Acoustic Emissions

a (brief) review

& the D-DIA Set-up at GSECARS
WHAT’s an ACOUSTIC EMISSION (AE)?

An acoustic emission corresponds to:

- the HF radiated acoustic waves emitted by a fast propagating crack
- average magnitudes Mw : -8 to -4, ie femto to nano earthquakes
- Corner frequency 1MHz ~ crack is only a few mm long (if Vr ~ Vrayleigh)
- Displacement ~ few tens of microns

In metals, dislocations, twinning, martensitic phase transitions can also produce AEs
PZT based sensor

The heart of the transducer is the piezoelectric ceramic:
- converts voltage to mechanical strain, and vice-versa.
- one side is connected to signal, the other side to ground.
- aspect ratio of crystal is linked to resonant frequency.

Some companies: Boston Piezo-optics, PI Ceramics.
Sensor assembly: example

Cheap: this is about £40. Commercial sensors are much bigger, not better, and cost generally more than £500!
Connections

AEs are recorded passively and the detection of events is crucially affected by the noise level. Limit noise issues by

- using coaxial wiring from the sensors to the preamps (use sample impedance all the way! typically 50Ω);
- using coaxial leadthroughs (brand: Kemlon) if possible. Takes space (about 1 cm dia. per lead);
- separating the grounds of all sensors (i.e., use 2 leads per channel);
- avoiding to connect the grounds of sensors to the rig frame directly, but connect the frame to the ground of the recording chassis;
- limiting the cable length before preamplification;
- increase preamplification when needed.
The workhorse

Recording systems: PAC, Mistras, Vallen, ASC. Most systems (except ASC) not designed to work on small rock samples.

Components:

- *trigger logic* (how to decide to trigger the recording ?), from the simplest (one channel threshold) to the most advanced (combination of thresholds, duration, channels).

- *multichannel digital oscilloscope* with common timebase: check the range of sampling rate (best above 10 MHz), sample number, dynamic range, etc. E.g., our ASC system at UCL: 50 MHz, 200 mV to 80 V, up to 32k samples. ASC minirichter system (at ENS): continuous streaming of all channels.

- *acquisition software*: real-time analysis of data.

Homemade systems also exist and might perform better (GFZ), but require a lot of work (especially the acquisition software and the analog logic). NI would sell you the acquisition cards for quite cheap!
Beware of noise
AEs follow the Gutenberg-Richter law (Mogi 1962):

Fig. 18. Frequency distributions of maximum trace amplitude of elastic shocks in each specimen (Granite G(K2)).
Location

AE Location workflow

- pick arrival times on at least 4 channels (best > 10),
- assume or measure a velocity structure,
- invert

\[ t_{arr} = t_0 + \frac{\sqrt{(X-x)^2 + (Y-y)^2 + (Z-z)^2}}{\langle V \rangle} \]

Methods

- Autopicking: RMS, AIC... Need trial and error for each type of test.
- Ideally: measure wavespeeds (see next part), and interpolate in time.
- The whole arsenal of inversion methods: least-square, simplex, grid-search, etc.
- Refinements possible using modern seismological tools: double-differences, cross-correlations.
Historical note

Scholz, JGR 1968: Uniaxial compression. Quite crude locations, only 22 events!
A masterpiece (Lockner et al., 1991)
The brittle field - Failure of granite = Benchmark

Acoustic emissions recordings

La Peyratte Granite
\( \phi_0 \approx 0.5\%, P_c = 15\text{MPa} \)
Effect of lithology

Continuous ultrasonic records of failure (10MHz)

Basalt vs. granite

Icelandic basalt
\( \phi_0 \sim 1\%, P_c=15\text{MPa} \)

La Peyratte Granite
\( \phi_0 \sim 0.5\%, P_c=15\text{MPa} \)
Effect of lithology
Continuous ultrasonic records of failure (10MHz)

Sandstone vs. granite

Fontainebleau sandstone
$\phi_0 \sim 8\%$, wet $P_{eff}=15\text{MPa}$

La Peyratte Granite
$\phi_0 \sim 0.5\%$, $P_c=15\text{MPa}$
OTHER MECHANISMS?

