



Highly explosive basaltic eruptions: magma fragmentation induced by rapid crystallisation

Fabio Arzilli

Giuseppe La Spina, Mike R. Burton, Margherita Polacci, Nolwenn Le Gall,
Margaret E. Hartley, Danilo Di Genova, Biao Cai, Nghia T. Vo, Emily C.
Bamber, Sara Nonni, Robert C. Atwood, Richard Brooker; Heidi Mader;
Edward W. Llewellyn & Peter D. Lee

Abstract

Basaltic eruptions are the most common form of volcanism on Earth and planetary bodies. The low viscosity of basaltic magmas generally favours effusive and mildly explosive volcanic activity. Highly explosive basaltic eruptions occur less frequently and their eruption mechanism still remains subject to debate, with implications for the significant hazard associated with explosive basaltic volcanism. Particularly, highly explosive eruptions require magma fragmentation, yet it is unclear how basaltic magmas can reach the fragmentation threshold.

In volcanic conduits, the crystallisation kinetics of an ascending magma are driven by degassing and cooling. So far, the crystallisation kinetics of magmas have been estimated through *ex situ* crystallization experiments. However, this experimental approach induces underestimation of crystallization kinetics in silicate melts. The crystallization experiments reported in this study were performed *in situ* at Diamond Light Source (experiment EE12392 at the I12 beamline), Harwell, UK, using basalt from the 2001 Etna eruption as the starting material. We combined a bespoke high-temperature environmental cell with fast synchrotron X-ray microtomography to image the evolution of crystallization in real time. After 4 hours at sub-liquidus conditions (1170 °C and 1150 °C) the system was perturbed through a rapid cooling (0.4 °C/s), inducing a sudden increase of undercooling. Our study reports the first *in situ* observation of exceptionally rapid plagioclase and clinopyroxene crystallisation in trachybasaltic magmas. We combine these constraints on crystallisation kinetics and viscosity evolution with a numerical conduit model to show that exceptionally rapid syn-eruptive crystallisation is the fundamental process required to trigger basaltic magma fragmentation under high strain rates. Our *in situ* experimental and natural observations combined with a numerical conduit model allow us to conclude that pre-eruptive temperatures <1,100°C can promote highly explosive basaltic eruptions, such as Plinian volcanism, in which fragmentation is induced by fast syn-eruptive crystal growth under high undercooling and high decompression rates. This implies that all basaltic systems on Earth have the potential to produce powerful explosive eruptions.

Examples of basaltic Plinian eruptions

122 B.C. Etna basaltic Plinian eruption (Italy)



Masaya complex basaltic Plinian eruptions (60 ka and 2.1 ka) (Nicaragua)



Fontana Lapilli Triple Layer

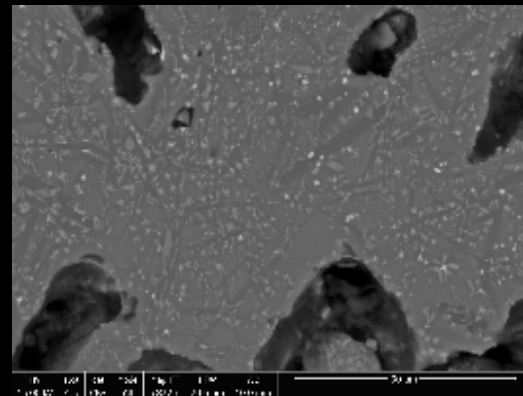
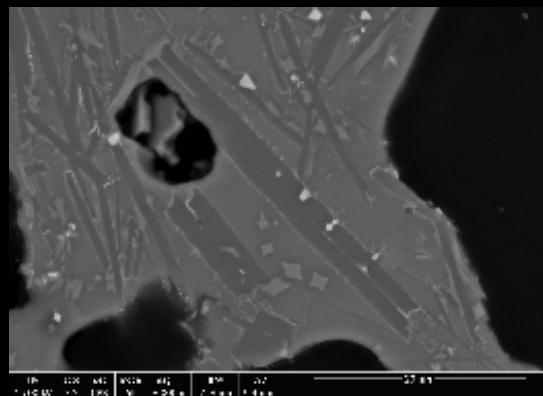
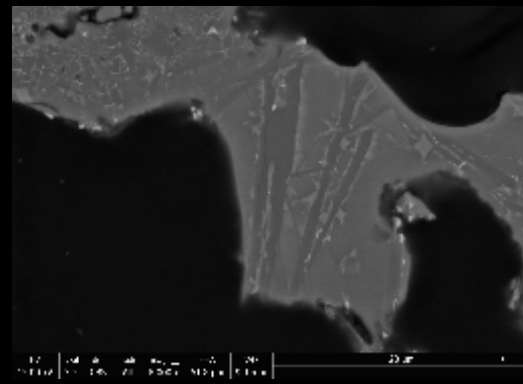
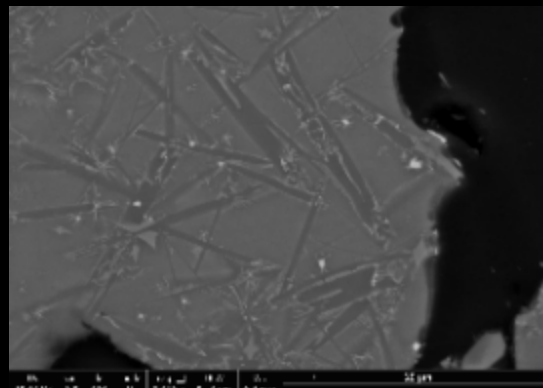
1886 Tarawera basaltic Plinian eruption (New Zealand)



