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# Observations of rapid-fire event tremor at Lascar volcano, Chile

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## Abstract

During the Proyecto de Investigación Sismológica de la Cordillera Occidental (PISCO '94) in the Atacama desert of Northern Chile, a continuously recording broadband seismic station was installed to the NW of the currently active volcano, Lascar. For the month of April, 1994, an additional network of three, short period, three-component stations was deployed around the volcano to help discriminate its seismic signals from other local seismicity. During the deployment, the volcanic activity at Lascar appeared to be limited mainly to the emission of steam and $SO_2$. Tremor from Lascar is a random, «rapid-fire» series of events with a wide range of amplitudes and a quasi-fractal structure. The tremor is generated by an ensemble of independent elementary sources clustered in the volcanic edifice. In the short-term, the excitation of the sources fluctuates strongly, while the long-term power spectrum is very stationary.

**Key words** *volcano seismology – volcanic tremor – rapid-fire events – Lascar volcano*

## 1. Introduction

During the first half of 1994, an array of digital three-component seismometers was deployed in Northern Chile between 19.5° and 25.5°S and between the coast Cordillera and the Altiplano in the Central Andes as part of the Proyecto de Investigación Sismológica de la Cordillera Occidental 94 (PISCO '94). The array consisted of twenty short-period, three-component seismometers (L-4), augmented by four STS-2 and four Guralp broadband instruments (fig. 1). This deployment was part of an investigation of active deformation processes in the Central Andes. The continuous recordings with a high sampling rate and a large dynamic range obtained during the four month deployment will help to produce a detailed picture of the local and regional distribution of seismicity with the aim of precisely locating the depth of the subducting plate.

Near the center of the study region is the volcano Lascar. After a long period of dormancy, it renewed activity on 18 April 1993 with its largest historical eruption (Bulletin of the Global Volcanism Network (GVN), April, 1993; Gardeweg and Medina, 1994). Accompanying ash, which rose more than 25 km into the atmosphere, several large pyroclastic flows descended the north and south flanks of the volcano. By the time of the PISCO '94 deployment, the level of activity had decreased considerably (GVN, March, 1994). Plumes of water and $SO_2$ were visible above its summit at all times. Nonetheless, Lascar remained the source of a wide spectrum of seismic signals. To monitor these signals, three short-period, three-component seismometers were placed close to the volcano during the month of April, 1994, to augment the STS-2 seismometer located on the NW flank of the volcano during the entire deployment (fig. 2). The broadband-station was located about 5.5 km from the active vent near the upper end of the Talabre gorge. The short-period stations were located to the SW, the S and the NE of Lascar. Digital recording was continuous with sampling rates of 100 Hz for the broadband seismometer and 200 Hz for the short-period stations. During these seismic observations, the volcano showed no visual signs of a change in the level of its activity.

