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Evidence for Static Stress Changes Triggering the 1999 Eruption of Cerro Negro Volcano, Nicaragua and Regional Aftershock Sequences

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Evidence for static stress changes triggering the 1999 eruption of Cerro Negro Volcano, Nicaragua and regional aftershock sequences

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[1] Remarkable evidence of coupling between tectonic and magmatic events emerges from investigation of three tectonic earthquakes, aftershock sequences and eruption of Cerro Negro volcano, Nicaragua in 1999. Here, we explain this coupling through static stress changes following three Mw 5.2 earthquakes. We use focal mechanism solutions to estimate fault system geometry and magnitude of slip from these events, which are then used to calculate the change in minimum horizontal principal stress (σ_3) for the region and the change in Coulomb failure stress on optimally oriented fault planes. Results of these simulations indicate that σ_3 was reduced by ~0.08 MPa and that Coulomb failure stress was raised by 0.001 to 0.2 MPa in the region. A Kolmogorov-Smirnov test demonstrates spatial correlation of Coulomb failure stress changes and triggered seismicity and volcanism, and suggests that these small changes in static stress can trigger subsequent geophysical events under appropriate circumstances. **Citation:** Díez, M., P. C. La Femina, C. B. Connor, W. Strauch, and V. Tenorio (2005), Evidence for static stress changes triggering the 1999 eruption of Cerro Negro Volcano, Nicaragua and regional aftershock sequences, Geophys. Res. Lett., 32, L04309, doi:10.1029/2004GL021788.

1. Introduction

[2] Recent observations at numerous volcanoes have suggested coupling between volcanic activity and increased tectonic earthquakes [e.g., *Nostro et al.*, 1998; *Toda et al.*, 2002]. This coupling may exist across large spatial and temporal scales [*Hill et al.*, 1993, 2002]. Triggering of eruptive activity by earthquakes, or vice versa, relies on the idea that small changes in static and dynamic stresses (~1 bar or 0.1 MPa) in the crust can prompt such activity because these systems exist at a point near failure. The triggering mechanisms are not completely understood, but possible mechanisms for eruption triggering include; a) relaxation of the minimum principal stress (σ_3) such that magma conduits open to magma flow [*Nostro et al.*, 1998]; b) increase in σ_3 compressing magma chambers or similar reservoirs [*Bautista et al.*, 1996; *Nostro et al.*, 1998], and c) rectified diffusion of volatiles in the magma and other magma chamber processes caused by passage of seismic waves, resulting in higher magmatic pressures [*Linde et al.*, 1994;

Sturtevant et al., 1996]. In addition, clear evidence exists for initiation of earthquake swarms in response to magma intrusion [*Hill*, 1977; *Toda et al.*, 2002].

[3] The 1999 eruption of Cerro Negro volcano, Nicaragua and regional seismicity, provide a remarkable example of how three small (~M_w 5) earthquakes in close proximity to a volcano can trigger a small volume eruption (~0.001 km^3, DRE) and regional aftershock sequences [*La Femina et al.*, 2004] (Figure 1). *La Femina et al.* [2004] demonstrate that conduit flow models of the 1999 eruption are consistent with low magmatic overpressures, indicating that the eruption could have been triggered by dilation along the Cerro Negro - La Mula volcanic alignment. Here, we present results of static stress change calculations that indicate the three earthquakes decreased the minimum horizontal principal stress and increased the Coulomb failure stress in the region promoting eruption and triggered seismicity, respectively. As static stress changes calculated are on the order of those found to trigger earthquakes elsewhere [*Ziv and Rubin*, 2000], our observed correlations suggest that even small magnitude events, in close proximity to one another, may be linked by static stress changes.

