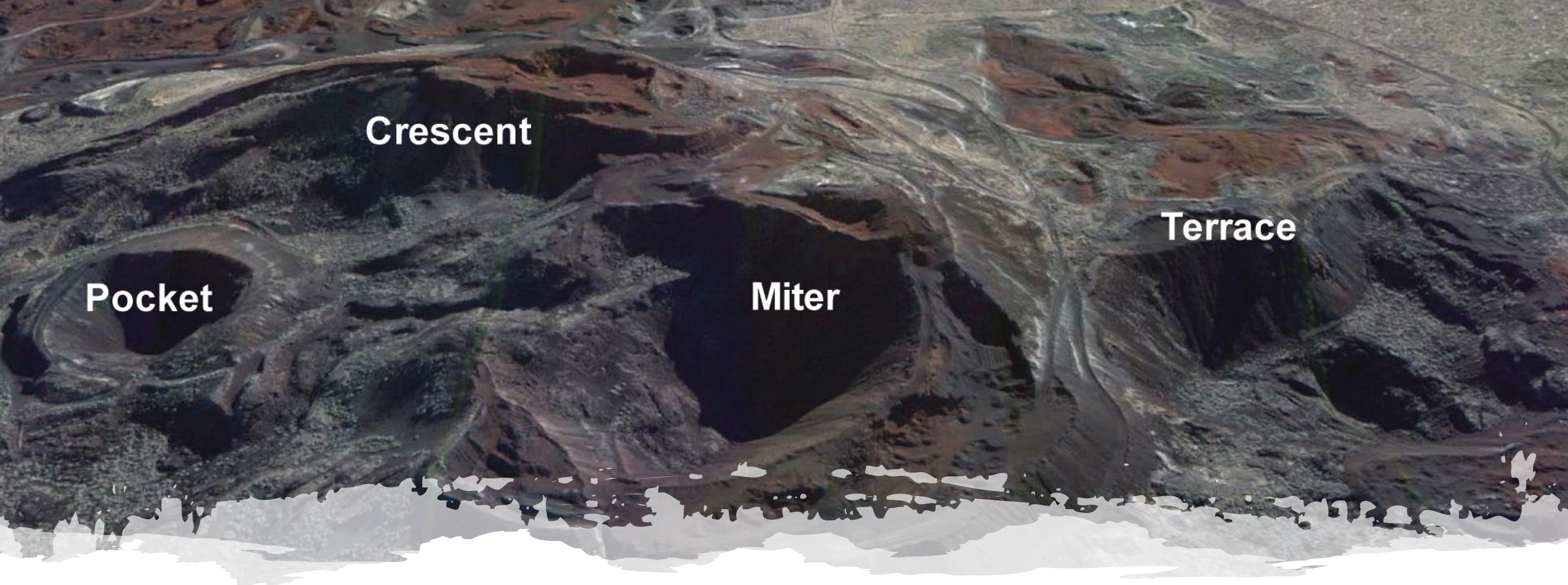

Young Volcanism in Millard County: Ice Springs Volcanic Field

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Utah Geosites
2019

Utah Geological Association Publication 48

M. Milligan, R.F. Biek, P. Inkenbrandt, and P. Nielsen, editors

COVER IMAGE: Aerial photo of Pocket, Crescent, Miter and Terrace craters. View to the east (from Google Earth).

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Utah Geosites showcases some of Utah's spectacular geology, both little-known localities and sites seen by visitors to Utah's many national and state parks and monuments. The geosites reflect the interests of the many volunteers who wrote to share some of their favorite geologic sites. The list is eclectic and far from complete, and we hope that additional geosites will be added in the coming years. The Utah Geological Survey also maintains a list of geosites https://geology.utah.gov/apps/geosights/index.htm.

We thank the many authors for their geosite contributions, Utah Geological Association members who make annual UGA publications possible, and the American Association of Petroleum Geologists—Rocky Mountain Section Foundation for a generous grant for desktop publishing of these geosite papers.

Design and desktop publishing by Jenny Erickson, Graphic Designer, dutchiedesign.com, Salt Lake City, Utah.

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Presidents Message

I have had the pleasure of working with many different geologists from all around the world. As I have traveled around Utah for work and pleasure, many times I have observed vehicles parked alongside the road with many people climbing around an outcrop or walking up a trail in a canyon. Whether these people are from Utah or from another state or country, they all are quick to mention to me how wonderful our geology is here in Utah.

Utah is at the junction of several different geological provinces. We have the Basin and Range to the west and the Central Utah Hingeline and Thrust Belt down the middle. The Uinta Mountains have outcrops of some of the oldest sedimentary rock in Utah. Utah also has its share of young cinder cones and basaltic lava flows, and ancient laccoliths, stratovolcanoes, and plutonic rocks. The general public comes to Utah to experience our wonderful scenic geology throughout our state and national parks. Driving between our national and state parks is a breathtaking experience.

The "Utah Geosites" has been a great undertaking by many people. I wanted to involve as many people as we could in preparing this guidebook. We have had great response from authors that visit or work here in the state. Several authors have more than one site that they consider unique and want to share with the rest of us. I wanted to make the guidebook usable by geologists wanting to see outcrops and to the informed general public. The articles are well written and the editorial work on this guidebook has been top quality.

I would like to personally thank Mark Milligan, Bob Biek, and Paul Inkenbrandt for their editorial work on this guidebook. This guidebook could not have happened without their support. I would like to thank Jenny Erickson for doing the great desktop publishing and the many authors and reviewers that helped prepare the articles. Your work has been outstanding and will certainly showcase the many great places and geology of Utah. Last, but not least, Thank you to the American Association of Petroleum Geologists, Rocky Mountain Section Foundation for their financial support for this publication.

Guidebook 48 will hopefully be a dynamic document with the potential to add additional "geosites" in the future. I hope more authors will volunteer articles on their favorite sites. I would like to fill the map with locations so that a person or family looking at the map or articles will see a great location to read about and visit. Enjoy Guidebook 48 and enjoy the geology of Utah.

Peter J. Nielsen
2019 UGA President

INTRODUCTION

Geoscientists, naturalists, and rock-hound enthusiasts have explored Ice Springs volcanic field (ISVF) for nearly 130 years because it is one of the youngest, extension-related volcanic centers in Utah and the Southwest U.S. Ice Springs received its name due to the presence of ice within its expansive a'a lava flows (Davis, 2014), which have an interesting age discrepancy. Previous work on Ice Springs dated the ISVF as 660 years old (Valastro and others, 1972), but we now introduce an age date of 9,800 to 11,100 years old. Although the eruptive and effusive deposits (more explosive vs passive, respectively) capture our imagination today, it is possible that they were natural hazards for the early Paleo-Indians of the region.

