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Statistical investigations on diurnal and annual periodicity and on tidal triggering of local earthquakes in Central Europe

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Abstract. Two regional earthquake catalogues are analysed in order to investigate the existence of diurnal, annual and earth-tide related periodicities of the occurrence time of seismic events. The first earthquake catalogue covers the total region of the Federal Republic of Germany for the time period 1021-1979 (1530 events) and is investigated with respect to the existence of diurnal and annual periodicities. With the help of the graphical representation for Schuster's test, a midnight and a midday maximum are separated for different intensity classes. A winter maximum present in the data prior to 1930 is absent in the more recent data. It is argued that both diurnal and annual maxima are artifacts due to data sampling problems.

The second earthquake catalogue refers to the western part of Germany (Lower Rhine Graben, Rhenish Massif) and the time period 1979–1984 (1012 events of magnitude $M_L = 0.0$–5.1). For the events of this catalogue, a tidal phase is computed according to a model for the triggering of the predominant dip-slip earthquakes. The distribution of phases supports the triggering hypothesis (at the 99% significance level if Schuster's test is applied).

Key words: Earthquakes – Periodicities – Tidal triggering – Rhenish Massif – Lower Rhine Graben

Introduction

Earthquake prediction research at the beginning of this century mainly dealt with the question of triggering of earthquakes by external forces like weather phenomena or, often in linkage with this first aspect, with the question of lunar and solar periodicities. Nowadays, research is concentrating on the search for and the explanation of precursory phenomena and, still, on triggering by tidal forces. In the recent past it has, however, seldom been tried to check earthquake catalogues for the existence of diurnal and annual periodicities which, for example, Tams (1926) and Davison (1938) had detected some 50 years ago [see Karnik (1971), Shimshoni (1971), Schneider (1975) and McClellan (1984) for more recent investigations of these periods].

In the first of this paper we demonstrate that both diurnal and annual periods can be found in a catalogue of German earthquakes. The reasons leading to these periodicities are discussed. The second part of this study deals with the hypothesis of tidal triggering attributable to the most significant partial tides having semi-diurnal or diurnal periods. The basic idea of the hypothesis is that an earthquake should be released when tidal stresses enhance the tectonic stresses actually causing it, while it will be delayed when tidal and tectonic stress oppose each other. We shall derive a simple relation between the triggering tidal stress and the tidal linear strain in the direction of the minimum tectonic stress axis. The relation is valid for normal-fault mechanisms predominating in the Lower Rhine Graben and Rhenish Massif Area which is covered by the second catalogue used.

Methods

When looking at earthquakes in relation to a given period, each event is assigned to a phase which is determined by its location within this period (the hour within a day, the day within a year, ...). The event times are tested against the null hypothesis of a uniform distribution of such phases (i.e. no periodicity) by applying the conventional χ^2-test and Schuster's test [proposed by Schuster (1897) and described in detail by Chapman and Bartels (1951)]. Schuster's test, based on a random walk model, is specially designed for investigations of phase distributions. Its graphical representation, which is itself a powerful tool for the control and interpretation of the statistical results, is widely used in this study and is considered below.

Each event corresponds to a unit vector, the orientation of which is determined by the phase angle (Fig. 1). The sum of all vectors is a hodograph, the origin of the axes being the starting point of the vector sequence. The distance between the origin and the end of this sequence is R, measured in multiples of the unit length. R will be small when there is no phase preferred in the data; it will be large when a periodicity is real.

A uniform probability of all phases will be the null hypothesis in all following statistical investigations. Using N events out of a multitude fulfilling this null hypothesis, the probability for the resultant distance to be larger than R is, according to Schuster's test, $PR = \exp(-R^2/N)$. We reject the null hypothesis when PR is found to be lower than or equal to 1%, equivalent to a significance level of $1\text{-}PR = 99\%$.

As Schuster's test only uses the values of R and N it will not take into account whether the vector sequence (and therefore the statistical significance) is influenced by any persistencies (Chapman and Bartels, 1951; refer also to next section). Such persistencies can, however, be seen in the

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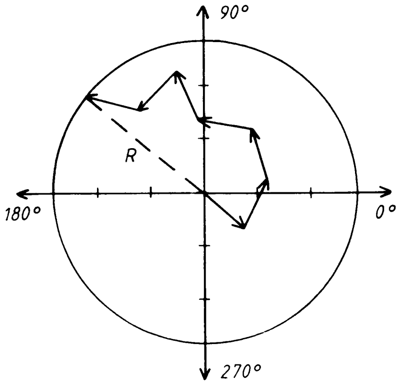

Fig. 1. Hodograph consisting of $N=7$ unit vectors. The sum vector of $R=3$ units is represented by the *broken line*. The phase of the first vector is 315°; with respect to the diurnal period, this vector would represent an event at 21 UT

hodograph which, in this way, proves to be a valuable tool for identifying effects within the data influencing a suspected periodicity.

