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Acoustic emission in geophysics: a reminder about the methods of analysis

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Abstract - Acoustic emission is a diagnostic tool of unexpected heuristic potential, although inadequately exploited at present. Its applications deal with the general problem of non-destructive testing of mechanical structures, including a wide span of environmental problems. Some basic methodological items are briefly highlighted. A correct approach in terms of clear concepts is fundamental for an effective and successful application of such a remarkable diagnostic tool.

1. The rationale

Acoustic emissions (AE) that originate from solid bodies occur every time some chemical bonds yield. Such atomic or molecular scale phenomena have, therefore, a sub-microscopic nature, though they can be detected only after suitable integration both in space and time. Such a requirement has different implications, depending on the kind of phenomena investigated.

A key aspect is the propagation capability, or teleconnection, of the AE signal from the source through its detector. AE propagation reaches distances of practical relevance only in the presence of some non-fragmented (i.e. compact) solid conductor, or of a fluid such as water, while its propagation rapidly dampens off when passing through loose ground. From a practical viewpoint, in general, a single atomic or molecular event cannot be detected. The feeblest detectable effect depends on the sensitivity of the sensor, on its distance from the source, and on the transmission capability of the signal. Moreover, in general, every monitoring device has its own typical recovery time, by which it can record only signals above some given threshold, having some minimum time duration, and with a time rate not faster than some given constraint, related for example to the electronics of the data logger.

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Owing to such unavoidable limitations, every AE investigation requires a (and never obvious) premise, or first step, which is the formal definition of the "AE event", resulting, in any case, after a suitable space- and time-integration. Moreover, such definition is in general not unique for every given system. It depends on the investigation being considered. Scientific understanding is made up of simple concepts that must be suited for the human mind and reasonably akin to the complexity of natural reality. An event defined in one way is suited for investigating some given phenomenon at some given level of detail, while other details of the system may require a different definition of event. Differently stated, this is like a logical sieve, whose target or effectiveness depends on the a priori choice of the size of its holes. For instance, in the applications tested by the authors, "AE burst" is called a raw record, with a certain high-time resolution; "AE microevent" is a record of the sum of the maximum amplitudes of all bursts occurring within a given time interval of ~ 10 ms, and an "AE event" is similar to a microevent, although in terms of a much longer averaging time interval. In the specific geophysical applications exploited by the authors an event was characterised by an amplitude, which is the average amplitude of all microevents falling inside some given pre-chosen acquisition time-lag (normally ~ 25 s). Moreover, an event is said to occur whenever its magnitude is above some pre-chosen threshold.

The second step deals with typical time-sequences of such events, called macroevent. Its prime origin can be different in different case histories. It derives from a progressive yielding of bonds (by borrowing a term from seismology) within the focal volume where AE is released. In any case, a macroevent denotes a phenomenon that has a clearly recognisable beginning, and an end, which occurs after some characteristic time lag, due either 1) to the physical relation between trigger and evolution of phenomena, or 2) to the intrinsic internal physical structure of the system, or also 3) to the physical nature of the forcing factors (an accessory aspect, subsequent to the trigger) that determine the evolution of the macroevent.

The third step will be to consider the temporal sequence either of the events or of the macroevents. In general, a macroevent is an entity that is composed of details, every one of which is an event.

The rationale and algorithms used to investigate one macroevent are considered first, subsequently the time-series of events or macroevents.

2. Definition and analysis of a macroevent: the *probit* diagram

Different definitions of macroevent are required for investigating different time- and/or space-scales, being a strict requirement deriving from the human need for simplicity. Small-scale phenomena can be tackled by considering two different basic trends or mechanisms. One phenomenon is characterised by a space distribution of the AE sources, spread out almost isotropically into a 3D space (such as for example a hot fluid diffusing through the pores of a solid). By contrast, a different morphology is observed when bonds yield, preferentially, along some plane (such as a cleavage plane of a crystal, or the plane of a tectonic fault), where the force that opposes the stress is the sum of some very large number of atomic or molecular bonds (in the following let us call them simply microbonds). Whenever one such microbond yields, its nearby microbonds will probably also yield in sequence, much like in a chain reaction. Such new and different aspects, compared to the aforementioned case history of a 3D distribution, can be recognised through a suitable analysis of the time-sequence of the AE events released during every one of such time-integrated AE macroevents.

For clarity, first consider a simple case history later, to be generalised. Let us assume that the system, behaves approximately, according to the law that is typical of a public service. For such purpose, it is conventionally supposed that the probability that a user is going to request a performance at a given time by that given public service is proportional to the total number of people who already use it at the same time (this is the mathematical translation of the concept of rush hour). The same criterion applies to the hypsometric curve of the Earth or of a planet, and to the height distribution of sand specks in a pile, etc., because a given sample of matter is located at some height only if some corresponding amount of matter is located underneath it in order to support it. Several sociological items are also of similar concern. Upon consideration of such a great variety of different applications of the same rationale, the only observed mathematical fact (i.e. observing that one given variate has some specific distribution) is not necessarily *per se* synonymous of being associated with some given physical law. Rather, it reflects some general statistical property that belongs to some wide class of logically analogous, though eventually physically much different, case histories.

