Comité Français de Mécanique des Roches

Experimental study of mechanical and thermal damage in crystalline hard rock

Mohammad Keshavarz

Réunion Technique du CFMR - Thèses en Mécanique des Roches

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Overview

- **Introduction**
- **Characterization of North African gabbro**
- **Acoustic emission (AE) monitoring of intact rocks during uniaxial tests**
- **Damage and rock properties evolution due to mechanical and thermal loadings**
- **Conclusions**

Main objectives of the research

- **To study crack propagation and to predict failure of rock subjected to:**

  - high pressure

  - high temperature

- **To relate to:**

  - Acoustic Emission

  - Sonic waves velocity

  - Micro-crack evolution

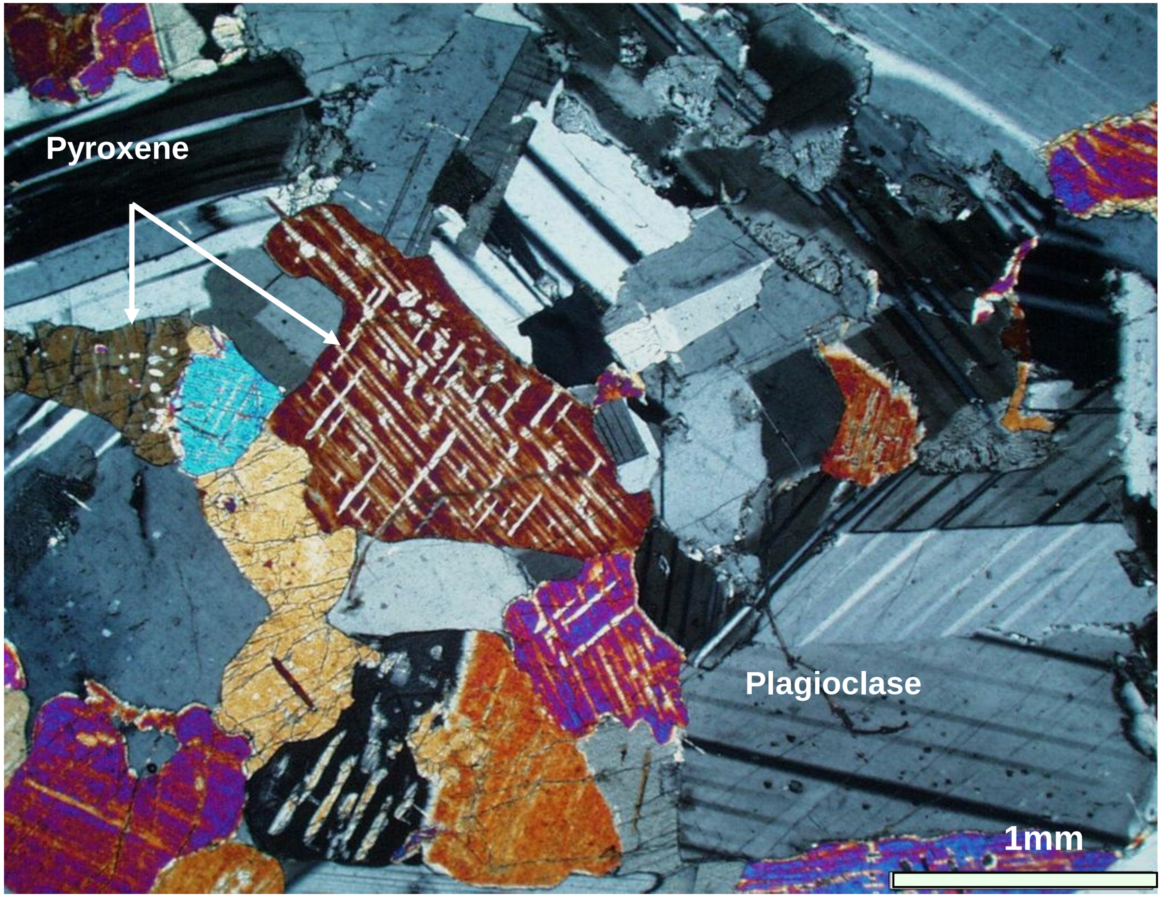
in order to investigate damage in crystalline intact rock

Failure precursors study in laboratory

- **Rock deformation data;**
- **Acoustic emission (AE) and sonic wave velocity changes;**
- **Infrared radiation (IR) and thermal anomalies;**
- **Rock electrical resistivity changes ;**
- **Electromagnetic emissions and anomalies;**
- **…**

Characterization of North African gabbro

Microscopic investigation under polarized light



North African gabbro

Mechanical tests and physical parameters measurements

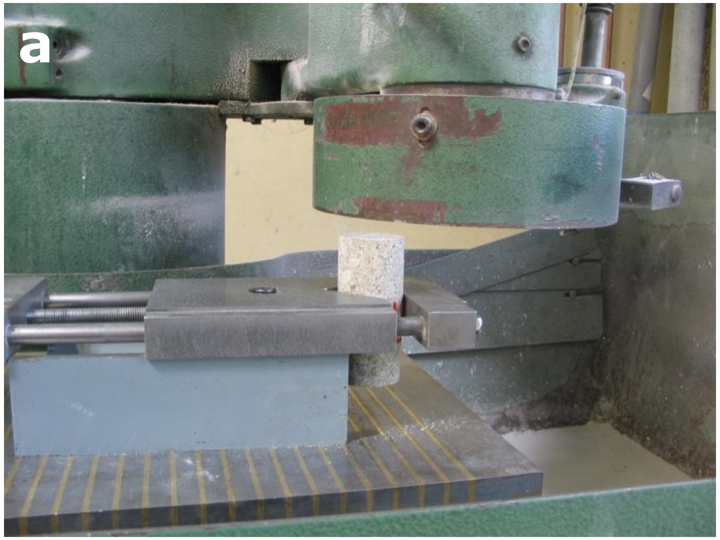
- **Uniaxial compression tests**
  - **Elasticity modulus, E**
  - **Poisson's ratio, v**
  - **Max. uniaxial compressive strength, σ_{cmax}**

- **Brazilian tests**
  - **Tensile strength, σ_{ct}**

- **Triaxial tests**
  - **Mohr-Coulomb, c, φ**
  - **Hoek & Brown, s & m**

- **Sonic wave velocity measurements**
  - **Primary elastic wave velocity, Vp**
  - **Shear wave velocity, Vs**

