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Acoustic Emission (*AE*) for Monitoring Stress and Ageing in Materials, Including Either Manmade or Natural Structures, and Assessing Paroxysmal Phases Precursors

Giovanni P. Gregori[1], Gabriele Paparo[1,2], Maurizio Poscolieri[1], Claudio Rafanelli[1] and Giuliano Ventrice[3]
[1]CNR-IDASC - Institute of Acoustics and Sensors "O. M. Corbino", Rome,
[2]Italian Embassy, Buenos Aires,
[3]P.M.E. Engineering, Rome,
[1,3]Italy
[2]Argentina

1. Introduction

A preliminary assessment of the basic logical framework is essential in order to avoid misunderstandings and/or misconceptions.

1.1 "Elasticity" vs. "plasticity" - "continuity" vs. "quantum bonds" – the space scale and detail

A few definitions have to be recalled: "solid", "liquid", "continuity", and "homogeneity".

"Solid" means that the atomic or molecular bonds prevail on all other forces (thermal, gravitational, etc.). "Liquid" means that gravity forces prevail. Natural reality never fits with either one such an abstraction. Therefore, it is customary to refer to "plastic" materials, or to "viscous" fluids. By this, we afford in keeping a "simple" scheme based on an arbitrary abstraction, and, at the same time, we can approximately fit observations by means of a few *ad hoc* corrections. "Elasticity" is a concept that derives from - and applies to - either an ideal "solid" or an ideal "liquid" body. An ideal "elastic" body is such that some potential "elastic" energy is transformed into "kinetic" energy and vice versa, while this entire process strictly implies no energy loss of any kind. The concept of "elasticity" is closely related to the concept of matter "incompressibility", which is usually taken for granted, although it should deserve consideration being an additional key abstraction.

"Continuity" is related to the abstraction implied by "infinite" and "infinitesimal" quantities that *per se* are not a requirement of natural reality. Until the past XIX century, science was a daughter of Newton and Leibniz, due to their differential and integral calculus.

The infinity of the universe is debated. In contrast, since the discovery of quantum effects, it is well assessed that infinitesimal quantities do not exist. For instance, the van der Waals equation is a simple correction that introduces in some approximate way the intrinsic non-vanishing volume of a gas molecule. This simple correction, however, can only justify some metastable trend of a gas-liquid mixed system, while a correct description of its equation-of-state must unavoidably appeal to quantum phenomena.

Owing to this same reason, classical electromagnetism alone (Maxwell laws, Faraday, Coulomb, Ampère, Gauss, etc.) has never permitted the exploitation of modern electronics, which rather relies on solid state physics. Quantum bonds play a key role. Quantum phenomena are a fundamental aspect of natural reality. They can even be managed by avoiding formal reference to the Schrödinger equation, Hilbert spaces, Feynman graphs, etc. The cleavage plane of a crystal – hence the ageing of a material - shall never be justified by any model based on "continuity", rather it must rely on atomic bonds. Atoms are incompatible with "infinitesimal" quantities, hence with "continuity" (in its strict sense of mathematical analysis). "Homogeneity" is an additional abstraction aimed at fitting the requirements for "simplicity". It correctly applies to manmade structures. But – when dealing with subsystems of the natural environment - it can be applied only within suitable approximations. "Homogeneity" is closely related to the damping of "elastic" waves, which can be propagated through a medium only as far as the wavelength is larger than the mean gaps in the material (these gaps violate homogeneity and continuity).[1]

The present paper deals with records of acoustic emission (*AE*) typically inside a manmade structure – such as a machinery, a building, a bridge, a pipeline, a dam, a rail or road embankment. But *AE* monitoring can also be carried out in the field, for monitoring crustal stress, volcanic precursors, land slide hazards, etc.

As a standard every application is biased by some perturbations that affect the raw *AE* records. Therefore, a few somewhat different criteria are required while approaching data analysis and interpretation in every specific application. Upon concrete exploitation of this whole approach, the results were found to be heuristically very effective for different algorithms, when they are comparatively applied to different physical systems – either in the laboratory or in the field. The comparison between the different applications resulted very useful for understanding the physics of phenomena that – when considered in every single application alone – could be hardly understood. The present discussion refers therefore to *AE* records measured both in the laboratory and/or in the field.

In general, the intensity of the measured *AE* signal depends (*i*) on the intensity of its primary original (either known or unknown) source, and (*ii*) on the damping of the signal – hence on the acoustic impedance, which is different for different probes, and for different *AE* frequencies, temperatures, etc. Let us recall that the acoustic impedance $Z = \rho V$ of a

[1] Communication between different scientific communities is important. A specification on terms is therefore important. Consider a sample of matter, and an energy input to it. If the input and output energies are compared with each other, it is found that some energy was lost. Therefore, it is claimed that some energy has been "absorbed", or that the signal has been "damped" in the process, or that some energy has been "radiated" outside by "scattering loss", or it was released by any other speculated mechanism, etc. All these terms are equivalent in Earth's sciences. In other scientific communities specific "technical" distinctions eventually result from undeclared agreements. This evidently seems to be a matter of semantics, while it has little concern when dealing with the scientific interpretation of phenomena. Engineers distinguish damping and absorption, while this distinction has less meaning to Earth's scientists.

material is defined as the product of its density ρ and its acoustic velocity V. This is important for the determination of wave transmission and reflection at the boundary of two materials, for assessing the wave absorption, and for designing ultrasonic transducers.

In the last respect, however, it should be pointed out that laboratory measurements are easily carried out in a liquid. For instance, one can measure the acoustic impedance inside water and determine its dependence on temperature, frequency, pressure, etc. In contrast, this is impossible in the case of most solid media. The reason is that the propagation of an "elastic wave" inside a solid object - hence its apparent acoustic impedance - is critically controlled by the geometrical shape of the body, due to wave reflection (and refraction) across the outer boundaries of the object. In the case of water these measurements are carried out inside a pool, with an *AE* source located at its centre. But this is not possible for a solid medium.

The concept of density ρ implies the continuum approximation. The concept of velocity V refers to physical effects observed at different times and different sites. The acoustic impedance $Z = \rho V$ relies on the same assumptions. In contrast, fracturing events rely on quantum effects.

The propagation or damping of an elastic wave through a medium is related to how much longer the wavelength is, compared to the typical scale size of the heterogeneities of the medium. The Earth is approximately homogenous for seismic waves (*~0.5-1 Hz*), because the spatial scale of heterogeneities in the Earth's body cannot affect these wavelengths. At shorter wavelengths, such as ultrasounds, the Earth appears much more heterogeneous, and ultrasound can be transmitted only through rocky bodies, etc. That is, transmission and damping are related not only to ρ but also to frequency. Therefore, transmission critically depends, more or less, on the ideal homogeneity of the medium. In addition, the temperature of the medium makes more or less effective the crystal bonds, hence it affects the capability to transmit an elastic wave.

The density ρ influences absorption, hence also the acoustic impedance Z. Otherwise, one could show that V is exactly proportional to $1/\rho$, by which $Z=\rho V$ is constant. According to a treatment in terms of elementary approximations, it can be shown (by an abstraction) that for a homogenous infinite medium it is $V = \sqrt{const/\rho}$, where *const* depends on whether one considers P-waves, or S-waves, or surface waves at the boundaries of the medium. In reality these conditions can hardly be attained even in the laboratory, while in the field the granular structure of the system raises serious problems, such as e.g. the difficult implications of the sand pile theory, etc. It is therefore concluded that also $Z= V\rho \sim \sqrt{const \cdot \rho}$ depends on ρ.

All this appears as a mere academic exercise, while physical reality behaves according to its specific laws, which are much more complicated compared to any human schematization by means of a "simple" model. This also originates misunderstanding between different scientific communities. A correct interdisciplinary communication therefore requires a fundamental clarification.

Let us point out that the meaning of "transmission", "conduction", "transport", and "advection" are very similar, and sometimes closely related to one another. In Earth sciences the choice of any one term is determined by intuitive criteria, in order to give some feeling about the nature of the speculated underlying process. In contrast, engineers, who are concerned with manmade systems, agree on some often undeclared conventional choices, by which they use these terms only with specific meanings. For instance, it is customary to talk about “thermal energy conduction” (which is different e.g. from advection), or about “electric energy conduction” - hence about “electrical conductors” etc. Thermal advection, charge transport by motion of an ionized medium, or transport of sound inside a moving mass of matter such as the noise of a train listened when we are down-wind with respect to the train, etc., all these phenomena imply a “conduction” of energy, but they are better described as “transport” phenomena.

Engineers claim that an elastic wave is “transmitted” through a medium, Earth’s scientists may sometimes consider the transmission of an elastic wave much like en electric signal that goes through a “conductor”, etc. The motion of an ion is a transport phenomenon, i.e. an advection phenomenon. But it is the same as an electric current. All ions move through the atmosphere and they compose the atmospheric electrical circuit. But also a lightning strike is an electric current. However, it is different to deal with the gentle wave of the surface of a pond, and with a catastrophic tsunami. The physics are the same, but energy and implications are much different. Terms can be different. But processes are clear. Therefore, the authors apologize to a reader who is not familiar with these matters of lingo, and kindly ask her/him to consider the physics of the process, rather than the terms used for explaining it.

In terms of the physics of the process, a fundamental point is that this entire item is closely related to the space domain of phenomena, which determines the required number of points where *AE* recordings are to be carried out. For clarity purposes, let us refer to a few case histories.

Consider a bridge or a building. Everything in natural reality is always subjected to stress, hence to fatigue and ageing. But some specific structural knots of the bridge or of the building experience a comparatively greater stress, hence they are likely to suffer by a comparatively earlier loss of performance. Every structural component of a bridge or of a building, however, is composed of material (either steel or concrete) that is a good *AE* conductor. Hence, it is sufficient to monitor a limited number of points of the entire bridge, depending on its length and structural details. The same argument applies to a pipeline, where, however, the concern is more about the time scale, rather than about the space scale (see section 1.2).

A different concern deals with a rail embankment or with land-slide hazards. In general, soil is insufficiently compact for ensuring a good transmission of the *AE* signal. Hence, there is need for monitoring some “solid” structure – such as a house, or a building of any kind, or a pall, etc. – which is embedded into the “loose” soil material (e.g. for a rail embankment one can use the palls for the power supply to the railway).

In either case, the spatial detail that is effectively attained by *AE* monitoring is defined by the number of monitoring points that are located inside the given system. That is, it depends on the number of “solid” probes that can be used. If they are insufficient for the required needs, some newly built “solid probes” should be set up.

Concerning a volcanic edifice, the *AE* array can be reasonably small, as the primary agent, i.e. the time-varying pressure of the endogenous hot fluids, is likely to affect simultaneously a large fraction of the entire volcanic edifice, and a few measuring sites can therefore be sufficient to monitor the entire system.

Comparatively much more complicate is the case history of seismic monitoring. The tectonic setting, and structural details, of the interested area play a critical role in the choice of the *AE* array. In general, these features are also poorly known. Hence, a careful multidisciplinary modelling is required in order to choose the hopefully "optimal" location of the *AE* array.

Summarizing, the space scale of the required *AE* monitoring depends on the specific application of concern, and on the spatial detail that is required.

1.2 The time domain – the *AE* trigger

Figure 1 is a cartoon that shows the time dependence vs. frequency of the observed *AE*. The physical principle is that every former "solid" sample – which originally has almost no flaws - suffers by the formation of some small flaws, which are associated with some comparatively high frequency (*HF*) *AE*. On the occasion of every additional stress - which is subsequently applied to the same sample – some new flaws will be originated. This will occur preferentially close to the crystal bonds that have already yielded. At these points the material is comparably weaker.

Hence, new comparatively larger flaws will be generated by coalescence of the previous smaller flaws. The process can be illustrated in terms of a progressive implosion of small flaws to generate larger flaws, almost like in a chain reaction. An analogy is the well known game of domino tiles that drop one after the other in a time sequence.

According to this physical rationale, we know with certainty that - owing to specific physical reasons - we would expect to observe different phenomena involving first some comparatively *HF AE* time series, and subsequently *LF* (low frequency) *AE*.

A key aspect of concern - about the time scale - deals with the primary driver of the process, which originates the *AE*.

Some phenomena are characterized by some "long" time scale. Indeed, some phenomena certainly occur – and therefore ought to be detected in some way - during some "long" time lag preceding the incoming "catastrophe" of the system (this remark applies either to an earthquake, or also to simple crustal stress propagation, or to a land slide, or to the loss of performance of a bridge or of any other manmade structure due to material ageing, etc.).

