Changes in the Earth’s rotational energy induced by earthquakes

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SUMMARY
The kinetic energy of the Earth’s rotation can be separated into two parts: the spin energy and the polar-motion energy. Here we derive rigorous formulae for their changes, where the polar-motion energy change is related to the polar-motion excitation function via a treatment of reference frames. The formulae are then used to compute co-seismic energy changes induced by the static displacement field produced in an idealized earth model by a total of 11,015 major earthquakes that occurred during the period 1977 to 1993. An extremely strong statistic is found for the earthquakes’ tendency to increase the Earth’s spin energy; the rate during 1977 to 1993 was $+6.7 \, \text{GW}$, about the same as the total seismic-wave energy release. The corresponding polar-motion energy changes are $10^{-6}$ times smaller and had no detectable statistical tendency in their signs.

Key words: earthquakes, rotational energy.

1 INTRODUCTION
Mass redistributions of material in or on the Earth will produce two independent global geodynamic effects. It will change the Earth’s rotation via the conservation of angular momentum. It will also change the Earth’s gravitational field according to Newton’s gravitational law. An earthquake faulting generates a large-scale static displacement field in the Earth, so the Earth’s rotation and gravitational field, as well as their associated energy, will change as a result. Chao & Gross (1987) have formulated and computed earthquake-induced changes in the Earth’s rotation and low-degree gravitational field. The present paper focuses on the corresponding change in the rotational energy, while a companion paper (Chao et al. 1995a) treats the changes in the gravitational energy.

Munk & MacDonald (1960) have shown that, to a first-order approximation, variations of the Earth’s rotation vector as seen in the terrestrial reference frame can be separated dynamically into spin variation and polar motion. We shall derive formulae for the rotational kinetic energy change from first principles in parallel to their linearization scheme. It will be shown that the rotational energy change can also be separated, to first order, into spin energy change and polar-motion energy change. It should be mentioned that the first-order expression for spin energy change can be derived alternatively, in a straightforward manner, from the conservation of the axial component of angular momentum (cf. Dahlen 1977; see also eq. 5 below). By the same token, the change in the polar-motion energy can be derived from the expression for the total polar-motion energy of an elastic Earth, which is formally equivalent to that associated with the Eulerian motion of a rigid body (e.g. Landau & Lifshitz 1976). However, as we will see, careful interpretation of the associated reference frame is necessary.

Chao & Gross (1987) made extensive computations for 2146 major earthquakes that occurred during 1977–1985 and found a strongly non-random behaviour of earthquakes in their production of co-seismic rotational and gravitational changes. In particular, they found that earthquakes have an extremely strong tendency to speed up the Earth’s spin, albeit slightly. This happens because the earthquakes tend to move mass towards the rotation axis, just as drawing the arms closer to the body would speed up a skater’s spin. The spin energy will increase in the process because work is done against the centrifugal force. In this paper we apply the rotation energy formulae to the co-seismic mass redistribution associated with the earthquake-induced static displacement field in the Earth. We compute both spin energy and polar-motion energy changes caused by 11,015 major earthquakes that have occurred between 1977 January 1 and 1993 July 31. In parallel to Chao & Gross (1987) and Chao et al. (1995a), we examine the magnitude and statistics of these rotational energy changes.

2 GENERAL FORMULATION
Consider a rotating earth model for which some terrestrial (body) reference frame is defined. We fix the origin of the coordinate system at the centre of mass. The Cartesian $x, y$
and $z$ coordinate axes are oriented along the 0° (Greenwich) Meridian, the 90°E Meridian, and the Earth’s mean rotation axis, respectively. The choice of this $z$ axis defines the zero polar motion energy, which corresponds to zero wobbling motion. The instantaneous rotation velocity vector can be written as

$$\Omega = \Omega(m_1 \hat{x} + m_2 \hat{y} + (1 + m_3) \hat{z}),$$

(1)

where $\hat{r}$ denotes a unit vector, $\Omega = 7.291 \times 10^{-5}$ s$^{-1}$ is the mean (sidereal) rotation rate of the Earth, and $m_i$ are small dimensionless perturbations, $m_1$ describing variations in the spin and $m_1$, $m_2$ describing polar motion. To first order in $m$, the centrifugal potential generated by $\Omega$ at location $r$ in the Earth is (e.g. Wahr 1985)

$$S(r) = \frac{1}{2}[r^2(2) - (r \cdot (r \cdot 2))]$$

$$= \frac{1}{2}\Omega^2[(x^2 + y^2)(1 + 2m_1) - 2m_1xz - 2m_2yz].$$

(2)

The centrifugal acceleration is given by $\nabla S(r)$.

