

**LARGE SCALE MAPPING AND NEW INTERPRETATION OF THE GEOLOGY IN
PROXIMITY TO THE VISITOR CENTER: EVIDENCE FOR A MISSING CINDER CONE AND
REFINED MAPPING OF VOLCANIC FEATURES, CRATERS OF THE MOON NATIONAL
MONUMENT AND PRESERVE, IDAHO**

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Abstract – Recent detailed field mapping near the visitor center at Craters of the Moon National Monument and Preserve (CRMO) revealed proof for a missing cinder cone, named the South Highway cinder cone (SHC), partially swallowed during magma chamber collapse and rafted away by younger flows. To support hypothesis by previous workers at CRMO, we present evidence for five potential remnants of SHC. In addition to mapping the missing cinder cone, we present here a sequence of events explaining the creation and destruction of SHC.

A volume analysis of SHC was conducted to compare with previous volume calculations of rafted material near the mapping area that show the volume of rafted material is too great to be contained within existing cone edifices. The volume of SHC remnants would reduce the volume of excess rafted material by 10% and yet the total volume of SHC remains too large to be accounted for simply through rafted blocks. Thus, collapsing magma chamber appears to be a reasonable mechanism for the removal of a moderately sized cinder cone.

Finally, we generated a 1:12,000 digital geologic map of our reinterpretations and a Points of Interest section. We identified previously unmapped eruptive and non-eruptive fissures that provide relative ages for cinder cones and vent complexes in the mapping area. The map and accompanying section promotes mapping and understanding of volcanic terrains by offering the reader a series of features with explanations for their formation. The publication is available to the public via the CRMO website (www.nps.gov/crmo) and encouraged for use by geology field camps.

INTRODUCTION

Geologic Setting

Craters of the Moon National Monument and Preserve (CRMO) surrounds the Great Rift on the eastern Snake River Plain (ESRP), Idaho (Figure 1). The ESRP formed as a result of the North American plate passing over the Yellowstone hotspot beginning 17-16 million years ago (Pierce and Morgan, 1992). Rhyolitic volcanism dominated the ESRP, including the CRMO area, and produced large calderas as the

surficial expression of the hotspot track (Leeman, 1982; Pierce and Morgan, 1992). Recent seismic imaging places the current location of the hotspot beneath Yellowstone National Park (Waite, et al., 2006). Following rhyolitic volcanism at CRMO, Basin-and-Range extension dominated and allowed basaltic magma to rise to the surface. This rift-volcanism began at CRMO's northern most lava field, the Craters of the Moon field, 15,000 years ago and became dormant 2,000 years ago. Twenty-five cinder cones and over 60 lava flows were produced during this period (Kuntz, et al., 1986a).

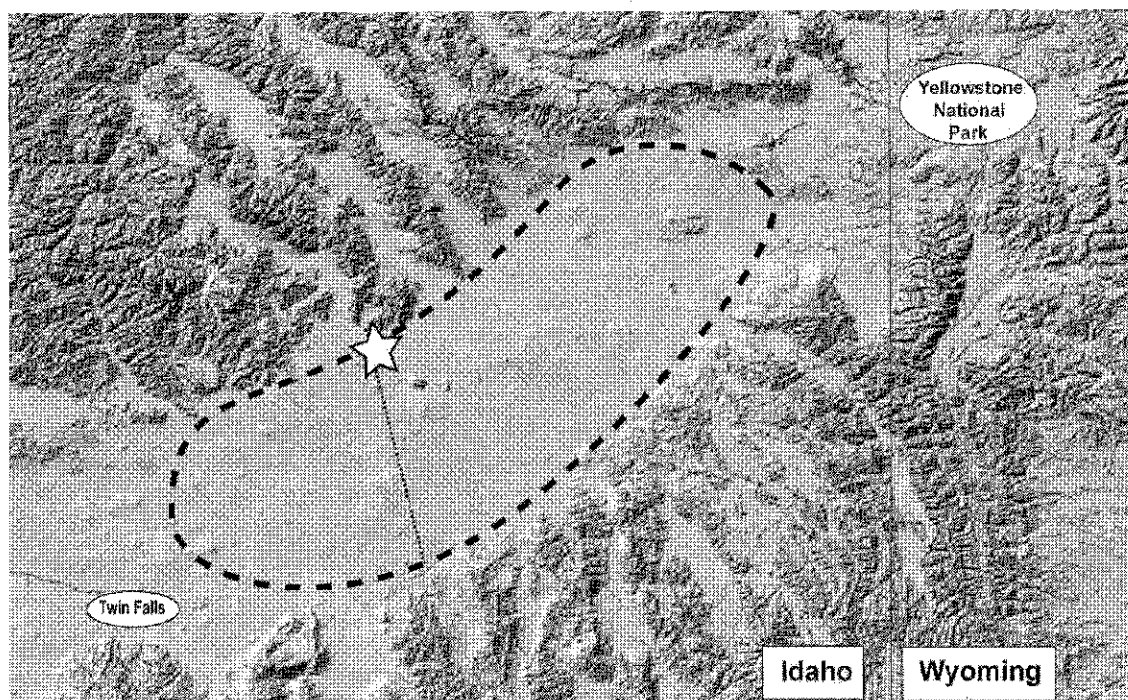


Figure 1. Shaded relief map showing study area (star) within Craters of the Moon National Monument and Preserve in relation to the Great Rift (dotted line), the eastern Snake River Plain (dashed line) and Yellowstone National Park. Map generated from Seamless Data Distribution System, Earth Resources Observation and Science (EROS), part of the U.S. Geological Survey at a scale of approximately 1:2,750,000. <http://seamless.usgs.gov>.

Previous Work

North Crater cinder cone (NC) is a monogenetic volcano whose northwestern flank has been breached by at least one high silica (54-64 wt. %) flow (Kuntz, et al., 1986a). Breaching of the NC flank demonstrates the ability of high silica flows to destroy cinder cones and carry off rafted blocks. These blocks are transported by the lava

flows and can leave dissimilar piles of welded cinders standing high in the flows. Recognition of a potentially missing cinder cone first came from Brossy, Jordan, and Champion (2007a) during a volume analysis of the rafted blocks associated with NC in the Devils Orchard and Serrate Flows. In their research, the authors found that the volume of rafted material was $46 \times 10^6 \text{ m}^3$; too great a volume to be contained

within the modern breached wall of NC. The authors offer three explanations for the excess volume of cinder material. They explain that a very large paleo-NC could have existed, that the existing NC was built and destroyed several times, or one or more other small cones were constructed and rafted away. To further support their hypothesis, recognition of a dissimilar area along the northern flank of NC prompted the authors to take rock cores for paleomagnetic data analyses. The authors concluded from this data that other cinder cones could have existed to the north of NC and were most likely coeval with NC.

