Forecasting the effects of the Andaman Islands - Sumatra megathrust earthquakes (Dec. 2004 and Mar. 2005) on volcanoes in the surrounding area.

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Abstract

The Andaman Islands - Sumatra earthquake ($M_w = 9.3$, Dec. 2004) and the subsequent Sumatra earthquake ($M_w = 8.7$, Mar. 2005) represent one of most energetic sequence of earthquakes ever recorded. Since both events occurred in a strongly active volcanic region, their exceptionally strong stress perturbation gives the opportunity to understand the effects of stress perturbations on volcanic systems. Here, we set the rules for a forward test of the causal relationship between stress perturbation and subsequent volcanic eruptions, by means of the comparison of the spatio-temporal distribution of the eruptions which follow the earthquakes with the co- and the post-seismic stress field due to the earthquakes. In practice, we forecast that the volcanic activity of the next 30 years will be significantly promoted by the stress perturbation; thus, we define the rules for an objective test of such an hypothesis. Given the extremely high values of stress perturbation due to this sequence of earthquakes, the results of our test will definitively provide a reliable evaluation of the possible statistical impact of earthquake-eruption interaction on long-term volcanic hazard assessments.

Key words: Earthquake-volcano interaction, stastical model, stress field, Sumatra, volcanology, postseismic deformation, non-parametric statistical test

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1 Introduction

Some researchers have suggested that stress perturbations due to tectonic earthquakes that occurred close to volcanic regions may have triggered volcanic unrest at different spatio-temporal scales; such a coupling has been proposed as the most relevant phenomenon that may control the timing of volcanic eruptions [1–10]. A better knowledge of such an interaction may be the basis of significant improvements for the long-term forecasting of location and time of next volcanic eruptions.

The stress perturbation field due to an earthquake may be divided into three different phases, with different spatio-temporal distributions: i) the dynamic stress variations, due to the passage of seismic waves, ii) the coseismic field, due to the elastic rebound of the crust to the dislocation, and iii) the postseismic field, due to the viscoelastic readjustment of the layers beneath the crust [11–15]. The dynamic field is characterized by strong variations within short time windows [e.g. [16]]; the coseismic field is instead an almost instantaneous stress variation which affects only the region around the epicenter; the postseismic field gives stress variations that may affect a huge area (up to thousands of kilometers far from the seismic source) for tens of years [11–15,17]. Thus, the post-seismic field has been proposed to be responsible for earthquake-eruption long-term interaction [10,18].

Some papers have tested such a coupling hypothesis by using different retrospective correlation analysis [3,5,8,10]. Selva et al. [18] proposed a validation procedure (the Validation Test VT) through a forward test of correlation between the stress field due to strong tectonic earthquakes and the spatio-temporal distributions of eruptions in the same area. VT consists of modeling the co- and post-seismic field due to some selected earthquake that occurred close to a volcanic region by means of a spherical, layered, viscoelastic and self-gravitating Earth model [11,12], then of comparing the spatio-temporal distribution of the eruptions that occurred before and after the earthquake in the volcanic area, weighting each volcanic event with the stress perturbation induced by the earthquake at the volcano at the time of the eruption. This procedure rules out any unconscious overfitting of the data, and gives an objective way to validate the hypothesis of significant coupling between time and location of the eruptions and the stress field due to tectonic earthquakes.

Here, we follow the scheme of VT with some important modifications (see Section 3), and we apply this procedure to the Andaman Islands - Sumatra earthquakes. This sequence is one of most energetic seismic sequences ever recorded; their perturbation field will affect a huge volcanic area, from Sumatra and Java to the Philippines islands, one of most active volcanic areas in the world. These earthquakes give a unique opportunity of an effective and definitive test to validate through a large statistics of volcanic events the hypothesis of the causal relationship between stress perturbations and volcanic eruptions.

