Magma fragmentation and ash generation … and what experiments can help

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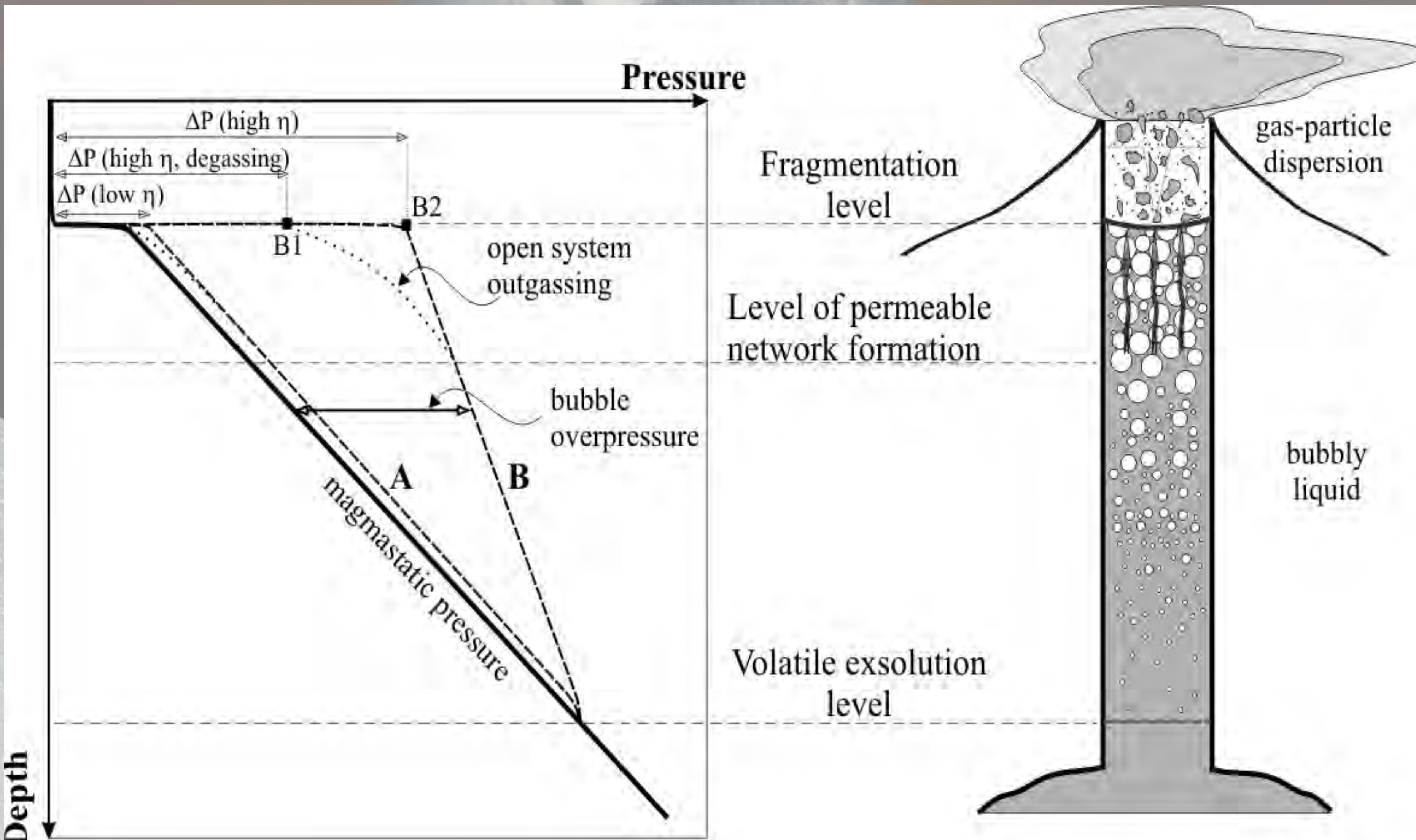
MeMoVolc workshop
"Dynamics of volcanic explosive eruptions"
Geneva 29 – 31 January 2014

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

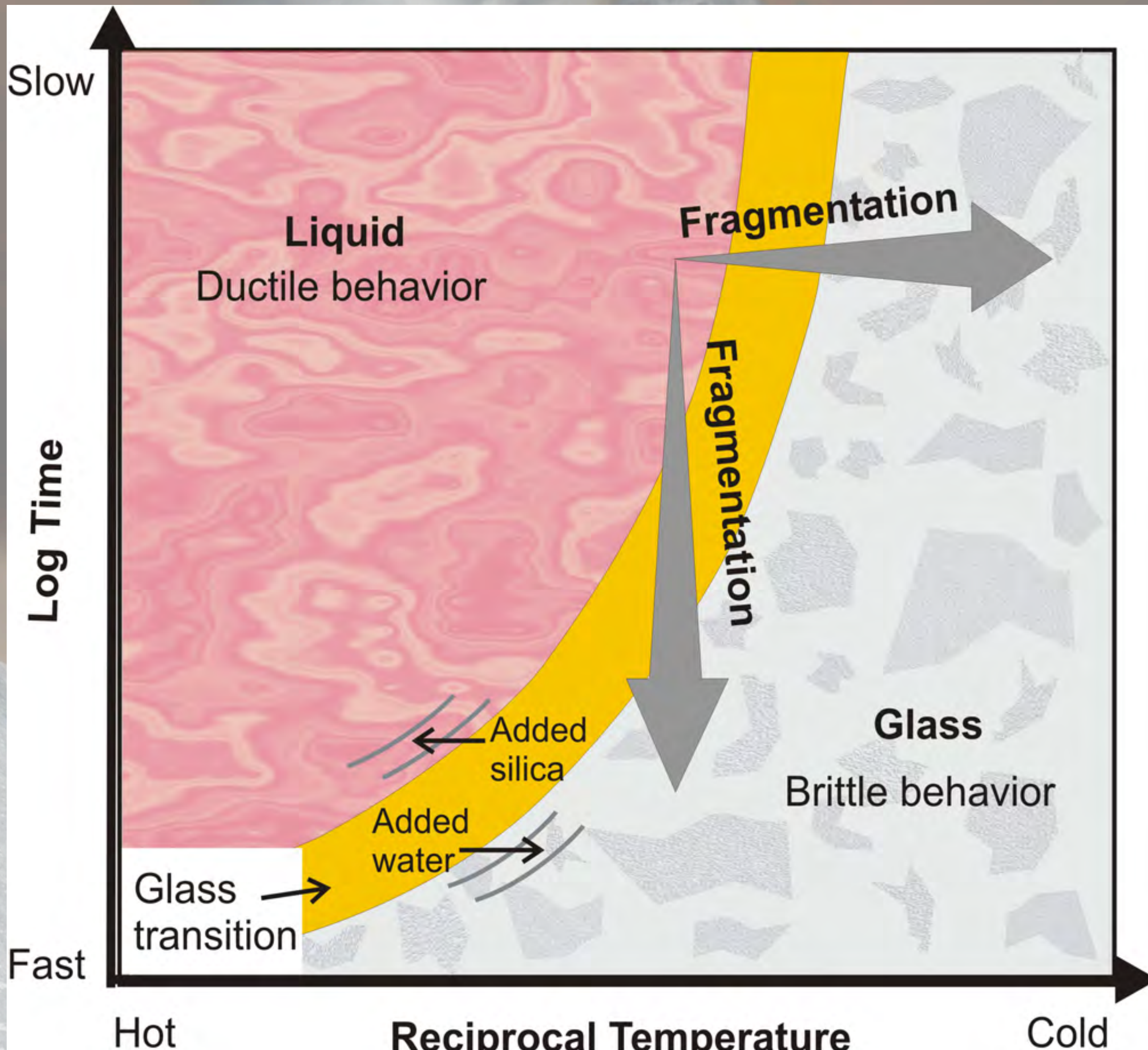
Measuring and MOdelling of VOLCano eruption dynamics
MeMoVolc

Conduit processes prior to fragmentation



Mueller et al., Geology, 2008

Material failure – why and when?



(mod. after Dingwell, Science, 1996)

Processes to break magma/lava

1) The acting **„strain“** is too high to be dissipated by elastic deformation.
   -> deformation rate
   (Gilbert and Sparks, 1998; Papale et al., 1998; 1999; Cashman et al., 2000)

2) The acting **„stress“** exceeds the yield strength of the magma.
   -> gas overpressure

Breaking magma/lava by strain

Flow/deformation rates too high

- changes in geometry [bottleneck in conduit, increase in slope angle]
- changes in rheology [crystalisation, vesiculation, cooling]

-> in conduit I: tuffisites

-> in conduit II: pyroclast formation

-> in PDCs/on steep slopes: Abrasion

-> in lava flows: change of surface morphology

Breaking magma/lava by stress

Gas overpressure overcomes lithostatic pressure

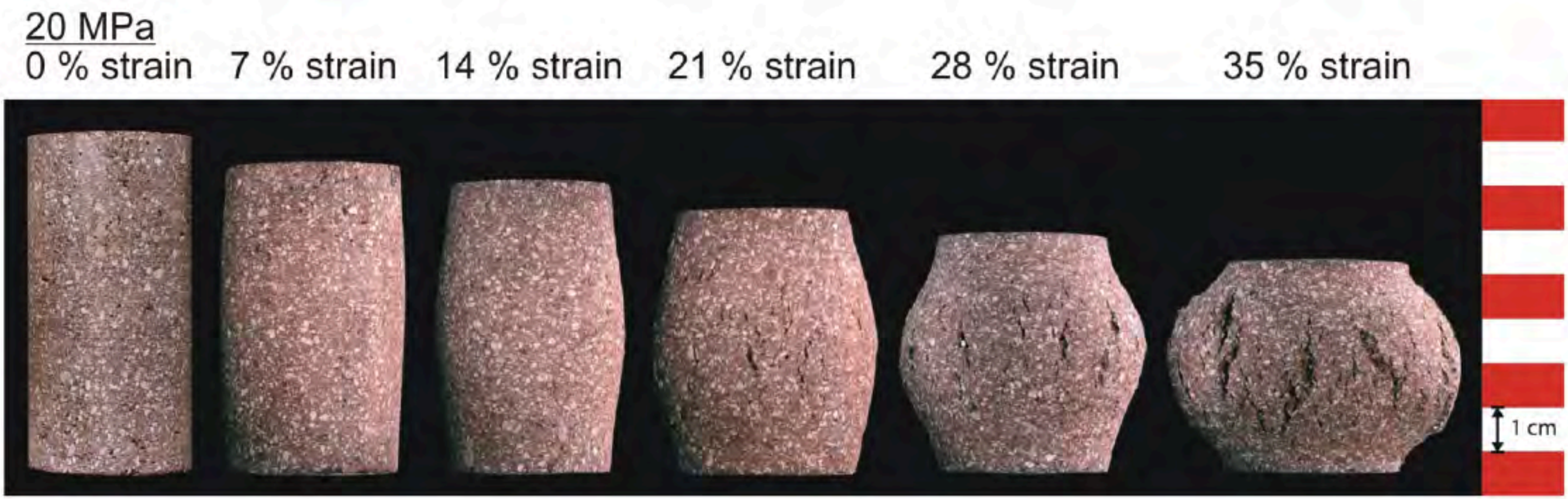
Origin of overpressure:

-> magmatic volatiles (magmatic fragmentation)

-> boiling of external water under confinement, volume increase 1600 %! (phreatomagmatic fragmentation)

Phreatomagmatic = Phreato + magmatic! (i.e., external water is an additional source of energy

Breaking magma by shearing I

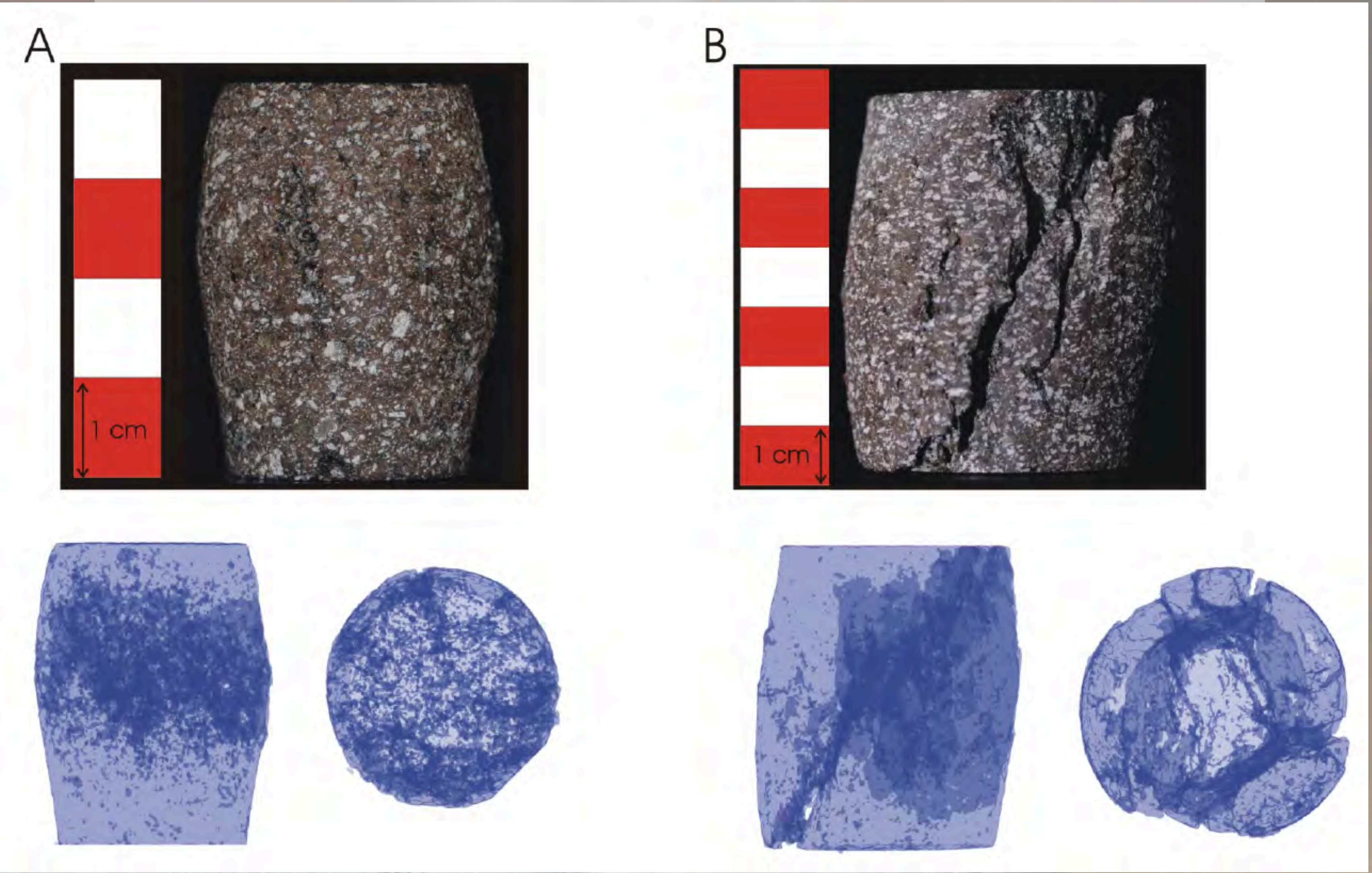


Colima, 890 °C, 20 MPa uniaxial load (no confinement)

-> Large-scale ductile behaviour, small-scale brittle failure

Lavallee et al., 2013

Breaking magma by shearing II



At higher strain rates, large scale failure starts earlier.