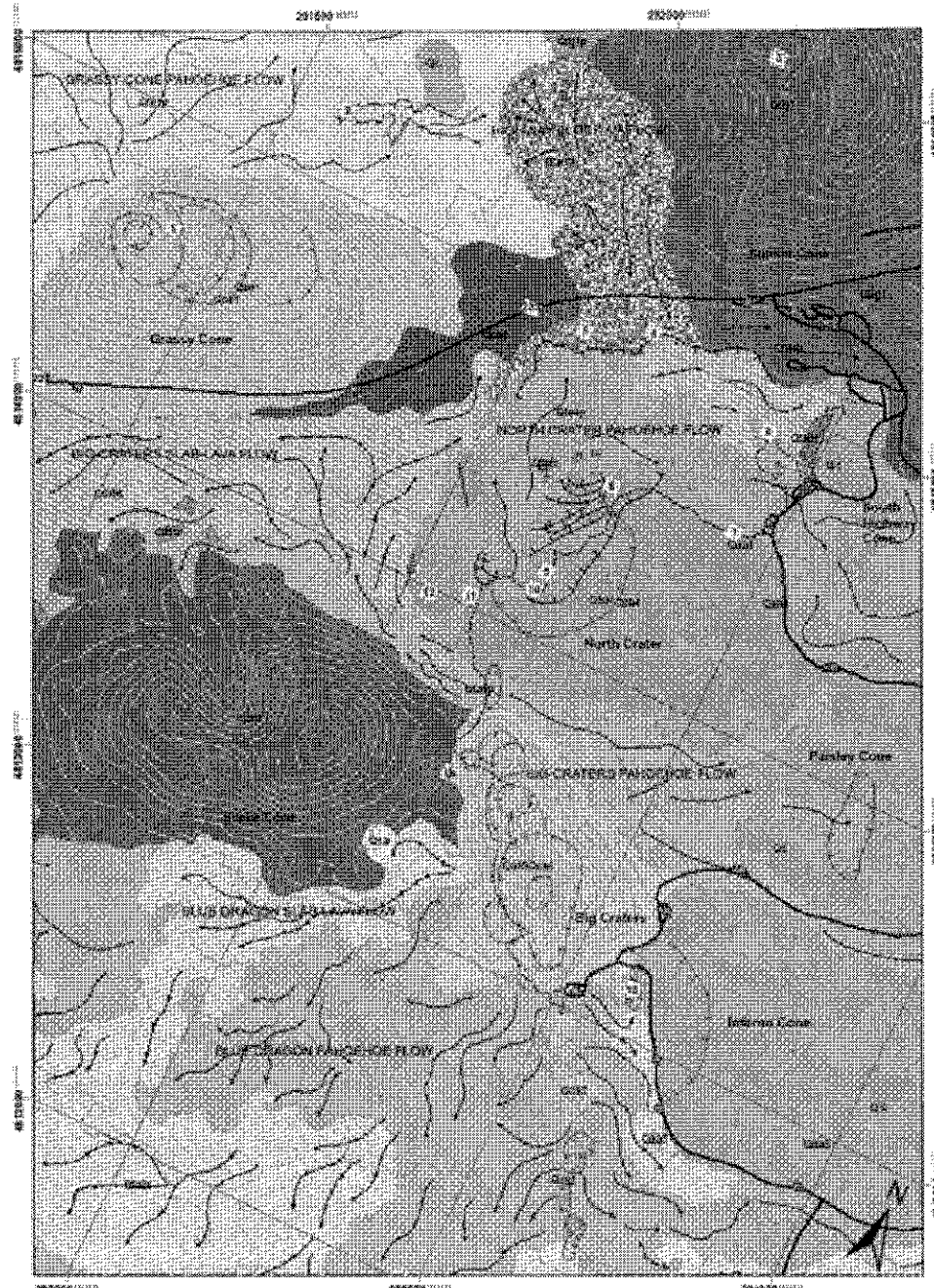
A study by Caress and Owen (2005) focused on dynamics of the Highway Flow, a trachyandesite block a'a flow with local pahoehoe. During field investigations, the authors extended the Highway Flow further to the east, noticing how the flow seemed to be channeled behind a now-missing cinder cone, which they termed the South Highway cinder cone (SHC). In the eastward extension, Caress and Owen found entrained rafted material and noted how the flow onlaps onto a potential SHC remnant at Campground Hill. The authors suggest that the entrained rafted material and in situ cone remnant may account for a portion of the excess volume of rafted material calculated by Brossy, et al. (2007a). Finally, Caress and Owen (2005)

recognized an area at the southern boundary of the Highway Flow where the block a'a abruptly transitions to pahoehoe and drapes over the South Highway fault scarp. This led the authors to conclude that the flow and fault were contemporaneous and that the fault may represent the collapse of a magma chamber.

Our work presents additional evidence for the existence of SHC. Through detailed field mapping and the use of aerial photographs, we mapped five areas that are interpreted as remnants of SHC. We present a refined 1:12,000 geologic map for the area near the visitor center (Figure 2) which identifies these cone remnants, locates previously unmapped fissures and faults, and provides the reader with a series of geologic points of interest available for public viewing. The Points of Interest section (Appendix) offers readers the chance to learn about the formation and significance of a variety of unique features found in a volcanic terrain. Finally, we present a proposed sequence of events based on field evidence to assign relative ages to flows, cinder cones, features, and processes. This timeline is valuable to understanding the evolution of cinder cones and the volcanic processes that have created the Craters of the Moon landscape.

Geologic Map of the Visitor Center Area Craters of the Moon National Monument and Preserve

Tiffany A. Rivera, Sheina M. Keane, and Douglass E. Owen



Source: USGS Data & Maps, Geologic Quadrangle 1920
 Projected Using North American Datum 1983
 1000-m Universal Transverse Mercator grid, zone 12
 Created in ArcGIS 9 using ArcMap for
 Craters of the Moon National Monument
 and Preserve, 2007



METHODS

Field mapping of SHC was undertaken by Geologist in the Park T.A. Rivera, Volunteer in the Park S.M. Keane, and Park Geologist D.E. Owen during the summer of 2007. Locations of cinder cone remnants and other features were determined using a handheld GPS unit set to UTM NAD83 Zone 12N datum. Aerial photographs were used to help with planning of field mapping and to better resolve areas that needed reinterpretation. Points of interest were collected using the same datum. The data were digitized and plotted on a 1:12,000 geologic map using ArcGIS 9 ArcMap version 9.2. Point, line, and polygon layers were added to the previous map to represent our findings. Original data files were not modified in order to preserve the integrity of pre-existing data.

RESULTS

Evidence for a Missing Cinder Cone

The largest independent area of reinterpretation is Campground Hill (Figure 3). Previously mapped as rafted blocks (Kuntz, et al., 1989), closer inspection shows that loose cinders comprise the majority of this hill and the area to its south. Extensive jostling occurs during rafting; it seems unlikely that such a large volume of loose cinders could survive transport. Additionally, no current edifice is in close proximity to this area, eliminating the possibility that these cinders were deposited from an eruption of another vent, such as Big Craters. The large amount of cinder material comprising these two areas leads us to propose that these are in situ pieces of SHC (Figures 3).



Figure 3. South Highway cinder cone remnants. A) Campground Hill; B) the area to its south (foreground). Both photographs show that loose cinders compose the majority of the two areas. The block lava in the upper photograph is the Highway Flow, which onlaps South Highway cinder cone.

The monoliths surrounded by the North Crater Pahoe Flow are interpreted as volcanic necks. These conduits may be one of several that contributed to the construction of SHC, which

follows the interpretation of Maley (1994). This was the only area lacking loose cinders to be interpreted as part of SHC (Figure 4).

