# An examination of the possibility of earthquake triggering by the ionosphere–lithosphere electro-mechanical coupling*

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**ABSTRACT:** This paper is concerned with the verification of the recently reported correlation between the quiet-day diurnal geomagnetic (Sq) variation and the diurnal seismicity rates. This effect is attributed to the electromechanical coupling between the Ionosphere and the Lithosphere, in which the current vortices induced in the solid Earth by the Sq variation and flowing through the main geomagnetic field, exert a force and a stress surcharge that albeit small, may topple faults balancing on the verge of failure. The local expression of the effect is expected to depend on the configuration (geometry) of the tectonic fabric in relation to the spatiotemporal distribution of the induced current. The hitherto experimental investigation of the effect has not been independently verified. This work attempts an *ab initio* empirical examination for the existence, extent and properties of the effect with data from two different seismogenic areas, Greece and central California, USA. The results lend marginal support to the hypothesis of earthquake triggering by the quiet-day diurnal geomagnetic variation: they indicate that the effect appears rather sporadically and depends on the right concert of fault geometry, tectonic stress loading and geomagnetic stress surcharge. For instance (and to a first approximation), at most 12%-15% of the earthquakes with magnitude $M \geq 4$ observed in Greece during 1974.0–2002.58, could have been triggered by the Sq variation. The sporadic nature of the effect is unfavourable with respect to predictability. Therefore, whereas the possibility of earthquake triggering by the diurnal geomagnetic variation cannot be rejected, a lot of work is still needed before the effect becomes sufficiently palpable.
**Key-words:** *Sq variation, telluric currents, earthquake triggering, seismicity, Ionosphere – Lithosphere coupling.*

**ΠΕΡΙΛΗΨΗ:** Η παρούσα εργασία ασχολείται με την διακρίβωση της πρόσφατα παρατηρηθείσας συσχέτισης μεταξύ της ημερησίας μεταβολής του γεωμαγνητικού πεδίου (Sq) και του ημερήσιου ρυθμού σεισμικότητας. Το φαινόμενο έχει αποδοθεί σε *ηλεκτρομηχανική ζεύξη (HMZ)* μεταξύ της έδρας των ημερησίων μεταβολών (Ιονόσφαιρα) και της Λιθόσφαιρας, κατά την οποία οι στρόβιλοι των τελλουρικών ρευμάτων που επάγονται στην Λιθόσφαιρα από την μεταβολή Sq, ρέοντες μέσω των δυναμικών γραμμών του κυρίου γεωμαγνητικού πεδίου εφαρμόζουν δύναμη και επιφόρτιση που προστίθεται στην τεκτονική φόρτιση και μπορεί να επηρεάσει την σταθερότητα ρηγμάτων που ευρίσκονται πλησίον του κατωφλίου αστοχίας. Η τοπική έκφραση του φαινομένου αναμένεται ότι θα εξαρτάται από την διαμόρφωση (γεωμετρία) του τεκτονικού ιστού σε σχέση με την χωροχρονική κατανομή του επαγόμενου ρεύματος. Η μέχρι τώρα πειραματική διερεύνηση του φαινομένου δεν έτυχε ανεξαρτήτου ελέγχου και επιβεβαίωσης. Η παρούσα εργασία επιχειρεί μία *εξ αρχής* εμπειρική εξέταση της ύπαρξης, έκτασης και ιδιοτήτων του θεωρουμένου φαινομένου με δεδομένα από δύο διαφορετικές σεισμογενετικές περιοχές (Ελλάδα και Καλιφόρνια). Τα αποτελέσματα προσφέρουν οριακή υποστήριξη στην υπόθεση της διέγερσης σεισμών από την ημερήσια μεταβολή Sq: δείχνουν ότι η πιθανή επίδραση της HMZ ζεύξης Ιονόσφαιρας – Λιθόσφαιρας επί των διεργασιών διέγερσης σεισμών εκφράζεται σποραδικά και εξαρτάται από την κατάλληλη συγκυρία γεωμετρίας ρηξιγενούς ιστού, τεκτονικής φόρτισης και γεωμαγνητικά επαγόμενης επιφόρτισης. Σε πρώτη προσέγγιση, *το πολύ* 12%-15% του συνόλου των σεισμών μεγέθους $M \geq 4$ και οι οποίοι έλαβαν χώρα στην Ελλάδα και την άμεση γειτονία της κατά την περίοδο 1974.0–2002.58 έχουν πιθανότητα να οφείλονται στην ημερήσια μεταβολή. Η σποραδική φύση του φαινομένου έχει σαφώς αρνητική επίπτωση στην προβλεψιμότητά του. Έτσι, καίτοι η δυνατότητα της διέγερσης σεισμών από την ημερήσια γεωμαγνητική μεταβολή δεν μπορεί να απορριφθεί, απαιτείται ακόμη σημαντική ερευνητική προσπάθεια πριν καν γίνει αρκούντως κατανοητή.
**Λέξεις-κλειδιά:** *Ημερήσια μεταβολή, μεταβολή Sq, τελλουρικά ρεύματα, διέγερση σεισμών, σεισμικότητα, ζεύξη Ιονόασφαιρας – Λιθόσφαιρας.*

## INTRODUCTION

The possibility of a cause-and-effect relationship between geomagnetic activity and geodynamic phenomena has been considered by only a handful of investigators. For instance, much of the earlier work has focused on researching a possible correlation between changes in the Earth's magnetic field and rotation rate, making only general and passing statements about their possible relationship to earthquake activity (e.g. VESTINE, 1953; LEMOUËL & COURTILLOT, 1981).Very few authors have attempted to research the processes that may beget a causal relationship between geomagnetic variations and seismicity (e.g. PRESS & BRIGGS, 1975). More recent research has produced some significant evidence pointing towards the existence of a causal relationship between earthquake activity and regional geomagnetic field changes (e.g. FLORINDO & ALFONSI, 1995; FLORINDO *et al*., 1996), as well as between earthquake activity and quiet-day diurnal geomagnetic variations (e.g. DUMA & VILARDO, 1998; DUMA & RUZHIN, 2003). In particular, the work by Duma and co-workers strongly indicates that there's a coherent variation between quiet-day diurnal geomagnetic variations and diurnal changes in the seismicity rate and that this correlation is global. These purported correlations have *no* relationship to the 'tecto-magnetic' and 'seismomagnetic' effects that have often been investigated as sources of *transient* magnetic precursory phe-

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nomena to certain large earthquakes. Instead, they refer to changes in the rate of earthquake occurrence over a broad spectrum of time scales, from one solar day to several decades.

This paper will focus on investigating the possible influence of diurnal geomagnetic variation on seismicity rates. The origin of this geomagnetic effect is well known *(ionospheric dynamo)*, therefore, if it has any consequence on earthquakes, it will have to be through some kind of *Electromechanical Coupling* between the source of the geomagnetic phenomenon (the Ionosphere) and the source of earthquakes (the Lithosphere/Schizosphere). The postulated effect will henceforth be referred to as the *Ionosphere–Lithosphere Electromechanical Coupling (ILEMC)*. An ILEMC model than may explain the possible correlation between the quiet-day geomagnetic variation (Sq) and diurnal seismicity rates has recently been proposed by Duma & Ruzhin (2003) and is outlined below.

