21
Al ₂ O ₃	12.34	12.55	12.80	12.62	12.16	12.10
FeO ^t	1.84	1.43	1.96	1.42	1.30	1.34
MnO	0.03	0.03	0.03	0.02	0.03	0.03
MgO	0.22	0.23	0.28	0.16	0.48	0.31
CaO	1.94	0.61	1.95	0.43	3.45	2.51
Na ₂ O	3.22	3.04	3.40	3.55	3.22	3.07
K ₂ O	5.38	5.59	5.08	5.11	5.24	5.39
P ₂ O ₅	0.05	0.05	0.05	0.05	0.05	0.05
	Selected Whole Rock Trace Element Concentrations, ppm**					
Rb	240		220		222	
Ba	930		1110		943	
La	72		85		84	
Ce	148		175		165	
Nd	57		73		74	
Sm	10		14		13	
Eu	1.3		2.1		1.4	
Tb	1		2		1	
Yb	5		7		6	
Lu	0.8		1		0.9	
Sc	2		6		3	
Hf	9		8		11	
Sr	58		32		22	
Zr	220		222		230	

*All analyses are recalculated to total 100% on a volatile-free basis with total iron as FeO.

**By instrumental neutron activation, except Sr and Zr determined by X-ray fluorescence.

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TABLE 5. Rb and Sr Contents and Sr-Isotopic Compositions of Samples From the Heise Volcanic Field

Unit	Sample	Margin of Plain		%K	Rb	Sr	$^{87}\text{Sr}/^{86}\text{Sr}_\text{O}$	$^{87}\text{Sr}/^{86}\text{Sr}_\text{I}$
Tuff of Kilgore	B263G	north	WR	4.48	169	25	0.7117	0.7106
Tuff of Kilgore	E2251	north	WR	4.41	177	21	0.7123	0.7109
Tuff of Kilgore	E2250	south	WR	4.66	184	24	0.7117	0.7104
Tuff of Kilgore	69-9	south	WR	4.21	147	53	0.7110	0.7105
Tuff of Blue Creek	B263D	north	S	----	38	327	0.7128	0.7128
Tuff of Blacktail	B258B	north	S	----	37	352	0.7117	0.7117
Tuff of Blacktail	B-177	south	S	----	38	358	0.7115	0.7115

WR, whole rock; S, sanidine; Rb and Sr are in ppm.

Analyses by W. P. Leeman at the U. S. Geological Survey, Denver. Observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are reported relative to a value of 0.7080 for the Eimer and Amend SrCO_3 standard and are precise to ± 0.0002 . Initial strontium ratios were calculated using the average age of each unit and Rb/Sr ratios from XRF analyses; precision of initial strontium values is about ± 0.0003 for the whole rock samples and $\pm$ for the feldspar separates.

initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate that each ignimbrite was derived from an isotopically distinct magma and that all these rhyolites contain significant components of upper crustal material [cf. Doe et al., 1982].

Sources for Ignimbrites of the Heise Volcanic Field

The presence of large buried silicic eruptive centers beneath the eastern Snake River Plain is suggested by (1) extensive rhyolitic ignimbrite sheets along margins of the plain with no exposed sources; (2) thickening of the individual ignim-

brite units toward the plain; (3) apparent lateral variations in the proportions and abundances of crystals, pumice, and lithic clasts and associated volcanic facies [cf. Wilson and Walker, 1982]; (4) possible ring fracture and related faults in mountains along margins of the plain [Prostka et al., 1979; Bonnicksen, 1981; McBroome, 1981]; (5) rhyolitic domes and flows nearly contemporaneous with the major ignimbrites that may be distributed along ring fractures as has been shown by Smith and Bailey [1968] for other large caldera systems; and (6) great thicknesses (more than 2500 m) of rhyolitic