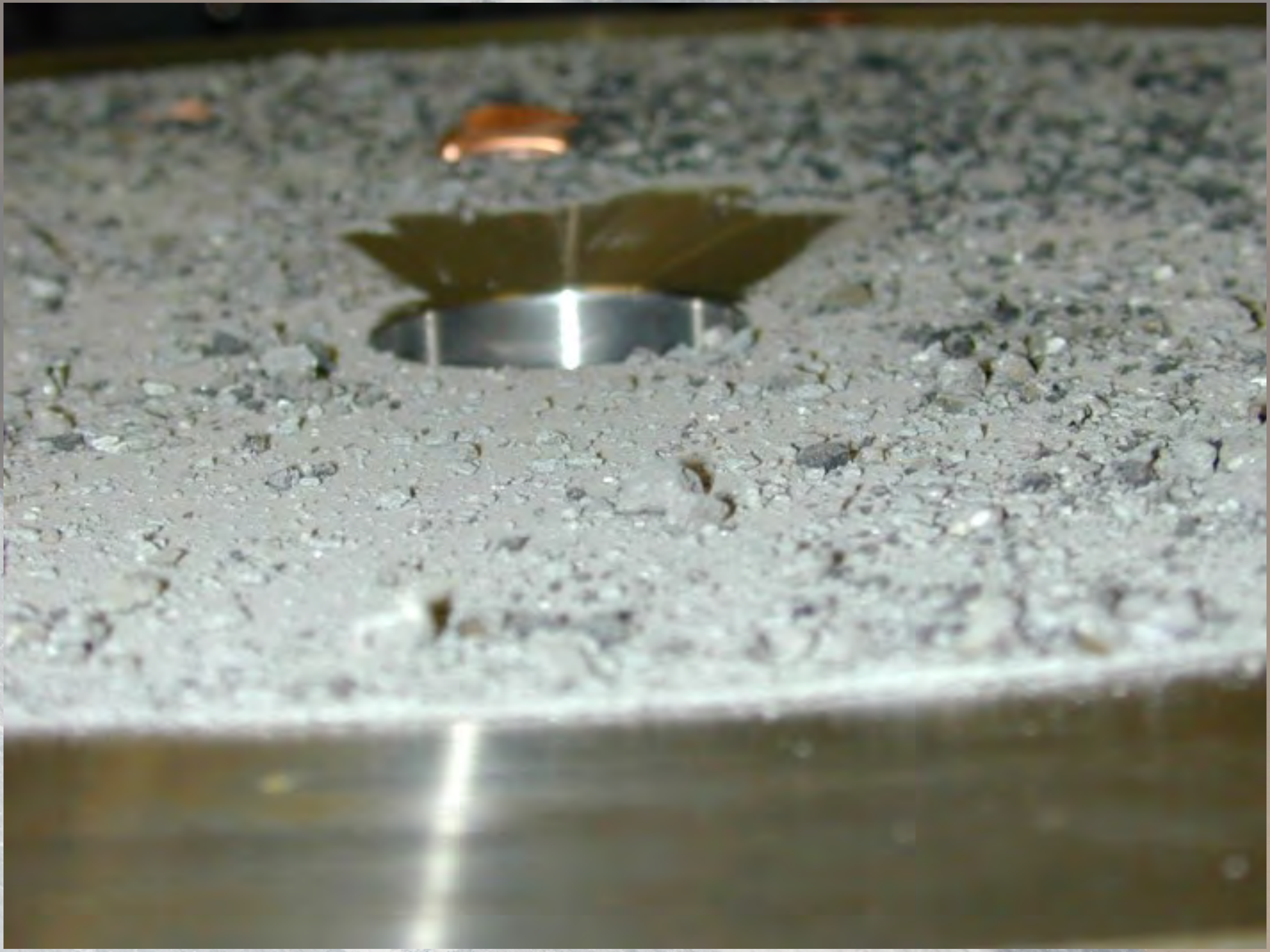
If filled cracks are welded -> Tuffisites

Lavallee et al., Geology 2013

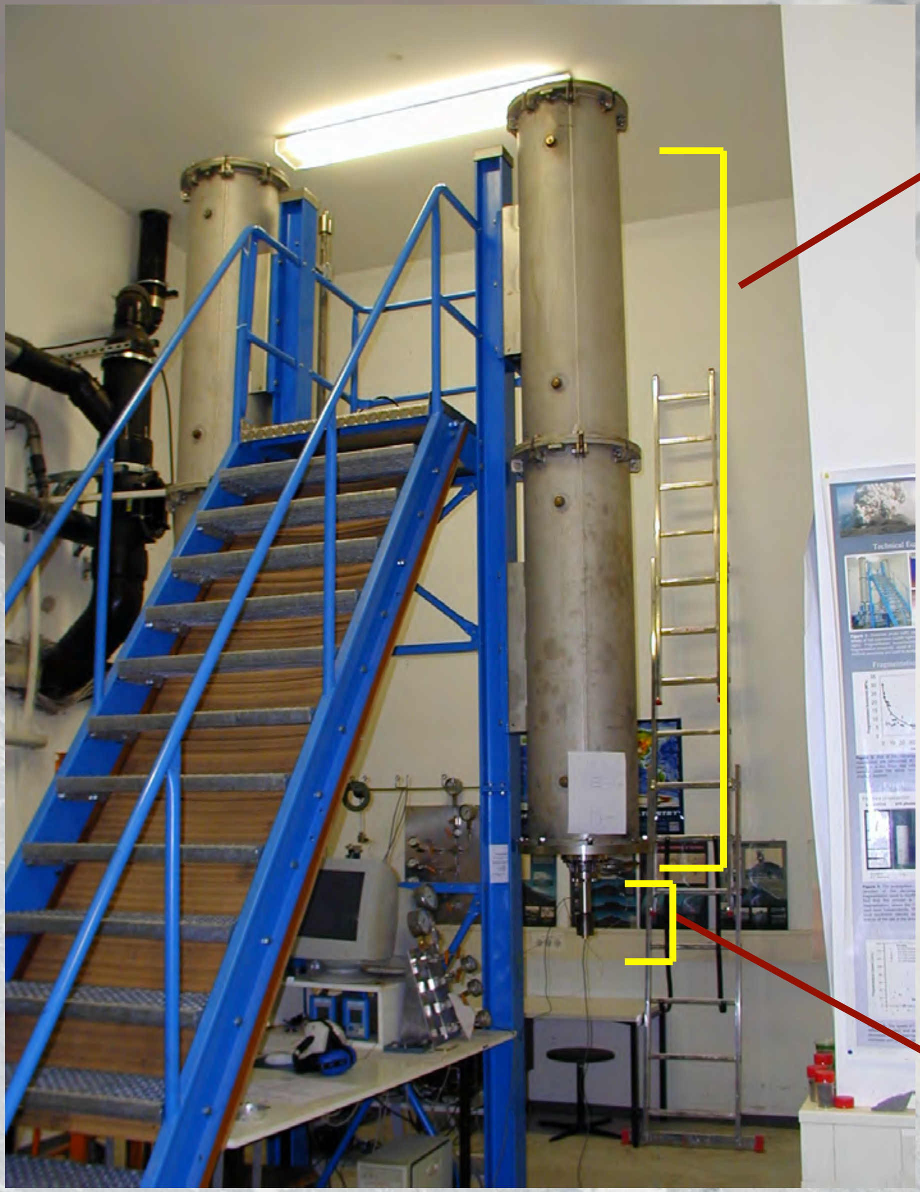
Breaking magma by gas expansion (natural)

Etna (I) on 3 Nov 2002

Experimental ash generation



Breaking magma by gas expansion (lab)



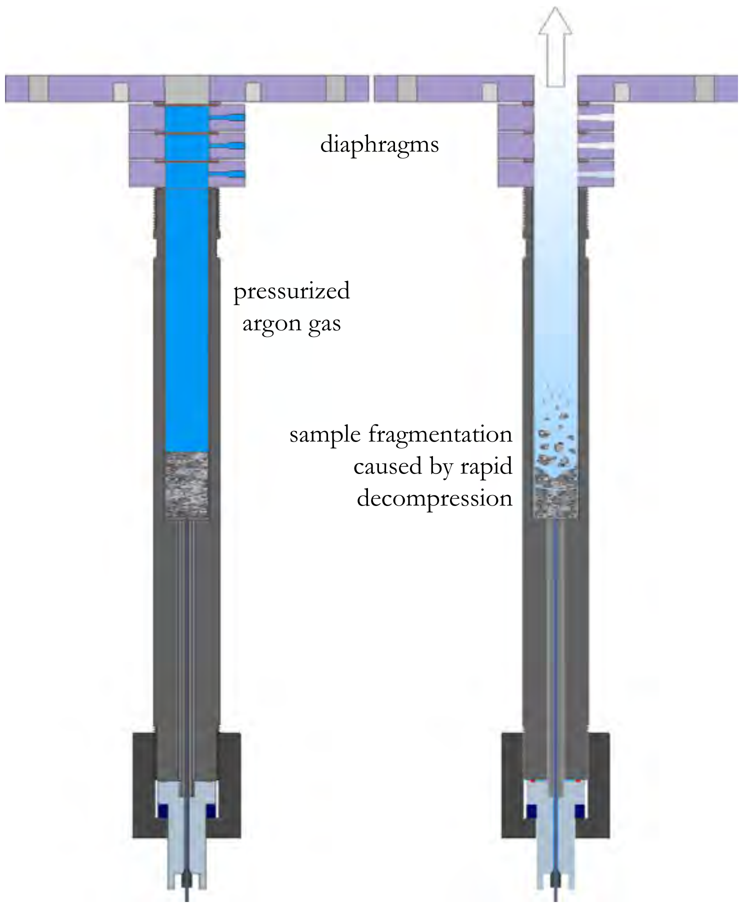
Upper Chamber (low P)

- shock-tube experiments

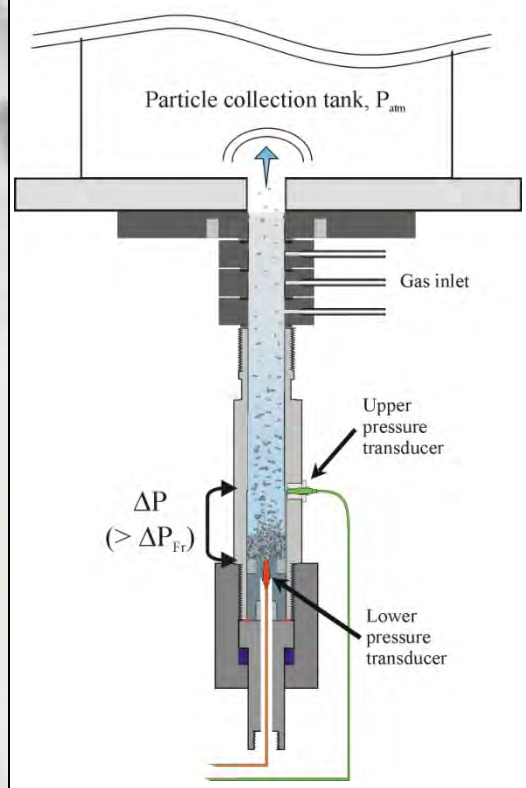
  --> fragmentation due to gas overpressure in vesicles
- gas pressure (Argon)
- set of 1-3 diaphragms
- varying sample size (mm): 17x50, 25x60, 60x60, 34x70
- P-T conditions: 0.1 - 50 MPa & 20 - 900 °C
- several pressure transducers
- high-speed video recording: 1.000 to >50.000 fps
- Complete particle sampling