The ISVF is an important economic resource. Hoover (1974) reported that mining has occurred here since the mid-1950s. In the mid-1970s, Red Dome, Inc. began its crushed and broken stone mining and quarrying operations at ISVF. These operations continue today and supply decorative stone and road gravel to the region and beyond.

From a geologic perspective, ISVF is part of a zone of young volcanism—dated as less than 2 million years old and extending from northwest Arizona to west-central Utah (e.g., Best and Brimhall, 1974). This area in west-central Utah is known as the Black Rock Desert and is part of the "Sevier thermal area" (Mabey and Budding, 1987, 1994) that contains power plants, hot springs, therapeutic baths, and tropical fish ponds (Blackett and Wakefield, 2002).

Previous workers have been instrumental in our current understanding of ISVF. Gilbert (1890) first described ISVF in his United States Geological Survey (USGS) monograph on prehistoric Lake Bonneville. More recent work has concentrated on the age relationships, study of volcanic deposits, and geochemical trends (i.e., changes in rock chemistry) between the various basaltic lava fields of the Black Rock Desert (Condie and Barsky, 1972; Hoover, 1974; Lynch and Nash, 1980; Johnsen and others, 2010). Mapping for both the Delta and Richfield 30' x 60' quadrangles (Hintze and Davis, 2002; Hintze and others, 2003) culminated in a Utah Geologic Survey Bulletin on the Geology of Millard County (Hintze and Davis, 2003). Detailed geochemical studies of ISVF by Thompson (2009) and Patzkowsky and others (2017) have improved lava field mapping. Additional work at The College of Wooster continues on the age and details of lava field features at ISVF. These deposits of the ISVF record a history of post-Lake Bonneville eruptive events (Oviatt, 2015).

This paper aims to (1) provide the physical location and geologic setting for ISVF, (2) outline the unique geologic characteristics of the crater complex and associated lava fields, and (3) summarize recent research at ISVF regarding lava field structure and form, age of the flows, and eruptive sequence of events. Many visitors each year explore the crater remnants and their eruptive deposits and then wander among the a'a and pahoehoe lava, investigating one of the many lava tubes within the Ice Springs complex. It is our hope that visitors to the lava field will enjoy the wonders of Utah's youngest volcanic feature.

LOCATION

The ISVF is located in Millard County, west-central Utah. It comprises one of the many volcanic fields in Utah's Black Rock Desert, east of the Cricket Mountains and west of the Pahvant Range. The ISVF is a 7.7 mi^2 (20 km^2) volcanic area consisting of a crater complex and basaltic lava flows that erupted onto ancient Lake Bonneville deposits after the lake receded from its Provo-level shoreline. The volcanic crater complex and lava field are readily seen from a distance, standing in stark contrast to the agricultural fields of the valley floor. The entrance road to mining operations is ~8.7 mi (14 km) west of Main Street in Fillmore, Utah (figure 1A). Although the lava fields extend outward from the several craters in all directions, the approximate center of the complex—informally referred to as "The Cinders"—is at 38°57.740'N, 112°30.348'W. ISVF is near two other volcanic centers: immediately to the south is the Tabernacle Hill lava fields and nearly 12 miles (20 km) to the northwest is Pahvant Butte.

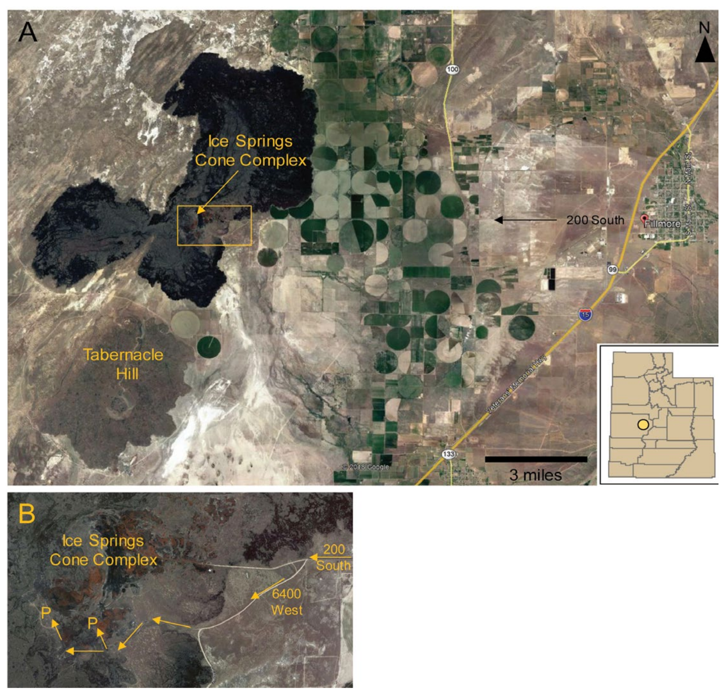

Figure 1. A. Location of Ice Springs volcanic field (black area at top left) in relation to Tabernacle Hill to the south and Fillmore, Utah, to the east (modified from Google Earth). Inset map of Utah counties shows the ISVF location in Millard County (from Utah AGRC). B. Aerial photo of the southeast side of ISVF cinder cone complex. Arrows indicate possible driving routes to avoid mining operations. The "P" symbols mark suggested parking areas (modified from Google Earth).

SUGGESTED DRIVING DIRECTIONS

The ISVF is easily accessible from the north or south via I-15. From the north, take I-15 south to exit 167 (Fillmore). Proceed south on Cedar Mountain Road, which becomes N. Main Street and continues into Fillmore. Once in Fillmore, proceed west on 200 South toward ISVF. When driving from the south, take I-15 north to exit 163 (Fillmore). Proceed north on State Route 99, which becomes 500 South and curves to S. Main Street into Fillmore. Proceed west on 200 South toward ISVF. Once the edge of the lava flows is reached, the safest way to access the geology is from the south or west sides of the crater complex, and these directions follow. While on 200 South, there is a "Y" junction (38°57.869'N, 112°29.088'W); proceed southwest (left fork) on S 6400 West for ~0.5 mi (1 km). At the 2nd "Y" junction (38°57.552'N, 112°29.697'W), proceed west (right fork) on an unmarked unimproved dirt road. From here, you can either proceed west to go to the lava fields (38°57.458'N, 112°30.284'W) or north to the crater complex center (38°57.467'N, 112°30.263'W) at the second junction to parking areas (figure 1B). Please remember: If visiting the crater complex and its nearest lava fields, please obtain permission from Red Dome, Inc., at the office at the entrance to the quarry. All visitors, even those accessing remote lava fields adjacent to major roads, should please watch for traffic and stay clear of all mining operations.

