

# RECONSTRUCTING A BREACHED CINDER CONE AT CRATERS OF THE MOON NATIONAL MONUMENT AND PRESERVE: A GEOGRAPHIC INFORMATION SYSTEMS APPROACH

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## ABSTRACT

North Crater is a breached basaltic cinder cone in the Pleistocene to Holocene Craters of the Moon lava field located within Craters of the Moon National Monument on the eastern Snake River Plain of southern Idaho. Large portions of the cone were rafted away by lava flows issuing from its base between about  $2,222 \pm 100$  and  $2,400 \pm 300$  years ago. The volume of cone material rafted from North Crater was documented utilizing a Geographic Information Systems (GIS) approach and far exceeds the volume which the breach in North Crater can contain. The breach in the northwest side of North Crater has a volume of only  $1.23 \times 10^6 \text{ m}^3$ . Putting the  $46 \times 10^6 \text{ m}^3$  of rafted material back onto the current North Crater edifice would create a paleo-North Crater with a volume of  $88 \times 10^6 \text{ m}^3$ , requiring a footprint area of  $1.52 \times 10^6 \text{ m}^2$ , a radius of 700 m, and a height of 175 m. It is possible, however, that one large, monogenetic paleo-North Crater that size

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never existed. An alternative model is that a series of smaller paleo-North Craters were built at this location and destroyed by eruptions causing block rafting, the last of these being the existing, breached North Crater.

## **INTRODUCTION:**

### **Geologic Setting:**

Craters of the Moon National Monument and Preserve (CMNMP) is situated along the Great Rift, an 85 km-long, 2 to 8 km-wide volcanic rift zone in the eastern Snake River Plain of southern Idaho (Kuntz and others, 1986; Pierce and Morgan, 1992). The Great Rift has produced the Kings Bowl, Wapi, and Craters of the Moon lava fields (Kuntz and others, 1986). The latest Pleistocene to Holocene Craters of the Moon (COM) lava field comprises 8 eruptive fissure systems, 25 cinder cones, and more than 60 lava flows covering  $\sim 1,600 \text{ km}^2$  (Kuntz and others, 1986).

North Crater is a breached basaltic cinder cone in the northern portion of Craters of the Moon lava field (Kuntz and others, 1986). Five lava flows, the Highway, Devils Orchard, Serrate, Big Craters Northeast ( $2,400 \pm 300 \text{ yrs B.P.}$ ), and North Crater flows ( $< 2,205 \pm 25 \text{ yrs B.P.}$ ), erupted from vents within, or nearby, North Crater (see Fig. 1) (Kuntz and others, 1989). Three of these flows, the Highway, Devils Orchard, and Serrate flows, are particularly high in silica (54–64 wt%), and are properly classified as basaltic-trachyandesite to trachyandesite (for a complete discussion of the chemistry of COM lava flows see Kuntz and others, 1986). They erupted violently as viscous block/a'a flows that damaged the northwest side of the cinder cone. These flows carried rafted blocks, pieces

of bedded and oxidized spatter, agglutinated cinders, and ash from North Crater, as far as 13 km to the northeast.

Rafted blocks are often tens of meters in width and length and up to ~17 m high. As rafted blocks were carried by lava flows, they broke up into smaller pieces and became incorporated into the transporting flow. The results are lava flows with large patches of agglomerated cinders, jagged chunks of spatter, and rarely small patches of ash and cinders. In some locations, as much as 100% of the surface of the lava flow is blanketed by a layer of disaggregated rafted blocks. More commonly, the transporting lava flow contains domains where 30-50% of the lava flow is covered with disaggregated rafted blocks from North Crater. Later, younger pahoehoe flows buried many of the domains of disaggregated rafted blocks. Only the largest and most coherent blocks, which poke through the younger lava flows, are easily seen.

The volume of the material rafted from North Crater can be approximated by summing the volumes of exposed rafted blocks. The depth below the surface that partially buried blocks extend can only be estimated. Where the rafted blocks maintained a discrete form as they rafted, generating a volume calculation is relatively simple. Also, an unknown number of blocks have been partially or fully buried by as many as four later flows, depending on location. Since there is no way to estimate the volume of rafted blocks that are buried by lava flows, any calculation of the volume of material rafted from North Crater is a minimum estimate.

### **Previous Studies:**

Other than the geologic maps produced by Kuntz and others (1989), little work has been done to describe the block rafting events at COMNMP. Rafted volcanic blocks have been described in detail in only a few other locations (Foshag and Gonzalez, 1956; Simons and others, 1966). Harwood (1989) and Riggs et al. (2004) conducted the most detailed studies to date on breached cinder cones in the San Francisco volcanic field of north central Arizona.

