Modelization of the Static Coulomb Stress Evolution after the 2001 Earthquakes in El Salvador.

J. Martinez Díaz[2] and B. Benito[1]

1. Dpto de Geodinámica. Universidad Complutense Madrid
2. E.U.I.T. Topografía. Universidad Politécnica de Madrid

SUMMARY

This paper presents a study of the stress transfer after the two main shocks occurred in El Salvador during 2001, on January 13 th and February 13 th. The study is complementary to those presented in this volume related to the spatial and temporal distribution of the 2001 events in that country. The results contribute to explaining the quoted fact: some events with M>5 acted as triggers of other shocks with the same or different origin (subduction or local faults). The Coulomb stress transfer has been studied, and some models have been developed, considering the rupture parameters derived from the geometric distribution of aftershocks. These models seem to confirm the interaction between the different series, the fact being relevant that the February 13 th event occurred in a zone where the Coulomb stress increased after the January 13 th event. In its turn, some of the further events with magnitude around 5 were located in other zones of stress increase associated to the two main previous shocks. All of which has contributed to infer conclusions about the mentioned interaction and to explain the intense activity by the triggering mechanism which apparently presents itself.

Key words: Coulomb stress transfer, subduction, volcanic chain events, aftershock distributions.

1. INTRODUCTION

The space-time evolution that have been seen for the two main earthquakes and their aftershocks series make special interesting the study of possible genetic relations between both events and the analysis of the dynamic modifications induced by such seismicity in its environment. These modifications could produce changes at short and medium time in the seismic hazard around the seismogenic sources in the region, as it has been proposed in other areas, for instance the Marmara area after the Izmit earthquake (Parsons et al, 2000).

For this reason we have carried out a modelization of the stress transfer produced by the main shocks on January 13 and February 13. Besides to know that possible changes, the aim of this study is identify the possible triggering process generated by the January earthquake, with magnitude M=7.7, which may explain the occurrence of the second main shock on February, M=6.6. The interest of the study is remarked by the evidence of that in the historical period often large seismic sequences of subduction events along the Cocos and Central America plates boundary with magnitude higher that 7 were followed by shallower crustal earthquakes in the volcanic chain in time intervals of years or months (Bommer 2002) The evidence suggest the existence of a more or less systematic mechanism related with a dynamic interaction.

It is known that the stress drop on a fault plane due to the occurrence of an earthquake, produces increase of effective shear stress around the rupture area (Chinery, 1963). This cosesimic transfer of the static stress may explain the generation and location of aftershocks and other main shocks at large distances of the fault, even at tens of kilometres, in those zones where the increase of the Coulomb failure stress (*CFS*) is higher than 1 bar. This fact has been recognized in numerous works in different geodynamic frameworks since 1980; i.e. Stein and Lisowsky, 1983; Jaume and Sikes, 1992; King et al, 1994; Toda et al, 1998). The peculiarities of the El Salvador seismic sequences give special interest to this kind of analysis, which is described as follows.

2. METHODOLOGY

After the failure criteria of Coulomb, a fault plane is activated when the Coulomb stress (*CFS*) exceed a value given by the equation 1:

$$CFS = \tau_{\beta} - \mu\,(\sigma_{\beta} - p) \qquad (1)$$

where τ_{β} is the shear stress over the fault plane, σ_{β} is the normal stress, p if the fluid preasure and μ is the frictional coefficient.

During the last ten years an important fact has been recognized: for different seismogenic areas and different magnitudes, modifications of *CFS* even minor to 1 bar, generated by a seismic event, are able to induce the reactivation of nearby faults which are close to its strength threshold; either as aftershocks activity or as larger earthquakes. This process has been described as a triggering process (King at al, 1994; Harris et al. 1995). It has been also observed that the triggering process involves not only the generation of aftershocks or major shocks, but also in the change of the seismic activity rate in a certain zone, increasing or decreasing it, during several months after the main shock (Stein, 1999).