STRUCTURAL GEOLOGY

ISVF is located in the thermally active Black Rock Desert near the eastern border of the Basin and Range Physiographic Province. The Basin and Range is known for its north-trending alternating ranges (horsts) and valleys (grabens) that formed as a result of extensional tectonics. Specifically, extension of Earth's crust in the region of the Black Rock Desert since 10 Ma has been orientated WNW-ESE (Christensen and Yeats, 1992; Nelson and Tingey, 1997). Structurally, the Black Rock Desert represents an intra-graben area bounded to both the west and east by large normal faults of the Cricket Mountain and the Pahvant Range, respectively (Hoover, 1974; Hintze and Davis, 2003). These north-south striking faults resulted from this Basin and Range extensional regime. Fault movement facilitated migration of magma to the surface, creating the many volcanic fields that give the Black Rock Desert its name. Numerous other smaller faults and fractures within the Black Rock Desert resulted from the same tensional stress (Hintze and Davis, 2002; Hintze and others, 2003).

GEOLOGIC HISTORY

Volcanic Fields

The Black Rock Desert was first described by Gilbert (1890) and later by Condie and Barsky (1972) and Hoover (1974). Originally, Condie and Barsky (1972) identified seven distinct volcanic fields using age, geography, and composition; from north to south, these fields are Deseret, Pahvant Butte, Ice Springs, Tabernacle Hill, Kanosh, Black Rock, and Cove Fort (figure 2). The divisions of the Black Rock Desert were redefined due to more detailed mapping (Hoover, 1974) and subsequently by grouping into fewer volcanic subfields (Johnsen and others, 2010). The volcanic fields of the Black Rock Desert are generally Pleistocene in age and are fault-controlled (Hintze and Davis, 2003), inferring that the volcanism was emplaced along or near to the north-south striking faults in the region. The composition of Black Rock Desert deposits vary from basalt to andesite, with even some dacite to rhyolite (Best and others, 1980). Previous interpretations by Hintz (2008) suggested that the fields are monogenetic volcanoes, implying small volume eruptions fed from one or more magma batches (Németh and Kereszturi, 2015).

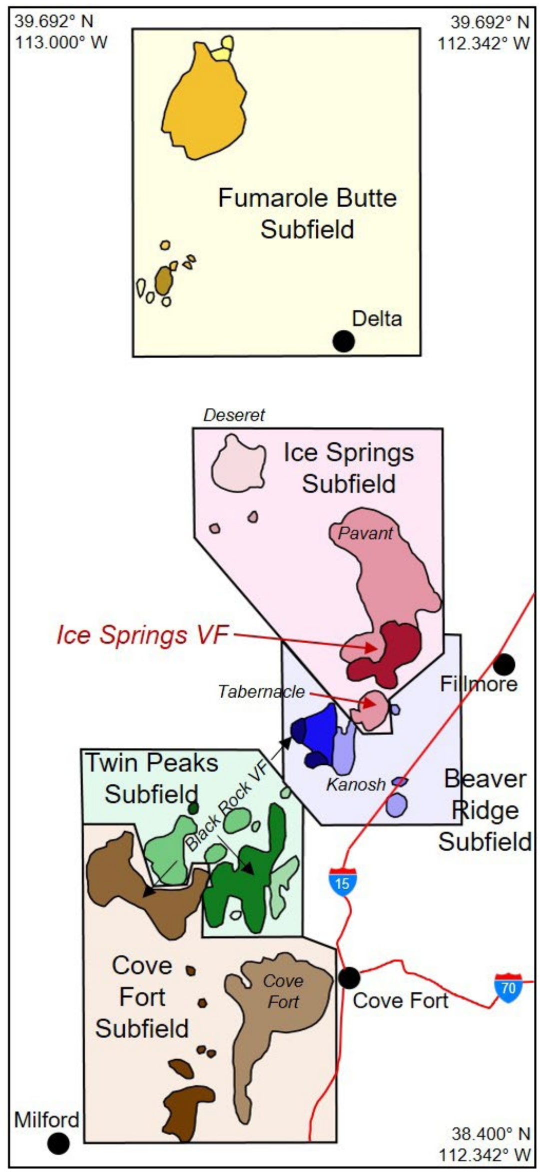

Figure 2. Generalized geologic map of the primary lava fields of the Black Rock Desert. The seven major fields of Condie and Barskey (1972) are identified in italics, along with the five subfields of Johnsen and others (2010). ISVF is the bright red region in the center of the map (modified from Johnsen and others, 2010).

Lake Bonneville

Correlating the timing of eruptive episodes to the extent of Lake Bonneville is one of the more important geologic stories of the Black Rock Desert. Hoover (1974) classified the eruptions of the Black Rock Desert into three episodes centered around the presence or absence of the lake. Episode 1 consisted of eruptions before the lake's rise, including those in the Beaver Ridge subfield (Johnsen and others, 2010). The lake eroded (in some cases severely) some of these cinder cones in the region that existed prior to its inception. Episode 2 included two more eruptions above lake level in the Ice Springs subfield (Johnsen et al, 2010), specifically at Pahvant Butte, as well as underwater eruptions into Lake Bonneville shortly afterwards at Pahvant Butte (White, 1996; White 2000) and Tabernacle Hill (Hintz, 2008). Episode 3 includes eruptions of the Tabernacle and Ice Springs volcanic fields after the lake receded. These youngest volcanic deposits lack any Lake Bonneville sediments on or terraces cut into them, and this lack of Bonneville data demonstrates that its volcanism occurred after the lake receded from the area. This final episode represents the youngest volcanism in the Black Rock Desert (Hoover, 1974).

Recent work identifies Lake Bonneville's lake level oscillations over a 17,000-year interval during the Late Pleistocene (Oviatt, 2015; Oviatt, 2016). Formed ~30,000 years ago, lake levels fluctuated markedly but overall rose until ~18,000 years ago, the maximum extent of Lake Bonneville in the region (Oviatt, 2015). Known as the Bonneville shoreline, this maximum areal extent produced observable shoreline features such as beach gravel barriers and wave-cut notches and platforms throughout Utah (Chen and Maloof, 2017). At ~18,000 years ago, Lake Bonneville breached and catastrophically drained near Red Rock Pass, Idaho, causing a precipitous drop in lake levels to begin formation of the Provo shoreline (Oviatt, 2015). The Provo shoreline ended ~15-16,700 years ago (Miller and others, 2013; Oviatt, 2015), with another drop in lake levels. Oviatt (2015) infers that Lake Bonneville levels dropped to those matching the Great Salt Lake by 13,000 years ago. This timeline suggests that Lake Bonneville had receded from the vicinity of ISVF well before 9,800 to 11,100 years ago—our age date for its lava field.

