Changes in Global Gravitational Energy Induced by Earthquakes

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Abstract. Besides operating its own energy budget, an earthquake acts as an agent transferring a much greater amount of energy among the Earth's rotation, elastic field, gravitational field, and internal heat. This paper computes the co-seismic globally-integrated gravitational energy change induced by 11,015 largest earthquakes that occurred during 1977-1993. The result shows an extremely strong tendency for the earthquakes to decrease the global gravitational energy. Thus, energy is being extracted from the Earth's gravitational field by the action of earthquakes. The average rate over the studied period is found to be rather constant at about 2.0 TW (TW = 10^{12} watt), larger by far than the 0.0067 TW for the average rate of the earthquake-induced rotational energy increase and 0.0047 TW for that of total seismic wave energy release during the same. period. Assuming the inability of the Earth in indefinite build-up of elastic energy, it is argued that earthquakes, by converting gravitational energy, may contribute a significant amount to the global heat flow.

1. Introduction

on a non-gravitating, non-rotating Earth, an earthquake operates a simple energy budget. Initially stored as elastic energy at the fault, seismic energy is released in two forms during an earthquake process: local frictional heat and seismic wave energy which radiates outward and eventually dissipates into heat as well.

For a self-gravitating, rotating Earth, however, other forms of mechanical energy are involved. Besides producing the oscillatory displacement field (the seismic waves), the co-seismic action of the faulting also produces a static displacement field in the Earth. Integrated over the globe the mass redistribution associated with this displacement field change.s the Far th's moments of inertia, and hence its rotation and rotational energy via the conservation Of angular momentum. That problem is treated in the companion paper by Chao & Gross (199'1). The displacement field also produces changes in the gravitational field, and hence gravitational energy, according to Newton's gravitational law. This is the subject of the present paper. A theoretical treatment under idealized situations has been given by Dahlen (1 977).

Chao & Gross (19s7, henceforth Paper I) have computed the co-seismic changes in the Earth's rotation and gravitational field induced by 2146 major earthquakes that occurred during 1977- 19S5. They found strongly non- random behavior in these changes. In pal-titular, it was found that earthquakes have a strong tendency to make the Ear th more spherical and more compact. l'bus, one should expect a corresponding, decreasing trend in the global gravitation] energy. in this paper we shall first extend the I-c.suits of Paper I to include 11,015 major earthquakes that have occurred during the period **from** January 1, 1977 to July 31, 1993, We will then examine. their gravitational energy changes and discuss the physical implications insofar as it relates to the global energetics.

2. Formulation

An earthquake faulting is here modeled as a point source with a step-function history which occurs at some instant $t=0$, giving rise, in the end, to a static displace.ment field $\mathbf{u}(\mathbf{r})$ in the Earth. l-he displacement **u(r)** is assumed to be infinitesimal so that linear theory suffices. The position vector **r** ofa material particle refers to the Lagrangian (as opposed to Eulerian) description, allowing volume integrations to be performed over the undeformed body in the linear approximation.

The change in the gravitational potential energy E_g is equal to the work done against the gravitational force by the Earth's material undergoing the displacement **u(r)**. Thus, to first order,

$$\Delta E_g = - \int \rho(\mathbf{r}) \, \mathbf{u}(\mathbf{r}) \cdot \mathbf{g}(\mathbf{r}) \, dV \tag{1}$$

where $\rho(\mathbf{r})$ is the mass density and $\mathbf{g}(\mathbf{r})$ the gravitational acceleration in the Earth, $\cdot$ denotes (tensor) inner product, and the integration is over the volume V of the Earth.

To obtain an expression for $\mathbf{u}(\mathbf{r})$ produced by a given earthquake source, we follow Paper I and employ the normal mode expansion (Gilbert 1970):

$$\mathbf{u}(\mathbf{r}) = \sum_k \omega_k^{-2} \mathbf{u}_k(\mathbf{r}) \, \mathbf{M} : \mathbf{E}_k^*(\mathbf{r}_f), \; t>0 \tag{2}$$

