

## Amphibole thermometers and barometers for igneous systems and some implications for eruption mechanisms of felsic magmas at arc volcanoes

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### ABSTRACT

Calcic, igneous amphiboles are of special interest as their compositional diversity and common occurrence provide ample potential to investigate magmatic processes. But not all amphibole-based barometers lead to geologically useful information: recent and new tests reaffirm prior studies (e.g., Erdman et al. 2014), indicating that amphibole barometers are generally unable to distinguish between experiments conducted at 1 atm and at higher pressures, except under highly restrictive conditions. And the fault might not lie with experimental failure. Instead, the problem may relate to an intrinsic sensitivity of amphiboles to temperature ( $T$ ) and liquid composition, rather than pressure. The exceptional conditions are those identified by Anderson and Smith (1995): current amphibole barometers are more likely to be useful when  $T < 800$  °C and  $Fe\#^{Amp} = Fe^{Amp}/(Fe^{Amp}+Mg^{Amp}) < 0.65$ . Experimentally grown and natural calcic amphiboles are here used to investigate amphibole solid solution behavior, and to calibrate new thermometers and tentative amphibole barometers that should be applicable to igneous systems generally.

Such analysis reveals that amphiboles are vastly less complex than may be inferred from published catalogs of end-member components. Most amphiboles, for example, consist largely of just three components: pargasite [ $NaCa_2(Fm_4Al)Si_6Al_2O_{22}(OH)_2$ ], kaersutite [ $NaCa_2(Fm_4Ti)Si_6Al_2O_{23}(OH)$ ], and tremolite + ferro-actinolite [ $Ca_2Fm_5Si_8O_{22}(OH)_2$ , where  $Fm = Fe+Mn+Mg$ ]. And nearly all remaining compositional variation can be described with just four others: aluminio-tschermakite [ $Ca_2(Fm_3Al_2)Si_6Al_2O_{22}(OH)_2$ ], a Na-K-gedrite-like component [ $(Na,K)Fm_6AlSi_6Al_2O_{22}(OH)_2$ ], a ferri-ferrotschermakite-like component [ $Ca_2(Fm_3Fe_2^+)Si_6Al_2O_{22}(OH)_2$ ], and an as yet unrecognized component with 3 to 4 Al atoms per formula unit (apfu), 1 apfu each of Na and Ca, and <6 Si apfu, here termed aluminous kaersutite:  $NaCaFm_4Ti(Fe^{3+},Al)Si_5Al_3O_{23}(OH)$ . None of these components, however, are significantly pressure ( $P$ ) sensitive, leaving the Al-in-amphibole approach, with all its challenges, the best existing hope for an amphibole barometer. A new empirical barometer based on  $D_{Al}$  successfully differentiates experimental amphiboles crystallized at 1 to 8 kbar, at least when multiple  $P$  estimates, from multiple amphibole compositions, are averaged. Without such averaging however, amphibole barometry is a less certain proposition, providing  $\pm 2$  kbar precision on individual estimates for calibration data, and  $\pm 4$  kbar at best for test data; independent checks on  $P$  are thus needed. Amphibole compositions, however, provide very effective thermometers, here based on  $D_{Ti}$ ,  $D_{Na}$ , and amphibole compositions alone, with precisions of  $\pm 30$  °C. These new models, and tests for equilibrium, are collectively applied to Augustine volcano and the 2010 eruption at Merapi. Both localities reveal a significant cooling and crystallization interval ( $>190$ – $270$  °C) at pressures of 0.75 to 2.2 kbar at Augustine and Merapi, respectively, perhaps the likely depths from which pre-eruption magmas are stored. Such considerable intervals of cooling at shallow depths indicate that mafic magma recharge is not a proximal cause of eruption. Rather, eruption triggering is perhaps best explained by the classic “second boiling” concept, where post-recharge cooling and crystallization drive a magmatic system toward vapor saturation and positive buoyancy.

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