Texture of basaltic Plinian eruptions

Etna 122 BC Plinian eruption

The microlite crystallisation in basaltic Plinian eruption products (i.e. Fontana Lapilli, Masaya Triple Layer, Tarawera 1886 and Etna 122 BC) is considered a consequence of large undercooling due to rapid magma ascent that increases the effective viscosity of the magma. This process theoretically should drive a basaltic magma to the fragmentation in a brittle manner analogous of silicic eruptions (Sable et al., 2006; Houghton and Gonnermann, 2008; Sable et al., 2009; Costantini et al., 2010; Szramek, 2016; Bamber et al., 2020). However, the main question is whether or not rapid magma ascent can inhibit crystallization within the conduit. This aspect has strong implication on the magma rheology during ascent as if crystallization occurs fast may change dramatically the magma viscosity, which can favor magma fragmentation.



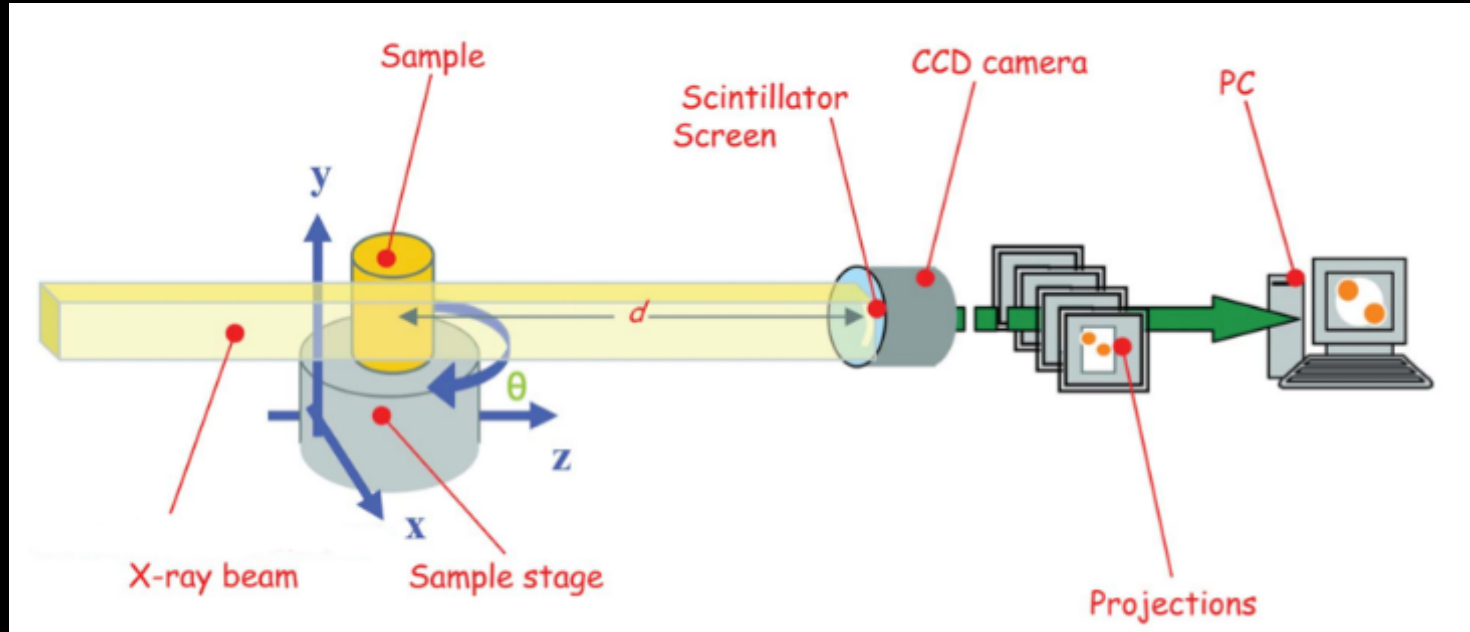
In situ High Temperature X-ray microtomography experiments

Diamond Light Source

The aim of these experiments is to constrain the timescales of plagioclase and pyroxene crystallization in real time during a fast perturbation of temperature conditions, imposing rapidly a large undercooling to the system. The experiments were performed at Diamond Light Source (beamline I12), Harwell, UK. For these experiments we used small cylindrical chips of Etna 2001 basaltic glass, which were heated in-situ in the Alice furnace up to 1250 °C for 30 minutes. After the initial annealing period, crystallisation was induced by decreasing temperature isobarically from 1250 °C to 1170 °C and 1150 °C, and then holding at the final temperature for 4 h. After this step, final cooling rates of 24 °C/min simulate rapid cooling in order to reach large undercooling in short time.

