The correlation between the phase of the moon and the occurrences of microearthquakes in the Tamba region through point-process modeling

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Abstract

We study the correlation between the phase of the moon and the occurrence of microearthquakes, close to the fault of the 1995 Kobe earthquake, in the Tamba region. First, having suggested the existence of the correlation during the two-year period following the Kobe earthquake in a previous study, in this study we investigate the statistical significance of such correlation. Using point-process modeling and AIC (Akaike Information Criterion), we confirm that the existence of the correlation is statistically significant. Second, we investigate the temporal variation of the correlation during the four-year period following the Kobe earthquake. The result of the second analysis indicates that the correlation is strongest just after the Kobe earthquake and that it then becomes weaker year by year.

The objectives in this study

-- To investigate ***the statistical significance of the correlation*** between ***the phase of the moon*** and ***the occurrence of microearthquakes*** in the Tamba region, Japan
-- To investigate ***the temporal variation*** of the strength of the correlation

A. Data

-- Microearthquakes (MEs) listed in the catalogue compiled by Disaster Prevention Research Institute (DPRI), Kyoto University, Japan
-- Occurred in the Tamba region, which neighbors the focal region of the 1995 Kobe earthquake (Fig. 1)
-- Tested two rectangular areas, to show that the results are independent of the selection of the area.
-- The earthquake of $M \geq 1.4$ (larger area; area A) and 1.2 (smaller area; area B), considering the detection capability

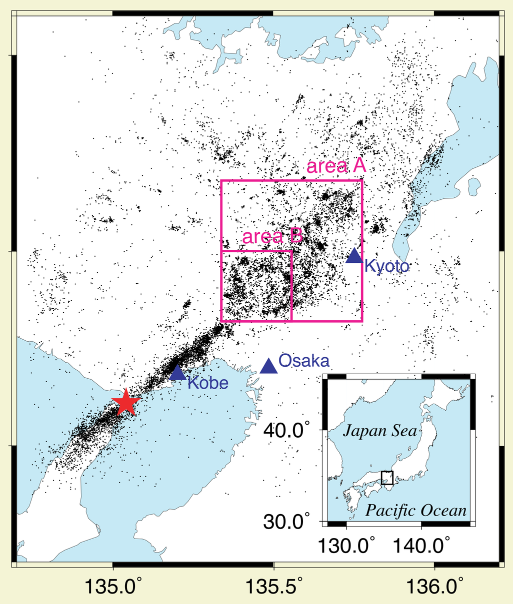

Fig. 1
Epicenters of MEs of $M \geq 1.2$ in Kinki District of Japan from 17 January 1995 to 17 January 1999 reported by Disaster Prevention Research Institute, Kyoto University, Japan. The red solid star indicates the epicenter of the Kobe earthquake.

B. Results in Katao[2002] (K2002)

-- K2002 investigated ***the frequency distributions of the phase angles*** (Fig. 2), related to the phase of the moon at which the MEs occurred in the focused areas.
-- ***After a new/full moon*** (i.e., 0 or 180 degree), ***the number of MEs is larger*** compared with that in other periods (Fig. 3)

Is this feature ***statistically significant***?

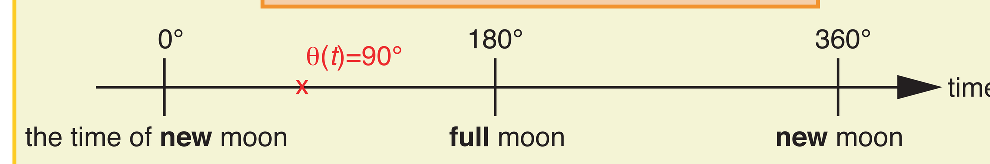

Fig. 2
Schematic diagram of the definition of the phase angle, related to the phase of the moon at which the MEs occurred.