Such a global problem can be treated only by means of the so-called Kapteyn class distributions (Kapteyn and van Uven, 1916; Arley and Buch, 1950) which makes it possible to investigate the distribution of a set of events within a macroevent, whenever it is known a priori that their occurrence probability should fit within some pre-assessed mutual relation, of either a physical law or other. One such specific case history is the aforementioned public service planning, where it is formally and straightforwardly shown that the events must satisfy a lognormal distribution.

One aspect, however, deals with the aforementioned AE reaction chain and if it conforms or not to such a simple law, typical of a public service. Realistically speaking, it rather characterises the progressive yield of microbonds along some almost flat surface (i.e. along some almost 2D or, better, within some thin 3D-slice in 3D space).

On the other hand, from a more understating viewpoint, one realistic possibility is that even the appearance of one such temporal structure could be biased and respond to some unknown constraint (molecular for a cleavage, or tectonic for a fault plane, etc.) other than the former speculated chain-reaction mechanism. In such a case of underestimation, the temporal trend of a macroevent may be of any type, i.e. not necessarily leading to a lognormal distribution. In every such case history, the probit diagram appears to be an effective heuristic algorithm for dealing with such an assessment.

For brevity the reader who is interested can refer to the account given for example by Arley and Buch (1950), or also see Paparo and Gregori (2002). We just wish to remind the reader that a mere law similar to a public service leads to a straight line drawn within the probit diagram.

In such a case, the macroevent is characterised by a lognormal distribution of events, a fact that implies some specific constraints on the kind of physical control of the system. By contrast, every additional degree of freedom (d.o.f.), which in some way characterises the system, shall correspond to some additional parameter within the probit diagram, that describes the deviation of the diagram from a merely linear trend. In this way, the probit diagram is fairly suited to foresee how many additional d.o.f. are eventually required, and it actually provides a way of computing them, and their temporal evolution. The physical meaning and specific definition of every such additional parameter is eventually unknown. However, it is important to be able to know the existence of how many additional d.o.f. are needed, and how to deal with them in terms of quantitative estimates. Their respective physical meaning and the details depend on the specific physical definition and structural properties and composition of the system, etc. That is, such an aspect is no more a matter of some general mathematical statistical property, concerned with a data handling that holds for any given non-better-specified physical system, but rather it enters into the physics of the system.

It can be noted, however, that, owing to the aforementioned intuitive reaction-chain argument, it seems general by likely that the phenomenon ought to behave, at least as a first order approximation, like a lognormal distribution.

A basic concern deals with the total time span of such composite and presumably approximate lognormal AE macroevent. Suppose that this whole argument can be correctly applied: the time-resolution Δt that is needed for detecting such trend has to be assessed. One such indication is derived from one example borrowed from the literature (Cousland and Scala, 1983; Scott, 1991), regarding an experiment on special Al alloys (7050- and 7075-T7351) where a stress elapsing after several minutes was applied. It clearly produced a trend of the AE counting rate vs. t that, looks much like a lognormal distribution upon direct visual inspection. A convenient definition of macroevent appears to be determined by the externally applied stress function vs. t, although in such a case the general resulting trend denoted an AE rate which was apparently similar to the user-number of a given public service. This fact alone already envisages the correctness of the aforementioned mechanism where the subsequent bonds yield along preferential, and already pre-broken, planes. However, as a formal physical addition to this, the probit diagram allows us *per se* to check such trial inference, and guess an eventual slightly different law that should be characterised by a greater number of d.o.f. It can be conclude therefore that, while experimenting on alloy specimens in the laboratory, i.e. while being concerned with microcrystal features of a material, a total time-range of a few minutes appears sufficient for an effective monitoring of such chain-reaction mechanism, although in such example the chosen duration of a macroevent is a consequence of the external trigger. However, it appears important that there is no need to appeal to some much higher temporal resolution of the recording apparatus.

In this same respect, Lòpez Pumarega et al. (1999) investigated the AE of specimens put under stress in the laboratory, while presuming no a priori expectation on the form of their distribution. Upon formal statistical analysis, they showed that the distribution definitely appears lognormal, and not for example, Weibull's, etc.

However, when dealing with large-scale geophysical phenomena, such as a land slide or tectonic faulting for example, in principle, there is no need for such a temporal range to be the same, as the prime, leading physical processes are substantially different, and it appears reasonable to expect that the phenomena ought to occur on a time-scale which is much longer than the span of just very few minutes. Summarising, the macroevent duration has to be chosen depending on the physical system of concern, and on the level of observational details considered.