2 Modeling the Andaman Islands - Sumatra earthquakes

2.1 Earth Model

The postseismic relaxation effects involve the state of the whole Earth, so that a complex modeling approach is required in order to study these processes. Megathrust events deform very large areas, comparable with the dimension of a tectonic plate, and the mass redistribution is so large that the gravitation variations and the sphericity provide important contributions in the postseismic deformation field. Therefore, in order to evaluate the stress field associated to the Andaman Islands - Sumatra earthquakes, we used the Earth model proposed by [11,12], that estimates the stress variations in a layered Earth taking into account also sphericity, viscoelasticity, and self-gravitation.

The density and the shear modulus are obtained for each layer by volume-averaging the PREM values [19]. The asthenosphere and the upper mantle are characterized by a viscoelastic reology, and the viscosities are fixed to 10^{18} and 10^{21} Pa s respectively. These values lead to a stress evolution with a characteristic time of tens of years [20]. The stratification parameters chosen are compatible with a wide range of previous studies [18,4,21].

On the other hand, previous studies have suggested that the evolution of the stress perturbation might be better modeled with a nonlinear readjustment of the astenosphere [22,14] ; this nonlinearity may be modeled by varying the viscosity of the astenosphere as a function of the time lag from the earthquake. We obtain the same conclusion even if we consider a linear viscosity and a huge afterslip following the great seismic events. In general, just after an earthquake, the time behavior of the stress perturbation seems to be in agreement with values of the viscosity even smaller than 10^{18} Pa s, so that the effective perturbation might evolve quicker than how it does in our Earth model; on the other hand, for longer time lags, viscosities up to 10^{20} Pa s have been estimated (e.g. [14,23]). Given the goal of this paper, and the relatively short time of the forward test (30 years, see Appendix A), a viscosity of the astenosphere of 10^{18} Pa s is preferred, and is both reliable and conservative. However, the effect on the forward test of this choice is discussed in the Appendix A.

Accordingly to Selva et al. [18], for the 2005 Sumatrian event we adopt the CMT focal mechanism (CMT catalog [24]), and the physical dimension of the fault is modeled as in Walker et al. [25].

The CMT solution for the Dec. 2004 earthquake leads to a severe underestimation of the energy effectively released by this earthquake [26,27]. Therefore, we adopt a more detailed model which has been proposed by Lay et al. [27], where the earthquake occurs in a fault system (3 segments) involving the whole Burma Plate, with a seismic moment of $6.5 \cdot 10^{22}$ N m. Furthermore, Lay et al. [27] highlighted that the Northern part of the plate could have experienced a significant slow slip, whose seismic moment is estimated to be $3.0 \cdot 10^{22}$ N m. However, Vigny et al. [28] ran out this possibility by means of a dynamic GPS analysis. The same conclusions are reported in Tsai et al. [29]

Since these opposite statements and the lack of any constrain about a possible slow slip, we decided to neglect its effect in our calculations even though it surely has increased the stress perturbations due to the 2004 event. Nevertheless, if we reasonably suppose a mechanism similar to the fast component, our simulation simply underestimates the stress values by a factor in all the points of our grid; as will be discussed further on (see Appendix A), this cannot influence the results of the forward test that we propose.

Note that more detailed focal mechanisms, and even higher seismic moment have been proposed [e.g. [29]] . For our purposes, these further more detailed models are equivalent to the one adopted in this paper, since we focus on a general analysis of the stress mainly located in the far field.

3 Forward test and discussion

The procedure that will be followed for the forward test is reported in appendix A. This procedure is based on the one proposed in Selva et al. [18], with some important modification.