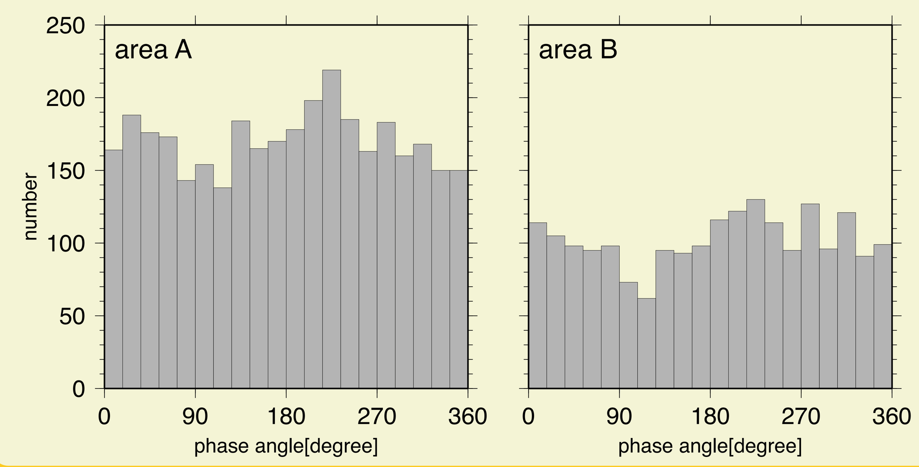

Fig. 3
Histogram which show the frequency distributions of the phase angles at which the ME occurred in the focused areas during the period from 31 January 1995 to 11 December 1996.

C. Statistical significance of the correlation

With point-process modeling [e.g., Ogata, 1999], to investigate the periodicity of the seismicity, Ogata [1983a] suggested the following form as intensity function $\lambda(t)$ (occurrence rate of earthquakes in unit time);

$\lambda(t) = \mu +$ (trend) + (cluster) + (periodicity)

(trend): polynomial function; (cluster): ETAS model [Ogata, 1988]; (periodicity): trigonometric function

$$\lambda(t) = \mu + \sum_{k=1}^{N} a_k t^k + \sum_{i;t_i<t} \frac{K\exp(\alpha(M_i - M_z))}{(t - t_i + c)^p}$$
$$+ A_1 \sin\theta(t) + B_1 \cos\theta(t) + A_2 \sin(2\theta(t)) + B_2 \cos(2\theta(t))$$
$(a_k, K, c, p, \alpha, A_1, B_1, A_2, B_2$: parameters)

We consider four cases of constraints:

case
(i) $A_1 = A_2 = B_1 = B_2 = 0$ ...... ***no triggering effect*** related to the phase of the moon
(ii) $A_2 = B_2 = 0$ ...... an effect ***only*** related to a ***synodic month***
(iii) $A_1 = B_1 = 0$ ...... an effect ***only*** related to a ***half-synodic month***
(iv) no constraint ...... an effect related to ***both a synodic and a half-synodic month***

To examine which case is best, we searched the best parameters using maximum likelihood method for each case. Then we compare the goodness-of-fits of the four cases using AIC (Akaike Information Criterion) [Akaike, 1974].

Note: The order of polynomial function (N) representing trend is also determined using AIC.
$\theta(t)$ and $2\theta(t)$ correspond the phase angle related to a synodic and a half-synodic month, respectively

Results

1) The ***case (iv)*** (where we assume the triggering effect related to both ***a synodic and a half-synodic month***) shows the ***best fit*** to the observed time series among the four cases (Table 1(a)). Using ***the difference of AIC*** [e.g., Ogata, 1983b], the estimated probabilities of the null hypothesis the fit of the second best model (case (iii) for area A, and case (ii) for area B) is better than the case (iv) are 3.98% and 7.21%, which are ***too small to accept the null hypothesis***; the correlation between the activity of the MEs and the phase of the moon is found to be statistically significant.
2) The feature of the intensity function of the trigonometric part (which is representing the periodicity) is ***similar*** to that of the histograms (Figs. 3 and 4); our ***modeling*** is ***reasonable***.
3) On the other hand, concerning the two-year period prior to the occurrence of the Kobe earthquake, the ***case (i)*** (where we assume ***no triggering effect***) is chosen as the best one; ***no significant correlation*** is found (Table 1(b)).

(a) after the Kobe earthquake

area	A				B			
number	3477				2116			
constraints	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
N	3	3	3	3	2	2	2	2
AIC	-4771.56	-4773.94	-4779.01	**-4781.45**	-1160.80	-1168.13	-1162.00	**-1169.39**

(b) before the Kobe earthquake

area	A				B			
number	517				344			
constraints	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
N	2	2	2	2	2	2	2	2
AIC	**539.80**	543.23	541.91	545.46	**412.95**	416.23	416.60	420.05

Table. 1
The AICs and the order N of the polynomial function representing trend: (a) for the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 11 December 1996; (b) from 0:00 on 17 January 1993 to 0:00 on 17 January 1995.