Specimen preparation and testing equipment



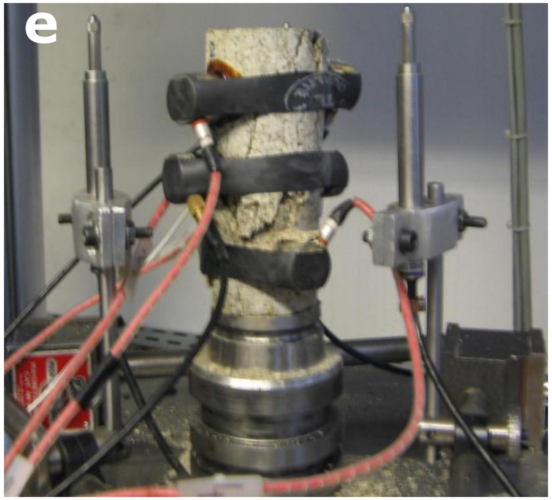
a. **Grinding machine**

b. **Measuring of parallelism**

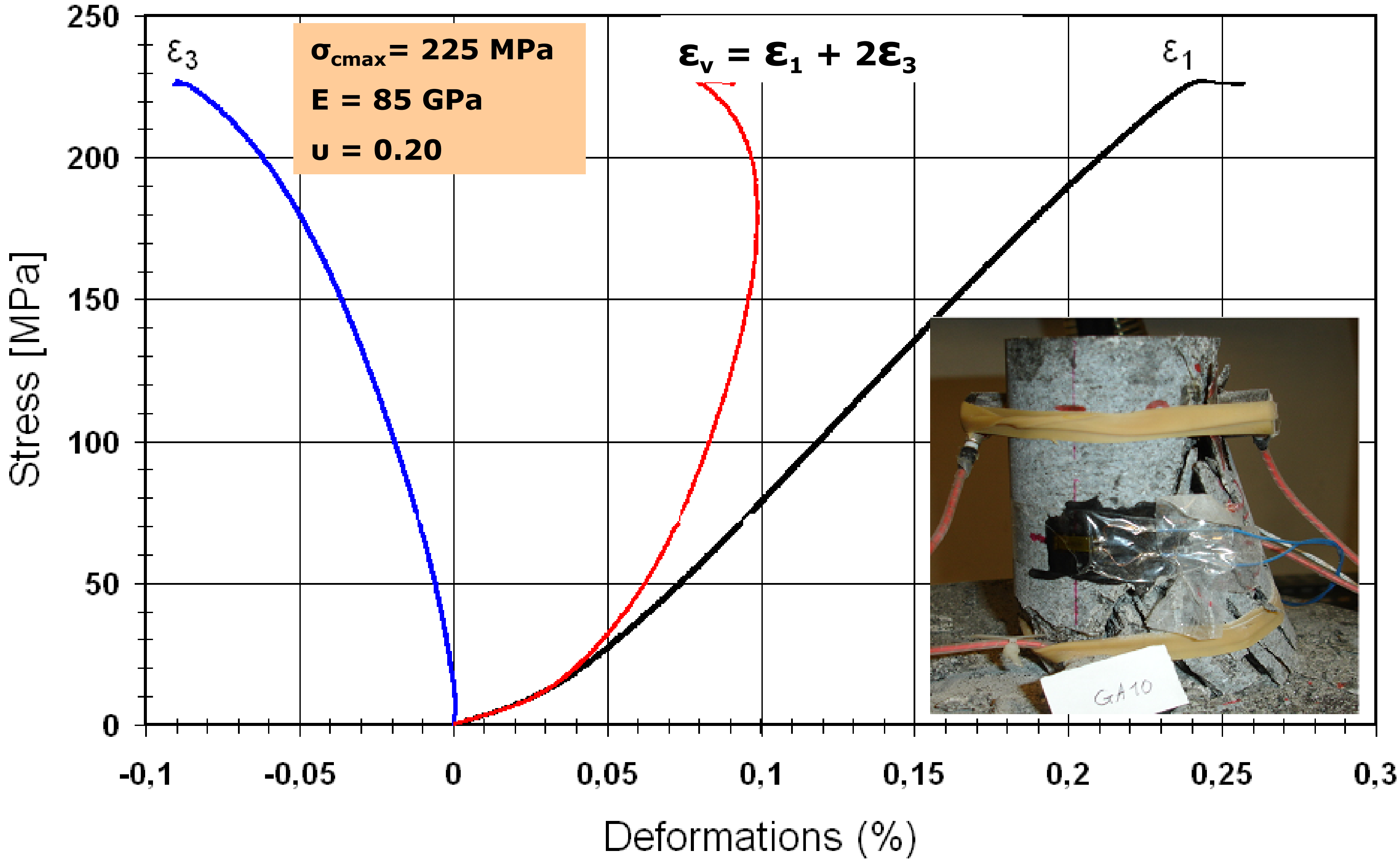
c. **Elastic wave measurement**

d. **Schenck press**

e. **Close view of specimen after uniaxial test**

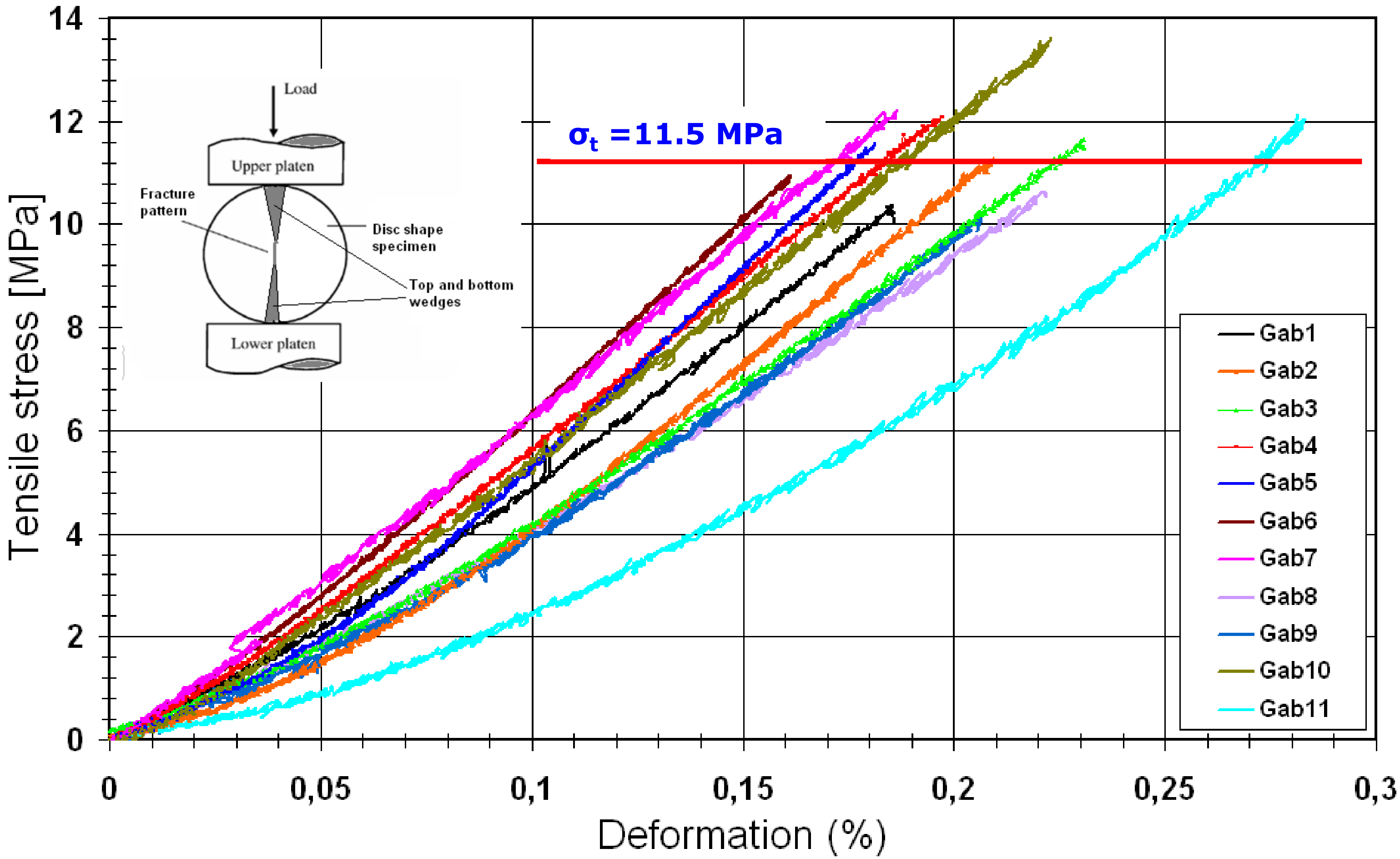


Uniaxial compression test on North African gabbro



Specimen Ga10

Brazilian tests on gabbro



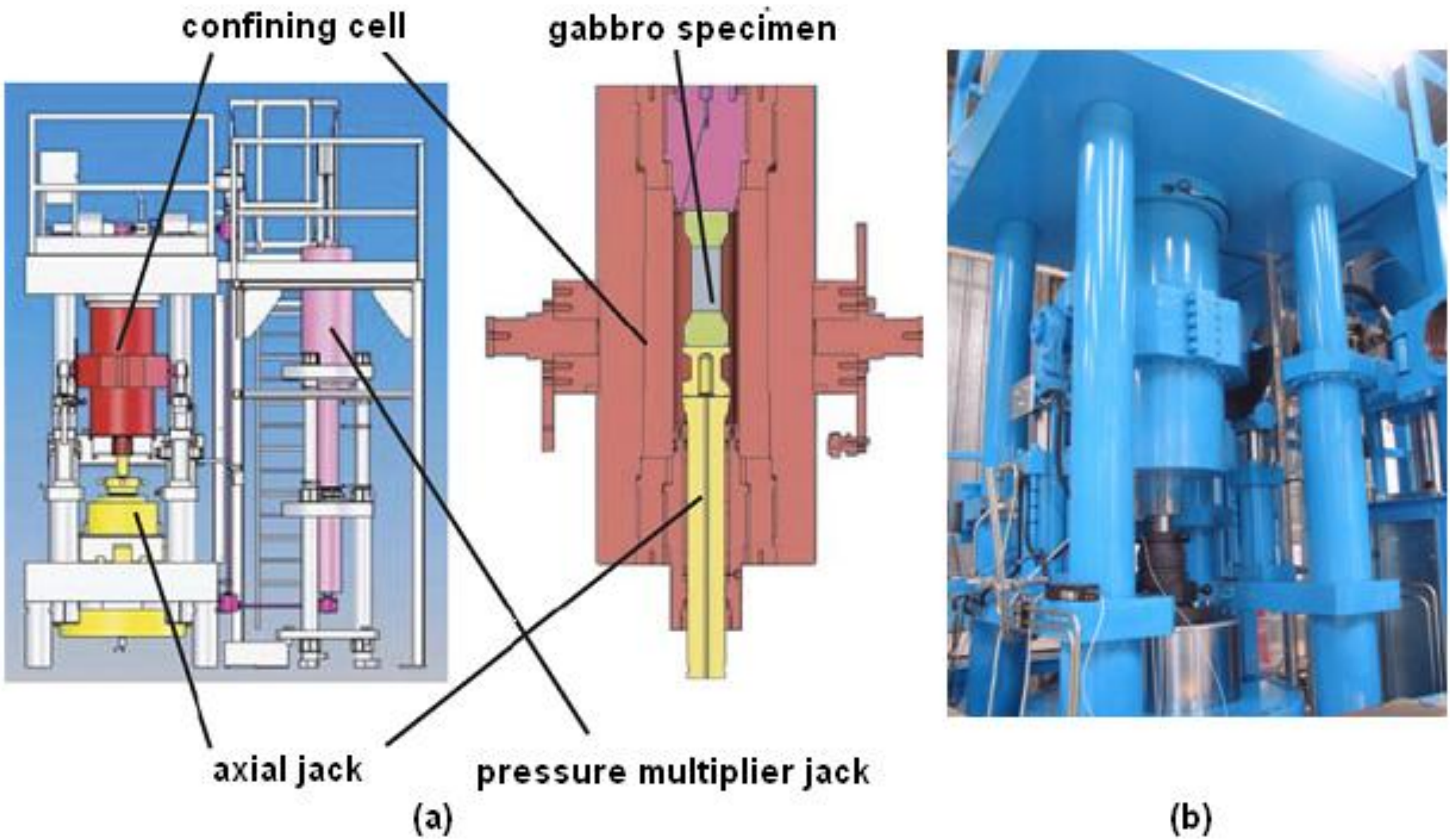
Gab1 to Gab6 = ø <u>70 mm</u>

Gab7 to Gab11 = ø <u>40 mm</u>

No size effect

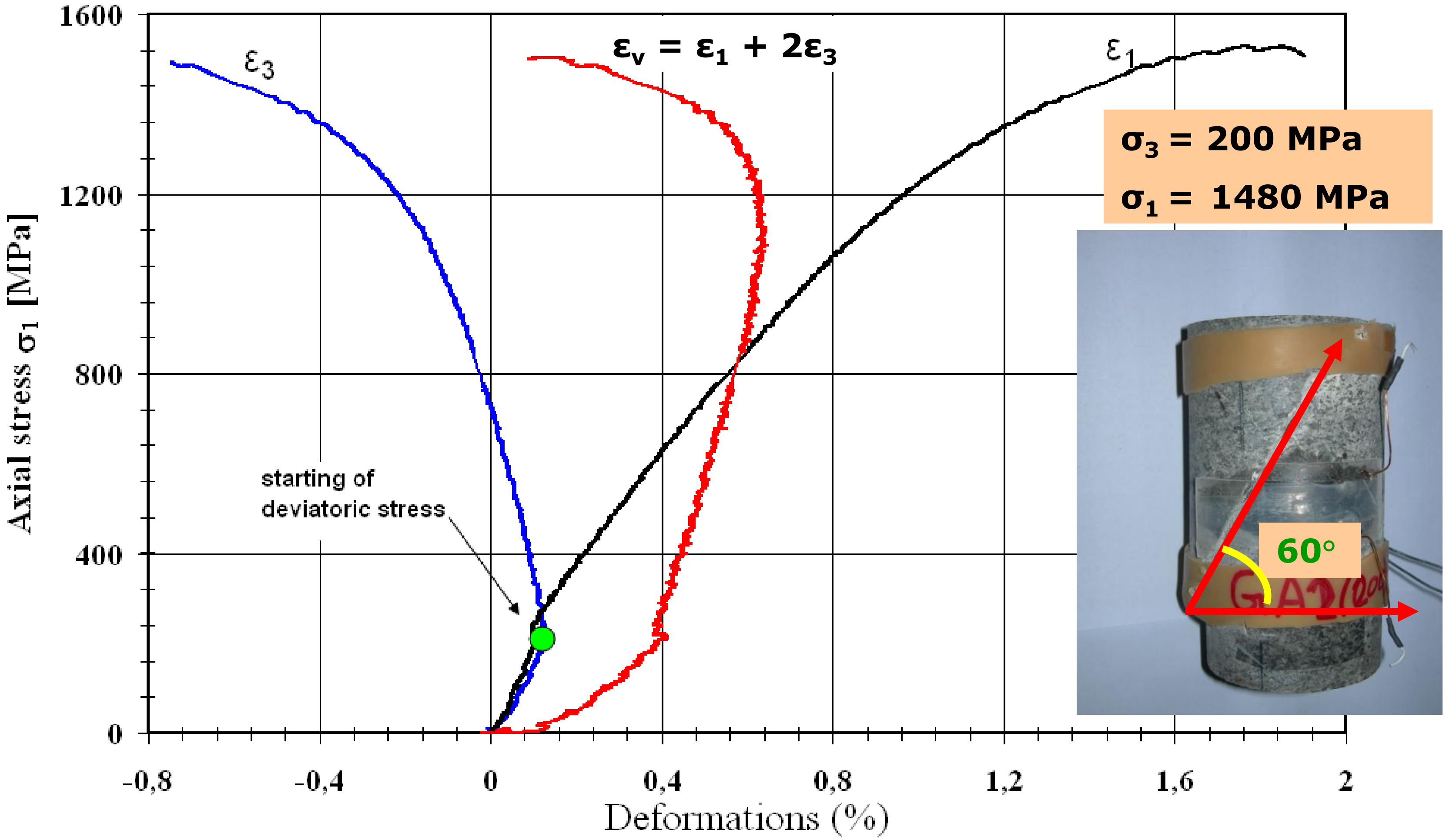
Ultra high triaxial compression test by Giga press