Age of Volcanism

The age of ISVF has long been intriguing because it is the youngest volcanic field in Utah and one of the youngest in the southwest U.S. Only one age has been reported for ISVF (Valastro and others, 1972), based on radiocarbon dating of a piece of root fragment found underneath a lava flow from the northeast portion of the lava field. Valastro and others (1972) dated the ISVF as 660 ± 170 years old, and this age has been repeated for decades even though Hoover (1974) estimated the maximum age of ISVF as 1000-4000 years old based on the fact that it has less soil cover and erosion compared to nearby Tabernacle Hill.

We recently redated the ISVF using cosmogenic ^{36}Cl-dating, which provides an estimate for the length of time a rock has been exposed at the surface (Patzkowsky and others, 2017). Five samples of pahoehoe (lava with a smooth ropy texture) were collected from ISVF lava flows, yielding an age estimate of approximately 10,000 years old (Table 1). The lava flows appear to be older than previously estimated. We noticed that the surfaces of the pahoehoe samples are no longer iridescent and glassy. When a lava flow erupts, a layer of volcanic glass forms on the surface. The iridescent glass cracks as the lava cools and is easily eroded by mechanical weathering. For comparison, the McCarty's flow in the Zuni-Bandera volcanic field, which is in a similarly arid climate, has been dated at ~4000 years old and still has some of its glassy, iridescent surface (Dunbar, 1999). Furthermore, large areas of the ISVF lava flows are covered with a thin layer of soil and meter-high sagebrush, suggesting the lava flows are older than previously suspected.

Overall, the Black Rock Desert captures the fascinating interactions between volcanic eruptions and changing shorelines. The ISVF ^{36}Cl ages are older than anticipated, but they still adhere to the established timeline of Black Rock Desert volcanic events. Because there are no lake terraces cut into the ISVF, we know that ISVF was erupted after Lake Bonneville's Provo-level shoreline receded ~13,000 years ago (Milligan and McDonald, 2017). Our age estimates also show that the ISVF is younger than nearby Tabernacle Hill, which has been carved by Lake Bonneville and has an absolute ^{14}C age of 17,440 (±120) years (Cerling and Craig, 1994; Oviatt, 1991). ISVF is clearly younger than other Black Rock Desert volcanic fields, but older than we thought. It was a short-lived, complex eruption that produced volcanic features worthy of exploration.

STRATIGRAPHY

Cinder Cone Stratigraphy

The center of ISVF is a complex of originally four distinct cinder cones (figure 3A): Crescent, Miter, Pocket, and Terrace (Hoover, 1974; Lynch and Nash, 1980). Crescent, Miter, and Terrace were named by Gilbert (1890), and Pocket was named by Hoover (1974). Crescent and Terrace are the largest and least well-preserved, each with large sections of their original cinder cones removed by eruptive activity or decades of mining. Although Pocket is the smallest and most completely preserved (i.e., least affected by mining), Miter best reveals the geologic history of the crater complex.

While Crescent may have once been the largest crater (diameter estimate: 2600 feet; 800 m), less than half of the original crater remains because of mining on the eastern flank since the mid-1950s (Hoover, 1974). Crescent's exposed eastern crater flank contains red and black beds of cinder up to 50 ft (15.2 m) thick, sloping

Table 1. *Cosmogenic ^{36}Cl data and dates for the ISVF. Major elements were measured at The College of Wooster by XRF following the methods of Pollock and others (2014) and are reported in weight percent (wt.%). Trace elements were measured at Actlabs by ICP-MS and are reported in parts per million (ppm). 36-Chlorine was measured at Purdue PRIME lab by AMS and is reported in atoms per gram of sample. One sample was analyzed in duplicate to assess analytical reproducibility. The age calculation in the CRONUS 36Cl Exposure Age Calculator (v2.0; Marrero and others, 2016) uses the following values: an average measured bulk density of 2.24 g/cm3, 0 ppm CO2, and the Lifton-Sato-Dunai (SF) scaling framework (Lifton and others, 2014). Assuming a realistic erosion rate of 1 mm/kyr, our age estimates range from 9.8 (±1.6) - 11.1 (±1.7) kyr. These ages were older than expected, so we reanalyzed the samples to make sure we removed all the meteoric 36Cl and found the same results. Even using high erosion rates (up to 5 mm/kyr) to estimate minimum ages, we do not calculate dates any younger than 9.2 (±1.7) - 10.9 (±1.6) kyr.*

Sample ID	KeckIS1701	KeckIS1707	KS15CD02A	KS15CD02B	KS15CD05	KS15CD05 (Duplicate)
Latitude °N	38.968	38.9597	38.959518	38.959518	38.957569	38.957569
Longitude °W	112.504	112.512	112.515	112.515	112.51	112.51
Elevation (ft)	4757.2	4757.2	4732.0	4732.0	4752.0	4752.0
Sample Thickness (cm)	4	4	9	9	10	10
^{36}Cl (atoms per gram sample)	386549	378680	334589	279622	287599	278045
SiO_2 (wt.%)	49.61	49.53	50.53	49.42	49.23	48.67
TiO_2	1.87	1.9	1.77	1.82	1.81	1.82
Al_2O_3	14.41	14.58	14.45	15.06	15.51	15.11
Fe_2O_3	11.45	11.68	11.04	11.34	11.48	11.55
MnO	0.19	0.18	0.18	0.18	0.19	0.18
MgO	6.83	6.98	6.77	6.75	7.52	7.66
CaO	11.08	10.64	11.03	11.21	10.12	11.06
Na_2O	2.71	2.72	2.39	2.47	2.53	2.45
K_2O	1.20	1.13	1.22	1.12	1.00	0.89
P_2O_5	0.58	0.58	0.57	0.58	0.55	0.55
LOI	2.29	1.29	3.68	3.24	1.47	2.22
Cl (ppm)	251	203	144.9	122.6	112.4	100.4
B	1	1	0	0	0	0
Sm	7.7	7.4	6.6	6.8	7	6.6
Gd	7.8	7.9	6.3	6.6	7	6.5
U	1.1	0.9	1.7	1.3	1.1	1.1
Th	3	2.5	4.9	3.6	3.7	2.8
Cr	155	137	103	95.5	172	160
Li	12.8	11.5	20.6	15.2	19.3	12.8
Age (kyr at 1 mm/kyr erosion rate)	9.8 (±1.6)	11.1 (±1.7)	10.5 (±1.7)	9.6 (±1.4)	11.1 (±1.5)	11 (±1.3)
Age (kyr at 5 mm/kyr erosion rate)	9.2 (±1.7)	10.6 (±1.6)	10.2 (±1.6)	9.4 (±1.4)	10.9 (±1.6)	10.9 (±1.5)