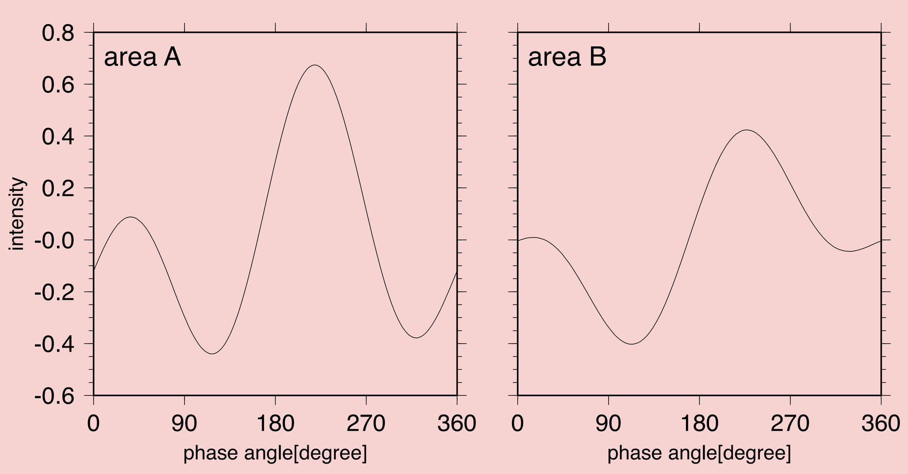

Fig. 4
The intensity functions of the trigonometric part obtained by the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 11 December 1996.

D. Temporal variation of the correlation

Does the strength of the correlation have the temporal variation?

The model is modified; the parameters in the trigonometric function are assumed to have temporal changes, which are represented by polynomial function.

$$\lambda(t) = \mu + \sum_{k=1}^{N} a_k t^k + \sum_{i;t_i<t} \frac{K\exp(\alpha(M_i - M_z))}{(t - t_i + c)^p}$$
$$+ \sum_{k=0}^{L_1} A_{1k} t^k \sin\theta(t) + \sum_{k=0}^{L_1} B_{1k} t^k \cos\theta(t) + \sum_{k=0}^{L_2} A_{2k} t^k \sin(2\theta(t)) + \sum_{k=0}^{L_2} B_{2k} t^k \cos(2\theta(t))$$
$(a_k, K, c, p, \alpha, A_{1k}, B_{1k}, A_{2k}, B_{2k}$: parameters)

Note: The orders of polynomial functions concerning trend (N) and periodicity (L_1 and L_2) are determined using AIC.

We consider four cases of constraints:

case
(i) $L_1 = L_2 = 0$ ...... ***no triggering effect*** related to the phase of the moon
(ii) $L_2 = 1$ ...... ***only*** temporal variation of the effect related to a ***synodic month***
(iii) $L_1 = 1$ ...... ***only*** temporal variation of the effect related to a ***half-synodic month***
(iv) $L_1 \geq 1, L_2 \geq 1$ ...... temporal variation of the effect related to ***both a synodic and a half-synodic month***

Results

1) The ***case (iv)*** (where we assume the temporal variation of the triggering effect related to ***both a synodic and a half-synodic month***) shows the best fit to the observed time series among the four cases (Table 2(a)).
2) The feature of the temporal variation of the intensity function of the trigonometric part (which is representing the periodicity) shows that the value of the intensity functions ***after the appearance of a new/full moon is generally higher*** compared with that in other periods (Fig. 5).
3) According to the plots (Fig. 6) of

$$g_i(t) = \sqrt{\left(\sum_{k=0}^{L_i} A_{ik} t^k\right)^2 + \left(\sum_{k=0}^{L_i} B_{ik} t^k\right)^2} \quad (i = 1,\ 2),$$

which denotes the absolute value of the intensity functions related to a synodic or a half-synodic month, the ***strength of the correlation is greatest just after the occurrence of the 1995 Kobe earthquake***, and generally ***decreases as time elapsed***.
4) Concerning the four-year period prior to the occurrence of the Kobe earthquake, the ***case (i)*** (where we assume ***no triggering effect***) is chosen as the best one; ***no significant correlation*** is found even if we consider the temporal variation of the correlation (Table 2(b)).