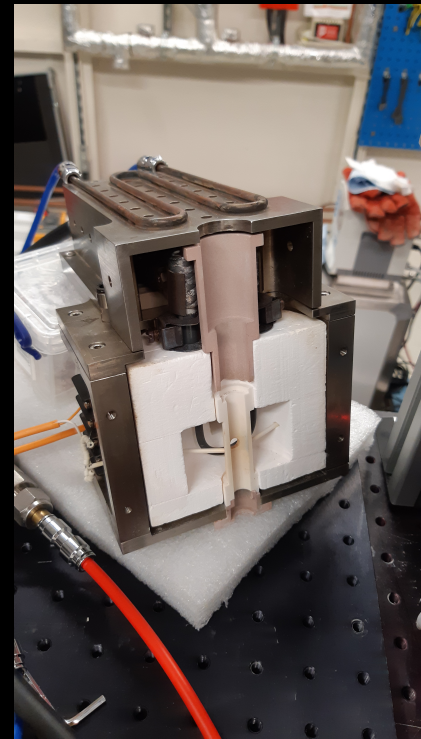
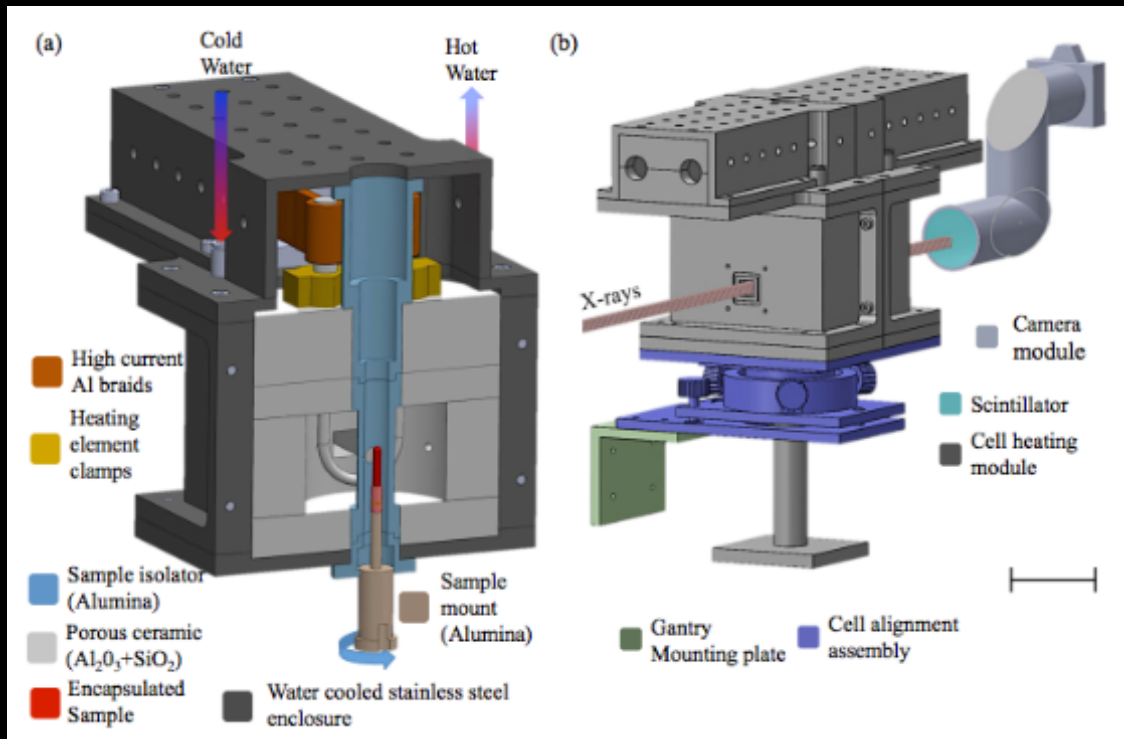


