Using Anisotropy of Magnetic Susceptibility to determine the source of the Lower Bonanza Tuff, Colorado

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INTRODUCTION

Purpose

The purpose of this paper is to find a source for the lower, dacitic tuff in order to present a comparison for future interpretations about the location of the source of the upper tuff. The Lower Bonanza Tuff is dacitic in composition and lies directly beneath the rhyolitic Upper Bonanza Tuff. The transition between these two tuffs is marked by a distinct cooling break, with no intermediate layers of rhyodacitic composition (*Varga and Smith*, 1984). The sequence of these tuffs is unusual; during a normal eruption the lighter, rhyolitic tuff is emplaced first, followed by the denser, dacitic tuff due to differentiation in the magma chamber. One possible explanation for the discrepancy at the Bonanza Caldera is that the Upper and Lower Bonanza Tuffs have different sources, however, I have only determined the source of the dacitic lower tuff. Until the source of the rhyolitic tuff is found, there is controversy as to what factors lead to this unusual stratigraphy.

Background Geology

The early Oligocene Bonanza Caldera lies in the northeast corner of the mid-Tertiary San Juan Volcanic Field in Southwest Colorado. The caldera, with its trapdoor structure, is highlighted by the crescent shaped faults along the western side of the caldera (Figure1). The Lower Bonanza Tuff was formed primarily as a pyroclastic flow 36 million years ago in the San Juan Volcanic Field. The similar composition of the erupted material before, during and after this eruptive sequence suggests that the magma was not strongly compositionally zoned, and therefore did not become compositionally zoned between the eruptions of the lower and upper tuffs.

In 1981 Varga analyzed field and microscopic indicators of flow direction in order to determine the source of the Lower Bonanza Tuff. His placement of the source was at a vent area now occupied by the Porphyry Peak and Sheep Mountain igneous complex.

Description of Anisotropy of Magnetic Susceptibility (AMS)

AMS uses the principle that the magnetic susceptibility of a rock may be anisotropic due to various factors, including lineations in the petrofabric created during flow. The shear caused by flow produces an alignment of minerals parallel to the direction of flow, with an imbrication that dips towards the source. The long axes of the magnetic minerals in the tuff have a higher magnetic susceptibility than the intermediate or minimum axes. An ellipsoid representing this anisotropy can be created using data collected using AMS.

METHODS

Field and Laboratory Methods

In the field we used gasoline powered drills with one inch diamond bits to drill 3-24 cores in 22 outcrops of the Lower Bonanza Tuff, covering an area of 750 km^2. Water pumps were used to keep the bit cool from the friction created when drilling. Once a core was drilled, the azimuth and hade were recorded, and then a sun compass reading was taken in order to correct for possible interference of the azimuth reading by magnetic rocks. Each core was marked in place so the original orientation would not be lost, and then taken out of the outcrop. A measurement of the foliation was taken for each site in order to correct for tilting that occurred after the emplacement of the tuff. At each site we measured a GPS position in order to accurately locate the sites on the map.

The 138 solid, cylindrical samples were cut to a length of 0.89 inches with a diameter of 1 inch in order to most closely approximate a sphere and reduce the shape effect of the sample. I used the Kappabridge KLY-2 located at the Scripps Oceanographic Institute in San Diego to measure the magnetic susceptibility of the samples.

Statistical and Mathematical Methods

The data from the Kappabridge KLY-2 were used to find AMS ellipsoids for each sample. These ellipsoids were then changed to geographic coordinates and corrected for post-emplacement tilting. The ellipsoids were put through the F-test for evaluating whether the sample is anisotropic. The F-test compares the lengths of the axes in order to determine whether the sample is statistically anisotropic. The mean tensor elements and 95% confidence ellipses were calculated using the bootstrap method described by Constable and Tauxe (1990).

RESULTS

Data

The orientation of the average maximum axis in the AMS ellipsoid (Kmax) is displayed in Table 1 for each site. The flow direction was determined by adding 180º to the declination. The declination dips toward the source due to the imbrication of the minerals; the flow is in the opposite direction. Also, the number of samples drilled at each site and the number of samples in the final calculations are shown.

In order to visualize these results, the Kmax declinations for each site were plotted as arrows in Figure 1.

