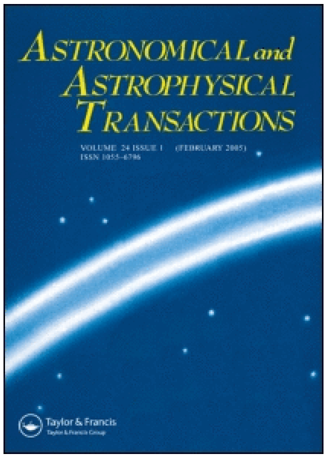

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Tidal elastic energy in planetary systems and its dynamic role

Yu. V. Barkin [a]; J. M. Ferrandiz [b]
[a] Sternberg Astronomical Institute, Moscow, Russia
[b] Alicante University, Alicante, Spain

Astronomical and Astrophysical Transactions
Vol. 23, No. 4, August 2004, pp. 369–384

TIDAL ELASTIC ENERGY IN PLANETARY SYSTEMS AND ITS DYNAMIC ROLE

YU. V. BARKIN[a,*] and J. M. FERRANDIZ[b]

[a]*Sternberg Astronomical Institute, Universitetskij Prospetct 13, Moscow 119992, Russia;*
[b]*Alicante University, San Visente del Raspeig, Alicante 03080, Spain*

(Received 9 June 2004)

An analytical expression for the elastic energy of the planet tidal deformations induced by other bodies in the planetary system and by a central star has been obtained. It was shown that the elastic energy is not additive sum of the elastic energies of separate pairs of bodies but contains additional terms of mutual character. In particular, we have obtained a formula for the elastic energy of superposition of lunisolar tides, of which also contains additional terms of mutual character caused by the mutual influence of the Moon and the Sun. These additional terms are remarkable. They are characterized by significant amplitudes of variations and play an important role in the geodynamic life of the Earth. Differential equations of the tidal evolution of planetary systems must describe the effects of mutual transformation of elastic energy to the energy of the translatory–rotary motion of the planet and by the dissipation of tidal energy the transformation to warm energy. The correlation of extreme variations in the elastic tidal energy of the Earth with large earthquakes and moonquakes (in the period 1971–1976) was studied.

Keywords: Tides; Superposition; Elastic energy; Earthquakes; Moonquakes

1 INTRODUCTION

The Earth's mantle is a non-spherical inhomogeneous cover with a quasiconcentric distribution of densities. Let R_0 be the mean radius of the Earth and $\tilde{R}_0$ the radius of the larger sphere that we can put in the mantle cavity (we assume that the centre of this sphere coincides with the Earth's centre of mass).

We shall consider the mantle as a deformable elastic body which is subjected to the attraction of the system's external celestial bodies $\mathrm{P}_\sigma (\sigma = 1, 2, \ldots, N)$ (in particular from the Moon and the Sun). Deformations of the Earth produced by these bodies will be described by the classical model (Takeuchi, 1950) which was studied in detail in the papers by Getino and Ferrandiz (1991), Getino (1992, 1993) and Ferrandiz and Getino (1993) for construction of the rotation theory of the deformable Earth.

Let us consider the main Cartesian reference system Cxyz with its origin at the Earth's centre of mass and with axes directed along its principal axes of inertia in the undeformed state. Let $\boldsymbol{r}$ and $\boldsymbol{r}'$ be the radius vectors of an arbitrary point (or a elementary volume dm) of the mantle in the absence of deformations and in the deformable state. As usual, we assume that particles of the deformable solid mantle deviate slightly from the positions that they occupy in the absence

* Corresponding author. E-mail: barkin@inbox.ru

ISSN 1055-6796 print; ISSN 1476-3540 online
DOI: 10.1080/10556790410001733800

of deformation. The small displacement vector $\boldsymbol{u}(r, t)$ in the considered case is presented as a sum of elastic displacements of the mantle particle caused by every external celestial body separately:

$$\boldsymbol{r}(t) = \boldsymbol{r}_0 + \boldsymbol{u}(\boldsymbol{r}_0, t) \Longrightarrow (x, y, z)(t) = (x_0, y_0, z_0) + (u, v, w)(x_0, y_0, z_0; t),$$
$$u = \sum_{\sigma=1}^{N} u_\sigma, \quad u = \sum_{\sigma=1}^{N} u_\sigma, v = \sum_{\sigma=1}^{N} v_\sigma, w = \sum_{\sigma=1}^{N} w_\sigma, \tag{1}$$

where (x, y, z) are the positional coordinates of the particle of the deformable body and (x_0, y_0, z_0) are the coordinates that the same particle would have in the absence of deformations, (u, v, w) being the components of the full displacement vector caused by system of external bodies, and $(u_\sigma, v_\sigma, w_\sigma)$ being the components of the displacement vector $\boldsymbol{u}_\sigma$ caused by the concrete body P_σ.

The components of the displacement vector $\boldsymbol{u}_\sigma$ during the deformation of mantle under Newtonian attraction of the external bodies (the Moon and the Sun) are defined as (Takeuchi, 1950)

$$(u_\sigma, v_\sigma, w_\sigma) = \sum_{n=1}^{\infty} F_n(r_0) \frac{\partial W_{\sigma n}}{\partial(x, y, z)} + G_n(r_0)(x, y, z) W_{\sigma n}, \tag{2}$$

where $W_{\sigma n}$ is the harmonic of the nth order of the tidal potential caused by gravitational attraction of the perturbing body P_σ, and $F_n(r)$ and $G_n(r)$ are Takeuchi's functions which depend only on variable $\boldsymbol{r}$.

2 TIDAL PERTURBING POTENTIAL FROM SYSTEM OF CELESTIAL BODIES

We study tidal deformations of a celestial body that moves and rotates in the gravitational field of the system's other celestial bodies $\mathrm{P}_\sigma (\sigma = 1, 2, \ldots, N)$. The general tidal potential from the system of these bodies can be presented in the following form (Getino, 1992):

$$W = \sum_{\sigma=1}^{N} \sum_{n=2}^{\infty} W_{\sigma n} = \sum_{\sigma=1}^{N} \sum_{n=2}^{\infty} \sum_{m=0}^{n} W_{\sigma n m} \tag{3}$$

where $W_{\sigma n}$ is the harmonic of the nth order of the tidal potential caused by gravitational attraction of the perturbing body P_σ and is given by

$$W_{\sigma n} = \frac{G m_\sigma}{r_\sigma} \sum_{n=2}^{\infty} \left(\frac{r}{r_\sigma} \right)^n P_n(\cos S_\sigma), \tag{4}$$

where G is a gravitational constant and P_n are Legendre's functions. S_σ is the angle between the radius vector of perturbing body with the coordinates $x_\sigma, y_\sigma, z_\sigma$ and an arbitrary point of the elastic mantle (x, y, z).

