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"Storms of crustal stress" and AE earthquake precursors

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Abstract. Acoustic emission (AE) displays violent paroxysms preceding strong earthquakes, observed within some large area (several hundred kilometres wide) around the epicentre. We call them "*storms of crustal stress*" or, briefly "*crustal storms*". A few case histories are discussed, all dealing with the Italian peninsula, and with the different behaviour shown by the AE records in the Cephalonia island (Greece), which is characterized by a different tectonic setting.

AE is an effective tool for diagnosing the state of some wide slab of the Earth's crust, and for monitoring its evolution, by means of AE of different frequencies. The same effect ought to be detected being time-delayed, when referring to progressively lower frequencies. This results to be an effective check for validating the physical interpretation.

Unlike a seismic event, which involves a much limited focal volume and therefore affects a restricted area on the Earth's surface, a "*crustal storm*" typically involves some large slab of lithosphere and crust. In general, it cannot be easily reckoned to any specific seismic event. An earthquake responds to strictly local rheological features of the crust, which are eventually activated, and become crucial, on the occasion of a "*crustal storm*". A "*crustal storm*" lasts typically few years, eventually involving several destructive earthquakes that hit at different times, at different sites, within that given lithospheric slab.

Concerning the case histories that are here discussed, the lithospheric slab is identified with the Italian peninsula. During 1996–1997 a "*crustal storm*" was on, maybe elapsing until 2002 (we lack information for the period 1998–2001). Then, a quiet period occurred from 2002 until 26 May 2008, when a new "*crustal storm*" started, and by the end of 2009 it is still on. During the 1996–1997 "*storm*" two strong earthquakes occurred (Potenza and Colfiorito) – and (maybe) in 2002 also the Molise earthquake can be reckoned to this "*storm*". During the "*storm*", started in 2008, the l'Aquila earthquake occurred.

Additional logical analysis envisages the possibility of distinguishing some kind of "elementary" constituents of a "*crustal storm*", which can be briefly called "*crustal substorms*". The concept of "*storm*" and "*substorm*" is a common logical aspect, which is shared by several phenomena, depending on their common intrinsic and primary logical properties that can be called *lognormality* and *fractality*. Compared to a "*crustal storm*", a "*crustal substorm*" is likely to be reckoned to some specific seismic event. Owing to brevity purposes, however, the discussion of "*substorms*" is given elsewhere.

AE is an effective tool for monitoring these phenomena, and other processes that are ongoing within the crust. Eventually they result to be precursors of some more or less violent earthquake. It should be stressed, however, that the target of AE monitoring is *diagnosing* the Earth's crust. In contrast, earthquake *prediction* implies a much different perspective, which makes sense only by means of more detailed multiparametric monitoring. An AE array can provide real physical information only about the processes that are objectively ongoing inside different and contiguous large slabs of the crust. The purpose is to monitor the stress propagation that crosses different regions, in order to envisage where and when it can eventually trigger a catastrophe of the system. The conclusion is that continental – or planetary – scale arrays of AE monitoring stations, which record a few different AE frequencies, appear to be the likely first step for diagnosing the evolution of local structures preceding an earthquake. On the other hand, as it is well known, the magnitude of the shock is to be related to the elastic energy stored in the focal volume, rather than to the trigger that starts it.

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1 The physics of the process

A correct understanding of crustal phenomena – by avoiding a frequent misunderstanding and/or misconception – strictly requires a preliminary assessment of the logical frame. Simplifying assumptions often become "generally agreed" beliefs, and finally paradigms. During the last several years the authors assessed that the following premises resulted essential for clarifying this bias, and the meaning and content of the results that are discussed in the present paper.

A few fundamental logical benchmarks are highlighted in the sub-sections of the introduction. They are essential for evaluating the concrete physical content and implications of the present analysis. They deal with the physics of the process, with the spacetime teleconnection of its effects, and with its intrinsic *lognormality*, *fractality*, and SOC behaviour.

The database and the algorithms are described in Sects. 2 and 3, respectively, while Sect. 4 illustrates the results. Section 5 contains the discussion of available evidence and future perspectives.

1.1 Abstraction and "simplicity" – the "natural probe"

"Simplicity" is a first requirement by the human mind, attained by abstractions. A few crucial definitions are to be recalled: "*solid*", "*liquid*", "*continuity*", and "*homogeneity*".

A body is said to be "*solid*" whenever its atomic or molecular bonds prevail on other forces (thermal, gravitational, etc.). In contrast, it is said to be "*liquid*" if gravity forces prevail. Natural reality *never* fits with any kind of abstraction, which is *always* ultimately motivated *only* by the need for simplicity by the human mind, not by physical reality.

It is customary to refer to "*plastic*" materials, or to "*viscous*" fluids. By this, some corrections are empirically introduced inside an oversimplifying logical frame. A "simple" scheme is thus achieved based on arbitrary abstractions, while a few additional ad hoc approximations permit to fit observations.

"*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. Nevertheless, the entire process strictly implies *no energy loss*.

"*Continuity*" is related to the abstraction of "*infinite*" and "*infinitesimal*" quantities, which are *not* a requirement of natural reality. Until the end of the XIX century, science was a daughter of Newton and Leibniz (differential and integral calculus), and during the early XX century the logical monument of mathematical analysis was implemented.

The *infinity* of the universe is debated. In contrast, since the discovery of quantum effects, it is well known that infinitesimal quantities do *not* exist. For instance, the van der Waals equation is a very simple correction that introduces the intrinsic non-vanishing volume of a gas molecule. By it, however, we can justify only some metastable trend of a gas-liquid mixed system, while a correct description of phase transformations must rely on quantum phenomena. Owing to this same reason, classical electromagnetism alone had never permitted the exploitation of modern electronics, which rather must rely on solid state physics.

As far as the application is concerned to *fracturing* processes – such as it typically occurs in the Earth's crust – the cleavage plane of a crystal shall never be justified by any model based on "continuity". The justification of a cleavage plane *must* rely on atomic bonds inside the crystal structure: atoms are incompatible with "infinitesimal" quantities and with "continuity".

"*Homogeneity*" is an additional abstraction, which is used for "simplicity". It is the most obvious frame for applying "continuity". "Elasticity", when applied to a "homogenous" medium (either "solid" or "liquid"), leads to the concept of *ideal* "elastic waves" that cross through the medium, with *no energy damping*. It is rather assumed that potential and kinetic energies transform between each other, in a steady "continuous" way. They last in space as far as the medium is extended, and in time as long as the entire lifespan of the survival of the physical system of concern.

As far as the *real* natural system is concerned, i.e. the Earth's crust, it can be likened to an approximately "solid" body. The simplest way is to conceive it like an approximately "homogenous" medium, crossed by vibrations that – as a first order approximation – are considered "elastic waves". This model, however, results from a sum of several approximations, which often have to be mitigated to interpret observations.

A first concern is about "homogeneity". This is crucial for clarifying the propagation and damping of "elastic waves". The mechanism by which potential and kinetic energy can propagate, or not, depends on the gaps inside the medium, which violate the "homogeneity" assumption. That is, one must consider some typical physical distance between contiguous "homogenous" constituent elements – such as e.g. sand grains, or pebbles, or other components of soil and/or crust. If the wavelength of the wave is larger compared to these typical gaps, the wave shall imply linear displacements of matter of a scale size larger than the gap size: hence, the wave can propagate. In contrast, when the wavelength is less than this typical gap size, every component of the medium (sand grain, pebble, or other) shall be simply moved inside the gap, while it cannot transfer kinetic energy to its contiguous component. Hence, the wave shall be damped.

Seismic waves certainly have a wavelength much larger than the aforementioned gap size. Hence, earthquakes are the classical tool for investigating the rheological features of the crust and of deep Earth. The same applies to prospecting and profiling by seismic reflection.

However, this cannot apply to ultrasounds, i.e. to AE. Hence, AE can propagate *only* along sufficiently *compact* bodies, i.e. such that the gaps between different component parts (every one of which can be approximately considered "homogenous") are such as to introduce no relevant damping of the AE wave. This condition is often encountered in the natural environment.

For instance, refer to some mineral ores, or rocky bodies, such as granite, limestone, dolomia. Otherwise, consider even some much compressed moraine bodies, which resulted to be very effective AE propagators. Typically the huge igneous dikes extending underground resulted to be much efficient "natural probes" crossing some large – although unknown – fraction of a huge volcanic edifice.

"*Natural probe*" is a much general concept. We can, and we must, keep advantage of natural probes, as they are a most efficient tool for monitoring phenomena on some large spatial scale, which could be achieved by no manmade probe (e.g. see Sect. 1.4, while dealing with Vesuvius).

A concern is about the *fractures* that in general must be realistically expected to occur along every "natural probe". AE is recorded on the outcrop of any given "natural probe". If the natural probe suffers by a fracture, the recorded AE signal will display a step-wise discontinuity. This drawback is mitigated by the role of water (or in general of fluids). Water is an excellent conductor for ultrasounds. Water has a great mobility underground, and whenever it is present, it fills the gaps of fractures inside the "natural probe". A consequent – and often observed – drawback shall therefore be that an AE signal shall eventually display some unexpected and apparently irregular abrupt discontinuities vs. time, depending on the time varying soil hydrology.

Therefore, we know about this bias, and we can – and must – suitably take it into account while carrying out data analysis. Unlike the AE records in the laboratory, this drawback can be easily recognized on the plots of the AE records measured in the field. They display some temporary – and eventually repeated several times – abrupt discontinuities that we call the MFE (minor fracture events). See Sect. 4.

