Evidence for seismogenic fracture of silicic magma

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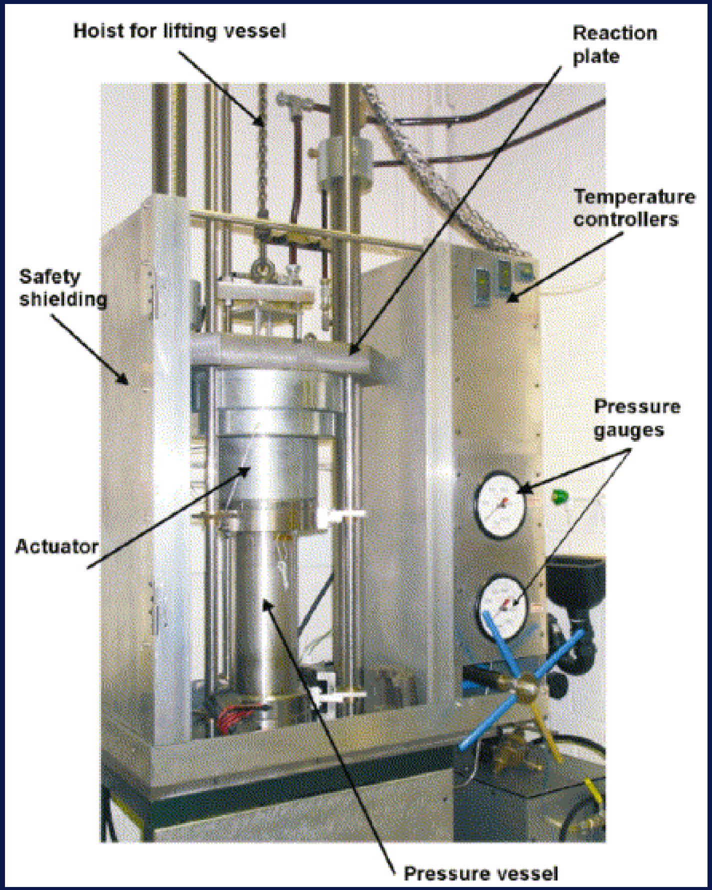
Introduction

- A lot of small (magnitude M $<$ 3), low frequency earthquakes occur during lava dome growth, typically tightly clustered aroud the conduit and dome $<$ 2km from the surface.
- The source mechanisms of these events have long been controversial.
- Researcher (ex. Tuffen et al., 2004) have recently recognized that small-scale brittle-ductile faults are abundant in silica rich lavas and display remarkably similar characteristics to tectonic faults.
- This has led to the hypothesis that seismic events may be triggered by fracture and faulting within the erupting magma itself.
- This hypothesis is further supported by recent observation of dome growth at Unzen volcano (Goto, 1999).
  - Seismological observation of Unzen revealed the activity of earthquakes in the lava dome.
  - The lava flowed down after the appearence to the surface.
  - This suggests that fluid lava failed brittly and excited seismic wave.
- To test the hypothesis authors have done deformation experiments on lava samples at temperaure up to 900 deg.C