Max. capacity of machine; σ_3 = 650 MPa and σ_1 =2400 MPa

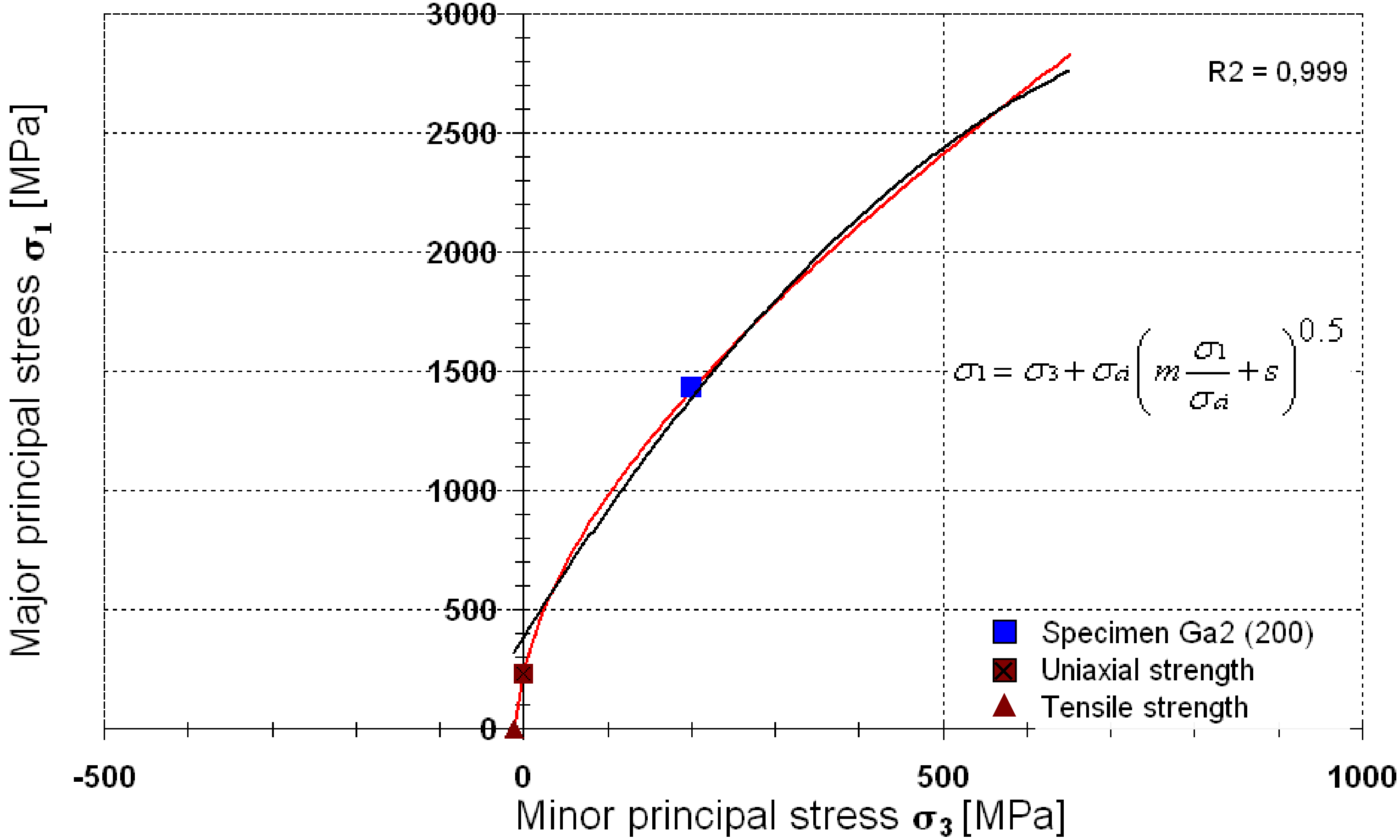


Giga press and confinement cell (a) photo of the cell of the press (b) (Gabet et al, 2006 with modification)

Triaxial test result on gabbro specimen Ga2(200)



Hoek-Brown and Mohr-Coulomb criteria for gabbro



Mohr-Coulomb: *c* = 68 MPa and φ = 43°

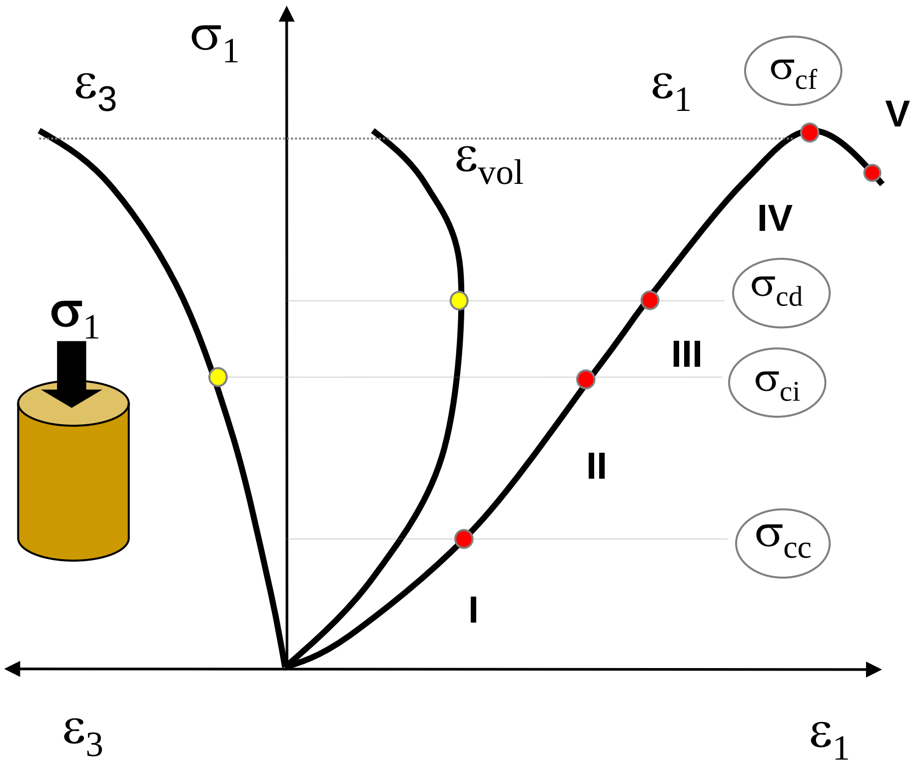
Hoek and Brown: s = 1 and m = 30

Summary of mechanical tests and physical measurements

Properties	North African Gabbro		
	Mean values	Standard deviation	Number of tests
ρ_b (g/cm3)	2.90	± 0.05	3
Porosity (%)	<0.5	± 0.05	3
Vp (m/s)	6560	± 99	16
Vs (m/s)	4078	± 76	16
υ	0.21	± 0.03	3
E [GPa]	88	± 2.5	3
σ_{ct} [MPa]	11.5	± 1.5	11
σ_{cmax} [MPa]	226	± 11	3

Acoustic emission (AE) monitoring and deformation data during uniaxial tests on intact rock

Damage evolution and stress – deformation curves



Step I : Cracks closure, σ_{cc}

Step II : Elasticity, reversible strains, Cracks initiation stress, σ_{ci}

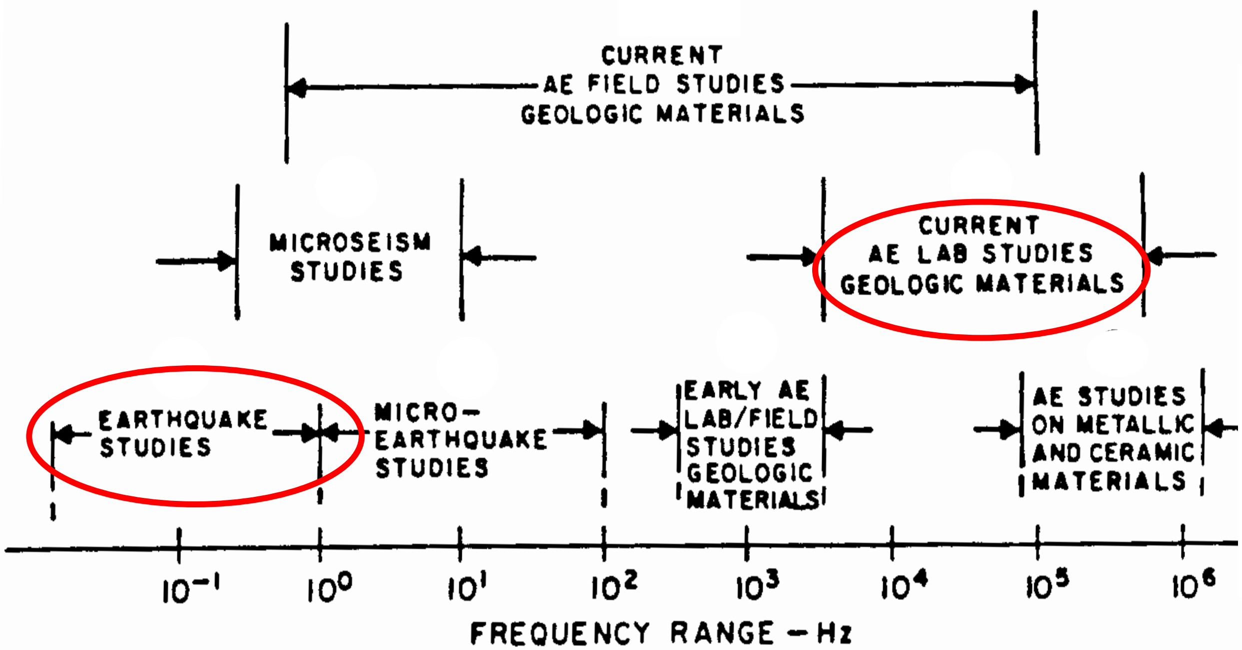
Step III : Crack damage threshold, maximum contraction, σ_{cd}

Step IV : Peak strength, failure stress, σ_{cf}

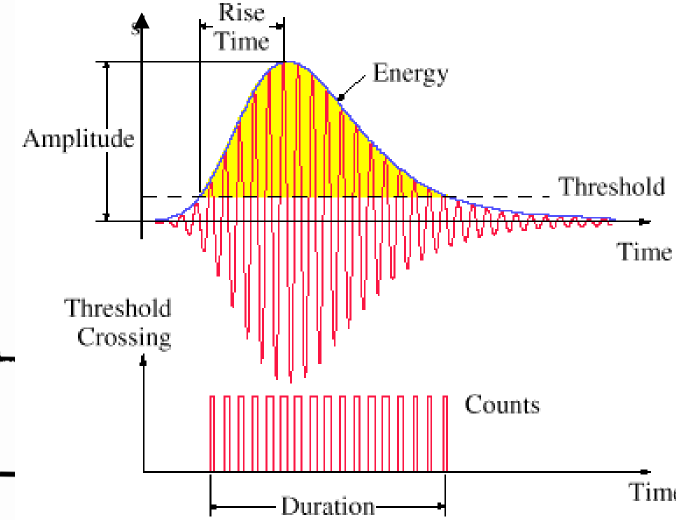
Step V : Post- failure, strain softening

