Fragility and an extremely low shear modulus of high porosity silicic magma

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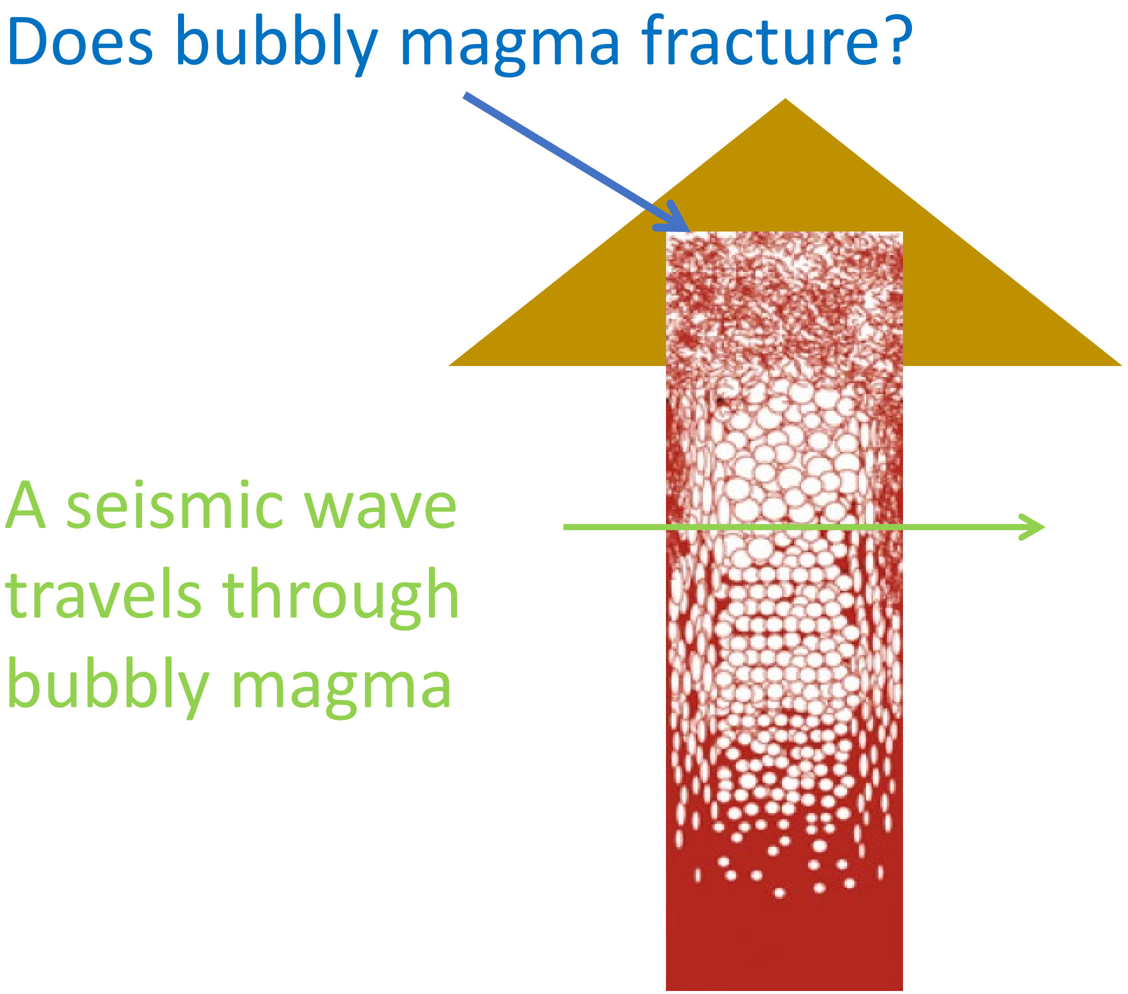
To understand the eruption dynamics, we measured the rheology and strength of high porosity rhyolite magma at 500–950 °C.