The main part of the Sq field is generated at the Ionosphere, by *tempestuous winds* transporting ionized material (plasma) across the main geomagnetic field lines and producing strong currents of total intensity 1-3×$10^5$ A. Due to the rotation of the Earth the current forms two counter-rotating vortices, one dextral above the northern hemisphere and one sinistral above the southern hemisphere. It also induces a magnetic field (*the Sq field*) with amplitude reaching a few tens of nT. The daytime Ionosphere is intensely ionized (more conductive) generating stronger a Sq field, while at nighttime ionization processes diminish (in the absence of solar radiation) and the Sq field weakens considerably. Thus we have a diurnal geomagnetic variation with maximum at local noon. The Sq variation induces currents (*telluric currents*) in the conducting crust, which are thought to mediate the ILEMC. The telluric currents form two counter-rotating vortices in the northern hemisphere and two counter-rotating vortices in the southern hemisphere, as in Fig. 1 (for additional information see Lanzerotti & Gregori, 1986). Any current loop of intensity I in the vortices, flowing in the crust and through the horizontal (H) and vertical (Z) components of the main geomagnetic field, will respectively generate vertical and horizontal forces against the crustal rocks and structures (Fig. 2a). The magnitudes of the forces will be respectively proportional to the magnitudes of the diurnal geomagnetic variations ΔH(I) and ΔZ(I). Fig. 2b demonstrates how a horizontal current loop or radius $r$, flowing through the horizontal component H of the Earth's main field, will generate a magnetic moment $M=\mu_0 \cdot I \cdot (\pi r^2/4)$ in the vertical direction and a torque T=M×H. The magnitude of the torque is proportional to the diurnal variation ΔH(I). In areas with significant lateral conductivity variations, such as may be the regional faulting structures, vertical electric currents flowing through the horizontal and vertical components of the main field may generate additional effects! In consequence, the diurnal geomagnetic variation exerts in the crust a small albeit finite stress *(surcharge),* which is added to the tectonic stress and may affect the state of metastable faults. The magnitude

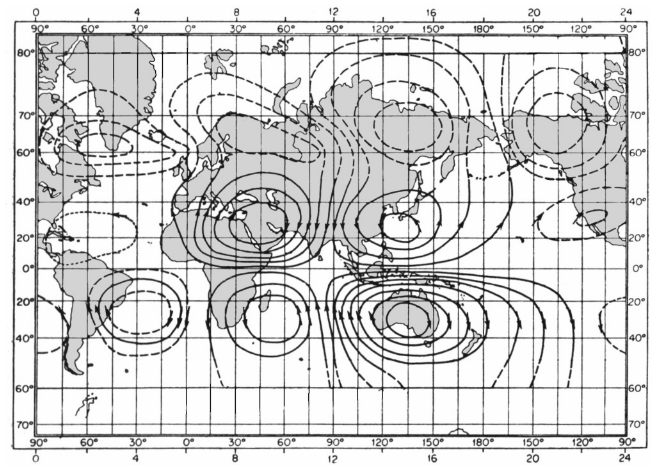

Fig. 1. Average telluric current vortices induced by the Sq variation, at 06:00 GMT (modified from Howell, 1959).

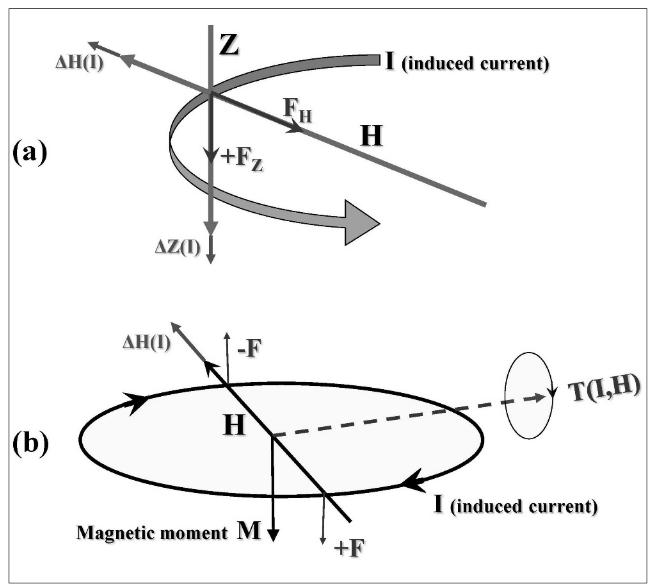


Fig. 2. Schematic representation of the forces and torque applied on the elements of the lithosphere, due to an induced current loop (I) flowing across the horizontal component of the main geomagnetic field. The horizontal component of the Sq variation (ΔH) determines the magnitude of the forces and torque exerted on the lithosphere.

of the torque and energy dissipated in this way can be appreciable. It may easily be shown that for a current loop of diameter of R∪≈ 600 km around the centre of the vortex (I ≈ -62.5×$10^3$ A), the torque is of the order 6×$10^{11}$ Nm, approximately equivalent to an earthquake of moment magnitude 4.7. It is therefore clear that the amount of energy transferred from the Ionosphere to the Lithosphere and dissipated in the form of mechanical deformation is significant. Accordingly, the probability that this energy may trigger (accelerate) the occurrence of some earthquakes should also be significant. Thus, the diurnal geomagnetic variation may produce eternal, daily changes in the regional seismicity rates.

It is easy to see that the effectiveness of the geomagnetic surcharge will depend on the configuration of the triad {I,

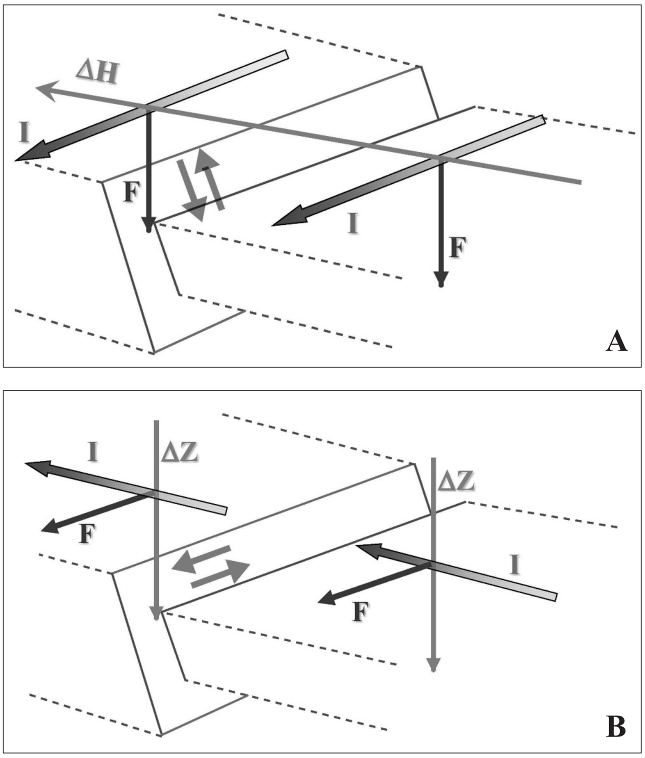


Fig. 3. The force applied on a fault depends on the configuration of the fault with respect to the induced current and magnetic field components. **(A)** Vertical force on a normal fault due to a transverse horizontal magnetic variation (ΔH) and a tangential current. **(B)** Horizontal force parallel to a strike-slip fault due to the vertical magnetic variation (ΔZ) and a transverse current.

ΔH(I), ΔZ(I)} with respect to the geometry of the tectonic fabric and will be influenced by local conductivity anomalies. An example is given in Fig. 3. In the depicted two configurations where the telluric current is transverse or tangential to the strike of the fault, the forces (surcharge) will maximize. When the current is oblique to the strike of the fault, the forces will be weaker and so will be their effect. It is therefore reasonable to expect that the effectiveness of earthquake triggering by the ILEMC process will depend on local – regional tectonics and will vary accordingly. In general terms, one should expect that only a small fraction of the energy released by earthquakes (*seismic release*) will be associated with the diurnal geomagnetic variation.

