The evolution of elastic moduli with increasing crack damage during cyclic stressing of Etna basalt

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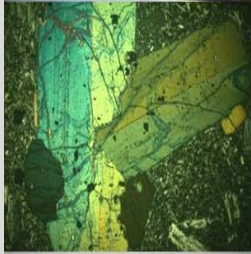
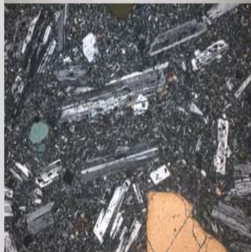
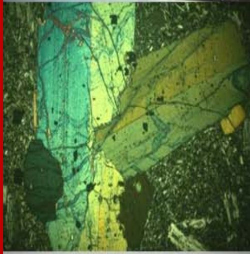




Contents

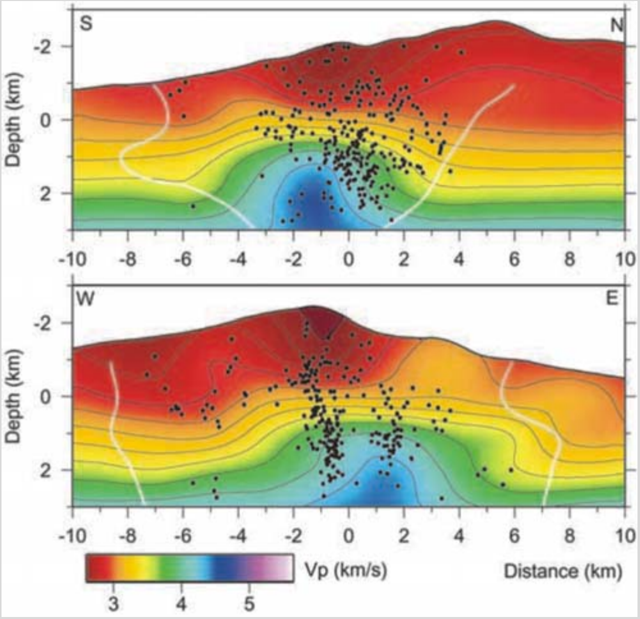
- Why are mechanical and elastic data important?
- Stress-cycling in a volcanic edifice
- Stress-cycling in the laboratory
- Conclusions





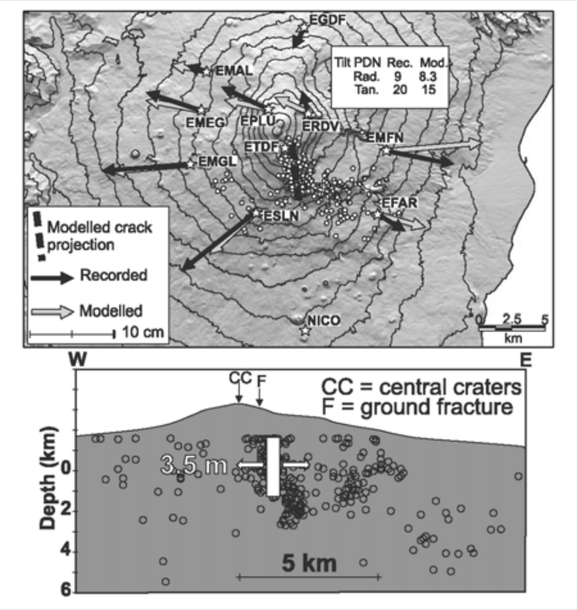
Why are mechanical and elastic data important?

Mount Etna Tomography



[Patane *et al*., 2002]

Mount Etna - Ground deformation



[Bonaccorso *et al*., 2002]

Needs accurate velocity data

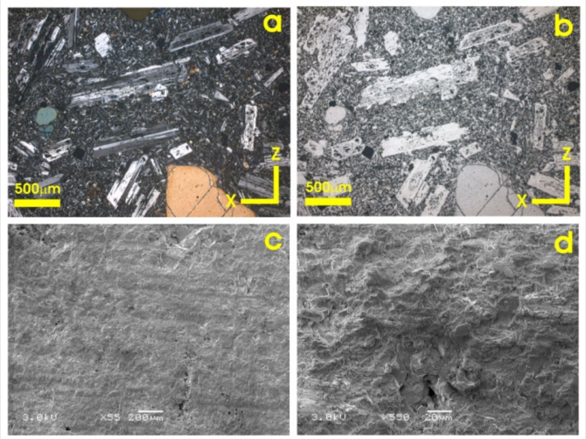
Needs accurate mechanical data

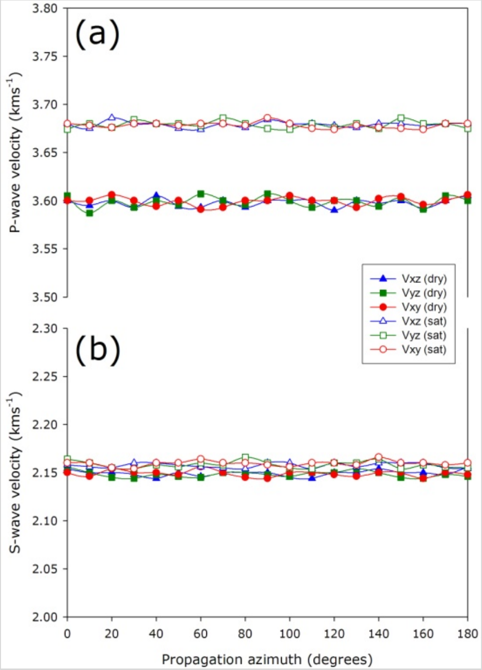
Stress-cycling in a volcanic edifice

- Volcanic edifices are subject to pressurization and depressurization cycles over extended periods of time [Allard *et al.*, 2006; Carbone and Greco, 2007 and references therein] due to repeated episodes of magma emplacement from deep reservoirs to shallow depths.
- Such repeated episodes of deformation can lead to an increase in the level of crack damage within the rocks of the edifice, and hence changes in their elastic properties.
- However, the effect of stress-cycling on mechanical and elastic properties of volcanic rock remains largely unknown. Modelling of Mt. Etna has previously assumed values of Young's modulus ranging from 50-100 GPa and a Poisson's ratio of 0.25 [Cayol and Cornet, 1998; Bonaccorso and Davis, 1999].
- Here we report new results from stress-cycling deformation experiments on Etna basalt. These experiments attempt to characterize the changes in elastic properties with increasing cyclic damage.

