Earthquake Sounds From Aftershocks Following the 1986 May 20 Hualien Earthquake

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ABSTRACT

A 24-hour continuous sound recording was made after the 1986 May 20 earthquake. During the 24 hour period, 25 aftershocks with a magnitude greater than 2 were recorded by a temporary seismographic network. Comparing the seismograms with the recorded sounds, we found that 5 of these aftershocks were accompanied by earthquake sounds, and all of these sounds preceded the P-wave arrivals by 0.2 to 1.1 *seconds*. These 5 aftershocks possessed common characteristics of greater magnitude, shallower focus, and being closer to the recording site than other aftershocks. The predominant frequencies of the earthquake sounds ranged from 25 to 100 *Hz*. These predominant frequencies were relatively lower when the focus was deeper. Based on these discoveries, we infer that, before the main faulting which resulted in the earthquakes, there were associated cracks that sent out acoustic waves with frequencies higher than those detected by the seismographs.

1. INTRODUCTION

The sounds of earthquake have been heard frequently by people in areas near the epicenter. The first paper on earthquake sounds was published by Davison (1938). He collected many reports of earthquakes in Great Britain and Italy, and found that, when an earthquake occurred, accompanying earthquake sounds reported by the local people were very common. According to these reports, the earthquake sounds similar to distant thunder, a blast of wind, or an explosion. The audibility was greater when earthquake intensity was higher. A high percentage of the earthquake sounds were reported to arrive prior to

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the ground motion. He also sorted the earthquake sounds according to a high or low tone, and found that the farther the earthquake source is from the reporter, the lower the tone. Until now, such earthquake sounds have still rarely been recorded by instruments. According to the catalog of earthquake sound records edited by Steinbrugge (1974), most of the earthquake sound records were obtained by accident. Thus, the quality was poor and lacked synchronous seismographic records for comparison. Prior to our study, there were only two earthquake sound records with synchronous seismic records. They were obtained by the Japan Meteorological Agency (1968) from the Matsushiro earthquake swarm and by Hill *et al.* (1976) from earthquakes in the Imperial Valley in California. On their records the earthquake sounds came nearly at the same time as the P-wave arrivals (the differences were no more than 0.02 *seconds*) and with little relation to the S waves.

Earthquake sounds and seismic waves from the many aftershocks of the 1986 May 20 Hualien Earthquake in eastern Taiwan were recorded synchronously. In this paper, these records were analyzed in order to better understand the characteristics of the earthquake sounds and the relationship between earthquake sounds and the seismic waves. Among the results, we found that all the recognizable earthquake sounds preceded the seismic waves recorded by the seismograph. This differs from the observations by Hill *et al.* (1976) and the Japan Meteorological Agency (1968).

2. DATA RECORDING AND PROCESSING

Shortly after the occurrence of the 1986 May 20 Hualien Earthquake (Magnitude M_L: 6.5; Location: 24.082° N, 121.592° E; Focal depth: 15.8 *km*; Origin time: 05 : 25 *GMT*; Chen and Wang, 1986) to the northwest of Hualien city in eastern Taiwan, a team led by one of the authors (C. Wang) was sent by the Institute of Earth Sciences, Academia Sinica, to deploy a temporary seismographic network using MEQ800 seismographs (Kinemetrics product) to observe the aftershocks. Figure 1 shows the location of the seismographic stations with local geological settings (see Liaw *et al.*, 1986, for the observed aftershocks). In the first few days, aftershocks were frequent, and many distinct earthquake sounds accompanying the aftershocks were heard. Therefore, the recording of these earthquake sounds became desirable, in order to compare them with recorded seismic waves, and a sound recording system was also set up in Hualien city .

In Hualien city, the Central Weather Bureau (CWB) of the Ministry of Communication, R.O.C., has a seismographic station with a digital seismograph (the CWBSN station). We needed the digital seismograms from this station for the comparison of earthquake sounds and seismic waves. The time system in