Operatively, in general MFEs can be managed by dividing the raw AE database into two subsets, each one including records above (or below) a suitable threshold. Only on a few occasions there has been need for dividing the original data base into three subsets: (i) with no MFEs, (ii) with positive MFEs only, and (iii) with negative MFEs only, respectively. However, an exhaustive phenomenology of MFE was not yet investigated.[1]

A somewhat analogous phenomenon has also to be emphasized. On very few occasions some events (every one lasting, say, $\sim$12 h) display some comparatively very large signal, and they disquietingly appear to precede some strong earthquake.[2] Compared to MFEs they appear much different, as they do *not* appear like step-like discontinuities. They rather display some *internal structure* of the temporal evolution of the signal. They look almost like some kind of short-lived "*crustal substorms*" (see Sect. 1.4). They are real and disquieting. In the following we can tentatively call them "*crustal impulses*". But the very limited number of the presently available observed case histories is still insufficient for attempting any reliable interpretation.

Summarizing, every AE record must be measured on top of a reasonably compact outcrop. The outcrop is to be considered as the terminal – emerging from ground – of some "natural probe". The extension and elongation of the "natural probe", however, is unknown. It has to be decided a posteriori whether the measured AE records are compatible – or not – with the assumption that we deal with some long "natural probe". This methodological approach is shared by *every* analysis of AE observations. When we find agreement, we can reasonably presume that model and measurements are self-consistent. If not, either we change model, or we have to improve observations and change the measured outcrop.[3]

The intensity of the measured AE signal depends (i) on the intensity of the original (and 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 just recall that the acoustic impedance $Z = \rho V$ of a material is defined as the product of its density ρ and acoustic velocity V. It is important either for the determination of wave transmission and reflection at the boundary of two materials, and/or for assessing the wave absorption, and/or for designing ultrasonic transducers. In general, the acoustic impedance depends on frequency, on temperature, and on the rheological characteristics of the medium. But these items are not here of direct concern.

In this last respect, it is easy to measure the acoustic impedance e.g. inside water and its dependence on temperature, frequency, pressure, etc. In contrast, this is impossible in the case of a solid medium, where the propagation of any "elastic wave" through it – hence its apparent acoustic impedance – is controlled by the geometrical shape of the body. The role of wave reflection (and refraction) across the outer boundaries of the object has to be taken into account. In the case of water, a measurement can be carried out inside a pool with an AE source embedded into it. But this is impossible for a compact solid medium.

Summarizing, in the case of the Earth's crust, we can realistically only collect AE records on the outcrop of some "natural probe", although, in principle, we have no possibility either of envisaging its extension, or its acoustic impedance, and their respective eventual changes with the time.

[1]Some case histories of MFE are shown in the following (e.g. when dealing with Fig. 11).

[2]Case histories of this kind are shown here below while discussing Figs. 6 through 10.

[3]An analogous criterion is applied as a standard by several other kinds of measurements in the field, e.g. when measuring geothermal flow, when some drill holes are neglected as they are likely to be perturbed by thermal advection by underground hydrology.

1.2 The space domain – teleconnection

Two drivers are well known to affect the astronomical motion of the whole Earth.

On the one hand, since several decades it is well known that the increase of the length of the day (l.o.d.) – which is associated with the tide caused by the Moon and partly by the Sun – is *not* originated by the tidal action inside the body of the Earth. Rather, it is mainly caused by the so-called "*loading tide*": the tide displaces 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 spin rate of the Earth.

This mechanism implies a violent stress on the planetary scale through the whole Earth's crust. Gregori et al. (2007) and Poscolieri et al. (2006a) reported a variation of the crustal stress, detected by AE records in central Italy (Orchi) and in the Cephalonia Island (Greece). The effect was found to be synchronous at the two sites[4] and it was tentatively interpreted as a possible evidence of the role of the loading tide. But a final confirmation ought to require a check by some AE station located somewhere in central Asia.

On the other hand, consider that the telluric currents are stray currents that are the presumable origin of torques, which produce some otherwise unexplained observed variations of the l.o.d. (Meloni et al., 1983, and references therein).

In any case, depending on either one of these two drivers (i.e. loading tide, or electromagnetic) – and very likely depending on both of them – it appears reasonable to expect that *planetary scale* phenomena of crustal stress *must* occur as a standard, being a permanent feature, although varying vs. time and site.

Consider that the telluric currents are channelled through regions of comparatively greater electrical conductivity σ. It has been estimated that σ varies by a factor $\sim$40 000 when comparing sea water with dry rocks (Lanzerotti and Gregori, 1986). Much in the same way, the propagation of the aforementioned planetary scale crustal stress must depend on the heterogeneities of the crust, hence on the space and time variations of its acoustic impedance at the different AE frequencies. These heterogeneities are also affected by the local explosive geochemical implications of *serpentinization* (Judd and Hovland, 2007, and references therein).

Therefore, when analysing an AE time series – which is monitored at every given frequency – we have to allow for phenomena that – as a first order approximation – can appear reasonably similar through a suitably large region, which behaves almost like a unique large *slab* of lithosphere.[5] The concern is about stress propagation alone, through a non-homogenous medium, by considering suitable and separate *slabs* of lithosphere. Every slab has to be approximately defined in such a way that the AE records, which are collected at different AE stations located on it, appear comparatively similar.

The size of every given *slab* can be much different in different regions of the Earth. In order to fix ideas, the case histories here discussed show that the Italian peninsula behaves in an approximately "uniform" way, while the Ionian sea area results to be concerned with a much different tectonic setting (e.g. refer to the analysis of AE records collected at Cephalonia on the occasion of the Lefkas earthquake; Lagios et al., 2004; Poscolieri et al., 2006b).

On other circumstances we have to refer also to some smaller scale size. The smallest observed scale size deals with the typical focal volume of an earthquake, i.e. just a few cubic kilometres.

Crustal stress is a ubiquitous feature. It applies to every point of the crust, *everywhere* and at *every time*. In addition, some paroxysm eventually crosses through a given area, etc. However, the final yield, i.e. the "catastrophe" of the system, shall involve *only* some much *limited* specific volume of the crust. This volume, however, cannot be a "point".

An earthquake must release a given amount of elastic potential energy that was accumulated somewhere. Every given elementary "solid" sample of crust cannot accumulate more than some given amount of total potential energy: in the opposite case the sample ought to yield much before the occurrence of the earthquake. Hence, the total potential energy that is released by a given earthquake cannot be "compressed" and stored inside a vanishing volume of crust. When the earthquake occurs, some finite – suitably extended – volume of crust shall release altogether its stored energy.

Therefore, the *smallest* scale size of concern for crustal stress studies is the *focal volume* of a seismic event; but also some *intermediate* scale sizes are to be considered between the aforementioned *slab* and the *focal volume*.

Some effect shall appear morphologically similar through a whole given *slab* (e.g. through the Italian peninsula). But at the same time this does *not* imply that just *one and the same* effect is observed – everywhere – through the entire *slab*, which appears to precede one and the same seismic event. Indeed, an earthquake involves only some much localized *focal volume*.

But we have to expect that some AE stations – suitably close to the epicentre – ought to detect some additional effect, similar to what is typically and specifically observed right on top the focal volume. Differently stated, the AE stations eventually located inside some given smaller fraction of the *slab* shall monitor some effect more closely correlated with that earthquake and that is not observed at other locations on the *slab*.

Summarizing, we have to distinguish: (i) planetary scale phenomena, (ii) other phenomena that involve in some "uniform" or "similar" way some large *slab*, (iii) some smaller

[4]See Figs. 4, 5, 8, and 11 here below.

[5]According to plate tectonics, one could tentatively identify either one of these slabs with one given plate, although the entire argument here discussed implies no geodynamic model.

comparatively more restricted or intermediate sub-areas, of every given slab, and finally (iv) the earthquake itself, which is released inside a *focal volume* at a typical frequency of 0.5–1 Hz.

Therefore, in the ultimate analysis, some apparent *teleconnection* shall be eventually observed between the AE recorded at different AE stations, which sometimes are even located at some relative distance much larger than the size of the focal volume.

Suppose that two much similar AE effects are almost simultaneously observed at different sites far apart from each other. This means that – concerning that given effect, although only concerning *that specific* kind of event and *not* necessarily concerning *all* kinds of events – the two AE stations are located on the same slab, or sub-portion of it, such that, as far as that kind of event is considered, they shall result to react "uniformly" or "similarly".

Differently stated, when a planetary scale phenomenon is monitored, it has to be observed everywhere, eventually with some suitably time delay depending on the propagation speed of crustal stress.

In contrast, if a phenomenon is monitored that involves only some lithospheric *slab* of some given and limited size, we have to observe "similar" events at all AE stations located on the same *slab*.

The next step is concerned with effects that appear closely associated with some more local features around the epicentre area – e.g. when we deal with the same "local" crustal micro-deformations that can be detected by the AE recording apparatus operated in the epicentre area. These "local" effects shall be observed only inside some limited area around the epicentre. Hence, we have to observe "similar" events only at AE stations that are "suitably" close to the epicentre. The size and figure of this area "suitably" close to the epicentre depends on the specific case history of concern, as it reflects – in general – the tectonic setting of the region, its faulting, the shape of the natural probe, and its time variation of acoustic impedance.

For the sake of completeness, let us mention that when we eventually observe "similar" events at any two given AE stations, an alternative explanation is supposing that some kind of AE "wave-guide" exists between the two stations, e.g. a much compact mineral ore or the aforementioned *serpentinization* effect (although with some time delay), or other. As a general occurrence, when the distance between the AE stations is large, this mechanism appears unrealistic. Moreover, it is likely that the serpentinization effects ought to be associated with some (presently unknown) time delay (M. Hovland, personal communication, 2009).

Much more credible appears supposing that a signal of some much longer wavelength is the carrier of some perturbation, by which some large entire lithospheric slab is perturbed. This perturbation finally triggers some local AE signal, which is therefore a *local* response to a perturbation that affects some much *larger* region. This way of arguing is, however, just the same as the aforementioned teleconnection justification, although expressed by different words.

