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RESEARCH ARTICLE

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Eruption-induced modifications to volcanic seismicity at Ruapehu, New Zealand, and its implications for eruption forecasting

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Abstract Broadband seismic data collected on Ruapehu volcano, New Zealand, in 1994 and 1998 show that the 1995–1996 eruptions of Ruapehu resulted in a significant change in the frequency content of tremor and volcanic earthquakes at the volcano. The pre-eruption volcanic seismicity was characterized by several independent dominant frequencies, with a 2 Hz spectral peak dominating the strongest tremor and volcanic earthquakes and higher frequencies forming the background signal. The post-eruption volcanic seismicity was dominated by a 0.8–1.4 Hz spectral peak not seen before the eruptions. The 2 Hz and higher frequency signals remained, but were subordinate to the 0.8–1.4 Hz energy. That the dominant frequencies of volcanic tremor and volcanic earthquakes were identical during the individual time periods prior to and following the 1995–1996 eruptions suggests that during each of these time periods the volcanic tremor and earthquakes were generated by the same source process. The overall change in the frequency content, which occurred during the 1995–1996 eruptions and remains as of the time of the writing of this paper, most likely resulted from changes in the volcanic plumbing system and has significant implications for forecasting and real-time assessment of future eruptive activity at Ruapehu.

Keywords Volcanic seismicity · Ruapehu · Spectra · Eruption induced changes · Source process · Eruption forecasting

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Introduction

Ruapehu is a 250,000-year-old, active, predominantly andesitic, composite volcano located in the center of the North Island of New Zealand at the southern end of the Taupo Volcanic Zone. Very minor phreatic eruptions, involving water doming within the crater lake, typically occur several times a year. Larger eruptions, which are characterized by the ejection of ash and mud and the generation of lahars, occur every few years. All historic activity has occurred through the summit crater, which except for periods following the 1945 and 1995–1996 eruptions has been occupied by a warm-water lake.

Unlike the majority of volcanoes worldwide, volcanic seismicity at Ruapehu is ongoing and often varies considerably without any perceptible change in volcanic activity. Volcanic earthquakes often occur unaccompanied by eruptive activity. Similarly, changes in the amplitude and frequency content of volcanic tremor frequently occur independently of any eruptive activity or changes in the crater lake. Furthermore, changes in seismicity prior to eruptions are often minor and may not be discernible as such. In particular, geochemical, geodetic, and seismic precursors to the 1995 eruptions were both minor and ambiguous in nature while precursory seismic activity prior to the 1996 eruptions was perceptible, although not extremely obvious (Bryan and Sherburn 1999). Consequently, in order to recognize any subtle changes in seismicity that may be precursors to a Ruapehu eruption, it is important to well-characterize the ongoing seismicity. Furthermore, if the occurrence of an eruption significantly changes the long-term seismicity pattern at Ruapehu, it is necessary to recognize and understand these changes if deviations from the background seismicity pattern are to be used to forecast future eruptive activity.

In this study, we compare and contrast the characteristics of the volcanic tremor and volcanic earthquakes at Ruapehu before and after the 1995–1996 eruptions. A significant change in the seismicity from narrow band to wideband occurred during the 1995 eruptions and this new style of seismicity continued during the 1996 activity (Bryan and Sherburn 1999). In order to use characteristics of seismicity to forecast future eruptive activity, it is necessary to determine if these changes were long-term, continuing beyond the 1996 activity, or whether the seismicity returned to that which was typical of the 25 years preceding the 1995 eruptions.

We first describe the pre-eruption seismicity using broadband data collected in early 1994. We then use broadband data collected in 1998 to characterize the post-eruption seismicity and to describe changes from the 1994 seismicity in detail, concentrating on changes in the lower frequencies. Finally, we discuss our results in the context of source processes, hazard assessment, and the forecasting of future eruptions. We do not discuss the short-period, low-dynamic range, permanent seismic network data collected for routine volcano surveillance as the poor quality of these data, the clipping of large volcanic earthquakes, and the lack of recording of continuous data prior to 1997 make these data inadequate to address the goals of this study.

Previous work

Seismic studies at Ruapehu date from the 1940s and have included analyses of the characteristics and source processes of volcanic and volcano-tectonic seismicity and the relationships between seismicity and eruptive activity (Dibble 1974; Latter 1981; Hurst 1992, 1998; Bryan and Sherburn 1999; Sherburn et al. 1999). Volcanic earthquakes result from the movement of magmatic fluids (McNutt 1996) and are common at Ruapehu (Sherburn et al. 1999). Although they have accompanied all significant historic phreatomagmatic or magmatic eruptions from Ruapehu, many $M_L \geq 3$ volcanic earthquakes have occurred without an accompanying eruption (Sherburn and Bryan 1999). There are no discernible differences in the waveforms, spectral content, or particle velocities of the eruptive and non-eruptive volcanic earthquakes (Hicks et al. 1999). At Ruapehu, volcanic earthquakes are often multiple events, composed of two or more distinct phases (Sherburn et al. 1999). They are generally emergent, with the waveform gradually rising out of the background tremor signal. Between 1971 and early October 1995, most volcanic earthquakes at Ruapehu were monochromatic, with a prominent 2 Hz spectral peak at both the summit and flank seismic sites. Approximately 3 weeks into the 1995 eruptive sequence, following the largest of the 1995 eruptions, the 2 Hz volcanic earthquakes were replaced by broadband (2–10 Hz) volcanic earthquakes (Bryan and Sherburn 1999; Sherburn et al. 1999), many of which showed a high-frequency (6–10 Hz) onset and appeared similar to the hybrid events recorded at Galeras, Redoubt, and Pinatubo (Chouet 1996). This coincided with the ejection of the remaining water in Crater Lake and a change in eruptive style from phreatomagmatic to magmatic. Seismicity associated with the recommencement of eruptive activity in June 1996 had identical frequency characteristics to that of the post-mid-October 1995 activity, suggesting that there were no significant changes in the volcanic plumbing system in the intervening period and that the style of eruption was similar to that during the latter part of the 1995 eruptions (Bryan and Sherburn 1999). Small eruptions in late 1997 and early 1998 were accompanied by volcanic earthquakes similar in shape to the pre-1995 earthquakes, but slightly lower in dominant frequency, and without a high-frequency onset.

Volcanic tremor studies at Ruapehu have shown the existence of tremor of several dominant frequencies (Fig. 1). For the 25 years preceding the 1995 eruptions, the strongest tremor recorded at Ruapehu had a prominent 2 Hz spectral peak, frequency range ~1.8–2.3 Hz, at both the summit and flank seismic sites. Large fluctuations in the amplitude of the 2 Hz tremor often did not correlate with changes in eruptive activity. Hurst (1992) showed that although both 2 Hz tremor and 2 Hz volcanic earthquakes probably originated from the same source, the tremor was not the result of the repeated occurrence of small volcanic earthquakes. Short intervals of shallow volcanic tremor with a peak frequency of 3 Hz were common from 1985 to 1988. This tremor was inferred to be related to regular periods of lake heating (Sherburn et al. 1999). Shallow tremor with a spectral peak of 6–7 Hz has been recorded nearly continuously since December 1993. Until just prior to the 1995 eruptions, its amplitude at DRZ remained constant at ~1 μm/s, and minor variations in its amplitude were independent of even large changes in the amplitude of the 2 Hz tremor (Sherburn et al. 1999). Tremor of ~0.8 Hz frequency was recorded at Ruapehu for periods of a few hours at a time during the first 1.5 weeks of the 1995 eruptions and was inferred to represent magma intrusion to shallow depth within the volcano (Bryan and Sherburn 1999). Broadband (2–10 Hz) tremor was first recorded 3 weeks into the 1995 eruptions, appearing at the same time as the broadband volcanic earthquakes, and continued throughout the 1996 eruptions (Bryan and Sherburn 1999). This tremor was particularly strong during large ash eruptions.

Volcano-tectonic earthquakes involve brittle failure due to stresses within the volcanic edifice, but are not directly related to the movement of magmatic fluids (McNutt 1996). At Ruapehu, they are believed to occur adjacent to the region in which volcanic seismicity originates. As they neither appear to be directly related to eruptions, nor do they occur as unambiguous precursors to volcanic activity at Ruapehu, we will not discuss them any further in this paper.

Broadband deployments

Broadband seismographs were deployed on Ruapehu for 6.5 weeks in 1994 and 6 months in 1998. The 1994 deployment, lasting from 28 January until 13 March, consisted of 14 Guralp CMG3 sensors and included four stations surrounding Crater Lake and two stations on the upper flanks of the volcano within 5.5 km of the summit

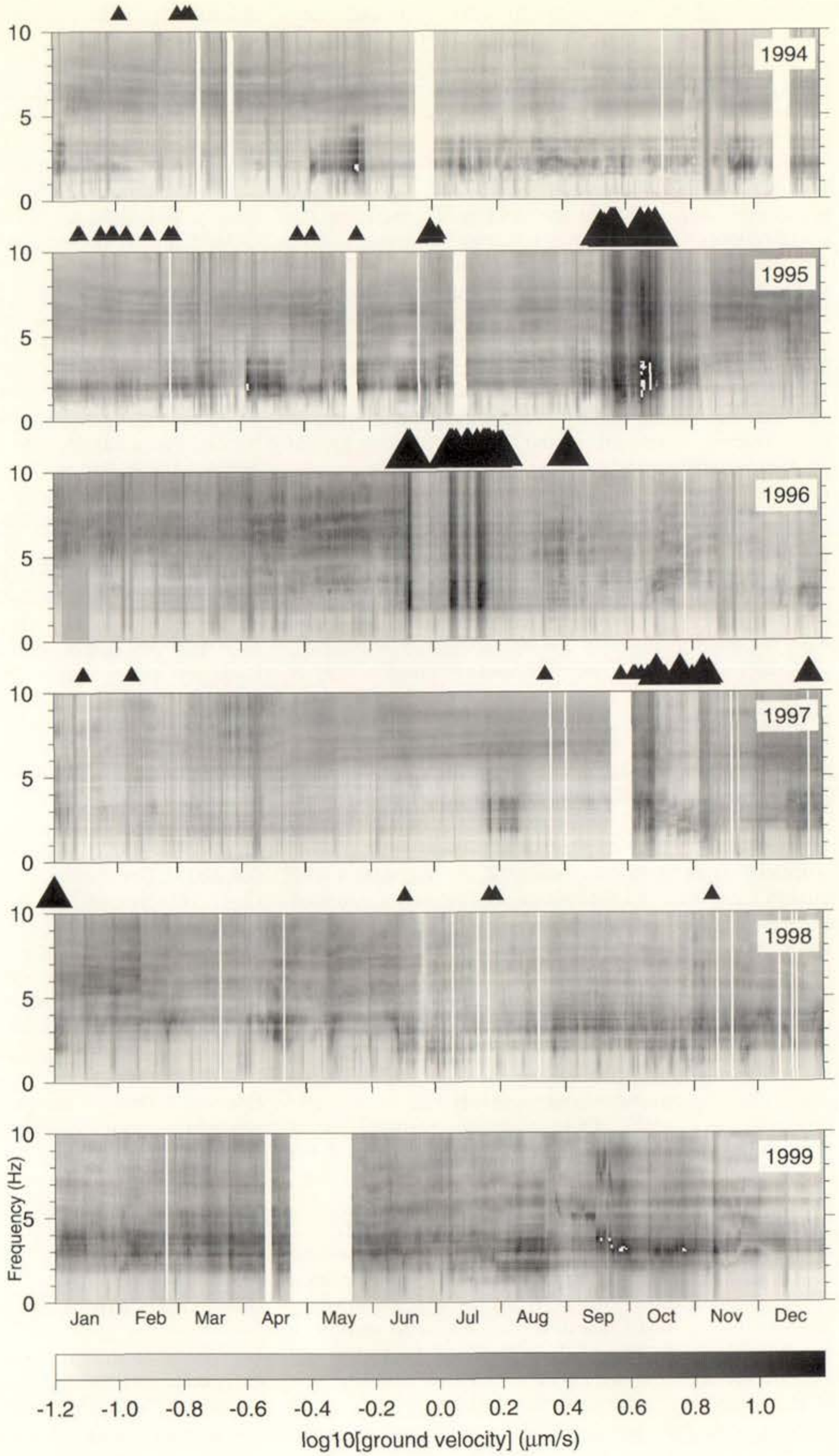


Fig. 1 Tremor spectrograms at Ruapehu from 1994 until 1999. Spectrograms were calculated using daily average spectra at DRZ. Spectra were initially calculated every 10 s, with a 50% overlap and a frequency resolution of 0.1 Hz. These were averaged to produce 5-min spectra from which the daily average spectra were then calculated. *White vertical bands* indicate periods when no data were available. The *triangles* above the spectrograms represent eruptions with the triangle size corresponding to the size of the eruption on a semi-quantitative scale of 1–5 (Sherburn et al. 1999)

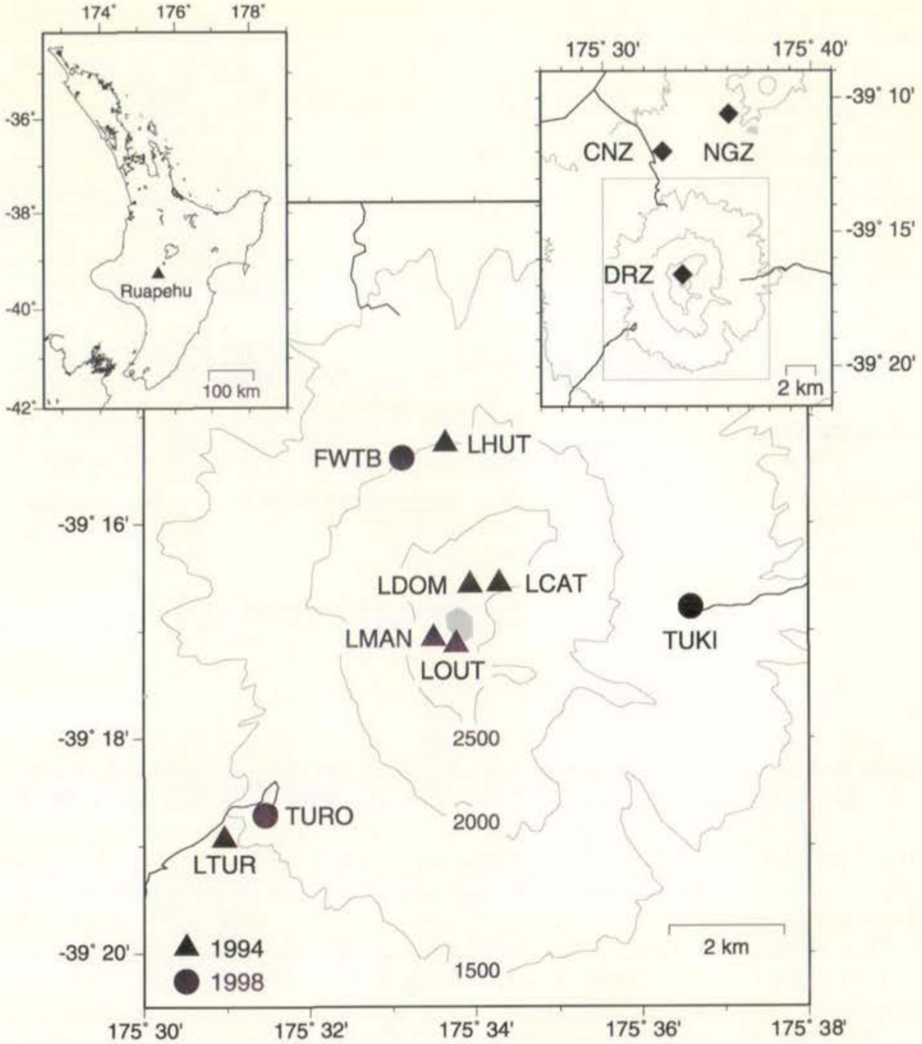


Fig. 2 Map showing the locations of the seismic stations during the two broadband deployments. The upper mountain stations of the 1994 deployment are shown by *triangles* and those of the 1998 deployment by *circles*. Contours at 500 m intervals are shown by the *light solid lines*, and roads by the *dark solid lines*. Ruapehu Crater Lake is shown as a shaded area in the center of the map. The *left-hand inset* shows the location of Ruapehu in the center of the North Island of New Zealand. The *right-hand inset* shows the stations (*diamonds*) of the permanent, short-period, vertical component, seismic network used to monitor volcano-seismic activity of Ruapehu that are mentioned in the text. Contours at 500 m are shown by the *light solid lines* and roads by the *dark solid lines*. The *box* shows the area of the main figure

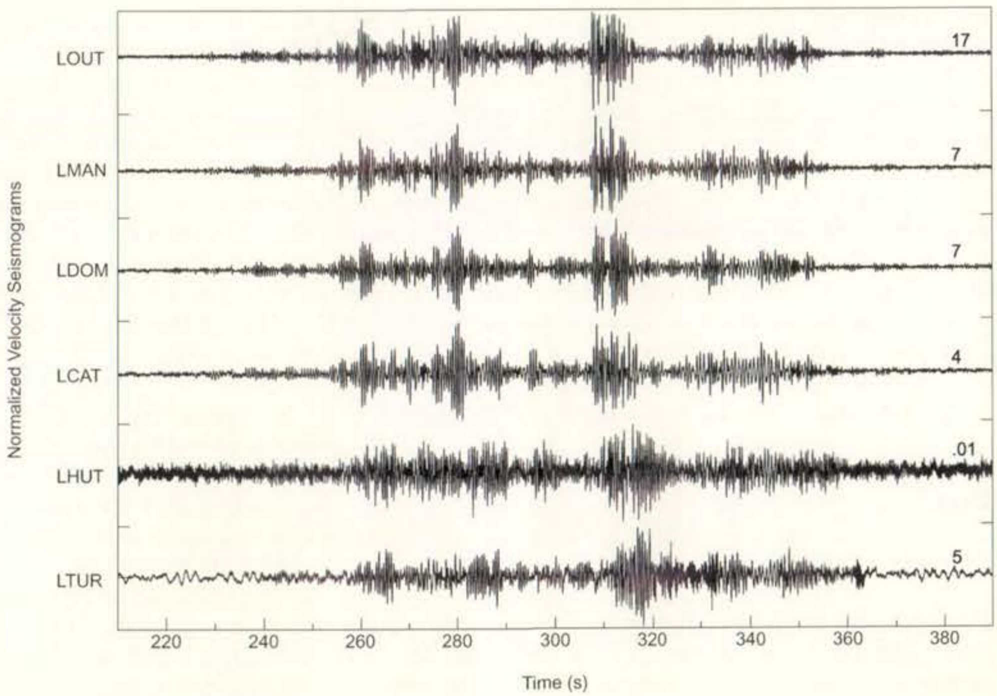


Fig. 3 Waveforms of a typical 1994 volcanic earthquake (30 January 1994 03:43 UT) high-pass filtered at 0.7 Hz. Waveforms are arranged, from top to bottom, by increasing distance from the summit crater. Waveforms are similar at all sites for all events. The maximum amplitude (μm/s) of each high-pass-filtered velocity seismogram is given on the right-hand-side of the waveform