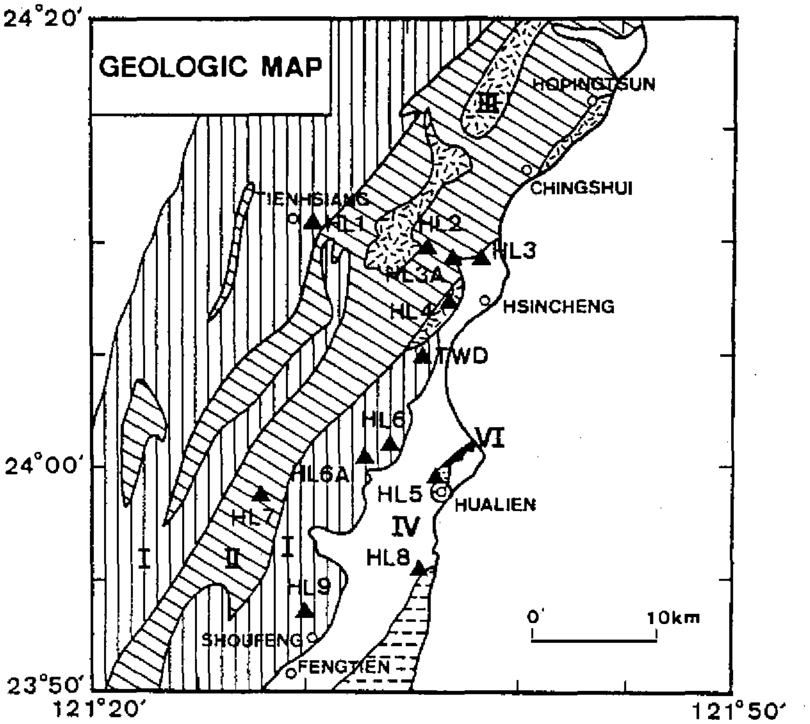

Fig. 1. The temporary seismographic stations (solid triangle) which were set up to observe the aftershocks of the 1986 May 20 Hualien Earthquake. The sound recording site is at the CWBSN station in Hualien city. The geological setting: Region I, black schist, green schist, and silicate schist; Region II, crystal limestone; Region III, gneiss and hybrid rocks; Region IV, sedimentary strata; Region V, shale, sandstone, conglomerate; Region VI, Meiloon conglomerate.

this station produces a clear sound signal every minute. The MEQ800 seismographs which we used in the temporary seismographic network produces a clear "tick" sound signal every second. Thus, we set up a simple recording station to continuously record the sounds by putting an MEQ800 seismograph which was synchronized with other stations of the temporary seismographic network and an ordinary tape recorder near the time system of the CWBSN station. In this way, the tape recorder recorded the "second" signal from the MEQ800 seismograph, the "minute" signal from the CWBSN time system and the sound from the ground synchronously. The recorded "second" and "minute" signals were necessary for making time comparisons and corrections in order to put the time history of a recorded earthquake sound and the seismogram into the same time scale. The recording went on for 24 hours from the fourth day after the 1986 May 20 Hualien Earthquake, i.e., from May 24 to May 25. During this 24-hour recording period, 25 earthquakes (Table 1 and Figure 2) were recorded by the temporary seismographic network. Corresponding to each earthquake,

Table 1. Parameters of earthquakes in the sound recording period.

No.	T	M_L	H	Δ	D	I
	May 24, 1986		(*km*)	(*km*)	(*km*)	
1	3:43:0.8	2.6	11.8	18.2	15.8	1
2	4:35:38.7	2.7	9.7	9.1	13.3	1
*3	9:58:15.5	5.0	8.0	6.1	9.3	4
*4	10:2:11.0	4.7	6.9	7.9	10.5	4
5	10:14:1.9	2.7	6.9	6.0	8.8	1
*6	10:21:28.7	3.9	8.2	2.5	8.7	3
7	11:5:28.3	3.6	9.5	6.9	11.8	2
8	11:56:52.1	2.0	7.1	9.0	11.4	0
9	13:16:0.6	2.5	11.7	2.3	11.9	0
10	15:1:57.1	3.6	12.8	7.3	14.7	0
11	17:55:28.3	2.5	8.8	7.8	11.7	1
12	17:56:29.5	2.7	9.6	9.8	13.7	0
13	18:10:22.0	2.9	9.2	4.7	10.3	1
14	18:45:34.2	2.6	9.3	3.2	9.9	0
15	19:0:12.3	2.1	9.7	3.9	10.5	0
16	19:1:27.0	2.8	7.6	4.6	8.9	2
17	20:12:52.0	2.7	9.2	2.5	9.5	1
18	20:35:59.1	2.8	11.6	2.5	11.8	1
19	21:0:4.2	2.6	9.9	4.5	10.9	1
20	21:41:13.6	3.4	9.4	2.6	10.3	2
*21	21:45:0.8	3.8	9.1	3.1	9.8	3
22	21:52:13.2	2.7	8.8	3.6	9.8	1
23	23:53:3.4	2.6	15.8	13.1	20.5	1
	May 25, 1986					
24	2:17:53.9	3.2	8.4	5.1	9.4	2
*25	4:32:45.4	3.4	9.4	3.0	9.8	3

T : P-wave arrival time in the CWB time system
M_L : Local magnitude
H : Focal depth
Δ : Epicentral distance to the CWBSN station
D : Hypocentral distance to the CWBSN station
I : Intensity in Hualien (the CWB scale)
* : Earthquake accompanied by earthquake sound

there was a set of digital seismograms from the CWBSN station and a sound record on tape.