The significance levels obtained by Schuster's test and the χ^2-test can differ considerably. For example, consider a case where the events exhibit the following phases: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°. Let us assume that the phases 0°, 45°, 90° and 135° are met by 30 events and the rest by 20 events each. In the case of the χ^2-test, the eight groups represent counts of phases in sectors of equal size centered at 0°, 45° etc.. Then the expected number for each of these eight groups is $(4*30+4*20)/8=25$ (according to the null hypothesis "uniform distribution"). With $\chi^2=8$, the significance level reached is only 50%. With Schuster's test, $R^2=683$ is obtained which, with $N=200$, gives $PR=3.3\%$.

This difference in significance levels appears to be unreasonable at first sight, but it may be explained in the following way. The χ^2-test does not take into account the order of the groups; so any ordering of the groups with four containing 30 events and four containing 20 would be equivalent for this test. In contrast, the result of Schuster's test may differ considerably from the one obtained above if the phases are arranged in a different way. For instance, if 30 events were attached to 0°, 90°, 180° and 270° and 20 events to each of the other four phases, a value of $PR=100\%$ would be reached (corresponding to $R=0$).

So, for investigations of distributions of phases, Schuster's test which is especially designed for this problem, should preferably be used. The results of the χ^2-test (histogram and significance) are still valuable for comparison.

Filtering

Special attention must be given to aftershocks and other forms of interdependency of earthquakes, since both χ^2- and Schuster's test assume that events occur independently of each other. The catalogues used here are influenced by some form of interdependency, as shown by tests on serial correlation by Ulbrich (1985). To remove such effects we used a special filter procedure. Any event preceded by another one during a time interval of 36 h or less was eliminated from the catalogue. For the sake of brevity we call this procedure a 36-h filter. The filter was applied without differentiating the events according to epicentre location, magnitude or other properties of the events. As an example: if the catalogue consisted of events occurring once every hour (or once every K hours, $K \leqq 36$), only the first event would be left after application of the 36-h filter, since this would be the only event without a predecessor within 36 h. The time window (filter length) of 36 h is chosen because it appears to be destructive on diurnal periodicities, and we believe that a destructive filter will make our results more reliable. This filter length, on the other hand, is somewhat arbitrary because there are other possible lengths with the same effect. The time window of 36 h has the advantage that not too many events are excluded from the catalogues. Furthermore, it appears to be efficient enough to eliminate serial correlations to a significant degree (Ulbrich, 1985).

For reasons of data comparability this filter length is also used for tests regarding the annual periodicity and the tidal triggering hypothesis, though the applicability is not clear a priori and must be discussed in the corresponding chapters.

The catalogues

Two catalogues have been used for the investigations: the earthquake catalogue of the Federal Republic of Germany, compiled by G. Leydecker at the Bundesanstalt für Geowissenschaften und Rohstoffe (Hannover, West-Germany) in cooperation with many seismological observatories in Germany and neighbouring countries (extended version published by Leydecker, 1986); and the catalogue of the Rhenish Massif and Lower Rhine Graben Area (= catalogue of the Rhine Area), compiled by L. Ahorner at the seismological observatory of the University of Cologne (unpublished).

The catalogue of the Federal Republic of Germany in its original form consists of 1530 events that occurred between the years 1021 and 1979; only 157 of them are dated before 1800. Most events are described in strength by the macroseismic intensity I (MSK-Scale). Missing intensity values are computed from the local magnitude M_L and focal depth if possible, using an empirical formula from Ahorner (1983a). After removing all events classified as non-tectonic as well as those assigned to a more distant region (e.g. Italy), 1348 events are left. The intensities range from I to IX–X with an average value of IV–V. It must be emphasized that the data sources used for the compilation of this catalogue are heterogeneous, and thus the data are very inhomogeneous in quality and completeness. This is reflected by the graph of the distribution of events with time (Fig. 2).

In contrast to this catalogue, the earthquake catalogue of the Rhine Area can be regarded as relatively homogeneous. It is based on recordings from a seismic network set up for the registration of micro-earthquakes in this area (see Ahorner, 1983b). This catalogue consists of 1012 events that occurred between 1979 and 1984. All events have been carefully checked on their tectonic origin. Local magnitudes range from $M_L=0.0$ to $M_L=5.1$ with an average value of $M_L=0.8$. Only 27 events have a magnitude greater than or equal to 3.0.

An inhomogenity in the seismic activity of this area is found in June 1982 and is due to a series of events near the town of Bad Marienberg (Ahorner, 1983b) which result in rates of activity considerably higher than the average level of this region (Fig. 3).