Suppose an infinitesimal displacement field $u(r)$ is produced in the otherwise unperturbed Earth. This displacement does mechanical work against the centrifugal force, and the rotational energy change is equal to this work integrated over the volume of the Earth:

$$\Delta E = - \int \rho(r)u(r) \cdot \nabla S(r) \, dV,$$

(3)

where $\rho(r)$ is the Earth’s density distribution. The position vector $r$ of a material particle refers to a Lagrangian (as opposed to Eulerian) description which, under the conservation of mass, allows volume integration to be carried out over the undeformed body.

Combining eqs (2) and (3), one obtains

$$\Delta E = -\frac{1}{2}\Omega^2 \left[ (1 + 2m_3) \int \rho(r)u(r) \cdot \nabla(x^2 + y^2) \, dV 
+ 2m_1 \int \rho(r)u(r) \cdot \nabla(-xz) \, dV 
+ 2m_2 \int \rho(r)u(r) \cdot \nabla(-yz) \, dV \right].$$

(4)

valid to first order in $u$. The first term in the bracket gives the change in the spin energy, $\Delta E_s$, whereas the remaining two terms give the change in the polar-motion energy, $\Delta E_{pm}$. To first order in $m$ and $u$, they separate in a natural and convenient manner.

The energy changes can be simplified, at least conceptually, as follows. Let $C$ be the polar moment of inertia of the Earth about the $z$ axis: $C = \int \rho(r)(x^2 + y^2) \, dV = 8.0378 \times 10^{37}$ kg m$^2$. Then the first integral in (4) is precisely the change in $C$, $c_{33}$, due to the displacement $u(r)$ in the Lagrangian description. Thus, to first order in $u$,

$$\Delta E_s = -\frac{1}{2}\Omega^2 c_{33},$$

(5)

where a term proportional to $m_1 \rho \ll 1$ has been neglected.

By the same token, the remaining two integrals in (4) are recognized as the Lagrangian description of the changes in the $x$ and $y$ components of the inertia tensor ($-\rho xz \, dV$ and $-\rho yz \, dV$, respectively). Denote these changes as $c_{13}$ and $c_{23},$

$$\Delta E_{pm} = -\Omega^2 m \cdot c,$$

(6)

where for brevity we have written $m = (m_1, m_2)$, and $c = (c_{13}, c_{23})$ as 2-D vectors. Here $m$ is expressed in radians; typically $|m| \approx 10^{-6}$ from observation (see Fig. 1).

The quantities $c_{33}$, $c_{13}$ and $c_{23}$ are usually computed for geophysical processes with no regard to any induced rotational deformation of the (elastic) Earth. In reality, the extra centrifugal force arising from the rotational change itself can cause and extra change in the above parameters, the size of which depends on the Earth’s elastic properties. Numerically, however, this contribution can be neglected because its relative magnitude is only of the order of $10^{-3}$, as shown by Munk & MacDonald (1960, eq. 6.1.8).

It is instructive to derive the total polar-motion kinetic energy from eq. (6). This can be done in terms of the polar-motion excitation function due to a mass redistribution computed with respect to the Tesserand’s frame, $\Psi = k_m/(C - A)$, where $k_m = 1.43$ is the polar-motion transfer function (Munk & MacDonald 1960), and $A = 8.0115 \times 10^{37}$ kg m$^2$ is the Earth’s equatorial moment of inertia. Hence

$$\Delta E_{pm} = -\Omega^2 (C - A) m \cdot \Psi / k_m.$$  

(7)

Following the argument of Chao (1984, eqs 13–15), it can be shown that the instantaneous change in the polar motion caused by $\Psi$ is

$$\Delta m = -k_m(C/A)\Psi.$$  

(8)

Substituting eqns (7) and (8) into (6) leads readily to the expression for the total polar-motion energy:

$$E_{pm} = \frac{1}{2}\Omega^2 (A(C - A)/C) m \cdot m.$$  

(9)

This equation is formally identical to the well-known expression for the kinetic energy of the Eulerian wobble of a rigid body.