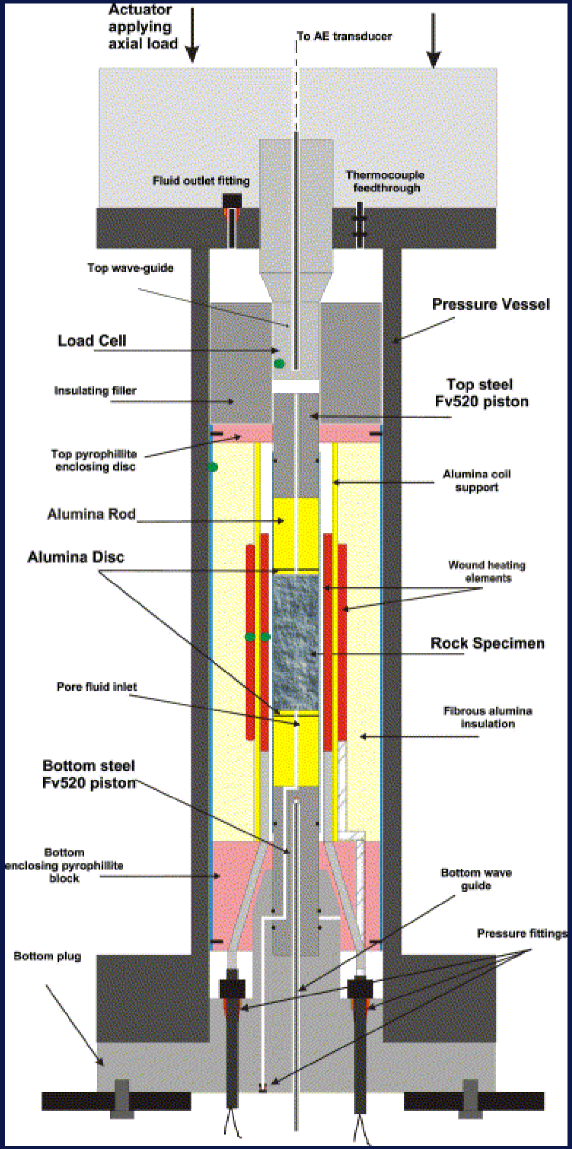
Experimental Apparatus



- Deformation experiments were carried out by using a new triaxial deformation apparatus (Rocchi et al., 2004).
- The apparatus was designed to test rock at temperatures up to 1000 deg.C and pressure up to 50 MPa.
- The gratest novelty of this apparatus compared with other high temperature triaxial cells is the large sample size (25 mm diameter by 75 mm long).
- The large specimen size is necessary to test volcanic rocks with their large crystals and vesicle.
- Finding the best compromise between pressure vessel size, specimen size and space for insulation was the key issues in the design of a new and efficient furnace.

- Temperature gradients along the length of the specimen:
  - less than 1 deg.C (at atmospheric pressure).
  - about 20 deg.C (at high pressure)

Experimental



- Procedure
  - Cylindrical samples 75 mm in length and 25 mm diameter were deformed in compression in a high-pressure, high-temperature triaxial cell.
  - An all-round hydrostatic pressure was first applied to the sample and maintained at a set value (the confining pressure). (Argon gas)
  - The sample was heated and maintained at a set temperature using an internal heater.
  - An axial load was applied to the rock sample at constant displacement rate (that is, constant strain rate).
  - Accoustic emissions were detected continuously.

Experimental conditions

- Samples
  - The glassy lava was aphyric bubble-free rhyolitic obsidian from Krafla, Iceland (100% glass)
  - The clystalline lava was porphyritic andesite (21 % phenocrysts $<$ 2.5 mm long, $<$2% glass) from Mt Shasta, California.
- Samples were deformed at a range of constant strain rates (from $10^{-4.3}$ to 10^{-5}s^{-1}, with total strains of $\leq$ 4 %) and temperatures in order to attain both brittle and ductile deformation behaviour.

Table 1. Summary of experimental conditions

Sample	Material	Confining pressure (MPa)	Temp. (deg.C)	Strain rate (s^{-1})	Sample behaviour
SA45	Andesite	0.3	900	10^{-5}	Some ductile deformation, brittle shear failure
SA43	Andesite	10	900	10^{-5}	Predominantly ductile deformation with some shear cracking
SA42	Andesite	10	600	10^{-5}	Elasic-brittle
H15-3	Obsidian	0.3	645	$10^{-4.3}$	Some ductile deformation, axial cracking
H6	Obsidian	0.3	645	$10^{4.9}$	Ductile barrelling
H15-4	Obsidian	0.1	20	10^{-5}	Elastic-brittle

