Thermal History of Magmas; the Low Pressure Reference Point

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Thermal history of magmas; the low pressure reference point

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A simple model of volcanic plumbing, which predicts that many observed mineralogical and geochemical features of basalts are products of near-surface fractional crystallization, also predicts that erupted lavas may be 100–250 °C cooler than the parental magma entering the magma chamber, as well as considerably reduced in mass. Observations of the energy of erupted lavas do not, therefore, form a useful reference point from which to attempt to reconstruct the thermal budget of the igneous process and provide only a lowest estimate of the rate at which thermal energy could be extracted from an active volcano on a long term basis.

Introduction

Considerations of the energy budget of ascending magmas might use either of two possible reference points to characterize the energy content of the system.

The first of these is the temperature, pressure and composition of the primary magma produced by partial melting at depth. Because these details are not directly observable, the appropriate values have to be inferred. The resultant values are subject to uncertainties which arise mainly from the assumptions which are made about the volatile content of the upper mantle, the percentage of partial melting achieved, and, to a lesser extent, from the assumed chemical composition of the silicate fraction of the upper mantle.

The alternative reference point is the temperature and composition of a magma batch on eruption, which may be directly observed in active volcanoes, or determined for older lavas by the combination of petrographic observations and experimental studies. These data can only be used directly as a reference point for reconstruction of the thermal history of an ascending magma batch if it can be demonstrated that the erupted magma is truly primary in composition. This is, in general, untrue for the common basalts (O'Hara 1965, 1968*a*, *b*). The purpose of this paper is to draw attention to one of the problems which are involved in any attempt to reconstruct the composition and temperature of the magma batches which are fed into the high level magma chamber from the observation of those lava batches which escape from it.

Energy changes during high level magma evolution

Figure 1 is a schematic model of an active central volcano, in an oceanic setting. It is assumed that a relatively thin, high level magma chamber is periodically fed by batches of parental magma rising through the active conduit. Each parental magma batch may be small relative to the volume of liquid remaining in the chamber. On addition to the chamber, the new magma batch mingles with the old.

Fractional crystallization of the magma in the chamber is assumed to be a continuous process, leading to the imposition of low pressure cotectic (and porphyritic) compositions and temperatures on the residual liquids. Periodically, and most probably at the moment when a new parental magma batch is forced into the chamber, some of the residual liquid in the chamber is forced to the surface as a lava flow.

Below the magma chamber, a pile of gabbro and peridotite cumulates is gradually built up. Space for this accumulation might be created in three ways; by subsidence of the cumulate column; by dilation of the volcanic superstructure and by assimilation (digestion) of the previously erupted basaltic superstructure.

The geochemical evolution of the magmas within such a magma chamber is discussed elsewhere (O'Hara 1977). The differences of composition which can be set up between the parental magma batches and the erupted lavas are profound, and not intuitively obvious. The lava batches are at or below their liquidus temperatures (i.e. they are porphyritic) and these liquids are geochemically evolved by fractional crystallization relative to the parental magma batches (assumed to be at or even above their liquidus temperatures). The temperature of the erupted lava will therefore be lower, possibly much lower, than that of the parental magma. It is possible for the MgO content of the parental liquid to be 1.5 to 2 times that of the erupted lava (which may contain *ca.* 10 % MgO), implying a probable difference of liquidus temperature which may be as large as 250 °C. The energy content of the lava per unit mass will be different from that of the parental magma not only by virtue of its lower temperature but also by virtue of its changed composition.

Energy budget of the evolving and advancing magma chamber

In each cycle of magma addition, mixing, fractional crystallization and eruption proposed in this model, the energy budget of the chamber may be drawn up.

On the credit side there are (1) the energy of the parental magma batch, (2) the release of latent heat as cumulate crystals are formed, and (3) a contribution of heat flow from lower levels. On the debit side there are (4) the energy of the lava batches erupted, (5) the energy required to digest any roof rocks replaced and (6) heat losses by conduction and convective circulation.

Clearly credits must balance or exceed debits if the volcano is to have a long life. In the model proposed, entry (4) must be considerably less than (1), (5) will be less than (2) but entry (6) will exceed (3).

Unless entry (5) is substantial, it is difficult to produce sufficient cumulates to account for the observed chemical evolution of erupted lavas relative to plausible primary or parental magmas, without exceeding the acceptable heat flow at the surface (i.e. entry (6) is required to become larger than actually observed).

Each batch of parental magma which enters the magma chamber, if it could be followed through all the mixing, fractionation and eruption cycles, eventually ends up partly as a contribution to the cumulates and partly as a contribution to the lava pile. Provided the volcano is in a steady state, these contributions may be simply integrated, so that, approximately:

energy of periodic parental magma batch = (energy of periodic lava batch erupted) − (latent heat of crystallization of the cumulate fraction) + (energy required to heat the assimilated mass of previously erupted lava from 'cold' to the magma temperature, and to digest it). (1)

The geochemical evidence and much field and geophysical evidence suggest that the last two terms on the right hand side of equation (1) are large relative to the first.

The last two terms in equation (1) will only cancel each other by chance, and they can only be assumed to be negligible if the erupted lavas are truly primary magmas. Any attempt to assess the energy budget and rate of work of a volcano of the type modelled here solely in terms of the observed energies of the lavas erupted may, therefore, be seriously in error.

The simple consequence of these considerations is that the total thermal energy available per unit time from an active volcanic region will be greater, possibly very much greater, than indicated by the rate of energy output as lava.

The model conveyed by figure 1 also permits the possibility that the gabbro layer of the oceanic crust has been built up by replacement of previously erupted basalt, hence the conclusions may be equally applicable to consideration of the volcanic heat budget at the mid-ocean ridges.

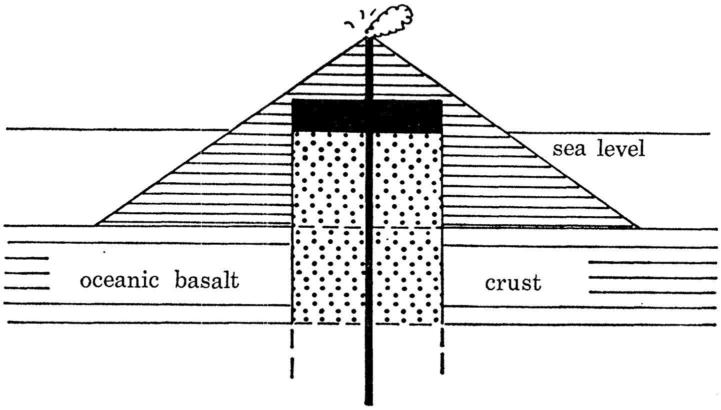

FIGURE 1. Section of a model central volcano in an oceanic setting (from O'Hara 1977) illustrating previously erupted basalts (shaded), cumulus gabbro (stippled) and active magma volumes (solid).

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