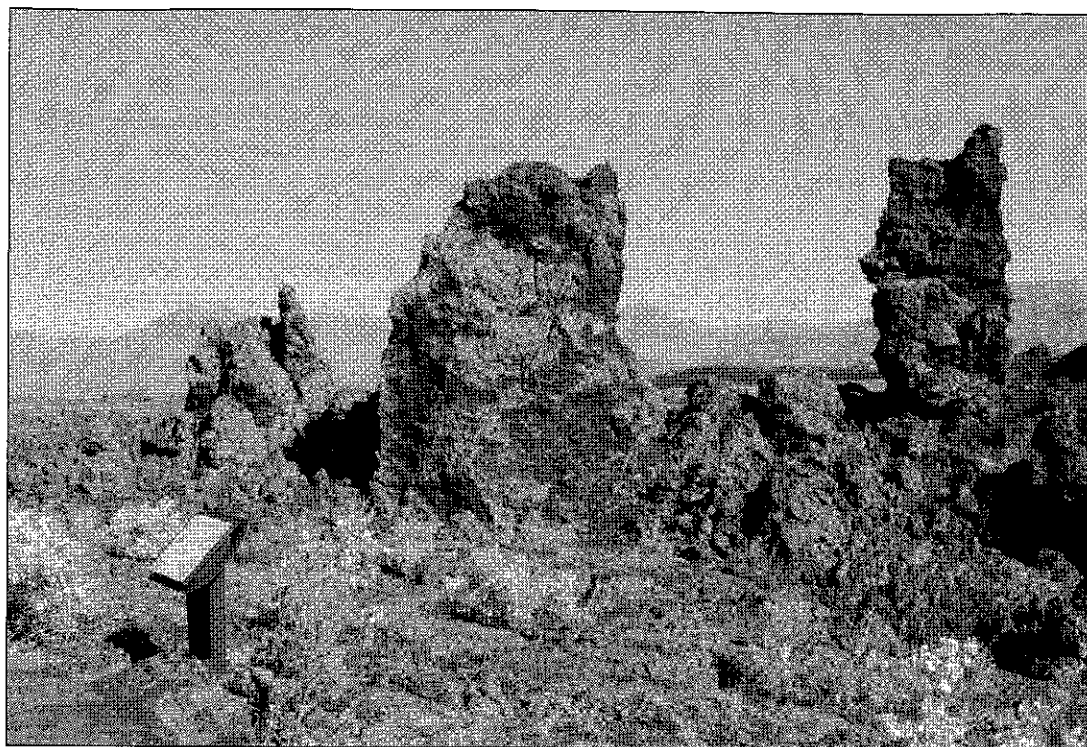


Figure 4. Volcanic necks, or possible conduits, that may have contributed to the construction of South Highway cinder cone.

Immediately south and southwest of the Highway Flow is another area with a large volume of loose cinders. Previously mapped as cinder mounds associated with NC, the welded cinders in this area do not resemble the material comprising NC, but more closely resembles the material in Campground Hill. The physical distance between NC and this area would require NC to be twice its current width.

The interpreted footprint of SHC is a minimum of 1300m long by 550m wide. Cinder cones within the immediate vicinity of SHC have comparable dimensions (Table 1). Big Cinder (Table 1) is the largest cinder cone within the lava field. If NC were twice its current width, it would fit within these dimensions. While a paleo-NC twice its modern width is possible, based on average sizes of cinder cones, it seems much more likely that SHC existed.

Cinder Cone	Length (m)	Width (m)	Height (m)
North Crater	1250	775	110
Inferno Cone	1600	800	100
Grassy Cone	1370	840	110
Paisley Cone	1100	780	80
Big Cinder	2600	1700	230
South Highway	1300	550	100

Table 1. Approximate dimensions for cinder cones in the vicinity of South Highway cinder cone (SHC). The length of SHC was measured east-west from the remnant south of the Highway Flow to the area south of Campground Hill. The width was measured from the remnant on the north flank of North Crater cinder cone to the South Highway fault scarp. The height was calculated as an average of heights for the four cinder cones in closest proximity to SHC.

Platy jointing was found at several locations within the Highway Flow (Figure 5). This type of jointing is common in high silica flows and occurs when the flow cannot move naturally due to internal friction at the edges of the massive

interior (White, pers. com). This feature suggests impingement and channeling of the Highway Flow against SHC, agreeing with Caress and Owen (2005).



Figure 5. Platy jointing in the Highway block a'a flow. This type of jointing occurs in high silica flows as a result of internal shear within the flow. It is probable that the Highway Flow tried to flow uphill when it encountered South Highway cinder cone, creating the platy jointing, then channeling to the east and west behind the cone.

Refined Mapping of Volcanic Features

Detailed field mapping shows several previously unmapped features and provides data for an alternate interpretation of the geology. A

description of our findings follows. Refer to the geologic map (Figure 2) and Points of Interest

(Appendix) for locations and additional information.

Two Eruptive Fissures and a Series of Non-eruptive Fissures

Two eruptive fissures were mapped cutting the western flank of NC. The east fissure (minimum 130m long by maximum 11m wide) is partially filled by the North Crater Pahoeohoe Flow, while the west (minimum 100m long by maximum 10m wide) fissure is completely filled by the Big Craters Slab-lava Flow. The east fissure is along strike with the Big Craters fissure system. This simple cross-cutting relationship may suggest that NC is older than Big Craters (Figures 6A and 6C). Identification of the west fissure was recognized from the presence of spatter capped cinder mounds (Figures 6A and 6D).

Several non-eruptive fissures are located along the west side of Big Craters (Figures 6A and 6B). The longest continuous fissure measures as a minimum of 50m long by a maximum 2m wide. These fissures are not part of the eruptive system; however, they are parallel to the main

Big Craters fissure system. Although the physical size of the fissures is an order of magnitude smaller, the geometry is consistent with the pattern predicted by Kuntz, et al. (2002) who suggest that non-eruptive fissures, or tension cracks, form parallel to vent systems at regularly spaced intervals as sub-surface dike emplacement occurs.

Gravity Faults at Big Craters

Two gravity faults were recognized along the northwestern flank of Big Craters nearly perpendicular to the fissure system (Figures 6A and 6E). The larger of the two is more apparent as wildlife has used it as a game trail. The smaller mapped fault is topographically higher than the first; however, it is less prominent. The eruptive center for the Big Craters Pahoeohoe Flow is just north of the faults. We propose that these faults represent slumping of the crater wall back towards the eruptive center and that the faults are associated with the eruption of the pahoeohoe flow rather than with the creation of the Big Craters cinder cone.

