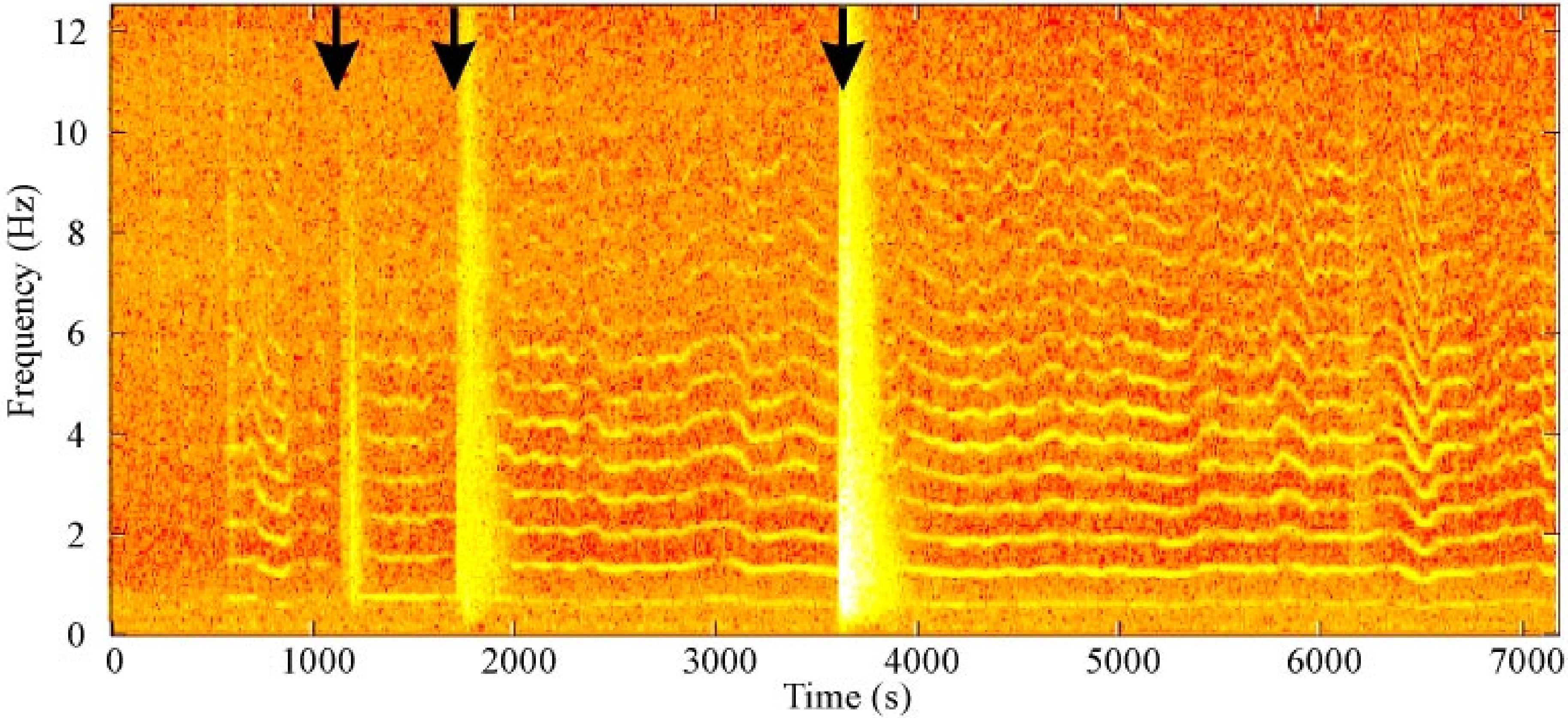

Figure 2.12 Spectrogram of two hours taken from the E-component at station LA2 starting at 01:30 on 18 April 1994. The data were resampled to 25 Hz. The spectrogram was calculated using data windows 10.24 s long and 50% overlapping. Arrows mark regional earthquakes.

This unusual form of tremor has a high signal-to-noise ratio in the recordings from Lascar. Because it has rarely been observed, it has not yet been analyzed and no models exist for its generation. Perhaps the results from an analysis of harmonic tremor from Lascar can offer new insights in the the physical processes occuring in volcanoes.