In the following sections the distinction between "*storm*", "*substorm*", and *seismic* event is going to be defined. For clarity purposes, their distinction can be anticipated by the following example. Consider a table, with several glasses on it, every one partly or totally replenished with water. Hit and shake the table. The water in every glass shall start to oscillate. If a glass is full or almost full, the "catastrophe" shall occur and its water shall get out of the glass.

The table is the Italian peninsula. Every glass is the focal volume of a forthcoming earthquake – we cannot know where and when it will occur, but somewhere and sometimes it shall occur. The "*crustal storm*" is the sequence of impulses that shake the table. A "*crustal substorm*" is some short duration morphological feature of the observations. By means of AE records we know when a "*storm*" is ongoing. But we cannot know where and when a glass is going to be full of energy for causing a catastrophe. That is, we make a diagnosis, *not* a forecast.

1.3 The time domain

Figure 1 is a cartoon that shows the time dependence vs. frequency of the observed AE. The physical principle is that every former sample of crust – which originally has almost no flaws – suffers by the formation of some small flaws, which are associated with some comparatively high frequency (HF) AE. Smaller size objects vibrate with shorter wavelengths.

On the occasion of every additional stress – which is subsequently applied to the same sample – some new flaws are originated, which occur preferentially close to the crystal bonds that already yielded, because at these points the material is comparably weaker.

Hence, new comparatively larger flaws are going to 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. Another expressive picture is in terms of a huge set of domino tiles that drop one after the other in a time sequence.

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

For clarity purposes, as mentioned above, it has to be stressed anew that AE are a tool for monitoring crustal stress and for *diagnosing* the state of the crust, *not* necessarily for searching for earthquake *prediction*. In this respect, suppose that the AE station is monitoring the focal volume of a potential future earthquake. According to the aforementioned rationale, an HF AE paroxysm is observed. Then, analogous paroxysms are observed in a cascade of subsequent comparatively lower AE frequency. An obvious inference is that

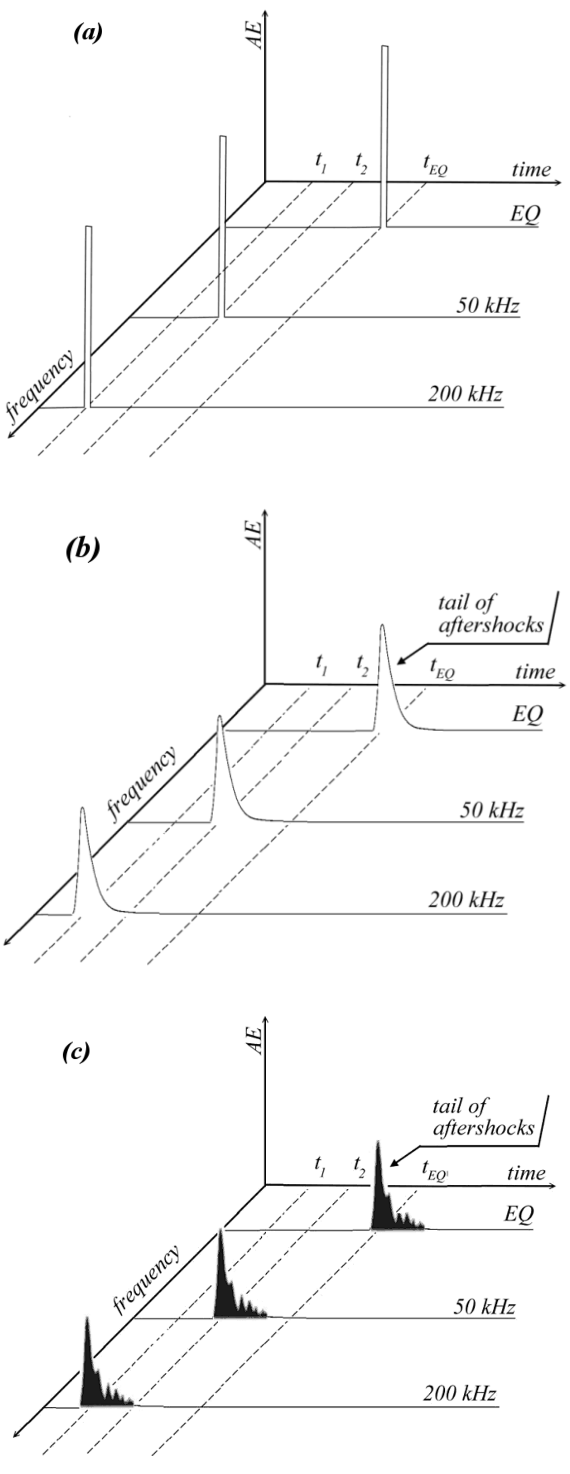

Fig. 1. Cartoon showing how the recorded AE signals are first released at comparatively HF, corresponding to the yield of smaller pores. The signals are not Dirac δ-function distributions **(a)** rather lognormal distributions **(b)**, which are eventually modulated such as by tide effects, e.g. on the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

when the paroxysm is observed in the final frequency band – which is typical of an earthquake i.e. ~0.5–1 Hz – an earthquake must occur. That is, this is a "prediction".

On the other hand, two physical facts must be taken into account.

The first drawback derives from the fact that a given focal volume eventually changes its boundary conditions. Hence, the stress that is applied to it by its contiguous Earth's crust is changed during the evolution of the time series of subsequent AE paroxysms. Therefore, this time series is eventually physically interrupted, due to the changed crustal environment.

The second drawback is that the aforementioned "prediction" cannot specify the magnitude of the earthquake. This depends, rather, on the amount of elastic energy that is stored inside the focal volume. In contrast, the AE "prediction" is concerned only with its trigger, and with the timing of events, not with their intensity. The magnitude of a possible earthquake has to be investigated by means of a completely different rationale, ultimately relying on the old-fashioned so-called "seimic gap" criterion. This is a classical and much investigated item, which is outside the concern of the AE information.

Concerning AE records, the real difficulty is therefore that – while making measurement in the field and unlike when experimenting in the laboratory – every small-magnitude shock can be potentially associated with a time series of observed AE paroxysms. AE is a diagnostic tool, not a forecaster.

An additional remark deals with the well known difficulty, in the search for earthquake precursors of every kind, of distinguishing precursors and aftershock phenomena. This drawback does not apply to AE monitoring, because by means of AE we know what *must* be observed first and what second, depending on the AE frequency. Several AE frequencies, thus, provide with a time series of analogous precursors, according to a well defined time sequence.

Just in order to fix ideas, it can be pointed out that, in the case of an earthquake, one should detect first HF AE effects, then LF AE effects, then effects involving progressively lower frequencies, until the seismic roam, which shall precede the vibration of some structures of a building, and lastly the final shock (at ~0.5–1 Hz).

Another aspect of concern deals with the time scale of the primary driver of the AE triggering process.

Compared to the human space-time size, some phenomena are characterized by some "long" time scales. Indeed, some phenomena certainly occur – and therefore ought to be detected in some way – during some "long" time lag preceding the incoming "catastrophe". This applies either to an earthquake, or 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 effect can be originated only by an action lasting a few ten seconds, such as e.g. when using an electric drill on a solid sample in the laboratory.

This requires a much higher time rate for AE data acquisition, in order 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.

Summarizing, the time scale of concern depends on the physics of the catastrophe that is monitored while it occurs to the given physical system.

1.4 Lognormality

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

The 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). Although it entered into textbooks (e.g. Arley and Buch, 1950), apparently it was generally almost forgotten in the subsequent literature (Paparo and Gregori, 2003; Gregori and Paparo, 2010).

Its rationale is shared by several phenomena, typically by every public service, whenever 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, therefore, intrinsically shared by every physical phenomenon, whenever the occurrence of an event is proportional to the number of similar events that are already occurring. Typical examples (refer to Gregori and Paparo, 2010 for more extensive discussion and references) are e.g. the hypsometric curve 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 a financial crisis when the psychological impact determines the *lognormality* of the event, etc.

For future reference, let us explicitly recall a historical and classical example. Geomagnetic storms (Chapman and Bartels, 1940) are assessed by the North-South horizontal (H-component) geomagnetic field. In contrast, since the geomagnetic signal is excessively perturbed for permitting an unambiguous assessment, a magnetospheric substorm – which is shown to be some kind of more elementary component of a magnetospheric (or geomagnetic) storm – was recognized, since Akasofu (1964), by means of polar auroras. That is, one and the same phenomenon involves one and the same physical system. But it eventually requires to be monitored by means of different diagnostic tools.

In the case of a magnetospheric *substorm*, typically elapsing $\sim$2–3 h, it is the physical consequence of the progressive lack of particle supply from the particle reservoir represented by the plasma sheet inside the tail of the magnetosphere (Gregori, 1998, 1999, 2002). The exhaust of the particle inflow from the tail is reflected in the lognormal trend of a *substorm*. Similarly, concerning a geomagnetic storm, which typically elapses $\sim$ a few days, it reflects a state of the flux of solar wind. A storm is composed of a formal disordered sequence of overlapping *substorms*. When the solar wind exhausts its "anomalous" flux, owing to a progressive fading off of its primary trigger, the decaying trend of the storm results lognormal, while the magnetosphere evolves towards a new equilibrium state.

Therefore, *lognormality* is a much frequent mathematical feature observed in a large variety of phenomena. It is just a mere and common observational fact. Owing to the same reason, also the AE monitored at a given frequency must be expected to occur according to a lognormal trend. Its physical interpretation, however, is to be better specified after discussing its *fractality* (see Sect. 1.5). For the time being let us just point out that the AE sources operate according to the aforementioned rationale, as shown in Fig. 1b.

The tail of the lognormal distribution eventually results modulated by an external action. For instance, in a few case histories Paparo and Gregori (2003) afforded to recognize a tidal modulation, either on AE records collected on Vesuvius, or – although maybe less clearly – on some occasions in a tectonically active area. For the lowest frequency, i.e. at $\sim$0.5–1 Hz being the typical frequency of a seismic shock, the tail of the lognormal distribution (Fig. 1c) shall be identified with the aftershock sequence.