2. 1999 Aftershock Sequences and Eruption of Cerro Negro

[4] Cerro Negro volcano is an active cinder cone, most recently erupting in 1992, 1995, and 1999 [*Roggensack et al.*, 1997; *McKnight and Williams*, 1997; *Hill et al.*, 1998]. The volcano is located on the Quaternary volcanic arc of western Nicaragua (Figure 1). It is the most recent volcano formed in a field of basaltic cinder cones and maars on the north and west flanks of the El Hoyo volcano complex. Cerro Negro forms the southern portion of the north trending, 3.5-km-long Cerro La Mula - Cerro Negro vent alignment. Vents formed on the edifice of Cerro Negro and just off its south flank in 1968, 1995, and 1999 extend this overall trend. Continuing development of this alignment is consistent with the inferred orientation of the stress field in this area. In this part of Nicaragua, trench parallel dextral shear of approximately 8–14 mm/yr [*DeMets*, 2001; *Turner et al.*, 2003] results in a maximum horizontal principal stress oriented between N350°E and N10°E. This stress is accommodated largely by slip along northeast-trending left-lateral faults and by east-west extension along volcanic alignments, rather than directly by dextral slip on trench parallel faults [*La Femina et al.*, 2002]. This tectonic setting sets the stage for interaction between closely spaced active volcanoes and faults.

[5] On August 5, 1999 three earthquakes, two Mw 5.2 and one Mw 5.1, occurred during a period of three hours, ~1–2 km east-northeast of Cerro Negro [*Instituto Nicaraguense*

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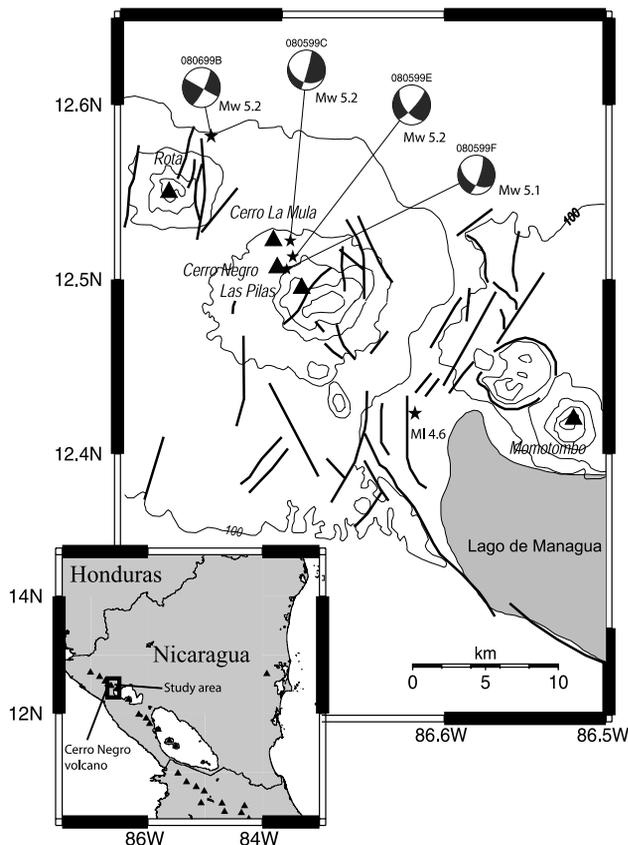
Figure 1. Location map for Cerro Negro volcano and nearby Quaternary volcanoes Las Pilas, Rota, Cerro La Mula and Momotombo (black triangles). Epicenter locations (black stars) and focal mechanisms are shown for $M_w > 5$ earthquakes on 5–7 August, 1999 (see Table 1). Solid black lines are known Quaternary faults. Note faults striking NE (left-lateral), NW (right-lateral) and N-S (dip-slip). 100 m topographic contours are shown as light gray lines. Study area shown inset (black box), within Central America volcanic Arc (historically active volcanoes shown with black triangles).