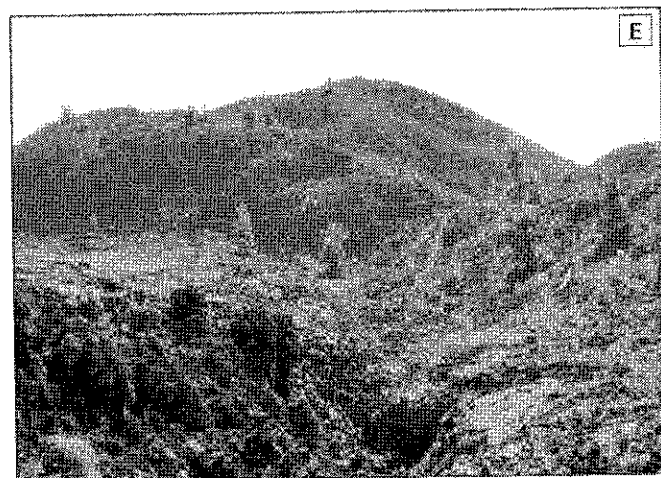
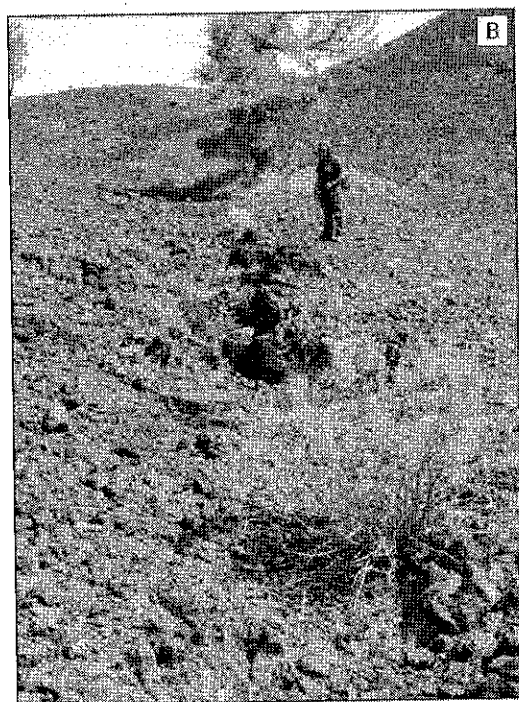
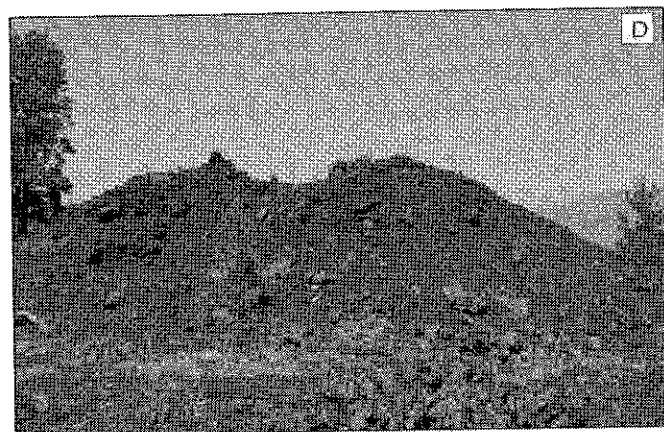
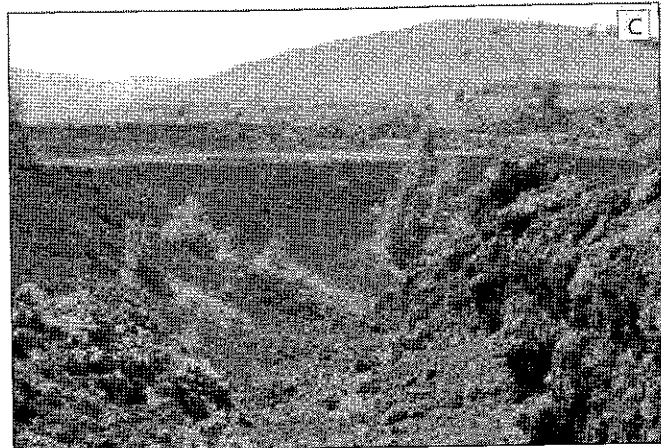
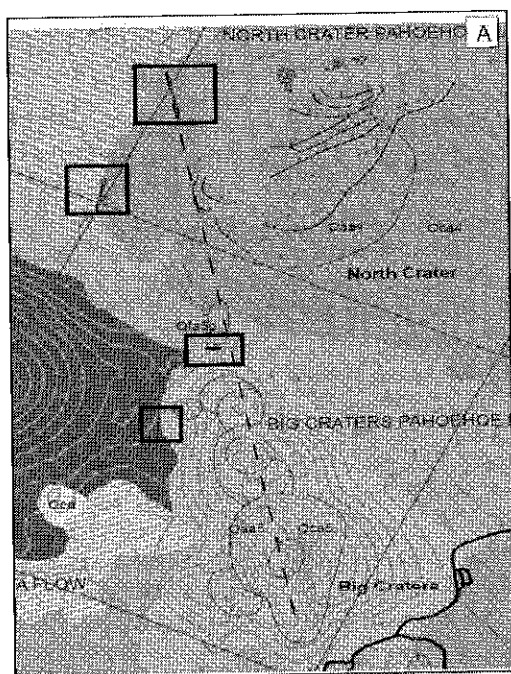


Figure 6. A) Geologic map emphasizing locations of newly mapped faults and fissures (boxed areas). Solid thick dark lines represent both eruptive and non-eruptive fissures. Solid line marks the location of the gravity faults. Dashed line shows connection between eruptive fissure at North Crater cinder cone and the Big Craters eruptive fissure system. Refer to the legend (Figure 2) for explanations of other symbols and map units. B) Longest continuous non-eruptive fissure on the western flank of Big Craters. C) View looking northwest into the east fissure cutting the western flank of North Crater cinder cone. D) Spatter-capped cinder cones represent nearby fissure. E) Photograph showing the two newly mapped gravity faults along the northern flank of Big Craters. Photograph taken looking south from the eruptive fissure (foreground) that produced the Big Craters Slab-lava Flow.

Extending the Highway Flow

We mapped the Highway Flow extending 300m west beyond what is currently mapped, between SHC and cinder mounds of unknown source and age, beyond what is currently mapped. Caress and Owen (2005) previously recognized the extension of the flow to the east. Platy jointing is found only in the western lobe signifying impingement of the Highway Flow against SHC.

Geologic Points of Interest

This section (Appendix) is designed for use by visitors with a passion for geology and students of geology, such as geology field camps. Each listed feature has UTM coordinates, a photograph, and a brief description of its formation. This section is designed to familiarize the reader with volcanic landscapes and to understand the processes involved in creating this unusual terrain. Recognizing and mapping the geologic features presented here demonstrates the importance and need for large-scale mapping at CRMO.

Assessing the Volume Problem

Previously stated, Brossy, et al. (2007a) calculated an excess of rafted material in the Devils Orchard and Serrate flows having a volume of $46 \times 10^6 \text{ m}^3$. Using the equation derived by Brossy, et al. (2007a), we calculate the volume of in situ SHC remnants previously mapped as rafted blocks to be $4.4 \times 10^6 \text{ m}^3$, approximately 10% of the excess material. However, from measurements given in Table 1, the calculated volume of SHC is $71.5 \times 10^6 \text{ m}^3$. If the excess rafted material was derived only from SHC, there would still be at least $25 \times 10^6 \text{ m}^3$ of SHC that is missing. We suggest a collapsing magma chamber swallowed this volume of SHC, represented by the South Highway fault scarp. Shallow magma chambers can range in size and volume from small, several inch thick dikes to the massive Bushveld intrusion in South Africa, roughly 10^5 km^3 (Marsh, 2000). South Highway Cone's much smaller volume can easily be accounted for through subsidence of an empty shallow magma chamber.

DISCUSSION

Compilation of evidence for the SHC, previously unmapped features, and geologic points of

interest led us to determine a sequence of events slightly different from current thought but in partial agreement with one model proposed by Kuntz, et al. (1982). We believe that the events described below happened relatively close in time although the exact amount of time is not well constrained. The following events are listed chronologically, starting with the oldest event.

1. Construct North Crater and South Highway cinder cones. We could not determine which was built first as the contact between the two is not distinct.
2. Construct Big Craters cinder cone. The newly mapped eastern eruptive fissure on the western flank of NC suggests Big Craters is younger than NC. This is also supported by the Big Craters Pahoeohoe Flow overlapping onto NC. Big Craters has a radiocarbon age of 2400 ± 300 years before present (Kuntz, et al., 1986a; Kuntz, et al., 1986b). While there is no absolute age for NC, we believe that these two cinder cones are relatively close in age (100 years or less).
3. Eruption of high silica Devils Orchard and Serrate Flows (not shown on map). These flows were capable of rafting away pieces of cinder cones and most likely originated in the NC neighborhood although vent locations have not been found.
4. Eruption of the Highway Flow. The flow was channeled behind SHC and impinged against the northern to create platy jointing in the high silica flow.
5. SHC and NC began to be torn apart by the three high silica flows mentioned above creating the rafted blocks strewn throughout the Devils Orchard and Serrate Flows. Either the Devils Orchard or Serrate Flow (or both) breached the northwest flank of NC.
6. Eruption of these high silica flows close in time emptied the underlying magma chamber.
7. The empty chamber collapsed back into itself, creating the South Highway fault scarp, draperies in the Highway Flow, and swallowing part of SHC.
8. Eruption of a lower silica North Crater Pahoeohoe Flow from the previously breached wall of NC as an isostatic response to the collapse and addition of SHC material into the empty chamber, displacing residual magma.
9. North Crater Pahoeohoe Flows partially covered the Serrate and Devils Orchard

Flows, flowed around rafted blocks of NC and SHC, and buried remaining evidence for SHC.