Now we introduce the spherical coordinates r, θ, φ for the elementary mass dm of the mantle and $r_\sigma, \delta_\sigma, \alpha_\sigma$ for the perturbing body P_σ (here θ and δ_σ are the latitude and colatitude respectively, and φ and α_σ are the longitudes). With Cartesian coordinates (x, y, z) of the mantle point and Cartesian coordinates $(x_\sigma, y_\sigma, z_\sigma)$ of the perturbing body these variables are connected by the formulae:

$$x = r \cos\varphi \cos\lambda, \quad y = r \cos\varphi \sin\lambda, \quad z = r \sin\varphi,$$
$$x_\sigma = r_\sigma \sin\delta_\sigma \cos\alpha_\sigma, \quad y_\sigma = r_\sigma \sin\delta_\sigma \sin\alpha_\sigma, \quad z_\sigma = r_\sigma \cos\delta_\sigma. \tag{5}$$

All coordinates (5) are defined with respect to the main reference system Cxyz:

$$P_n(\cos S_\sigma) = q_{nm} P_n^m(\sin\delta_\sigma) P_n^m(\cos\theta)[\cos(m\alpha_\sigma)\ \cos(m\varphi) + \sin(m\alpha_\sigma)\ \sin(m\varphi)], \quad (6)$$

where

$$q_{nm} = \frac{(n-m)!}{(n+m)!}(2-\delta_{0m}) = \frac{2(n-m)!}{(n+m)!\,\delta_m} \quad (7)$$

are numerical coefficients (here δ_{0m} is a Kronecker symbol and $\delta_m = \delta_{0m} + 1$).

Now we can present the general tidal potential in the special form that was used for calculations of the tidal energy in the case of one perturbing body (Getino, 1992). Here we shall follow the general features of the potential given by Getino. So we have

$$W = \sum_{\sigma=1}^{N}\sum_{n=2}^{\infty} W_{\sigma n} = \sum_{n=2}^{\infty}\sum_{m=0}^{n} r^n (A_{cnm}^* B_{cnm} + A_{snm}^* B_{snm}), \quad (8)$$

where

$$\begin{aligned} A_{cnm}^* &= G\sum_{\sigma=1}^{N}\frac{m_\sigma}{r_\sigma^{n+1}} P_n^m(\sin\delta_\sigma)\ \cos(m\alpha_\sigma), \\ A_{snm}^* &= G\sum_{\sigma=1}^{N}\frac{m_\sigma}{r_\sigma^{n+1}} P_n^m(\sin\delta_\sigma)\ \sin(m\alpha_\sigma), \\ B_{cnm} &= P_n^m(\cos\theta)\ \cos(m\varphi), \\ B_{snm} &= P_n^m(\cos\theta)\ \sin(m\varphi). \end{aligned} \quad (8')$$

For the perturbing potential (8) and (8′) a solution of the problem about elastic deformations can be presented by Hergolz' formulae in Cartesian coordinates (Getino, 1992):

$$\begin{aligned} u &= \sum_{n=2}^{\infty} u_n = \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(F_n(r)\frac{\partial W_{nm}}{\partial x} + G_n(r) x W_{nm}\right), \\ v &= \sum_{n=2}^{\infty} v_n = \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(F_n(r)\frac{\partial W_{nm}}{\partial y} + G_n(r) y W_{nm}\right), \\ w &= \sum_{n=2}^{\infty} w_n = \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(F_n(r)\frac{\partial W_{nm}}{\partial z} + G_n(r) z W_{nm}\right), \\ W_{nm} &= r^n (A_{cnm}^* B_{cnm} + A_{snm}^* B_{snm}). \end{aligned} \quad (9)$$

Solution (9) presents a linear superposition of solutions of a classical problem for one perturbing body. It is important to remark that the form of solution (8) and (8′) is identical with classical formulae that were used in paper by Getino (1992) for calculation of the analytical expression for the energy of tides. This means that we can use almost all intermediate non-trivial analytical transformations of the above-cited paper to calculate the elastic energy for the more general case of the superposition of tides considered here.

Here the functions $F_n(r)$ and $G_n(r)$ similar to $K_n(r)$ are functions of r only, which can be obtained as a solution of a system of ordinary differential equations. For Takeuchi's models and for modern models of the Earth (models 1066A and 1066B described by Gilbert and

Dziewonski (1975)) in the cases when $n = 2, 3$ these functions were determined by Getino and Ferrandiz (1991), Getino (1992, 1993) and Ferrandiz and Getino (1993). These functions do not depend on the action of the perturbing bodies.

In spherical coordinates the components of the displacement vector are determined by the following well-known formulae:

$$\begin{aligned} u_r &= \sum_{n'=1}^{\infty} \frac{1}{r} l_{n'} W_{n'}, \\ u_\theta &= \frac{1}{r} \sum_{n'=1}^{\infty} F_{n'} \frac{\partial W_{n'}}{\partial \theta}, \\ u_\varphi &= \frac{1}{r \sin\theta} \sum_{n'=1}^{\infty} F_{n'} \frac{\partial W_{n'}}{\partial \varphi}, \end{aligned} \tag{10}$$

where

$$l_{n'} = n' F_{n'} + r^2 G_{n'}.$$

3 ELASTIC ENERGY

If an elastic isotropic body obeying Hooke's law is deformed by the gravitational attraction of the external celestial bodies, an elastic deformation energy is produced. This energy per unit volume is expressed as

$$E = \frac{\lambda}{2}(e_{xx} + e_{yy} + e_{zz})^2 + \mu(e_{xx}^2 + e_{yy}^2 + e_{zz}^2) + 2(e_{xy}^2 + e_{xz}^2 + e_{yz}^2). \tag{11}$$

The e_{ij} values are components of the deformation, which relate to the displacement vector $\bar{\boldsymbol{u}} = (u, v, w)$ by means of

$$\begin{aligned} e_{xx} &= \frac{\partial u}{\partial x}, \quad e_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \\ e_{yy} &= \frac{\partial v}{\partial y}, \quad e_{xz} = \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \\ e_{zz} &= \frac{\partial w}{\partial z}, \quad e_{yz} = \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right). \end{aligned} \tag{12}$$

The components of the displacement vector were obtained as a solution of the problem of the theory of elasticity and are defined by equations (8), (8′) and (9).

To obtain expression for the deformation energy it is sufficient to insert the series (9) into equations (11) and (12) and then to calculate the corresponding volume integral spread over the entire elastic shell in its initial state:

$$E_{\mathrm{d}} = \int_r^R \int_0^\pi \int_0^{2\pi} E r^2 \sin\theta \,\mathrm{d}r \,\mathrm{d}\theta \,\mathrm{d}\varphi, \tag{13}$$

where R is the mean radius and r is the inferior radius of the elastic shell.

Here we shall use detailed calculations of the integral (13) for the classical problem of the lunar tides (Getino and Ferrandiz, 1991; Getino, 1992) but we shall take into account some generalization of our problem to the system of perturbing bodies.

