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Analysis of Vesicular Basalts and Lava Emplacement Processes for Application as a Paleobarometer/Paleoaltimeter: A Reply

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The use of vesicular basalts as a tool for the measurement of paleoelevation is based on the calculation of atmospheric pressure from the difference between vesicle sizes in the tops and bottoms of flows. Assuming that the bubbles were a well-mixed population at eruption from the vent, the difference in size is caused by the pressure of the lava overburden relative to external atmospheric pressure. Thus, if the flow thickness and density are known or measured and the size distributions can be determined, atmospheric pressure and thus elevation can be calculated. In this analysis, the two most difficult (and thus critical) measurements are the vesicle sizes and flow thickness. A method to measure the former has been developed (Ketcham and Carlson 2001; Proussevitch and Sahagian 2001) so that the remaining practical limitation on using the technique of Sahagian et al. (2002*a*, 2002*b*) is the ability of the field geologist to determine that the measured flow thickness represents the thickness of the flow at the time that the upper and lower 10 cm or so (from which samples would be taken) solidified to "lock in" the vesicle sizes.

The primary concern regarding thickness is that there may have been deflation or inflation of the flow after the top and bottom solidified (Bondre 2003). While it may be optimal to identify a thin lobe or breakout where late-stage inflation would not be expected, as suggested by Bondre (2003), this is not always possible because of incomplete field exposures, especially for older flows. Consequently, flows must be examined critically in the field in cross section. For the study of Sahagian et al. (2002*a*) in Hawaii, we did not sample strictly from thin lobes or breakouts but rather from all parts of the flows—near the vent, on the flank of the volcano, and around Hilo. The criteria for establishing simple emplacement were unrelated to lateral geometry but rather were based on vesicle population structure in vertical cross section. The characteristic features of simple emplacement can be recognized in flows of any age or exposure quality, provided there is a complete cross section through the flow.

The question becomes how to identify simple emplacement in the field. In flow cross sections, there are often confounding features—such as multiple vesicular zones, discontinuities in the vesicularity profile, very large vesicles, pipes, evidence of shear deformation, and "xenoliths" of previously solidified lava—that should represent a red flag to the field geologist and make it easy to disqualify flows with such complexities. The absence of such obvious features is not necessarily a guarantee that the flow experienced simple emplacement, so the vesicularity profile, thickness of upper vesicular zone relative to flow thickness, and size distribution profiles must be critically examined relative to the profile expected for simple emplacement.

Inflation, even if continuous rather than pulsed, would disrupt the rise and coalescence of bubbles that result in the appropriate bimodal or trimodal size distribution in the upper vesicular zone and is identifiable on that basis. If inflation occurs relatively early in the emplacement process, before solidification of the upper and lower 10 cm or so of the flow (and before significant bubble rise and coalescence), the vesicle sizes will adjust to accommodate the "new" thickness, in which case the analysis would apply to the inflated thickness of the flow, and paleoelevation studies could be conducted with the thickness measured in the field. Also, once there is a thick upper crust that makes it possible to generate internal lava pres-

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sures greater than hydrostatic (Hon et al. 1994), it no longer matters what the internal pressure is because the upper (and lower) vesicles have been frozen in already. However, it is not clear how to determine whether inflation occurred before or after the upper and lower parts of the flow (to be sampled) were solidified, so it is best not to use inflated flows at all.

The "ideal" profile of Sahagian et al. (1989) involves thickness of upper and lower vesicular zones, bulk vesicularity profile, and size distribution as a function of stratigraphic position within the flow. These distributions depend on flow thickness, so there is no single set of values that can be cited as "ideal." However, there are some commonalities. Vesicles in the lower vesicular zone become smaller, and vesicularity decreases upward from the bottom (because of the slowing of the lower crystallization front with time). Vesicles in the upper vesicular zone become larger, and vesicularity increases downward from the top (because of the upper crystallization front trapping rising and coalescing bubbles as it slows) (Sahagian 1985). In flows in the 1–2 m range, the size distribution in the lower part of the upper vesicular zone should be bimodal (because of coalescence), and for thicker flows it can be trimodal (Sahagian et al. 1989). If the above features have the correct distributions for a given flow thickness, the field geologist can be reasonably certain that there were no post-emplacement processes such as inflation or deflation to invalidate the analysis for paleoelevation studies.

Bondre (2003) suggests using the thickness of the upper crust (Hon et al. 1994) as a measure of flow thickness, but the suggested relation depends on time during cooling and is not readily measured in the field for paleoelevation studies. An alternative might be to estimate the bulk vesicularity in the upper vesicular zone. Simple emplacement should ideally lead to an increase in vesicularity with depth from the top (Sahagian 1985). In contrast, observations have suggested that inflated flows show a decrease in vesicularity with depth (Cashman and Kauahikaua 1997). If this is true, this might also be used as a discriminator between simple and inflated flows.

The "bottom line" indication of our ability to identify simply emplaced flows is figure 9 in Sahagian et al. (2002*a*), which tests the analysis of recent flows along the flanks of Mauna Loa, Hawaii. If we were to accept Bondre's (2003) assertion that these flows were inflated after solidification of the upper and lower parts that we sampled, then we would need to correct for this by moving all the data points up in elevation. This would move the data cluster away from their actual elevations, as depicted by the slope = 1 line. Another way to consider this is that if there had been any inflation (or deflation), the data points would lie consistently beneath (or above) the line with slope = 1. The agreement of our analysis with the actual elevations from which the samples were taken is the acid test of our ability to select appropriate flows for sampling. The same selection criteria were used on the Colorado Plateau (Sahagian et al. 2002*b*).

In general, no single feature of the vesicularity profile should be considered as reliable alone, and all observable aspects of the profile should be examined in concert to establish simple emplacement. We take the conservative approach of not attempting to correct for inflated (or deflated) flows but simply of disqualifying such flows from our analyses. As further investigations lead to a more detailed understanding of flow emplacement processes, it may be possible to relax some of the stringent restrictions we have placed on our sampling sites, thus opening up a much wider range of potential field applications and increasing the efficiency by which large numbers of samples can be collected for analysis.

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