Among the seismogram sets and sound records for the 25 earthquakes listed in Table 1, the first two are not used for there were no audible earthquake sounds at all on tape. The NO.5 earthquake was also given up because the minute signal on the digitized sound data was missed, so we did not know the actual time on the graph. The NO.11 earthquake which was not detected by

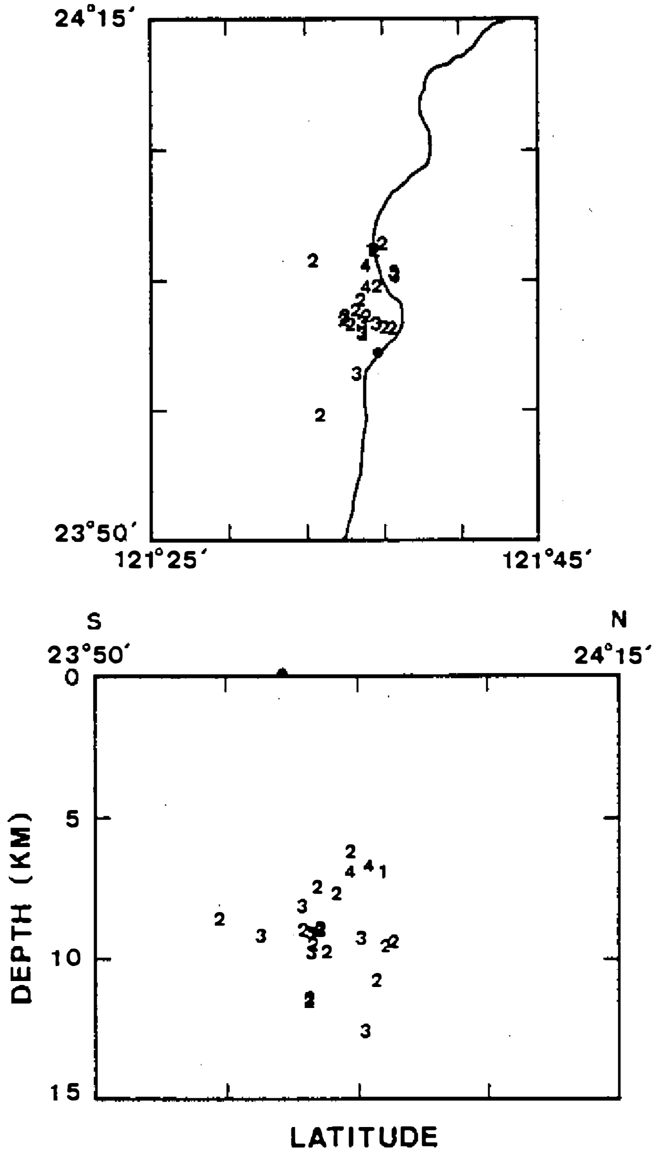

Fig. 2. Earthquakes located by the temporary seismographic network during the period of 24-hour continuous sound recording at the CWBSN station in Hualien city. Above: Epicentral distribution; below: focal depth profile along in a NS direction. The black dot on the surface represents the site of sound recording.

the seismograph of the CWBSN station at all, was ruled out too. Thus, we had 21 sets of eligible sound-seismic wave correlated records. The data processing procedure follows:

1. Digitize 30 to 60 seconds of sound record from the tape for each earthquake. Make sure the time period covers the P-arrival and ten seconds before it. The digitizing rate chosen was 4000 points per second, that is,

the minimum rate to tell the "second" and "minute" time signals whose frequencies were around 1000 *Hz*.

2. Plot the digitized record of sounds, and locate the position of minute and second signals on it.
3. Use the Moving-Window (MW) method (an average method in the time domain) to suppress the unneeded high frequency noises (See Figures 3a through 3e for comparison of the original and noise-suppressed records).
4. Find the relevant signals (earthquake sound), making sure they are not any known artificial sound. Then, read their arrival times.
5. Analyze the frequency content of these earthquake sounds using the Fast Fourier Transform (FFT) method. The 2048 points (about half a second long) of original data (before MW processing) right after the earthquake sound arrival were used.

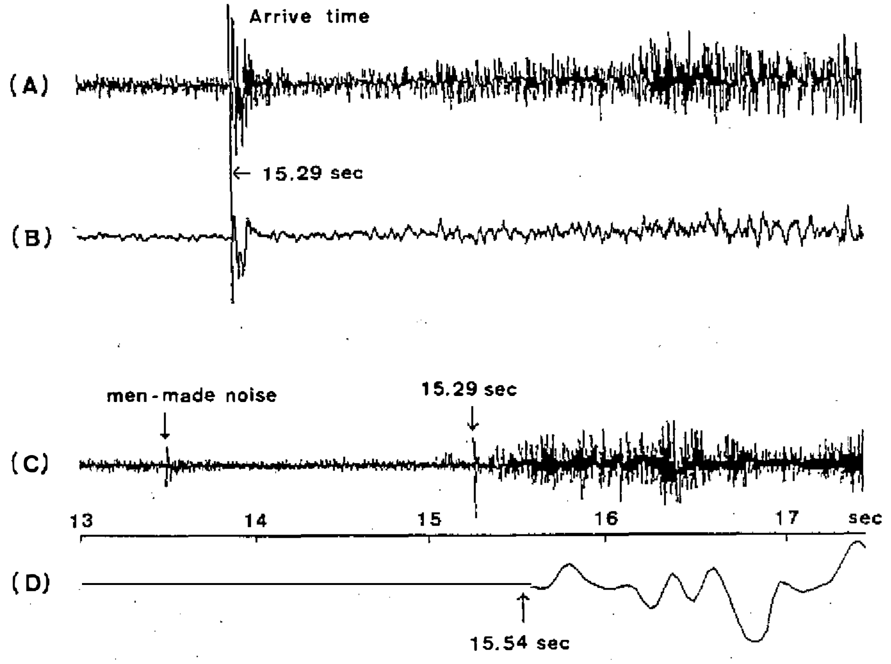

Fig. 3a. Above: Comparison of the time history of the original sound digitized from tape (A), and the corresponding noise-suppressed record (B) by the Moving Window method for picking the arrival of the earthquake sound corresponding to the No.3 earthquake. The total length of (A) or (B) is 0.5 *seconds*. Below: The noise-suppressed record of sound (C), and seismogram (D) for the No.3 earthquake for comparison of the arrivals of the earthquake sound and the P wave. The same CWBSN time scale is used for both (C) and (D).

