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The correlation between geomagnetic field reversals, Hawaiian volcanism, and the motion of the Pacific plate

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Abstract
The correlation between geomagnetic field reversals and volcanism is investigated, according to the speculated consequence on volcanoes of the transient electric currents in the geodynamo, through Joule's heating, before and after every reversal event. We evaluate the temporal variation during the last ~70 Ma both of the magma emplacement rate $Q(t)$ from the Hawaii hot spot, and of the speed $v(t)$ of the Pacific plate, by means of the observed volumes of islands and seamounts along the Hawaii/Emperor Seamounts chain, and their respective radiometric datings. Results confirm expectations. A justification of the volcanic crises that lead to the generation of the large igneous provinces during the last ~250 Ma also emerged. We describe in detail the complex pattern of the timings of the different effects. Joule's power is generally responsible for ~75-80% of magmatism, and friction power only for ~20-25%; but, on some occasions almost ~100% is fuelled by friction alone. The visco-elastic coupling between lithosphere and asthenosphere results ~96% viscous, and ~4% elastic.

Key words *geomagnetic reversals – volcanism – Hawaii's hot spot – Pacific plate*

1. Introduction

The main rationale of the present analysis is explained in Gregori (1993, 1994), a consequence of which is that on the occasion of a geomagnetic field reversal (FR) some transient electric currents of the geodynamo ought to affect global volcanism because of Joule's heating. The purpose of the present investigation was an attempt to search for the correlations between the magma release from the Hawaii hot spot, the speed of the Pacific lithospheric plate, and the occurrence of FR's during the time interval spanned by the chain of the Hawaii/Emperor Seamounts, *i.e.* during the last ~70 Ma.

An inference discussed by Gregori (1993), and that is relevant for the following, is that a major fraction of the electric currents of the dynamo flow on the core-mantle boundary (CMB) and are directly short-circuited up to the magma chamber of a hot spot volcano such as Hawaii's. Such a short-circuiting occurs along a «pipeline» composed of matter, that has a greater electrical conductivity than its surrounding medium. Such an inference is the consequence of Hamilton's variational principle, by which the electric currents push out-

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ward, much like an «electric soldering iron pushing against a block of ice».

The present paper is a concise presentation of the highlights of a much longer analysis, a full account of which is given elsewhere (Gregori and Dong, 1995a, 1995b; Gregori *et al.*, 1995a, 1995b).

2. The interpolation

The chain of the Hawaii/Emperor Seamounts is composed of 108 volcanoes (fig. 1). Bargar and Jackson (1974) and Clague and Dalrymple (1987) report on the observed volumes of its youngest 107 volcanoes, as well as the radioisotopic datings of 36 of them. On the basis of such 107+36 figures, plus their respective latitudes and longitudes, it is possible to evaluate the variation *vs.* time both of the magma yield $Q(t)$ of the Hawaii hot spot, and of the velocity $v(t)$ of the Pacific plate. Such a computation required some specifically designed algorithms.

We had to reject 6 radiometric datings (otherwise $v(t)$ had to reverse direction), depending on the fact that presumably the dragged basalt-samples were not the oldest ones available at their respective sites. The final result is shown in fig. 2. Each such curve was chosen among 10, and 30, different interpolating lines, respectively, the criteria for each choice being based both on mathematical and physical arguments. We could also infer a realistic guess about their respective error bars.

A periodicity of ~28. Ma was clearly evidenced. Either $Q(t)$ or $v(t)$ experienced during the last ~70 Ma three distinct peaks, almost

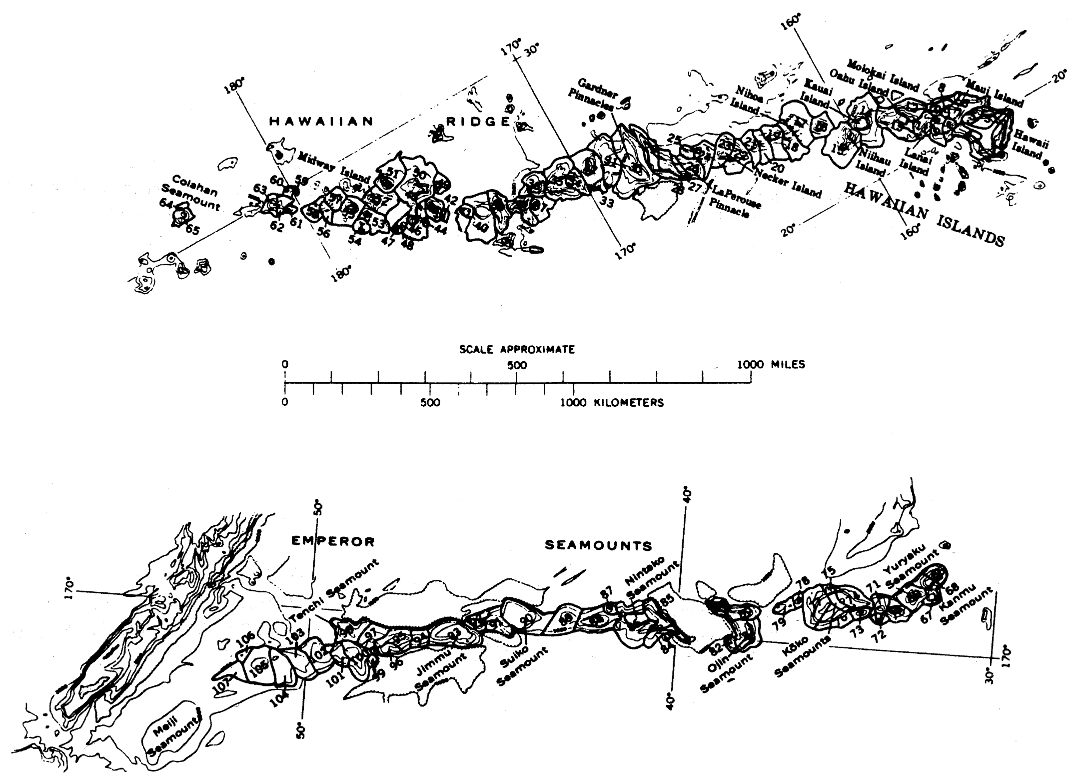

Fig. 1. Identification codes of the islands and seamounts along the Hawaiian chain according to Bargar and Jackson (1974) (figure adapted from them). Figure and caption after Gregori *et al.* (1995a).

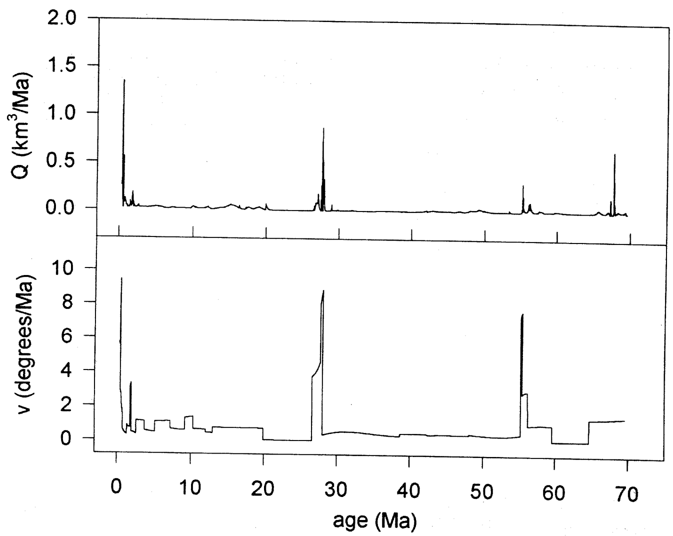

Fig. 2. Plot of $Q(t)$ and of $v(t)$ *vs.* t. Figure and caption after Gregori and Dong (1995a).

