

**A GEOGRAPHIC INFORMATION SYSTEMS APPROACH TO CINDER CONE
RECONSTRUCTION AT CRATERS OF THE MOON NATIONAL MONUMENT**

by:

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A GEOGRAPHIC INFORMATION SYSTEMS APPROACH TO CINDER CONE RECONSTRUCTION AT CRATERS OF THE MOON NATIONAL MONUMENT

ABSTRACT

North Crater is a breached basaltic cinder cone in the Pleistocene to Holocene Craters of the Moon lava field within Craters of the Moon National Monument in the eastern Snake River Plain of southern Idaho. North Crater is composed of bedded spatter, agglutinated cinders, and ash. Large portions of the cone were rafted away by lava flows issuing from its base between about 4000 and 2100 years ago. Utilizing a Geographic Information Systems (GIS) approach, the volume of cone material rafted from North Crater was documented and far exceeds the volume which the breach in North Crater can contain. The breach in the northwest side of North Crater is 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 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 700 m, and a height of 175 m. It is possible, however, that one large, monogenetic paleo-North Crater that size never existed. An alternative model is that several smaller paleo-North Craters were built, destroyed by eruptions causing block rafting, and rebuilt at this location.

INTRODUCTION:

The research presented in this thesis was undertaken as part of a project to construct an interpretive poster for Craters of the Moon National Monument (COMNM). The interpretive poster will describe the geology of North Crater Cinder Cone both before and after a series of eruptions broke up the cone and rafted large portions away. The poster will discuss the processes controlling the rafting of volcanic blocks in lava flows. North Crater is easily viewed from the monument visitor center and many visitors hike up a trail along its north flank. Visitors who drive the loop road, and who stop at the Devil's Orchard parking area, cannot help but see rafted blocks from North Crater.

Geologic Setting:

The Snake River Plain (SRP) is a curved topographic depression 50-100 km wide stretching for over 600 km across southern Idaho (Kuntz and others, 1986; Pierce and Morgan, 1992) (see Fig. 1).

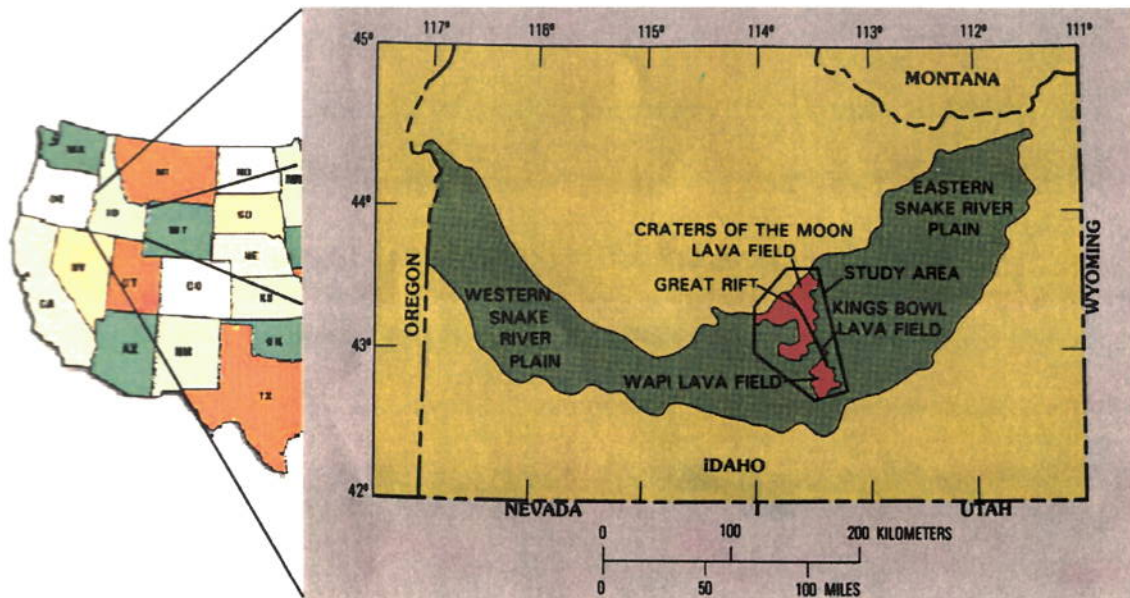


Figure 1: Map of southern Idaho showing the Snake River Plane and Craters of the Moon National Monument

The Plain is bordered on the southwest by the Owyhee Plateau. The eastern and central SRP are bordered on the northwest and southwest by block faulted mountains caused by Cenozoic Basin and Range extension. The western SRP is actually a Basin and Range graben. Some of the central SRP also abuts Mesozoic to lower Tertiary intrusives of the Idaho Batholith to the north. The eastern SRP is floored by silicic calderas covered by Pleistocene to Holocene basaltic lava flows as well as interbedded discontinuous loess, eolian sand, and alluvium (Pierce and Morgan, 1992; Kuntz and others, 1986). The northeast margin of the Plain is flanked by upper Tertiary and Quaternary rhyolites and basalts of the Yellowstone Plateau. Silicic calderas of the SRP are part of an age progression of volcanism over the past 16 Ma from near the Idaho-Oregon-Nevada border to its current location at Yellowstone in northwest Wyoming (Pierce and Morgan, 1992; Smith and Braile, 1993). Many workers believe that the eastern SRP is a result of plate motion over the Yellowstone hotspot, widely interpreted as a mantle plume.

Craters of the Moon National Monument is situated along the Great Rift, an 85 km long, 2 to 8 km wide volcanic rift zone in the eastern SRP (Kuntz and others, 1986). The latest Pleistocene to Holocene Craters of the Moon (COM) lava field is one of three basaltic lava fields within Craters of the Moon National Monument managed cooperatively between the Bureau of Land Management (BLM) and the National Park Service (NPS) (see Fig. 2). The 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).