In contrast, sometimes some *AE* can be originated only by an action that lasts a few ten seconds (such as e.g. when operating an electric drill on a solid sample). This requires a much higher time resolution for *AE* data acquisition, as there is need to monitor the rapid evolution of the system until the opening of the drill hole.

But even much more rapid *AE* data acquisition is sometimes required, if we want e.g. to monitor the time evolution of the performance of the system while it is disrupted by an explosion. For instance, consider a pipeline that is broken by a cold chisel struck by a hammer triggered by explosive.

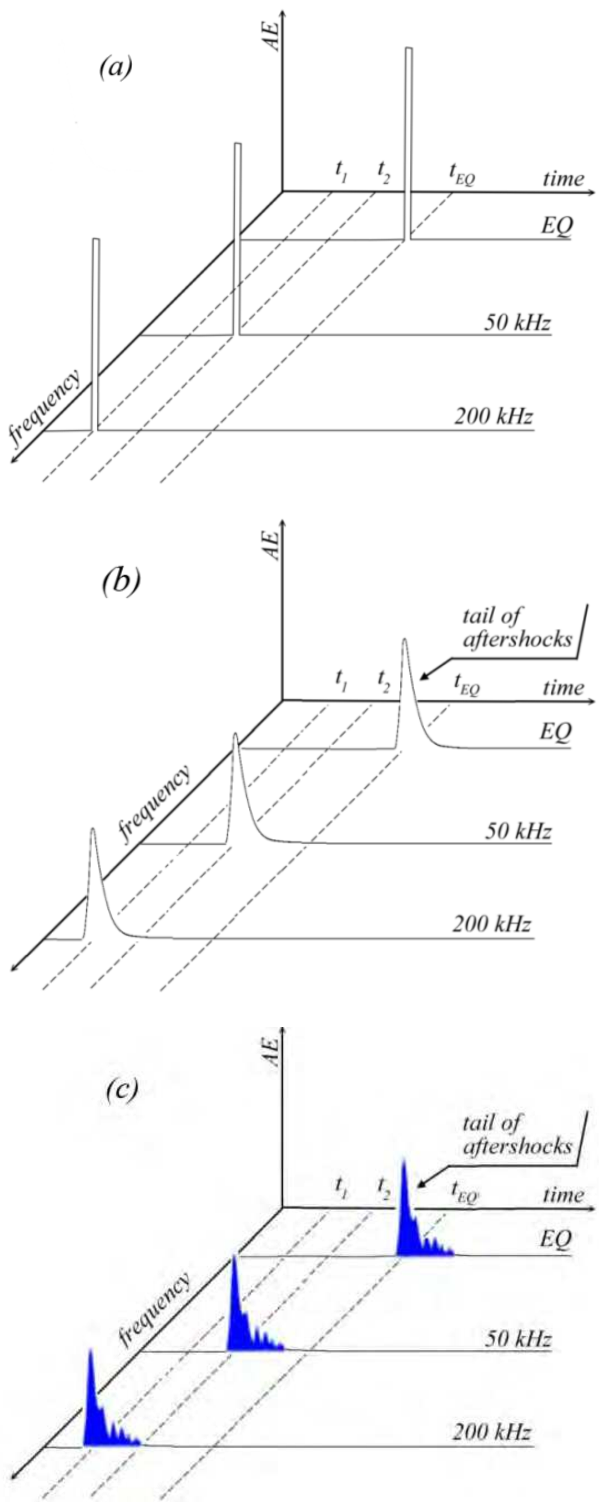

Fig. 1. Cartoon showing how the recorded *AE* signals are first released at comparatively *HF*, corresponding to the yield of smaller flaws, and subsequently to progressively lower frequencies. The signals are not Dirac δ-function distributions *(a)*, rather lognormal distributions *(b)*, which are eventually modulated such as by tide effects *(c)*, e.g. observed on the volcanic edifice of Vesuvius, displaying some apparently damped oscillation, just analogously to the aftershocks of an earthquake (here denoted by *EQ*). See text. After Paparo & Gregori (2003)

In this case it is important to focus on the need for specifying - as a needed logical prerequisite in every data analysis – the target of concern. Long time scales (compared to the human standards) are to be considered when one wants to monitor the evolution of the system towards its possible "catastrophe" in order to intervene. In contrast, when the typical duration of a phenomenon is much shorter compared to the typical human standards (e.g. in the case of an explosive event), the required information is to assess where and when the "catastrophe" already occurred in order to repair the damage.

Summarizing, the time scale of concern depends on the application required by the *AE* information.

Independent of whether the primary *AE* trigger has a long or short time scale, in general some trigger always exists, being the ultimate reason by which everything is ageing in the universe.

As far as any kind of manmade structure is concerned, thermoelasticity is an important trigger for *AE*. Figure 2 shows the case history of records collected on Gran Sasso (Paparo et al., 2002; Gregori & Paparo, 2004). It is the largest mountain massif in the central Apennines, composed of dolomia and limestone. The diurnal variation of the recorded *AE* signal (for operative details refer to section 2) shows a maximum in the very early hours of the day (local time) when the mountain is cooling. In fact, when the comparatively outer layers of rocks warm up, they expand with respect to the inner cooler layers. In contrast, when the mountain cools, the outer layers contract over their respective internal warmer – hence more expanded – layers. Therefore, some cracks occur. It is the same principle by which in an old country house, with no heating, during cold nights the furniture releases noisy cracks in the early hours of the day.

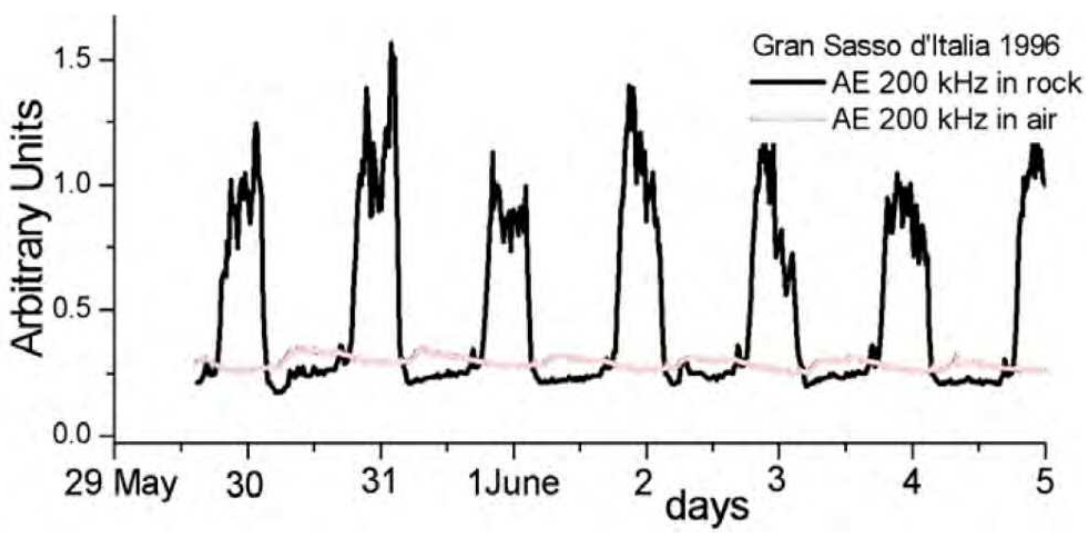

Fig. 2. *AE* recorded on the Gran Sasso mountain (Apennines, central Italy). The large diurnal variation has a maximum during night time when the mountain cools. An identical transducer suspended in air measures a negligible signal (light grey line). The difference between different days very likely depends on different meteorological and insolation conditions, i.e. the observed effect shows all features consistent with a mere thermoelastic effect. See text. Figure after Gregori & Paparo, 2004 and (simplified) after Paparo et al. (2002)

Thermoelasticity is the main cause for weathering for rocks in Sahara or other desert areas. But it is also a steady and permanent feature e.g. in a bridge, or in a concrete or steel building in open air. This fact is quite useful for monitoring the different response – hence the progressive ageing and loss of performance - of the materials that compose that structure.

Other triggers for *AE* - e.g. on a bridge - can be the transit of a train or of a heavy vehicle, or a slow land slide affecting its basement, etc. The same applies e.g. to a possible unexpected rupture of a pipeline.

In general, one can envisage either a steady, real-time, monitoring of the ageing and loss of performance of a structure, or – whenever the loss of performance is very slow - one can envisage some periodical check of the structure e.g. of a crane, of a rail car, etc.

In the case of steel structures it is even possible – at least in principle - to take advantage of the magnetic hysteresis cycle of its ferromagnetic components. For this, one can use – apart the concern about a suitable intensity of the applied external field - a device that in principle is similar to a standard metal detector that has an oscillating circuit with a resonance frequency that depends on the inductance, which is altered by the presence of a metal object. The Weiss domains of the metal structure experience a hysteresis cycle. But, while they change the inductance of the oscillating circuit, they also cause an *AE* release from the metal. Owing to the action-reaction principle, if the metal object causes an effect on the metal detector, the metal detector causes an effect on the metal object, and this can be monitored by *AE*. Upon applying suitable algorithms to this signal (see section 3), one can evaluate the stage of ageing of the material. This technique can apply e.g. to making a periodical check of the performance of specific ferromagnetic components of machinery, a rail car, etc.

Summarizing, the time scale to be considered depends either on the ultimate target of the application of *AE* monitoring, or on the typical time scale of the primary trigger of the observed *AE*.

1.3 Lognormality

Unless otherwise stated, let us refer to one given *AE* frequency at a time. A key point of concern deals with the trend of the observed *AE* record. The signal is the result of some "*fog*" of primary *AE* sources, which are identified with the flaws of some specific size that release that observed *AE*.

Let us begin by an abstraction. The definitions of entire mathematics, geometry, fractality, set theory, abstract algebras, group theory, probability theory, etc., all rely on abstractions or analogies. The same logics apply to many different material systems. All these analogies are therefore crucial for understanding different phenomena in terms of a unique rationale shared by different systems and processes.

The *AE* rationale is the same as the typical justification of a distribution of the Kapteyn class, known as "lognormal distribution". It was defined by Kapteyn (1912) and Kapteyn et al. (1916). It was also included in some textbooks (e.g. Arley & Buch, 1950). But apparently it was generally almost forgotten in the subsequent literature (Paparo & Gregori, 2003; Gregori & Paparo, 2010).

Its leading motivation is shared by several phenomena, typically by every public service, i.e. in every case history when the probability that a user takes advantage of that service is proportional to the number of users that already use it.

The same rationale is shared by every physical phenomenon, whenever the occurrence of an event is proportional to the number of events that are already occurring. Typical examples (refer to Gregori & Paparo, 2010 for more extensive discussion and references) are the hypsometric curve (i.e. number of points at a given height above sea level) of the Earth or of a planetary object, or a geomagnetic storm (Campbell, 1996), or a magnetospheric substorm (which is an "elementary" component of a geomagnetic storm; Akasofu, 1968), or with a financial crisis when the psychological impact determines the lognormality of the event, etc.

The same rationale can be applied to the *AE* release from the "*fog*" of elementary *AE* emitters inside a given "solid" structure, where crystal bonds are progressively broken with a higher probability of rupture wherever the structure is comparatively weaker, etc.

Historically, the first discipline where this important logical feature was clearly assessed was geomagnetism and polar auroras. Hence, let us borrow their terms for applying them to other disciplines. For future reference, let us therefore recall that a "geomagnetic storm" is assessed by the North-South horizontal ("H-component") geomagnetic field (Chapman & Bartels, 1940). In contrast, a "magnetospheric substorm" - which is shown to be some kind of more elementary component of a magnetospheric (or geomagnetic) storm – was clearly recognized by Akasofu (1964) by means of polar auroras, as the geomagnetic signal is excessively perturbed for unambiguous assessment. That is, one and the same phenomenon involves one and the same physical system, but it eventually requires to be monitored by different diagnostic tools.

In the case of a magnetospheric substorm – which typically elapses ~ *2-3 hours* - the process is the consequence of the progressive lack of particle supply from the particle reservoir represented by the plasmasheet inside the tail of the magnetosphere (Gregori, 1998, 1999, 2002): hence, the progressive exhaust of particle inflow from the tail is reflected in the lognormal trend of a substorm.