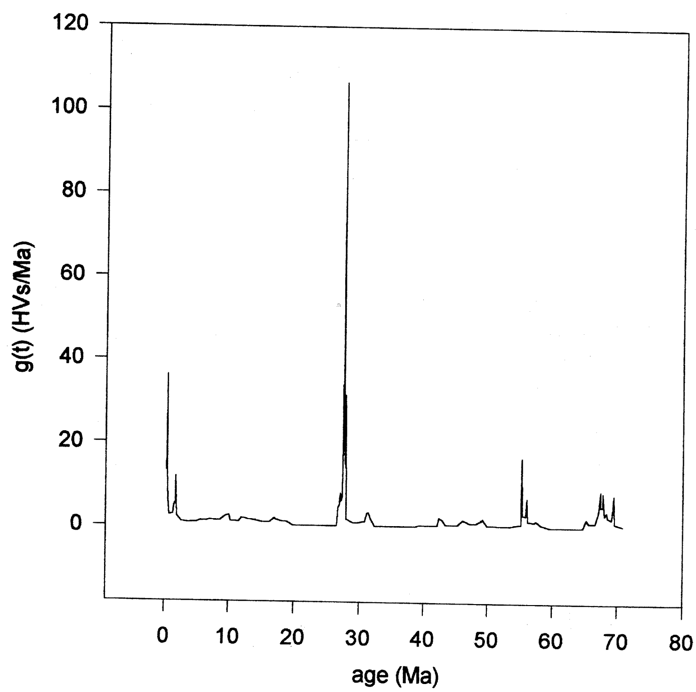

Fig. 3. Average number $g(t)$ of volcanoes per million years along the Hawaiian chain. The same «electrocardiogram» feature as fig. 2 is found, envisaging that a large magma emplacement rate $Q(t)$ from the hot spot is manifested as a larger number of volcanoes, rather than as a constant number of volcanoes of larger size. Figure after Gregori and Dong (1995a).

like «beeps» within an «electrocardiogram»: one is going on at present, one occurred ~28 Ma ago, and another one ~56 Ma ago. But the hot spot generated 108 volcanoes, rather than a strip of magma superimposed over the drifting lithospheric plate: hence, the output from the hot spot was pulsed. The average volume of every volcano, however, remained roughly constant in time, and an eventually greater $Q(t)$ implied the generation of a larger number $g(t)$ of volcanoes per unit time, rather than volcanoes of larger size. Thus, $g(t)$ also shows (fig. 3) the same «electrocardiogram» feature as $Q(t)$ and $v(t)$.

The «electrocardiogram» feature (one «beep» every ~28 Ma) appears consistent with the available datings of the large igneous provinces (LIP), *i.e.* the large magma floods that eventually outpoured over some wide area, somewhere over the globe. Although it is difficult to infer a high time-resolution for their occurrence time, it can be shown that they appear consistent with the hypothesis that they followed an approximate «beep» sequence, with a ~28 Ma pace, at least during the last ~250 Ma.

Our analysis verified that the volume of every volcano apparently suffered from a thermal contraction *vs.* t, possibly according to a law proportional to $\sqrt{t}$, but the evidence appears perturbed. In fact, we give evidence of clear oscillations that can be interpreted as a variation *vs.* t («rejuvenation») of the prime heat supply from the hot spot, better than as a «rejuvenation» of the lithosphere. In any case, the error bars appear critical, and a better assessment is likely to be attained only when it is possible to compare with each other the results of the same analysis applied also to the trails of hot spots other than Hawaii's.

3. Four powers

We consider four different kinds of power (fig. 4). One is the *endogenous* (or *Joule*) power that is assumed proportional to the Joule heating released by the dynamo currents on the occasion of FR's: hence, it is proportional to fB^2, where $f(t)$ is the number of FR's per unit time, and $B(t)$ is the intensity of the palaeomagnetic field. A second one is the *kinetic* power, either given to, or taken from, the lithospheric motion: it is proportional to $\Delta v^2(t)$, *i.e.* to the increment of $v^2(t)$ computed during a given time interval of 1 Ma. A third one is the *friction* power, originated by the motion of the plate over the asthenosphere: hence, it is proportional to $v(t)$, times a displacement Δs along the trail of the hot spot, divided by a time increment Δt, *i.e.* it is proportional to $v^2(t)$. The fourth one is the *thermal* or *volcanic* power and it is assumed proportional to $Q(t)$.

Such 4 powers can be identified with 4 coordinate axes of a 4D space, some kind of a «phase space» that we call the «4-power-space». The evolution of the system can be thus investigated in terms of a track within such a space, by which every «beep» of the aforementioned «electrocardiogram» appears in such a «4-power-space» like a «butterfly wing».

Perhaps, the most interesting feature is that a «kick» of fB^2, that occurred ~12 Ma in advance, produces an increase in the kinetic power that always precedes an increase in the friction power. Other analogous evidence (although somewhat less clear) are related to an increase in the kinetic power preceding an increase in volcanism, and to an increase in friction preceding an increase in volcanism.

4. Time-delayed correlations

The next step in our analysis is the discussion of time-delayed correlations between such 4 powers. We apply 3 different approaches.

The first one (case A) is a simple *bi-variate correlation* analysis between any pair of such powers, suitably time-delayed with respect to each other. The effect on $Q(t)$ appears to occur ~12.3 Ma after the occurrence of an FR. But, the evidence appears much disturbed, clearly envisaging that phenomena are intrinsically much more complex than can be allowed for by such a simple bi-variate approach.