de Estudios Territoriales (INETER), 1999; Dziewonski et al., 2000]. Following these events, seismicity was increased in the region for five days (597 earthquakes) and included an M_w 5.2 earthquake on August 6 and M_l 4.6 on August 7. Aftershocks were triggered northwest and southeast of the initial epicenters and clustered on alignments that are consistent with mapped northeast-trending left-lateral faults. The aftershock sequences exhibit a power law decrease with time that matches models of seismic swarm behavior [Toda et al., 2002]. Cerro Negro erupted 11 hours after the initial earthquake, along a ~200 m long north trending fracture south of the volcano's edifice. Fire fountaining associated with this activity occurred to heights of 300 m from two scoria cones that coalesced along the initial fracture. Real-time seismic amplitude measurements (RSAM) were at background levels prior to the three earthquakes. There were no other geophysical signs of precursory volcanic activity [La Femina et al., 2004]. Cerro Negro does not typically have long periods of geophysical unrest prior to eruptive activity, however, for larger volume and longer duration

eruptions, such as 1995, eruptive activity may progress from phreatic to magmatic activity over days to months. Cumulatively this is the smallest and shortest duration eruption (3 days versus a mean of 18 days for eruptions with known durations) to have occurred at Cerro Negro since its formation in 1850 [Hill et al., 1998].

3. Fault Geometry and Slip

[6] We use Harvard CMT focal mechanism solutions and earthquake relocations from the INETER seismic network [INETER, 1999; Dziewonski et al., 2000] to calculate static stress changes induced by the three earthquakes. The former data are used to derive fault geometry and slip parameters [Wells and Coppersmith, 1994]. All fault and stress field parameters required to estimate the stress change associated with these earthquakes are provided in Table 1.

[7] Stress changes are calculated using methods proposed by Chinnery [1961, 1963] and implemented in the computer code POLY3D [Thomas, 1993]. In these models the upper crust is represented as an elastic half-space and faults are rectangular dislocation surfaces in this half-space. We consider changes in σ_3 (Figures 2a and 2b) and Coulomb failure stress changes associated with slip on only the northeast-trending fault planes. We consider dilation (σ_3) perpendicular to the N-S trending volcano alignment. Coulomb failure stress changes (CFSC) are calculated for planes with an optimal orientation for failure fixed by the regional stress field [King et al., 1994], and map the tendency for N30°E faults to slip (Figure 3). The CFSC was calculated for each of the three earthquakes, indicating that the first event could have triggered the second event and that the first and second in turn could have triggered the third. The auxiliary nodal fault planes (i.e., northwest-trending dextral faults) were modeled, however, the results were not consistent with observations.

4. Results

[8] Model results indicate that the static stress change resulting from the three ~Mw 5 earthquakes reduced σ_3, and increased Coulomb failure stress on northeast oriented fault

Table 1. Fault Geometry and Slip For Three Earthquakes on 5 August, 1999 (Figure 1)

	080599C	080599E	080599F
Date	8/5/1999	8/5/1999	8/5/1999
Time (GMT)	4:35:55	5:31:52	7:11:20
Latitude	12.522N	12.512N	12.506N
Longitude	86.695W	86.693W	86.697W
Depth (km)(to center of fault plane)	10	10	10
M_w	5.2	5.2	5.1
Strike	17°	44°	20°
Dip (west)	87°	78°	75°
Rake	−51°	−33°	−43°
SRL[a] (km)	4.5	4.5	4
RA[b] (km^2)	18	18	14.8
AD[c] (cm)	2.2	2.2	1.8
Dx[d] (cm)	1.4	1.8	1.3
Dy[e] (cm)	1.7	1.2	1.2

[a]Surface rupture length.
[b]Rupture area.
[c]Average displacement.
[d]Horizontal component of displacement.
[e]Vertical component of displacement.