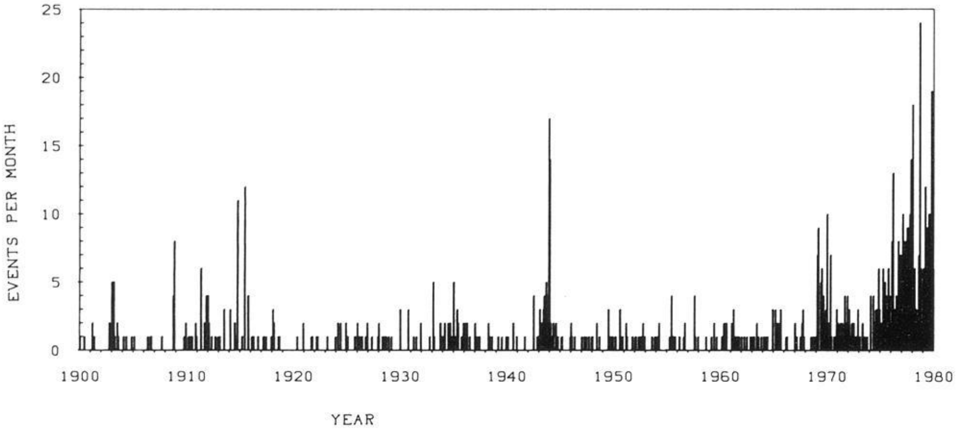

Fig. 2. Number of events per month in the catalogue of the Federal Republic of Germany. Years before 1900 are not shown

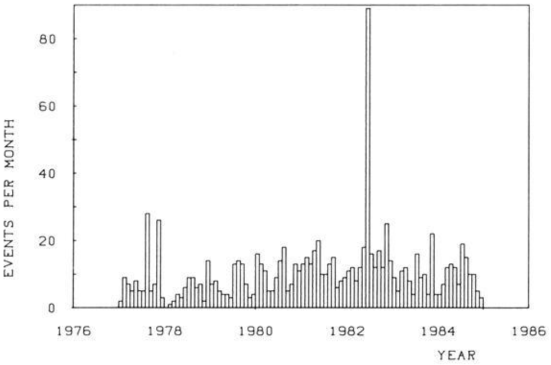

Fig. 3. Number of events per month in the catalogue of the Rhine Area

Table 1. Statistics for the diurnal periodicity. Probability p for the χ^2-test is given for 23 degrees of freedom. Only events whose origin time is known to an accuracy of 1 min are used

Intensity	Filter	Number of events	χ^2-test		Schuster's test
			χ^2	p (in %)	PR (in %)
Catalogue of the Federal Republic of Germany					
All	none	1197	28.5	30	1.9
All	36 h	852	28.1	30	2.5
$I \geqq$ IV	36 h	633	46.2	1	2.1×10^{-4}
$I <$ IV	36 h	219	30.6	30	0.2
Catalogue of the Rhine Area					
All	1 h	741	30.4	30	18.6
All	36 h	403	30.4	30	36.8

Results and discussion

The diurnal periodicity

Using all events left application of the 36-h filter, the catalogue of the Federal Republic of Germany does not show any significant diurnal variation (Table 1). The corresponding hodograph (Fig. 4) clearly displays that the high value of PR of Schuster's test (meaning low significance) is caused by two parts of the vector sequence opposing each other: a tendency towards midnight dominates until about the year 1975, followed by a period of time when earthquakes seem to occur more often around midday.

A cumulative hodograph, where all events of the same intensity are represented by their vector sum (Fig. 5), provides a clue for understanding these trends: events with intensity $I \geqq$ IV generally contribute to the midnight maximum, while the weaker events (included only in the latest part of the catalogue) show the opposite tendency. When considered separately, both intensity ranges lead to highly significant deviations from a homogeneous distribution of events (Table 1). The destructive interference of the two contradictory effects is also clearly displayed in the bar diagram (Fig. 6).

It can be taken for granted that the lunchtime maximum in the number of minor events is caused by the inclusion of quarry blasts which have not been marked as non-tectonic events in the catalogue (Mayer-Rosa, 1986, personal communication).

It is interesting to note that no midnight maximum can be found for earthquakes whose intensity has been computed from the magnitude M_L. This gives strong evidence that the reason for this maximum is a change of the subjective impression of the strength of an earthquake with daytime; at night the same earthquake is assigned a higher macroseismic intensity than during the day. This explanation is preferred over the explanation of a possible lack of completeness of weaker events at daytime (e.g. Schneider, 1975) for, in the latter case, a homogeneous distribution should have been found for the strongest earthquakes.

The catalogue of the Rhine Area does not show any significant accumulation of events at a certain time of day. The hodograph (Fig. 7) displays some persistencies of irregular length. Applying Schuster's test on such parts of the vector sequence, one may find significance levels of 99% ($PR=1$%) or better. Yet they appear to be of no special meaning regarding the overall vector sequence. Furthermore, there exists no obvious explanation for these findings. It is highly probable that it is a fortuitous result.

The annual periodicity

Only the catalogue of the Federal Republic of Germany is tested for an annual periodicity, since the length of record of the Rhine Area catalogue is insufficient.