Therefore, we tried the second approach and we searched for the *energy balance* between such 4 powers. We applied it in two ways. In the first attempt (case B1) we allowed only for one time delay between the endogenous power

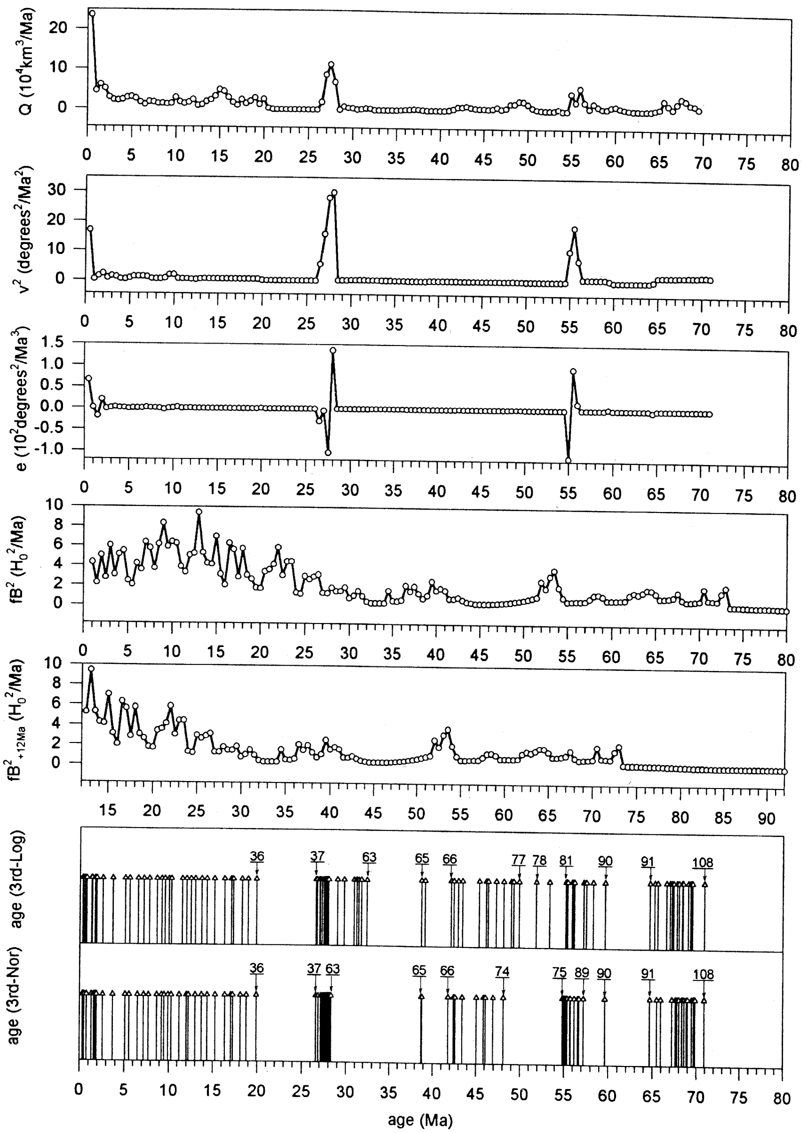

Fig. 4. Top to bottom, plot of the four forms of power considered in this study: thermal, friction, kinetic, and endogenous (or Joule's), respectively. Every such power was smoothed by means of a running average over a window of 0.5 Ma width. Compare the scale-sizes in the $Q(t)$ plot in fig. 2, and check by this the effect of smoothing over 0.5 Ma. The fifth plot shows the same endogenous power as above, but after applying a time-delay of 12 Ma (see text). The two bottom plots show the timing of the birth-dates of every volcano along the Hawaiian chain, where the underlined numbering denotes the codes of the different volcanoes, according to their definition of fig. 1. The difference between such two time series depends on the method of interpolation, used while estimating the ages of the non-dated volcanoes. The 3rd-log interpolation is likely to be better, while the other case (3rd-nor) helps in recognizing the amount of indeterminacy of the age of every volcano: such an error bar varies in time, depending on the density of the available measured volcanoes along the strike of the chain. Figure after Gregori and Dong (1995a).

and the release of all other powers, that are *a priori* assumed to occur simultaneously with each other. In the second attempt (case B2) we allowed all 4 powers to have any arbitrary mutual time delay.

In the case B1 we found that an FR precedes all other powers by ~12.4 Ma, and the balance of the percent contributions of the 4 powers can be conveniently represented as follows

$$p_Q(t) + p_e(t) \equiv p_{fB^2}(t) + p_{v^2}(t) \qquad (4.1)$$

where every p stands for a percent value, and every subscript is self-explanatory, except e that denotes the kinetic power. The position, on either side of (4.1), of every given term derives from the sign resulting from the formal mathematical evaluation of its respective coefficient, within the linear interpolation expressing the energy balance([1]). Figure 5 shows the result.

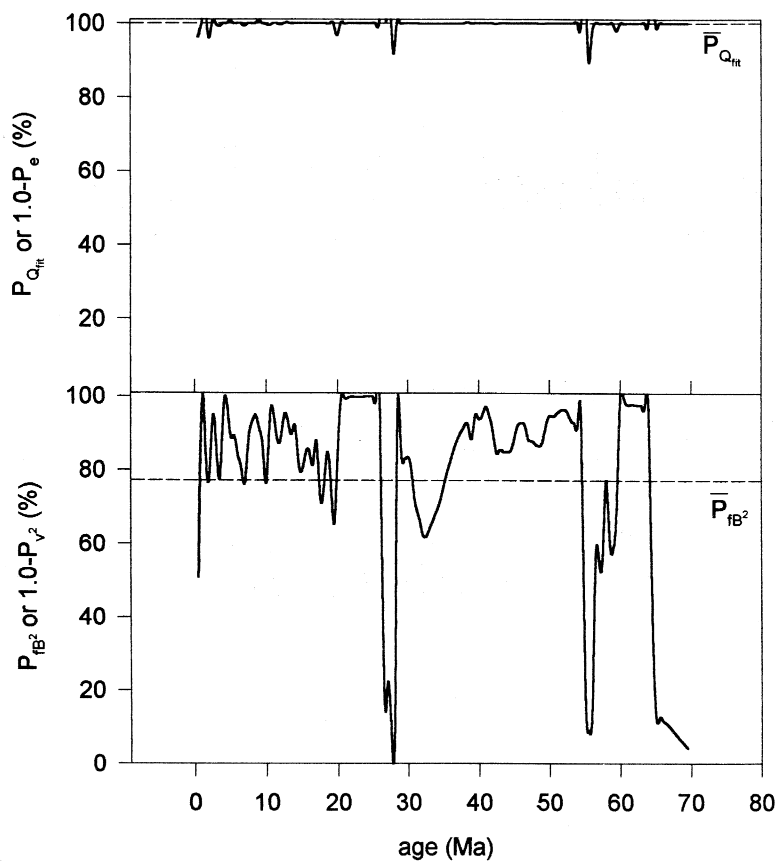

Fig. 5. Plot *vs.* t of the percentages $p_Q(t)$, $p_e(t)$, $p_{fB^2}(t)$, and $p_{v^2}(t)$ defined by (4.1). The top horizontal line of both diagrams was drawn at 1.01 (instead than at 1.00) in order to avoid confusion with the plotted line. Two horizontal lines indicate the averages $\overline{p}_Q$ and $\overline{p}_{fB^2}$. In general, the kinetic power is definitely negligible compared to volcanism (upper plot). Vulcanism is supplied ~20-25% by the friction power and ~75-80% by Joule's heating (lower plot). Such a conclusion changes on the occasion of the «beeps» of the «electrocardiogram», as the kinetic power can be even as much as ~10%, while volcanism is only ~90%, and almost ~100% of the power is fuelled by friction alone. Figure and caption after Gregori and Dong (1995b).