Material investigated

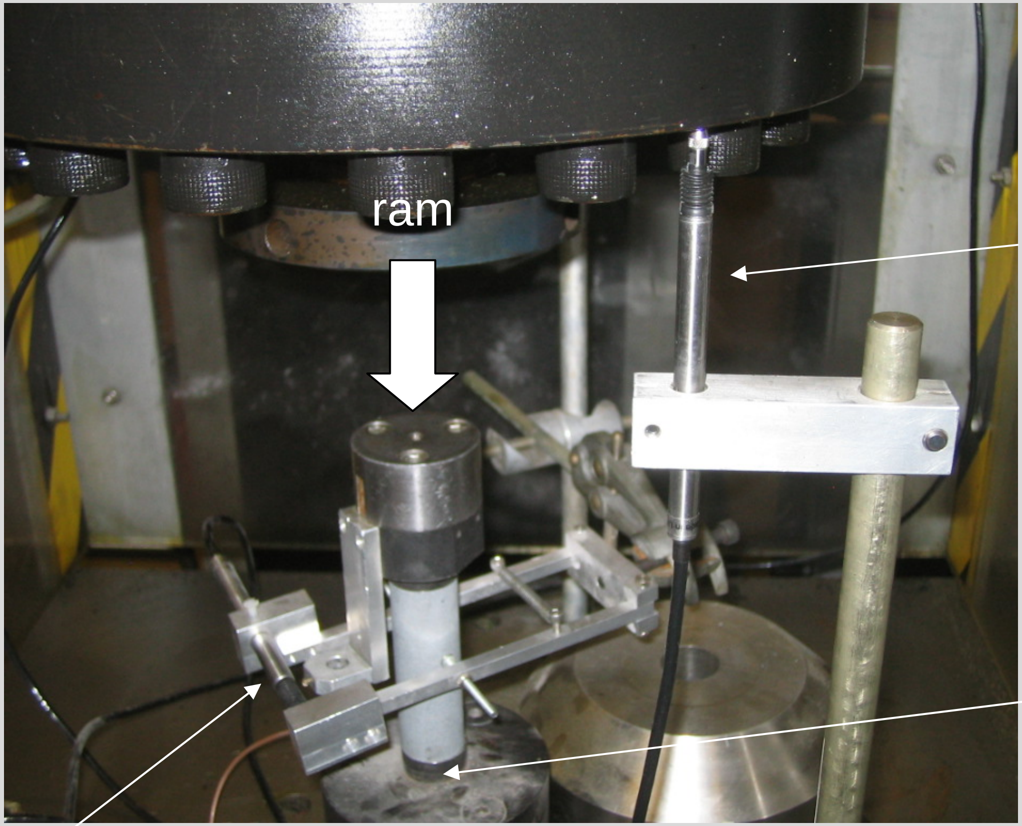
Extruded lava flow basalt (Mount Etna, Italy) - EB





EB contains a high level of pre-existing crack damage and gas bubbles (pores) that are isotropic and interconnected [Vinciguerra *et al.*, 2005]. EB contains a porosity of 4.4%.

