The Boycott effect in magma chambers

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[1] We investigate the plausibility of the stratified Boycott effect as a source of layering in magma chambers. Crystal settling within the magma chamber will generate buoyant fluid near the sloping sidewalls whose vertical ascent may be limited by the ambient stratification associated with vertical gradients in SiO_2. The resulting flow may be marked by a layered structure, each layer taking the form of a convection cell spanning the lateral extent of the magma chamber. Using parameters relevant to magma chambers, we estimate that such convection cells would be established over a timescale of a month and have a depth on the order of 4m, which is roughly consistent with field observations of strata within solidified chambers.   INDEX TERMS: 8145 Tectonophysics: Physics of magma and magma bodies; 8429 Volcanology: Lava rheology and morphology; 8439 Volcanology: Physics and chemistry of magma bodies. Citation: Blanchette, F., T. Peacock, and J. W. M. Bush (2004), The Boycott effect in magma chambers, Geophys. Res. Lett., 31, L05611, doi:10.1029/2003GL019235.

1. Introduction

[2] Magma chambers are large reservoirs of molten material contained in solid rock within the earth's mantle. Their geometries vary from roughly spherical to planar, with characteristic dimensions ranging from 100m to 10km [Smith, 1979]. Convective motions and crystal settling have long been thought to play a role in the dynamics of magma chambers [Darwin, 1844]. The chamber is typically filled rapidly with hot magma from the Earth's mantle and subsequently isolated; however, reinjections of magma from a source conduit may also arise [Huppert et al., 1982]. The system is generally cooled from above so that thermally-driven convection may be present. The temperature difference across the chamber is diminished by the convective mixing, and viscosity increases as the chamber cools until thermally-driven convection becomes untenable [Jaupart and Tait, 1995]. Through magma differentiation, compositional gradients may develop and render the chamber unstable to compositional convection [Spera et al., 1986]. Crystals, either present when the chamber was initially filled or formed as the chamber cools, and small bubbles of gas or low viscosity liquids (volatiles) [Greenough et al., 1999] may subsequently come to dominate the dynamics of the magma chamber [Jellinek and Kerr, 2001]. As the chamber cools, the concentration of crystals increases until a crystal matrix

forms and the interior of the magma chamber effectively becomes a porous medium. Eventually all the magma solidifies and interior motion is suppressed.

[3] At the base of solidified magma chambers, compositionally distinct layers are often observed. These layers have been reported in Greenland [Hodson, 1998] and South Africa [Jaupart and Tait, 1995], and their origins are the subject of this letter. The individual layers are typically less than one meter deep and the strata may span up to 100m. In the majority of cases, the composition of the layers varies monotonically with height and the mean density within each layer decreases with height. Vesicular rock layers, those exhibiting high concentrations of volatiles, have been seen in Taiwan [Greenough et al., 1999] and Washington state [McMillan et al., 1989]. Vesicular layers form near the top of the chamber and usually only a few such layers are observed, with depths of order 20cm. A variety of mechanisms have been proposed to explain the formation of layers in solidified magma chambers, but have been difficult to confirm owing to the complexity of the system, the number and indeterminacy of the governing parameters and difficulties in obtaining reliable data.

[4] One explanation for the existence of layers at the bottom of a magma chamber is the repeated injection of melt [Huppert et al., 1982; Jaupart and Tait, 1995]: new magma is introduced periodically at the base, each injection leading to the formation of a new layer. An alternative mechanism relies on episodic crystal settling from a convecting chamber cooled from above [Sparks et al., 1993]; when the concentration of crystals becomes sufficiently large, convection is unable to keep them in suspension, leading to a deposition event. The repetition of this process yields a layered deposit. Irvine [1987] and subsequently Hodson [1998] proposed that layers are the result of deposition from particle-driven gravity currents; if a large quantity of crystalline matter generated within the chamber is suddenly released from the top of the chamber, it will sink and spread as a gravity current along the base of the chamber. Particles then sediment out as the current spreads, leaving a deposit that thins with distance from the source. While the dynamics of both high [Bonnecaze et al., 1993] and low [Huppert, 1982] Reynolds number gravity currents are well understood, the origin of the required large mass of particles is unclear.