High-Pressure Autoclave

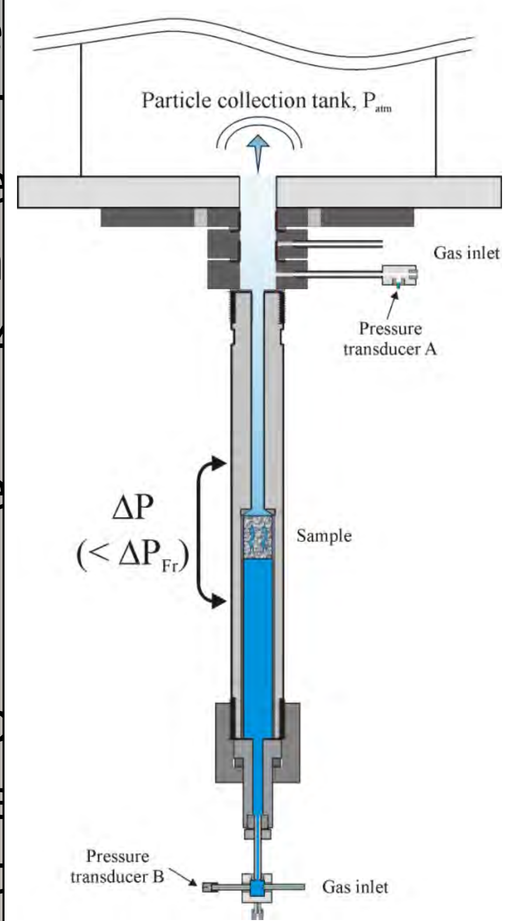
Different questions -> different setups



Fragmentation Threshold (ΔP_{Fr})
Up to 850°C



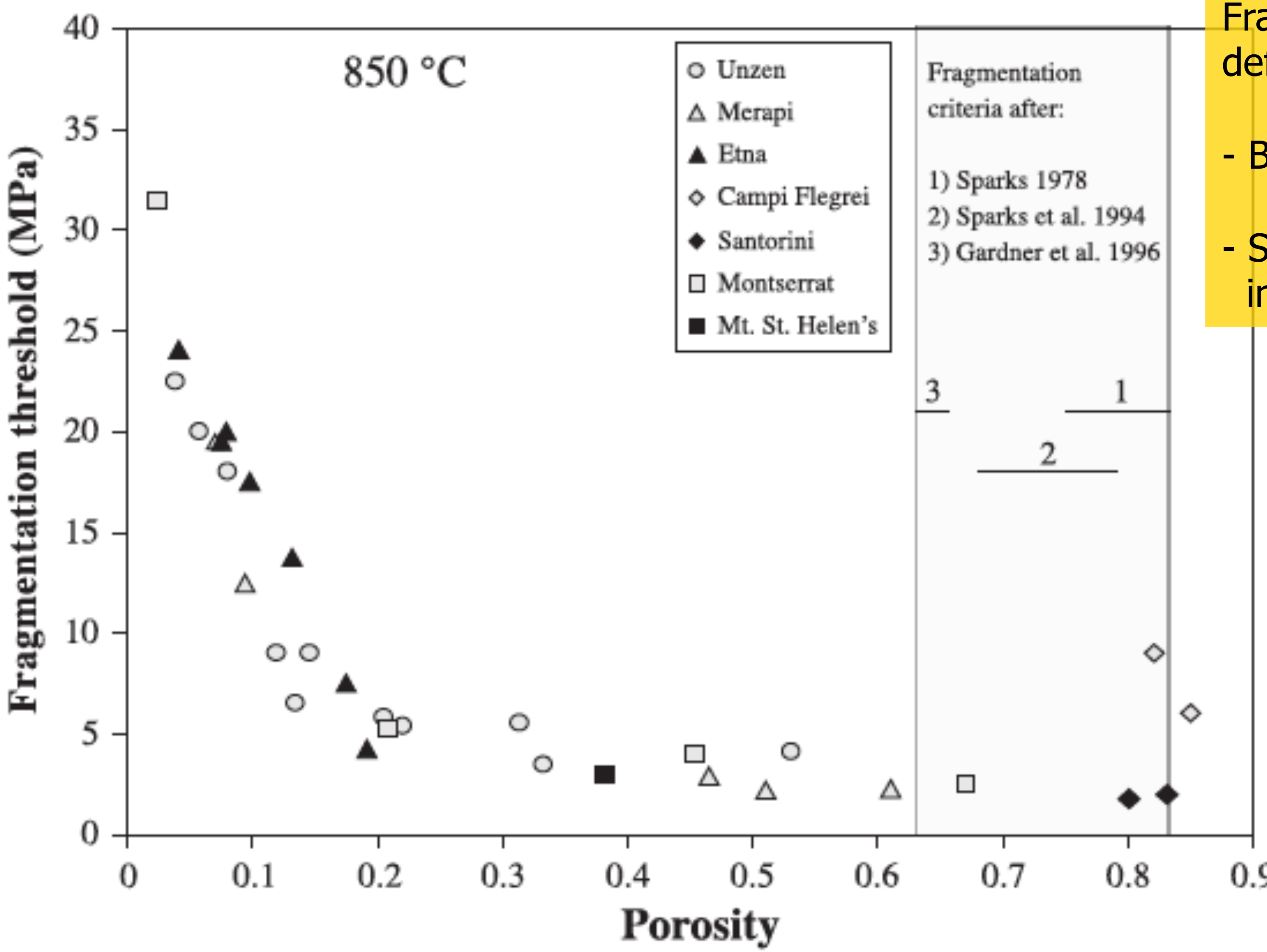
Fragmentation Speed
Up to 300°C



Permeability

(mod after: Scheu et al., JVGR, 2008)

Fragmentation threshold

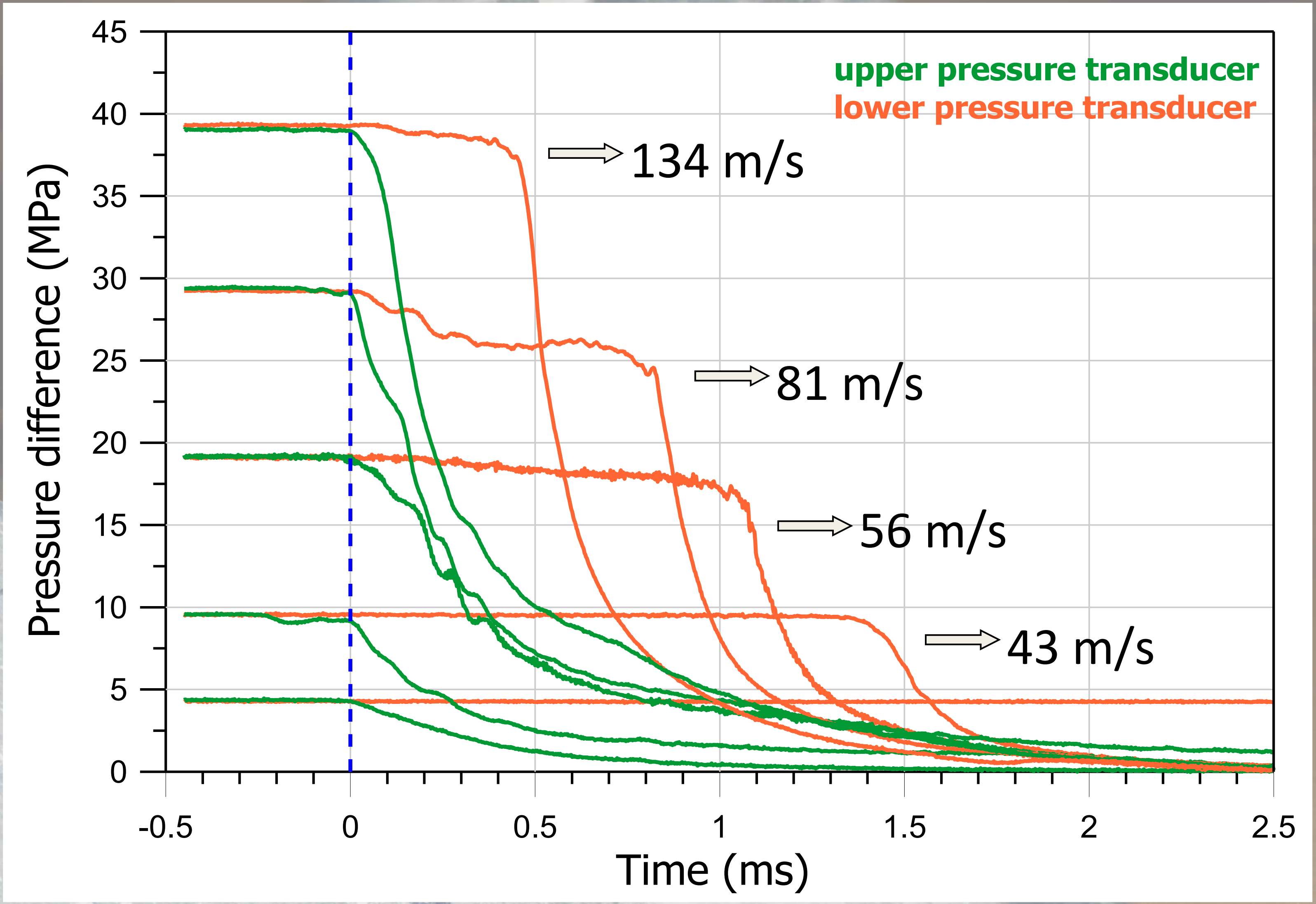


Fragmentation defined by:

- Bubble coalescence (1, 2)
- Shear induced foam instability (3)

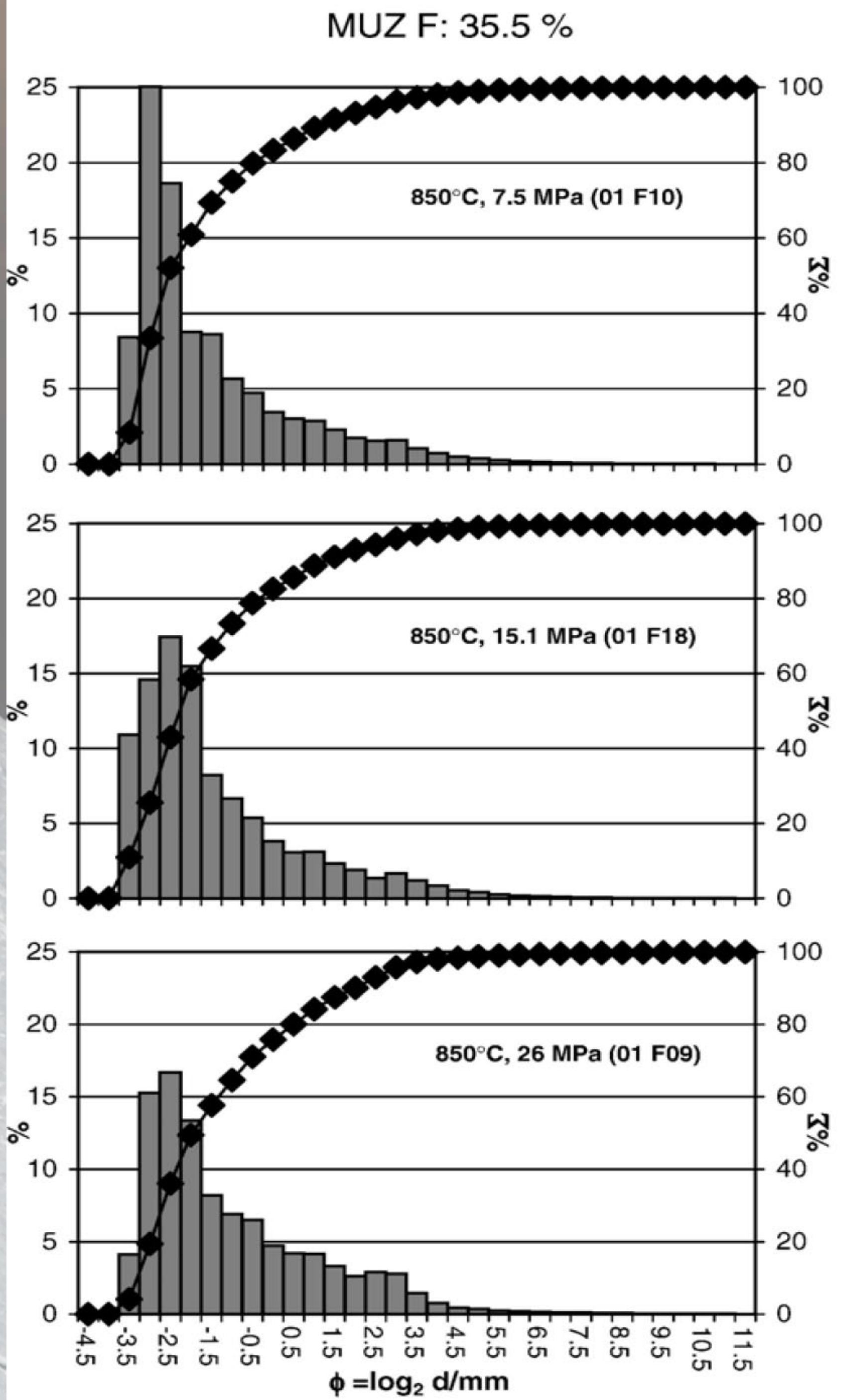
(Spieler et al., EPSL, 2004)

