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STUDY OF POLE TIDE TRIGGERING OF SEISMICITY

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Abstract. The pole tide (PT) is generated by the centrifugal effect of polar motion on the chandler (f_{cw} = 0.84 cpy) and annual (f_a = 1.0 cpy) frequencies. These frequencies, their beat frequency (0.16 cpy) and doubled frequency of chandler wobble (1.66 cpy) were revealed in seismic intensity spectrum of weak ($M < 5$) earthquake. The failure time for the weak earthquakes with magnitudes $3 < M_W < 5$ averages 1-10 years for various regions that is in a good agreement with the periodicity of stress oscillations excited by PT. The CMT global seismic databases (1976 – 2014) were used for search of the pole tide influence on the intensity of seismic process. For 32.2 thousand seismic events from CMT were calculated normal and shear stresses excited by PT using strike, dip and rake angles of the earthquake fault plane from this catalogue. The phases of the PT stresses for each earthquake were assessed and subsequently were used for statistical estimation of pole tide influence on seismicity. The PT stress oscillations excite the weak earthquakes of thrust-slip fault type on 95% significance level by χ^2 and Schuster's statistical tests.

MOTIVATION

The triggering of seismicity by the lunisolar tide (LST) is widely discussed last decades. But there is some confirmation of the PT influence on seismic process also, i.e. it can be found in the papers (Levin, Sasorova, 2002; Gamburtsev et al., 2004). The direct exciting of slow slip seismic events by PT was revealed in the work (Shen et al., 2007). The influence of PT on seismicity was revealed by test research in our previous work (Gorshkov, Vorotkov 2012). There was searched the seismic reaction on PT induced variations of vertical displacement in earthquake location.

There is periodicity of intensity of seismic process in pole tide (PT) frequency band (0.6, 1.2 and 6 – 7 years) as it can be seen at fig.1 where were used seismic events for 1973-2009 from data base NEIC (http://earthquake.usgs.gov/regional/ neic).

The most obvious excitation factor of these seismic intensity variations is PT. But excited stress variations in the crust by PT are less 1kPa while LST stress variations achieve 5 kPa. Why PT can trigger seismicity but it is almost impossible to reveal earthquake triggering by more powerful LST? First of all PT is significantly powerful than LST in above-mentioned frequency band while LST is the most powerful near 0.5 – 1 day periodicity. Secondly the failure time t_n is depend on energy of seismic event and t_n = 1 – 10 years for magnitude $3 < M < 5$ (Sadovsky, Pisarenko, 1985).

Thus preparation time t_n for weak earthquakes coincides with frequency band of PT induced stress variations. So it is intuitively obvious that LST are added to stress accumulation process in fault zone as powerful high-frequency noise while PT acts as systematic, nearly synchronous component for preparation of weak earthquakes.

The objective of this work is to estimate PT triggering of seismicity by using of earthquake focal mechanism from CMT catalogue (http://www.globalcmt.org/CMTfiles.html).