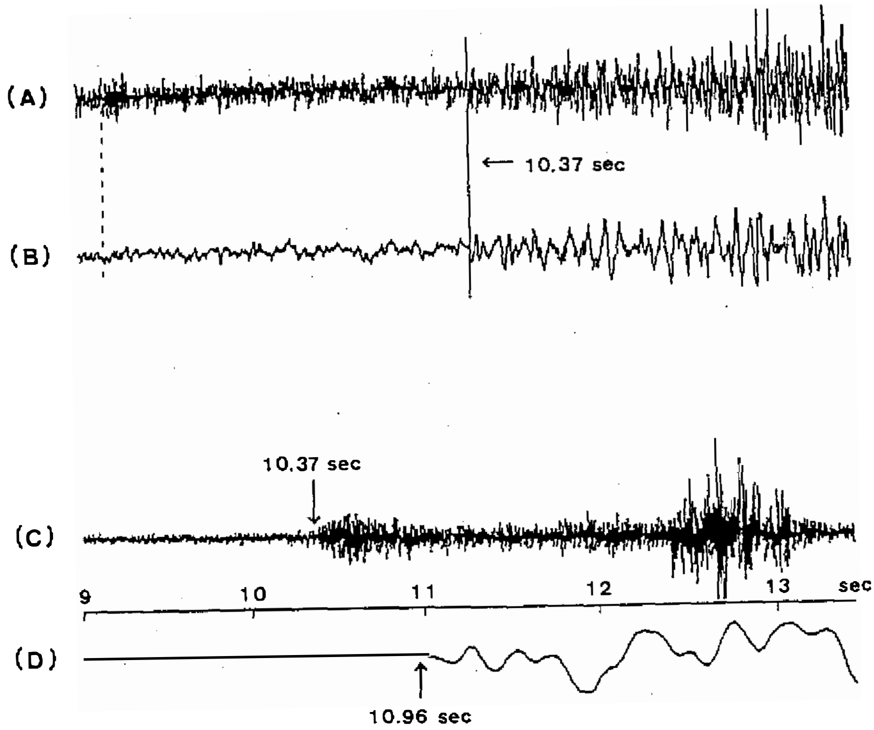

Fig. 3b. Time history of earthquake sound and seismogram for the No.4 earthquake. See the caption of Figure 3a for further description.

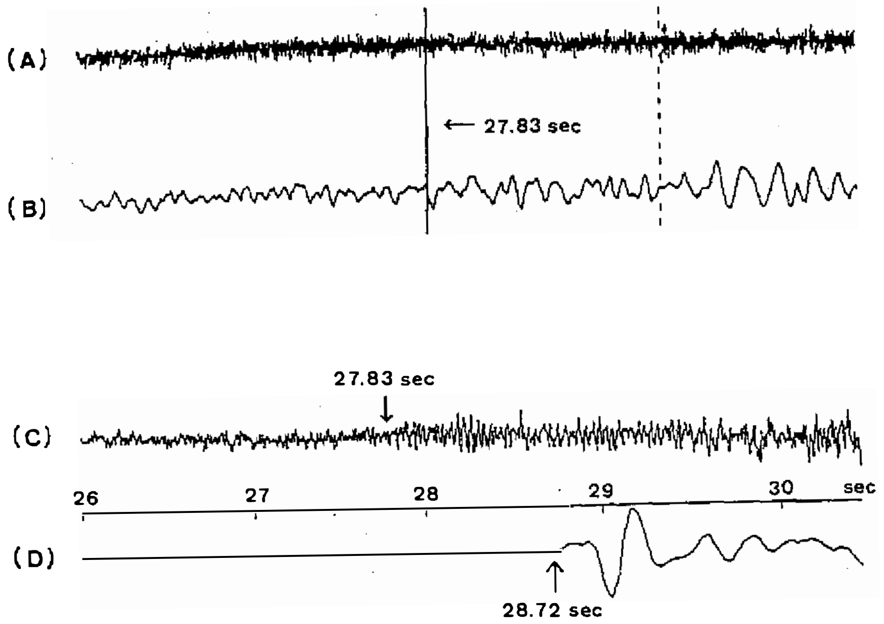

Fig. 3c. Time history of earthquake sound and seismogram for the No.6 earthquake. See the caption of Figure 3a for further description.