Monotonic Compression Tests and Typical Thresholds during unconfined compression test

Acoustic emission and related parameters

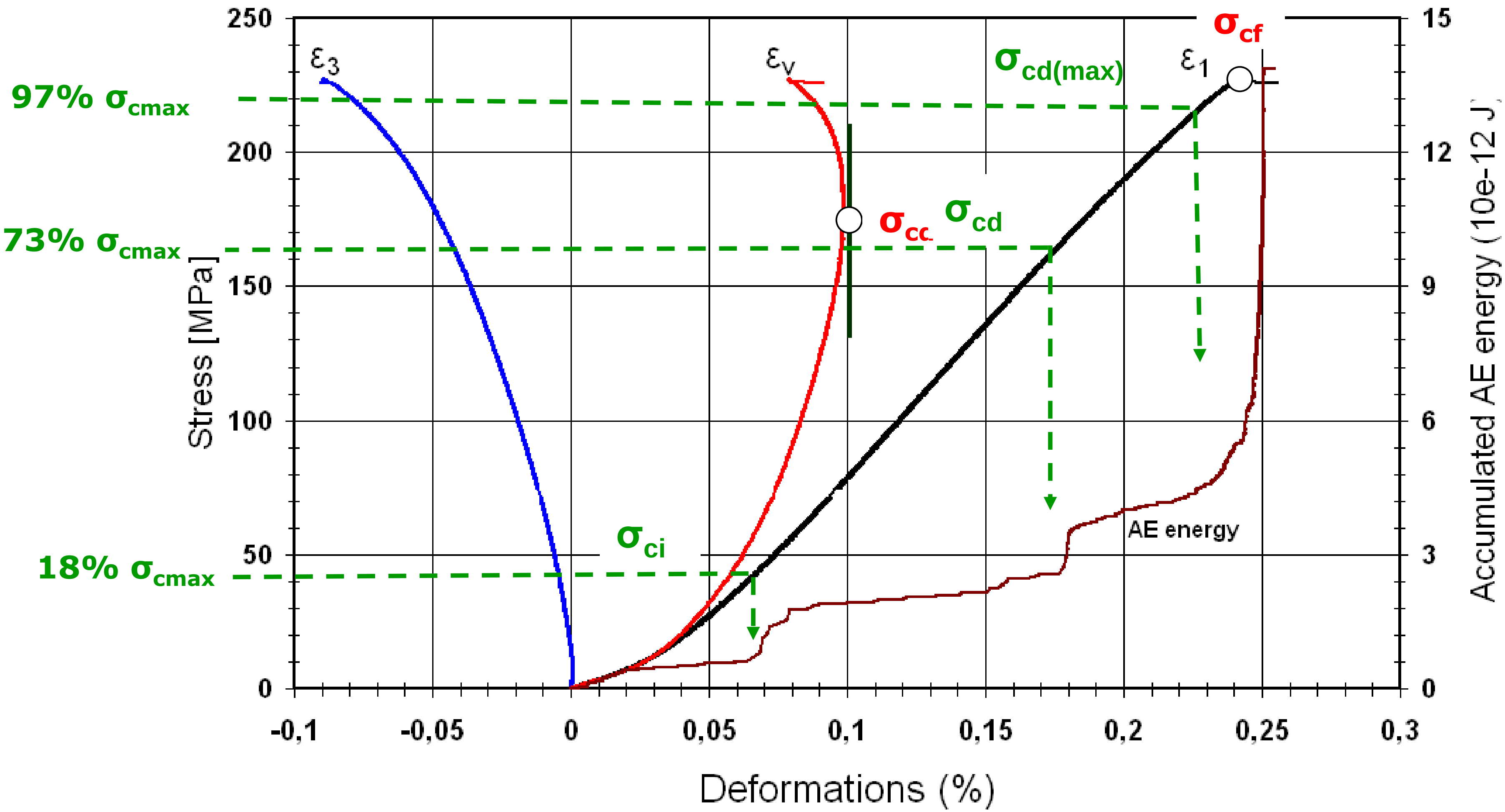


Frequency ranges over which AE and other associated studies have been conducted (Hardy, 2003)



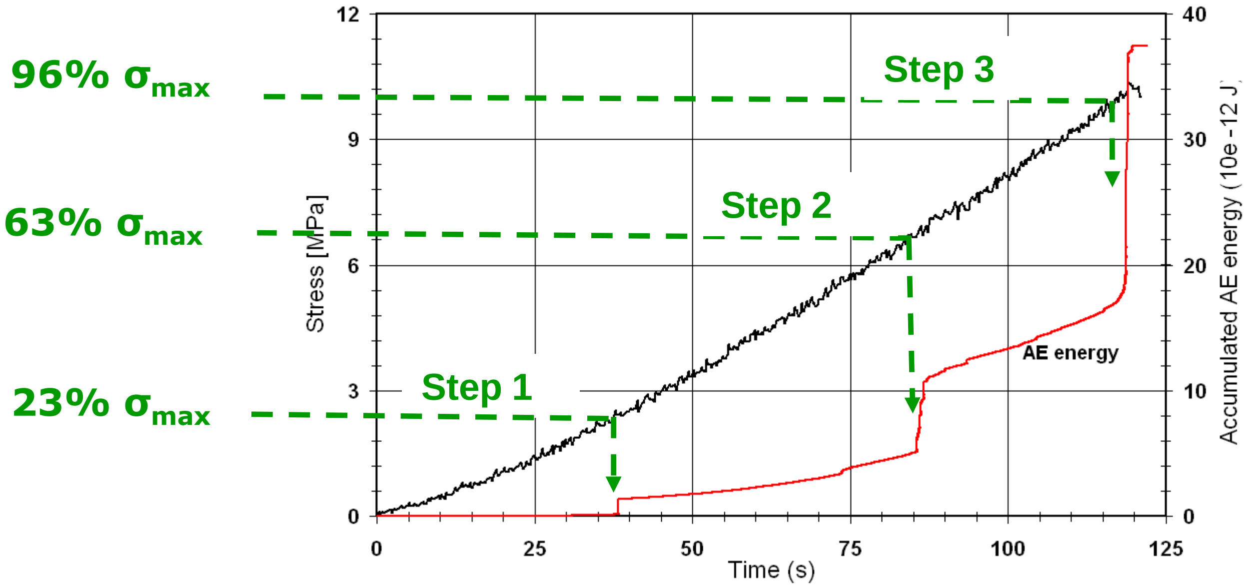
Main parameters of an acoustic emission hit (Huang et al., 1998)

Comparison of AE records and Stress – Deformation data

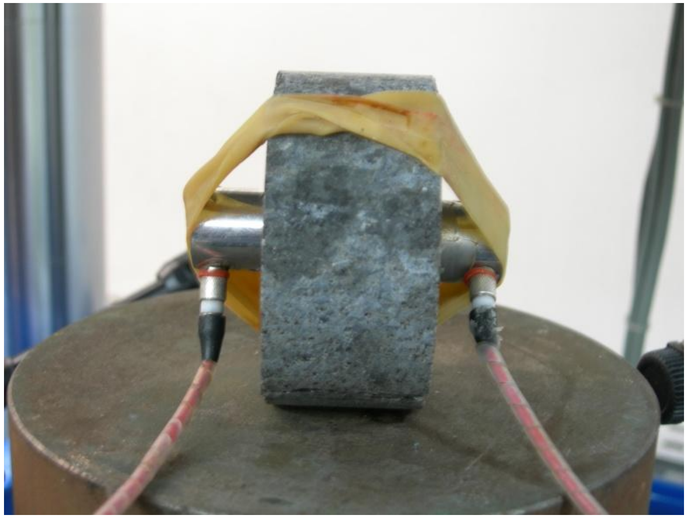


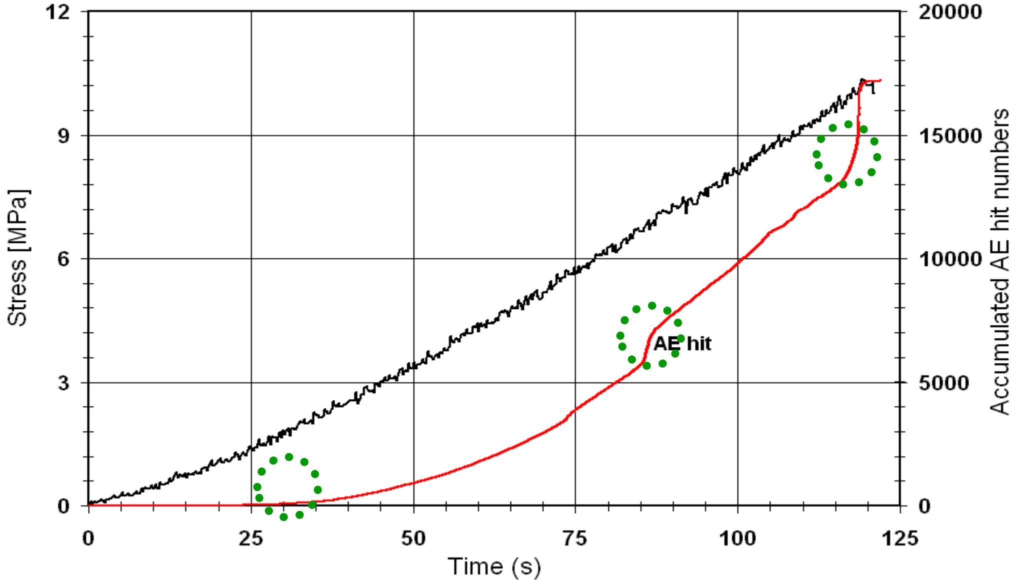
Identification of damage thresholds in gabbro specimen Ga10 by AE energy parameter

AE monitoring during Brazilian test on gabbro



Identification of damage thresholds in gabbro specimen Gab1 by AE energy and AE hit parameters





