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Global postseismic stress diffusion and fault interaction at long distances

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Abstract

By means of a new theoretical model of global postseismic deformation we compute the time-depending postseismic stress field associated with eight of the greatest events of the century on an area extending for almost half of the Earth's surface. We evaluate the stress transferred by these big earthquakes to all the seismogenic structures of the Pacific belt that have generated earthquakes with $M \geq 5$ in the last years. We discuss the effect of this stress field on the state of the faults: the distribution of favoured and not favoured events is not uniform. The modeling suggests the existence of a physical connection among the patterns of release of seismic moment by the different plate margins of the Pacific area and the possibility of a self-organised geometrical configuration of the tectonic plates system.

Keywords: global; faults; stress; failures; shear modules; earthquakes

1. Introduction

The primary role of fault interactions in seismic hazard assessment at the local and regional scales is supported by a great deal of phenomenological and modelistic evidence and is now widely accepted [1]. Though there are several indications also suggesting the possibility of interaction between seismogenic faults on a global scale, we feel that the scientific community is rather sceptical about this possibility [2].

The idea of remote triggering of earthquakes and of fault interactions at great distances was proposed by Romanowicz [3], who suggested that the pattern of seismic energy release was characterised by alternating periods of prevalent strike-slip and dip-slip activity at the opposite margins of the Pacific ring. Though subsequent investigations have shown that the proposed correlation has a large probability to be observed by chance [4], the debate on the remote triggering of earthquakes is far from being ended [2,5]. In particular, Pollitz et al. [5], analysing the spatiotemporal correlation between the viscoelastic relaxation process following the great Alaska earthquakes of the 1950s and 1960s and the following seismic activity of the north-east Pacific area, gave some convincing evidence of long-distance fault interaction. Our goal is to test the plausibility of the hypothesis of fault interaction on a global scale. To achieve this result we per-

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form a detailed analysis of the features of the postseismic stress diffusion on the whole circum-Pacific area, taking advantage of a modeling approach developed in the last years [6,7].

When an earthquake occurs, the Earth reacts elastically and deforms instantaneously. This deformation (called coseismic) tends to create a permanent state of stress since a seismic event occurring within an elastic portion of the Earth acts as a permanent distribution of body forces. Owing to their long-term fluid behaviour, the viscoelastic mantle and asthenosphere cannot sustain the elastic shear stresses generated by the earthquake, therefore they will deform, superimposing a time-dependent deformation process on the elastic static coseismic contribution (postseismic deformation). During this process, while the shear stress within the mantle tends to vanish, the elastic lithosphere is loaded by a (time-dependent) further amount of stress that increases the coseismic contribution.

In Section 2 we consider the time-dependent postseismic stress field associated with eight of the greatest seismic events of the previous century ('source earthquakes' in the following) [8] and, in order to assess the effect of this stress field on the subsequent seismicity, we compute the value of the Coulomb failure function (or Coulomb stress) variation (ΔCFF [1]) on more than 8000 seismogenic structures that have ruptured in the last 25 years in the whole circum-Pacific area.

In Section 3 we perform a series of Monte Carlo simulations in order to assess the statistical significance of our results. In Section 4, also by means of some further numerical simulations, we discuss a possible interpretative framework for our findings.

2. Numerical simulation

2.1. Modeling approach

The main investigative tool to study the interaction between the residual stress field due to earthquakes and preexisting seismogenic structures is represented by the CFF method [1]. This method is based on the evaluation of the normal (σ) and tangential (τ) components of the stress field (associated with one or more earthquakes) on a particular seismogenic structure. The CFF is then defined as:

$$\mathrm{CFF} = \tau + \eta\sigma$$

where η is a constant depending on the static friction coefficient, the hydrostatic pressure and the pore fluid pressure [9]. The knowledge of the variation of the CFF on a particular fault allows us to predict if the imposed stress field acts to facilitate (positive variation) or to oppose (negative variation) the dislocation on the fault [9].