Another example is 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 slide occurs here and there. The system is said to be in a state of "self-organized criticality" (SOC) (e.g. Bak et al., 1987; Sornette et al., 1990; Sornette and Davy, 1991; Cowie et al.,1993; Main, 1995; Cowie, 1998; Cello, 2000, and references therein). This critical state shall last until the sand pile has attained its final equilibrium.[6]

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

As mentioned above, an event observed in the crust at a given AE frequency is to be expected to be roughly depicted, in some ideal situation, like a lognormal phenomenon. It can be likened to a "*storm of crustal stress*", or in brief to a "*crustal storm*". However it is a SOC phenomenon,

[6]Sand pile theory is now the object also of science popularization (e.g. Barrow, 2009).

characterized by some irregular superposition of overlapping "*crustal substorms*".

The purpose of the analysis of an observed AE time series – or of a set of different AE time series every one referring to a given frequency – shall therefore be aimed at recognizing "AE *storms*" and its "AE *substorms*".

The present paper is only one first step, i.e. AE applied to crustal monitoring in order to recognize "crustal storms" and "crustal substorms". Only the direct AE records are here considered, while for brevity purposes some other mathematical treatments are given in Gregori et al. (2010).

1.5 Fractality and SOC

Fractality is a crucial aspect of AE time series (Petri et al., 1994; Vespigani et al., 1995). The general discussion of *lognormality* and *fractality* is reported in Gregori and Paparo (2010).

Every time series of events, either of AE or of any other kind, in general is found to be more or less randomly distributed in time (concerning algorithms refer to Sect. 2 and references therein). In the case of "perfect" or "ideal" randomness, its fractal dimension D_t must result equal to 1. This is only a matter of definition, or just one possible way of rigorously defining whether a time series of events is randomly distributed or not. That is, this is tautological.

In contrast, suppose that an event keeps a "memory" of the previously occurred events. It shall be found that the fractal dimension $D_t < 1$. 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 definition, in a strict sense, not of physics.

Physically, we monitor a system and collect a time series of AE "events" (for the definition of "event" see Sect. 3). We evaluate its D_t computed by referring to a specific running time interval of records of the AE series. The D_t shall 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 is the randomness, the more "aged" is the material sample – because flaws occur close to previous flaws – and the closer it shall be to its "catastrophe". For instance, a steel bar monitored in the laboratory (see here below) was found to be close to final rupture when $D_t \sim 0.45$ (Biancolini et al., 2006).

In reality, however, it has to be stressed that when referring to the crust and to AE records measured in the field, the computed D_t refers to AE emitters that fully yielded, i.e. their contribution in general is to be expected to be $D_t \ll 0.45$.

An additional concept, which is much relevant for understanding observations, is related to the distinction between the observations of *one* single AE source, compared to a "*fog*" composed of some *large number* of AE sources.

Consider the case history of *one single source* alone. For instance, consider one steel bar (Zanini, 2004; Biancolini et al., 2006). Bend it e.g. 10 000 times. Then, bend it once more while monitoring its AE (at one and always the same given frequency). Evaluate its D_t . Bend it anew for additional 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 $D_t \sim 0.45$ the bar is found to be close to final rupture. A curious effect is that, during its evolution, after a while the steel temporarily recovers (instead of steadily losing) its performance. This is the consequence of a transitional re-adjustment of the micro-crystals of its alloy, in such a way that, for a while, the micro-crystals improve the steel performance, soon before, however, experiencing the final evolution towards "catastrophe".

Similar results were obtained by carrying out experiments on concrete cubes, 15-cm size (Guarniere, 2003). In addition, upon bending only a few times a steel blade of a VIRGO super-attenuator, it was even found that it is possible to monitor how many times the blade was bent after its casting (Braccini et al., 2002).

One output of the data analysis (see Sect. 3) is the so-called "*hammer effect*", which is expressed by an index H (Gregori et al., 2007). When dealing with a single AE emitter, it is possible to distinguish – on an instant basis – whether

1. the system ($H = +1$) emits AE because it suffers by some action applied from its exterior, or rather

2. it experiences ($H = -1$) a transitional evolution towards its new equilibrium after having suffered by some external perturbation.

Differently stated, we know that the AE signal has to be likened to a lognormal distribution (Sect. 1.4), although this is an ideal situation. In contrast, in general the AE records shall appear much perturbed compared to this simple ideal 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 rationale, it can be claimed that – when dealing with *one single* AE emitter – whenever $H = +1$ the material suffers by some external action and whenever $H = -1$ it is during a temporary recovery stage.

However, in reality, *one single* AE emitter is an ideal condition that can be only approximately implemented in the laboratory, while only more seldom it occurs in the field. A more realistic condition is in terms of a suitable *subdomain* of the physical system, which in the case of the Earth's crust is composed by some given lithospheric slab, or by some given portion of it, etc. see Sect. 1.2. This *subdomain* is composed of a "*fog*" of "elementary" AE emitters.

Suppose that, during some given time interval of finite duration, the flaws *of a given size*, inside this subdomain, collectively experience their decay, while they coalesce towards larger size flaws, etc. During this given time interval, the measured AE shall be the result of the sum of several "elementary" AE signals, everyone with some very small D_t i.e. let us say with $D_t \sim 0$.

But, the number of these "elementary" AE emitters shall decrease vs. time, according to a lognormal trend (see Sect. 1.4).

That is, it is possible to express in brief this entire mechanism by the term: "*lognormal fog*". Or every aforementioned *subdomain* is responsible for an appearance in the observed AE series of a trend that recalls some approximate lognormal distribution (with reversed ordinate axis). This effect, however, depends on the decrease of the population of "elementary" AE emitters, rather than – unlike it occurred in the case of *one single* AE emitter – on the ageing of its material.

In general, at different times different *subdomains* shall experience a similar phenomenon. The final effect is that all their respective outputs appear to overlap with one another, in some apparently erratic way. Their trend shall occur according to a SOC rationale.

On the other hand, we know (Sect. 1.1) that the raw AE datum suffers by the uncertainties related to the arbitrary and unknown variations of the acoustic impedance of the "natural probe". That is, while assessing and recognizing the contribution of every single *subdomain*, the intrinsic unavoidable physical difficulty is further increased by the unknown and arbitrary variations of the intensity of the recorded AE signal.

Therefore, it appears more effective appealing to D_t much better than to the raw AE signal, because D_t is a physically expressive parameter that is independent of the arbitrariness of the amplitude of the original raw AE datum. Also the index H can result, sometimes, heuristically much effective.

Summarizing – by means of an analogy and by using the same terms used for the geomagnetic field and for the magnetosphere (or for the sand pile; see Sect. 1.4) – 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 of "*stress substorms*", every one being associated with some suitable (though unknown) aforementioned *subdomain*.

Let us recall that (Sect. 1.4) a geomagnetic storm is recognized by means of the morphology of geomagnetic records, unlike magnetospheric substorms, which are recognized by polar auroras. That is, the physical system and the observed phenomenon is always the same, although different morphological features can be more or less reliable for diagnosis purpose.

Much 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.

The distinction between "*stress storm*" and "*stress substorms*" also has a likely relation with the space domain of the involved phenomena. A "*stress storm*" appears to exhibit some large-scale occurrence (in the aforementioned case history, say, e.g. the entire Italian peninsula). In contrast, a "*stress substorms*" involves a comparatively more limited portion of lithosphere or crust. If this guess is correct, a "*stress substorm*" should be detected only inside some comparatively more restricted area around the epicentre of a potential future shock.

Every final assessment about this – as well as about every other inference – requires collecting observations during several years' operation of an array of AE stations within some given region of concern. Every station should be operated by recording a few different AE frequencies in order to monitor a time series of different paroxysms (see Sect. 1.3).

A final assessment is, therefore, that, when dealing either with any kind of phenomenon in Earth Sciences, or with financial crises, or with a public service, or with psychology, etc., different facets of *one and the same* logics are denoted by different names, such as "*lognormality*", "f*ractality*", "SOC", or the concepts of "*storm*" and "*substorm*" of the given system. Every facet is eventually monitored and diagnosed by means of different observational information – and the composition and drivers of the system are comparatively much different – but the logics is the same.

2 The data base

As far as the Italian peninsula is concerned – and the diagnosis of its crustal stress – the records used by the authors during several years rely on HF AE (typically 150–200 kHz) and on LF AE (typically 25–30 kHz).

A hole (about 50 cm deep) is made by drilling a rocky outcrop. A glass bar is put inside the hole, which is then filled with concrete. In fact, the glass cannot be affected by electromagnetic induction, although also a metal bar can be used, with no bias (Paparo et al., 2002; Gregori and Paparo, 2004). An AE transducer is fixed on top of the glass bar (one bar for HF, one bar for LF). A linear preamplifier is applied to every transducer. Then the signal gets into an amplifier and data logger. A GSM connection permits remote acquisition.

The measured datum is an rms amplitude, averaged over 3 ms. In past applications, the data logger stored one datum averaged every 30 s. If the concern is about more rapid phenomena – such as when carrying out experiments in the laboratory, or e.g. whenever one wants to monitor the Earth's tide spectrum, or the free oscillations of the Earth (Ruzzante et al., 2008) – these parameters are to be changed consequently.

According to the aforementioned physical rationale, the HF AE reflect a process in the crust of comparatively much earlier "ageing". Hence, HF AE better reflect the primary "external" trigger components that cause some effect in the crust, such as e.g. the planetary scale propagation of the loading tide stress (see Sect. 1.2; Gregori et al., 2005, 2007; Paparo et al., 2006; Poscolieri et al., 2006a, 2006b).