The asterisk denotes complex conjugation, $\mathbf{u}_k(\mathbf{r})$ is the eigenfunction of the kth normal mode of the Earth's free oscillation normalized according to $\int \rho \, \mathbf{u}_k^* \cdot \mathbf{u}_k dV = 1$, ω_k and $\mathbf{E}_k = \frac{1}{2}[\nabla \mathbf{u}_k + (\nabla \mathbf{u}_k)^T]$ (where superscript T denotes transpose.) are the corresponding eigenfrequency and elastic strain tensor, respectively. Equation (2) sums over the infinite set of normal modes. The earthquake has been assumed to be a point source at location $\mathbf{r}_f$. The seismic moment tensor $\mathbf{M}$ is symmetric owing to the indigenous nature of the earthquake which exerts zero net torque. The advantages of using normal modes in both formulation and computation have been pointed out in Paper I: 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 explicit consideration in equation (2). Furthermore, this formulation lends itself to a particularly efficient algorithm in computation (see below).

For simplicity, we fix the origin of the coordinate system at the Earth's center of mass. We consider normal modes belonging to an Earth model which is a spherically symmetric, non-rotating, elastic and isotropic (so-called SNREI) approximation of the real Earth. Since the Earth's departure from such an SNREI model is relatively small (the rotation and the ellipticity, by far the largest deviations, are only of the order 1/300), the error committed in the eigenmodes is negligible to this order. The density distribution is then a function of radial distance only, i.e., $\rho(\mathbf{r}) = \rho(r)$. The normal modes $\mathbf{u}_k$ of an SNREI Earth are of two kinds: spheroidal and toroidal. The toroidal modes, being divergence-free, have no effect on the mass density and drop out of the summation (2). The spheroidal modes can be written as

$$\sigma_{nlm}(\mathbf{r}) = \hat{\mathbf{r}} \, U_{nl}(r) \, Y_{lm}(\theta,\lambda) + V_{nl}(r) \nabla_1 Y_{lm}(\theta,\lambda) \tag{3}$$

where ^ denotes unit vector; 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}, V_{nl} are the radial eigenfunctions; Y_{lm} are the fully normalized, complex surface harmonic functions of latitude θ and longitude λ; and ∇_1 is the surface gradient operator: $\hat{\theta}\partial_\theta + \hat{\lambda} \sec\theta \partial_\lambda$. The radial eigenfunctions and the eigenfrequencies, being functional of the interior structure of the Earth, are independent of the order m because of the assumed spherical symmetry.

In an SNREI Earth model, the gravitational acceleration g(r) is given by

$$g(r) = -4\pi G \hat{r} \int_0^r \rho(r') r'^2 dr' / r^2 \tag{4}$$

where G is the gravitational constant. Substituting equations (2-4) into (1) yields

$$\Delta E_g = G M : \sum_n^\infty H_n E_{n00}(r) \tag{5}$$

where

$$H_n = 8\pi^{3/2} \omega_{n0}^{-2} \int_0^a \rho(r) U_{n0}(r) \left[\int_0^r \rho(r') r'^2 dr' \right] dr \tag{6}$$

The eigenfrequency ω_{nl} is that of the (n,l)th multiplet, while E_{nlm} is the strain tensor associated with the (n,l,m)th singlet mode. The summation is over the infinite set of spheroidal overtones for $l = m = 0$. The algebra has been greatly simplified thanks to the orthogonality of the spherical harmonics. Note that the horizontal displacement associated with the second term in the spheroidal mode (3) has no effect on ΔE_g and hence drops out of equation (6).

3. Results

3.1 Changes in the Earth's Rotation and Gravitational Field

To put the present study in perspective, we first revisit and extend the results of Paper I. Paper I computed the changes in the Earth's rotation and low-degree gravitational field caused by 2146 major earthquakes that occurred during 1977 -- 1985. The earthquake data were taken from the Harvard catalog of seismic centroid-moment tensor solutions. For the SNREI Earth model and its eigenelements the 1066B Model of Gilbert & Dziewonski (1975) was adopted. Here we recapitulate a major finding of key bearing on the present study. That is, extremely strong statistical tendencies of non-randomness were found in the earthquake-induced changes in the following parameters: the dynamic oblateness (J_2), the trace of the inertia tensor (T), the length of day (LOD), and the sum ($I_{xx}+I_{yy}$) of as well as the difference (J_{22}) between the two equatorial principal moments of inertia. They are all inclined toward negative changes, indicating the tendency of earthquakes to make the Earth more spherical and more compact by pulling in mass toward the interior of the Earth.