Similarly, concerning a geomagnetic storm - which typically elapses ~ *a few days* - it reflects the time variation of the flux of solar wind. As mentioned above, a storm is composed of a formal disordered sequence of overlapping substorms. When the solar wind flux exhausts its "anomalous" flux, the decaying trend of the storm will result lognormal due a progressive fading off of its primary trigger. In the meantime the magnetosphere attains a new equilibrium state, after taking advantage of the availability of particles in the reservoir of its plasmasheet.

The same logical sequence of "storm" and "substorm" can be applied (see below) to *every* phenomenon, even to the *AE* technological or environmental applications here of concern.

That is, lognormality is a frequent mathematical feature observed in a large variety of phenomena. This is just a matter of a mere observational fact. And also the *AE* monitored at a given frequency is expected to occur according to a lognormal trend. Its basic physical interpretation and implications, however, are to be better specified after discussing its fractality (see section 1.4). For the time being, let us point out that the *AE* sources operate according to the aforementioned rationale, hence the *AE* signal - at every given frequency - will display a lognormal distribution, as shown in figure 1(b).

In addition, the tail of the lognormal distribution will eventually be modulated by some external action. For instance, at the lowest frequency - i.e. at ~ *0.5 – 1 Hz* which is the typical frequency of a seismic shock - the tail of the lognormal distribution [figure 1(c)] will be identified with the classical aftershock sequence. Seismologists have recognized only the tail of this distribution. They call it the Omori law. The lognormal distribution is comparatively sharper when the typical timing of the evolution of the system is faster. Stein and Liu (2009) found that the faster the slip-rate along a fault (in the range 0.1 - $100\ mm\ year^{-1}$), the shorter the aftershock time series (in the range *a few – a few thousand years*).

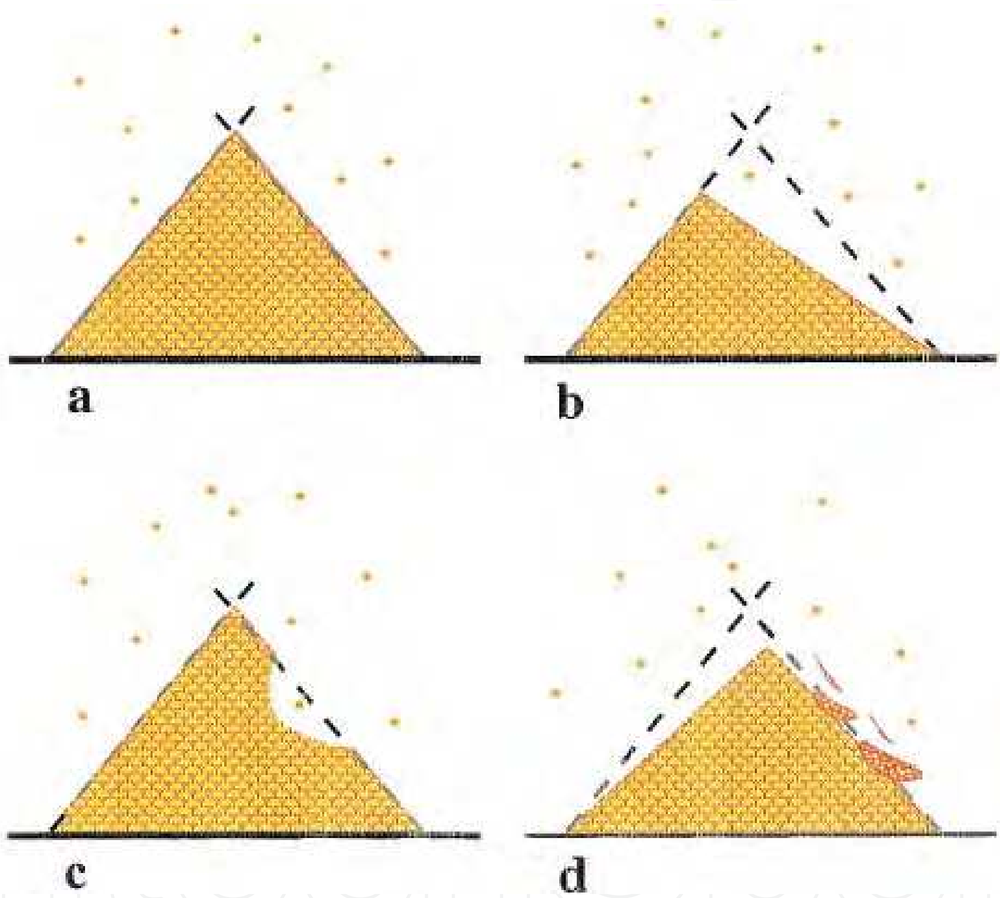

Fig. 3. "*Grains of sand (small dots) being added slowly to a sandpile.* (a) *All sides of the sandpile have reached the angle of repose whereby additions of sand result in instabilities, i.e., avalanches, of various sizes.* (b) *A large avalanche has taken place along one small range of azimuths of pile taking that zone out of a self-organized critical state and making it incapable of being the site of a large avalanche for a long time (until grains of sand are added to it to bring its slope back to the angle of repose; large avalanches can still occur at any time along other azimuths.* (c) *A small avalanche occurs along one azimuth but does not affect its entire downdip slope; small avalanches can still occur along other portions of slope either up or downdip of that small avalanche.* (d) *Moderate-size avalanches occur as a given azimuth approaches or reaches a state of instability prior to a large avalanche. Large and small avalanches correspond to large and small earthquakes …*". Figure and captions after Sykes et al. (1999)

Consider another example pertinent to the present discussion: a sand pile which is in a state of critical equilibrium (Buchanan, 1997; Coontz, 1998; Sykes et al., 1999). Once in a while, some part of the pile falls down, and some small sand slide occurs here and there (figure 3). The system is said[2] to be in a state of "self-organizing criticality" (*SOC*). This critical state will last until the sand pile has attained its final equilibrium.

In terms of an analogy with the geomagnetic storm - which as mentioned above is composed of an irregular sequence of overlapping magnetospheric substorms - it is possible to liken the entire process, of the collapse of the sand pile towards its final equilibrium, to a "storm" of the system. In addition, this "storm" is composed of the irregular sequence of overlapping "substorms", each identified with a partial sand slide of the pile. Altogether the system, which implies a "storm" and its "substorms", is a *SOC* process.

Concerning the applications, one has first to define the time scale of the process (section 1.2): even a structure, which is destroyed by a huge explosion, has its "history" and timing of every different yielding component, although the time scale of the evolution of the explosion, i.e. of "catastrophe" of the system, is not comparable with the typical human time scale.

After having defined and assessed the time scale of concern, the yielding process has some typical temporal evolution of every part of the system – e.g. consider a building made of concrete, or a Medieval tower made of bricks or stones, or a bridge made either of steel or of concrete, or any kind of manmade object. This evolution will reflect some progressive loss of performance of either one part, or "elementary", component of the system. All this appears to occur similar to the aforementioned sand pile theory.

An engineering-designed object, such as a bridge or a building - compared to the case history of a sand pile - will respond to a more deterministic and less erratic trend. But, within suitable approximations, one can liken this to a *SOC* process with the progressive loss of performance of every ageing component of a bridge or building.

Summarizing - upon borrowing the same terms and concepts used in geomagnetism - an observed *AE* event (for definition of "event" see section 3) can be likened to a "*stress storm*" (at every given *AE* frequency) provided that - as mentioned above - the process can be expected to occur according to some ideal situation to be approximately depicted by a lognormal phenomenon. In any case, the entire phenomenon, i.e. the "*stress storm*", will appear like a *SOC*, characterized by some irregular superposition of overlapping "*stress substorms*".

From a comment by Cliff Ollier, whom we deeply thank, the term "*stress storm*" can sometimes be misleading, as "*stress*" *per se* is not "*strain*". Hence, one should call "*crustal storm*" one phenomenon that occurs inside the Earth's crust etc., or one could use the term "strain storm" instead of "stress storm". On the other hand, ideal "elasticity" is only an abstraction. Hence, in natural reality every non-ideal elastic deformation always causes the yield of some crystal bonds, hence some *AE* release. Therefore, for simplicity, let us use either term "*stress storm*" or "*strain storm*", or briefly "*storm*" that can be applied to every case history, either in Earth sciences, engineering, or other disciplines.

[2] It was formerly defined by Bak et al. (1987). Or see also e.g. Sornette et al. (1990), Sornette & Davy (1991), Cowie et al. (1993); Main (1995), Cowie (1998), Cello (2000), and references therein. It is even reported by science popularization books (e.g. Barrow, 2009).

Thus, the purpose of analyzing an observed *AE* time series - or set of different frequency *AE* time series - is to recognize, within the observed *AE* records, both "*AE storms*" and their constituent "*AE substorms*".

1.4 Fractality and SOC

Fractality is a crucial aspect of an *AE* time series. It is the result of an abstraction, similarly also is lognormality. Concerning the general and more exhaustive discussion of lognormality and fractality refer to Gregori and Paparo (2010).

Every time series of events, either of *AE* or any other kind, in general is found to be more or less randomly distributed in time (concerning algorithms etc. refer to section 3 and references therein). In the case of "perfect" or "ideal" randomness, the fractal dimension D_t of the *AE* series is equal to *1*. This is just a matter of mere definition, or just one possible rigorous way of formally defining whether a time series of events is randomly distributed or not.

In contrast, suppose that some event has a "memory" of the previously occurred events – or equivalently that it has "memory" of the events that are to come in the future; in fact for our purposes either one possibility is the same. It shall be found that the fractal dimension must be $D_t < 1$. In the case of "total memory" - i.e. in the case that all events occur altogether at the same instant of time - it must be found $D_t = 0$. These are just matters of mathematical definition, in a strict sense.

Physically, we monitor a system and we collect a time series of *AE* events. We evaluate its D_t by means of a specific *AE* data series that spans some pre-chosen and given total time interval. The D_t will reveal whether during that given time lag the *AE* sources are activated more or less randomly. The greater is the randomness, the less "aged" is the material that releases the observed *AE*. The less randomness means that the *AE* sources are closer to their final cleavage micro-plane, hence the more "aged" is the material sample, and the closer it will be to its final "catastrophe". For instance, a steel bar, monitored in the laboratory (see below), was found to be close to final rupture when $D_t \sim 0.45$.

In reality, however, when referring to data measured while the "solid" structure is actually yielding, the computed D_t refers to *AE* emitters while they are fully yielding, i.e. the actual contribution of every "elementary" *AE* emitter in general is to be expected (in the aforementioned case history of a steel bar) to be $Dt << 0.45$.

An additional fundamental concept, which is important for understanding our observations, is the distinction between two different logical models, i.e. whether it is supposed *(i)* that the observation refers to *one* single *AE* source, or *(ii)* to a "*fog*" of some *huge number* of *AE* sources operating together, although not synchronously.

Another result of the data analysis (see section 3) is the so-called "*hammer effect*", which is expressed by an index *H*. When dealing with a single *AE* emitter, it is possible to recognize - on an instant basis - whether the system ($H=+1$) is releasing *AE* because it suffers by some action applied from its exterior, or rather ($H=-1$) it experiences a transitional evolution towards a new equilibrium state, after having suffered some external trigger.

Differently stated, we know that the *AE* signal is likened to a lognormal distribution (section 1.3), although this is an ideal situation. In contrast, in general the *AE* records will appear highly perturbed compared to this simple logical scheme. On the other hand, we can evaluate *H* objectively, on an instant basis. We can therefore state – and this can be shown by formal mathematics applied to its specific algorithm - that during the *rising* stage of the (instant) lognormal distribution it is $H=+1$, and during its *tail* stage it is $H=-1$.

Based on this argument, it can be claimed - when dealing with *one single AE* emitter - that whenever $H=+1$ the material is subject to some external action, and whenever $H=-1$ it is during its recovery stage.

In natural reality *one single AE* emitter is an ideal condition that can be only approximately simulated in the laboratory, while it is seldom observed in the field. A more realistic model is therefore to be considered in terms of some suitable *subdomain* of the physical system. Every subdomain is composed of a "*fog*" of some huge number of "elementary" *AE* emitters. Suppose that - during some given time interval of some finite duration - the flaws of a given size inside this subdomain collectively experience their decay, while they coalesce towards larger size flaws. During that given time interval, the measured *AE* will be the result of the sum of several "elementary" *AE* signals, all having some very small D_t , let us say $D_t \sim 0$. But, the number of these "elementary" *AE* emitters will decrease *vs.* time, according to a lognormal trend (see section 1.3). So, we call this entire mechanism a "*lognormal fog*" of "elementary" *AE* emitters.