3. The analysis of a time-series of events or of macroevents

Incompleteness - An important premise deals with the fact that, in general, time-series of natural occurrences are most often incomplete, and every datum, within every one given, and the same series can be affected by error bars (both of time-instant and of ordinates) that can be different among each other. Moreover, an AE time-series monitored on a homogeneous object, such as on a metal-bar in the laboratory for example, has no teleconnection problems. Therefore, the available records contain no data gaps for sure. By contrast, in general, every time-series of natural occurrences shall contain some unknown percent of missing data or gaps. For instance, the occurrence of some phenomenon is eventually reported, although in general no information specifies whether that same kind of occurrence happened or not at other times and under presumably similar or comparable situations. Sometimes such lack of information can be correctly interpreted as implying that, actually, no such occurrence happened (i.e. whenever no specification of "yes" is given, we can presume that this is equivalent to specifying a "no"). Sometimes this is not correct however, as this was due only to the fact that no one was available to give a report, sometimes due to cultural problems, or to temporary social or economic difficulties, etc. Whatever the reason, all such factors determined a sum of biases. In general, such a drawback can never be avoided. It is therefore important that every algorithm that is applied to historical time-series should be reasonably robust with respect to gaps or to a variable error-bar vs. t. In the case of AE records, the data are collected by putting the acoustic transducer on top of some rocky outcrop, which is presumed to represent a dyke, or some large block of limestone, etc. Differently stated the entire monitoring apparatus is composed of the acoustic transducer *per se*, and, as an essential and fundamental component of the same monitoring apparatus, also of the rock-block, whose spatial underground extension is unknown. This implies that the AE monitoring apparatus available samples AE from some partial subvolume of the entire underground system. The recorded AE time-series in principle contains gaps that are no more related to the availability or not, or to the scientific sensitivity and culture of a chronicler, rather to the fact that only some unknown sample of underground volume is probed.

Robustness - The best known algorithm to treat a continuous function $f(t)$ of t, which represents the evolution of a natural phenomenon, is to analyse it in terms of a Fourier series (whenever it is known a priori that it is governed by a phenomenon having some fundamental known period, such as in the case of, for example, all phenomena controlled by the diurnal rotation of the Earth, or by its annual cycle, or by the lunar orbit, etc.). If no such fundamental period is known, it is customary to apply the Fourier transform (generally the FFT). However, such algorithm *per se* strictly requires a uniform data series, with no gaps, with uniform error-bars, etc., i.e. it is non-robust, and its use for environmental long time-series is well known to have sometimes led to misleading conclusions, harsh debates, and misunderstandings. Such a warning should be suitably taken into account when dealing with every other algorithm. This crucial aspect ought to be a main responsibility of the geophysicist, because a mathematician generally prefers to start from some pre-chosen assumption about the nature of some prime time-series of occurrences (in fitting with his own logical models or speculations), and thus derive his theorems, implications, and conclusions. The geophysicist, on the other hand, knows that no a priori knowledge about the nature of a given observed time-series of occurrences can be presumed. Therefore, he should, rather, consider algorithms that can allow for a wide variety of possible assumptions concerning data completeness, uniformity, and steadiness. The optimum algorithm should require only some very-last-moment decision, i.e. a posteriori rather than a priori, dealing with the guessed nature of the original database.

Point-like processes - A time series of events or of macroevents is treated like a point-like process, i.e. a sequence of "yes-occurrences", every one having (as a first order approximation to carry out data handling) a supposedly approximately identical intensity, and a duration Δt that is supposed to be negligible compared to the total time duration L spanned by the entire time-series. Therefore, in the following, every element of the time-series is considered almost like a Dirac δ-function. Differently stated, the analysis of point-like processes is concerned only with the abscissa time of every "yes", while it neglects the intensity or ordinate of such "yes" completely. In practical applications, a threshold has to be pre-chosen, where we can decide that a "yes" occurs every time that the phenomenon being investigated lies above such a threshold. In general, one does not know how to choose such a threshold. A practical, effective criterion is to try different choices, and to compare their results among them. One should discover that the final result is independent of such a threshold, provided that it is not chosen excessively low to permit the noise, or part of it, to enter into the data handling. The choice of the threshold is therefore a reasonably robust component of the entire data handling, in the fact that, for every choice that is above some suitable value, the result will always display the same conclusive inference.

As far as the AE time-series are concerned, they can be considered as a witness, or as an index, of some phenomenon that is in progress, while every event or macroevent normally deals *per se* with some definitely irrelevant and negligible energy content. Moreover, in general, owing to the aforementioned teleconnection limits, the recorded AE are representative of, or can actually monitor only, a subvolume of the physical system of concern, and are therefore only a fraction of the AE phenomena that effectively occur within the system being monitored (this, at least, is a realistic bias affecting natural time-series, unlike laboratory monitoring of confined and homogenous solid objects). It appears therefore reasonable to conclude that (in general, unless otherwise specified) the observed total AE energy is severely biased by large and unpredictable error-bars. Rather, AE information is most relevant when considering (rather than the intensity of every event) its time pace, although upon allowing the database to contain eventual, unpredictable gaps. Summarising, an AE time-series can be considered like a series of "yes", eventually containing some substantial amount of unknown gaps.