The present paper extends the computation to include a much greater number of earthquakes whose moment tensor solutions have become available since Paper 1, altogether 11,015 events. These are events with body-wave magnitude larger than about 5 that have occurred during 1977-1993 (Dziewonski et al. 1993, and references therein) The cumulative changes of the five parameters named above are shown in Figure 1. For 1977-1985 the time series are visually indistinguishable from those in Paper 1 because the additional events for this period are relatively small. The continuation of the trends past 1985 in a virtually linear fashion is remarkable.

Following Paper 1, our task here is to examine these trends quantitatively by means of two statistics in testing the randomness of the changes: the normalized χ^2 statistic of the sign of the changes and the normalized Wilcoxon statistic W on the rank sum. Non-random changes are indicated by large χ^2 and W values (compared, say, against the following selected critical values: $\chi^2 = 6.63$ and $W = \pm 2.33$ at the 1% significant level; $\chi^2 = 10.83$ and $W = \pm 3.00$ at 0.1% significant level). The statistics are computed for "All Events" and a subset of "Large Events Only". The latter consists of those 945 events with scalar seismic moment larger than 3.6×10^{18} N m which nominally corresponds to a body-wave magnitude of 6.0 (Giardini 1984). This subset presumably contains few aftershocks. The results are summarized in Table 1. Strong tendencies in the above-mentioned parameters in Paper 1 are generally found to be even stronger here. On the other hand, random changes in other parameters (indicated by small χ^2 and W values) remain random, such as the zonal gravitational coefficients J_l with l greater than 2. Instead of presenting the details, we state that our extension of Paper I, now based on a much larger statistical sample, strengthens the conclusions of Paper 1.

3.2 Gravitational Energy Change

Using equations (5,6) we then compute the change in the gravitational potential energy ΔE_g due to those 11,015 earthquakes as above. The convergence of the summation is rapid, usually with the value of ΔE_g obtained after summing only two overtone modes being well within 1% of its final ~'able, although we actually summed over 26 overtone modes having periods longer than 45 s. ']-he cumulative $\Delta E_g(t)$ is plotted in Figure 2.

"l-k statistics of ΔE_g are given in the last entry of Table 1.1 ike the parameters named above, ΔE_g also exhibits an extremely strong tendency for negative values. This phenomenon, not surprisingly, is consistent with the finding that earthquakes tend to make the Earth more spherical and more compact by pulling in mass toward the interior of the Earth. In particular, a comparison of the $\Delta E_g(t)$ and $\Delta T(t)$ (the cumulative change in the trace of the Earth's inertia tensor) shows a remarkable similarity (Figures 1b and 2). A comparison of equation (1) with the expression $\Delta T = 4\int \rho(\mathbf{r})\mathbf{u}(\mathbf{r})\cdot\mathbf{r}dV$ (see equation 19 of Paper I) provides a qualitative explanation. Since - g and r are virtually parallel (equation 4), and since the primary contribution to the integrals conic.s from near surface where the displacement u is largest and where the small variations in g and r are inconsequential, the two integrals arc virtually proportional to each other (also evident in Table 2, see below). in fact, we found that their signs are identical.

From Figure. 1, the average rate of this earthquake-induced gravitational energy release is about -6.3 $\times$ 10^{19} J yr^{-1}, or -2?.0 terrawatt (or TW 10^{12} watt), during 1977-1993,

3.3 A sample 1 ist

For the purpose. of illustration, we single out in Table 2 the computed ΔE_g for the following seven largest earthquakes in recent ciec?.ties (with seismic moment M_0 exceeding 10^{21} N m):

1 Event 1: May 22, 1960, Chile

Event 11: March 2S, 1964, Alaska, USA

Event 111: August 19, 1977, Sumba, Indonesia

Event IV: March 3, 1985, Chile

Event v: September 19, 1985, Mexico

Event VI: May 23, 19S9, Macquarie Ridge

Event VII: June 9, 1994, Bolivia

'l-he source mechanism of Events I and 11, not included in the Harvard catalog, are taken from Kanamori & Cipar (1 974) and Kanamori (1970), respectively. Event VII in 1994 is also outside our studied period. It is a deep-focused event and has the largest seismic moment since Event III in 1977.

IIS seismic moment tensor solution (adopted from the preliminary Harvard catalog) is considered preliminary at this writing.