Figure 3. ***A.*** *Aerial photo of Pocket, Crescent, Miter and Terrace craters. View to the east (from Google Earth).* ***B.*** *The east flank of Crescent showing volcanic stratigraphy with its red and black cinders. View to the west.* ***C.*** *Volcanic stratigraphy at the eastern rim of Miter crater.* ***D.*** *Close-up of C, illustrating the vesicularity (small cavities) of the volcanic bombs.*

away from the rim at 25°-30°, capped by scoriaceous spatter (formed from frothy lava fragments; figure 3B). The scoriaceous spatter marks the evolution of Crescent from a cinder cone into a spatter cone, commonly observed at Ice Springs. On the inner slope of Crescent, welded spatter and cinders slope at 45°-50° (Hoover, 1974). Crescent was the source for the most northern flows in the ISVF, although the lava flow outlet was obscured when the entire western side of Crescent was destroyed by the formation of slightly younger cinder/spatter cones, Miter and Terrace, and their respective lava flows (Gilbert, 1890; Hoover, 1974). Our research focused on Miter's volcanic history due to its better preservation when compared to Crescent or Terrace. Miter (diameter: 900 feet; 275 m) is dominated by cinder deposits and capped by a resistant layer of welded spatter. Due to its physical characteristics, we infer a Strombolian eruption style, which is common for basaltic eruptions producing cinder cones. Miter reveals a 27.3 ft (8.3 m) eruptive sequence at its crest (figure 3C). From bottom to top, three units were identified within the sequence: (1) a lower unit of poorly welded spatter and large bombs, (2) a middle unit of increased welded spatter but small bombs, and (3) a highly weathered top unit of scattered bombs and blocks, welded spatter, and ash lapilli. These bombs are poorly to highly vesicular (classification of Houghton and Wilson, 1989), with greater vesicularity typically in the rind than the core of the bombs. Further, many bombs are fluidally shaped, suggesting that they were partially molten upon impact (figure 3D).

Pocket is a small (diameter: 330 feet; 100 m), symmetrical, cinder cone that formed after Crescent (figure 3A). Compared to the others in the complex, Pocket produced only a small volume of lava (Lynch and Nash, 1980). Terrace (diameter: 800 feet; 245 m) is relatively low-lying and built on the southern side of the Crescent-Miter complex. It is dominated by layered spatter and a'a flows (lava with a blocky, jagged texture) underneath a veneer of ejected rock fragments (tephra) (Hoover, 1974). Terrace is the source for the southeastward flows in the ISVF. Gilbert (1890) gave the Terrace its name based on speculation that a molten lake left behind terraces, although mining activities have destroyed most evidence of this.

Lava Field Stratigraphy

Lava Flow Fields

Gilbert's (1890) field observations are especially important for understanding the eruptive history of ISVF because they preceded mining activity. He identified lava channels emanating from the western edge of the crater complex that connected the cones to specific lava flows. The lava channels are partially disrupted by mining, but building on Gilbert's (1890) observations, Hoover (1974) provided a detailed summary of eruptive events (figure 4). The eruption began with lava flows from Crescent advancing primarily to the north. The Crescent lava flows were followed by eruptions from Miter and Pocket, producing lava flows that were initially channeled to the north then to the west and southwest. Toward the end of the Miter eruptions, lava flows from Terrace advance to the south.

Ice Springs lava flows are dominated by a'a lava except near the crater complex, where pahoehoe can be identified by its smooth, ropy surfaces. In hand sample, the lavas are very fine-grained basalt with few to no visible crystals, although green olivine crystals up to four millimeters in diameter can be found in the a'a flow west (38°57.905'N, 112°31.143'W) of the crater complex. Granitic rock fragments up to about an inch (several centimeters) across are sparsely distributed in the lava flows; and, light-colored, glassy, highly vesiculated fragments (xenoliths) are found in the scoria at the crater complex (Condie and Barsky, 1972; Hoover, 1974; Thompson, 2009).

Although ISVF lava flows appear similar to the eye, they can be separated into two groups based on their geochemical compositions (figure 4). The northern field, which formed during Crescent

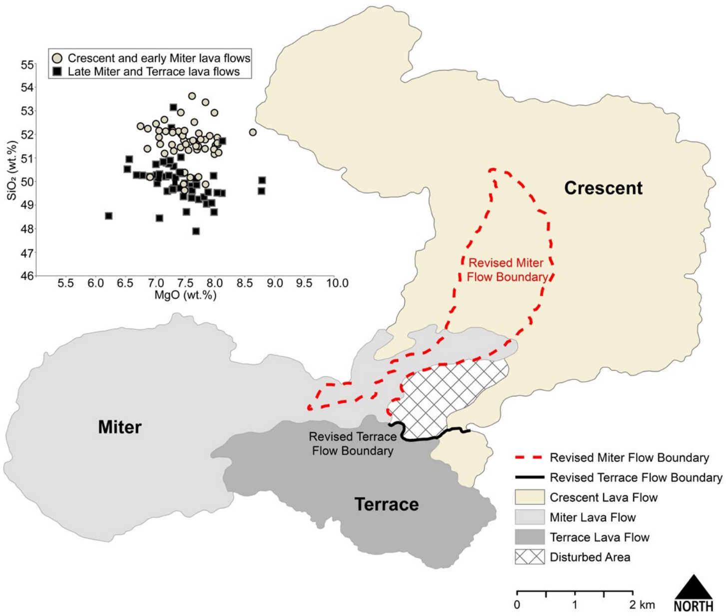

Figure 4. *Location of Crescent (tan), Miter (light gray), and Terrace (dark gray) lava flows according to Lynch and Nash (1980). Proposed boundaries for the Miter lava flow (red dashed line) and Terrace lava flow (black solid line) are based on our work. Crosshatched area is disturbed by mining activity. Inset shows SiO2 vs MgO in weight percent for samples mapped as Crescent and early Miter lava flows (tan circles) and as late Miter and Terrace lava flows (black squares). Some samples mapped as a late Miter lavas fall into the high-silica compositional group while some samples mapped as Crescent and early Miter lavas fall into the low-silica compositional group. Data from this study and Lynch and Nash (1980), Nelson and Tingey (1997), and Thompson (2009).*

and early Miter eruptions, comprises lava that is relatively higher in silica (SiO_2) compared to the southern and western fields, which formed during late Miter and Terrace eruptions (Condie and Barsky, 1972; Lynch and Nash, 1980; Thompson, 2009). The high silica lavas are also consistently higher in potassium (K_2O) and lower in iron (FeO*) and titanium ($Ti\ O_2$).