3. APPLICATION OF THE METHOD

For the seismic series of 2001 in El Salvador, we have estimated the change in the static Coulomb failure stress by the expression given in the equation 2:

$$\Delta CFS = \Delta\tau_{\beta} - \mu\,(\Delta\sigma_{\beta} - p) \qquad (2)$$

where $\Delta\tau_{\beta}$ is considered positive in the sense of the slip fault, and $\Delta\sigma_{\beta}$ is also positive in compressional regime. The positive values for ΔCFS are interpreted as promoting the faulting, while negative values inhibit the activity.

We have estimated the stress change in an elastic half-space following the Okada (1992) method, taking for the shear modulus a value of 3.2* 10^{10} Nm^{-2} and for the Poisson coefficient a value of 0.25. The friction coefficient is taken as 0.75, which is a commonly observed value in deep drillings and is coherent with the experimental observations carried out in different lithologies (Byerlee law). Anyway the introduction of different values for the frictional coefficient, ranging from 0.4 and 0.8 doesn't produce significant changes in the obtained results. A compressive regional stress field has been considered, with σ_3 vertical and σ_1 horizontal, following the direction N35 ºE, agree with the convergence between the two litospheric plates in the Cocos-Caribean subduction zone. The absolute values taken for the stress are σ_1 = -500 bar (negative compression) and σ_3 = 500 bar, which are the common values *in situ* stress obtained in depth hole (Harris, 1998).

A model of stress transfer has been built for the rupture associated to the January 13 event, and other for that on February 13. The dimension and orientation of the surface ruptures are those obtained in the study of the spatial distribution presented in this volume, taken into account the focal mechanisms calculated in previous works. The ruptures are modelled as rectangles with the same area and the same shape factor as the ellipses calculated from the aftershocks.

The surface rupture estimated for the January earthquake (m=7.7) is around 2532 km^2 The focal mechanism calculated by Harvard, USGS, Buforn et al. (2001) and Bommer et al (2001), using different approaches (CMT and waves polarities) give practically the same orientation for the fault plane solution, between N 120º and 129º. This azimut agree with the azimut of the horizontal axis of the ellipse fitted with the aftershocks sequence. A bigger discrepance is found for the dipping of the fault, ranging from 48º NE to 63º NE, according to the different solutions. Taking into account the tridimensional geometry of the aftershocks, our model has been built by means of the introduction of a rupture plane oriented N128º E dipping 60º NE, in agreement with the mechanism of Buforn et al. (2001), and with the rupture solution given previously in this paper. The pitch of the slip vector used, is 98º, which corresponds with a normal fault. The aftershocks sequence draws the extension of the rupture between 15 and 78 km in depth.

In the case of the February event (m=6.6), the aftershocks distribution, as well as the focal mechanism estimated by USGS and Buforn et al (2001), hold a dextral strike slip rupture plane almost vertical, oriented N94º E dipping 70º SW, with a pitch of 180º. The rupture area previously estimated from the aftershocks distribution is 471 km^2. Either January as February rupture surface estimated are coherent with the empirical relationships magnitude/rupture area of Wells and Coppersmith (1994).

4. RESULTS AND INTERPRETATION

The application of the previous method allowed us to obtain a model of Coulomb failure stress change for the January 13 event, which is included in figure 1. The section A represents a Map view of the model for the January M 7.6 earthquake made for an horizontal plane at 14 km in depth, which is the focal depth of the 13 February, M 6.6 earthquake. The colour scale represent the different values in bars of the static coulomb stress change generated by the rupture on planes parallel to the local fault reactivated in February 13 (N 94º, 70º S). The epicentres of the main shocks and the aftershocks produced 48 hour after the two main shocks are also projected. Section B represents a cross section of the same model as showed in A. This figure shows that the February sequence occurs in an area where the January event produced an increase of CFS.