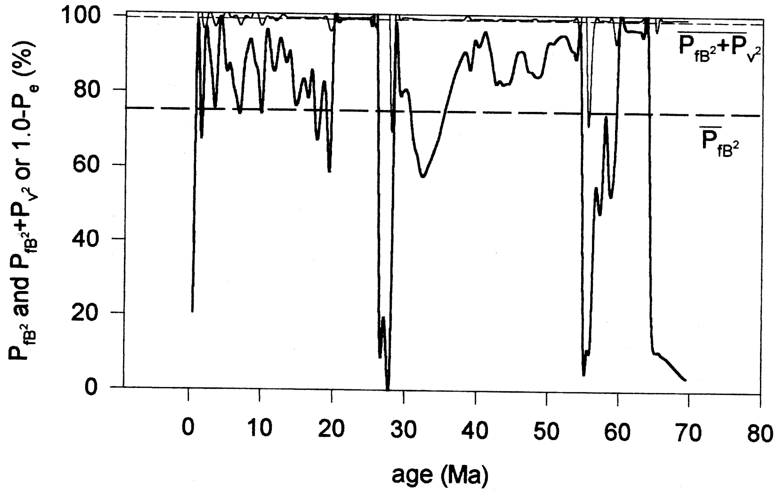

Fig. 6. Plot *vs.* t of the percentages $p_{fB^2}(t)$, $p_{v^2}(t)$, and $p_e(t)$ defined by (4.2). The average values are also indicated $\bar{p}_{fB^2}$ and $[\bar{p}_{fB^2}+\bar{p}_{v^2}]$. Figure and caption after Gregori and Dong (1995b).

Also in the case of B2 we find that an FR precedes all other powers by ~12.4 Ma, while either the kinetic or the friction power precedes volcanism by ~0.1 Ma. The result can be conveniently expressed as

$$1 = p_{fB^2}(t) + p_{v^2}(t) + p_e(t) \qquad (4.2)$$

that is plotted in fig. 6, the computation of which formally results more robust than in the case of fig. 5.

We consider a third case B3 (fig. 7a), by which we also allow for a possible visco-elastic coupling between lithosphere and asthenosphere (see Gregori and Dong, 1995b for details). We find the same relative time delays as in case B2, while the final result can be conveniently expressed as

$$p_Q(t) + p'_e(t) = p_{fB^2}(t) + [p_{v^2}(t) + p_e(t)] \qquad (4.3)$$

where $p'_e(t)$ is concerned with the elastic contribution to the coupling between lithosphere and asthenosphere. We note that, in either fig. 5 or 6 or 7a, $e(t)$ is sometimes negative.

Figures 5, 6 and 7a,b show that the $e(t)$ and $e'(t)$ terms, *i.e.* the kinetic power and the role of the elastic component, respectively, are generally negligible, except during every «beep». The prime energy source is generally ~75-80% by Joule's heating, and ~20-25% by friction. During every «beep», however, the prime source is almost ~100% originated by friction, while concerning the elastic component of the coupling, it apparently increases up to ~30%, while $Q(t)$ absorbs through viscous coupling and friction heat the remaining ~70%. Such a conclusion, however, is hampered by the fact that we find, contrary to expectations, a negative interpolating coefficient for the kinetic energy term. Hence, the errors are likely to be relevant, at least for attempting at assessing the actual role of the elastic *vs.* the viscous component of the coupling. In any case, it is interesting to consider the ratio $|p_{v^2}(t)|/[|p_{v^2}(t)| + |p'_e(t)|]$ *vs.* t. This is plotted in fig. 7b, that shows that the viscous component accounts for ~96% of the coupling, while the elastic component only for ~4%. Hence, we guess that the error bars are likely to be ≥4%. In any case, although such a datum can be eventually severely biased by the errors, it is interesting to reconsider it in the third approach (see below).

The conclusion is that the analysis of case histories of hot spot trails other than Hawaii's

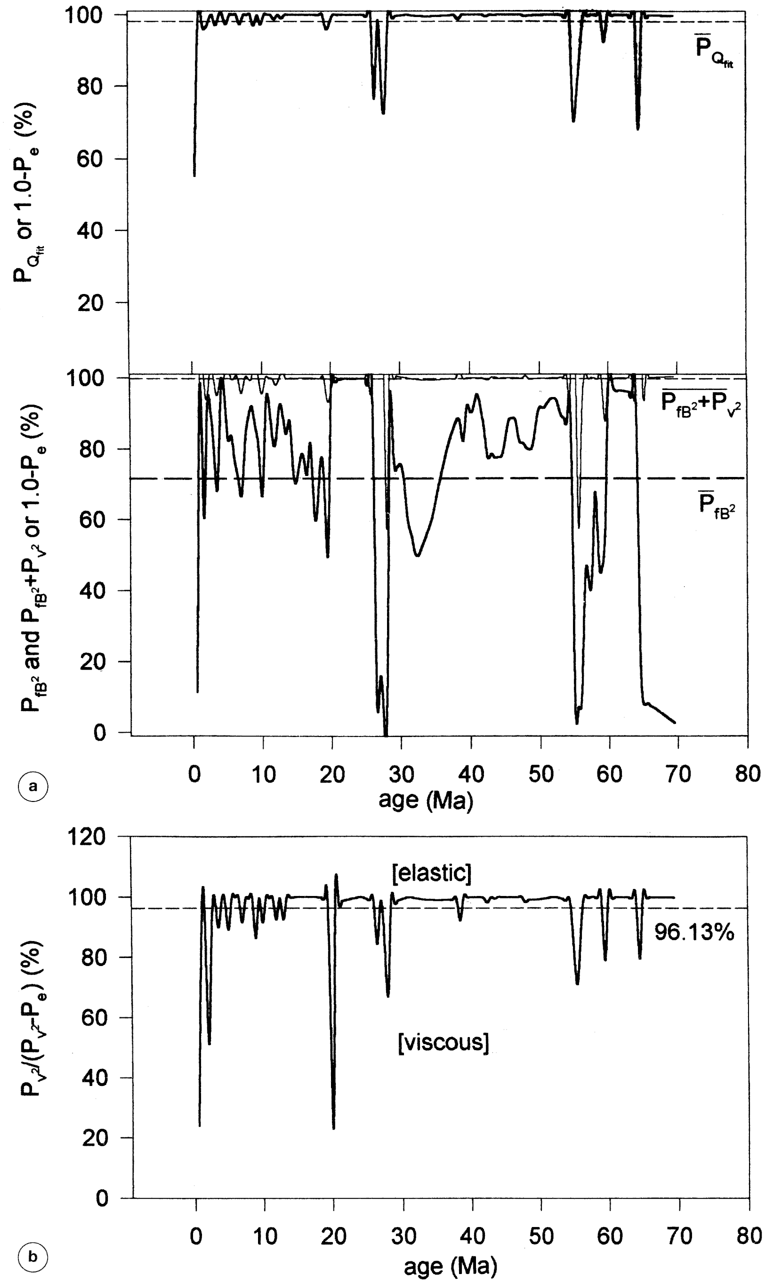

Fig. 7a,b. a) Plot *vs.* t of the percentages $p_Q(t)$, $p'_e(t)$, $p_{fB^2}(t)$, $p_{v^2}(t)$, and $p_e(t)$ defined by (4.3). The average values are also indicated $\overline{p}_Q$, $\overline{p}_{fB^2}$, and $[\overline{p}_{fB^2}+\overline{p}_{v^2}]$. Figure and caption after Gregori and Dong (1995b); b) plot *vs.* t of $|p_{v^2}(t)|/[|p_{v^2}(t)|+|p'_e(t)|]$ for inspecting the relative contribution of the viscous *vs.* the elastic component in the coupling between lithosphere and asthenosphere. The prevailing role, as expected, is viscous, and it amounts to ~96%. Figure and caption after Gregori and Dong (1995b).

are needed prior to giving any better assessment. In any case, the similarity of the p_{fB^2} and p_{v^2} diagrams in figs. 5, 6 and 7a,b appears remarkable, while the p_e and $p_{e'}$ terms play a minor role. The fact that during «beep» time almost 100% of the prime heat supply is originated by friction, implies that the ~28 Ma modulation of the «electrocardiogram» is not caused by the FR's, but rather by the mechanism of heat propagation through the Earth (see below). This inference is also supported by the afore-mentioned fact that the ~28 Ma periodicity apparently holds backward in time, at least until ~250 Ma BP.