Since the early Seventies, point-like processes have become a classic topic in statistical analysis of time series (e.g. Brillinger, 1975; or references in Pavese and Gregori, 1985). In the following, an additional distinction is made, which is normally neglected by formal mathematical treatments, depending on whether the time-series is more or less complete, or rather affected by some unknown amount of gaps. The applicability of either one of the following algorithms depends on the (a priori unknown) accuracy and completeness of the available data series. A practical, effective criterion is to try to apply, whenever possible, every such guessed algorithm, and to judge a posteriori, whenever possible, the apparent reliability and physical significance of results.

Five different logical scenarios can (or must) be envisaged (Gregori, 1998).

1) Suppose that the data series contains some (partial at least) periodical component. The superimposed epoch criterion (ARP operator) seems to be the best algorithm.
2) Suppose that data respond to some energy saturation threshold: in such a case a calorimetric criterion and the Imbò algorithm are best suited.
3) Some extreme phenomena occur only because of a substantial change of the boundary conditions of the system.
4) An alternative possibility, often considered in the literature, deals with the assumption of an instability of nonlinear equations, attractors, chaos, etc.
5) Whenever the data series does not seem to fit with anyone of the aforementioned constraints and algorithms, either due to an insufficient knowledge of the system or due to an excessive amount of gaps, fractal analysis seems to be the best possible choice.

For clarity, let us consider a few such specific examples. The rupture, either of a dam or of a river embankment, dramatically changes the water flow regime, causing certainly a change of boundary conditions, triggered by some cause that in general can be external to the system. A magnetospheric substorm can be expressively interpreted and modelled by considering the effect of a temporary gap of electric charges within the solar wind flow (a so-called plasma cavity), by which the usual Eulerian description of the magnetosphere in terms of magneto-hydrodynamics (MHD) temporarily fails down. Either a temporary, or a long-lasting, reversal of the geomagnetic dipole field (known as field reversal, or also geomagnetic excursion when the constant-polarity duration is < 150,000 years) is generally tentatively explained by the standard MHD geodynamo models in terms of numerical instabilities of the nonlinear equations of the speculated classical homogeneous MHD geodynamo model. On the other hand, it can be much more convincingly explained in terms of an external trigger (Gregori, 2002). El Niño and La Niña are normally explained in terms of a clever numerical treatment of instabilities deriving from nonlinear interactions (Philander, 1990; Diaz and Markgraf, 1992; and references therein). Such proposed explanations are *per se* remarkable mathematical achievements. However, since the available observational evidence of such planetary-scale phenomena is unavoidably biased by error-bars and uncertainties, sometimes it can appear difficult to decide whether some model actually fits observations or not. It has to be stressed that in any case no absolutely certain explanation exists for every given phenomenon, only more or less reasonable guesses, depending on the accuracy and detail of the observational database available. In particular, we know very little about heat exhalation from the ocean floor, and it is presently impossible to assess whether such unknown parameter can or cannot affect the occurrence of such dramatic phenomena (e.g. Gregori, 2002). In the late Sixties it was unanimously claimed that the minor atmospheric constituents have no role in atmospheric physics, due to their irrelevant mass contribution. Later, it was realised that such minor constituents are extremely critical for determining the amount of solar energy that is captured by the atmosphere. Today they claim that the geothermal heat flow within the atmosphere/ocean system is energetically small. However, nobody considers that it can dramatically control water evaporation and gas exhalation from the ground, hence the greenhouse effect, hence the total energy of the system. Other catastrophic phenomena, such as a lightning stroke for example, or a hail storm, or a flash flood, or the mascaret (i.e. a soliton-wave penetrating upstream along a river, triggered by the oceanic tide), or a landslide, or a snow-slide, or coastal erosion, or an earthquake, or a volcanic eruption, etc. sometimes seem to be explained by some model, sometimes not, and in any case one has to make some preliminary assumption before attempting to give any kind of interpretation. In general, one should consider that different explanations should always be proposed for the same occurrence, at least compatibly with the quality of the available observational information. The five aforementioned mechanisms cannot be compatible with each other, and natural phenomena should be capable, in general, of choosing the correct solution. Relying on only one such kind of attempt can be misleading. The implementation of some clever mathematical model does not necessarily imply having always caught the correct physical content of phenomena.