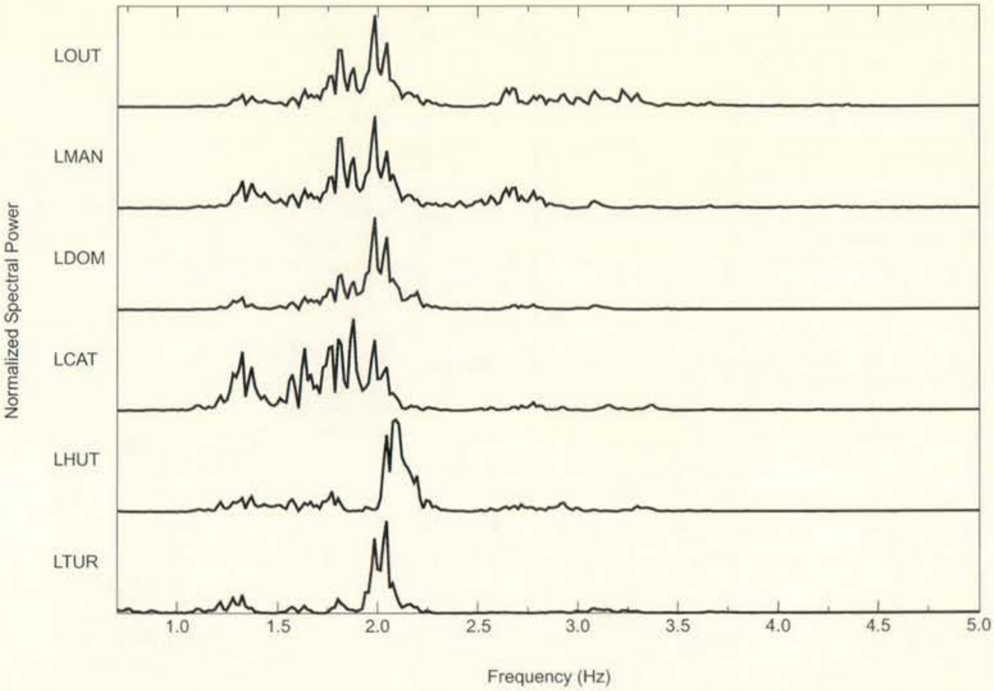


Fig. 4 Normalized spectral power for 180 s of data for the volcanic earthquake of Fig. 3. Power density spectra were calculated from velocity seismograms uncorrected for instrument response using five successive 60-s data windows with 50% overlap. Spectra are cut off at 0.7 Hz due to the predominance of microseism at lower frequencies. All energy is contained in the band 1–3.5 Hz, with a prominent spectral peak at about 2 Hz. Spectra are arranged, from top to bottom, by increasing distance from the summit crater

(triangles, Fig. 2). The four sensors surrounding Crater Lake and the sensor at site LHUT had identical response functions; however, the response function of the sensor at site LTUR differed from the others. We used only these six stations of this deployment in our analysis as the rest of the stations were too far from the summit to record the signals of interest.

The 1998 deployment (4 February to 3 August) consisted of three Guralp CMG3 sensors (circles, Fig. 2), all with identical response functions and sited within 5 km of the summit. Two sites occupied in the 1998 deployment were within 1 km of sites occupied in 1994, thus minimizing both path and site effects due to the differing receiver locations. Furthermore, the response functions of the various instruments were identical at the frequencies of interest in this study. Thus, we can readily compare the seismic signals recorded before the 1995–1996 eruptions with those recorded after the eruptions.

All data for both the 1994 and 1998 deployments were recorded at a sampling rate of 62.5 Hz using Lennartz MARS-88 dataloggers with magneto-optical disks. Seismometers often could not be buried so thermal insulation was achieved by protecting the sensors with a large plastic pipe filled with Styrofoam beads. Sites were visited approximately weekly to change disks and to check the instruments. Timing was provided by GPS.

Data

1994, pre-eruption

Ruapehu was both seismically and volcanically quiet during the 1994 deployment. Only a few small volcanic earthquakes (M_L<2) were recorded during the deployment and there were no periods of strong volcanic tremor [reduced displacement (D_R)≥0.1 cm^2 at CNZ].

Ten of the larger volcanic earthquakes were analyzed. They were typical of the 2 Hz volcanic earthquakes that formed the background seismicity at Ruapehu prior to the 1995 eruptions. All waveforms were similar at all sites (Fig. 3), suggesting that the waveforms reflect source, rather than path or site effects. The events were dominated by energy in the band 1–3.5 Hz, with the maximum energy at about 2 Hz (1.75–2.25 Hz) (Fig. 4). There was no very-long-period energy (T>1 s) in these earthquakes. There were only minor differences between sites, with most of these being in the relative amplitudes of the different spectral components. Waveform envelopes of vertical and horizontal components had the same shape and very similar amplitude ratios. Furthermore, spectrograms showed no apparent variation in the frequency content with time for any individual event; nor did the time delay between sites vary with time. Thus, the partitioning of energy into vertical and horizontal components, and, consequently, the source process and source locations of the individual pulses, did not change during the event.

During this 6-week deployment, volcanic tremor was never recognizable by eye on the analog seismograms from the short-period, permanent network site located at CNZ (inset, Fig. 2), a distance of 9 km from the Crater Lake, a site that usually records episodes of moderate-to-strong tremor. However, analysis of digital data showed that although 7 Hz tremor formed the background signal in 1994, there were many periods when 2 Hz tremor was predominant. As we were primarily interested in the lower frequencies historically associated with volcanic activity, we selected for analysis several periods of background noise in which these frequencies were present. Spectra for these periods were dominated by spectral

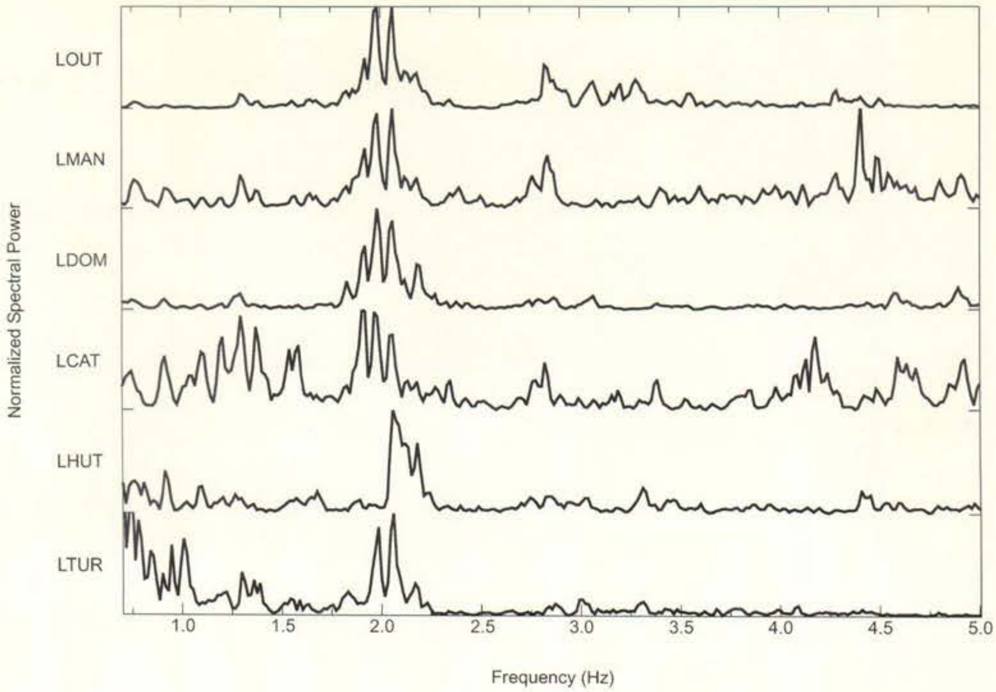


Fig. 5 Normalized spectral power for 180 s of data for volcanic tremor (30 January 1994 14:00 UT). Spectra are calculated as in Fig. 4. Spectra are arranged, from top to bottom, by increasing distance from the summit crater. Spectra are dominated by peaks at ~2 Hz with lesser peaks at ~1.3, ~2.8, and ~4.0–4.5 Hz

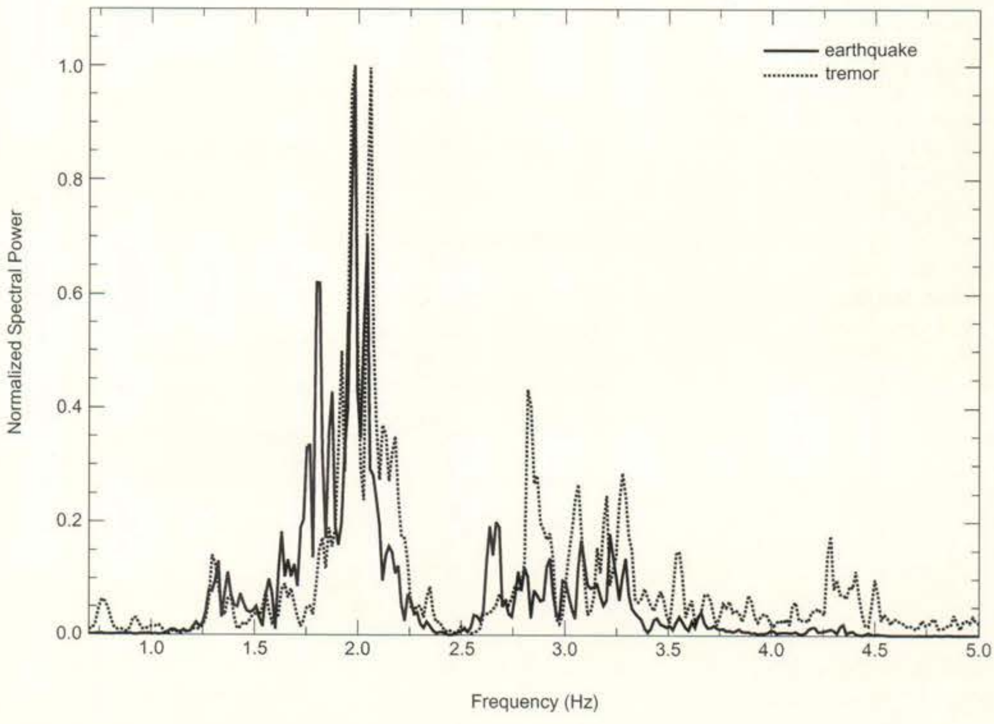


Fig. 6 Comparison of the spectra at LOUT of the 1994 earthquake of Fig. 4 and tremor of Fig. 5. The frequency content of the volcanic earthquake is almost identical to that of the tremor

peaks of ~2 Hz, with a lesser peak at ~2.8 Hz, especially at the sites closest to Crater Lake (Fig. 5). Although this signal was not recognizable by eye as such, it was weak volcanic tremor, and except for the effect of the lower signal/noise ratio, its spectrum was very similar to that of the volcanic earthquakes (Fig. 6).

In summary, in 1994, seismicity was typical of that of the preceding 25 years and thus represents the dominant, stable, pre-eruption seismicity. Volcanic earthquakes and volcanic tremor had the same spectral characteristics, supporting Hurst's (1992) conclusion that volcanic earthquakes and tremor arose from the same source.

1998, post-eruption

Ruapehu was volcanically quiet during the 1998 deployment. However, this deployment followed a 4-month pe-

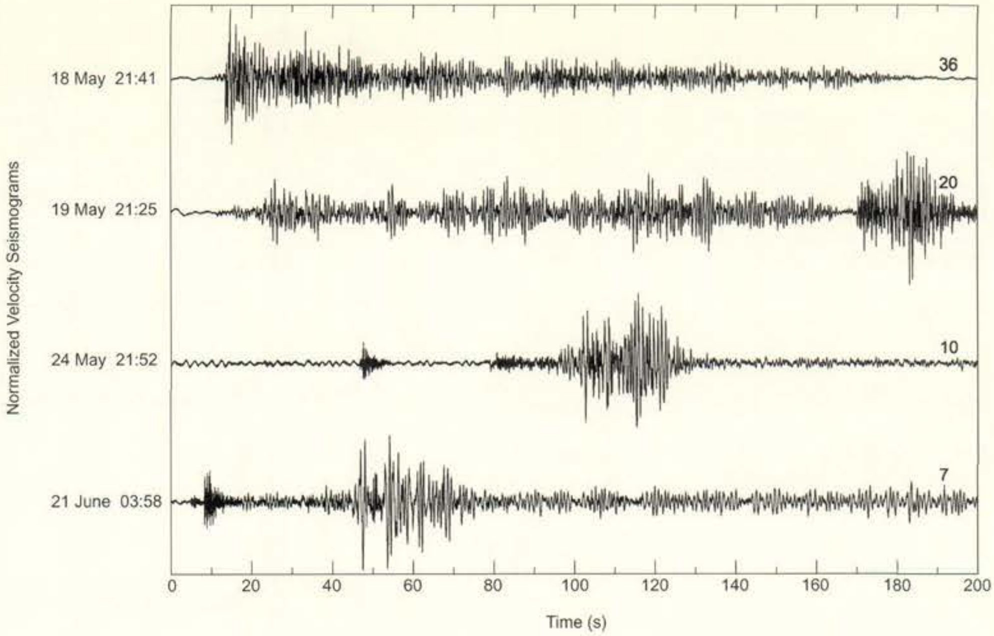


Fig. 7 Waveforms of some 1998 volcanic earthquakes recorded at FWTB. The two earlier events (*top of figure*) are typical of the pre-1995 volcanic earthquakes, while the two later events (*bottom of figure*) show high-frequency onsets not seen in the earlier events. The maximum amplitude (μm/s) of each velocity seismogram is given on the right-hand-side of the waveform

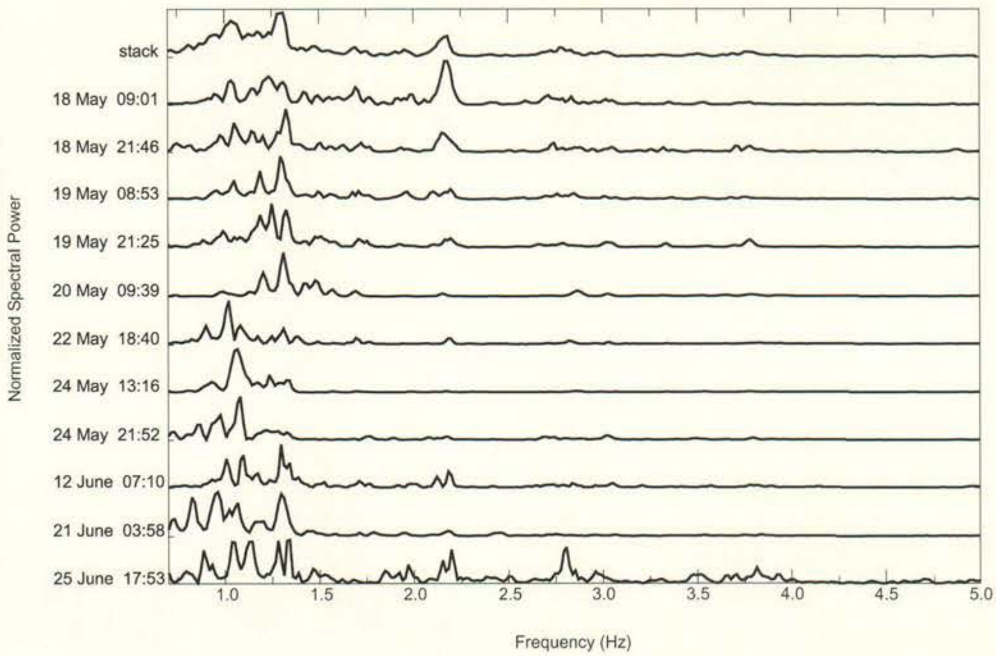


Fig. 8 Individually normalized spectra of 1998 volcanic earthquakes recorded at FWTB. Power density spectra were calculated from uncorrected velocity seismograms using nine successive 60-s data windows with 50% overlap. All are dominated by frequencies of 0.8–1.4 Hz, with a lesser peak at ~2.2 Hz

riod of sporadic, small, discrete eruptions and slightly elevated volcanic tremor (Fig. 1). There were several moderate (M_L 2.0–2.6) volcanic earthquakes during the deployment, including an intriguing series of six events in May 1998 that were separated in time by 12±1 h. Although these earthquakes were accompanied by a change in the color of Crater Lake, there was no eruptive activity.

Waveforms of the 1998 volcanic earthquakes were highly variable. Some events appeared similar to typical pre-1995-eruption, emergent, volcanic earthquakes, whereas other events showed an impulsive, high-frequency onset (Fig. 7). This low-energy, high-frequency phase is similar to that which was common during the 1996 eruptions (Bryan and Sherburn 1999) and these events, to volcanic earthquakes in 1983, all of which were preceded by a few minutes by small volcano-tectonic earthquakes (Sherburn et al. 1999). The high-frequency phases have the particle motion of a P-wave, a source direction coincident with the crater, and an incidence angle at the surface of about 45°. Although dependent on the poorly-defined velocity model, this incidence angle suggests a source for this phase of 1–2 km below Crater Lake. The particle motion of the lower-frequency main phase is complex, but probably represents several types of waves, with lots of scattered energy.