Site	Flow Dir.	D	I	# Drilled	# in Calculations	Sigma
71699-1	213.1º	33.1º	11.1º	6	5 (F-test)	.00051
71799-1	194.6º	14.6º	.5º	5	4 (other)	.00089
72599-1	301.0º	21.0º	0.9º	24	15 (other)	.00033
72599-2	177.3º	357.3	1.8º	11	10 (other)	.00049
72599-3	290.0º	110.0	4.3º	4	4	.00143
72999-5	74.2º	254.2	77.3º	6	6	.00101
72999-2	289.8º	109.8	6.8º	12	11 (other)	.00004
72899-2	227.7º	47.7º	5.3º	10	10	.00063
72899-1	179.1º	359.1	32.2º	9	9	.00044
72799-2	101.0º	281.0	24.9º	3	3	.00115
72199-1	161.3º	341.3	16.2º	6	5 (other)	.00072
72099-1	202.9º	22.9º	3.9º	5	5	.00072
72099-2	34.0º	214.0	4.9º	4	4	.00106
72099-3	303.1º	123.1	.5º	5	5	.00058
71999-5	230.4º	50.4º	5.8º	6	6	.00086
71999-4	273.8º	93.8º	3.1º	7	5 (F-test)	.00133
l72799-1	------	------	------	3	0 (F-test, other)	------
l72599-1	122.6º	302.6	0.0º	3	3	.00189
l72399-3	130.8	310.8	12.9	3	3	.00173
l72399-1	283.0º	103.0	5.4º	3	3	.00054
l72399-2	161.1º	341.1	7.8º	3	3	.00096

Table 1: The number of samples drilled at each site, along with the number in the final calculations. D is the declination, I is the inclination and Sigma is the error value for Kmax.

The F-test and F12-test eliminated several cores. Several other samples were deleted from the equations for reasons other than the F-tests. These included samples that were drilled in out-of-place rocks or poorly welded rocks, or human error created an inaccuracy.

DISCUSSION

Using AMS data to find a volcanic source

The data gathered by using AMS on the cores can be manipulated to give a line in space that correlates to the directions of maximum, intermediate and minimum susceptibilities of the petrofabric. This direction, in turn, can be assumed to be the same as the flow direction of the ash due to factors that align particles during flow. The source of the tuff is assumed to be the point from which the flow lines radiate. One possible way to find the source of the tuff is to extend the directional lines and find the point where the most lines intersect (*Ellwood*, 1982).

In order to eliminate the problem of human bias, I contoured the intersections in order to find the highest concentration (*Hillhouse,* 1991). Figure 15 has two obvious peaks in the number of intersections, one to the east of Antora Mountain (A) and the other on the eastern edge of Findlay Ridge (C). Two large concentrations of intersections imply two source areas, which is improbable. More likely, the southern concentration (C) is caused by an abundance of sample sites in the area. This large amount of sampling in one area may have caused an inaccurately high amount of intersections to occur there. Although there is also a large number of sites scattered around concentration A, there is not a single high concentration directly related to the center of the contours, which implies the northern contours accurately depict the source of the Lower Bonanza Tuff.

Using Previous Data to find the Source

The northern concentration site (A) is near the previously proposed source area on the north/northwest caldera margin (*Varga*, 1981 and *Varga and Smith*, 1984). Also, a source near the western side of the caldera correlates well with the trapdoor collapse structure of the caldera. If the material were erupted from the western side, the roof of the magma chamber on that side would not be supported and may therefore collapse.

Varga (1981) found flow directions in this area using both microscopic and field evidence. Using the same methods with these data places the source (B) to the east of the source I found using the AMS data. One possible explanation for this slight variance is that many of Varga's sites are to the east of the concentration (B) found using his data. Possibly the location of the maximum number of intersections is at an intermediate location between the source area and concentration of many sites

Interpreting known Sources into estimated Flow Lines

There are some areas of sharp disagreement between the flow direction arrows and the estimated flow lines. Some sites flow in a direction completely opposite of the proposed flow. One explanation is that the maximum axis for these sites have shallow inclinations, near horizontal, and large confidence intervals, represented as sigma in Table 1. The combination of these two factors may include flow possibilities going in either direction. Several sites are close to perpendicular to the direction of flow. Most of these sites also have large confidence intervals and shallow inclinations, which encompass the estimated flow direction. Other samples have large ellipses, but not large enough to include the interpreted flow lines. These irregularities may have been caused by rheomorphism or topography affecting emplacement. Rheomorphism is the movement of the tuff after emplacement, often on a slope.

Another factor that might affect the accuracy of some of these sites is that many of the samples have an oblate anisotropy. An oblate ellipsoid will often have a larger error associated with it for the maximum axis than a prolate ellipsoid. Anisotropy's that are too oblate to calculate a flow direction within error are eliminated by the F-test, but a large error is still associated with the maximum axis.

I compared samples near the upper and lower contacts of the tuff. There is not much difference in the shapes of the ellipsoids between the two areas, although the samples near the lower contact are a little more oblate. I expected that stronger shearing near the bottom of the flow would cause a prolate ellipsoid, but a different explanation may be that the welding of the lower portion of the tuff created a horizontal, oblate fabric. The upper contact of a tuff is not densely welded, which may be the reason the fabric has a more prolate shape than the fabric that has been welded.