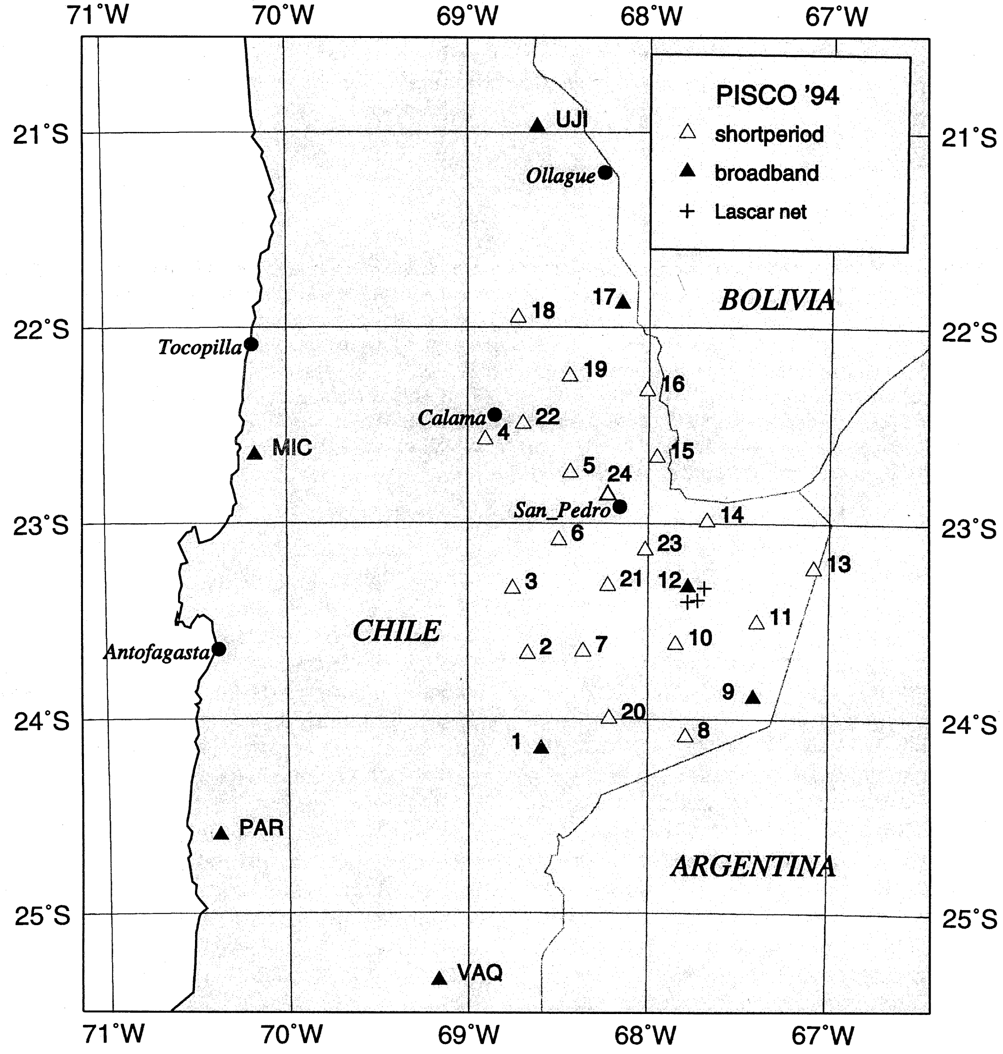


**Fig. 1.** Map of PISCO '94 digital seismic network. Hollow triangles are Mark L-4 three-component seismometers (1 Hz), filled triangles of stations 1, 9, 12 and 17 are STS-2 broadband seismometers. The stations of the Lascar net (+) were equipped with L-4 three-component seismometers. Stations VAQ, PAR, MIC and UJI were equipped with Guralps.