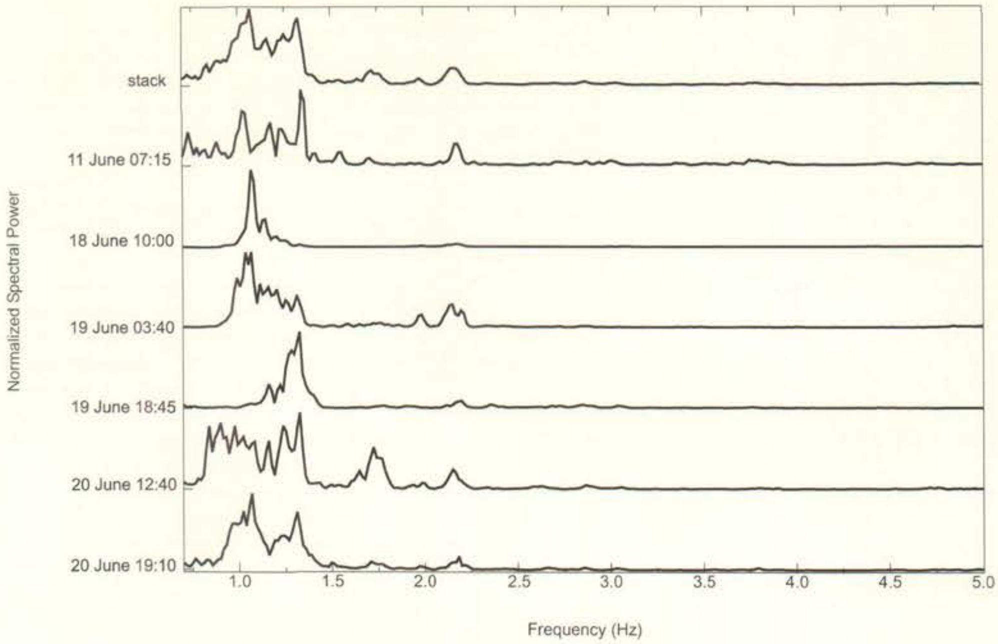


Fig. 9 Normalized spectra of strong 1998 tremor recorded at FWTB. Spectra are calculated as in Fig. 8. Strong tremor is dominated by frequencies of 0.8–1.4 Hz, with a lesser peak at ~2.2 Hz

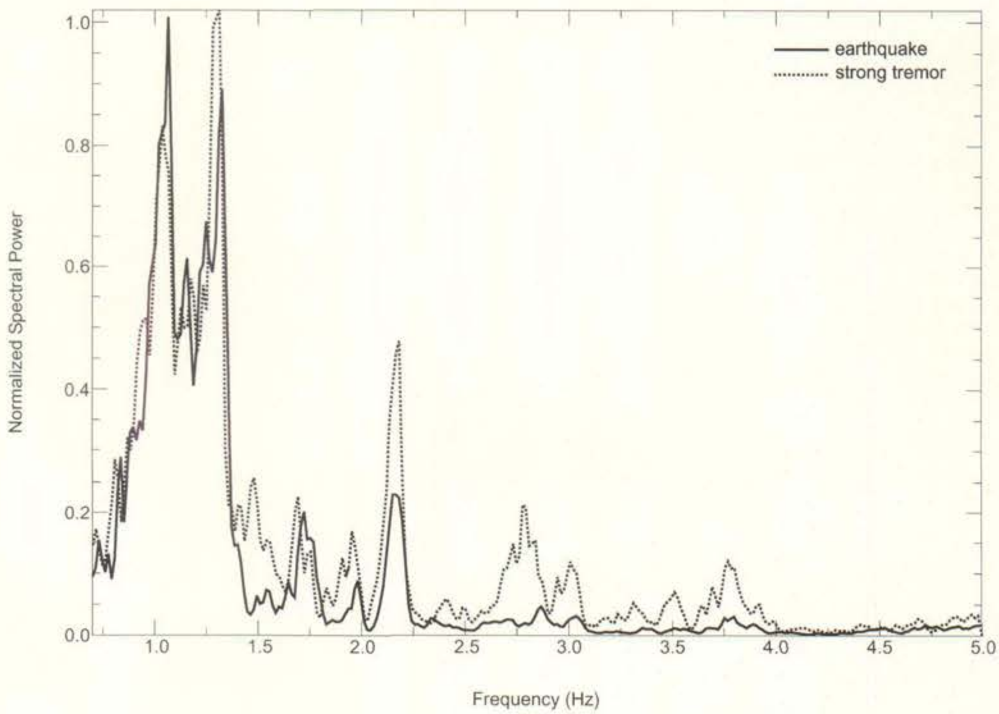


Fig. 10 Individually normalized, stacked spectra of the 1998 volcanic earthquakes and strong tremor recorded at FWTB. The frequency content of the volcanic earthquakes is very similar to that of the strong tremor

The volcanic earthquakes were dominated by frequencies of 0.8–1.4 Hz, with lesser peaks at ~2.2 and ~2.8 Hz (Fig. 8). They were generally similar at each site, although the relative amplitudes of the dominant frequencies were somewhat site dependent. 1998 tremor was divided into two groups: strong and weak. Strong tremor was defined as having a reduced displacement $D_R \geq 0.1$ cm^2 at CNZ, this being the approximate cut-off at which tremor was distinguishable by eye on the analog seismograms recorded at that site. Spectra were calculated for 300-s-long segments of tremor of reduced displacement $4.7 \leq D_R \leq 10.7$ cm^2 at CNZ. Individual periods of strong tremor were quite similar and were dominated by frequencies of 0.8–1.4 Hz with a lesser spectral peak at 2.2 Hz (Fig. 9). These frequencies were almost identical to those of the volcanic earthquakes (Fig. 10), further supporting Hurst's (1992) conclusion that at Ruapehu volcanic earthquakes and tremor originate from the same source process.

For the weak tremor, we examined 300-s segments of tremor beginning at 01:00 UT of each day for the months

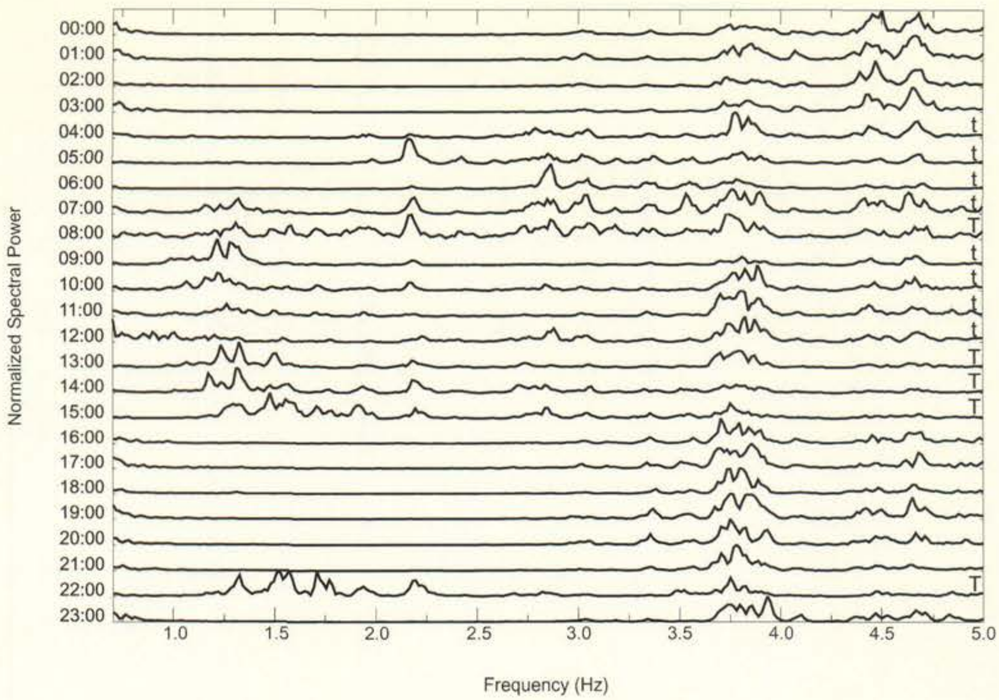


Fig. 11 Individually normalized tremor spectra for 300-s segments of data at FWTB beginning on the hour for every hour of 9 June 1998. Spectra are calculated as in Fig. 8. The *uppercase T's* at the right side of the plot indicate times when the tremor was strong, and the *lowercase t's*, times at which the tremor was moderate. At all other times, the tremor was weak. The higher frequencies of tremor are present at all times, while the lower-frequency components are generally present only when the tremor is moderate-to-strong in intensity

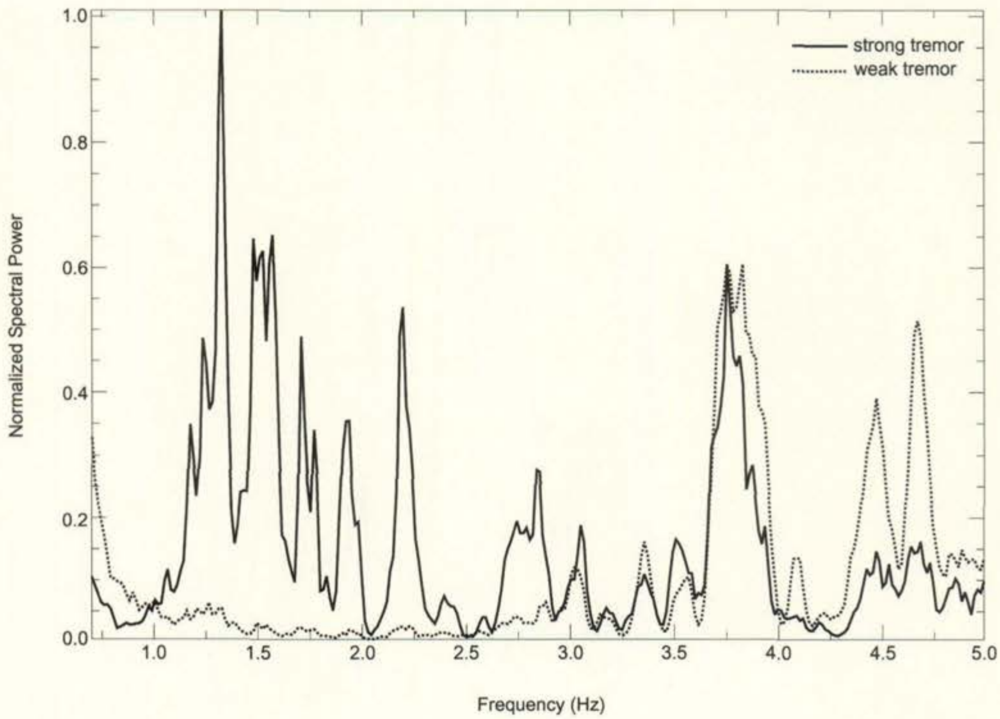
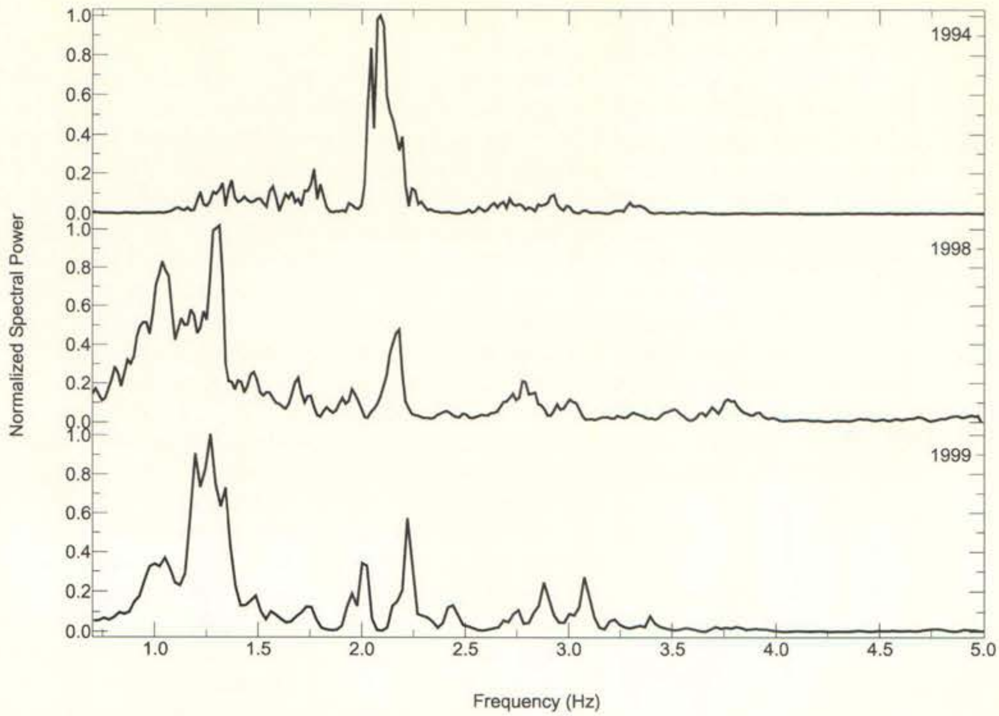


Fig. 12 Stacked spectra of the strong and weak tremor recorded at FWTB during 1998. The spectra are scaled so that the amplitudes at 3.75 Hz are the same. Strong and weak tremor show similar spectral characteristics at frequencies ≥3 Hz. However, the strong tremor contains spectral peaks not observed in the weak tremor. When present, these low-frequency components dominate the tremor spectrum

of March, May, and June 1998, excluding from the analysis only those time segments during which either earthquakes occurred or wind noise, as evidenced by its flat spectrum, dominated the signal. We also selected 300-s segments of data beginning on the hour for every hour of 4 days during which strong tremor was present for at least part of the day. Figure 11 shows tremor spectra for every hour of 9 June. The uppercase T's at the right side of the plot indicate times at which the tremor was strong, and the lowercase t's, times of moderate tremor. At other times, the tremor was classified as weak. Although the dominant tremor frequency varied with time, tremor with frequencies ≥3.5 Hz was almost always present whenever tremor was recorded. However, the lower frequencies (3≤Hz) were present only when the tremor was moderate or strong (Figs. 11, 12). Comparison of the relative spectral amplitudes of the strong and weak tremor suggested that whenever the lowest-frequency tremor was present,

Fig. 13 Spectra from volcanic earthquakes at Ruapehu in 1994, 1998, and 1999. Spectra are calculated as in Figs. 4 and 8. In 1998 and 1999, a broad spectral peak of frequency 0.8–1.4 Hz was apparent that was not observed in 1994. The ~2 Hz spectral peak that dominated spectra in 1994 was present in 1998 and 1999, but was subordinate to the 0.8–1.4 Hz energy



it dominated the tremor spectrum (Fig. 11). This suggests that the tremor of frequency ≳3.5 Hz forms the background tremor at Ruapehu while the low-frequency tremor source, which is linked to the source of the volcanic earthquakes, is only intermittently active, but is dominant when activated.

Discussion

Temporal variations in spectral characteristics of Ruapehu seismicity

A striking change in the frequency content of tremor and volcanic earthquakes at Ruapehu occurred between 1994 and 1998 (Fig. 13). In 1998, a broad spectral peak of frequency 0.8–1.4 Hz was apparent in volcanic earthquakes and periods of strong tremor that was not observed prior to and including 1994 (Hurst 1992; Hurst and Sherburn 1993; Sherburn et al. 1999). The ~2 Hz spectral peak that dominated the earlier spectra was present in 1998, but was subordinate to the 0.8–1.4 Hz energy. Observations from a permanent broadband sensor installed at FWTB in 1999 confirm that volcanic earthquakes at Ruapehu remained dominated by energy of 0.8–1.4 Hz in 1999.

The exact timing of this frequency change is unknown. Sub-1-Hz tremor was first observed at Ruapehu during the days preceding the start of the 1995 eruptions although volcanic earthquakes at that time continued to be dominated by a 2 Hz signal (Bryan and Sherburn 1999). Wideband volcanic seismicity, both earthquakes and tremor, then became predominant with the change in eruptive style from phreatomagmatic to magmatic and continued through the 1996 eruptions. The wideband seismicity observed during these eruptions did not persist, but, rather, was replaced by a style of seismicity similar, although not identical to, that which characterized the pre-1995 eruptive period. In particular, the previously dominant ~2 Hz volcanic seismicity was replaced by seismicity dominated by frequencies of 0.8–1.4 Hz. We attribute this change in the spectral characteristics of the volcanic seismicity to changes in the volcanic plumbing system resulting from the 1995–1996 eruptions.

Spectral variation in tremor at volcanoes worldwide

Long-term data on the frequency content of volcanic tremor are not widely available as prior to the development of the SSAM software (Rogers and Stephens 1995) continuous, efficient collection of these data was difficult. However, at Ruapehu, spectral data are available with only minor interruptions since 1985 (Hurst 1985). Several notable changes in the frequency content and amplitude of volcanic tremor have been recorded in recent years (Fig. 1); however, many of these changes have occurred independently of any change in any other measured parameter at the volcano.

Spectral and amplitude data from other volcanoes generally show less variation than those from Ruapehu. At Masaya, variations with time in the amplitude and frequency content of tremor are minor (Métaxian et al. 1997). During 1989–1992, when volcanic activity was minor and stable, the dominant 2 Hz spectral peak varied between 1.8 and 2.2 Hz. In 1993, a lava lake appeared and the tremor amplitude increased by a factor of four, but the dominant frequency did not change (J-P. Métaxian, pers. comm. 2000). At Etna, although there are changes in the frequency of volcanic tremor within a few hours of eruptions, when not erupting, the tremor frequency remains very stable (Ereditato and Luongo 1994). At Pavlof, the frequency spectra of strong volcanic tremor generated during eruptions are indistinguishable from those of weaker tremor occurring during non-eruptive periods (McNutt 1987). In addition, the frequency content of tremor does not change appreciably with time, with similar spectra recorded during eruptions in 1973, 1974, 1981, and 1983. In contrast, volcanic tremor spectra at Klyuchevskoy show temporal variations. Gordeev et al. (1990) showed that over periods of a few days in 1984 and 1986, the spectra of tremor at Klyuchevskoy were unchanged although the tremor amplitude varied more than twentyfold. However, when they repeated observations in 1987, Gordeev et al. (1990) noticed that although the number and position of spectral peaks remained the same, the later tremor contained more low frequencies, particularly on transverse components. We conclude that, from a worldwide perspective, spectral variability of tremor at Ruapehu is unique, or at least very unusual.

Tremor duration

The occurrence of long-lived volcanic tremor at Ruapehu without concomitant eruptive activity or correlated changes in lake temperature or other monitored geochemical or geodetic parameters is relatively unusual. In a study of 650 references to volcanic tremor and related phenomena at 160 volcanoes worldwide, McNutt (1994) noted that the occurrence of volcanic tremor is widespread with 35% of tremor episodes occurring without an accompanying eruption. However, he also noted that although the duration of individual tremor episodes ranged from minutes to years, at only 3% of volcanoes did tremor continue for weeks or longer. Continuous tremor episodes with durations longer than one year occurred at Etna, Stromboli, Arenal, Kilauea, and Oshima, and were often associated with ongoing eruptions. Masaya also exhibits almost continuous tremor that is associated with degassing in the lava lake or in a shallow magma body (Métaxian et al. 1997). Thus, the long-lived tremor at Ruapehu, which appears to be primarily associated with the vent-lake hydrothermal system rather than solely with a magmatic system, is uncommon, if not unique.

