SOME SEISMOLOGICAL OBSERVATIONS AT INFERNO CRATER LAKE, WAIMANGU GEOTHERMAL FIELD, NEW ZEALAND

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SUMMARY - During this survey a total of 52 earthquakes were recorded in 29 days of operation of a network, which consisted of four 1-Hz seismometers. Thirty-eight of the events were classified as near events on the basis of their S-P intervals. Earthquakes in this group had a magnitude less than 1.8, and a characteristic frequency spectrum with a peak between 10-20 Hz. Earthquakes occurred in swarms, but showed no relationship between their frequency of occurrence and water level change at Inferno Crater Lake. Despite a positive correlation between acoustic noise and water level being found in previous work, we did not observe any strong acoustic noise.

1.0 INTRODUCTION

Earthquakes and acoustic (seismic) noise associated with geothermal activity have been reported in several geothermal fields (e.g. Bromley et al., 1982; Tosha et al., 1993). As the earthquakes are small ($M \leq 3$), they are called microearthquakes. It is not clear why microearthquakes occur in the geothermal fields; some are caused by normal tectonic stress, but others are associated with geothermal systems. One possible mechanism for non-tectonic events is an increase of pore pressure by the geothermal fluid. Strong acoustic noises may also occur in geothermal systems due to bubble collapse and/or explosion in liquid water (e.g. Kieffer, 1984).

Waimangu is a major geothermal field in Taupo Volcanic Zone and was affected on 10 June 1886 by the eruption of nearby Mt. Tarawera (Simmons et al., 1993). The eruption created several craters in the field along a southwest-northeast line (Fig. 1). The largest hydrothermal eruption after the 1886 Tarawera eruption happened in 1917 and it re-excavated and enlarged southern Echo Crater, which filled with water to form Frying Pan Lake. Present surface hydrothermal activity is dominated by Frying Pan and Inferno Crater lakes. The most interesting geothermal features at Waimangu are Inferno Crater and Frying Pan lakes which display interrelated cyclic changes.

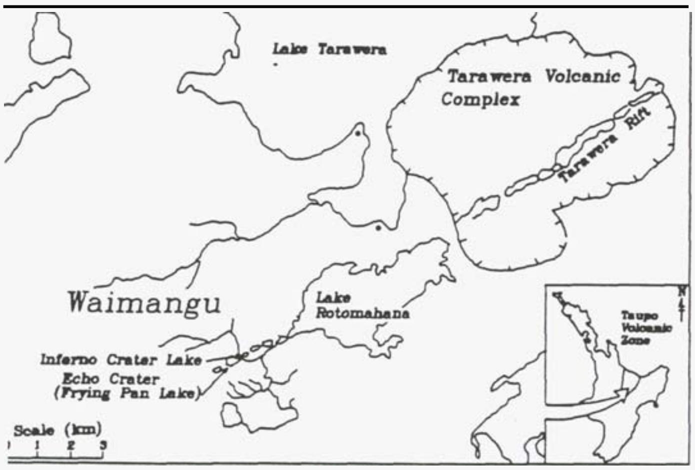

Figure 1. Location map of Waimangu Geothermal Field and Mt Tarawera.

Several experiments have been made to examine a correlation between the water level change in Inferno Crater Lake and acoustic noise. A preliminary study at Inferno Crater Lake during 1974-75 showed a positive correlation between the water level change and acoustic output (Scott, 1976). There was a high level of seismic noise present during the rise of water level and the main overflow. This paper reports the results of a seismological survey to obtain acoustic output as well as microearthquakes to investigate the movement of fluid and the mechanism of the cyclic change of water level in Inferno Crater Lake.