Schematic illustration of X-ray μ -CT acquisition and reconstruction processes



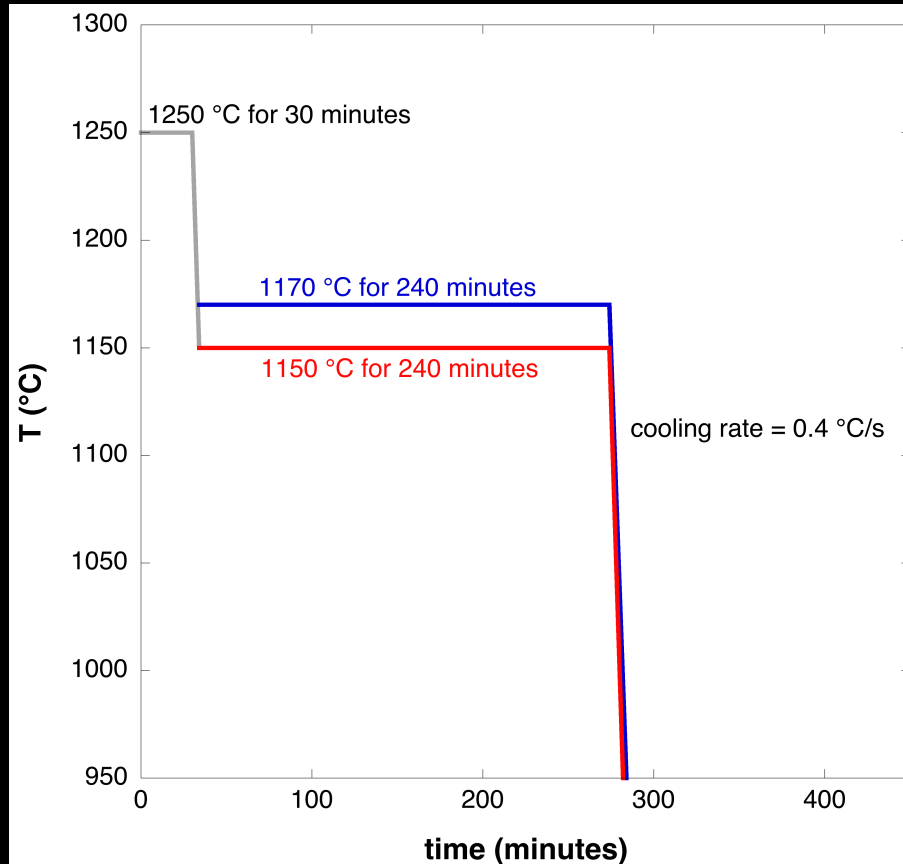
Alice furnace

Schematic of one half of environmental cell with heating and sample module and (b) schematic of the environmental cell setup at the I12 beamline of Diamond Light Source (Azeem et al. 2017). Scale bar = 32.5 mm.