The stress change produced by the February event is in general lower, but the shallower character of the rupture produce strong effects in the surrounding area. Figure 2a. shows a Map view of the stress change produced by this strike slip event over planes parallel to the January rupture plane, calculated for a 5 km depth horizontal plane (focal depth of the 17 February event). The February 17 th, M 5.1, occurred on a lobe where CFS increased more than 0.8 bars. We also observe that the aftershocks area of the January event suffers either relative increase or also decrease of CFS. Figure 2b represents the model of CFS change produced by the two main ruptures (M 7.6 and 6.6) on planes parallel to February plane of rupture. After this event, significant areas of the continental volcanic zone are affected by increase of CFS higher than 0.5 Bars. The aftershocks with magnitude higher than 4.5 of Feb. 17, Feb. 24 and Nov. 11 occurred in areas of stress increase (Figure 2b). However, the two aftershocks of May 8 happened in lowered stress area. Nevertheless, these two aftershocks are very close to the rupture area of Feb. 13 event, where the dynamic development of static stress may be more complex. More transfer models should be performed to understand the interaction between this lower magnitude events.

Models using lower dipping (40º) of the rupture plane for the January 13 event, as values given by the statistical fit done purely with the aftershocks cloud without take into account the focal mechanism, produce a worse fit of the aftershocks. This may be other criteria for given a higher weight to plane of the model of the figure 1a, which is also agree with the focal mechanisms of Harvard (CMT) and Buforn et al. (2001

In summary we can conclude that the stress transfer generated by the January 13 event induced an increase of stress higher than 0.7 bars in the hypocentral zone of the February 13 event. 96,07 % of the aftershocks occurred during the 48 hours after the February main shock are located in an area of increased CFS and most of the aftershock drawing the rupture are located in the area with increase higher than 1.5 bars. In its turn, this February 13 shock produced other increase of 0.4 bars in the hypocentral zone of the February 17 event (figure 2 A).

On the other hand, the evolution of the aftershocks rate for the January sequence seems to show a complex short term dynamic evolution in the aftershocks area. The change of CFS produced by the February strike slip event induced an increase of CFS up to +0.2 bars in the western part of the January rupture area and decrease of CFS up to –0.18 bars in the eastern part. This process, repeated for all the local events with m>4.5, may induce alternatively stress increase and stress decrease either in the time as in the space, generating the observed complex evolution in the aftershocks rate.

The correlation between CFS increasing zones and observed seismicity in 2001, together with the historical evidences about the succession of events in the two different sources types, hold in a clear way the triggering mechanism in the region. According to this mechanism, the events of high magnitude bigger than 7, generated in the subducted Cocos plate converging with the Caribean plate in the Middle America Trench, are able of reactivate strike slip faults in the continental plate. The magnitudes produced by the events in these faults are smaller, but its destructive potential is higher due to they are very shallow ruptures. This process must be study in depth, with the aim of quantifying its influence at short and medium time in the activity rate in the zone, with the subsequent reflect in the transitory modifications of the seismic hazard at the zone.