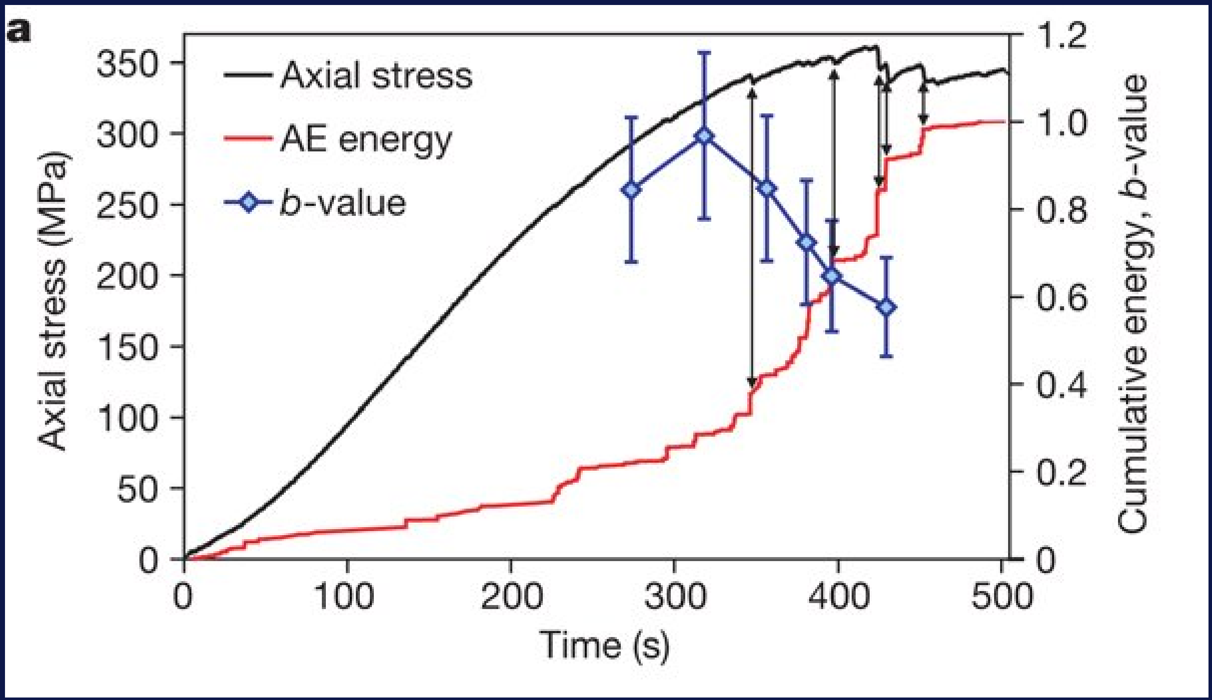
Acoustic Emission

- Stress waves produced by dynamic processes in materials are known as acoustic emissions (AE).
- A close analogy exists between AE produced from materials undergoing brittle failure at the laboratory scale and seismic waves caused due to earthquakes.
- AE technique can be used for monitoring and understanding the mechanisms of dynamic processes in rocks at several scales and earhquakes.

b-value

- b-value can be calculated using the 'cumulative frequency-magnitude' distribution data and applying the Gutenberg-Richter relationship, which is widely used in seismology.
- The equation is as follows: $log_{10}N = a - bM$ where M is the Richter magnitude of earthquakes (or AE), N is the number of earthquakes (or AE events) with magnitude greater than M,a an emprical constant and b is the b-value which is mostly $\sim$ 1.0.
- A high b-value arise due to a large number of small earthquakes (or AE events) representing new crack formation and slow crack growth.
- A low b-value arise due to a large number of large earthquakes (or AE events) representing faster or unstable crack growth.

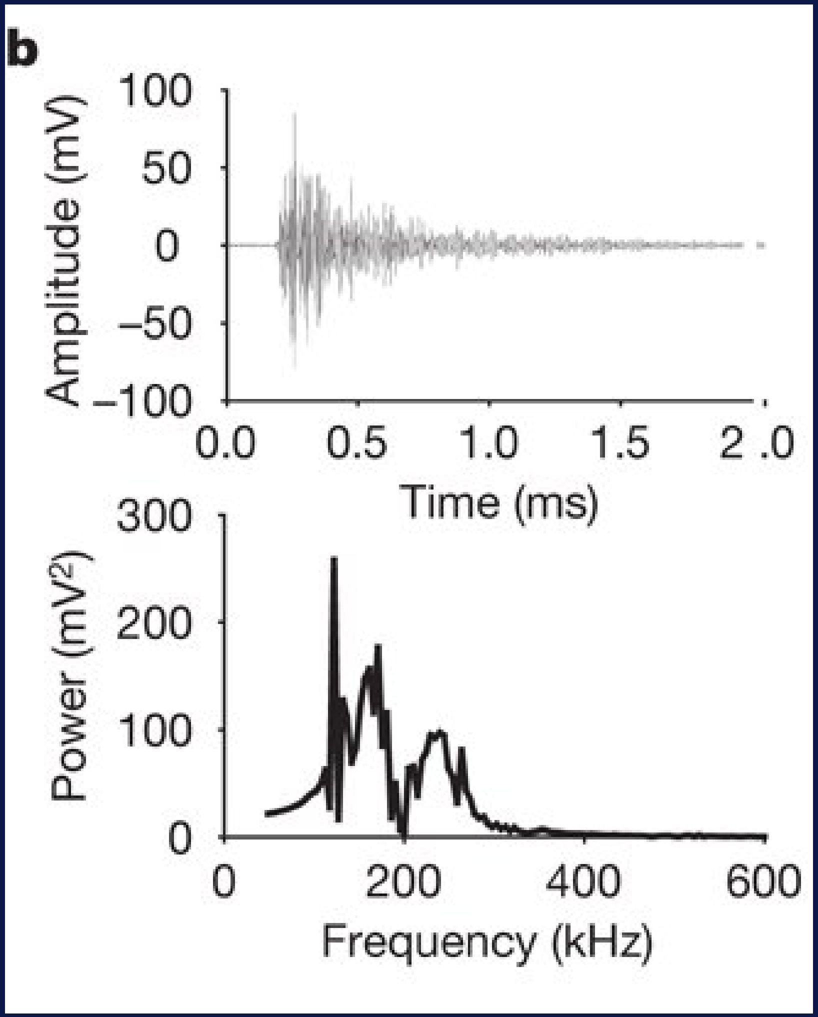
Fig 1a. Experimental results of rhyolitic obsidian at 645 deg. C (close to its glass transition) and 10 $^{-4.3}s^{-1}$