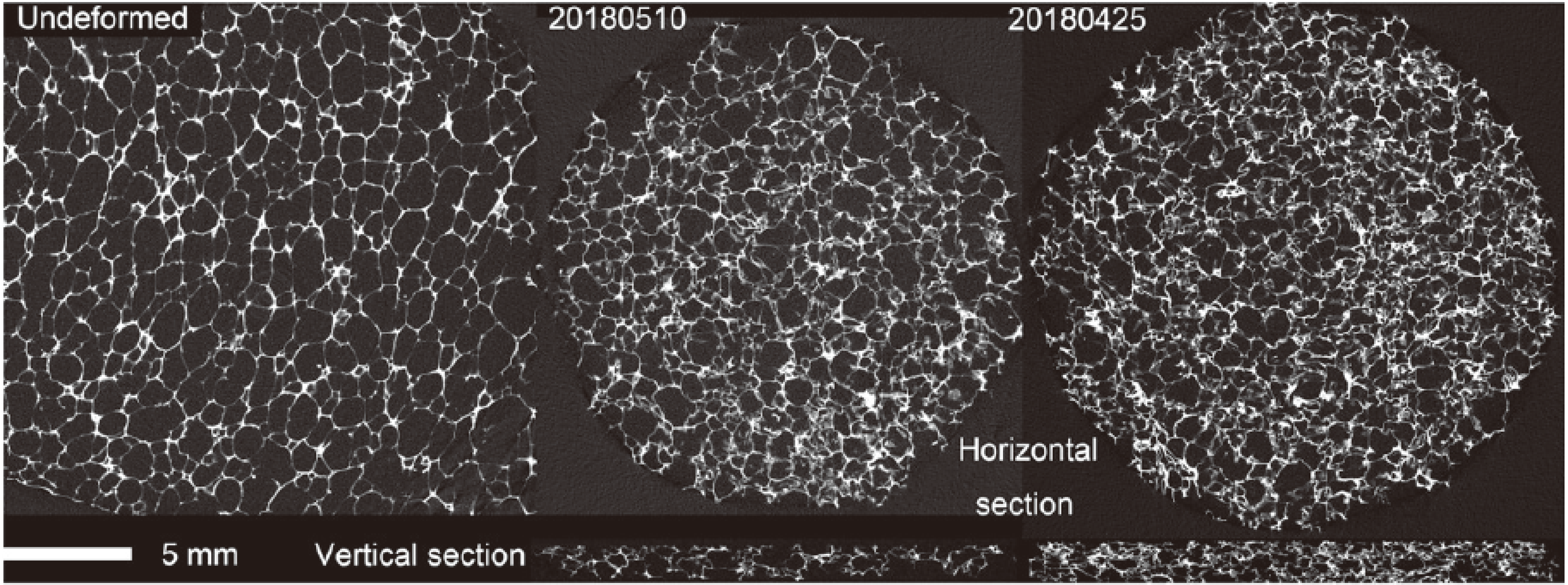
Motivation:



- Strength of the bubbly magma determines the possibility of fragmentation, which in turn regulates the possibility of explosive eruption.
- Shear modulus of bubbly magma determines the S-wave velocity.
- Q (inverse of the attenuation) of magma should represent the condition of magma.

We need to know Q, the strength and shear modulus of the bubbly magma.

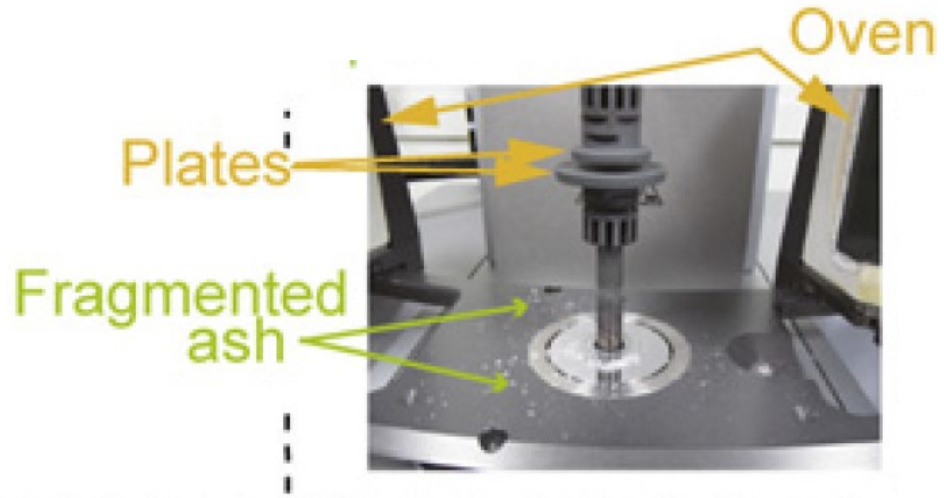
Used sample: we baked obsidian and made a high porosity samples, ϕ>0.86.



