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Possible Cause-Effect Relationships Between Vrancea (Romania) Earthquakes and Some Global Geophysical Phenomena

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Abstract. The possibility that the Earth's tides are a triggering factor of Vrancea subcrustal earthquakes is investigated in the first part of this paper. A possible correlation between Vrancea subcrustal earthquakes and geomagnetic jerks is demonstrated in the second part. The last part of the paper presents a number of results concerning a possible relationship between the regularities of strong Vrancea subcrustal seismicity and the Chandler nutation parameters. An attempt is made to integrate all of these phenomena in a more general framework that takes into account physical processes in the Earth mantle and core. A long-term prediction of the next strong Vrancea earthquake is finally attempted.

Key words: Vrancea subcrustal earthquakes, Earth tides, geomagnetic jerk, Chandler nutation, couple-impulses, earthquake prediction.

1. Introduction

Attempts were made in a series of previous papers to correlate seismic Vrancea activity to other geophysical and astronomical phenomena. Thus, Anghel (1979) made a first attempt, trying to correlate some regularities of the strong and very strong ($M > 6.0$) Vrancea seismicity with solar activity (namely sunspots). He found a possible relationship in which solar activity (cause) could be a triggering factor of Vrancea earthquakes (effect). Zugravescu *et al.* (1989) as well as Enescu and Moldoveanu (1992) indicated a relationship between the Vrancea subcrustal seismic activity and the diurnal component of tides. Souchay *et al.* (1995) established a connection between the moments at which major Vrancea earthquakes occur and the tidal harmonic of 18.613-year period. Their main finding is that 70% of Vrancea earthquakes of magnitudes $M \geqslant 7.0$ occurred within half the 18.613-year period centered on phase zero.

The possible existence of some complex cause-effect relationships between the phenomena of tides, geomagnetic jerks and Chandler nutation, and Vrancea subcrustal seismic activity is inferred in this paper, and some possible explanations for such relationships are given. A time window and a magnitude window for the next strong Vrancea earthquake are inferred from the data.

2. Vrancea Subcrustal Earthquakes and Tides

Taking into account the shape of the time variation of gravity at Caldarusani Geodynamic Observatory, which is located in the vicinity of the Vrancea seismic zone, the interval between two successive inflections of the same sign can be approximated by the sinusoid

$$\Delta g = \Delta g_0 \sin \omega t, \tag{1}$$

and has the shape given in Figure 1(a). The sinusoid (1) refers to the gravity effects of the Earth's tides over a 24-hour period.

Figure 1(b) shows a histogram of the distribution of events in time. It suggests a dependence between the number N of Vrancea subcrustal earthquakes and their position with respect to the sinusoid. The figure refers to a set of 961 Vrancea subcrustal earthquakes (of magnitudes $3.0 < M \leqslant 7.0$) occurring between 1 April 1977, and 1 August 1987 (Zugravescu *et al.*, 1989). The data were selected so as to cover a time interval when the equipment of our seismic stations had been improved in the wake of the major (M = 7.2) earthquake of 4 March 1977.

These representations suggest that Vrancea subcrustal earthquakes mostly occur during a maximum or minimum of the tidal curve, and also during the positive or negative inflections of the tidal curve (Figure 1).

As is likely to happen in any model, the approximation of the gravity tide curve by the sinusoid in Figure 1 may have given rise to some errors; in other words, it may have led to a wrong or distorted assignment of some earthquake occurrence moments to some particular phases of the gravity tide curve (maximum, minimum, etc.).

Let us assume the representations in Figure 1 are free of errors or exaggeration, and let us see exactly how significant they are. To this end, we calculated the probability P_{ph} that a Vrancea subcrustal earthquake does occur during a maximum of the tidal curve, during a minimum, in one of the inflection zones of the curve, or in other phases. Using the notation N_{t} for the total number of Vrancea subcrustal earthquakes recorded over the selected period and N_{ph} for the number of earthquakes corresponding to a particular gravity tide phase, we obtained the following results:

Phase	**Number of events,** N_{ph}	$P_{\mathrm{ph}} = N_{\mathrm{ph}}/N_{\mathrm{t}}$
maximum	155	0.16
minimum	142	0.15
inflection	157	0.16
other phases (total)	507	0.53

where N_{t} = 961 earthquakes.