Experimental approach

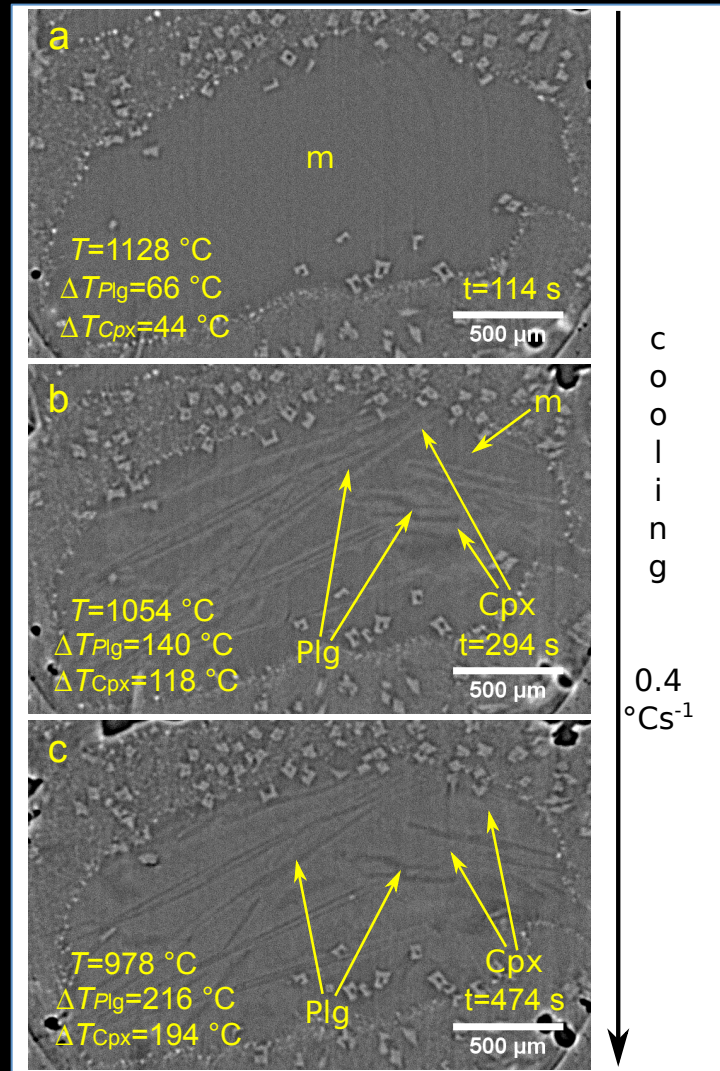
In situ 4D crystallisation experiments



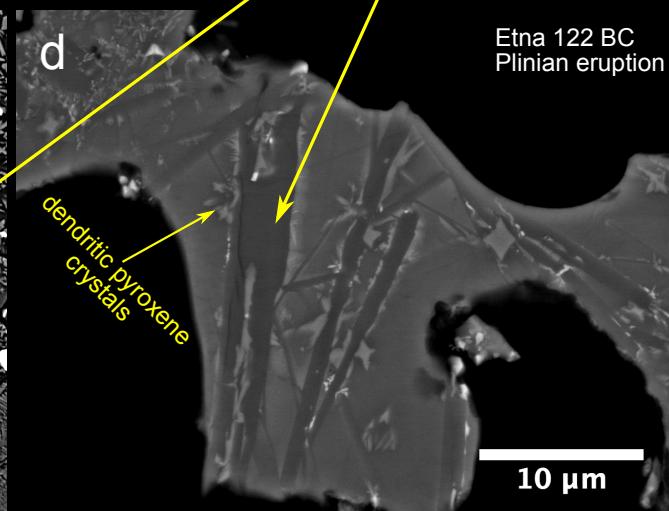
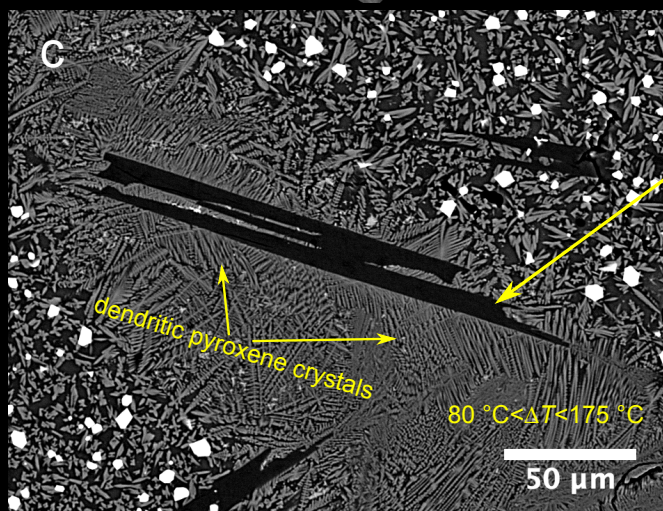
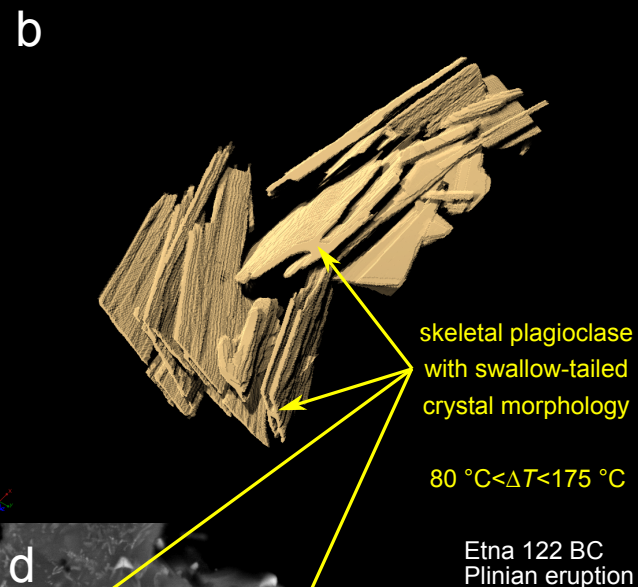
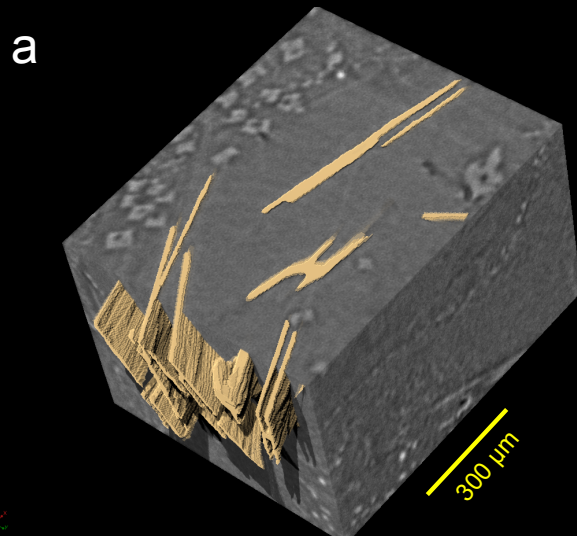
Schematic representation of the thermal paths used in this study.

Arzilli et al. 2019
(Nature Geoscience)

Crystallization through time during continuous cooling experiment from 1150 °C. Reconstructed axial slices during continuous cooling at 0.4 °C s⁻¹. a, The texture after 114 s from the onset of the cooling during which the temperature ranged between 1,144 and 1,112 °C (average 1,128 °C). b, The texture after 294 s during which the temperature ranged between 1,073 and 1,034 °C (average 1,054 °C). c, The texture after 474 s during which the temperature ranged between 997 and 959 °C (average 978 °C). m, melt; Plg, plagioclase; Cpx, clinopyroxene. The acquisition time of each frame is 90 s.