Recommended Future Work

In order to better examine the amount of time required to construct and destroy a moderately sized cinder cone, detailed absolute dating analyses on the flows and cinder cones are needed. Vent locations for the Serrate and Devils Orchard Flows need to be investigated. These flows are assumed to have surfaced from vents near NC but finding the actual vents may provide further evidence for SHC. Finally, geochemical analyses need to be performed in order to determine compositional variability within individual cones and between several cones. If there is a significant difference between cones, trace element data would allow for identification of rafted block source and possibly refine volume estimations for the cinder cones.

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REFERENCES

- Brossy, C.C., Jordan, B.T., and Champion, D.E., 2007a, Reconstructing a breached cinder cone at Craters of the Moon National Monument and Preserve: A geographic information systems approach, *in* Hughes, S., Orr, B., Freiberg, D., and Boyack, D., eds., *Proceedings of the Great Rift Science Symposium*, Pocatello, Idaho, October 2005, Idaho Museum of Natural History and Department of Geosciences, Idaho State University, p. 67-72.
- Brossy, C.C., Jordan, B.T., and Champion, D.E., 2007b, A GIS approach to reconstructing a breached cinder cone, Craters of the Moon lava field, Idaho: Geological Society of America Abstracts with Programs, vol. 39, no. 6, p. 124.
- Caress, M.E. and Owen, D.E., 2005, The Highway Flow in the Craters of the Moon lava field; a new interpretation of eruption history: *Eos* (Transactions, American Geophysical Union), vol. 86, Abstract V53B-1565.
- Hooper, P.R. and Hawkesworth, C.J., 1993, Isotopic and geochemical constraints on the origin and evolution of the Columbia River Basalt. *Journal of Petrology*, vol. 34, p. 1203-1246.
- Kuntz, M.A., Anderson, S.R., Champion, D.E., Lanphere, M.A., and Grundwald, D.J., 2002, Tension cracks, eruptive fissures, dikes, and faults related to late Pleistocene-Holocene basaltic volcanism and implications for the distribution of hydraulic conductivity in the eastern Snake River Plain, Idaho, *in* Link, P.K. and Mink, L.L., eds., *Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colorado, Geological Society of America Special Paper 353*, p. 111-133.
- Kuntz, M.A., Champion, D.E., Spiker, E.C., Lefebvre, R.H., and McBroome, L.A., 1982, The Great Rift and the evolution of the Craters of the Moon lava fields, Idaho, *in* Bonnicksen, B. and Breckenridge, R.M., eds., *Cenozoic Geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26*, p. 423-437.
- Kuntz, M.A., Champion, D.E., Spiker, E.C., and Lefebvre, R.H., 1986a, Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho: *Geological Society of America Bulletin*, v. 97, p. 579-594.
- Kuntz, M.A., Spiker, E.C., Rubin, M., Champion, D.E., and Lefebvre, R.H., 1986b, Radiocarbon studies of latest Pleistocene and Holocene lava flows of the Snake River Plain, Idaho: Data, lessons, interpretations: *Quaternary Research*, v. 25, p. 163-176.

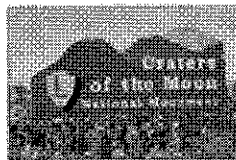
- Kuntz, M.A., Lefebvre, R.H., Champion, D.E., Skipp, B.A., 1989, Geologic map of the Inferno Cone quadrangle, Butte County, ID: U.S. Geological Survey Quadrangle Map GQ-1632, scale 1:24,000.
- Leeman, W.P., 1982, Development of the Snake River Plain-Yellowstone Plateau province, Idaho and Wyoming: an overview and petrologic model, *in* Bonnichsen, B., and R.M. Breckenridge, eds., *Cenozoic Geology of Idaho*: Idaho Geological Survey Bulletin 26, pp. 155-177.
- Maley, T.S., 1994, *Field geology illustrated*, 2nd ed.: Mineral Land Publications, Boise, Idaho, 704 p.
- Marsh, B., 2000, Magma chambers, *in* Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., and Stix, J., eds., *Encyclopedia of Volcanoes*, Academic Press: New York, pp. 191-206.
- McCurry, M., Hackett, W.R., and Hayden, K., 1999, Cedar Butte and cogenetic Quaternary rhyolite domes of the eastern Snake River Plain, *in* Hughes, S.S. and Thackray, G.D., eds., *Guidebook to the Geology of Eastern Idaho*: Idaho Museum of Natural History, p. 169-179.
- Murtaugh, J.C., 1961, *Geology of Craters of the Moon National Monument, Idaho*: Moscow, University of Idaho, M.S. thesis, 99 p.
- Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: volcanism, faulting and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.P., eds., *Regional Geology of Eastern Idaho and Western Wyoming*, Geological Society of America Memoir, v. 179, pp. 1-53.
- Waite, G.P., Smith, R.B., and Allen, R.M., 2006, V_p and V_s structure of the Yellowstone hot spot from teleseismic tomography: evidence for an upper mantle plume. *Journal of Geophysical Research*, v. 111 B04303.

APPENDIX

Points of Interest section with photographs, UTM coordinates, and description of the feature's formation. This section is preceded by general rules, regulations, and safety concerns for exploring CRMO geology. Accompanying this section are the several pages of reinterpretation, along with the geologic map and legend (Figure 2), that complete the entire publication available on the CRMO website.

Geologic Points of Interest near the Visitor Center Area

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Before exploring Craters of the Moon geology, please be aware of the following rules, regulations, and safety concerns.

•UTM Coordinates

The points of interest on the accompanying pages are given in UTM coordinates. This point data was collected using a handheld GPS unit and collected using NAD83 Zone 12 Datum.

•North End Points

We encourage the exploration of the North End of Craters of the Moon; however, a day use permit is required and are available free of charge at the visitor center.

•Group Campsite

We offer a group campsite in the North End by reservation only. For groups up to 35 people we suggest camping here, rather than at multiple tent sites within the Lava Flow campground. Availability and reservations can be obtained by calling Park Headquarters. Cost is \$30 per night.

•No Collecting

Many of the unique specimens you will see on your visit to Craters of the Moon may tempt you to collect them. All rocks must be left behind as there is no collecting permitted within Craters of the Moon without a research permit. Please leave specimens for future students and visitors to enjoy.

•Off-Trail Travel

We prefer that our visitors stay on the trails as much as possible. However, to see exciting geology sometimes requires drifting from these trails. This is possible in most areas throughout the park, but prohibited in three areas.

Please stay on trails at the following areas:

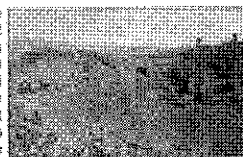
North Crater Flow Trail
Big Craters Trail
Spouter Crater Area

•Firearm Safety

Visiting Craters of the Moon in the summer poses several different safety concerns. In summer months we suggest at least one gallon of water per person per day. It is also wise to wear sturdy sneakers and protect yourself from the sun by wearing a hat and sunscreen. If you decide to go off-trail, please be aware of our seasonal loop road, we recommend bringing along a flashlight. Exploration of other areas may require multiple sources of light, a helmet, and kneecaps.

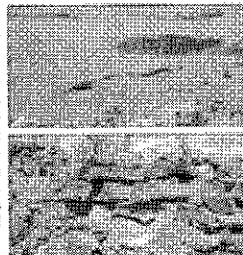
1 Grassy Cone Crater Complex N 4014055 E 290230

The crater complex at Grassy Cone gives visitors a view of the crater rim. This view looking at the south crater wall shows the vent area for the most recent flow, roughly 7300 years ago. Grassy Cone's crater complex consists of five nested craters, each contributing to the building of the 150 meter high cone.