In order to compute the postseismic CFF variation on any fault plane in the Pacific area at the time of its rupture we have to know the time evolution of all six components of the stress tensor in the whole area under analysis. To accomplish this task, we have suitably developed the model of time-dependent viscoelastic postseismic deformation proposed by Piersanti et al. [6,7]. This model is based on a normal mode decomposition of the observable physical quantities in order to solve semi-analytically the equilibrium equation for a spherical Earth subject to a seismic excitation. It includes the effects of self-gravitation and assumes incompressibility. The model is laterally homogeneous; the radial stratification includes an 80 km thick elastic lithosphere, a 200 km thick asthenosphere, a uniform mantle, both characterised by a Maxwell viscoelastic

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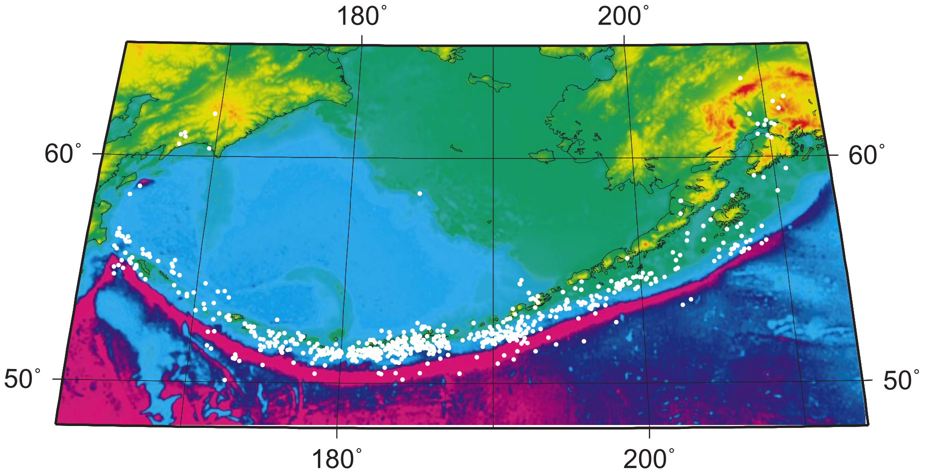
Fig. 1. Functional relationships among the parameters of the nodal planes for all the CMT events occurring along the Aleutian trench zone. We noticed that mechanisms are mainly thrust type, i.e. rake $>0°$ (a, c), as expected along a subduction zone, first nodal planes of CMT mainly having dip $<45°$ (a, b). First nodal planes with dip $<45°$ prevalently show strike in agreement with the subduction direction (i.e. strike angles between 210° and 300°) while their complementary nodal planes have strike directions between 30° and 90°, which are incompatible with a northward subducting plate boundary (b, c). Red ellipses enclose the nodal planes we selected as actual fault planes, while blue ellipses enclose their complementary ones.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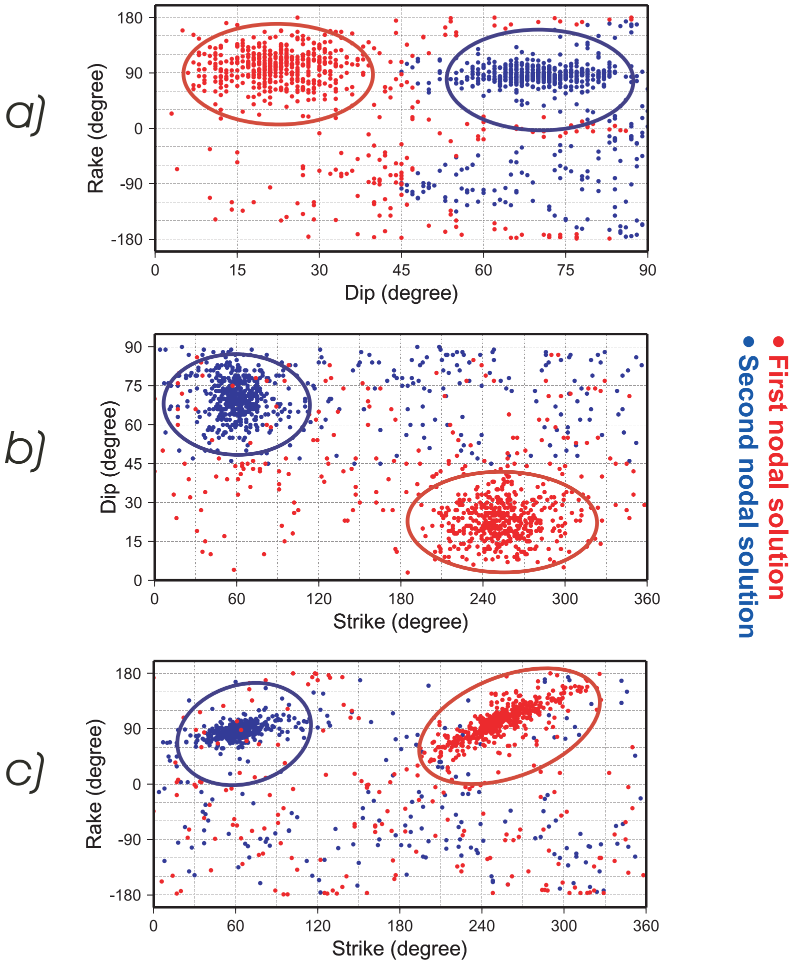
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● Second nodal solution