[5] While a number of explanations for the existence of layers in solidified magma chambers rely on the presence of convecting layers within the molten chamber [Hodson, 1998], the origin of such layers remains uncertain. Double-diffusive convection has been suggested as a possible
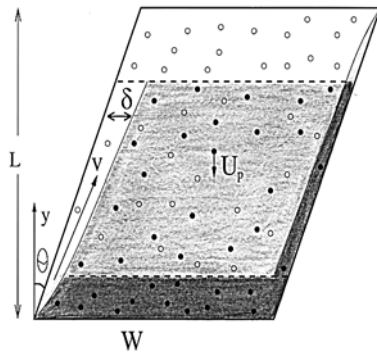
Figure 1. Heavy particles (dark circles) settling beneath an inclined wall give rise to an upward flowing, particle-free Boycott layer, seen as the pale layer. Conversely, bubbles (light circles) rising above an inclined wall generate a downward flowing, bubble-free Boycott layer, seen as the dark layer.

origin [*Jaupart and Tait*, 1995]; however, in magma chambers the temperature and compositional gradients are not independent, and numerical simulations suggest that no such steady layers may form [*Spera et al.*, 1986]. Time dependent layers may form by the heating from below of a compositional gradient [*Turner*, 1968; *Huppert and Linden*, 1979]. Other plausible layer-forming mechanisms include sidewall cooling (or heating) of stable a density gradient associated with either compositional variations [*Jaupart and Tait*, 1995; *Huppert and Turner*, 1980], or sedimenting particles. *Mendenhall and Mason* [1923] observed layers when a polydisperse suspension, vertically stratified through differential settling, was heated from the side; numerical simulations of this phenomena were performed by *Hosoi and Dupont* [1996].

[6] The layer-forming mechanism we consider relies on the interaction of suspended crystals and/or bubbles with sloping walls and an ambient stratification. *Boycott* [1920] reported that the settling of a suspension is enhanced in an inclined container relative to that in a vertical one owing to the convective motions associated with the buoyant particle-free layer that forms by particle settling beneath the sloping upper wall. A theoretical description of the flow was later given by *Hill et al.* [1977] and *Acrivos and Herbolzheimer* [1979]. The influence of an ambient stratification on the Boycott effect has recently been investigated by *Peacock et al.* [2004]. The authors report that layers form throughout the system if the ambient stratification is sufficiently strong, thus modifying the transport of both particles and fluid. In section 2 we review the dynamics of the stratified Boycott effect and the resulting layering. In section 3 we consider its relevance to magma chambers.

2. The Boycott Effect

[7] The Boycott effect occurs when a suspension of relatively dense particles underlies an inclined wall (Figure 1). The standard theoretical description of the Boycott effect applies provided the particle Reynolds number is small and the particle concentration sufficiently low that particle-particle interations may be neglected ($\phi \leq$

10%), [*Acrivos and Herbolzheimer*, 1979]. Particles settle away from the wall, creating a clear fluid layer whose thickness, δ, and tangential velocity, v, scale as

$$\delta \sim L\Lambda^{-1/3}, \qquad v \sim U_p\Lambda^{1/3}, \qquad (1)$$

where U_p is the particle settling speed, $\Lambda = (L/a)^2\phi$, a the particle size, L the height of the container and ϕ the particle volume fraction. In the context of magma chambers, Λ is typically large, of the order of 10^6. In the absence of a source of particles, the Boycott effect is maintained as long as particles remain in suspension i.e., for a time $t_b \sim L/U_p$. The Boycott effect also occurs when fluid containing buoyant particles, such as bubbles, overlies an inclined wall; here, bubbles rise away from the wall leaving relatively dense fluid that sinks accordingly. In a magma chamber, both effects may occur simultaneously, giving rise to Boycott layers on both the upper and lower chamber walls, as shown schematically in Figure 1.

[8] The presence of a stratified ambient may significantly alter the Boycott effect. If the ambient is stably stratified, the buoyancy of the fluid ascending within the Boycott layer diminishes progressively with height. Provided the vertical density gradient, $d\rho/dy$, is sufficiently strong, the ascent of fluid in the Boycott layer will be arrested at a height