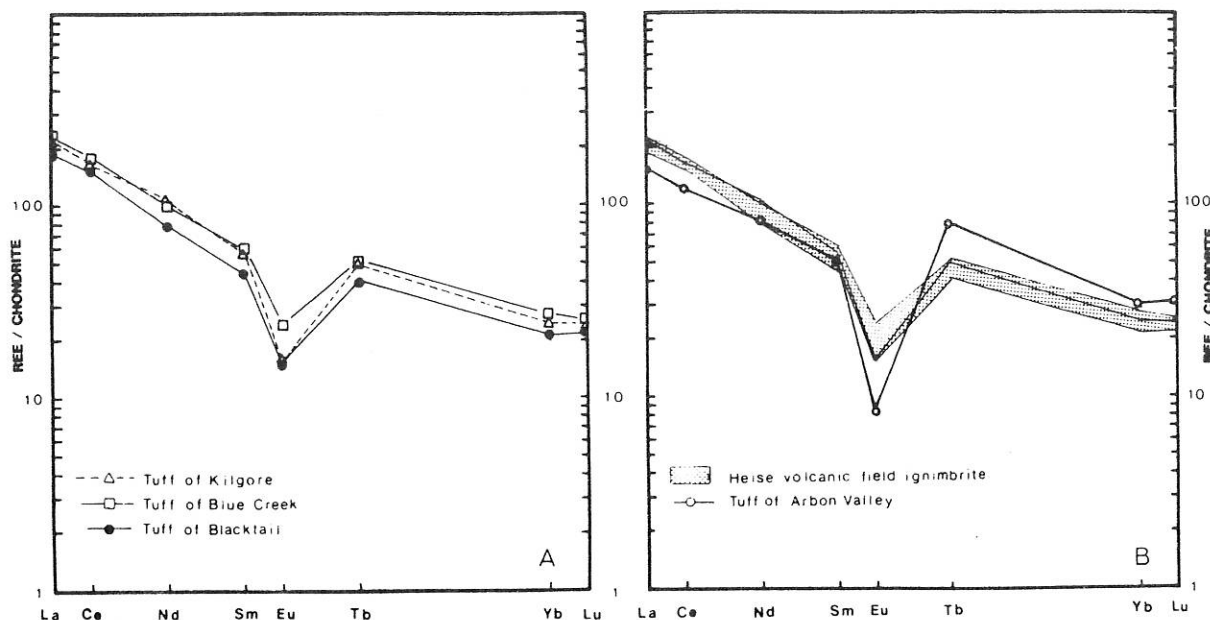


Fig. 4. (a) Average REE abundances for the major ignimbrites of the Heise volcanic field normalized to values for the Leedy chondrite [Matsuda et al., 1973]. (b) Chondrite-normalized REE abundances for the tuff of Arbon Valley compared with chondrite-normalized REE abundances of the Heise volcanic field. The tuff of Arbon Valley is an older Miocene rhyolitic ignimbrite exposed in foothills near the Pocatello area.