In the above-mentioned papers for the calculation of energy (13), spherical coordinates have been used. In this case the spherical components of the displacement vector are defined by the following formulae (Takeuchi, 1950):

$$\begin{aligned} u_r &= \sum_{n=1}^{\infty} u_{rn} = \sum_{n=1}^{\infty}\sum_{m=0}^{n} \left(\frac{n}{r} F_n(r) + r G_n(r)\right) W_{nm}, \\ u_\theta &= \sum_{n=1}^{\infty} u_{\theta n} = \sum_{n=1}^{\infty}\sum_{m=0}^{n} \left(\frac{1}{r} F_n(r)\right) \frac{\partial W_{nm}}{\partial \theta}, \\ u_\varphi &= \sum_{n=1}^{\infty} u_{\varphi n} = \sum_{n=1}^{\infty}\sum_{m=0}^{n} \left(\frac{1}{r \sin\theta} F_n(r)\right) \frac{\partial W_{nm}}{\partial \varphi}. \end{aligned} \tag{14}$$

On the other hand in these coordinates the elastic energy per unit volume is

$$E = \frac{\lambda}{2}(e_{rr} + e_{\theta\theta} + e_{\varphi\varphi})^2 + \mu(e_{rr}^2 + e_{\theta\theta}^2 + e_{\varphi\varphi}^2) + 2(e_{r\theta}^2 + e_{r\varphi}^2 + e_{\theta\varphi}^2), \tag{15}$$

where the components of the deformations are

$$\begin{aligned} e_{rr} &= \frac{\partial u_r}{\partial r}, \quad e_{\theta\theta} = \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r}, \\ e_{\varphi\varphi} &= \frac{1}{r\sin\theta}\frac{\partial u_\varphi}{\partial \varphi} + \frac{1}{r}(u_r + u_\theta \cot\theta), \\ e_{r\theta} &= \frac{1}{2}\left(\frac{1}{r}\frac{\partial u_r}{\partial \theta} - \frac{u_r}{r} + \frac{\partial u_\theta}{\partial r}\right), \\ e_{r\varphi} &= \frac{1}{2}\left(\frac{1}{r\sin\theta}\frac{\partial u_r}{\partial \varphi} - \frac{u_\varphi}{r} + \frac{\partial u_\varphi}{\partial r}\right), \\ e_{\theta\varphi} &= \frac{1}{2}\left(\frac{1}{r\sin\theta}\frac{\partial u_\theta}{\partial \varphi} - \frac{1}{r}\cot\theta\, u_\varphi + \frac{1}{r}\frac{\partial u_\varphi}{\partial \theta}\right). \end{aligned} \tag{16}$$

Inserting equations (16) into equation (15), and considering the spherical harmonics W_n gives

$$\frac{\partial W_n}{\partial r} = \frac{n}{r} W_n, \tag{17}$$

After some calculations we obtain the formulae (Getino, 1992)

$$e_{ST} = \sum_{n,m} e_{STnm},$$

where

$$(S, T = r, \theta, \varphi) \text{ and } \sum_{n,m} = \sum_{n=1}^{\infty}\sum_{m=0}^{n}, \tag{18}$$

and the coefficients in equation (18) are defined by the following formulae:

$$
\begin{aligned}
e_{rrnm} &= Q_{1n} W_{nm}, \quad e_{\theta\theta nm} = Q_{3n} \frac{\partial^2 W_{nm}}{\partial \theta^2} + Q_{2n} W_{nm}, \\
e_{\varphi\varphi nm} &= Q_{3n} \frac{1}{\sin^2\theta} \frac{\partial^2 W_{nm}}{\partial \varphi^2} + Q_{2n} W_{nm} + Q_{3n} \cot\theta \frac{\partial W_{nm}}{\partial \theta}, \\
e_{r\theta nm} &= \frac{1}{2} Q_{4n} \frac{\partial W_{nm}}{\partial \theta}, \quad e_{r\varphi nm} = \frac{1}{2\sin\theta} Q_{4n} \frac{\partial W_{nm}}{\partial \varphi}, \\
e_{\theta\varphi nm} &= Q_{3n} \left(\frac{1}{\sin\theta} \frac{\partial^2 W_{nm}}{\partial\theta \partial\varphi} - \cot\theta \frac{\partial W_{nm}}{\partial \varphi} \right).
\end{aligned}
\tag{19}
$$

In equation (19) the following new notation was used:

$$
\begin{aligned}
Q_{1n} &= n\frac{\dot{F}_n}{r} + n(n-1)\frac{F_n}{r^2} + \dot{G}_n r + (n+1)G_n, \quad Q_{2n} = n\frac{F_n}{r^2} + G_n, \\
Q_{3n} &= \frac{F_n}{r^2}, \quad Q_{4n} = \frac{\dot{F}_n}{r} + 2(n-1)\frac{F_n}{r^2} + G_n, \quad \dot{F}_n = \frac{\mathrm{d}F_n}{\mathrm{d}r}.
\end{aligned}
\tag{20}
$$

In this notation the deformation energy can be presented in the following way:

$$
E = \sum_{n,m} \sum_{n',m'} E_{nn'mm'}, \tag{21}
$$

where

$$
\begin{aligned}
E_{nn'mm'} = {} & \frac{\lambda}{2} (e_{rrnm} + e_{\theta\theta nm} + e_{\varphi\varphi nm})(e_{rrn'm'} + e_{\theta\theta n'm'} + e_{\varphi\varphi n'm'}) \\
& + \mu \left[e_{rrnm} e_{rrn'm'} + e_{\theta\theta nm} e_{\theta\theta n'm'} + e_{\varphi\varphi nm} e_{\varphi\varphi n'm'} \right. \\
& \left. + 2(e_{r\theta nm} e_{r\theta n'm'} + e_{r\varphi nm} e_{r\varphi n'm'} + e_{\theta\varphi nm} e_{\theta\varphi n'm'}) \right].
\end{aligned}
\tag{22}
$$

After some reduction of expression (21) the calculations of the integral of the energy (13) are reduced to calculations of the series table integrals and some integrals of the standard combinations of Legendre's associated functions and their derivatives. Also we point out that all integrations with respect to the angular variables θ and φ are identical with those in Getino's paper.

Using these remarks and the full series of calculations in Getino's paper we obtain the final expression for the energy of deformation (13) in the following compact form:

$$
E_\mathrm{d} = \sum_{n=2}^{\infty} \sum_{m=0}^{n} \frac{2\pi}{2n+1} q_{nm} \left(I_n^\lambda + 2 I_n^\mu \right) \left[(A_{cnm}^*)^2 + (A_{snm}^*)^2 \right], \tag{23}
$$

where $q_{nm} = [(n-m)!/(n+m)!](2-\delta_{0m})$, and the elastic constants I_n^λ and I_n^μ are defined by the following integrals:

$$
I_n^\lambda = \int_r^R \lambda r^{2(n+1)} \left(n\frac{\dot{F}_n}{r} + r\dot{G}_n + (n+3)G_n \right)^2 \mathrm{d}r, \tag{24}
$$

$$I_n^{\mu} = \int_r^R \mu r^{2(n+1)} \left[n(4n^3 - 4n^2 - n + 1)\frac{F_n^2}{r^4} + 2n(2n^2 - n - 1)F_n \left(\frac{\dot{F}_n}{r^3} + \frac{G_n}{r^2} \right) \right.$$
$$+2n(n-1)\frac{F_n \dot{G}_n}{r} + \frac{1}{2}n(3n+1)\frac{\dot{F}_n^2}{r^2} + 3n(n+1)\frac{\dot{F}_n G_n}{r} + 2n\dot{G}_n \dot{F}_n$$
$$\left. +\frac{1}{2}(3n^2 + 5n + 6)G_n^2 + 2(n+1)G_n \dot{G}_n r + \dot{G}_n^2 r^2 \right] \mathrm{d}r. \tag{25}$$