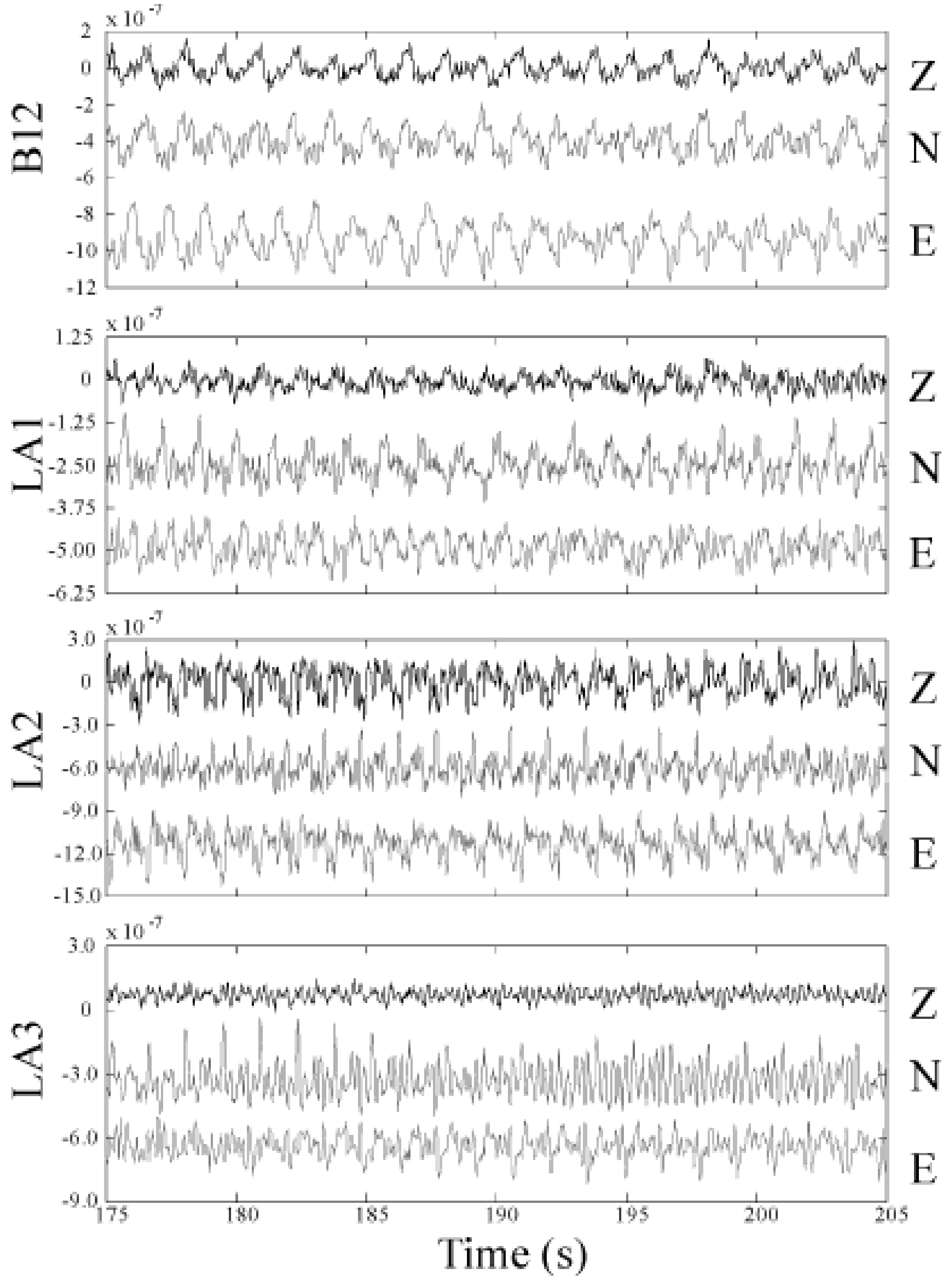

Figure 2.11 Thirty seconds of harmonic tremor at all stations. Here the broadband seismograms for station B12 are bandpass-filtered between 0.5 and 20 Hz and resampled to 50 Hz, as they have been for all other figures with no specific notes. Data for the short period stations have been lowpass-filtered and resampled to 50 Hz. The velocity amplitude is given in m/s.

the component with the largest amplitude at each of the stations (Figure 2.8) show energy is present at these frequencies during the entire recording. The physical process which generates tornillos is not yet known, although several models have been proposed [JULIAN, 1994, CHOUET 1996, SEIDL et al, 1998].

The Lascar stations also recorded a second type of tornillo, one with much higher characteristic frequencies. Figure 2.9 shows the recording and a spectrum from station LA2 for one of these high frequency events. The characteristic frequencies for this event,11.50 Hz and 12.27 Hz, are present at all four Lascar stations (Figure 2.10). The interaction between these two neighboring frequencies is clearly visible as beating in the seismograms. Similar, high frequency events have also been observed at Galeras Volcano in Colombia [R. TORRES and D. GÓMEZ, personal communication, 1998].

2.3.3 Harmonic tremor

The recordings at Lascar also captured a new form of volcanic tremor characterized by harmonic spectra with a fundamental frequency near 0.6 Hz and many integer overtones with large amplitudes. In the past, volcanic tremor which is nearly sinusoidal has been called harmonic, however, here the signals with harmonic overtones will be called harmonic tremor (Figure 2.11). On each component, the tremor's shape changes slowly as a function of time. As this happens, the fundamental frequency changes, as do the amplitude of the cycle, the frequency content (amplitudes of overtones) and the polarization at each of the stations. At Lascar, harmonic tremor is not associated with volcanic explosions and may continue for several hours (Figure 2.12) with only small changes in the frequency of the fundmental. At Lascar on 18 April 1994, for example, harmonic tremor was recorded for more than 15 hours. Regional earthquakes (arrows) have no apparent effect on the frequency of the tremor. Similar signals observed at other volcanoes usually occur during a short interval following a triggering event and have only a few overtones [KAMO et al., 1977, MORI et al., 1989, SCHLINDWEIN et al., 1995, BENOIT and MCNUTT, 1997, HAGERTY et al., 1997, LEES et al, 1997]. The only place where similar tremor may have been observed is Galeras Volcano, Colombia, in 1989 [GIL-CRUZ, 1999].