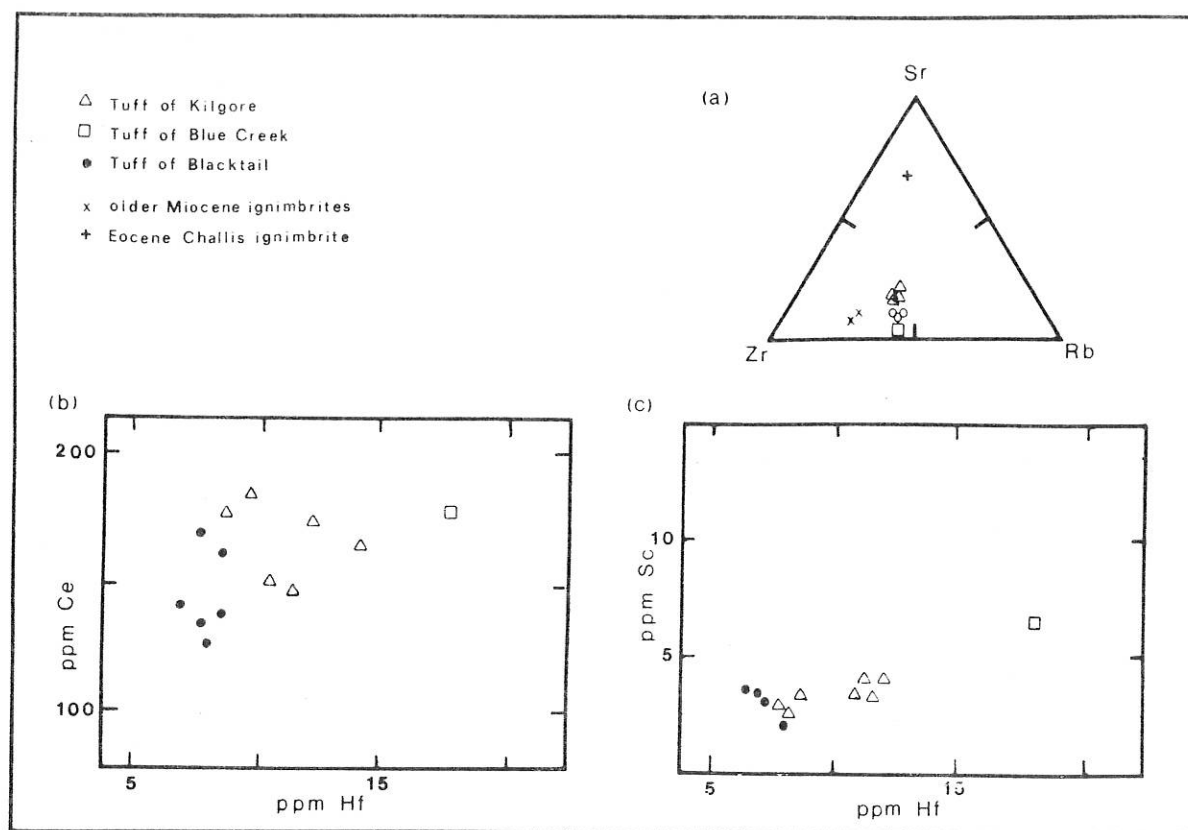


Fig. 5. Correlation of abundances of selected elements in the three major ignimbrites of the Heise volcanic field.

ignimbrites, intercalated with minor lava flows and ash, present in the Snake River Plain and found in geothermal exploration well, INEL-1, underlying 660 m of basalt [Figure 2; Doherty et al., 1979]. Seismic refraction surveys [Pankratz and Ackerman, 1982] and Bouguer gravity data [Mabey, 1978a, b] also support the presence of large silicic calderas beneath the plain.

Proposed source vents for ignimbrites of the

Heise volcanic field are refined by detailed granulometric studies on each major ignimbrite (L. A. Morgan, unpublished data, 1983). These studies allow interpretation of the proximity to source vents. Detailed measurements of sizes and proportions of crystals, pumice, and lithic clasts in each ignimbrite define lateral variations and vertical zonations of the components within individual flow units [cf. Smith, 1960]. Lithic-clast type has been documented in an attempt to distinguish erupted lithics from those picked up locally by the pyroclastic flows.

To date, no exposures of lag breccias [Walker, 1984], thick ground layers [Walker et al., 1981], intracaldera megabreccias [Lipman, 1976], or other features characteristic of vent areas or intracaldera subsidence have been identified in the Heise volcanic field. The ignimbrites are outflow facies; however, systematic changes in granulometric characteristics suggest that intracaldera facies exist beneath younger deposits of the plain.

The Blacktail Caldera

Field relations and lateral changes in the tuff of Blacktail, in addition to spatially and temporally associated volcanic units, indicate that the source structure for this ignimbrite is larger and more complex than proposed previously by Prostka et al. [1979] and McBroome et al. [1981]. Ring fracture vents for the tuff of Blacktail are not limited to the Rexburg area near the southern margin of the plain but are

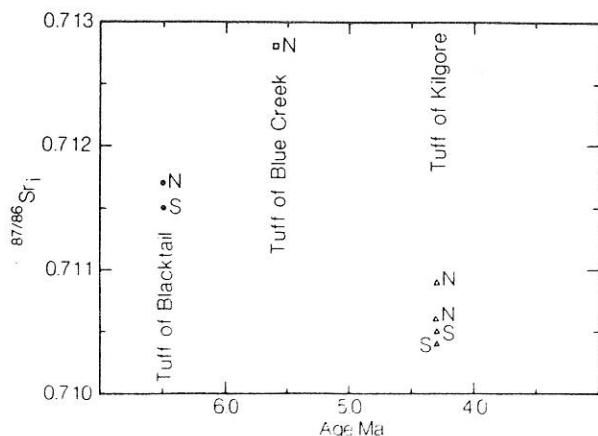


Fig. 6. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the three major ignimbrites of the Heise volcanic field versus time. The symbols N and S refer to samples collected from exposures on the north and south margins of the eastern Snake River Plain, respectively.