4. Geophysical Discussion

The direct energy release by an earthquake consists of local frictional heat and radiated seismic wave energy. Kanamori (1 977) has shown that, under certain general conditions, the two forms of energy release are comparable in quantity and that the seismic wave energy, E_w, is proportional to the. scalar seismic moment M_0 in the following empirical relation:

$$E_w = M_0 / (2 \times 1\,0^4) \quad (-1)$$

With the M_0 provided by the Harvard catalog, the cumulative $E_w(t)$ for the studied earthquakes arc computed and shown in Figure 3. '1 he time rate of $E_w(t)$ is rather constant and average about 0.0047 TW during 1977-1993.

Table 2 also gives E_w for the seven earthquakes examined above, and the.ir ratio $|\Delta E_g|/E_w$. "1 his ratio is on the order of 10^3, except for Event VI which is considerably smaller. '1-his can be understood qualitatively in light of the following: (i) The gravitational acceleration is about 300 times the centrifugal acceleration near the Earth's surface. Since the dominant contribution to the energy integrals (equation 1) comes from near surface where the largest displacement occurs, we expect (as first pointed out by Dahlen 1 977) in general ΔE_g to be typically 300 time.s larger in magnitude than the corresponding change. in the Earth's spin energy, ΔE_s Event VII is somewhat anomalous by being smaller in this ratio presumably becuase of its deep focus and its particular source machanism. (ii) ΔE_s, in turn, is computed in the companion paper Chao & Gross (1994) (ΔE_s is directly proportional to - ΔLOD, see Figure 1 c). It is found to be typically about 3 times the magnitude of E_w, except for events that are predominantly strike-slip, such as Event VI, which has a relatively smaller effect on the spin and gravitational change. The time rate of increase of $\Delta E_s(t)$ is about + 0,0067 '1-W during 1977- 1993 (Chao & Gross 1994), indeed 300 times smaller in magnitude than the ΔE_g rate.

'1-bus, our observation so far is that net energy is being extracted by earthquakes from the gravitational field at a rate which is several hundred times larger than the seismic wave energy release, while at the same time being pumped into the Earth's spin by earthquakes at a rate comparable to the seismic energy release.

Let us then focus on the dominant gravitational energy loss. Assuming an Earth model under mechanical equilibrium prior to the earthquake, Dahlen (1 977) showed that the sum of earthquake-induced changes in the gravitational and spin energy is co~lntcr-balanced by changes in the elastic energy associated with the prestress integrated over the entire Earth, except on the fault surface where the excess elastic energy can be identified with the seismic wave energy. The latter energy involved being relatively small (as described above), the primary energy effect of earthquakes would have to be a net energy transfer from the gravitational field to the elastic field. This would mean an overall build-up of elastic energy in the Earth, contrary to the general notion that seismicity acts to relieve the Earth's elastic energy.

To resolve the dilemma, we examine Dahlen's (1977) energy balance which is based on a pre-seismic initial condition of' a (ze]-olh-order) mechanical equilibrium of the prestress with the body force (gravitational force plus rotational centrifugal force) The (first-order) work done by the displacement field against the action of the body force then balances with that against the prestress, except at the. fault surface. The precise energy balance happens after an indefinite period of time over which the Earth relaxes (anelastically) to the. same equilibrium condition. The reality, however, must deviate to first-order from the idealized equilibrium initial condition, otherwise earthquakes would not occur spontaneously in the first place. Moreover, this initial condition is, strictly speaking, violated because an earthquake would create for the next earthquake an elastic stress field in the Earth that destroys that initial condition it itself enjoyed. I'bus, for a given earthquake the net co-seismic change in the gravitational energy does not necessarily lead to a compensating change in the elastic energy in the Earth. Exactly how much gravitational energy is converted to elastic energy depends on the nature of the initial condition for the earthquake. Ultimately, however, the long-term destination of the net gravitational energy 10sS is of greater interest.