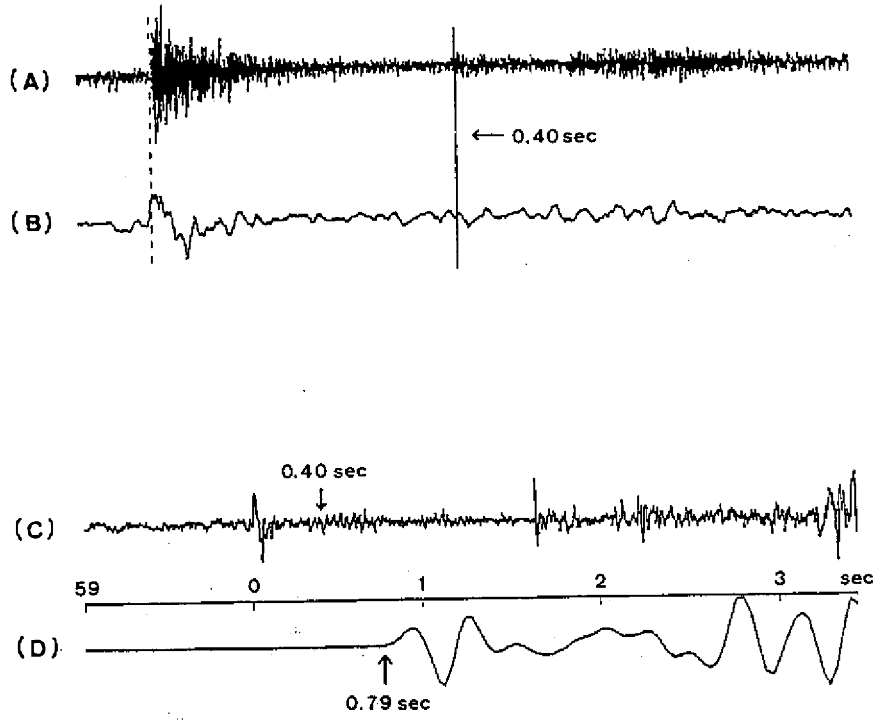

Fig. 3d. Time history of earthquake sound and seismogram for the No.21 earthquake. See the caption of Figure 3a for further description.

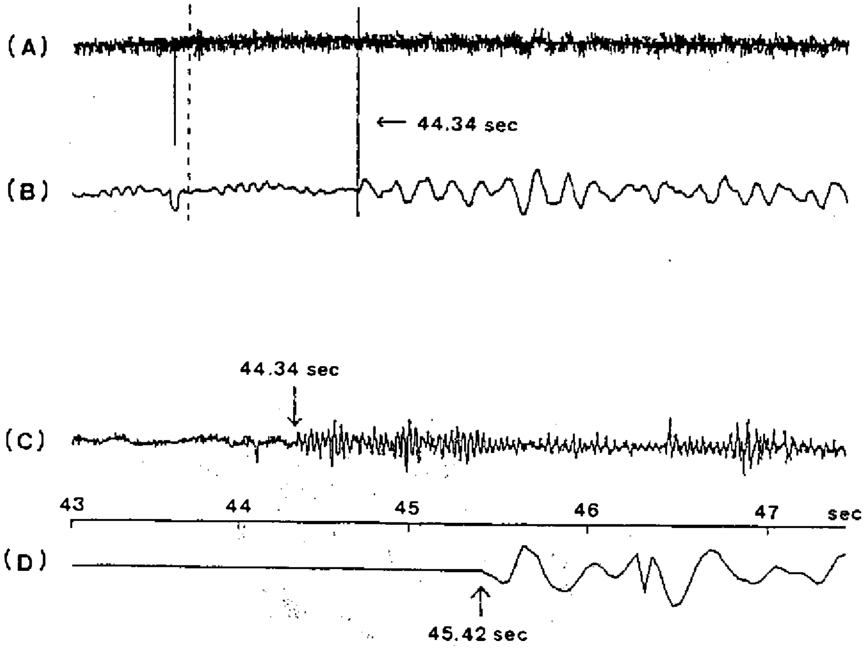

Fig. 3e. Time history of earthquake sound and seismogram for the No.25 earthquake. See the caption of Figure 3a for a further description.

Since there was little in the literature to which we could refer when we read and identify the earthquake sound signals on the sound wave graph, we made some criteria to identify them given below:

1. The amplitude was higher than the background noise.
2. The waveform or wave period obviously differed from the background.
3. Make sure they were not any known artificial sounds.
4. The arrival time is close to the P-arrival on the seismogram.

All earthquake sounds which we discuss in this paper meet at least three of the above criteria.

3. DATA ANALYSIS

a. Time Domain:

After the processing procedure described in the previous section, we found that 5 of the 21 earthquakes were accompanied by prominent sounds. By comparing the "second" and "minute" time signals from the MEQ800 seismograph and the CWBSN, we found that the clock of the CWBSN is 0.12 *seconds* faster than the clock of the MEQ800. All the records discussed below were corrected to the CWBSN time system.