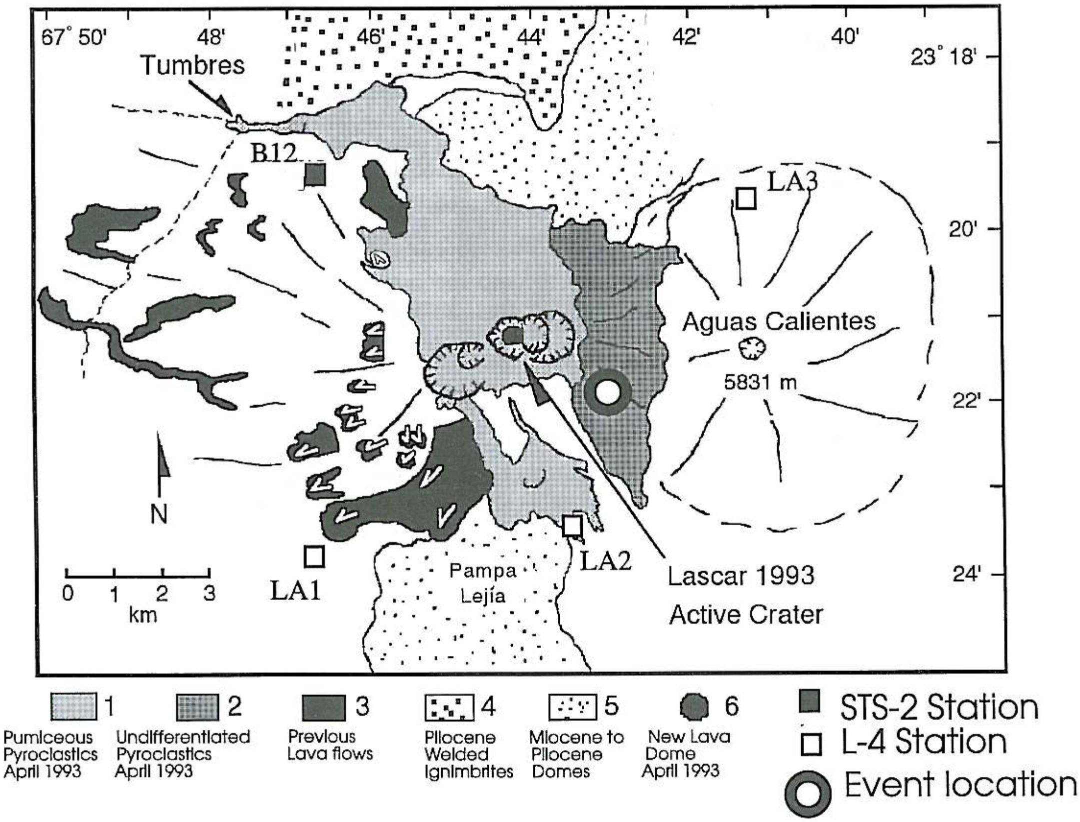


**Fig. 2.** Sketch of Lascar-Aguas Calientes volcanic complex after the April 1993 eruption taken from April 1993 GVN with permission of M. Gardeweg. The Lascar network consists of one broadband station (B12) and three short period stations. The bold circle marks the approximate location determined for three very large Lascar events.

## 2. Observations

While the classification of tremor waveforms is fundamental to monitoring volcanic activity, its quantitative characterization is currently evolving as observations from disparate volcanos become available. The features of recorded tremor which lend themselves for use in classification are the pattern of the waveforms, described by their randomness, and ensemble characteristics such as stationarity and regularity. Tremor with predominantly random character has been described as stationary, non-stationary (*e.g.*, banded tremor) or as having a regular envelope (*e.g.*, beating tremor). Among other characteristics, regular tremor forms may have a harmonic signature (*e.g.*, harmonic tremor or tornillos, Julian, 1994). Regular tremor may be generated by oscillations of geometrically simple gas or magma bodies within the volcano. Random tremor with peaked power spectra can either be generated by the random excitation of resonators, such as turbulent variations in the pressure of gases or the flow of fluids, or by the superposition of signals from many uncorrelated but similar sources (Julian, 1994).

The tremor observed at Lascar has an unusual form. Figure 3 shows a representative sequence of signals during a four-hour interval recorded at the stations of the Lascar network. The signal has a «rapid-fire» structure (Hill *et al.*, 1990) with amplitude variations of more than a factor of 100. For the broadband station, the first hour has been excerpted in fig. 4a, showing a large event and numerous smaller events. If we expand the time and amplitude scales for an interval with apparently low activity, as in fig. 4b, we again see the same pattern of large and small events interspersed. The similar appearance of successive expansions to shorter time intervals and lower amplitudes suggests that, above the amplitude level of background tremor, the time series may have a fractal structure. Because we have not as yet investigated this phenomenon quantitatively, we shall refer to this apparent similarity at high and low amplitude levels as being «quasi-fractal».

The power spectrum of the interval shown in fig. 4b has two dominant peaks at 1.8 and 2.4 Hz and other smaller peaks between 0.5 and 8 Hz (fig. 5a). The power of each peak is determined by the duration of its excitation and the instantaneous excitation amplitude. In figs. 5b and 6, the details of the excitation are displayed in a contour diagram and a three-dimensional surface plot of the time-frequency spectrum. The bands of contours and the ranges in the surface plot correspond to the series of events in fig. 4b. The main peaks repre-