$$H = \frac{\phi\Delta\rho}{d\rho/dy}, \qquad (2)$$

where $\Delta\rho$ is the density difference between particles and the ambient fluid: the fluid intrudes at a height where the density difference due to the absence of particles is matched by that due the stratifying component [*Peacock et al.*, 2004]. If the layer height exceeds the vertical extent of the container, $H > L$, the Boycott effect simply serves as a mixing mechanism in transporting relatively dense fluid from the base to the top of the tank and so eroding the initially stable density gradient. If $H < L$, fluid in the Boycott layer becomes neutrally buoyant and intrudes into the bulk, giving rise to a series of well-mixed convecting layers with vertical extent of order H (see Figure 2). We note that this physical picture requires that the settling time
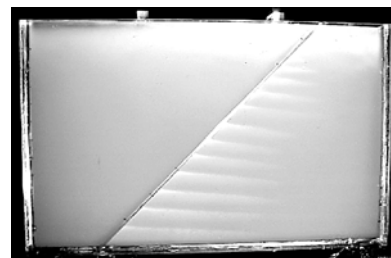
Figure 2. Laboratory demonstration of layers resulting from the combination of the Boycott effect and ambient stratification. The container shown here is 25cm high and contains salt stratified water ($d\rho/dz = -150$kg/m^4) in which a suspension of 4μm glass particles of volume fraction 0.3% is left to settle. Clear fluid intrudes in the ambient from the inclined wall, thus forming a sequence of convecting layers.

Table 1. Estimates for the Range of Relevant Physical Parameters in Magma Chambers

Parameters	Value	References
Height	100m to 10km	*McMillan et al.* [1989], *Spera et al.* [1986], *Smith* [1979]
η	10^1 to 10^{10} Poise	*Shaw* [1972], *McMillan et al.* [1989]
ρ	2.5 to 3.0 g/cm^3	*McMillan et al.* [1989], *Sparks et al.* [1993]
ϕ Crystals/Bubbles	0% to 10%vol.	*Sparks et al.* [1993], *McMillan et al.* [1989]
Crystal/Bubble size	0.1mm to 3cm	*Jellinek and Kerr* [2001], *Sahagian and Maus* [1994]
$\frac{\Delta\rho}{\rho}$	0% to 5%	*McMillan et al.* [1989], *Hodson* [1998], *Spera et al.* [1986]
κ	10^{-11} to 10^{-13} m^2/s	*Jellinek and Kerr* [2001]

of particles across the Boycott layer, t_s, be less than the diffusion time of the stratifying component, t_d, i.e.,

$$t_s = \frac{\delta}{U_p} \ll \frac{\delta^2}{\kappa} = t_d \qquad (3)$$

where κ is the diffusion constant of the stratifying component. Assuming particles settle at low Reynolds number, and using equation (1), this condition is satisfied provided

$$1 \ll \frac{t_d}{t_s} \sim \frac{a^{8/3} L^{1/3} g \Delta\rho}{\phi^{1/3} \kappa \eta}. \qquad (4)$$

where η is the fluid viscosity. This inequality is generally satisfied for magma chambers, as discussed in section 3; we thus anticipate that the Boycott effect provides a plausible mechanism for layer formation within magma chambers.

3. Relevance to Magma Chambers

[9] Layer formation through the stratified Boycott effect requires the combination of three factors: sloping walls, positively or negatively buoyant suspended material and a stratified ambient. The geometry of magma chambers is such that the presence of sloping walls is inevitable. Crystals are present in magma chambers [*Sparks et al.*, 1993] and those that do not attach themselves to the boundaries will settle in the bulk. Similarly, volatiles nucleating throughout the chamber will be suspended in the magma [*Jaupart and Tait*, 1995]. As the magma chamber cools sufficiently that thermal convection is suppressed, thermal or compositional gradients may result in a stable stratification [*Hodson*, 1998]. Thus all the components necessary for the formation of convecting layers through the stratified Boycott effect are generally present in the latter stages of magma chambers evolution. We proceed by describing the relevant parameters in more detail.

[10] The size of crystals and bubbles in magma chambers varies widely, but is usually assumed to be of the order of 1mm [*Sahagian and Maus*, 1994]. The density difference between crystals and the ambient magma is approximately 0.5g/cm^3, while that of bubbles is approximately -2.5g/cm^3 [*Sparks et al.*, 1993]. Bubble volume fractions are usually less than 10% [*Sahagian and Maus*, 1994] while crystal concentrations may be arbitrarily large. The Boycott effect is only significant for concentrations greater than 0.1%: if too few particles are present, the upflow in the Boycott layer is comparable to the particle settling speed. Temperature and compositional variations, in addition to the presence of particles, significantly affect the magma viscosity. A typical estimate for the viscosity of the molten magma, η, is 5 $\times$

10^5 Poise [*Shaw*, 1972], but estimates vary by a factor of 10^4. Throughout the body of the chamber, compositional gradients may form through magma differentiation, and it is commonly thought that the total density changes by approximately 5% from top to bottom, SiO_2 being the principal stratifying agent [*Spera et al.*, 1986; *Hodson*, 1998]. The parameters relevant to the dynamics of magma chambers are summarized in Table 1.