Consequently, 47% of earthquakes occurred during the maximum, minimum and inflection zones of the gravity tide (that is within a four-hour time), and 53% of

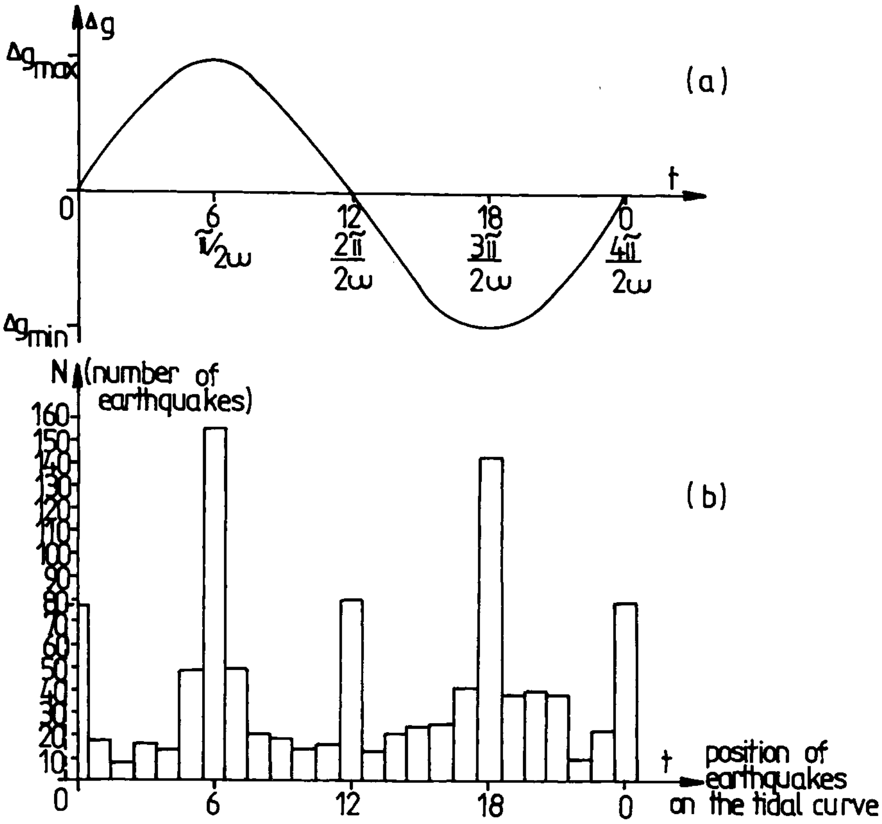

Figure 1. (a) Sinusoid (1); (b) Histogram showing the dependence between the number of Vrancea subcrustal earthquakes N and their position on the sinusoid (1); the histogram refers to a set of 961 Vrancea subcrustal earthquakes that occurred between 1 April 1977, and 1 August 1987 (after Zugravescu *et al.*, 1989).

the earthquakes occurred during other phases of the curve (that is within a 20-hour time). It follows that, in the first category, we have about 12% of events happening in an hour, and in the second, only about 3% of events in an hour. So $12/3 \cong 4$ times more earthquakes occur during the main phases of tides than in any other phases of a diurnal cycle, which is a rather significant finding.

It is quite unlikely that the tide-induced stress should act as a trigger for the majority of Vrancea subcrustal earthquakes, because the tectonic stress build-up in time is neither smooth nor gradual to allow tidal and tectonic stresses to be combined in a simple manner. Besides, in many cases, the faulting does not occur as soon as a critical stress is reached. This may, in turn, be due to some time delay characteristic of deep faulting, stress history in the region, or even the mode of faulting itself as a unique and unexplained phenomenon at such high pressures and temperatures.

3. Vrancea Subcrustal Earthquakes and Geomagnetic Jerks

A geomagnetic jerk is a rapid change, taking place in a year or two, in the slope of the curve of secular variation of the geomagnetic field, and in a step function in the secular acceleration.

