Nonvolcanic Tremor Activity in the Parkfield-Cholame Region of California

U33A-0046

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2008 AGU FALL MEETING 15-19 DECEMBER · SAN FRANCISCO

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Abstract

We investigate the possible relationship between nonvolcanic tremor (NVT) activity and fault zone processes responsible for the generation of earthquakes. NVTs correlate with deep slow slip events along subduction zones in Japan and Cascadia and recently it has been observed that tidal stresses as well as dynamic stress changes produced by the passage of surface waves from large teleseisms are capable of inducing NVT activity. These observations suggest that tremor rate changes are closely related to and even stimulated by stress changes in deep fault zones. The computed values of tidal and dynamic stress changes also appear to be small, on the order of a few kilopascals, indicating that NVTs are more sensitive to stress changes than triggered earthquakes.
We present a multi-year analysis of the NVT activity since August 2001 along the San Andreas Fault near Cholame, California detected and located using envelope cross-correlation methods. During this period two strong earthquakes occurred in proximity of the tremor-generating region: the 2003 M6.5 San Simeon and 2004 M6.0 Parkfield earthquakes. We qualitatively and quantitatively show that since these two events, long-term background NVT activity rates have increased. Our calculations of static Coulomb stress changes induced by the two earthquakes show that the amplitude of the static stress changes is small (below a few tens of kilopascals) but that they are enough to activate tremor activity and that the degree of stress change transmitted into the tremor zone correlates with the degree of tremor activation. Finally we show that a new pattern in the NVT activity has also emerged following the 2004 Parkfield event with the occurrence of quasi-periodic tremor episodes that have persisted well into 2008. Our results suggest that NVT activity can provide clues to variations in fault zone stress levels at tremor depth.

A. Nonvolcanic tremor activity

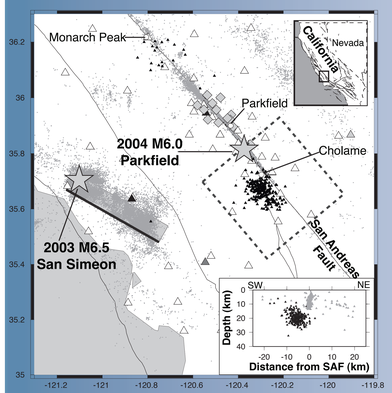

Figure 1: Map and cross-section of the NVT activity along the San Andreas Fault at Parkfield.
The black dots represent the best NVT locations for 2006 and 2007. The background seismicity (M>=0) is shown by the gray dots. The dashed box defines the area (40 by 40 km) considered in our study. The stars indicate the epicenters of the 2003 M6.5 San Simeon and 2004 M6.0 Parkfield earthquakes.

- Since August 2001
- Similar techniques for the detection and location as previously described by Obara
- Precise location: double-difference and bootstrap

- Locations constrained within a 25 km radius zone
- 90 % around the town of Cholame
- Deep: between 15 and 30 km depth
- Use of different smoothings

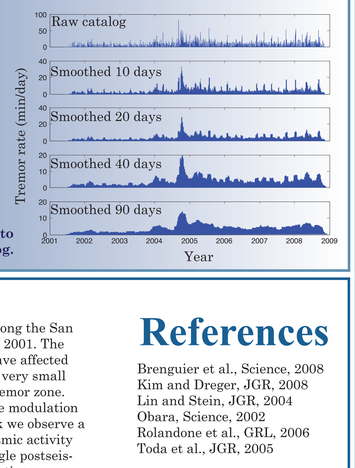

Figure 2: Various smoothings applied to the tremor catalog.

