## Magma Dynamics

### Applications of the refined clinopyroxene-based hygrometer from this study to magma dynamics at Mt. Etna volcano

The plumbing system at Mt. Etna is governed by frequent inputs from mantle depths of primitive, volatile-rich magmas into shallower crustal reservoirs (Ferlito et al. 2008; Corsaro et al. 2013; Mollo et al. 2015a). This continuous magma supply causes an almost constant degree of differentiation for the erupted products that are systematically buffered to the composition of a trachybasalt (Armienti et al. 2004). Despite the apparent uniformity of the trachybasalt eruptions, however, volcanic activity is none the less supplied by magma batches that retain subtle differences in their *P*-*T* paths of ascent (Armienti et al. 2013). Prehistoric eccentric cones at Mt. Etna had occasionally erupted primitive (MgO > 7 wt.%) basaltic lava flows (i.e., Mt. Maletto eruption) dominated by olivine and clinopyroxene phenocrysts (~7 vol.%) with plagioclase confined to the groundmass. At high pressure, most of the volatiles are retained into the magma and/or exsolve very slowly allowing efficient degassing and hindering bubble growth, being this latter the parameter dictating the volume expansion and acceleration of magma (Gonnermann and Manga 2012). At $P >$ 400 MPa and $T >$ 1,150 °C, Armienti et al. (2013) found that most of the primitive, deep-seated Etnean magmas migrate very slowly with initial ascent velocities of 0.4–4 × $10^{-3}$ m/s. These primitive magmas tend to preserve their original compositions during slow ascent at depth; in fact, fractional crystallization modelling (Corsaro et al. 2013), thermodynamic calculations (Mollo et al. 2015a) and phase equilibria experiments (Vetere et al. 2015) point out that the segregation of 10–20 vol.% of phenocrysts at depth is the maximum admissible value to explain the persistent eruption of magmas buffered to trachybasaltic compositions.

Conversely, at shallower crustal levels, Etnean magmas are more differentiated (MgO < 6 wt.%) and undergo strong degassing and crystallization while travelling from the conduit to the surface (Métrich et al. 2004; Spilliaert et al. 2006; Collins et al. 2009). Melt inclusion data document as volatile-rich magmas decompressed from 400 to 100 MPa become extensively depleted in $CO_2$ (~0.05 wt.%) but still keep a relatively high $H_2O$ content (~2.5 wt.%). Coherently, the refined hygrometer from in this study predicts that extensive magma fragmentation and crystallization of the most energetic lava fountains is accompanied by a substantial degassing ($H_2O$ < 2.5 wt.%) in the uppermost portions ($P <$ 100 MPa) of the volcanic conduit (Fig. 2d). Similarly, S (~0.3 wt.%), Cl (~0.3 wt.%), and F (~0.15 wt.%) start to exsolve from the Etnean trachybasaltic magmas at the low pressures of ≤140 MPa, <100 MPa, and ≤10 MPa, being eventually degassed at >95%, 22–55%, and ~15% during eruption (Spilliaert et al. 2006). Degassing-driven crystallization is also the key mechanism controlling the final crystal growth when most of the $H_2O$ dissolved in the melt is rapidly exsolved (Mollo et al. 2015a), in concert with the upward acceleration of magma in the shallower parts of the plumbing system (Armienti et al. 2013 and references therein). This applies to lava fountain episodes at Mt. Etna volcano ascending with fast velocities of 0.01–0.31 m/s (Mollo et al. 2015b) that are close to those measured in other open-conduit degassing systems, e.g., Hawaii (0.01-0.04 m/s; Rutherford 2008; Gonnermann and Manga 2012), Unzen (0.01-0.07 m/s; Toramaru et al., 2008) and Mount St. Helens (0.01-0.15 m/s; Rutherford and Hill 1993). If volatiles are released to a vapor phase retained in the magmatic suspension, the buoyancy of the whole magma increases significantly providing explanation for the increasing ascent velocity with decreasing pressure. Indeed, both rapid decompression and shallow $H_2O$ exsolution lead to expansion-driven acceleration by bubble coalescence with the consequent formation of a sustained magma fountain above the volcanic vent (Gonnermann and Manga 2012 and references therein).

Differently to primitive, volatile-rich magmas stored in the deeper parts of the plumbing system, the crystallization of Etnean magmas travelling in the upper conduit regions is strictly controlled by volatile exsolution and degassing. Under such circumstances, the near-equilibrium crystal growth condition in the magmatic reservoir shifts to a rapid crystal growth condition from the conduit to the surface. This is particularly evident for the crystallization of plagioclase and titanomagnetite phenocrysts that is controlled by strong disequilibrium effects caused by magma undercooling and decompression (Applegarth et al. 2013; Giacomoni et al. 2014; Mollo et al. 2015a). On eruption, the phenocryst and microphenocryst content of magma is up to 50 vol.% but a great number of plagioclase and titanomagnetite nucleate and grow by degassing- and cooling-driven crystallization mechanisms (Applegarth et al. 2013). The crystal-rich nature of Etnean products mostly reflects the rapid growth of plagioclase and titanomagnetite upon the effects of magma undercooling and fast ascent times in the order of 0.2–7 h (Applegarth et al. 2013). While the use of plagioclase-based hygrometers is restricted to the final segment of the volcanic conduit, the refined hygrometer from this study has the noteworthy implication that clinopyroxene starts to equilibrate at depth recording the entire decompression and degassing path of magmas at Mt. Etna volcano (Fig. 2d).