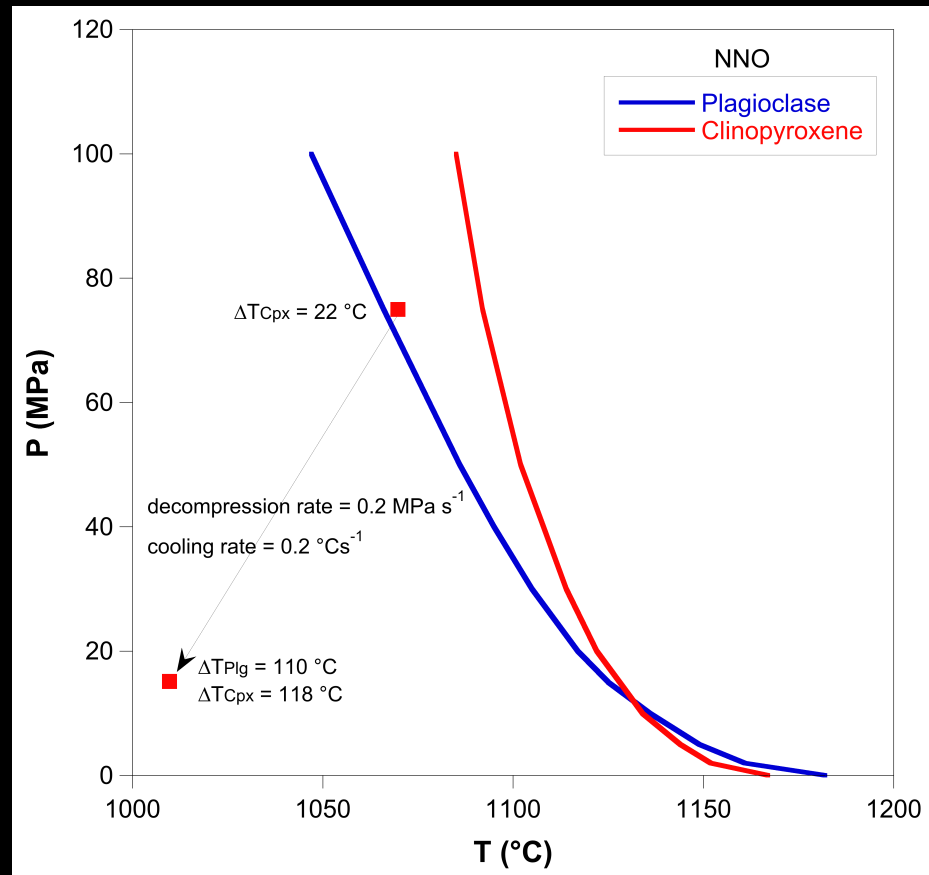
Plagioclase crystal morphology. **a**, The 3D volume rendering of sample cooled from 1150 °C shows the morphology and the spatial distribution of plagioclase crystals that formed during the rapid cooling at $80 < \Delta T < 175$ °C. **b**, 3D view of the plagioclase with a swallow-tailed crystal morphology. **c**, Back-scattered electron (BSE) image of plagioclase with a swallow-tailed crystal morphology. **d**, BSE image of plagioclase with a swallow-tailed crystal morphology produced during the Etna 122 bc Plinian eruption. Note the heterogeneous nucleation of pyroxene around plagioclase, seen as a light-coloured halo, and similar to that seen in Fig. 1b.



Ex situ crystallisation experiments using a TZM apparatus (University of Bristol)

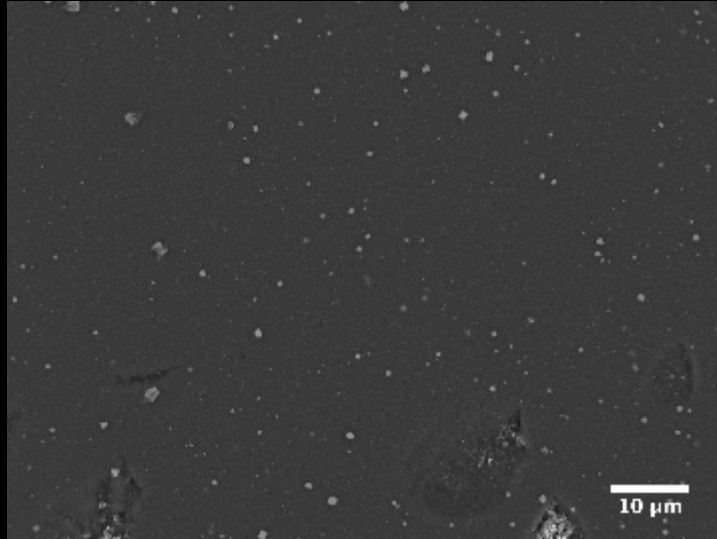
Ex situ experimental conditions of rapid cooling and decompression experiment. The experimental approach consisted of holding the sample for 30 minutes at 75 MPa and 1070 °C before decompressing and cooling. The first experiment was quenched after 30 minutes at 75 MPa and 1070 °C, in order to characterise the sample mineralogy and texture at the thermodynamic conditions prior to applying fast decompression and cooling. In the second experiment, after 30 minutes the pressure and temperature were decreased continuously over 300 s at rates of 0.2 MPa s⁻¹ and 0.2 °Cs⁻¹ respectively, reaching final conditions of 15 MPa and 1010 °C. The final pressure is the most probable fragmentation pressure as determined from numerical modelling. Decompression and cooling rates were predicted from the conduit model for magma ascent during basaltic Plinian eruptions. Plagioclase and clinopyroxene liquids were obtained with Rhyolite-MELTS software (version 1.2; Gualda et al., 2012; Giorso and Gualda, 2015), using the 2001 Etna trachybasaltic composition in H₂O saturated conditions.

Arzilli et al. 2019 (Nature Geoscience)



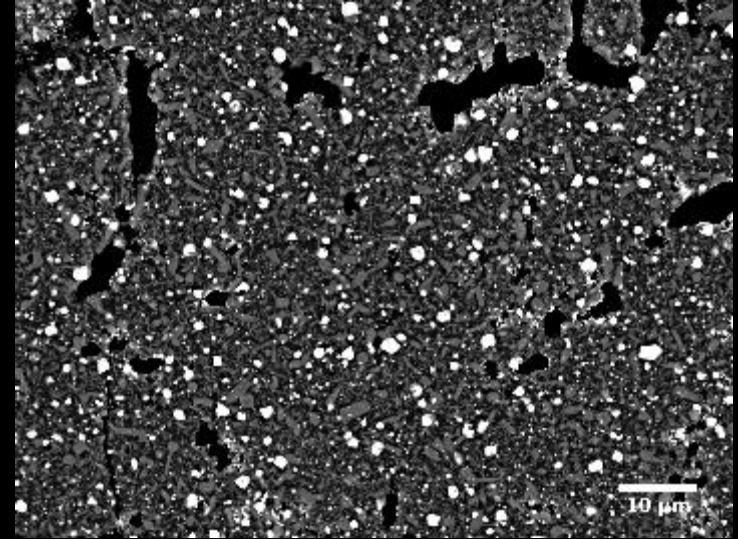
Results of *ex situ* crystallisation experiments