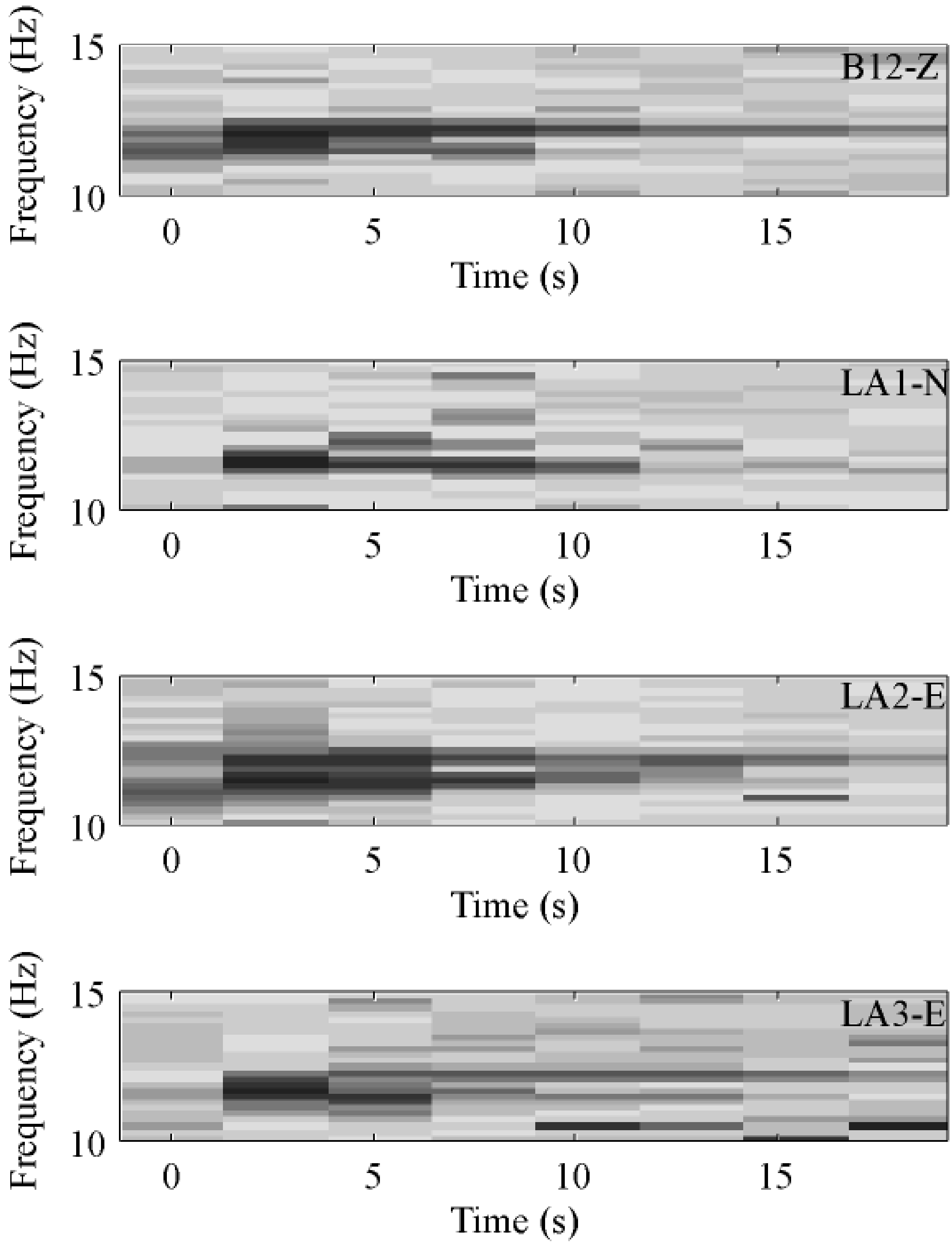

Figure 2.10 Spectrograms of the high frequency tornillo shown in Figure 2.9. For each station, the spectrogram is calculated and plotted for the component with the largest amplitude.

frequencies which usually lie between 1 Hz and 8 Hz. Similar events have also been observed at Asama-yama and Sakura-jima Volcanoes in Japan [SEKIYA, 1967, HAMADA *et al.*, 1976, and SAWADA, 1998]. Figure 2.7a shows a tornillo recorded at Lascar on 16 April 1994 at 15:43:26 UTC. The recordings have unusually long codas which look like sine waves with decreasing amplitude. The amplitude spectrum for the E component shows that the characteristic frequencies for this tornillo are 3.52 Hz and 6.24 Hz (Figure 2.7b). Spectrograms for

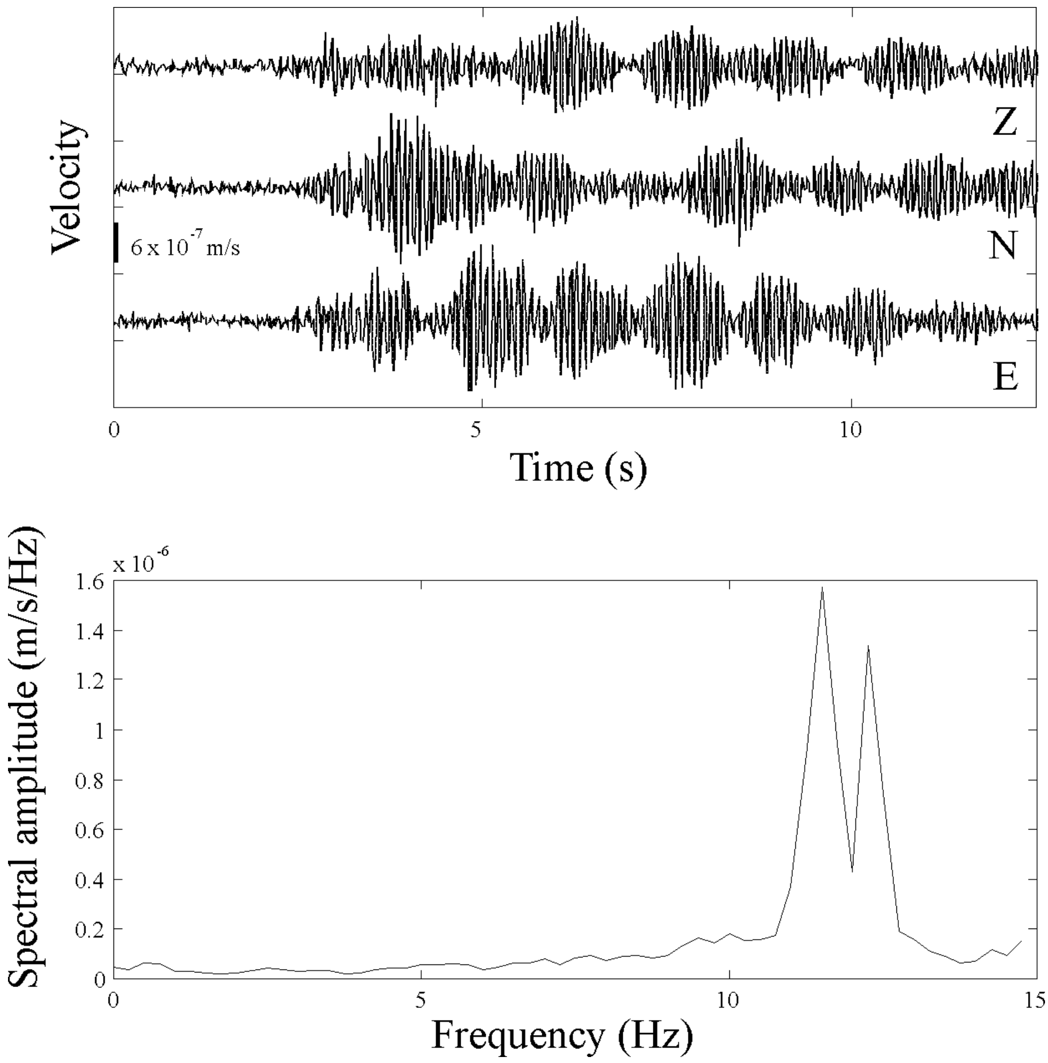

Figure 2.9 High frequency Lascar tornillo. (top) Seismograms of a high frequency tornillo (onset time 17 April 1994, 13:57:27 UTC) recorded at station LA2. The amplitude scale is marked by a bar on the left. (bottom) Spectrum of the high frequency tornillo from the E component of the recording at LA2.