Minimum Principle Stress (MPa)
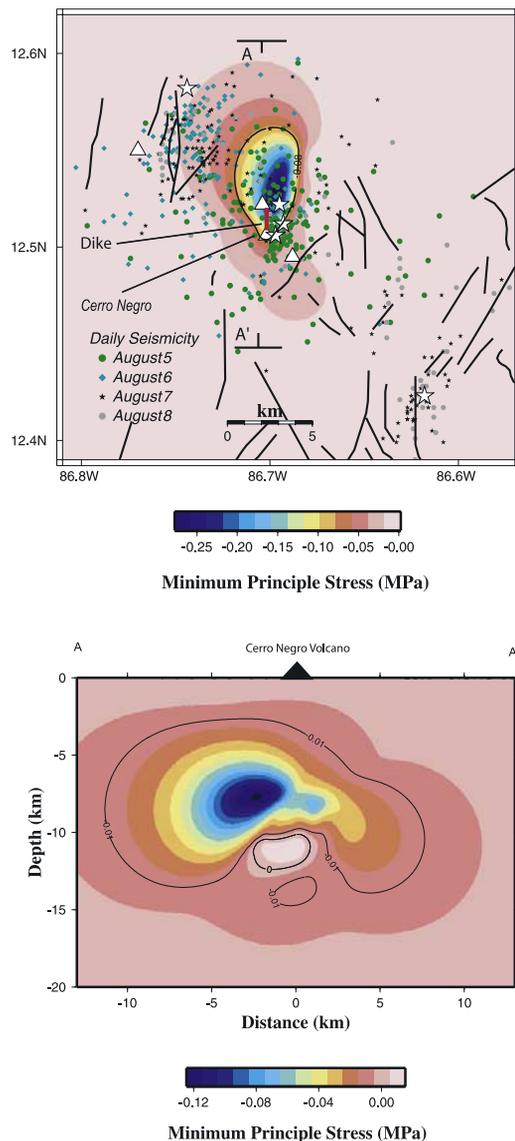

Minimum Principle Stress (MPa)

Figure 2. (a) Map of calculated change in σ_3 resulting from slip on three fault planes (Table 1) with epicenters shown as white stars. Daily seismicity is indicated for 5–8 August. Note stress reduction at Cerro Negro, consistent with dike injection following 5 August seismicity. Other symbols as in Figure 1. Cross section (Figure 2b) indicated by A-A′. (b) Stress change in σ_3 calculated for a N-S plane through Cerro Negro volcano (Figure 2a), using fault geometry shown in Table 1. Note stress reduction and stress gradient in this plane, consistent with dike injection.

planes in the region. Near Cerro Negro volcano, σ_3 was reduced by up to 0.08 MPa at a depth of 7 km (Figure 2a). These values are within the range of stress changes observed to precede eruptions in other volcanic systems [*Nostro et al.*, 1998]. The greatest reduction in σ_3 is estimated north of Cerro Negro; however, volcanoes in this region (e.g., Cerro La Mula) are inactive and not likely underlain by a magma reservoir. The model predicts that high stress gradients will occur within a north-south oriented plane, located beneath the Cerro La Mula – Cerro Negro alignment (Figure 2b). Parts of this plane experience stress reduction in response to the seismicity, aiding the tendency for fractures to dilate.
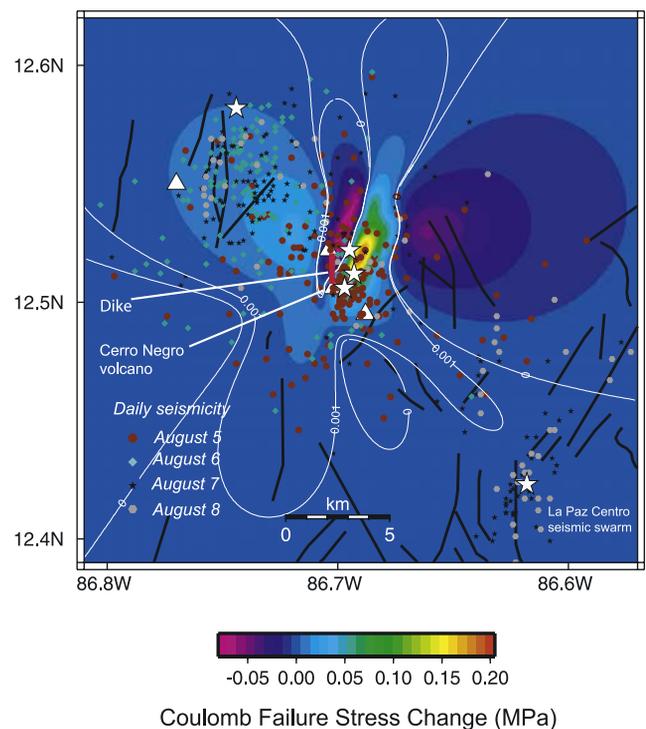