Initial conditions



1070 °C – 75 Mpa – 30 minutes

After cooling and decompression



1070 => 1010 °C: cooling rate $0.2\text{ }^{\circ}\text{C s}^{-1}$
75 => 15 MPa: decompression rate 0.2 MPa s^{-1}
Cooling and decompression last 5 minutes

Timescales of crystallisation

Characteristic time of crystallisation ($\tau^{(c)}$)

Characteristic time is a measure of how fast a process will approach equilibrium (i.e., within seconds, hours, days, or weeks)

Formally, the characteristic time reflects the time required to reduce the difference between the initial and the equilibrium value to e^{-1} ($\sim 37\%$) of the initial difference. This means that, if β_0 is the initial value of a physical parameter β (which, in our case, is the crystal volume fraction), and β^{eq} is the equilibrium value in response to a perturbation of the system, at the characteristic time t , we have

$$\beta(\tau) = \beta^{eq} + e^{-1} \beta_0 - \beta^{eq}.$$

Regarding the crystallisation process, the smaller the $\tau^{(c)}$, the faster crystals reach their equilibrium abundance

La Spina et al. (2016) demonstrate that ~ 5 times $\tau^{(c)}$ is the time required to reach the equilibrium crystal fraction in basalts

Constant conditions or slow perturbation of the $\Delta T \Rightarrow$ crystallisation time to reach equilibrium crystal abundance is ~ 2 hours $\Rightarrow \tau^{(c)} \sim 1000s$
(Arzilli et al 2015 CMP; La Spina et al 2016 Nat. Comm.)

Characteristic times

Rapid perturbation of ΔT

In situ crystallisation experiments

Plg crystallisation occurs in ~ 100 s \Rightarrow Characteristic time is ~ 20 s

Cpx crystallisation occurs in ~ 200 s \Rightarrow Characteristic time is ~ 40 s

Ex situ crystallisation experiments

Crystallisation occurs in 300 s \Rightarrow Characteristic time for crystallisation is ~ 60 s

Simulating conduit dynamic of 122 B.C. Etna Plinian eruption

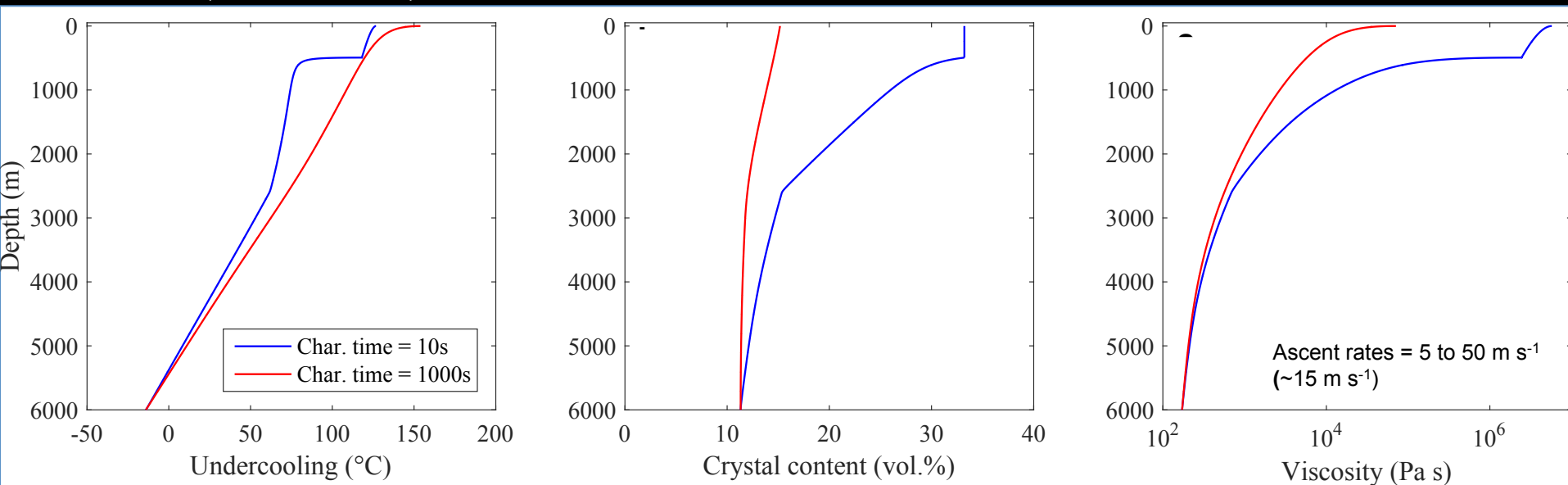


Conduit model developed by La Spina et al. 2016 (Nature Communications)