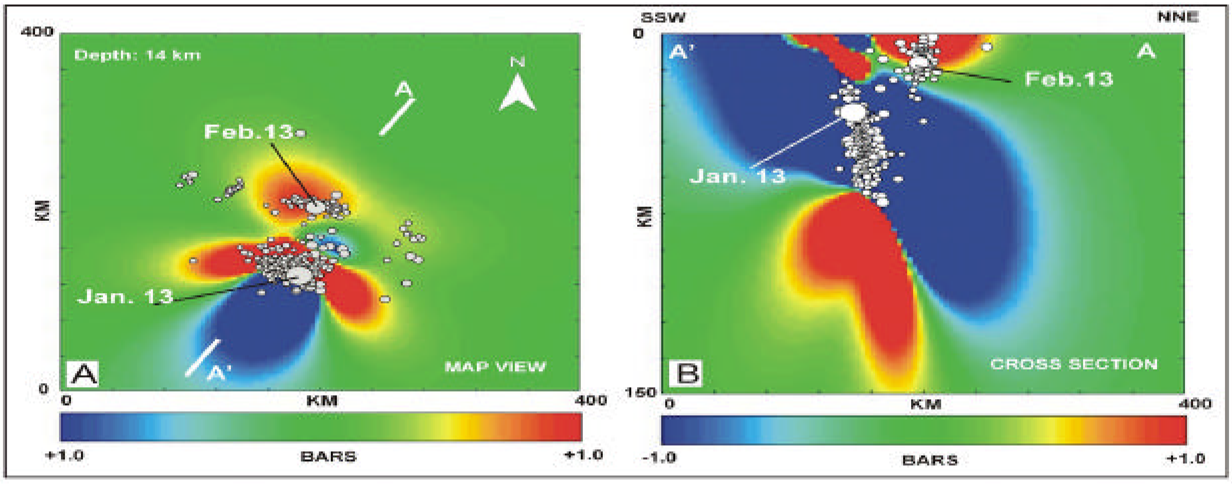

Figure 1. ***Coulomb stress transfer produced by the January 13 2001 subduction earthquake. Yellow and red colours show the areas where the stress are increased, and blue represents the areas where stress decrease. A: map view for an horizontal plane 14 km depth. B: NE-SW Cross section view. The epicentres and hypocentres of the aftershocks occurred within the 48 hour after the two main shocks (13 January and 13 February) are showed. The location of the February sequence seems to be controlled by the lobe of increased stress produced by the first event.***

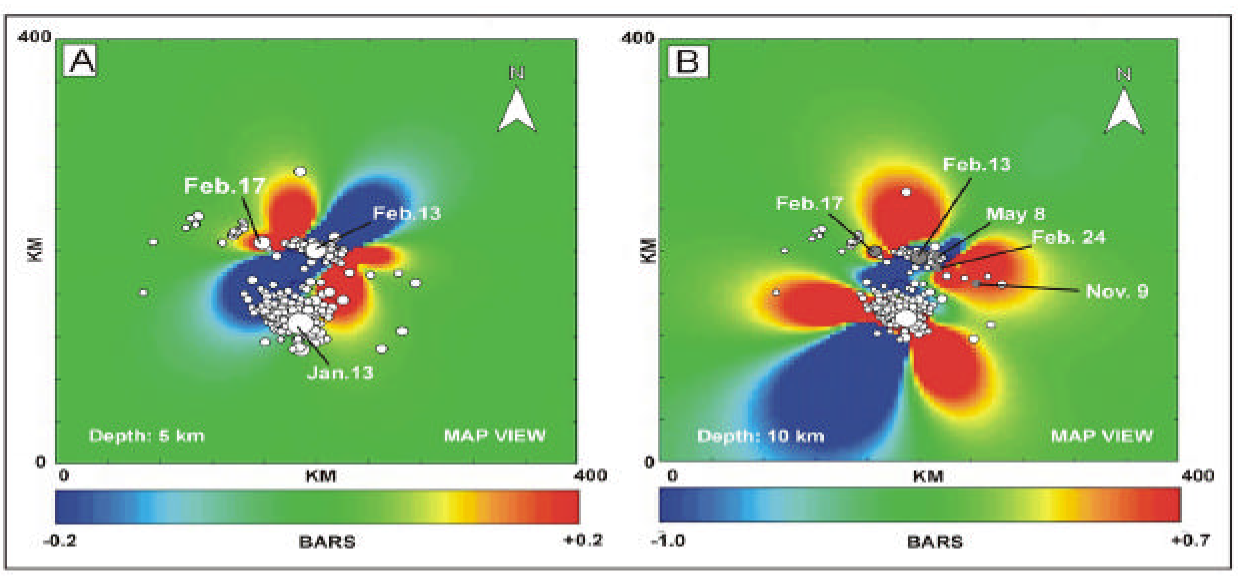

Figure 2. ***Coulomb stress transfer produced by the February 13 2001 local strike slip earthquake. A. Model in map view for an horizontal plane at the focal depth of the february 17 event (5 km). This event occurred in a lobe of stress increase. B: Stress transfer model for the two main shocks together in map view for an horizontal plane 10 km depth. The grey circles are the aftershoks of the volcanic area with magnitude higher than 4.5 that occurred after the 13 February event. Only the aftershocks of May 8 occurs in an area with lowered.***