Stress-cycling in the laboratory

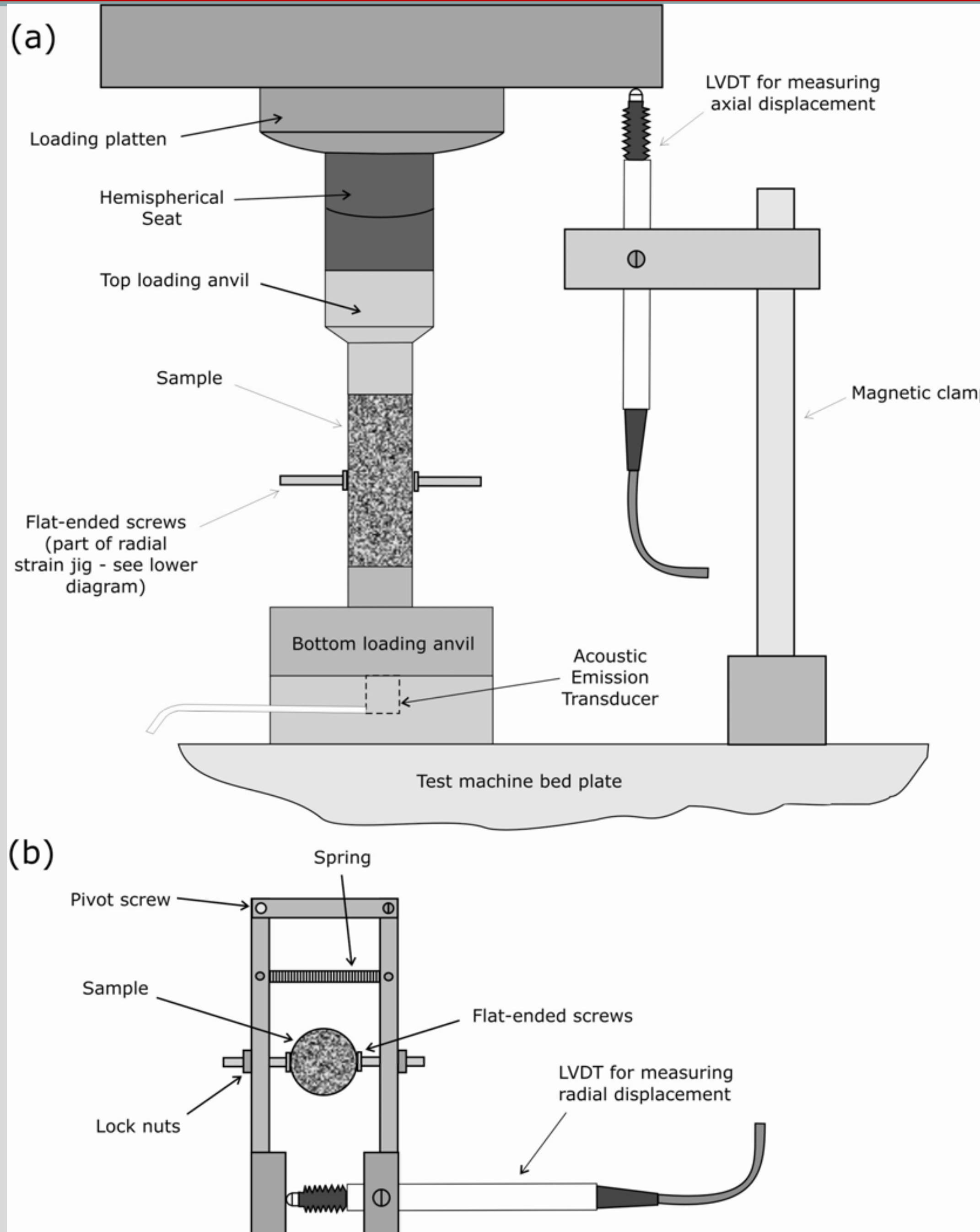


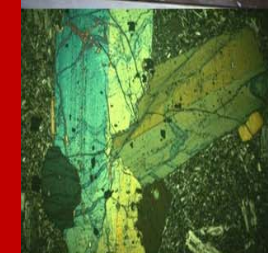
Axial strain transducer

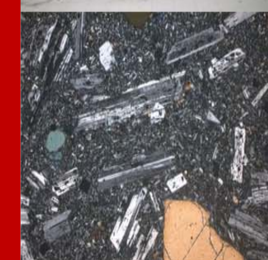
Acoustic emission transducer

Radial strain transducer

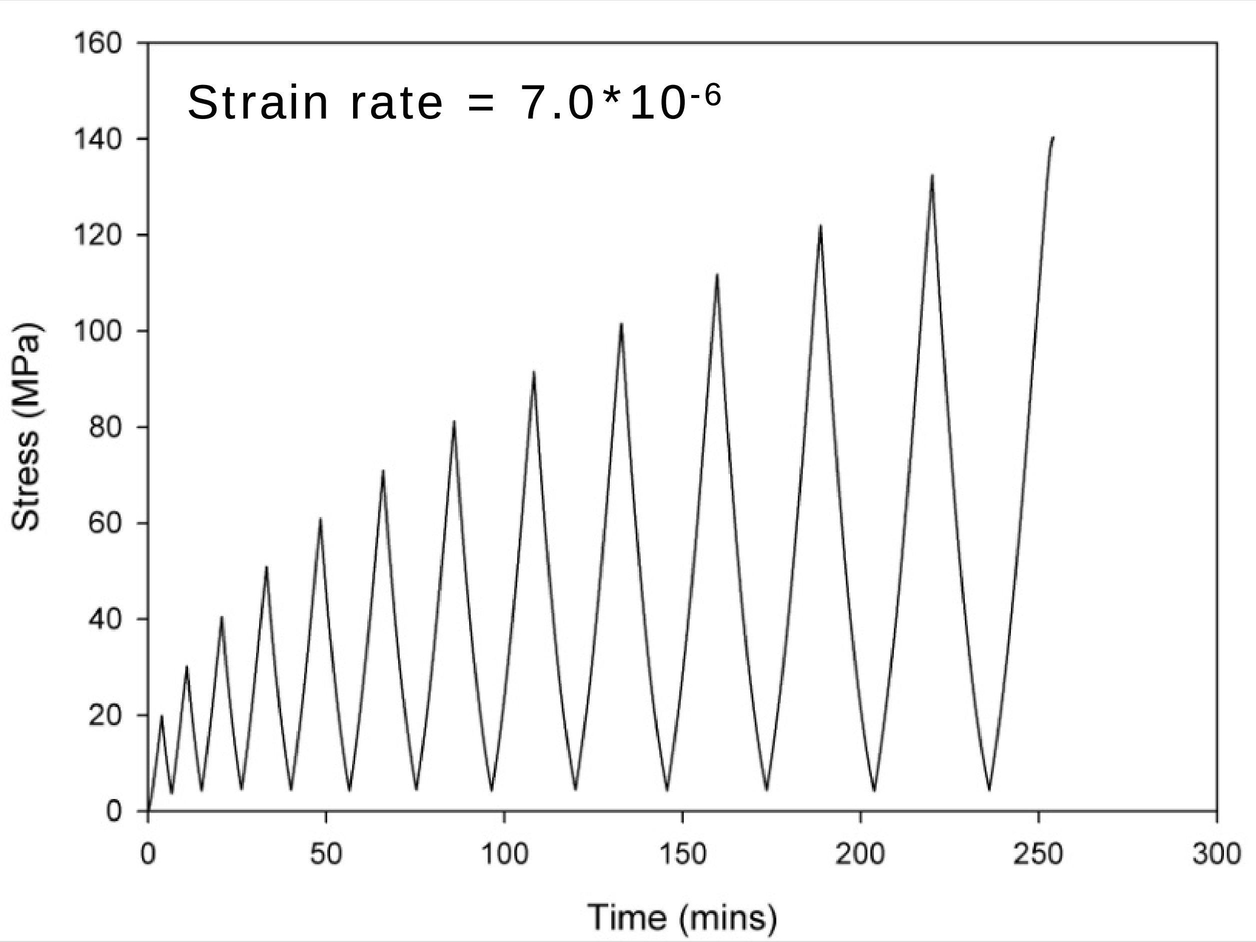
All experiments performed on servo-controlled, uniaxial compression apparatus


(a)
LVDT for measuring axial displacement
Loading platten
Hemispherical Seat
Top loading anvil
Sample
Magnetic clamp
Flat-ended screws (part of radial strain jig - see lower diagram)
Bottom loading anvil
Acoustic Emission Transducer
Test machine bed plate
(b)
Spring
Pivot screw
Sample
Flat-ended screws
Lock nuts
LVDT for measuring radial displacement