(a) after the Kobe earthquake

area	A				B			
number	5438				3178			
constraints	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
N	3	3	3	3	5	5	5	5
AIC	-4933.03	-4934.31	-4941.58	**-4742.14**	-296.05	-297.34	-307.61	**-309.42**
attained (L_1, L_2)	(0, 0)	(1, 3)	(3, 1)	(3, 3)	(0, 0)	(1, 4)	(3, 1)	(3, 4)

(b) before the Kobe earthquake

area	A				B			
number	933				568			
constraints	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
N	4	4	4	4	4	4	4	4
AIC	**1803.59**	1806.65	1804.42	1807.46	**1348.64**	1351.37	1351.46	1351.46
attained (L_1, L_2)	(0, 0)	(1, 0	(0, 1)	(1, 1)	(0, 0)	(1, 0)	(4, 1)	(4, 1)

Table. 2
The AICs and the orders N, L_1, and L_2 of the polynomial function representing trend, temporal variations related to a synodic and a half-synodic month: (a) for the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 17 January 1999; (b) from 0:00 on 17 January 1991 to 0:00 on 17 January 1995.

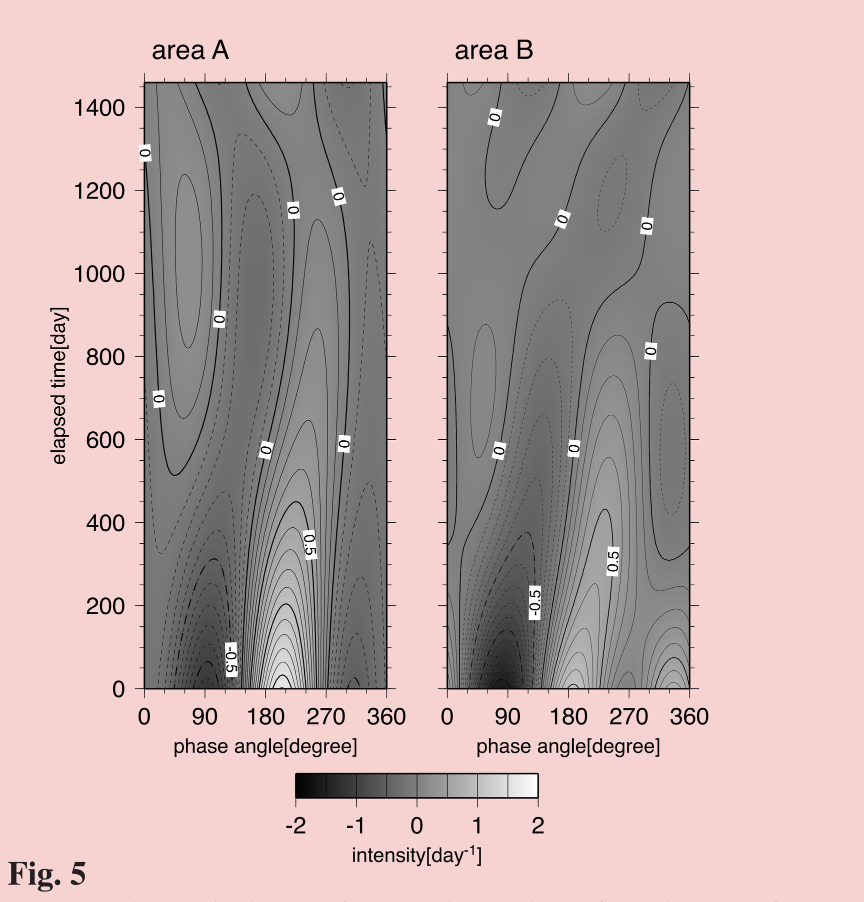

Fig. 5
Temporal variation of the intensity functions of the trigonometric part obtained by the analyses of the MEs from 12:00 on 17 January 1995 to 12:00 on 17 January 1999. The vertical axis indicates the elapsed time (day) since 12:00 on January 1995.