First we shall make two observations: (i) The statistical trend we have found in the earthquake-induced changes in the Earth's spin and the gravitational field and the associated gravitational energy is a long-term geophysical process. 'l-his is because the sign of these changes is dictated by the earthquake source mechanism, and the latter in turn is dictated by the grand scheme of plate tectonics which operates on time scales longer than millions of years. The fact that earthquakes strive to reduce the gravitational energy supports the notion that the ultimate driving force for earthquakes is probably gravity. This is consistent with the assertion of Forsyth & Uyeda (1975) and Backus et al. (198 1) that the gravitational pull on the subducting slabs is the main driving force for tectonic plate motions. (ii)

The Earth obviously does not sustain a net, long-term build-up of elastic stress. As in any (natural) heat engine operating under the second law of thermodynamics, the bulk (if not all) of any increase in the elastic energy (such as that converted from gravitational energy by earthquakes) will eventually be dissipated by internal friction and find its way into heat whether seismically or aseismically. Conceivably, some oft his energy, and indeed some of the earthquake-induced gravitational energy decrease, can turn into other forms of mechnical energy, such as back into gravitational energy in the P1OCCSS of crustal uplifting or mountain building, but this amount appears relatively trivial for the Earth (Verhoogen 1 980).

We conclude thus far that the primary energy effect of earthquakes is an ot'era]] transfer of gravitational energy into terrestrial heat, at a rate of?. O TW during 1977-1993, several hundred times that released by the earthquakes themselves through faulting. How large is Ibis energy, and what role does it play, in terms of global energetics?

The total heat flow of the Earth is about 40 TW. In the. mantle heat engine, this total heat flow provides power to drive all internal geophysical processes, including tectonic plate motions. Stacey (1 977) estimated the power needed 10 drive mantle convection, which is ultimately responsible for plate tectonics, to be on the order of 1 TW. It is interesting to note that ΔE_g rate is more than adequate 10 supply for the plate motions. This seems to suggest a positive-feedback mechanism in the Earth's energetics: Under the action of gravity, the mantle heat engine (40 TW) drives, among others, the plate motion (1 TW). The plate motions, in turn, cause earthquakes. These earthquakes, besides radiating seismic energy (0.0047 TW during 1977- 1993), trigger a release of gravitational energy (- 2.0 TW during 1977-1993). The latter energy adds to the heat engine to help drive various geophysical processes, including the plate motions and earthquakes.

The contribution of ΔE_g to the total global heat flow can bc surprisingly large. During 1977--1993 it only amounts to 5%. This period, however, is believed to be low in seismic activity, judging from past records in this century (e. g., Kanamori 1977). For example, the seismic activity during 1950-*1965 is* probably an order of magnitude higher, implying that a contribution as large as 50% may not be impossible. In particular, a total of 1.3×10^{22} J of gravitational energy was released during 1960-1964 by Events I and II alone (Table 2). 'l'his energy equals 10 years worth of the total global heat flow! This energy release is distributed globally and will not be sensed immediately on the Earth surface because of the long time lag of thermal conduction in the mantle.

A final conclusion then is that earthquakes appear to contribute a significant fraction to the total global heat flow by converging gravitational energy into terrestrial heat. The terrestrial heat is believed to come primarily fi om two sources: (primordial) gravitational energy and internal radioactivity. Both arc potentially sufficient to account for a majority of the observed am ount; but their present share is rather uncertain (e. g., Verhoogen 1980). In the case of gravitational energy source, a substantial role may be played by the separation of the outer core and that Of the inner core (e. g., Verhoogen 19S0). Our study, in contrast, demonstrates that earthquakes, concentrated near the Earth sur face and active at the present time, may be an important mechanism in converting gravitational e nergy int o heat. The latter happens as part of the plate tectonic motion which, in turn, is a manifestation of the mantle heat engine.

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Table 1. Statistics of the predicted earthquake-induced changes in: the zonal J_l (l=2-5) coefficient of the gravitational field; the trace T of the inertia tensor; the length-of-day LOD; the sum Of the two equatorial principal moments of inertia $I_{xx}+I_{yy}$; the normalized (positive) difference J_{22} between the two equatorial principal moments of inertia; longitude ϕ_{22} of the (equatorial) principal axis of least moment of inertia. listed are the normalized χ^2 statistic of the sign of the changes (Δs being the difference between the positive and negative signs), and the normalized Wilcoxon statistic W of the rank sum, for 'All Events' and 'Large Events Only'.