In recent years, such sudden changes (i.e., jerks) in the secular variation of the geomagnetic field have been reported in several papers (Courtillot *et al.*, 1978; Courtillot and Le Mouël, 1984; Golovkov *et al.*, 1989, 1995; Alexandrescu *et al.*, 1995; Cafarella and Meloni, 1995; Florindo and Alfonsi, 1995; etc.).

The first questions raised by this phenomenon were obviously related to its sources (whether external or internal) and its extension on a global scale. Supporters of an external origin believe these jerks are an effect of solar activity (see, for example, Alldredge, 1985). However, it has been ascertained that jerk occurrence does not follow the 11-year sunspot cycle. Spherical harmonic analyses favor an internal origin of the jerks (Malin and Hodder, 1982; McLeod, 1985, 1992; etc.). Other researchers have tried to associate this phenomenon with minima in Earth rotation velocity resulting from some kind of core-mantle coupling.

In a recent paper, Florindo and Alfonsi (1995) consider that strong earthquakes could excite processes impacting on the geodynamo and, particularly, the vectorial configuration of the velocity field of the outer fluid core layers.

Since subcrustal earthquakes are likely to offer more reliable information, we are trying in this section to correlate Vrancea seismic activity with jerk occurrence. As reliable information on jerk occurrence is limited to this century alone, we took into account the Vrancea subcrustal earthquakes occurring after 1900. Figure 2 shows the distribution of the number of earthquakes (N), characterised by magnitudes $M \geqslant 6.0$ (and a variant with $M \geqslant 6.5$), occurring in this century. Dashed lines are used to show four jerks: one in 1910 (Courtillot and Le Mouël, 1984); another in 1947 (Golovkov *et al.*, 1989, 1995); a third one in 1978 (Alexandrescu *et al.*, 1995); and a fourth one in 1990 (Cafarella and Meloni, 1995). Figure 2 shows three seismic events of magnitudes $M > 6.0$ for the decade 1970–1980, since the major earthquake of 4 March 1977 is considered a multishock consisting of three main shocks (Müller *et al.*, 1978): two former shocks of nearly equal magnitude ($M = 6.5$) and a later one of magnitude $M = 7.2$ (Peterschmitt, 1977).

A different way of presenting data is shown in Figure 3c where the seismic energy variation (E), annually emitted by Vrancea subcrustal earthquakes, is used. It is worth mentioning that the four jerks, which are also shown in Figure 3, took place not just over Europe but over much of the northern hemisphere as well.

The seismic energy E was calculated using the formula by Gutenberg and Richter (1956):

$$\log E(\text{ergs}) = 11.8 + 1.5M \tag{2}$$

and the magnitudes M (of Gutenberg–Richter type) were taken from the Earthquake Catalogue, edited by Constantinescu and Mârza (1980), and some reports of