The third approach (case C) relies on a four-variate correlation analysis by means of *Gram's determinant.* Let us first separate the contribution to $Q(t)$ into three components, all of them positive,

$$Q(t) = Q_0(t) + Q_1(t) + Q_2(t) \tag{4.4}$$

where $Q_0(t)$ is the contribution that is erupted «almost simultaneously» with a given FR, and that ought to be the consequence of the «pipeline» that already exists at the time of occurrence of the FR being considered, $Q_1(t)$ is the bulk of the thermal release through volcanism and it reflects the largest part of the power $fB^2(t+T_{fB^2})$, generated some time lag T_{fB^2} in advance, and $Q_2(t)$ is the contribution to volcanism deriving from the friction power, that is proportional to $v^2(t+T_{v^2})$, which is the friction power originated some time lag T_{v^2} in advance. That is, $Q_0(t)$ is a consequence of the FR occurring almost at the same epoch t of $Q(t)$, while both $Q_1(t)$ and $Q_2(t)$ reflect FR's which occurred some suitable time in advance. Let us also assume that

$$Q_0(t) \ll Q_1(t) + Q_2(t). \tag{4.5}$$

Let us consider how a former input by the endogenous power is separated into different releases, with eventually different time delays, *i.e.* let us consider a percent balance as follows

$$1 \approx p_0(t) + p_1(t) + p_2(t) + p_3(t) \tag{4.6}$$

where $p_3(t)$ is the release of kinetic power. That is, the total power originated by the FR at time t is manifested as a sum of effects (suitably time delayed) of the kind either $Q_0(t)$ or $Q_1(t)$ or $Q_2(t)$ or kinetic. The formal expression (4.6) derives after some algebra (see details in Gregori and Dong, 1995b). Our actual computation was based on neglecting $p_0(t)$, and searching for a 4-variate time-delayed linear regression analysis in terms of Gram's determinant (Courant and Hilbert, 1953; sometimes called «moment determinant», or «correlation matrix», etc.). The 4 variates are the former endogenous power, plus 3 suitable linear combinations of the terms as above with subscripts 1, 2, and 3, respectively.

The synthesis of the resulting final evidence is as follows:

i) there is very clear indication for no preferred value for the time-delay between an FR and its effect on $Q(t)$:

ii) there is evidence of an effect associated with the ~28 Ma periodic structure of $Q(t)$ and $v(t)$ («electrocardiogram» trend);

iii) there is clear evidence of a periodic modulation of the system associated with a ~0.410 Ma period, that is one main periodical component of the variation of the eccentricity of Earth's orbit;

iv) the time delays between the FR and its effects on either one of the other powers has, as a first order approximation, some common value, that can range anywhere in between ~0. and ~28 Ma, consistently with the hypothesis that it ought to depend on the state of the «pipeline» that already exists and that feeds the hot spot at the time of occurrence of the FR;

v) as far as one is concerned with the minor relative differences between the time delays referring to either one of the different powers, with respect to the former FR input, the situation appears much complex and it is synthesized by the sketch of fig. 8. Namely, there appears to occur first an effect on the kinetic power, followed after ~0.1 Ma by an effect both on volcanism and on the friction power; then, after an additional time lag of ~0.1 Ma volcanism causes one further effect on the kinetic power.

Therefore, one should envisage an algorithm that allows for every FR to have *its own*

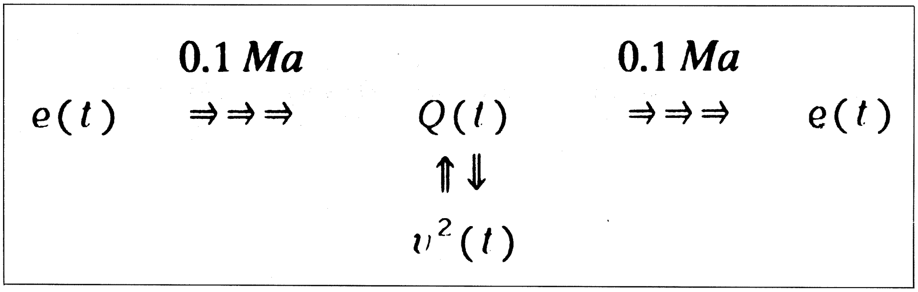

Fig. 8. Sketch of the proposed apparent relations between the kinetic power $e(t)$, the friction power $v^2(t)$, and volcanism $Q(t)$. It is proposed that the effect is first seen on the kinetic energy. Then, after ~0.1 Ma, the effect should be seen on volcanism and on the friction power. Then, volcanism apparently causes, ~0.1 Ma later, a new effect on the kinetic power. Figure and caption after Gregori and Dong (1995b).

specific set of time delays, concerning its manifestation in terms of different forms of power. Such an intrinsic bias applies to all afore-mentioned analyses. Hence, we decided to approach the problem according to some substantially different rationale, as explained in the next section.

In any case, every «beep» of the «electrocardiogram», or every burst of volcanism, is almost entirely originated by a burst of friction power, released by the burst of the speed of the plate which occurred some ~0.1 Ma in advance. Hence, this effect appears to be mainly a plate-kinematic phenomenon, rather than being externally driven.

5. Resonance and forced oscillation

Therefore, the key for interpretation is likely to rely on the almost periodical time variations of either $Q(t)$ or $v(t)$. We approached the problem in terms of three different targets, briefly summarized as follows (an exhaustive discussion is given in Gregori *et al.*, 1995b).

We investigated first the quantitative inferences about $Q_0(t)$. Then, as a second target, we inspected the character of the oscillations of either one of the 4 powers, in order to infer their presumable origin. Finally, as a third target, *we allowed for a different time delay*, between every given FR and its corresponding different forms of output observed on the Earth surface, and we repeated, correspondingly, the afore-mentioned analyses as for cases B1, B2, and B3.