rheology, and a fluid inviscid core [10,11]. The viscosity of the mantle is fixed to 10^{21} Pa s, whereas the asthenospheric viscosity is fixed to 10^{18} Pa s [12]. The density and shear modulus of each layer are obtained by volume-averaging the PREM reference model corresponding values [10].

2.2. Earthquake selection

The eight source earthquakes (i.e. those generating the postseismic stress field) are: the 1960 Chile earthquake, the 1964 Alaska earthquake, the 1952 Kamchatka earthquake, the 1957 Aleutian earthquake, the 1963 South Kurils earthquake, the 1968 Japan earthquake, the 1977 Java earthquake and the 1989 Maquarie Ridge earthquake. These eight events alone account for more than 70% of the total seismic moment released by large shallow earthquakes in the previous century [8]. In fact, our source earthquakes are not exactly the greatest of the century, since we have adopted some discriminating criteria. First, we have preferred, between two similar events, the more recent one (i.e. with more reliable fault parameters) even if it had a slightly lower seismic moment. Second, if two of the eight greatest events occurred in the same area and exhibited a great difference in energy release, then we did not consider the smaller one (since its stress field would be negligible with respect to that of the other earthquake). This in practice resulted in not considering some events near Alaska, Aleutian and Chile, since the exceptional events of 1952, 1957, 1960 and 1964 dominated all the others.

After choosing the earthquakes generating the postseismic stress field we had to select the maximum number of seismic rupture planes on which to project it to retrieve the ΔCFF. In order to do this we have to know all three focal parameters describing the fault plane. The best source for our simulation is represented by the Centroid Moment Tensor (CMT) project catalog [13], which contains more than 9000 events in the Pacific area. The initial list of events used in this study includes all the earthquakes, reported in the CMT catalogue, which occurred down to 80 km depth with coordinates ranging from 120° to 300° longitude and from $-60°$ to 80° latitude (near half the whole Earth surface). A set of 9658 events matching these criteria was selected. The CMT solutions provide strike, dip and rake for the two nodal planes of the best double couple for each event [13]. We had to discriminate the actual fault plane between these two possibilities. With this in mind we divided the whole circum-Pacific area into smaller areas enclosing plate boundary segments of roughly coherent geometry and fault type mechanism, and analysed the functional relationships between strike, dip and rake of the nodal planes for all the earthquakes occurring within each of these areas. A suitable analysis allowed us to perform a semi-automatic choice of the actual fault plane for the majority of the CMT events, as shown in Fig. 1. As a first step we basically selected the plane with dip angle $< 45°$ for the thrust-type earthquakes, while for the normal-type events we selected the plane with dip angle $> 45°$ [14]. An a posteriori inspection of each plate boundary was made to verify the reliability of the selected strikes. The choice of the actual fault plane for the strike-slip-type earthquakes was made isolating the groups of events occurring along the same tectonic structures (i.e. the same transform fault) and selecting case by case the appropriate mechanism between the left and right laterals. At the end of this selection process we obtained 8112 fault planes (out of 9658): 5290 thrust, 1834 normal and 988 strike-slip mechanisms (Fig. 2). For the about 1500 discarded CMTs the uncertainties on the actual plane were not solvable with the adopted criteria.