### **METHODS:**

#### **Sub-Aerial Volumes of Discrete Blocks:**

By combining data on the block dimensions collected in the field with a 2002 National Park Service inventory of rafted blocks and digitized USGS geologic maps viewed in ArcView 3.2a (ESRI, 1999), we calculated the volume of discrete, coherent rafted blocks greater than 30 m<sup>2</sup> in area. The maximum height, typical width, and typical length of each block were multiplied together and the sub-aerial volumes of all the blocks were then summed.

#### **Sub-Aerial Volumes of Disaggregated Blocks: The Domain Approach**

The volumes of disaggregated blocks were also determined using ArcView 3.2a (ESRI, 1999). Domains of varying percentages of rafted material were identified by examining stereo air photos and delineated on digitized air photos in ArcView 3.2a (see

Fig. 2). The percent rafted material in each domain was estimated after careful examination of stereo air photos and review of field notes. Domains covered by younger flows were assigned percentages of rafted material from the most appropriate nearby domain.

We developed a method to add up all the disaggregated cone material, creating an equivalent area that the disaggregated cone material would occupy if it were all put back into a coherent block. By multiplying the area of a domain, the percent of rafted material within it, and the maximum height of blocks in the domain together, the total above surface volume can be determined. The sub-surface volume is accounted for by multiplying by a correction factor for the coherent block roots determined in the density analysis discussed below.

### **Sub-surface Volumes: Correction Factor for Sub-surface Roots of Blocks**

We adopted a model where the transporting block/a'a lava flow was viscous enough to retard the isostatic rebound forces generated by the reduction in the block mass from disaggregation. This leaves a block root buried at some depth beneath the surface of the flow (see Fig. 3). By comparing the specific gravities of the transporting trachyandesite a'a lava and the rafted block material, the depth to which the blocks sink in the transporting flow (like the isostasy of icebergs floating in the ocean) can be determined and a complete volume can be calculated. The total volume of rafted material ( $V_t$ ) can be determined from the volume of exposed rafted material ( $V_e$ ) and the densities of the transporting lava ( $\rho_{lava}$ ) and rafted blocks ( $\rho_{block}$ ) based on the following equation:

$$V_t = \frac{\rho_{lava} \times V_e}{\rho_{lava} - \rho_{block}} \quad (1)$$

The densities of the Devil's Orchard and Serrate transporting flows were calculated by using major-element analysis data from Kuntz and others (1985) in MAGMA software (Wohletz, 2002).

### **Volume, Area, and Height Relationships:**

In order to relate the calculated volume of paleo-North Crater to its footprint area and height, we examined the relationships between these parameters for eight relatively symmetrical cinder cones in the COM lava field. Ten meter USGS digital elevation models were used for this analysis in ArcView 3.2a with the Mila Grid Utilities and Xtools extensions.

### **RESULTS:**

Based on the methods described above, the volume of rafted material above the surface was calculated to be  $21 \times 10^6 \text{ m}^3$ . We calculated the average specific gravity of the rafted blocks to be  $1.42 \text{ g/cm}^3$  and estimated, from major element analysis of the lava flows (Kuntz and others, 1985) and MAGMA software, that the density of the Serrate and Devil's Orchard lava flows ranges between  $2.59$  and  $2.82 \text{ g/cm}^3$ . Plugging these numbers into equation 1 shows the ratio of total volume of rafted material to volume of rafted material exposed at the surface ranges between 2.01 and 2.21. Multiplying by the correction factor of 2.11 (the average of the two end-members) recovers the subsurface rafted material and gives the total rafted material:  $46 \times 10^6 \text{ m}^3$ . Using the relation between cone footprint area and cone volume, as well as the current volume of North Crater, we

determined that the breach in the northwest side of North Crater is only  $1.23 \times 10^6 \text{ m}^3$ . Our calculations show there is over 38 times more rafted material than fits back into the hole in North Crater. Putting the  $46 \times 10^6 \text{ m}^3$  of rafted material back onto the current North Crater would create a paleo-North Crater with a volume of  $88 \times 10^6 \text{ m}^3$ , a footprint area of  $1.52 \times 10^6 \text{ m}^2$ , a radius of 697 m, and a height of 175 m.

### **Uncertainty:**

Despite any errors which may have resulted in overestimation of the amount of rafted material (in particular rafted block densities too high and percent rafted material in domains too great), the total volume of rafted material calculated is probably still a minimum. Perhaps as much as half the area which could contain rafted blocks is covered by younger lava flows that obscure any rafted blocks which may be there. Due to inadequate air photo coverage, almost a third of the area which could contain rafted blocks remains unanalyzed.