The model is simple and reasonable, almost convincing. Nevertheless, the ILEMC is far from having been shown to be a definite and unequivocal fact of nature. It is noteworthy that hitherto, (and given the innovative subject matter of this field of research), there has been no *independent* confirmation of the findings by Duma and co-workers. This paper marks the beginning of a systematic investigation of possible coupling between the Ionosphere and the Lithosphere and focuses on the empirical analysis of the correlation between the Sq variation and seismicity. In effect, it comprises an *ab initio* feasibility study for the existence, extent and general properties of such phenomena at different seismically active areas of the planet.

## STUDY OF THE HELLENIC TERRITORIES

The present analysis uses geomagnetic data from the Magnetic Observatory of Penteli (PEG, φ = 38° 05′ B, λ = 23° 56′ A, h = 380 m), operated by the Institute of Geological and Mining Research (i.e. the Hellenic Geological Survey). As of 1/1/1999 PEG publishes its data electronically, in the HDZ coordinate system, where H is the horizontal geomagnetic component, Z is the vertical component and D is the declination. The total field *F* can be calculated by the relationship $F = Z\sin J + H\cos J$, where *J* is the inclination and *J*∪≈ 53,6° for the period 1999–2003. In order to identify the solar –quiet days and extract a representative Sq field (without external influences), use was made of the Planetary Geomagnetic Activity indices $K_p$, retrieved from the International Service of Geomagnetic Indices of the IAGA and the World Data Center for Geomagnetism at Kyoto. Herein, quiet days are defined to be those, for which the daily sum of the three-hourly $K_p$ indices ($\Sigma K_p$) is less than, or equal to 30. At mid-latitudes, this guarantees that the observed geomagnetic field is virtually free of rapid variations and other phenomena related to the solar wind. Fig. 4 shows the mean quiet-day diurnal variation for the period 1999 – 2003. Given the origin of the diurnal variation, the Sq field is not expected to show appreciable mid- and long-term changes. In consequence, the data of Fig. 4 can also be used for long-term comparisons with diurnal seismicity rates, provided that these do not extend very far back into the past.

The seismicity data used herein were taken from the catalogue of Makropoulos *et al.* (1989), as expanded by the author until July 2002 using the same data sources and editing procedures (Fig. 5). The expanded catalogue is homogeneous by construction; its completeness has been checked with the method of Stepp (1971) and has been shown to vary as in Table 1.

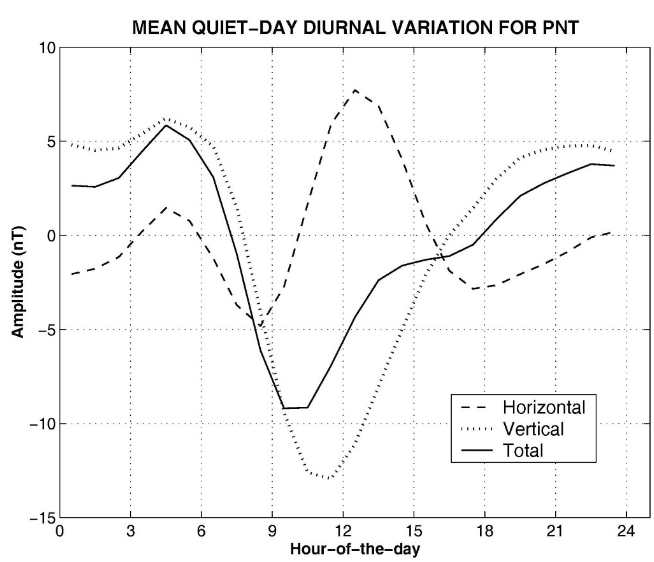


Fig. 4. The average quiet-day diurnal geomagnetic (Sq) variation at PEG, for the period 1999 – 2003.7.

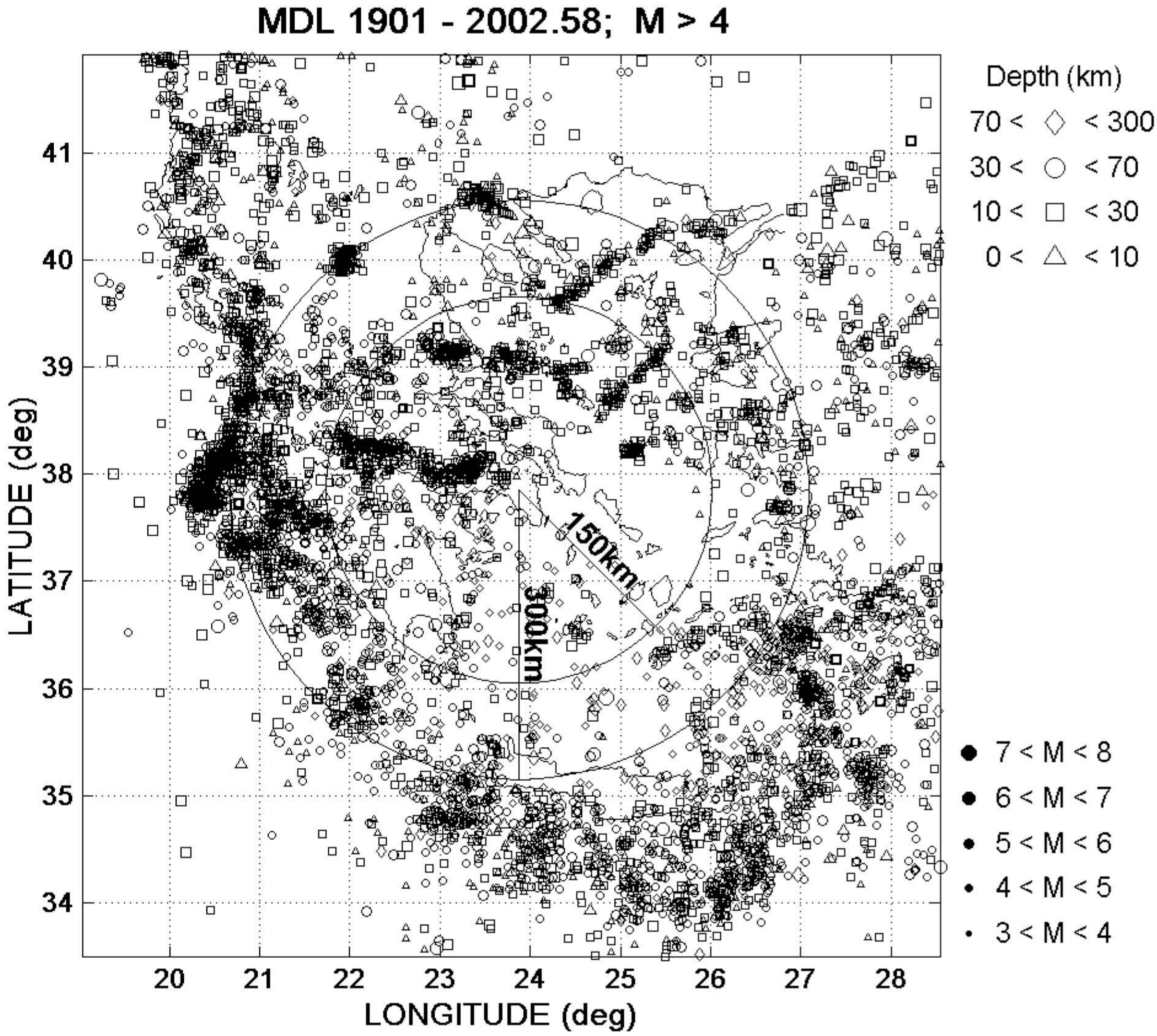


Fig. 5. The catalogue of MAKROPOULOS *et al*. (1989), extended by the author to the epoch 2002.58. The circles indicate distances from the observatory PEG.