Twinning
The “cry’ of tin
The “cry’ of tin

An explanation by Dr Jessica Gwynne, Materials Science and Metallurgy, University of Cambridge.
OTHER MECHANISMS?

Acoustic emissions and shear instabilities during phase transformations in Si and Ge at ultrahigh pressures

Charles Meade & Raymond Jeanloz

ACOUSTIC emissions are commonly observed at low pressures as they are characteristic of brittle deformation\textsuperscript{1,2}. Most solids are ductile above a few gigapascals (GPa), and acoustic emissions have not been recorded from solids above 5 GPa. Here we describe acoustic emissions and shear instabilities that are associated with the $\beta$-Sn $\rightarrow$ simple-hexagonal phase transformation in Si and Ge to pressures as high as 70 GPa, well above the brittle–ductile transitions of both elements. We propose that the events are driven by rapid atomic motions across displacive phase transformations, and not by fracturing or cracking of the samples. These phenomena may be relevant to the processes that generate deep-focus seismicity in the Earth’s mantle.

Nature 1989

FIG. 3 Acoustic emissions from a Si sample in the diamond cell detected by a piezoelectric transducer mounted directly on one of the diamond anvils. The resonant frequency of the transducer is 20 MHz. The peak pressure in the sample is 19 GPa. Audible events have durations close to 1 ms $$(a)$$. Inaudible events, visually correlated with displacements through to sample have shorter durations of $\sim 20 \mu s$ $$(b)$$. 


OTHER MECHANISMS?

Transformation induced

Tetragonal-to-monoclinic phase transformation in CeO₂-stabilised zirconia under uniaxial loading

G. Rauchs\textsuperscript{a,1}, T. Fett\textsuperscript{b,*}, D. Munz\textsuperscript{a, \textsuperscript{b}}, R. Oberacker\textsuperscript{c}
OTHER MECHANISMS?

Three-Dimensional Mapping of Dislocation Avalanches: Clustering and Space/Time Coupling

Jérôme Weiss\(^1\) and David Marsan\(^2\)

Science 2002
Former studies in multi-anvils

- Antigorite dehydration
- AE recorded on 2 sensors only above and below 3GPa (no influence of ΔV).

Limits:
- 2 sensors only: 1D location
- No in-situ measures (stress, reaction progress)
Former studies in multi-anvils

Jung et al. 2009: 4-6 Gpa..

- 4 sensors: 1D-2D?
- Poor amplifications (10-20dB): real signal or noise?
D-DIA Experimental set-up

The **Richter continuous acoustic recording system**

- One sensor behind each anvil - so 6 sensors in total *(Possibility of AE location)*
- Continuous acoustic recording *(ie complete AE catalogue)* + Triggered systems
- Focal mechanisms inversion

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**CONTINUOUS DATA**
- 1TB ~ 1h
- 4 channel digital oscilloscope sampling freq. 10MHz

**TRIGGERED DATA**
- 6 channel digital oscilloscope sampling freq. 50MHz
- Rate ~ 16-60 events /s
D-DIA Experimental set-up

Minor mods compared to standard set-up

- mirror polishing behind anvils
- sensors isolated with ceramic plate
- coaxial cables

Oscilloscopes
Amplifiers
Continuous recorder
Triggerbox
D-DIA Experimental set-up

- Deformation-DIA
- University of Chicago, Advanced Photon Source (synchrotron)
Calibration
Using Max80 in Hamburg and quartz beads – 100μm initial grain-size

Gasc et al, 2012
Calibration

Using Max80 in Hamburg and quartz beads – 100μm initial grain-size

Gasc et al, 2012
Calibration

In the DDIA - quartz beads – 100µm initial grain-size – January 2010 (?)
Ge-olivine-spinel transition

Sintered Mg$_2$GeO$_4$ – 30µm grain size
Effective mean stress $(\sigma_1+2\sigma_3)/3 = 4$GPa ±0.25
Strain rate = $10^{-4}$/s