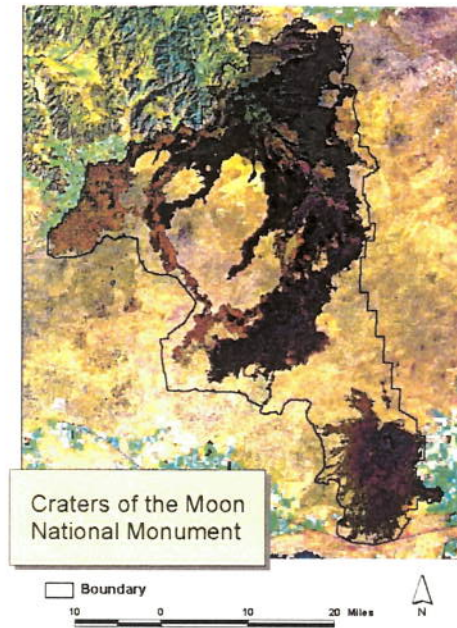


Figure 2: LANDSAT satellite image of Craters of the Moon National Monument showing the Wapi, Kings Bowl and Craters of the Moon lava flows.

COM lava flows are described as iron-, alkali-, and phosphorous-rich basalts to latites in Cox and others' (1979) terminology, and to alkaline basalts in Irvine and Baragar's (1971), and Macdonald and Katsura's (1964) terminology. Total silica ranges from 44.4 to 63.8 wt. %. For a complete discussion of the chemistry of COM lava flows see Kuntz and others (1986).

North Crater is a breached basaltic cinder cone in the northern portions of Craters of the Moon basaltic lava field (Kuntz and others, 1986) (see Fig 3). It is composed of bedded and oxidized, spatter, agglutinated cinders, and ash (see Fig. 4). The northwestern portion of the cone was breached and large portions were rafted away on lava flows flowing to the east. The most recent lava flows from North Crater began about 4000 yrs ago and ceased 2076 ± 45 years ago (Kuntz and others, 1989).

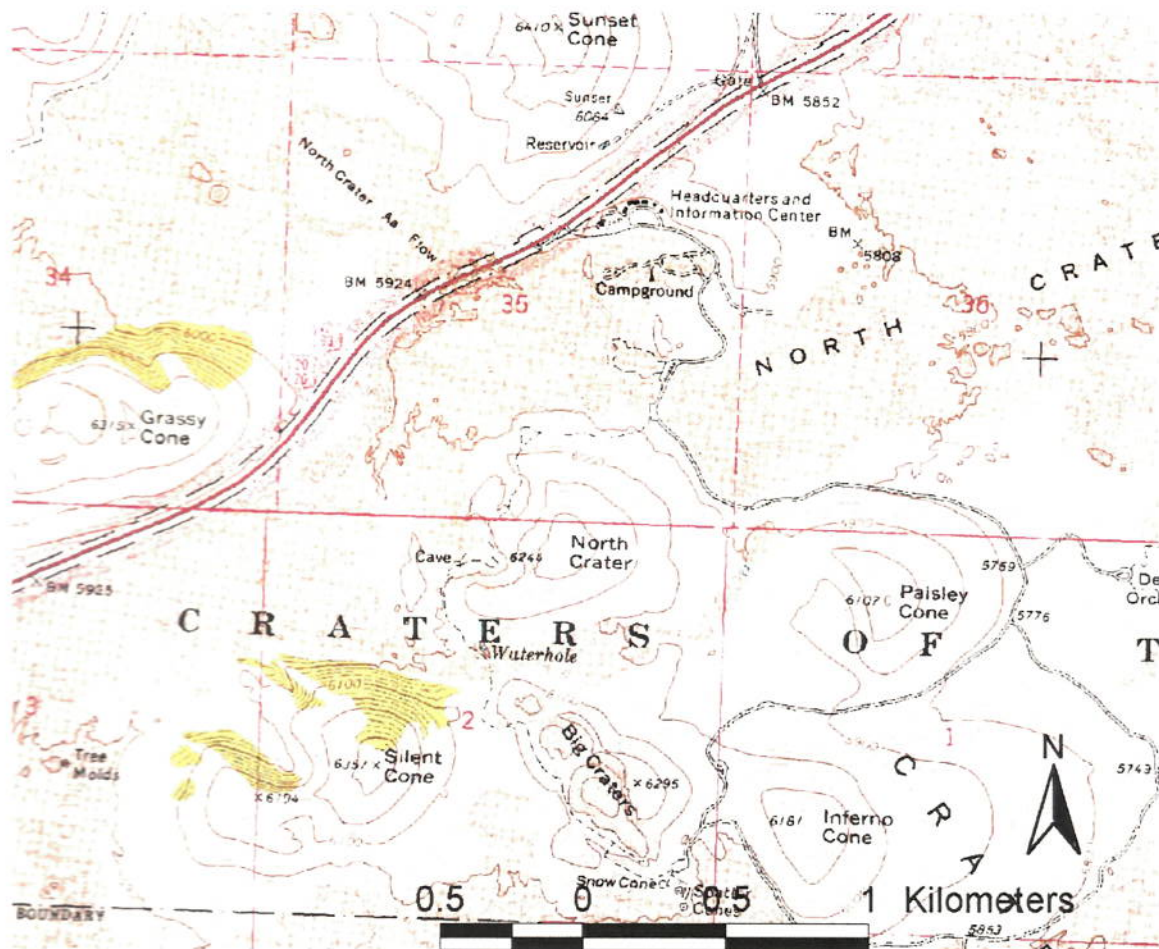


Figure 3: Portion of USGS 7.5 minute Inferno Cone Quadrangle map showing location of North Crater.

The Highway flow is the oldest lava flow to issue from North Crater. It may have rafted away pieces of North Crater which are presently buried by younger flows. The Devil's Orchard flow is the second oldest lava flow from North Crater to contain rafted material and it is presumed to be the first flow to transport substantial amounts of material from the cone. Stratigraphic relations between the Highway flow, rafted blocks, and more recent flows are difficult to determine in many places, especially near the campground and amphitheater. The Serrate flow contains the most rafted material.