The comparison between the quiet-day diurnal geomagnetic variation and diurnal seismicity changes are made with a rudimentary, yet powerful method. All earthquakes above a given magnitude threshold (always greater than, or equal to the magnitude of completeness) and occurring at days with $\Sigma K_p \leq 30$, are cast into a histogram of earthquake number per hour of the day, henceforth dubbed to be *cumulative hourly earthquake count (CHEC)*. The histogram (always shown in light grey shading) is smoothed with a moving, 3-point Hamming window and is compared with the average diurnal variation of a geomagnetic field component. Because the geomagnetic variations (cause) should only affect the varying part of the CHEC (effect), a simple but effective measure of the similarity and causality between of the two quantities can be afforded by calculating their cross-correlation function in the sense Sq-leads-CHEC. Apparently, causal connection would be indicated by a decaying cross-correlation function with significant correlation coefficients at zero or very short lags (i.e. a very few hours), and low correlation coefficients at longer delay times. It should be emphasized though that this is a necessary, but certainly not a sufficient condition. For reasons of comparison, earthquakes occurring at days with $\Sigma K_p > 30$ are also cast into a similar histogram, which is always shown in dark grey shading. It should also be noted that $K_p$ indices are being produced *only* for the period *after* 1932.0. Accordingly, the seismicity data forming the CHEC of both quiet and disturbed days are necessarily limited to the interval 1932.0–2002.5.

The above analysis can be done by selecting (winnowing) seismicity data on the basis of different geographic or geotectonic criteria. The results reported herein will be based on *geotectonic* criteria. An advantage of this approach is that the results can be interpreted –at least partially – in terms of the theoretical predictions allowed by the ILEMC model (e.g. Fig. 3). To this effect, Fig. 6 shows a map of the horizontal projection of the major stress axis $\sigma_1$, as computed with the

TABLE 1
Completeness analysis of the extended catalogue of MAKROPOULOS *et al.* (1989).

| Magnitude Range | Completeness Interval |
|---|---|
| M ≥ 4.0 | 1975 – 2002 |
| M ≥ 4.5 | 1964 – 2002 |
| M ≥ 5.0 | 1950 – 2002 |
| M ≥ 5.5 | 1920 – 2002 |
| M ≥ 6.0 | 1911 – 2002 |
| M ≥ 6.5 | 1900 – 2002 |

method of MICHAEL (1984, 1987) on the basis of the Harvard CMT focal mechanism catalogue for the Hellenic Territories and their immediate neighbourhood (203 earthquakes of $M_w$ > 4.5, spanning the interval 1977.0–2003.0). Although the map of Fig. 6 should be seen as an approximation (due to the relatively limited data set), it nevertheless is quite useful and sufficient for the purposes of this reconnoitring analysis.

Fig. 7 presents the comparison of the total Sq field (*F*) with the CHEC resulting from the entire catalogue of the Hellenic Territories and their immediate neighbourhood (see inset map). It is clear that the correlation of the diurnal variation with the a.c. component of the CHEC is *very good* and that the cross-correlation function indicates a causal relationship between the two quantities (it is monotonically decreasing, with largest coefficient the one at zero lag, $R_0$= 0.87). Inspection of Fig. 4 indicates that the same high correlation does not hold for the horizontal component of the Sq field. It is also clear that the d.c. component of the CHEC is very significant, indicating that the investigated phenomenon (earthquake triggering by ILEMC) appears sporadically, as will fully be discussed below (see Discussion).

Scrutiny shows that the high correlation observed in Fig. 7 is mainly due to the contribution of the seismicity of the central and northern Hellenic Territories (Fig.8, $R_0$=0.85). The total field diurnal variation and the CHEC of the southern territories – SE and South Hellenic Arc – exhibit quite low correlation (Fig. 9, $R_0$= 0.28), although it could be appreciably better, had it not been for the inexplicable concentration of earthquake occurrences observed at around 11:00 GMT and 24:00 GMT. It is also noteworthy that the region of low correlation almost coincides with areas of significant changes in the tectonic regime (see Fig. 6). Specifically, high correlation is observed at regions where the axis $\sigma_1$ has SE-NW, E-W and SW-NE orientations, while low correlation is observed at regions where $\sigma_1$ has a general N-S orientation (SE–S Hellenic Arc).

Further scrutiny of the central and northern territories shows the existence of significant differences in the local and

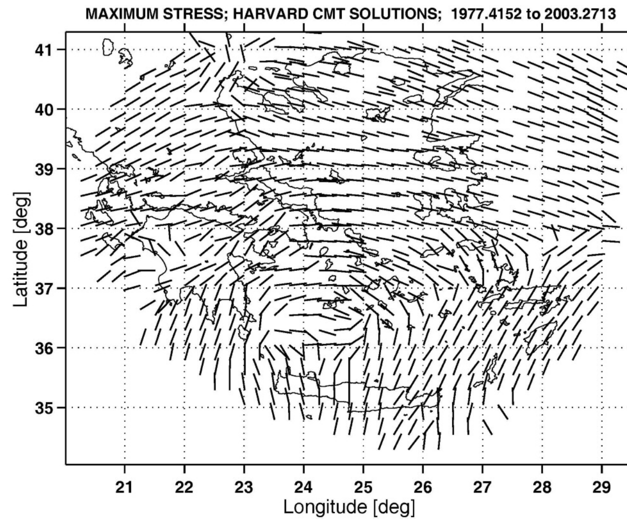


Fig. 6. Horizontal projection of the maximum stress axis $\sigma_1$, resulting from the application of MICHAEL's (1984, 1987) stress inversion method on the catalogue of Harvard CMT focal mechanisms for Greece and its neighbourhood.

regional correlation between the diurnal geomagnetic variation and the diurnal seismicity rates (Fig. 10). In particular, Fig. 10a shows the comparison of the total field diurnal variation and the CHEC at the area of the Gulf of Corinth (see inset map), where the regional tectonic modes are predominantly extensional and expressed with SE-NW to E-W normal faults and a SW-NE oriented $\sigma_1$ axis. The correlation is rather moderate ($R_0$= 0.51), but the cross-correlation function retains the characteristics expected of a causal relationship (monotonically decreasing). Fig. 10b shows the corresponding comparison for the SW margin of the Hellenic Arc at the Kefallinia Transform Zone, where the $\sigma_1$ axis is oriented in the WSW-ENE direction. Here the correlation is definitely low ($R_0$= 0.37) and the shape of the cross-correlation function indicates a marginally causal relationship. Conversely, at the North Aegean area (Fig. 10c), where SW-NE strike-slip faults predominate and $\sigma_1$ is oriented in the SE-NW to E-W directions, the correlation is very good ($R_0$= 0.78) and definitely causal (monotonically decreasing).