Very-long-period energy

Recent studies using broadband seismometers have shown that very-long-period volcano seismicity, with periods of 3–20 s, originates at depths of less than 1.5 km under some active volcanoes (Kawakatsu et al. 1992, 1994; Neuberg et al. 1994; Kaneshima et al. 1996; Cruz and Chouet 1997; Ohminato and Ereditato 1997; Rowe et al. 1998). This corresponds to the depth range within which most of the volcano seismicity at Ruapehu originates. However, although our broadband observations at Ruapehu were capable of recording such signals, none were observed. In particular, no very-long-period signals were observed in 1994 (J Neuberg, pers. comm. 1999) and none as part of several moderate-sized volcanic earthquakes in May 1998. McNutt (1999) noted that very-long-period signals have not been observed at several active, erupting volcanoes where broadband instruments have been deployed; therefore, their absence at Ruapehu is not unusual.

Source process and location

At a number of volcanoes, volcanic earthquakes and volcanic tremor have been found to have the same spatial and temporal characteristics, suggesting a common source process for these types of seismicity (Fehler 1983; Mori et al. 1989; Julian 1994; Chouet 1996). This correlation has recently been further extended to include relationships between classical long-period seismicity and seismicity which is intermediate in character between long- and short-period (Lahr et al. 1994; Chouet 1996), and, more recently, all low-frequency seismic events (Neuberg et al. 1998).

Ruapehu also exhibits this very strong similarity within apparently different styles of volcano seismicity. Similar spectral characteristics for volcanic earthquakes and tremor at Ruapehu in 1994 suggest that, at that time, these two types of volcanic seismicity were generated by the same source process. In 1998, this similarity between volcanic earthquakes and tremor continued, provided that tremor was strong. However, Ruapehu differs from other volcanoes in the temporal spectral variability of its volcano-seismicity. Spectral frequencies contained in the 1994 volcano-seismicity are generally observed in the strong 1998 seismicity, suggesting continued intermittent activity of the source process active in 1994. However, at times in 1998, a new low-frequency spectral peak was present in the strong tremor and volcanic earthquakes, requiring the existence of an additional tremor source.

Similar to Gordeev et al.'s (1990) observation at Klyuchevskoy, we found that, in 1998, the lower frequencies dominated the tremor spectra at Ruapehu only when the tremor was strong. However, unlike at Klyuchevskoy, the lowest frequencies of tremor do not appear to be present at Ruapehu when the tremor is weak. Gordeev et al. (1990) proposed that the increase in the low-frequency components of the Klyuchevskoy tremor relative to the higher-frequency components arose from an increase in the tremor source dimensions with larger source dimensions corresponding to periods of stronger tremor. This may explain the changes in the tremor frequencies at Ruapehu.

Another possible explanation is that the low-frequency tremor source is distinct from and independent of the high-frequency tremor source. Comparison of the rela-

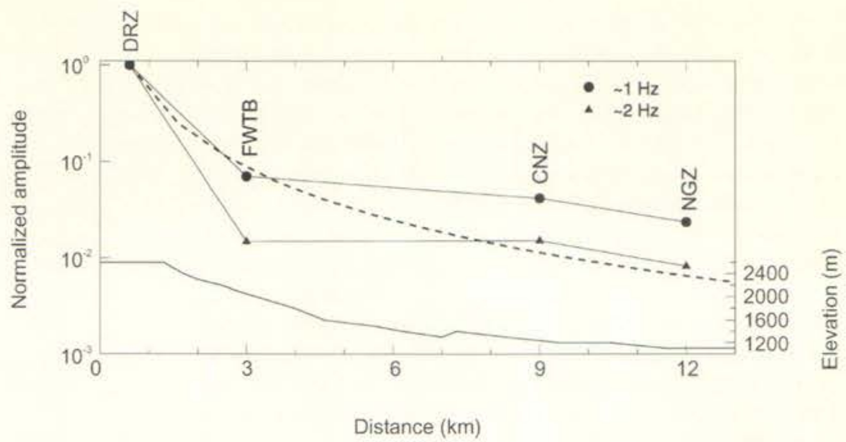


Fig. 14 Amplitude decay with distance for signals with frequencies of 0.8–1.4 and ~2 Hz. Data points are from DRZ, FWTB, CNZ, and NGZ. The data are normalized such that the amplitude at DRZ is identical for both frequencies. The *dashed line* represents a 1/(distance)^2 decay. Ruapehu's topography is shown at the bottom of the figure

tive amplitudes of the ~0.8–1.4 Hz tremor and the 2 Hz tremor recorded in 1994 and 1998 shows that the lower frequency tremor attenuates much more slowly with distance from the summit than the 2 Hz tremor (Fig. 14). This suggests a deeper source for the 0.8–1.4 Hz tremor than for the 2 Hz tremor. Unlike the high-frequency tremor source which may be almost always active, this low-frequency tremor source may only be sporadically active.

Conclusions

The characteristics of the seismicity at a volcano are routinely used for real-time assessment of the state of that volcano. A critical assumption is that the long-term relationships between seismicity and eruptive activity do not vary with time, and, furthermore, that they are not affected by eruptions. We tested these hypotheses by analyzing the characteristics of the volcano-seismicity at Ruapehu prior to and following the 1995–1996 eruptions. This is of particular importance, as, to our knowledge, no one has studied the long-term effects of an eruption on seismicity.

We have shown that the 1995–1996 eruptions changed the characteristic volcanic seismicity at Ruapehu. An initial change from near monochromatic 2 Hz volcanic seismicity to wideband signals in October 1995 occurred concomitantly with the change in eruptive style from phreatomagmatic to magmatic and the ejection of the last of the water remaining in Crater Lake (Bryan and Sherburn 1999). After the eruptions, this wideband seismicity disappeared and there was a partial return to the monochromatic pre-eruption seismicity; however, there was a clear decrease in the dominant frequency of strong volcanic signals from 2 to 0.8–1.4 Hz. In terms of eruption forecasting at Ruapehu, this decrease in dominant frequency is perhaps the most significant change in volcanic seismicity as seismic precursors to eruptions at Ruapehu are especially subtle. The exact timing of this frequency change is unknown. The new, low frequencies were not observed during the 1995–1996 intra-eruptive period; however, there were no volcanic earthquakes nor any strong tremor at that time.

If the ejection of Crater Lake and the resultant removal of a confining pressure of ~10 bar allowed either the activation of more volcano-seismic resonator sources or a change in the volcano-seismic source dimensions, it is possible that the higher-frequency (≳2 Hz) spectral characteristics of the volcanic seismicity will revert to those present prior to the 1995–1996 eruptions when Crater Lake refills. At the present rate of refilling of Crater Lake, it will be several years before we can determine if these observed changes in the volcanic seismicity are merely a temporary response to short-term changes in the volcanic plumbing system or if they will become long-lived features of Ruapehu's characteristic volcanic seismicity. This, however, neither explains the appearance of nor has any implications for the length of existence of the lower (sub-2 Hz) frequencies now present.

Our results have significant implications for the real-time assessment of volcanic activity and hazard at Ruapehu. Not only does the change in the characteristic seismicity affect our ability to forecast future eruptions of Ruapehu, it also affects our ability to use seismic data to forecast the likely course of an ongoing eruption. In particular, real-time volcano seismicity data are used to immediately notify New Zealand Civil Defence, industry, and the public about possible eruptions of New Zealand's volcanoes, with the present focus being primarily on Ruapehu and White Island, currently, the most active New Zealand volcanoes. Several studies of Ruapehu seismicity prior to the 1995–1996 eruptions identified the characteristics of the seismicity preceding and accompanying eruptions, results which proved extremely useful is assessing the status of the volcano during the 1995–1996 eruptions when the summit was not visible. Results of these studies were also used in the design of a system for remote instrumental detection of eruptions of Ruapehu and in the setting up of a system for automated detection of changes in the amplitude of Ruapehu's characteristic tremor. Although those systems provide significant advances in safeguarding people and property on the mountain, as well as those living and working in the vicinity of the volcano, both on the ground and in the air, they are dependent on the characteristics of the seismicity not varying greatly. At present, strong volcanic seismicity at Ruapehu remains dominated by low-frequency (≤ 2 Hz) signals so these systems still work well; however, should a more drastic change occur in the characteristic eruptive seismicity at Ruapehu, the functioning of these systems could be rendered less than ideal unless they were re-tuned to take into account the new seismic characteristics. Hence, it is important to recognize and account for any changes in the characteristic seismicity that may occur as a result of extrusive or intrusive processes. Considered in the wider context, our documentation of short- (if not long-) term change in the characteristic seismicity at a volcano that has recently erupted has significant implications for the future assessment of the status of any volcano that has recently erupted.

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Effects of the 1995/96 Ruapehu Eruptions: Has the Seismicity Changed?

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Non-technical Abstract

High quality seismic data were collected on Ruapehu volcano in 1994 and 1998. These data bracketed the 1995-96 eruptions, the largest eruptions of Ruapehu in 50 years. Analysis of these data showed a clear difference in the frequency content of some of the seismic signals. In particular, a new low-frequency signal in some of the earthquakes and tremors was observed in 1998. This new signal, which probably first appeared during or soon after the 1995-96 eruptions remains as of this time (May 2000). It most likely resulted from changes in the volcanic plumbing system and has significant implications for forecasting and real-time assessment of future eruptive activity at Ruapehu.

ERUPTION INDUCED MODIFICATIONS TO VOLCANIC SEISMICITY AT RUAPEHU, NEW ZEALAND AND ITS IMPLICATIONS FOR ERUPTION FORECASTING

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FINAL REPORT FOR EQC PROJECT NUMBER 99/377 – EFFECTS OF THE 1995/96 RUAPEHU ERUPTIONS: HAS THE SEISMICITY CHANGED?

Abstract

High quality, three-component, broadband seismic data were collected on Ruapehu in 1994 and 1998. These data bracket the largest eruptions to have occurred on Ruapehu in 50 years. We focus our analyses on the stronger, low-frequency, volcanic seismicity during this period with the aim of quantifying eruption related changes that may affect our ability to forecast future eruptions. Although there were significant differences in the frequency content of the seismicity in the periods prior to and following the 1995-1996 eruptions, the types of seismicity and their individual relationships to volcanic processes did not change. The pre-eruption volcanic tremor was characterized by several independent dominant frequencies, with a 2 Hz spectral peak dominating the strongest tremor and volcanic earthquakes and higher frequencies forming the background signal. The post-eruption volcanic seismicity was dominated by a new 0.75-1.5 Hz spectral peak, although the 2 Hz and higher frequencies remained. The similarity of the dominant frequencies of the volcanic tremor and the volcanic earthquakes suggests that during each of these time periods, the volcanic tremor and earthquakes were generated by the same source process. The change in the frequency content, which occurred during the 1995-1996 eruptions and remains as of the time of the writing of this paper, most likely resulted from changes in the volcanic plumbing system and has significant implications for forecasting and real-time assessment of future eruptive activity at Ruapehu.

Keywords

volcanic seismicity; Ruapehu; frequency spectra; source process; eruption forecasting

Introduction

Ruapehu is a 250,000 year-old, active, predominantly andesitic, composite volcano located in the center of the North Island of New Zealand at the southern end of the Taupo Volcanic Zone. Very minor phreatic eruptions, involving water doming within the lake, typically occur several times a year. Larger eruptions, which are characterized by the ejection of ash and mud and the generation of lahars, occur every few years. All historic activity has occurred through the summit crater, which except for periods following the 1945 and 1995-1996 eruptions has been occupied by a hot-water lake.

Unlike the majority of volcanoes worldwide, volcanic seismicity at Ruapehu is ongoing and often varies considerably without any perceptible change in volcanic activity. Volcanic earthquakes often occur unaccompanied by eruptive activity. Similarly, changes in the amplitude and frequency content of volcanic tremor frequently occur independently of any change in eruptive activity. Furthermore, changes in seismicity prior to eruptions are often minor and may not be discernible as such. In particular, geochemical, geodetic, and seismic precursors to the 1995 eruptions were both minor and ambiguous in nature while precursory seismic activity prior to the 1996 eruptions was perceptible, although not extremely obvious (Bryan and Sherburn, 1999). Consequently, in order to recognize any subtle changes in seismicity that may be precursors to a Ruapehu eruption, it is important to well-characterize the ongoing seismicity. Furthermore, if the occurrence of an eruption significantly changes the long-term seismicity pattern at Ruapehu, it is necessary to recognize and understand these changes if deviations from the current seismicity pattern are to be used to forecast future eruptive activity.

In this study, we compare and contrast the characteristics of the volcanic tremor and volcanic earthquakes at Ruapehu before and after the 1995-1996 eruptions. A significant change in the seismicity occurred during the 1995 eruptions and the new style of seismicity continued during the 1996 activity (Bryan and Sherburn, 1999). In order to use characteristics of seismicity to forecast future eruptive activity, it is necessary to determine if these changes were long-term, continuing beyond the 1996 activity, or whether the seismicity returned to that which was typical of the 25 years preceding the 1995 eruptions. We first describe the pre-eruption seismicity using broadband data collected in early-1994. We then use broadband data collected in 1998 to characterize the post-eruption seismicity and to describe changes from the 1994 seismicity in detail, concentrating on changes in the lower frequencies. Finally, we discuss our results in the context of source processes, hazard assessment, and the forecasting of future eruptions. We do not discuss the short-period, low-dynamic range permanent seismic network data collected for routine volcano surveillance as the quality of these data are inadequate to address the goals of this study.

Previous work

Seismic studies at Ruapehu date from the 1940's and have included analyses of the characteristics and source processes of volcanic and volcano-tectonic seismicity and the relationships between seismicity and eruptive activity (Dibble, 1974; Latter, 1981; Hurst, 1992; Hurst, 1998; Sherburn et al., 1999; Bryan and Sherburn, 1999). Volcanic earthquakes result from the movement of magmatic fluids (McNutt, 1996). Although they have accompanied all significant historic phreatomagmatic or magmatic eruptions from Ruapehu, many $M_L \geq 3$ volcanic earthquakes have occurred without an accompanying eruption (Sherburn and Bryan, 1999). There are no discernible differences in the waveforms, spectral content, or particle velocities of the eruptive and non-eruptive volcanic earthquakes (Hicks et al., 1999). At Ruapehu, volcanic earthquakes are often multiple events, composed of two or more distinct phases (Sherburn et al., 1999). They are generally emergent, with the waveform gradually rising out of the background tremor signal. Between 1971 and early-October 1995, most volcanic earthquakes at Ruapehu were monochromatic, with a prominent 2 Hz spectral peak at both the summit and flank seismic sites. Approximately three weeks into the 1995 eruptive sequence, following the largest of the 1995 eruptions, the 2 Hz volcanic earthquakes were replaced by broadband (2-10 Hz) volcanic earthquakes (Bryan and Sherburn, 1999; Sherburn et al., 1999), many of which showed a high-frequency (6-10 Hz) onset and appeared similar to the hybrid events recorded at Galeras, Redoubt, and Pinatubo (Chouet, 1996). This coincided with the ejection of the remaining water in Crater Lake and a change in eruptive style from phreatomagmatic to magmatic. Seismicity associated with the recommencement of eruptive activity in June 1996 had identical frequency characteristics to that of the post-mid-October 1995 activity, suggesting that there were no significant changes in the volcanic plumbing system in the intervening period (Bryan and Sherburn, 1999). Small eruptions in late-1997 and early-1998 were accompanied by volcanic earthquakes similar in shape to the pre-1995 earthquakes, but slightly lower in dominant frequency, and without a high-frequency onset.

Volcanic tremor studies at Ruapehu have shown the existence of tremor of several dominant frequencies (Fig. 1). For the 25 years preceeding the 1995 eruptions, the strongest tremor recorded at Ruapehu had a prominent 2 Hz spectral peak, frequency range ~1.8-2.3 Hz, at both the summit and flank seismic sites. Even large fluctuations in the amplitude of the 2 Hz tremor often did not correlate with changes in eruptive activity. Hurst (1992) showed that although both 2 Hz tremor and 2 Hz volcanic earthquakes probably originated from the same source, the tremor was not the result of the repeated occurrence of small volcanic earthquakes. Short intervals of shallow volcanic tremor with a peak frequency of 3 Hz were common from 1985 to 1988. This tremor was inferred to be related to regular periods of lake heating (Sherburn et al., 1999). Shallow tremor with a spectral peak of 6-7 Hz was recorded nearly continuously from December 1993. Until just prior to the 1995 eruptions, its amplitude at DRZ remained constant at ~1 μm/s, and minor variations in its amplitude were independent of even large changes in the amplitude of the 2 Hz tremor (Sherburn et al., 1999). Tremor of sub-1 Hz frequency was recorded at Ruapehu for periods of a few hours at a time during the first 1½ weeks of the 1995 eruptions and was inferred to represent magma intrusion to shallow depth within the volcano (Bryan and Sherburn, 1999). Broadband (2–10 Hz) tremor was first recorded three weeks into the 1995 eruptions, appearing at the same time as the broadband volcanic earthquakes and continued thoughout the 1996 eruptions (Bryan and Sherburn, 1999). This tremor was particularly strong during large ash eruptions.

Volcano-tectonic earthquakes involve brittle failure due to stresses within the volcanic edifice, but are not directly related to the movement of magmatic fluids (McNutt, 1996). At Ruapehu, they are believed to occur adjacent to the region in which volcanic seismicity originates. As they are neither directly related to eruptions, nor do they occur as unambiguous precursors to volcanic activity at Ruapehu, we will not discuss them any further in this paper.

Broadband Deployments

Broadband seismographs were deployed on Ruapehu for 6½ weeks in 1994 and six months in 1998. The 1994 deployment consisted of 14 Guralp CMG3 sensors and included four stations surrounding Crater Lake and two stations on the upper flanks of the volcano, within 5.5 km of the summit (triangles, Fig. 2). The four sensors surrounding Crater Lake and the sensor at site LHUT had identical response functions; however, the response function of the sensor at site LTUR differed from the others. We used only these six stations of this deployment in our analysis as the rest of the stations were too far from the summit to record any signals of interest.

The 1998 deployment consisted of three Guralp CMG3 sensors (circles, Fig. 2), all with identical response functions and sited within 5 km of the summit. Two sites occupied in the 1998 deployment were within 1 km of sites occupied in 1994, thus minimizing both path and site effects due to the differing receiver locations. Furthermore, the response functions of the various instruments were identical at the frequencies of interest in this study (Fig. 3). Thus, we can readily compare the seismic signals recorded before the 1995-1996 eruptions with those recorded after the eruptions.

Data

1994, pre-eruption

Ruapehu was both seismically and volcanically quiet during the 1994 deployment. Only a few small volcanic earthquakes ($M_L < 2$) were recorded at this time and there were no periods of strong volcanic tremor ($D_R \geq 0.1$ cm^2).