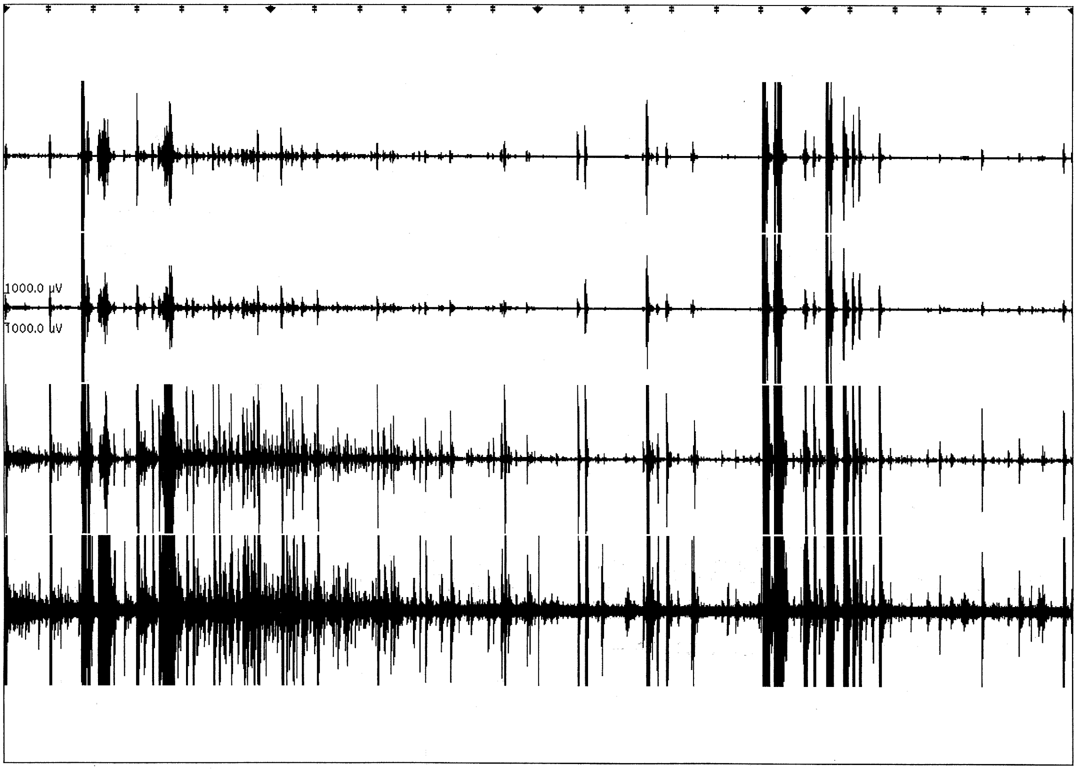


**Fig. 3.** Vertical seismograms for four hours from the Lascar network. The largest events are clipped on all traces. The recordings show a «rapid-fire», random series of events with very large dynamic range. The one hour interval shown in fig. 4a is marked by the bar.

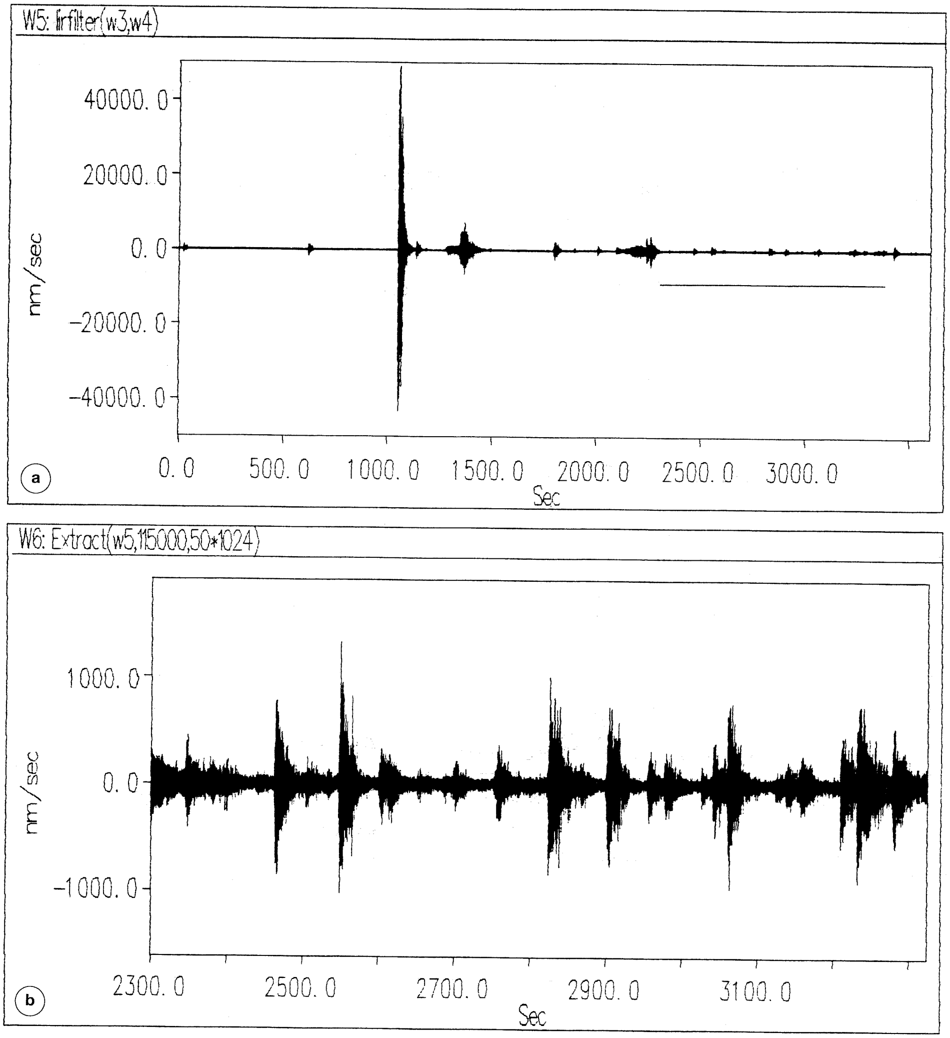


**Fig. 4a,b.** a) One hour segment from the broadband vertical component, taken from the time interval marked in fig. 3 and high-pass filtered. b) 1024 s interval with higher time resolution from the segment marked in (a). The «rapid-fire» pattern of events has a quasi-fractal structure in the time domain over a broad dynamic range.