Using equations (9) and (23)–(25) now we obtain a new form for the energy:

$$E_{\mathrm{d}} = \sum_{n=2}^{\infty} \frac{2\pi}{2n+1} \left(I_n^{\lambda} + 2I_n^{\mu} \right) \sum_{m=0}^{n} q_{nm} \left[(A_{cnm}^*)^2 + (A_{snm}^*)^2 \right]$$
$$= \sum_{n=2}^{\infty} \frac{2\pi G^2}{2n+1} \left(I_n^{\lambda} + 2I_n^{\mu} \right) \sum_{m=0}^{n} q_{nm} \left[\left(\sum_{\sigma=1}^{N} \frac{m_\sigma}{r_\sigma^{n+1}} P_n^m(\sin\delta_\sigma)\cos(m\alpha_\sigma) \right)^2 \right.$$
$$\left. + \left(\sum_{\sigma=1}^{N} \frac{m_\sigma}{r_\sigma^{n+1}} P_n^m(\sin\delta_\sigma)\sin(m\alpha_\sigma) \right)^2 \right] = \sum_{n=2}^{\infty} \frac{2\pi G^2}{2n+1} \left(I_n^{\lambda} + 2I_n^{\mu} \right)$$
$$\times \sum_{\sigma=1}^{N} \left(\frac{m_\sigma}{r_\sigma^{n+1}} \right)^2 \sum_{m=0}^{n} q_{nm} \left\{ \left[P_n^m(\sin\delta_\sigma)\cos(m\alpha_\sigma) \right]^2 + \left[P_n^m(\sin\delta_\sigma)\sin(m\alpha_\sigma) \right]^2 \right\}$$
$$+ 2\sum_{n=2}^{\infty} \frac{2\pi G^2}{2n+1} \left(I_n^{\lambda} + 2I_n^{\mu} \right) \sum_{\substack{i,j=1\\ i>j}}^{N} \frac{m_i}{r_i^{n+1}} \frac{m_j}{r_j^{n+1}}$$
$$\times \sum_{m=0}^{n} q_{nm} \left\{ P_n^m(\sin\delta_i) P_n^m(\sin\delta_j) \left[\cos(m\alpha_i)\ \cos(m\alpha_j) + \sin(m\alpha_i)\ \sin(m\alpha_j) \right] \right\}. \tag{26}$$

The spherical additional theorem allows us to introduce the very simple relations

$$\sum_{m=0}^{n} q_{nm} \left\{ \left[P_n^m(\sin\delta_\sigma)\cos(m\alpha_\sigma) \right]^2 + \left[P_n^m(\sin\delta_\sigma)\sin(m\alpha_\sigma) \right]^2 \right\}$$
$$= \sum_{m=0}^{n} q_{nm} \left\{ P_n^m(\sin\delta_\sigma) P_n^m(\sin\delta_\sigma) [\cos(m\alpha_\sigma)\cos(m\alpha_\sigma) + \sin(m\alpha_\sigma)\sin(m\alpha_\sigma)] \right\}$$
$$= P_n(\cos 0) = 1, \tag{27}$$
$$\sum_{m=0}^{n} q_{nm} \left\{ P_n^m(\sin\delta_i) P_n^m(\sin\delta_j) \left[\cos(m\alpha_i)\cos(m\alpha_j) + \sin(m\alpha_i)\sin(m\alpha_j) \right] \right\} = P_n(\cos S_{ij}).$$

Here S_{ij} is the angle between the radius vectors of the body P_i with longitude and latitude (α_i, δ_i) and the body P_j with longitude and latitude (α_j, δ_j).

As a result we obtain

$$E_{\mathrm{d}} = \sum_{i=1}^{N} \sum_{n=2}^{\infty} e_n \left(\frac{m_i}{r_i^{n+1}} \right)^2 + 2 \sum_{\substack{i,j=1\\ i>j}}^{N} \sum_{n=2}^{\infty} e_n \frac{m_i}{r_i^{n+1}} \frac{m_j}{r_j^{n+1}} P_n(S_{ij}), \tag{28}$$

where we have introduced the new elastic parameter

$$e_n = \frac{2\pi G^2}{2n+1}\left(I_n^\lambda + 2I_n^\mu\right). \tag{29}$$

Thus equations (28) and (29) determine the elastic energy E_d as a function of the internal structure of the external shell (through I_n^λ and I_n^μ) and of the masses of bodies and the mutual differences between the center of mass and deformed body and perturbing bodies but not depending on its angular position.

From only the main second harmonic of tides for their elastic energy we obtain the following expression:

$$E_\mathrm{d} = e_2 \sum_{i=1}^{N} \frac{m_i^2}{r_i^6} + 2e_2 \sum_{\substack{i,j=1\\ i>j}}^{N} \frac{m_i m_j}{r_i^3 r_j^3} P_n(S_{ij}), \tag{30}$$

where we have

$$e_2 = \frac{2\pi G^2}{5}\left(I_2^\lambda + 2I_2^\mu\right). \tag{31}$$

In equation (31) we have

$$\begin{aligned} I_2^\lambda &= \int_r^R \lambda r^6 \left(2\frac{\dot F_2}{r} + r\dot G_2 + 5G_2\right)^2 \mathrm{d}r, \\ I_2^\mu &= \int_r^R \mu r^6 \left[30\frac{F_2^2}{r^4} + 20F_2\left(\frac{\dot F_2}{r^3} + \frac{G_2}{r^2}\right) + 4\frac{F_2\dot G_2}{r}\right. \\ &\quad \left. + 7\frac{\dot F_2^2}{r^2} + 18\frac{\dot F_2 G_2}{r} + 4\dot G_2 \dot F_2 + 14G_2^2 + 6G_2\dot G_2 r + \dot G_2^2 r^2\right] \mathrm{d}r. \end{aligned} \tag{32}$$

The formula

$$E_{\mathrm{d}i} = e_2 \frac{m_i^2}{r_i^6} \tag{33}$$

presents the elastic energy of deformation caused by gravitational attraction by the perturbing body P_i on the assumption that other bodies are absent. In this notation for the full elastic energy we obtain

$$E_\mathrm{d} = e_2 \sum_{i=1}^{N} E_{\mathrm{d}i} + 2e_2 \sum_{\substack{i,j=1\\ i>j}}^{N} (E_{\mathrm{d}i} E_{\mathrm{d}j})^{1/2} P_n(S_{ij}). \tag{34}$$

Equation (34) will be used for the analysis of individual and mutual contributions of the tides from different celestial bodies to the general elastic energy.