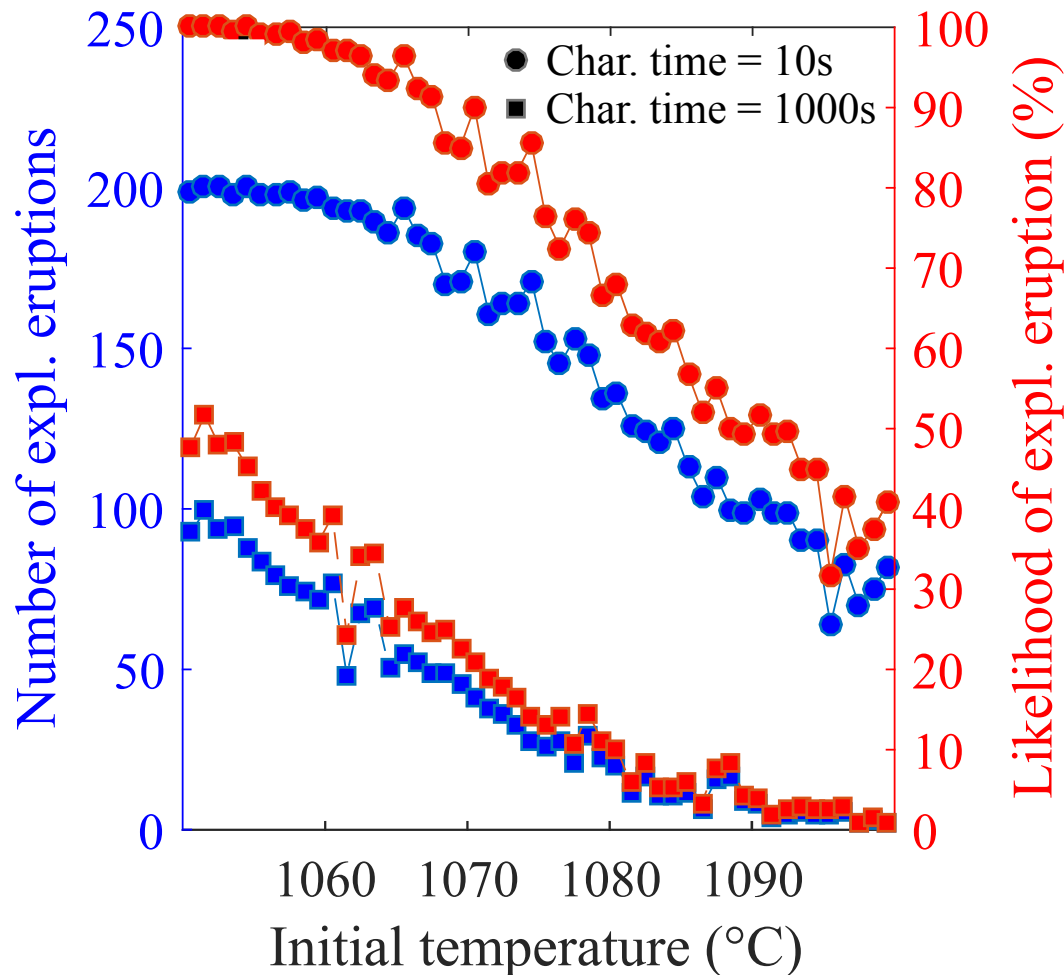
fragmentation model: strain rate criterion introduced by Papale (1999):

$$\dot{\gamma} = k \frac{G_{\infty}}{\mu}$$

Model results during magma ascent. **a**, Undercooling as a function of depth, calculated for $\tau(c) = 10$ (blue) and 1,000 s (red). Cooling is driven by the adiabatic expansion of gas, mitigated by the latent heat of crystallization, particularly in the fast crystallizing case. **b**, The crystal content demonstrates the rapid increase in crystal load when $\tau(c) = 10$ s. **c**, The magma viscosity demonstrates that the higher crystal load produces a 3–4 orders of magnitude increase in viscosity, which leads to fragmentation. Char, characteristic. Arzilli et al. 2019 (Nature Geoscience)



Frequency of explosive eruptions versus the magma temperature before ascent. Sensitivity analyses show that a lower initial temperature and a higher pre-eruptive crystal content result in a greater likelihood of explosive eruptions. This is consistent with estimates of pre-eruptive temperatures obtained for the Etna and Fontana Plinian eruptions, which range between 1,000 and 1,060 °C (Geopfert and Gardner, 2010).



Conclusion

Novel *in situ* experiments combined with conduit model reveal that fast perturbation of the system and high undercooling drive exceptionally rapid (minutes) crystallisation, inducing a step-change in viscosity that triggers magma fragmentation

Conditions that promote rapid crystallisation, a step-change in viscosity and triggering magma fragmentation:

Magma temperatures $< 1100\text{ }^{\circ}\text{C}$

$\Delta T = 80\text{-}175\text{ }^{\circ}\text{C}$

High decompression rates $> 0.1\text{ MPa s}^{-1}$

Fast ascent rates = $5\text{ to }50\text{ m s}^{-1}$

Syn-eruptive crystal content $> 30\text{ vol.}\%$

magma viscosity $\geq 10^6\text{ Pa s}$

all basaltic volcanoes have the potential to produce highly explosive eruptions