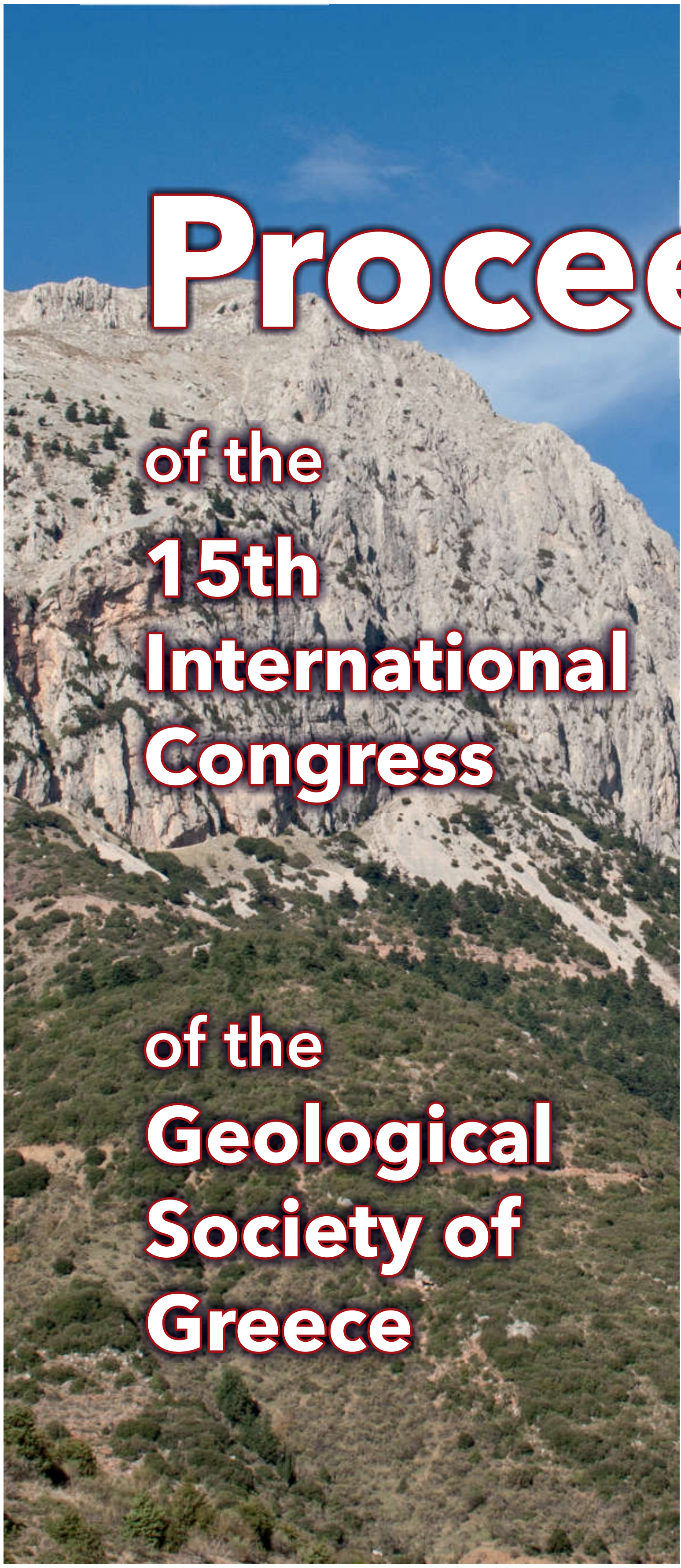
Bulletin of the Geological Society of Greece
Special Publication No. 7, 2019



Proceedings of the 15th International Congress of the Geological Society of Greece

ΕΓΕ 2019

15th International Congress of the Geological Society of Greece

Athens, 22-24 May 2019

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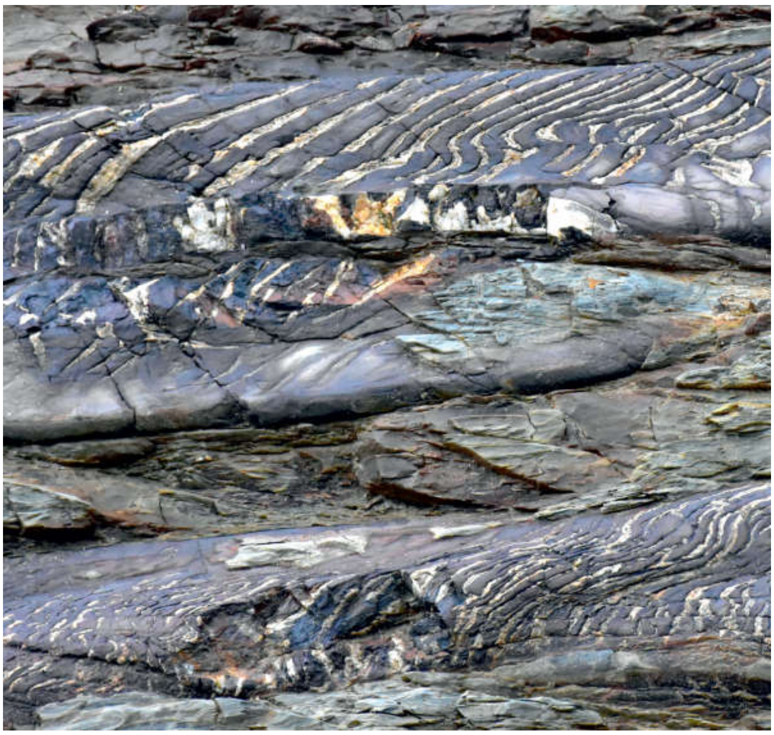