4 ELASTIC ENERGY OF SUPERPOSITION OF THE EARTH'S TIDES: A NEW COMPONENT AND ITS ROLE IN GEODYNAMIC PROCESSES

4.1 Goal of Study

We have obtained the formula for the elastic energy of superposition of lunisolar tides. It was shown that the full energy is not the additive sum of the elastic energies of the separate tides and contains additional terms of mutual character, which play a significant role in the geodynamic life of the Earth. Correlation of the extreme variations in the elastic tidal energy of the Earth with earthquakes and moonquakes (in the period 1971–1976) was established. This regular pattern of the seismic process has been used for the prediction of the dates of some large earthquakes in 2003. In particular the date of the phenomenal Hokkaido quake of 25 September 2003 ($M = 8.3$) was predicted with high accuracy.

The Earth's oceanic and elastic shells are deformed owing to lunar–solar attraction, as a result of non-inertial rotational effects in pole motion and others. Different types of tides are observed on the Earth. We have introduced also a new class of tides due to the inner nature of the Earth. These tides are caused by gravitational attraction of the moving core (rigid and liquid). In the classical approximation all these tides are described by the linear theory of elasticity, and the full effect of the Earth deformations is presented as a linear superposition of all tides. The tensional state of the Earth is characterized by the elastic energy stored in the superposition of tides.

We have obtained a formula for the elastic energy of tide superposition. The full energy is not the additive sum of the elastic energies of separate tides and contains additional terms of mutual character. For example the mutual action of the Moon and Sun on the Earth's mantle generates additional energy with a maximal value of about 91.6% of the elastic energy E_M that is generated by the Moon separately. The full elastic energy of the lunisolar tides is changed in diapason, 212.6% E_M – 75.2% E_M. This large change is observed in every orbital period of the Moon.

These additional terms of energy are very important. They are sufficiently large and lead to marked, conditionally periodic variations in elastic energy. So the variation is 137.4% E_M, which is considerably more than variation in energy caused by the eccentricity of the Moon's orbit, 67.8% E_M. The full variation in the elastic energy is 209.4% E_M. Also the superposition of the rotational tide and lunisolar tides leads to additional elastic energy terms.

Some of the elastic energy dissipates and changes to warm energy and to energization of different geodynamic processes in definite rhythms. In this paper we discuss correlation of the extreme variations in the elastic tidal energy of the Earth with earthquakes and moonquakes (in the period 1971–1976). The established regular patterns of the seismic process have let us predict the dates of some large earthquakes including the phenomenal Hokkaido quake of 25 September 2003 with magnitude $M = 8.3$.

4.2 Elastic Energies of Lunisolar Tides in the Earth's Mantle

We discuss here the expression for and the numerical value of the full energy of mantle deformations caused by lunar and solar attractions. Let us introduce the following geometrical and dynamic notations.

(i) x_M, y_M, z_M and x_S, y_S, z_S are the Cartesian coordinates of the Moon and Sun respectively.
(ii) $r_M = (x_M^2 + y_M^2 + z_M^2)^{1/2}$ and $r_S = (x_S^2 + y_S^2 + z_S^2)^{1/2}$ are the corresponding distances between the Earth's centre of mass and the Moon and the Sun respectively.
(iii) $\cos S_{MS} = (x_M x_S + y_M y_S + z_M z_S)/r_M r_S$ is the cosine of the angle S_{MS} between the geocentric directions to the Sun and to the Moon.
(iv) a_M and a_S are unperturbed values of major semiaxes of the lunar and solar orbits respectively.
(v) e_M and e_S are the unperturbed values of eccentricities of lunar and solar orbit.
(vi) e_2 is a elastic coefficient that can be calculated, for example, from the classical solution of the elasticity theory problem about lunisolar tide deformations for some models of the Earth (Getino and Ferrandiz, 1991).

Getino and Ferrandiz (1991) and Getino (1992) showed that the elastic energies of the Earth's tides caused by solar attraction are determined by the formulae

$$E_{\mathrm{M}} = e_2 \frac{m_{\mathrm{M}}^2}{r_{\mathrm{M}}^2}, \quad E_{\mathrm{S}} = e_2 \frac{m_{\mathrm{S}}^2}{r_{\mathrm{S}}^2}. \tag{35}$$

We have shown that the full elastic energy E of the lunisolar tides does not equal the sum of the above-mentioned energies (Barkin and Ferrandiz, 2003a, b) ($E \neq E_{\mathrm{M}} + E_{\mathrm{S}}$). This effect is caused by the quadratic structure of elastic energy and by the geometry of the Earth's mantle deformations. We describe the final expression for the elastic tidal energy of the Earth taking into account only the second harmonic as:

$$E = e_2 \left(\frac{m_{\mathrm{M}}^2}{r_{\mathrm{M}}^6} + \frac{m_{\mathrm{S}}^2}{r_{\mathrm{S}}^6} + 2\frac{m_{\mathrm{M}} m_{\mathrm{S}}}{r_{\mathrm{M}}^3 r_{\mathrm{S}}^3} P_2(\cos S_{\mathrm{MS}}) \right). \tag{36}$$

Equation (37) for the elastic energy contains the new additional term

$$E_{\mathrm{MS}} = e_{\mathrm{MS}} P_2(\cos S_{\mathrm{MS}}), \tag{37}$$

where

$$e_{\mathrm{MS}} = 2e_2 \frac{m_{\mathrm{M}} m_{\mathrm{S}}}{r_{\mathrm{M}}^3 r_{\mathrm{S}}^3}.$$

It is easy to see that $e_{\mathrm{MS}} = E_{\mathrm{MS}}$ when $S_{\mathrm{MS}} = \pi/2, 3\pi/2$. In these cases the geocentric directions to the Moon and to the Sun are orthogonal. e_{MS} is the maximal value of energy E_{MS}. The real values E_{MS} change in the domain $((e_{\mathrm{MS}}, -e_{\mathrm{MS}}/2)$. It is worth remarking that the energy (37) presents only the main term (of second order) of the full expression for elastic energy. A general expression was also obtained but we omit it in this paper. We confirm and shall show below that this additional term of energy is significant and plays an important role in geodynamic and geophysical processes.

4.3 Evaluation of the Energy Values

Let us assume the following values of the parameters of the Earth–Moon–Sun system:

$$\begin{aligned} &1\,\text{astronomical unit (AU)} = 149\,597\,870\,\text{km}, \ a_{\mathrm{S}} = 1.000\,001\,017\,78\ \text{AU}, \\ &a_{\mathrm{M}} = 384\,000\,\text{km}, \quad \frac{m_{\mathrm{M}}}{m_{\mathrm{E}}} = 0.012\,300\,038, \\ &\frac{m_{\mathrm{E}}}{m_{\mathrm{S}}} = 3.003\,489\,6 \times 10^{-6}, \quad e_2 = 3.252 \times 10^{35}\ \text{cgs}. \end{aligned} \tag{38}$$

Let us note some simple relations between the energies of the Sun and the Moon:

$$E_{\mathrm{S}} = E_{\mathrm{M}} \frac{m_{\mathrm{S}}^2 r_{\mathrm{M}}^6}{m_{\mathrm{M}}^2 r_{\mathrm{S}}^6}, \ e_{\mathrm{MS}} = 2(E_{\mathrm{M}} E_{\mathrm{S}})^{1/2} = 2e_2 \frac{m_{\mathrm{S}} m_{\mathrm{M}}}{r_{\mathrm{S}}^3 r_{\mathrm{M}}^3}, \ e_{\mathrm{MS}} = 2E_{\mathrm{M}} \frac{m_{\mathrm{S}} r_{\mathrm{M}}^3}{m_{\mathrm{M}} r_{\mathrm{S}}^3}. \tag{39}$$

Here e_{MS} is the coefficient for $P_2(\cos S_{\mathrm{MS}})$ in the additional term to the full energy (37).