Figure 4: View of North Crater looking into the breach from the northwest. Photo taken from Highway 93 at the base of Grassy Cone.

It rafted blocks nearly eight kilometers eastward from North Crater, many of which have begun to disaggregate.

The National Park Service is particularly interested in the size of North Crater prior to cone breach and the rafting of cone material by lava flows. An approximation of volume of the material rafted from North Crater can be made by adding up the volumes of rafted blocks. However, a number of complications arise in determining this calculation. 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. However, in some areas blocks have broken up as they were transported, creating domains of disaggregated rafted material that have been largely incorporated into the transporting Serrate Flow. An unknown number of blocks have been partially or fully buried by as many as four later flows, depending on location. Methods to determine the depth to which blocks extend below the surface and determine the amount of rafted material in disaggregated domains were devised. 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 likely 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 COMNM. Several authors working in other areas have described rafted volcanic blocks related to breached cinder cones but offer little insight into the details involved in their transport (Foshag and Gonzalez, 1956; Simons and others, 1966). The notable exception is Harwood (1989), who studied breached cinder cones in the San Francisco volcanic field of north central Arizona. He offers three models for cone breach, (1) lava lake model; (2) dike intrusion model; and (3) magma body intrusion model. Harwood (1989) also describes five local controls on breaching mechanisms: (1) local topographic stress regimes; (2) local fault/joint system control; (3) wind direction/cone strength; (4) vent location of breaching lava; and (5) substrate buttressing. Searches in the literature for methods of reconstructing breached cinder cones and estimating their pre-breach volume were unsuccessful.

METHODS:

Field Work:

During the summer of 2002, Glenn Mutti (NPS) mapped previously unmapped discrete rafted blocks larger than 30 m² in area proximal to North Crater using Global Positioning System (GPS) equipment (see Fig. 5). Among the characteristics he

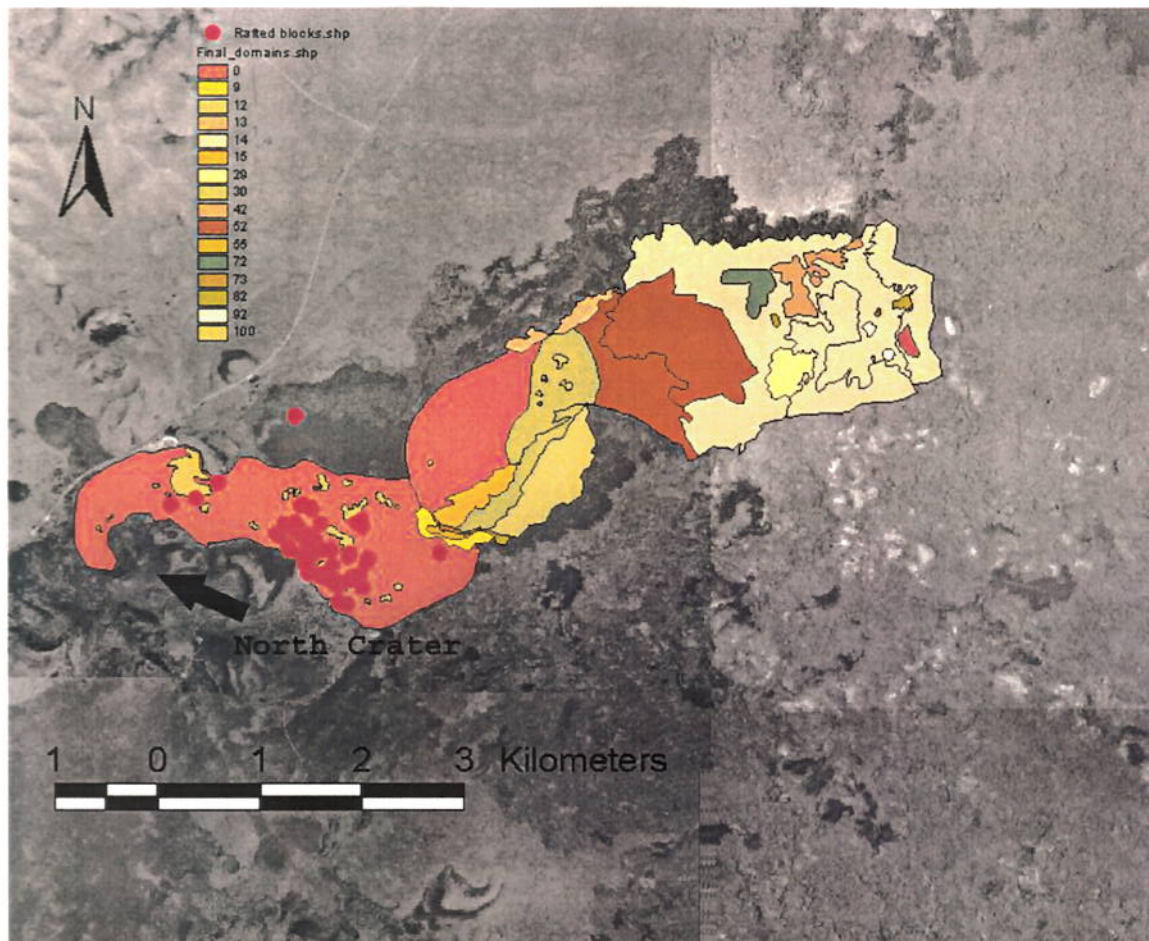


Figure 5: Digital photograph of the northern portion of COMNM. Black arrow shows location of North Crater, red dots denote discrete rafted blocks mapped by Glenn Mutti.

described were maximum height, typical width, and typical length. Lengths and widths were determined with a 30 m tape measure and height calculations were made using a clinometer, 30 m measuring tape and trigonometry. Length and width measurements included any small scree or talus slope that may have been present at the base of the block.