Athens, Greece | 22-24 May 2019

Earthquake Recurrence Intervals in Complex Seismogenetic Systems: A Proemial Analysis

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Principles and Objectives

A recurrence interval (RI) is a statistical estimate of the likelihood of an earthquake to occur, typically based on historical data; its standard definition is the number of years on record plus one divided by the number of events, and assumes that the events are generated by Poissonian processes so that events of similar size are mutually independent and have a stationary probability of occurrence. The number of events is typically taken from, or estimated on the basis of the Frequency–Magnitude distribution or its modifications/ extensions. Although indisputable, the F-M distribution is static and says *nothing* about the dynamic state of fault networks. Accordingly, standard and "improved" RI estimators are mere *approximations* of the *long-term average*. This might lead to misestimation if the dynamics of a seismogenetic system is *not* Poissonian.

A parameter *obviously* associated with the RI *and* the dynamic state is the *interevent time* (IT), i.e. the lapse between consecutive earthquakes over a given area and above a magnitude threshold. The IT has generally *not* been used in the estimation of earthquake recurrence intervals. This may be due to a majority endorsement of the idea that seismogenesis is Poissonian in time. If so, the statistics of IT should observe the exponential distribution whereas they generally *do not*: contrary to "expectation", Frequency–Interevent Time distributions are power laws that cannot possibly fit into the Poissonian context. Several Authors attempted to resolve the contradiction by working out *ad hoc* theories that are generally well formulated and elegant, albeit unavoidably multi-parametric, unnecessarily complicated and possibly defying the principle of maximum parsimony.

An alternative approach is Complexity. In this view seismicity expresses a fault network (system) that evolves in a fractal-like spacetime and may be sustainably *non-equilibrating* (Complex), sustainably equilibrating (Poissonian), or transitioning between equilibrating and non-equilibrating states. Complex States require a significant proportion of successive earthquakes to be *dependent* through short and long range interaction that introduces delayed feedback: this is known as *correlation* and confers memory manifested by power-law distributions of dynamic parameters such as interevent times. The statistical and entropic properties of Complex States can be studied with Non-Extensive Statistical Physics (NESP), which is a direct generalization of Boltzmann-Gibbs thermodynamics to non-equilibrating systems (e.g. Tsallis, 2009).

Previous studies (Efstathiou *et al*., 2017, 2015; Efstathiou and Tzanis, 2018; Tzanis *et al.*, 2018; Tzanis and Tripoliti, 2019) have appraised the dynamics of seismogenesis on the basis of correlation, as this is specified by the *temporal entropic index* associated with the distribution of IT: it was found that it can be very different, from SOC to Poissonian, that the level of correlation may be influenced by the geodynamic setting and that it can change with time. Herein we revisit the temporal entropic index, but this time in direct association with another important dynamic parameter, the *q-relaxation interval* (*q*RI) which is the NESP generalization of the relaxation time and comprises an *alternative definition* of the RI: it is the *characteristic time* required to produce an earthquake above a given magnitude and is expected to relay information about the dynamic state of the system. For instance, a critical system should generate earthquakes of *any* magnitude *shortly* after *any* event. Conversely, a Poissonian system should generate earthquakes within intervals exponentially increasing with event size.

We examine many different seismogenetic systems of the northern Circum-Pacific Belt: the transformational plate boundaries and inland seismic regions of California, Alaska and Southwest Japan, the convergent plate boundaries and Wadati-Benioff zones of the Aleutian, Ryukyu, Izu-Bonin and Honshū arcs, and the divergent plate boundary of the Okinawa Trough. Objectives are: a) to confirm and clarify results of previous work; b) to explore how and why the geodynamic setting may affect the entropic state of seismogenetic systems; c) to assess the statistical effects of blending the seismicity of different systems in a single catalogue.