2.3. CFF results

For each of the 8112 selected CMT earthquakes we computed the total postseismic stress field at the time of occurrence of the CMT event itself, that is to say, for each CMT earthquake the computed stress field is composed of the elastic (coseismic) static contribution of the source earthquakes plus the time-depending contribution due to the viscoelastic relaxation of the mantle and asthenosphere. This means that our simulation implied the calculation of the stress field associ-

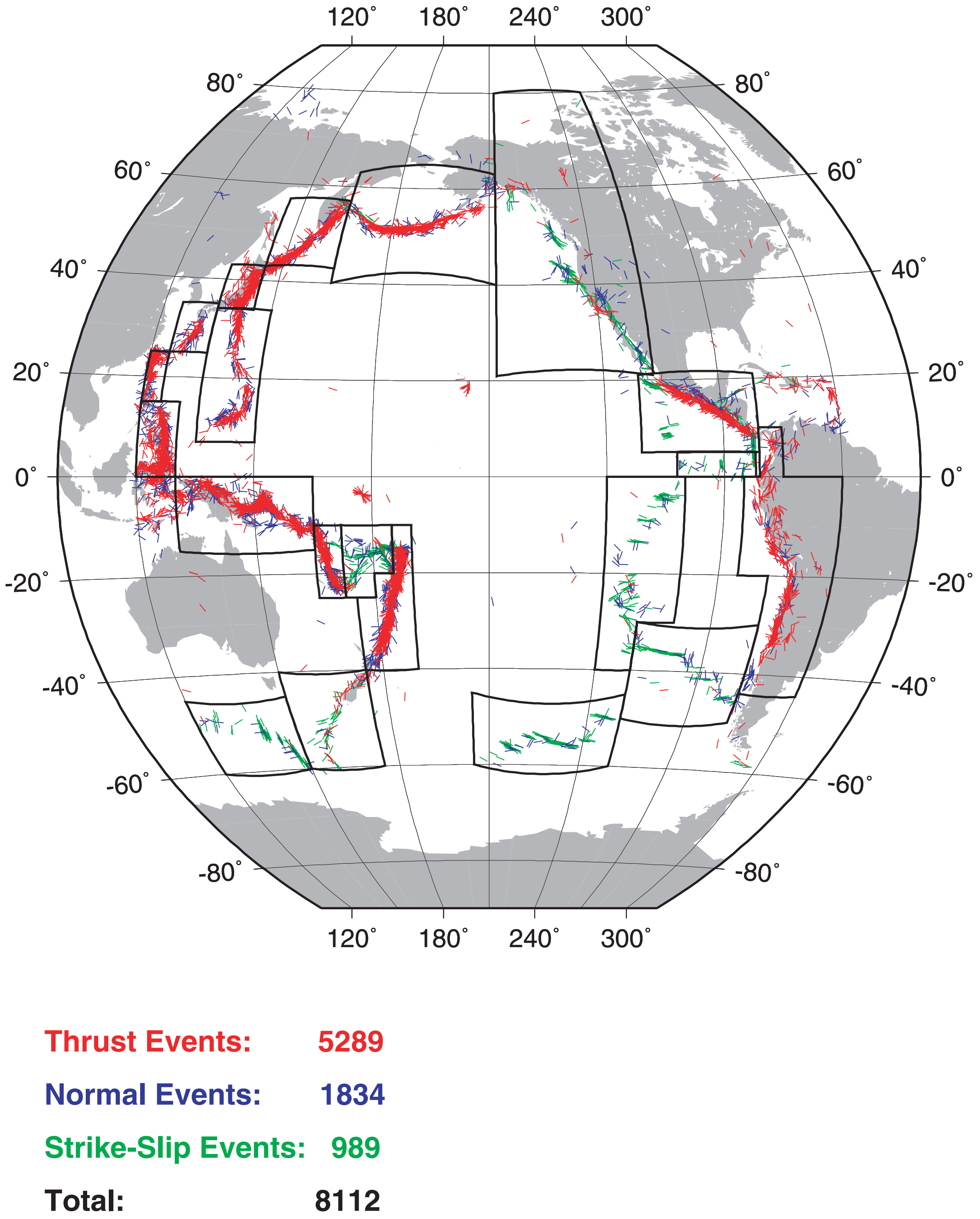

Fig. 2. Mechanisms of the 8112 CMT earthquakes as resulting from our selection process. The segments are oriented parallel to the strike of the fault and their length is proportional to the logarithm of the seismic moment. The selection of the actual fault planes was made dividing the circum-Pacific belt into 20 areas of roughly coherent geometry and fault-type mechanism and analyzing the focal parameters functional relationships of events into each of these areas. Events occurring outside the displayed areas were analysed separately.

ated with the source earthquakes at 8112 points in space and 8112 points in time; the global simulation took approximately 2 months of CPU time on a Digital Alpha Server 1000A. After computing the stress field, we projected it on the fault plane of the CMT events in order to retrieve the variation of the CFF (Fig. 3).

Our results show that the distribution of the sign of the CFF variations is not uniform and that the positive variations (4346, about 54%) are in excess with respect to the negative ones (3766). Since the real value of the asthenospheric viscosity is still a matter of debate and the proposed values range roughly from 10^{17} to 10^{20} Pa s [5,12–15], we ascertained that these numbers are almost insensitive to the value of this parameter (what is sensitive to it is the magnitude of the CFF variation; we will discuss this question in Section 4).

As a final result our simulation predicts that the number of seismic ruptures in the last years in the whole Pacific area favoured by the postseismic stress field associated with the greatest earthquakes of the century is larger than the number of ruptures opposed by this stress field.

