Physical Controls of Nucleation, Growth, and Migration of Vapor Bubbles in Partially Molten Cumulates

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The interstitial melt in partially molten cumulate piles in layered intrusions must at some point reach saturation with a volatile phase such as water vapor or hydrosaline melt. A number of models have been proposed in which orthomagmatic fluids migrate through partially solidified cumulates and participate in the formation of ore deposits. Here I examine the topology of the crystal-melt-vapor system in a cumulate and relate this to the role of capillary forces in governing the size and mobility of individual vapor bubbles. Small bubbles can rise unimpeded through the pore network, but their small sizes place limits on the distances they can travel by Stokes flow—if they rise more slowly than new crystals are deposited at the top of the pile, then they will never escape. Small bubbles tend to grow by Ostwald ripening even if the melt is not supersaturated with vapor, thereby becoming stranded in pore chambers where four crystals meet. The capillary force preventing them from squeezing from pore chambers into the narrower pore throats along three-crystal contact lines greatly exceeds their buoyancy and also exceeds the force imposed by upward flow of interstitial melt during compaction. Capillary forces will play a dominant role in setting the number density and sizes of bubbles. If bubbles are forming by homogeneous nucleation, then calculations with classical nucleation theory show that it is possible that nucleation will occur after considerable supersaturation, at widely spaced sites, allowing for the growth of a small number of bubbles large enough that their buoyancy overcomes the capillary forces. However, homogeneous nucleation is highly unlikely given the large number of possible sites for heterogeneous nucleation in a compacting cumulate; indeed, it is likely that geometric effects promote metastable vapor saturation even before the amount of dissolved volatiles in the bulk interstitial liquid has reached its equilibrium vapor saturation concentration.

In any cumulate rock with crystals smaller than several cm in diameter, bubbles of the postcumulus aqueous phase will generally be unable to migrate away from their sites of nucleation and growth. Although bubble stranding does not preclude the eventual loss of volatile constituents from the cumulate after complete solidification, it does prevent such constituents from migrating while the system remains partially molten and therefore prohibits them from participation in magmatic-hydrothermal interactions within the magma chamber. I conclude that vapor transport of metals through cumulates is not a viable mechanism for the generation of ore deposits while silicate melt persists in the system. Instead, volatile transport of metals must occur either while the magma is predominantly composed of liquid or after solidification is complete.