Method of analysis

NESP predicts that the Cumulative Probability Function associated with a real variable $\Delta t \in [0,\infty)$ is

$$P(>\Delta t) = \exp_q\left(-\Delta t \cdot \Delta t_0^{-1}\right) = \left[1-(1-q_T)\left(-\Delta t \cdot \Delta t_0^{-1}\right)\right]^{(1-q_T)^{-1}}$$

where Δt represents the IT, Δt_0 the *q-relaxation interval* and q_T the *temporal entropic index*; $\exp_q(.)$ is the *q-exponential function* which for $q_T \neq 1$ is a Zipf-Mandelbrot power law, while for $q_T=1$ $\exp_q(-\Delta t/\Delta t_0) = \exp(-\Delta t/\Delta t_0)$ reducing to the exponential distribution (Poissonian process). Our analysis comprises modelling of empirical functions $P(>\Delta t : M \geq M_{th})$ from many different seismogenetic systems, so as to enable a comparative study of the resulting $\Delta t_0(M_{th})$ and $q_T(M_{th})$; M_{th} is a magnitude threshold. Because $\Delta t_0>0$ and $q_t \in [1, 2]$, modelling is performed with the trust-region reflective algorithm together with least absolute residual minimization to suppress possible outliers.

Results and Conclusions

The joint examination of Δt_0 and q_T assumes that they are indivisibly associated with the dynamic state of a system which, in turn, can be evaluated by the level of correlation (q_T) and classified as: *insignificant* when q_T<1.15, in which case the system is Poissonian; *weak* when 1.15≤q_T<1.3, *moderate* when 1.3≤q_T<1.4 and *significant* when 1.4≤q_T<1.5, in which cases the system is Complex and possibly non-critical; *strong* when 1.5≤q_T<1.6 and *very strong* when 1.6≤q_T, in which cases the system is Complex and possibly critical.

Our results indicate that the q-exponential distribution is a *universal descriptor* of IT statistics. It is also clear that the duration of q-relaxation intervals is *reciprocal* to the level of correlation (q_T). Both parameters may change with time and across boundaries so that neighbouring systems may co-exist in *drastically* different dynamic states.

Crustal systems in transformational plate boundaries are generally correlated: 56.3% of q_T estimators indicate correlation above moderate, 46.6% above significant and 37.9% above strong. However, the cases of very strong correlation are quasi-stationary and the corresponding q-relaxation intervals very short, very slowly increasing with magnitude and vastly incomparable to the exponentially increasing standard RI: on occurrence of any event, such systems appear to respond swiftly by generating any magnitude anywhere within their boundaries – these are hallmarks of Self-Organized Criticality.

Crustal systems in convergent and divergent plate margins are generally weakly–moderately correlated: approximately 56.9% of q_T estimators indicate weak, 17.6% moderate 19.6% significant to strong correlation. In *significantly to strongly correlated crustal* systems, the q-relaxation and standard recurrence intervals both increase exponentially with magnitude but diverge, with the standard RI escalating much faster than the q-RI. In *insignificantly to significantly correlated crustal* systems, the q-RI and standard RI both increase exponentially with magnitude and generally congruent within the range of observations and possibly beyond.

- Given that the standard RI assumes Poissonian statistics while Complexity accommodates a broad range of dynamic states, the above observations imply that fault networks with moderate to strong correlation and q-relaxation intervals exponentially increasing but *shorter* than the standard, are Complex and but possibly sub-critical or non-critical.

Sub-crustal and Wadati-Benioff zone systems are definitely uncorrelated (quasi-Poissonian); in these cases the q-relaxation and standard recurrence intervals increase exponentially with magnitude and are *congruent*. Finally, the blending of earthquake populations from adjacent but dynamically different fault networks *randomizes* the statistics of the mixed catalogue and over large seismogenetic provinces, *reduces the apparent level of Complexity*.

A partial explanation of our results is based on simulations of small-world fault networks and posits that free boundary conditions at the surface allow for self-organization and possibly criticality to develop, while fixed boundary conditions at depth do not. The development of criticality in transformational crustal fault networks may be associated with the degree of connectivity and synchronization of the contiguous segments of large transform faults that continuously "push" against each other and facilitate longitudinal, long-range transfer of stress. In the crust of convergent plate boundaries the large faults are essentially low-angle mega-thrusts whose contiguous segments do *not* push against each other and are thus *not* as highly connected as large transform faults. Finally, the physical conditions of sub-crustal fault networks inhibit connectivity, only allowing earthquakes to occur as a series of quasi-independent events. Future research will show if all this holds water!

The standard RI may overestimate the seismicity rate of non-Poissonian systems and for what it is worth, underestimate earthquake hazard. There is no doubt that the information introduced by q-relaxation intervals, regarding the effect of the dynamic state on the RI, might be useful in improving earthquake hazard analysis. Exactly how it can be applied, however, requires significant additional research: it is certain that nothing new has to be done if a system turns out to be quasi-Poissonian but in the general case of Complexity things are far more complicated.

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