Using the 36-h filter, a clear winter maximum appears in the frequency of events (Fig. 8, Table 2). The corresponding hodograph (Fig. 9) leads to the conclusion that this result is strongly influenced by certain periods of increased

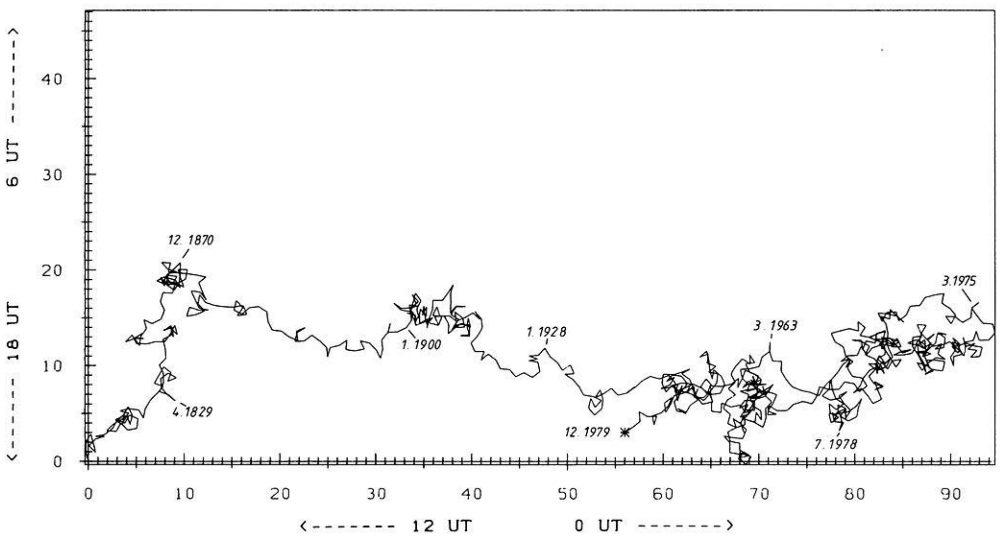

Fig. 4. Diurnal periodicity. Hodograph for events from the catalogue of the Federal Republic of Germany with application of the 36-h aftershock filter

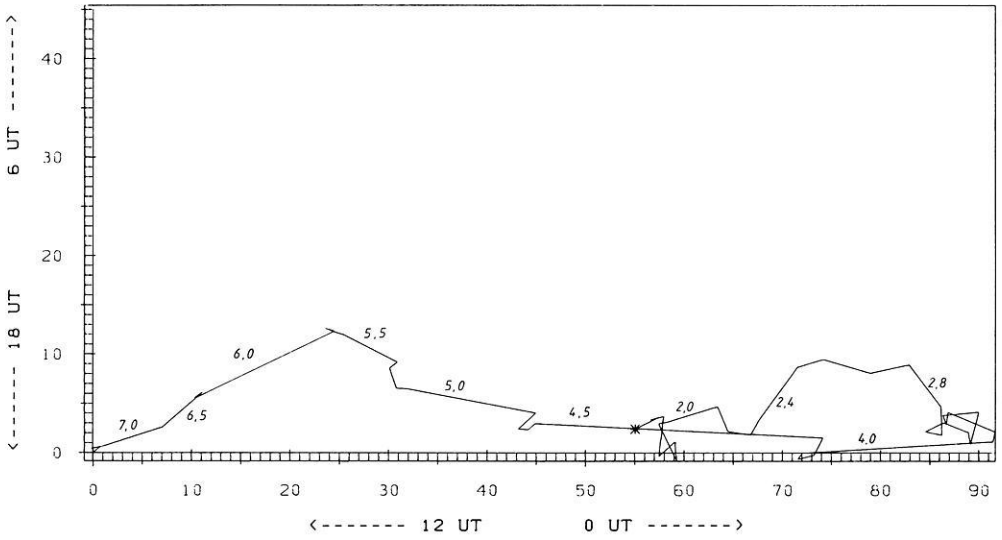

Fig. 5. Diurnal periodicity. Data as in Fig. 4. Vectors shown are the vectorial sum of all vectors of events with the same intensity (as indicated in the figure)

earthquake activity in the early part of the catalogue (e.g. from the year 1869 until 1871). It is possible that these increases are not of natural origin but are caused by the variability of human attention paid to the occurrence of earthquakes. Therefore, it is necessary to exclude such a possibility affecting the statistics and we introduced a more effective filter by increasing the filter length to 480 h. Though this filter probably does not eliminate all possible interdependencies, it removes the intervals of increased activity from the catalogue (figure not shown). However, the winter maximum is still evident, at least until about the year 1930. For 269 events before this year, $PR = 0.000028$. Thus, whatever the cause of these intervals is, they are not alone responsible for the winter maximum.

Trends are not seen in the more recent data (Fig. 9, 36-h filter) and we conclude that there is no winter maximum in the latest part of the catalogue. In this part, so many events per month are included that single years are reflected almost by circles in the vector sequence.

A possible explanation for the winter maximum in the early part of the recorded period and its disappearance in the later part is that people usually spend more time in buildings in the winter (with an increased chance for the detection of earthquakes). This effect disappears in the later part of the catalogue due to the improvement of the density and quality of the seismographic network, thus decreasing the fraction of non-instrumental recordings in the catalogue.

Tidal triggering

It has often been suggested that tidal forces on earth are capable of triggering earthquakes, but in most cases no statistical evidence for this hypothesis could be found. This negative result has been attributed to the masking effect of averaging over large regions with different local earthquake mechanisms (Young and Zürn, 1979). There may also be time dependencies in the fault-zone rheologies. Additionally, pore fluid flow may have a strong impact on tidal stresses, causing the periodic effective stress to differ in its phase by up to 180° from a simple calculation of tidal stress (Klein, 1976). Furthermore, as Souriau et al. (1982) pointed out, triggering can only be detected when the build-up rate of the tectonic stress is low compared to the rate of variation imposed by tidal stresses.