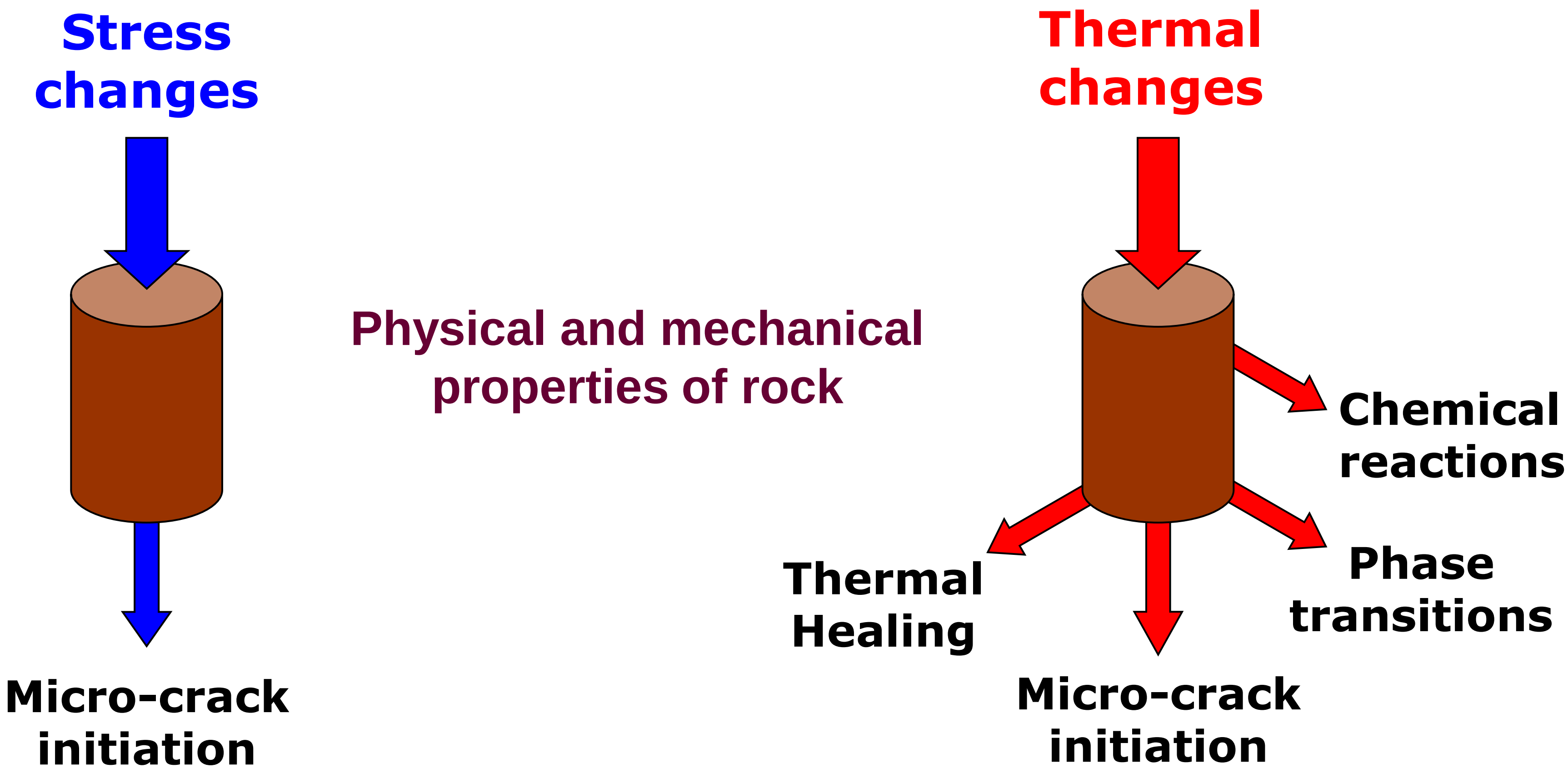
Comparison of AE monitoring and stress – deformation data

- **AE monitoring is more accurate than stress-deformation curve to determine damage thresholds,**

- **AE energy parameter is a more effective parameter than the conventional AE hit number to detect different stages of the rock failure process,**

Damage investigations on mechanically and thermally loaded specimens

Different effects of mechanical and thermal changes on rocks



Damage investigations on mechanically and thermally loaded gabbro

Thermal damage:

Specimens subjected to high temperature

150°C <T<1000°C

Mechanical damage:

Specimen subjected to high confining pressure

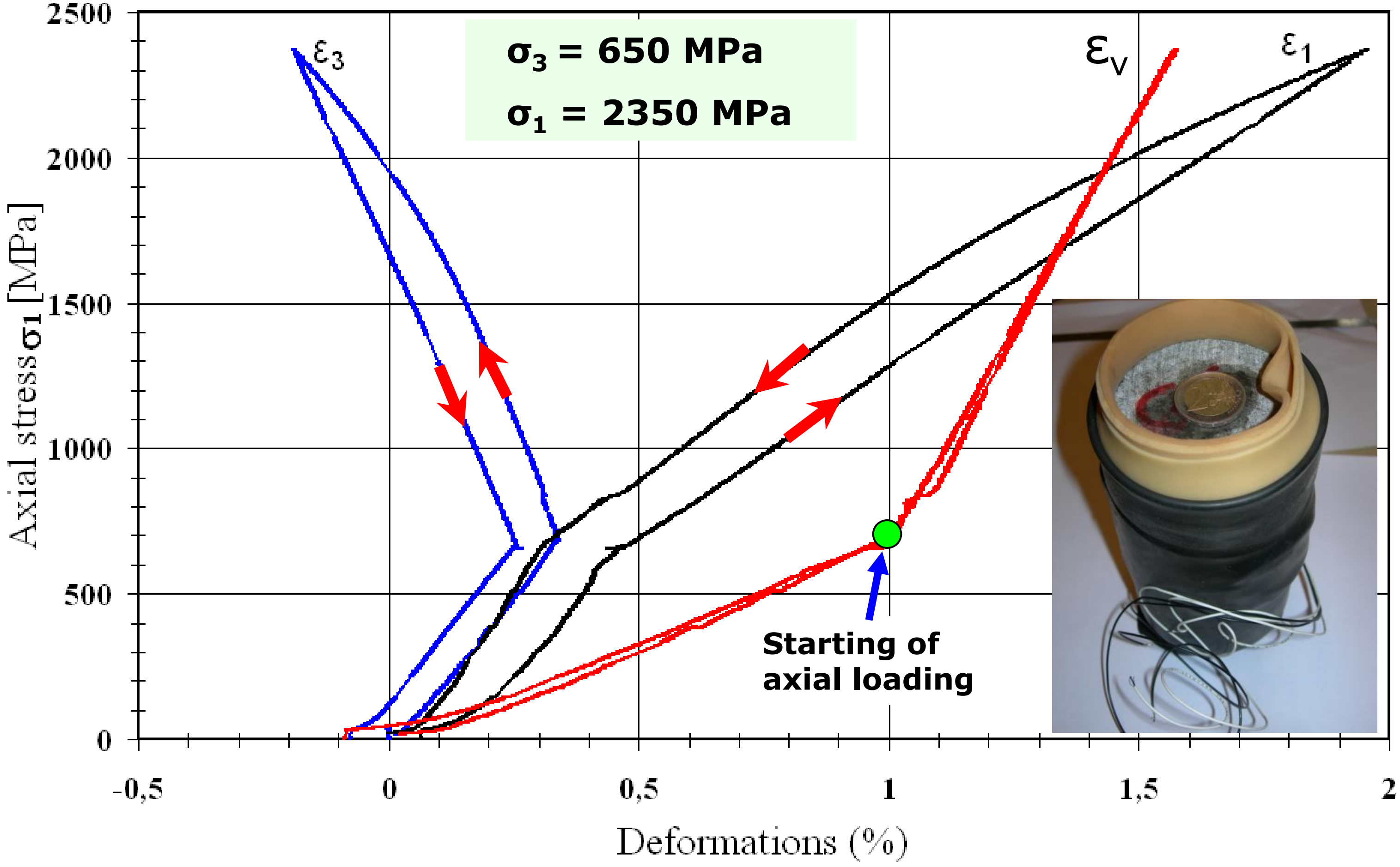
σ_3 = 650 MPa

σ_1 = 2350 MPa

To evaluate the magnitude of damages in both T. & M. methods, we've used,

- **Uniaxial compression tests (σ_{cmax}, E, υ, …),**
- **Elastic wave velocity measurements (Vs and Vp),**
- **AE monitoring,**
- **Microscopic investigation.**

Mechanical damage investigation



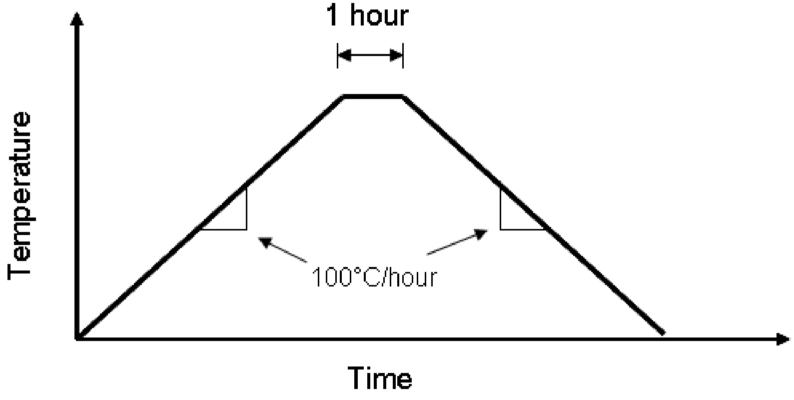
Ultra high pressure triaxial test on gabbro specimen Ga1(650)

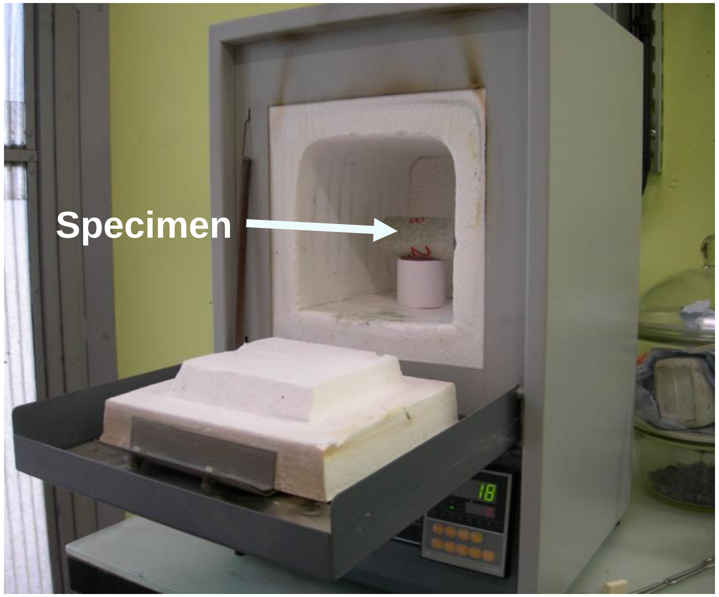
Thermal damage investigation

Nominale temperature:

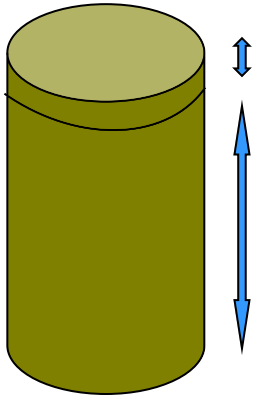
150, 300, 450, 500, 600, 700, 800 and 1000 °C