We focussed on the first target by multiplying $Q(t)$ by the value $p_{fB^2}(t)$ that was evaluated in case B2, in order to skip all contributions to $Q(t)$ that derive from energy sources other than mere Joule's heating. Then, we applied the superimposed epoch criterion, by considering every FR as a time origin. After a suitable analysis of the statistical error bars, we found that the effects on volcanism, occurring within a few million years with respect to every FR, showed an increase in volcanism of ~1.10^3 km^3 Ma^{-1} that is observed ~0.9 Ma prior to every FR, and another increase of ~1.10^3 km^3 Ma^{-1} that is observed ~1.65 Ma after it. There appeared to be no significant difference when considering separately either the cases of normal to reversed field, or vice versa. In this specific respect, we note that the record of one FR, by means of palaeomagnetic methods, is concerned with a much shorter time interval during which the change of direction of the geomagnetic field was directly monitored. But, such a short time interval is the «apex» of an event lasting a much longer time, by which electric currents first have to decay (hence they release some extra amount of Joule's heating), while, later on, some new transient effects produce new electric currents of the opposite-polarity field. Such transient electric currents take some time before stabilizing, and during such a transient stage they release some extra Joule's heating. That is, the entire phenomenon is much longer than the simple duration of the «apex» that is directly recorded by the standard palaeomagnetic data alone.

The second target clearly shows that phenomena can be interpreted as the result of the interference between two effects: the first is an intrinsic «resonance» of deep Earth processes having a typical periodicity of ~27.4 Ma, and that displays the shape of the sharp «electrocardiogram» trend, either in the speed of the plate, or in the friction power; the second one is an external forcing with an indicative approximate periodicity of ~14 Ma (a trend, however, that appears less regular than the ~27.4 Ma «internal» period). Such an external forcing is presumably to be associated with the encounters with interstellar clouds by the solar system during its motion around the centre of the galaxy (Gregori, 1994).

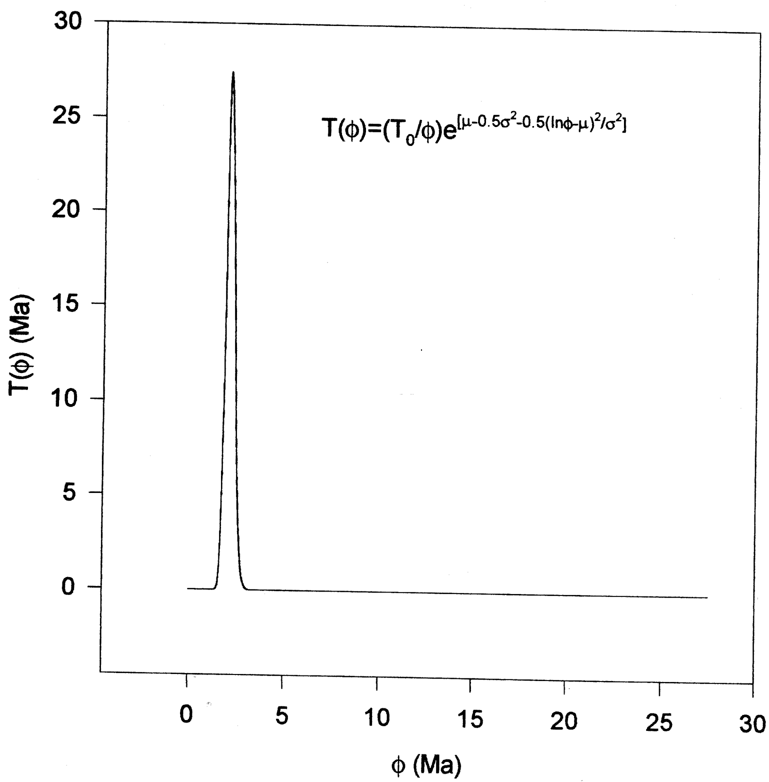

Fig. 9. Time-delay $T(\phi)$ for the effect observed at Earth's surface corresponding to an FR occurred at a time ϕ (Ma) reckoned with respect to the last preceding «beep». The computed model supposes that $T(\phi)$ is expressed by a log-normal distribution of parameters μ and σ. The present plot is a superposition of 3 different curves, every one evaluated by means of either one of the 3 pairs of values μ and σ computed by cases B1M, B2M, and B3M, respectively. All 3 plots almost coincide with each other. The result appears sharply peaked, envisaging a $T(\phi)$ that vanishes practically everywhere, except during a short period of time for which it is $T(\phi) \sim 27.5$ Ma (but, the average T during the last ~70 Ma concerned with 185 FR's is ~12.4 Ma). Hence, the «pipeline» closes and «re-opens» during a comparatively short time interval. Figure after Gregori *et al.* (1995b).

The third target clearly shows that the bulk of the energy output, associated with the anomalous Joule heating originated by the FR's within the dynamo, is released after some suitable time-delay, ranging between ~0 Ma and ~27.4 Ma after every given FR. The mechanism is interpreted in terms of a log-normal distribution, being a function of the time-span elapsed since the occurrence of the last «beep». This is what has to be expected, on the basis of the logical motivation derived from Kapteyn's class distributions, similarly to the case of the frequency distribution related to every public service (such as a telephone switchboard, a water supply, an electric energy supply, public transportation, etc.) or to the hypsometric curve of a planet, etc. That is, this entire phenomenon looks much like in the case that every «pipeline», that transports energy from the CMB up to the Earth surface, is periodically closed and re-opened, and the actual time required by the bulk energy following every given FR to reach the Earth surface is a function of the actual extension of the «pipeline» at the time of occurrence of the FR itself. The final result is that Joule's heating normally takes a comparatively negligible time-lag to arrive up to the Earth surface. Only when the FR oc-

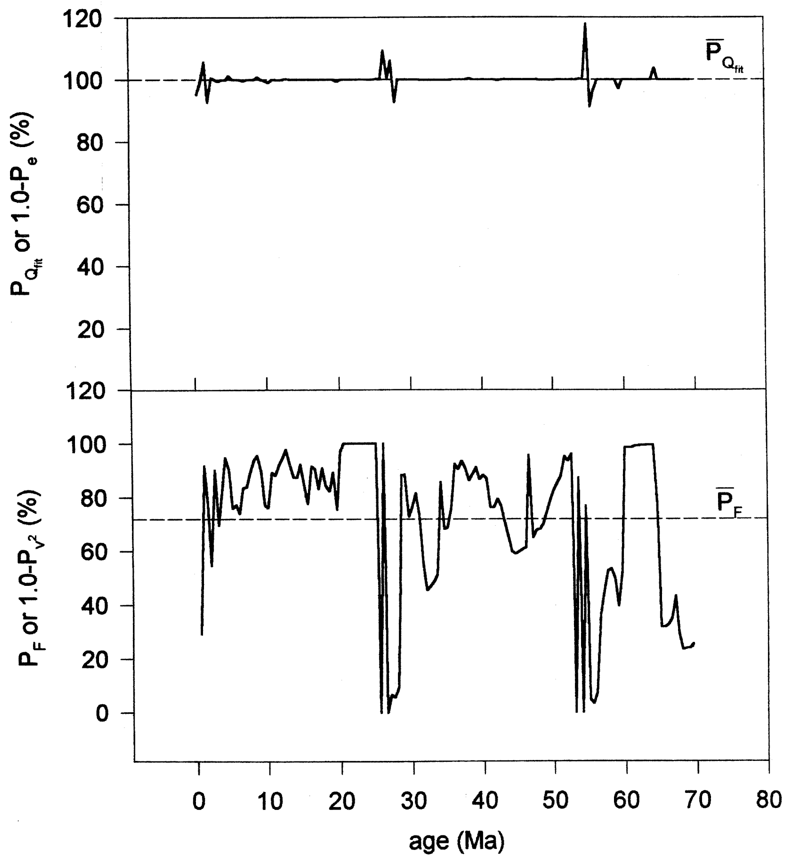

Fig. 10. Related to (5.2), showing the relative role, as percent values, of the different powers. The variations of volcanism, and of the kinetic and friction power are assumed to occur at the same time instant. Notice that sometimes $p_e(t) < 0$. Figure after Gregori *et al.* (1995b).