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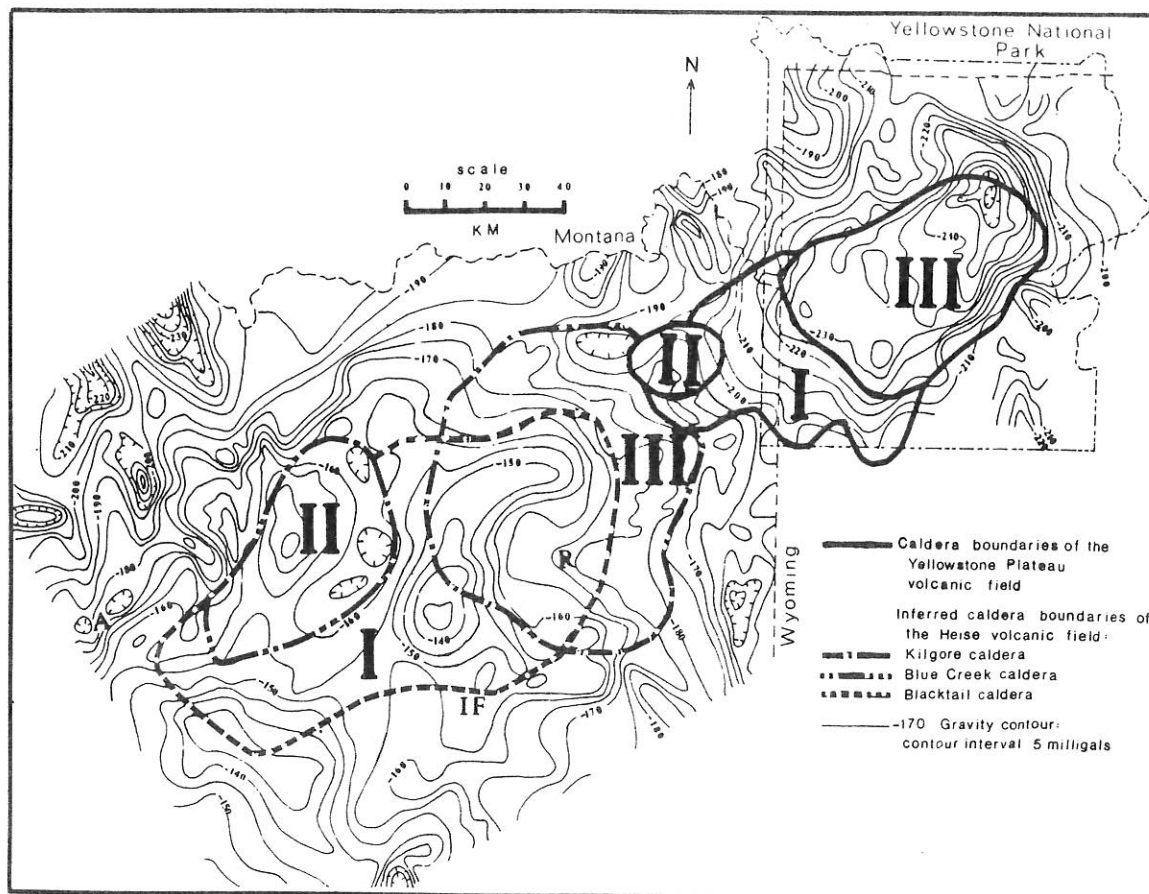


Fig. 7. Bouguer gravity map of the eastern Snake River Plain and Yellowstone Plateau from Mabey et al. [1974] and Blank and Gettings [1972]. Interpretation of caldera locations for the Yellowstone Plateau volcanic field from Christiansen [1983] and Smith and Christiansen [1980]. Spatial relations of major calderas of the Heise and Yellowstone Plateau volcanic fields are similar in stages of caldera development and areal extent. Each field began with a major climactic eruption resulting in the development of an immense caldera (stage I). Subsequent eruptive activity resulted in formation of smaller calderas (stages II and III) that were confined, for the most part, within the original perimeter of the stage I caldera. Localities abbreviated are A, Arco; IF, Idaho Falls; and R, Rexburg.

present also near the northern margin of the eastern Snake River Plain.