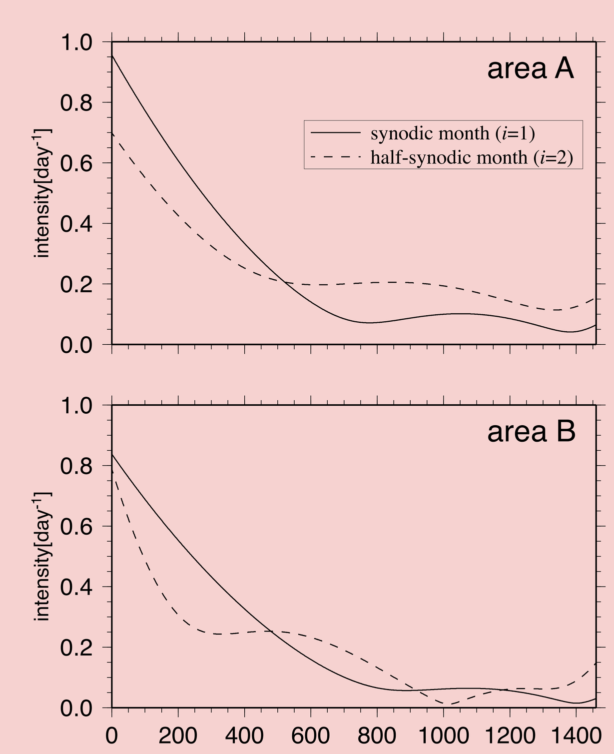

Fig. 6
Temporal variation of the absolute value of the intensity function of the trigonometric part $g_i(t)$ (i=1, 2), corresponding to the strength of the correlation. The horizontal axis indicates the elapsed time (day) since 12:00 on January 1995.

E. Discussion

1) Why can the occurrence of MEs ***correlate*** with the phase of the moon?

The ***amplitude of stress/strain changes*** due to the earth tide ***varies according to the phase of the moon*** (Fig. 7). Recent laboratory experiments [Lockner and Beeler, 1999] and the observation of the seismic velocity in a vault [Yamamura et al., 2003] suggest the changes in amplitude of the stress/strain could affect the seismicity or the physical property of the earth, supporting our results.

2) Why is the correlation observed in the Tamba region?

This would be related to ***the Kobe earthquake***. The rupture of the Kobe earthquake makes ***a critical stress/strain state*** in the Tamba region. After the Kobe earthquake, the seismicity rate in the Tamba region increased compared with before, and this increase is assumed to be caused by an increase of static stress due to the main rupture of the Kobe earthquake [e.g., Toda et al., 1998].

We found the significant correlation only after the Kobe earthquake and not before. The correlation is most remarkable just after the Kobe earthquake, after which it becomes weaker. These feature supports the interpretation as shown above.

3) Why did we find that the seismicity change of the periodicity related to ***not only a half-synodic month but also a synodic month.***

The cause of this feature is that the ***maximum amplitude of the stress/strain changes varies with the new and full moon.*** The theoretical strain changes in the Tamba region, in some periods, it is remarkable that the maximum amplitude of the strain changes varies near the time of new and full moons. This variation could influence the occurrence of earthquakes.

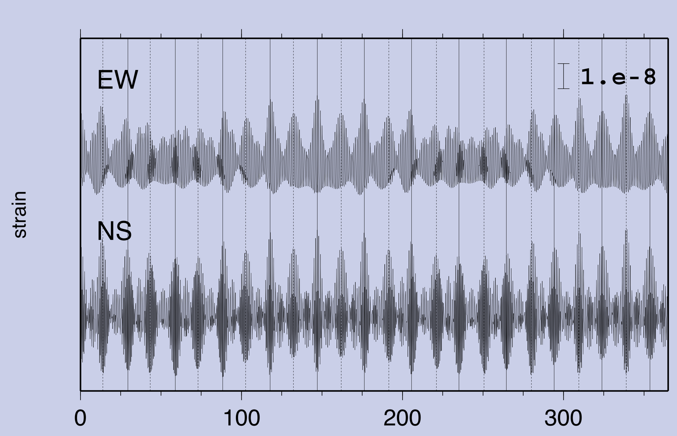

Fig. 7
Example of the theoretical strain changes due to earth tide in the Tamba region using the program of Agnew [1997]. The dotted line and solid lines correspond to the times of new and full moons, respectively. The horizontal axis indicates the elapsed time (day) since 12:00 on 17 January 1995.

Conclusion

We confirmed the statistical significance of the correlation between the phase of the moon and the occurrence of MEs in the Tamba region, suggested by Katao[2002]. Additionally we found that the correlation is strongest just after the Kobe earthquake, which would be a cause of the correlation, and that it then becomes weaker as the time elapsed.

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