That is, every aforementioned subdomain is responsible for an appearance - in the observed *AE* series – of a sequence that recalls some approximate lognormal distribution (in the D_t *vs.* *t* plot it will appear like a lognormal trend with a *reversed* ordinate axis). This feature depends on the decrease *vs.* time of the population of "elementary" *AE* emitters, rather than – as it occurred in the case of *one single AE* emitter – on the ageing of its material.

In general, at different times, different subdomains will experience a similar phenomenon. The final effect is that all their respective outputs will appear to overlap with one another, in some apparently erratic way, due to the huge number of unknown degrees of freedom of the system – hence due to some erratic number of overlapping different subdomains. Their trend can therefore be said to occur according to a *SOC* process.

Differently stated, everyone of the aforementioned "reversed" lognormal trends, associated with one given "*lognormal fog*" of "elementary" *AE* emitters, will more or less erratically overlap one with the other, almost like "*stress substorms*". They will compose the final general observed morphology of the "catastrophe" or "*storm*" that affects the system.

Therefore, in order to recognize a "*substorm*" of the system, it appears more effective to appeal to D_t. It is much better than to appeal to the raw *AE* signal, because D_t is a physically expressive parameter, which is independent of the arbitrariness of the amplitude of the original raw *AE* datum. Also the index *H* can be sometimes heuristically more effective.

Summarizing, by means of an analogy and by using the same terms used for the geomagnetic field and magnetosphere, or for the sand pile (see section 1.3), we can call "*stress storm*" an entire paroxysm observed in the raw *AE* record at a given and pre-chosen fixed frequency. Then, we can claim that every "*stress storm*" is the result of some apparently erratic and disordered superposition and overlapping of "*stress substorms*", all being associated with some suitable (though unknown) aforementioned physical subdomain.

In addition, let us recall that a geomagnetic storm can be recognized by means of geomagnetic data, unlike its “elementary” components i.e. the magnetospheric substorms, which are recognized by polar auroras. That is, the physical system and the observed phenomenon are always the same, although different morphological features can be more or less clear, detectable, and reliable for diagnosing its state and its evolution.

In a similar way, a “*stress storm*” is recognized by means of the raw *AE* records, while its component parts, i.e. the ”*stress substorms*”, can be better recognized by D_t.

From the physical viewpoint, the distinction between “*stress storm*” and ”*stress substorms*” also has a relation with the space domain of this process. In fact, a “*stress storm*” appears to be some large-scale occurrence, i.e. it involves the entire system of concern. In contrast, a ”*stress substorms*” involves some much more limited and specific structural fraction of the whole system. The same holds also for the Earth’s magnetosphere, where the scale size of the trigger of a “storm” is much different compared to the case of a “substorm”.

A final assessment is therefore that - when dealing with any kind of phenomenon either in Earth’s sciences, or about financial crises, or about a public service, or about psychology, etc. - different facets of one and the same set of logics can be considered. The logical facets are named “lognormality”, “fractality”, *SOC*, and “*storm*” and “*substorm*”. Every facet can be monitored and diagnosed by means of different observational information. But the ultimate logic is unique and all the same.

2. The data base

The records that were used by the authors over several years - mainly for field measurements but also for laboratory tests - rely on *LF AE* (typically *25-30 kHz*) and on *HF AE* (typically *150-200 kHz*). Different data acquisition procedures are used in specific applications, depending on the total duration of the experiment, and the required time resolution of records.

An acoustic transducer, tuned at a given pre-chosen frequency, is posed in close contact with the “solid” object to be monitored. When operating in the field, a hole (about *30-50 cm* deep) is drilled into a rocky outcrop. A glass bar is put inside the hole, which is then filled with concrete. The *AE* transducer is fixed on top of the glass bar (one bar for *HF* and one for *LF*). But, when operating on a manmade structure, in general there is no need for drilling the sample.

The outcrop is the terminal on the Earth’s surface of some generally much extended “natural probe” crossing underground through some unknown volume, eventually displaying rapid changes of *AE* transmission capability (or briefly let us vaguely state that the acoustic impedance of the “natural probe” suffers by step-wise time variations). In any case, our experimental setting in the field always resulted in an effective probe, because eventual cracks in the rocky body are filled with water, which is an excellent medium for *AE* propagation.[3]

A linear preamplifier is applied to the output of the transducer, before its transfer to a data logger, where amplification occurs before data storage. When operating in the field a *GSM* connection with a remote acquisition centre permits data analysis at any desired time.

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[3] On several occasions we observed (see Gregori et al., 2010) step-like changes of the *AE* signal that we called *MFE* (minor fracture events) and that we interpreted in this way.

The measured datum is transformed into a *rms* amplitude, and in general it is averaged over *3 msec*. When operating in the field, the data logger was set in order to store one average datum (of the *3 msec* signals) every *30 sec*. When operating in the laboratory, one datum is stored at a time rate of a pre-chosen and given Δt, the range of Δt being chosen, say, between *50 msec - 200 msec*. For more rapid events, such as when they are triggered by an explosion, the time resolution must be pushed at least to, say, $\Delta t \sim 1$ *msec*.

If the concern is about monitoring the Earth's tide spectrum, or the free oscillations of the Earth, $\Delta t = 30$ *sec* is certainly exceedingly long, as the typical tidal frequencies are defined with a precision higher than *30 sec*.

An important and generally unnoticed twofold warning deals with over-saturation and under-saturation of the recorded *AE* signal. In fact, owing to the unknown and arbitrary time changes of the acoustic impedance of the "natural probe" (see above), the amplifier in the data logger is arbitrarily set, in order to get some output signal to be recorded typically ranging, say, e.g. up to *~10 V*, with a sensitivity of the order of *~1 mV*.

Some equivalent intuitive criterion is also used in laboratory experiments. When carrying out e.g. a drill into a bar, the recorded signal eventually gets into over-saturation. The optimum amplification has to be attained by trial and error. In any case, the algorithms for data analysis resulted to be reasonably robust with respect to this drawback.

But in the field, if the amplification setting is carried out during "quiet" conditions, some important *AE* information during perturbed periods can be lost by over-saturation, and this must be avoided. On the other hand, if one sets a lower amplification in order to avoid over-saturation during strong perturbations, the opposite drawback has to be eventually faced, i.e. under-saturation. Indeed, according to the authors experience, under-saturation was often encountered in field records, although the algorithms used for data analysis were still robust even for very weak *AE* signals. The optimum instrumental setting, perhaps, ought to foresee a change of the amplification of the signal depending on the average *rms AE* signal of the preceding day.

There are different physical implications for *HF AE* as compared to *LF AE*.

According to the aforementioned physical rationale, *HF AE* reflect a much earlier "ageing" of the sample (Gregori et al., 2005; Paparo et al., 2006; Poscolieri et al., 2006b). This fact was confirmed by the expected effects associated with the so-called "*loading tide*". This effect was clearly observed in *HF AE*, while *LF AE* was more perturbed by local tectonic features, which are much more sensitive to a comparably later ageing stage of the Earth's crust.

The "*loading tide*" is the cause of the well known almost steady increase of the length of the day (*l.o.d.*). This effect is of tidal origin, but its main component does not derive from the Earth's tide. Rather, the lunar plus solar tide moves a large mass of *ocean* water that piles up on continental shelves. Hence, it pushes on continental masses, and this originates a torque that slows down the observed spin rate of the Earth. This mechanism implies violent stress propagation through the crust. Poscolieri et al. (2006a) and Gregori et al. (2007) report a seasonal variation of the crustal stress, detected by *AE* records in central Italy (Orchi) and at Cephalonia (Greece), which are synchronous at the two sites. The average background trend also appears to display large oscillations with a peak-to-peak time lag apparently compatible with the leading lunar tide modulation. A final confirmation of this interpretation could be checked by some *AE* station located somewhere in central Asia, by which the propagation speed of crustal stress could be monitored.

In contrast, as mentioned above, the *LF AE* appear to be comparatively more affected by the *regional* or *local* tectonic evolution, i.e. they are much better suited for diagnosing the evolution of the crust at some time closer to its final eventual "catastrophe", i.e. an earthquake. They give better and more reliable information about the specific actual state of the crust inside some limited lithospheric slab, rather than referring to some planetary scale feature.

All these aforementioned inferences resulted from repeated investigations carried out during over a decade in many different tectonic settings.

A special mention is deserved about a very remarkable confirmation of this regular modulation which is an updating of Gregori et al. (2010). Superconducting gravimetry (*SG*), and its complementary absolute gravimetry (*AG*), is a comparatively recent achievement that is beginning to give unprecedented evidence of some lesser effects related to several phenomena of different origin (de Linage et al., 2007; Crossley & Hinderer, 2008, 2009; Longuevergne, 2008; Wiese et al., 2009). They are exhibiting great modelling skills at correlating many different observational inputs, atmospheric, hydrological, tidal, etc. They also correlate their records with *InSAR* monitoring and with the records of the *GRACE* satellite (Crossley et al., 2005). They monitor all gravitational effects associated with transport of solid and fluid matter in the Earth system originated by any kind of driver. They find temporal trends (Zerbini et al., 2007; Wilmes et al., 2009; Rosat et al., 2009) that look very similar to the aforementioned *HF AE* seasonal modulation that Poscolieri et al. (2006a) envisaged as a loading tide effect.

Compared to *AE*, their observations are different. *SG* monitors a time change of gravity, while *AE* monitor a time change of the stress field. Stress is expected to be maximum when the *speed* of the gravity related deformation is maximum, rather than the *intensity* of the gravity field.

But several irregularities are observed both in the *SG* and *AE* series - e.g. unexplained background trends, changes of phase or of synchronism, *LF AE* appear heavily perturbed compared to *HF AE*, etc. These facts are clearly indicative of phenomena associated with tectonic setting and geodynamic actions.

SG and *AG* envisage sub-continental size phenomena (Crossley et al., 2005) that cannot be planetary-scale tidal phenomena, but rather they appear more likely related to crustal stress effects. By similar methods also coseismic effects were evidenced, by means of *GRACE* data, of the Sumatra-Andaman *Dec 26, 2004* earthquake (de Linage et al., 2009).

It appears therefore very important to be capable to recognize "storm" and "substorm" time phenomena in either *SG* and/or *AE* records, in order to achieve a more detailed morphological classification and assessment of events during their trigger and evolution.

A wide and important perspective of unprecedented ways of monitoring crustal phenomena is thus being envisaged. The key role ought to be stressed of the mutually complementary information provided by *SG, AG, InSAR, GRACE* and *AE*, aimed at monitoring different observational facets of one and the same system and phenomenon.

In addition, crustal stress propagation ought not to be expected to be isotropic, being rather more effectively controlled by serpentinization and serpentosphere (Judd & Hovland, 2007).

3. The data analysis

The details already appeared in several papers (Gregori & Paparo, 2004; Gregori et al., 2002, 2005, 2007, 2008; Paparo et al., 2001; 2002; 2006; Poscolieri et al., 2006a, 2006b) and, owing to brevity purposes, they are not repeated here. Only some highlights are presented. A standard software was progressively implemented and improved during past years. The present data handling can be synthesized by the acronym *OFTH*, and is explained as follows.

"*F*" denotes a weighted running average of the raw *AE* datum, over a given pre-chosen time lag. The weight is defined by a triangular system function, aimed at reducing the perturbation originated by the side lobes of a simple non-weighted running average. For field applications we used a time lag of *24 hours* in order to reject all effects associated with diurnal variation, including mostly the aforementioned thermoelastic effects (see section 1.2), and also some fraction of tidal effects, although not all of them.

"*T*" denotes loss of performance *vs.* time or "ageing", being quantitatively estimated by means of the aforementioned D_t. It is computed by the standard box counting method (refer to any book on fractal analysis).

"*H*" is the aforementioned parameter of the "*hammer effect*" (Gregori et al., 2007). It derives from a combined analysis of the raw database, of its "*F*" and of its residual, and their respective time derivatives. It is formally shown that, when the system is subject to some forcing originated from its exterior, an index *H* is computed being necessarily $H=+1$. In contrast, when the system is recovering towards a new equilibrium state after having been subject to some external perturbation, it must be $H=-1$.