curs during a comparatively shorter time-range within the time interval in between any two subsequent «beeps», does Joule's heating take almost ~27.4 Ma to arrive from the deep energy source up to the Earth surface. The law that gives such a time-delay is shown by fig. 9, where the parameters μ and σ have to be suitably evaluated by least square fitting. We emphasize that fig. 9 actually deals with three different plots superimposed over each other, according to the three different computations of cases B1M, B2M, and B3M defined below, and such three different curves practically coincide with each other. The resulting average time-delay, for all 185 FR's recorded during the last ~70 Ma, is ~12.4 Ma (consistently with the afore-mentioned preliminary evidence).

A few details are as follows. We assume that the time delay $T(\phi)$ between an FR and its arrival at the Earth surface is a function of the «phase» ϕ of the FR, defined as the time elapsed since the last «beep» of the «electrocardiogram». Owing to the afore-mentioned argument related to Kapteyn's class distributions, we assume that

$$T(\phi) = \frac{T_0}{\phi} \exp\left[\mu - \frac{\sigma^2}{2} - \frac{1}{2\sigma^2}(\ln \phi - \mu)^2\right] \quad (5.1)$$

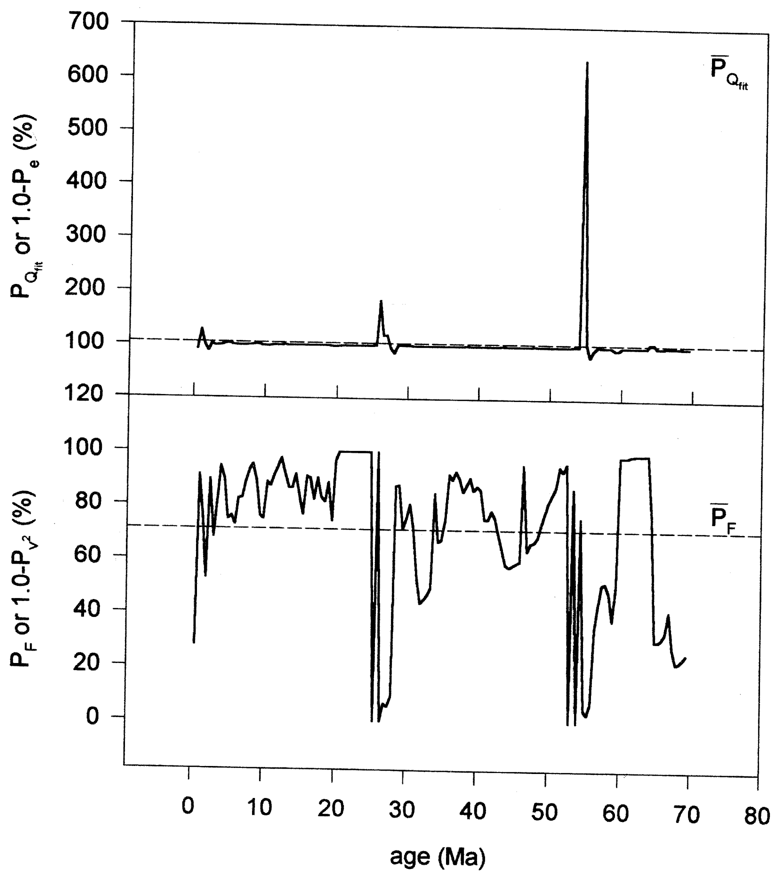

Fig. 11. Related to (5.3), showing the relative role, as percent values, of the different powers. The variations of volcanism, of the kinetic power, and of the friction power can occur at different times. Note that sometimes $p_e(t) < 0$, and its magnitude can even be very large. Figure after Gregori *et al.* (1995b).

Then, we search for its fitting in terms of the same afore-mentioned analyses carried out for cases B1, B2, and B3, respectively. Within such a fitting, we substitute, however, the power input that is associated with the prime Joule heating, with a new function $F(t)$ that formally takes into account some time-varying effects, associated with the energy propagation from the CMB up to the Earth surface. Differently stated, all forms of powers, except Joule's heating, are concerned with observational data directly monitored at the Earth surface, hence there is no need to assume any time-delay between the actual recorded quantities and the present time-instant of concern. Instead, the prime supply of endogenous energy is concerned with an effect that occurred on the CMB at the time of some given FR, and that takes some time-delay $T(\phi)$ prior to arriving at the Earth surface.

In three such cases, let us call them B1M, B2M, and B3M, respectively, we obtain the

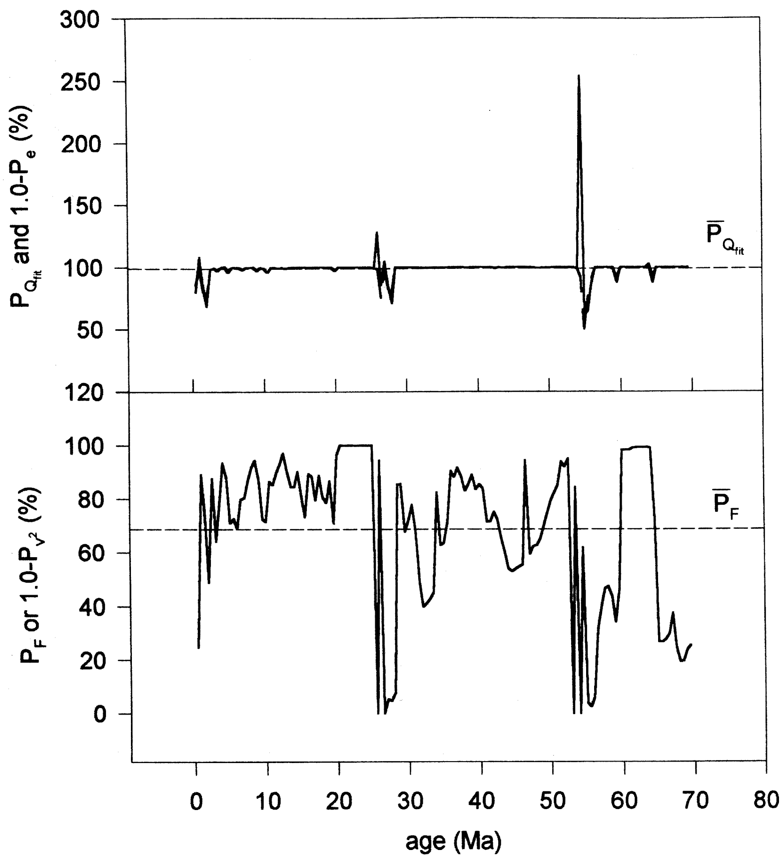

Fig. 12. Related to (5.4), showing the relative role, as percent values, of the different powers. The variations of volcanism, of the kinetic power and of the friction power can occur at different times. A new term is here considered, compared with fig. 11, namely the e' term, the relevance of which should be indicative of the possible role of an elastic component in the visco-elastic coupling between lithosphere and asthenosphere. The upper plot shows two diagrams, namely $p_Q(t)$ and $p_Q(t) + p'_e(t) \equiv 1 - p_e(t)$, where sometimes it is $p_e(t) < 0$, while $p'_e(t)$ results basically negligible. Figure after Gregori *et al.* (1995b).