B. Tremor evolution

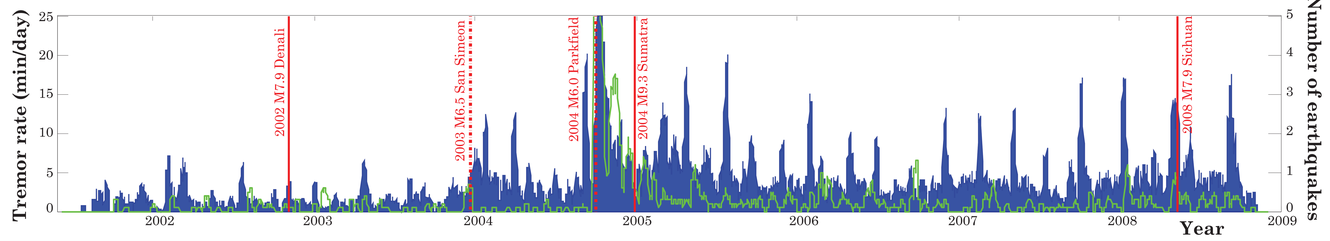

Figure 3: Time evolution of the NVT and earthquake activities in the Parkfield-Cholame region.
More than seven years of NVT detection are presented in blue, smoothed over a 10-day period. The green line representing the M>=0 earthquake activity located in the dashed box of Figure 1 allows a direct comparison of the time evolution of the two types of seismic events.
One can notice the occurrence of the 2003 M6.5 San Simeon and 2004 M6.0 Parkfield earthquakes and compare their effects on the NVT and earthquake activities. Also for information, three large earthquakes are indicated here: the 2002 M7.9 Denali, 2004 M9.3 Sumatra and 2008 M7.9 Sichuan earthquakes.

C. Stress transfer and tremors

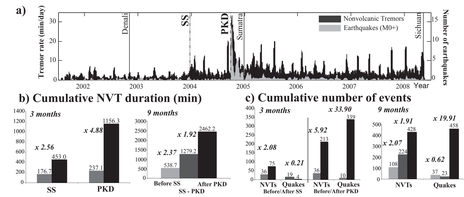

Figure 4: Comparison of the effects of the 2003 M6.5 San Simeon and 2004 M6.0 Parkfield earthquakes on the NVT activity and the seismicity in the vicinity of Parkfield-Cholame.
Sensitive increases in the cumulative duration as well as in the cumulative number of tremors are observed following the two moderate regional earthquakes over 3-month and 9-month periods.
In comparison no significant change is observed after the San Simeon earthquake in the seismicity but there is a very strong increase of the earthquake rate after Parkfield.

- Significant increase of the NVT activity after San Simeon and Parkfield earthquakes
- Contrasts in the seismicity rate after the two mainshocks: no change after San Simeon.
- Computation of static Coulomb, shear and normal stress changes for the two mainshocks
- NVTs in the positive lobes of the Coulomb and shear stress changes
- Very small changes: in the order of the kiloPascal (0.01 bar = 1.0 kPa)

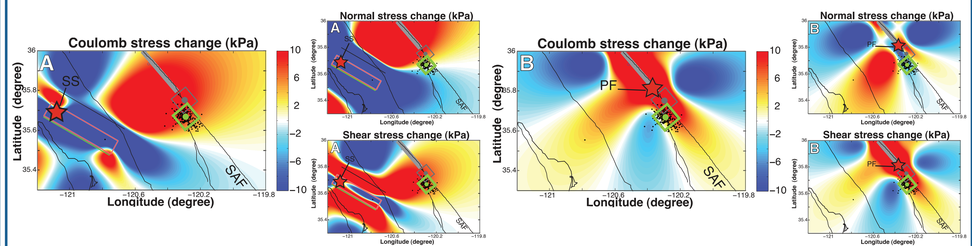

Figure 5: Static stress change maps at 20 km depth for the 2003 M6.5 San Simeon (A) and 2004 M6.0 Parkfield (B) earthquakes.
The stress changes are computed for planes with orientation of the San Andreas Fault at Parkfield (140 strike, 90 dip and 180 rake) using Coulomb3.1 and the finite-source models of Rolandone et al., 2006 and Kim and Dreger, 2008. The red stars locate the epicenters of the events, the green box defines a 10 by 10 km region centered on the best locations of the tremors, and the gray box, also 10 by 10 km, delimits the earthquake region from the 40 km by 40 km area defined in Figure 1.

Stress changes in 10 km by 10 km box (kPa)			Minimum	25%	Mean	75%	Maximum
Tremor zone 20 km depth	San Simeon	Coulomb	4.95	6.71	8.05	9.40	11.52
		Shear	5.83	6.80	7.54	8.36	10.33
		Normal	-3.08	-0.39	1.02	2.69	5.14
	Parkfield	Coulomb	-1.97	2.26	6.87	10.87	21.56
		Shear	-1.91	3.62	8.11	11.79	21.69
		Normal	-5.96	-3.85	-3.02	-2.01	-0.14
Earthquake zone 8 km depth	San Simeon	Coulomb	11.35	14.01	15.57	17.37	21.77
		Shear	8.35	9.78	10.78	11.91	13.68
		Normal	4.51	8.66	12.29	15.63	21.76
	Parkfield	Coulomb	-484.90	-18.33	23.43	46.31	642.25
		Shear	-325.59	-14.03	24.96	49.75	640.40
		Normal	-398.28	-14.04	-4.99	13.02	453.63