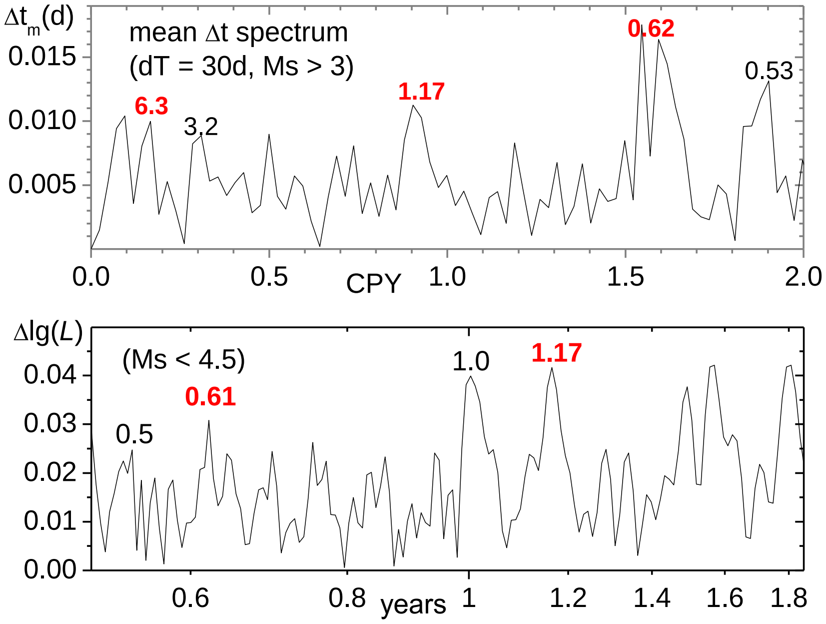

Figure 1. Amplitude FFT spectrum of seismic intensity (mean interval between earthquakes averaged in dT = 0.05 year) (*up*). Increments of maximum logarithmic likelihood function (Δlg(*L*)) for periodic point seismic process by method of Lyubushin (1998) for detecting of hidden periodicities within flow of events (*below*).

STRAIN AND STRESS EXCITED BY POLE TIDE

Centrifugal polar motion perturbation in the potential *ΔU* (Wahr, 1985) is equal:

$$\Delta U(r,\lambda,\theta) = -0.5(\Omega r)^2 \sin 2\theta (X\cos\lambda - Y\sin\lambda),$$

where Ω = 7 292 115×10^{-11} rad s^{-1} – the mean angular velocity of rotation of the Earth, *r* – geocentric distance to the station, *λ*, *θ* – longitude and colatitude (90º – φ) of the station, *X(t)* и *Y(t)* – polarr motion coordinates (EOP C04, http://hpiers.obspm.fr/eop-pc/) after removing of mean polar motion.Corresponding displacement of any point on the Earth's surface is equal (IERS conventions, 2003):

$$S_r = \frac{h}{g}\Delta U = -\frac{h}{2g}(\Omega r)^2[\sin 2\theta (X\cos\lambda - Y\sin\lambda)]$$

$$S_\theta = \frac{l}{g}\partial_\theta \Delta U = -\frac{l}{g}(\Omega r)^2[\cos 2\theta (X\cos\lambda - Y\sin\lambda)]$$

$$S_\lambda = \frac{l}{g\sin\theta}\partial_\lambda \Delta U = \frac{l}{g}(\Omega r)^2[\cos\theta (X\sin\lambda + Y\cos\lambda)],$$

where *h* = 0.60267, *l* = 0.0836 – Love numbers for PT frequency band. Positive displacement is upwards, south and east and don't exceed 25 and 7 mm for vertical and horizontal displacement, respectively.

The strain tensor elements are the partial derivatives of displacements:

$$\varepsilon_{rr} = \partial_r S_r = -h\frac{\Omega^2 r}{g}[\sin 2\theta (X\cos\lambda - Y\sin\lambda)]$$

$$\varepsilon_{\theta\theta} = (\partial_\theta S_\theta + S_r)/r = (2l - h/2)\frac{\Omega^2 r}{g}[\sin 2\theta (X\cos\lambda - Y\sin\lambda)]$$

$$\varepsilon_{\lambda\lambda} = (\partial_\lambda S_\lambda/\sin\theta + S_\theta ctg\theta + S_r)/r = (l - h/2)\frac{\Omega^2 r}{g}[\sin 2\theta (X\cos\lambda - Y\sin\lambda)]$$

$$\varepsilon_{\theta\lambda} = (\partial_\lambda S_\theta/\sin\theta - S_\lambda ctg\theta + \partial_\theta S_\lambda)/2r = -l\frac{\Omega^2 r}{g}[\sin\theta (X\sin\lambda + Y\cos\lambda)].$$