The same effect associated with the minus sign in eq. (8) explains the minus sign in eq. (7). $E_{pm}$ increases if $\Psi$ is opposite to $m$ in direction: as viewed in the terrestrial frame, the centre of the new $m$ moves away from the original $m$, increasing $|m|$ and hence $E_{pm}$. The reverse is true if $\Psi$ is parallel to $m$. $E_{pm}$ remains unchanged if $\Psi$ is perpendicular to $m$.

A word of caution is in order here with respect to the definition of $m$. As described above, our formula applies to the location of the rotational pole relative to the ‘mean pole’, which in turn is our reference level corresponding to zero polar-motion energy. Two complications arise as a result. First, the ‘reported’ pole position measurement is the location of the celestial ephemeris pole, rather than the rotation pole (Gross 1992). The dynamic difference is proportional to the time derivative of the excitation $\Psi$. Chao (1984) has shown that, for an abrupt displacement such as an earthquake faulting, the difference is numerically negligible on the order of the Earth’s oblateness ($\sim 1/300$). In fact, the excitation $\Psi$ given above neglects the time derivative terms for the same reason. The second complication is a more obvious one. That is, the pole position is normally given relative not to the mean pole but to
the Conventional North Pole, which is defined to be the mean pole for the period 1900–1905. The North Pole no longer coincides with the present mean pole as a result of a polar secular drift over the years. Hence an empirical shift of the origin needs to be invoked so that the polar-motion series can be free from the polar drift as much as possible (only the 'wobbling' motion remains). This will be done below. Note that our definition of \( m \) thus gives the scalar quantity eq. (9) an invariant, positive-definite form with respect to coordinate transformation, as it should.

We now apply the theory to the co-seismic, static displacement in the Earth produced by an abrupt, step-function earthquake faulting. Following Chao & Gross (1987) and using the normal-mode theory (Gilbert 1970), this displacement can be expressed as an infinite sum of the Earth's free oscillation normal modes:

\[
\mathbf{u}(r) = \sum_k \omega_k^2 \mathbf{u}_k(r) \mathbf{E}_k(r), \quad t > 0. \tag{10}
\]

The asterisk denotes complex conjugation, ': ' indicates the 2nd degree tensor inner product, \( \mathbf{u}_k(r) \) is the eigenfunction of the \( k \)th mode normalized such that \( \int \mathbf{u}_k \cdot \mathbf{u}_k \, dV = 1; \ \omega_k \) and \( \mathbf{E}_k = (\mathbf{V}_k + (\mathbf{V}_k)^T)/2 \) (where superscript T denotes transpose) are the corresponding eigenfrequency and elastic strain tensor, respectively; \( r \) and \( \mathbf{M} \) are the focus and the seismic moment tensor of the earthquake, respectively. The global spatial scale and the long temporal scale under consideration allow the simplified representation of an earthquake as a point source with a step-function time history. \( \mathbf{M} \) is symmetric owing to the indigenous nature of the earthquake which exerts zero net torque. The advantage of using normal-mode theory has been pointed out by Chao & Gross (1987): since the eigenfunctions already account for the elastic and gravitational forces as well as the physical boundaries in the Earth, none of these complications need be taken into consideration explicitly. Furthermore, the formulation is particularly efficient in computation (see below).

To evaluate \( \mathbf{u}(r) \), we consider a simple earth model which is a spherically symmetric, non-rotating, elastic and isotropic approximation of the real Earth (so-called SNREI earth model). Since the Earth's deviation from spherical symmetry is relatively small (the rotation and the ellipticity, by far the largest deviations, are only of the order 1/300), the error produced in using an SNREI representation is negligible to this order.