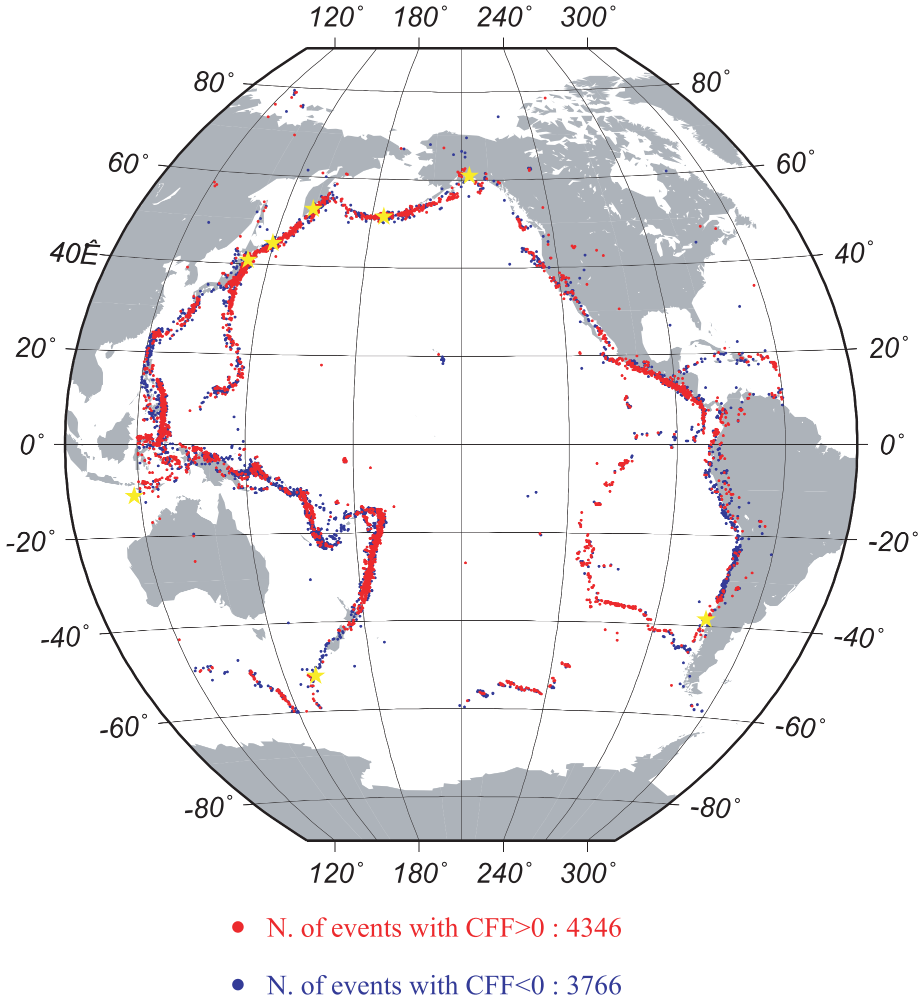

Fig. 3. Distribution of the sign of the CFF generated by the eight source earthquakes, indicated by the yellow stars, on the 8112 selected CMT earthquakes in the Pacific ring. Red dots stand for positive variation, blue dots for negative variation. The number of events with positive ΔCFF is 53.6% of the total.

3. Statistical analysis

To test the statistical significance of the results reported in Section 2, we performed three Monte Carlo simulations creating different kinds of synthetic seismic catalogs (Fig. 4). First we generated 1000 seismic catalogs each composed of 8112 earthquakes having completely random focal parameters (S1). The major limitation of this statistical test is connected to the distribution of the focal parameters of the synthetic earthquakes that, unlike the real one, is uniform. As an alternative approach, we assumed fixed the focal parameters of each CMT earthquake, assigning randomly to it one of the locations of the other 8111 events (S2). Finally, to check the stability of our results, we repeated all the previous analyses (CFF computation and statistical analysis) considering only CMT earthquakes with $M_w \geq 6$. In this way we excluded any possible perturbative effect due to the presence of mainshock–aftershocks sequences, at the cost of a significant reduction of our statistical population (from 8112 to 1647 earthquakes) and, consequently, of the statistical significance of our results. In all these statistical simulations we obtained almost a perfect normal distribution of the CFF variations, the difference with the real CFF distribution displayed in Fig. 3 being, in the worst case, greater than 4 S.D.

4. Discussion and conclusion

Our statistical analysis shows with remarkable significance, that the evidence reported in Section