Unperturbed values of energies are obtained on the basic values (38) and equations (39) by using $r_{\mathrm{M}} = a_{\mathrm{M}}$ and $r_{\mathrm{S}} = a_{\mathrm{S}}$. Using 1 unit $= 10^{23}$ cgs we determine that

$$E_{\mathrm{M}}^{(0)} = 5.473 \text{ cgs}, \; E_{\mathrm{S}}^{(0)} = 1.148 \text{ cgs } e_{\mathrm{MS}}^{(0)} = 2(E_{\mathrm{M}}^{(0)} E_{\mathrm{S}}^{(0)})^{1/2} = 5.0132 \text{ cgs}.$$

4.4 Variations in the Elastic Tidal Energy

The maximal value of the full elastic energy of the Earth (the full Moon) is

$$E_{\mathrm{SM}}^{\max} = E_{\mathrm{S}}^{(0)} + E_{\mathrm{M}}^{(0)} + 2(E_{\mathrm{S}}^{(0)} E_{\mathrm{M}}^{(0)})^{1/2} = 11.6342 \text{ cgs}.$$

The minimal value of this energy (the Moon in quadratures) is

$$E_{\mathrm{SM}}^{\min} = E_{\mathrm{S}}^{(0)} + E_{\mathrm{M}}^{(0)} - (E_{\mathrm{S}}^{(0)} E_{\mathrm{M}}^{(0)})^{1/2} = 4.1144 \text{ cgs},$$

and variations in the full energy are $\Delta E_{\mathrm{SM}} = 3(E_{\mathrm{S}}^{(0)} E_{\mathrm{M}}^{(0)})^{1/2} = 7.5198 \times 10^{23}$ cgs (every synodic month).

The lunar and solar eccentricity variations in the Earth's tidal energy (pericentre–apocentre positions) are determined by the formulae

$$\Delta E_{\mathrm{M}} = E_{\mathrm{M}}^{(0)} \left(\frac{1}{(1-e_{\mathrm{M}})^6} - \frac{1}{(1+e_{\mathrm{M}})^6} \right) = 0.6776 E_{\mathrm{M}}^{(0)} = 3.7084 \times 10^{23} \text{ cgs},$$

$$\Delta E_{\mathrm{S}} = E_{\mathrm{S}}^{(0)} \left(\frac{1}{(1-e_{\mathrm{S}})^6} - \frac{1}{(1+e_{\mathrm{S}})^6} \right) = 0.2015 E_{\mathrm{S}}^{(0)} = 0.2314 \times 10^{23} \text{ cgs}.$$

This means that a full variation in the tidal energy can be evaluated as 11.4596×10^{23} cgs.

Figure 1 illustrates the variations in the elastic energy of the Earth due to the influences of the Moon and Sun and the variation in the full elastic energy of the Earth taking into account the mutual additional term (37). For illustration we have restricted the interval of time to 1 January 2004–1 January 2005. The behaviours of the curves in Figure 1 are in accordance with simple evaluations of the average values and of the amplitude of the variations in the elastic energy given above.

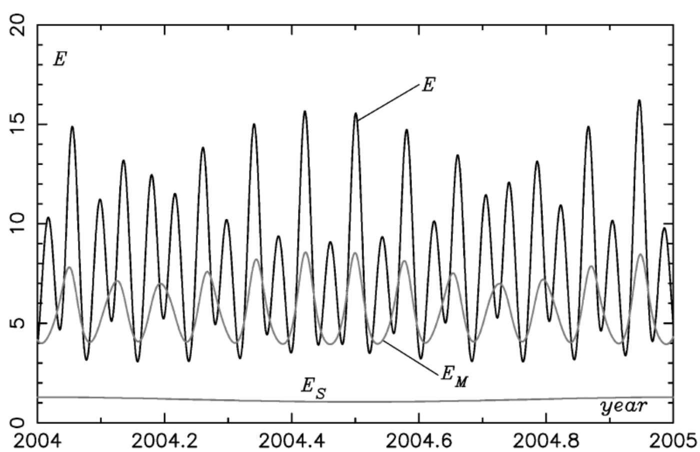

FIGURE 1 Elastic energy variations in the year 2004 (1 unit $= 10^{23}$ cgs).

4.5 Correlation of Earthquakes and Moonquakes with Variations in Elastic Energy

Here we study the correlation of the moments of earthquakes and moonquakes with the moments of extreme values of the Earth's elastic energy and Moon's elastic energy. We have studied theoretical curves of the change in the elastic energy of lunar–solar deformations of the Earth mantle and terrestrial–solar deformations on the Moon in the period 1971–1976. It was shown that the moments of quakes are usually extremely close to the moments of extreme values of elastic energy. The moments of large earthquakes (of magnitude 7 or 8 and more) and moonquakes in the considered period of time correlated with moments of elastic energy extremes.

On this basis we can suggest that variations in elastic energy are connected with seismic activity. Of course this means that correlation between the orbital motions of the Moon and Sun and the planetary seismic process is real. The mutual term of elastic energy is sufficiently large and significantly controls and dictates the seismic process. This seems natural. Some of the elastic energy with every orbital cycle of the Moon (and Sun) dissipates to inner geodynamic processes.

However, it is possible that another mechanism exists which controls seismic processes. At the present time we are studying the rule of mechanical interaction between core and mantle (and between lithosphere plates) of the Earth induced by the gravitational action of the Moon and Sun on the Earth's non-spherical shells (Barkin, 2002).

To illustrate this, we used the dates of about 26 large shallow earthquakes (with $M > 7$) and about 28 shallow moonquakes from the work of Shirley (1985–1986) in which an analysis of their mutual temporal correlation in 1971–1976 was given. Here for simplicity we plot the temporal positions of earthquakes (grey full circles) and moonquakes (grey stars) indirectly on the curve of elastic energy variations (Figure 2) only for 1975. A simple tendency can be clearly observed here; 12 of the 14 quakes are situated close to the extremes of elastic energy curve. The positions of three of these correspond to an elastic energy value of about 7.7 units.

Analysis of the total period 1971–1975 shows that 45 of 54 quakes (grey symbols) are situated close to the extreme peaks of elastic energy. 14 points are occupied positions with an average character value of 6.0–7.7. These particularities are probably general for a longer period of time (for hundreds, thousands and millions of years) and are regular features of the seismic process.