	All Events (11,015)		Large Events Only (945)	
	χ^2 (Δs)	W	χ^2 (Δs)	W
ΔJ_2	62.1 (-s27)	-8.40	12.6 (-109)	-3.63
ΔJ_3	13.5 (385)	5.20	2.14 (45)	0.93
ΔJ_4	0,60 (-s1)	-2.72	0.3s (-19)	-0.ss
ΔJ_5	0.32 (59)	3.31	0.086 (-9)	1,41
ΔT	301 (-1s21)	-21.1	74.3 (-265)	-10.6
ΔLOD	147 (-1273)	-13.9	27.4 (-161)	-6.98
$\Delta(I_{xx}+I_{yy})$	131 (-1?01)	-12. s	32.4 (-175)	-6.90
ΔJ_{22}	131 (-1201)	-10.4	22.2 (-145)	-4.33
$\Delta \phi_{22}$	11.1 (-349)	-0.64	2.33 (-47)	--0.06
ΔE_g	301 (- 1821)	-20, s	74.3 (--265)	--10.4

Table 2. Predicted energy changes for six great earthquakes in recent decades.

Event	I	II	III	IV	V	VI	VII
(M_0, 10^{21} N m)	(270)	(75)	(3.6)	(1,0)	(1.1)	(1.4)	(3,0)
E_w (10^{18} J)	13.5	3.8	0.)s	0.050	0.055	0.070	0.15
ΔE_g (10^{18} J)	8510	-4490	228	-69	-61	-11,6	60
$\lvert\Delta E_g\rvert/E_w$	630	11s0	1270	1380	1105	170	400

Figure Captions

Fig. 1, Cumulative changes, induced by 11,015 major earthquakes during 1977-199.3, in: (a) the zonal J, (/ 2- 5) coefficient of the gravitational field; (b) the trace T of the inertia tensor; (c) the length-of-day LOD; (d) the sum of the two equatorial principal moments of inertia $I_{xx}+I_{yy}$; (e) the normalized (positive) difference J_{22} between the two equatorial principal moments of inertia. The Earth's spin energy change is proportional to ΔLOD as indicated in (c). ,

Fig. 2. Cumulative gravitational energy change in the Earth induced by 11,015 major earthquakes that occurred during 1977-1993.

Fig. 3. Cumulative seismic wave energy of 11,015 major earthquakes that occurred during 1977-1993.

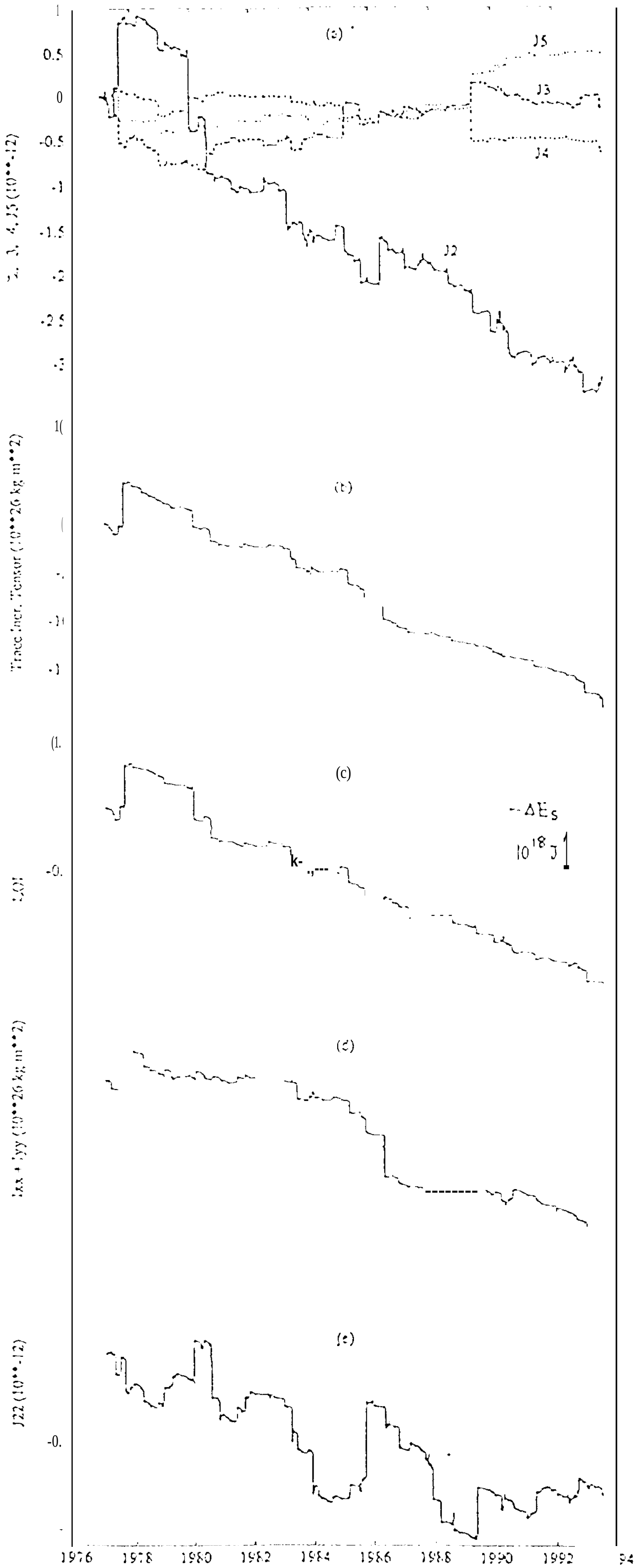
(a)
J5
J3
J4
J2
(b)
(c)
-ΔEs
10^18 J
(d)
(e)
Trace Iner. Tensor (10**26 kg m**2)
Ixx + Iyy (10**26 kg m**2)
J22 (10**-12)
1976
1978
1980
1982
1984
1986
1988
1990
1992
94