Volcanism in the Rexburg area may have been active prior to development of the Blacktail caldera, as is indicated by the presence of the rhyolite of Hawley Spring (7.2 Ma, Table 2) and the tuff of Newby Ranch (8.6 Ma, Table 2). However, eruption of a large volume of the tuff of Blacktail from vents near Rexburg, at the southern margin of the plain, is indicated by:

1. Rhyolitic lava flows and domes along and within a partly exposed caldera margin define part of a ring fracture zone related to the Blacktail caldera (Figures 2 and 3). Near Heise, these include the rhyolite of Kelly Mountain (5.7 Ma, Table 2), in addition to local ignimbrites such as the tuffs of Wolverine Creek (between 5.6 and 5.7 Ma) and Dora Springs (between 5.7 and 6.5 Ma). Proximity to source is indicated in the tuff of Wolverine Creek by base surge deposits, ignimbrite units that contain large pumice and lithic clasts, and coarse ash- and lapilli-fall deposits. Doherty [1976] proposed that the tuff of Wolverine Creek represents a postcollapse

event that occurred along reactivated portions of ring fractures originally developed during eruption of the tuff of Blacktail. The tuff of Dora Springs is capped by tuffaceous lacustrine sediments that may have been formed in a caldera lake environment.

2. The tuff of Blacktail thickens progressively from the southern margin toward the plain. At Heise the unit is 175 m; at Rexburg it thickens to 215 m. Large folds in the tuff of Blacktail that appear to have formed shortly after emplacement of the unit, concurrent with caldera faulting and collapse, are exposed near Heise. Paleomagnetic studies are in progress to refine this interpretation.

3. A circular 15-mgal negative Bouguer gravity anomaly (Figure 7) [Mabey, 1978b] centered near Rexburg may be related to a buried caldera or other volcanic structure.

4. Large pumice clasts are present in thick welded-fall deposits at the base of the tuff of Blacktail at the Blacktail recreation area near Heise. Lithic clasts having diameters as large as 15 cm are present low in the ignimbrite at the

north end of the Big Hole Mountains.

Features at several localities along the northern margin of the plain (Figure 3) indicate proximity to the structural margin of a caldera:

1. Seismic refraction studies by Pankratz and Ackerman [1982] reveal the presence of two probable high-angle subsurface faults about 1.8 and 6.0 km east of the Arco Hills (Figures 1 and 3). Displacements of about 1000 and 500 m, respectively, bring the volcanic sequence down into contact with the local basement of Paleozoic limestones. These probable faults strike parallel to a steep north-south gravity gradient [Mabey, 1978b], very different from the strikes of local basin-range faults (Figure 7). These faults may be parts of caldera ring fractures associated with eruption of the tuff of Blacktail.

2. A 2.5-m section of coarse, nonwelded ash- and pumice-fall material that is exposed at the base of the tuff of Blacktail in the Arco Hills has near-vent characteristics. Large pumice (to 6.9 cm) and lithic (to 9.4 cm) clasts are concentrated at the top and base, respectively, of the ignimbrite. This exposure supports the interpretation that the subsurface faults indicated by the geophysical data are ring fractures associated with the Blacktail caldera.

3. In the Kilgore area, on the northern margin of the plain (Figure 1), lava flows including the rhyolites of Ching Creek (6.3 Ma, Table 2) and Opal Mountain (6.9 Ma, Table 2) are identical in age, within analytical uncertainty, to the emplacement of the tuff of Blacktail. Because the tuff of Blacktail is poorly exposed at this locality, stratigraphic relations are not clear, but the overlap in ages with the tuff of Blacktail suggests that these lavas may have been erupted from the Blacktail caldera. Isotopic and trace element studies are in progress to refine these relationships.