The data series of the instant value *H* is somewhat scattered, although in reality the result appears much more stable than expected, thus denoting a robust physical significance. Some derived parameters are e.g. (in field *AE* records) the hourly means or the *24 hour*-means of the *H* instant values, or equivalently the percent number of $H=+1$ evaluated inside a given running time interval, or one can re-define a new index = ± 1 depending on whether the prevailing *H* inside a given running time lag is either *+1* or *-1*, etc. Analogous criteria can be applied to any other kind of application. In every case, the physics of the information of the instant *H* is always the same. The concern is rather about its graphical representation, and about smoothing the possible scatter of the *H* instant data series. That is, the optimum choice is arbitrary and it depends on the specific application of concern.

"*O*" denotes outliers. An outlier is a datum that does not fall into a Gaussian distribution defined by its nearby data. Consider a running time lag, and analyze the distribution of all *AE* records contained inside it. Finally reject the data that manifestly do not fit with a Gaussian distribution. This can be achieved by formally evaluating a suitable parameter. Refer to the aforementioned papers for details. The outliers are rejected twice: a first time by referring to the data series of the raw *AE* records; the next time by referring to the residual signal, after subtracting the "*F*" series from the original raw datum. The two "*O*" series being thus obtained generally differ only by a few percent. But it is worthwhile to repeat the

"*O*" evaluation as this is helpful for getting rid of the drawback from possible over-saturation of the signal. The subsequent data handling can be carried out separately *(i)* on the given data series, after being "cleaned" from its outliers, and *(ii)* also on the data series of the rejected outliers, as they have a different, though significant, physical meaning.

Outliers are not only simply concerned with isolated point-like perturbations. In fact, the algorithm is like a logical sieve that selects unusual objects, and it operates after having arbitrarily defined the size of the sieve holes. We expected that, when the size of the holes is sufficiently large, the number of outliers rapidly damps off. In contrast it was found that a conspicuous number of outliers always remains. The physical reason is that the measured *AE* is composed of asymmetric "elementary" events, every one reminding about the lognormal distribution (as in figure 1). In contrast, the aforementioned test for Gaussianicity is concerned with a *symmetric* distribution. Hence, the *asymmetric* tail will always give a large number of formal outliers.

At present, the outliers were mainly useful for analysing *AE* data collected on volcanoes, as every volcano unexpectedly seemed to be almost like a high precision stopwatch for monitoring Earth's tides (see section 4.1). More in general, a suitable standard software (in preparation) can transform every *AE* station into a station for monitoring both the spectrum of Earth's tides, and the free oscillations of the Earth.

Whenever we implement some given technological monitoring device, every different output of the *OFTH* set is to be evaluated and physically interpreted. The physical information is, however, entirely contained only inside the original raw *AE* data series of observations. Different logical tools are applied in order to provide evidence of different aspects of a given natural phenomenon. Then, after exploiting a suitable exhaustive physical interpretation, the optimum *OFTH* parameters – which are specifically best suited for that given application – are to be selected for routine operation, eventually in real time. In general, however, when dealing with different applications different optimal *OFTH* parameters are to be used.

For completeness sake, we later realized that, in his classical study carried out on micro-tremors records recorded on smoked paper, Imbò (1954) applied a similar rationale that can be, at least partly, generally likened to part of the aforementioned *OFTH* approach. An extensive historical account is in preparation.

4. Case histories

It is impossible to mention here all the different case histories that were investigated, including volcanic phenomena, and seismic events. They were important and effective tests for improving algorithm and software performance. Here we mention only a few studies that are more closely analogous to possible extrapolations toward technological applications.

Just for completeness sake, let us mention (see Gregori et al., 2010 for details) that – concerning field measurements carried out in Italy and on the Cephalonia Island (Greece) - the Italian peninsula is (as expected) tectonically very distinct compared to the Balkan peninsula. Refer to Table 1. During *1996-1997* a violent "*stress storm*" crossed the Italian peninsula, and two strong earthquakes occurred during this period. No information is available during *1998-2001*. But in *2002* the Molise earthquake occurred. Then from *2002* through the very end of *May 2008* the Italian peninsula experienced a period of great quietness. This period was later interrupted by a violent "storm" beginning at the end of *May 2008*, and by the end of *2009* it was still ongoing. During this period the L'Aquila earthquake occurred. A few related case histories are here recalled in the following.

Name	Date	Start time (GMT)	Lat. (N) of epicentre	Long. (E) of epicentre	Magni-tude	Depth (km)
Potenza	3 Apr 1996	13: 04: 35	40.67°	15.42°	4.9	8
Colfiorito, Italy (only shocks with M ≥ 5.0)	*26 Sep 1997*	*00: 33: 12.89*	*43.022°*	*12.891°*	*5.7*	*3.5*
	26 Sep 1997	*09: 40: 26.73*	*43.014°*	*12.853°*	*6.01*	*9.9*
	03 Oct 1997	*08: 55: 22.02*	*43.042°*	*12.824°*	*5.25*	*12.05*
	06 Oct 1997	*23: 24: 53.23*	*43.027°*	*12.846°*	*5.46*	*3.91*
	12 Oct 1997	*11: 08: 36.87*	*42.906°*	*12.920°*	*5.22*	*0.05*
	14 Oct 1997	*15: 23: 10.61*	*43.898°*	*12.898°*	*5.65*	*7.3*
Molise	*31 Oct 2002*	*10: 32: 58*	*41.695°*	*14.925°*	*5.8*	*10.0*
Lefkas	*14 Aug 2003*	*05: 14: 03*	*38.81°*	*20.56°*	*6.3*	*10.0*
L'Aquila	06 Apr 2009	01: 32: 39	42.334°	13.334°	6.3	8.8
Albania	06 Sep 2009	21: 49: 42	41.49°	20.43°	5.5	3.0

Table 1. Data from six different seismic events cited in the text **(**values in Italic taken from the catalogue **cpt08_1991-2006)**

4.1 Model with one *AE* source alone – the "Potenza effect"

Consider the observational case histories that can be interpreted according to the logical model (see section 1.3) of *one single source* alone.

Consider just one steel bar (Zanini, 2004; Biancolini et al., 2006). Bend it, say, *10,000 times*. Then, bend it once more while monitoring its *AE* (at one and always the same given frequency) and evaluate its D_t . Bend it anew, say, *10,000 times*, and repeat the same procedure, etc. Finally plot D_t *vs.* the number of times the bar was bent. The gentle decrease of D_t reveals the "ageing" of the steel that composes that bar. When D_t *~0 .45* the bar is found to be close to final rupture. Figures 4 and 5 refer to two groups of measurements. "*The first test was performed applying a load of* 48 N, *corresponding to a bending moment equal to* Mf=3.35 Nm, *obtaining nominal stress* σnom = 370 MPa *and maximum stress* σmax = 521 MPa. *The specimen fatigue life was estimated approximately to* 700000 cycles. *The second test was performed applying a load of* 63 N, *corresponding to a bending moment* Mf = 4.4 Nm, *estimating nominal stress to* σnom = 498 MPa, *maximum stress* σmax = 700 MPa *and the fatigue life to* 200000 cycles."

A curious effect is to be pointed out. After a while, the steel temporarily recovers (instead of steadily losing) its performance. This is the consequence of a transient re-adjustment of the micro-crystals of its alloy, in such a way that for a while they ameliorate the steel performance, soon before, however, experiencing the final evolution towards the final "catastrophe".

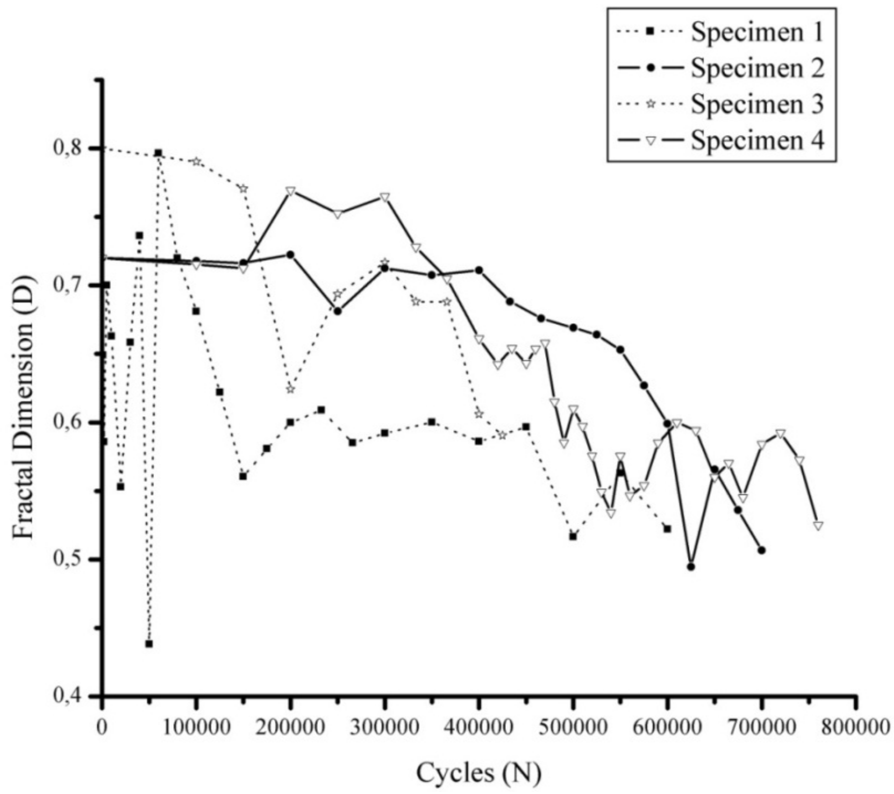

Fig. 4. Fractal dimension – Fatigue cycles (group 1). See text. After Biancolini et al. (2006)

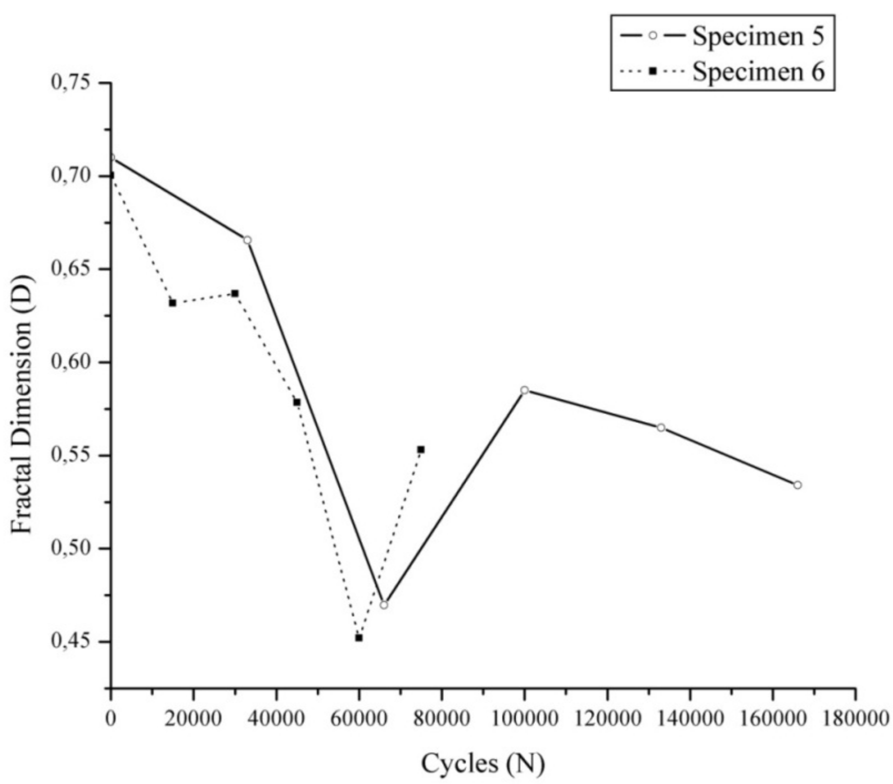

Fig. 5. Fractal dimension – Fatigue cycles (group 2). See text. After Biancolini et al. (2006)

In addition, *AE* were recorded on a steel blade of the *VIRGO* super-attenuator, while the blade was forced to its standard operative charge. The blade is casted by some special alloy etc. It was found (Braccini et al., 2002) that it is possible to assess, by means of *AE*, how many times the blade was bent after its casting.