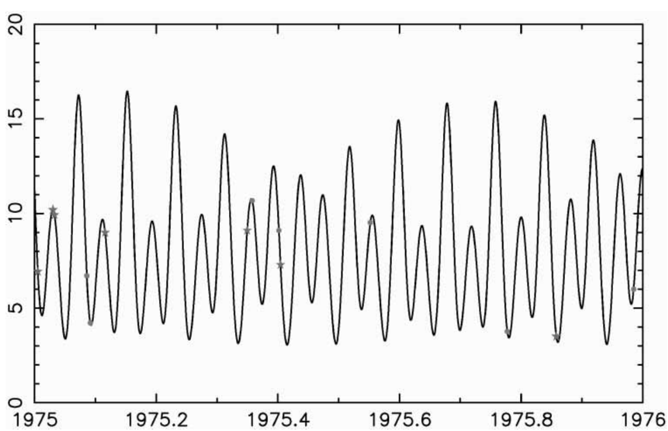

FIGURE 2 Earthquakes and moonquakes in 1975 and variations in the Earth's elastic energy (1 unit = 10^{23} cgs).

The predicted dates of possible large earthquakes in 2004 and corresponding values of the elastic energy E of the Earth (1 unit $= 10^{23}$ cgs) are presented in Table I.

4.6 Prediction of Large Earthquakes

Of course, earthquakes and moonquakes are not observed for all extreme tidal variations. Probably the quakes are caused by the process of accumulation of seismic energy, but in any case we can predict in a definite statistical sense the dates of future large earthquakes and moonquakes. As a result of the analysis of the theoretical curve of elastic energy of lunisolar tides we have determined the dates of possible large earthquakes in 2003. These dates are as follows: 2.3, 10.4, 18.4, 25.2 and 31.9 (January); 8.8, 16.9 and 24.0 (February); 2.5, 10.2, 18.3 and 25.7 (March); 1.3, 8.6, 16.5 and 24.2 (April); 1.1, 8.0, 15.7, 23.7 and 30.9 (May); 6.5, 13.9, 22.1 and 29.7 (June); 6.2, 13.3, 21.4 and 29.4 (July); 5.0, 11.7, 19.8 and 28.0 (August); 3.9, 10.4, 18.2 and 26.3 (September); 3.6, 10.1, 17.6 and 25.6 (October); 2.1, 8.9, 16.0 and 23.8 (November); 1.6, 8.7, 15.5, 23.1 and 31.0 (December). The first figure of the date specifies the day of month, and the figure after the decimal point specifies the time of earthquake in decimal shares of that day.

On the same dates, moonquakes can be expected on the Moon. The approach gives does not allow us to determine the region of earthquakes but only to analyse the dates of extreme perturbed states of the Earth caused by gravitational influence of external celestial bodies.

TABLE I Dates of potential large earthquakes in 2004.

N	*E*	*Date*	*Month*	*N*	*E*	*Date*	*Month*
1	10.3	7.3	January	25	15.6	1.8	July
2	4.7	13.9	January	26	3.5	9.8	July
3	14.9	21.1	January	27	9.3	17.1	July
4	3.2	29.2	January	28	4.5	23.7	July
5	11.2	6.0	February	29	14.7	31.1	July
6	5.1	12.6	February	30	3.2	8.2	August
7	13.2	19.5	February	31	10.1	15.9	August
8	3.1	27.6	February	32	5.0	22.3	August
9	12.5	6.6	March	33	13.5	29.4	August
10	5.2	13.4	March	34	3.1	6.6	September
11	11.5	20.0	March	35	11.5	14.6	September
12	3.1	28.0	March	36	5.3	21.2	September
13	13.8	5.1	April	37	12.1	27.9	September
14	5.0	12.2	April	38	3.1	6.0	October
15	10.2	18.7	April	39	13.1	14.1	October
16	3.2	26.3	April	40	5.1	21.0	October
17	15.0	4.5	May	41	10.9	27.6	October
18	4.4	11.9	May	42	3.2	4.3	November
19	9.4	18.5	May	43	14.9	12.5	November
20	3.5	25.7	May	44	4.6	19.7	November
21	15.7	2.7	June	45	10.2	26.3	November
22	3.9	10.4	June	46	3.4	3.8	December
23	9.1	17.3	June	47	16.2	11.8	December
24	4.0	24.2	June	48	4.1	19.3	December
				49	9.8	26.1	December

4.7 Prediction Date of Japan Quakes in September 2003 the Large Earthquake with $M = 8.3$

In our studies (Barkin *et al.*, 2003b) we pointed out that one of the large earthquakes must take place on 26.3 September 2003. This date with high accuracy coincides with the date of the real Japan quake on 25.8 September (19:50:06 Universal Time Coordinated (UTC)) with large magnitude $M = 8.3$. This phenomenal earthquake took place on Hokkaido Island with the epicentre location at 41°78 N, 143°86 E, and with a depth of 27 km. This earthquake was accompanied by a tsunami with an estimated wave height of 4.0 m along the southeastern cost of Hokkaido. At least 589 people were injured, extensive damage, landslides and power outages occurred and many roads were damaged in southeastern Hokkaido. This earthquake was felt strongly in much of Hokkaido (Seismosurfing the Internet for Earthquake Data, 2004).

Closer to the predicted date of the large earthquake was a second Japan quake on 25 September 2003 with $M = 7.0$. It took place on 25.9 September (21:08 UTC) with a large magnitude $M = 7.0$ on Hokkaido Island. The epicentre had the coordinates 41°81 N, 143°51 E, and with a depth of 33 km.

Previous very severe earthquakes in this region took place on 4 March 1952 ($M = 8.1$), 16 May 1968 ($M = 7.9$) and 15 January 1993 ($M = 7.6$).

The last large earthquake (of magnitude 8 or greater) in the world had a magnitude of 8.4 that occurred on 23 June 2001 near the coast of Peru.

4.8 About the Mechanism of Earthquakes

In accordance with interpretation (Seismosurfing the Internet for Earthquake Data, 2004) it is implied that the Hokkaido earthquake occurred as the result of thrust faulting on the plate interface between the overriding North American plate (which extends into the northeast corner of the Eurasian landmass) and the subducting Pacific plate. The Pacific plate is moving west–northwest at a rate of about 8.2 cm year^{-1} relative to the North American plate. In addition to experiencing large thrust earthquakes that originate on the interface between the plates, eastern Hokkaido experiences large earthquakes that originate from the interior of the subducted Pacific plate. The earthquakes of 4 March 1952 and 16 May 1968 were interface-thrust earthquakes, whereas the earthquake of 15 January 1993 occurred within the interior of the subducted Pacific plate. The recent Hokkaido earthquake appears to have involved rupture of the same section of the plate interface that ruptured in 1952.

Earthquakes of magnitude 8 and greater are capable of devastating large areas. The shallow 25 September Hokkaido earthquake occurred about 60 km offshore. If the earthquake had occurred directly beneath a populated region, damage would have more severe.

However, from our research it follows that the Moon has a dynamic influence on seismic process and, in particular, on the Hokkaido earthquake discussed here. To what extent does the Moon participate in the process described above? Apparently, tidal deformations of the Earth, as well as the extreme joint influence of the Moon and the Sun, result in additional influences on lithosphere plates resulting in an arch. Thus they prove to have miscellaneous effects along the borders of plates depending on the tidal displacement on the surface of the Earth. In some areas, as happened in Hokkaido, they achieve the maximal values. As a result, conditions for ‘gearing’ plates in certain areas of the interface of the cooperating plates (both free standing and immersed) in the region of the island of Hokkaido were created. Further more powerful relative movement of the specified plates results in failure -and pushes at the specified point which represents the epicentre of the earthquake. This is actually the description of the trigger mechanism of earthquakes, as dictated by the attraction of the Moon.