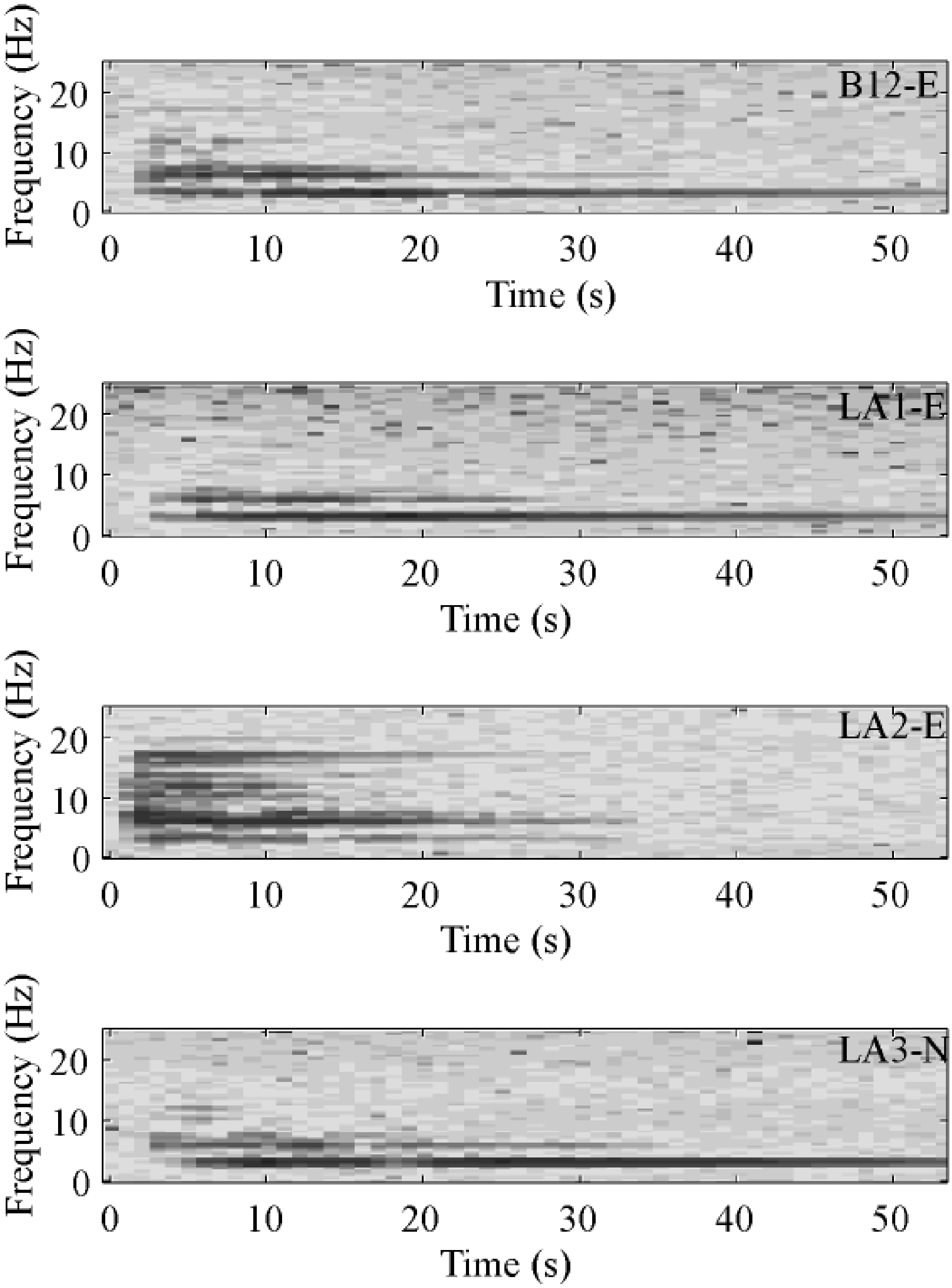

Figure 2.8 Spectrograms from the recordings of the tornillo in Figure 2.7. For each station, the spectrogram is calculated and plotted for the component with the largest amplitude.

2.3.2 Tornillos

In contrast to spectra measured from the seismograms of earthquakes or explosions, spectra of volcanic events and tremor often have well defined peaks at one or more frequencies. This is particularly true for an unusual type of event identified at Galeras Volcano in Colombia [Gómez and Torres, 1997, Narváez et al, 1997, Torres et al, 1996]. These events are called tornillos, because their shape on a seismogram looks like a screw with a long, sinusoidal, slowly decaying coda. Each of these events has one or two predominant

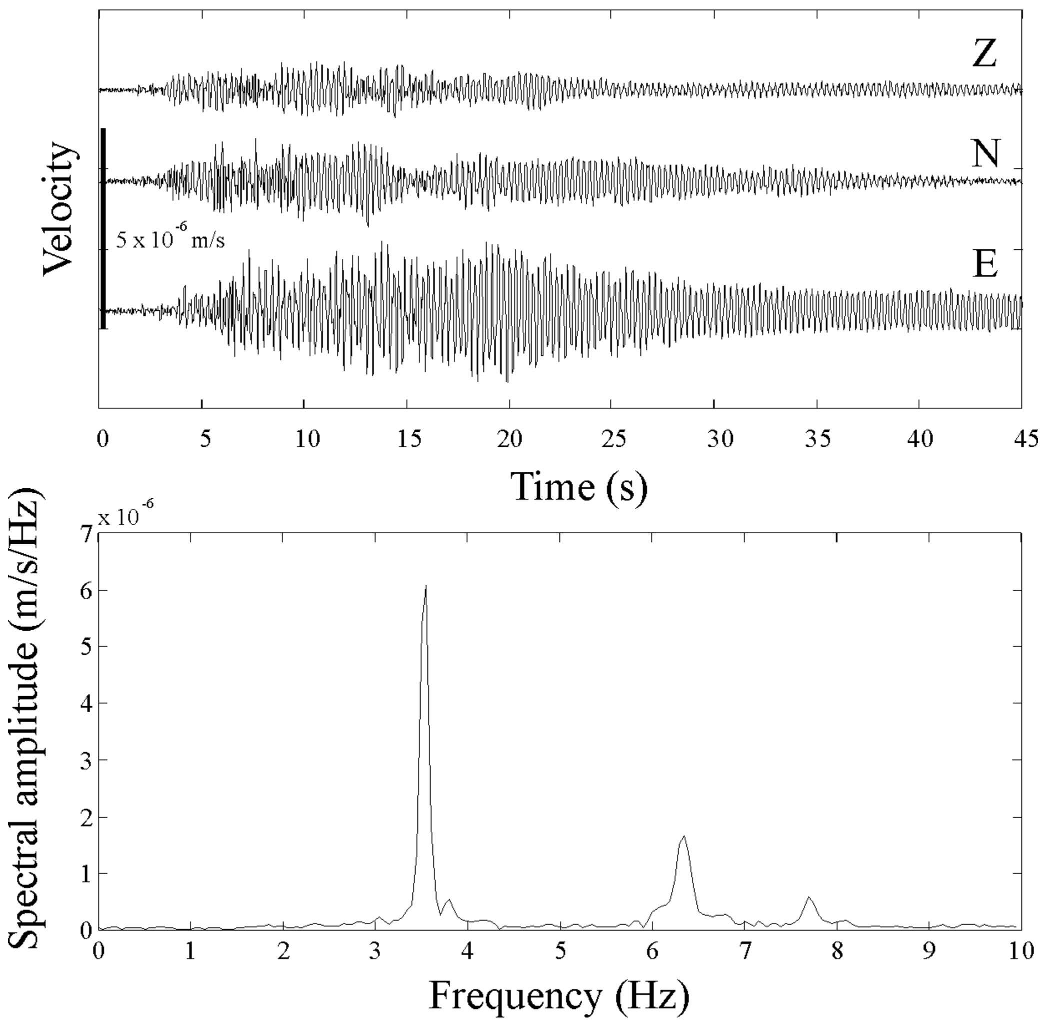

Figure 2.7 Lascar tornillo. (top) Seismograms of a tornillo (onset time: 16 April 1994, 15:43:26 UTC) recorded at station LA1. The amplitude scale is marked by a bar on the left. (bottom) Spectrum of the tornillo from the E component of the recording at LA1.