In practice, the procedure consists in modeling the stress field through time induced by the earthquakes in a fixed region (the perturbed area PA) around the earthquake sources; then, the stress perturbation Θ^a that affects the volcanoes located in PA at the time of the eruptions that follow the earthquakes within a time window of 30 years are evaluated; the distribution of Θ^a , which depends on the spatio-temporal distribution of the eruptions, is compared to an uncorrelated distribution (Θ^b), which is obtained by using the eruptions occurred in the same area, but in a 30 years long time window preceding the earthquakes. Finally, the distributions of Θ^a and Θ^b are compared through a 1-tail Wilcoxon test, where the null hypothesis H_0 is $M_a \leq M_b$ (where M_a and M_b are the medians of Θ^a and Θ^b respectively). If strong stress perturbations significantly promote volcanic eruptions, such events will tend to occur where Θ is greater, so that M_a will be larger than M_b, and H_0 will be rejected. To the contrary, if volcanic eruptions will not be significantly promoted, similar values of the medians are expected (see the examples in Figure 1). More details can be found in Appendix A.

The major modifications of this method respect to the one proposed by Selva et al. [18] consist of i) a new procedure to evaluate the perturbed area PA, taking into account the exceptional size of the Sumatra sequence, and ii) the use of the 1-tail Wilcoxon test, instead of the 2-tails Wilcoxon test, and thus the modification of its relative null hypothesis H_0. Moreover, respect to the proposed tests of the Denali (Alaska, Nov. 2002) and Engano (Sumatra, Jun. 2000) [18], the Andaman Islands - Sumatra earthquake sequence has some crucial advantage: i) the extremely strong stress perturbation field will be hardly overcome by other perturbations (which is the case, for example, of the Engano earthquake), then the results of the test will be representative of the earthquake-volcano interaction due to the Sumatra 2004/2005 sequence only; ii) if the earthquake-eruption coupling actually exists, it has to be seen with such a strong perturbation, and, to the contrary, if it will not be seen, the test will show that such a coupling is statistically negligible (except for isolated cases), given that stronger stress fields are unlikely and smaller earthquakes have exponentially smaller effects; iii) the PA is huge and the number of volcanoes involved in the test is consequently large, so that the number of the eruptions in the testing period will be large enough for an efficient statistical analysis (where, for example, eruptions in the Denali's PA are probably too few to have statistically significant results); iv) a huge amount of GPS data is available, so that it will possible a constrain of the deformation field evolution parameters and, in particular, of both the viscosity of the asthenosphere and the role of the afterslip.

The reference (uncorrelated) Cumulative Density Function (CDF) of Θ^b is reported in Figure 2. The CDF of Θ^a can be computed only at the end of VT (Apr. 2035); its preliminary versions will be updated every year in the web site www.bo.ingv.it/∼jacopo.

The main rational of fixing here the rules of the test and the uncorrelated disctribution in Figure 2 is to rule out any unconscious overfitting of the data that can affect all retrospective analysis (the so-called retrospective realism). Under this perspective, forward tests are the only statistical procedures that can effectively validate the statistical significance of causal relationships between different physical phenomena.

In practice, we forecast that the volcanic activity in the PA will be significantly affected, and we set the rules for a quantitative test of such a prevision. The results of this test will definitively verify the hypothesis of causal relationship between stress perturbations due to earthquakes and the volcanic eruptions, and will evaluate the possible impact of earthquake-eruptions interaction on volcanic long-term hazard programs. In fact, if H_0 will be rejected, i.e., the earthquake-volcano interaction will be found to be statistically significant, the efficiency of such an interaction will be proved and consequently measured; in this case, long-term hazard programs will be improved significantly by considering the effects of the stress field due to strong earthquakes occurred in volcanic areas.