2.0 INFERNO CRATER

Inferno Crater Lake has shown water level variations since at least 1901, when it was affected by the Waimangu Geyser cycle. The Waimangu Geyser was active between 1900 and 1904 and was known as the world's largest geyser, erupting up to 400 metres high. Waimangu Geyser cyclicity (36 hours) and variations of the water level at Inferno Crater Lake are the first recorded examples of interrelated cyclic variations, which are now seen at Inferno Crater and Frying Pan lakes. Scientific instrumentation was first installed in 1970 to investigate the hydrological aspects of Frying Pan and Inferno Crater lakes. Lloyd (1973, 1974) was the first to report on a cyclic and inverse relationship between the water level of Inferno Crater Lake and the discharge of Frying Pan Lake. Scott (1976) described and ordered distinct stages in the cyclic behaviour of Inferno Crater Lake based on a study of seismic noise. Stanton (1978) selected the start of the cycle at the lowest water level and his ordering is now adopted. The mean cycle length, between the water level minima, is 37.7 ± 9.7 days and four distinct stages are recognized within the cycle (Scott, 1992; Fig. 2):

1. **An** initial rise of water level lasting 7.7 ± 1.8 days. The water level rises 4.7 ± 1.4m and the temperature rises 17.3 ± **4.5** "C. Lake volume increases by about 23800 m^3.

2. **A** period of oscillating water level lasting **14.7 ± 5.9** days. The water level rises 3.89 ± 1.14 m and the temperature rise and falls with water level but remains about a mean of 60.7 ± 2.2 °C. Lake volume increases by about 22000 m^3.

3. ***An*** overflow stage of 51.3 ± 26.1 hours during which time 79.1 ± 11.0 litre sec^{-1} is discharged. The temperature at the commencement of ovefflow is 66.5 & 5.1 "C, and at the end is 71.9 ± 5.0 °C. The total flow volume is **14.0 ± *5.6* x** 10^4 m^3.

4. **A** recession stage for 15.1 ± ***5.6*** days. The water level recedes 7.9 ± 2.0 m and the temperature falls 26.4 ± 6.1 °C. Lake volume decreases by about 45000 m^3.

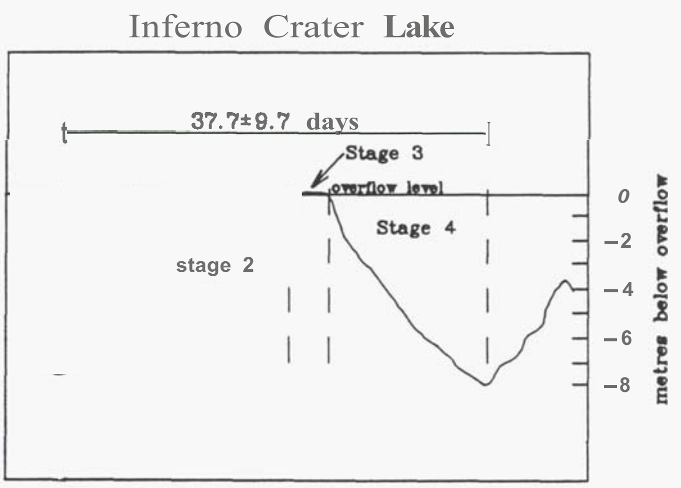

Figure 2. Plot of water level changes at Inferno Crater Lake showing the 4 stages.

3.0 SEISMIC ACTIVITY IN GEOTHERMAL FIELDS

Earthquakes and high amplitude seismic noise (>2 pm sec^{-1}) in geothermal fields are similar to those observed at many volcanoes. Microearthquakeswhich have clear P-wave breaks, and bubblequakes which are associated with the collapse of bubbles, resemble A-type and B-type volcanic earthquakes (Minakami, 1960), respectively. High amplitude seismic noise is similar to tremor before and during volcanic eruptions. Microearthquakes and tremor have been used to investigate ?he structure and processes associated with eruptions, suggesting that analysis of similar data may be used to investigate geothermal systems.

Both liquid and gas play important roles in the generation of microearthquakes and high amplitude seismic noise in geothermal fields. **A** sequence of induced earthquakes is often observed during the operation of well-head valves and it is interpreted as being associated with the movement of geothermal fluid in the reservoir (Sugihara and Tosha, **1988).** Closing the valve causes an increase in pressure of geothermal fluid, resulting in an increase in pore pressure, which triggers earthquakes. Microearthquakes can thus be useful to monitor the flow of fluid in the reservoir.