sented in the power spectrum are excited during each of the events, but their excitation amplitudes are uncorrelated between events. During many events, the main peaks are present at all stations and on all components, indicating that they are generated in or near the source rather than as path or site effects. The smaller peaks appear to be excited randomly and are not present at all stations. Thus, the tremor signals of individual events appear to be generated by an ensemble of elementary, uncorrelated sources. In comparison, long-term power spectra of subsequent intervals show only small variations in shape and level. Therefore,

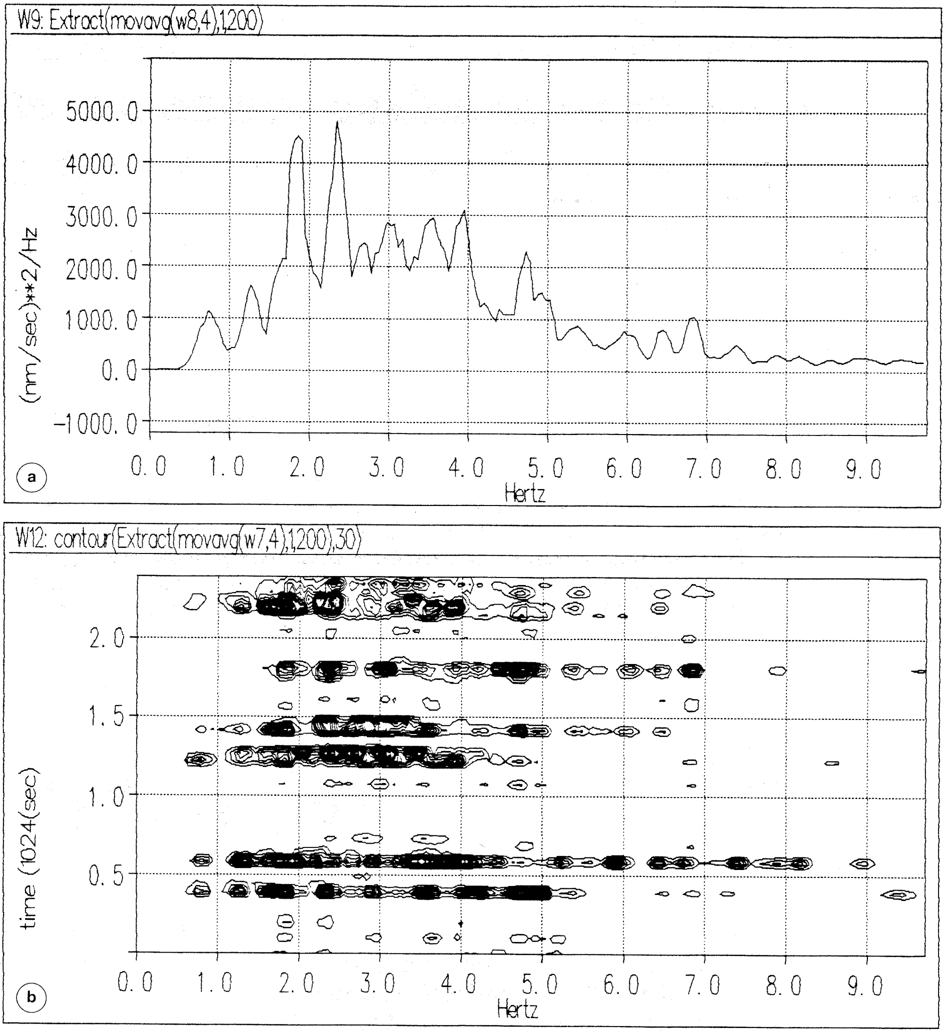
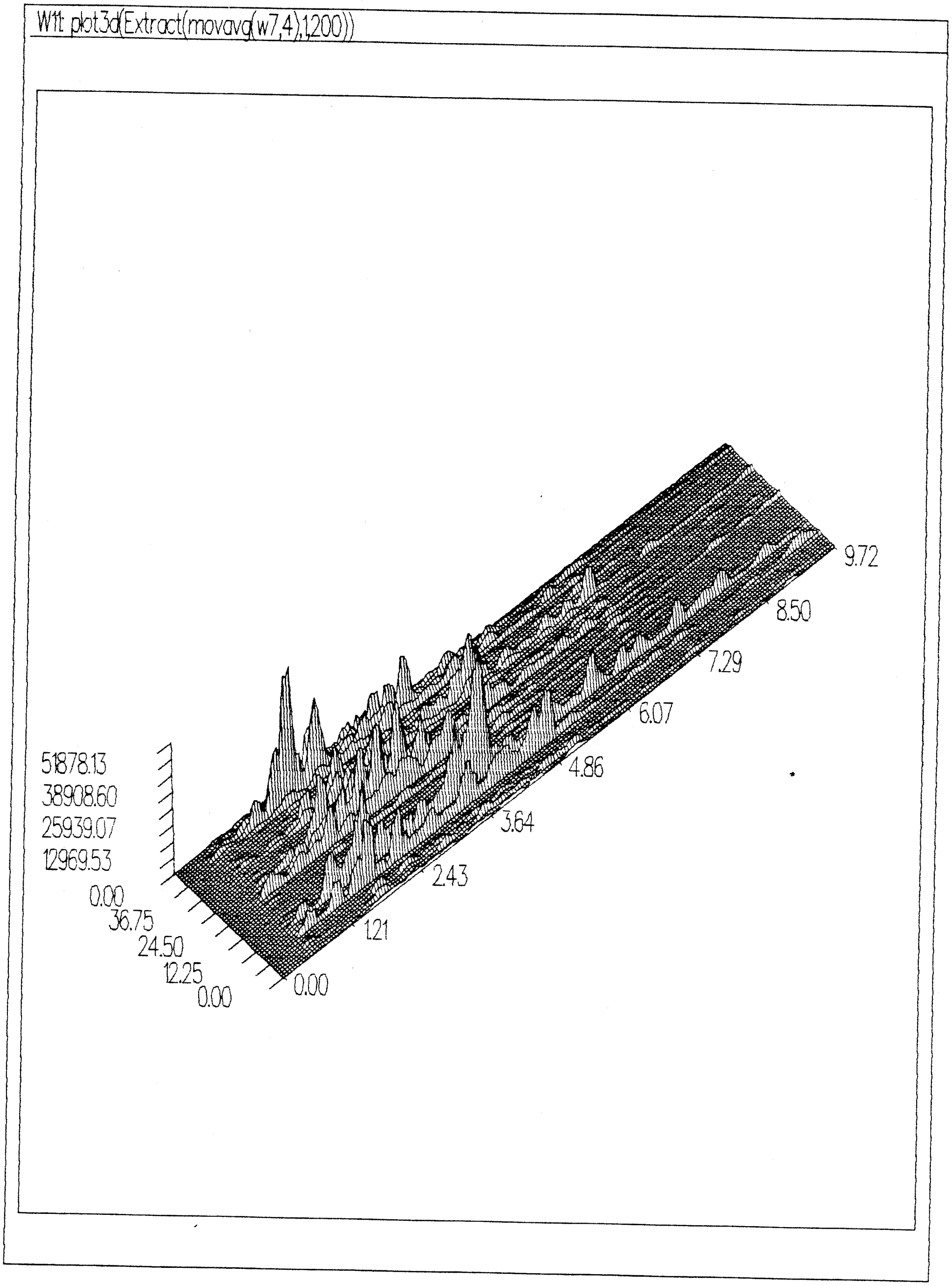


**Fig. 5a,b.** a) Power spectrum averaged over the 1024 s interval shown in fig. 4b. b) Time-frequency power spectrum of this segment. The horizontal bars of high amplitude are the power spectra of the strongest events during this interval. The vertical axis corresponds to 1024 s, divided into arbitrary units.

the radiation of the total source ensemble remains stationary.

The recordings of two events, differing in amplitude by a factor of 50, are displayed in fig. 7 along with their spectra. Despite the difference in size, nearly all the peaks represented in the spectrum of the large event are present in the small event, and the pattern of relative excitation is also similar. The amplitude spectra of the seismograms are a product of the source spectrum and the transfer function of the medium. From the similarity of these spectra, we deduce that the signals are generated by similar source mechanisms and that the



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W1t: plot3d(Extract(movavg(w7,4),1,200))
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**Fig. 6.** Three-dimensional plot of the time-frequency power spectrum in fig. 5b showing the relative level of excitation of each frequency during the events. Units on the vertical axis show the relative amplitude of the peaks. The axis to the right shows frequency in Hz, while on the axis to the left, the 1024 s time interval is divided into arbitrary units.