Finally, it should be noted that several investigations

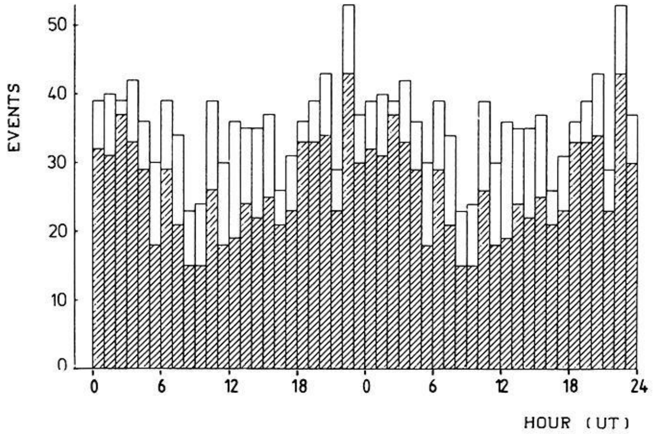

Fig. 6. Diurnal periodicity. Data as in Fig. 4. For better display of the periodicity, the time range 0–24 UT is given twice. Counts for intensities. $I \geqq 4$ are *hatched*

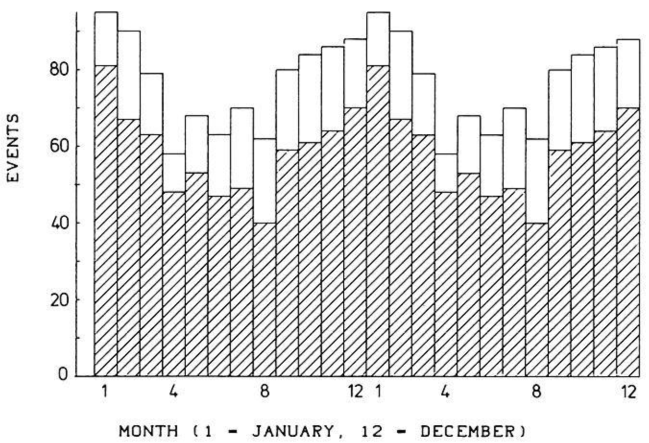

Fig. 8. Annual periodicity. Histogram for events from the catalogue of the Federal Republic of Germany with application of the 36-h filter. The period January (=1) to December (=12) is displayed twice. Counts for intensities $I \geqq 4$ are *hatched*

Table 2. Statistics for the annual periodicity. Probability p for the χ^2-test is given for 11 degrees of freedom. Only events whose origin time is known to an accuracy of 1 h are used

Intensity	Filter	Number of events	χ^2-test		Schuster's test
			χ^2	p (in %)	PR (in %)
Catalogue of the Federal Republic of Germany					
All	none	1273	69.3	0.1	8.9×10^{-9}
All	36 h	923	23.6	2.5	1.1×10^{-2}
All	480 h	462	13.1	30	0.7
$I \geqq$ IV	36 h	702	25.9	1	1.5×10^{-3}

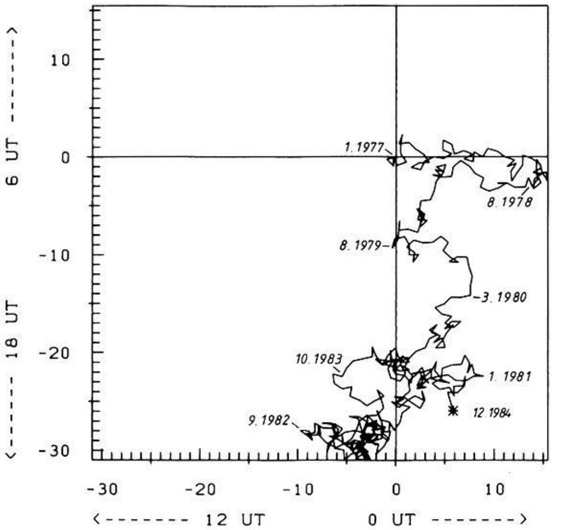

Fig. 7. Diurnal periodicity. Hodograph for events from the catalogue of the Rhine Area, with application of the 36-h filter

on tidal triggering exist which are not explicitly based on a physically founded triggering hypothesis, but simply use the tidal potential instead of the tidal stress sympathetic to the tectonic stress. Ulbrich (1985) has emphasized that the use of the tidal potential implies the hypothesis that tidally caused volume expansion/contraction is the trigger force. He showed that this hypothesis leads to a negative result when applied to the same earthquake data.

We now derive a simple relation between the tidal linear strain (which was available from computations) and the tidal triggering stress valid for the tectonic setting of the Rhenish Massif and Lower Rhine Graben Area.