- A sequence of small, abrupt stress drops and associated reduction in compliance characterize brittle-ductile behavior.
- There is a clear correlation between stress drops and burst of acoustic emission (jumps in AE energy).
- This indicate that cracking of the sample is associated with release of acoustic energy.

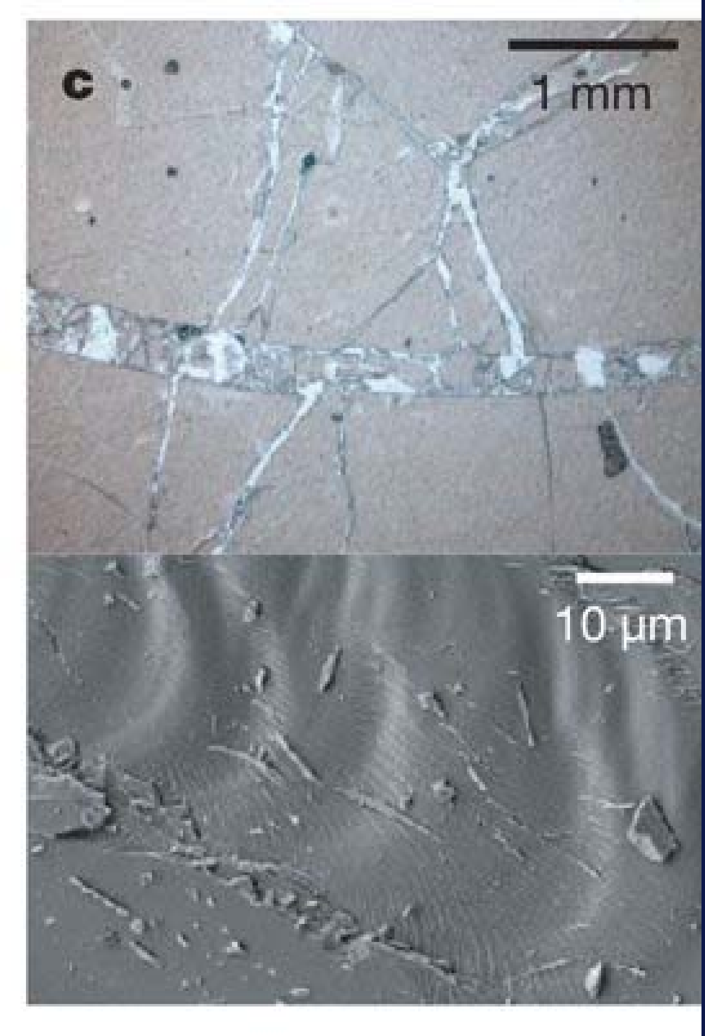
- The seismic b-value decreases as the peak stress is approached.
- This decrease is indivative of microcrack extension and coalescence occuring with ongoing sample deformation.