In contrast, the LF AE – compared to HF AE – appear much more affected by regional or local tectonics. Hence, LF AE are better suited than HF AE for diagnosing the evolution of the crust during some time closer to its final eventual "catastrophe". They give much better and reliable information about the specific actual state of the crust at some comparably later stage, during of its loss of performance. In addition, they refer to some region contained inside some much more limited "*slab*", compared to planetary scale features. All these inferences resulted after discussing repeated investigations in much different tectonic settings (Gregori et al., 2005, 2007; Paparo et al., 2006; Poscolieri et al., 2006a, 2006b).

According to our past experience, an important – and generally unnoticed – twofold warning resulted to be *over-saturation* or *under-saturation* of the signal.

Owing to some unknown time changes (see Sect. 1.1) of the acoustic impedance of the "natural probe", the signal amplification in the data logger is arbitrarily set at the beginning of the record operation - in order to get some output typically ranging, say, e.g. up to ∼10 V, with a sensitivity of the order of ∼1 mV.

For field applications, this set-up of the amplification is often chosen during "quiet" conditions. In this case, however, when a "*storm*" is on, some important AE information is eventually lost.

In contrast, if the set-up is made with a lower amplification – in order to avoid over-saturation during "*storm*" time – the opposite bias, i.e. under-saturation, has to be eventually faced.

According to our past experience, under-saturation was often encountered. On the other hand in general, the algorithms used for data analysis resulted to be robust even in the case either of over- or of under-saturation.

Summarizing, while carrying out a given application – such as e.g. field measurements – it is worthwhile to allow for some large excursions of the input signal. The natural environment is much scattered, compared to any "mean" and approximately more or less "steady" model. In addition, the large variations of the AE signal are the ultimate target of our diagnosis, as they reflect some basic aspects that we would never be able to monitor by any mean, other than by AE measurements.

3 The data analysis

The details of the following algorithms already appeared in several papers (Gregori and Paparo, 2004; Gregori et al., 2002, 2005, 2007; Paparo et al., 2001, 2002, 2006; Poscolieri et al., 2006a, 2006b). Hence, only some highlights are given here. The following analysis is presently being carried out by standard software, which was progressively implemented, extensively tested, and improved. We synthesize our present know-how of data handling by the acronym OFTH.

"F" denotes a weighted moving average of the raw AE datum, carried out over a given pre-chosen time lag. The weight is defined by a triangular system function, aimed at reducing the role of the side lobes of a simple non-weighted running average.

For field applications we used a moving time lag of 24 h in order to filter out all effects associated with diurnal variation, including mostly the thermoelastic effects and also some fraction of tidal effects, although not all of them. The thermoelastic effect was clearly evidenced e.g. in the Gran Sasso records (Paparo et al., 2002; Gregori and Paparo, 2004).

"T" denotes loss of performance vs. time, or "ageing", being quantitatively estimated by means of the aforementioned D_t (see Sect. 1.5). It is computed, as usual, by means of the box-counting method, applied to the time series of AE "*events*". An "*event*" is defined as follows.

Compute the data series of the *residuals* of the raw data series after subtracting the "F" data series. Every maximum in this residual data series, when its value is above some pre-chosen *threshold*, is defined as one "*event*" independent of its actual height.

This *threshold* was optimized as follows. Take some representative and limited subset R of the original residual data series. Compute its rms value s. Then, apply a trial threshold equal to $[s/k]$ (with $k=1,2,\ldots,10$). Finally, for every threshold defined in this way, evaluate the D_t for the entire R.

If the threshold is too small, several false "*events*" will be included, because they are noise. Hence, D_t shall correspondingly result comparatively large, i.e. closer to 1.

Upon increasing the threshold, D_t shall monotonically decrease, as the noise contribution is progressively damped off. When the threshold is such that the noise is fully rejected – while only the true "events" are left – then D_t shall no more decrease, when the threshold is further increased. Thus, D_t reflects the true physics of phenomena, not noise.

Therefore, compute for every aforementioned k its corresponding $D_t(k)$. Plot $D_t(k)$ vs. k, and realize that for some given k a step like variation of $D_t(k)$ occurs. This is the optimum threshold. In our applications it was found that the optimum choice is $k=4$.

"H" is the aforementioned parameter of the "*hammer effect*" (Gregori et al., 2007). The data series of the *instant* values H results eventually somewhat scattered, although it was found to be more stable than expected. This fact corroborated its real physical significance. Some derived parameters are e.g. the hourly means, or the 24-h-means, of the H instant values, or equivalently the percent number of $H=+1$values falling inside a given running time interval, etc. Alternatively, 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.

In either case, the physics of the information is always the same, and nothing other than that. The different choices are only concerned with graphical representation, and with the smoothing of the possible scatter of the instant data series of H.

"O" denotes "outliers". An outlier is a datum that does not partake to a Gaussian distribution of a given data set. Given a data series (either raw AE, or residuals), consider a running time lag, and analyze the distribution of all records contained inside it. Reject the data that do not fit with a Gaussian distribution. This job can be achieved by formally evaluating a suitable parameter. Refer to the aforementioned papers for details. Finally, a different analysis has to be separately applied to the data series "cleaned" of its outliers, and to the outlier data set.

In our analysis, the outliers were rejected twice. A first time on the raw AE records. The next one on the residual signal, after subtracting the "F" series from the original raw datum. The two "O" series being thus computed were found to differ only by a few percent. But it appeared worthwhile to repeat the "O" evaluation, as this resulted to help for getting rid of the drawback by possible over-saturation of the signal.

Contrarily to expectation, the outliers were found not to be simply concerned with isolated sporadic events. The algorithm operates like a sieve that selects unusual objects – and it operates after having arbitrarily defined the size of the sieve holes. When the size of the holes is sufficiently wide, the number of outliers should rapidly damp off. In contrast, it was unexpectedly found that a conspicuous number of outliers always remain.

The physical reason is that the measured AE is a "fog" of asymmetric "elementary" events (see Sect. 1.4), everyone reminding about a lognormal distribution (as per Fig. 1). The aforementioned test for *Gaussianicity* applied for outlier rejection seeks a symmetric distribution. Hence, an asymmetric tail always implies formal outliers.

At present, the outliers resulted quite useful mainly for analysing AE data collected on volcanoes, because every volcano unexpectedly resulted to be almost a high precision stopwatch for monitoring Earth's tides (Paparo and Gregori, 2001; Paparo et al., 2004, 2004a; Gregori and Paparo, 2006; Ruzzante et al., 2005, 2008).

More in general, a suitable standard software (in preparation) can transform every AE station into a station for monitoring the spectrum of Earth's tides, and also the free oscillations of the Earth.

For completeness sake, a mention ought to be given to Kenzô Sassa (1936) and Giuseppe Imbò (1954), who have been forerunners in the study of volcanic precursors. They used smoked paper records, and analyzed volcanic microtremors by visual inspection. It can be shown (in preparation) that some logical tools that they applied can be reckoned to a few of the aforementioned OFTH criteria.

4 Some case histories of "crustal storm"

We report some case histories of earthquakes. Epicentres and location of AE stations are shown in Fig. 2. Sometimes some comparison could be made with AE records on the Cephalonia island (Greece). The analysis here reported is only concerned with the raw AE datum (both HF and LF), and with its "F". Hence only "*crustal storms*" are here evidenced. In contrast, owing to brevity purposes, the evidence inferred by other parameters (mostly "T" and "H"), i.e. the evidence of "*crustal substorms*", is to be given elsewhere (Gregori et al., 2010).

Tables 1 and 2 include some coordinates and parameters relevant for the following discussion.

The Colfiorito, Molise and l'Aquila earthquakes were preceded by HF and LF "*crustal storms*", as shown in Figs. 3, 4, and 5, according to the approximate timing listed in Table 3 (improved after Gregori and Paparo, 2004). Also two case histories of "*crustal impulses*" (see here below) are tentatively included, although it should be stressed that their interpretation is not yet fully assessed in terms of a phenomenon analogous to a "*crustal storm*".

In reality, concerning the Potenza earthquake (Fig. 3), it was later realized that a possible LF AE precursor was detected some days before the Colfiorito earthquake. But owing to the large distance of the AE station from the epicentre area, it was not believed credible. Rather, it was considered a coincidence. But, a strong "*crustal storm*" was in progress in the entire Italian peninsula. The large signals, which often go in oversaturation, appearing in Fig. 3 are such that it is impossible to make any significant correlation between LF AE signals and shocks. It is rather more significant claiming that the entire peninsula had been experiencing a "stormy" crustal period during 1996 and 1997.

After the Colfiorito earthquake, we decided to transfer our AE station from Giuliano to Orchi (Foligno, PG), close to the epicenter of the Colfiorito earthquake. At Orchi we detected the "*crustal storm*" that preceded the Molise earthquake (see Table 3). The HF AE record (Fig. 4) displayed an unusually large oscillation. The LF AE record abruptly started displaying a large and steady oscillation, with amplitude of the order of, say, $\sim$20 times larger than before the onset of the "*crustal storm*". As far Vesuvius is concerned (see mention in Table 3), refer to Paparo et al. (2004) for discussion.

Another case history was monitored on the Cephalonia island, showing both HF and LF AE paroxysms preceding the Lefkas earthquake, and a *Rn* release, almost simultaneous with the HF AE paroxysm (Lagios et al., 2004; Poscolieri et al., 2006a, b).