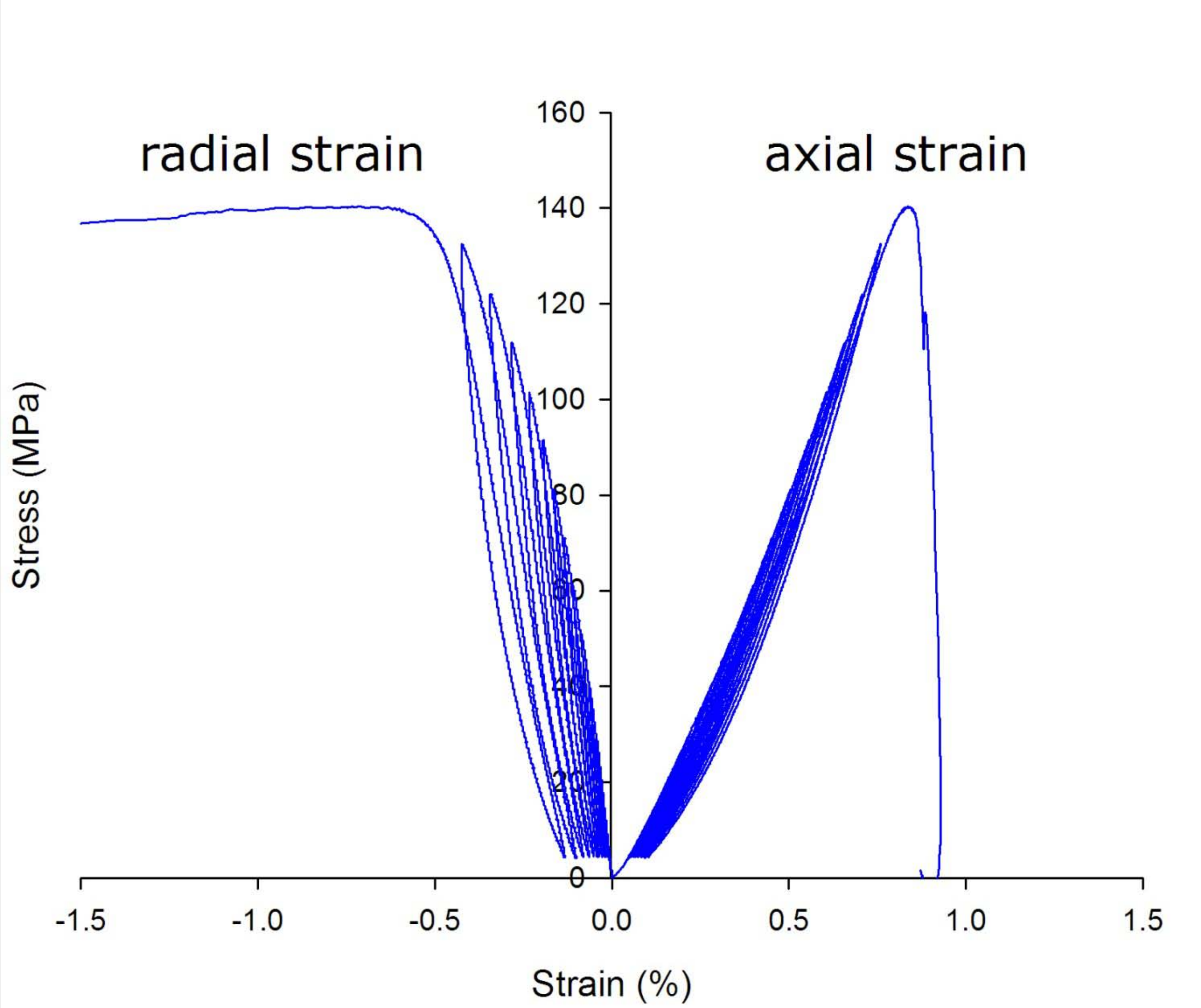


Stress-cycling in the laboratory

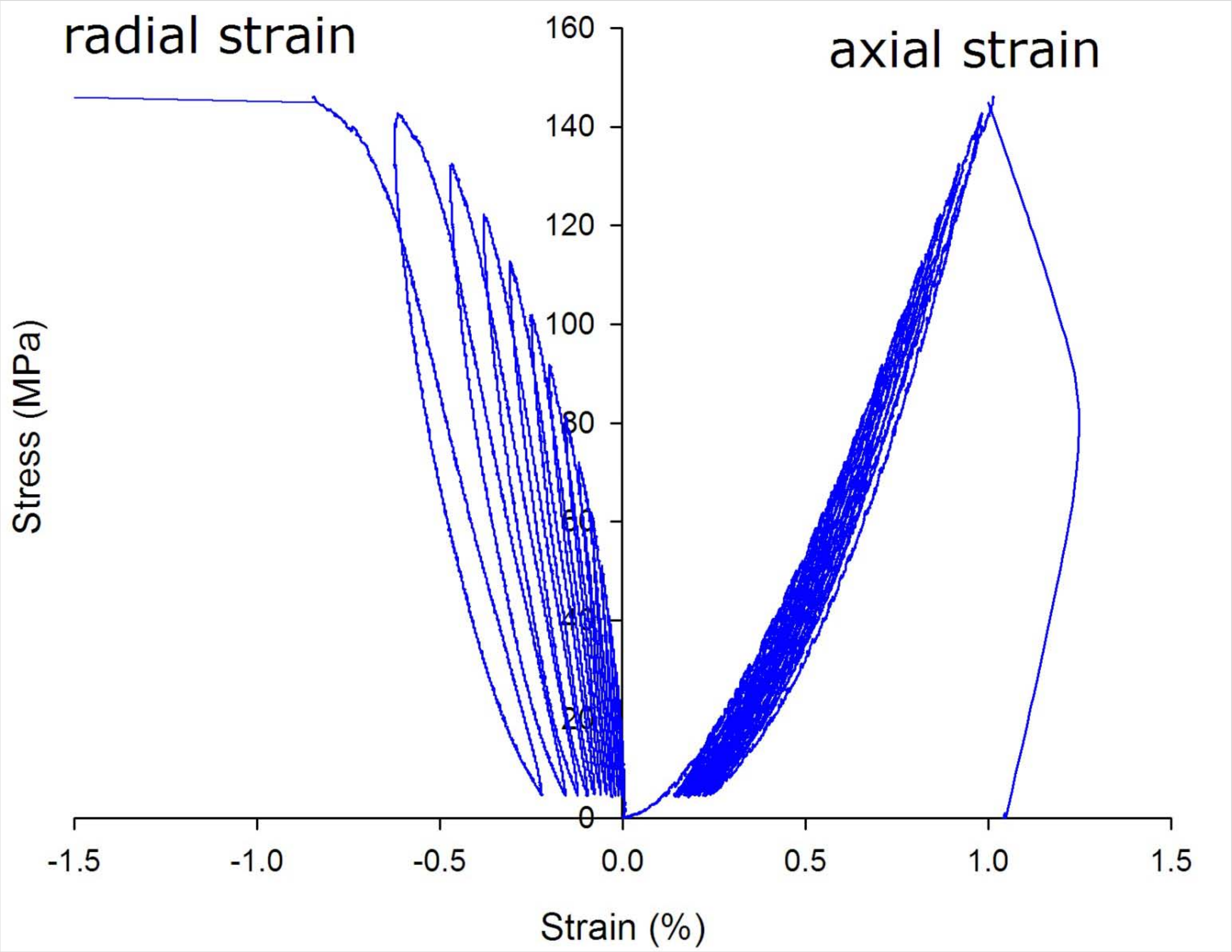


Experiments were peformed on both dry and water-saturated samples of EB.

Dry test

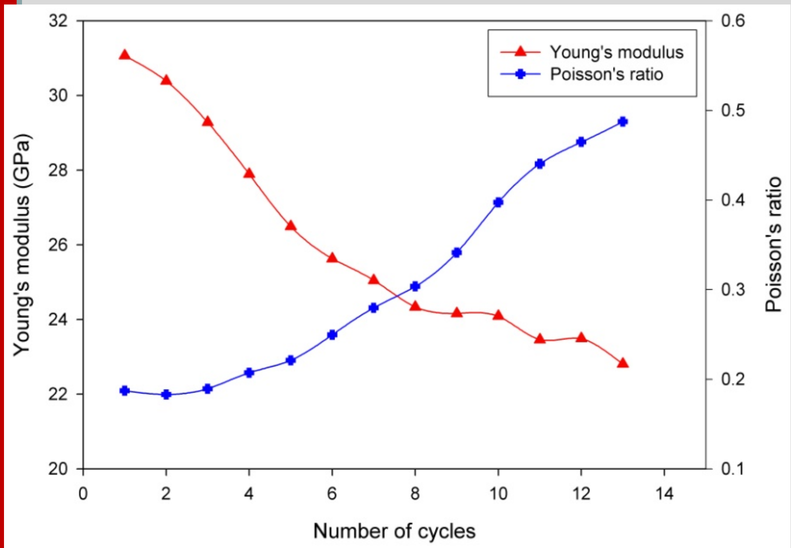

radial strain
axial strain
Stress (MPa)
Strain (%)
0
20
40
60
80
100
120
140
160
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