Ten of the larger volcanic earthquakes were analyzed. They were typical of the 2 Hz volcanic earthquakes that formed the background seismicity at Ruapehu prior to the 1995 eruptions. All waveforms were similar at all sites (Fig. 4). The events were dominated by energy in the band 1–3.5 Hz, with the maximum energy at about 2 Hz (1.75-2.25 Hz) and a lesser peak at about 3 Hz (Fig. 5). There was no very-long-period energy (< 1 Hz) in these earthquakes. There were only minor differences between sites, with most of these being in the relative amplitudes of the different spectral components. Waveform envelopes of vertical and horizontal components had the same shape and very similar amplitude ratios. Furthermore, spectrograms showed no apparent variation in the frequency content with time for any individual event; nor did the time delay between sites vary with time. Thus, the partitioning of energy into vertical and horizontal components, and, consequently, the source process and source locations of the individual pulses, did not change during the event.

During this deployment, volcanic tremor was never recognizable by eye on the analog seismograms from the short-period, permanent network site located at CNZ (inset, Fig. 2), a distance of 9 km from the Crater Lake, a site that usually records episodes of moderate-to strong tremor. Although 7 Hz tremor formed the background signal in 1994, there were many periods when the 2 Hz tremor was predominant. As we were primarily interested in the lower frequencies historically associated with volcanic activity, we selected for analysis a series of 10-minute sections of background noise in which these frequencies were present. Spectra for these periods were dominated by spectral peaks of c. 2 Hz, with a lesser peak at c. 3 Hz (Fig. 6). Although this signal was not recognizable by eye as such, it was weak volcanic tremor, and except for the effect of the lower signal/noise ratio, its spectrum was very similar to that of the volcanic earthquakes (Fig. 7).

In summary, in 1994, volcanic earthquakes and volcanic tremor had the same spectral characteristics. This supports Hurst's (1992) conclusion that volcanic earthquakes and tremor arose from the same source. This seismicity was typical of that of the preceding 25 years and thus represents the dominant, stable, pre-eruption seismicity.

1998, post-eruption

Ruapehu was volcanically quiet during the 1998 deployment. However, this deployment followed a 3-month period of sporadic, small, discrete eruptions and slightly elevated volcanic tremor. There were several moderate (M_L 2-2.6) volcanic earthquakes during the deployment, including an intriguing series of six events in May 1998 that were separated in time by 12±1 hour, but none of which was accompanied by eruptive activity.

Waveforms of the 1998 volcanic earthquakes showed some variability. Some events appeared similar to typical pre-1995 eruption, emergent, volcanic earthquakes, whereas other events showed an impulsive, high-frequency onset (Fig. 8). This low-energy, high-frequency phase is similar to that which was common during the 1996 eruptions (Bryan and Sherburn, 1999) and to volcanic earthquakes in 1983, which were all preceded by a few minutes by small volcano-tectonic earthquakes (Sherburn et al., 1999). The high-frequency phases have the particle motion of a P-wave, a source direction of the crater and an incidence angle of 45°. The particle motion of the lower frequency, main phase is complex, but probably consists of waves of several types, with lots of scattered energy.

The volcanic earthquakes in 1998 were dominated by frequencies of 0.75-1.5 Hz, with lesser peaks at c. 2.2 Hz, c. 2.8 Hz, and c. 3.75 Hz (Fig. 9). The volcanic earthquakes are generally similar at each site, although the relative amplitudes of the dominant frequencies are site dependent. In particular, at TUKI the spectral peak at c. 2.2 Hz is stronger than at other sites, while proportionally, there is less energy at frequencies of less than ~1 Hz.

1998 tremor was divided into two groups: strong and weak. Strong tremor was defined as having a reduced displacement $D_R \geq 0.1$ cm², this being the approximate cut-off at which tremor was distinguishable by eye on the analog seismograms recorded at CNZ (insert, Fig.2). Spectra were calculated for 15-120-minute segments of strong tremor ($4.7 \leq D_R \leq 10.7$ cm² at CNZ), with the length dependent on the duration of the tremor. Individual periods of strong tremor were quite similar (Fig. 10). In addition, the frequency content of the strong tremor was almost identical to that of the volcanic earthquakes (Fig. 11), further supporting Hurst's (1992) conclusion that volcanic earthquakes and tremor arose from the same source process.

For the weak tremor, we selected 10-minute segments of tremor beginning at 0100 UT of each day for the months of March, May, and June 1998, excluding from the analysis only those time segments during which either earthquakes occurred or the signal was dominated by wind noise. We also selected 10-minute segments of data beginning on the hour for every hour of four days during which strong tremor was present for at least part of the day. In Figure 12, for June 1998, it is clear that not only was the dominant tremor frequency changing with time, but also that tremor with frequencies $\gtrsim 3\frac{1}{2}$ Hz was almost always present whenever tremor was recorded. Figure 13 shows tremor spectra for every hour of June 9. The uppercase T's at the right side of the plot indicate times at which the tremor was strong, and the lowercase t's, times of moderate tremor. At other times, the tremor was classified as weak. Again, the higher frequencies of tremor were present at all times. However, the lower frequencies ($\lesssim 2$ Hz) were present only when the tremor was strong. Comparison of the relative spectral amplitudes of the strong and weak tremor suggested that whenever the low-frequency tremor was present, it dominated the tremor spectrum (Fig. 14). However, the strong tremor continued to have the same characteristics as the volcanic earthquakes, suggesting that the strong tremor and the volcanic earthquakes remained linked (Fig. 11).

Discusssion

<u>*Spectral Variation and Tremor Duration*</u>

The occurrence of long-lived volcanic tremor at Ruapehu without concomitant eruptive activity or correlated changes in lake temperature or other monitored geochemical or geodetic parameters is relatively unusual. In a study of 650 references to volcanic tremor and related phenomena at 160 volcanoes worldwide, McNutt (1994) noted that the occurrence of volcanic tremor is widespread with 35% of tremor episodes occurring without an accompanying eruption. However, he also noted that although the duration of individual tremor episodes ranged from minutes to years, at only 3% of volcanoes did tremor continue for weeks or longer. Continuous tremor episodes with durations longer than one year occurred at Etna, Stromboli, Arenal Kilauea, and Oshima, and were often associated with ongoing eruptions. Masaya also exhibits almost continuous tremor that is associated with degassing in the lava lake or in a shallow magma body (Métaxian et al., 1997). Thus, the long-lived tremor at Ruapehu, which appears to be primarily associated with the vent-lake hydrothermal system rather than solely with a magmatic system, is uncommon, if not unique. However, changes in a deeper magmatic system do affect, at least in the short term, the volcanic seismicity (Bryan and Sherburn, 1999).

Long-term data on the frequency content of volcanic seismicity are not widely available as prior to the development of the SSAM software (Rogers and Stephens, 1995) continuous, efficient collection of these data was difficult. However, at Ruapehu, spectral data are available with only minor interruptions since 1985 (Hurst, 1985). Several notable changes in the frequency content and amplitude of volcanic tremor have been recorded since 1991 (Fig.1)

Spectral and amplitude data from other volcanoes generally show less variation than that from Ruapehu. At Masaya, variations with time in the amplitude and frequency content of tremor are minor (Métaxian et al., 1997). During 1989-1992, when volcanic activity was minor and stable, the dominant 2Hz spectral peak varied between 1.8 and 2.2 Hz. In 1993, a lava lake appeared and the tremor amplitude increased by a factor of four, but the dominant frequency did not change (J-P Métaxian pers comm., 2000). At Etna, although there are changes in the frequency of volcanic tremor within a few hours of eruptions, when not erupting, the tremor frequency remains very stable (Ereditato and Luongo, 1994). At Pavlof, the frequency spectra of the strong volcanic tremor generated during eruptions are indistinguishable from those of the weaker tremor occurring during non-eruptive periods (McNutt, 1987). In addition, the frequency content of tremor does not change appreciably with time, with similar spectra recorded during eruptions in 1973, 1974, 1981, and 1983. In contrast, volcanic tremor spectra at Klyuchevskoy show temporal variations. Gordeev et al. (1990) showed that over periods of a few days in 1984 and 1986, the spectra of tremor at Klyuchevskoy were unchanged although the tremor amplitude varied more than twentyfold. However, when they repeated observations in 1987, Gordeev et al. (1990) noticed that although the number and position of spectral peaks remained the same, the later tremor had more low-frequencies, particularly on transverse components.

Very-Long Period Energy

Recent studies using broadband seismometers have shown that very-long period volcano seismicity, with periods of 3-20 seconds, originates at depths of less than 1.5 km under some active volcanoes such as Stromboli (Neuberg et al., 1994), Aso (Kaneshima et al., 1996; Kawakatsu et al., 1994), Sakurajima (Kawakatsu et al., 1992), Galeras (Cruz and Chouet, 1997), Satsuma Iojima (Ohminato and Ereditato,

1997) and Erebus (Rowe et al., 1998). This corresponds to the depth range within which most of the volcano seismicity at Ruapehu originates. However, although our broadband observations at Ruapehu were capable of recording such signals, none were observed. In particular, no very-long period signals were observed in 1994 (J Neuberg pers. comm., 1999) and none as part of several moderate-sized volcanic earthquakes in May 1998. McNutt (1999) noted that very-long period signals have not been observed at several active, erupting, volcanoes where broadband instruments have been deployed; therefore, their absence at Ruapehu is not unusual.

Source Process and Location

At a number of volcanoes, volcanic earthquakes and volcanic tremor have been found to have the same spatial and temporal characteristics, suggesting a common source process for these types of seismicity (Fehler, 1983; Julian, 1994; Chouet, 1996). This correlation has recently been further extended to include relationships between classical long-period seismicity and seismicity which is intermediate in character between long- and short-period. The hybrid earthquakes first recognized at Redoubt have been interpreted to result from a source process similar, if not identical, to that which produces volcanic earthquakes. (Lahr et al, 1994; Chouet, 1996). Similarly, at Langila volcano, Papua New Guinea, Mori et al. (1989) have shown that there is a range of events that form a continuum between low-frequency volcanic earthquakes and high-frequency airwaves, all of which have related source mechanisms. Furthermore, non-harmonic tremor is also observed at Langila and is produced by a continuous string of low-frequency events. More recently, Neuberg et al. (1998) have shown that all low-frequency seismic events at Monserrat (eg. long-period earthquakes, hybrid earthquakes, and volcanic tremor) have the same source mechanism.

We have studied, in detail, the spectral characteristics of the 1994 and 1998 volcanic tremor and volcanic earthquakes at Ruapehu. In 1994, volcanic earthquakes and tremor had identical spectral characteristics, suggesting that they were generated by the same source process. The spectral characteristics of the weak tremor present in 1998 were similar to those of the 1994 seismicity, suggesting continuation of the source process active in 1994. However, at times in 1998, a new low-frequency spectral peak was present in the strong tremor and volcanic earthquakes, requiring the existence of an additional tremor source.

Similar to Gordeev et al.'s (1990) observation at Klyuchevskoy, we found that the lower frequencies dominated the tremor spectra at Ruapehu only when the tremor was strong. However, unlike at Kluychevskoy, the lowest frequencies of tremor do not appear to be present at Ruapehu when the tremor is weak. Gordeev et al. (1990) proposed that the increase in the low-frequency components of the Klyuchevskoy tremor relative to the higher-frequency components arose from an increase in the tremor source dimensions with larger source dimensions corresponding to periods of stronger tremor. This may explain the changes in the tremor frequencies at Ruapehu. Another possible explanation is that the low-frequency tremor source is different from and independent of the high-frequency tremor source. Although the high-frequency tremor source may be almost always active, the low-frequency tremor source may only be sporadically active.

Comparison of the relative amplitudes of the c. 0.75-1.5 Hz tremor and the 2 Hz tremor shows that the lower frequency tremor attenuates much more slowly with distance from the summit than the 2 Hz tremor. This suggests a deeper source for the 0.75-1.5 Hz tremor than for the 2 Hz tremor. Bryan and Sherburn (1999) suggested that the ejection of Crater Lake and the resultant removal of a confining pressure of ~10 bars may have contributed to the change in volcanic seismicity from that dominated by a frequency of 2 Hz to broadband during the 1995 eruptions. As a change in confining pressure should preferentially affect shallow tremor sources, it is unlikely that ejection of Crater Lake is directly responsible for activation of the lower-frequency tremor source.

While there were clear differences in the types of tremor recorded at Ruapehu in 1998, there were overall striking similarities among the various types of seismicity. Similar to Mori et al.'s (1989) observations at Langila, during and since the 1996 eruptions, the earthquake types observed at Ruapehu have formed a continuum. During the initial decline in the 1995 eruptive activity, short-duration, shallow, volcano-tectonic earthquakes similar to the hybrid events recorded at Galeras, Monserrat, Pinatubo, and Redoubt (Lahr et al., 1994; Chouet, 1996; Neuberg et al., 1998) became common at Ruapehu (Bryan and Sherburn, 1999). Although these events were classified as volcano-tectonic based on the shape of the waveform and the frequency content at the summit seismic site, at flank sites (7–12 km from the summit), they were characterized by a low-amplitude, high-frequency onset followed by a dominant low-frequency, high-amplitude arrival, resulting in the majority of the energy being contained in the same frequencies as the pre-eruption volcanic earthquakes. These events are thus intermediate in character between the classically defined "volcano-tectonic" and "volcanic" earthquakes. The classic volcanic earthquakes then graded into the volcanic tremor as shown by the identical spectral characteristics of the appropriate data subsets.

Conclusions

The characteristics of the seismicity at a volcano are routinely used for real-time assessment of the state of that volcano. A critical assumption is that the long-term relationships between seismicity and eruptive activity do not vary with time, and, furthermore, that they are not affected by eruptions. We tested these hypotheses by analyzing the characteristics of the volcano-seismicity at Ruapehu prior to and following the 1995-1996 eruptions. This was of particular importance, as to our knowledge, no-one has studied the long-term effects of an eruption on seismicity.

We have shown that the 1995-1996 eruptions changed the characteristic volcanic seismicity at Ruapehu. Periods of strong volcanic tremor and the larger volcanic earthquakes continue to be dominated by low frequencies. An initial change from monchromatic 2 Hz volcanic to hybrid earthquakes occurred at the time of the ejection of the last of the water remaining in Crater Lake. In terms of eruption forecasting, perhaps a more significant change in eruption accompanying seismicity was the decrease in the dominant frequency of the strong volcanic signals from 2 Hz to 0.75-1.5 Hz. The timing of this change is unclear. Low frequencies were not observed during the 1995-1996 intra-eruptive period; however, there was no strong tremor at that time and the 1998 data show that the sub-2 Hz frequencies are seen only when the tremor is strong.

If the ejection of Crater Lake and the resultant removal of a confining pressure of ~10 bars allowed either the activation of more volcano-seismic resonator sources or a change in the volcano-seismic source dimensions, it is possible that the higher-frequency ($\gtrsim$ 2 Hz) spectral characteristics of the volcanic seismicity will revert to those present prior to the 1995-1996 eruptions when Crater Lake refills. At the present rate of refilling of Crater Lake, it will be several years before we can determine if these observed changes in the volcanic seismicity are merely a temporary response to short-term changes in the volcanic plumbing system or if they will become long-lived features of Ruapehu's characteristic volcanic seismicity. This, however, neither explains the appearance of nor has any implications for the length of existence of the lower- (sub-2 Hz) frequencies now present.

Our results have significant implications for the real-time assessment of volcanic activity and hazard at Ruapehu. Not only does the change in the characteristic seismicity affect our ability to forecast future eruptions of Ruapehu, it also affects our ability to use seismic data to forecast the likely course of an ongoing eruption. In particular, real-time volcano seismicity data are used to immediately notify New Zealand Civil Defence, industry, and the public about possible eruptions of New Zealand's volcanoes, with the current focus being primarily on Ruapehu and White Island, currently, the most active New Zealand volcanoes. Several studies of Ruapehu seismicity prior to the 1995-1996 eruptions identified the characteristics of the seismicity preceding and accompanying eruptions, results which proved extremely useful is assessing the status of the volcano during the 1995-1996 eruptions when the summit was not visible. Results of these studies were also used in the design of a system to remotely instrumentally detect eruptions of Ruapehu and in the setting up of a system to automatically detect changes in the amplitude of Ruapehu's characteristic tremor. Although those systems provide significant advances in safeguarding people and property on the mountain, as well as those living and working in the vicinity of a volcano, both on the ground and in the air, they are dependent on the characteristics of the seismicity not varying greatly. At present, strong volcanic seismicity at Ruapehu remains dominated by low-frequency signals; however, should a more drastic change occur in the characteristic eruptive seismicity at Ruapehu, the functioning of these systems could be rendered less than ideal unless they were re-tuned to take into account the new seismic characteristics. Hence, it is important to recognize and account for any changes in the characteristic seismicity that may occur as a result of extrusive or intrusive processes. Considered in the wider context, our documentation of short- (if not long-) term change in the characteristic seismicity at a volcano that has recently erupted has significant implications for the future assessment of the status of any volcano that has recently erupted.

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Figure Captions

Fig. 1. Tremor spectrograms at Ruapehu from 1991 until 1998. Spectrograms were calculated using daily average spectra at DRZ (Fig. 2). White areas indicate periods when no data were available.

Fig. 2. Map showing the locations of the seismic stations during the two broadband deployments. The upper mountain stations of the 1994 deployment are shown by triangles and those of the 1998 deployment by circles. Contours at 500m intervals are shown by the light solid lines, and roads by the dark solid lines. The right-hand inset shows the location of Ruapehu in the center of the North Island of New Zealand. The left-hand inset shows the stations (diamonds) of the permanent, short-period, vertical component, seismic network used to monitor volcano-seismic activity of Ruapehu that are mentioned in the text. Contours at 500 m are shown by the light solid lines and roads by the dark solid lines. The dotted box shows the area of the main figure.

Fig. 3. Velocity response of the 1994 and 1998 broadband seismometers. All 1998 instruments had identical responses in the frequency range of interest. Similarly, all 1994 instruments except for that at LTUR had identical responses in the frequency range under consideration. Curves are offset for clarity.

Fig. 4. Waveforms of a typical 1994 volcanic earthquake high-pass filtered at 0.5 Hz. Waveforms are arranged, from top to bottom, by increasing distance from the summit crater. Waveforms are similar at all sites for all events.

Fig. 5. Individually normalized, stacked earthquake spectra for the ten 1994 volcanic earthquakes studied. All energy is contained in the band 1–3.5 Hz, with no very-long period (< 1 Hz) energy. Spectra are arranged, from top to bottom, by increasing distance from the summit crater.

Fig. 6. Normalized spectra of 10-minute segments of background tremor recorded at LOUT on 30 January 1994. Spectra are dominated by peaks at c. 2 Hz with lesser peaks at c. 3 Hz and c. 1.3 Hz. The peak at c. 0.5 Hz is microseism.