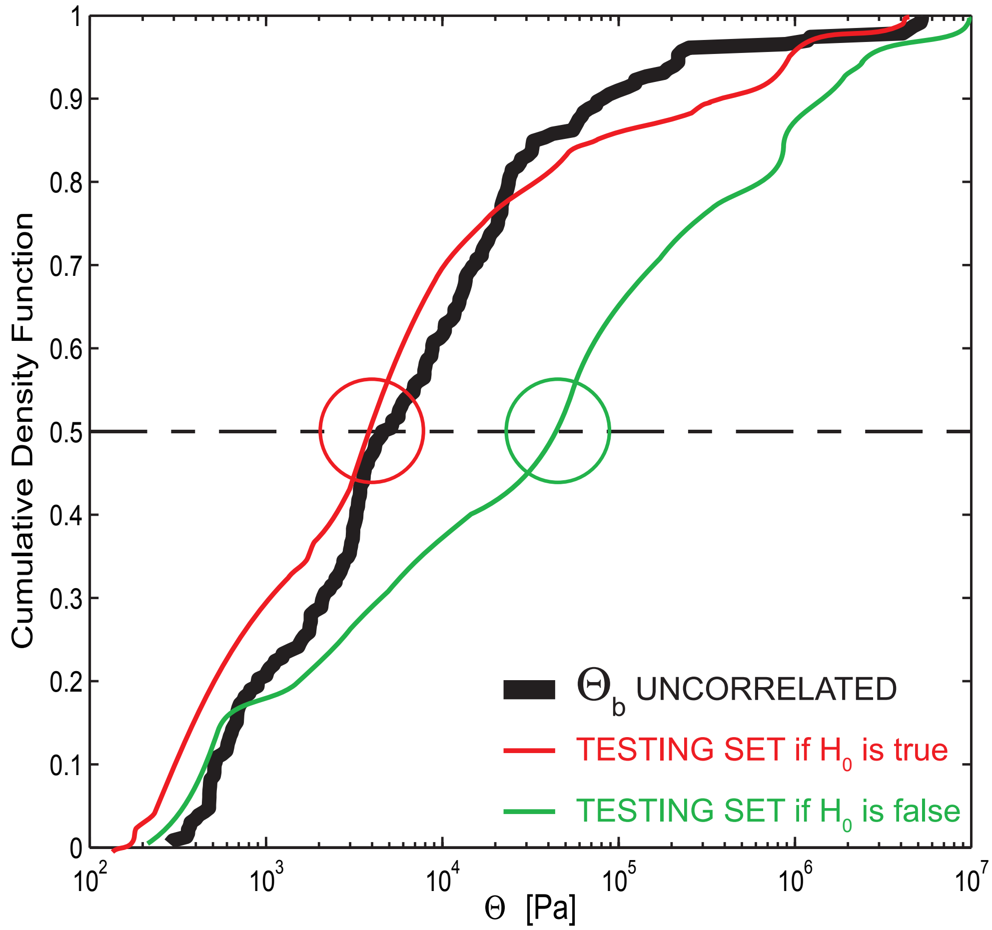

Fig. 1. Examples of possible outcome of the forward test. The zero hypothesis H_0 states equal median for uncorrelated (30 years before the 2004 event) and correlated (30 years after the 2005 event) distributions.