Positive ε_{ii} are tension, positive $\varepsilon_{\theta\lambda}$ – right-hand shift. In view of free surface boundary condition (Melchior, 1978) $\tau_{rr} = \tau_{r\theta} = \tau_{r\lambda} = 0$, therefore stress tensor elements are:

$$\tau_{\theta\theta} = 2\mu\varepsilon_{\theta\theta} + \Lambda\Sigma$$
$$\tau_{\lambda\lambda} = 2\mu\varepsilon_{\lambda\lambda} + \Lambda\Sigma$$
$$\tau_{\theta\lambda} = \mu\varepsilon_{\theta\lambda},$$

where $\Sigma = \varepsilon_{rr} + \varepsilon_{\theta\theta} + \varepsilon_{\lambda\lambda}$ – dilatation, $\mu(d)$ - shear modulus, $\Lambda(d)$ – elastic modulus of the Earth according PREM (Dziewonski, Anderson, 1981), d – depth of Earth's layer. Taking into account the displacement value restrictions, limitations for stress tensor elements are the next: $|\tau_{\theta\theta}| < 0.9$, $|\tau_{\lambda\lambda}| \leq 0.9$, $|\tau_{\theta\lambda}| \leq 0.1$ kPa.

Hence normal and shear stresses are (Zhu P., 2013):

$$\sigma_n^0 = \tau_{\theta\theta}\cos^2\alpha + \tau_{\lambda\lambda}\sin^2\alpha + \tau_{\theta\lambda}\sin 2\alpha$$
$$\tau_s^0 = 0.5(\tau_{\lambda\lambda} - \tau_{\theta\theta})\sin 2\alpha + \tau_{\theta\lambda}\cos 2\alpha.$$

At last for free oriented fault these stresses are:

$$\begin{aligned} \sigma_n &= \sigma_n^0 \sin^2\delta \\ \tau_s &= \tau_s^0 \sin\delta\cos\psi + 0.5\sigma_n^0 \sin 2\delta \sin\psi, \end{aligned} \qquad (*)$$

where α, δ, ψ – strike, dip and rake angles of earthquake fault plane. Fig. 2 demonstrates the common view of coordinate and time dependences of PT induced stresses.