The density distribution is then a function of radial distance only: \( \rho(r) = \rho(r) \). The normal modes \( \mathbf{u}_k \) of an SNREI earth are of two kinds—spheroidal and toroidal. The toroidal modes, being divergence-free, have zero first-order effect on the mass density, so they drop out of the modal sum (10). The spheroidal modes can be written as

\[
\mathbf{u}_{nml}(r) = \mathbf{r}U_{nl}(r)Y_{nm}(\theta, \lambda) + \mathbf{V}_{nl}(r)\mathbf{V}_1 Y_{nm}(\theta, \lambda), \tag{11}
\]

where \( n, l, m \) are respectively the overtone number, degree and order of the normal modes (\( n, \ l = 0, 1, 2, \ldots, m = -l, \ldots, l \)). \( U_{nl} \) and \( V_{nl} \) are the radial eigenfunctions; \( Y_{nm} \) are the fully normalized, complex surface harmonic functions of latitude \( \theta \) and longitude \( \lambda \); and \( \mathbf{V}_1 \) is the surface gradient operator \( \partial/\partial \lambda + \lambda \sec \theta \partial/\partial \theta \). The eigenfrequencies of the \( (n, l) \)th (spheroidal) multiplet will be denoted by \( \omega_{nl} \). The eigenmodes are functions of the interior structure of the earth, and independent of \( m \) under the assumed spherical symmetry.

The task now is to substitute eq. (11) into (10) and then use it to calculate \( \mathbf{c}_{n3} \) and \( \mathbf{c} \). The details of this procedure have been presented by Chao & Gross (1987). Substituting this result into eqs (5) and (6) yields

\[
\Delta E_{a} = \Omega^2 M \sum_n [G_{n}E_{n00}(r_{t}) + F_{n}E_{n20}(r_{t})], \tag{12}
\]

\[
\Delta E_{pm} = -(\sqrt{5}/6 \Omega^2) M \left[ \sum_n F_{n}\{F_{n}\mathbf{E}_{n21}(r_{t}), \mathbf{F}_{n}\mathbf{E}_{n22}(r_{t})\} \right], \tag{13}
\]

where the summations are carried out over the infinite set of spheroidal overtones. \( F_{n} \) and \( G_{n} \) are the following functionals of the SNREI earth model:

\[
F_{n} = (4\sqrt{\pi}/3\sqrt{5})\omega_{n2}^{-2} \int_{0}^{\infty} r \rho(r) U_{n2}(r) + 3V_{n2}(r) \, dr, \tag{14}
\]

\[
G_{n} = -(4\sqrt{\pi}/3)\omega_{n0}^{-2} \int_{0}^{\infty} r \rho(r) U_{n0}(r) \, dr, \tag{15}
\]

where \( a \) is the mean radius of the Earth.

Only the spheroidal overtones with \( l = 0 \) or \( (l = 2, m = 0) \) contribute to \( \Delta E_{a} \), while only the spheroidal overtones with \( l = 2 \) and \( m = 1 \) contribute to \( \Delta E_{pm} \).

3 DATA

Following Chao & Gross (1987), we adopt the 1066B earth model of Gilbert & Dzielskowi (1975) for the SNREI earth parameters and normal-mode eigenvalues. For the earthquake moment tensors \( \mathbf{M} \) we use the centroid-moment tensor solutions published in the Harvard catalog (e.g. Dzielskowi et al. 1993), which consists of 11015 earthquakes that occurred during the period 1977 January 1 to 1993 July 31 with body-wave magnitude larger than about 5. In terms of energy release, one need only consider the major earthquakes. Small earthquakes, although numerous, involve relatively little energy and can be ignored completely.

The pole position \( \mathbf{m} \) is also needed to compute \( \Delta E_{pm} \). We choose to use the 'Space93' time series (Gross 1994). The series consists of daily pole determinations from a Kalman-filter combination of all independent space geodetic observations. The same time span as that of the earthquake series is taken. As explained above, the polar offset and secular drift need be removed from the polar-motion data in an optimal fashion, so as to move the origin for \( \mathbf{m} \) to the mean pole. We accomplish this by least-squares fitting a linear combination of an annual term, a Chandler term, plus a second-degree polynomial to each of the \( x \) and \( y \) components of the pole position. The polynomial (which turned out to be nearly linear) is then subtracted. The resultant pole path of \( \mathbf{m} \) during 1977 January 1 to 1993 July 31 is displayed in Fig. 1.

4 RESULTS AND DISCUSSION

We then compute \( \Delta E_{a} \) using eq. (12) and \( \Delta E_{pm} \) using (13). The convergence of the summation was found to be quite rapid, usually with the value obtained after summing only
two overtone modes being well within 1 per cent of its final value, although we actually summed over 26 overtone modes having periods longer than 45 s. The results are shown in Fig. 2. The cumulative energy changes are given in Fig. 3.