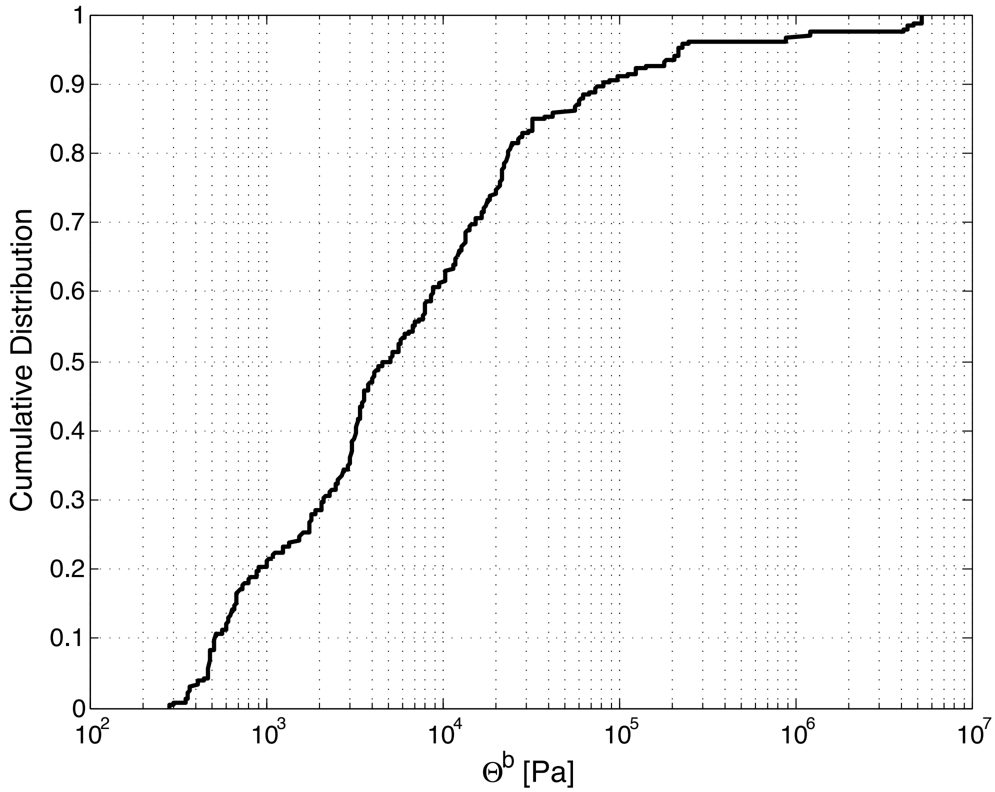

Fig. 2. The reference (and uncorrelated) cumulative distribution Θ^b.