### **DISCUSSION:**

The reconstruction of North Crater presented above results in a paleo-North Crater that is substantially bigger than the current North Crater, ~60 m higher with a radius nearly 200 m larger. The large size of this paleo-North Crater is reasonable based on several observations. First, cinder cones of this size exist today in the lava field. Paleo-North Crater would have been approximately the size of modern Big Cinder Butte, 4 km to the south of North Crater. Second, there are pyroclastics which may be insitu lower

flanks of a paleo-North Crater near the highway to the north, and near the campground to the northeast of North Crater (D. Owen and M. Kuntz, personal communication). If these represent the northern-most extent of a paleo-North Crater's footprint, and the current North Crater marks the southern extent, then the calculated paleo-North Crater with a radius of ~700 m fits quite well.

An alternative explanation to the large, monogenetic cone model is the possible presence of other, smaller monogenetic cinder cones that were completely rafted away (Caress and Owen, 2005). The apparent insitu cone deposits near the highway and campground may be remnants of possible neighbors to North Crater. These cones may have been parasitic or flank cones, having the same or different magma chamber and plumbing system as North Crater. Confirmation of these cones' existence is difficult because lava flows from North Crater or other younger vents may have rafted them away and buried any evidence. However, recent paleomagnetic studies of the northeast side of North Crater may support the existence of now absent neighboring cinder cones. Paleomagnetic data shows that a flat bench previously considered to be either a slumped section of North Crater or a large rafted block has the same orientation as the rest of North Crater and has not rotated to the west or east at all as a slump or rafted block might. That is, the bench could be the insitu margin of a former neighbor of North Crater that formed at nearly same time as North Crater.

Another explanation is provided by Foshag and Gonzalez (1956). They observed the development, destruction, and subsequent reconstruction of cinder cones throughout the early eruptive phases of the Parícutin volcano in Mexico. This repeated breaching and repair of cinder cone walls could generate substantially more material than would fit in

the existing hole in North Crater. The presence of rafted blocks within two distinct lava flows (the Devil's Orchard and Serrate flows) suggests that at least two distinct periods of block rafting, and probably cone breaching and repair, took place. Instead of paleo-North Crater being one large, monogenetic cone, several smaller paleo-North Craters, perhaps similar in size to the present one, may have formed in the same location and been nearly completely destroyed.

### **Suggestions for Future Work**

Close inspection of the contact relations between the lava flows issuing from North Crater might offer more clues as to the timing of the rafting events. Further investigation of how deep disaggregated material lies under the surface of transporting flows would be helpful in refining the certainty of volume calculations. Inquiry into the composition of transporting flows in locations where they contain rafted blocks would help assign the lavas more accurate densities and methods to determine the yield stress the blocks needed to overcome to sink into the transporting flow would further improve the analysis.

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Figure 1: Map showing the location of North Crater in relation to the Craters of the Moon National Monument visitor center, Highway 20/26/93, and related lava flows.

Figure 2: Map showing location of domains containing rafted blocks and disaggregated rafted material and related lava flows.

Figure 3: Schematic showing the above and below ground volumes of a rafted block.