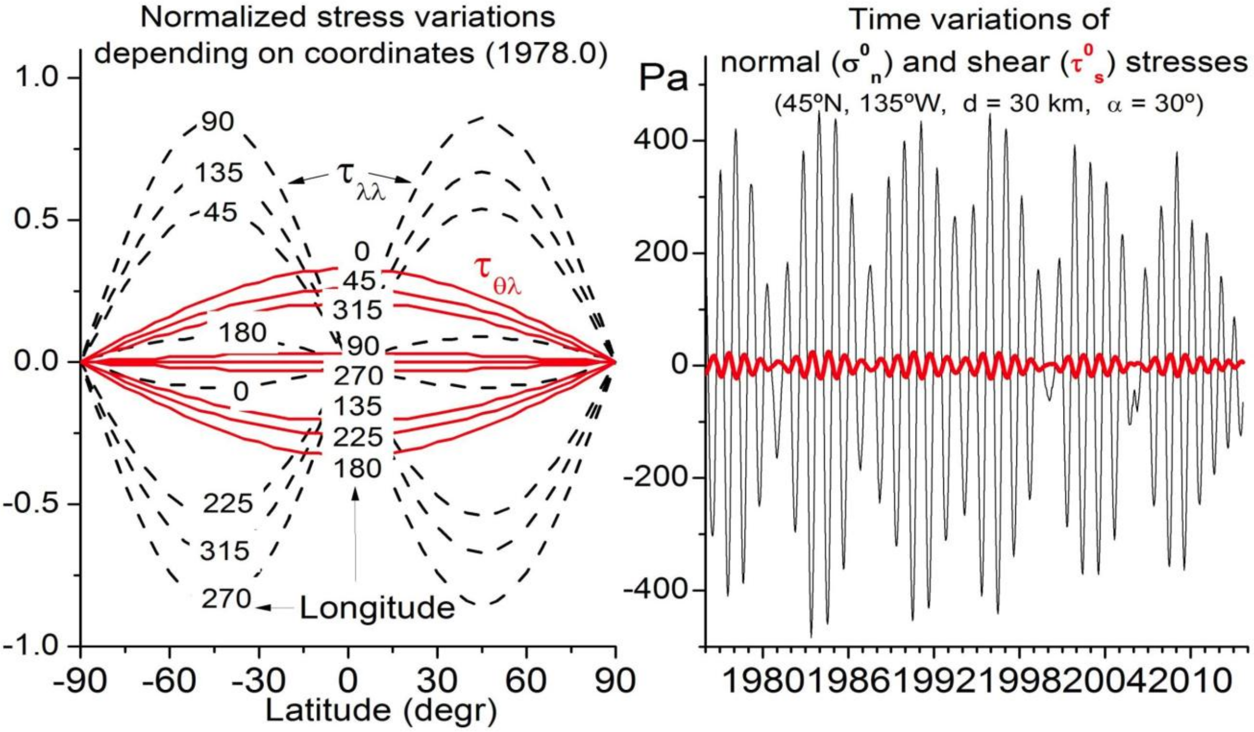

Figure 2. Coordinate ((left) and time (right) dependences of PT induced stresses.

DATA AND METHOD

There were used 32264 seismic events from CMT (1976-2014) to search the trace of PT in seismicity after declustering for strong earthquakes with Mw > 7.2 as CMT is full only for $M > 5.2$. The modified window algorithm (Uhrhammer, 1986) was used for declustering: $\Delta L(km) = 1.2exp(0.8M_W - 1.0)$ for spatial distribution of aftershocks and $\Delta t(days) = 1.2\exp(0.8M_W - 2.9)$ for temporal one with 1.2 year Δt limitation. The fig.3 shows the PT generated shear τ_s and normal σ_n stresses for CMT (points) against background of pole variations (X, Y).

It is obvious that approximately 90% of seismic events are indifferent to the coordinate variations of the Pole and hence to the corresponding stress variations. The rest of events (~10%) repeat time variations of the Pole. It is remarkable that ~ 10% events in CMT have magnitude $M_w < 5.1$. What are these earthquakes? This question is resolved by study of shear stress distribution for various kind of earthquake fault plane.