Heating rate: 100°C/hour





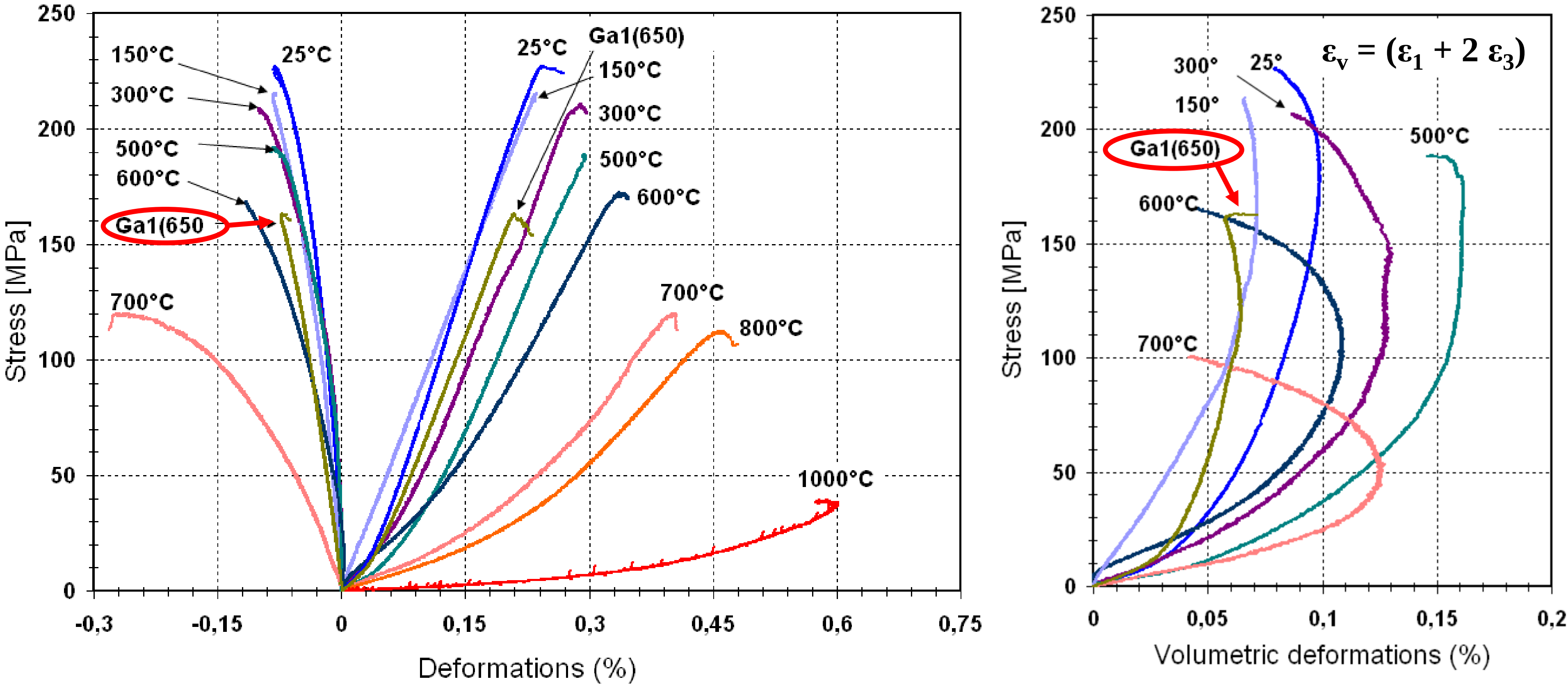
Programmable electrical furnace



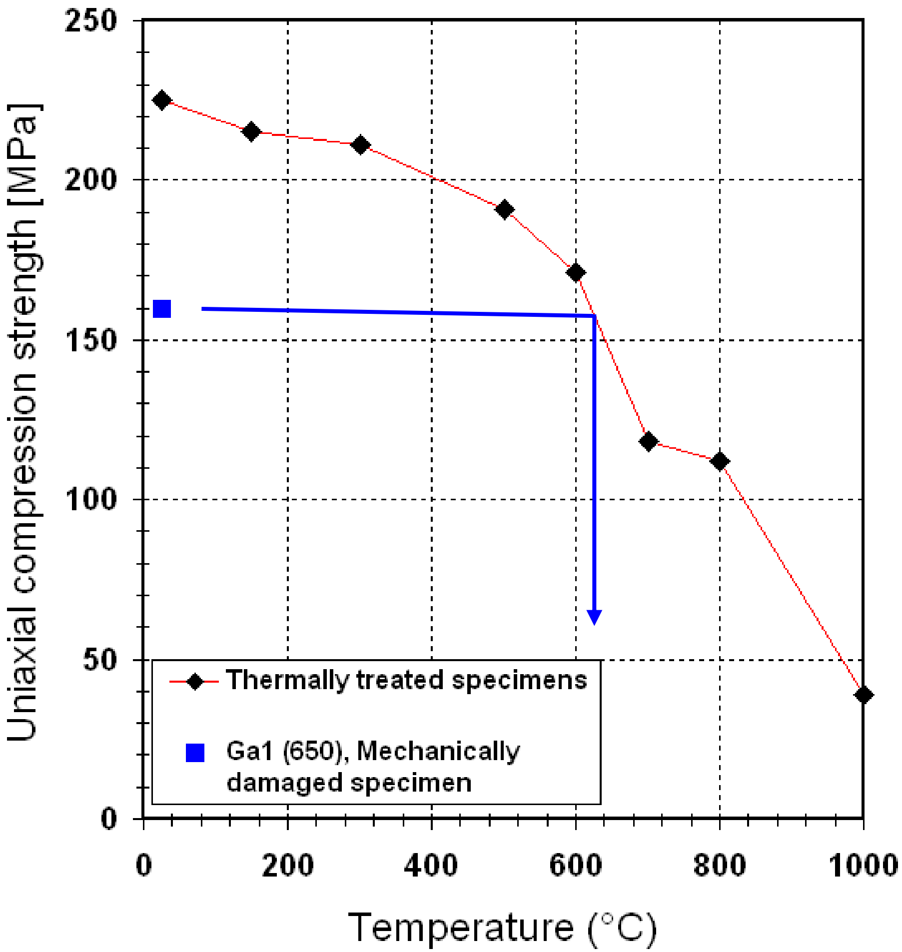
10 mm (for microscopic investigations)

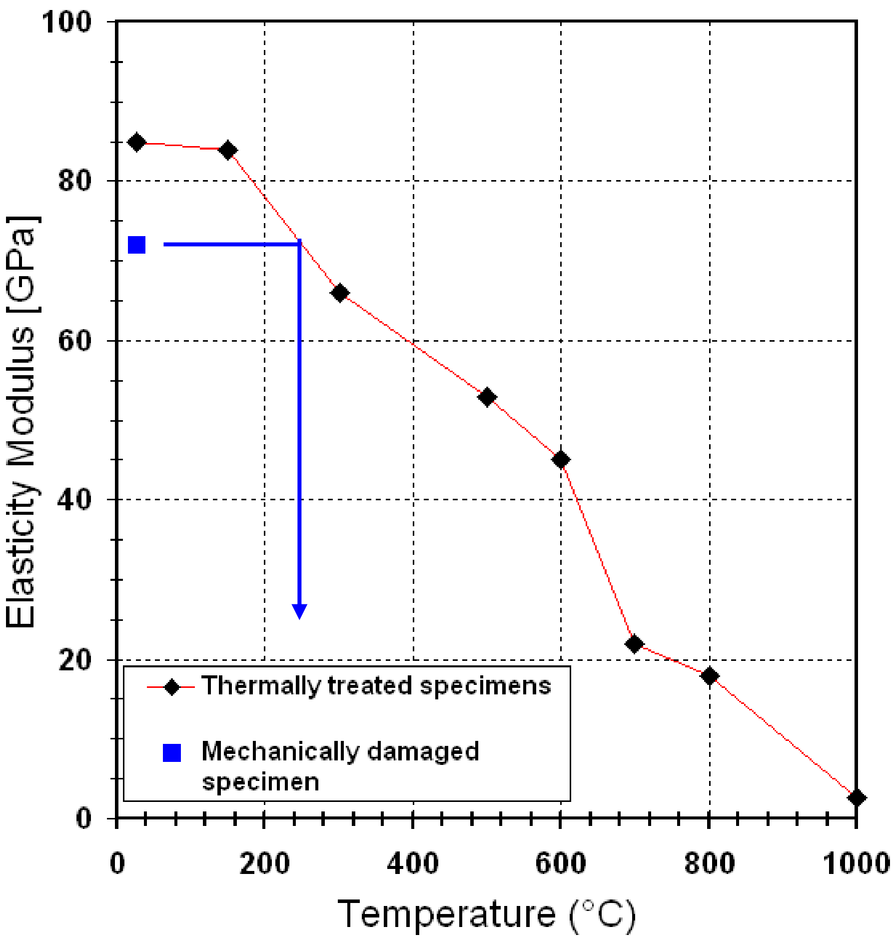
80 mm (Sonic wave velocity measurements and uniaxial compression test)

