

## DISCUSSION AND REPLY

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

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### Introduction

Sahagian et al. (2002a, 2002b) have developed a methodology for determining paleoelevations of highlands using observed vesicularities of lava flows. Since vesicular lavas preserve a record of paleoatmospheric pressure during the time of emplacement, they can be used to directly infer paleoelevations. Their model could act as a powerful tool, particularly in view of the uncertainties induced by other methods. As their data suggest, elevations could be estimated within ~400 m. However, their work also raises the issue of emplacement of pahoehoe lobes and flows.

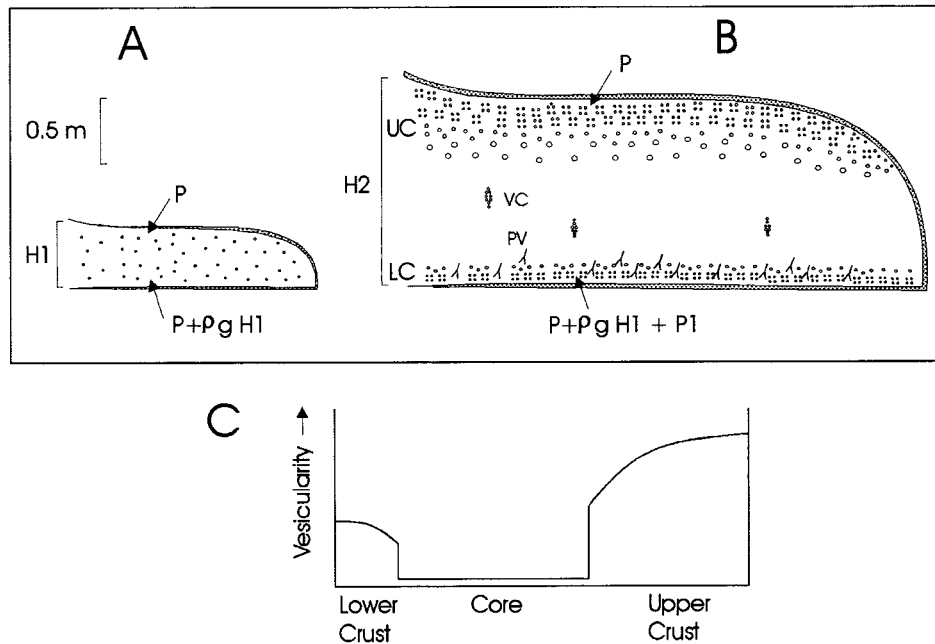
Sahagian et al. (2002a, 2002b) state that only flows with a simple emplacement history can be used to estimate paleoelevations from paleopressures. Critical to their model is the flow thickness at the time the bubbles at the top and bottom of the flow solidified. It is important that the upper and lower 10 cm or so of the flow solidified after the flow reached its final thickness. The question is whether the flow or flow lobe presently observable in the field was originally emplaced with the same thickness or whether it has undergone endogenous growth or deflation. To infer flow emplacement history, Sahagian et al. (2002a, 2002b) rely on a comparison of the observed vesicularity profile with "ideal" vesicularity (fig. 1 in Sahagian et al. 2002a), as discussed by Sahagian (1985) and Sahagian et al. (1989). According to them, multiple layers of small vesicles in a relatively thick flow are suggestive of inflation, while a vesicle profile similar to that in their figure 1 (Sahagian et al. 2002a) suggests a simple, noninflated mode of emplacement. They did not provide information about the vesicularity profiles of the flows used in their

study; hence, I cannot comment on how closely their observed profiles matched the ideal. It is clear, however, that they have studied pahoehoe flows.

### Inflation of Pahoehoe Flows

Numerous recent studies have highlighted the importance of inflation in pahoehoe lava flow lobes (e.g., Walker 1991; Hon et al. 1994; Self et al. 1998; Thordarson and Self 1998; Bondre et al. 2000). In fact, inflation is so ubiquitous in pahoehoe flow lobes that it is difficult to find one that does not show evidence of inflation. As Self et al. (1998) observed, the mere presence of a P-type pahoehoe lobe (cf. Wilmoth and Walker 1993) is sufficient to deduce that it evolved by inflation. Observations by Hon et al. (1994) suggest clearly that actively inflating pahoehoe lava flows (~4 m) grew by coalescence and inflation of small lobes (~0.1–0.5 m). Thick flows are not the only evidence for inflation. Relatively thin (~1–3 m) flows also display unambiguous evidence of thickening by endogenous growth (see fig. 8 in Self et al. 1998). These flows show the same three-part structure observed in the "ideal" profile in Sahagian et al.'s (2002a) figure 1. There is, however, a rapid downward decrease in vesicularity of the upper crust in most observed flows, as opposed to the "ideal" profile. Many inflated pahoehoe lobes (e.g., from the Deccan Volcanic Province and several Hawaiian lobes) do not show prominent vesicle banding or multiple layers of small vesicles. Such features have been observed in very thick flows such as the Birkett flow (Walker et al. 1999), but this flow is not representative of most thinner (~10 m or less) pahoehoe flows and lobes. Walker et al. (1999) also observe that not all inflated flows would display vesicle layering.