A few additional details, which are most relevant for AE data handling dealing with fractal analysis, are recalled here. Until the middle Seventies, when no other aforementioned algorithm could be applied, the unique approach to such a case history appeared to rely on the probability theory, much like playing with some ideally perfect die, etc. This is, however, a viewpoint that strongly underestimates the physical aspect which is what a mathematician needs. By contrast, physically speaking, the geophysicist is convinced that nothing occurs by chance, and he wants to infer some concrete physical inference focusing on the non-randomness of observations.

For centuries, the ultimate rationale from such mathematician's viewpoint was only in considering a perfect ideal determinism (according to Laplace or Lagrange). Otherwise, the unique alternative was by assuming perfect randomness and probability theory. After the discovery of fractals, however, such extreme dichotomy became milder, due to the fact that a hierarchy of intermediate levels was envisaged, leading to the so-called theory of chaos, defined by means of a parameter known as fractal dimension. This is now a classical algorithm in data analysis (e.g., see Feder, 1988, or Peitgen et al., 1992, or Turcotte, 1992, or every textbook on fractals). No mention will be made here except about one specific, and one of the most elementary, algorithms, i.e. the box counting method (bcm). From the viewpoint in question, only the fundamental, intuitive, simple, immediate, essential, intrinsic, easily understandable properties that lie behind the fractal approach are needed. The application of some less elementary algorithms is to be considered, whenever necessary, only at a second stage. The revolutionary new perspective opened by fractals *per se*, and independent of such mathematical technicality, ought to be emphasised. Several improvements were proposed and discussed in the literature (see e.g. just a few mentions in Gregori, 1998). However, every algorithm is effective only when the database is suited for its implicit a priori assumptions, a fact that in general can be assessed only a posteriori.

The bcm has relevant implications for recognising random vs. non-random point-like processes, or 3D vs. 2D focal sources of AE. Consider an ideal, perfectly random point-like process. Owing to the aforementioned inference, just by a matter of definition, the fractal dimension can be shown to be $D = 1$. Suppose, instead, that some (even unknown) law governs the point-like process. We cannot know or even envisage such law. We rather just observe its consequences. We need only to assume that the gaps and violations of uniformity of the database have no regular bias, such as to false our apparent subsequent inferences. Then, we know that it must always be $D =< 1$, and the greater the deviation (with respect to $D = 1$) the greater the organisation of the time-series of the point-like process, and the larger the control by such unknown law.

In the case of a time-series of AE events or macroevents, one such concrete case history is found when considering the prime AE sources within every given AE focal volume. For instance, suppose that a metal-bar, which has never been stressed after casting, is stressed. Since it cannot be a strictly ideal perfect elastic body, every time that it is stressed some microdeformations will occur within its crystal structure. Moreover, every time that the stress is repeatedly applied, the newly formed microdeformation will occur preferentially along the same cleavage planes where the previous microdeformations already occurred. Differently stated, the AE time-series ought to reflect a progressively less random, or more ordered, temporal sequence. This will occur until the metal of the bar attains some final regime, or saturation behaviour, after which microdeformations will still occur, while the metal-bar will reveal some quasi-steady performance, and its subsequent strain will reflect long-time-range behaviour before its final complete fatigue, yield, and rupture. During such saturation regime, AE monitoring can eventually be used to detect the unexpected application of some unwanted or unexpected stress, originated by any cause, with a presumable sensitivity that is higher than by means of any other monitoring device.

Another example is concerned with repeated warming and cooling of an object, such as a rock block, or furniture, etc., due to diurnal temperature variation for example. Since such object is warmed from the outside, its outermost layers progressively warm up and expand. The opposite occurs when it cools: the outmost layers cool first and contract. However, while contracting, they find the inner layers still warmer and more expanded. Hence, such contraction requires some microdeformation and sliding preferentially along planes. Such phenomenon is observed e.g. on Gran Sasso, or in every furniture in a cool home during wintertime. Another example is concerned with the effects of a hot fluid penetrating into the pores of a rock by diffusion for example. Since diffusion is isotropic, AE are associated with the yielding of microcavities, which are 3D distributed in space in some random way. In every such case, the submicroscopic nature of monitored phenomena ought to be emphasised. The capability of such method to detect such minor features ultimately relies on the fact that the natural phenomena apparently display the identical fractal behaviour on the single microbond scale and/or on the much larger time- and space-scale resulting after the needed integration in order to be able to detect the phenomenon. All this is expressed *tout court* by stating that scale invariance of such fractal properties exists. This is just empirical evidence, not a mathematical fact. Analogously, we know that several geophysical underground phenomena are associated with the yield of planes along faults. Although the ultimate physical process is different from what occurs in a single crystal, or within a metal alloy, a reasonable inference is that perhaps the final catastrophic yield of the fault shall occur when the AE sources attain some apparent comparatively better organisation, along some preferred 2D geometrical structure (compared to the previous more 3D and random pattern).