A very intriguing case history, which seems to fit well with a *one single source* model, was measured in *1996* at the station of Giuliano (close to Potenza). See figure 6. During several weeks before the shock (*M=4.5*, with epicentre located at *~29.7 km* from the *AE* station; see Table 1) it was found that D_t decreased from $D_t \sim 1$ down to $D_t \sim 0.45$, when the shock occurred. Hence, this can be called "*Potenza effect*".

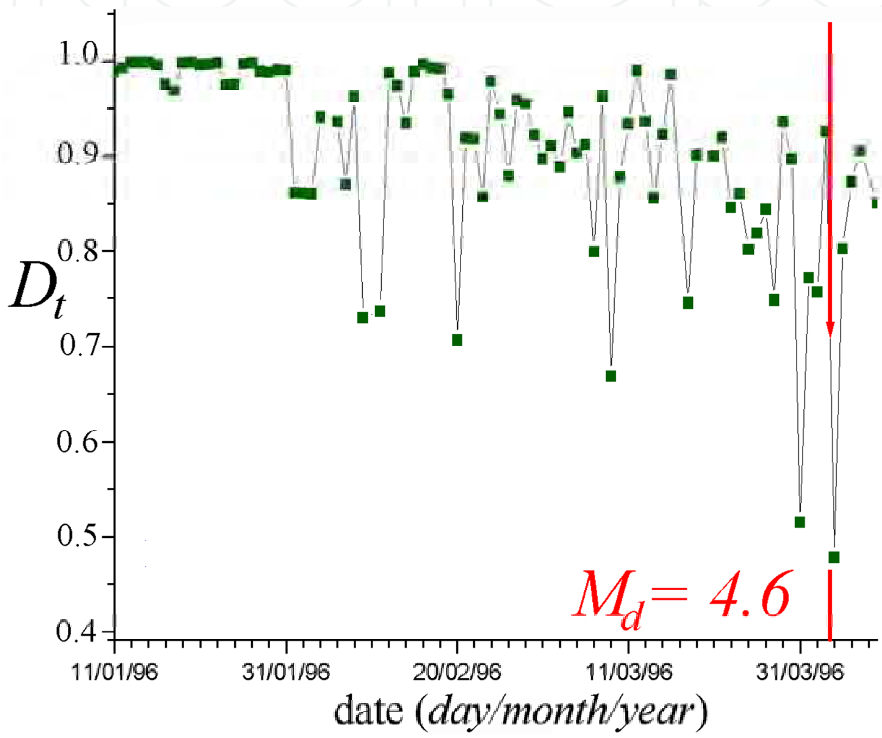

Fig. 6. Fractal dimension D_t of *LF AE* records carried out at *~29.7 km* from epicentre of the Potenza earthquake. See text. Redrawn after Paparo et al. (2006)

We observed another similar case history in *2009* in the Cephalonia (Greece) records on the occasion of the Albania earthquake (see Table 1, and figure 7).

The guessed physical interpretation is that the strain that precedes an earthquake is observed only in a limited region around the epicentre - unlike the much wider set of phenomena associated with a "*stress storm*", which is *not* necessarily associated with a *local* final fracture of a fault. Hence, if the *AE* station is located inside this limited region of the crust, it monitors what precedes the final shock. The size of this limited region is, however, different in different areas, depending on the specific respective tectonic setting. In fact, while referring to the two aforementioned case histories, the distance between *AE* station and epicentre was *29.7 km* at Potenza, and *369 km* for the *2009* Albania event.

The model in terms of *one single source* alone is likely to be observed in every technological application, whenever the concern is about one single structural element alone. In contrast, sometimes the system is composed of several potential *AE* emitters that overlap one with

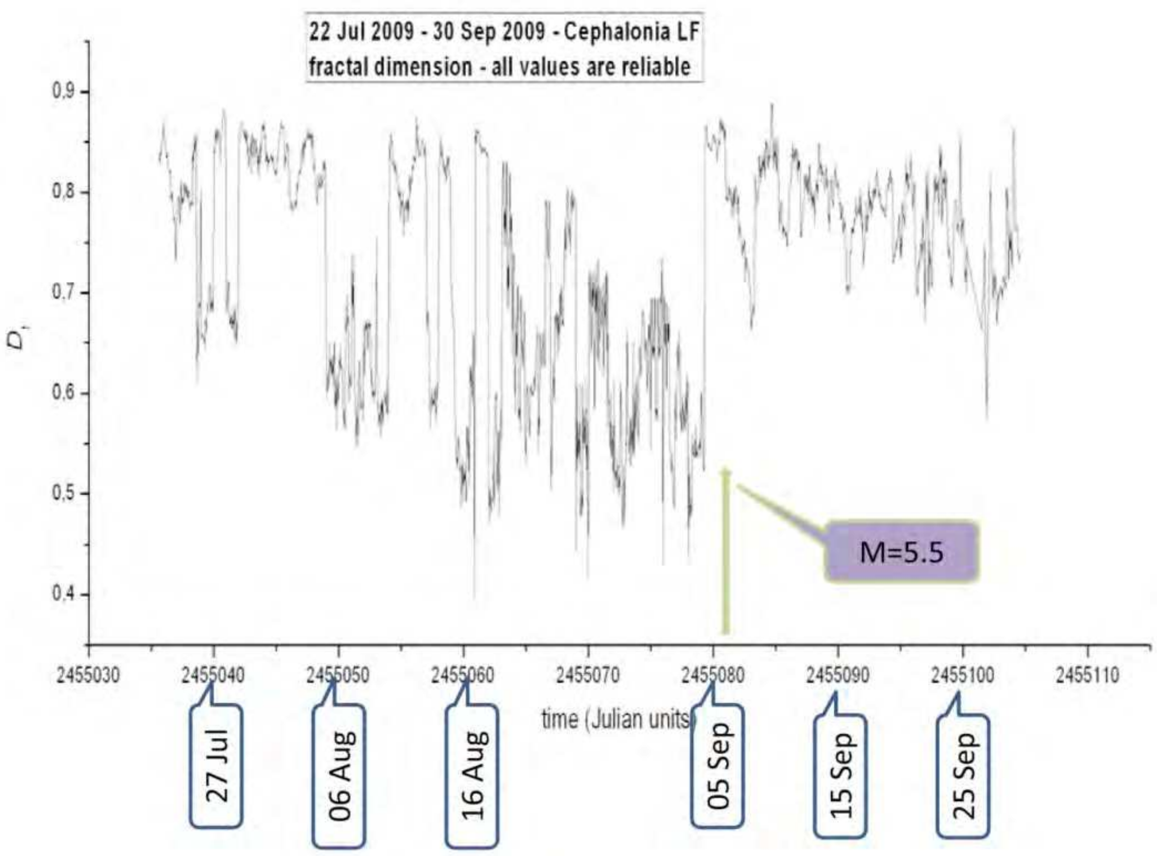

Fig. 7. "*Potenza effect*" observed at Cephalonia (Greece) preceding the Albania earthquake (see Table 1)

the other. For instance, a bridge is composed of a finite set of structural elements, which are all potential *AE* emitters. A bridge is therefore an intermediate situation. The extreme case history - opposite to the single source alone – is found when a "*fog*" of *AE* emitters has to be considered. This is the case history that is found as the standard for Earth's crust, and in some laboratory experiments. This is the concern of the next section.

4.2 A "fog" of *AE* sources

One case history of this kind appears to be a precursor of the L'Aquila earthquake. In this respect, it should be strongly emphasized that *AE* provides no earthquake "*prediction*". Rather *AE* is a *diagnostic* tool, much like in medical sciences one or several different tools can diagnose the health of a patient, although they cannot forecast the time of her/his passing away. In addition, it should be stressed that phenomena are not repetitive. Every earthquake is a different case, either because it occurs in a different tectonic setting, or because – even when it occurs in the same area - the general environmental conditions have evolved: the direction of the arrow of time is always the same, and everything is permanently ageing (recalling a famous adage by Heraclitus).

This case history is significant for envisaging some possible applications to technological or security problems, whenever we need to monitor the timing evolution of performance loss of a system.

Figure 8 shows D_t evaluated *vs.* time both for *HF AE* and *LF AE*, monitored by the *AE* station of Valsinni (province of Matera, Basilicata, southern Italy, located at *354 km* from the epicentre of the L'Aquila earthquake). The large ellipse in figure 8, denoted as *HF*, shows the reversed lognormal distribution associated with the "*lognormal fog*" of the flaws that released the *HF AE*. At some later time, the analogous "*lognormal fog*" associated with the *LF AE* is also shown by another large ellipse in figure 8.

If *AE* records had been available at some additional frequencies (e.g., say, at *20, 15, 10, 5, 2.5, 1 kHz*, ...) analogous evidence for every available frequency should be expected to be found corresponding to a time series of "*lognormal fogs*".

In any case, the temporal evolution of the system was such that, in the case history of the L'Aquila earthquake, the typical frequency for an earthquake - i.e. *~ 0.5-1 Hz* - was attained approximately close to the completion of the *LF AE* "*lognormal fogs*" (at *25 kHz*).

In general, however, it must be stressed that this is not a condition that is expected to be repeated on the occasion of *every* other earthquake. Other case histories can have different speeds of evolution. Consider that this is a precursor phenomenon that lasts several weeks (or maybe even longer). If the (unknown) physical system remains in an approximately steady and "quiet" state during a sufficiently long time interval, the full temporal "evolution" can complete its transformation - which precedes the earthquake and determines the precursor morphology. In this way the final earthquake will occur after the full exhibition of the precursor. But if this approximately steady and "quiet" state is perturbed by some newly occurred changes of its boundary conditions, the temporal "evolution" of its transformation will be abruptly interrupted. In this case, some earlier fraction of the entire precursor will be observed, but no earthquake will occur. That is, one can claim that, in general, some much irregular overlapping of "*crustal substorms*" can sometimes cancel the simple regularity shown in figure 8. In a laboratory experiment, however, the operative conditions are much better - and more regular and controlled - compared to field *AE* records.

An earthquake is a *local* event: the focal volume is just a small amount of cubic kilometres. But it occurs only due to a *local* yield, following some *large scale* phenomenon, to be identified with a "*stress storm*" involving some *much larger* slab of lithosphere and crust. A "*storm*", however, is composed of "*substorms*", which are phenomena spanning – compared to a "*storm*" - a much shorter total time lag, and they involve some limited fraction of the aforementioned large slab. In addition, compared to the very strong although much general evidence provided by a "*storm*", the possibility to recognize a time series of "*substorms*" detected by progressively decreasing *AE* frequencies sometimes permits to guess the expected time of a forthcoming earthquake.

It should be pointed out that this *AE diagnostic* tool is unsuited for envisaging the *location* of the epicentre, which should rather be inferred upon considering e.g. the elastic energy *locally* stored at different sites (this is a classical topic, the object of a wide range of literature and not here of concern).

Similarly, the magnitude of a forthcoming earthquake cannot be estimated by *AE* records. The intensity of the *AE* recorded signal depends both on intensity of the source, and on the unknown characteristics of the "natural probe" (see section 2). The physically significant information given by the *OFTH* algorithms is rather concerned with the *timing* of the *AE* signals, not with its intensity.