Also in the summer of 2002, I spent several days among the distal rafted blocks in the Serrate, Big Craters Northeast, and Blue Dragon lava flows. In these locations, blocks were rafted between three and seven kilometers from North Crater and had begun



Figure 6: Photo of disaggregated rafted blocks approximately 5 km from North Crater.

to disaggregate (see Fig. 6). The transporting a'a trachyandesite flow incorporated the disaggregating cinder cone material (see Fig. 7). Foot travel in these areas is quite precarious and slow, limiting the ease of fieldwork. 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 disaggregated rafted blocks from North Crater.

In the 1980s, the U.S. Geological Survey (USGS) mapped discrete representative blocks which had maintained their shape in these areas. I visited each block and measured its sub-aerial height for later volume calculations using a clinometer, tape



Figure 7: Photo of disaggregated rafted material approximately 7 km from North Crater. Leather Gloves (for scale) sit on agglutinated cinders and spatter.

measure and trigonometry. I recorded the area of each block from digitized geologic maps viewed ArcView (ESRI, 1999).

Lab Work:

Lab work was undertaken to determine the volume of the rafted blocks. Since block heights were gathered in the field, the area of each block was needed to determine its volume. Combining the volumes of all the rafted blocks would give a reasonable volume for a paleo-North Crater.

Discrete Blocks:

The volume of discrete rafted blocks which had not been disaggregated was calculated in a simple manner. The typical length, typical width and maximum height of each block were multiplied together. The volumes of all the blocks were then summed.

Disaggregated Blocks: The Domain Approach

The volumes of disaggregated blocks were determined with the help of ArcView (ESRI, 1999). Domains of varying percentages of rafted material were identified by examining stereo air photos and delineating the extent of the domain on digitized air photos in ArcView (see Fig. 8). 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, if one existed.

I 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 (see appendix 1). 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 the correction factor for the coherent block roots determined in the density analysis discussed below. Since an unknown amount of material is buried by younger flows, and lost within the transporting flow, any calculation will likely be a minimum.

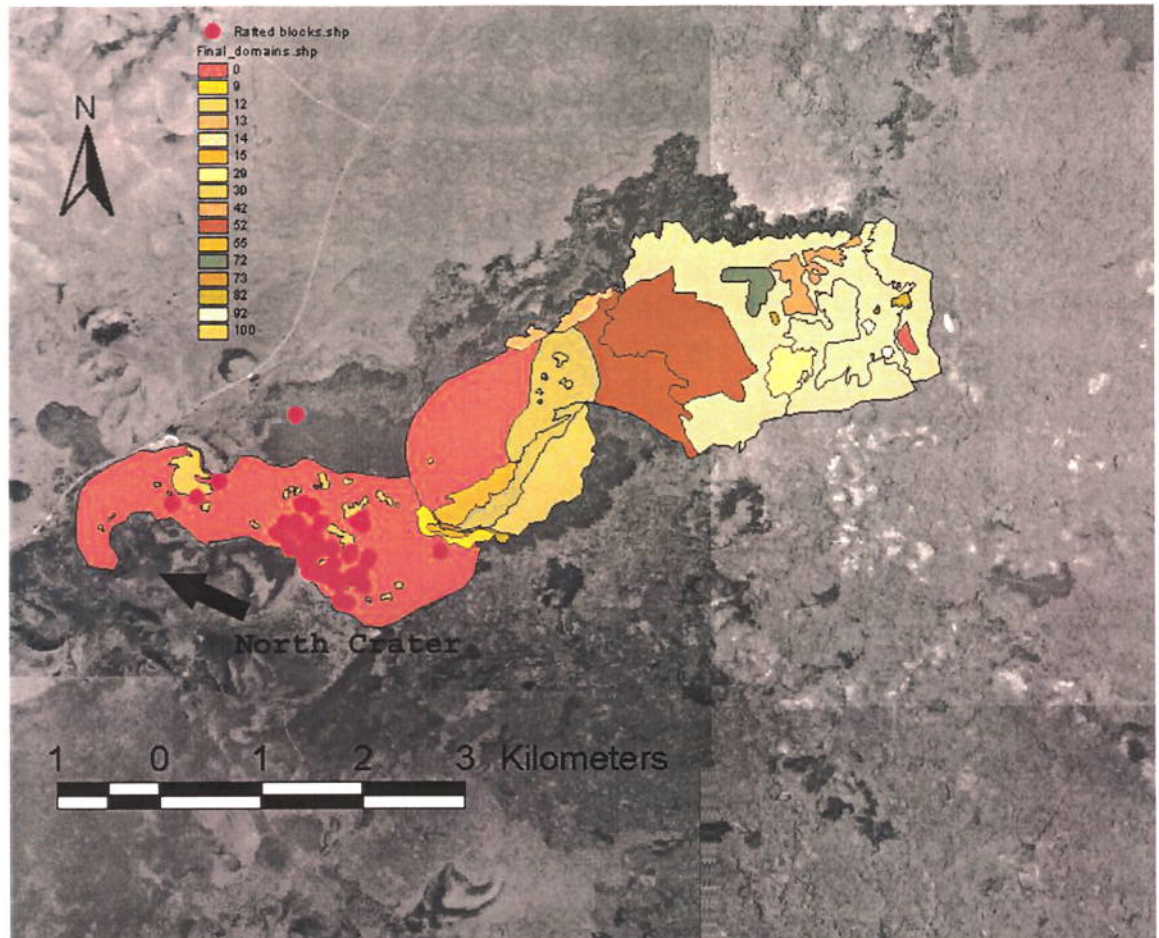


Figure 8: Digital photograph of the northern portion of COMNM. Black arrow shows location of North Crater, domains of rafted material shown as autumn colored polygons. Key shows percentages of rafted material for each domain.