Thus exposures near both the southern and northern margins of the eastern Snake River Plain probably are within 5-10 km of ring fracture vents of the Blacktail caldera. The size of this caldera is estimated to be approximately 100 by 60 km (Figure 3) based on the criteria already discussed. These dimensions are extremely large in relation to those of many calderas described in other parts of the world, but given the available data, these dimensions are good approximations for the actual size of the caldera and are comparable to dimensions of the calderas at Yellowstone.

The Blue Creek Caldera

Evidence for location of the Blue Creek caldera is best defined in the southern Lemhi Range and the southern Beaverhead Mountains (Figures 1 and 3):

1. Pumice and lithic clasts decrease in size away from the southern Lemhi Range and Beaverhead Mountains on the northern margin of the plain. Exposures in these areas contain relatively thick ash- and lapilli-fall deposits (1.5-2 m) that grade upward from nonwelded to slightly welded at the base of the tuff of Blue Creek.

2. Rhyolitic lava flows and domes in the southern Beaverhead Mountains overlap the tuff of Blue Creek in age; the rhyolite of Reno Gulch is

6.2 Ma and the rhyolite of Lidy Hot Springs is 5.4 Ma (Table 2). Stratigraphic relations between these rhyolite lavas and the tuff of Blue Creek are not clear because of poor exposures.

3. Two groups of major faults developed shortly after emplacement of the tuff of Blue Creek in the southern Lemhi Range. Those trending north-northwest probably were reactivated basin-range structures [Skipp, 1983]. Those trending nearly east-west are restricted to the south end of the range and apparently formed synchronously with collapse of the Blue Creek caldera. At the extreme southern tip of the Lemhi Range, evidence for a wall of the Blue Creek caldera is most compelling along a major fault that displaces outflow facies of the tuff of Blue Creek from its intracaldera ignimbrite by about 75 m. This fault separates a southern, slumped block containing tight flowage folds, strong flow lineations, and numerous subparallel tensional fractures that are lined with vapor-phase minerals, from a northern block of outflow facies having predominantly planar flowage features; thicknesses of the tuff of Blue Creek are comparable on either side of this fault. Structural deformation present on the southern block probably resulted from faulting associated with collapse near a ring fracture shortly after emplacement of the tuff of Blue Creek while the unit was still plastic. This conclusion is supported by paleomagnetic remanence directions that do not vary across secondary flowage features, regardless of location on the slumped block or attitude of the folds indicating plastic deformation while the welded tuff was above its Curie temperature [McBroome, 1981]. Additional evidence for close proximity to the margin of the Blue Creek caldera in the southern Lemhi Range is the presence of closely spaced normal faults (200-300 m) displaced downward toward the plain and cutting the tuff of Blue Creek with displacements that average 3-5 m; some displacements are as great as 300 m [McBroome, 1981]. Furthermore, zones of autobrecciation (poorly sorted, angular clasts of tuff of Blue Creek within a white, fine-grained, vapor-phase matrix of tuff of Blue Creek) are concentrated along these faults and appear to be restricted to caldera-margin settings.

4. A 20- to 25-mgal positive gravity anomaly [Mabey et al., 1974] south and east of the Lemhi Range and south of the Beaverhead Mountains (Figure 7) indicates a buried body denser than the surrounding rocks. The circular shape of this anomaly, in contrast to elongate anomalies related to basin-range structures north and south of the plain, suggests that the gravity high may be related to a buried caldera or other volcanic depression. Alternatively, this anomaly could correspond to a crystallized intrusive in the volcanic pile or to a thick accumulation of basalt in a caldera. A series of negative gravity anomalies along the eastern boundary of the proposed ring fracture zone (Figure 7) may represent thick tuffaceous lacustrine sediments in a caldera moat.