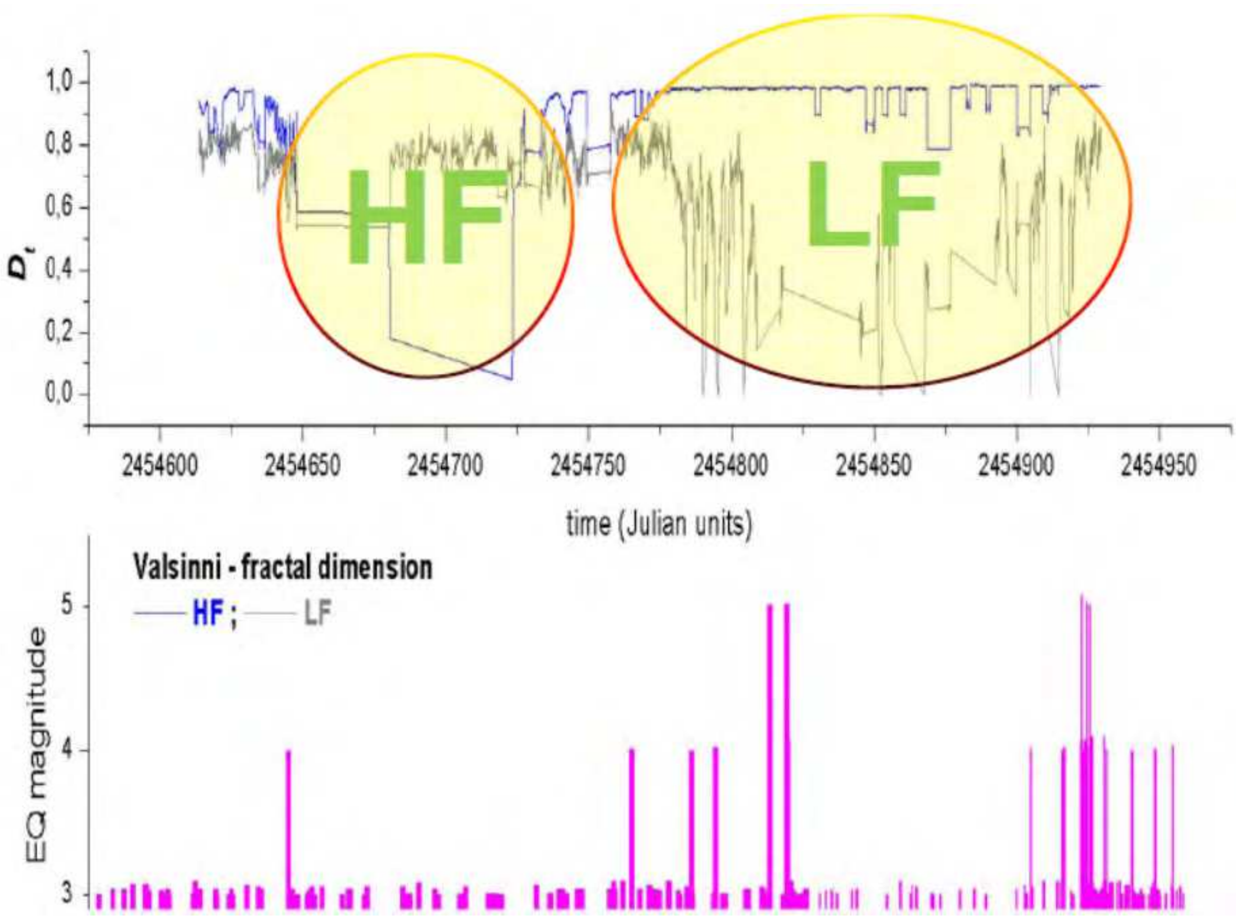

Fig. 8. Fractal dimension D_t of both *HF AE* and *LF AE* records carried out at Valsinni, at *354 km* from the epicentre of the L'Aquila earthquake. The "*stress substorm*" at either *HF AE* or *LF AE* is denoted by a large ellipse. The L'Aquila earthquake occurred at the completion of the *LF AE* "*substorm*", although in general different earthquakes can have a different speed of evolution in time. See text.

Consider e.g. the aforementioned experiment carried out on a steel bar (see section 4.1; Biancolini *et al*., 2006), where the bar was, say, *~20 cm* long. But one can imagine repeating the identical experiment either with a tiny steel needle, or with a huge steel girder of a bridge. The trend of the fractal dimension D_t is the same, independent of the size of the object. But the amount of elastic potential energy is much different, which is stored inside the object and is eventually released when the catastrophe occurs.

Differently stated, an earthquake ought to occur every time the same precursor phenomenon is observed, including its complete temporal evolution. But if the earthquake magnitude is small, no information is given by seismologist or mass media. So it appears to be an unsuccessful precursor, although the precursor was correct. But nobody knows the physical extension of the physical system that is yielding, which is the source of the observed *AE* signal.

This basic drawback has distinct implications, for earthquakes, volcanoes, landslides, or technological applications.

In the case of earthquakes, it is essential to use an array of *AE* recording stations, in order to determine the spatial extension of the *AE* sources and the general tectonic setting of the area.[4] A planetary *AE* array is necessary for understanding crustal stress, much like a meteorological array is needed for synoptic meteorology.

Global meteorological charts are provided, and the different national meteorological services use them for issuing a forecast for their respective region of interest. Flight assistance uses the global maps for security purposes. But, if one wants to issue an exact forecast for specific purposes (sports issues or others), in general this can result practically impossible. Much in the same way, a real time chart of the global pattern and evolution of crustal stress can be used by national services for issuing more or less accurate seismic forecast for the regions of respective concern.

In general, earthquake precursors can be distinguished by separating concerns about *(i)* magnitude, *(ii)* site, and *(iii)* time. *AE* are suited for the time concern.

Earthquake prediction is impossible in a strictly deterministic sense. However, it has to be correctly taken into account like a probabilistic estimate according to the same criterion used for insurance.

In addition, owing to economic, humanitarian, and catastrophe management implications, it is a deontological obligation to recognize that - much like it is certainly possible to assess whether a person is a child or an old man - it is *certainly* possible to get a reliable monitoring and diagnosis of the state of the Earth crust, by operating *AE* arrays combined with other information.

Compared to earthquakes, volcanoes are a much simpler problem in two respects. The site is known. In addition, the primary cause is the long-lasting increase of the pressure of endogenous hot fluids, and this is associated with well recognisable *AE* effects. Volcanic forecasting is therefore realistically and reliably feasible.

In the case of a landslide, in general, monitoring can be very effectively carried out. But the prediction reliability depends on how detailed is the knowledge of the geological structure of the hazard area, and on the number of available *AE* recording points. An advantage is the much slower process that precedes the occurrence of a catastrophe.

In the case of technological applications, predictability is much easier, because the composition, the size, and the structure of the system, and the timing of the primary drivers are well known.

Concerning technological applications, suppose e.g. to monitor a bridge, or some old building, or a rail embankment, or an unstable slope of a slow land slide, etc. The "catastrophe" of the system will happen during a "*stress storm*". But, for practical purposes in order to monitor the timing and evolution of the structure towards its "catastrophe" - it is useful to detect the occurrence of "*stress substorms*". For instance, when a bridge is in

[4] The maximum magnitude of an earthquake that can hit a given area can be inferred by a fractal analysis applied to the 2D fault distribution on the Earth's surface (by a method first exploited by the late Giuseppe Cello). The greater the crustal fracturing, the less the maximum magnitude is of an occurring shock. Refer to mentions and references in Gregori *et al.* (2010). This analysis, however, requires the availability of long secular historical seismic data series.

yielding hazard, a "*stress substorm*" could be triggered just due to the diurnal thermoelastic deformation (section 1.2), or when some heavy truck or a train is crossing over it. The comparative morphology of the "*stress substorm*" is likely to be much different depending on the ageing of the system. The same rationale can be applied to other systems, e.g. to the response of a building located on the slope of a hill that is sliding down, or of a rail embankment that is yielding at some site, etc. That is, the "*storm*" and "*substorm*" rationale is a logical abstraction that applies to different case histories, and it helps with interpretation of the observations. But the real phenomena depend on the specific physical nature of the system.

But an occurrence is often characterized by a "*lognormal fog*" of *AE* emitters, which is very different compared to the aforementioned aspect. In the aforementioned physical case history the system is a "*fog*" of *AE* emitters that coalesce and evolve towards flaws of larger size, which emit lower frequency *AE*. That is, the system is in a state of *passive evolution* towards a new equilibrium state.

In contrast, a much different physical phenomenon occurs in the opposite case history, when the system is subject to an *increasing* action by some external trigger.

Let us consider the case history of a volcano. A much different logic is applied. In fact, volcanism is strongly affected by the exhalation - under pressure - of endogenous hot fluid, and this pressure can either increase or decrease.

When the endogenous heat supply increases, the pressure from hot fluids also increases, and a large number of flaws will yield within the volcanic edifice. The hot fluids diffuse in 3D, implying a corresponding 3D disordered distribution of "elementary" *AE* emitters. Hence, it shall be found $D_t \sim 1$. It can be said that the volcano is "inflating". A large number of *instrumental* seismic events will then be detected.

When the opposite effect occurs, the volcanic edifice collapses under its weight, while it is no longer sustained by the pressure, which is decreased. Hence, the *AE* will be released along micro-cleavage planes of the structures that collapse under the weight of the volcanic edifice. A micro-cleavage planes is *per se* derived from a 2D micro-process, and $D_t < 1$. It can be said that the volcano is "deflating". A comparatively much smaller number of seismic events will be observed, although with comparatively larger intensity, which is due to the rupture of 2D cleavage planes.

"Inflation" and "deflation", and their seismic association, were observed by *AE* on Vesuvius (Paparo et al., 2004, 2004a). The same concept was however already mentioned in the classical paper by Sassa (1936).

Every volcano is a much different "animal" in the "zoo" of all volcanoes of the world. The volcano Peteroa (on the Andes, at the border between Argentina and Chile) - owing to its comparatively much greater weight associated with a much thicker lithosphere or crust - is such that its edifice operates much like the weight of a security valve of a pressure cooker. The result is that it operates like a high precision watch for monitoring several spectral lines of the Earth's tide (Ruzzante et al., 2005, 2008).

Stromboli appears very intriguing, when we extrapolate its observational evidence and use it for technological applications. The progressive evolution of its system was nicely monitored by *AE* records (figure 9) until its final unusual and violent paroxysm occurred at the end of *December 2002* (Paparo & Gregori, 2001; Paparo et al., 2004; Gregori & Paparo, 2006).

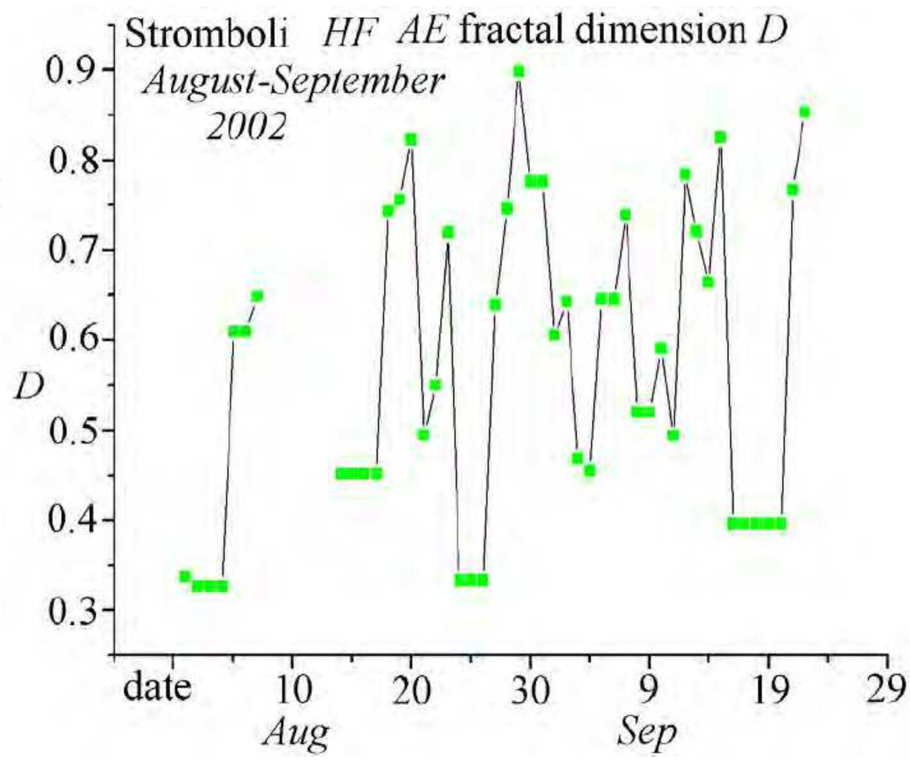

Fig. 9. Fractal dimension D_t computed on the point-like process that results after subtracting the ± *12 hours* running-average from the unsmoothed raw data set (i.e. every raw datum is an average over *15 min*). The point-like process is defined by choosing only "YES" events that result above some given threshold. Every D_t value was computed for one day. Whenever the number of "YES" events available for one given day resulted insufficient, several subsequent days were considered altogether, and they are here plotted like several days with the same D_t . The significant circumstance ought to be pointed out by which, when the volcanic edifice is "deflating" and D_t results comparatively low (see text), the *AE* events in the point-like process seldom occur, due to a temporary reduction, or lack, of any primary energy breeding to the volcano. The measurements were unfortunately interrupted when a lightning discharge stroke the recording system late in September. Figure after Paparo et al. (2004) and Gregori & Paparo (2006).