The NO.3 Earthquake (see Figure 3a)

Earthquake sound preceded the P-arrive by 0.25 *seconds*. The earthquake sound had a very strong, prominent arrival (Figure 3a-B), it then decreased in amplitude rapidly to the background level and then became louder and louder (Figure 3a-B,C), finally embedded in noises caused by the ground shaking due to seismic waves. The signal which appeared at 13.5 *seconds* on the graph was an artificial sound, resembling metallic scratch sound when we listen to the sound tape.

The NO.4 Earthquake (see Figure 3b)

Earthquake sound preceded the P-arrival by 0.59 *seconds*. The sound amplitude grew gradually to a maximum 0.3 *seconds* later. There was no significant sound at the P-arrival time. The signal shape was like a wave packet. We can see in this record, there was no significant noise induced by P waves.

The NO.6 Earthquake (see Figure 3c)

This was a smaller earthquake in magnitude, and therefore had lower earthquake sound. The amplitude of the sound was not significantly larger than that of the background noise, but the wave period of the earthquake sound was longer than that of the background noise. The arrival time of the earthquake sound preceded the P-arrival by almost a second.

The NO.21 Earthquake (see Figure 3d)

The earthquake sound in this record appeared right after a "minute" time signal. The amplitude was not larger than that of the NO.6 event, but the background noise was lower, so that we could tell the sound signal easily by the relatively larger amplitude. The waveform of the sound signal, like a wave packet, preceded the P-arrival by 0.39 *seconds*.

The NO.25 Earthquake (see Figure 3e)

This sound signal preceded the P-arrival by 1.08 *seconds*, the fastest of all five records. The waveform was stable and clear. The arrival was sharp and clear too. The whole signal formed a few wave packets.

The most important fact is that all five recognized earthquake sounds preceded the seismic P waves from a quarter to more than one second, which is different from the earthquake sounds recorded by Hill *et al.* (1976) and the Japan Meteorological Agency (1968).

b. Frequency Domain:

We compared the amplitude spectra of the earthquake sounds with those of the background noise to understand the frequency content of the earthquake sounds. To avoid the noises caused by seismic waves, we used only the first half second of the earthquake sound for each record which did not overlap with the seismic waves. Also, one half second of the background noise for each earthquake sound was used; a half second window of noise was chosen from the background noise within two seconds before the earthquake sounds arrival.

For the NO.4 Earthquake (see Figure 4a), the strongest peak appeared at 90 *Hz*. The energy was concentrated in a relatively higher frequency range. For the NO.6 Earthquake (see Figure 4b), the background noise was large and random in the frequency domain. The main earthquake sound peaks appeared at 28, 46 and 70 *Hz*. For the NO.25 Earthquake (see Figure 4c), background noise was quite low. The dominant frequency of the earthquake sound appeared at 33 *Hz*.

We can see that the frequency content of the earthquake sounds was mainly within 200 *Hz*. The predominant frequencies fall within 30 to 100 *Hz*. These sound waves are audible, but can not be recorded by ordinary seismographs because they are beyond the frequency range of the recording.

c. Other Characteristics:

In Table 1, we list the parameters of the 25 aftershocks, including their magnitude, intensity, epicentral distance, and focal depth etc. We can see that the five earthquakes that had prominent accompanying sounds have some common characteristics:

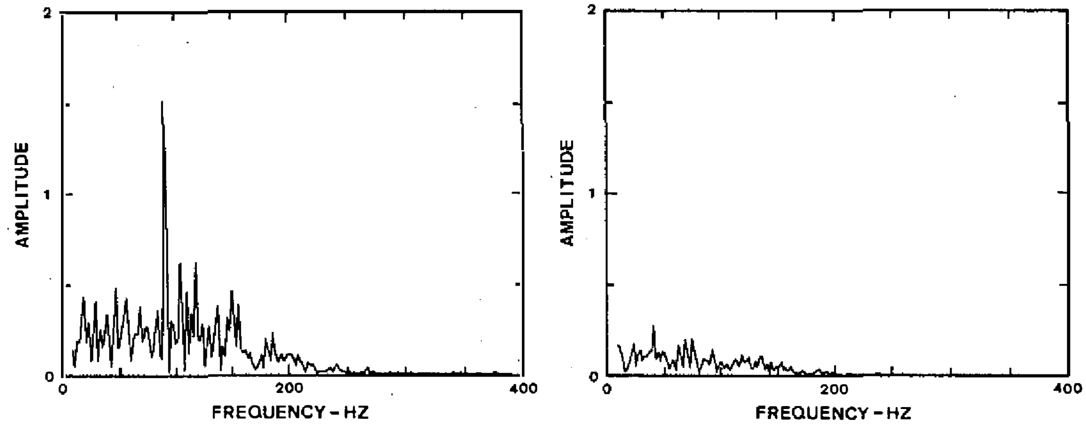

Fig. 4a. Amplitude spectra of the earthquake sound (left) for the No.4 earthquake and the background noise (right). See text for description.