Summarising, in general, AE monitoring must be applied to some compact rocky body like an underground probe of unknown extension. Whenever any known or unknown physical cause makes its internal stress distribution change, some AE are released. This is ultimately the prime rationale of AE monitoring in geophysics. The prime cause can be the warming and cooling from outside, fluid internal diffusion through its pores, or simply a change of its statics depending on some tilt of the orientation of its bedrock or support. In every such case history, the fractal dimension is different, and this can be used as an unprecedented and much sensible gauge for monitoring such phenomena in real time, e.g. in terms of a varying gas exhalation from ground.

4. A methodological summary

It can be concluded that AE can be analysed from different viewpoints, by focusing on either one of the following general aspects. The single observed occurrences (events) have a time-duration that depends both on the recording apparatus and on the kind of phenomenon that is being investigated. Some kind of apparently typical time-sequences of such events, i.e. a macroevent, should reveal a temporal trend capable of envisaging (eventually) some inference on the prime mechanism responsible for AE. The distinction between event and macroevent is essentially a pre-chosen conventional way of dealing with different aspects of the same physical reality, where a macroevent is called an entity that is composed of details, every one of which is called event. This is a vague statement, and although in general we refer to a macroevent with this idea in mind, the same rationale can be eventually applied also to a time-series of events provided that one can know some temporal details of the evolution of every event in terms of some occurrence of shorter time duration. The temporal sequence of such macroevents (or of events) can be likened to a point-like process. It should be stressed that this is *per se* an abstraction, which implies some logical approximation, because the concept of point-like process has a precise mathematical definition. A natural time-series of occurrences on the othe hand, in general, is affected by error-bars and deviations with respect to any speculated ideal uniformity, where one has always to consider that the rigorous algorithms envisaged by mathematicians can sometimes result as inadequate for the observational database available.

5. Applications

As far as geophysical applications are concerned, AE are a convenient diagnostic tool for investigating microscale processes associated with ground deformation, microfracturing, and porosity variations. Such an application ought to be concerned 1) either with the study of matter exchanges across soil surface (either with the atmosphere or with sea/ocean), or 2) with a few different processes that occur within ground and that are associated (a) either with thermal variations, (b) or with tectonic activity, (c) or with hydrothermal or volcanic phenomena.

All interpretations seen at the atomic or molecular scale are intuitive and speculative, and have to be confirmed by a specific, suitable, laboratory investigation. Extensive reviews of such a complete topic are given, for example, by Heiple and Carpenter (1987), Evans and Kohlstedt (1995), Lockner (1995), Crampin and Zatsepin (1996), and Tsang (1999). Moreover, as far as an explicit calculation of the associated formal Schrödinger equation is concerned, this appears a difficult job even for the computing of the crystal structure of a pure substance alone, while it is essentially impossible for every unknown and general texture of different substances such as occurs in natural rocks or in the ground (e.g. Eberhart, 1999). In principle, in the present study the cleavage plane of a crystal is treated analogously to the plane of a tectonic fault, although, in terms of physics, a substantial gap exists between two such case histories. Let us try to fill such a gap in terms of some intuitive argument dealing with rolling and sliding friction, with no presumption for rigour, because in any case we must rely on heavily simplified models.

A perfect elastic body produces no AE as it deforms back-and-forth with no viscosity, nor with energy dispersion. No such perfect body, however, exists, as every stressed object suffers from some minor strain and flaw, resulting from a few yielding chemical bonds, while some constitutive microcrystals rearrange themselves, they originate the AE, and leave flaws. Even in the case of an almost perfect elastic body (such as e.g. when dealing with some special steel), after every test, the microcrystalline structure of the body never strictly recovers back to its previous condition. Consider the cases of either a stone-ball rolling on a flat and smooth rock-surface, or of a stone-cube sliding over it. The ball experiences rolling friction, which makes the two contact surfaces penetrate into each other, some micro-surfaces slide against each other along very inclined or almost vertical planes; the mechanism reminds us of some microscopic teeth of two sprocket wheels, while a gentle AE is observed. By contrast, the cube experiences either static or dynamic friction. When it is at rest, and a force is applied to make it slide, the static friction is the result of all forces that are exerted between the two contact surfaces, and as a first approximation they do not yield, and appear to react approximately like an elastic bond. However, when the applied force goes beyond some threshold, the system behaves as when all such microbonds yield almost simultaneously, and altogether they release AE as a unique event. One can apply the bcm to the AE time-series released during such a process, provided that the data records have a sufficient time resolution. After such a start, the dynamic friction is much less than in the aforementioned static situation, due to the lack of capability of the two contact surfaces to fully recover the former bond. The cube will, therefore, continue to slide, provided that a sufficient force is applied to it, while releasing AE, etc. This also reminds us that the AE is always released whenever a smooth object is posed over another smooth object, because the imperfections or deviations from an ideal plane of their respective smooth contact surfaces always originate a reciprocal penetration of minor uplifts (this is sometimes called spike effect).