Water-saturated test

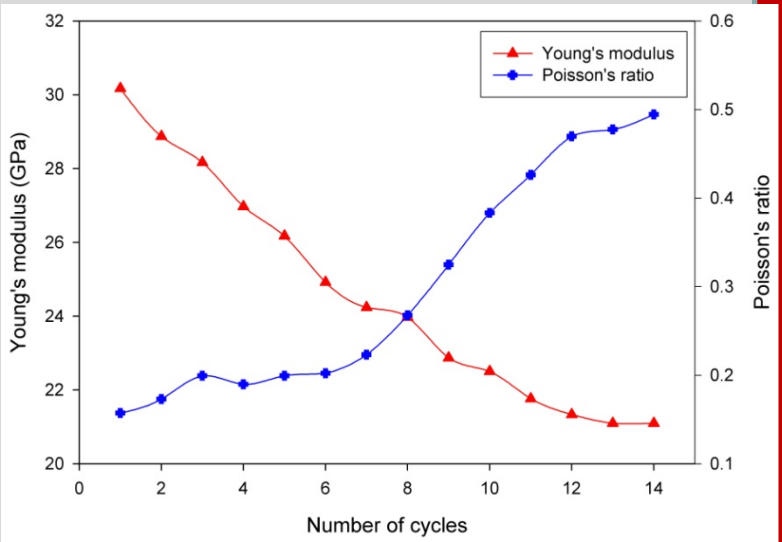


Static moduli results

Dry



Water-saturated



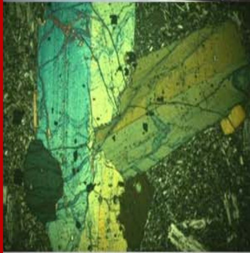
Young's modulus decrease of ~30%

Poisson's ratio increase of ~150%

Young's modulus decrease of ~30%

Poisson's ratio increase of ~200%

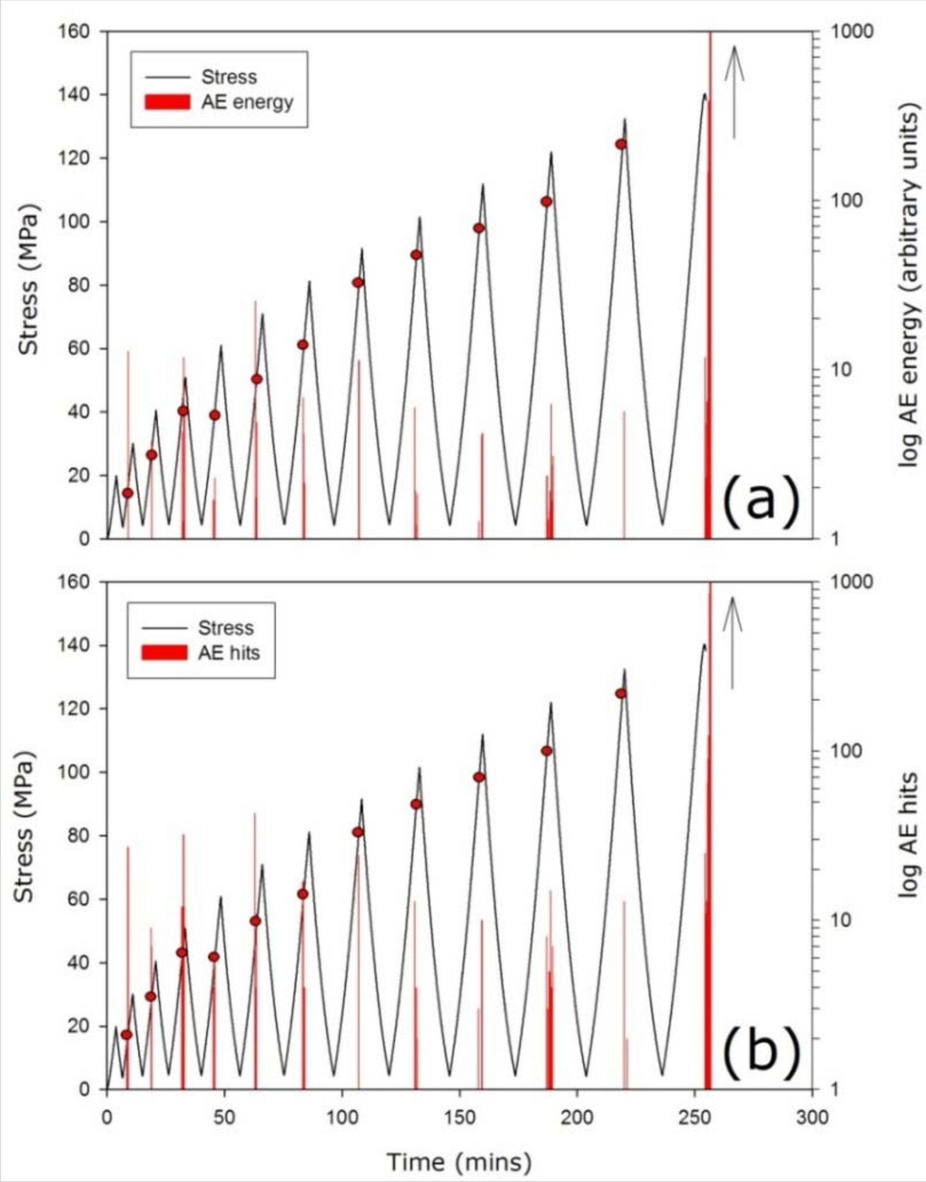
- Cyclic loading leads to the progressive degradation in sample stiffness. This is due to the progressive growth and propagation of pre-existing microcracks.
- As microcrack damage accumulates within the sample, predominantly in an axial crack orientation, then the radial strain increase becomes more prevalent relative to the axial strain. Hence the Poisson's ratio increases as crack damage is accumulated in the sample.