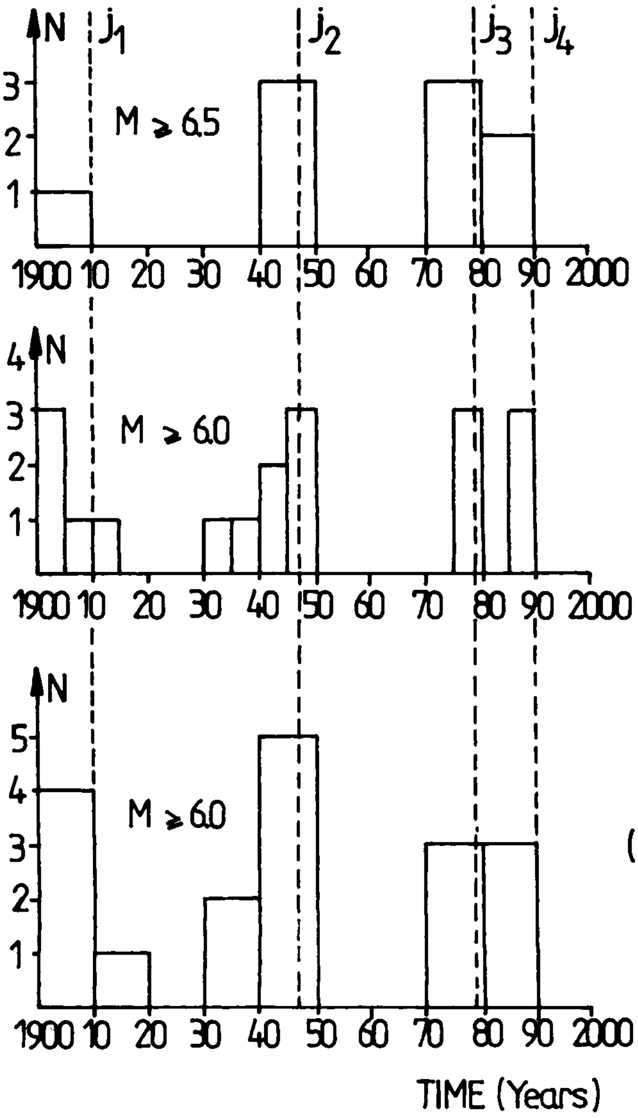

Figure 2. Distribution of the number of Vrancea subcrustal earthquakes N that occurred in this century: (a) Earthquakes characterized by magnitudes $M \geqslant 6.0$ within 10-year time intervals; (b) earthquakes of magnitudes $M \geqslant 6.0$ within 5-year time intervals; (c) earthquakes of magnitudes $M \geqslant 6.5$ within 10-year time intervals. Dashed vertical lines mark the times of occurrence of four geomagnetic jerks.