In computing $\Delta E_{pm}$, the interim (but physically meaningful) parameter of the seismic excitation function $\Psi$ is obtained. The cumulative series for $\Psi$ in terms of its x- and y-components are presented in Fig. 4. The statistical tendency previously found by Chao & Gross (1987) for the direction of $\Psi$, $\arg(\Psi)$, to cluster around 140°E becomes even stronger here with the inclusion of additional data in the years since 1985 (Chao et al. 1995b), even though the apparent-linear trend in Fig. 4 is weaker.

For the purpose of illustration, we single out in Table 1 the results for the following eight largest earthquakes in recent decades (with seismic moment $M_0$ exceeding $10^{21}$ N m):

| Event I | 1960 May 22, Chile |
| Event II | 1964 March 28, Alaska, USA |
| Event III | 1977 August 19, Sumba, Indonesia |
| Event IV | 1985 March 3, Chile |
| Event V | 1985 September 19, Mexico |
| Event VI | 1989 May 23, Macquarie Ridge |
| Event VII | 1994 June 9, Bolivia |
| Event VIII | 1994 October 4, Kuril Is., Russia |

The source mechanisms of Events I and II, which occurred before the span of the Harvard catalog, are taken from Kanamori & Cipar (1974) and Kanamori (1970), respectively. The pole positions $\mathbf{m}$ at the times of these two events (needed to compute $\Delta E_{pm}$) are taken from the International Latitude Service data: $(-154$ mas, $42$ mas) and $(-194$ mas, $-171$ mas), after removal of an offset and long-term drift as described above. Events VII (a deep-focused event) and VIII in 1994 are also outside our studied period. Their corresponding pole positions are $(126$ mas, $64$ mas) and $(-115$ mas, $113$ mas) after detrending (Ma, 1994, personal communication). The moment tensor solution of event VIII and the corresponding pole position are considered preliminary at the time of writing. The seismic-wave energy $E_w$ is computed according to the empirical relation (Kanamori 1977) $E_w = M_y/(2 \times 10^6)$ (see also Chao et al. 1995a).

We shall now study the statistics of the rotational energy changes. We do so by examining the $\chi^2$ statistics of the sign of the $\Delta E_s$ and $\Delta E_{pm}$ values. $\Delta E_s$ is proportional to $c_{53}$, which in turn is proportional to the change in the length-of-day, $\Delta LOD$. Hence it has the same $\chi^2$ statistics as $\Delta LOD$, which has been calculated in Chao et al. (1995a). There are many more positive $\Delta E_s$ values than negative ones: out of the 11,015 events, the difference is as high as 1273, much greater than the $\sqrt{n} = 105$ expected from a binomial distribution for random fluctuations, implying an extremely low probability that this phenomenon is due purely to random fluctuations. In other words, earthquakes produce positive $\Delta E_s$ much more readily than negative $\Delta E_s$, as is clearly evident in Fig. 2(a) and the increasing trend in S(a). The corresponding $\chi^2$ is as high as 147 (far higher than, say, the critical values of 6.64 at a 1 per cent significance level or 10.8 at a 0.1 per cent significance level). Physically, it indicates that the earthquake mechanisms are such that the resultant seismic displacement tends to act against the spin centrifugal force. Thus earthquakes have a strong tendency to decrease the Earth's greatest moment of inertia $C$, causing a faster spin and greater spin energy in the process. The situation is analogous to a spinning skater gaining spin energy by drawing the arms closer to the body against the centrifugal force while the angular momentum stays constant. Geodynamically, this phenomenon seems to be connected to the fact that most seismic moment release is in the form of compression and that the extensional stresses are often located in north-south-trending zones (Farrell & Rice 1988, personal communication). From Fig. 3(a), the average rate of $\Delta E_s$ increase is fairly steady, at about $2.1 \times 10^{17}$ J yr$^{-1}$, or 6.7 GW (1 GW = $10^{9}$W), during 1977–1993.