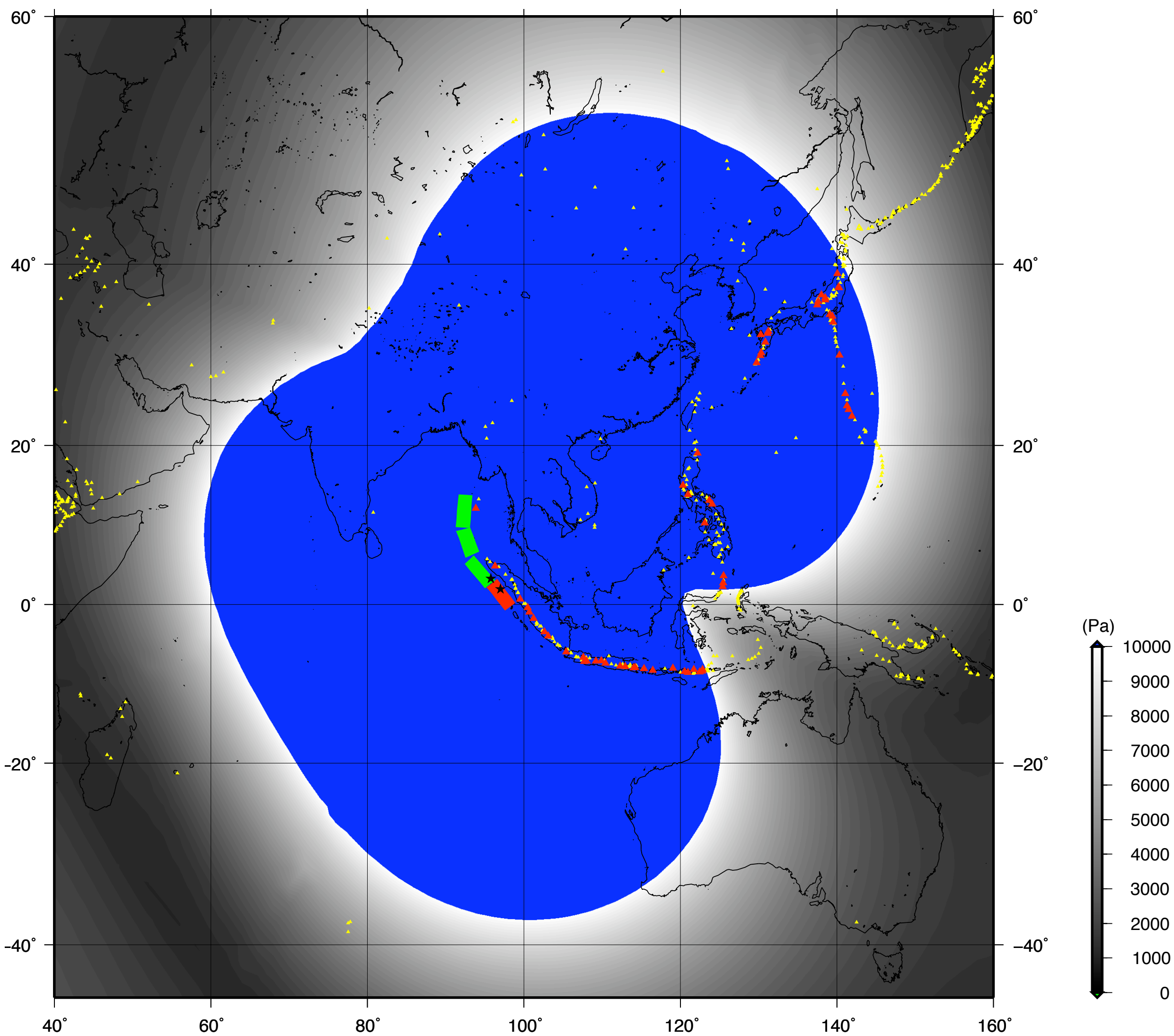

Fig. 3. Perturbed Area (blue area) due to the Sumatra -Andaman Islands earthquakes sequence. Green and red boxes indicate the source faults of the 2004 and the 2005 earthquakes respectively (the stars are the epicenters). Red triangles are all the volcanoes that erupted in the 30 years before the 2004 event inside the PA; yellow triangles represent all the other volcanoes.

A Perturbation field computation and validation test VT

The problem of a lack in the knowledge of the deep configuration of a volcano prevents us from projecting the stress on a precise structure. Therefore, as suggested by Marzocchi et al. [4] and Selva et al. [18], we evaluate the general behavior of the co- and post-seismic stress fields by means of the invariants of the stress tensor. The first invariant I_1 is defined as

$$I_1 = \sigma_{ii} \tag{A.1}$$

and it indicates pressure variations. The second invariant of the deviatoric stress tensor is defined as

$$J_2 = \frac{I_1^2}{3} - \frac{\sigma_{ii}\sigma_{kk} - \sigma_{ij}\sigma_{ij}}{2} \tag{A.2}$$

and it indicates shear stress variations. A discussion about the physical meaning of I_1 and J_2 can be found in Marzocchi et al. [4]

Far from the seismic source the invariants are approximately steady in depth, therefore they are computed at an intermediate depth (10 km).

The goal of the Validation Test (VT) is to verify the hypothesis of correlation between the stress field due to a tectonic earthquake and the spatio-temporal distribution of the volcanic eruptions that occur in its surrounding area in the 30 years after the earthquake. The basic idea of this test has been proposed and applied to the Denali (Alaska, Nov. 2002) and Engano (Sumatra, June 2000) earthquakes by Selva et al. [18]. Here, we follow this idea with some crucial variation.

VT is based on the earthquake-eruption correlation parameter Θ. Given the i-th eruption occurred after an earthquake, Θ_i is defined as

$$\Theta(\vec{x}_i, \Delta t_i) = |I_1(\vec{x}_i, \Delta t_i)| + \sqrt{J_2(\vec{x}_i, \Delta t_i)} \qquad [\mathrm{Pa}] \tag{A.3}$$

where $\vec{x}_i$ is the location of the volcano where the eruption occurs, and Δt_i the time lag between the earthquake and the eruption. In other words, Θ_i weights each eruption with the stress perturbation that the volcano received at the time of the eruption.