Fragmentation speed



vulcanian vs. plinian

Scheu et al., Bull Volc 2006



Grain size distribution

Unzen dacite

Φ = 35.5 %

$T_{experimental}$: 850°C

ΔP = 7.5, 15.1 and 26 MPa

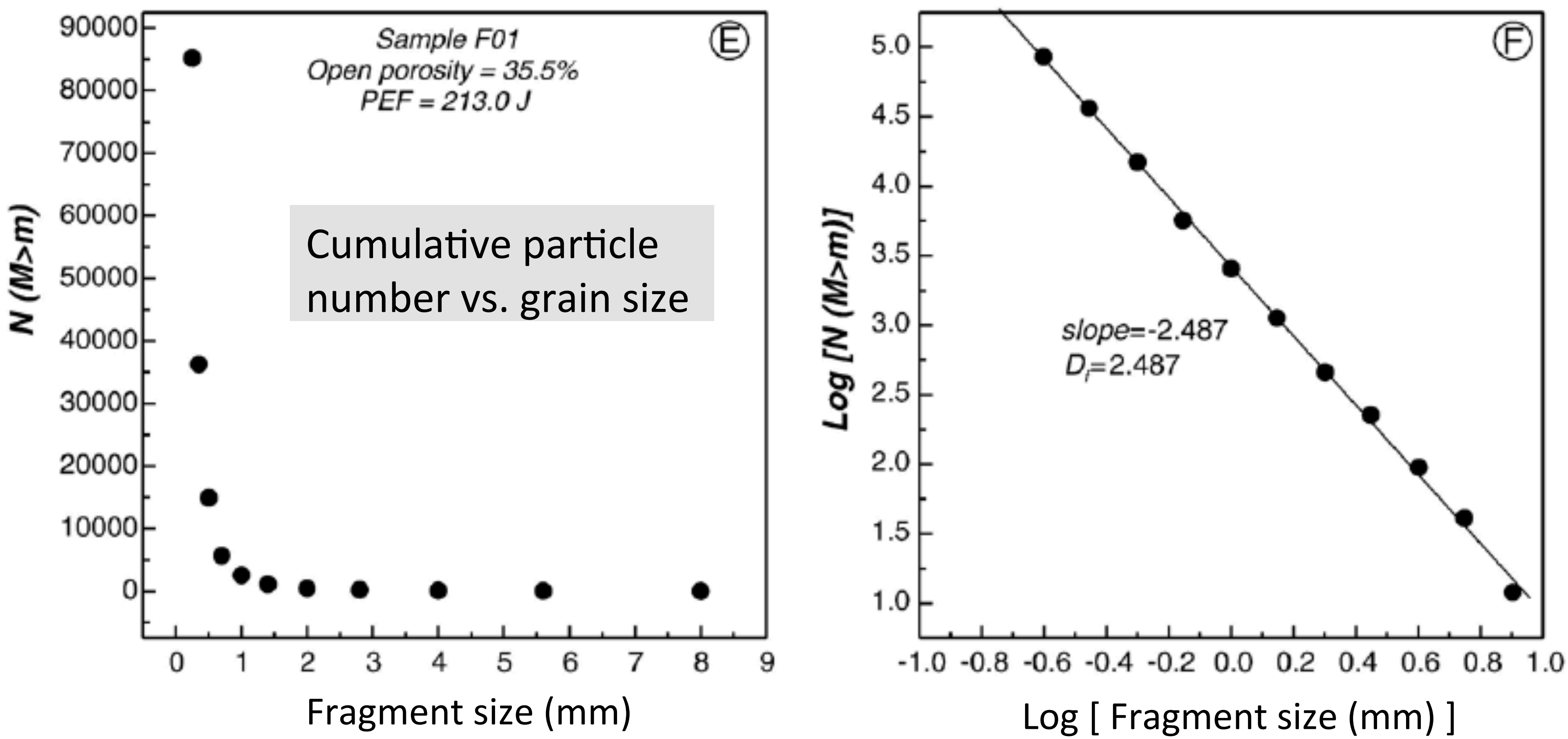
-> different energy

Higher energy => more fines

BUT no finer particles!

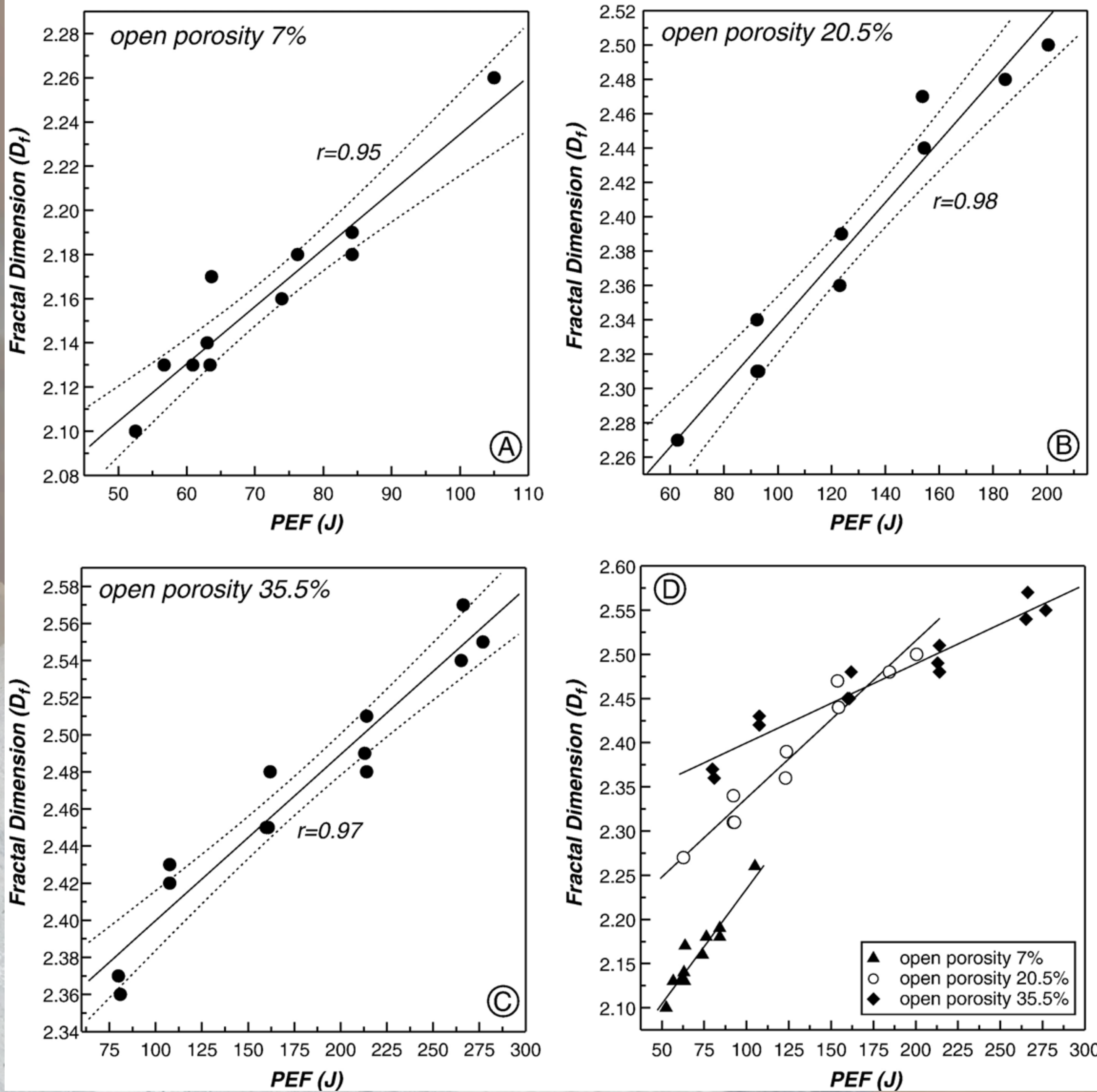
(Kueppers et al., JVGR, 2006)

Fractal analysis I



Kueppers et al., EPSL 2006

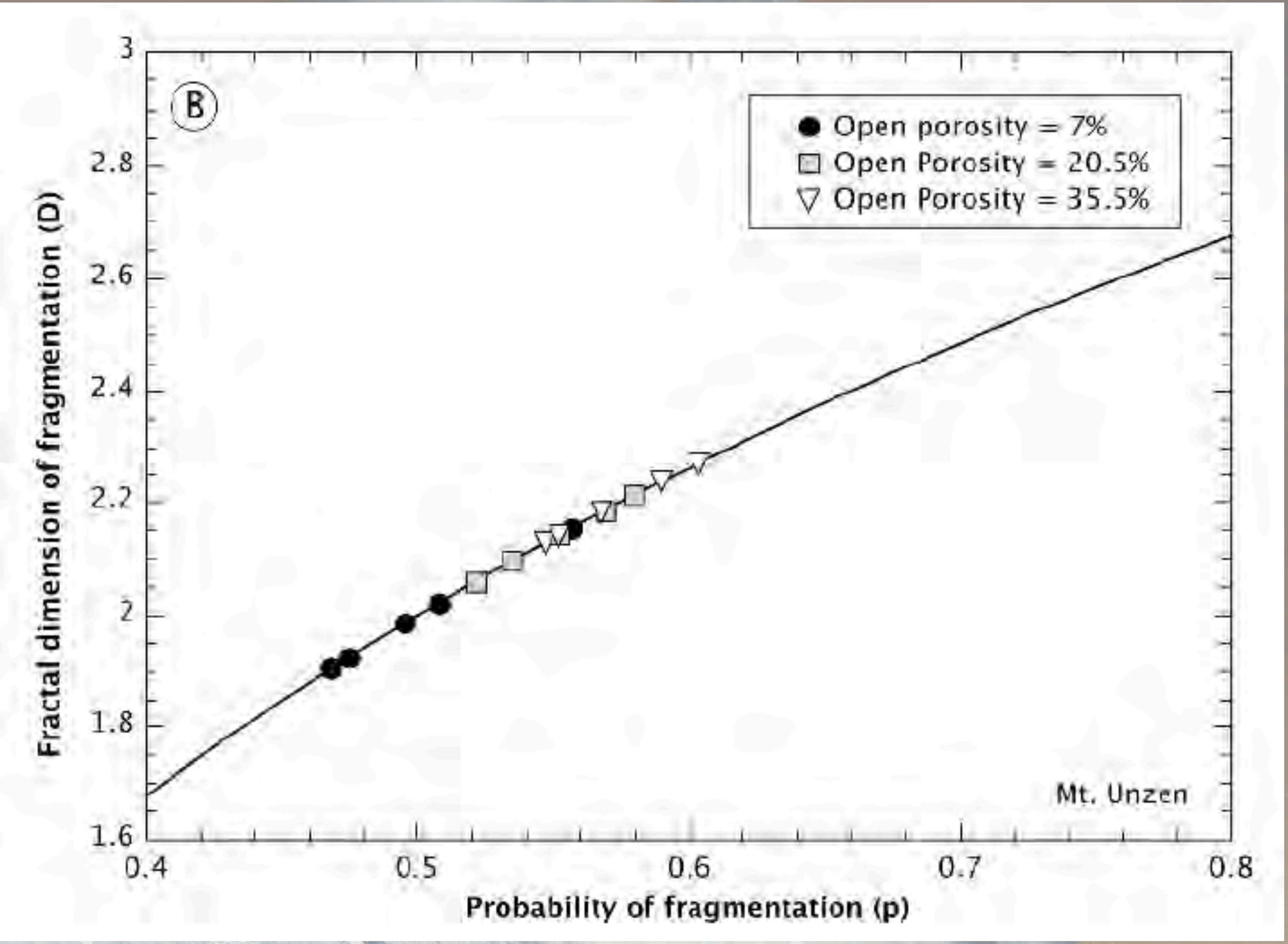
Fractal Analysis II



PEF: potential energy for fragmentation

Kueppers et al., EPSL 2006

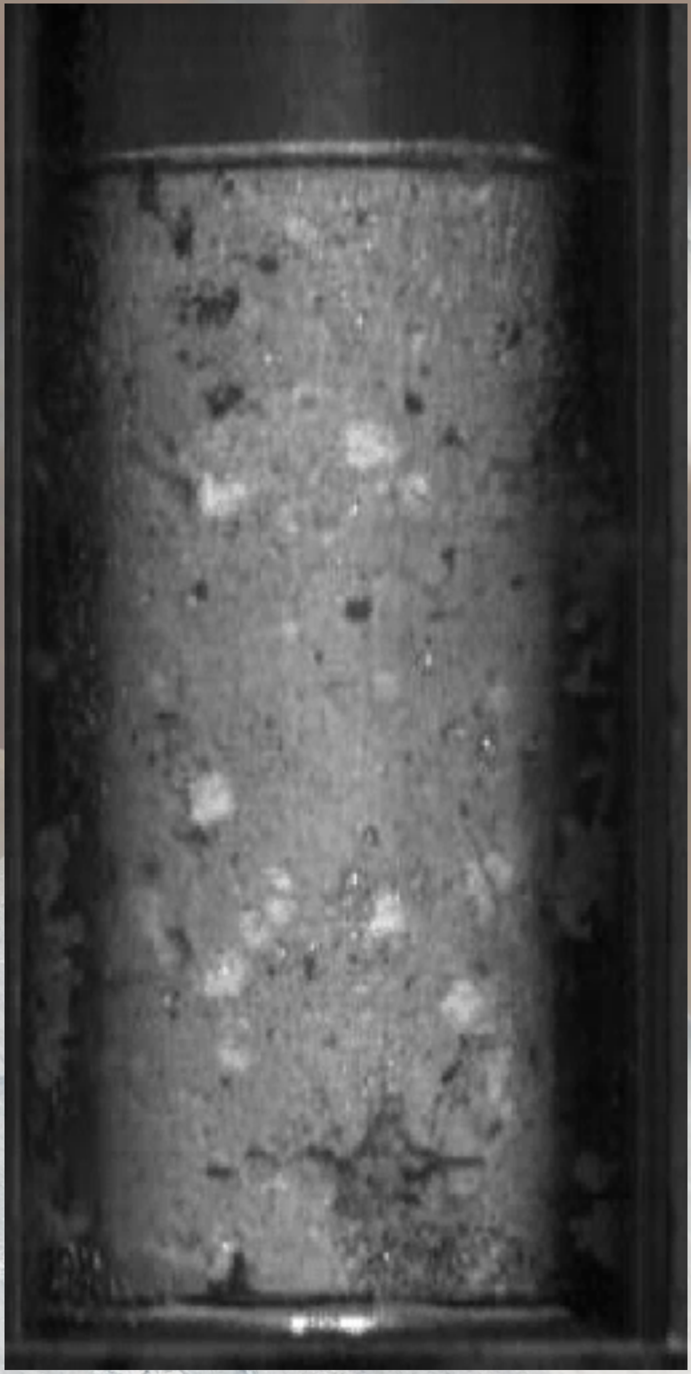
Fractal analysis III



Turcotte (1986): Probability of fragmentation = 1
if a cube breaks in 8 cubes of equal dimensions