Kieffer (1984) investigated Old Faithful Geyser, USA. She found monochromatic and high frequency (20-60 **Hz)** events every 0.2 to 0.3 sec period resembling unsustained harmonic tremor and/or B-type volcanic earthquakes, and suggested that

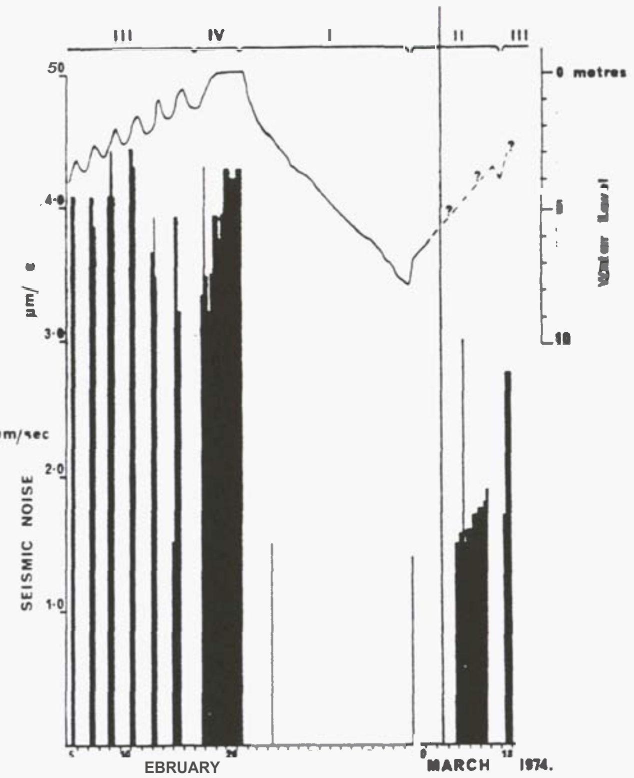

Figure 3. Plot showing maximum amplitude of seismic noise and water level change at Inferno Crater Lake (after Scott, 1976).

these strong seismic signals are generated by bubble collapse or expansion. Preliminary seismic monitoring (Scott, 1976, Fig. 3) at Waimangu showed there was a high level of seismic noise present during the rises of each oscillation in Stage 2 and during the main overflow in Stage 3. Stanton (1978) carried out more a detail study on the characteristics of the acoustic noise in Inferno Crater Lake by using two hydrophones, four geophones, and an automatic recording system. He confirmed and qualified the positive relationship between the rise of water level and the strong signal of acoustic noise. However, the geophones he used had low sensitivity and the measured frequency spectra showed no consistent characteristics. Leigh (1985) made a similar survey using a four-element, directional, seismic array with 1 Hz seismometers; the data obtained were analyzed by a cross correlation method and revealed the acoustic noise appeared to come from the centre of Inferno Crater Lake. However, there was no significant variation with time in the power spectrum and power of acoustic noise.

4.0 INSTRUMENTS

Seismometers with 1 Hz resonant frequency, Mark Product L-4C, were used in this study. One 3-component seismometer was placed close to outlet of Inferno Crater Lake, two single-component seismometers were placed on the north and east ridges around the lake, and a third was installed between Inferno Crater and Frying Pan lakes (Fig. 4). Each seismometer was buried in a shallow (< 1m depth) hole to get good contact with surrounding rocks. The horizontal distance between the seismometers was typically about 100m, and the greatest elevation difference between WMG2 (on the north

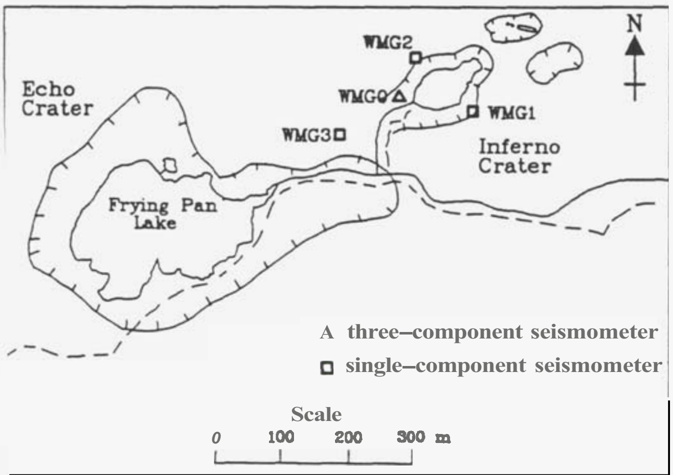

Figure 4. Sketch map of Echo-Inferno craters area showing location of the seismic network.

ridge) and WMGO (outlet) was about 43 m. Table 1 lists the location of each seismometer.