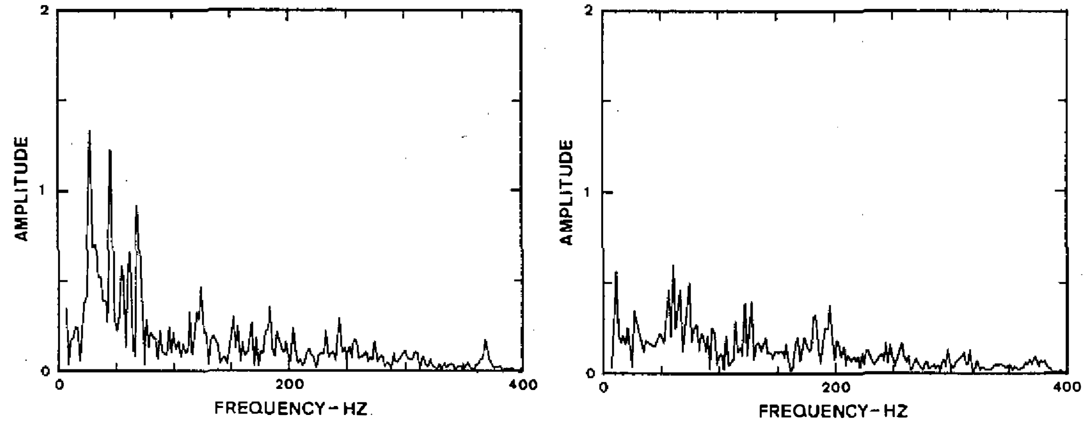

Fig. 4b. Amplitude spectra of the earthquake sound (left) for the No.6 earthquake and the background noise (right). See text for description.

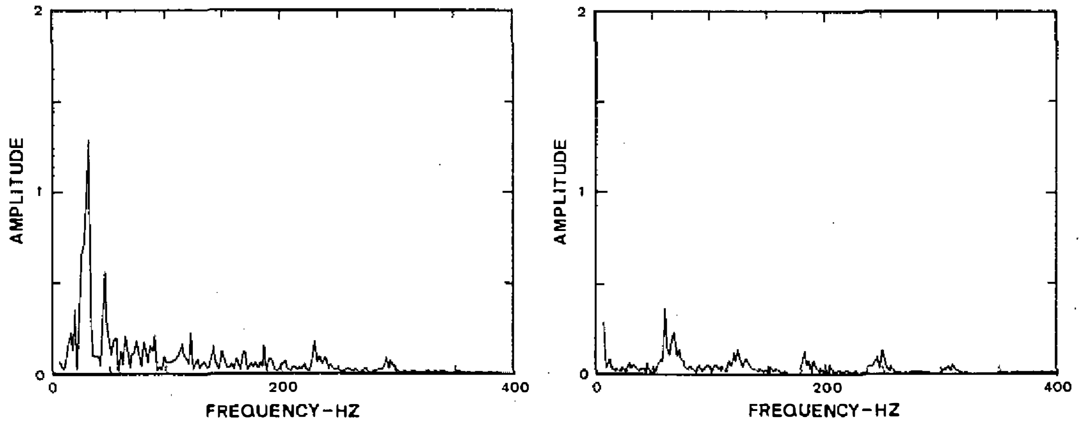

Fig. 4c. Amplitude spectra of the earthquake sound (left) for the No.25 earthquake and the background noise (right). See text for description.

1. Strong intensity. They were the five most intense of all 25 earthquakes.
2. The magnitude was larger. They were ranked in the top four and the 7th among all 25 earthquakes.
3. They were relatively closer to the station. The hypocentral distance of these five earthquakes ranked 1st, 4th, 8th, 9th, and 13th among all 25 earthquakes.
4. They had a relatively shallower focus than others. Their focal depths were ranked from 12th to 24th among all the earthquakes. The deepest one was only 9.4 *km*. And the strongest two earthquake sounds (NO.3 and NO.4) were the shallowest two earthquakes ranked 23rd and 24th.
5. The epicentral distance is not the only strong parameter for having an earthquake sound, but all these five events had epicentral distances shorter than 8 *km*.

Table 2 listed the parameters of the earthquake sources and the corresponding earthquake sounds. The corresponding data of Hill *et al.* (1976) was also listed. We can see that earthquakes studied in this paper and those by Hill *et al.* (1976) have the same characteristics of short hypocentral distance and shallow focus. In fact, the earthquakes and sounds analyzed in this study are stronger than those in Hill *et al.* (1976).

d. Possible Mechanism:

Table 2. Source and sound parameters for the five earthquakes studied in this paper.

No.	3	4	6	21	25	Hill et al. (1976)
M_L	4.7	4.7	3.7	3.6	3.4	2.0~2.8
I	4	4	3	3	3	
H	7.1	6.9	8.3	9.3	9.4	7.0~7.8
Δ	6.1	7.9	2.5	3.1	3.0	~3.0
D	9.3	10.5	8.7	9.8	9.8	7.6~8.3
FT	Thrust	—	Thrust	Thrust	—	Strike-Slip
DT	+0.25	+0.59	+0.89	+0.39	+1.08	±0.02
PF		90	28, 46, 70		33	50~70 (*Hz*)

M_L : Local magnitude
I : Intensity
H : Focal depth
Δ : Epicentral distance to the CWBSN station
D : Hypocentral distance to the CWBSN station
FT : Fault plane solution from Tsai (1987)
DT : Arrival time difference between earthquake sound and seismic wave
PF : Predominant frequency

Laboratory experiments on rock mechanics (e.g. Mogi, 1962; Brace, 1968; Scholz, 1968) have shown that, when compressional stress in the rock sample reaches about half the breaking stress, microcracks begin to appear. As the stress increases, the microcracks grow and then coalesce to form one or more principal fractures in the final stage. This phenomenon may also happen in the lithosphere to cause earthquakes. The earthquake sounds recorded and recognized in this study may mean that the number of microcracks increases tremendously in the earthquake source area shortly before the major faulting of the earthquake.