Uniaxial compression tests on specimen having experienced high temperature

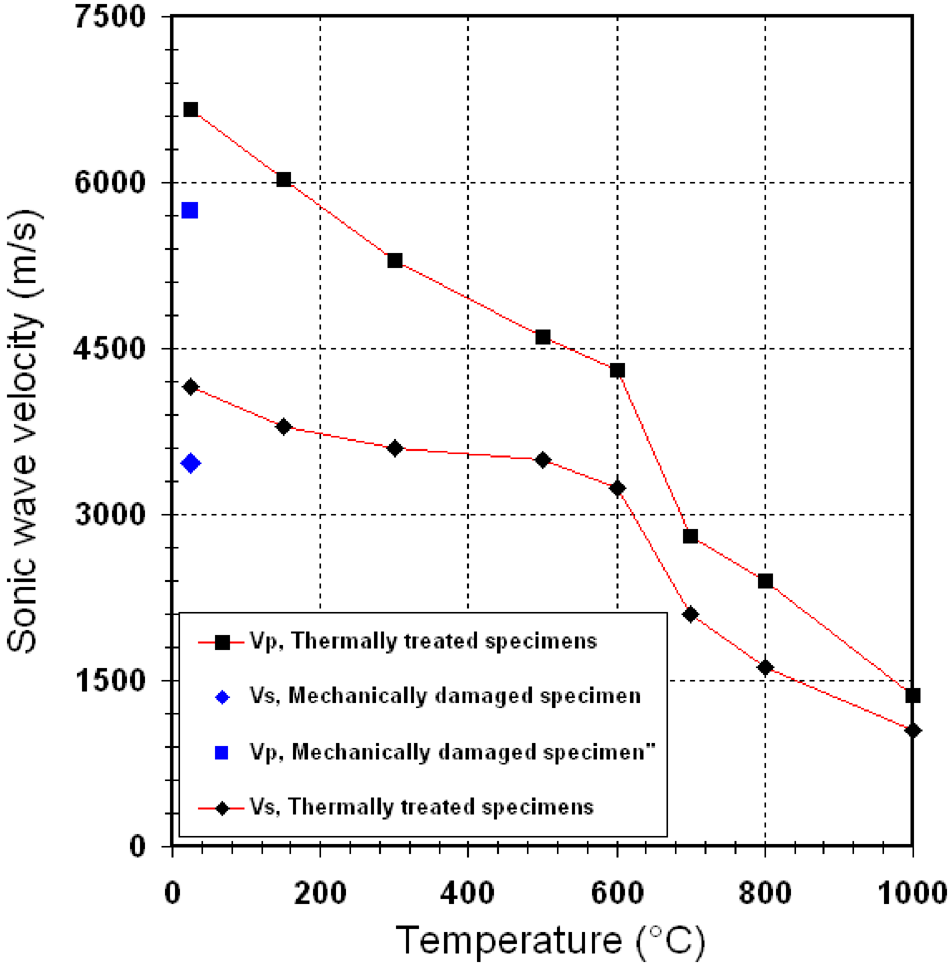


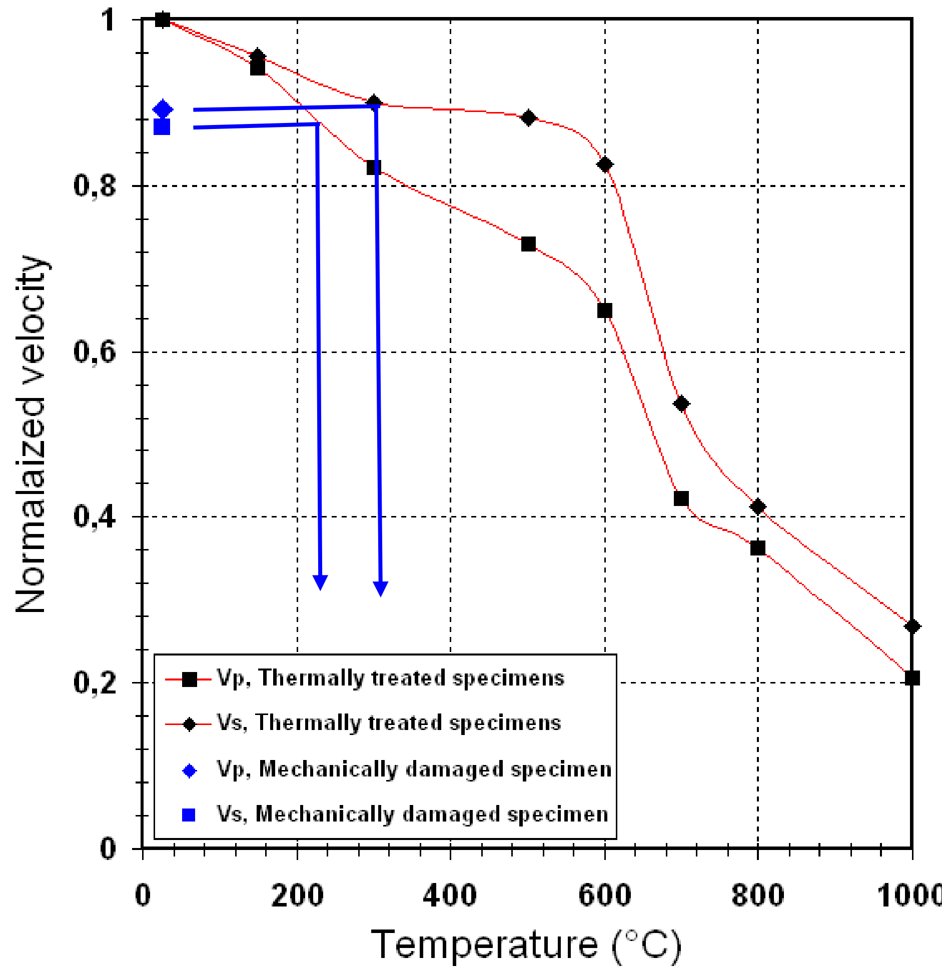
Uniaxial strength and elastic modulus changes



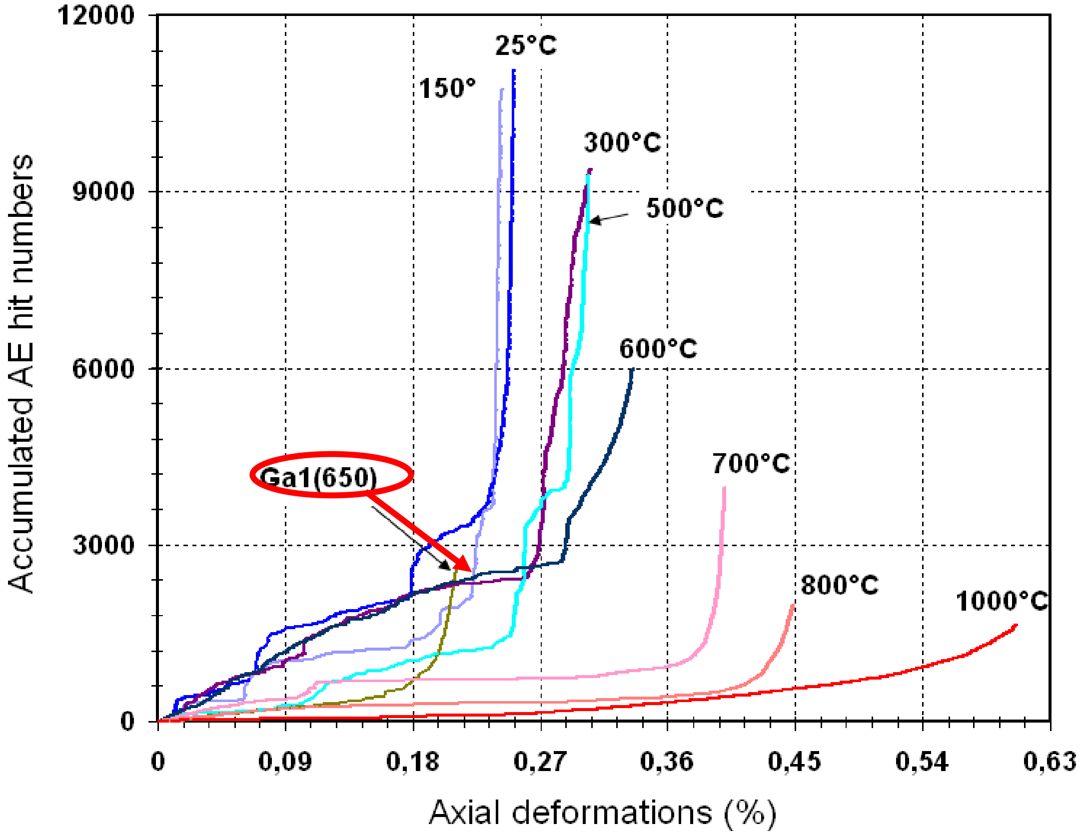


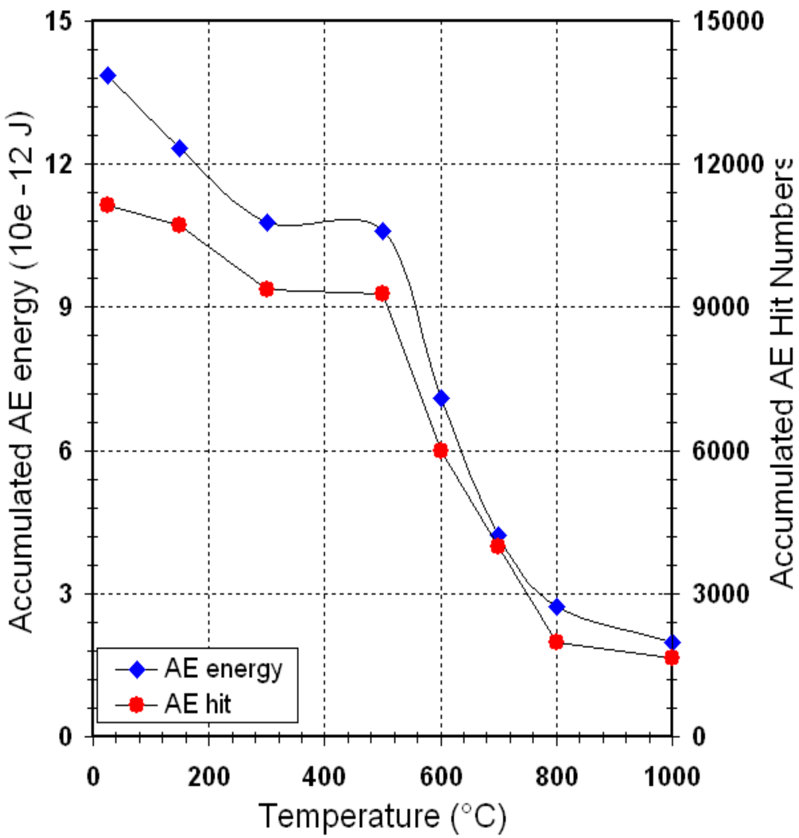
Sonic wave velocity changes (Vs and Vp)





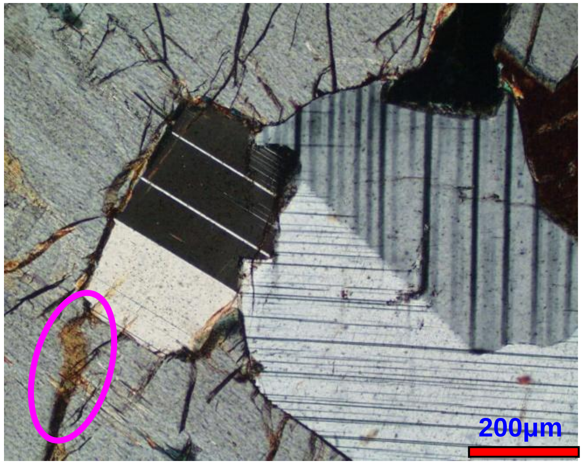
Acoustic emission monitoring



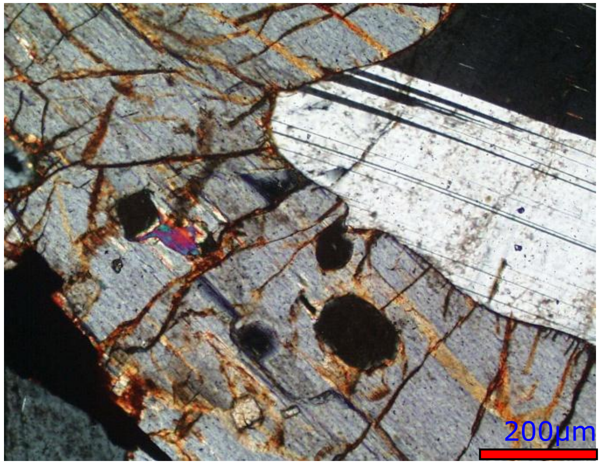


Photos of specimen – macroscopic failure

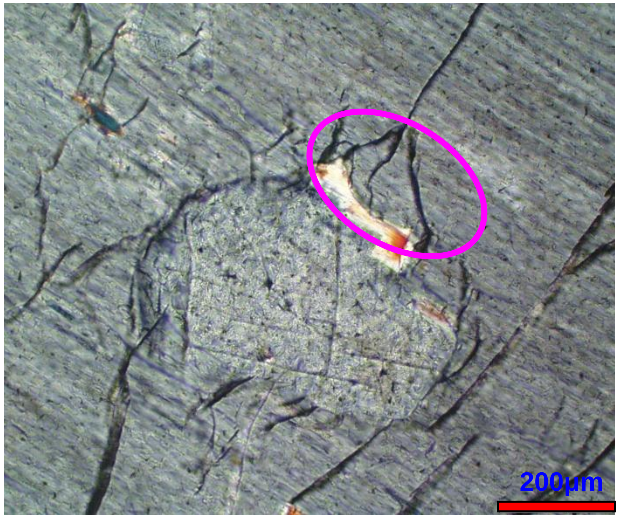
Microscopic investigations of thermally treated specimens