Let us recall that fluid exhalation from soil is one of the former classical earthquake precursors, reported by a large amount of literature. The evidence, however, often resulted much controversial. Maybe, the greatest systematic approach was carried out by the school of Tang Mao-Cang who used over half a century of temperature profiles ("geotherm")

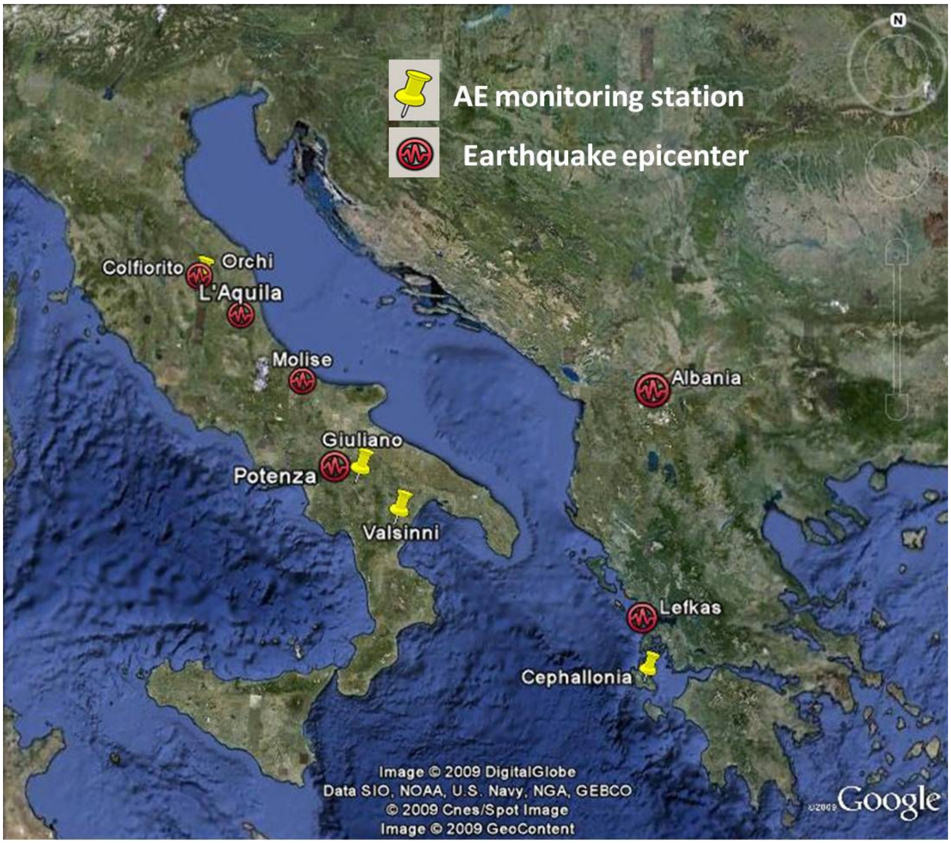

Fig. 2. Map showing the location of different AE stations and epicentres mentioned in the text.

underground, collected twice a day in the array of the Chinese meteorological station. Every "geotherm" was measured in a ~3.5 m deep hole. The leading idea is that whenever some underground crustal structure is broken, the geogas – or any kind of fluid – can get out, thus affecting gas exhalation, and also the "geotherm" by thermal advection. The Tang school thus found that the Himalaya plateau is a region with an anomalous high geothermal flux. Their data were mainly used for systematic and steady long-range forecast of average rainfall over large regions of China. The literature is in Chinese. No details are here pertinent. As far as *Rn* is concerned, since it suffers by no chemical reaction, it is considered to be an effective and reliable tracer of deep Earth phenomena.

Fluid exhalation measurements, however, have intrinsic unpredictable perturbations, and the signal-to-noise ratio is generally poor. This depends (i) on the erratic occurrence of underground fractures, (ii) on the great and fast mobility of fluids underground, and (iii) on the comparatively much limited spatial extension of the area monitored by measuring fluid exhalation (unless one uses and extended array such as in China). On the other hand, fluid exhalation is, maybe, almost the unique monitoring device with sensitivity comparable to AE records.

Table 1. AE stations.

Site	Latitude	Longitude	Period of operation
Giuliano (PZ)	40°41′03″ N	15°46′21″ E	1995–1999
Orchi (Foligno, PG)	43°01′00″ N	12°47′00″ E	since 2002
Valsinni (MT)	40°10′05″ N	16°26′35″ E	since 2008
Cephalonia (Greece)	38°10′37″ N	20°35′19″ E	since 2003

On two occasions we attempted, therefore, to correlate the scanty available data with our AE records. One case history was the Molise earthquake. We found some correlation with the chemistry of a warm spring (increase of CH_4) at Bagno di Romagna in the central Apennines (Paparo et al., 2006). The other case history was concerned with Stromboli, where several measurements were available (Gregori and Paparo, 2006). The agreement appeared certainly satisfactory, although it suffered by the aforementioned signal-to-noise ratio of the geochemical data.

The concern, however, is about whether any case history ever occurred of a "*crustal storm*" that did *not* precede an earthquake. Up to our available database, some 8 years of

Table 2. Data from six different events (values *in italic* taken from catalogue cpt08_1991–2006).

Name	Date	Start time (GMT)	Lat. of epicentre (N)	Long. of epicentre (E)	M	Depth (km)
Potenza	3 Apr 1996	13:04:35	40.67°	15.42°	4.9	8
Colfiorito, Italy	*26 Sep 1997*	00:33:12.89	43.022°	12.891°	5.7	3.5
(only shocks	*26 Sep 1997*	*09:40:26.73*	*43.014°*	*12.853°*	6.01	9.9
with $M \geq 5.0$)	*3 Oct 1997*	*08:55:22.02*	*43.042°*	*12.824°*	5.25	12.05
	6 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, Greece	*14 Aug 2003*	*05:14:03*	*38.81°*	*20.56°*	6.3	10.0
L'Aquila	6 Apr 2009	01:32:39	42.334°	13.334°	6.3	8.8
Albania	6 Sep 2009	21:49:42	41.49°	20.43°	5.5	3.0

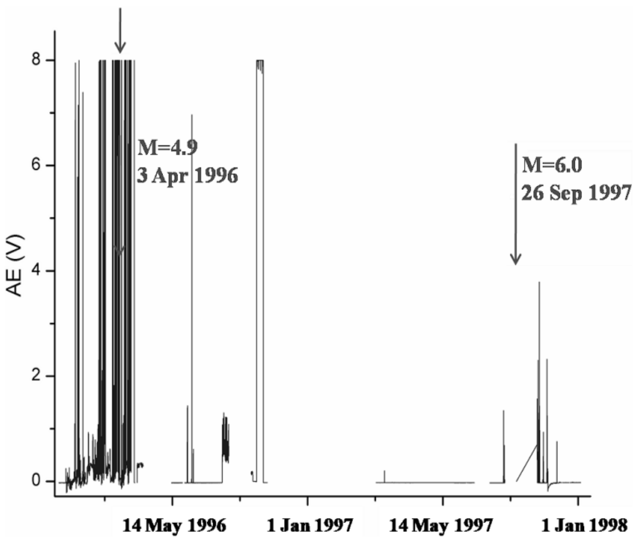

Fig. 3. LF AE records from Giuliano (raw 15 min integrated AE signal). Some comparatively stronger seismic shocks are indicated by arrows. See text. After Paparo et al. (2006).

AE records are available from the Orchi AE station. The data series contains some gaps, but the database is reasonably complete. Figure 6 shows the "F" value of the LF AE for all 8 years superposed, with an offset in order to distinguish different years. One unique large peak appears, just a "*crustal impulse*" lasting ∼12 h, displaying intensity impressively larger than the signal implied by a "*crustal storm*". It preceded the l'Aquila earthquake by ∼32 days . After this event the signal stabilized its intensity on a higher value (presumably because the acoustic impedance of the "natural probe" had been changed).

Figure 7 shows a detail of this peak from the raw LF AE data. It exhibits some internal structure, being the likely evidence of some lines of the tidal spectrum and/or by some

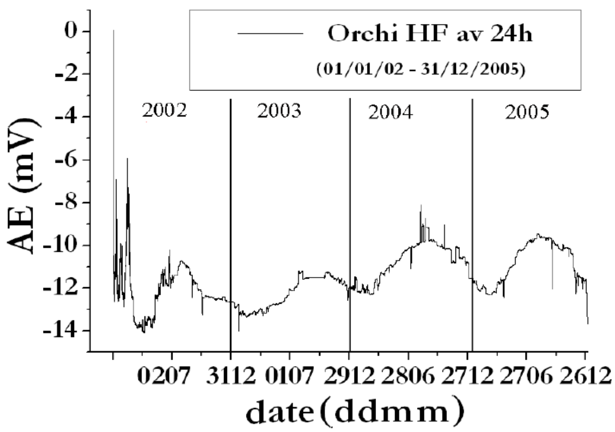

Fig. 4. HF AE records at the Orchi site (Foligno, PG). The much regular seasonal variation is clearly shown, and the anomalous "*crustal storm*" during early 2002. See text. After Poscolieri et al. (2006a).

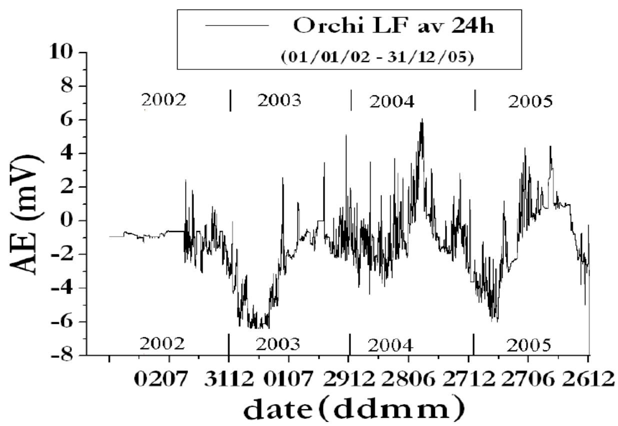

Fig. 5. LF AE records at the Orchi site (Foligno, PG). The much regular seasonal variation is clearly shown, and the anomalous "*crustal storm*" beginning on 12 August 2002. See text. After Poscolieri et al. (2006a).

free oscillation of the Earth (this item is to be investigated by means of the outlier series; see Sect. 3). In any case, this peak is much different compared to a MFE (Sect. 1.1).