Coulomb Failure Stress Change (MPa)

Figure 3. Coulomb failure stress change (CFSC) calculated using fault geometry and slip data of the three earthquakes (Table 1) and methods of *Thomas* [1993] and *King et al.* [1994]. Note the asymmetry of the CFSC pattern, possibly due to dip-slip components along the fault planes. An exception is seismicity near Cerro Negro volcano, attributed to dike injection and eruption. Other symbols as in Figure 1.

[9] The distribution of epicenters associated with the aftershock sequences in relation to CFSC is considered in Figure 3. We used the Kolmogorov-Smirnov test [*Davis*, 2002] to calculate the probability of the epicenters occurring
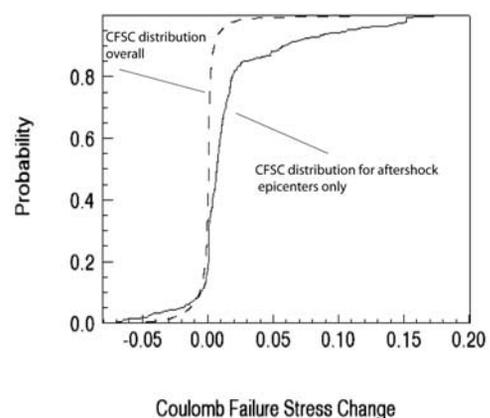

Figure 4. Comparison of the Coulomb failure stress change (CFSC) distribution over the entire area of study and the CFSC distribution where epicenters in the aftershock sequences occurred (August 5, 6, 7 and 8). The distribution of epicenters is not random with respect to the CFSC model with greater than 99% confidence (Kolmogorov-Smirnov test for cumulative distributions). That is, epicenters of the aftershock sequences have a statistically significant tendency to occur in areas of high CFSC.

randomly versus being located in zones of positive CFSC (Figure 4). Hypocenter clusters tend to occur in regions of positive CFSC on the order of 0.01–0.04 MPa. Specifically, aftershocks including an Mw 5.2 earthquake occurred August 6 near Rota volcano, approximately 5 km NNW of Cerro Negro volcano. This aftershock sequence is located within a zone of positive CFSC. Epicenters north of Cerro Negro are in a zone of negative CFSC. Models of CFSC for dike opening indicate that these earthquakes occur in regions of negative CFSC. Two days later, an aftershock sequence occurred at La Paz Centro following a M_l 4.6 earthquake, where modeled CFSC < 0.001 MPa (Figure 3).

5. Discussion and Conclusions

[10] This study relies on the close temporal and spatial association of earthquakes and the volcanic eruption to infer stress triggering of these events. Eruptive activity at Cerro Negro before 1999 occurred in 1995. The 1995 eruption, like others from Cerro Negro, was larger volume than the 1999 eruption and not preceded by tectonic earthquakes. No record exists of a regional triggered magma-tectonic activity like the one that occurred August 5–8, 1999, ever occurring in this area before. In light of this comparative paucity of prior coupled activity, we do not regard the coincidence of the three earthquakes, the regional after-shock sequences and eruption, as possibly occurring by random chance.

[11] Our model of static stress change indicates that reduction in σ_3 on the order of 0.01–0.1 MPa is sufficient to trigger the eruption, and suggests that these stress changes can accompany even small magnitude earthquakes, if they are located sufficiently close to the magma reservoir. Stress reduction, up to 0.08 MPa (Figures 2a and 2b), is particularly effective at depths of 5–10 km. Other parts of this plane (depth $\geq$ 10 km) experience compression. Compression at depth and dilation closer to the surface may drive upward magma flow [*Nostro et al.*, 1998].

[12] In conclusion, the remarkable geophysical events in the area about Cerro Negro volcano on August 5–8, 1999, clearly indicate that a finely balanced state of stress exists along the volcanic arc. In this one example, small changes in this state resulted in dramatic effects.

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