The Kilgore Caldera

Detailed mapping of the tuff of Kilgore indicates that several major flow units are

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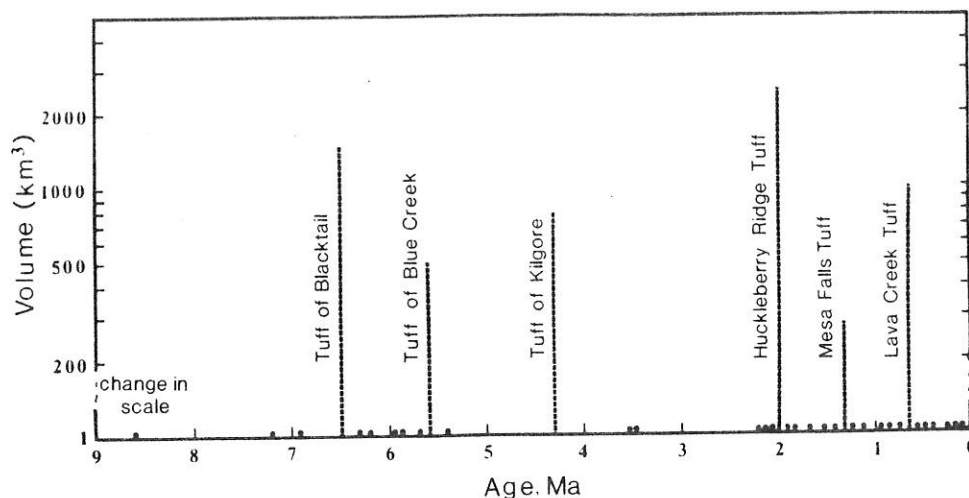


Fig. 8. Ages of eruptions of major caldera-forming ignimbrites versus estimated total volume of individual ignimbrite units. The schematic relations depicted in this diagram are a simplification, because of errors in determining ages and estimating volumes. The periodicity of major eruptive events and volumes of the associated eruptive ignimbrites from the Heise and Yellowstone Plateau volcanic fields are comparable. The absence of voluminous ignimbrites with ages between 1.9 and 4.3 Ma may indicate that a lag time of approximately 2.0 Ma is necessary for the evolution of immense magmatic systems. The small dots represent rhyolitic lavas associated with caldera development; volumes of lavas are not to scale and are generally less than 1 km^3 . Data from the Yellowstone Plateau volcanic field are from Christiansen [1983]; Christiansen and Blank [1972]; and Smith and Christiansen [1980].

present within this ignimbrite. Preliminary evidence suggests that several localities on both the northern and southern margins of the plain are proximal to eruptive fissures.

1. Rhyolitic lava flows and domes slightly younger than the tuff of Kilgore occur on both margins of the plain along apparent ring fracture zones (Figures 2 and 3). These postcaldera lavas include the rhyolite of Sheridan Reservoir (4.0 Ma, Table 3) near Kilgore, a 3.5-Ma flow (Table 2) in geothermal exploration well 3 (Figures 1 and 2) [Embree et al., 1978], and the 3.5-Ma rhyolite of Long Hollow near Rexburg (Table 2).

2. An arcuate tonal anomaly on ERTS imagery [Doherty and Nash, 1977] coincides with a negative Bouguer gravity anomaly in the Kilgore area (Figure 7). The northern half of this tonal anomaly reflects the previously discussed lava flows.

3. Near Spencer and Heise, the tuff is characterized by strong flow lineations and especially large and abundant phenocrysts and pumice fragments. The enrichment of phenocrysts present in the groundmass relative to the amount of phenocrysts in the pumice and the flow lineations in the ignimbrite are characteristic of near-vent features.

Thus evidence is seen for ring fracture zones related to the Kilgore caldera on both the northern and southern margins of the eastern Snake River Plain. The estimated area encompassed by the Kilgore caldera is approximately 60 by 80 km.

Discussion

The tuff of Blacktail is the oldest (6.5 Ma), most voluminous ($>1500 \text{ km}^3$), and most widespread ($>12,000 \text{ km}^2$) unit of the Heise volcanics. Its

eruption produced a caldera approximately 100 by 60 km, with probable ring fracture vents extending near both margins of the eastern Snake River Plain and encompassing most of the area of younger calderas in the Heise volcanic field. The next major caldera-forming event was eruption of the 5.6-Ma tuff of Blue Creek (500 km^3), most of which remained close to its source caldera. Its eruption resulted in a caldera estimated as approximately 30 by 35 km on the basis of its estimated volume and identification of part of its caldera. The third major eruption of the Heise field produced the 800-km^3 tuff of Kilgore 4.3 Ma ago. The caldera resulting from its eruption is about 60 by 80 km and, for the most part, lies within the Blacktail caldera (Figures 3 and 7).