Stress – strain curve
AE waveforms: Picking and location

- WC anvil top
- WC anvil bottom
- WC anvil 3
- Dia anvil 1
- WC anvil 4
- Dia anvil 2

$\Delta t = 0.02 \mu\text{sec}$
$\text{i.e. } \Delta z \sim 0.2\text{mm}$

$\Delta t = 0.82 \mu\text{sec}$
$\text{but } \Delta t_{\text{WC-Dia}} = 0.75 \mu\text{sec} \text{ i.e. } \Delta x \sim 0.6\text{mm}$

$\Delta t = 0.64 \mu\text{sec}$
$\text{but } \Delta t_{\text{WC-Dia}} = 0.75 \mu\text{sec} \text{ i.e. } \Delta y \sim 1\text{mm}$
Ge-olivine-spinel transition

Sintered Mg$_2$GeO$_4$ – 30 μm grain size
Effective mean stress \( (\sigma_1 + 2\sigma_3)/3 = 4\text{GPa} \pm 0.25 \)
Strain rate = \(10^{-4}/s\)

**Stress – strain curve**

<table>
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<tr>
<th>Temperature (°K)</th>
<th>Deviatoric Stress (GPa)</th>
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![Stress-strain curve graph](image)

\( \varepsilon = 10-20\% \)

\( WC1 \)

\( bot \)
Ge-olivine-spinel transition

Sintered Mg$_2$GeO$_4$ – 30µm grain size
Effective mean stress $(\sigma_1 + 2\sigma_3)/3 = 4$ GPa +/- 0.25
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Ge-olivine-spinel transition

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Relative AE release rate (min)

\( \varepsilon = 25-30\% \)
Ge-olivine-spinel transition

Sintered Mg$_2$GeO$_4$ – 30µm grain size
Effective mean stress $\frac{\sigma_1+2\sigma_3}{3} = 4\text{GPa} +/- 0.25$
Strain rate = $10^{-4}$/s

Stress – strain curve
Comparison with an acoustic record of cold compression of quartz at HP
For info, cold compression (grain crushing) of Ge-Olivine corresponds to AEs signals <80mV

Sintered Mg$_2$GeO$_4$ – 30µm grain size
Effective mean stress $(\sigma_1+2\sigma_3)/3 = 4$GPa +/-0.25, T=1273°K, $\sigma_1-\sigma_3 = 2$GPa +/-0.1
Strain rate = $10^{-4}$/s

Cold compression of Quartz (100 µm initial grain size)
Two complete AE catalogues
D1247 Effective mean stress \( \frac{\sigma_1+2\sigma_3}{3} = 4 \text{GPa} \pm 0.25 \)
D1253 Effective mean stress \( \frac{\sigma_1+2\sigma_3}{3} = 5 \text{GPa} \pm 0.25 \)
Strain rate = \( 10^{-4} \text{s}^{-1} \)

Sonification:
courtesy to Ben Holtzman
LDEO, U. Columbia NY
Visiting prof. ENS 2015
Experimental set-up Mechanical & Acoustic Microstructure Discussion

AE waveforms: Picking and location
Ge-olivine-spinel transition

Moment Tensor inversion for 42 largest AE events (unclipped)

- 90% Shear, i.e. less than 10% volumetric component
- Up to 70% CLVD (compensated linear vector dipole)
Focal mechanisms
High Resolution Xray microtomography

Horizontal section

Microstructure - Sintered Mg₂GeO₄ – 30μm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10⁻⁴/s

Ge-olivine-spinel transition

42 largest AEs
Focal plane preferential strikes
Correlating X-ray tomography and AE location

Double difference relocation (Waldhauser and Ellsworth 2000),
(cross-correlation technique)
Looking into the AE source
Approximately 20% of the AEs have a complex source functions

*Double source or long nucleation phase?*
Serpentine dehydration at HP
Corner frequency $f_c \approx \frac{V_r}{L}$
Serpentine dehydration at HP
Damage -- DECOMPRESSION IS CRITICAL

# AES

500-550 °C Faulting Observed