In general terms, low to moderate correlations are detected at areas with SW-NE oriented $\sigma_1$ axis and fair to good correlation at areas with SE-NW oriented $\sigma_1$ axis. Within the context of the ILEMC model, these observations may have a reasonable explanation: The 3-D regional configuration of the stress tensor determines the configuration of the active tectonic fabric (geometry of the faults) which, in turn affects the magnitude of the stress surcharge applied on the faults by the diurnal geomagnetic variation. In consequence, the surcharge may differ between regions and may even be very weak. Since the quality of the correlation (i.e. the effectiveness of earthquake triggering) depends on the surcharge, it is also expected to vary between regions and deteriorate at regions where the surcharge is weak. This is a reasonable argument but a word of caution is also in order, because it is

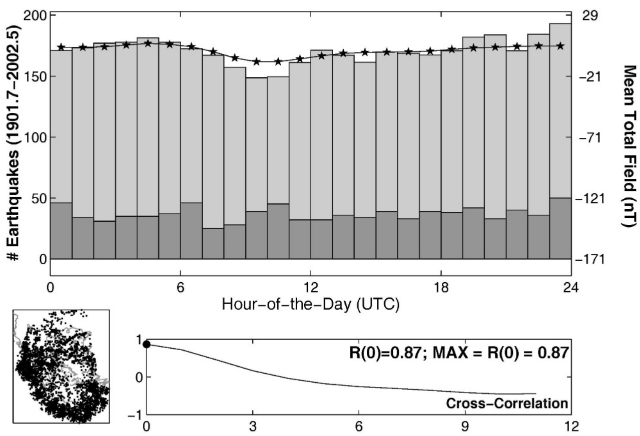


Fig. 7. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for the entire Hellenic Territory and adjacent areas (histograms). Magnitude threshold is 4. The light grey histogram is made with earthquakes observed on solar-quiet days ($\Sigma K_p \leq 30$). The dark grey histogram is made with earthquakes observed on disturbed days ($\Sigma K_p > 30$). The inset map (lower left) displays distribution of the epicenters used in the construction of the histograms.

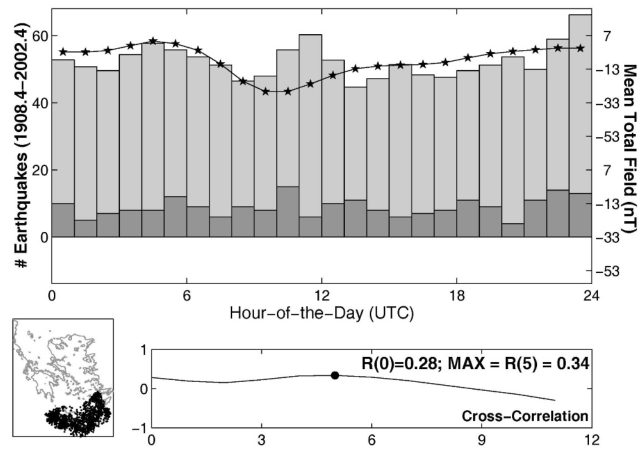


Fig. 9. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for the southern regions of Greece and magnitudes M≥4 (SE and S Hellenic Arc).

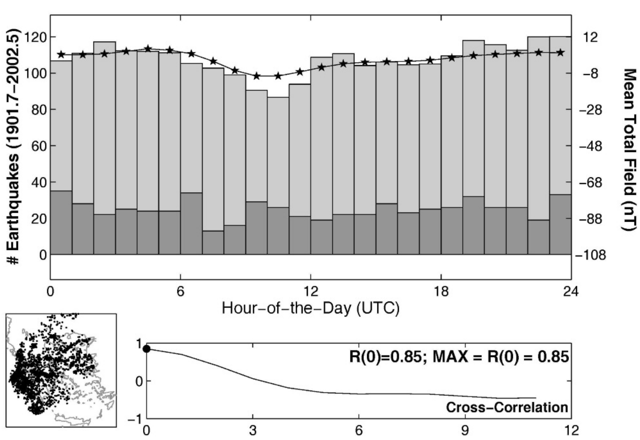


Fig. 8. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for the central and northern regions of Greece and magnitudes M≥4. The histograms and the inset map are as per Fig. 7.

still quite sketchy: a lot of theoretical and experimental work is needed before the details of how fault geometry – the *"effective tectonic fabric"* so to speak – influences earthquake triggering through the ILEMC process. Therefore, any explanation invoking this argument is still far from being definitive.

Additional physical and statistical properties of the ILEMC process follow by repeating the analysis with seismicity data observed *exclusively after* 1974, the year when the catalogue became complete for events with magnitudes M ≥ 4 (Fig. 11). The correlation definitely retains its causal characteristics, but with quite lower coefficients ($R_0$= 0.76). Given that prior to 1975 the catalogue contains events with magnitudes M ≥ 4.5, at first it might appear that the improvement in the correlation observed in Fig. 7 with respect to Fig. 11, would have to do with the size of the fault (the larger the fault, the larger the area exposed to the geomagnetic stress surcharge and the higher the probability of destabilization). This argument does not hold water if one considers the results of Fig. 12, which compares the mean total Sq field with the CHEC constructed from events with magnitudes M ≥ 5.5 within the interval 1932.0–2002.58 and over the entire Hellenic Territories and immediate neighbourhood (see inset map). Clearly, the correlation is rather poor ($R_0$= 0.35, $R_1$= 0.41) and marginally causal, whereas, if the reasoning was correct, one would expect to observe good correlation with definitely causal properties in spite of the limited data sample. It follows that the improvement observed in Fig. 7 is probably a statistical effect. When the analysis is extended to earlier times, a larger data sample is used in forming the histograms and, evidently, a larger number of events actually triggered by the diurnal geomagnetic variation, which follow its time dependence and add up to improve the observed correlation. Such reasoning renders support to the view that the observed effects of the ILEMC appear sporadically and not systematically (see also Discussion below).

The presentation of results from Greece will conclude with the general observation that there's *no* correlation between the diurnal geomagnetic variation and the CHEC of *solar-disturbed days,* which appears to be rather featureless. This absence of structure indicates, either that there's no pattern of earthquake triggering by transient geomagnetic disturbances, or that there's *no* triggering at all and that the earthquakes are due to the regular tectonic activity with no particular time dependence. The second possibility is more probably true, because geomagnetic field disturbances due to solar activity are produced by ring currents surrounding the Earth above the northern latitudes; at mid-latitudes, they cannot induce current vortices that would exert some stress surcharge on the metastable elements of the Schizosphere.

## STUDY OF CENTRAL CALIFORNIA, USA.

This section reports a concise presentation of a search for earthquake triggering by the ILEMC process at Central California, USA, as shown in the map of Fig. 13a. The analysis is based on geomagnetic data from the Magnetic Observatory of Fresno (FRN; φ= 37.0830°N, λ= -119.7170°W), which is operated by the U.S. Geological Survey. The data used herein is spanning the period 1980.0 – 2002.0 and was retrieved from the World Data Centre for Geomagnetism C1 (Copenhagen), in the form of hourly mean values of D, H, Z, X, Y and *J*. As previously, the solar-quiet days were recognized on the basis of the Planetary $K_p$ indices and are those for which $\Sigma\Sigma K_p \leq 30$. Seismicity data were extracted from the PDE catalogue (NEIC/ USGS). Herein, use was made of the subset reporting local magnitude ($M_L$), which is used extensively in California, spanning the period 1973.0–2003.0. Fig. 13a presents a map of this subset, for $M_L \geq 3$ and within a radius of 3.5° around FRN. This catalogue is homogeneous by construction. Fig. 13b shows the corresponding cumulative frequency – magnitude (Gutenberg – Richter) curve, demonstrating that the catalogue is complete for $M_L \geq 3$.

