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CRUSTAL STRESS AND ACUSTIC EMISSION (AE)

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Observation, Integration and Application
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ABSTRACT - Every *real* medium – subject to stress – releases acoustic (ultrasound) emission (AE), generated by the yield of some chemical bond of its "solid" structure. The rupture of such bonds amounts to an ageing of the "solid" structure of the medium, to "fatigue" and loss of performance. Passive monitoring of AE is therefore a most efficient diagnostic tool for monitoring crustal stress propagation on different spatial and temporal scales.
The frequency variation *vs.* time of the leading AE signal is associated with the increasing spatial dimension of the yielding bonds, depending on the coalescence of flaws to increasingly larger size. Hence, AE's of different frequency give insight into the history of the loss of performance and evolution of the structure of the medium.
We report about investigations carried out since several years in different tectonic and volcanic settings, also including some laboratory tests suited for environmental and technological applications.
The methodological approach – which is the main focus of the presentation - relies on four issues, briefly denoted by F, H, T, O.
• *F* denotes the amplitude of the signal, and its time and space history.
• *H* ("hammer effect") is associated with the assessment about whether the AE is released as a response to an external action, or, rather, as a consequence of the search for new equilibrium following the application of previous stress.
• *T* is the ageing of the medium, derived from fractal analysis of the AE time series.
• *O* is the outlier analysis, which results effective for different purposes, including measuring the spectral lines of Earth's tides and of the free oscillation of the Earth.

THE PHISICAL PRINCIPLE

- **An AE source** is associated with the release of energy from the yield of some chemical bonds within some crystal structure.
- **The reaction chain** concept: one additional chemical bond is more likely to yield close to the point where the mechanical strength of the solid object is comparatively weaker due to the presence of some previous flaw.
- **The time sequence of the frequency of the observed *AE***

  Small-size flaws are first detected, associated with comparatively higher frequencies (*HF) AE* .

  Smaller flaws coalesce into larger ones, and release lower frequencies (*LF) AE.*

  One example is enlightening, and it applies to every technological application: **seismic events.**

  A final shock (at ~ *0.5 ÷ 1. Hz*), related to the **seismic event**, precede *by several months* an *HF AE* (at ~ *200 kHz*) outburst, and by two or three *months* a *LF AE* (at ~ *25 kHz*) paroxysm.

  The seismic roar precedes the shock by *a few tens* to *several tens seconds* and the vibration of some specific components of buildings (e.g. glass of windows) precedes the shock by *a few seconds.*

- **The bulk of the frequency of the AE observations decrease vs time**

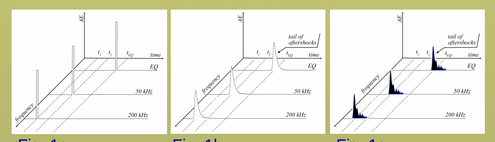


Fig. 1a Fig. 1b Fig. 1c

As a first order approximation, the phenomenon can be depicted in terms of Dirac δ-functions (Fig 1a).
Upon closer physical consideration, every δ-function ought to be substituted by a lognormal distribution (Fig 1b).
An eventual externally applied additional effect (such as e.g. tidal modulation) sometimes results into an apparent trend looking like a damped oscillation (Fig 1c).

DATA HANDING - ALGORITHMS

•***H*** (the "hammer effect", i.e. "forcing" vs. "relaxation" conditions)
The system can emit *AE* whenever it is subject to an external forcing. Otherwise it can emit *AE* whenever it is relaxing and searching for a new equilibrium after having suffered by an external forcing.
It is possible to define an instant index *H=+1* for forcing condition, and *H=-1* for relaxation condition, while *H=0* reflects an indeterminate status.

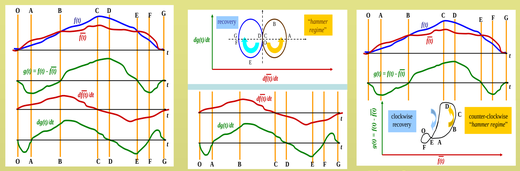


Fig. 2a Fig. 2b Fig. 2c

Fig. 2a: Qualitative cartoon showing an arbitrary observational datum *f(t)*, with its smoothing average over a suitable time interval, and its residual, and their time respective derivatives.
Fig. 2b: Qualitative cartoon, showing how to infer the "*hammer regime*" vs. the "*recovery regime"*.
Fig 3b: Qualitative cartoon, showing the "*hammer plot*" for inferring "*hammer regime*" *vs.* "*recovery regime*".