Since the events are all located within a small volume, the path to a given station, $g(t)$, is nearly the same for all wavegroups. We can therefore describe the source excitation for event n as:

$$s_n(t) = A_n\, s_0(t) \qquad (2.4)$$

where $s_0(t)$, the characteristic source function for RF-events, is independent of their size.

The time dependence of the event source excitation is independent of its energy and a general source function exists which, apart from an amplitude factor, A_n, can describe all RF-events. This is unlike tectonic events, where the waveform and spectral content depend on the energy released. It is therefore unlikely that the RF-events are tectonic-type events produced by rock fractures in the solid volcanic edifice. Rather, they must be generated as an interaction or movement of volcanic fluids, magma, water or gases. They may, for example, be caused by nearly instantaneously heating of water or other gases which then expand explosively.

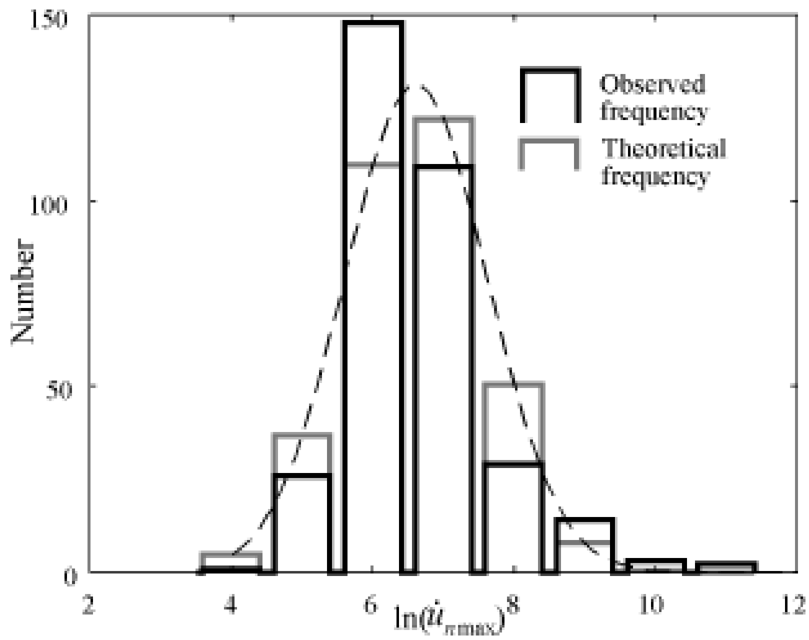

Figure 2.6 Histogram of the natural logarithm of the maximum RF-event amplitude, $\ln(\dot{u}_{n\max})$. The histogram is compared with the best-fitting normal distribution.

log-normally distributed variables are the sizes of bubbles or amounts of monthly rainfall. RF-events must stem from a similar process.

We can synthesize these observations to better define RF-tremor. Since the spectra of small and large events are similar [Asch *et al*, 1996], they can be described by a single function which varies only in amplitude. Thus, the linear correlation between $\log(\dot{u}_{max})$ and $\log(E_{nT})$ suggests that the nth rapid-fire event can be described as:

$$\dot{u}_n(t) = A_n \dot{u}(t), \qquad (2.2)$$

where $\dot{u}(t)$ is a characteristic function of time for all wavegroups and A_n is an amplitude factor determined by the event energy E_{nT}. An event n recorded at given seismometer site can also be described as a convolution between the source-time-function, $s_n(t)$, and the response function of the medium between the source and the station, $g(t)$,

$$\dot{u}_n(t) = s_n(t) * g(t) . \qquad (2.3)$$

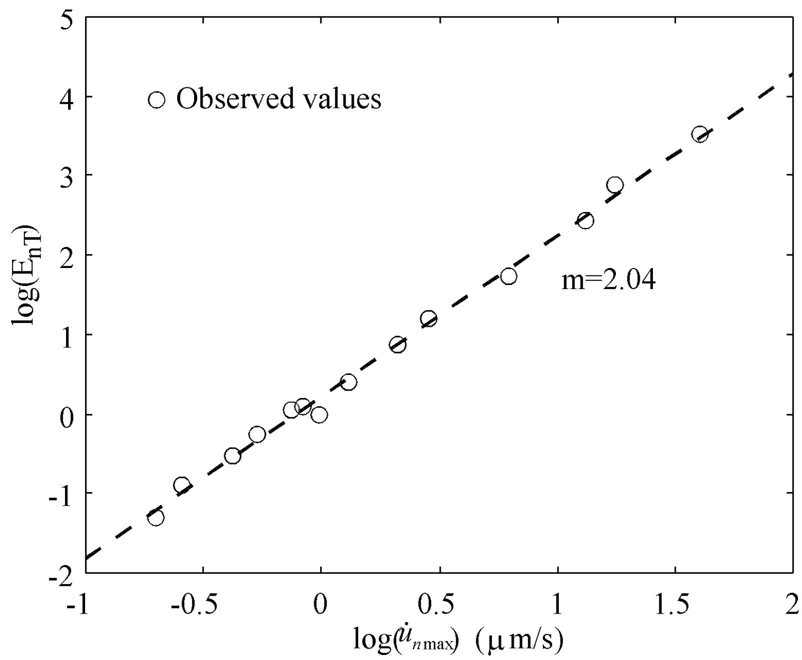

Figure 2.5 Relationship between $\dot{u}_{n\max}$ and the total RF-event energy E_{nT}. The slope of the dashed line, m=2.04, gives the exponent in the relationship in Equation 2.1

and the next in the RF-tremor sequence. The intervals between RF-events conform to a Poisson distribution, with the Poisson parameter λ = 117 s. This suggests that although the RF-events often appear to be almost continuous, they are independent of each other. That is, the occurrence of an individual RF-event is not influenced by previous events.