Figure 8 shows the original database, with no rejection of outliers, and no smoothing, with the ordinate scale limited to the range 0–0.1. The anomalous signals associated with the outliers can be recognized. These data were the objects of several papers (Gregori et al., 2005, 2007; Paparo et al., 2006; Poscolieri et al., 2006a). The vertical yellow rectangle indentifies the aforementioned "*crustal impulse*".

The central vertical arrow in Fig. 8 indicates the beginning of an increasing trend, which occurred since June 2008. It elapsed until the end of 2008 (right vertical arrow), and it continued through 2009 (left vertical arrow). This is a "*crustal storm*", as it better shown in Fig. 9 (raw input data), where the storm is monitored in HF AE and LF AE both at Orchi and at Valsinni. The storm appears to have started shortly before 26 May 2008, when the Valsinni station began to be operated. All four records, either HF or LF, either at Orchi or at Valsinni, seem to increase almost simultaneously (see Table 3).

Another case history of a "*crustal impulse*" was observed at Giuliano, on the occasion of the Potenza earthquake. This is shown in Fig. 10, reporting a multiparametric monitoring (Paparo et al. 2002). On this occasion, however, records suffered oversaturation. This "*crustal impulse*" lasted $\sim$12 h, and it preceded the Potenza earthquake by $\sim$2 days.

Figure 8 also displays a gentle seasonal modulation, which is much better evidenced in the HF AE (Fig. 11). This phenomenon was already investigated by Poscolieri et al. (2006a), upon comparing the HF AE data series from Orchi (see Fig. 4) with the same from Cephalonia. A close synchronism was found. The entire morphology appeared clearly suggestive of a possible evidence of the *loading tide* effect (see Sect. 1.2).

Another peculiarity of Fig. 11 is concerned with the aforementioned MFEs. As already mentioned (see Sect. 1.1), whenever needed the data analysis was sometimes carried out separately over three subsets, upon selecting the data set referring to positive MFEs, to negative MFEs, and to "normal" AE records, respectively.

For completeness sake, it should be mentioned that a few additional anomalous trends were also observed that preceded the l'Aquila earthquake.

At Valsinni, the LF AE outliers, smoothed by a weighted running average over 24 h, became about two times larger some $\sim$293–280 days before the main shock, and they displayed an abrupt peak $13^{hours}\,35^{min}\,13^{sec}$ before it. Another intriguing occurrence – maybe a possible precursor – was an apparent short duration and temporary fading off of the AE signal (at either one, or both, stations, and/or for HF and/or LF). But it appears difficult to envisage a mechanism capable of explaining it. These lesser phenomena require a much wealthier data base, and harder thinking.

A warning, however, is that – as mentioned in Sect. 1.3, likewise it occurs for every investigation of earthquake precursors of any kind – some uncertainty always remains about associating a given observed anomaly with a precursor or with a co-seismic occurrence, or with an aftershock. In contrast, AE records permit to know that HF AE do precede LF AE evidences. But sometimes this is not sufficient. For instance, in the case of the l'Aquila earthquake, another earthquake had occurred with epicentre in the northern Apennines (slightly North of the city of La Spezia, south-east of Genoa, on 23 December 2008; M=5.02). Hence, uncertainty always remains at least until a suitable array of AE stations is operated.

5 Diagnosis vs. prediction – improvements

We report sound evidence that a "*crustal storm*" is a large scale phenomenon involving the entire Italian peninsula that, however, can hardly be reckoned to any one specific given earthquake. The occurrence of an earthquake depends on the local response of the crust to a violent paroxysm that involves a wide region.

It is likely that only the analysis of "*crustal substorms*" (Gregori et al., 2010) can give (perhaps) some better evidence related to specific seismic events. But an array of AE stations is strictly required.

It is customary – for the Civil Protection of every country – to release alerts when a severe cold front crosses over a region. The alert elapses as long as the cold front is passed away. Local authorities know their respective hazard sites. A "*crustal storm*" gives an alert, involving however a large "slab" (such as the entire Italian peninsula), and its elapses several years. This is of little help. But, meteorological alerts rely on a large network of stations from all over the world, plus satellite data. The analysis here reported relies *only on one or two* AE stations with some sporadic comparison with the Cephalonia AE data. Even meteorology could get no useful alert by any comparably limited set of stations alone.

As far as the present study is concerned, it appears that during 1996–1997 the Italian peninsula suffered by a prolonged "*crustal storm*" during which the Potenza and Colfiorito earthquakes occurred. Maybe even the Molise earthquake in 2002 was still related to that paroxysm (but we lack information for 1998–2001). Then, the crust was apparently "quiet" until the paroxysm that began close to the end of May 2008, which triggered the l'Aquila earthquake. Our subsequent AE records definitely show that by the end of 2009 the "*crustal storm*" was still on.

Much misunderstanding is often found. Hence, for clarity purposes, it is important to stress that AE records can provide with no "prediction". They are rather a *diagnostic* tool, much like in medical sciences one or several different tools help in diagnosing the state of health of a patient, though they cannot forecast her/his passing away.

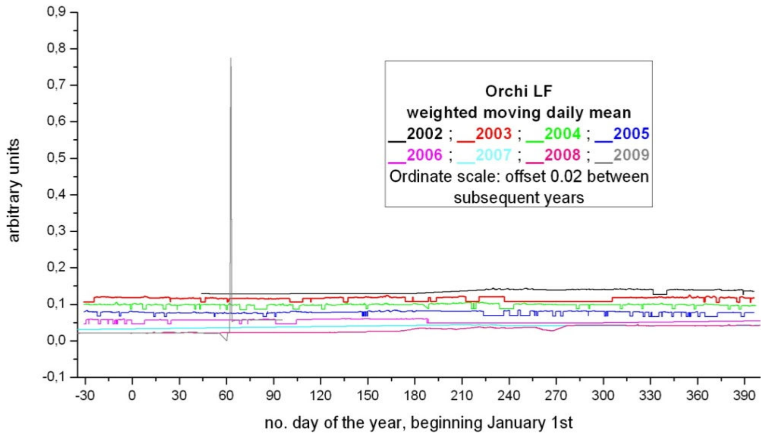

Fig. 6. Superposed LF AE records at Orchi. All strings of data, shown with a slight offset between different years in order to avoid overlapping, begin from 1 January of every respective year. See text.

Table 3. Precursor times for different case histories monitored at different AE stations.

Earthquake name	Date	Magn.	AE station	HF AE	LF AE	Distance from epicentre	Comments	Figure no.
Potenza	3 Apr 1996	4.9	Giuliano	(not available)	>2 months (71 days) beginning 23 Jan 1996	∼29.7 km	also D_t precursor (“Potenza effect”)	3
					2 days (very large LF AE lasting ∼12 h)	∼29.7 km	“short duration crustal storm”	10
Colfiorito	26 Sep 1997	6.0	Giuliano	(not available)	∼15 days (see text)	∼353 km	also D_t precursor	3
Molise	31 Oct 2002	5.8	Orchi	>8 months (it was over by ∼10 Feb 2002)	>2 months (80 days) beginning 12 Aug 2002	∼229 km	anomaly (spike on Vesuvius; LF AE and D_t). See text.	4 5
Lefkas	14 Aug 2003	6.3	Ceph.	>7–8 months	>2 months	∼68 km	also D_t and *Rn* variations	
l’Aquila	6 Apr 2009	6.3	Orchi	10 months (<26 May 2008)	10 months (<26 May 2008)	∼88 km	other possible precursors to be discussed elsewhere	6 8 9 11
			Valsinni	10 months (<26 May 2008)	10 months (<26 May 2008)	∼354 km	other possible precursors to be discussed elsewhere	6 8 9 11
			Orchi		32 days (very large LF AE lasting ∼12 h)	∼88 km	“short duration crustal storm”	6 7 8 9
Albania	6 Sep 2009	5.5	Ceph.			∼369 km	“short duration crustal storm”, also “Potenza effect”	

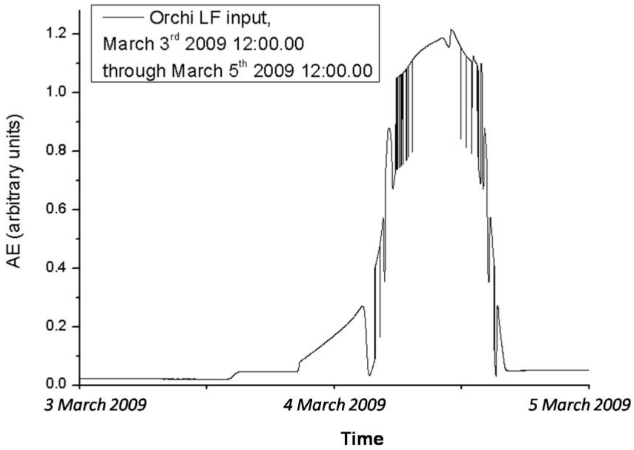

Fig. 7. Detail of Fig. 6 (but raw AE data, not "F"), showing the internal structure of the "*crustal impulse*" lasting ∼12 h and preceding by ∼32 days the l'Aquila earthquake. See text.

Earthquakes are a dramatic concern for society. Different roles are pertinent to different specialists.

1. AE observations – whenever suitably improved, see below – can help in diagnosing a possible or likely time interval (or "*storm*" time) when a "catastrophic" event (somewhere within some wide area, and of unknown intensity) could occur.

2. The site of the (possible) epicentral area cannot be assessed by means of one AE station alone, rather – at most – by a suitable array of AE stations (see below). Also the magnitude of a possible future shock cannot be inferred by AE records.

3. The operative procedures – in terms of potential causalities, costs, and feasibility – are to be decided by the Civil Protection of every country.