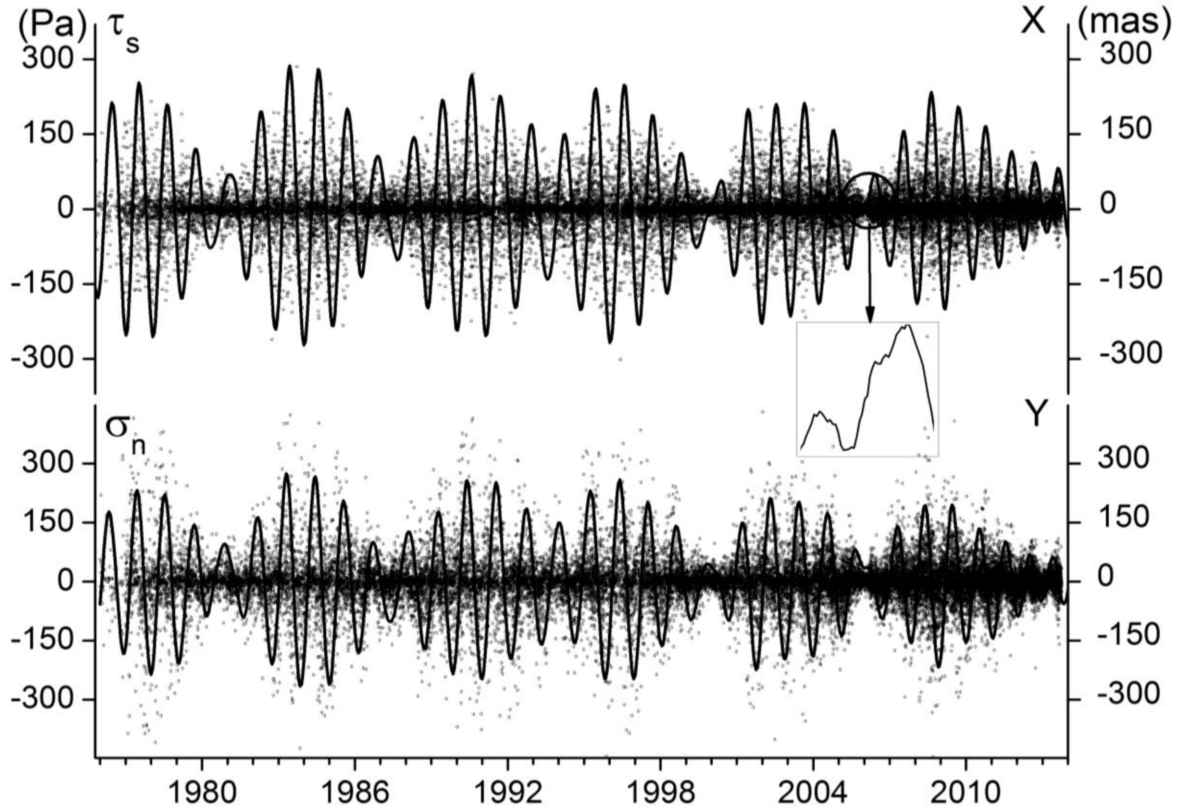

Figure 3. PT induced shear τ_S (up) and normal σ_n (bottom) stresses (points, in Pa) are shown against a background of coordinate variations of polar motion (X, Y in millisecond of arc, mas).

Phases β_i of σ_n and τ_S stresses were estimated for each earthquake as a part between its previous and following max/min values in each earthquake coordinate point. Time span between these extrema is considered as period of PT. There were used period estimations as between max-to-max (max) as between min-to-min (min) values.

The coordinates of the Pole (X,Y) are the real-time monitoring values and so they have some noise variations especially in time of its amplitude damping (less 100 mas). This leads to additional extrema as it can be seen in the fig.3 inset. In this connection coordinates (X,Y) were high-frequency filtered and then were interpolated with 0.02 year interval. That ensures the 5º – 6º measurement accuracy for β_i. The reduced data without damping time span (r) were used separately for more precise estimation of β_i.

The number of earthquakes n_k was counted in 30º phase boxes for next faulting type of earthquakes: normal-slip ($-120^\circ < \psi < -60^\circ$), thrust-slip ($60^\circ < \psi < 120^\circ$), strike-slip ($0^\circ < |\psi| < 30^\circ$, $150^\circ < |\psi| < 180^\circ$) and the rest – oblique strike-slip. The total number of earthquakes for these samples is $N_\psi = \sum_{k=1}^{12} n_k$. Schuster (1897) and χ^2 statistic tests were used for assessment of significance of phase concentration near some particular phase. Null hypothesis on random distribution of phase is rejected if probability $p_S = \exp(-R^2/N) \le 0.05$ for Schuster and $\chi^2 > \chi^2_{0.95} = 18.307$ for χ^2 statistic tests, where $C = \sum_{i=1}^{N_\psi} \cos\beta_i$, $S = \sum_{i=1}^{N_\psi} \sin\beta_i$ and $R^2 = C^2 + S^2$. The values $\cos\overline{\beta} = C/R,\ \sin\overline{\beta} = S/R$ allows to assess the most reliable mean $\overline{\beta}$.

RESULTS AND CONCLUSIONS

As it can be seen from tabl.1 PT induced stresses has an influence on seismic intensity with 95% confidence level only for thrust-slip earthquakes with magnitude $M_w < 5.5$. Other fault types of earthquakes are indifferent to PT influence according to used statistic. The study of depth distribution is complicated for insufficient data of weak earthquakes in CMT.