The presence of hematite has the potential to affect the AMS reading because it has a strong crystallographic effect (*Uyeda*, 1963). If hematite in a core has a strong enough effect, it may cause the results of AMS to deviate from a purely fabric-related reading. Prashad (2000, personal correspondence) thermally demagnetized several samples from the same sites that were drilled in this study and found evidence of hematite near the caldera. I compared the flow direction and anisotropy of samples with hematite to samples from the same site that did not contain hematite. Hematite caused no obvious differences. The effect of hematite is considered to be negligible in this study because of this lack of a difference between hematite containing samples and the other samples.

Roughly one-fifth of the samples used in this study were AF demagnetized before AMS readings were taken. According to Rochette et al. (1992) the main effect demagnetization has on AMS results is to remove the effect of remnant magnetization on the sample. Although demagnetization may be important when the anisotropy is very weak, in this study there was little difference in the results between demagnetized cores and cores with remnant magnetization.

Explanations for the Stratigraphy of the Upper and Lower Bonanza Tuffs

There have been several suggestions as to why the more dacitic Lower Bonanza Tuff lies beneath the rhyolitic upper tuff, when under most circumstances, zoning in the magma chamber causes the rhyolitic tuff to be erupted first. One possibility is that these tuffs have completely different sources, and are therefor not related to each other. This hypothesis can only be tested once the source of the upper tuff is determined. Other possibilities suggested by Marrs (1973) are that both tuffs originated from the Bonanza caldera, but the actual vents tapped different levels of composition in the magma chamber, allowing different compositions to be erupted simultaneously. Also, the compositions may have been affected by the amount of material that was assimilated from the chamber walls. Because there is no intermediate layer of rhyodacitic composition and the composition does not vary much between flows (*Varga and Smith*, 1984), the strongest hypothesis is that there are two different sources.

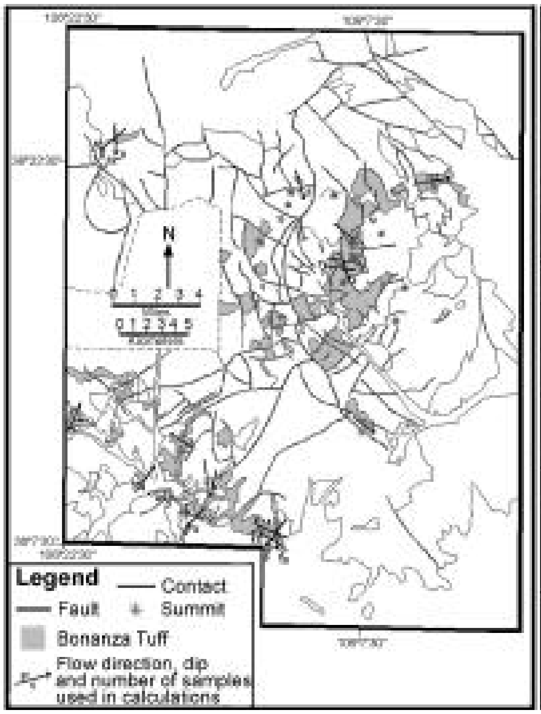

Figure 1: A map showing each site with an arrow indicating the direction of flow. The numbers represent the inclination of the arrow, and the number of samples used in the calculations for for that site.

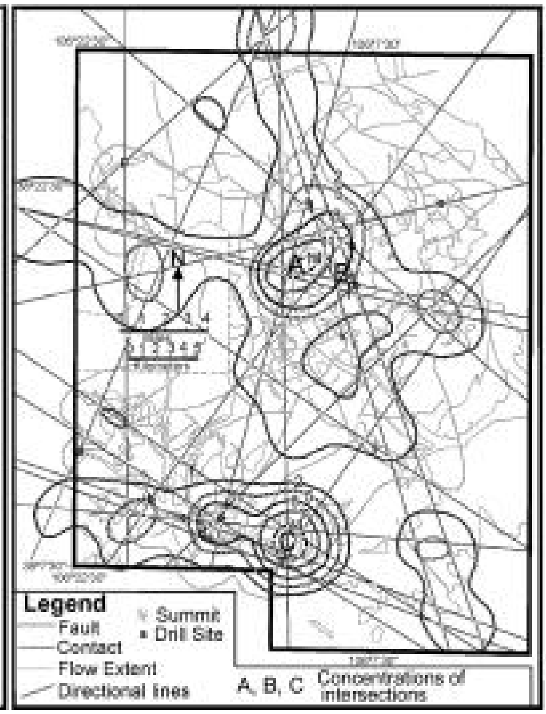

Figure 2: A method of finding the source of the Lower Bonanza Tuff by extending the arrows in both directions. The contours show where the highest concentrations of intersections are located.

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