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**Figure 1.** Initial (A) and late (B) stages in the inflation of a pahoehoe lobe.  $H1$  = initial thickness;  $H2$  = final thickness;  $UC$  = upper crust;  $LC$  = lower crust;  $P$  = atmospheric pressure;  $\rho$  = lava density;  $g$  = gravity;  $P1$  = excess pressure due to inflation;  $VC$  = vesicle cylinder;  $PV$  = pipe vesicle. C, Commonly observed vesicularity profile for pahoehoe lobes.

Cashman and Kauahikaua (1997) have reevaluated the implications of observed vesicle distribution in basaltic lava flows, especially pahoehoe flows, and they point out that the "ideal" distribution (Sahagian 1985; Aubele et al. 1988; Sahagian et al. 1989) does not satisfactorily explain the downward decrease in vesicularity found in most pahoehoe flows or lobes. Most pahoehoe lobes display an increase in mean bubble diameter near the transition of upper crust and the vesicle-poor core (Cashman and Kauahikaua 1997; N. R. Bondre, R. Duraiswami, and G. Dole, unpublished data); however, the number density per unit area is much lower than that at the top. Such a distribution can be better explained by continuous upper crustal growth during inflation of the flow or flow lobe rather than by postemplacement processes. In such a scenario, the larger vesicles at the transition may be formed by coalescence at the crust-melt interface (Cashman and Kauahikaua 1997). Aspects of inflation not yet well constrained are the time-scales and pulses involved (see Anderson et al. 1999, 2000; Self et al. 2000). It is likely that flows or lobes displaying pronounced vesicle banding reflect discrete pulses of lava (e.g., Walker et al. [1999] interpreted at least 19 injection events for the Birkett flow). In contrast, other flows or lobes without

layering still probably evolved by inflation; however, the pulses were not discrete and lava influx was continuous. The period involved in the evolution of inflated flows or lobes is on the order of hundreds of days (Hon et al. 1994; Cashman and Kauahikaua 1997; Thordarson and Self 1998).

#### Implications for Paleoelevation Studies Using Pahoehoe Flows

From the previous discussion, it is more than likely that pahoehoe flows or lobes have grown through a periodic or continuous influx of lava. It is quite likely that the 5-m-thick flow in figure 2 of Sahagian et al. (2002a) is an inflated flow. This calls into question the value of  $H$  used in Sahagian et al.'s (2002a) equation (1) to calculate paleopressure. The measured field value might not reflect the original thickness of the flow (fig. 1). Another implication of inflation is the possibility of excess pressures (greater than the overburden) within inflating lobes (fig. 1). Walker (1991) and Cashman and Kauahikaua (1997) observe that decrease in vesicularity in the upper meter of crust is larger than predicted (using the ideal gas law). This is clearly a result of either volatile escape during inflation through axial clefts (Walker 1991) or excess pressures operating

during inflation (Hon et al. 1994; Cashman and Kauahikaua 1997). Hon et al. (1994) observed that the internal pressure of an inflating pahoehoe flow greatly exceeded, and was independent of, the weight of the overlying crust alone. Evidence for such excess pressures has been documented by Duraiswami et al. (2001) in sheet lobes from the Deccan Volcanic Province. Hence, it is likely that the pressure at the base of the flow or lobe calculated from the volume of modal bubble sizes (Sahagian et al. 2002a, 2002b) was not simply that induced by the weight of overlying lava. For very young Hawaiian flows, the calculated elevations are close to actual values, almost certainly because thin lobes/breakouts were used. For flows from the Colorado Plateau region (Sahagian et al. 2002b), one cannot determine whether the calculated values accurately represent paleoelevations. Vesicularity profiles of those flows (provided in the table of Colorado Plateau sampling locations that has been placed in *The Journal of Geology's* Data Depository by D. L. Sahagian and coworkers) suggest that the average flow thickness was >3 m, and several flows had a thickness of 3–4 m. The authors mention that samples were collected from distal portions of flows since proximal areas are more susceptible to inflation or deflation. It would appear, however, that distal portions would inflate as much as proximal ones, if not more, because of slowing down of the flow front and continuous supply of lava to this portion.

It thus appears that rapidly ponded flows (where the flow achieved its final thickness very rapidly

because of external addition of lava) or solidified lava ponds and lakes would be better candidates for estimating paleopressures than are pahoehoe flows. If pahoehoe flows are used, thin lobes that occur as breakouts from larger ones should provide more accurate estimates. One possible way to correct modal vesicle volume measurements from inflated pahoehoe flows or lobes for effects of inflation would be to use the crustal cooling model in Hon et al. (1994):

$$C = 0.0779t^{1/2}.$$

Using this equation, the thickness  $C$  of the upper crust at a time  $t$  immediately after emplacement could be determined, and hence an estimate of flow thickness at that time could be made. That value, rather than the observed field thickness, could then be used in Sahagian et al.'s (2002a) equation.

### Conclusion

Sahagian et al.'s (2002a) work raises the issue of emplacement of pahoehoe lobes and flows, and their estimates of paleoatmospheric pressures could be potentially improved by recognizing that inflation is ubiquitous in pahoehoe flows. Notwithstanding this practical concern, their study highlights how little we know about lava flow emplacement and the variables involved. It also impels us to continue the study of flow emplacement, while the implications of such work justify the effort put into it.

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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. (2002a, 2002b) 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. (2002a) 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

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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 pressures 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 postemplacement 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. (2002a), 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. 2002b).

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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