Perugini & Kueppers, Acta Geophysica, 2012

Magma fragmentation



Unzen

Φ = 48%

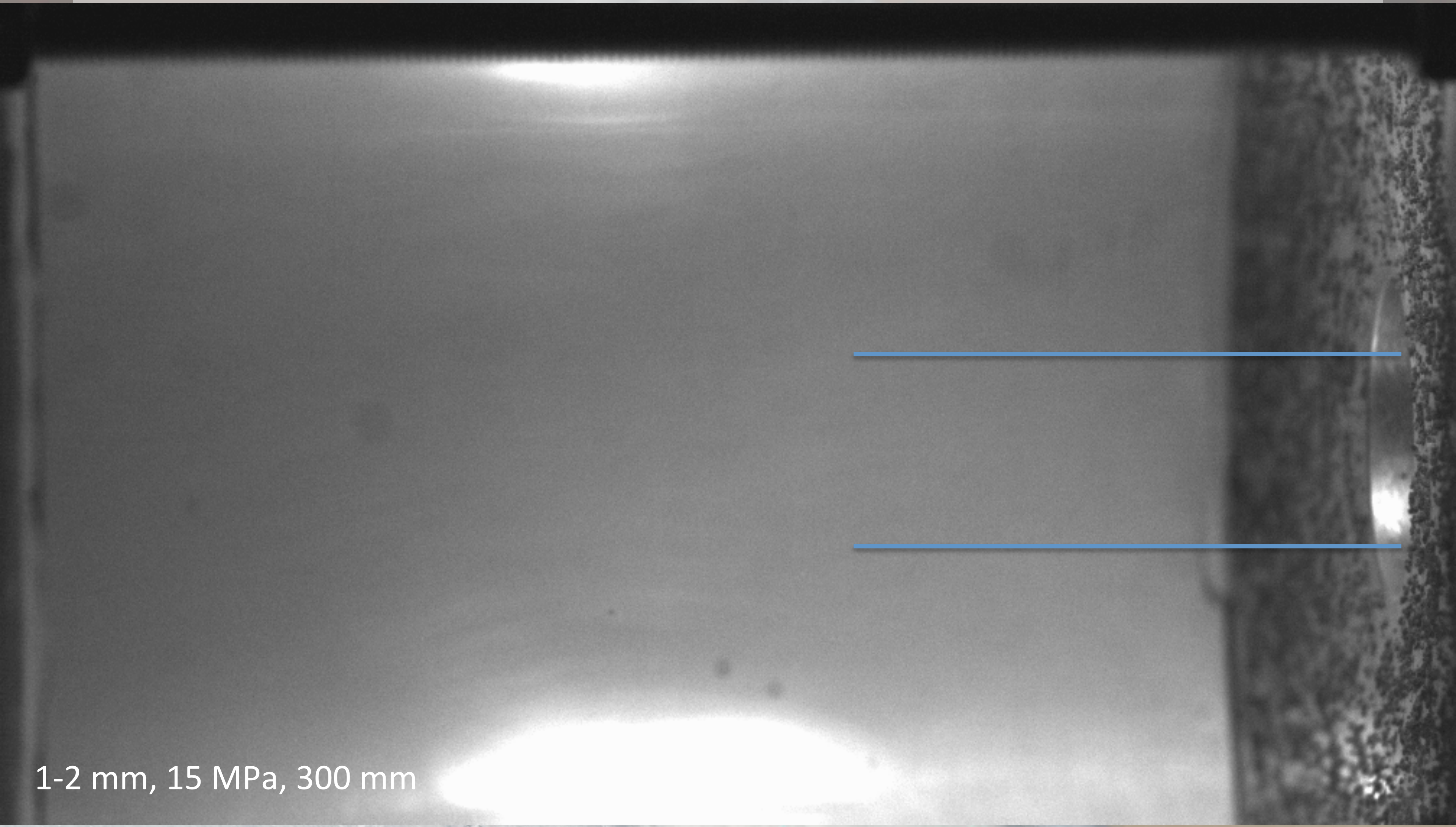
ΔP = 6MPa

Room T

Plexiglas autoclave

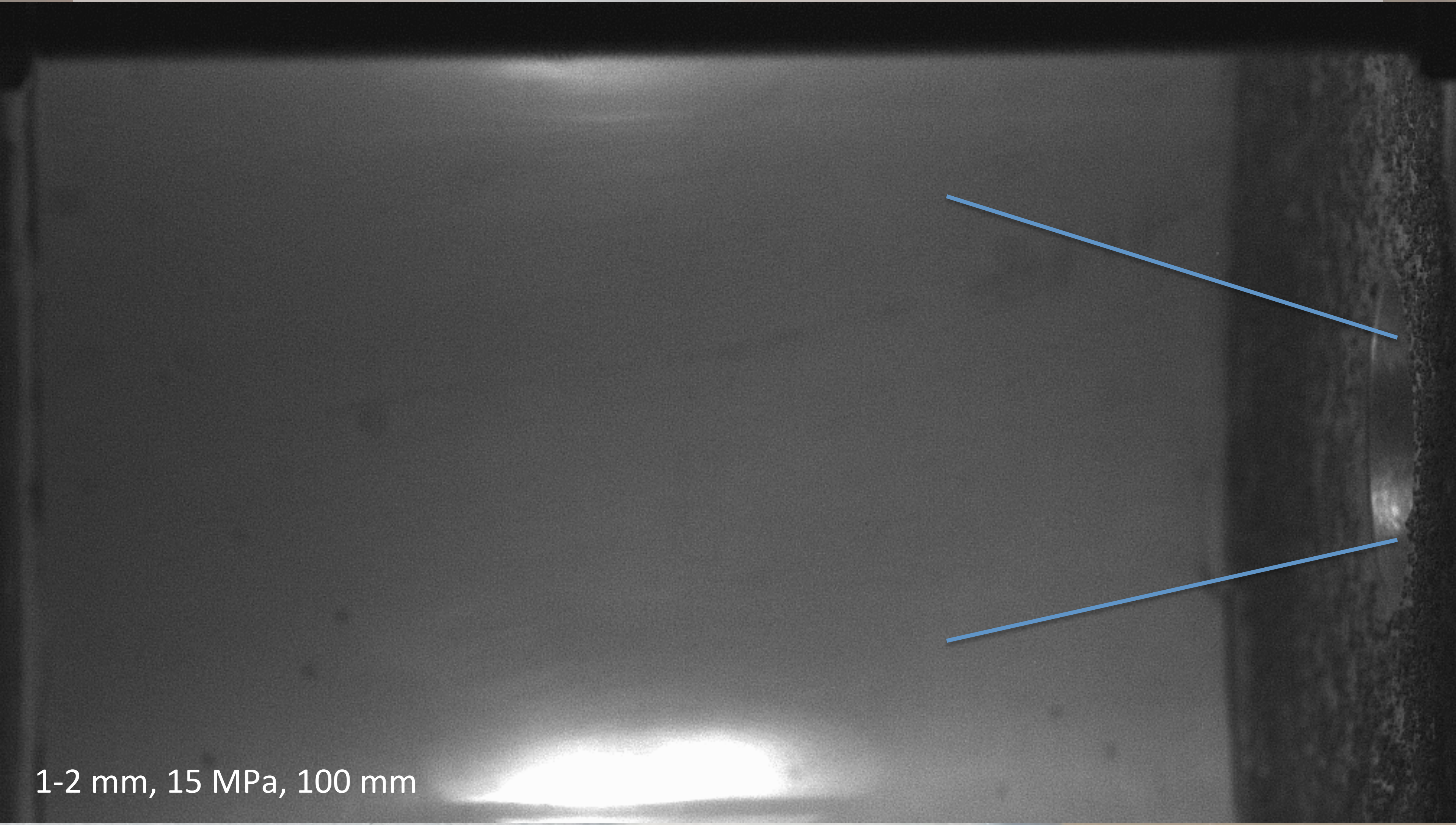
Fowler et al., Proceed. Royal Soc. A, 2010

Ejection velocity and opening angle



Kueppers et al., IAVCEI 2013

Ejection velocity and opening angle

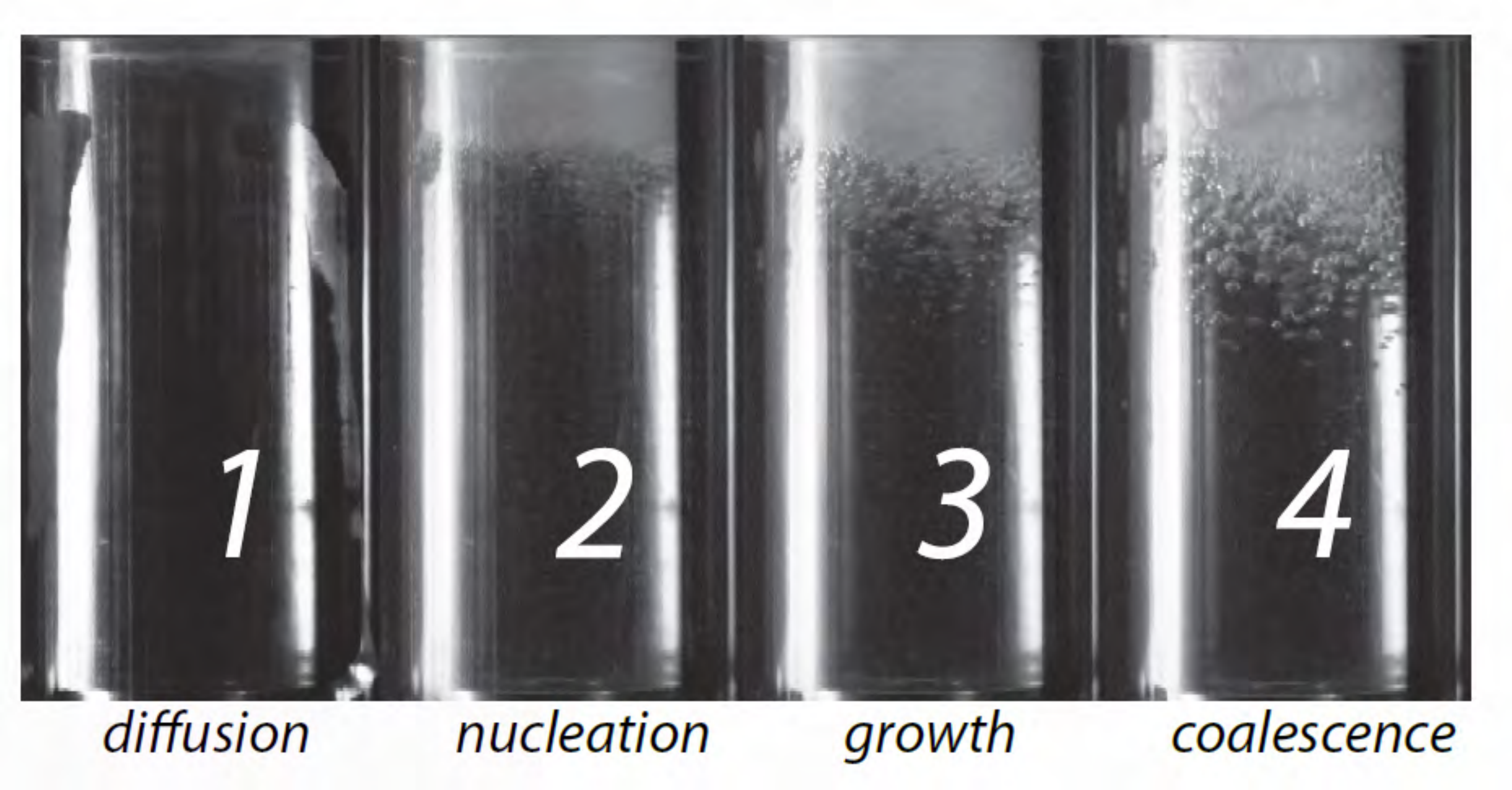


The fragmentation depth/overpressure at vent control the geometry of particle ejection.

Kueppers et al., IAVCEI 2013

Analogue experiments I

Silicon oil (100 Pas), Argon saturated for 24 hours, then rapid decompression



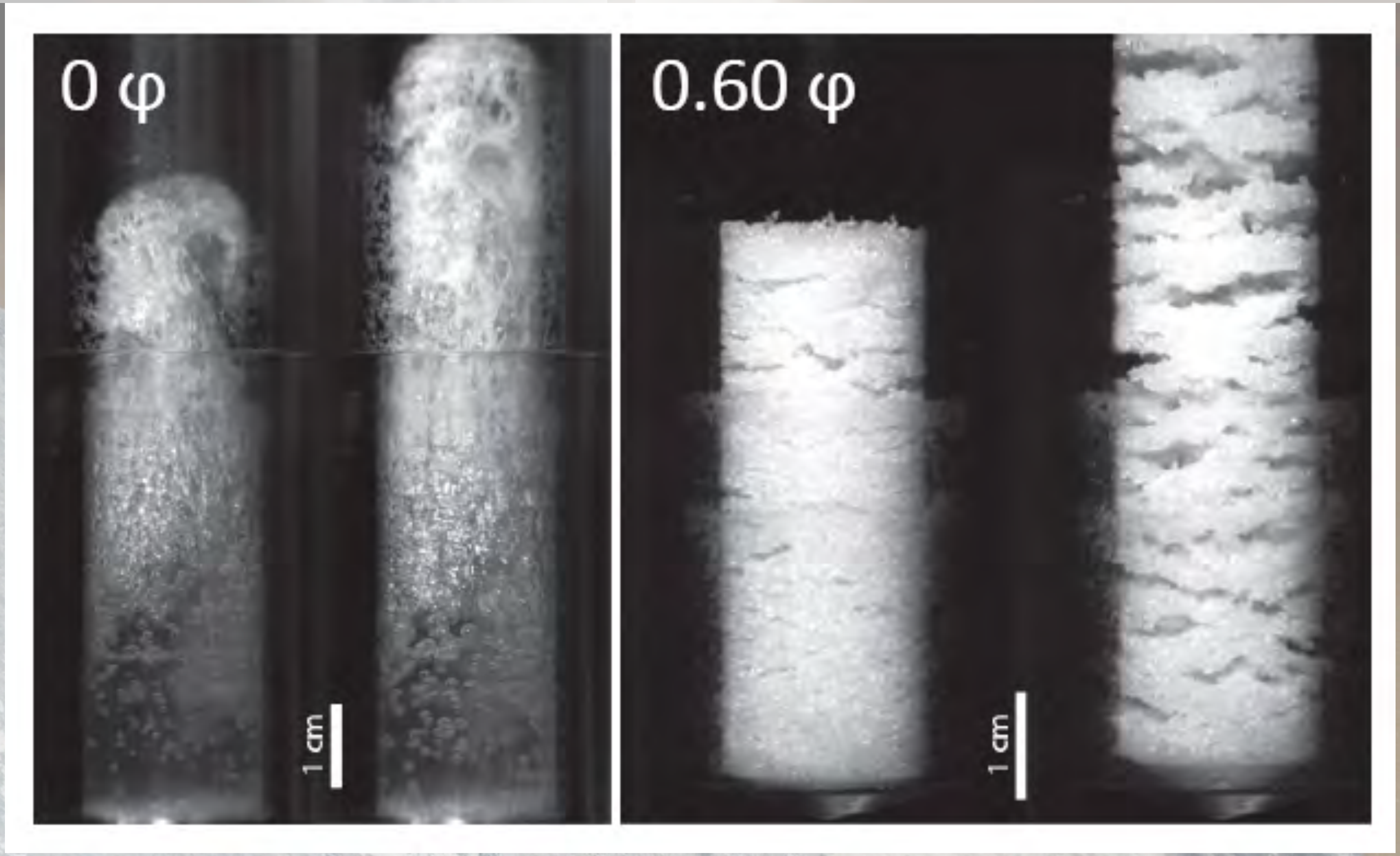
Cimarelli et al., AGU 2011

Transition of the fragmentation mechanism of multiphase magma analogs

Different response to decompression:

dilute suspensions: foaming and permeable outgassing
Expansion velocity: 0.1 m/s

60 % solid volume fraction: layer-by-layer fragmentation of discrete portions
Expansion velocity: 10 m/s