We used the geochemical "fingerprints" of the lava flows to better understand the eruption history at ISVF. Our sampling focused on the boundaries between lava flow fields, the area immediately west of the cones where most of the flows originate, and the interior of the lava flows, which are less accessible and represented a gap in the existing data set (table 2). Our work nearly doubles the number of geochemical data points for ISVF lava flows.

Overall, the additional geochemical data overlaps with the high-silica and low-silica compositional groups, but some samples fall into groups that are opposite to what was expected based on previous mapping (figure 4). For example, the olivine-rich a'a lava west of the crater complex was previously mapped as a late Miter lava flow, but it falls in the same high-silica compositional group as early Miter and Crescent flows (Sims and others, 2012). Additionally, samples in the northern field that were previously mapped as early Miter flows fall within the same low-silica compositional group as late Miter and Terrace lava flows (Patzkowsky and others, 2017). Our results suggest that the chemistry of ISVF is more complex than previously thought. We modified flow boundaries based on our recent geochemistry and mapping of lava field features (figure 4).

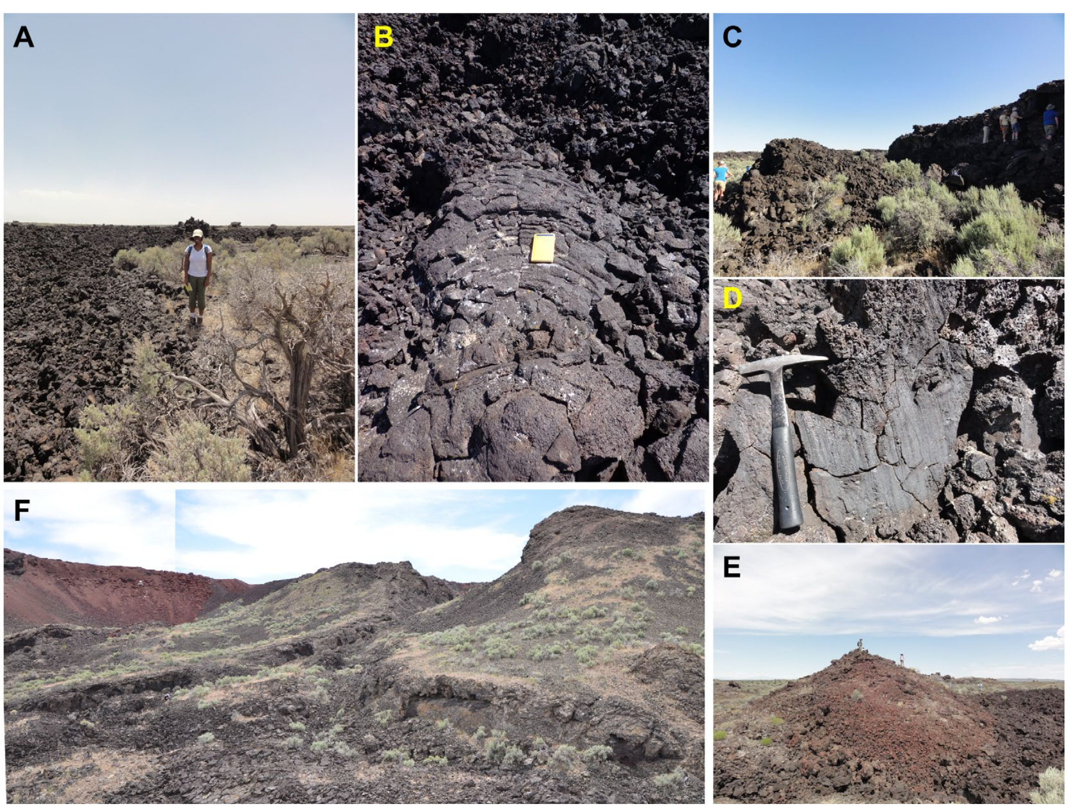

Figure 5. *Lava flow features.* ***A.*** *Boundary between a'a lava flow (left) and pahoehoe lava flow (right; 38°57.974'N, 112°31.119'W).* ***B.*** *Ropy pahoehoe surface adjacent to a'a lava (38°57.815'N, 112°30.777'W).* ***C.*** *A pressure ridge (tumulus) in lava channel with a smooth floor; students on lava channel walls (38°57.590'N, 112°30.873'W).* ***D.*** *Striae on tumulus.* ***E.*** *Distal cinder mound in an area of rugged volcanic topography (38°57.968'N, 112°30.770'W). F. Breached northern wall of Miter cone (38°57.807'N, 112°30.408'W).*

Table 2. *Representative geochemical analyses of samples from ISVF lava flows. All samples are from this study except for I-27, which is from Nelson and Tingey (1997). FeO* is total iron calculated as FeO.*

Sample ID	Keck17-07	M13-CM-19	M-12-WS-13	I-27	17-01
Mapped Lava Flow	Terrace	Miter	Miter	Crescent	Crescent
Low/High Silica Group	Low	Low	High	High	Low
SiO_2	50.36	48.71	52.15	52.01	50.38
MgO	7.43	7.52	7.49	7.44	7.49
FeO*	11.06	10.46	8.49	9.34	11.10
TiO_2	2.00	1.88	1.44	1.66	2.00
K_2O	1.14	0.92	1.50	1.45	1.25
Na_2O	2.86	2.72	3.05	2.97	2.82
Al_2O_3	14.99	15.88	16.06	15.55	14.74
CaO	9.30	11.11	9.24	8.99	9.35
P_2O_5	0.60	0.56	0.37	0.44	0.62
MnO	0.18	0.18	0.15	0.15	0.19
BaO	0.07	0.06	0.07		0.07
Sum	100.00	100.00	100.00	100.00	100.00

General Lava Field Features:

Visitors to ISVF can view breached craters, a'a and pahoehoe, inflated lava features such as pressure ridges (tumuli), lava channels and topographically depressed areas containing a'a and mounds of cinders on the lava flows (figure 5). Each of these are discussed briefly below.

Breached crater walls:

Pocket, Miter, and Terrace all show evidence of breached crater walls. The most complete illustration of the four cinder cones prior to mining was published by Gilbert (1890; figure 6). In his illustration, Gilbert (1890) interpreted breached crater walls from (1) the west side of Pocket, (2) the north and west sides of Miter, and (3) the west and south sides of Terrace (figure 3A, 6A). Mining operations have disrupted all the breaches except those on the west side of Pocket and the north side of Miter, which are clearly visible today. These breached crater walls represent the break-out of lava flows at the base of cinder cones, causing flank collapse (figure 5F).