In Figure 2.5 the total signal energy, E_{nT}, for several events is plotted as a function of the events' maximum velocity amplitude, $\dot{u}_{n\max}$, in a log-log representation. E_{nT} is calculated as the integral of the square of the velocity over the entire event, while $\dot{u}_{n\max}$ is measured as the maximum amplitude from the instrument-corrected seismograms. The least-squares fit line for this data has a slope of 2.04. This indicates that

$$E_{nT} \propto \dot{u}_{n\max}^2 . \qquad (2.1)$$

Thus, the maximum ground velocity of an RF-event can be used as an indicator for its total energy, and the distribution of event energies can be deduced from the distribution of event amplitudes. Because of this relationship, a histogram of the maximum velocity amplitude (Fig. 2.6) gives the distribution of the events' energies. These are distrubuted log-normally, which is confirmed by χ^2-testing. In general, variables which are distributed log-normally are the product of growth processes [TAUBENHEIM, 1969]. Typical examples of

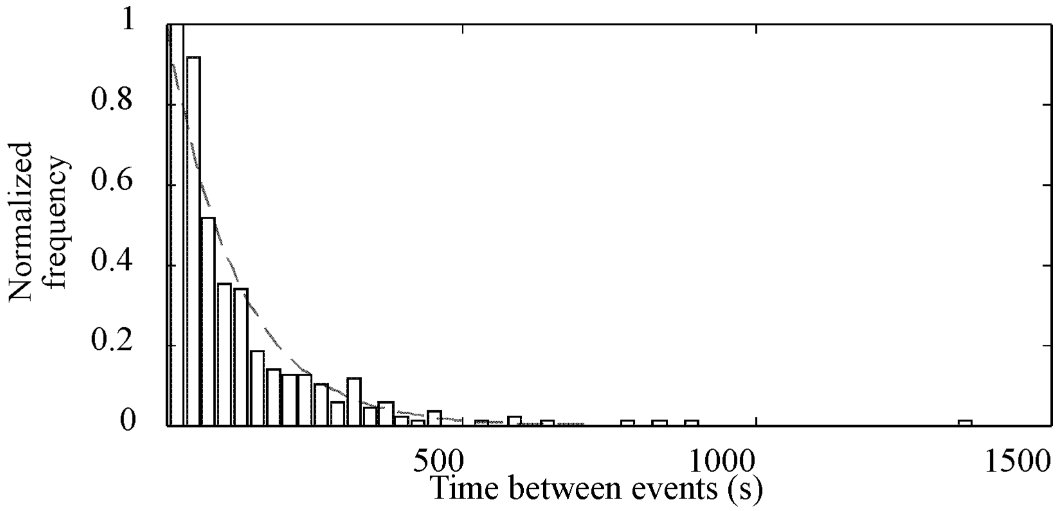

Figure 2.4 Histogram of intervals between RF-events. The dashed line shows the amplitude of a Poisson distribution with λ = 117 s.

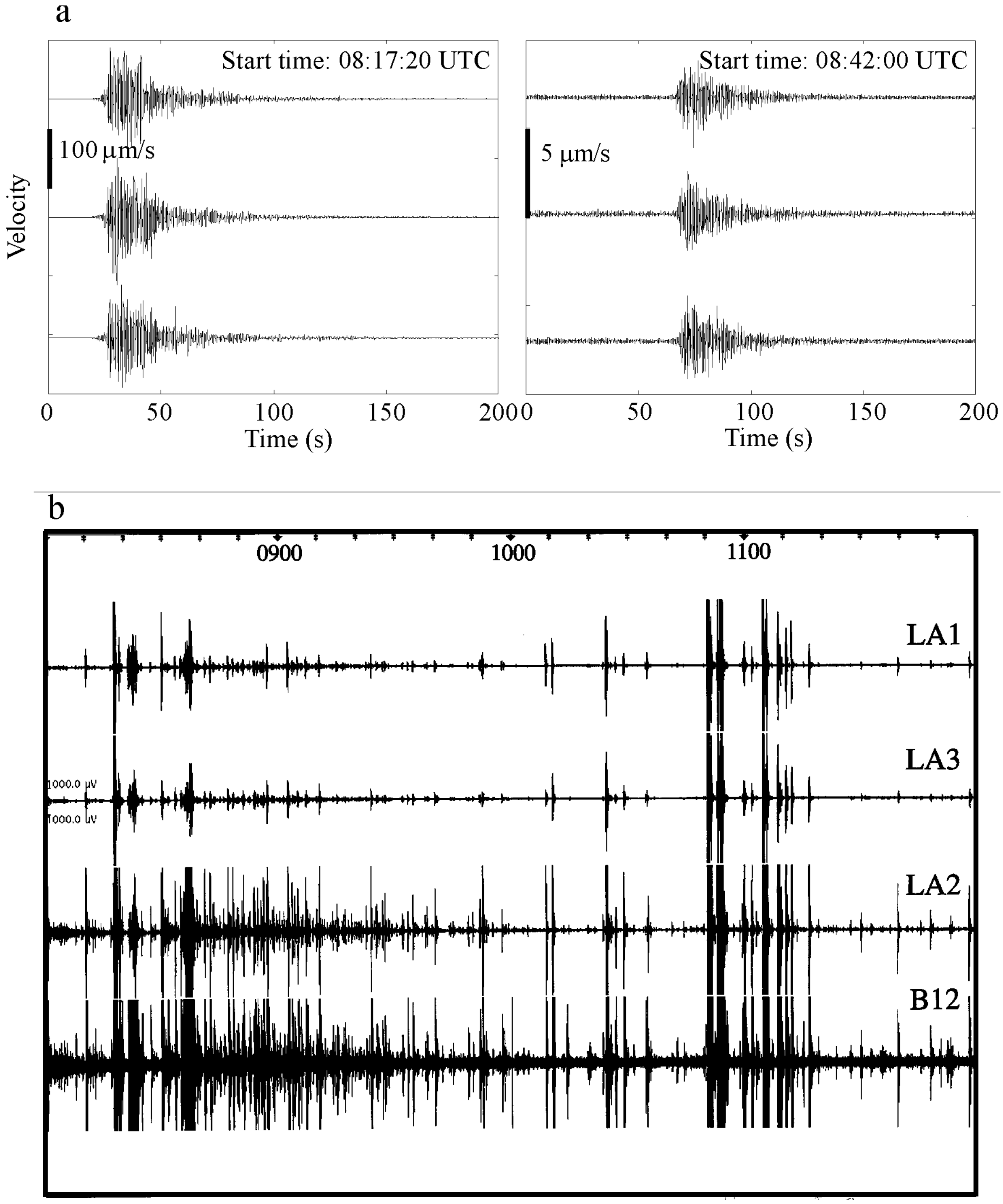

Figure 2.3 a) Three-component seismograms of two rapid-fire events of different amplitudes. b) Seismograms of the vertical components from the Lascar network from 08:00 to 12:00 UTC during the episode of RF-tremor on 6 May 1994. In this rendition, the largest events are clipped on all traces, so that small events can also be seen. The recordings show a 'rapid-fire', random series of events with very large dynamic range.