Correction Factor for Sub-surface Roots of Blocks

There are two possibilities for the volume of subsurface blocks in disaggregated domains. The first is that there are no “roots” to the disaggregated blocks. As the blocks rafted and broke up, their mass decreased and they rose isostatically until they were completely disaggregated. In this scenario, there are no subsurface (>2 m deep) coherent rafted blocks; the entire block was broken up and partially incorporated into the transporting flow. The second possibility is that the transporting block a’la lava flow was viscous enough to retard the isostatic rebound forces generated by the reduction in the

block mass from disaggregation leaving a block “root” buried at some depth beneath the surface of the flow. This scenario is favored from field observations and implicit in the calculations described below.

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 (see Fig. 9). According to equation 1,

$[\rho_{lava} \div (\rho_{lava} - \rho_{block}) = (V_t \div V_e)]$ 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 (ρ_{lava}) and rafted blocks (ρ_{block}).

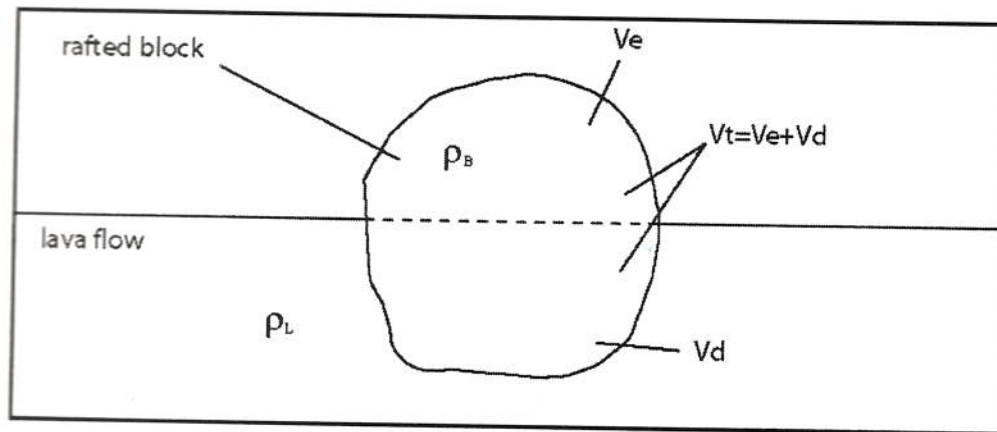


Figure 9: Sketch showing rafted block being transported by lava flow and block “roots” where ρ_B is density of rafted block, ρ_L is density of transporting lava flow, V_D is volume of the displaced lava, V_E is volume of exposed portion of block and V_T is total volume of rafted block.

I calculated the specific gravity of the rafted blocks by completely immersing samples in water and recording the volume change. The mass of the sample was divided by its volume. Samples were shrink wrapped to prevent water from entering the vesicles but this was only marginally successful. Nevertheless, I was able to correct for the water

trapped in the vesicles by reweighing the sample after immersion. 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).

Digital Elevation Models

In order to compare the calculated volume of a "paleo North Crater" to the volume of other cones at CRMO, the relationship between the area of a cone's footprint, its volume, and height were analyzed (see Fig. 10).

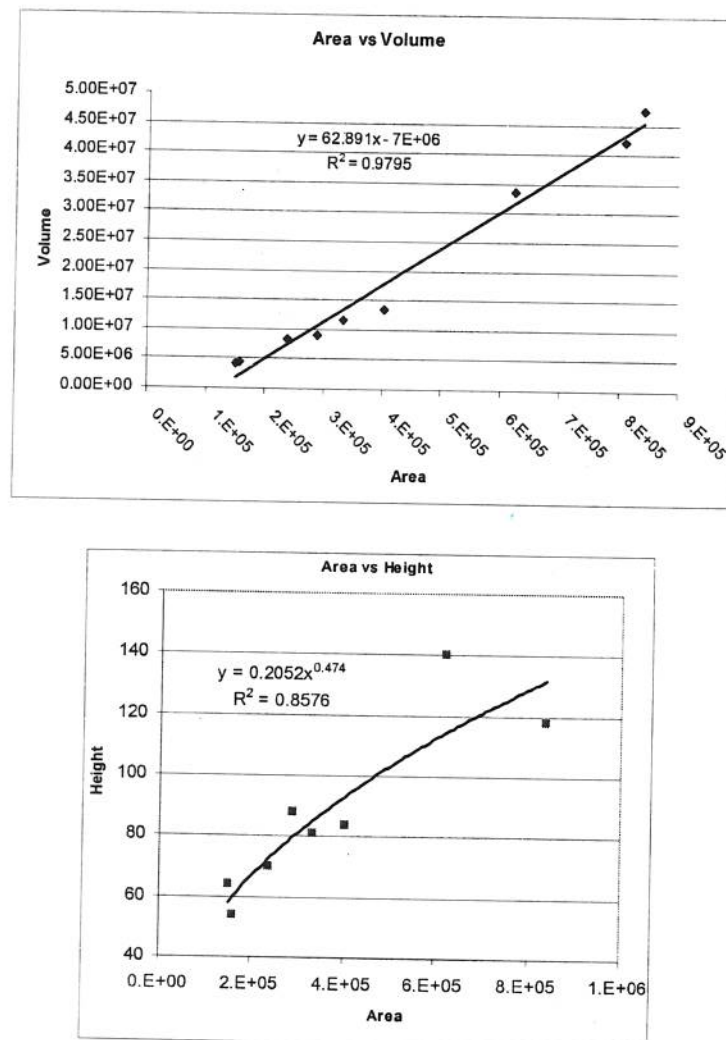


Figure 10: Graphs of Area vs Volume (above) and Area vs Height (below) from DEM analysis of intact cinder cones.

The models were also useful in determining the volume of the modern North Crater had its northwest side not been breached. Utilizing Mila Grid Utilities and Xtools extensions in ArcView (ESRI, 1999) and ten meter grid USGS Digital Elevation Models (DEMs), I examined eight fairly symmetrical un-breached cinder cones within Craters of the Moon lava field. Data analysis was completed in Microsoft Excel.

RESULTS:

Based on the methods described above the volume of rafted material above the surface was calculated to be $21 \times 10^6 \text{ m}^3$ (see appendix 1 for calculations). Consideration of the density analysis and correction factor for subsurface "roots" gives a more complete picture of the volume of rafted material.