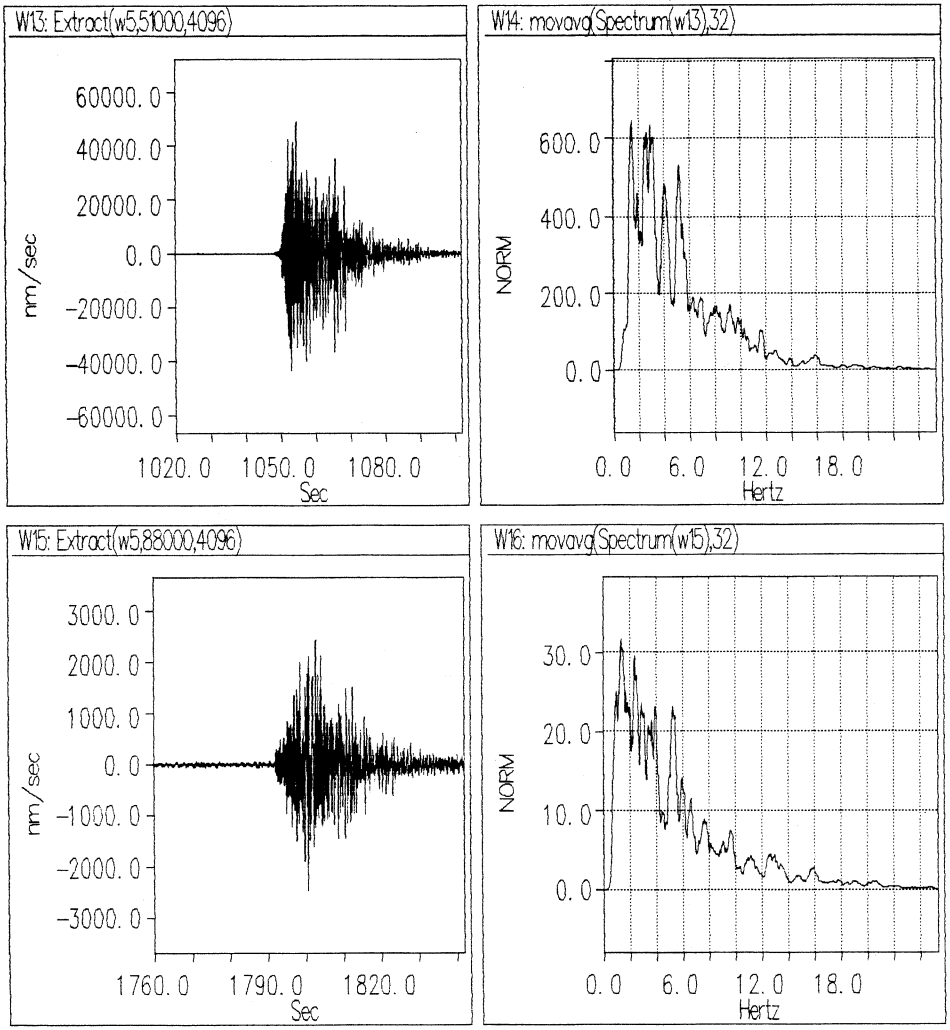

**Fig. 7.** Seismograms and amplitude spectra from two events. The maximum amplitude of the upper event is about 50 times larger than the lower.

source locations are nearly the same.

We have located several large events using HYPO71 (Lee and Lahr, 1975). The program uses *P*- and *S*-wave arrival times in conjunction with a flat-layered general velocity model to calculate travel times and locate the events. Because we have measurements at only four stations, and because HYPO71 does not permit the sources to be located at elevations in the volcanic edifice above the stations, the event depths could not be determined accurately. Neither could the depth be deduced reliably from the particle motion of the initial onset. The epicenter calculated for these events is represented by the bold circle in fig. 2. From the similarity of the spectral content in the large and small events, we infer that most Lascar tremor events are generated near this location.

A basic problem for the interpretation of the Lascar event series is the classification of the waveforms and the definition of a local magnitude, which relates the event's maximum signal velocity to the total energy released.