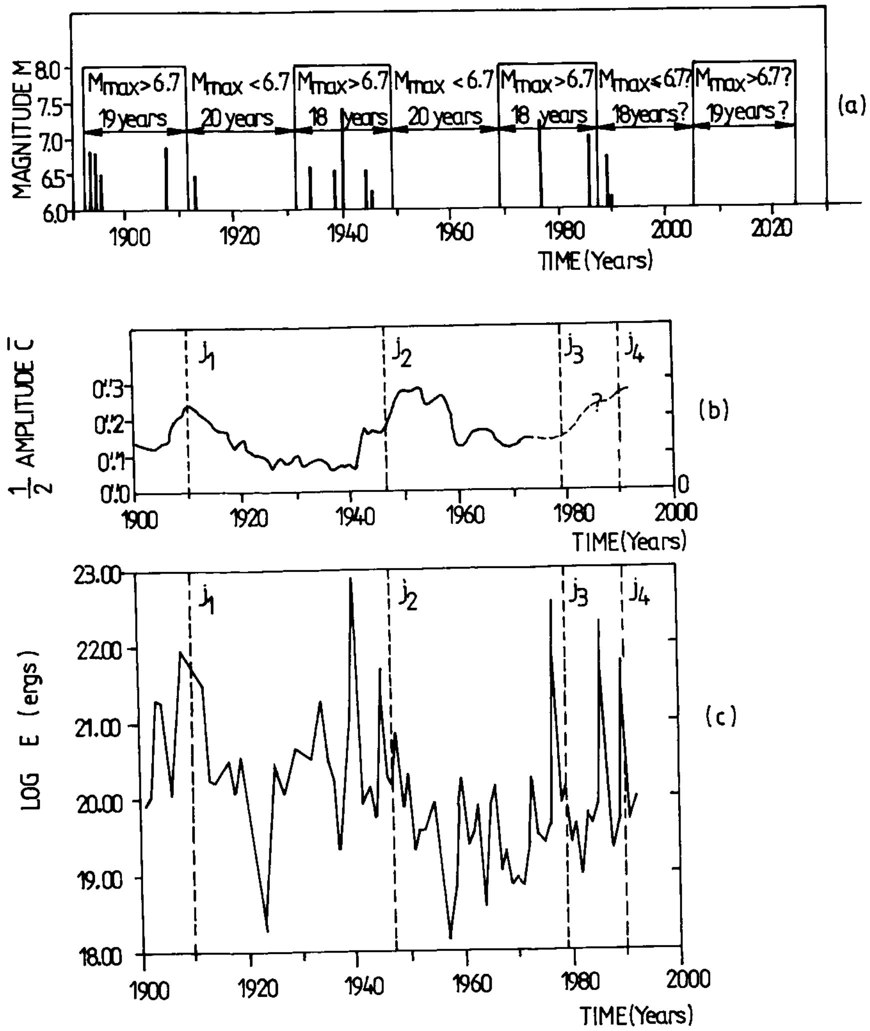

Figure 3. (a) Observed cyclicity in the magnitude distribution of Vrancea earthquakes in this century; an attempt at extrapolating the data in the future; the years are marked at the end of their span; (b) Amplitude variation curve of Chandler wobble in this century (after Guinot, 1976); this curve was extrapolated by us for the period after 1973; (c) Time distribution of seismic energy annually radiated by Vrancea subcrustal earthquake that occurred after the year 1900; dashed vertical lines mark the times of occurrence of four geomagnetic jerks.

the Romanian Seismological Department. The validity of relation (2) for Vrancea earthquakes has been demonstrated by many Romanian researchers (e.g., Constantinescu and Enescu, 1985).

Figures 2 and 3(c) point to a correspondence between the occurrence of strong ($M \geqslant 6.0$) Vrancea earthquakes (maxima of seismic activity) and the rapid, sudden variations of the geomagnetic field (jerks $J_1 - J_4$). A similar correspondence is found for all the strong ($M \geqslant 7.0$) seismic activity around the world and the seven jerks reported in this century (Florindo and Alfonsi, 1995).

One assumes that strong earthquakes (deep ones especially) could excite the Earth’s normal modes causing instabilities in the outer core convection cells where the magnetic field is generated.

The generation mechanism of the Earth’s magnetic field may also be affected by changing conditions at the core-mantle boundary. Thus, strong earthquakes could produce a deformation of the topography of this limit (Piersanti *et al.*, 1995), or cause a differential rotation between the outer core and the lower mantle. If the latter hypothesis is considered, the cause-effect chain seems to be as follows: earthquakes – mass redistribution – change in the Earth inertia momentum – change in the Earth rotation rate – differential rotation between the outer core and mantle – jerk.

In Won and Kuo’s opinion (1973), strong earthquakes could produce a state of oscillation of the solid inner core which, in turn, could induce disturbances in the fluid outer core. Even though data (Figures 2 and 3) point to a correspondence between the occurrence of strong Vrancea seismic events and geomagnetic jerks, it would be risky to assert a definite cause-effect relationship between the two phenomena, for there is no quantitative evidence to support such an assertion. Moreover, this correspondence is true for four jerks, while there have been seven of them so far this century.

4. Vrancea Subcrustal Earthquakes and the Chandler Wobble

The Chandler wobble is nothing but Euler nutation elongated by the Earth’s elasticity. The shape and amplitude variations of the Chandler nutation are represented in Figure 3b for the period 1901–1992.

As shown in the Appendix, the Vrancea seismicity reveals an intriguing alternation of time intervals of magnitudes $M_{\max} > 6.7$ and $M_{\max} \leqslant 6.7$, respectively. This alternation was very well confirmed over a long period of time (1196–1993). The two types of time intervals are of nearly equal lengths, namely 19.31 ± 1.24 years $\cong$ 18–21 years. We thus could talk of a cyclicity, with an average cycle length of about 36–40 years. This cyclical nature for solely the 20th century is shown in Figure 3a. Chandler nutation data are only available for this century. The existence of a $M = 6.7$ threshold is proved by data in Figures 3 and 5 and an extrapolation to the past (back to around the year 1200) of the alternating 18-to-21-year intervals of $M_{\max} \geqslant 6.7$ (6.5) and $M_{\max} \leqslant 6.7$ (6.5), a separation that was first uncovered for 20th century data. An error range of 0.2 unit magnitude was taken into account. Figure 3 reveals the same 38 to 40 years cycle length for both phenomena (i.e., the Vrancea seismic activity and Chandler nutation). A difference in time between the two phenomena is also noticed in Figure 3.

Many hypotheses have been advanced concerning the excitation source of the Chandler nutation. A very important one was proposed by Runcorn (1970), who studied the role of couple-impulses on both the Chandler oscillation and Earth's rotation rate. Runcorn (1970) suggested a short but intense electromagnetic coupling between core and mantle as the origin of these impulses.