2 Grassy Cone Flow Lava Channel and Cones N 4010230 E 291170 to N 4010475 E 291395

A well defined lava channel, identified by its levees, in the Grassy Cone Flow area can be seen from the crater rim of Grassy Cone (upper photograph, see Point of Interest # 1). The channel is oriented approximately east-west for 400m. It is about 100m wide, and 3m deep. In the levees, multiple patterns of lava can be identified (lower photograph). The channel terminates just south of two cones that are surrounded by the Grassy Cone Flow.

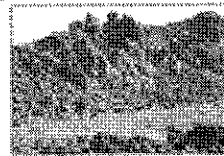


3 Sunset Cone Crater Complex N 4010905 E 2902324



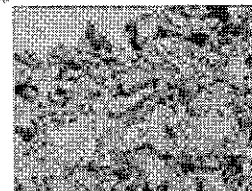
The main crater of Sunset Cone can be seen from US20 (left photograph); however, more spectacular views are from the crater rim (right photograph). Similar to Grassy Cone, Sunset Cone (ca. 12,000 years old) is composed of eight nested craters. The cone is roughly 140m tall and 1500m in diameter. These craters are accessible from the group campsite or from a small access road along the south side of the cone.

4 Overlook N 4010935 E 292352



The overlook of the North Crater and Highway Flow is just a short walk along an old road that angles off US20. It is best to reach this road by parking at the pullout along the Highway and walking outward toward the visitor center. Please use caution while walking along the highway. To the east, the Highway Flow fault scarp can be seen. Drizzly features are present, in which the Highway Flow was still molten as faulting occurred, allowing the flow to drop over the fault scarp (upper photograph). Looking south from the overlook, features of the Highway Flow can be distinguished from the surrounding grassy plateaus of the North Crater Flow (lower photograph). The features are thought to have been ripped away from the massive margin of the Highway Flow as faulting occurred and later surrounded by the North Crater Flow. Finally, ruffed blocks and volcanic debris can be viewed from this location (see Point of Interest #7).

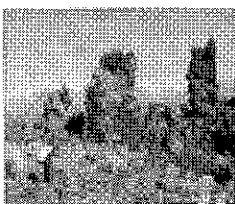
5 Platy Jointing N 4014042 E 292154 and N 4014065 E 292127



Platy jointing in the Highway Flow is a result of its high silica content allowing the flow to become extremely viscous during movement. This created an area of internal shear along the exterior of massive areas. This feature is most easily observed by parking at the aforementioned pullout along US20 and walking outward toward the visitor center. Use caution when walking along US20. This feature is seen near mile marker 226.5.

6 Monoliths N 4010910 E 292617

The monoliths along the North Crater Flow Trail have been interpreted in two different manners. First, they may be ruffed blocks, pieces of crater walls that were ripped away by a higher silica flow. Second, they are possibly volcanic necks, eroded conduits for a now missing cone (current map). As off-trail travel is prohibited along the North Crater Flow Trail please view the monoliths from the way-side trail.



Squeeze-Ups N 4814591 E 292861

If pressure is sufficient, lava can also up the tension fracture typically found in the top of an inflated flow ridge and squeeze out onto the surface. The squeeze-ups seen here have then flowed down the sides of the flow ridge. An official travel is prohibited on the North Crater Flow Trail, the best viewing area for this feature is from the North Crater Trail, as seen below.



Bomb Field N 4814543 E 292847



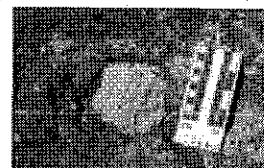
Many brecciated bombs can be found along the North Crater Trail. These bombs form as the porous molten interior continues to expand inside a cooled crust. This step presents several of varying sizes, as well as a spectacular view across the North Crater Flow.

Pumice Xenoliths N 4814207 E 292390

Pumice xenoliths in the vicinity of North Crater may be derived from material deposited when the Yellowstone Hotspot was beneath Craters of the Moon ca. 5mya. These xenoliths show that basaltic magma was interacting with the pumice, as basalt is stung through many of the pumice fragments. This alludes to assimilation of pre-existing rocks which would increase the silica content of the magma.



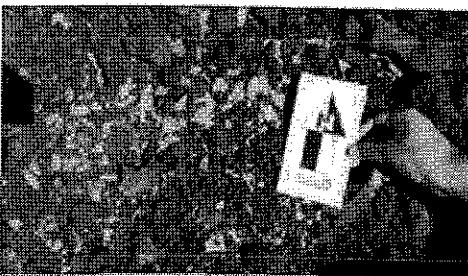
Granulite Xenoliths N 4814141 E 292355



Granulite xenoliths are present along the North Crater Trail. These xenoliths confirm that magma generation was occurring at greater depths. Since geologists assume granulite is the composition of the lower crust beneath the eastern Snake River Plain.

Rhyolite Chips N 4814033 E 292127

An area just off the North Crater Trail contains many chips of what appear to be rhyolite. These are presumed to be xenoliths; however, a larger source for the chips could not be located. Rhyolite xenoliths could represent the deposits associated with Yellowstone eruptions prior to the formation of the Craters of the Moon lava field. Conversely, these chips may be derived from the Challis Volcanic Group which surfaced during the Tertiary; however it is uncertain if Challis Volcanics can be this evolved. More thorough investigation of these chips is needed (photograph at top of right column).



Andesite Xenolith N 4813993 E 292070

Two xenoliths of possible andesite were collected off of the North Crater Trail. Although the Snake River Plain exhibits dominantly basaltic volcanism (trachyte and basalt only), the presence of intermediate volcanics has been noted at nearby Cedar Butte. Andesite xenoliths may reflect pockets of magma with varying composition due to higher amounts of crystal fractionation or may reflect an area beneath the Snake River Plain basalt which experienced a time of volcanism which created an intermediate composition. A third possibility is that these xenoliths represent underlying Challis volcanics. Since only two of these xenoliths have been found within Craters of the Moon, both have been collected for analyses, leaving collection localities marked by a prominent rock pile.



Spatter-capped Cinder Mounds N 4814022 E 291551



The presence of spatter-capped cinder cones (upper photograph) led to the identification of a previously unmapped eruptive fissure (lower photograph). The cinder mounds have been interpreted as part of the North Crater complex; however the spatter capping these mounds must indicate an eruptive fissure nearby. Presently, this fissure is filled in by the Big Crater Flow. For more information on this feature and other newly mapped features, please see the flow interpretation section.



Non-eruptive Fissures N 4813500 E 292345

A series of non-eruptive fissures have been identified on the west side of Big Craters. These fissures are parallel to, but offset from, the main eruptive vents for Big Craters. The largest and most prominent fissure is at least 35m long. This is the fissure mapped on the new 1:12,000 geologic map accompanying this publication. The non-eruptive fissures can be accessed easily from the Big Craters Trail.



Inferno Cone Vent N 4813145 E 291206



Many expect to find a vent at the top of Inferno Cone, but upon reaching the top, many are disappointed. The vent area for Inferno Cone lies to the south. As pyroclastics were emitted from the vent, the majority of the cinders were deposited to the north, although a smaller cinder cone was produced adjacent to the vent (right side of photograph). This may be due to strong winds blowing cinders to the north, an obstructed vent producing a fire hose effect, or a combination of both. The vent area is now filled in by the Blue Dragon Flow. To view this feature, park at the Spatter Cones then walk along the road back towards the top-road. Off-trail travel at the Spatter Cones is prohibited; please enjoy this feature from the roadside.