Lava morphology and inflated lava features:

At ISVF, pahoehoe is commonly located near the crater complex, something also noted by Condie and Barsky (1972) (figure 5B). Pahoehoe is widely exposed to the west and north of Miter in elevated regions of the flow field associated with inflation. Inflation of a sheet flow results when liquid lava is pumped underneath a chilled, solid crust, which then rises (Self and others, 1997; Gary and others, 2012). At ISVF, these pahoehoe flows are evidence of inflation events, which occur during eruptions with steady low rates (Bernardi and others, 2015).

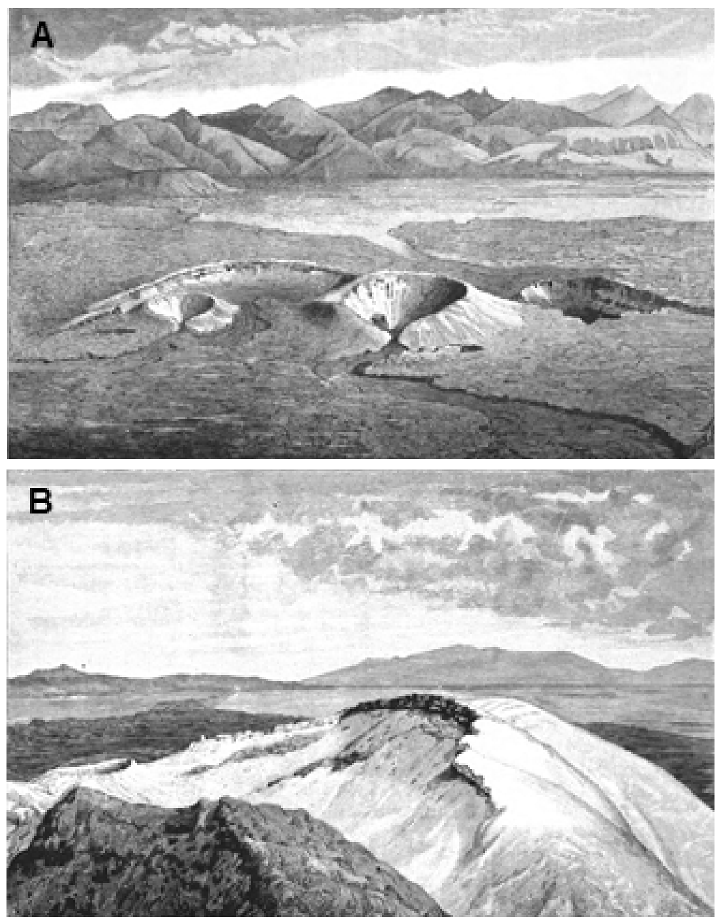

***Figure 6.** Illustrations of ISVF, contained in Lake Bonneville, U.S. Geological Survey Monograph 1, by G.K. Gilbert (1890). **A.** The crater complex at ISVF before mining operations. Left to right: Pocket, Crescent (arch remnant in back), Miter, and Terrace. Note the breached crater walls on the west side of both Pocket and Miter, in addition to the channels in the lava fields extending from each of these breaches. View to the east. **B.** View of Crescent as seen from the top of Miter crater. The top of Pocket can be seen in the left-center of the illustration. View to the north.*

If flow rate and slope conditions are favorable, inflated flows can contain lava tubes and surface features such as vertical striae, pressure ridges, and tumuli (figures 5C, 5D; Hon and others, 1994; Self and others, 1998; Anderson and others, 2012). The presence of numerous lava tubes within ISVF suggests a complex transport network from the source. Internal fluid in the tubes eventually would have drained, causing local collapse of the tube ceilings. Lava tubes locally contain structural drips and striae on their internal walls, suggesting fluctuating flow volumes during emplacement. At ISVF, pressure ridges and tumuli are apparent but unevenly distributed across the lava fields. Pressure ridges are best viewed to the southwest of Miter, where the direction of lava flow changes from northeast to due west. Tumuli, however, are more widespread and occur both to the southwest and north of Miter.

Lava channels:

There are several channels or topographically depressed areas in ISVF (figure 5C). Two examples of note are north and southwest of Miter. Both areas have direct ties to breached crater walls in Miter. The depression to the southwest of Miter has a smooth floor, whereas the channel extending north of Miter is filled with a'a, which typically results from "vigorous eruptions at high discharge" (Rowland and Walker 1990). A'a is consistently present in several areas of the flow field: (1) at the base of sinuous channels, (2) at the base of other depressed, ponded areas, and (3) at the extreme edges of the lava field (figure 5A). Condie and Barsky (1972, p. 340) suggested that the "basalts were very fluid at the time of eruption (forming pahoehoe), losing their volatiles and increasing in viscosity as they moved outward, thus developing a'a structure." This agrees with Rowland and Walker (1990), who suggested that the main controls on the formation of pahoehoe and a'a are lava viscosity, shear rate, volumetric flow rate, and changes accompanying degassing.

Mapping a lava flow channel:

A lava flow north of Miter Crater was surveyed using DGPS mapping techniques as an example of the complexities within the flow field. The purpose of the mapping was to outline features including cinder cone craters, tumuli and pressure ridges, and flow margins, and to create topographic profiles across the flow to determine heights, lengths, slopes, areas, and volumes of features. The lava field north of Miter can be divided into a laterally extensive, terraced, topographic upper unit that surrounds a narrow, sinuous, depressed lower unit (figure 7A). The terraced surfaces dip gently to the north and are dominated highly vesiculated platy rubble, interspersed with flat sheets or poorly developed columnar-jointed basalt and occasional rounded pahoehoe lobes. Partially collapsed, anastomosing lava tubes are present along the margins of the terraces, subparallel to the central, sinuous depression. The central depression trends 0.62 mi (1 km) north from a breakout in Miter's crater wall, and it is bounded on the east by Pocket and the remains of Crescent and modern mining operations. Topographic profiles were mapped across the central depression; these profiles show abrupt elevation changes at several mounds and at its edges (figures 7A, 7B, 7C). The central depression is interpreted as a transportation network—a collapsed master tube—for a single lava flow advancing northward from Miter. The flow eventually ponded within the wide, semi-circular, northern basin. Mounds scattered across its surface are interpreted as tumuli or rafted debris.