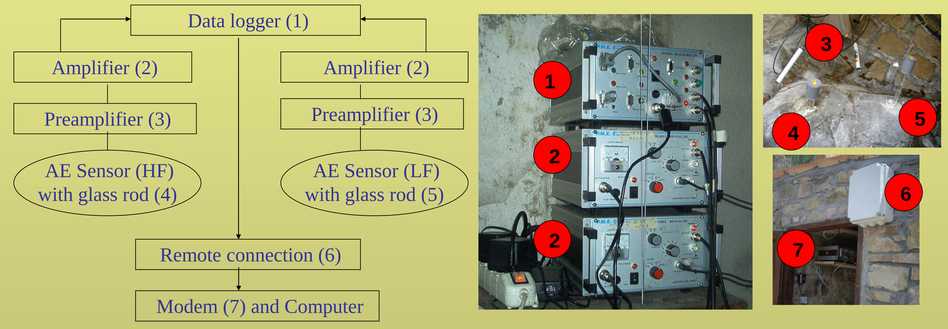
•***T*** (the role of time, ageing of materials, the capability of matter to react)
No "ideal" elastic body exists. Some crystal bonds always yield, micro-flaws are generated, and progressively increase their size. Every material is ageing, and with ageing its performance worsens.
The fractal dimension D_t of the time series of the recorded *AE* is en excellent index of such ageing.
When $D_t \sim 1$ the *AE* sources are randomly distributed in 3D space. Every yielding crystal bond has no memory about the preceding yielding bonds.
When $D_t \rightarrow 0$ (although, owing to definition, it is always $0<D_t<1$) the *AE* sources get progressively clustered in space around a 2D plane, which is the cleavage plane of the crystal structure. Every yielding crystal bond has a progressively increasing clear memory about the preceding yielding bonds, as a new bond yields with a higher probability of occurrence whenever it is close to a previously yielded bond.

•***F*** (the time variation of the applied external action)
The *AE* response is not linear with respect to the applied action. However, a greater AE intensity corresponds to a greater applied action.
It should be recommended applying a weighted moving average, e.g by applying most simply a triangular system function.

•***O*** (outliers, the way matter reacts)
With no outlier rejection, several algorithms result severely non-robust, therefore they must be rejected.
However, outliers keep own intrinsic information and represent deviations of the behaviour of the material compared to a symmetric distribution (such as a normal distribution)
Based on practical evaluation, the outlier series clearly resulted to contain an indication of the nature of the material. That is, an outlier denotes a "tail" of a lognormal distribution.
Therefore, analysing the time series of the outliers is indicative of the intrinsic physical features of the system. For instance, in the case of *AE* records collected in the field, the *AE* time series displays several spectral lines of the Earth's tides. In the case of a technological application to some given material, the outliers ought to be indicative of specific crystallographic features of the material. Investigations are in progress.
The algorithm for such investigation is the operator ARP which is based on the superposed epoch criterion applied to a point-like process according to a rationale generally applied e.g. to the analysis of synapse. The result shows that an AE station is well suited for monitoring Earth's tides and the free oscillations of the Earth.

AE MONITORING APPLICATIONS

When we monitor a natural structure with the AE, often we deal with structures that cannot be likened to a unique solid body – e.g. think about a terrain with landslide hazard, or about a slab of Earth's crust.
We need for some "solid" large object which can be likened to a probe inserted into the non-solid structure. Whenever the non-solid structure is affected by some structural change, implying a variation of its stress field, such stress shall be transferred to the "solid" probe.
Monitoring such "solid" probe is therefore an indirect way of monitoring the non-solid structure.
That is, the "solid" structure is to be conceived as a component of the sensor system used as measuring device, altogether with sensor, data logger etc.



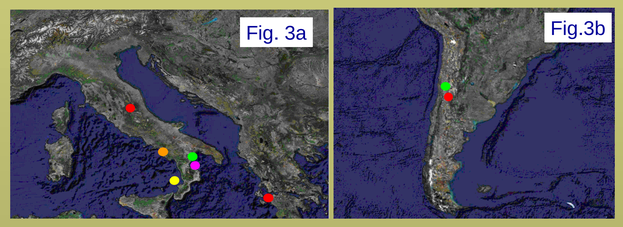
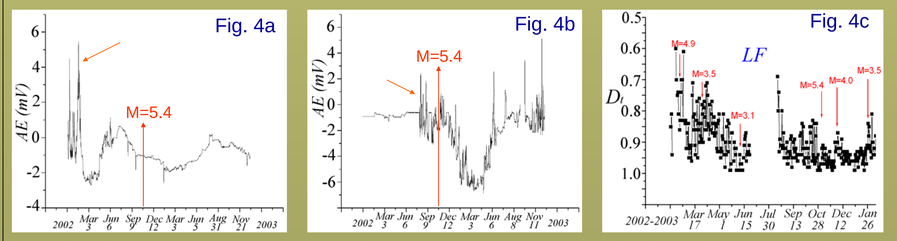


Fig. 3a
AE stations in **Italy**: *Orchi* *Vesuvio* *Potenza** *Valsinni* *Stromboli**
***Greece**: Cephalonia*

Fig. 3b
AE stations in **Argentina**:
Cerro Blanco *Peteroa*

* No more operation

EXAMPLE OF RESULTS



Relations between AE time series and seismic events at the Orchi site (Foligno, Pg, Italy).

(Fig. 4a) The *HF AE* paroxysm (the large burst pointed out by an orange arrow on the left part of the figure) that precedes by ~ 7 ÷ 8 months the Molise earthquake (31/10/2002, Magnitude (M)=5.4). (Fig 4b) The abrupt *LF AE* paroxysm (indicated by an orange arrow) starting almost exactly 2 months before the Molise earthquake. (Fig 4c) Trend of ^{LF}Dt. time series: reported are occurred earthquakes (M>3). Note the abrupt change towards lower ^{LF}Dt. values just before the seismic events, revealing a clear trend from random *AE* towards a progressively better organised phenomenon, characterised by rupture along some preferred plane (e.g. fault).

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