New Interpretation of the Geology in Proximity to the Visitor Center: Evidence for a Missing Cinder Cone and Refined Mapping of Volcanic Features

Tiffany A. Rivera, Shaina M. Kenna, and Douglas E. Owen

Refined Mapping of Volcanic Features

During the summer of 2007, detailed geologic field mapping of the area nearest the visitor center revealed several previously unmapped features and provided the opportunity to re-interpret the existing geology. Below is a description of our findings. For localities of these features, please refer to the accompanying geologic map and the Points of Interest section.

Two Eruptive Fissures and a Series of Non-eruptive Fissures

The two eruptive fissures were found cutting the western flank of North Crater cinder cone (Figure 1). The eastern of the two is now partially filled by the North Crater pahoehoe flow, while the western fissure is completely filled by the Big Craters ash-aren flow. The eastern fissure is along strike with the Big Craters fissure system suggesting that the North Crater cinder cone must be older than Big Craters. Identification of the western fissure was by recognizing spatter capped cinder mounds. As spatter represents the waning stages of eruption, the presence of spatter here must indicate a fissure nearby. Several non-eruptive fissures are located along the west side of Big Craters (Figure 1). Although these fissures are not part of the eruptive system, they are parallel to the main eruptive fissures.

Gravity Faults along Big Craters

Two gravity faults were recognized along the northwestern flank of Big Craters (Figure 1). The larger of the two stands out as it has been used as a game trail. The smaller mapped fault is topographically above the first; however it is less easily distinguishable. These features are nearly perpendicular to the fissure system and provide further evidence that slumping occurs along crater walls.

Eastward and Westward Extension of the Highway Flow

We recognized that the Highway Flow (an a'a block lava of trachyandesite with local pahoehoe) extends both east and west beyond what is currently mapped. Within the western lobe, platy pahoehoe is found in several areas. This feature is a result of internal friction at the base of the massive interior where the flow was unable to move naturally. Figure 2 shows the original mapping compared to more recent mapping.

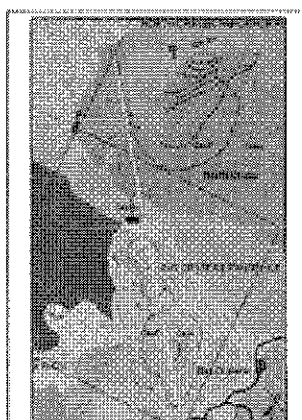


Figure 1. Newly mapped eruptive and non-eruptive fissures along the western flanks of North Crater and Big Craters cinder cones (left to right, exaggerated top map). White dashed line shows correlation between Big Craters vent system and the western eruptive fissure along North Crater cinder cone. Newly mapped gravity fault is shown as white dashed line.

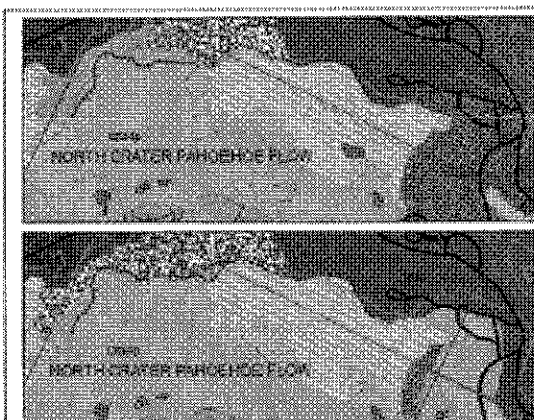


Figure 2. Upper map shows original interpretation of the Highway Flow. The block lava is shown as the red and white textured pattern in the upper part of the map and the pahoehoe section of the flow is shown as solid red extending to the east. Lower map shows new interpretation, including the extension of the Highway Flow both to the west and further to the east (symbolology same as upper map).

Evidence for a Missing Cone

Previous workers have speculated that a large cinder cone (named South Highway cinder cone) once existed between North Crater cinder cone, Highway US20, and the campground area. Recognition of a largely missing cinder cone agrees with work by Brosey, Jordan, and Champion (in press) showing the volume of material rafted from the North Crater cinder cone cannot be contained within the modern North Crater breach. These authors also collected paleomagnetic data from a South Highway cinder cone remnant on the north flank of North Crater cinder cone. Their data shows that these two cones may be coeval. The northern rim of South Highway cinder cone acted as a topographical boundary for the Highway Flow, diverting most of the flow eastward along the cone (Cress and Owen, 2005). This project further reinterprets the existing geology to reflect the locations of cone remnants and recreates a series of chronological events leading to the destruction of South Highway cinder cone. Figure 3 shows the location of South Highway cinder cone remnants.

•The campground hill area is the largest independent area of reinterpretation. This hill was previously mapped as a rafted block, as well as the cone remnant to the south. Inspection of these two areas show that loose cinders comprise the majority of these two areas. Extensive jostling occurs during rafting; it seems unlikely that such a large mass of loose cinders could have survived transport. The large amount of cinder material comprising these two areas leads us to believe that these rafted blocks are in situ pieces of the South Highway cinder cone wall (Figure 4).

•The rafted block in the North Crater pahoehoe flow has been reinterpreted as volcanic necks (Figure 5). These conduits may be one of several that contributed to the construction of South Highway cinder cone. This interpretation agrees with that of Mayo, 1994. This was the only rafted block lacking loose cinders to be reinterpreted as part of South Highway cinder cone.

•The area immediately south of the Highway block lava flow presented again an area with a large volume of cinders. Moreover, the physical distance between North Crater cinder cone and this area did not seem feasible when considering the average size of the cinder cones within the Monument. Additionally, the welded cinders in this area do not resemble the material comprising North Crater cinder cone, but resemble the material seen in the campground hill area. These differences suggest that this is a remnant of South Highway cinder cone.

•The area on the northern side of North Crater cinder cone (Figure 3) also resembles the welded cinder material comprising the other possible South Highway cinder cone remnants. It was along this flank that the paleomagnetic cores were sampled by Brosey, Jordan, and Champion (in press). Their data suggests that South Highway cinder cone was coeval with North Crater cinder cone. These workers may have been the first to recognize the potential for a missing cinder cone.

•The area of South Highway cinder cone is measured as a minimum of 1300m long by 500m wide. The nearby North Crater cinder cone measures 1300m long by 750m wide. Inferno cone, whose vent is south of the cone itself, has a footprint area of 1300m by 1000m. The largest cinder cone, Big Cinder Butte, has a measured footprint of 3000m by 1500m – nearly three times the size of South Highway cinder cone. The measured area of South Highway cinder cone is consistent with other cinder cones in the Craters of the Moon lava field, providing more evidence for its existence.

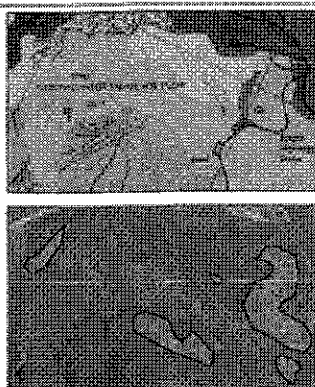


Figure 3. Map view and aerial interpretation of South Highway cinder cone remnants (in brown). The largest area for reinterpretation is in the foreground area. Paleomagnetic data was taken from the remnants on the northern side of North Crater cinder cone. Minimum length of South Highway cinder cone was measured from the western remnant to the easternmost. Width was measured from the area of paleomagnetic cores to the fault scarp.