Results presented in this paper (Figure 3) would rather sustain the hypothesis of strong earthquakes as one of the causes for the excitation of the Chandler wobble. This hypothesis actually dates back to the beginning of this century. It was dropped for a time, then revived by Mansinha and Smylie (1970), who studied the role of inertial momentum changes which accompany the mass redistributions during earthquakes.

It is possible that both hypotheses are valid, i.e., that the Chandler nutation could be caused by couple-impulses as well as earthquakes. It is also possible that processes (admitted by Runcorn) in the Earth's core be triggering factors for earthquakes in the zones where tensions reach a level close to the point of rupture (Guinot, 1976).

Some authors (e.g., Kanamori, 1977) have demonstrated that the amount of energy release in earthquakes on a global scale, which is some two orders of magnitude larger than the release for Vrancea, is much too small to affect the Chandler wobble significantly. Moreover, the data time series are obviously too short here. Thus, even if there were any significant correlation between the Chandler wobble and energy release in all (shallow and deep) earthquakes (Abe and Kanamori, 1979), the underlying causal relationship or physical mechanism remains unknown.

5. Discussions and Conclusions

Findings presented in this paper prove that earthquakes may impact on global geophysical phenomena and vice versa. We will now try to give a synthetic outline of the relations between various phenomena, which are presented as 'systems' in Figure 4.

According to data shown in Figure 1, the Earth's tides are a triggering factor for some Vrancea earthquakes. It is also important to note that earthquakes may trigger one or several listed phenomena, which are responsible for jerk occurrence (see Section 3 of this paper, Figures 2–4). The couple-impulses (Runcorn, 1970) may act as both an excitation source for Chandler oscillations and a triggering factor for some earthquakes. Earthquakes may in turn be a source of Chandler wobble (Figures 3 and 4).

The scheme in Figure 4 certainly does not account for all the geophysical phenomena that are correlated with one another and with earthquake (particularly Vrancea earthquake) occurrence. Interactions among geophysical phenomena are also extremely complex in nature. Consequently, the outline in Figure 4 is incomplete and open to considerable improvement.

A most important suggestion is found to arise from data in Figure 3 and the Appendix. An extrapolation of these data to the future (Figure 3) leads to the hypo-

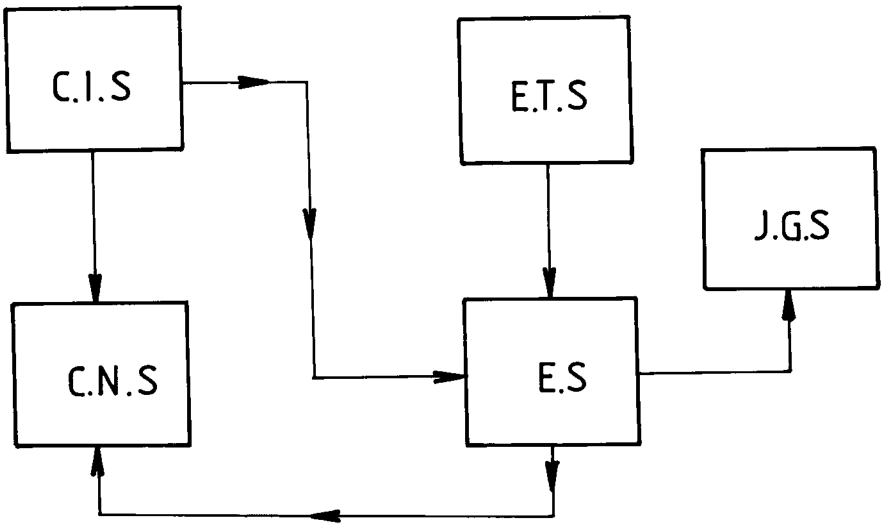

Figure 4. A very simplified sketch of the relations between phenomena taken into consideration in this paper, and represented as systems: C.I.S. – couple-impulses system (originating in the contact zone between mantle and Earth core); C.N.S. – Chandler-nutation system; E.S. – earthquake system; J.G.S. – jerk-generating system (one of the mechanisms listed in Section 3); E.T.S. – Earth-tide system.

thesis that the next strong Vrancea earthquake (of magnitude $M > 6.7$) will occur in the period 2006–2024. Within this time interval as many as 2–3 earthquakes of magnitude $M > 6.7$, including one as strong as $M \geqslant 7.0$, may be expected to occur.