I calculated the average specific gravity of the rafted blocks to be 1.42 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 flows ranges between 2.59 and 2.82 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 2.15 (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, I determined that the breach in the northwest side of North Crater is only $1.23 \times 10^6 \text{ m}^3$. My 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.

Error

Little is known about the timing of rafting during a lava flow. During a rafting event, most of the material is likely to be transported early in the history of the flow and moved far from the crater. This cannot be confirmed since the transporting flows proximal to the crater have been buried by the later North Crater and Big Craters Northeast flows and they cannot be compared to the exposed distal portions. However, it is safe to say that the distal portions of the Serrate flow contain high percentages of rafted material. Also, an unknown amount of the Serrate flow containing rafted material is buried by the Blue Dragon Flow. Rafted blocks poke through the Blue Dragon Flow more than a kilometer to the east of the easternmost extent of the Serrate Flow (see Fig. 11).

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 value 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 which obscure any rafted blocks which may be there.

DISCUSSION:

The reconstruction of North Crater presented above results in a paleo-North Crater that is substantially bigger, 40 m higher with a radius nearly 200 m larger, than the current North Crater. The large size of this paleo-North Crater is reasonable based on

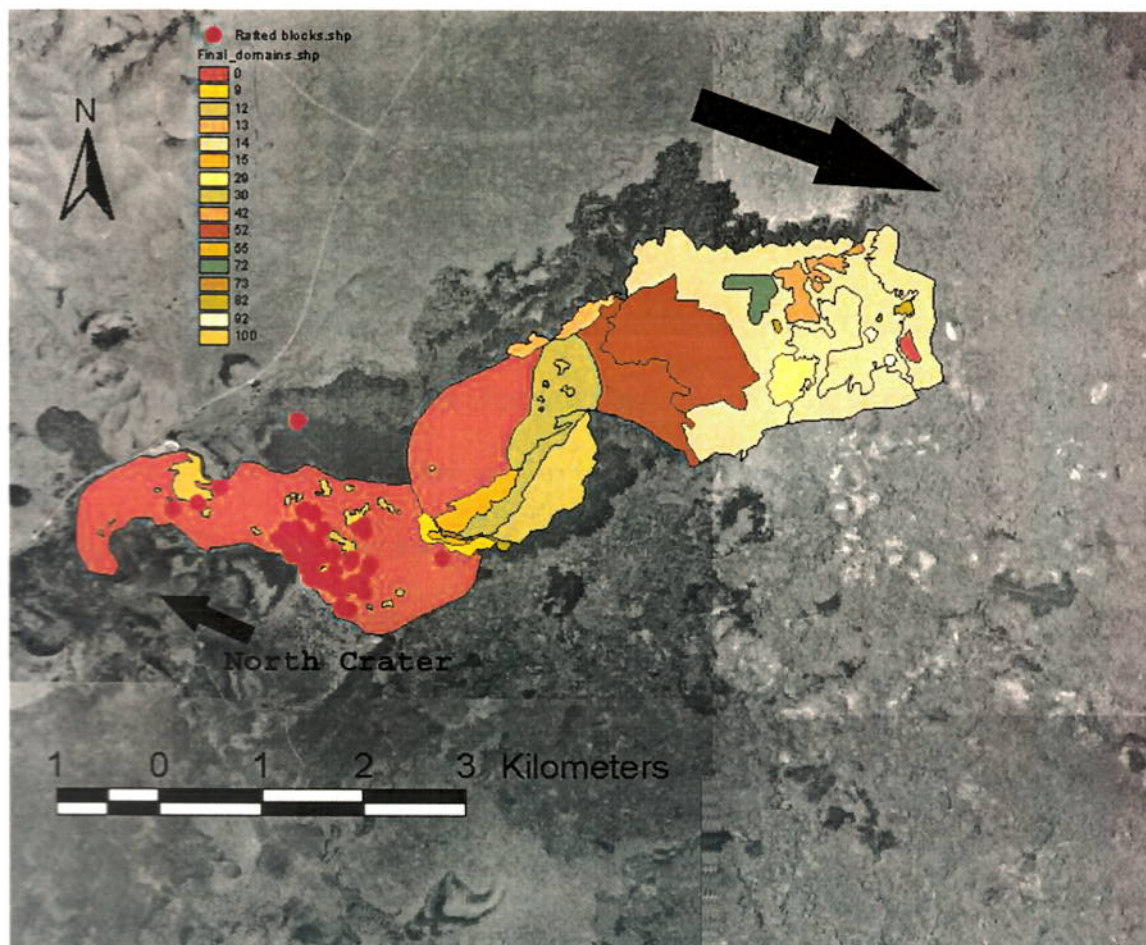


Figure 11: Digital photograph of the northern portion of COMNM. Black arrow shows location of North Crater, domains of rafted material shown as autumn colored polygons. Key shows percentages of rafted material for each domain. Large arrow shows location of rafted blocks nearly covered by Blue Dragon flow.

several observations. First, cinder cones of this size exist today in the lava field. For example, paleo-North Crater would have been approximately the size of Big Cinder Butte 4 km to the south of North Crater. Second, there are pyroclastics which may be insitu flanks of a paleo-North Crater near the highway to the north, and the campground to the northeast of North Crater (D. Owen and M. Kuntz, personal communication) (see Fig. 12). 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.

Field observations suggested that there is more than enough rafted material present throughout the Devil's Orchard, Serrate, Big Craters Northeast, and North Crater lava flows to fill the hole in the northwest flank of North Crater. Quantitative analysis has confirmed this speculation. An alternative explanation to the large, monogenetic cone model is the presence of other, smaller monogenetic cinder cones that were rafted away. These cones may have been parasitic or flank cones, having the same magma chamber and plumbing system as North Crater.