In contrast, earthquakes show no preference one way or the other in the sign of the polar-motion energy change, and no statistical tendency is detectable. The number of negative signs of the $\Delta E_{pm}$ values is larger than the number of positive signs by a mere 69, within that expected from random fluctuations. The $\chi^2$ of this particular realization is only 0.43, corresponding to a significance level of $\sim 50$ per cent. This non-trending nature of $\Delta E_{pm}$ gives Fig. 3(b) the characteristic of a random walk process. From Fig. 3(b), the overall fluctuation in $\Delta E_{pm}$ during 1977–1993 is of the order of $10^{12}$ J, or only $\pm 10^{-8}$ GW. The overall size of $\Delta E_{pm}$ is thus six orders of magnitude smaller than $\Delta E_s$. The reason is the following: assuming that $|e|$ and $|e_{53}|$ produced by earthquakes are comparable in size, eqs (5) and (6) lead to $\Delta E_{pm}/\Delta E_s \sim |m|$, which is of the order $10^{-6}$.

We can now compare the rate of some relevant geophysical energy changes (for reference, the total human
Figure 2. (a) Spin energy change $\Delta E_s$, and (b) polar-motion energy change $\Delta E_{pm}$, induced by 11015 major earthquakes during 1977–1993 (some of the largest values are off the scale).

- Total heat flow: $4 \times 10^4$ GW
- Spin-down caused by tidal braking: $-3 \times 10^3$ GW
- Earthquake-induced gravitational energy, 1977–93: $-2.0 \times 10^3$ GW (Chao et al. 1995a)
- Mantle convection: $1 \times 10^3$ GW
- Total seismic-wave energy, 1977–93: 4.7 GW (Chao et al. 1995a)
- Earthquake-induced spin energy, 1977–93: +6.7 GW (this study)
- Earthquake-induced polar-motion energy, 1977–93: $\pm 10^{-6}$ GW (this study)

We see that in general the earthquake-induced rotational
energy changes are relatively small in terms of the global energetics. At $+6.7$ GW, the steady increase of $\Delta E_s$ with time due to earthquakes is totally overwhelmed by the tidal braking in the Earth's spin, which amounts to a secular decrease in $\Delta E_s$ at a rate of about $-3 \times 10^9$ GW. However, so far as the seismic energetics are concerned, $\Delta E_s$ is not trivial: its magnitude is comparable to, and usually greater than, the total seismic-wave energy released by earthquakes (also cf. Table 1). $\Delta E_{pm}$, being six orders of magnitude smaller than $\Delta E_s$, is completely negligible.

What is the energy source for positive $\Delta E_s$ and the sink for negative $\Delta E_s$ (and, for that matter, the source and sink for $\Delta E_{pm}$)? As a mechanism of the plate tectonic movement, earthquakes are a surface manifestation of the mantle convection. The power required for the latter is about $10^9$ GW (e.g. Stacey 1977), representing a sufficiently large energy reservoir for $\Delta E_s$ (and $\Delta E_{pm}$). Chao et al. (1995a; see also Dahlen 1977) have demonstrated that, besides operating its own energy budget and changing the rotational energy, an earthquake induces a co-seismic gravitational...
energy change $\Delta E_\phi$ that is two to three orders of magnitude larger than its own energy budget. Fig. 5 shows the cumulative, earthquake-induced, gravitational energy change $\Delta E_\phi$ adopted from Chao et al. (1995a). While $\Delta E_\phi$ steadily increases, there is a similar and equally strong tendency for the earthquakes to reduce $\Delta E_\phi$. $\Delta E_\phi$ is generally a few hundred times larger than $\Delta E_\phi$, with the opposite sign (a positive $\Delta E_\phi$ is almost always associated with a negative $\Delta E_\phi$, and vice versa). The reason is simply that the gravitational force in the Earth is a few hundred times larger than the centrifugal force, and generally points in an opposite direction to the centrifugal force. It is conceivable that this $\Delta E_\phi$ could easily serve as a source and sink for $\Delta E_\phi$ (and $\Delta E_{pm}$) in the grand scheme of plate tectonics. Under this scenario, the dominant energetic effect of an earthquake is the transfer of the gravitational energy from and into other forms of energy. The accompanying change in the rotational energy is a secondary effect, but the physical mechanism for the energy transfer remains to be studied.
Earthquake-induced rotational energy change

Figure 5. Cumulative gravitational energy change in the Earth induced by 11015 major earthquakes that occurred during 1977–1993 (reproduced from Chao et al. 1995a).

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