The spatial dimension of the analysis is controlled by perturbed area PA. The PA is the area that experiences the greatest stress changes after the earthquakes. In Selva et al. [18] the PA was defined as the area where $\Theta(\Delta t \to \infty) \geq 10^4$ Pascal; thus, Θ was computed for $t \to \infty$, at the so-called fluid limit.

This definition was made because the perturbation of smaller earthquakes reaches its fluid limit in times comparable with the time window covered by the VT, i.e., 30 years. The Sumatra earthquakes have a much greater energy release than $M = 8.0$ events, so that the viscoelastic layers beneath the crust are much more perturbed, and then the fluid limit is achieved after much longer time periods [[11–15] By considering an area much larger than the one effectively perturbed during the 30 years of the test (correspondent to ($\Delta t \rightarrow \infty$ in eq. 4), we consider a large number of eruptions that do not receive any perturbation, so that the signal-noise ratio decreases significantly. To avoid this, we must limit the test only to that area that effectively is perturbed within the time window of the VT. Thus, here we define the PA as

$$\Theta(\vec{x}, \Delta t = 100 \text{ yr}) \geq 10^4 \qquad \text{Pascal} \tag{A.4}$$

The PA computed through equation A.4 is reported in Figure 3.

The choice of 100 years to evaluate the PA is quite arbitrary and deserves a specific discussion. The time window to be considered is strictly linked to the choice of the astenospheric viscosity, and the earthquakes' source models. As seen above, it has been proposed that just after an earthquake, the viscoelastic response of the Earth may be modeled with very low viscosity of the astenosphere, even smaller than the 10^{18} Pa s ueqsed here. Thus, the real evolution of the stress field may be quicker than what previewed by our model. Moreover, it is likely that the moment release of the December 2004 event is underestimated, because of the slow slip that we neglected. Both these things may lead to an effective underestimation of the area involved by significant stress perturbations. Therefore, the choice of 100 years instead of 30 years accounts for this possible underestimation, since it includes in the PA more distant volcanoes.

On the other hand, the only effect of a slightly larger PA is a small increase of the noise in the eventual signal due to the earthquake-eruption interaction. Therefore, $\Delta t = 100$ years seems to us to be a reasonable compromise.

Through equation A.3, the earthquake-eruption correlation parameter Θ_i can be computed for all the N_a eruptions that will occur within 30 years after the Sumatra earthquake of March 2005, in the PA (see Figure 3); if the stress perturbation and the eruptions are correlated, the distribution of Θ_i^a, i.e.,

$$\Theta_1^a, \Theta_2^a, ..., \Theta_{N_a}^a \tag{A.5}$$

must significantly differ from the one obtained with only uncorrelated volcanic events. This reference uncorrelated distribution can be obtained by using the volcanic eruptions that occurred in the same area in the 30 years before the

Andaman Islands - Sumatra earthquake of December 2004. In other words, an earthquake-correlation parameter Θ_i is computed for all the N_b eruptions occurred in the PA in the 30 years before this earthquake through the equation A.3 (using the absolute value of the time lag Δt), so that

$$\Theta^b_1, \Theta^b_2, ..., \Theta^b_{N_b} \tag{A.6}$$

is the uncorrelated dataset to be compared to the one in equation A.5.

The comparison between the two sets Θ^b and Θ^a (eq. A.5 and A.6) shows whether or not the earthquakes have significantly interacted with the following spatio-temporal distribution of volcanic eruptions. In practice, we will test the null hypothesis (H_0) of $M_a \leq M_b$ (where M_a and M_b are the medians of Θ^a and Θ^b respectively) through the non-parametric 1-tail Wilcoxon test [30], by using a significance level of 0.01. A non-parametric test is used because it is insensitive to strongly nongaussian distributions of data. The alternative hypothesis (H_1) is that $M_a > M_b$; H_1 means that the spatio-temporal distribution of the eruptions is significantly (and positively) correlated with the stress perturbation due to the earthquakes.

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