Tabl. 1. Reliability assessment of PT induced shear stress on exciting of earthquake with $d < 70$ km ($\chi^2_{0.95} = 18.307,\ \chi^2_{0.90} = 15.987,\ \nu = 10$)

Magnitude	4.0 – 5.0				5.0 – 5.5			5.5 – 6.0		
Fault type	N_ψ	p_s(%)	χ^2	$\overline{\beta}^\circ$	N_ψ	p_s(%)	χ^2	N_ψ	p_s(%)	χ^2
Normal	586	42.4	9.4	359	1457	60.3	10.5	440	22.3	9.3
(r)	317	86.3	10.8	14	1006	37.6	14.8	341	23.8	11.9
Thrust	535	**2.9**	**18.2**	152	2890	**2.6**	**16.6**	1472	68.1	6.3
(r)	282	**1.5**	**20.0**	154	1976	**2.2**	15.8	1025	55.3	10.1
Strike-slip	816	78.2	12.5	90	3502	68.6	9.1	1666	17.7	14.0
(r)	434	53.1	11.9	109	2307	92.3	7.1	1329	21.8	16.6
Oblique strike	488	31.1	17.1	172	2222	90.8	13.8	769	54.0	10.0
(r)	251	13.6	11.4	89	1580	61.1	10.5	616	17.5	12.0
Total	2425	17.8	11.4	349	10071	13.3	13.4	4347	95.9	11.3

The frequency distribution of phases β_i are shown in fig.4. It is evident that there are two but not equal maxima of PT influence on the thrust type of earthquakes. This result could explain 0.6-year periodicity in seismic intensity.

The PT influence on seismicity when Pole variation damping (less 100 mas) becomes actually noise as it was checked by independent estimations of Schuster and χ^2 statistics. Therefore the PT is the most probable reason of 6 – 7 years periodicity in seismic intensity.

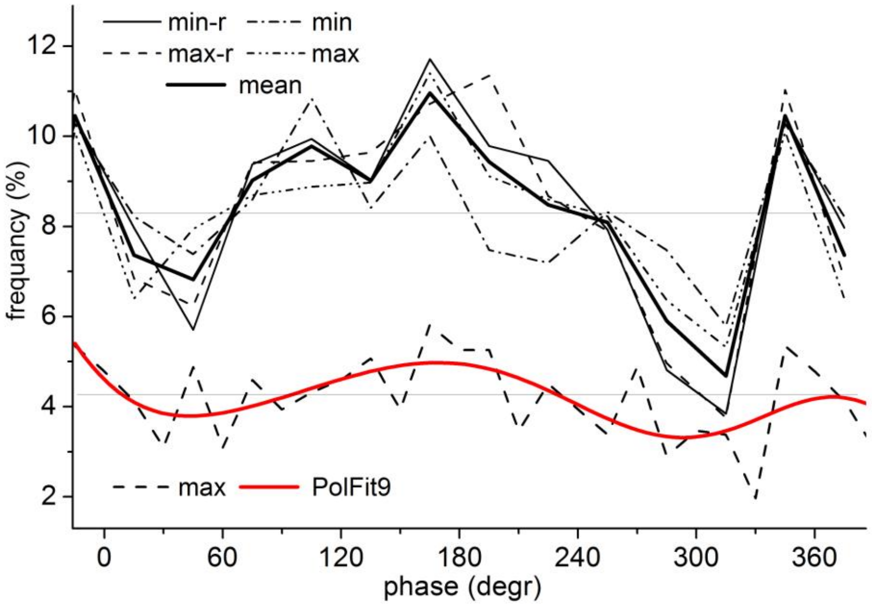

Fig. 4. (Up) - Frequency distribution of shear stress phases of thrust earthquakes for 30º phase boxes (k=12). Straight line corresponds to even distribution of phase (8.3%). The convergence of these plots gives view on the level of phase determination error. (Bottom) – The same for 15º phase boxes (k=24). Line of even distribution of phase is equal 4.15%.

So we may conclude:

- Pole tide influence on seismic intensity is revealed only for thrust-slip type of earthquake with 95% reliability.
- This influence falls with rise of magnitude and vanishes for $M_W > 5.5$.
- There are two maxima of this influence approximately coinciding with both extreme of shear stresses. This result can explain 0.6-year periodicity in seismic intensity.
- Pole tide influence on seismic intensity for time of Pole wobble damping (less 100 mas) is actually noise. This could explains 6 – 7-year periodicity in seismic process.
- Synphasing of shear and normal stresses for thrust-slip earthquakes (see equation (*) by ψ = 90º) could explain the exciting of these earthquakes by weak PT induced stress variations.

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