Fig 1b. Experimental results of rhyolitic obsidian at 645 deg. C (close to its glass transition) and 10 $^{-4.3}s^{-1}$



- A representative acoustic-emission waveform and power spectrum are shown in Fig 1b
- Energy is predominantly in the 100-300 kHz range.
- The onset is abrupt, and the waveform is typical of acoustic-emission events recorded during brittle failure of other crustal rock samples.
- It is similar to waveforms authors recorded during brittle failure of the obsidian at room temperature (Supplementary Figure 1).

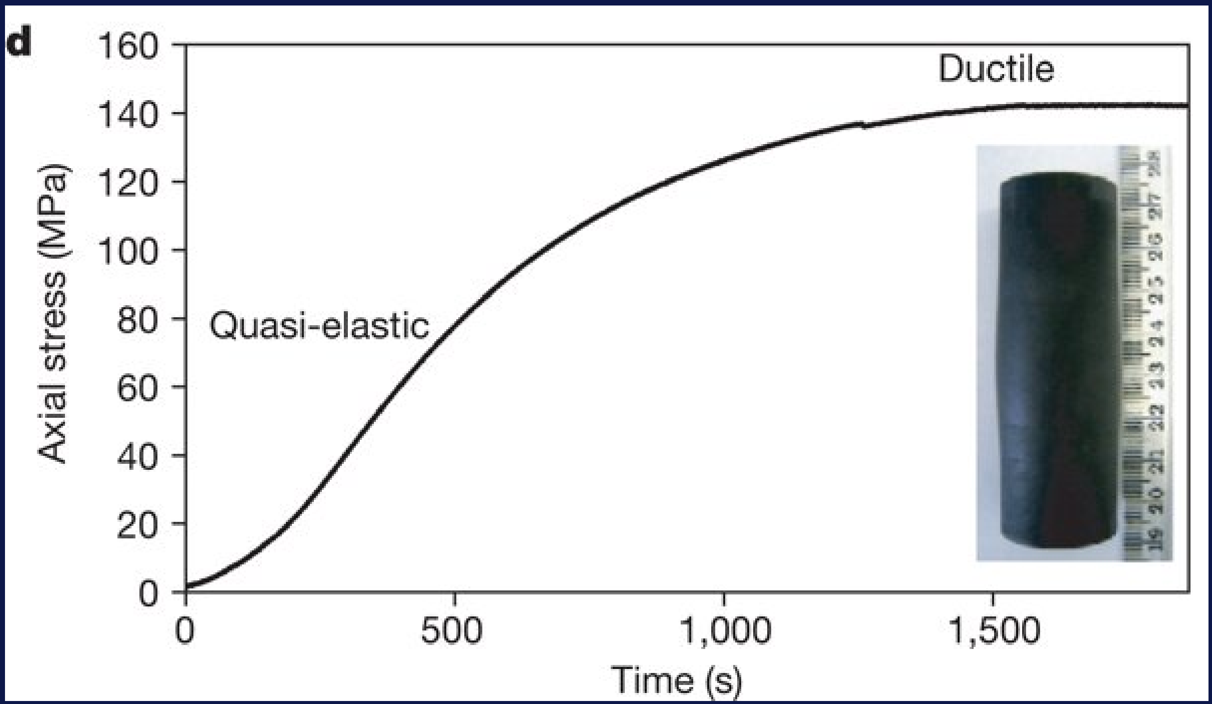
Fig 1c. Experimental results of rhyolitic obsidian at 645 deg. C (close to its glass transition) and 10 $^{-4.3}s^{-1}$



Post-experiment sample analysis showed that numerous predominantly axial cracks had formed, with curved, conchoidal surface and local zones of cataclasis.