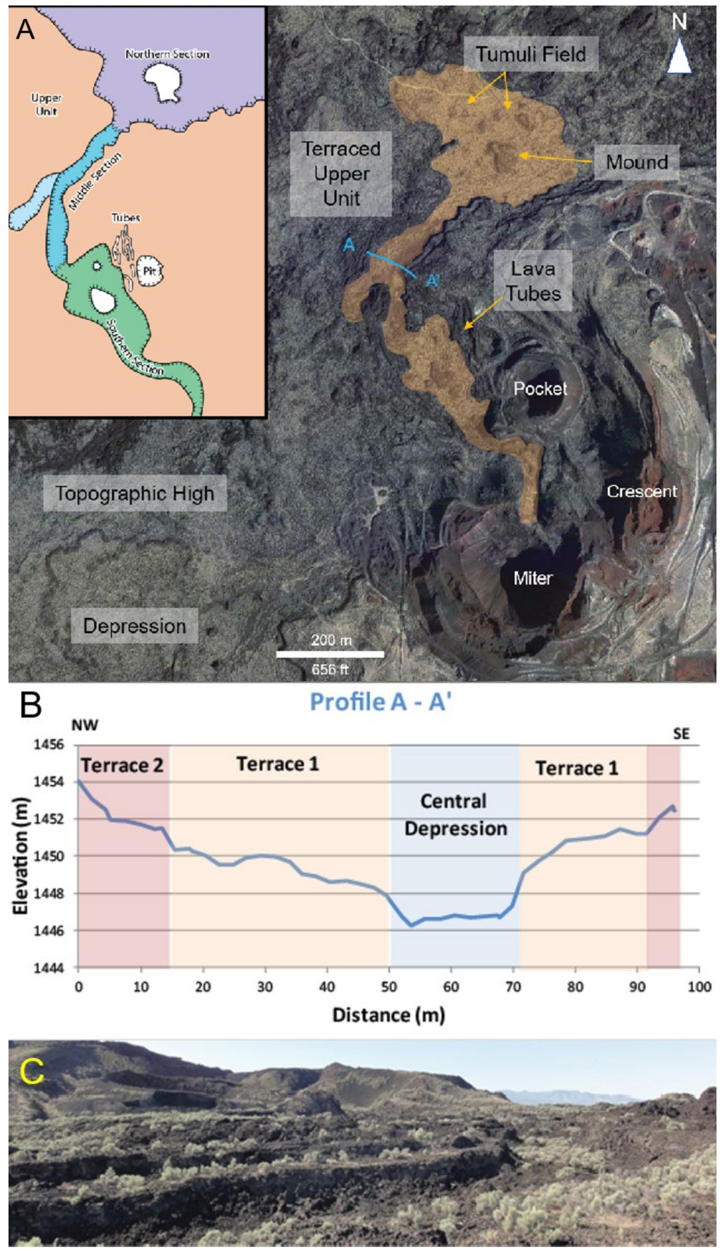

Figure 7. A. Location of the channel (opaque yellow) extending from the breached crater wall of Miter to the north, ending in a tumuli field (modified from Google Earth). B. Topographic profile A-A' across the terraced upper unit and the central depressed lower unit. C. Image of the topographic profile, showing the central channel and its terraced sides. View to the northwest.

Modeling the flow rate:

We calculated the average lava flow velocity at ISVF, and the results are similar to calculations at Hawaiian lava fields (Dragoni,1989; Harris and others, 2009). Using our topographic profile measurements, we calculated an average effusion rate necessary to emplace the entire edifice of ~58.6 yd^3/s (~44.8 m^3/s). We can use this effusion rate, along with a calculated total edifice volume, to calculate the total length of the eruption in hours: ~6.19 hours. With a 2789 ft (850 m) long flow, this implies that the flow advanced at an average velocity of 7.6 ft/min (2.31 m/min). This is within 8% of the average velocity of 8.2 ft/min (2.5 m/min) recorded during the 1983 Pu'u O'o eruption of Kilauea Volcano, Hawaii (Wolfe and others, 1988).

Cinder mounds:

West-northwest of Miter there is an anomalous area of rugged topography that is very different from the surrounding a'a and pahoehoe. This area contains mounds of red, commonly bedded, scoriaceous material (figure 5E). The volcanic layers dip outward from the area's center. The presence of bombs, lapilli, and glassy surfaces is similar to the volcanic material found at the main crater complex. The region is about the size of Miter and is previously undocumented in the literature of ISVF. Previously, Hoover (1974) described an eroded cinder mound on the northern lava flow, but none have been described from the flows to the west-northwest of Miter. Originally, we thought the mound was rafted material from Crescent due to its similar geochemistry; however, we now interpret the region as an unrecorded cone that erupted about the same time as Crescent. This is consistent with Hoover's (1974) interpretation that the cinder mounds on the northern lava flow were formed in place by eruptions along a north-south fracture system.

GEOLOGIC UNIQUENESS

ISVF is worth a visit for several reasons:

1. The active mining along the east flank of Crescent allows visitors to see the stratigraphy of a young cinder cone. Understandably, visitors cannot and should not interfere with active mining operations, so some of this volcanic stratigraphy must be viewed from a distance. Visitors should gain access at the mining office at the entrance to the quarry. However, in other places, such as Miter and Pocket, there is less mining and more opportunity to view cone stratigraphy up close. Please understand, though, that mining spoil piles can often conceal cinder flanks from year to year.

2. The age of the eruptions associated with ISVF are geologically young. Originally thought to be 660 ± 170 years old (Valastro and others, 1972), our new cosmogenic ages show it to be 9.8 (±1.6) to 11.1 (±1.7) thousand years old. ISVF remains the youngest volcanic center in Utah.

3. ISVF is the most complex volcanic field in the Black Rock Desert. It was constructed through a series of eruptions that produced overlapping cinder cones and lava flows of slightly different compositions. We consider ISVF to be a compound polygenetic volcano (defined in Németh and Kereszturi, 2015) due to its numerous cinder cones and production of chemically distinct lava flows.

4. ISVF is centrally located in the Black Rock Desert. With Pahvant Butte and Tabernacle Hill to the north and south and north, respectively, visitors can investigate diverse types and ages of Pleistocene volcanism. Pahvant Butte exhibits several eruptive stages, but it contains deposits that were clearly erupted into Lake Bonneville at its highest altitude, just prior to the initiation of catastrophic drainage near Red Rock Pass, Idaho (Oviatt, 2015). The eruption is dated between 18,000 and 14,000 (Oviatt and Nash, 1989; Oviatt, 1991; Cerling and Craig, 1994)—a time when Lake Bonneville covered the region. Age dates from Tabernacle Hill deposits span the Bonneville to Provo shoreline period of Lake Bonneville. The initial Tabernacle Hill eruptive phase suggests magma interaction with groundwater, while later stages show deposits erupted onto the lake beds of Bonneville. Ice Springs, the third volcanic field in the area, represents volcanism after Lake Bonneville had completely ceased to exist in Milliard County.

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