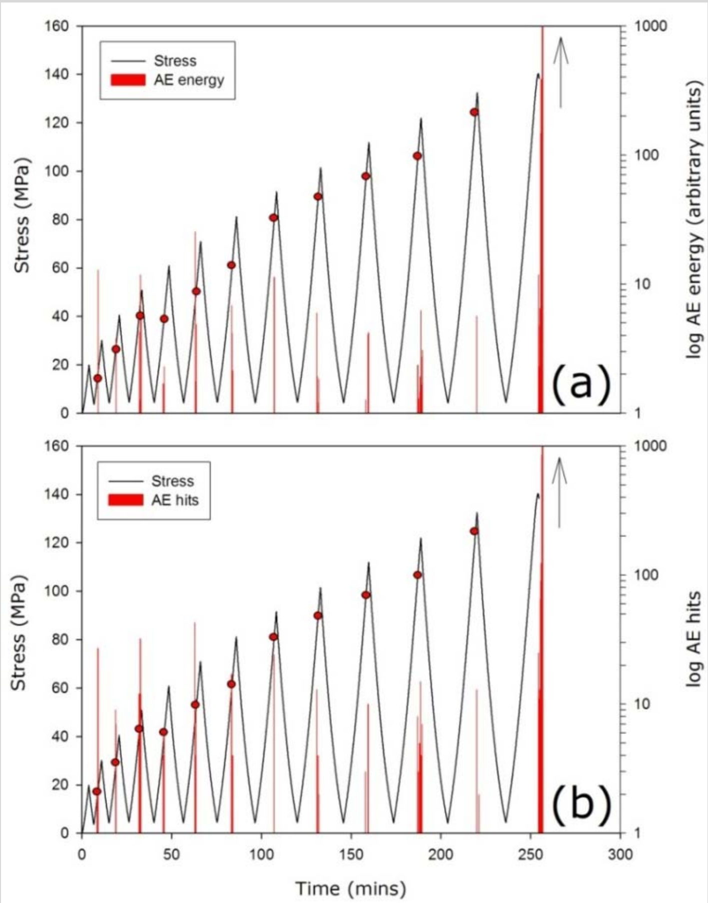
Sample failure mode

All samples failed by axial splitting

Observation of the Kaiser effect 1



Observation of the Kaiser effect 1

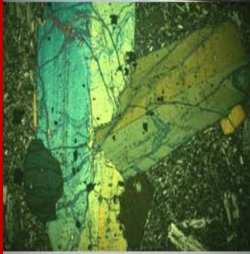


The Kaiser effect states that new AE activity output occurs only when the previous maximum stress has been exceeded.

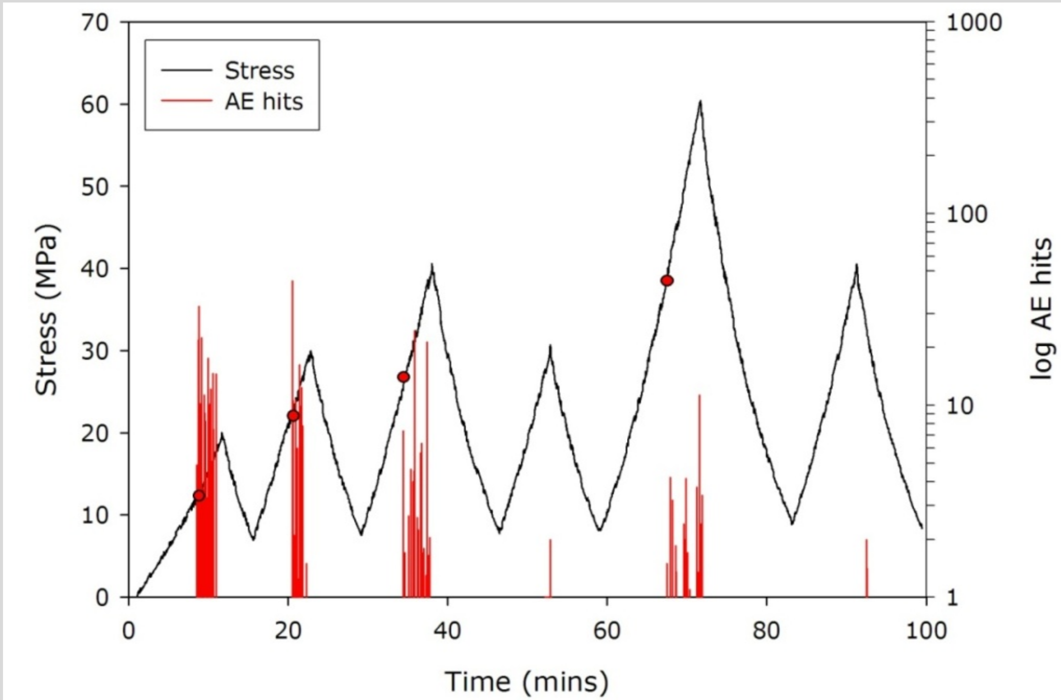
Our results show that AE activity commences just before the peak stress is exceeded. In general, AE activity starts at the stress it ceased at on the previous cycle. This is concerned with the time-dependency of the microcracking.

Since AE is generated by crack growth, this implies that new crack damage occurs only at this point.

This observation provides an independent support for our interpretation that the elastic changes are brought about by crack growth and initiation.



Observation of the Kaiser effect 2

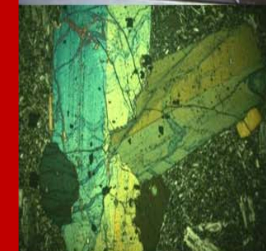


During the deformation history of volcanic edifices, however, the stress in each pressurization cycle may not always exceed that of the previous cycle.

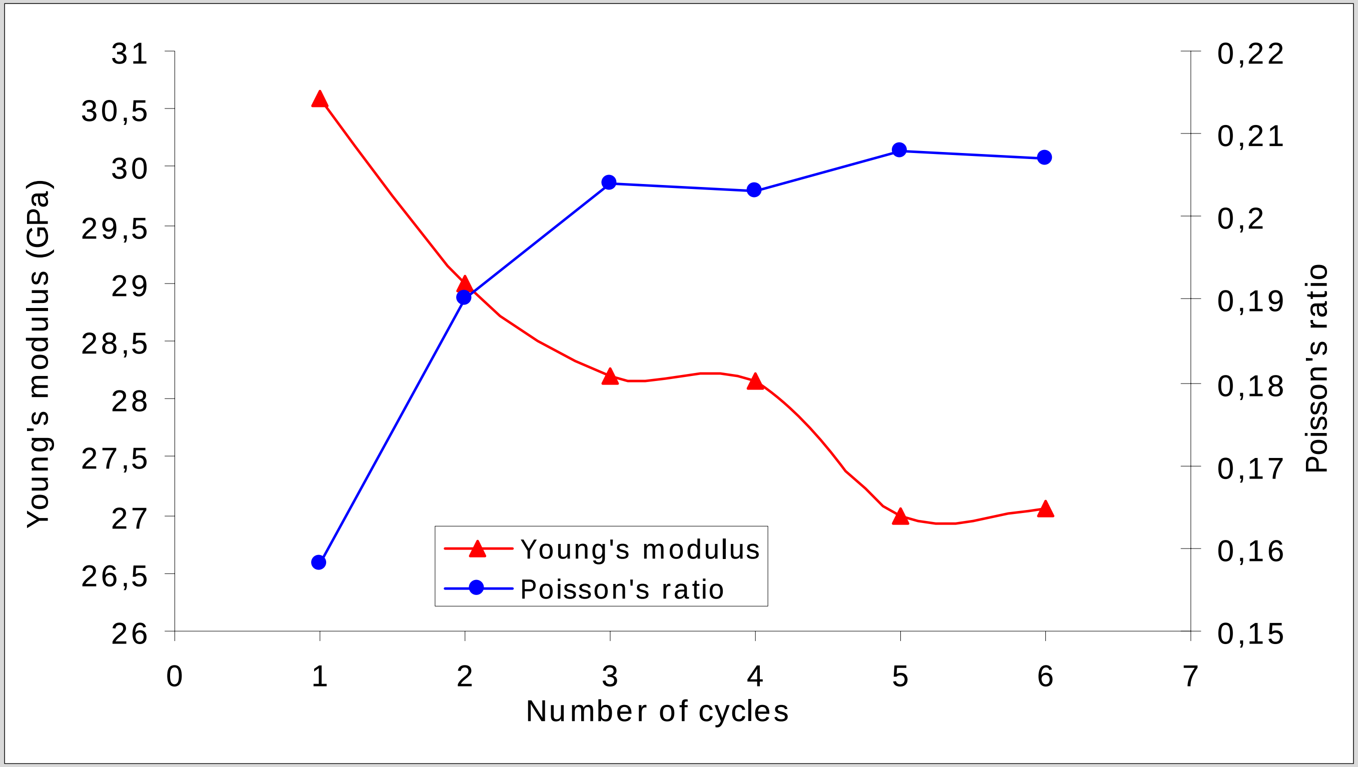
We devised a stress-cycling experiment in which a particular stress-cycle was not necessarily higher in stress than the previous cycle