Fig. 7. Individually normalized, stacked spectra of the 1994 earthquakes and tremor recorded at LOUT. The frequency content of the volcanic earthquakes is almost identical to that of the tremor.

Fig. 8. Waveforms of 1998 volcanic earthquakes recorded at FWTB. The two smaller events (top of figure) are typical of the pre-1995 volcanic earthquakes, while the two larger events (bottom of figure) show high-frequency onsets not seen in the smaller events.

Fig. 9. Individually normalized spectra of 1998 volcanic earthquakes recorded at FWTB. All are dominated by frequencies of 0.75-1.5 Hz, with lesser peaks at c. 2.2 Hz, c. 2.8 Hz, and c. 3.75 Hz.

Fig. 10. Normalized spectra of strong ($D_R \geq 0.1$ cm²) 1998 tremor recorded at FWTB. Strong tremor is dominated by frequencies of 0.65–1.35 Hz, with a lesser peak at c. 2.2 Hz.

Fig. 11. Individually normalized, stacked spectra of the 1998 volcanic earthquakes and strong tremor recorded at FWTB. The frequency content of the volcanic earthquakes is very similar to that of the tremor.

Fig. 12. Individually normalized spectra of 10-minute segments of tremor beginning at 0100 UT of each day for the month of June 1998 at FWTB. Although tremor frequencies change with time, tremor of frequency $\gtrsim$ 3.5 Hz is present whenever tremor is recorded.

Fig. 13. Individually normalized tremor spectra for 10-minute segments of data at FWTB beginning on the hour for every hour of 9 June 1998. The uppercase T's at the right side of the plot indicate times when the tremor was strong, and the lowercase t's, times at which the tremor was moderate. At all other times, the tremor was weak. The higher frequencies of tremor are present at all times, while the lower-frequency components are generally present only when the tremor is moderate-to-strong in intensity.

Fig. 14. Individually normalized, stacked spectra of the strong and weak tremor recorded at FWTB during 1998. Strong and weak tremor show very similar spectral amplitudes at frequencies $\gtrsim$ 2 Hz. However, the strong tremor shows spectral peaks not observed in the weak tremor. When present, these low-frequency components dominate the tremor spectrum.

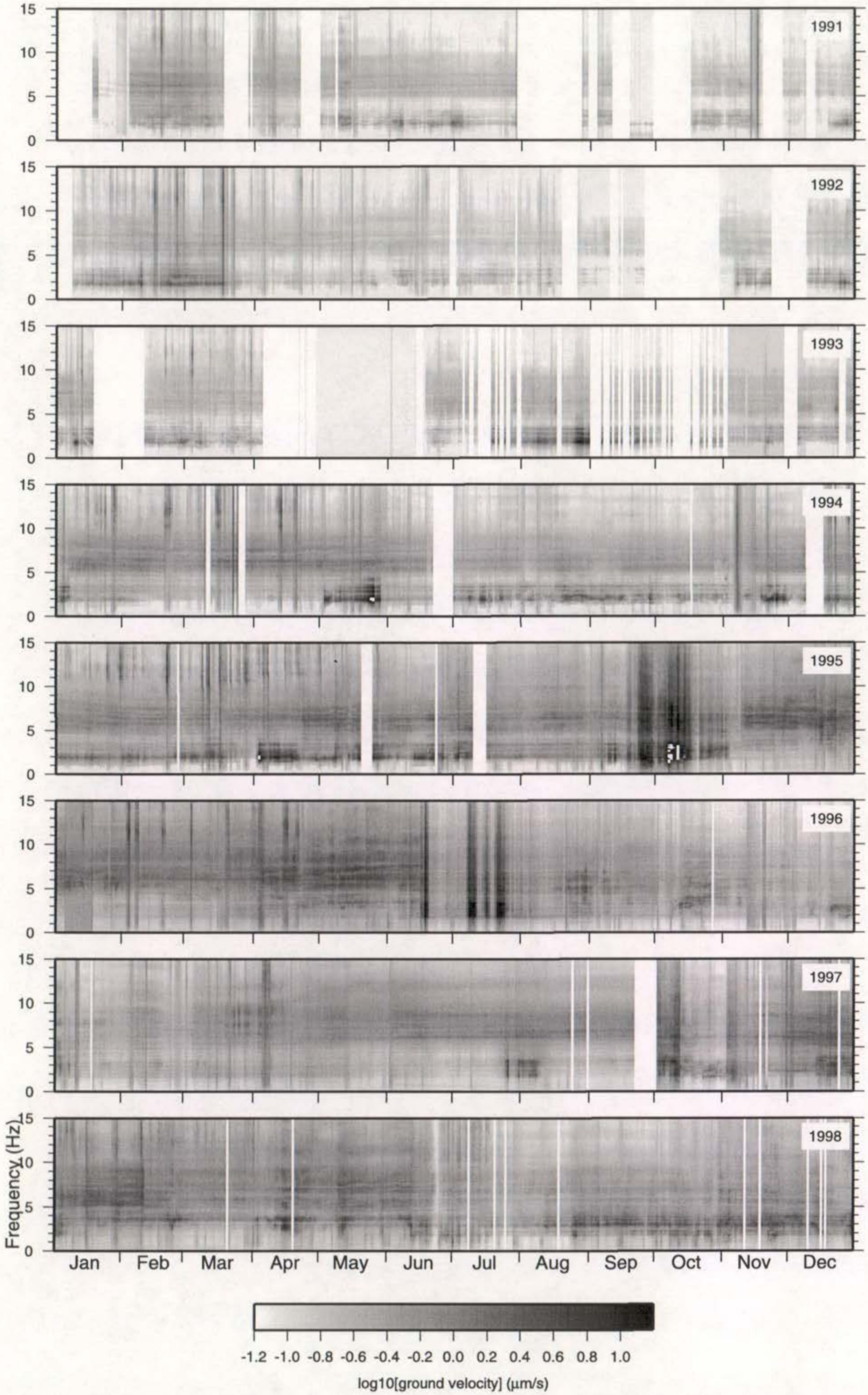

1991
1992
1993
1994
1995
1996
1997
1998
Frequency (Hz)
0
5
10
15
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
-1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
log10[ground velocity] (µm/s)

Fig 1

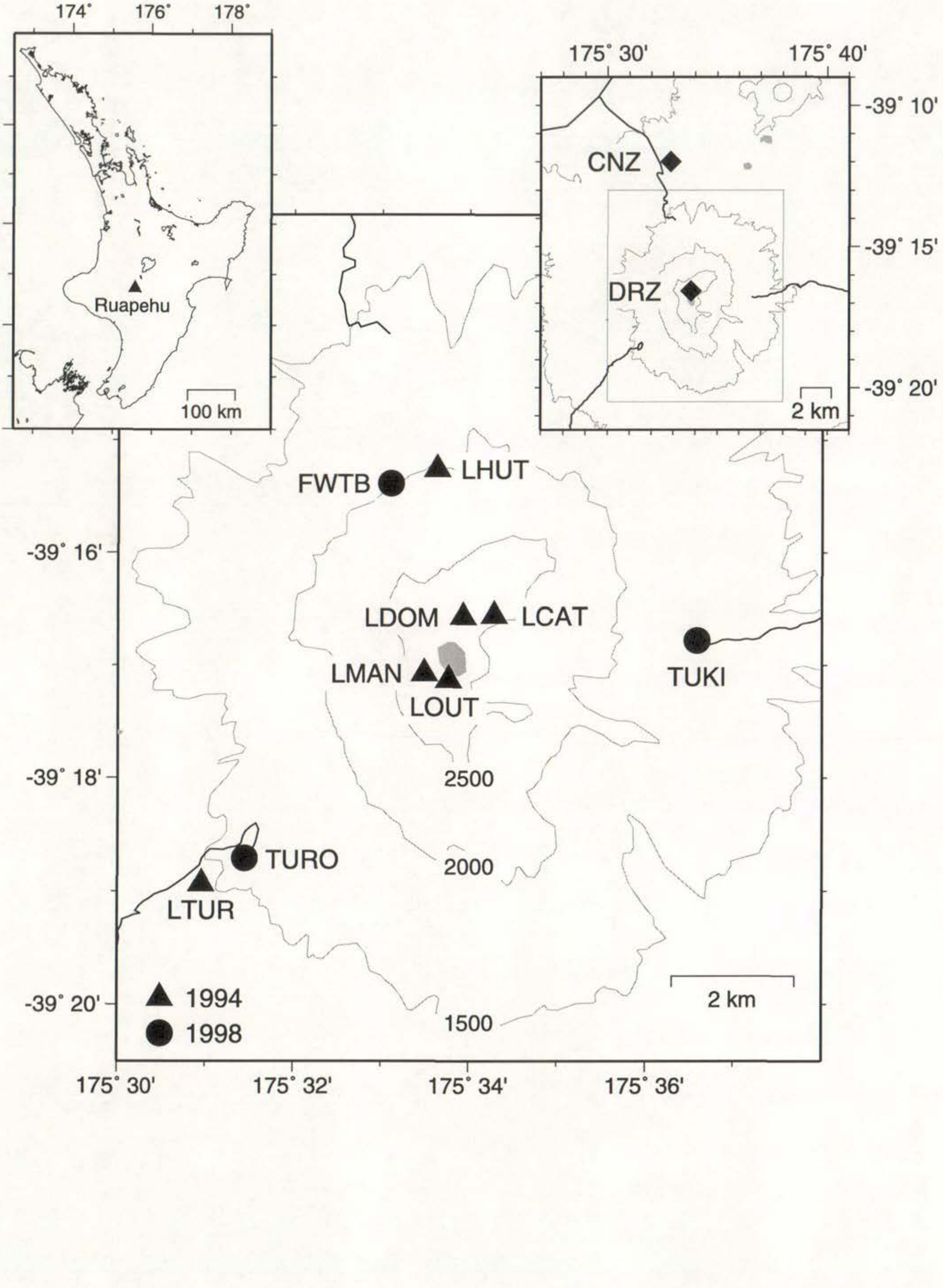
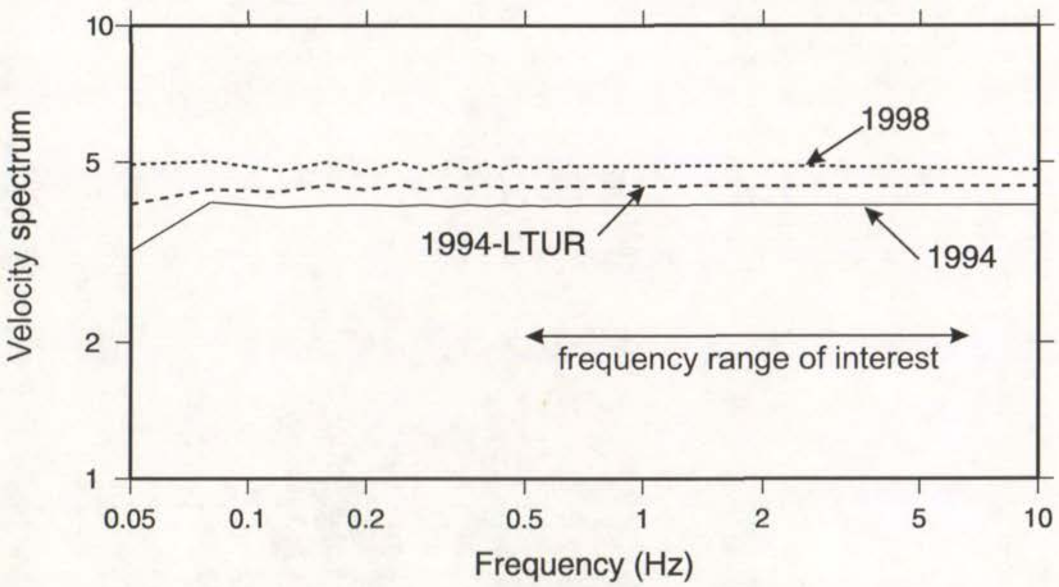

174°
176°
178°
-36°
-38°
-40°
-42°
Ruapehu
100 km
175° 30'
175° 40'
-39° 10'
-39° 15'
-39° 20'
CNZ
DRZ
2 km
FWTB
LHUT
-39° 16'
LDOM
LCAT
TUKI
LMAN
LOUT
-39° 18'
2500
TURO
2000
LTUR
1994
1998
2 km
-39° 20'
1500
175° 30'
175° 32'
175° 34'
175° 36'

Fig 2



10
5
2
1
Velocity spectrum
1998
1994-LTUR
1994
frequency range of interest
0.05
0.1
0.2
0.5
1
2
5
10
Frequency (Hz)

Fig 3

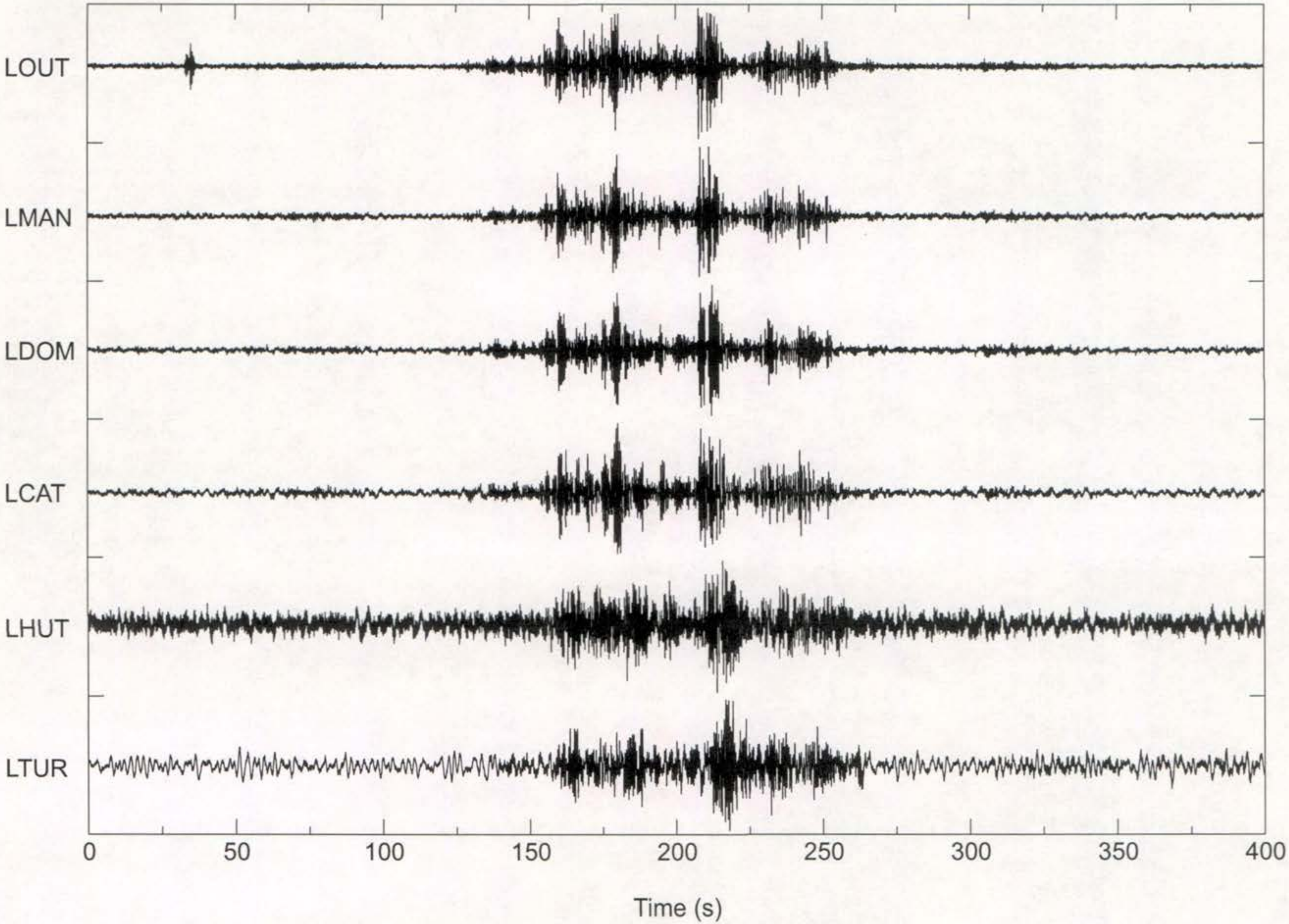

LOUT
LMAN
LDOM
LCAT
LHUT
LTUR
0
50
100
150
200
250
300
350
400
Time (s)