Table 1: Static stress values in the nonvolcanic tremor region following the two moderate regional earthquakes.
We compare the stress level received in the Parkfield -Cholame region at 8 km depth (seismogenic depth in the gray box of Figure 5) and at 20 km depth (tremor depth in the green area shown in Figure 5).

0.01 bars = 1 kPa

D. Tremor bursts

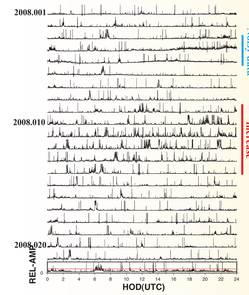

Figure 6: Significant tremor activity observed on a series of daily seismic envelopes, from 01/01/2008 to 01/22/2008.
2008.011 is the calculated middle time of this tremor burst. One can notice a relatively quiescence in the tremor activity before and after the peak, excluding a few noisy days before. The red line at the bottom materializes the threshold used in our tremor detection.

- Remaining elevated NVT activity
- Quasi-periodic peaks of tremors
- Estimation of the peak times with the 20- and 40- days smoothings

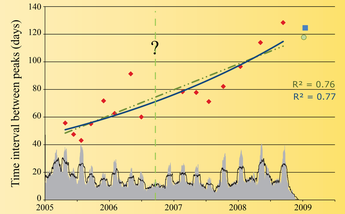

Figure 7: Peak time interval study after the Parkfield earthquake.
Bursts of tremors are observed following the Parkfield event. Using 20-day (gray fill) and 40-day (black line) smoothings we define the peak times and we estimate a time interval. The dashed green and blue curves are the linear and exponential fits, respectively.

- Postseismic relaxation after the Parkfield earthquake explaining the emergence of the peaks?
  - Time interval increasing with time
  - Decay of the NVT activity following Parkfield
- Influence of large worldwide earthquakes?
  - No direct correlation between the time of the earthquakes and the time of the peaks

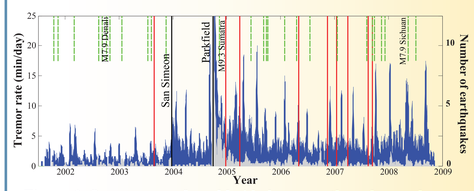

Figure 8: Occurrence of worldwide large earthquakes and comparison with the tremor activity in the Parkfield Cholame region.
M8+ earthquakes are indicated in red, and the dashed green lines represent the M7.5-7.9 earthquakes. Continuous nonvolcanic tremor activity at Parkfield in blue and seismicity (in light gray) do not show a strong correlation with the worldwide earthquakes.

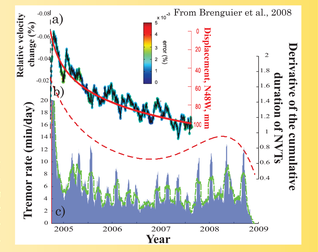

Figure 9: Postseismic relaxation at Parkfield after the 2004 Parkfield mainshock
a) Adapted from Brenguier *et al.*, 2008. Seismic velocity changes and surface displacements from GPS. The red curve shows the postseismic fault-parallel displacements along the San Andreas Fault as measured by GPS. b) Derivative of the cumulative duration of tremors at Parkfield since the Parkfield mainshock, fitted by a polynomial function (dashed red curve). c) Tremor rate observed at Parkfield, in blue (smoothed over 20 days) and in green (smoothed over 40 days).

Conclusions

A continuous NVT activity in Parkfield is detected along the San Andreas Fault in the Parkfield Cholame region since 2001. The 2003 San Simeon and 2004 Parkfield earthquakes have affected the tremor rate. We show that NVTs are sensitive to very small amounts of static shear stress transferred into the tremor zone. The modulation of NVTs appears to correspond to the modulation in the stress transfer. Following Parkfield mainshock we observe a decay of the NVT activity corresponding to a postseismic activity with quasi-periodic peaks of tremors. However, a single postseismic relaxation does not appear to explain our observations.

References

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