The area is characterized by shallow and low-magnitude seismic activity. The dominant faulting type is a tensional dip-slip mechanism with a vertical σ_1-axis (maximum tectonic stress) and a horizontal σ_3-axis (minimum stress) striking N 45° E (Ahorner et al., 1983). As the vertical tidal stress can be neglected close to the free surface (Melchior, 1978), only the horizontal tidal stresses modulating the tectonic stress have to be considered. Thus, for this special tectonic situation (which, for simplicity, we assume to be valid for every single event) only a modulation of the tectonic stress in the direction of the minimum stress axis, σ_3, may possibly be responsible for tidal triggering. In principle there are two possibilities for triggering by tidal stresses: via an increase of the shear stress on the fault or via a decrease of the normal stress (e.g. Young and Zürn, 1979). Here, considering a modulation of σ_3 is equivalent to a simultaneous treatment of these two possibilities. Their relative importance (depending on the dip) is not used in this study. When the tidal stress $\Delta\sigma_3$ is tensional, the occurrence of an earthquake should be supported. If ε_3 denotes the extensional tidal strain parallel to σ_3, ε_2 the extensional tidal strain in the horizontal direction orthogonal to σ_3, and ε_v the vertical tidal extensional strain, then $\Delta\sigma_3$ can be expressed by

$$\Delta\sigma_3 = 2\,\mu\,\varepsilon_3 + \lambda(\varepsilon_2 + \varepsilon_3 + \varepsilon_v), \qquad (1)$$

where μ and λ are Lamé's constants. Replacing

$$\varepsilon_v = -\frac{v}{1-v}(\varepsilon_2 + \varepsilon_3) \qquad (2)$$

(from Melchior, 1978; v = Poisson ratio) and

$$\mu = \lambda\,\frac{1-2\,v}{2\,v}, \qquad (3)$$

we finally get

$$\Delta\sigma_3 = \lambda\frac{1-2\,v}{v(1-v)}(\varepsilon_3 + v\,\varepsilon_2). \qquad (4)$$

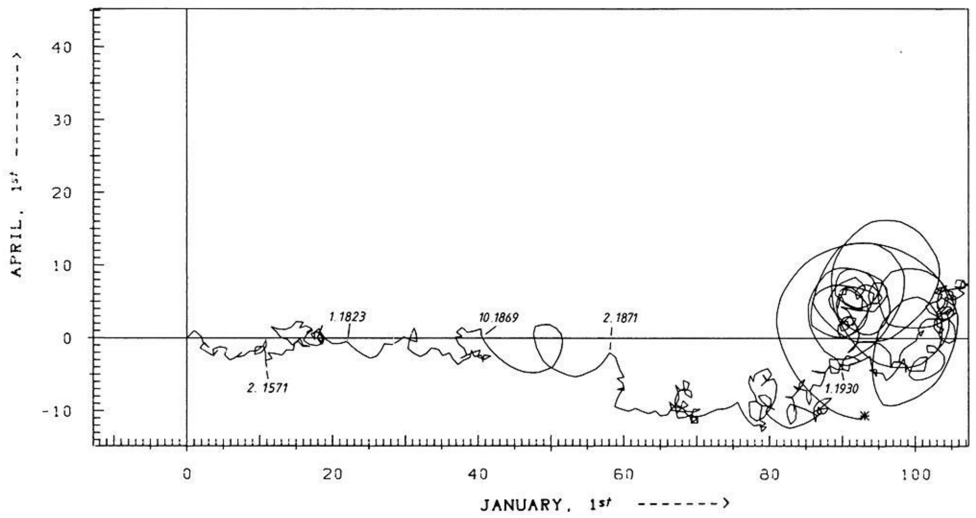

Fig. 9. Annual periodicity. Hodograph for the same data as in Fig. 8 (all intensities)

Table 3. Theoretical values of the eight strongest partial tides of the horizontal extension in direction N 45° E and N 135° E computed for the earth model Gutenberg-Bullen A (Wilmes, 1983) for Bonn, Federal Republic of Germany, for 1st January, 1976, 0 UT (Büllesfeld, 1985, personal communication)

Tide	Frequency (°/h)	Amplitude ($* 10^{-9}$)	Phase N 45° E	Phase N 135° E
Q1	13.398661	1.1225	317°, 8618	284°, 6913
O1	13.943036	5.8630	38°, 5712	5°, 4007
P1	14.958931	2.7284	13°, 8796	340°, 7091
K1	15.041069	8.8502	33°, 4575	0°, 2870
N2	28.439730	1.4209	276°, 8220	359°, 4755
M2	28.984104	7.4214	357°, 5314	80°, 1849
S2	30.000000	3.4527	332°, 8398	55°, 4934
K2	30.082137	0.9389	172°, 4177	255°, 0712

Table 4. Statistics for the investigation on tidal triggering. Probability p for the χ^2-test is given for 17 degrees of freedom

Intensity	Filter	Number of events	χ^2-test		Schuster's test
			χ^2	p (in %)	PR (in %)
Catalogue of the Rhine Area					
All	1 h	741	22.3	30	4.8
All	36 h	403	20.7	30	1.0
All	108 h	218	24.4	30	0.7

Thus, in the case of dip-slip faults the additional tidal stress suspected to trigger earthquakes can be computed from the horizontal linear strain parallel to the minimum tectonic stress axis and the strain parallel to the null-axis alone.