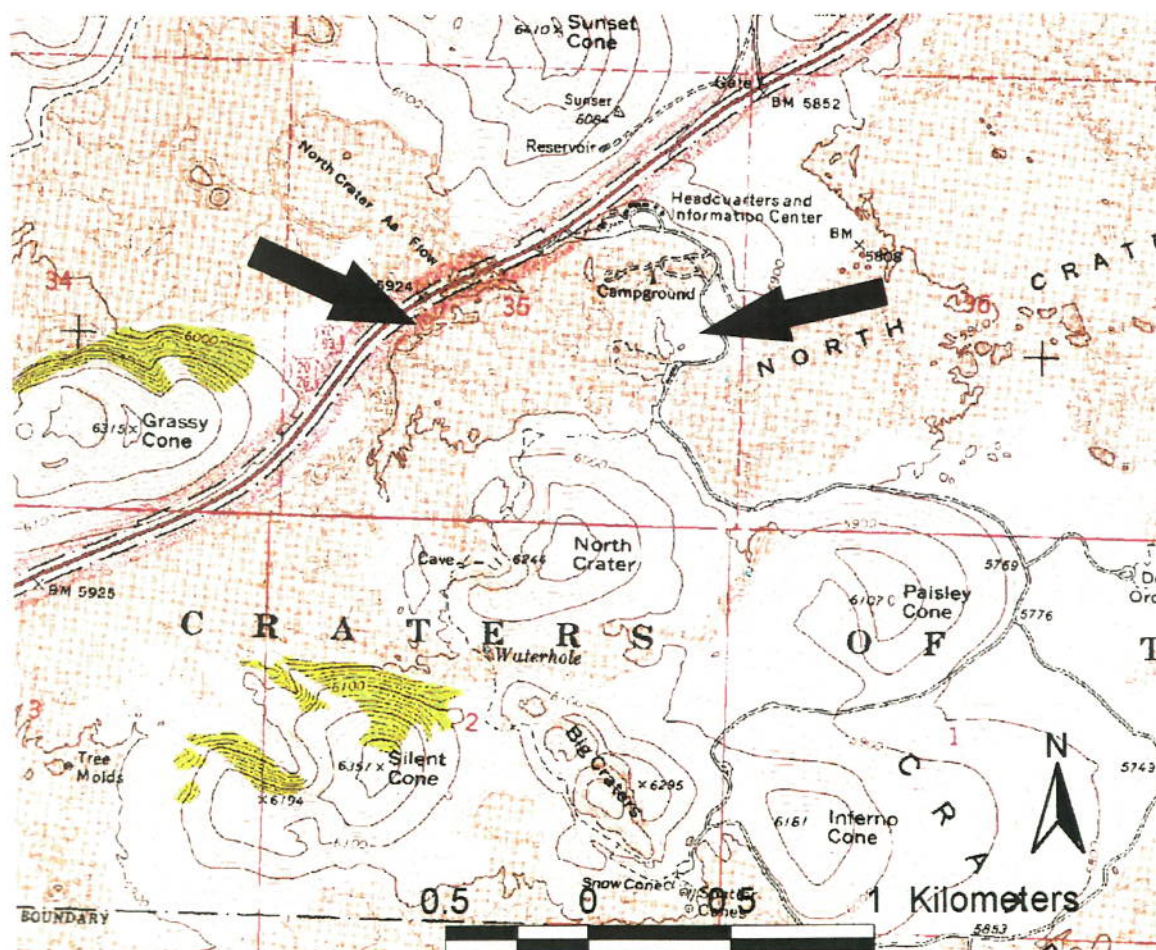


Figure 12: Portion of USGS 7.5 minute Inferno Cone Quadrangle map. Arrows show location of possible insitu remnants of North Crater.

Alternatively, they may also have been completely different cones having different vents and magma plumbing systems. Confirmation of these cones' existence is difficult because lava flows from North Crater or from their own vents may have rafted them away and younger flows from North Crater have buried any evidence. The apparent insitu cone deposits near the highway and campground may be remnants of possible neighbors to North Crater.

Another potential 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. Foshag and Gonzalez (1956) witnessed cone breaching, block rafting, and repair of the breach on the time scale of months and sometimes weeks. Though it is difficult to say conclusively, the Serrate flow appears large enough to have been issuing from North Crater for many months. In addition, 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 and been completely destroyed.

Much more field work needs to be completed to conclusively utilize Harwood's (1989) three models for cone breach (lava lake, dike intrusion and magma body intrusion) but I speculate that both the lava lake model and dike intrusion model have importance in the breaching of North Crater. The high percentage of spatter in the rafted blocks and in

the intact portions of the cone may suggest the intermittent presence of a lava lake within the cone. This lava lake may have overtopped the cone, flowing down the cone flanks, tearing apart North Crater. Nearly all breached cinder cones at COMNM have breaches which align in a NNW-SSE azimuth roughly parallel to the axis of the Great Rift. The regional extension causing the Great Rift orients the dikes parallel to the axis of the Great Rift. Dike injection into the flanks of the cone along this NNW-SSE azimuth would weaken the cone, making it more susceptible to gravitational collapse from its own weight as well as the weight of a lava lake within it.

Of the five local controls on breaching mechanisms Harwood identifies, four may have played a significant role in the breaching of North Crater: (1) local topographic stress regimes; (2) local fault/joint system control; (3) wind direction/cone strength; and (5) substrate buttressing. If one particular side of the cone accumulated more spatter, the topographically induced stress regime there would change. The extra weight of the spatter might initiate gravitational collapse at that location. That nearly all breached cinder cones at COMNM have breaches that lie parallel to the axis the Great Rift and Basin and Range extension suggests that local fault/ joint system control is also important. Wind direction/ cone strength and substrate buttressing are related to each other and have significance in the breaching of North Crater. Because the prevailing wind is generally from the west, pyroclastics accumulate on the east side of the cones, strengthening them. The west sides are generally steeper and might therefore be more susceptible to gravitational stresses whereas the east sides slope more gently because the wind spreads the pyroclastics out, creating a lower angle, more stable buttress.