From the similarity of the velocity amplitude spectra for weak and strong events at the Lascar broadband station (fig. 7), it can be assumed for the purpose of classification that most of the events have similar signals $a{*}f(t)$ with varying amplitudes $a$ and nearly constant time functions $f(t)$. For such an ensemble of event waveforms, the squared maximum signal velocity will be linearly related to the signal energy calculated from the time-integral over the squared velocity for the complete seismogram. In a heterogeneous medium and for short source distances, as is the case for the Lascar net, the local magnitude is correlated with the signal duration (Aki and Chouet, 1975; Lee *et al.*, 1972). Thus, for a cluster of sources with similar spectra over a wide dynamic range, we expect a correlation between maximum signal velocity and signal duration (Koyanagi *et al.*, 1987).

This is confirmed in fig. 8, where the maximum signal velocity is plotted logarithmically as a function of event duration. This relationship will be the basis for defining an empirical duration magnitude scale for the Lascar rapid-fire events when more data have been processed.

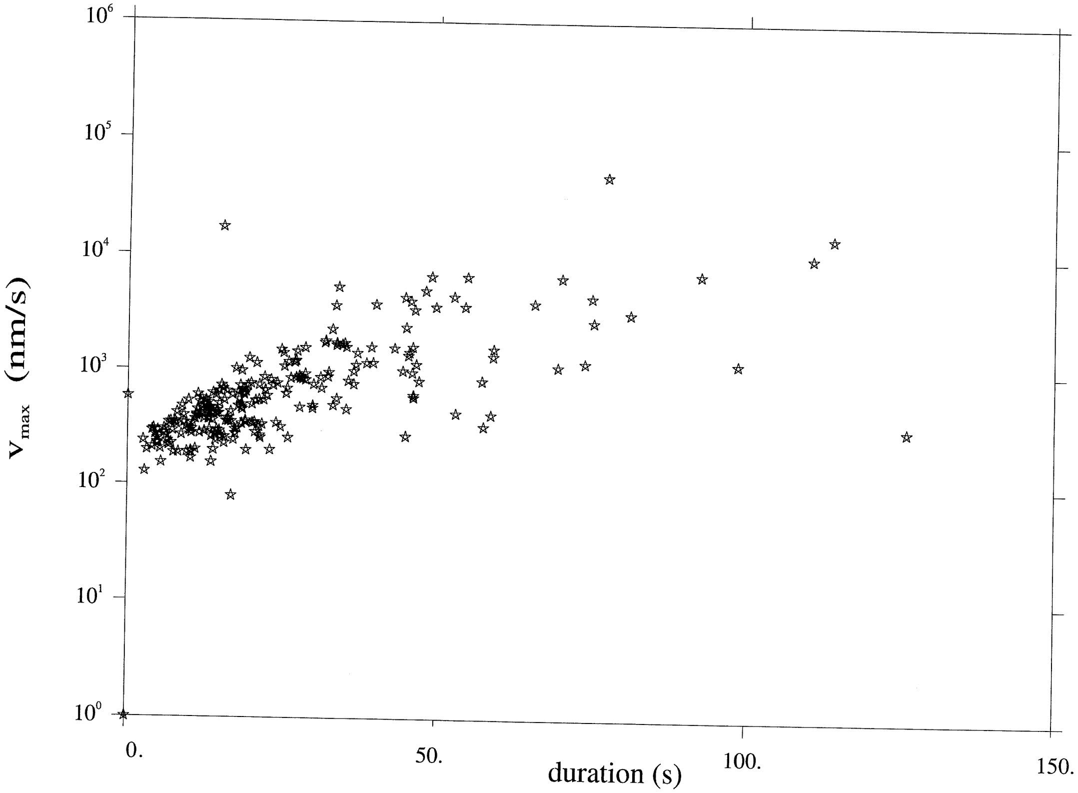

**Fig. 8.** Maximum velocity, $v_{\max}$, for each event in nm/s as a function of approximate event duration. The $v_{\max}$ scale is logarithmic.

## 3. Conclusions

The seismic wavefield at Lascar volcano is characterized by a superposition of continuous tremor and innumerable «rapid-fire» events. In the time domain, the recording appears to have a quasi-fractal structure ranging upwards in amplitude from small events which can barely be distinguished above the background signal. In the frequency domain many events have similar amplitude spectra, although their energies differ by orders of magnitude. The events appear to be generated by an ensemble of uncorrelated elementary sources clustered in a small region in the edifice of the volcano. The time-frequency domain power spectrum shows that the instantaneous spectra fluctuate, whereas the long-term average of the product of the excitation time with the amplitude of excitation is very stationary, as is described in the standard power spectrum. While the physical processes which produce the tremor and events are unclear, we suspect that they are produced by the same source process and differ only in their energy.

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