For the computations we used the eight strongest partial tides at Bonn (Table 3). The error that results from neglecting additional partial tides is insignificant for our purpose. The same holds for the indirect effect of the oceanic tides (compare Wilmes, 1983). Like other authors (e.g. Shlien, 1972; Heaton, 1975), we use a "tidal phase" for the statistical treatment which is defined as follows: two succeeding maxima of tidal tensional stress are assigned the phase values of 0° and 360°. An earthquake occurring within this cycle is represented by a phase value found by linear interpolation. If there is no tidal triggering, all phases should be equally likely. If our triggering hypothesis is correct, the events should tend to occur at phases somewhat less than 360° (Souriau et al., 1982).

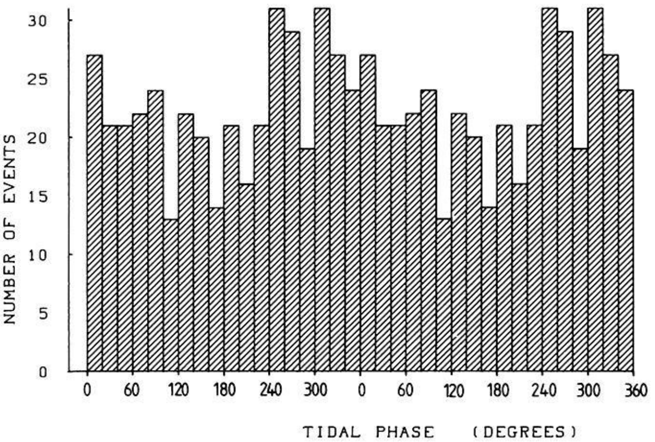

Fig. 10. Tidal triggering hypothesis. Histogram of the distribution of tidal phases as computed from the catalogue of the Rhine Area, with application of the 36-h filter

From the χ^2-test a deviation from a homogeneous distribution of phases should be regarded as insignificant (Table 4). However, the application of Schuster's test gives $PR = 1\%$, which means significance at the 99% level. On the basis of the arguments given earlier, we believe that the result from Schuster's test is to be preferred. As supported by the histogram (Fig. 10), the hodograph (Fig. 11) reveals a predominance of phase angles of about 310° which is consistent with our model of tidal triggering. A striking feature in Fig. 11 is the curvature of the vector sequence: starting from a mean direction of 45° in its first part, a steady change towards a mean direction of 260° in the final part can be seen. Such a long-term change of the dominant phase angle will negatively influence the significance computed from either of the statistical tests applied.

A possible hiding influence of an increased seismic activity (that is connected with an increased variability of the tectonic stress) was investigated by increasing the filter length so that only events with a prolonged preceding seismic quiescence were used. We have arbitrarily chosen 108 h

(=4.5 days) instead of 36 h. The effect is a minor decrease of the value of *PR* (Table 4). Though the predominant directions of the hodograph appear to be more distinct than before, the curvature itself remains and prevents a clear increase of the quotient R^2/N (Fig. 12).

As both the 36-h filter and the 108-h filter have time constants close to multiples of the semi-diurnal tidal periodicities, it must be assured that the significance is not caused by the application of these filters. For this we computed *PR* for filter lengths between 1 h and 200 h (Fig. 13). With the exception of some very short (e.g. 2 h, $N=704$, $PR=6.1\%$) and very long filter lengths (e.g. 200 h, $N=86$, $PR=9.6\%$), all values of *PR* lie below 5%. Neither the 36-h filter nor the 108-h filter produces an extremely low value of *PR*. Therefore, we conclude that our filtering procedure is not the cause of the significance.

The predominant phases as derived from the filtered catalogue agree rather well with those postulated by our model of tidal triggering. However, significance at the 1% level was only reached with Schuster's test, while the χ^2-test leads to an insignificant result. The hodograph clearly indicates a long-term change of the dominant phase angle, which definitely reduces the significance level reached in both tests. The cause for this change is not clear. Possible explanations are the irregular displacement of seismic activity to areas with different tectonic characteristics within the seismoactive region investigated or general changes of the tectonic stress. This would imply that an evaluation of tidal phases using individual focal solutions should yield better results. It must be noted, however, that Heaton (1982) could not find a significant effect for 100 shallow dip-slip and oblique-slip earthquakes, even though he used focal solutions and a triggering hypothesis similar to ours. In contrast to the events we used, his sample was gathered on a world-wide basis and included events of relatively high magnitude. One might speculate that the latter could be a cause for the negative result since a review of earthquake-tide correlations by Klein (1976) proposes that weak events might be more easily triggered by the earth-tides than strong events.