In general terms, the comparison of the mean Sq variation (computed for 1980.0–2002.0) and the a.c. component of the CHEC (1973.0–2003.0), yields results consistent with the observations made for Greece in Section 2 above. A similar dependence on the local – regional geographic and geotectonic characteristics is also observed. Specifically, at Central–West California (shaded area in Fig. 13a), and along the famous (dextral strike-slip, NNW oriented) San Andreas Fault, the mean *vertical* Sq component is well correlated with the CHEC for $M_L \geq 4$ ($R_0$= 0.82), as well as the mean total Sq field ($R_0$= 0.75, Fig. 14a). The area within a radius of 300 km to the east of FRN includes the broad zone of distributed, dextral, normal to oblique slip and approximately N-S oriented faults of the Sierra Nevada and the Basin-and-Range provinces. Here, the correlation of the mean vertical component and total field Sq variation with the CHEC for $M_L \geq 4$ is rather bad ($R_0$= -0.01, $R_2$= 0.21, see Fig. 14b). It is worth noting however, that the correlation is practically destroyed by the (unknown origin) anomalous concentration of events at around 15:00 GMT; otherwise the varying part of the CHEC appears to behave like the diurnal geomagnetic variation, albeit with a delay of approximately two hours.

When the magnitude threshold is smaller, for instance for $M_L \geq 3$, there's no apparent correlation (Fig.14c). This possibly means that the ILEMC process, if active in California, will only trigger intermediate–large size faults.

## DISCUSSION

The simple experiments presented above, show that on aggregate, the daily occurrence of earthquakes exhibits some degree of dependence on local time. In Greece at least, the long term behaviour of the cumulative hourly earthquake occurrence on solar-quiet days indicates that although by a small margin, there's some physical basis to the popular belief that "more earthquakes occur during the night than during the day". The generally fair correlation of the diurnal geomagnetic variation with the varying part of the CHEC also shows that it is rather difficult to exclude the possibility

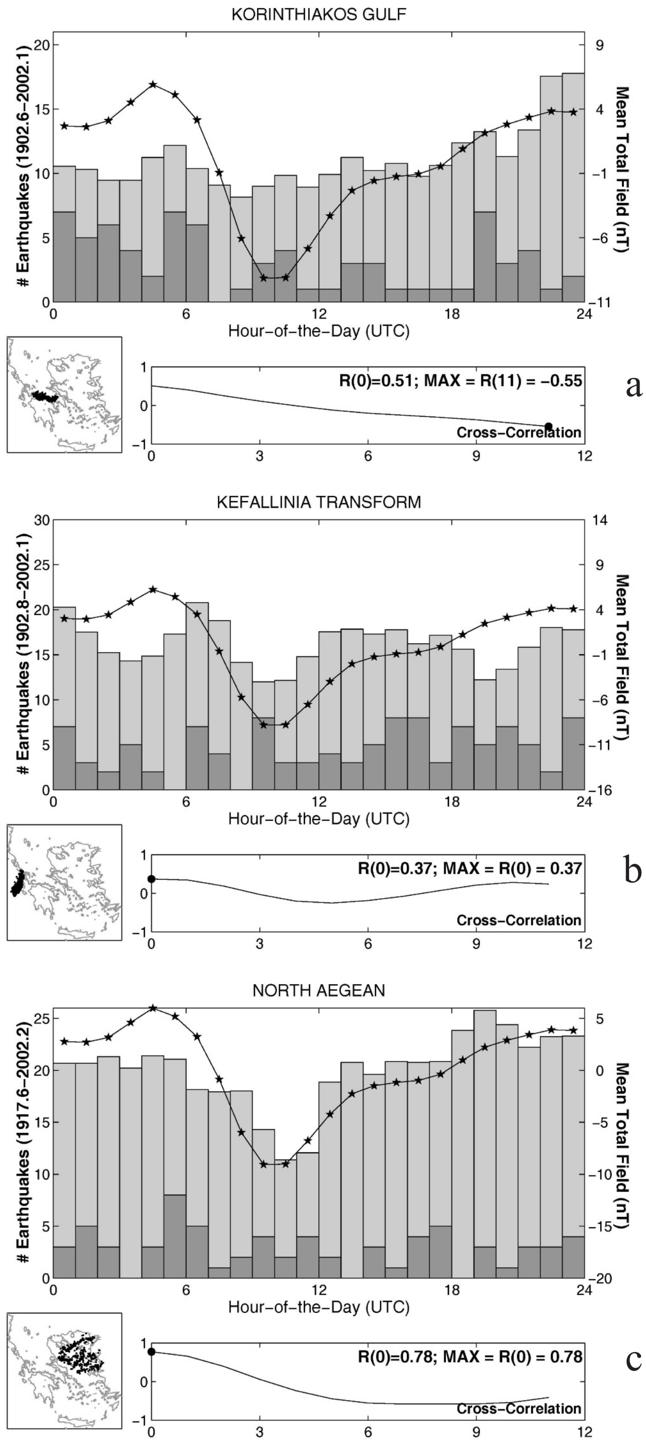


Fig. 10a. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count at the area of the Gulf of Corinth.
Fig. 10b. As per Figure 10a but for the NW Hellenic Arc (Kefallinia Transform).
Fig. 10c. As per Figure 10a but for the North Aegean region.

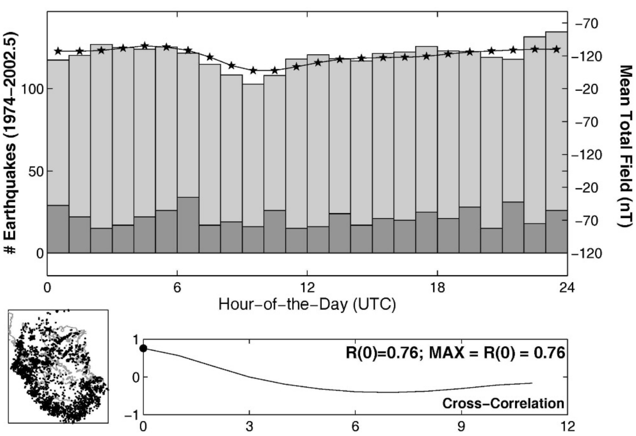


Fig. 11. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for the entire Hellenic territory and adjacent areas (histograms) over the period 1974.0 – 2002.58. The magnitude threshold is again M ≥ 4.

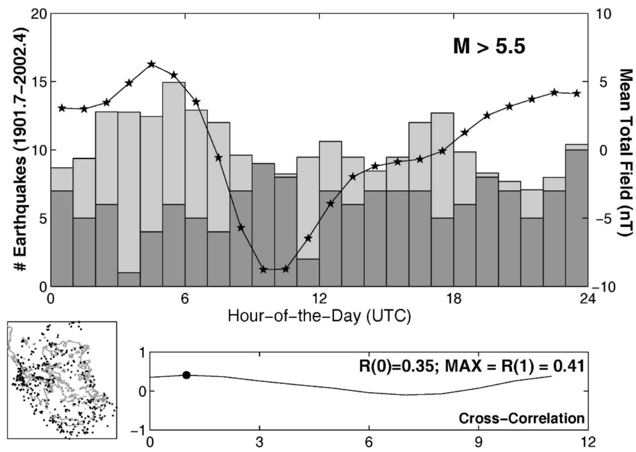


Fig. 12. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for the entire Hellenic Territory and adjacent areas (histograms) over the period 1932.0 – 2002.58. The magnitude threshold is now M ≥ 5.5.