following equations (by taking into account the sign of their respective interpolating coefficients)

$$p_Q(t) + p_e(t) = p_F(t) + p_{v^2}(t) \quad (5.2)$$

$$p_Q(t) + p_e(t) = p_F(t) + p_{v^2}(t) \quad (5.3)$$

$$p_Q(t) + p_e(t) + p'_e(t) = p_F(t) + p_{v^2}(t) \quad (5.4)$$

where the symbols are as above, and the subscript F denotes the contribution from Joule's heating after correcting it into the afore-mentioned function $F(t)$. The results are shown by figs. 10, 11, and 12, respectively.

Summarizing, we find a set of time-delays as in Table I.

The same results of cases B1, B2, and B3 are also confirmed by cases B1M, B2M, and

Table I. Time delays resulting from different approaches and computations.

Case	An FR precedes volcanism by	Volcanism is preceded by an increase in kinetic power of	Volcanism is preceded by an increase in friction power of
B1	12.4 Ma	0.0 Ma (by assumption)	0.0 Ma (by assumption)
B2	12.4 Ma	0.1 Ma	0.1 Ma
B3	12.4 Ma	0.1 Ma	0.1 Ma
B1M	Log-normal law	0.0 Ma (by assumption)	0.0 Ma (by assumption)
B2M	Log-normal law	0.250 ± 0.539 Ma	0.49998 ± 0.00002 Ma
B3M	Log-normal law	0.3320 ± 0.9593 Ma	0.4952 ± 0.3405 Ma

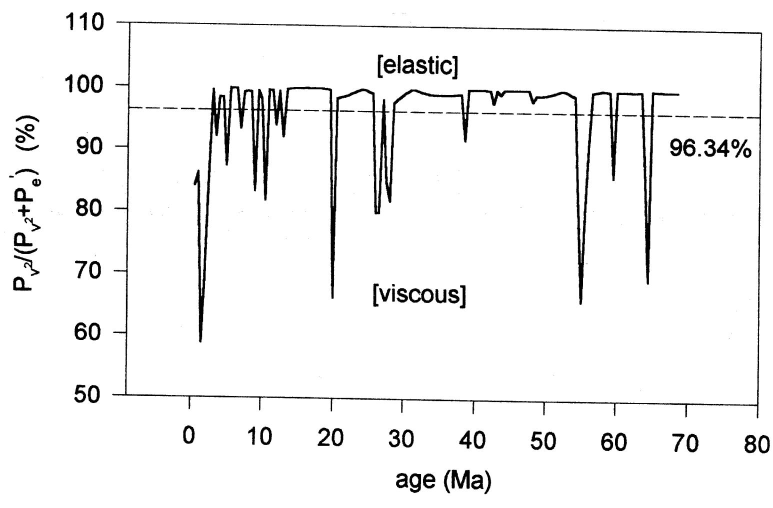

Fig. 13. Plot of $|p_{v^2}(t)|/[|p_{v^2}(t)| + |p'_e(t)|]$ *vs.* t aimed at indicating the relative percent of the viscous component and of the elastic component in the visco-elastic coupling between lithosphere and asthenosphere. The averages give ~96% for the viscous component and ~4% for the elastic component, with sporadic (and possibly non-significant) spikes that increase the elastic part at most up to ~30-40%. The similarity of this figure with fig. 7b definitely appears to support the possible significance of both of them. Figure after Gregori *et al.* (1995b) where a more extensive discussion is given.

B3M, in the fact that volcanism appears fuelled ~75-80% by Joule's heating, and 20-25% by friction power; but, during «beep» time volcanism is almost ~100% fuelled by friction power alone; the kinetic power of the Pacific plate results in any case almost negligible. We also find (fig. 13) the same result concerning the inference about the elastic *vs.* viscous contribution to the visco-elastic coupling between lithosphere and asthenosphere: ~96% is viscous, and ~4% is elastic. Therefore, one obtains almost identical estimates by means of substantially different approaches, based on different physical assumptions. This fact reveals that, perhaps, such results are more reliable than a mere formal analysis of their error bars can suggest.

6. Conclusions

This entire analysis gives a good agreement with the former guess that motivated its own being: verifying the consistency of the hypothesis that volcanism is supplied on the planetary scale by the solar-modulated electric currents of the dynamo.

The relative timing of the release of the different powers, the different percent values depending on «beep» or not, even the separation between elastic and viscous contributions to the coupling between lithosphere and asthenosphere, all appear intriguing and reasonable results.

The final picture is that a «pipeline», due to the «electric soldering iron» mechanism by which it is pushed upward due to Hamilton's principle, takes some time span that ranges in between ~0 Ma and ~27.4 Ma to reach the Earth surface, depending on how the «pipeline» was already developed at the time of occurrence of that given FR. Hence, the speed of propagation of the «pipeline» through the mantle and lithosphere is of the order of magnitude of ~10 cm year^{-}1. The first effect originated by the bulk energy-release (*i.e.* apart some minor almost simultaneous releases) that is observed at the Earth's surface is a bump of the surface, a «superswell», by which the lithospheric plate starts sliding away by gravity from the top of the «superswell», thus generating a large burst of kinetic energy and of geodynamic processes: speeds up to ~114.7 cm year^{-1} are observed. Some ~0.1 Ma later on, such a burst of kinetic energy is transformed into friction power, while volcanism appears supplied almost ~100% by friction alone.

Concerning future achievements, two steps appear most promising.

The first is the search for some analogous inferences by means of a few hot spot trails other than Hawaii's: since according to the rationale of Gregori (1993, 1994) the time variation of the prime supply by Joule's heating must be synchronous all over the globe, this ought to be verified by taking into account the different ϕ within the $T(\phi)$ relating to different hot spots.

The second step is concerned with the fact that the magma outpouring from mid-ocean ridges should also display some time variations similar to those inferred from hot spots. Differently stated, we infer $Q(t)$ and $v(t)$ by means of the trail of the Hawaii hot spot, but one can infer the same by considering the varying extension and depth *vs.* age (per unit length along any one given mid-ocean ridge) of the magnetic stripes of the ocean floors. There are previous studies of this kind in the literature (not here specified for reasons of brevity).

Acknowledgements

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NOTE

([1]) Such an energy balance formally coincides with a four-variate linear regression analysis over 4 quantities (powers) that are physically homogeneous with each other.

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