Cimarelli et al. (in prep)

Key points

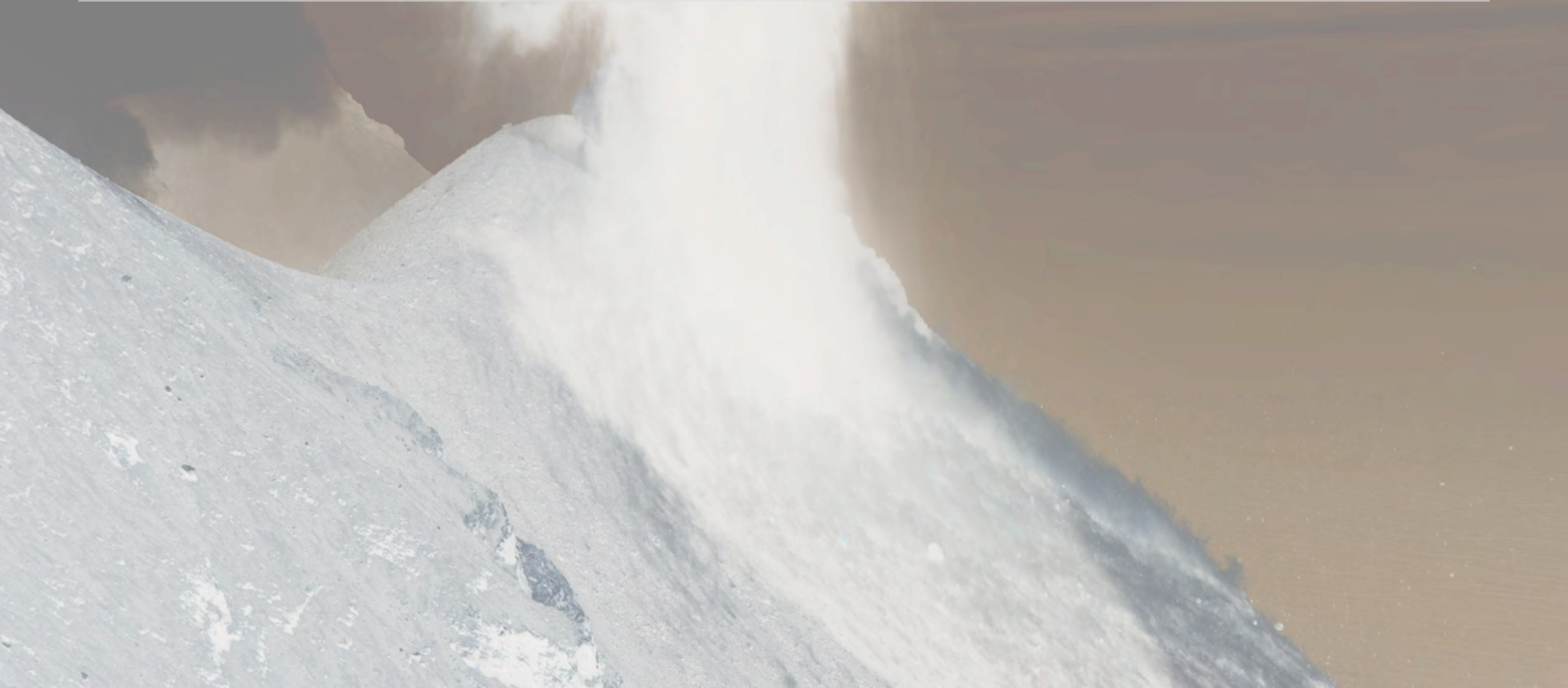
- Magma fragmentation is happening via a plethora of processes, including the expansion of internal (magmatic) and external (phreatomagmatic) volatiles, shearing, communition, quenching…..
  -> not only during explosive volcanism!
- Physical properties of clasts represent the state of the magma at fragmentation! (valid in most cases! Common exceptions: Breadcrust bombs, spatter clasts)
- Most fragmentation in volcanic systems is brittle. We should not mix a deformation mode with a fragmentation mode.

Merci!

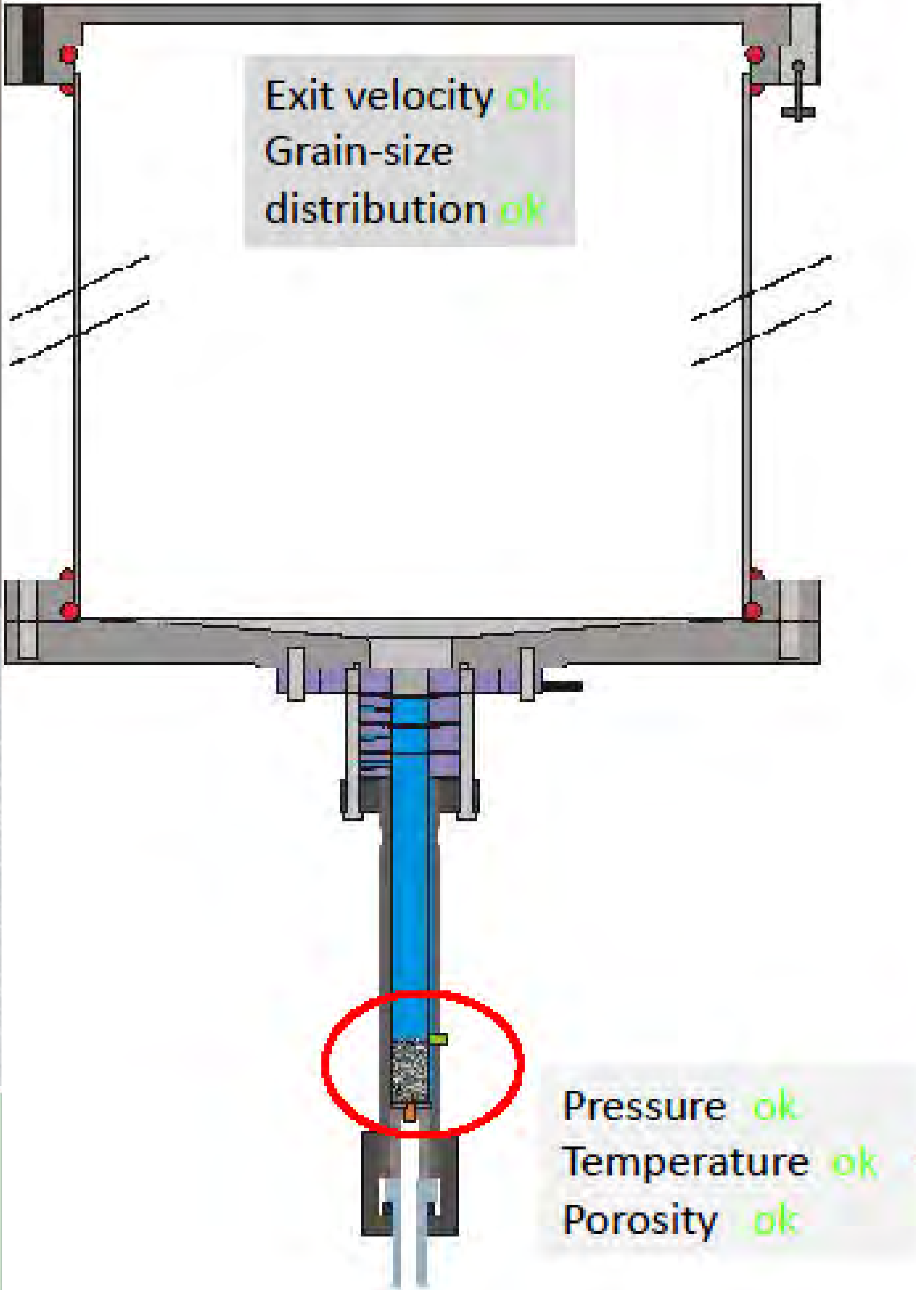
Collaborators and sources of more questions than answers:
Miguel Alatorre-Ibargüengoitia, Corrado Cimarelli, Ben Kennedy, Sebastian Müller, Diego Perugini, Piergiorgio Scarlato, Bettina Scheu, Jacopo Taddeucci

Extras....

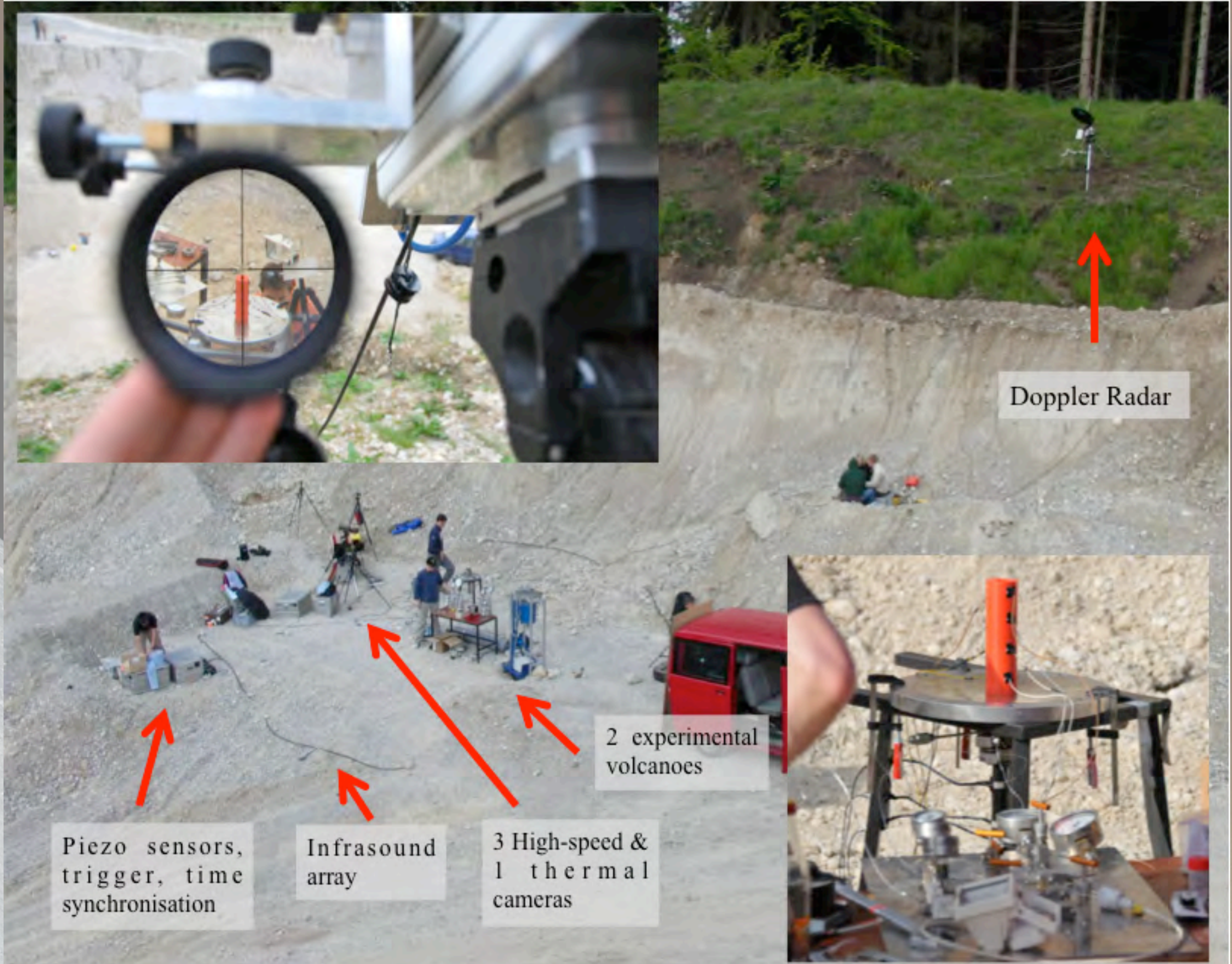
But…. After all this….
How can we better understand mechanistically what a volcano is doing?