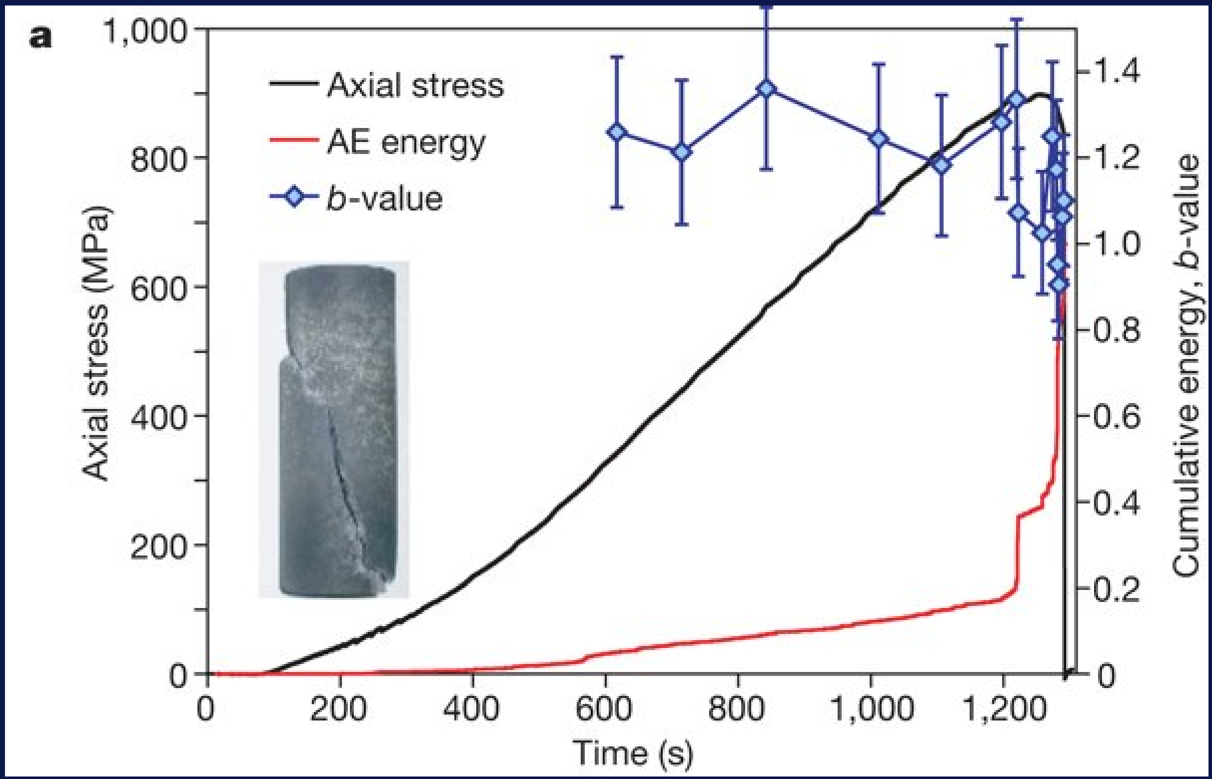
- (upper image) Photomicrograph of post-experiment obsidian sample, sectioned normal to applied load, showing formation of gouge on curved brittle fracture surface.
- (lower image) SEM image of typical fracture surface, showing micrometre-scale hackle markings typical of brittle glass fracture.

Fig 1d. Experimental results of rhyolitic obsidian at 645 deg. C (close to its glass transition) and lower strain rates of 10 $^{-4.9}s^{-1}$



- Fig 1d shows loading behaviour of obsidian deformed at 645 deg.C and $10^{-4.9}s^{-1}$
- Ductile deformation of the sample occured after initail quasi-elastic loading, leading to sample barrelling but without crack formation
- No acoustic emissions were detected during such ductile behaviour.
- Experimental results of Fig 1a (strain rate of $10^{-4.3}s^{-1}$) and Fig 1d (strain rate of $10^{-4.9}s^{-1}$) suggests that loading behaviour strongly depends on strain rate.
- Such strongly strain rate dependent ductile-brittle behaviour is typical of silicate melts