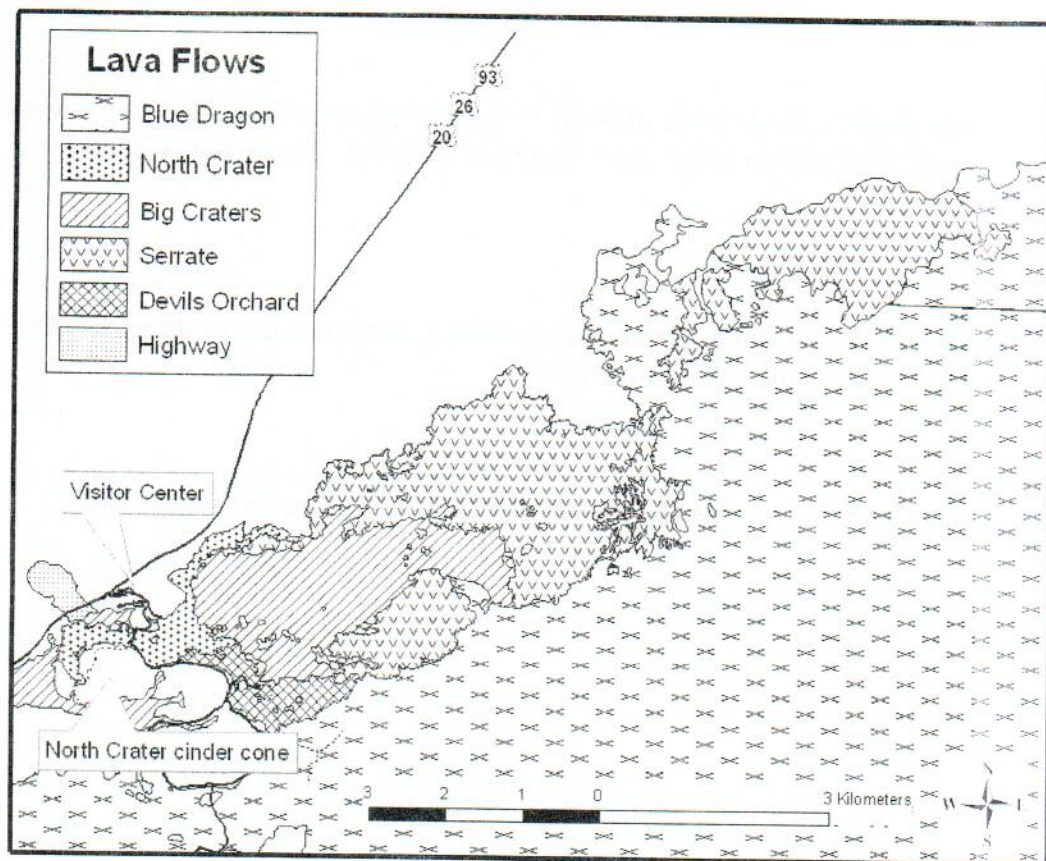


Fig.1

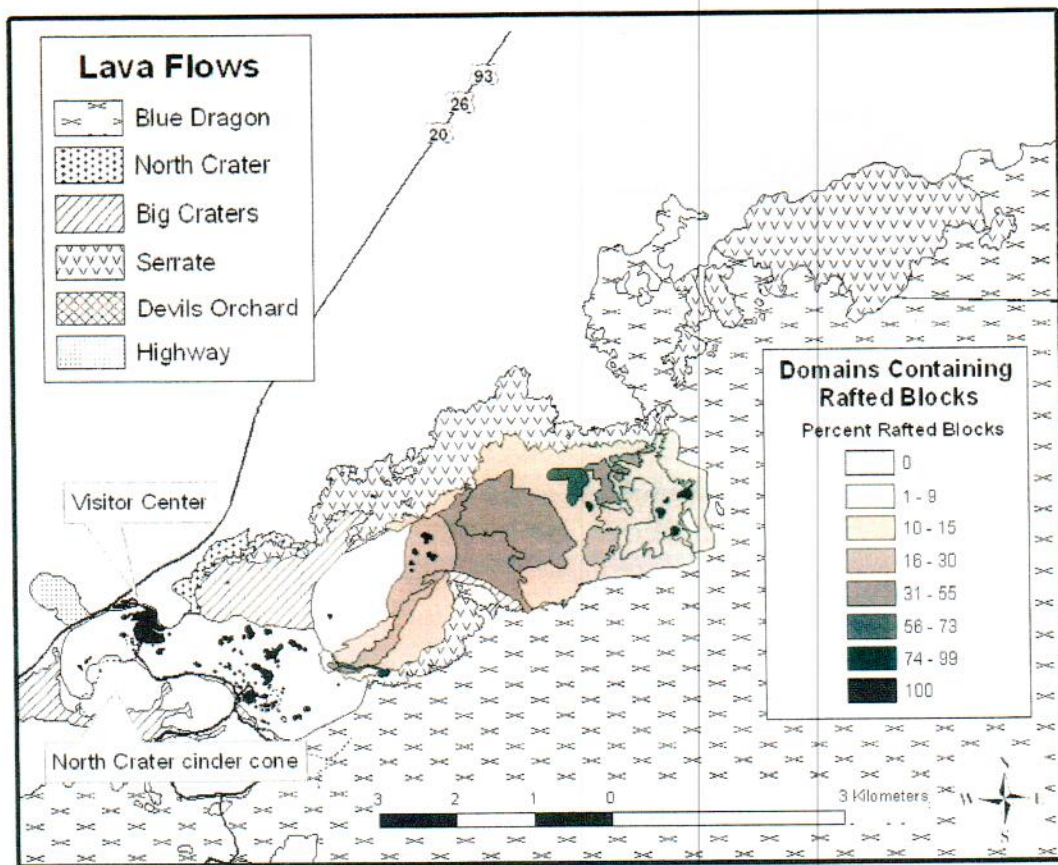


Fig 2

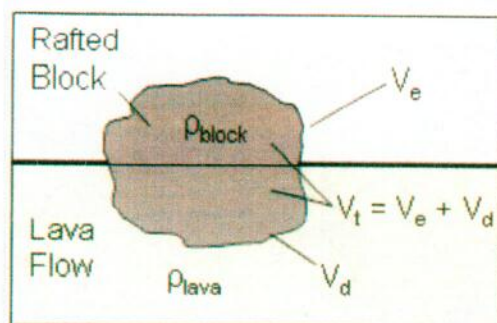


fig 3