Among earlier findings (Enescu *et al.*, 1974; Purcaru, 1974, 1979; Novikova *et al.*, 1995; Enescu and Enescu, 1996; etc.), there is one stating that in centuries for which historical or instrumental data are available, strong Vrancea earthquakes generally occurred within the first eight years, while one took place in the eleventh year. Two further exceptions are those earthquakes in 1196 and 1516. The former did not even occur at the beginning of a century. Still, both of them agree with the model briefly described in the Appendix, hence do not clash with our extrapolation to the future (see Figure 3). An attempt at predicting the next strong Vrancea earthquake, as outlined below, is in accordance with both the model shown in the Appendix and the fact that strong Vrancea earthquakes in the early part of a century, mostly occurred in years one to eight. Among them are earthquakes in the 17th–20th Centuries on which we have highly reliable data.

Based on this finding and the 2006–2024 time window mentioned above, it follows that the next strong ($M > 6.7$) Vrancea earthquake is likely to occur in the time window 2006–2008, or even more likely (almost a certainty) in the time window 2006–2011. Taking into account existing data from the past, we estimate the magnitude of such an earthquake will be higher than 7.0 but not exceeding 7.5.

The above deduced time window (2006–2008, or even the 2006–2011 variant) is much smaller than those inferred in previous papers (2000–2008, see Enescu *et al.*, 1974; 2000–2011, 1999–2013, see Mârza, 1982, 1996; Sandi and Mârza, 1996; etc.).

Appendix

The focal mechanism of Vrancea subcrustal earthquakes has been studied by many researchers. The focal mechanism characteristics of these earthquakes were well synthesized by Enescu and Enescu (1998) for about 200 seismic events of magnitudes $4.0 \leqslant M \leqslant 7.4$ occurring in the period 1929–1993. We shall only mention here the characteristics that refer to the tension (traction) axis, compression axis and orientation of the fault plane. Thus, a quasi-verticality of the tension axes and a quasi-horizontality of the compression axes have been found. Two main categories of earthquakes have been identified. One category is composed of earthquakes with a NW–SE orientation of the compression axes and NE–SW orientation of the fault planes. The second category includes earthquakes with NE–SW compression axes and NW–SE fault planes.

An analysis of the time variation of the main types of focal mechanism (in the above terms) of Vrancea earthquakes has been considered useful.

We have denoted by N_1 the number of earthquakes within a time interval δt, which belong to the first category in terms of focal mechanism solution, and by N_2 the number of second-category earthquakes in the same time interval. The time variation of the dominant type of focal mechanism was expressed by

$$\nu(t) = \sqrt{\frac{[N_1(t) - N_2(t)]^2}{N(t)}} = \frac{N_1(t) - N_2(t)}{\sqrt{N(t)}}; \; N(t) = N_1(t) + N_2(t). \qquad (3)$$

We calculated the parameter ν for each year (δt = 1 year), for which focal mechanism solutions were available (Figure 5(a)). One finds (Figure 5(a)) that, before 1932 there was a time interval, Δt, that was probably characterized by $\nu < 0$; the time interval 1932–1949 (Δt = 18 years) was characterized by $\nu > 0$; the time interval 1950–1969 (Δt = 20 years) was characterized by $\nu < 0$, and the time interval 1970–1987 (Δt = 18 years) was characterized by $\nu > 0$. Consequently, we find alternative Δt intervals of $\nu < 0$ and $\nu > 0$.

Figure 5(b) shows the magnitudes $M > 6.0$ for the time period 1929–1993. Comparing data in Figure 5(a) to those in Figure 5(b), one finds that: in intervals where the first focal mechanism category ($\nu > 0$) is dominant, maximum magnitudes are $M_{\max} > 6.7$, while in intervals dominated by the second focal mechanism category ($\nu < 0$), maximum magnitudes are $M_{\max} \leqslant 6.7$.