The catalogue of the Federal Republic of Germany was also examined with respect to tidal triggering. In this case there is also evidence that the hypothesized tidal triggering is efficient. Yet the statistical result is only significant at a rather low level (about 85% applying Schuster's test; Ul-

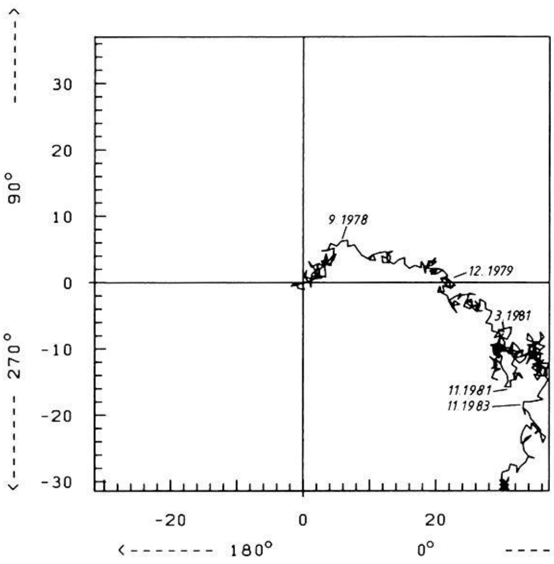

Fig. 11. Tidal triggering hypothesis. Hodograph for the same data as in Fig. 10

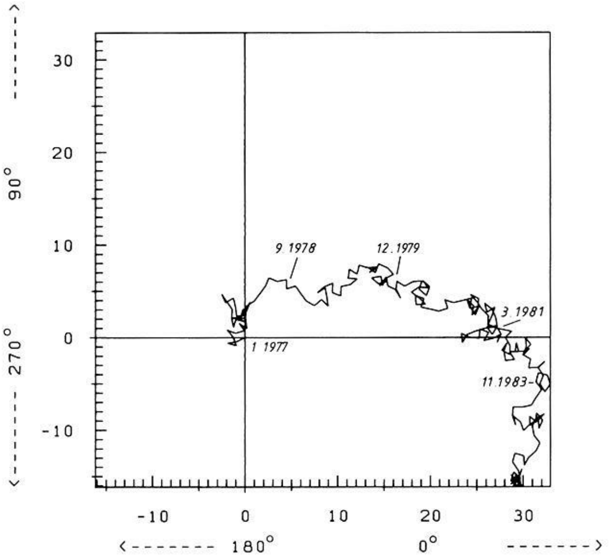

Fig. 12. Tidal triggering hypothesis. Hodograph of the tidal phases computed from the catalogue of the Rhine Area, with application of a 108-h filter

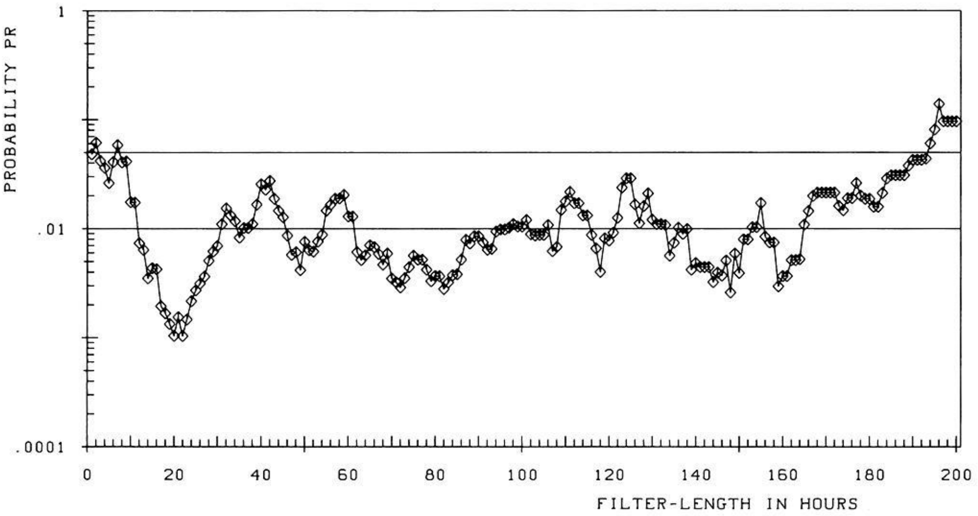

Fig. 13. Tidal triggering hypothesis. Probability *PR* from Schuster's test as a function of the filter length, using data from the catalogue of the Rhine Area. The *two horizontal lines* indicate $PR=5\%$ and $PR=1\%$, corresponding to significance levels of 95% and 99%, respectively

brich, 1985). A possible reason might be the inhomogeneity of the data.

Conclusion

We have demonstrated that both diurnal and annual periodicities can be found in the earthquake catalogue of the Federal Republic of Germany. However, a detailed investigation leads to the conclusion that these periodicities are not of physical origin but have to be attributed to the sensitivity of macroseismic observation varying with season and time of day, and to other sampling problems.

With regard to tidal triggering, we have found evidence that tidal stresses are able to influence the occurrence time of tectonic micro-earthquakes in the Rhenish Massif and Lower Rhine Graben Area. A long-term change in the predominant tidal phase at which an earthquake is released seems to exist.

Our investigations have shown that it can be useful not to rely on significance levels alone, but to also use the hodograph for displaying fluctuations of a periodicity that would otherwise have stayed undetected.

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