In this case we observed a more complex manifestation of the Kaiser effect, where AE output in any cycle was only observed when the stress in that cycle exceeded the highest stress at which AE ceased in any previous cycle.





Observation of the Kaiser effect 2



Elastic moduli are seen to only change during cycles that are commensurate with AE activity.

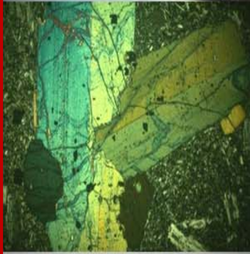
Conclusions

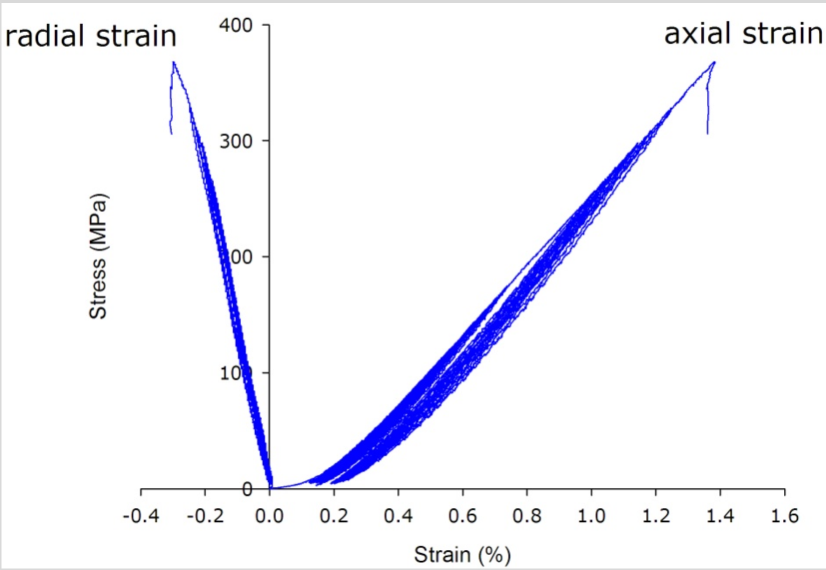
- Cyclic loading leads to the progressive degradation in sample stiffness. This is due to the progressive growth and propagation of both new and pre-existing microcracks. This interpretation is supported by AE activity.
- This equates to a decrease in Young's modulus and an increase in Poisson's ratio.
- AE activity only occurs once the stress at which AE activity ceased on the previous cycle is exceeded (in accordance with the Kaiser effect).

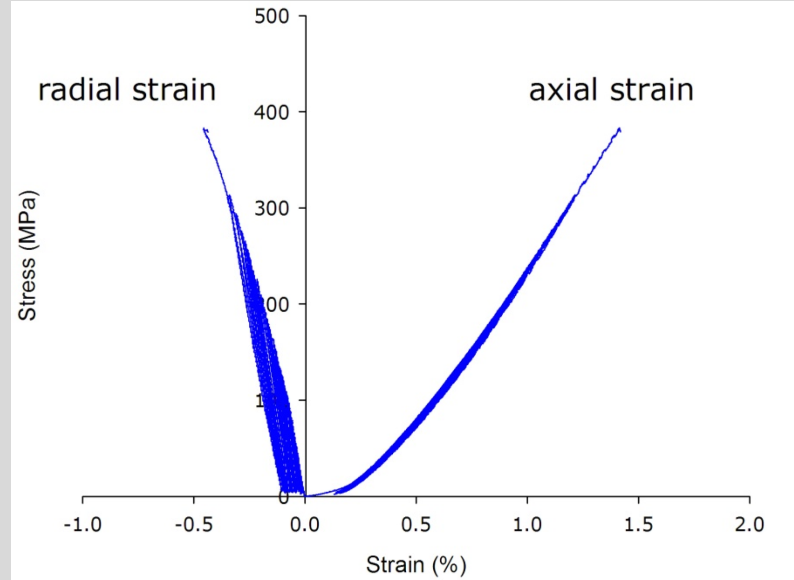
Conclusions

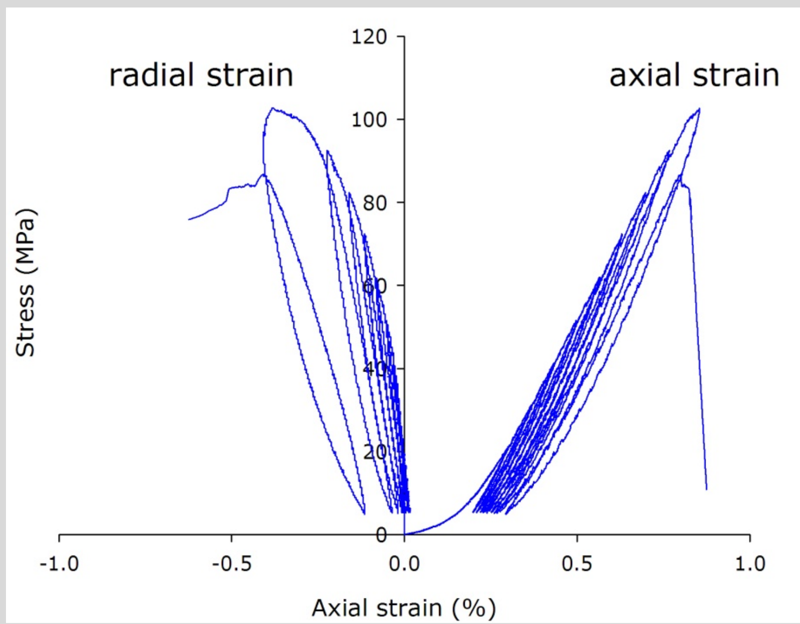
- Volcanoes are subject to cyclic loading due to magma pressurization/de-pressurization cycles. Only some cycles will be commensurate with volcano-seismicity.
- Where this leads to the generation of volcano-seismicity it implies an increase in crack damage within the edifice.
- This increase in crack density will affect both seismic velocities and elastic stiffness.
- This needs to be taken into account in seismic tomography and deformation modelling (e.g. dyke deformation patterns).
- It may even be possible with time-lapse tomography to invert for changes in elastic stiffness and thus estimate changes in crack damage.
- Current and ongoing work: cyclic tests on other extrusive basalts (Stromboli basalt) and intrusive columnar basalt (Icelandic basalt) and heat-treated EB.