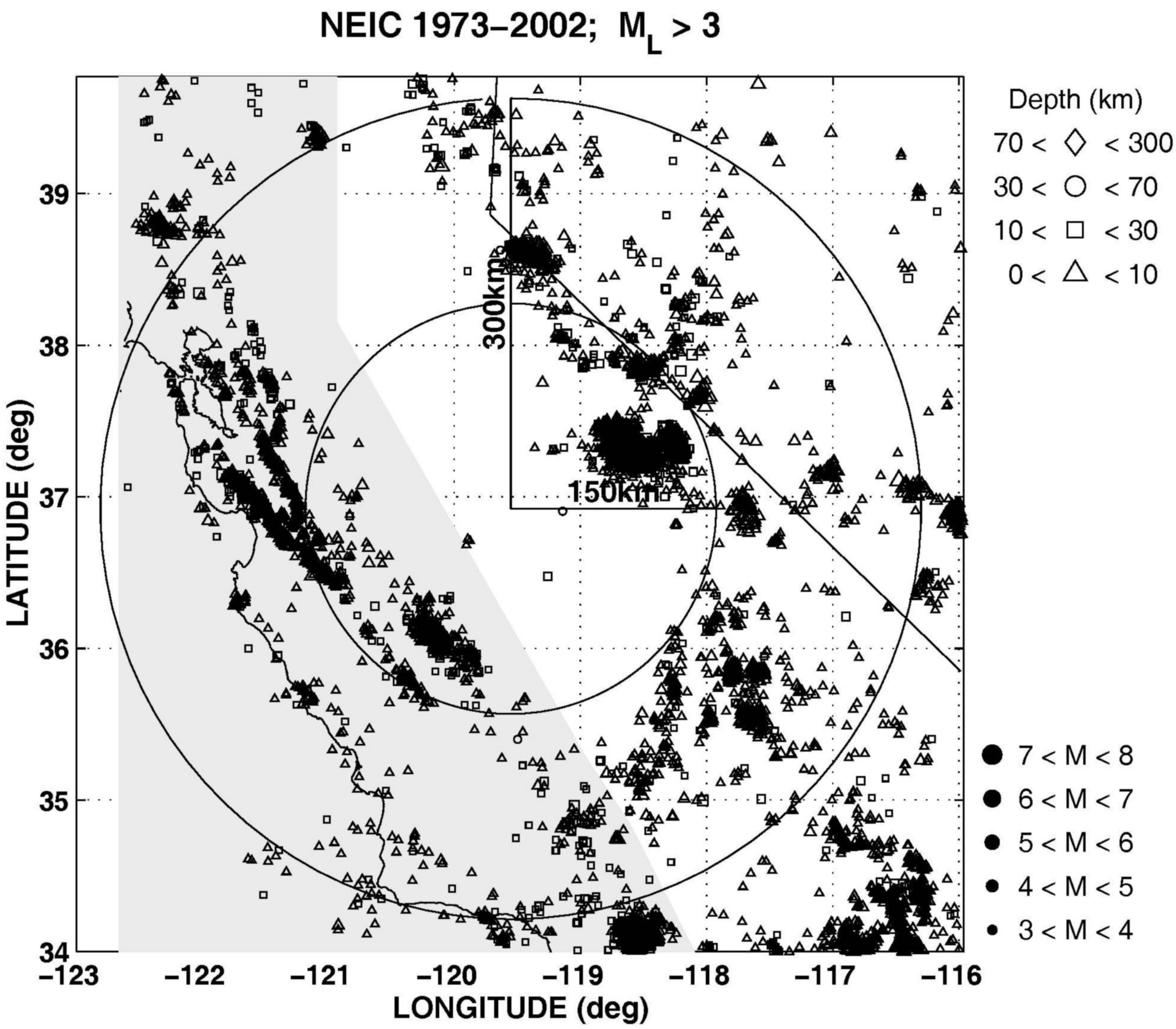


Fig. 13a. The study area in Central California. The depicted catalogue contains earthquakes with magnitudes $M_L \geq 3$, extracted from the PDE data set (NEIC / USGS) and spanning the period 1973 - 2002. The shaded area determines the area of San Andreas Fault and related structures. The circles determine distances from the observatory FRN.

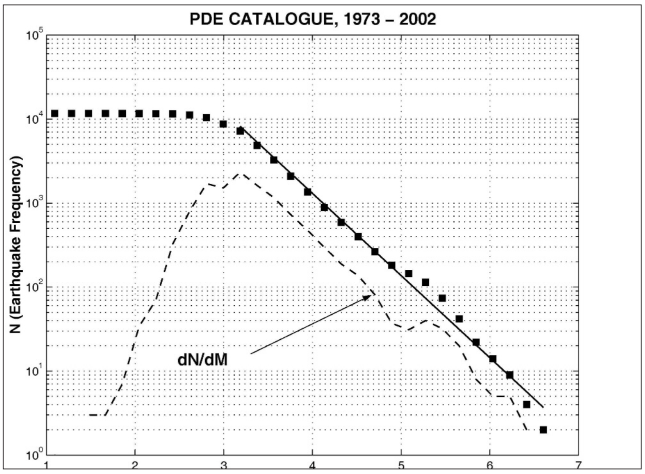


Fig. 13b. The cumulative Gutenberg – Richter curve for the catalogue shown in Figure 13α. The threshold of completeness is $M_L \sim 3$.

of some earthquake triggering due to the ILEMC process. Nevertheless, the influence of the geomagnetic variation appears to be *neither dominant, nor simple*.

To begin with, it does not appear uniquely at all spatial and magnitude scales and, very importantly, it does not appear at the small magnitude scales, at least in California. Notably, a similar absence of the effect at small magnitudes can be observed in Greece, (although with some reservation), if one uses the catalogue of the geodynamic Institute of the National Observatory of Athens which is complete for magnitudes $M_L \geq 3$, at least during the past decade. This means that 'small enough' faults do not 'sense' the effect of the stress surcharge at all!

In addition to the above, only a fraction of the observed cumulative hourly earthquake count and specifically its a.c. component (varying part) could be related to the Sq variation. Moreover, the values of the correlation coefficients show that only a fraction of this a.c. component, (the part correlated with the Sq variation) could have been triggered by the magnetic field. The correlated part varies between places and appears to be significantly dependent on the tectonic regime. This is foreseen by theory, (for instance see Fig. 3), but the verification and quantification of this dependence will require considerable additional effort. The remaining (uncorrelated) part shows that there are factors systematically influencing the diurnal seismic activity, which have their own (regular or irregular) time dependence and whose nature is not presently understood. Moreover, the CHEC has a very significant d.c. or background component, which presumably comprises of earthquakes triggered by regular tectonic activity.