Fig 4

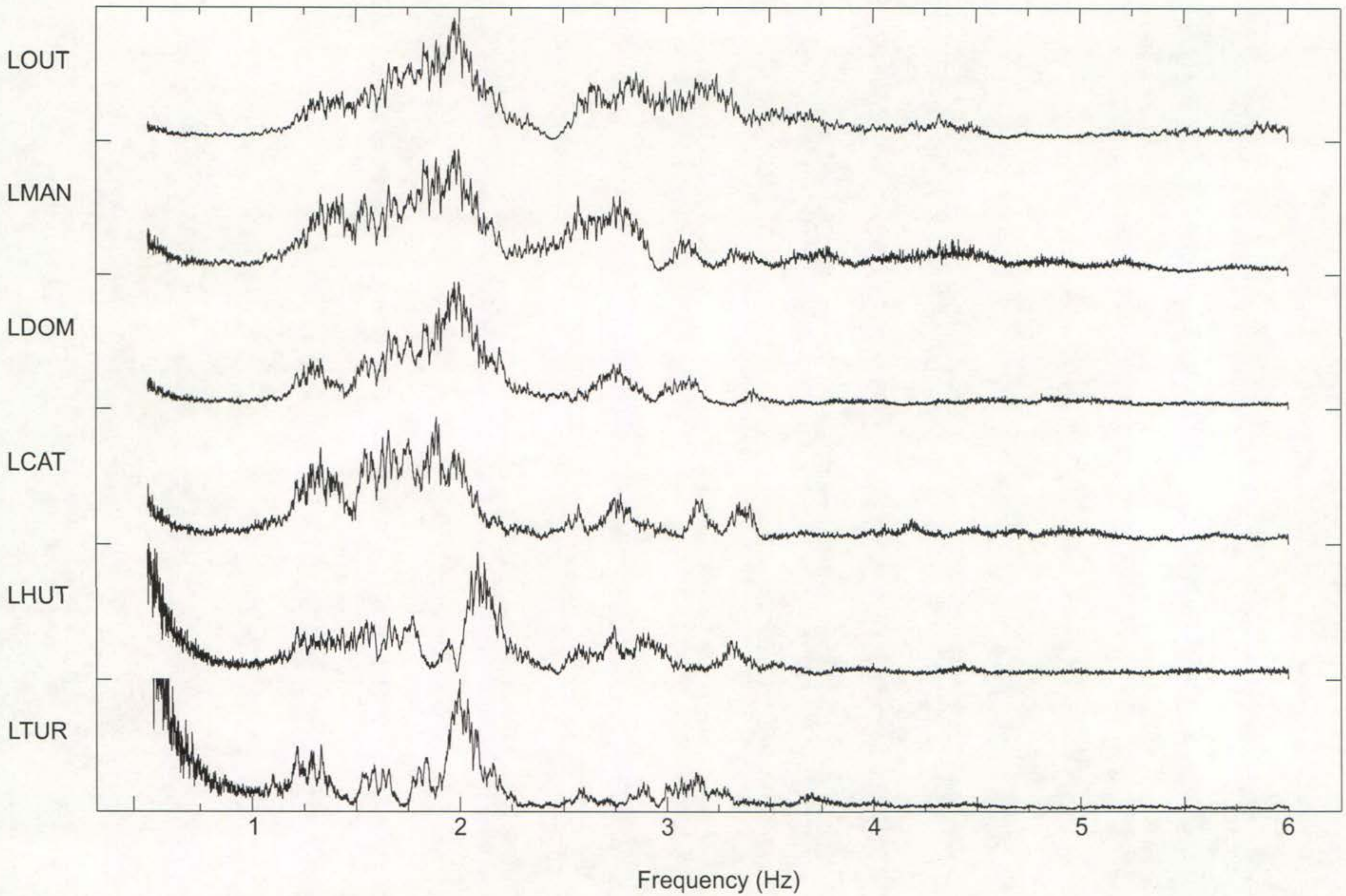


Fig 5

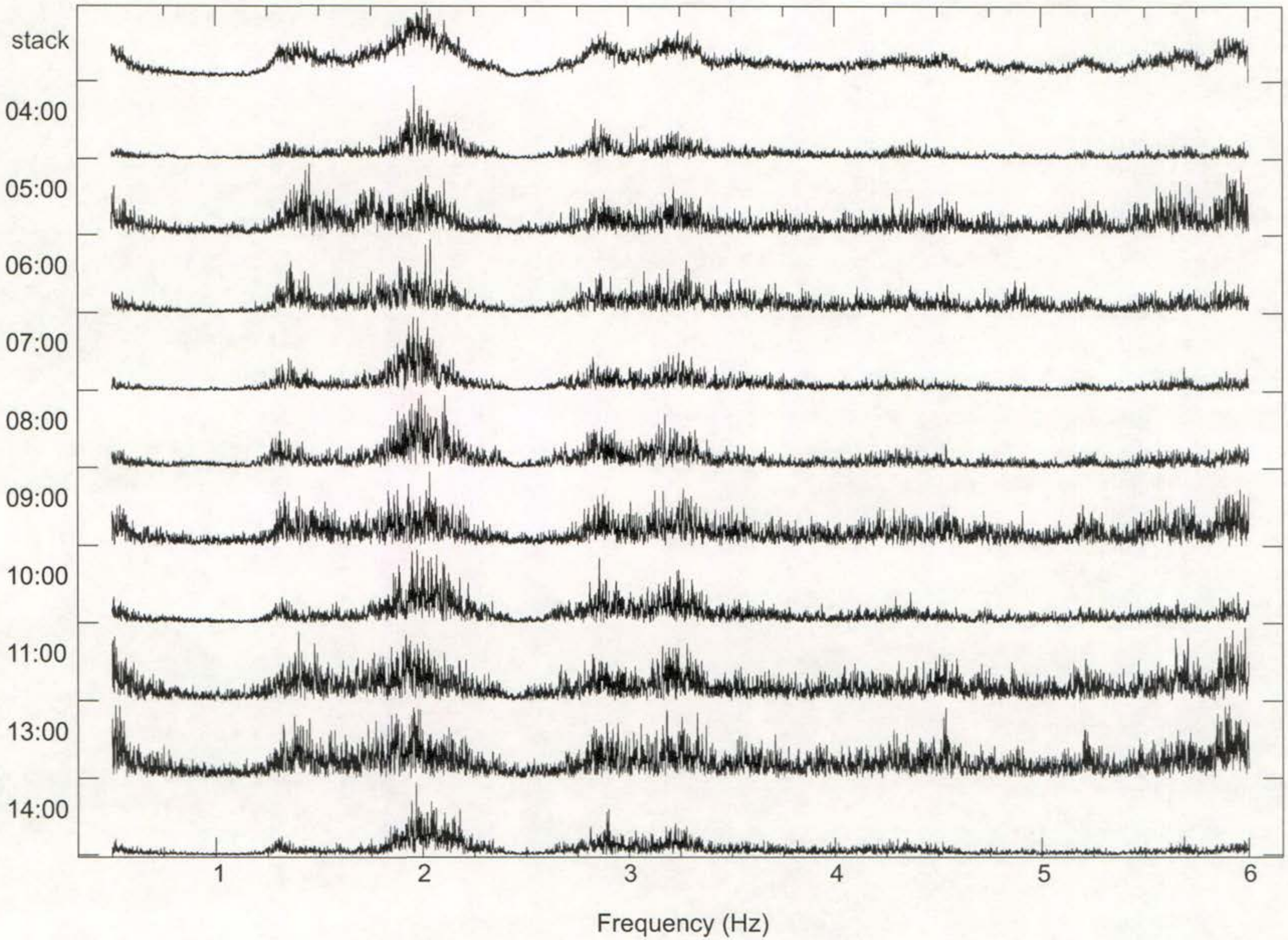

stack
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
13:00
14:00
1
2
3
4
5
6
Frequency (Hz)

Fig 6

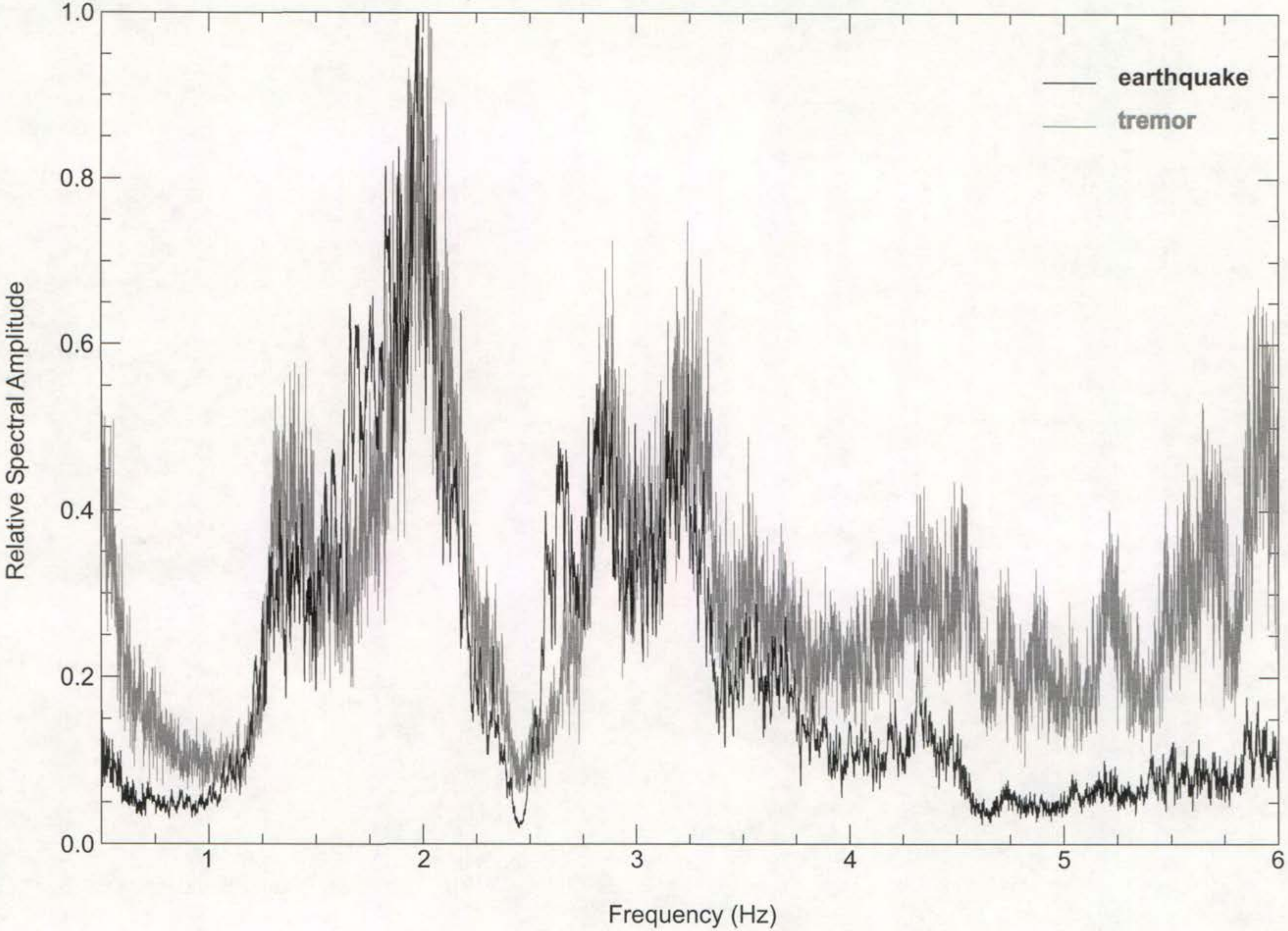

earthquake
tremor
Relative Spectral Amplitude
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
6
Frequency (Hz)

Fig 7

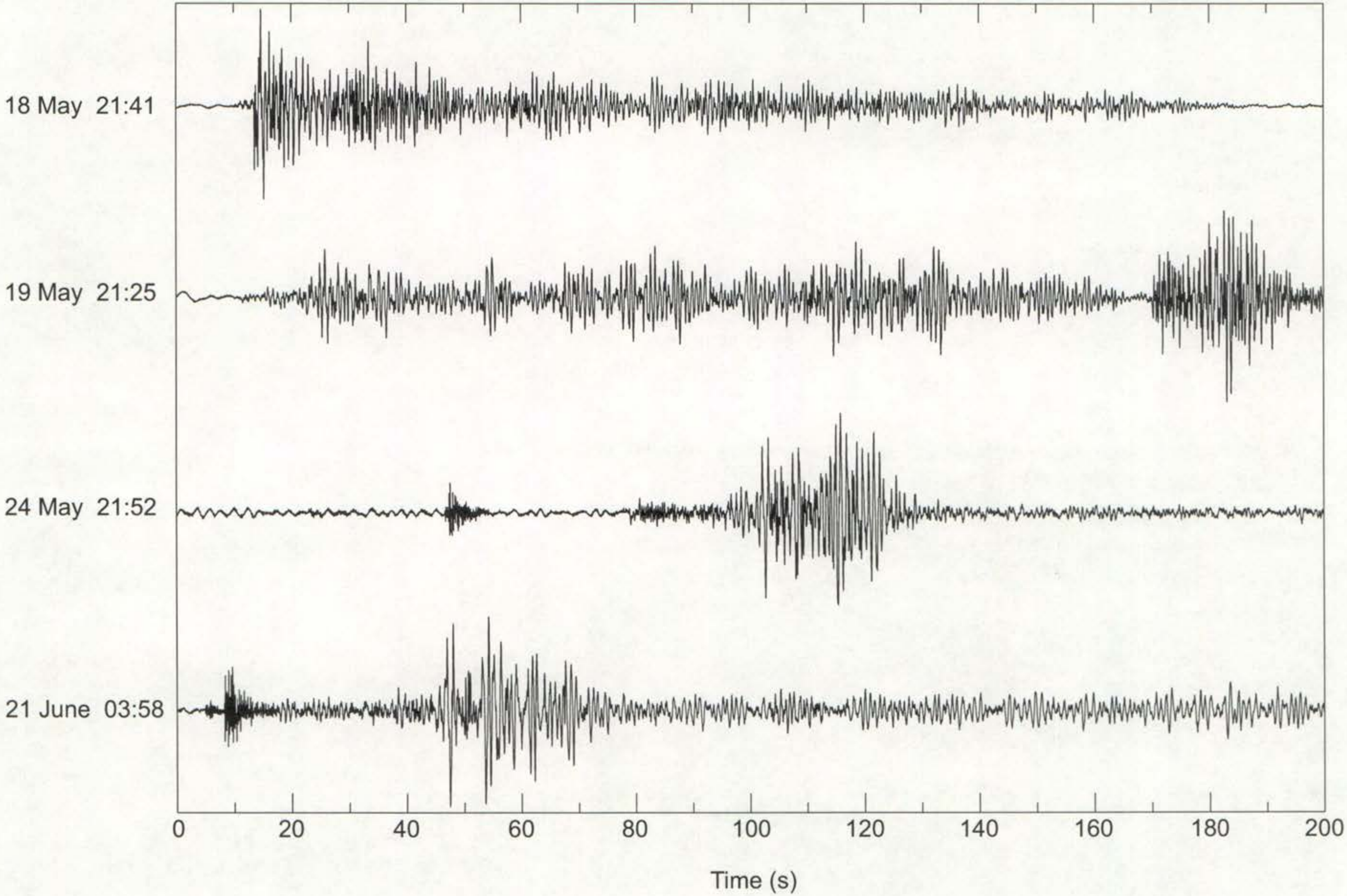

18 May 21:41
19 May 21:25
24 May 21:52
21 June 03:58
0
20
40
60
80
100
120
140
160
180
200
Time (s)

Fig 8

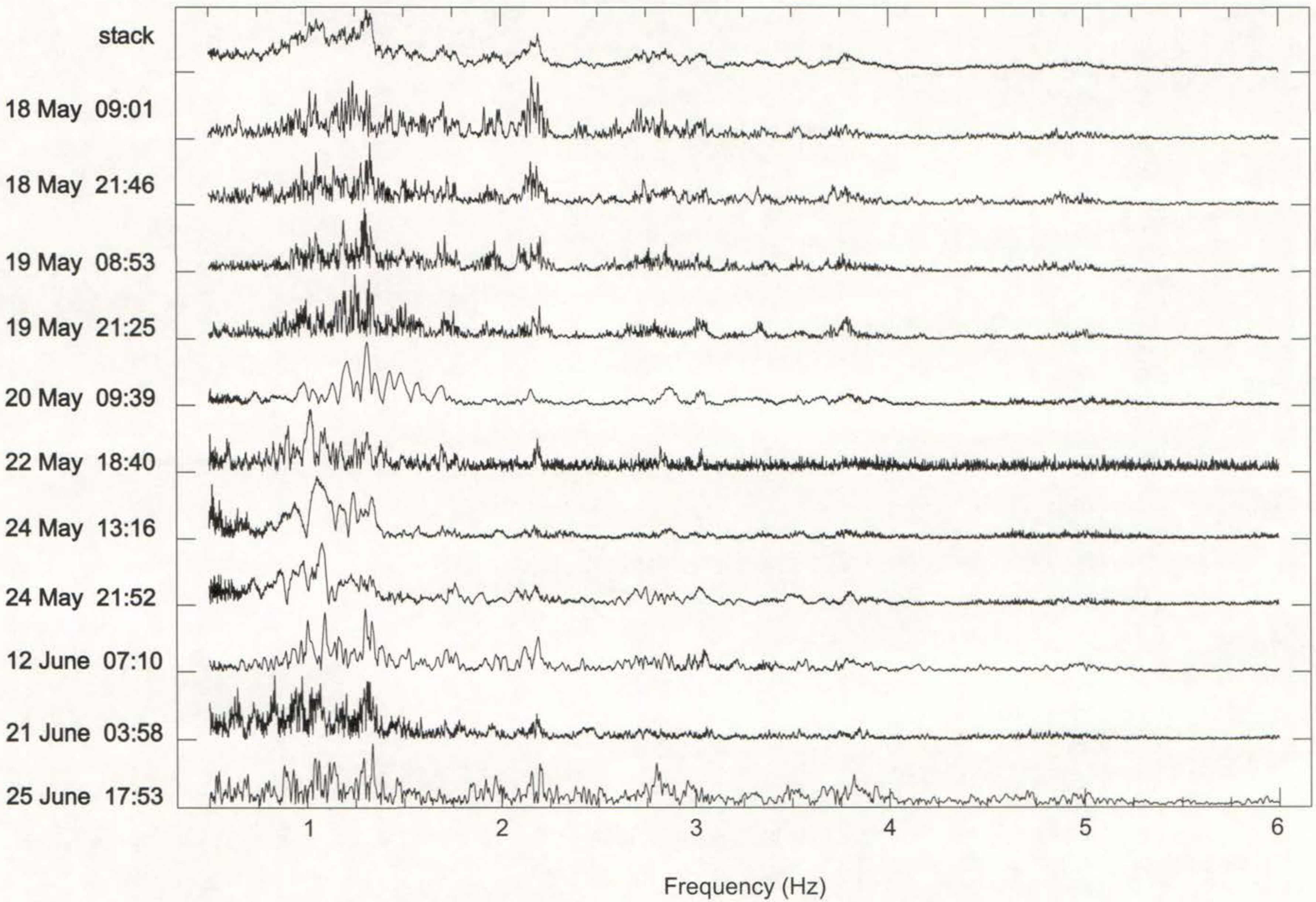

stack
18 May 09:01
18 May 21:46
19 May 08:53
19 May 21:25
20 May 09:39
22 May 18:40
24 May 13:16
24 May 21:52
12 June 07:10
21 June 03:58
25 June 17:53
1
2
3
4
5
6
Frequency (Hz)