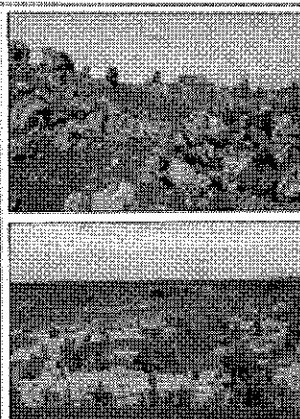


Figure 4. Reinterpretation of the foreground (top photograph) and large rafted blocks to the south (lower photograph, foreground) was based upon the extensive amount of loose cinder material comprising these previously mapped rafted blocks. Rafted blocks of welded cinders are visible in the background of the lower photograph.

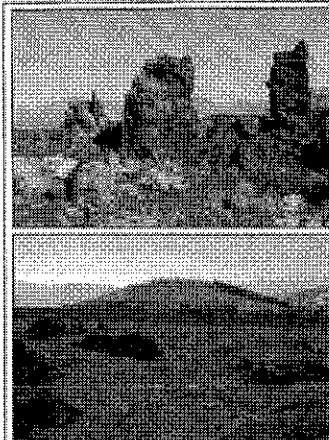


Figure 5. Previously mapped as rafted blocks, these monoliths (upper photograph) may be volcanic necks, or conchals, for the new largely missing South Highway cinder cone. The lower photograph shows rafted blocks composed of welded, rather than loose, cinders.

Sequence of Events

We present the following sequence of events from the creation to the destruction of South Highway cinder cone. This model is in partial agreement with one model proposed by Kunz, et al. (1962). We believe that these events all happened relatively close in time although the exact amount of time for these events to happen is not constrained. Detailed absolute dating analyses on the flows and cinder cones are needed in order to examine the amount of time required to construct and destroy a moderately sized cinder cone.

•Construct North Crater and South Highway cinder cones

•Construct Big Craters cinder cone

A newly mapped eruptive fissure suggests that Big Craters is younger than North Crater cinder cone. This is also supported by the Big Craters pahoehoe flow (Q566) overlapped onto the North Crater cinder cone. The amount of time by which Big Craters is younger has not been determined; however, we believe that these two cinder cones are relatively close in age (100 years or less).

•Eruption of Serrate and Devils Orchard Flows (not shown on map)

High silica flows capable of rafting away pieces of South Highway cinder cone. These flows most likely originated in the North Crater neighborhood although vent locations have not been found.

•Eruption of Highway Flow

Flow was channeled behind South Highway cinder cone; impingement against northern wall led to plety jointing.

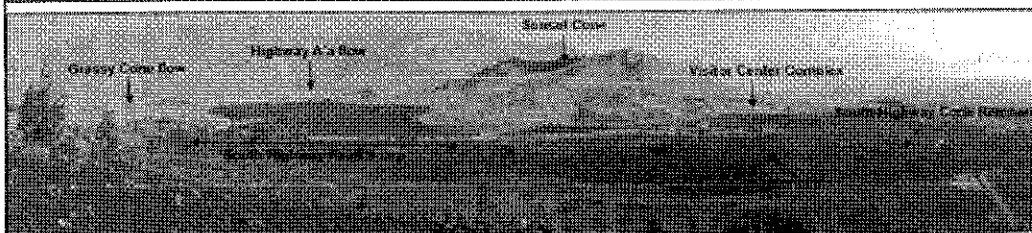
South Highway cinder cone and North Crater cinder cone began to be torn apart by the three flows mentioned above creating the rafted blocks shown throughout the Devils Orchard and Serrate Flows. Either the Serrate or Devils Orchard Flow breached the northwest flank of North Crater cinder cone.

Eruption of these high silica flows close in time emptied the underlying magma chamber, leaving a "hollow" cone.

The empty chamber collapsed back into itself, creating the South Highway fault scarp, and swallowing part of the South Highway cinder cone.

Collapse and addition of South Highway cinder cone material into the empty chamber led to the eruption of a lower silica North Crater pahoehoe flow from the previously breached wall of North Crater cinder cone.

North Crater pahoehoe flows from the previously breached crater wall of North Crater cinder cone, flowed around rafted blocks of North Crater and South Highway cinder cones, partially covered Serrate and Devils Orchard flows, and buried remaining evidence for the South Highway cinder cone.



Panoramic view across the North Crater pahoehoe flow taken from North Crater cinder cone

The Visitor Center area was first mapped by M. A. Kunz et al. (1966) through a series of publications by the USGS. The USGS published four separate 1:24,000 geologic maps that covered the northern portion of the Craters of the Moon lava field. These four quadrangles (10Q-1033, 1033, 1034, 1035) spanned to cover the boundaries of Craters of the Moon National Monument and Preserve. Detailed mapping of the visitor center area was undertaken by Tiffany A. Rivera, Shaina M. Owens, and Douglas S. Owen during the summer of 2007 as a continuation of the detailed Great Rift mapping that took place the previous three summers. The 1:12,000 map of the visitor center area will provide a more refined understanding of the volcanic history of the region. In addition, two pages highlighting points of geologic interest and three pages on reinterpretation were published in the summer of 2007. This detailed descriptions with photos will allow visitors to conveniently locate and visit unique geologic features. The reinterpretation contributes to the understanding of the construction and destruction of cinder cones, events that have not been witnessed in recent history at Craters of the Moon.

ACKNOWLEDGEMENTS

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REFERENCES

- Brossey, C.C., Jordan, B.T., and Champion, D.E., in press, Reconstructing a breached cinder cone at Craters of the Moon National Monument: A geographic information systems approach, *in* Hughes, S., Orr B., Freiberg, D., and Boyack, D., eds., *Proceedings of the Great Rift Science Symposium*, Pocatello, Idaho, October 2005.
- Brufet, B.R. and Chemtob, S.M., 2007, Geologic map of Echo Crater area: scale 1:12,000.
http://www.nps.gov/crmo/naturescience/upload/geomap_final_web.pdf
<http://www.nps.gov/crmo/naturescience/upload/echo%20legend.pdf>
http://www.nps.gov/crmo/naturescience/upload/geomap_final_web.pdf
- Caress, M.E. and Owen, D.E., 2005, The Highway Flow in the Craters of the Moon lava field; a new interpretation of eruption history, *Eos Trans. AGU*, 86(52), Fall Meet. Suppl., Abstract V53B-1565.
- Kuntz, M.A., Champion, D.E., Spiker, E.C., Lefebvre, R.H., and McBroome, L.A., 1982, The Great Rift and the evolution of the Craters of the Moon lava fields, Idaho, *in* Bonnichsen, B. and Breckenridge, R.M., eds., *Cenozoic Geology of Idaho*: Idaho Bureau of Mines and Geology Bulletin 26, p. 423-437.
- Kuntz, M.A., Lefebvre, R.H., Champion, D.E., Skipp, B.A., 1989a, Geologic map of the Inferno Cone quadrangle, Butte County, ID: U.S. Geological Survey Quadrangle Map GQ-1632, scale 1:24,000.
- Malay, T.S., 1994, *Field geology illustrated*, 2nd ed.: Mineral Land Publications, Boise, Idaho, 704p.
- McCurry, M., Hackett, W.R., and Hayden, K., 1999, Cedar Butte and cogenetic Quaternary rhyolite domes of the eastern Snake River Plain, *in* Hughes, S.S. and Thackray, G.D., eds., *Guidebook to the Geology of Eastern Idaho*: Idaho Museum of Natural History, p. 169-179.
- Mirraugh, J.C., 1961, *Geology of Craters of the Moon National Monument, Idaho*: Moscow, University of Idaho, M.S. thesis, 99p.
- Wetherell, K. A., Clennon, R. P., Trull, K. E., and Hansen, N., 2005, Geologic map of the Broken Top area: scale 1:12,000.
http://www.nps.gov/crmo/naturescience/upload/new_nmap2.pdf
<http://www.nps.gov/crmo/naturescience/upload/legend.pdf>