2.3 Characteristic Seismic Signals of Lascar Volcano

An active volcano produces many different types of seismic signals. These signals are measurable symptoms of its internal physical processes. Observations made from recordings of these signals can be used as a basis for modelling their sources.

In addition to the regional events recorded with the entire PISCO network during its deployment, the Lascar network recorded many events and episodes of tremor of the types typically observed at volcanoes. However, the recordings also captured several less common, but highly interesting volcanic seismic signals. Perhaps one of these signals will provide new insights into physical source processes, and thereby improve our understanding of how volcanoes work.

2.3.1 Rapid Fire Tremor

The seismic wavefield generated by Lascar Volcano during the PISCO'94 measurements often included a type of signal that has not been observed at many volcanoes. This tremor consists of an irregular sequence of event-like wavegroups with amplitudes that vary by several orders of magnitude. Often they occur so frequently that they appear to be almost continuous. Since HILL *et al.* [1990] report similar activity at Long Valley Caldera (California) which they describe as a sequence of “rapid-fire events”, I will call this type of signal rapid fire tremor (RF-tremor). On 6 May, during a particularly intense epsiode of RF-tremor at Lascar more than 1300 RF-events occurred during a twelve hour interval (Figure 2.3). ASCH *et al.* [1996] analyzed data from this episode. They showed that the spectra of the individual event-like wavegroups making up RF-tremor (RF-events) have peaks at many of the same frequencies at all stations, indicating that the frequencies are a characteristic of the source. RF-events differing in amplitude by a factor of 100 also have some of the same frequencies, which means they are probably generated by the same mechanism within a small volume. ASCH *et al.* [1996] determined that three of the largest events were located near the active crater.

Figure 2.4 shows the distribution of the length of the time interval between RF-event-onsets. These data are calculated as the difference between the onset times of one event

Although the instruments of the Lascar network were deployed for only five weeks, the data set it produced differs fundamentally from many prior seismological observations at volcanoes. It has

- continuous, digital recordings for an extended period of time,
- three components at each site, and
- data with a high dynamic range.

In addition, the data from the broadband station, B12, provide information on the complete bandwidth of signals generated by Lascar.

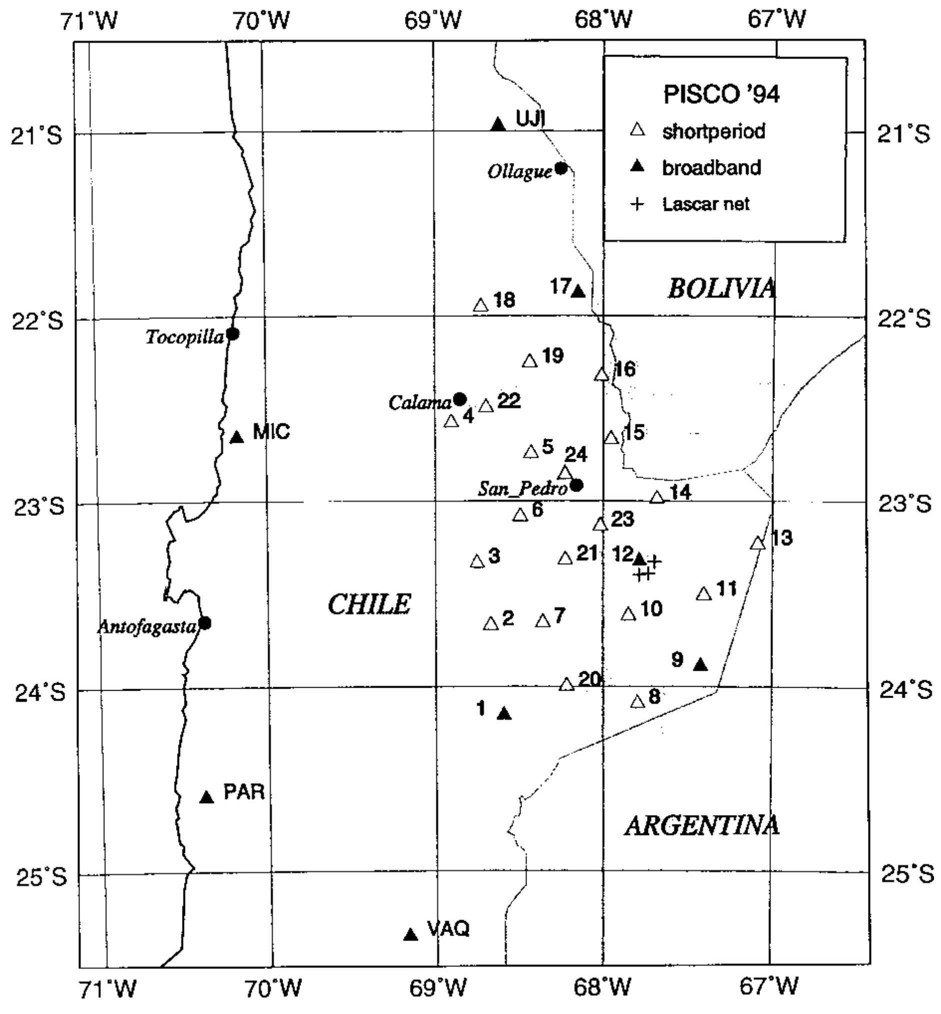

Figure 2.2 Seismic network of the PISCO'94 deployment. Lascar volcano is located near station 12. The short period stations of the Lascar network are marked by (+).