There are limitations in accurately defining the true dimensions of the calderas of the Heise volcanic field because of the exposures present along the margins of the plain and the vast amount of material buried by younger volcanic deposits on the plain. The estimated sizes of the calderas in this field are comparable to their counterparts in the Yellowstone Plateau volcanic field. Several temporal and spatial similarities exist between the Heise volcanic field and the younger Yellowstone Plateau volcanic field (Figures 7 and 8). The Yellowstone Plateau volcanic field has developed over the past 2.0 Ma [Christiansen and Blank, 1972; Christiansen, 1984a, b], which is comparable to the 2.2-Ma interval over which the Heise field developed beginning about 6.5 Ma ago. Elapsed time between successive major ignimbrite eruptions differs slightly: 1.0–1.3 Ma for the Heise volcanics compared with 0.7 Ma for the Yellowstone Group. In this region, absence of voluminous ignimbrites with ages between 1.9 and

4.3 Ma may indicate lag time between activities of successive fields and may suggest that several million years is required for the evolution of these voluminous magmatic systems, at least in the Snake River Plain-Yellowstone Plateau region.

Distribution, geometry, and size of calderas in the Heise and the Yellowstone Plateau volcanic fields are also similar (Figure 7); the earliest major eruption in both fields produced a large caldera within which later calderas were nested or largely overlapped. The second major eruptive event in each volcanic field was smaller than the initial event and occurred in the western part of the first caldera. The second event, which may be a phase of the initial event, was followed by a third major event to the northeast of the second caldera that overlapped the initial caldera. The distributions and ages of the major ignimbrites in the Heise volcanic field indicate that development of individual calderas within this volcanic field is complex and not monotonic. However, as suggested by Armstrong et al. [1975], major volcanic fields of the eastern Snake River Plain do show a general decrease in age to the northeast.

The dimensions of both fields and their respective calderas are also similar. The first calderas to form within each volcanic field, which resulted from the eruptions of the tuff of Blacktail and the Huckleberry Ridge Tuff, encompass areas crudely estimated to be 100 by 60 km and 45 by 85 km, respectively. Thicknesses of intracaldera cogenetic ignimbrites are comparable to their respective outflow sheets, suggesting that major caldera collapse occurs shortly after ignimbrite emplacement rather than contemporaneously [Smith and Bailey, 1968; Christiansen, 1984b; Lipman, this issue]. Evidence for intracaldera thickness is available for the Yellowstone caldera [Christiansen, 1984b] and for the Blacktail and Blue Creek calderas. The tuff of Blacktail present in exploration geothermal well INEL-1 (Figure 2) is an intracaldera facies; its thickness is no more than 500 m as inferred from ages and stratigraphy established in the borehole (Figure 2) [McBroome, 1981]. Evidence concerning comparable thicknesses between outflow and intracaldera facies is present for the tuff of Blue Creek in the southern Lemhi Range, as already discussed. Thus available information indicates that no significant accumulation of intracaldera ignimbrites is present within either the Blue Creek or Blacktail calderas. Calderas in the eastern Snake River Plain-Yellowstone Plateau volcanic province appear to have large surface areas but very shallow depths. In contrast, many calderas described for the western United States [Lipman, this issue] tend to encompass relatively smaller areas and have greater depths. This relationship may infer that a slightly different eruptive mechanism and/or tectonic setting is responsible for the formation of calderas present in the Snake River Plain-Yellowstone Plateau volcanic province.

Immense calderas, such as resulted from eruption of the tuff of Blacktail in the Heise volcanic field or the Huckleberry Ridge Tuff in the Yellowstone Plateau volcanic field [Christiansen, 1984a], record the evolution of long-lived magmatic systems. We envision the

emplacement at crustal levels of a large silicic magma body that may be replenished periodically by additional magma and that produces a number of major and minor eruptions during its lifetime.

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