Because of the high attenuation of sound waves in rock, the sedimentary layer or air, and the low percentage of sound energy which penetrates through the ground surface from the underground to the air, the fact that earthquake sounds are audible and can be recorded by an ordinary tape recorder means that the high frequency waves which can not be recorded by an ordinary seismograph must be very prominent and worth further study.

4. CONCLUSIONS

During the 24-hour sound recording period, 25 aftershocks following the 1986 May 20 earthquake were observed and located using a temporary seismographic network. By comparing the sound record and the digital seismograms obtained by the CWBSN station in Hualien city, we found that at least 5 of the 25 earthquakes were accompanied by earthquake sounds. In this study, characteristics of these earthquake sounds are obtained as follows:

1. All the earthquake sounds which we recorded and recognized preceded the P-arrival by 0.25 to 1.08 *seconds*.
2. The frequency contents of the earthquake sounds were mainly within 200 Hz. The predominant frequencies fell within 30 to 100 Hz.
3. The five earthquakes which had accompanying earthquake sounds had similar characteristics: larger magnitude, shallower focus, and being closer to the recording station.
4. We infer, from the above-mentioned characteristics of earthquake sounds, that some cracks in the crust must occur in the vicinity of the earthquake source shortly before the faulting which results in the actual occurrence of the earthquake. These cracks send out acoustic waves that are referred to as earthquake sounds, whose frequencies are too high to be detected by ordinary seismographs.

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REFERENCES

Brace, W. F., 1968: Current laboratory studies pertaining to earthquake prediction, *Tectonophysics*, **6**, 75–87.

Chen, K. C. and J. H. Wang, 1986: The May 20, 1986 Hualien, Taiwan Earthquake and it's aftershocks, *Bull. Inst. Earth Sci., Academia Sinica.*, **6**, 1–13.

Davison, C., 1938: Earthquake sounds, *Bull. Seism. Soc. Am.*, **28**, 3, 147–161.

Hill, D. P., F. G. Fischer, K. M. Lahr, and J. M. Coakley, 1976: Earthquake sounds generated by body-wave ground motion, *Bull. Seism. Soc. Am* ., **66**, 4, 1159–1172.

Japan Meteorological Agency, 1968: Report of the Matsushiro earthquake swarm, August 1965-December 1967, Technical Report of the Japan Meteorological Agency, 125–137.

Liaw, Z. S., C. Wang, and Y. T. Yeh, 1986: A study of aftershocks of the 20 May 1986 Hualien earthquake, *Bull. Inst. Earth Sci., Academia Sinica*, **6**, 15–27.

Mogi, K., 1962: Study of the elastic shocks caused by the fracture of heterogeneous materials and its relation to earthquake phenomena, *Bull. Earthquake Res. Inst.*, **40**, 125–173.

Scholz, C. H., 1968: Microfracturing and the inelastic deformation of rock in compression, *J. Geophys. Res.*, **73**, 1417–1432.

Steinbrugge, K. V., 1974: A catalog of earthquake related sounds, *Bull. Seism. Soc. Am.*, **64**, 5, 1409–1418.

Tsai, S. F., 1987: The May 1986 Hualien earthquake sequence and its relation with the regional tectonic stress, M. S. Thesis, Institute of Geology, National Taiwan University.

與1986年5月20日花蓮地震之餘震相關的地鳴之研究

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摘要

1986年5月20日花蓮地震之後數日間餘震頻繁，其中伴隨地鳴而至的地震爲數甚多。王正松和溫國樑先生於24～25日間做了連續約24小時的錄音，其間發生規模大於2.0的餘震25次。經分析處理後證實其中至少有五個地震伴隨地鳴到達。本文比較這五個地鳴與對應地震的P波到達時間，並分析這些地鳴之頻譜。我們發現地鳴到達測站之時間超前地震記錄的初達P波0.2～1.1秒不等，其主頻率約在25～100 Hz之間。經過震源參數的分析比較，我們發現伴隨地鳴之地震的共同特徵是規模較大、震源較淺、至測站間之距離較近。地鳴主頻率並有隨震源深度增加而降低的趨勢，這可能與高頻波在地層中的衰減比低頻波快有關。據此推測在震源破裂過程中可能有較高頻率之地震波在一般地震儀可記錄之較低頻波產生之前即已在震源區產生。這項結果顯示，在目前使用之地震儀的頻率接收範圍之外，仍有許多與地震有關的訊息，這些訊息所代表的意義有待進一步的研究。