4. Managing the drawback of possible false alerts is the responsibility of legislation. False alerts have a cost, although this is to be considered like an insurance cost aimed at limiting causalities or greater damages.

Improvements can be envisaged when dealing either with every single AE station, or with an array of AE stations. In either case, it should be stressed that phenomena are never repetitive. Every earthquake is a different case history, either because it occurs in different tectonic settings, or because – when it occurs in the same area – the general environmental conditions have evolved. The arrow of time is always in one direction, and everything is permanently ageing.

By means of one AE station alone, a substantial improvement of the reliability of the diagnosis can derive from monitoring the temporal evolution of the system by means of a greater number of frequencies, e.g. at 20, 15, 10, 5, 2.5, and 1 kHz, etc. By this, one and the same (or much similar) kind of precursor is to be expected to be observed in a temporal sequence from higher through lower frequencies. That is, in this way some "movie" of the evolution of the system can be given, with a capability of envisaging the critical time of a possible "catastrophe", with an increasing better temporal resolution. In addition, consider that every precursor is biased by some noise. Hence, the observed sequence of precursors can validate their respective significance and give an indication on their respective signal/noise ratio.

A drawback, however, is that the evolution of the physical system can eventually change during its development, due to an unexpected change of its boundary conditions in terms of a modified stress transfer from its contiguous crust. Another drawback is that a given AE precursor equally holds either for a violent or for a weak earthquake.

Whenever an array of AE stations will be available, on the one side the propagation of crustal stress through a given area can be traced, and – mostly – the crustal extensions can be assessed that can be approximately treated like a unique lithospheric slab (as per Sect. 1.2). In addition, if the array is characterized by a mean linear distance L between contiguous AE stations, it is possible, roughly speaking, to envisage the site of a possible forthcoming "catastrophe" of the system with a space resolution of the order of L. This is, however, only a much indicative and approximate guess.

An earthquake is a very bad indicator. It is a phenomenon characterized by a much erratic signal-to-noise ratio. It is likely that other methods can provide with easier and more reliable information for guessing the hazard sites. AE monitoring is rather just one much effective diagnostic tool, mainly for monitoring the *time* evolution of the system towards an eventual forthcoming "catastrophe".

Another crucial parameter of concern deals with the *magnitude* of an eventual forthcoming earthquake. Envisaging the possible time or site of an event does not necessarily mean that the seismic event shall be destructive, rather than being e.g. a seismic swarm. In this respect, the analysis by the late Giuseppe Cello appears noteworthy (see Cello, 1997, 2000; Cello et al., 2000, 2002). The principal idea is to consider the location of geologically recent faults inside a given area, based on standard geologic maps. Then carry out a fractal analysis in 2-D on their distribution inside every given area, and evaluate its 2-D fractal dimension D_s. In the case of a 2-D random fault distribution – i.e. when the crust is very "young" with no previous fracturing history – it must be $D_s = 2$. In the case of an "aged" crust, i.e. when the crust already suffered by several past fracturing events, it must be $D_s = 1$. Cello and co-workers proved that the maximum magnitude of an earthquake that – at any time in the past – hit a given area, is a linear function of D_s, according to the law (holding for central Italy)

$$M = 10.2 D_s - 6.5$$

That is, the larger D_s the greater is the maximum magnitude of an earthquake that can potentially hit that area.

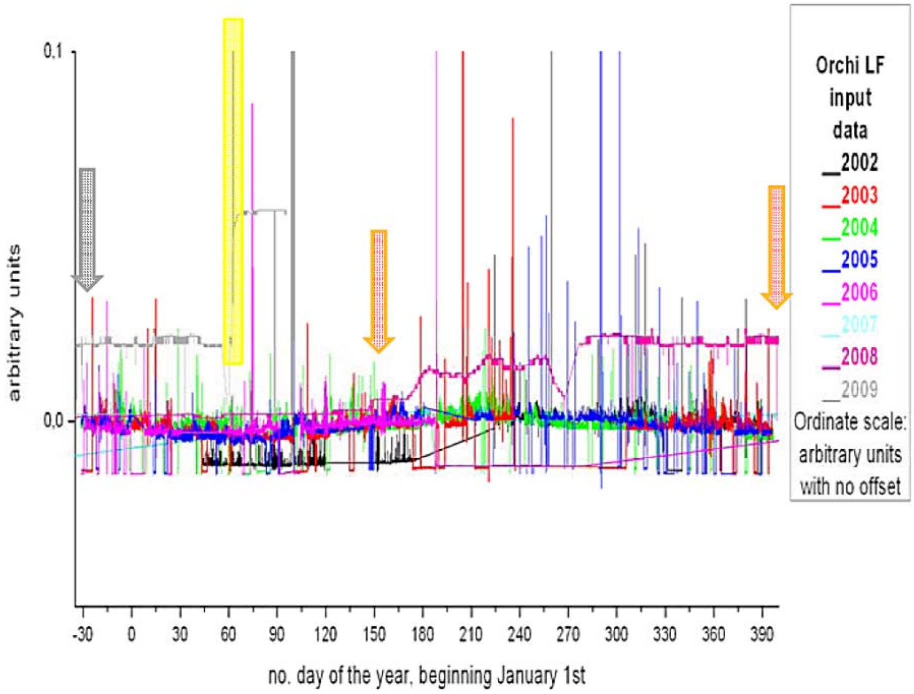

Fig. 8. Detail of Fig. 6, referring however to raw data, with no outliers rejection, and no smoothing. Note the gentle seasonal variation, and the "*crustal impulse*" (yellow rectangle). See text.

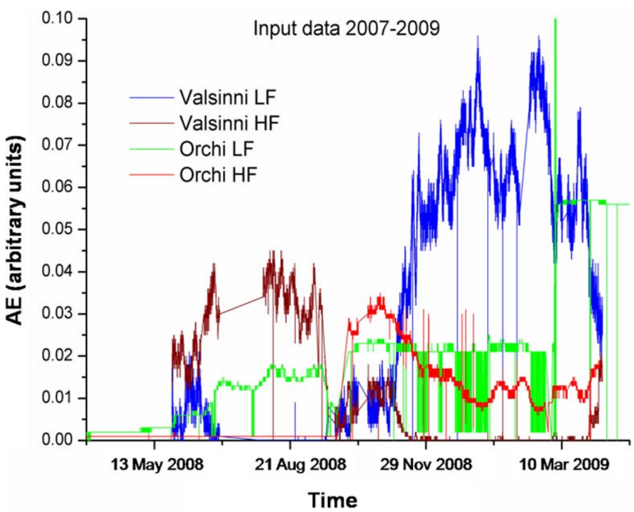

Fig. 9. Raw AE records at Orchi and Valsinni, showing the onset of the "*crustal storm*" that preceded the l'Aquila earthquake. The "*crustal impulse*" is also clearly shown (in green).

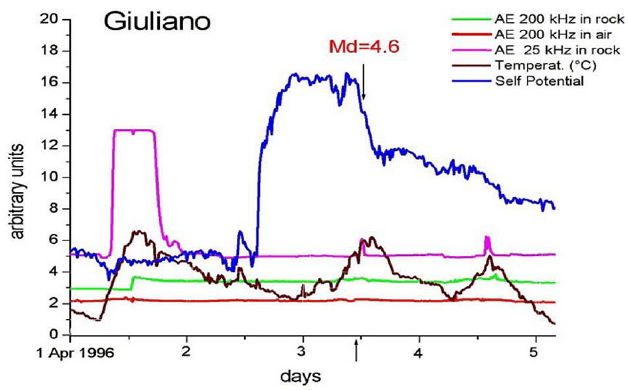

Fig. 10. Multiparametric monitoring, at the Giuliano AE station, of precursors of the Potenza earthquake. The signal here of concern is denoted as AE 25 kHz in rock, being the LF AE that went in over-saturation during the ∼12-h period of time of a "*crustal impulse*". Redrawn after Paparo et al. (2002). See text.

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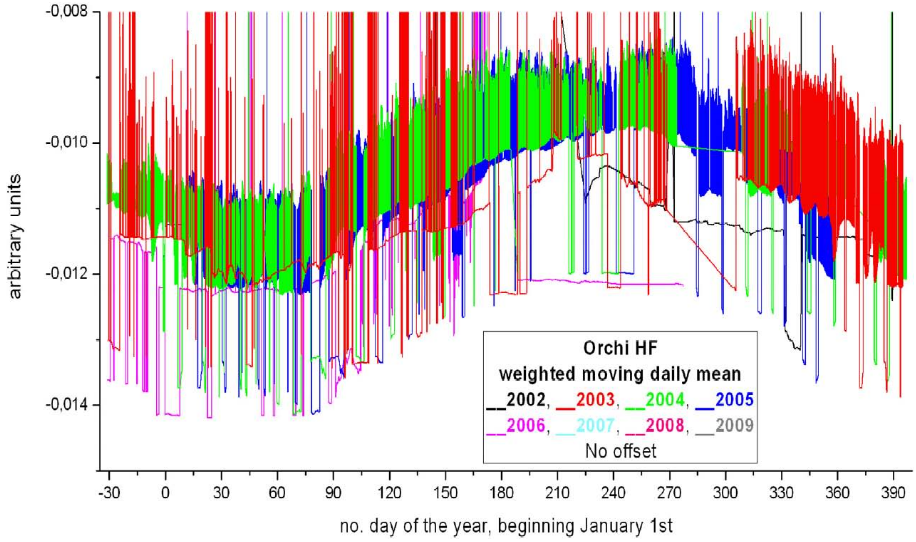

Fig. 11. HF AE raw signal at Orchi, superposing several years, every string beginning by its respective 1 January. This figure clearly shows the seasonal variation being the likely consequence of the loading tide. In addition the figure gives clear evidence of the MFEs, and the data analysis was carried out by considering three subsets ("normal" values, negative MFEs, positive MFEs, respectively). See text.

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