Experimental volcanology



Explosive eruptions



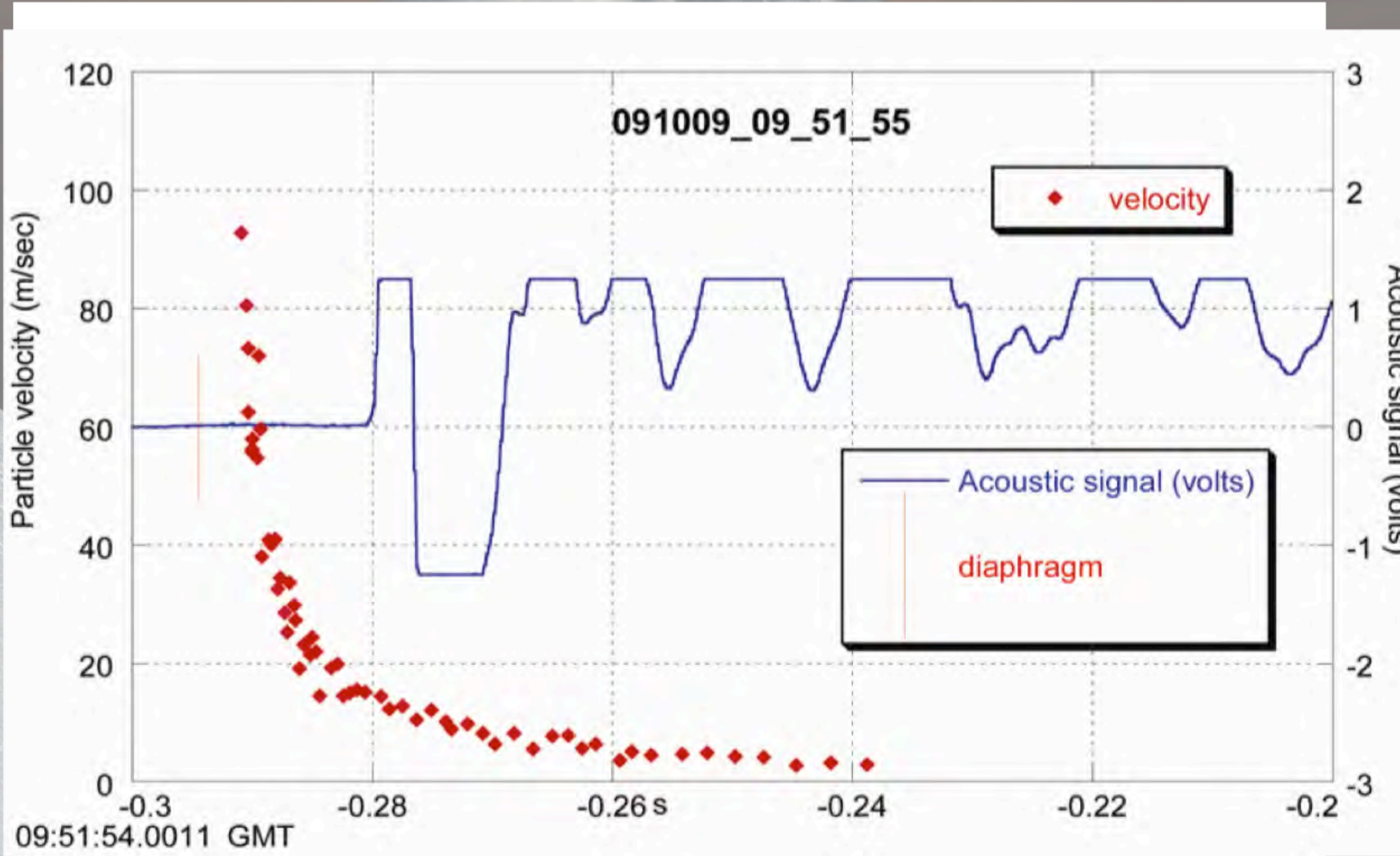
Kueppers et al., EGU 2012

Why all this?

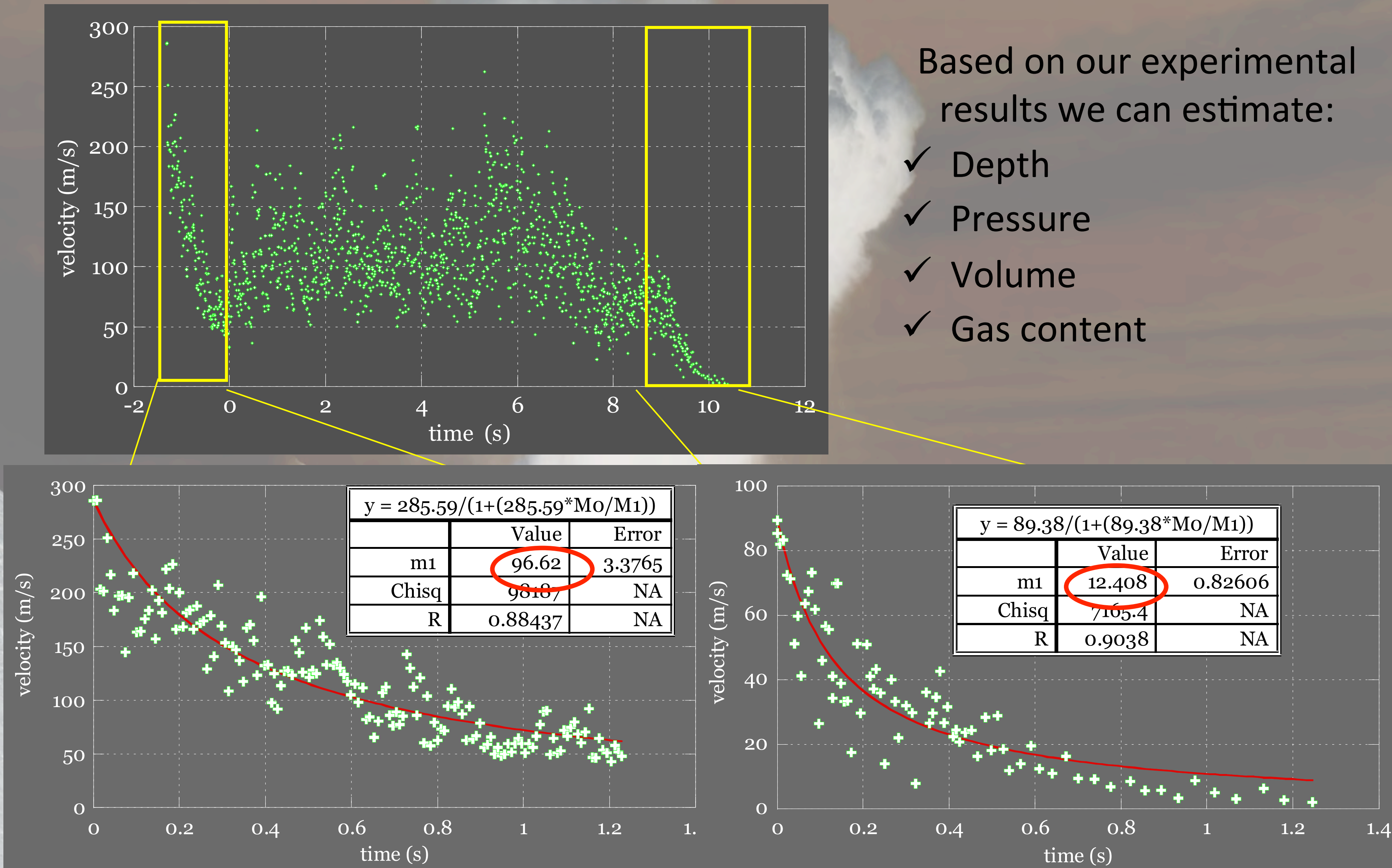
- Measure the particle ejection velocity with independent techniques (high-speed videos and Doppler Radar)
- Measure the thermal finger print of volcanic plumes
- Understand the acoustic signals of a volcano (“resonator”, conduit length, diameter…)

-> “Calibrate volcanoes”

Ejection speed of pyroclasts



Ejection velocities at Stromboli volcano (high-V videos)

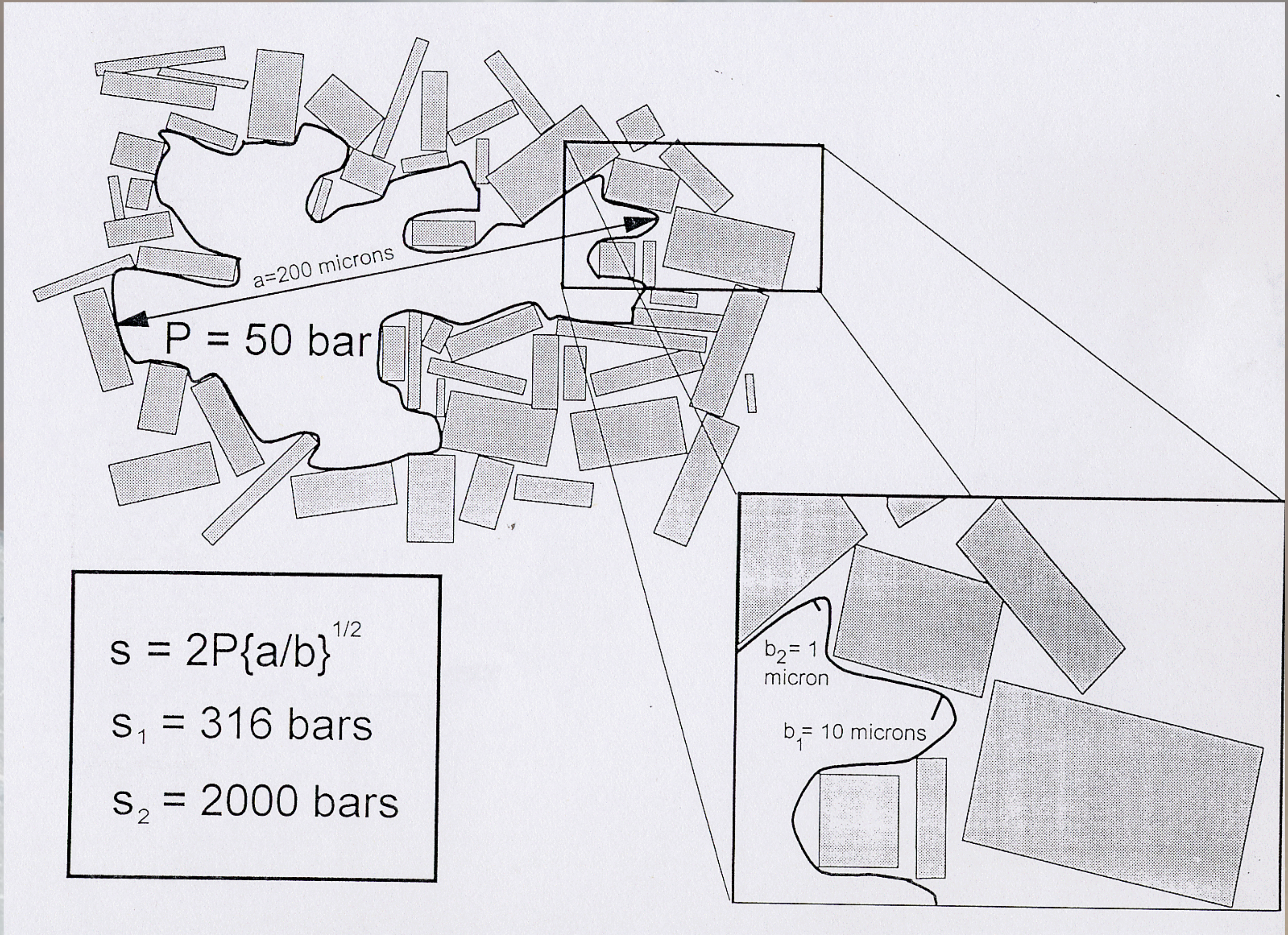


Based on our experimental results we can estimate:

- ✓ Depth
- ✓ Pressure
- ✓ Volume
- ✓ Gas content

Taddeucci et al. JGR 2012

Magma reality….

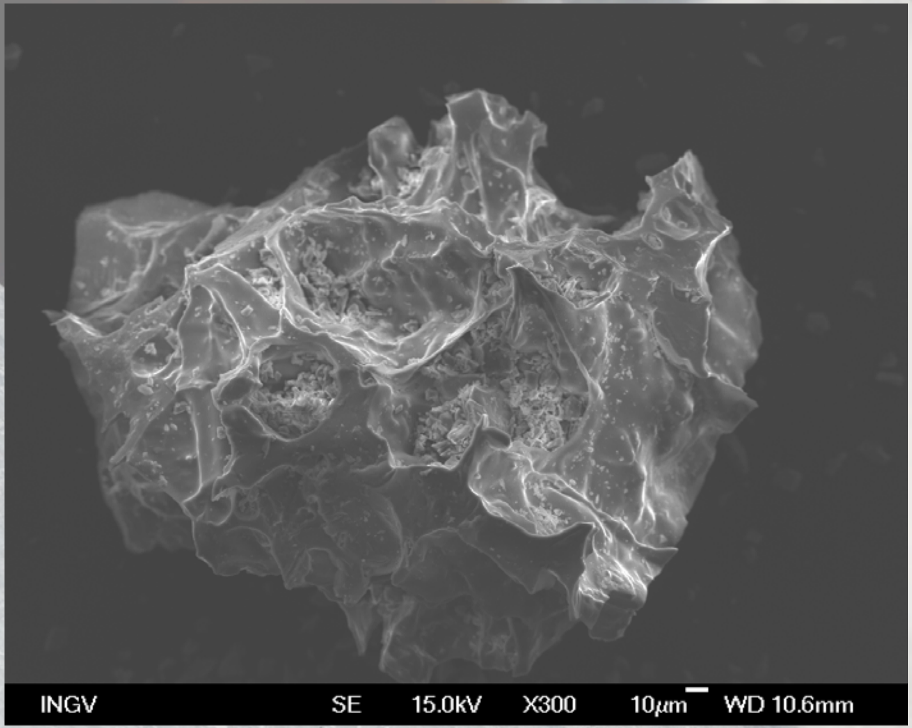


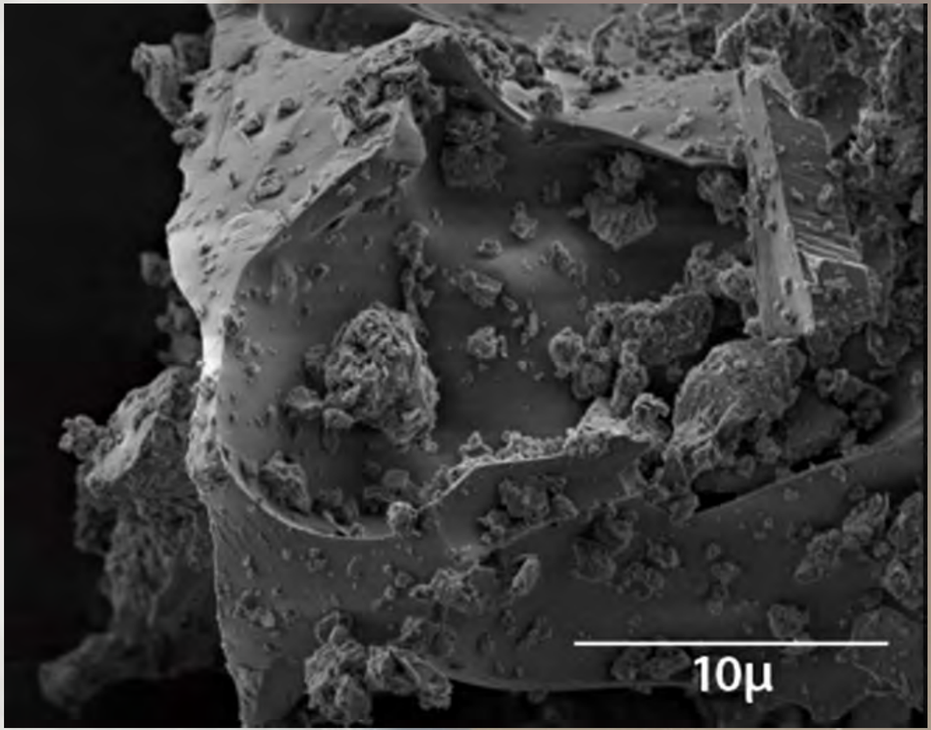
(Mungall et al., 1995)