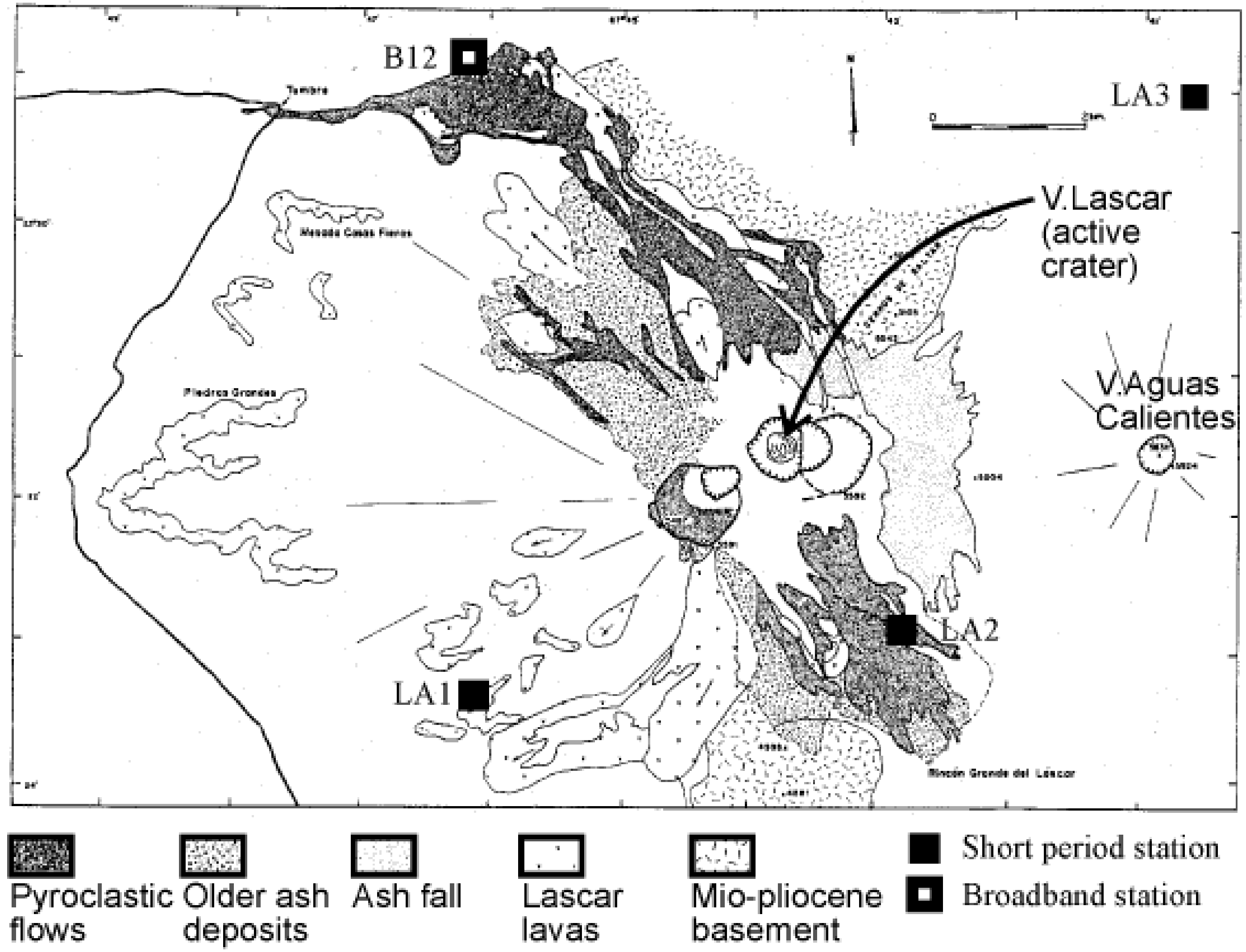

Figure 2.1 Map of the volcano Lascar with the stations of the Lascar network. The active crater is indicated by an arrow. Reproduced with the permission of Dr. Moyra Gardeweg, SERINGEOMIN, Chile.

map the subducting slab (Figure 2.2). The network included twenty shortperiod, three-component seismometers (L-4C), four STS-2 and four CMG-3 broadband instruments. Digital data were recorded continuously at all stations. The deployment was part of the German Research Foundation Collaborative Research Program (SFB) 267, "*Deformationsprozesse in den Anden*".

Station B12 of the PISCO network was a STS-2 seismometer installed about 6.4 km from the active crater on the NW flank of the volcano Lascar (Figure 2.1, Table 1). In April 1994, three additional shortperiod, three-component seismometers were deployed to the SW, SSE and NE of the volcano (LA1, LA2 and LA3, Table 1). Continuous data were recorded digitally on local hard disks using PDAS recorders in gain-ranging mode (140 dB dynamic range). As the data were recorded at sampling rates of 200 Hz (100 Hz for station B12), the disks were replaced every three days, and the data were archived on CDROMs. The four stations operated from 8 April until 12 May 1994 (Julian days 98 - 132).

Table 1

Station	Coordinates	Site Geology[1]	Dist/Az to Crater	Sensor		Gen. Constant (Vs/m)
B12	3950 m	At edge of	6.4 km		Z	1500
100 Hz	23°19'27" S	lava flow	128º	STS-2	N	1500
	67°46'43" W	in ash/tephra			E	1500
LA1	4000 m	On E flank of a valley	6.7 km		Z	272
200 Hz	23°23'55" S	near old lava flow,	49º	L4	N	280
	67°46'42" W	buried in ash/tephra			E	285
LA2	4750 m	Near wall of welded	3.5 km		Z	275
200 Hz	23°23'25" S	tuff protected by large	352º	L4	N	285
	67°43'27" W	boulder, in ash/tephra			E	284
LA3	4700 m	Buried in	5.5 km		Z	284
200 Hz	23°19'43" S	ash/tephra	231º	L4	N	276
	67°41'14" W	plain			E	279

1 A. Rudloff, personal communication

2 Lascar Volcano: The Wavefield

2.1 The Volcano

Lascar, a stratovolcano more than 5000 m in altitude, is located on the puna, Chile's altiplano, at 23° 22' S, 67° 44' W. Gardeweg and Medina [1994] note that it is the most active volcano in northern Chile. Reports of Lascar's activity begin in the sixteenth century with the arrival of the Spanish in the region and continue until the present. Its activity is mainly fumarolic, although the continuous degassing is occasionally interrupted by large explosions from the various craters in the summit region. Since 1986, Lascar has undergone several cycles of lava dome growth and collapse. The growth phases usually last several months and are accompanied by numerous small explosions.

On 19 April 1993, a dome growth phase culminated in the largest historically recorded eruption of Lascar [Bulletin of the Global Volcanism Network (GVN), April, 1993, Gardeweg and Medina, 1994]. After several hours of Vulcanian explosions, a series of Plinian eruptions generated ash columns and pyroclastic flows (Figure 2.1). Declining activity was followed on 20 April 1993 by an additional explosion and the formation of a new ash column. In the course of the following month, the activity decreased until it reached the usual level of continuous fumarolic activity with high levels of SO_2 emission. On the average, Lascar emits about 2400 Mg/day SO_2 [Andres and Kasgnoc, 1998].

On 17 December 1993 another, smaller eruption occurred [GVN, March, 1994]. Afterwards, the activity decreased to normal levels within several hours. As observed from San Pedro de Atacama between January and May 1994, Lascar's activity was limited to the emission of steam and SO_2 [G. Asch, personal communication]. Despite its low level of activity during this period, Lascar produced many interesting and unusual seismic signals.

2.2 The Measurements

In early 1994 Asch et al [1995, 1996] installed a network of seismometers in northern Chile as part of the "Proyecto de Investigación Sismológica de la Cordillera Occidental '94" (PISCO'94). The instruments were deployed in an area between 19.5° S and 25.5° S and between the coastal cordillera and the puna in order to study the region's seismicity and