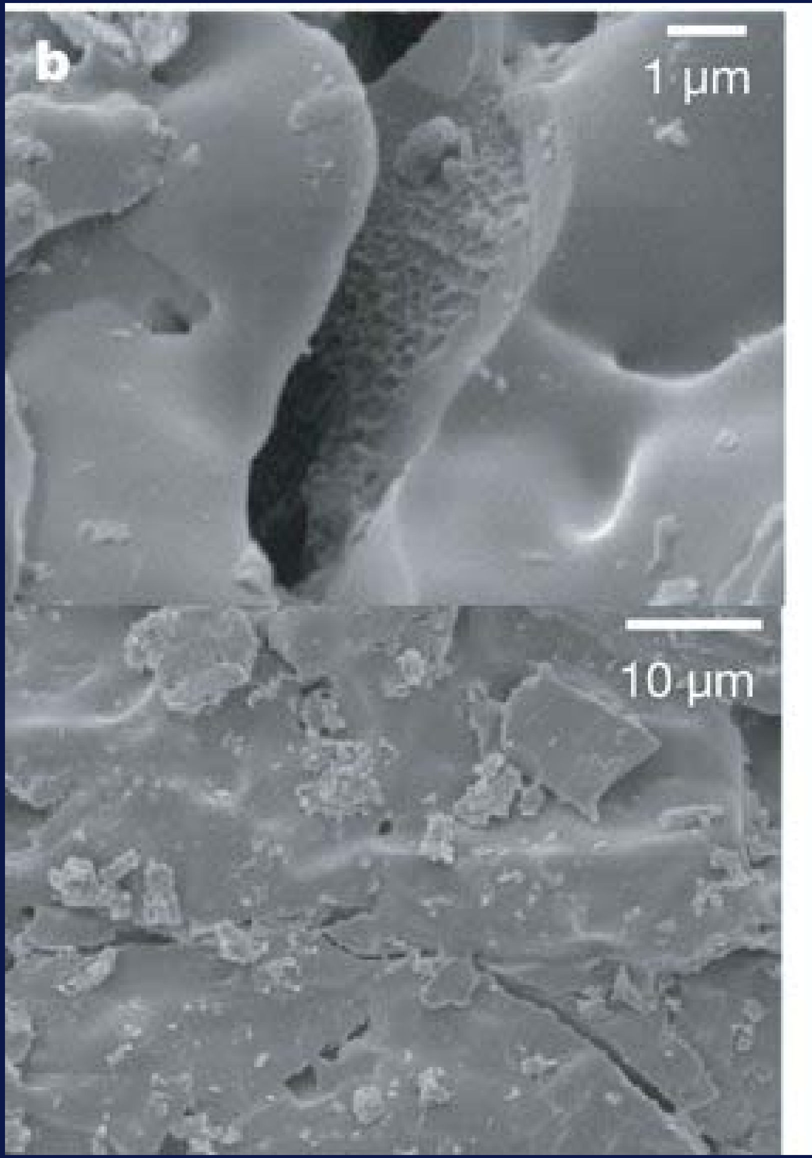
Fig 2a. Experimental results of andesite at 900 deg. C and $10^{-5}s^{-1}$



- After quasi-elastic loading, the sample undergoes strain hardening close to peak stress (of around 90 MPa) accompanied by strong acousitc-emission activity.
- Post-peak stress, the sample underwent a small but significant phase of strain softening deformation and accelerating acoustic-emission activity, leading to dynamic failure.

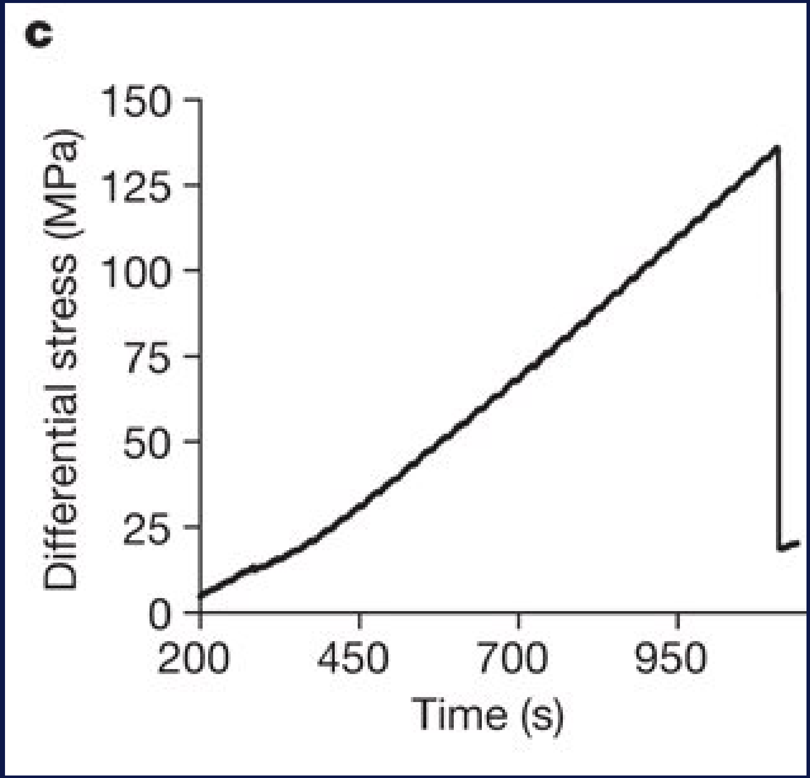
- The post-experiment sample displays a through-going shear fracture at 17 degree to the loading axis.