This is not a unique explanation. The Moon (Sun) has a differential influence on cooperating plates, forcing them cyclically to come together on to separate from each other (Barkin, 2002; Barkin and Ferrandiz, 2003a). This phenomenon is caused by the various dynamic structures of lithosphere plates. Thus this mechanism allows us to explain the dynamic role of the influence of the Moon on earthquakes. We discuss only assumptions that require empirical generalization and in the dynamic interpretation are stated here.

4.9 Earthquake in the Russia–Xinjiang Border Region with $M = 7.3$

This earthquake took place on 27.5 September (11:33:24 UTC) 2003. This date is also close to predicted date 26.1 September 2003 of a possible large earthquake.

This earthquake resulted from stresses originating from the collision of the Indian plate against the Eurasian plate. The collision of the two major plates generated the Himalayan mountains, far to the south of the epicentre of this earthquake, and produces deformation of the Earth's crust over a broad region of central and eastern Asia. In the epicentre region of southern Russia, northwestern China, eastern Kazakhstan and western Mongolia, earthquakes in past decades have been caused by strike–slip faulting (as with this earthquake) and reverse faulting.

This earthquake is the largest in this region since the earthquake on 20 December 1761 that is thought to have had a magnitude of about 7.7.

In accordance with our approach the gravitational influence of the Moon and Sun on the elastic Earth on 25, 26 and 27 September 2003 was very significant compared with other dates. As a result the Hokkaido quakes occurred. Later the gravitational attraction of the Moon and Sun (with the condition of the extreme value of elastic deformation energy) led to the realization of the trigger mechanism. 'Gearing' of Indian and Eurasian plates due to the Moon and Sun could only occur 252 years after the previous similar state.

4.10 About Correlation of Earthquakes and Moonquakes with Variations of Elastic Energy

The relative orbital motions of the Moon and the Earth are identical. Periodicities in their orbital motions of the same type influence the tidal processes on both celestial bodies and, consequently, rhythms at identical periods can be expected in the seismic processes for the Moon and for the Earth. The first confirmation of the above-mentioned correlations has been obtained for shallow earthquakes (with magnitude greater than 7.3) and shallow moonquakes in the period 1971–1976 (Shirley, 1985–1986). The tidal nature of moonquakes has been discussed with an interpretation of the results of their spectral analysis (Lammlein, 1977; Oleinic *et al*., 2000). In these papers the periods of the Moon orbital perturbations were found to be 27.4, 13.6 and 206 days and some others were also determined. Our spectral–temporal analysis of the full series of moonquakes from catalogue which has been kindly presented to us by Y. Nakamura (about 7500 depth events) allowed us to confirm the mentioned periods and to establish some fine structure of tidal periodicities (M. Garcia Ferrandez). The main cyclicities of the Moon's seismic process is characterized by half the draconic period (13.62 days), half the synodic period (14.77 days) and the draconic period (27.20 days). Also the variations in the Moon's seismicity with other periods that are multiples of orbital draconic, anomalistic and synodic periods were determined: 5.50, 6.75, 9.15, 9.80, 13.15, 22.8, 32.8 days and others. The obtained results were analysed and confirmed in comparison with similar results obtained for a random distribution of quakes. So, a celestial mechanical nature of the seismic rhythms on the Moon looks sufficiently clear. However, the spectral–temporal analysis has revealed some temporal instability of the rhythms observed (Oleinic *et al*., 2000). As known, the many processes from the Earth are characterized by a similar behaviour. This indicates that some contributions to the observed picture of seismicity could be caused by another (non-tidal) mechanism.

On the basis of these results we have studied the theoretical curves of the change in elastic energy of lunar–solar deformations of the Earth's mantle and terrestrial–solar deformations on the Moon in the period 1971–1976. Preliminary analysis has shown that the moments of quake are usually situated closely to moments of extreme values of elastic energy. Moments of large earthquakes (of magnitude 7.3 and more) and moonquakes in the above-mentioned period of time are correlated with moments of elastic energy extremes. In 1975, for example, 12 of 13 quakes are situated close to extremes of the elastic energy curve (with a deviation of 1–1.5 days).

Assuming that this particularity is general for longer periods of time we carried out a statistical analysis of the differences of dates of large earthquakes (in the last 30 years) and close dates of the extremes of elastic energy. The results obtained in general confirm the discussed tendency of a quake's temporal distribution and a new phenomenon of displacements of dates of the large quakes of 1.5–2.0 days with respect to the dates of extremes of elastic energy has been observed. However, the temporal distributions of earthquakes are characterized by a more complex structure than those of moonquakes. To explain the observed data we plan to study in future the possible role of the plate motion and the role of mechanical interaction between the non-spherical mantle and core of the Earth induced by gravitational action of the Moon and the Sun (Barkin, 2002; Barkin and Ferrandiz, 2003a).

Acknowledgement

Barkin's work was supported by Grant SAB2000-0235 from the Secretaria de Estado de Educacion y Universidades and by Grant 02-05-64176 from the Russian Foundation for Basic Research. Partial support of the Spanish research projects AYA-2001-0787 and ESP2001-4533-PE is also acknowledged.

References

Barkin, Yu. V. (2002) Izv. Sekzii Nauk Zemle RANS, No. 9, 45–97 (in Russian).
Barkin, Yu. V. Ferrandiz, J. M. and Navarro, J. (2003a) Proceedings of the EGS–AGU–EUG Joint Assembly, Nice, France, 7–11 April 2003. *Geophys. Res. Abstr.* **5**, Abstract 03227.
Barkin, Yu. V. and Ferrandiz, J. M. (2003b) *Abstracts of Microsymposium 37 on Comparative Planetology*, Moscow, Russia, 27–29 October 2003, CD - ROM, Topics in Comparative Planetology, Vernadsky Institute, Brown University.
Ferrandiz, J. M. and Getino, J. (1993) *Celestial Mech. Dynamics Astron.* **57**, 279.
Getino, J. and Ferrandiz, J. M. (1991) *Celestial Mech.* **51**, 17.
Getino, J. (1992) *Celestial Mech. Dynamics Astron.* **53**.
Getino, J. (1993) *Z. Angew Math. Phys.* **44**, 998.
Gilbert, F. and Dziewonski, A. M. (1975) *Lunar Planetary Sciences Conference, Phil. Trans. R. Soc.* **287A**, 187–269.
Lammlein, D. R. (1977) *Phys. Earth. Planetary Interiors* **14**, 224.
Oleinic, O. V., Galkin, I. N. and Gamburtsev, A. G. (2000) LPS XXXI.
Seismosurfing the Internet for Earthquake Data (2004) http://www.geophys.washington.edu/seismosurfing.
Shirley, J. H. (1985–1986) *Earth Planetary Sci. Lett.* **76**, 241.
Takeuchi, H. (1950) *Trans. Am. Geophys. Union* **31**, 651.