5. CONCLUSIONS

A study of the stress transfer after the two main occurred in El Salvador during 2001 has been carried out, which aims to confirm the results already found in the analysis of the spatial and temporal evolution. The January 13 th event seems act as trigger mechanism for other events.

In particular, the study of the stress transfer after the two main shocks lead us conclude that the February 13 th event occurred in a zone with an increase of Coulomb stress, (> 0.8 bar) due to the rupture effect of the January 13 th event. Something similar is observed with further events which took place on February 17 th, due to the stress modification after the two previous shocks. Besides to detect a triggering mechanism by the occurrence of the main shocks, the stress change seems also to have influenced the aftershock rate associated with the process. All of that may be of great importance to the seismic hazard of the region.

Finally it is worth emphasizing the importance of the behaviour of certain events as triggers of other events with a different origin in the seismic hazard of the region, and in other zones with similar tectonic regime. It would be convenient to investigate the conditions in which a subduction event may interact with other local events of the volcanic chain, and to repeat processes such as the one studied in this work, something which we propose as open research for the future. If the triggering mechanism is confirmed in a systematic way, it would be necessary to estimate the probability of the phenomena could be repeated in the future, with the subsequente variation of the seismic hazard at the region.

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REFERENCES

Bommer, J; B. Benito; M. Ciudad-Real; A. Lemoine; M. Lopez-Menjivar; R. Madariaga; J. Mankelow; P. Mendez-Hasbun; W. Murphy; M. Nieto-Lovo; C. Rodríguez and H. Rosa. The Salvador Earthquakes of January and February 2001: Context, characteristics and implications

Buforn, E; A. Lemoine; A. Udias and R. Madariaga (2001). Mecanismo focal de los terremotos de El Salvador**.** *2º Congreso Iberoamericano de Ingeniería Sísmica,* Octubre 2001, Madrid.

Chinery, M.A. (1963) The stress changes that accompany strike-slip faulting. *Bull. Seismol. Soc. Am*. 53, 921-932.

Harris, R.A., Simpson, R.W. and Reasenberg, P,A. (1995): Influence of static stress changes on earthquake locations in southern California. Nature, 375: 221-224.

Jaumé, S C y Sykes, L. R. (1992). Change in the state of stress on the southern San Andreas Fault resulting from the California earthquake earthquake of April to June 1992. Science, 258, 1325-1328.

King, G. C. P., Stein, R. S. y Lin, J (1994). Static stress changes and the triggering of earthquakes. *Bull. Seismol. Soc. Amer*. 84, 935-953.

Okada, Y. (1992): Internal deformation due to shear and tensile faults in a half space. *Bulletin of the Seismological Society of America*, 82, 1018-1040.

Parsons, T., Toda, S., Stein, R., Barka, A y Dieterich, J. (2000). Heightened odds of large earthquakes near Istanbul: An interaction based probability calculation *Science*, 288, 661-665.

Stein, R. S. y Lisowski, M. (1983). The Homestead Valley earthquake sequence, California: Control of aftershocks and postseismic deformations. *J. Geophys. Res*. 88, 6477-6490.

Stein, R. S. (1999). The role of stress transfer in earthquake recurrence. *Nature*, 402, 605-609.

Toda, S., Stein, RS, Reasenberg, P.A. y Dieterich, JH. (1998). Stress transferred by the Mw= 6.5 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities. *J. Geophys. Res*. 103, 24543-24565 of April to June 1992