Fig 9

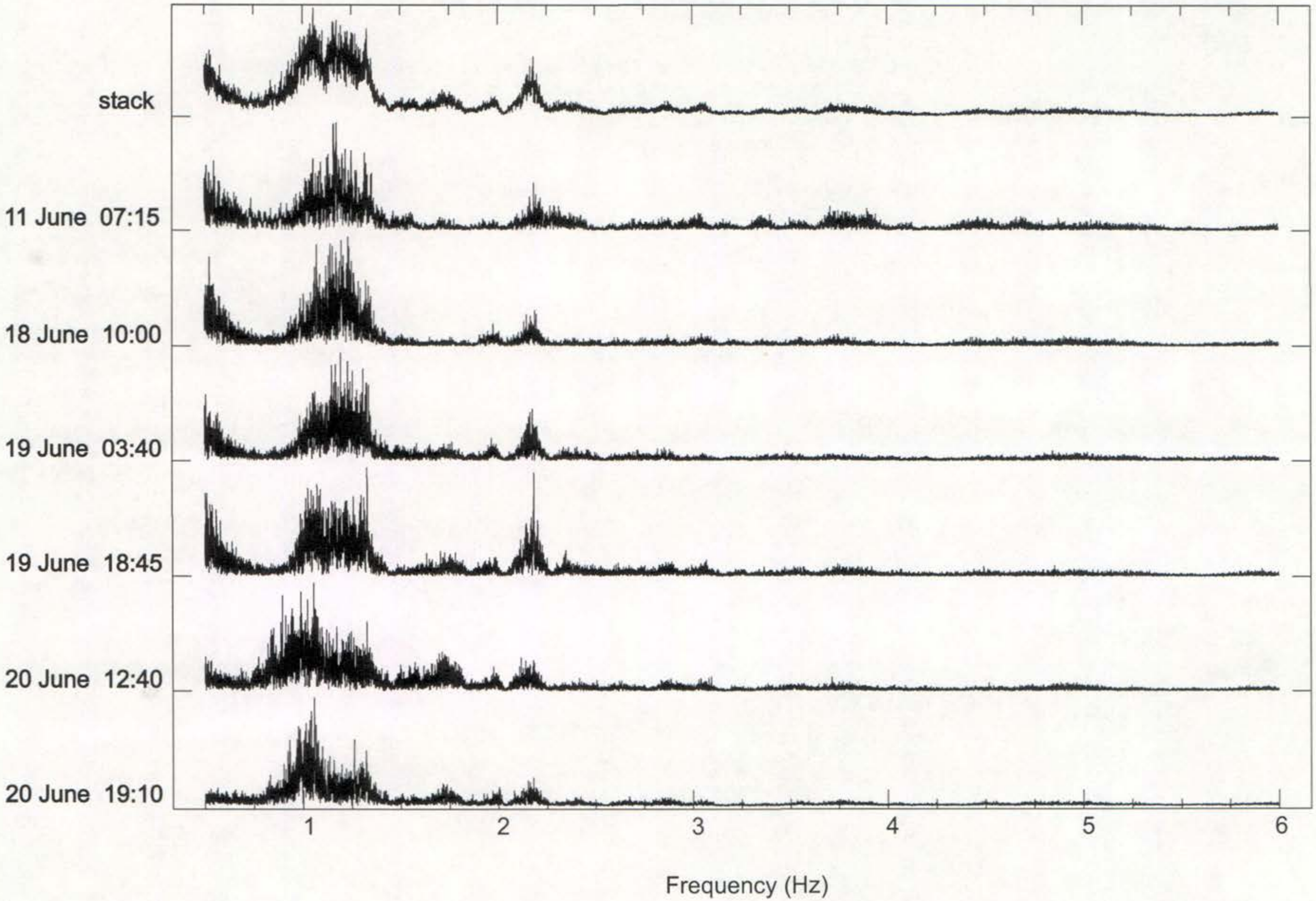
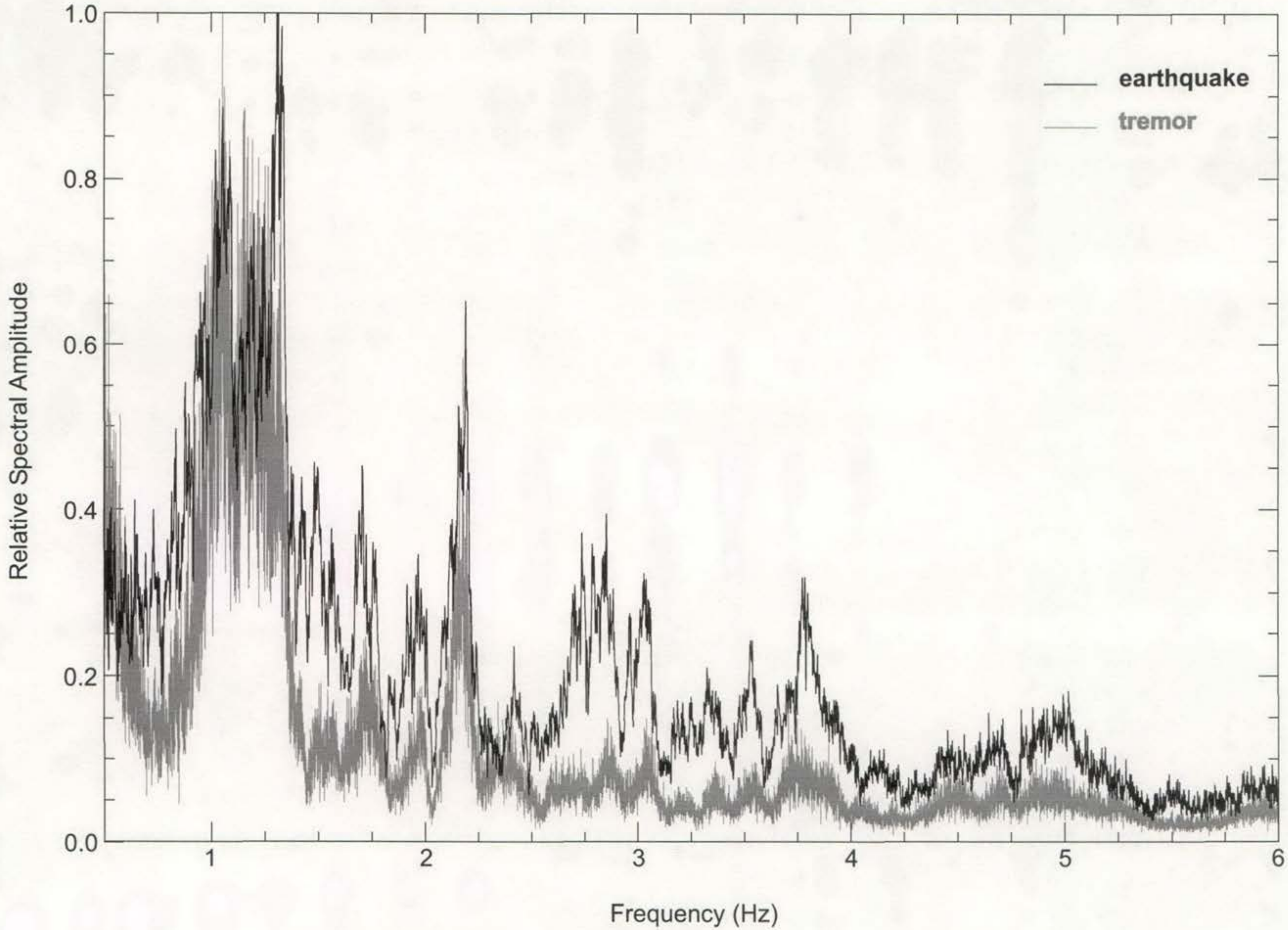

stack
11 June 07:15
18 June 10:00
19 June 03:40
19 June 18:45
20 June 12:40
20 June 19:10
1
2
3
4
5
6
Frequency (Hz)

Fig 10



earthquake
tremor
Relative Spectral Amplitude
Frequency (Hz)
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5
6

Fig 11

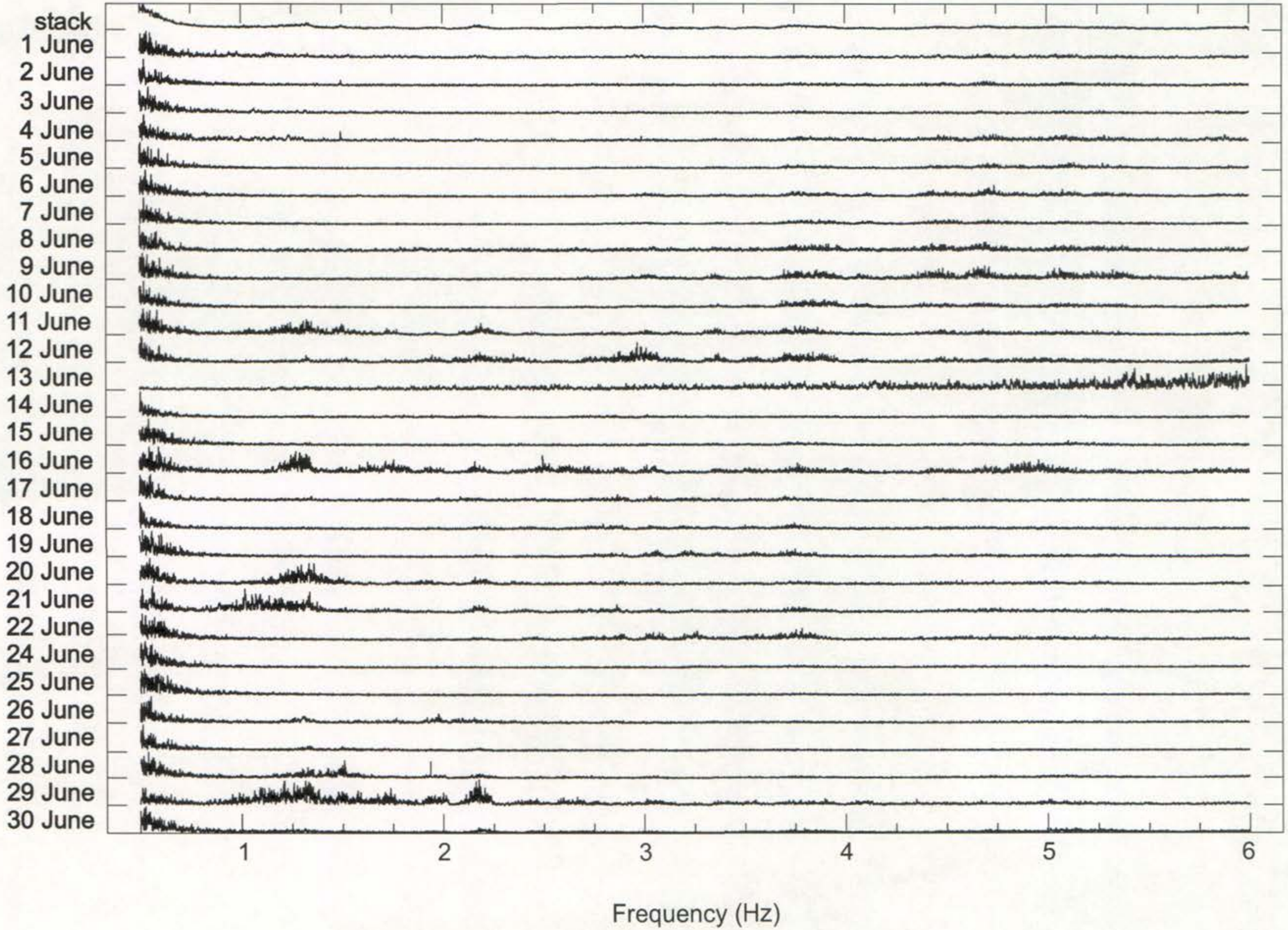

stack
1 June
2 June
3 June
4 June
5 June
6 June
7 June
8 June
9 June
10 June
11 June
12 June
13 June
14 June
15 June
16 June
17 June
18 June
19 June
20 June
21 June
22 June
24 June
25 June
26 June
27 June
28 June
29 June
30 June
1
2
3
4
5
6
Frequency (Hz)

Fig 12

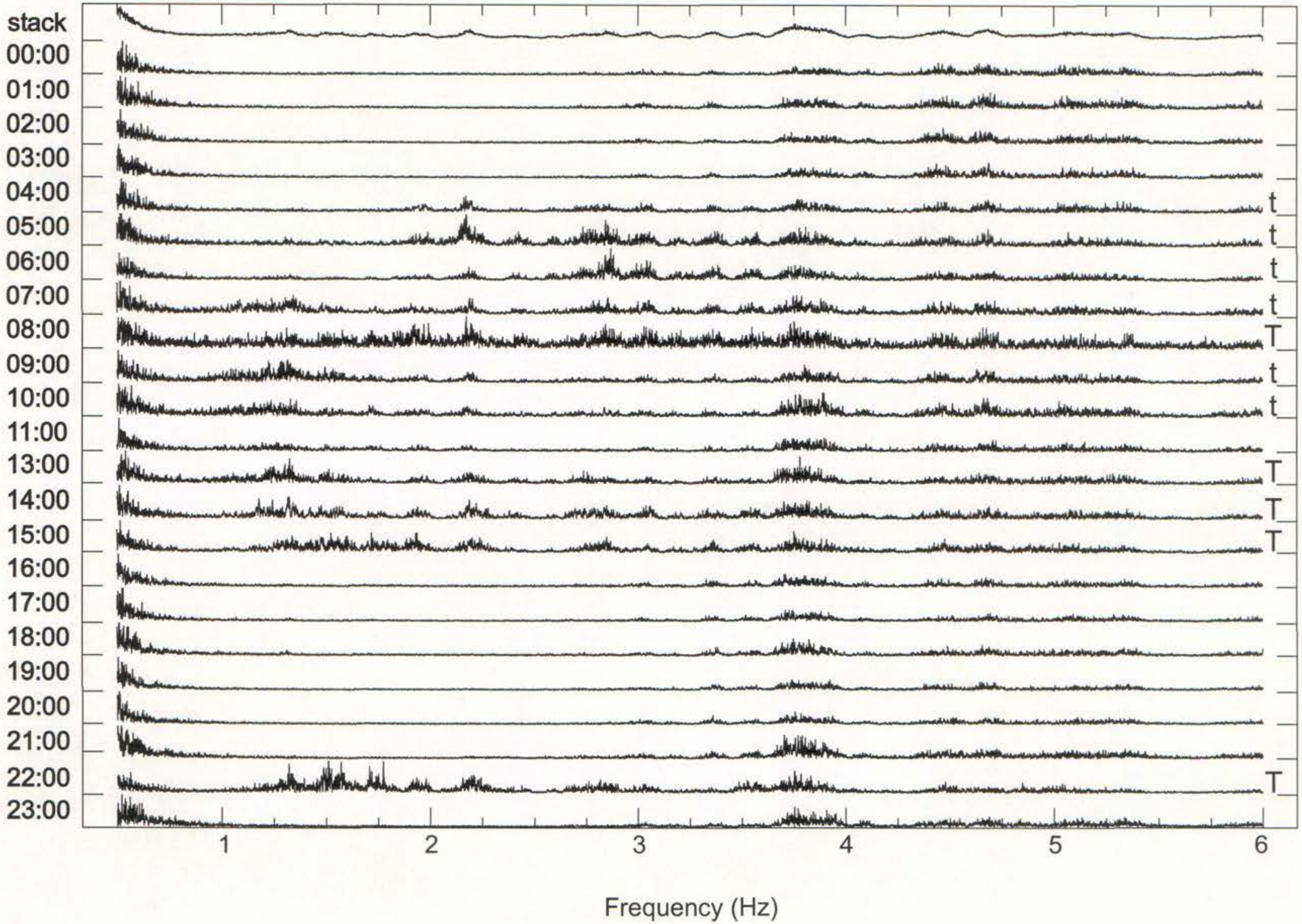
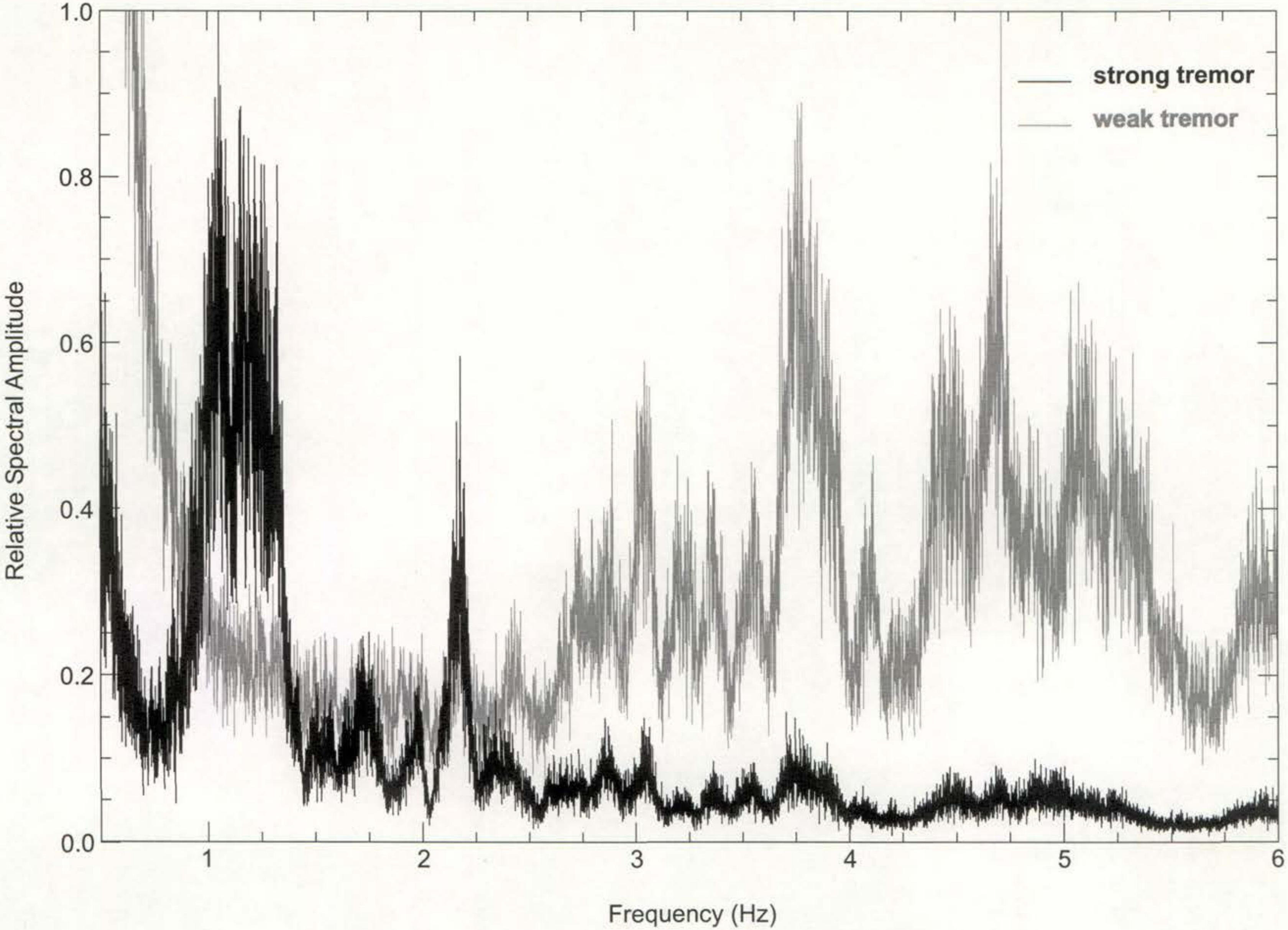

stack
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
t
t
t
t
T
t
t
T
T
T
T
1
2
3
4
5
6
Frequency (Hz)

Fig 13



strong tremor
weak tremor
Relative Spectral Amplitude
Frequency (Hz)
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6

Fig 14