**References**

Applegarth, L.J., Tuffen, H., James, M.R., Pinkerton, H., Cashman, K.V. (2013) Direct observations of degassing-induced crystallization in basalts. Geology, 41, 243–246.

Armienti, P., Tonarini, S., D'Orazio, M. and Innocenti, F. (2004) Genesis and evolution of Mount Etna alkaline lavas: Petrological and Sr-Nd-B isotope constraints. Periodico di Mineralogia, 73, 29-52.

Armienti, P., Perinelli, C. and Putirka, K.D. (2013) A new model to estimate deep-level magma ascent rates, with applications to Mt. Etna (Sicily, Italy). Journal of Petrology, 54, 795-813.

Collins, S.J., Pyle, D.M. and Maclennan, J. (2009) Melt inclusions track pre-eruption storage and dehydratation of magmas at Etna. Geology, 6, 571–574.

Corsaro, R.A., Di Renzo, V., Distefano, S., Miraglia, L. and Civetta, L. (2013) Relationship between petrologic processes in the plumbing system of Mt. Etna and the dynamics of the eastern flank from 1995 to 2005. Journal of Volcanology and Geothermal Research, 251, 75-89.

Ferlito, C., Viccaro, M. and Cristofolini, R. (2008) Volatile-induced magma differentiation in the plumbing system of Mt. Etna volcano (Italy): evidence from glass in tephra of the 2001 eruption. Bulletin of Volcanology, 70, 455–473.

Giacomoni, P.P., Ferlito, C., Coltorti, M., Bonadiman, C. and Lanzafame, G. (2014) Plagioclase as archive of magma ascent dynamics on "open conduit" volcanoes: the 2001–2006 eruptive period at Mount Etna. Earth-Sciences Reviews, 138, 371–393.

Gonnermann, H.M. and Manga, M. (2012) Magma ascent in the volcanic conduit. In: Fagents, S.A., Gregg, T.K.P., Lopez, R.C. (Eds.), Modelling Volcanic Processes: The Physics and Mathematics of Volcanism. Cambridge University Press, 55–84.

Métrich, N., Allard, P., Spilliaert, N., Andronico, D. and Burton, M. (2004) 2001 flank eruption of the alkali- and volatile-rich primitive basalt responsible for Mount Etna's evolution in the last three decades. Earth and Planetary Science Letters, 228, 1-17.

Mollo, S., Giacomoni, P.P., Coltorti, M., Ferlito, C., Iezzi G. and Scarlato, P. (2015a) Reconstruction of magmatic variables governing recent Etnean eruptions: constraints from mineral chemistry and P-T-fO2-H2O modelling. Lithos, 212-215, 311-320, DOI: 10.1016/j.lithos.2014.11.020.

Mollo, S., Giacomoni, P.P., Andronico, D. and Scarlato, P. (2015b) Clinopyroxene and titanomagnetite cation redistributions at Mt. Etna volcano (Sicily, Italy): Footprints of the final solidification history of lava fountains and lava flows. Chemical Geology, 406, 45-54, DOI: 10.1016/j.chemgeo.2015.04.017.

Putirka, K. (2008) Thermometers and barometers for volcanic systems. In: Putirka K, Tepley F (eds) Minerals, inclusions and volcanic processes, vol. 69, Reviews in mineralogy and geochemistry. Mineralogical Society of America, Chantilly, VA, USA, 61–120.

Rutherford, M.J. (2008) Magma ascent rates. Review in Mineralogy and Geochemistry, 69, 241–271.

Rutherford, M.J. and Hill, P.M. (1993) Magma ascent rates from amphibole breakdown: experiments and the 1980–1986 Mount St. Helens eruptions. Journal of Geophysical Research, 98, 19667–19685.

Spilliaert, N., Allard, P., Métrich, N. and Sobolev, A.V. (2006) Melt inclusion record of the conditions of ascent, degassing, and extrusion of volatile-rich alkali basalt feeding the powerful 2002 flank eruption of Mount Etna (Italy). Journal of Geophysical Research, 111, B04203.

Toramaru, A., Noguchi, S., Oyoshihara, S., and Tsune, A. (2008) MND (microlite number density) water exolution rate meter. Journal of Volcanology and Geothermal Research, 175, 156-167.

Vetere, F., Mollo, S., Giacomoni, P.P., Iezzi, G., Coltorti, M., Ferlito, C., Holtz, F., Perugini, D. and Scarlato, P. (2015) Experimental constraints on the origin of pahoehoe "cicirara" lavas at Mt. Etna Volcano (Sicily, Italy). Bulletin of Volcanology, in press, DOI: 10.1007/s00445-015-0931-1.