Since no focal mechanism solutions are available for earthquakes older than the year 1929, we extrapolated in the past only the time interval separation shown in Figure 5(b). The extrapolation was carried out back to the year 1196 (Enescu

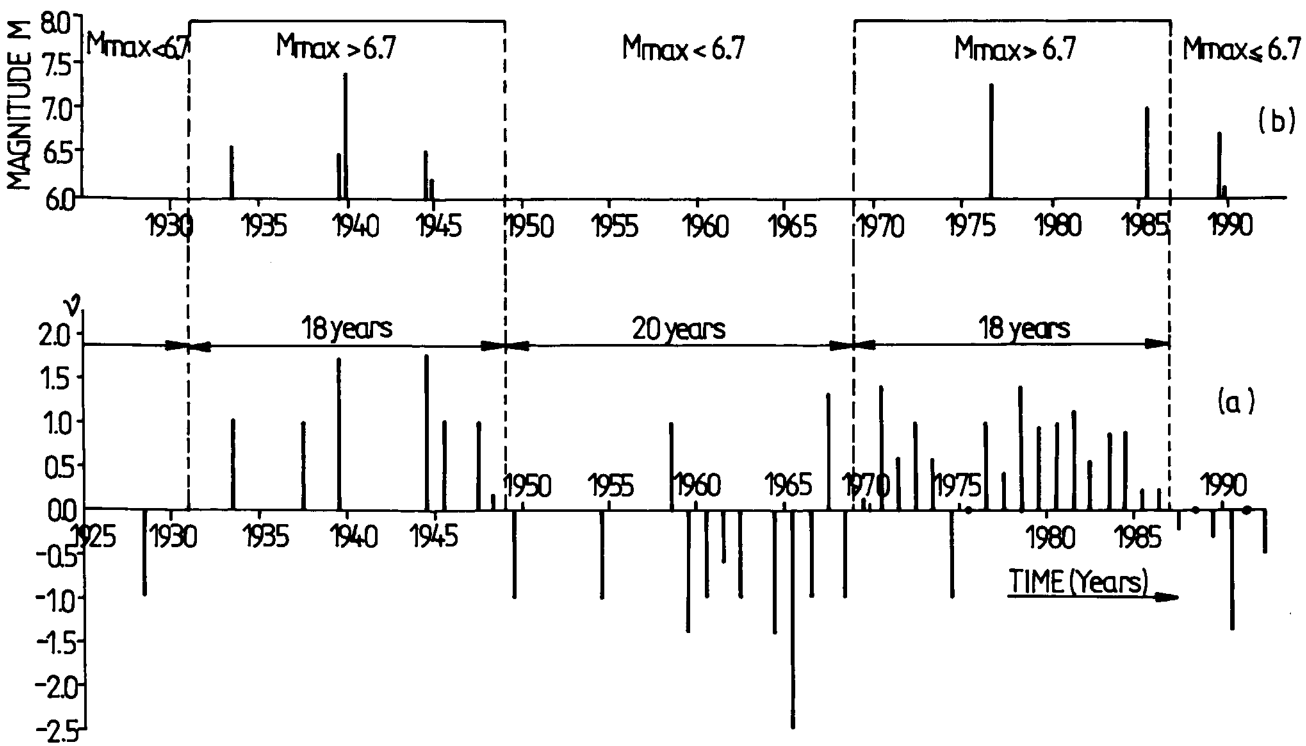

Figure 5. (a) Time variation (in the period 1929–1993) of the parameter ν; (b) Time distribution of the magnitudes $M > 6.0$ for the period 1932–1990; separation of the time intervals Δt characterized by $\nu > 0$ ($M_{\max} > 6.7$) from the time intervals characterized by $\nu < 0$ ($M_{\max} \leqslant 6.7$). The years are marked at the end of their span.

and Enescu, 1996) using the Earthquake Catalogue edited by Constantinescu and Marza (1980); data older than the year 1196 are of very little reliability. This extrapolation has demonstrated a nearly perfect alternation of time intervals characterized by $M_{\max} > 6.7$ and time intervals characterized by $M_{\max} \leqslant 6.7$; these intervals are quasi-equal to one another within a range of 18–21 years.

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