Before the deformation measurements

After the deformation measurements

Method: rheology measurement by oscillatory and one-directional shear deformation



We located the high porosity rhyolite between the plates and imposed shear deformation.

By oscillatory measurements, we obtain

$$\sigma_T = |G^*|\gamma_0 e^{i(\omega t+\delta)}$$

phase difference between the stress and strain.

From the phase difference, we obtain

$$Q = \frac{1}{\tan\delta} = \frac{G'}{G''}$$

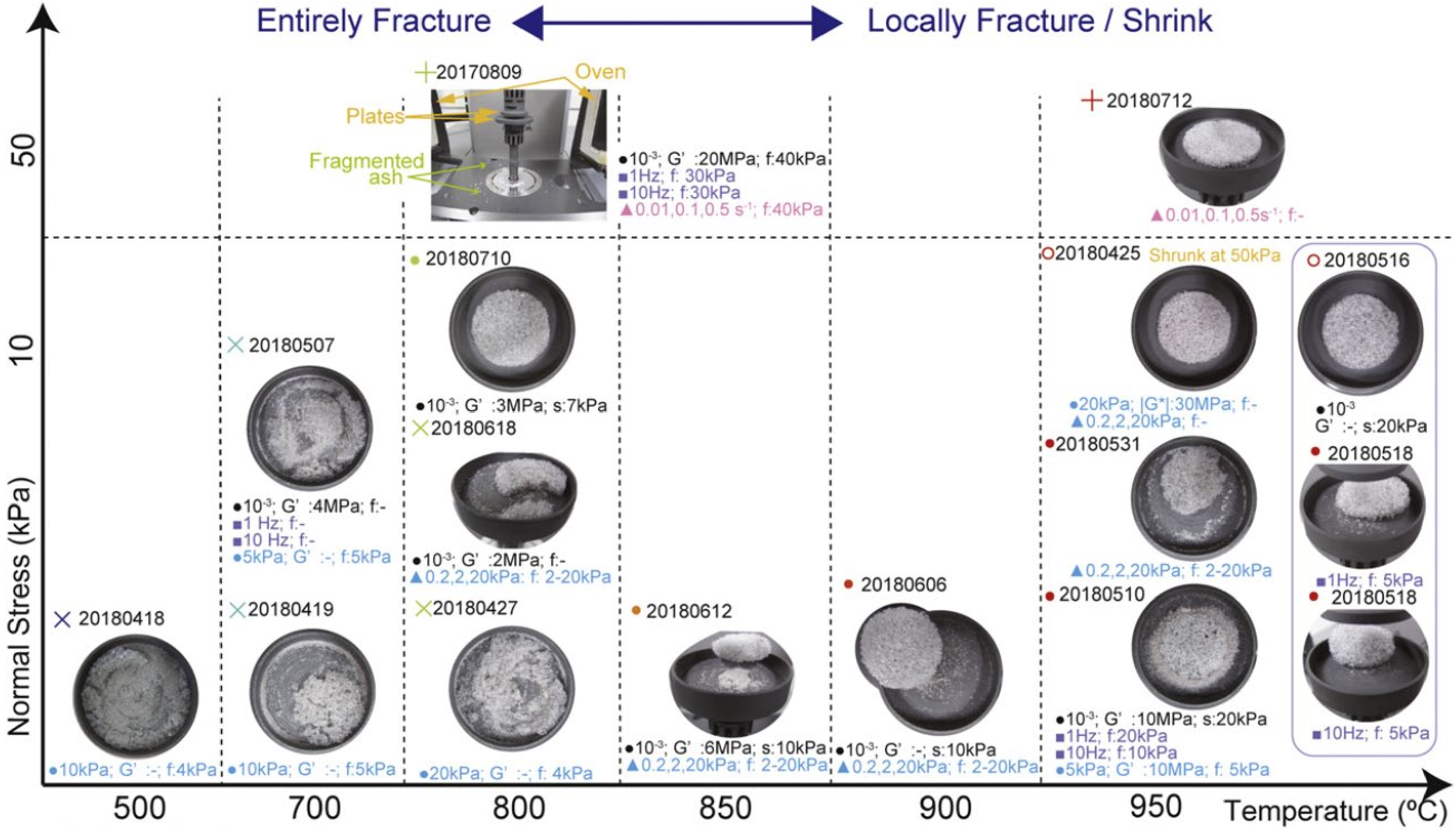
where,

Elastic term

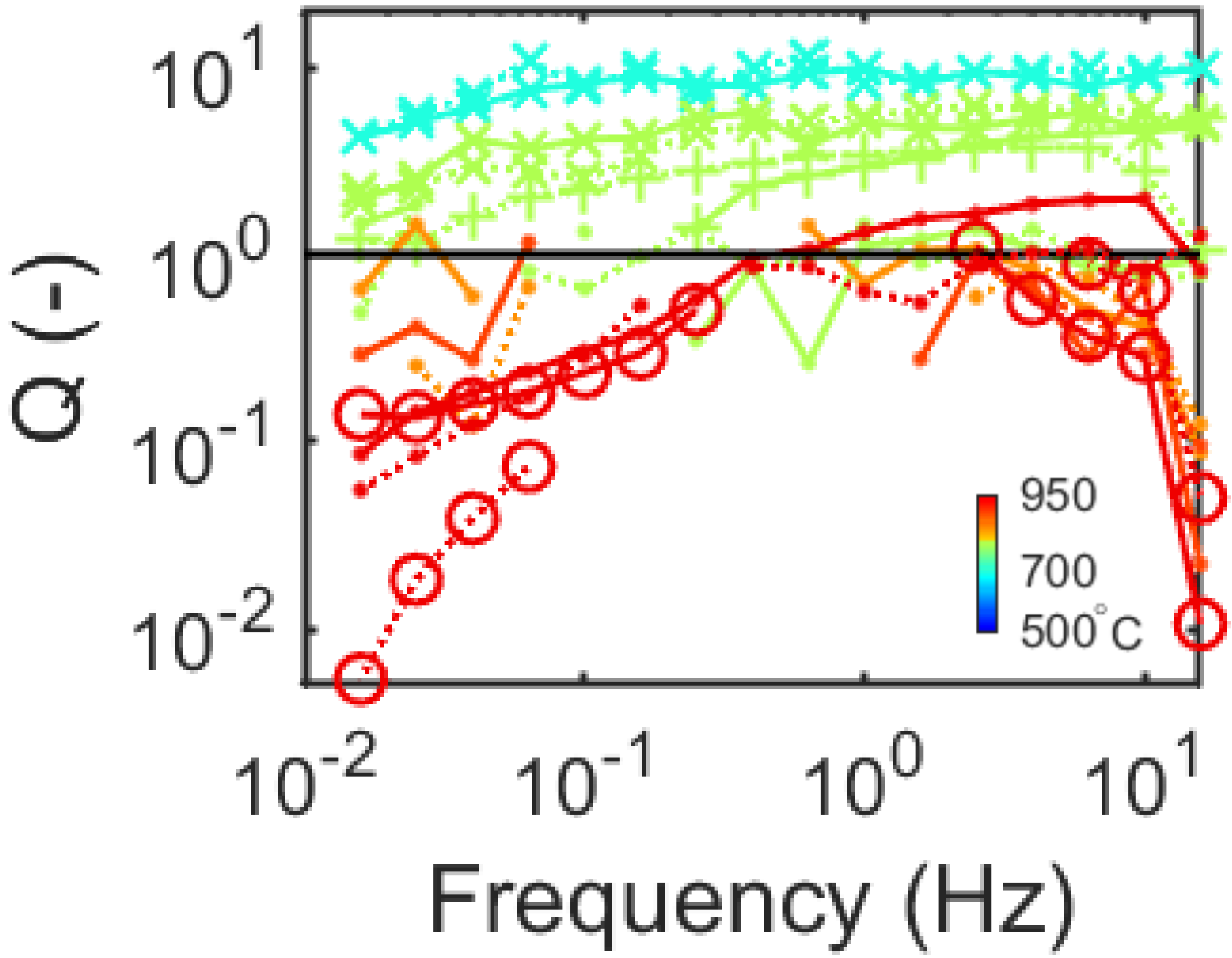
$$|G^*| = G' + iG''$$

Viscous term

Summary of the fractured/deformed samples after the measurements: Cold samples fragment entirely