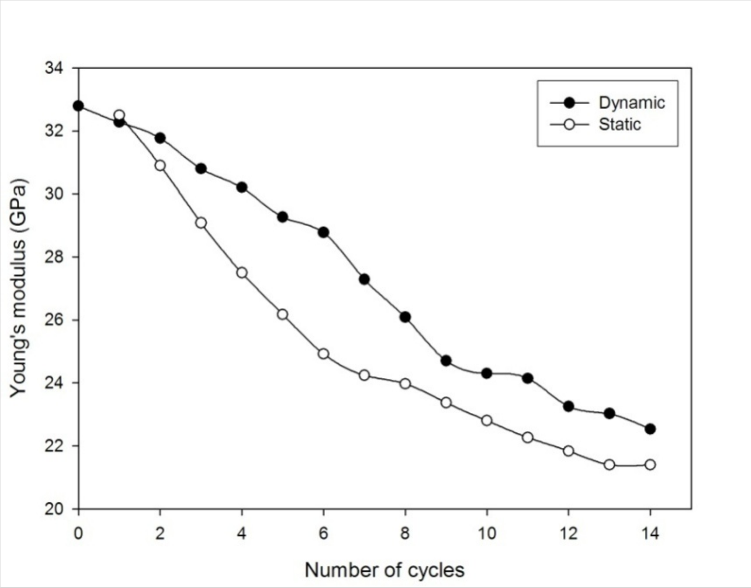

radial strain
axial strain
Stress (MPa)
Strain (%)
400
300
0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6


radial strain
axial strain
Stress (MPa)
Strain (%)
500
400
300
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0


radial strain
axial strain
Stress (MPa)
Axial strain (%)
120
100
80
0
-1.0
-0.5
0.0
0.5
1.0

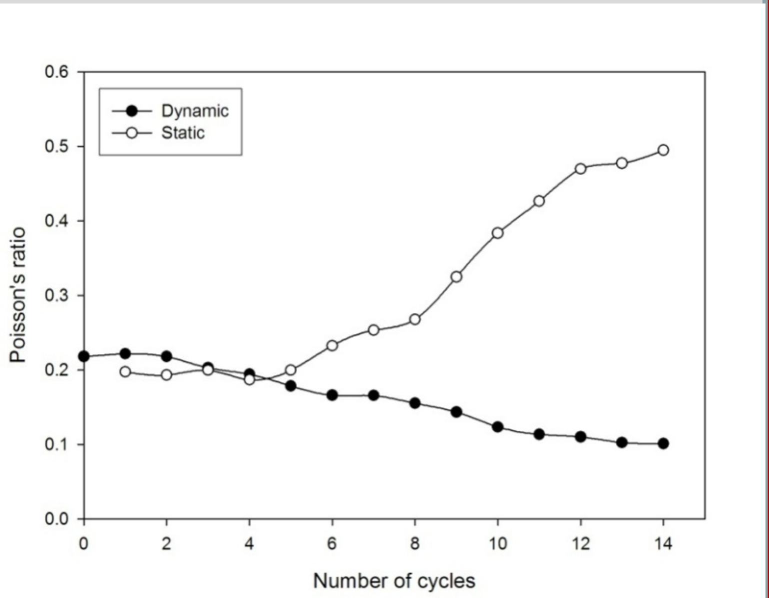
Dynamic Moduli Results

Young's modulus



Both decrease by ~30%
Very similar trends

Poisson's ratio

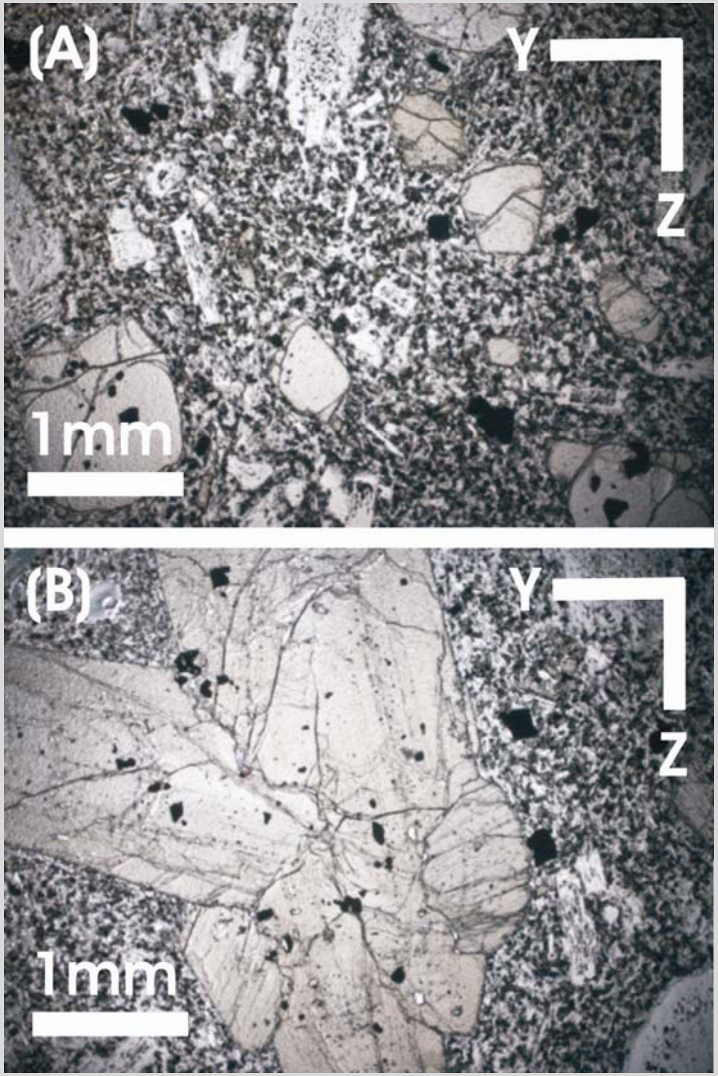


Dynamic Poisson's ratio decreases
Static Poisson's ratio increases
Static values measured from axial strains, dynamic values calculated from P- and S-wave velocities across the sample
Anisotropic nature of elastic moduli evolution?

Microscopic analysis

Undeformed

Deformed



Much more microcracks seen in the deformed samples