The sliding cube and its friction is some intuitive, intermediate situation between a crystal breaking along a cleavage plane, and a tectonic fault that is going to trigger an earthquake, although in both cases, in general, the phenomenon does not occur with such a sharp surface as in the aforementioned experiment of two sliding smooth surfaces. The leading idea used in the present study attempts at distinguishing the AE time-series associated with the rupture along a preferential plane (whether it is a cleavage plane in a crystal, or a fault plane in an earthquake, or any other intuitively equivalent occurrence), compared to the case of a 3D distribution of AE sources.

Either one of the following prime causes give origin to ground deformation: 1) thermal contraction and expansion; 2) tidal fluctuation; 3) tectonic strain; 4) endogenous pressure by a fluid (i.e. water, oil, geogas, etc.); 5) endogenous pressure by plutonic intrusion of lava. Every such process occurs on the atomic or molecular scale. It starts by the yielding of some bond that eventually propagates into some chain-reaction, leading either to a rupture or to a strain deformation, with morphology, timing, and speed that depend on the environment and on the triggering process. In such a respect, a mere compression e.g. by a hot fluid that penetrates into the pores can be expected to imply, perhaps, a different behaviour compared to the case of a lateral displacement, such as occurs in a crystal cleavage or in tectonic faulting.

All this recalls the several-years-old dilatancy hypothesis (Nur, 1972; Rikitake, 1976; Mogi, 1985) that was formerly introduced to explain different kinds of earthquakes precursors. According to the present rationale, however, such a theory ought to be considered just as a sub-class or a peculiar case history of a more general perspective. Thermal effects (warming and cooling) in general originate through some source that is external to the rock sample. This occurs typically in the case of the solar diurnal heating and cooling, which penetrates only down to several tens of centimetres. The contracting outer layers must slide along preferred planes over the more expanded and warmer internal layers. Tidal deformation, instead, applies uniformly within the entire Earth, depending only on the local gravitational gradient (rather than on gravity intensity). Hence, maybe, compared to thermal deformation, it is a smooth phenomenon, and it could emit some lesser AE, or even no AE at all. Tectonic strain should imply AE mainly originated by lateral displacement (as for thermal deformation). The endogenous pressure by a fluid ought to be a typical feature of every system dominated by hydrothermal or phreatic prime breeding, and it should have its own signature distinct from the strain's AE.

The endogenous pressure by plutonic intrusion of lava should be likened more to the case of a tectonic strain, rather than to the case of an endogenous pressure by a hot fluid. Water, oil, geogas, etc. are characterised by a typical great mobility, which allows them to reach the smallest pores easily and exert, almost randomly, a pressure that propagates rapidly by diffusion. By contrast, a plutonic body has some typical very low mobility, and produces only some very slow ground deformation, rather than diffusion and propagation of endogenous pressure into the pores (obviously this holds only as far as one does not consider the phreatic effects eventually associated to the plutonic intrusion). Hence, its main (although not unique) effect ought to be likened to a 2D large-scale tectonic deformation, rather than to a 3D process occurring on the atomic or molecular scale.

Consider the case of a laboratory experiment carried out by compressing a rock specimen. Suppose that it is kept strictly confined, so that it cannot widen transversally when applying compression. The AE is expected, perhaps, to be similar or analogous to the case of an endogenous pressure alone exerted by a hot fluid. When the specimen is not confined, some transversal displacement also occurs, and its associated strain's AE ought to be observed.

The main drawback of AE is its well-known intrinsic limitation which depends on its teleconnection capability. In fact, an incoherent medium very soon dampens off all AE. Therefore, AE monitoring can be applied only when the ground is composed of compact rock. Moreover, AE samples only those regions of subsoil that are in some way teleconnected with the AE recording site. All such inconveniences, however, do not concretely hamper the great heuristic potential of AE.

According to evidence that the authors collected over the last several years in different environments and case histories, it appears that, on some occasions at least, the teleconnection distance seems to be much larger (at least several 100 km) than formerly expected. Let us suppose that this is correct and let us consider a possible explanation for it. Three hypotheses can be envisaged. One is the existence of a wave-guide, a solid columnar body capable of providing a teleconnection; but this appears unrealistic. A second possibility is by envisaging the existence of a carrier represented by a signal of frequency much lower than AE's, which does not dampen through loose soil, and which is capable of triggering AE locally. Such an hypothesis, however, seems also ad hoc; moreover, if it is correct one should be capable of detecting in some way such speculated carrier. The third possibility is that some entire, large region is subject to non-uniform lesser deformations (in the millimetre or centimetre range) which at present can in no way be objectively detected by any means. In such a case, some local compact rocky bodies, such as dikes, or blocks of limestone, etc., which are eventually AE monitored, change their respective static settlement, originating eventual AE. In this respect, it comes as no surprise that a definitely unusual AE occurrence was apparently detected at Giuliano (Potenza, Southern Apennines) about 14 days before the Assisi earthquake (detailed analysis is in progress). In other words, we cannot investigate a river flood by considering only its catastrophic occurrence; rather, we first need to study its hydrologic regime, a smooth phenomenon, not just its extreme events. In the same way, an earthquake occurs wherever elastic energy has been accumulated, and an adequate trigger makes it be released: AE can monitor such a trigger that certainly occurs through out a much wider region, although their catastrophic consequences occur only in the epicentral area (like a flood occurs only where the embankments yield or in any case where it is incapable of containing the water flow).