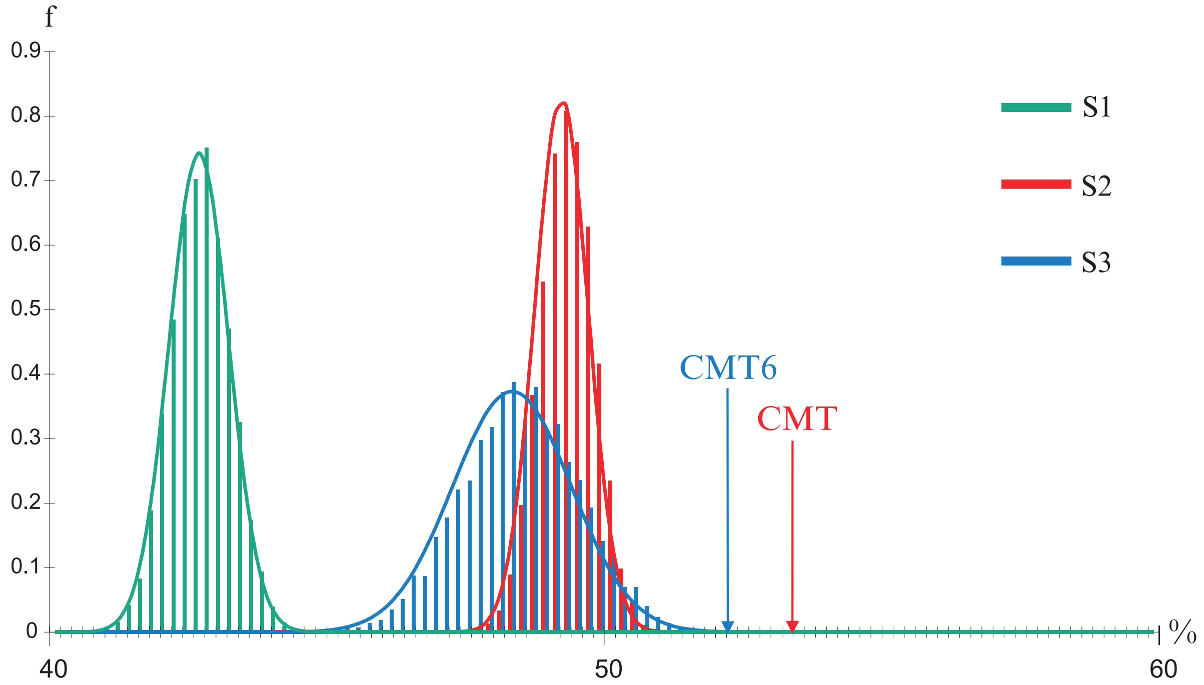

Fig. 4. Results of the three Monte Carlo simulation S1, S2, S3. The y-axis represents the frequency of occurrence (plotted as a vertical bar) of the particular CFF distribution corresponding to the percentage value in the x-axis. The curves are the best fitting normal distributions and the long vertical arrows indicate the CFF distribution obtained for the whole CMT catalog (CMT) and for the cut CMT catalog (CMT6). For S1 (completely random synthetic catalogs) we obtained a normal distribution of the CFF variations with a mean of positive events of 42.7% and a S.D. of 0.6%. For S2 (shuffled-CMT synthetic catalogs) we again obtained a normal distribution with a mean of 49.2% of events with positive CFF variations and a S.D. of 0.5%. For S3 (shuffled-CMT synthetic catalogs with magnitude >6) we again obtained an equidistribution of positive and negative CFF values: mean 48.3%, S.D. 1.1%. The increase in the S.D. value is clearly due to the reduction of the statistical population (from 8112 to 1647 events). The offset between the simulated and the real distribution of earthquakes exceeds, in the worst case, 4.8 S.D.

2.3 suggests the existence of a physical connection among the postseismic stress fields associated with the greatest events of the previous century and the subsequent seismicity in the whole Pacific area. The problem now is: can we identify this physical connection with a fault interaction phenomenon in the 'classical' sense [1], or do we have to consider it as pertaining to an alternative class of phenomena?

A possible explanation could be found in the fact that the relaxation from megathrust (interplate) events could increase converge rates temporarily along the same plate boundary increasing the positive correlation between the source earthquake and the following thrust seismic activity in that plate boundary. To investigate this hypothesis we analysed separately the effects of the Chile 1960 and Alaska 1964 events (the biggest of our source earthquakes). We computed separately the CFF distribution associated with these two events for the secondary thrust events on the same plate boundary of the source earthquake and compared it with the CFF distribution for thrust events on the other plate boundaries. If the previous hypothesis is correct we would expect a much higher number of positively correlated events on the same plate boundary of the source earthquake than on the other boundaries. (Incidentally, we would note that this condition is necessary but not sufficient, in fact a higher number of positively correlated events on the same plate boundary could simply be associated with the higher magnitude of the absolute values of transferred stress due to the smaller spatial scale involved). Actually we have found that this condition is weakly verified for the 1964 Alaska earthquake (64.8% of positive ΔCFF events on the same boundary, 63.1% on the other boundaries) and it is strongly not verified for the 1960 Chile earthquake (30.9% against 88.2%). Consequently we must conclude that our data do not support this hypothesis.

One of the most frequent objections to the hypothesis of remote earthquake interactions concerns the low level of stress transferred to distant faults [2]. Though this objection is reasonable, it must be remembered that the idea of the physical action of the mechanism of fault interaction does