Its heat supply violently increased during several months. The number of newly generated flaws - within a 3D space distribution – continuously increased. The system had intrinsic oscillations, the primary cause of which is still unclear, being possibly an effect associated with varying meteorological pressure, or just some intrinsic variations related to its energy balance (much like for a pressure cooker, etc.). But, apart from this intrinsic oscillation, the maximum D_t progressively increased towards $D_t \sim 1$. When it reached its maximum threshold, i.e. $D_t = 1$, the "catastrophe" occurred.

In any case, whatever the origin of this intrinsic oscillation is, the system responds differently in time to the trigger created by the increasing primary cause. Therefore, every oscillation can be likened to a "*substorm*", which characterizes the evolution of the system towards its final "catastrophe". It should be pointed out that we are unaware of any alternative diagnostic tools capable of monitoring the precursor stage and evolution of Stromboli towards it paroxysm. Only some gas exhalation within wells could be correlated with *AE* records, although *AE* data are much more reliable, having a comparatively much better signal-to-noise ratio (see references given above).

A much similar result was observed by stressing concrete cubes, *15 cm* size (figure 10; Guarniere, 2003) until their final collapse. In this experiment, a "*substorm*" is defined by every addition of a constant weight on top of the concrete cube. As this externally applied trigger increases, the system responds differently depending on its ageing.

In either the case for Stromboli or for a concrete cube, the final collapse, i.e. the "*storm*", is composed of "*substorms*". In the concrete experiment, we know that every "*substorm*" is the obvious consequence of the newly added weight. But when referring to any kind of physical

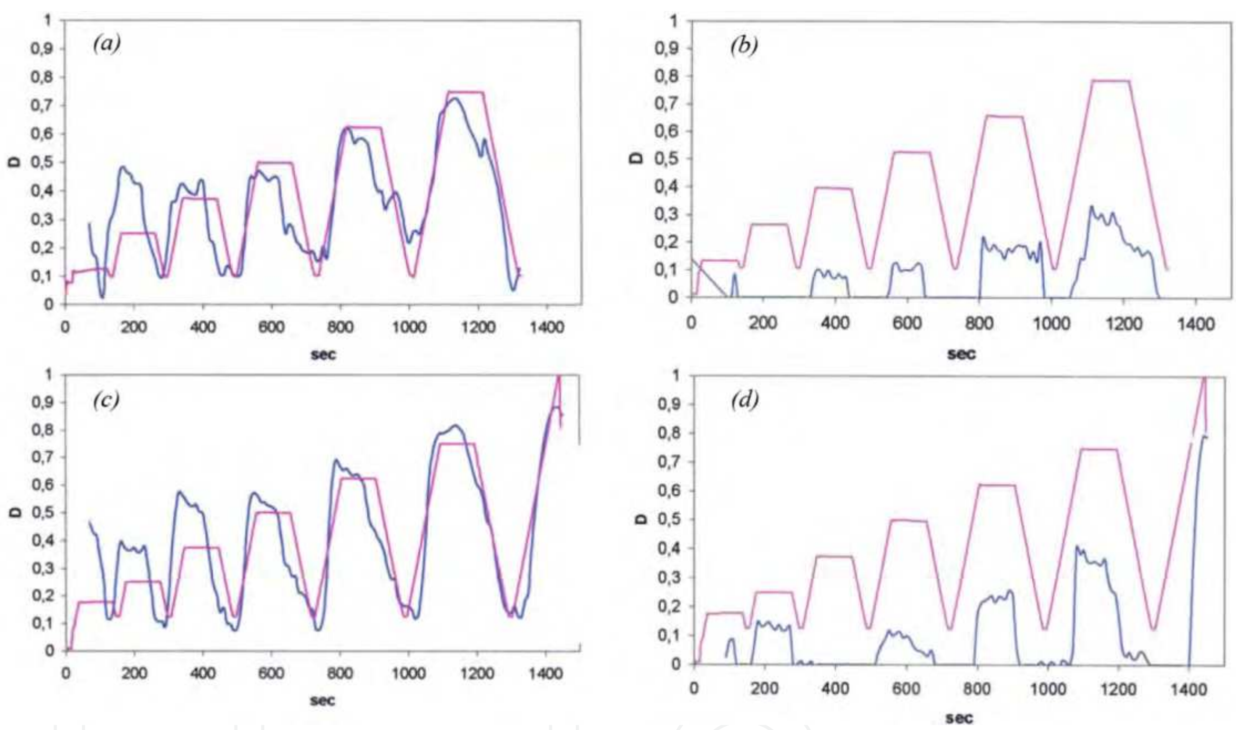

Fig. 10. a,b,c,d. Average fractal dimension D_t measured on two sets, of *10* elements each, of concrete specimens (cubes of *15 cm* side). All specimens are identical, made of identical concrete. Every specimen was stressed by adding progressive loads *50 kg* each, with unconfined uni-axial compression. The line with straight segments (in red) shows the applied load, normalized to rupture loading. The wavy line (in blue) is the average of the *10* computed D_t. The top row refers to the set of specimens that were not brought to final collapse, the bottom row refers to another set of specimens that were stressed until their final rupture. The left column refers to *HF AE* (*200 kHz*) and the right column refers to *LF AE* (*25 kHz*). The *HF* information refers to a much more preliminary stage of the fatigue process, as it deals with the rupture of much smaller crystal bonds, while the *LF* information deals with the yield of comparatively much larger flaws, i.e. when the specimen already suffered by some previous severe fatigue. The *HF* plot appears better representative of the starting process of deterioration of the solid structure of the specimen. After Guarniere (2003) and Gregori & Paparo (2006). The similarities appear impressive between figures 9 and 10. See text.

system that is being stressed by any kind of externally applied trigger, we lack the specific information about the primary cause of this applied trigger. Thus, the D_t trend is an effective diagnostic tool for assessing two bits of information: *(i)* when the system is suffering by a "*substorm*", and *(ii)* how the morphology of a "*substorm*" changes depending on the ageing of the structural elements of the system.

Summarizing, when we deal with a physical system that can be modelled by a "*fog*" of "elementary" *AE* emitters (better than in terms of *one single AE* emitter alone), we have to distinguish two different and competing case histories: *(i)* either the system responds to an internal evolution of its "*lognormal fog*"; or *(ii)* the system responds to the increase of an applied external trigger. In this case, the assessment and separation of its different "*substorms*" derives from some physical cause that determines some kind of more or less regular apparent "oscillation" of the system.

In either case, *AE* monitoring - and its *OFTH* parameters - are effective tools for monitoring the timing and evolution of the loss of performance of the system.

For the sake of completeness - and as a response to a comment by a referee, whom we thank - a mention is to be given to a closely related study in progress since over a decade (by one of the authors, Giovanni P. Gregori (GPG)). "Climate" is the environment where the biosphere can develop and survive. It is a condenser with an upper plate (ionosphere and magnetosphere) supplied by an electric current generator (the solar wind). The lower plate is much irregular, with spikes underground, and it is supplied by an electric power generator (the Earth's geodynamo; Gregori, 2002). All "climate" phenomena can be interpreted by this model. This includes long-range relations between observations of several different phenomena, such as endogenous heat generation and release, volcanism, orogenesis, geodynamics and seismicity, serpentinization, geomagnetism, astronomical motion of the Earth, transient luminous events, atmospheric electrical phenomena including lightning discharge activity, precipitation phenomena, carbon cycle, water cycle and balance, trigger of hurricane formation, and the fundamental role of the interaction within the biosphere, either supplied by solar energy or by endogenous energy, etc.[5]

A worldwide array of *AE* recording stations could be of paramount importance for monitoring stress propagation and teleconnection on the planetary scale providing one additional presently lacking key element of knowledge in the chain of cause-and-effect, within the whole aforementioned multidisciplinary scenario.

5. Conclusion

A comparison is heuristically useful between *AE* records measured in the field and *AE* records measured in the laboratory or in some technological application. Since most often

[5] This study also relies on a sum of several partial, much helpful, private inputs by outstanding scientists. GPG feels deeply indebted to them. In particular, a few of the most relevant inputs in alphabetical order are: Dong R. Choi, Ugo Coppa, Dong Wen-Jie, Gao Xiao-Qing, Raymond Hide, Martin Hovland, Alberto Incoronato, Tamara V. Kuznetsova, Louis J. Lanzerotti, Bruce A. Leybourne, Iginio Marson, Helmut Moritz, Nils-Axel Mörner, Cliff D. Ollier, Eugene N. Parker, Michel Parrot, John M. Quinn, Karsten M. Storevedt, Fumio Tsunoda, and Carlo Forese Wezel, ….. and the late Baron Paul Melchior, and Wilfried Schröder. But this list should be much longer.

case histories found in the field can rarely be reproduced in the laboratory, this comparison is an effective and concrete way of looking at different physical aspects of a difficult and multi-faceted problem.

The ultimate target is recognizing "*stress substorms*" or "*strain substorms*", or briefly "*substorms*" which are the same, since their timing is a more precise tool for monitoring the temporal evolution of the system compared to a general assessment of a vague occurrence of a "catastrophe" observed at the end of some "*storm*".

In the final analysis, when dealing with different case histories, the physics is always the same – i.e. all phenomena depend on the yield of atomic bonds inside "solid" structures. But the physical systems can be much different, as well as their respective primary *AE* drivers. The *OFTH* analysis appears very effective for applying some logical tools aimed at focusing on different morphological features of the observations.

When referring to some given physical system, however, different physical aspects can be more or less relevant depending on the specific type of information that is most useful for any given application.

In addition, it is possible to recognize "*stress substorms*" manifested at every given *AE* frequencies. Different *AE* frequencies permit the recognition of a time sequence of "*substorms*", hence a much better definition of the timing and evolution of the performance loss of the system.

A remarkable similarity with the *AE* records with several other lines of evidence should be pointed out for Earth's science applications. It is documented by time series records from superconducting gravimeters (*SG*) combined with absolute gravimeters (*AG*), and also correlated with *DInSAR* and *GRACE* records that with skilful analysis and data handling they are useful for modelling and subtracting several tidal and environmental phenomena. There is evidence that some relevant residuals appear likely related to tectonic and geodynamic actions.

A synergy of all these monitoring techniques - and the assessment of "*storm*" and "*substorm*" time – can clarify several morphological features of crustal phenomena and their time-space evolution.

This relevant potential achievement applies, however, to environmental investigations. Concerning engineering topics, *SG* appears to be of no practical help. In contrast, however, other monitoring techniques can be used in engineering structures that cannot be applied in the field. It should be emphasized that a multi-parametric monitoring of the same physical system can lead to an understanding of phenomena in a way that every technique alone could never attain.

Some harder thinking, additional criteria, and continued software development will certainly allow better evidence for some additional physical aspects of the *AE* records, and allow a better understanding of the specific physical drivers which will narrow the focus on observational aspects that are best suited for monitoring the hazard of concern in every given application.

6. Acknowledgements

We feel particularly grateful and indebted with Iginio Marson and with Martin Hovland, for calling our attention, respectively, on the important and much recent SG results, and on the crucial role of serpentinization in crustal stress propagation.

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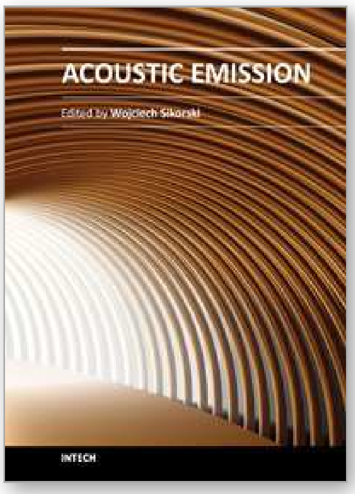

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Acoustic emission (AE) is one of the most important non-destructive testing (NDT) methods for materials, constructions and machines. Acoustic emission is defined as the transient elastic energy that is spontaneously released when materials undergo deformation, fracture, or both. This interdisciplinary book consists of 17 chapters, which widely discuss the most important applications of AE method as machinery and civil structures condition assessment, fatigue and fracture materials research, detection of material defects and deformations, diagnostics of cutting tools and machine cutting process, monitoring of stress and ageing in materials, research, chemical reactions and phase transitions research, and earthquake prediction.