	East (m)	North (m)	Latitude (S°)	Longitude (E°)	Hight (m)
WMGO	2807450	6318950	38.203797	176.399041	374.8
WMG1	2807560	6318945	38.283804	176.400300	398.7
WMG2	2897428	6319030	38.283084	176.398755	417.0
WMG3	2807345	6318927	38.284040	176.397852	386.5

TABLE1. Location of Seismometers

Seismic signals from the seismometers were amplified and transmitted through wirelines to a digital recorder. The analog signals were passed through a low-pass filter and digitized by a 16-bit A/D converter. A sampling frequency of 400 Hz was chosen to adequately record the high frequency signals. The recorder was triggered by the signal at WMGO (close to Inferno Crater Lake), when a ratio of STA (Short Time Average, 1 sec) **versus** LTA (Long Time Average, 32 sec) of the signal exceeded a threshold level.

5.0 RESULT AND DISCUSSION

Operation of the network commenced on 12 February and continued until 12 March 1993, however, no data were available during 19 to 23 February due to instrumental problems with the recorder. During the survey period, a total of 52 earthquakes were recorded by the network. As one 3-component seismometer was placed in the network, it was easier to pick a S-wave arrival time on the horizontal components than on the vertical component. The events are classified into three groups according to the duration of P wave coda (S-P interval): near events having S-P intervals less than 1 second; intermediate events having between 1 and 5 seconds; and distant events having S-P intervals of more than 5 seconds. Thirty eight and six of the 52 events were put to the near and intermediate event groups, respectively.

Fig.5 shows a typical example of the waveforms of a micro-earthquake recorded by the 3-component seismometer at WMGO. The top figure (5a) shows the vertical component of the seismometer and the next two figures (5b, 5c) are those of north-south and east-west components, respectively. All near events had a maximum amplitude of ground particle velocity less than 30 $\mu m\ sec^{-1}$. The arrival time of the P-wave is very clear, but the first break of S-wave is often obscure because of P-S conversion at acoustic impedance boundaries, small amplitudes of the signals or the seismic ray does not reach the seismometer vertically. The bottom figure (5d) shows a power spectrum of P wave coda in the vertical component. The data show the peak frequency for near events ranges from 10 to 20 Hz similar to A-type volcano-tectonic earthquakes at White Island (Scott, unpublished data).

The power spectra of background noise are shown in Fig. 6, where the top and bottom figures are time-domain waveforms and frequency-domain spectra, respectively. Leigh (1985) found that the acoustic noise had very similar levels, and a characteristic spectral shape with a 5-10 Hz peak, during his three days of measurements. The signal levels of acoustic noise we measured are similar to those reported by Leigh in a range less than 1 pm sec^{-1}, but the spectrum peak and shape are different, and seem to vary from day to day. The previous studies (Scott, 1976; Stanton, 1978) reported strong acoustic noise during the water level rises in the oscillation stage (Stage 2). Though the acoustic noise previously reported exceeded 3 pm sec^{-1}, they did not trigger the recorder during our survey. It is possible that we could not get a trigger because the amplitude of the acoustic noise increased very gradually during the water level rises and may not have activated the trigger algorithm. A continuous recording through a whole cycle would be necessary to determine any temporal variation in the level and spectral shape of acoustic noise.