Fig 2b. Experimental results of andesite at 900 deg.C and $10^{-5}s^{-1}$



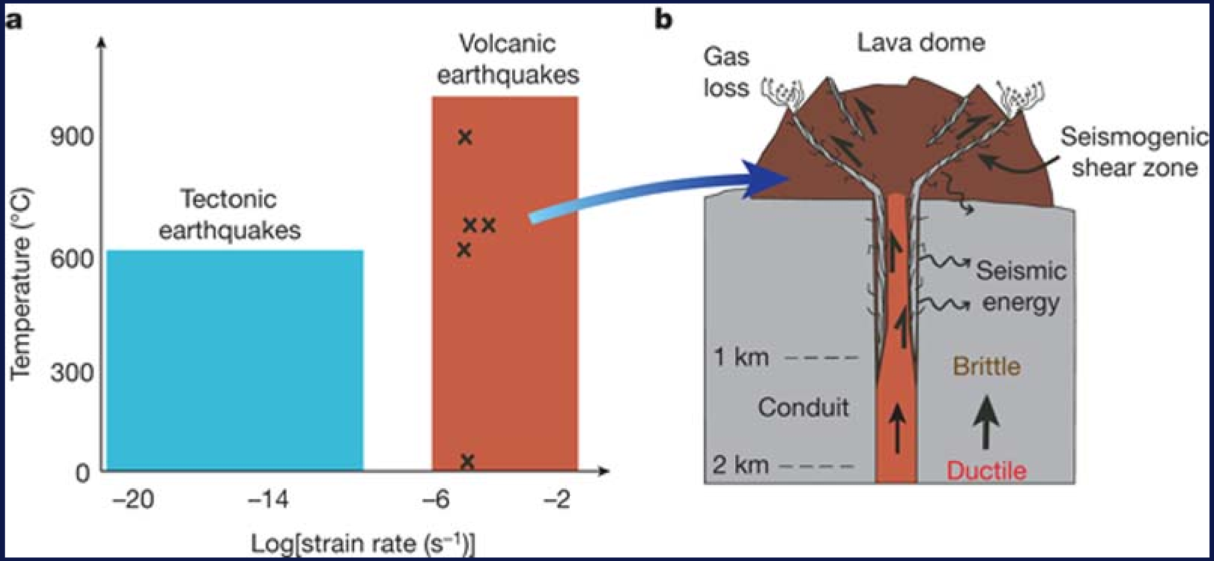
- SEM images of fracture surfaces in andesite deformed at 900 deg.C
- (upper image) Brittle-ductile textures preserved in glass on the shear fracture plane in SA43
- (lower image) quenched melt on a fracture surface in sample SH45
- Post-experiment analysis using the SEM shows that brittle-ductile deformation of a melt phase had occured on the fracture surface.

Fig 2c. Experimental results of andesite at 600 deg.C and $10^{-5}s^{-1}$



- Differencial stress against time for triaxial deformation of andesite (sample SA42) at 600 deg.C and $10^{-5}s^{-1}$ with 10 MPa confining pressure.
- Brittle failure occurs immediately after the peak stress.

Fig 3. Schematic diagrams comparing faulting in silicic magma to tectonic faulting



- Diagram showing the approximate range of temperatures and strain rates for seismogenic faulting in the lithosphere as a whole ('tectonic earthquakes') and in silicic magma ('volcanic earthquakes').
- Crosses indicate the conditions of the experiments described in this paper

- The experimental results extend the range of known conditions for seismogenic rupture to include magma at 900 deg.C.
- This is significantly greater than the 600 deg.C limit proposed for faulting elsewhere in the lithosphere.
- This owe to compositional effects (the high viscosity of silicic magmas) and abnormally high strain rates in magma (about ten orders of magnitude faster than the lithosphere as a whole)

Summary

- In order to test the hypothesis that high-T magma fracture is seismogenic, authors have done deformation experiments of silica-rich magmas under simulated volcanic conditions.
- The acoustic emissions recorded during experiments show that seismogenic rupture may occur in both crystal-rich and crystal-free silicic magmas at eruptive temperatures.