[11] We proceed by quantifying the time and length scales that would characterize layers formed in a magma chamber by the stratified Boycott effect. Considering a compositional diffusion coefficient of 10^{-12} m^2/s [*Jellinek and Kerr*, 2001], we see from equation (4) that $t_d/t_s \sim 10^5$; consequently, one expects the Boycott effect to operate within magma chambers and to dominate the layering mechanisms driven by double-diffusive effects. For a chamber height of 100m, if the density varies by 5% about a mean density of 2500kg/m^3, the resulting density gradient is $d\rho/dy = (0.05 \cdot 2500 \text{ kgm}^{-3})/100$m $= 1.25$kg/m^4. The particle weight fraction for magma containing 1% of crystals is approximately $0.01 \cdot 500$kg/m$^3 = 5$kg/m^3. Using equation (2), this yields a typical convecting layer size of about 4m. Given the broad range of particle concentrations and density gradients, however, this layer size could conceivably vary from 1m to 1km. Equation (1) yields a timescale of layer development $t = H/v$ of the order of one month; however, the wide range of particle sizes and viscosities allows for this timescale to vary from days to years. Finally, we note that crystallization in the bulk will continually drive the Boycott effect and thus maintain the convecting layers.

4. Discussion

[12] Magma chambers marked by the stratified Boycott effect may leave layered deposits such as those found in field observations via two distinct mechanisms. A schematic illustration of layering within a magma chamber prompted by the stratified Boycott effect is presented in Figure 3. The chamber can solidify as a whole, the layered rock structure thus being a record of the succession of frozen convecting cells either driven by crystals (point A in Figure 3) or bubbles (B). Alternatively the presence of convecting layers could generate layered deposits at the base of the chamber. Since each layer acts as a well-mixed convecting cell, one expects it to maintain a relatively uniform temperature within. The crystallization of an appreciable quantity of magma may occur when the temperature in the upper, and typically coolest, layer falls below a critical value, (point C in Figure 3); the resulting crystals might then sink and spread as a gravity current, depositing a layer of crystals (point D). We estimate the
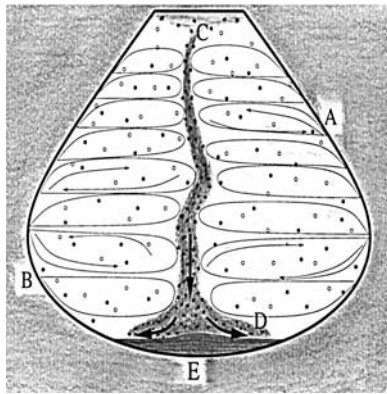
Figure 3. The stratified Boycott effect may form convecting layers in magma chambers (*A−B*). As the top layer cools (*C*), crystals may form and sink to the bottom, resulting in a particle-laden gravity current (*D*) that spreads and deposits a layer of crystals at the base of the chamber. Repetition of this process may yield a layered deposit corresponding to the strata observed in solidified magma chambers (*E*).

velocity scale, u_c, of the gravity current from the balance of buoyancy and viscous forces: $\eta\, u_c/H^2 \sim g\phi\Delta\rho$ which suggests a spreading time, $t_c \sim L/u_c$ of the order of a day. The thickness of this deposit is expected to be smaller than that of the convecting layers in the bulk of the chamber (and determined by the volume fraction of particles that settle out), and so be consistent with observations of layers having a thickness of order 20cm [*Hodson*, 1998]. The repetition of this process, through the crystallization of successive layers, then leads to an accumulation of chemically distinct layers at the base of the chamber (point *E*). According to this physical picture, the layers observed within the solidified chambers are a signature of the cooling of successive layers within the chamber.

[13] Our discussion of the Boycott effect has focused on the physical picture appropriate for monodisperse suspensions, but crystals and bubbles in a magma chamber are likely to be of various sizes. The influence of polydispersity on the Boycott effect was examined by *Schaflinger* [1985] who found that the dynamics of the flow are qualitatively unchanged; the layer formation mechanism and size are therefore not likely to be strongly influenced by polydispersity. Notice that crystal growth in the convecting layer occurs over a timescale of decades [*Cashman*, 1993], and so is expected to have a negligible impact on the convective motions driven by the Boycott effect. However, the simultaneous presence of volatiles and crystals in a magma chamber could lead to the formation of two Boycott layers, as shown in Figure 1. In a stratified ambient the Boycott layer with the largest volume flux is then expected to dominate and prescribe the vertical extent of the horizontal layers.

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