In order to obtain a measure of the above observations, consider the results of Fig. 11 which are obtained for the period 1974.0–2002.58, when the expanded catalogue of Makropoulos *et al*. (1989) is complete for magnitudes M ≥ 4. A total of 3406 earthquakes contributed in forming the histograms of Fig. 11, of which 2886 were observed during solar-quiet days and 520 during disturbed days. The a.c. com-

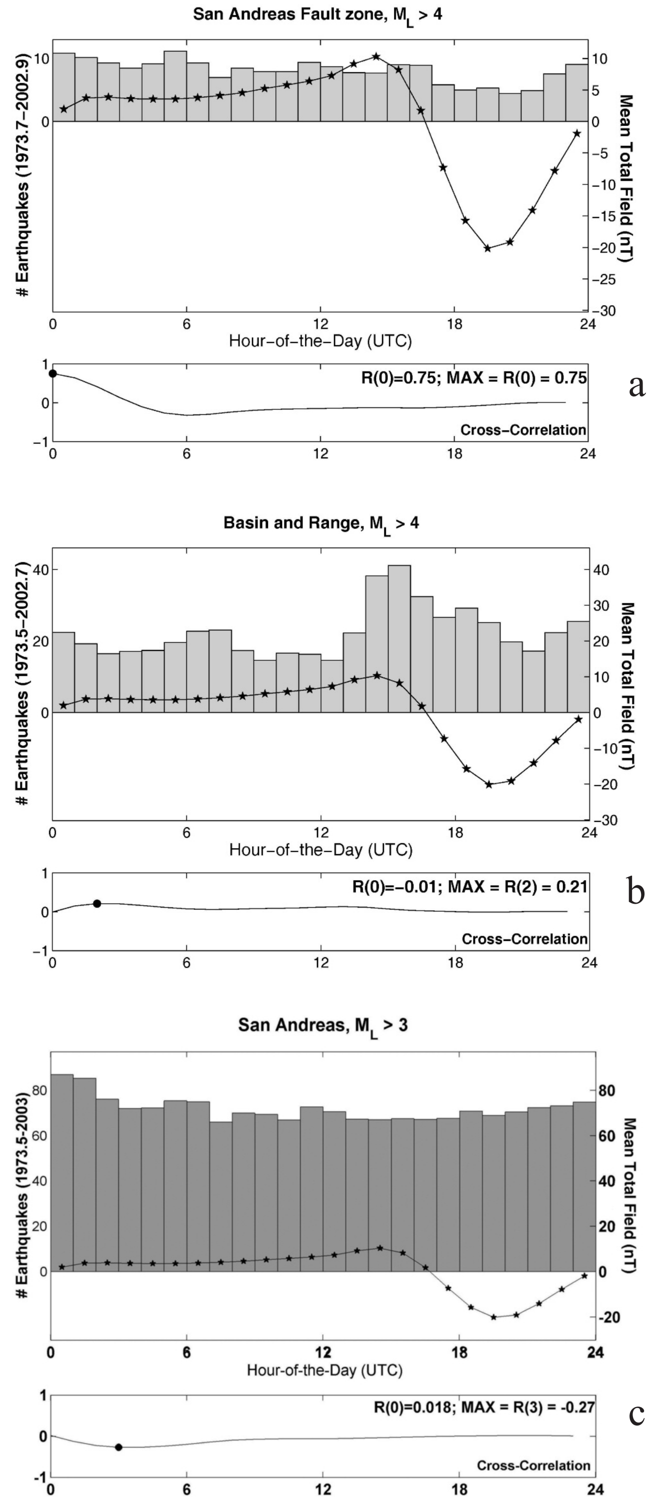


Fig. 14a Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for magnitudes $M_L > 4$ along the San Andreas fault (California, USA).

Fig. 14b. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for magnitudes $M_L > 4$ in the Basin-and-range region (E. California – W. Nevada, USA).

Fig. 14c. Comparison of the average total-field diurnal variation and the cumulative hourly earthquake count for magnitudes $M_L \geq 3$ along the San Andreas fault (California, USA).

ponent of the quiet-day CHEC includes *at most* 534 earthquakes. With a zero-lag correlation coefficient $R_0$= 0.76, it follows that *at most* 405 events could have been triggered by the Sq variation at the M ≥ 4 level, or else the 14% of the quiet-day events and 12% of the total number. In even simpler terms, out of 29 events with M ≥ 6 that have occurred during this period (potentially damaging – destructive earthquakes), at most 4 could have been triggered by the diurnal geomagnetic variation; this is a small albeit not insignificant number.

To conclude this discussion, it appears that earthquake triggering by the ILEMC process is possible but quite sporadic and heavily dependent on the right concert of fault geometry, tectonic stress load and geomagnetic stress surcharge. Therefore, a lot of work is still needed before the effect is sufficiently palpable. Still, it may comprise an additional and plausible earthquake triggering factor and appears to affect intermediate – larger sized faults, which are the most hazardous. These reasons make it worthy of continued attention and research and lend some practical value to the effort of trying to understand it.

## ACKNOWLEDGEMENTS

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## REFERENCES

DUMA, G. & Y. RUZHIN (2003). Diurnal changes of earthquake activity and geomagnetic Sq –variations, *Natural Hazards and Earth System Science,* 3, 171-177.

DUMA, G. & G. VILARDO (1998). Seismicity cycles in the Mt.Vesuvius area and their relation to solar flux and the variations of the Earth's magnetic field. *Phys. Chem. Earth,* 23, No. 9-10, 927-931.

FLORINDO, F. & L. ALFONSI (1995). Strong earthquakes and geomagnetic jerks: a cause-effect relationship ? *Annali di Geofisica,* 38, 457-461.

FLORINDO, F., ALFONSI, L., PIERSANTI, A., SPADA, G. & W. MARZOCCHI (1996). Geomagnetic jerks΄ and seismic activity. *Annali di Geofisica,* 39, 1227-1233.

HOWELL, B. JR. (1969). *Introduction to Geophysics*, McGraw-Hill, New York.

INTERNATIONAL SERVICE OF GEOMAGNETIC INDICES (ISGI) of the IAGA: URL *http://www.cetp.ipsl.fr/~isgi/homepag1.htm*

LANZEROTTI, L.J. & G.P. GREGORI (1986). Telluric Currents: The natural environment and interactions with man-made systems. *In*: *The Earth's Electrical Environment,* Studies in Geophysics Series, The National Academies Press, 232-257 pp. (βιβλίο διαθέσιμο στην URL http://www.nap.edu/books/0309036801/html/.

LEMOUËL, J.L. & V. COURTILLOT (1981). Core motions, electromagnetic core-mantle coupling and variations in the earth's rotation: new constraints from geomagnetic secular variation impulses. *Phys. Earth Planet. Int.*, 24, 236-241.

MAGNETIC OBSERVATORY OF PENTELI (PEG): URL *http://www.igme.gr/MAGNETIC.htm.*

MAKROPOULOS, K.C., DRAKOPOULOS, J. & J.B. LATOUSSAKIS (1989). A revised and extended earthquake catalogue in Greece since 1900,. *Geophys. J. Int.*, 98, 391-394.

MICHAEL, A.J. (1984). Determination of Stress from Slip Data: Faults and Folds, *J. Geophys. Res.*, 89, 11517-11526.

MICHAEL, A.J. (1987). Use of Focal Mechanisms to Determine Stress: A Control Study, *J. Geophys. Res.*, 92, 357-368.

PRESS, F. & P. BRIGGS (1975). Chandler wobble, earthquakes, rotation and geomagnetic changes. *Nature*, 256, 270-273.

STEPP, J.C. (1971). An investigation of Earthquake Risk in the Puget Sound Area by use of the type I Distribution of Largest Extremes, *Ph. D Thesis*, Pensylvania State University.

VESTINE, E.H. (1953). On variations of the geomagnetic field, fluid motions, and the rate of the earth's rotation. *J. Geophys. Res*., 58, 127-145.

WORLD DATA CENTER FOR GEOMAGNETISM, (Kyoto): URL *http://swdcdb.kugi.kyoto-u.ac.jp/index-j.html*

WORLD DATA CENTER FOR GEOMAGNETISM C1, (Kopenhagen): URL *http://web.dmi.dk/projects/wdcc1/*