Suggestions for Future Work:

Additional work would increase the understanding of North Crater and the events that led to its current morphology. 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. Additionally, detailed evaluation of the slumped northern portion of North Crater might provide information on gravitational collapse and erosion of the toe of the cone by flowing lava. Further investigation of how deep disaggregated material lies under the surface of transporting flows would be helpful in refining the certainty of volume calculations. This is very important in the distal reaches of the Serrate flow where the bulk of the rafted material resides in disaggregated form. The transporting flows are compositionally variable, and in the absence of data indicating the proportions of different composition types, I had to assume an average. Inquiry into the composition of transporting flows in locations where they contain rafted blocks would help assign the lavas more accurate densities.

CONCLUSION:

Reconstruction of North Crater by adding the volume of material rafted from North Crater to the current North Crater creates a paleo-North Crater that is much larger than the breach in the northwest side of North Crater can contain. The volume of rafted material is $46 \times 10^6 \text{ m}^3$ and the breach in North Crater is only $1.2 \times 10^6 \text{ m}^3$. Adding the rafted material ($46 \times 10^6 \text{ m}^3$) to the current North Crater ($42 \times 10^6 \text{ m}^3$) suggests Paleo-North Crater may have been as large as $88 \times 10^6 \text{ m}^3$. The radius and height of this large paleo-North Crater would have been nearly 200 m greater and 40 m higher than the

modern North Crater. It would have extended from North Crater's current position north to Highway 93 and east to the campground. Since North Crater has a prolonged and complex eruptive history, it is quite possible that several smaller paleo-North Craters existed through time, each being built, partially or completely destroyed by rafting events, and then rebuilt.

ACKNOWLEDGEMENTS:

This project would not have been possible without the computer assistance of Glenn Mutti (NPS), Mark O'Brien (BLM), and Ryan Gold. Glenn Mutti, Doug Owen (NPS) and Mel Kuntz (USGS) provided valuable background information regarding COMNM. Rick Vandervoet (BLM) offered much assistance with logistics between the BLM, NPS and Whitman College. I owe the most gratitude to my project advisor, Dr. Brennan Jordan. I could not have completed this project without his guidance. I also wish to acknowledge all my fellow geology majors in the class of 2003. Rock on!

REFERNCES:

- Environmental Systems Research Institute, Inc., 1999, ArcView GIS 3.2. Redlands, CA.
- Foshag, W.F., and Gonazalez, J.R., 1956, Birth and Development of Parícutin Volcano, Mexico: U.S. Geological Survey Bulletin 965-D, p. 355-489.
- Harwood, D.R., 1989, Cinder cone breaching events at Strawberry and O'Neill Craters, San Francisco Volcanic Field, Arizona: Masters Thesis, Northern Arizona University.
- Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of volcanic rocks: Canadian Journal of Earth Sciences, v 8, p.523-548.
- Kuntz, A. M., Elsheimer, H. N., Espose, L. F., Klock, P. R., 1985, Major-element analyses of latest Pleistocene-Holocene lava fields of the Snake River Plain, Idaho: USGS Open File Report 85-593, pp. 64.
- Kuntz, A. M., Champion, D. E., Spiker, E. C., Lefebvre, R. E., 1986, 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, A. M., Lefebvre, R. H., and Champion, D. E., 1989 Geologic map of the Inferno Cone quadrangle, Butte County, Idaho, Map GQ-1632.
- Macdonald, G.A., and Katsura, T., 1964, Chemical composition of Hawaiian lava flows: Journal of Petrology, v. 5, p. 82-133.
- Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hotspot: Volcanism, faulting, and uplift, in Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 1-53.
- Simons, F.S., Raup, R. B., Hayes, P.T., Drewes, H., 1966, Exotic blocks and coarse breccias in Mesozoic Volcanic rocks of southeastern Arizona: U.S. Geological Survey Professional Paper 550-D, p. D12-D22.
- Smith, R.B. and Braille L.W., 1994, The Yellowstone hotspot: Journal of Volcanology and Geothermal Research, v. 61, p. 121-188.
- Wohletz, K., 2002, Heat, version 2.46.088, downloaded 3/2003, <http://www.ees1.lanl.gov/Wohletz/Magma.htm>

APPENDIX 1:

Determining the amount of rafted material in each domain

A Domain	B amt transport flow, no rafted material (%)	C amt rafted discrete blocks (%)	coherent block equiv area of disaggregated blocks				H total % rafted material if were coherent blocks	comments $H = ((d \times e \times f)/g) + c$ (Note: columns B,C, and D should sum to 100; block heights in bold are from field measurement)
			D (%) area that is disaggregated rafted material	E amt of D actually cone material (%)	F thickness (m)	G height of coherent blocks in domain (m)		
52	10	40	50	90	2	7	53	block height for 32 seems too short
42	15	25	60	50	2	11	30	% material seems too small, used block 30s height
34	5	50	45	40	2	7	55	bold means field measure with some certainty
40	75	10	15	40	2	6	12	height from map estiamte (m.e.)
53	15	70	15	60	2	12	72	m.e.
41	60	10	30	50	2	6	15	m.e.
35	65	5	30	40	2	6	9	m.e.
34	10	70	20	50	2	6	73	m.e.
32							55	covered domain, appears like 34
33							9	covered domain, appears like 35
39	70	10	20	40	2	6	13	m.e.
37							30	covered domain, appears like 42
38							53	covered domain, appears like 52
44	60	10	30	40	2	6	14	m.e.
10	10	80	10	60	2	6	82	m.e.
51	30	40	30	60	2	15	42	final % seems too small

50	10	20	70	40	2	6	29	m.e.
49							14	covered domain, appears like 44
47	0	90	10	60	2	6	92	m.e.
48	0	90	10	60	2	6	92	m.e.
46	10	80	10	60	2	6	82	m.e.
45	5	80	10	60	2	8	82	m.e.
43							14	covered domain, appears like 44
36							0	seems too big and far away from others to determine