Frequency dependence of measured Q

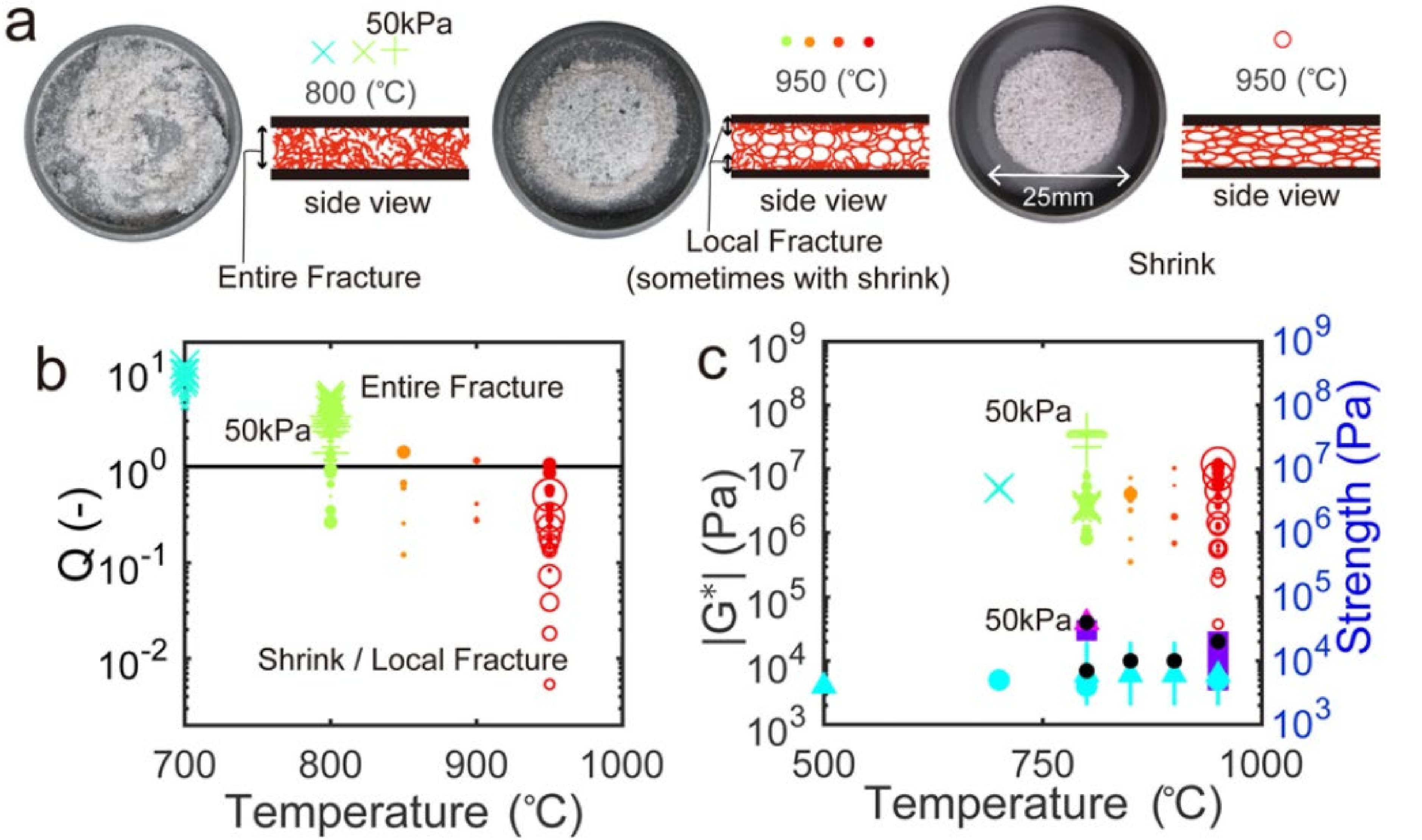


Q has frequency dependence.

At low frequency (f< 1Hz),
Q>1 for cold (<800℃) magma
Q<1 for hot (>900℃) magma

For Q>1, bubbly magma fragments entirely.

Shear modulus and strength differ ~10^3 orders of magnitude.



How is the critical stress related to the fragmentation threshold defined by a shear rate?