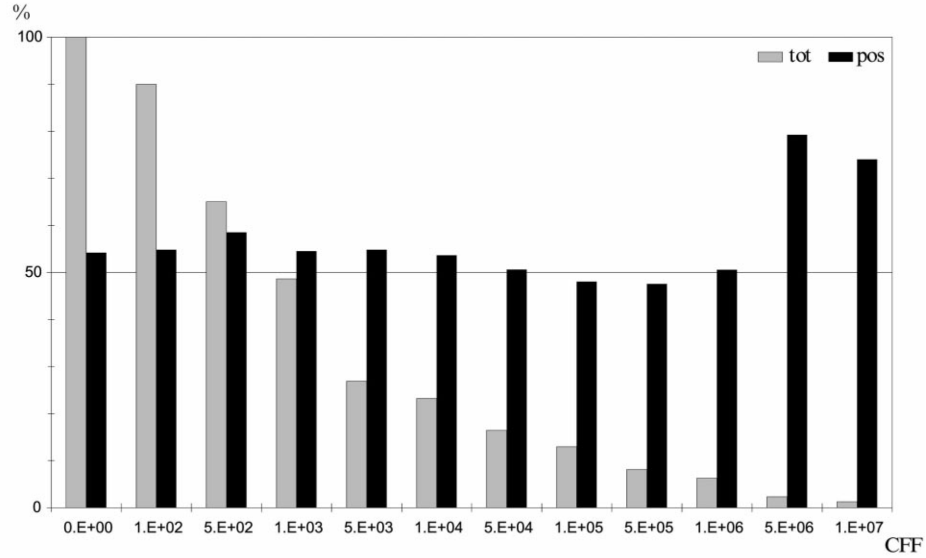

Fig. 5. Cumulative distribution of the magnitude of the postseismic CFF variation on the fault plane of the 8112 CMT earthquakes (light bars) and fraction of positive events as a function of the CFF variation (dark bars). 48.6% of the events show a $\Delta CFF \geq 10^3$ Pa, the magnitude of the tidal loading that some authors consider a threshold for the efficacy of the mechanism of fault interaction. The sharp increase in the fraction of positive events for very high levels of CFF variations strongly indicates that for these events an interaction mechanism 'in the classical sense' is acting. For low levels of transferred stress the physical reason of the asymmetry in the distribution of the CFF variations is still an open question.

not contain in itself the concept of a minimum level of transferred stress needed to trigger an event. Some authors consider the tidal load (of the order of 10^3 Pa) to be this minimum level [16] but it is important to note that, in determining an increase in the probability of a seismic rupture occurrence, it is important to consider not only the magnitude of the transferred stress but also its duration [17]. In this respect, the postseismic stress, with typical relaxation times of the order of 10^1–10^3 years [6,7], should be by far the more efficient loading mechanism in exciting fault interaction phenomena. All the above considerations are strengthened accepting the hypothesis, proposed by several authors in recent years, of earthquakes as a self-organised critical phenomenon [18]. This hypothesis, suggesting that a significant part of the crust is in a critical (i.e. very near to unstable) state, implies that a fault system can be made completely unstable by minute (in principle arbitrarily small) perturbations [19]. In Fig. 5 we report the cumulative distribution of values of the ΔCFF for the selected earthquakes of the CMT catalog, computed adopting our model of global postseismic deformation. 48.6% of the events shows values greater than 10^3 Pa (tidal load) and 23.2% greater than 10^4 Pa (this is a level of stress that is commonly accepted as able to trigger events in local-scale analyses [1,9,20]). We must also remember that, unlike what happens for the number of favoured and not favoured earthquakes (see Section 2.3), the magnitude of the transferred stress is greatly sensitive to the value of the asthenospheric viscosity: to a first approximation we can say that this magnitude scales with the viscosity value [6,12]. In Fig. 5 we also show the distribution of the fraction of events with positive ΔCFF as a function of the absolute value of transferred stress: the number of events with positive ΔCFF is greater for high values of transferred stress as one could expect in trigger phenomena, nevertheless also for extremely low values of ΔCFF we obtained an anomalous number of positively correlated events.

Given these considerations the answer to our original question is rather controversial; our opinion is that the magnitudes of transferred stress that we found in our simulations is probably too low to positively prove the existence of an interaction mechanism in the classical sense, nevertheless they are too high to rule out this possibility. The explanation of the real nature of the physical connection between the postseismic stress field associated with the Pacific giant earthquakes and the following seismic activity, evidenced by our analysis, is an open question that is to be added to the bundle of still unresolved geophysical problems.***[AC]***

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