Fig 1

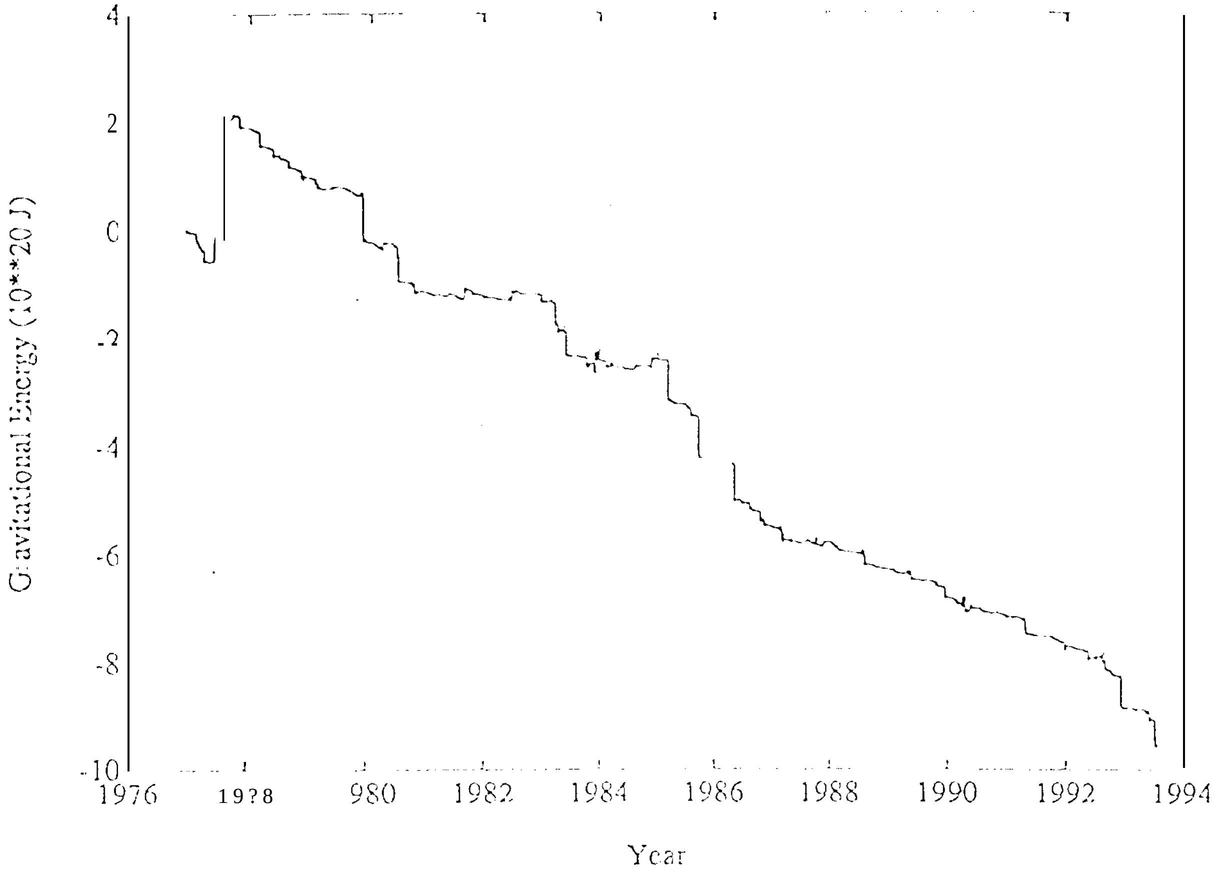
Gravitational Energy (10**20 J)
Year
4
2
0
-2
-4
-6
-8
-10
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994