Morphology of clasts

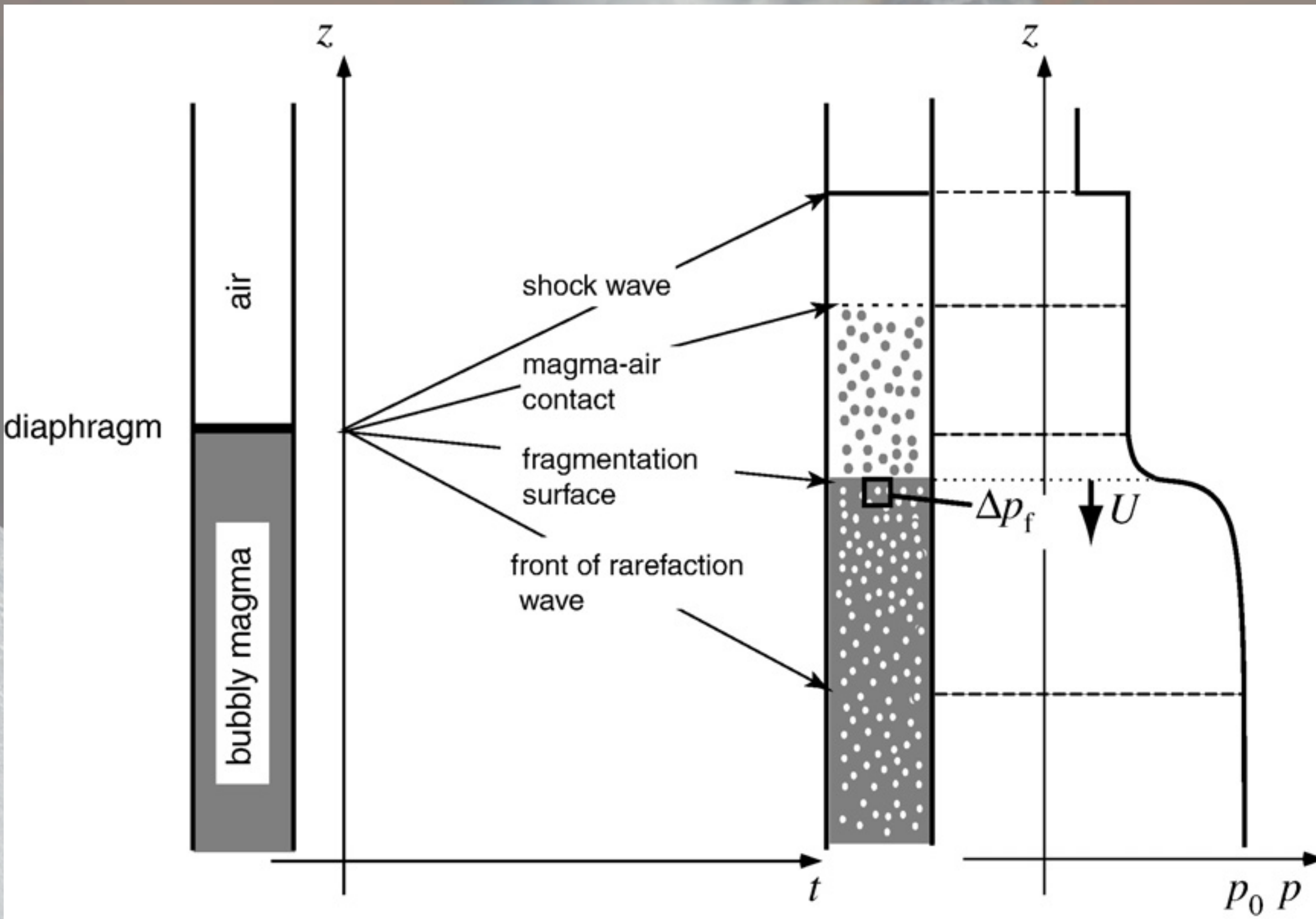
Unzen (experimental)

Eyjafjallajökull (natural)





The shock tube problem of viscous bubbly magma



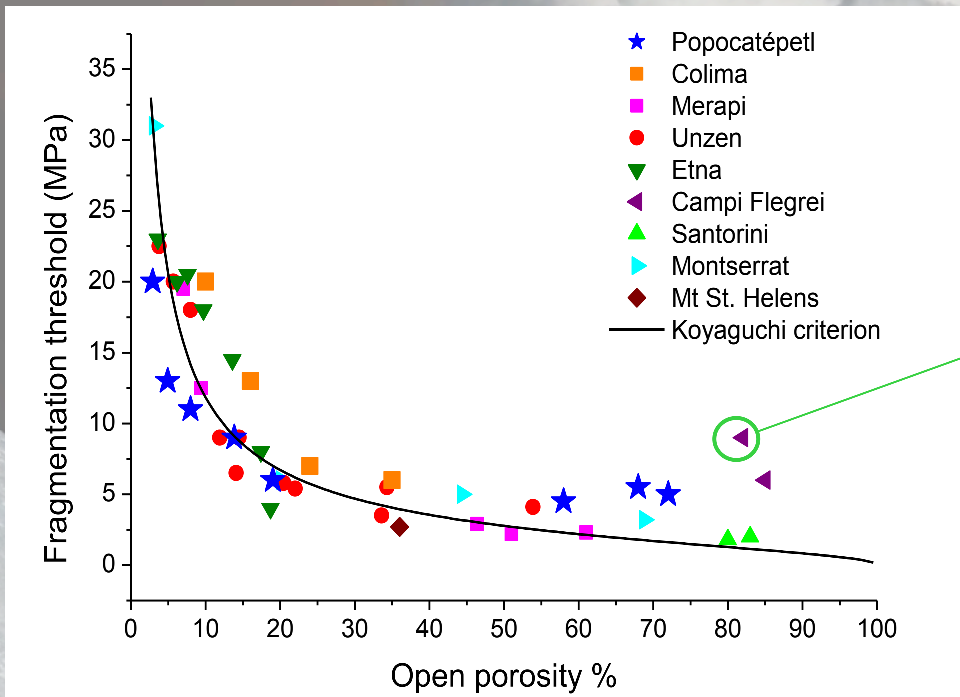
Δp_f: gas overpressure at the fragmentation surface;

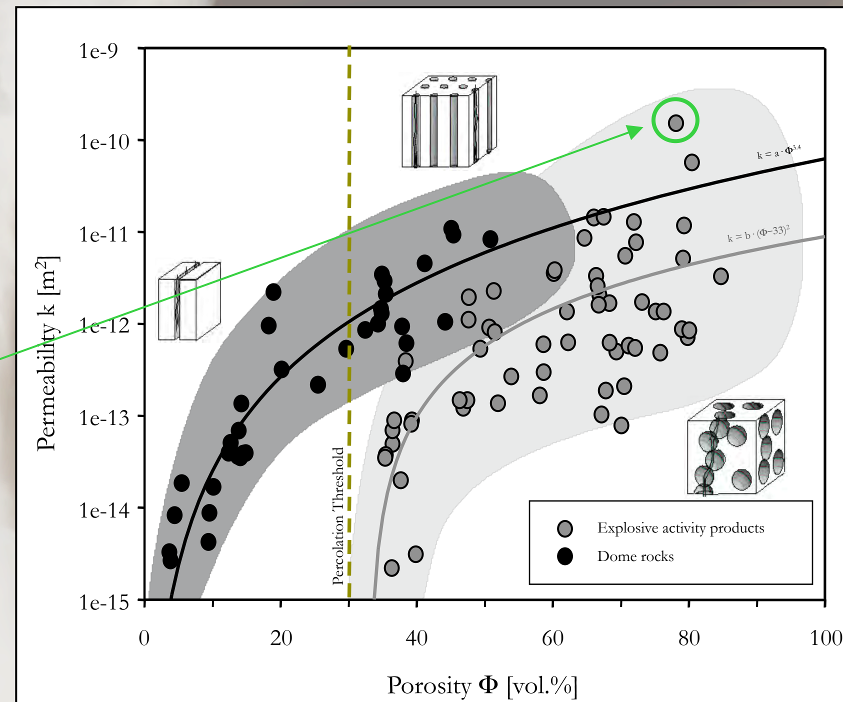
U: fragmentation speed.

Typical pressure profile after the diaphragm rupture: a shock wave propagates into the air and a rarefaction wave propagates into the bubbly magma.

(Koyaguchi et al., JVGR, 2008)

Permeability and fragmentation

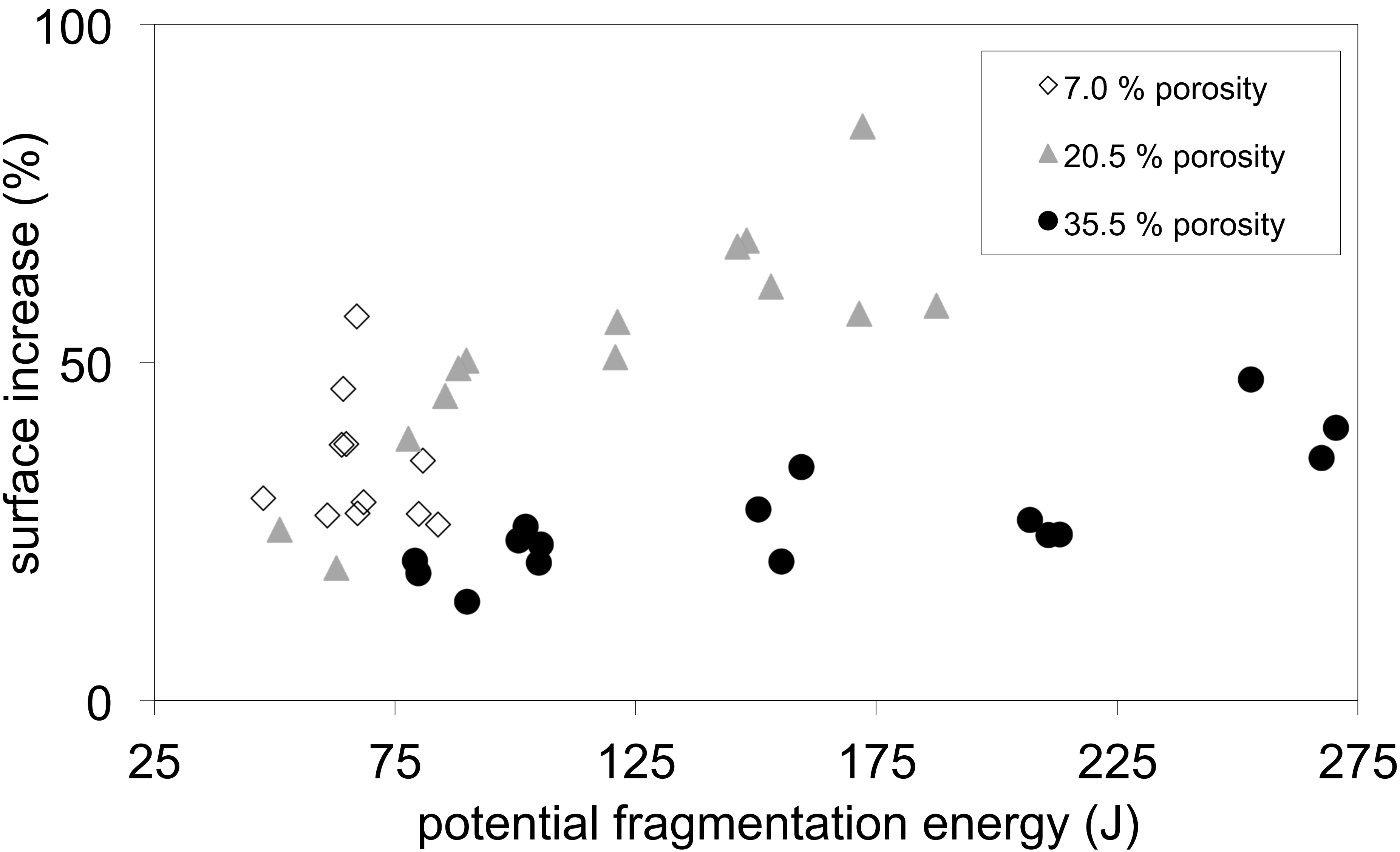




Alatorre-Ibargüengoitia et al. (EPSL, 2010),
Kueppers (PhD thesis, 2005), Spieler et al. (EPSL, 2004)

(modified after Mueller et al., Geology, 2008)

Fragmentation efficiency (energy conversion)



Kueppers et al., JVGR 2006