The fragmentation threshold is defined as

$$\dot{\gamma} > 0.01\frac{G}{\eta}$$

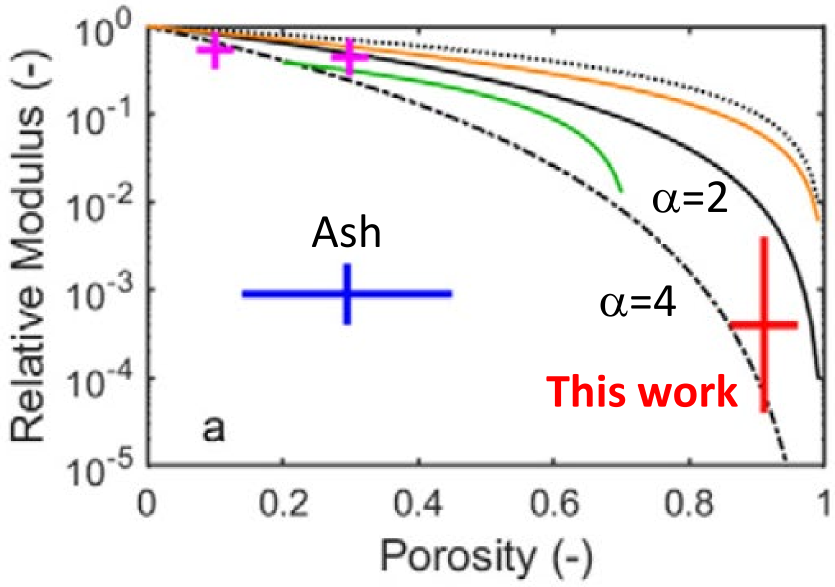
This equation is re-written as

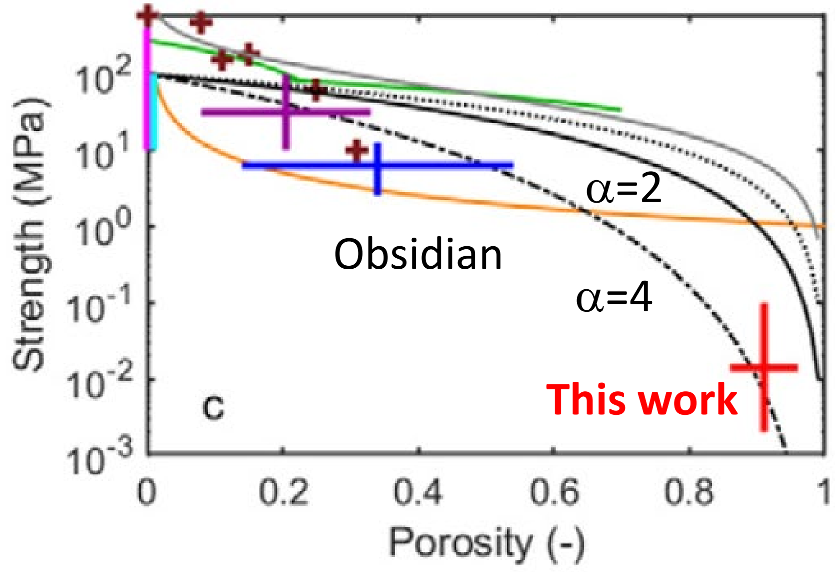
$$\eta\dot{\gamma} > 0.01G$$

Here, $0.01G$ means the stress caused by a strain of 0.01. That is fragmentation occurs when the strain exceeds 0.01 without viscous dissipation.

For our bubbly magma, the critical strain for fragmentation becomes 10^{-3}, smaller than that for bubble-free magma.

Comparison with previous works





We found

- Shear modulus and strength of bubbly magma dramatically decrease with porosity ϕ

Shear modulus with bubbles

$$\frac{G}{G_0} = C_1(1-\phi)^{\alpha}$$

* Black curves in left figures

Bubble-free melt

That is
Porosity of magma can be estimated by seismic wave velocity.
Highly vesiculated magma at shallow depths is certain to fracture during ascent. This hypothesis explains the fact that high porosity magma (ϕ> 0.8) is rarely found in the field, and a porosity of 0.8 has been considered to be another fragmentation threshold.

Summary

- We measured the rheology and strength of high porosity magma at 500–950 °C.
- Bubbles reduce the shear modulus and strength of magma by several orders of magnitude.
- The low strength explains the rarity of magma with porosity higher than 0.8.
- Bubbly magma can fracture entirely when the quality factor exceeds unity.
- The porosity and temperature of magma change the shear wave velocity and attenuation.

See details in Namiki et al., JVGR, 2020