In this same context, according to very recent evidence (presently being checked, as reported by Antonioli and Silenzi, 2001) derived from the TOPEX experiment, a decrease of the mean sea level in some parts of the western Mediterranean occurred simultaneously with an increase in the eastern Mediterranean and the Black Sea. This seems paradoxical and contradictory with global climate warming. On the other hand, the amount of solid material that is displaced on the Earth's surface every year (including orogenesis, weathering erosion, volcanism, and ocean floor expansion) is, roughly speaking, of the order of magnitude of, say, about 10-15 km^3 year^{-1}, with obvious implications, for example, on the Earth's moment of inertia and its spin rate, etc. The Earth is a planet continuously re-shaping itself due to its endogenous energy, subsequent steady orogenetic processes, and it is permanent by searching for an equilibrium that is consistent with its gravity field. It would be of no surprise, should it ever be proved, that some large area, including the entire western Europe for example, experienced some minor uplift, while the region around the eastern Mediterranean and the Black Sea slightly sank. The sea level, owing to its very definition, is identified with the geoid. However, suitable corrections, related to water density (hence temperature and salinity), to water (oceanographic) dynamics, and to atmospheric interaction (the atmospheric pressure is such as to affect sea level by an amount comparable to the tide) have to be considered. Suppose that, after taking into account all such warnings, corrections, and their respective error-bars, such TOPEX result is confirmed. It appears likely that, at present, no other monitoring device is capable of having any comparable sensitivity, and it is possible, and even reasonable, to guess that such large-scale lesser sinks and uplifts affect some large areas of the globe. As far as the authors can understand, the only feasible way of detecting them seems to be by means of some dense continental array of AE monitoring stations. AE are not capable of distinguishing whether a given dyke or limestone block or other rocky compact object is uplifting or sinking; however, it can monitor a change in its internal stress field. For instance, laboratory experiments in optics reguire optical benches, normally made of heavy bars of cast iron in order to ensure great stability and the possibility of attaining great accuracy in alignments, etc. The VIRGO experiment (Braccini et al., 2002) is one such experiment, carried out in a sedimentary river plane, composed of a Michelson interferometer with arms about 3 km long, while the plane is not a heavy bar of cast iron.

It shoul be emphasised that every natural system is largely heterogeneous, where should the AE monitoring respond to some large-scale teleconnection, it would ultimately perform a probing over some randomly chosen internal feature of the system located at some larger or shorter depth. Owing to this fact, the AE information ought to be considered as a 2D information spread over the Earth's surface, rather than a simple point-like record. Hence, spatial arrays of AE sensors are strongly recommended.

All such inference is concerned with the space-scale of AE. An analogous warning is concerns its time-scale. A common way of characterising some given area or region is in terms of being either tectonically stable or active. This is an oversimplification, as one should specify rather the time-scale concerned. In fact, over the several 10 Ga time-scale even a star is not stable; on several 100 Ma a continent is not stable; on several Ma large areas that are generally considered stable in reality are active. On the few 100 years, time-scale large areas that normally appear quiet occasionally experience great earthquakes, and are generally defined seismic. As far as AE monitoring is concerned, even in real time, it deals with a local phenomenon that is in progress, and in principle its implications for a perspective on some much larger space-scale and much longer time-scale are items that are outside its own intrinsic significance and rationale. For instance, the Gran Sasso area is seismic, according to the aforementioned definition, though, as far as AE records spanning a few years (rather than a few centuries) it has to be treated as a stable area.

An additional technological warning comes from the choice of a suitable probe, such as a metal or a glass bar to be inserted into the compact rock block over which the acoustic transducer is applied. In fact, in principle, a metal component could be biased by some e.m. disturbance originated, for example, either by the ionosphere or by the electric supply or by the electronics of the recording system, etc. For one such specific measurement, we were, however, able to exclude that such a kind of perturbation affects AE records.

The interested reader may refer for specific case histories to Petri et al. (1994), Vespignani et al. (1995), Cuomo et al. (2000), Gregori et al. (2001), Braccini et al. (2002), Paparo et al. (2002), or to Paparo and Gregori (2002), where the possible tidal modulation on the tail of a lognormal macroevent is specifically discussed.

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