Fig 2

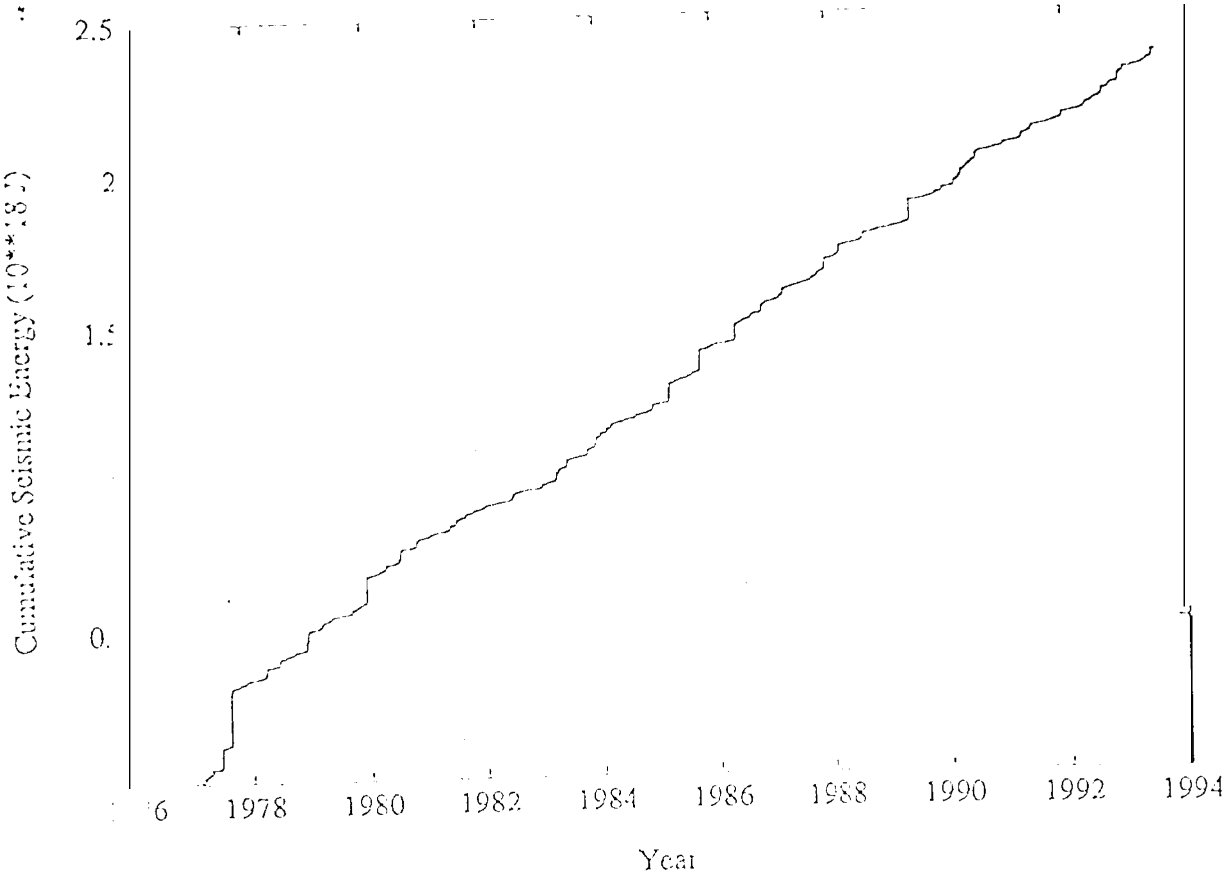
2.5
2
1.5
0.
Cumulative Seismic Energy (10**18 ?)
1978
1980
1982
1984
1986
1988
1990
1992
1994
Year

Fig 3