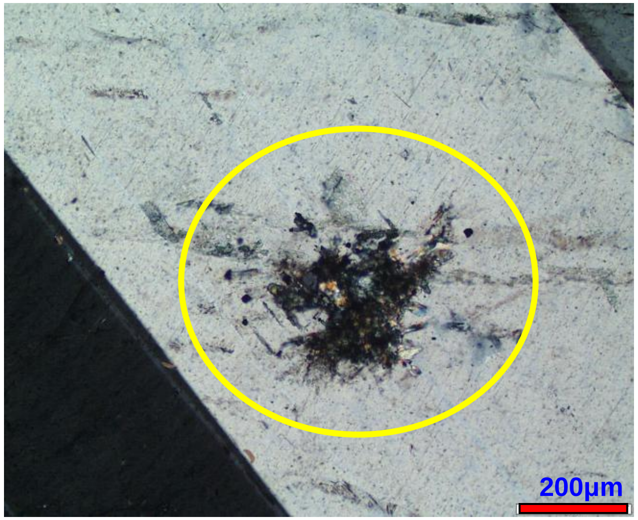
<u>Oxidation</u> appearance at 500°C



Oxidation development in pyroxenes at 800°C

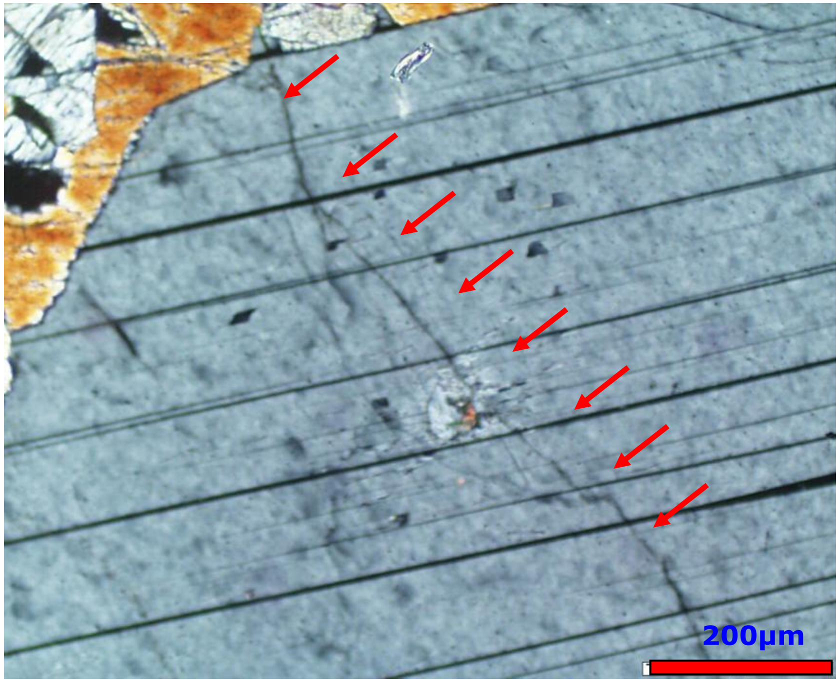


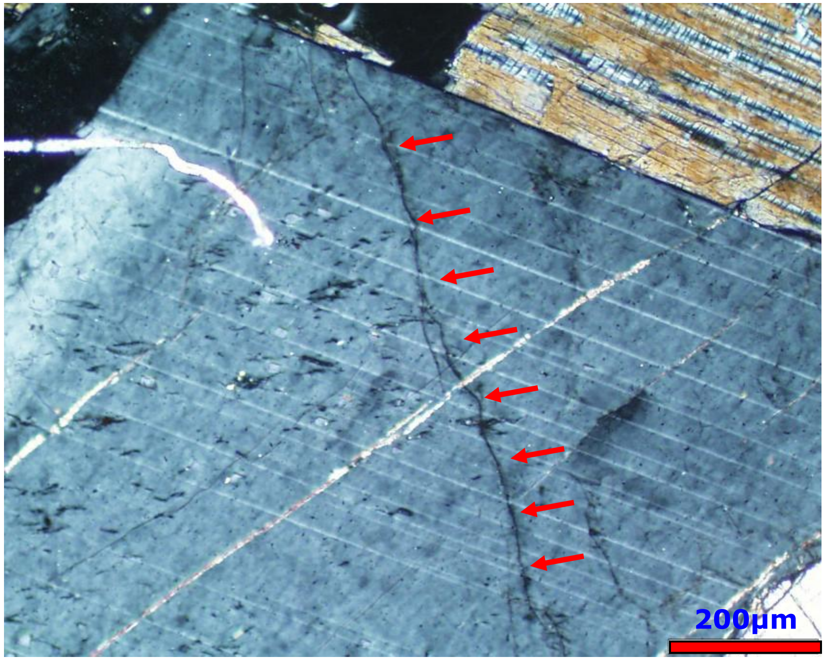
Micro-crack initiation due to different <u>thermal expansion coefficient</u> between pyroxene and a surrounded crystal



Blow up liquid and gas inclusion at 300°C effects

Microscopic investigations of Mechanically damaged specimens

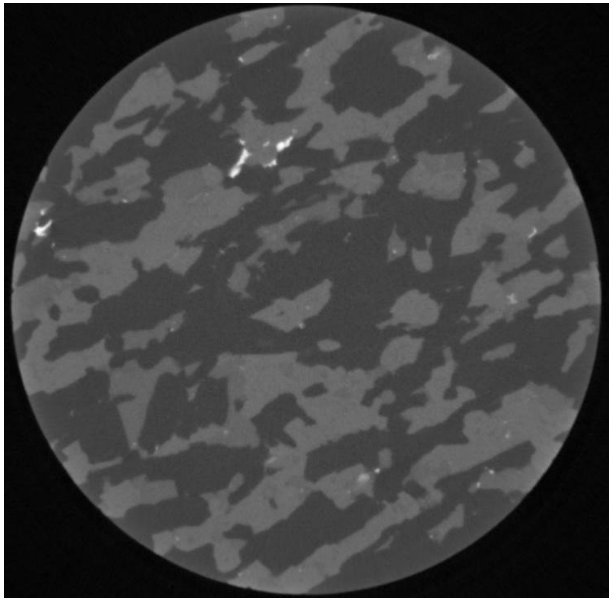




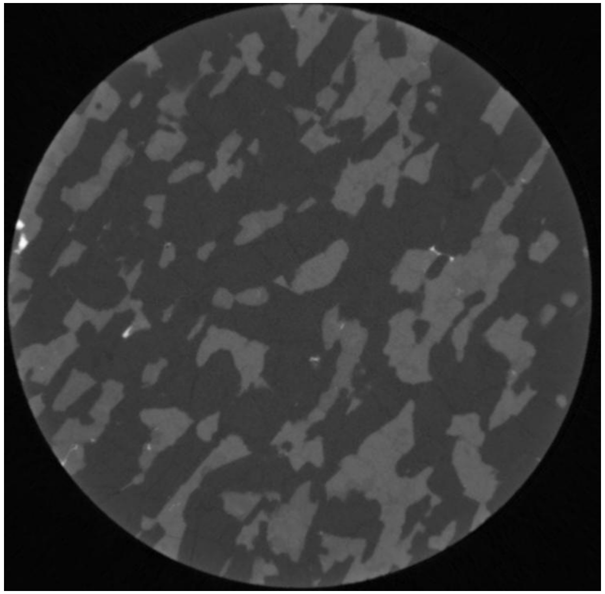
Evidences of ultra high triaxial mechanical damage in plagioclase

Tomography investigations

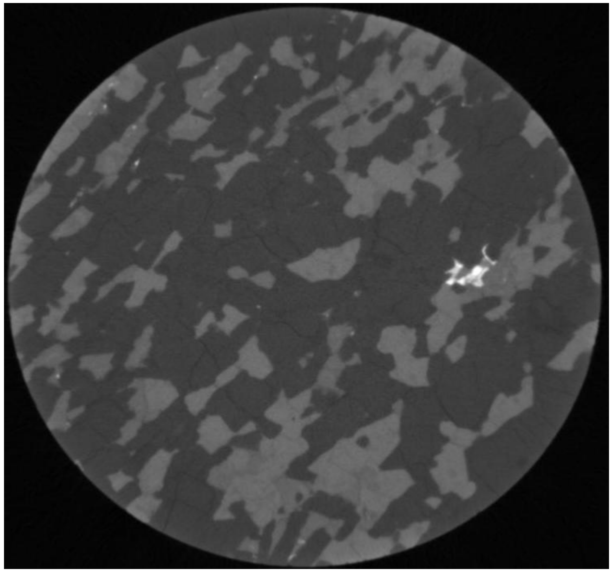
Intact rock



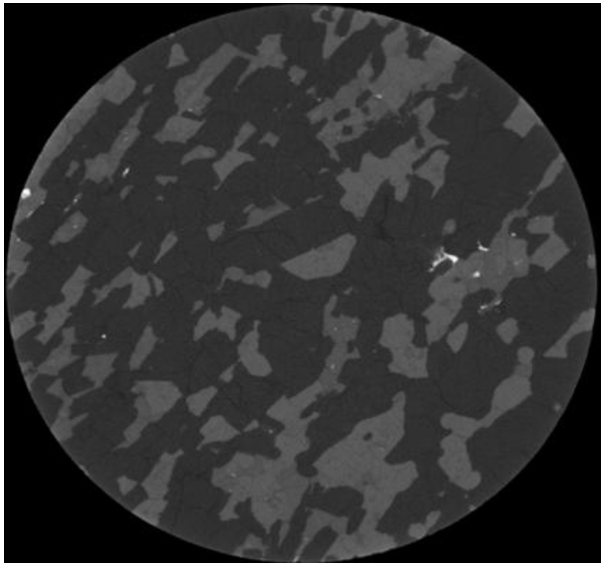
600°C loaded



800°C loaded



1000°C loaded



Conclusions

Conclusions (1/2)

Damage investigations on <u>intact rocks</u>:

- **AE monitoring is more efficient way than rock deformation data to determine damage thresholds during uniaxial compression tests,**
- **We found also that AE <u>energy</u> parameter delineates the different steps of rock failure procedures more accurately than conventional AE <u>hit number</u>,**

Conclusions (2/2)

Thermally treated rocks:

- **Physical properties (E, σ_{max}, Vp, Vs and AE energy and AE hit parameters) decrease with the temperature increase,**
- **Above 600°C mechanical properties of thermally treated gabbro drastically decrease,**
- **Oxidation in high temperature and different expansion coefficients between crystals are the main causes of damage in thermally treated specimens.**

Mechanically damaged rock:

- **In spite of ultra high pressure, the mechanical and physical parameters of rock decrease only up to 25 %. We conclude that this is due to smaller porosity of gabbro. However, AE monitoring demonstrates mechanical damage better than uniaxial test and sonic wave velocity measurements,**
- **In thin section studies, the development of micro-cracks through the crystalline structure is typical of mechanical damage.**

Thank you