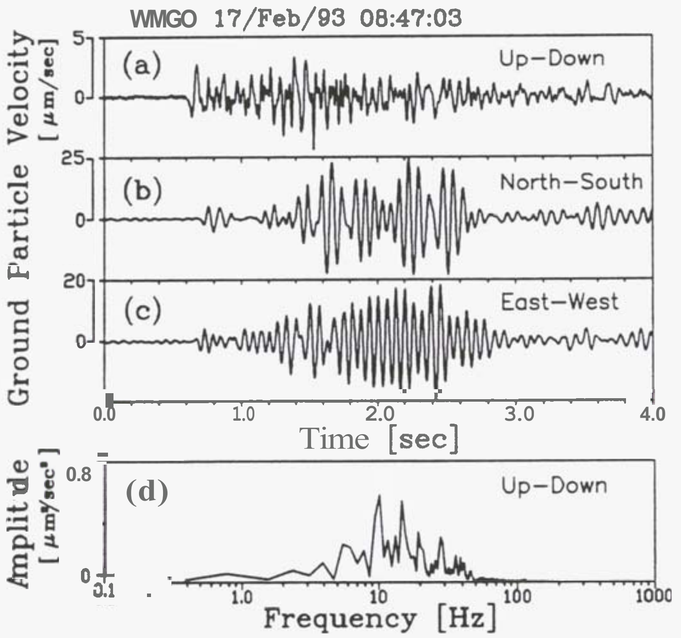

Figure 5. An example of waveform (a,b,c) and power spectrum (d) of a microearthquake (near event) recorded at WMGO. 5a is vertical component, 5a and 5b are longitudinal (north-south) and transverse (east-west) components, respectively.

Fig. 7(a) shows a frequency-time plot for the near events and 7(b) shows the corresponding change of water level in Inferno Crater Lake. It can be seen that the earthquakes occur in clusters and appear swam-like, similar to those in Kakkonda Geothermal Field, Japan (Sugihara and Tosha, 1988). Furthermore, there seems to be no correlation between earthquake occurrence and the cyclical change of the water level in Inferno Crater.

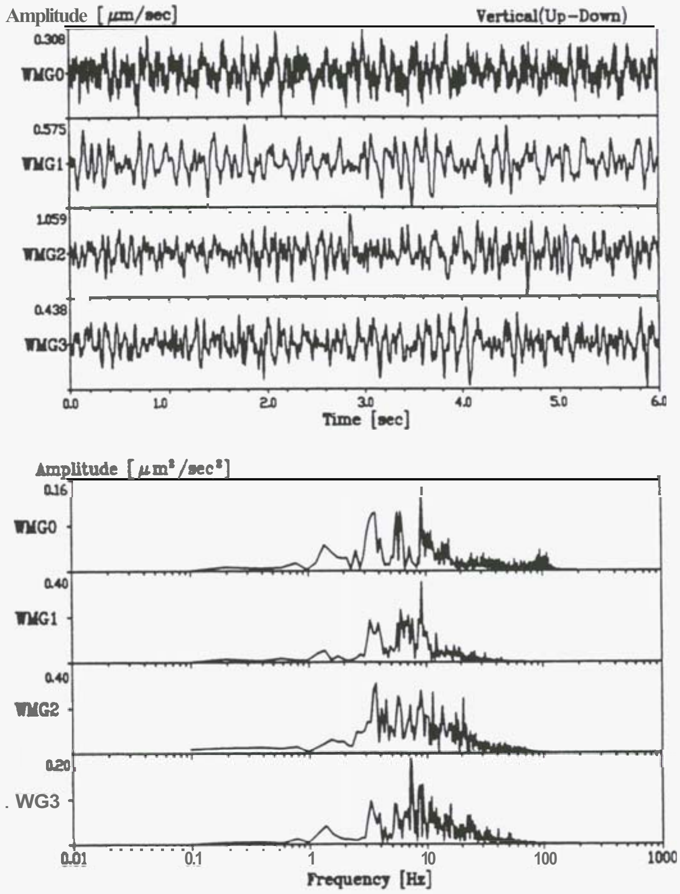

Figure 6. An example of waveform and power spectrum of background acoustic noise in the vertical component at all 4 seismic stations.

Magnitudes can be calculated in several ways. For this study we adopted the F-P method which uses the duration of P- and S-waves (F-P time, τ_{f-p}) to estimate magnitude. The magnitude is obtained from the equation:

$$M = a \log \tau_{f-p} + b$$

where a and b are empirical coefficients which depend on the geothermal field and the station within the field. Tsumura (1967) obtained values of a–2.85 and b--2.36 by analysing microearthquakes in Wakayama Prefecture in Japan, and a–3.0 and b=0 are used for earthquakes in the Taupo Volcanic Zone (Seismological Observatory, 1992). We tentatively adopted a–2.6 and b=-0.7 (Sherburn, personal communication). Magnitudes obtained from out data range from 0.4 to 1.8 for the near events. There were three earthquakes with magnitude of 1.8; one was clearly a multiple event in which two or more waveforms overlapped. Computed magnitude distribution as shown in Fig. 8.

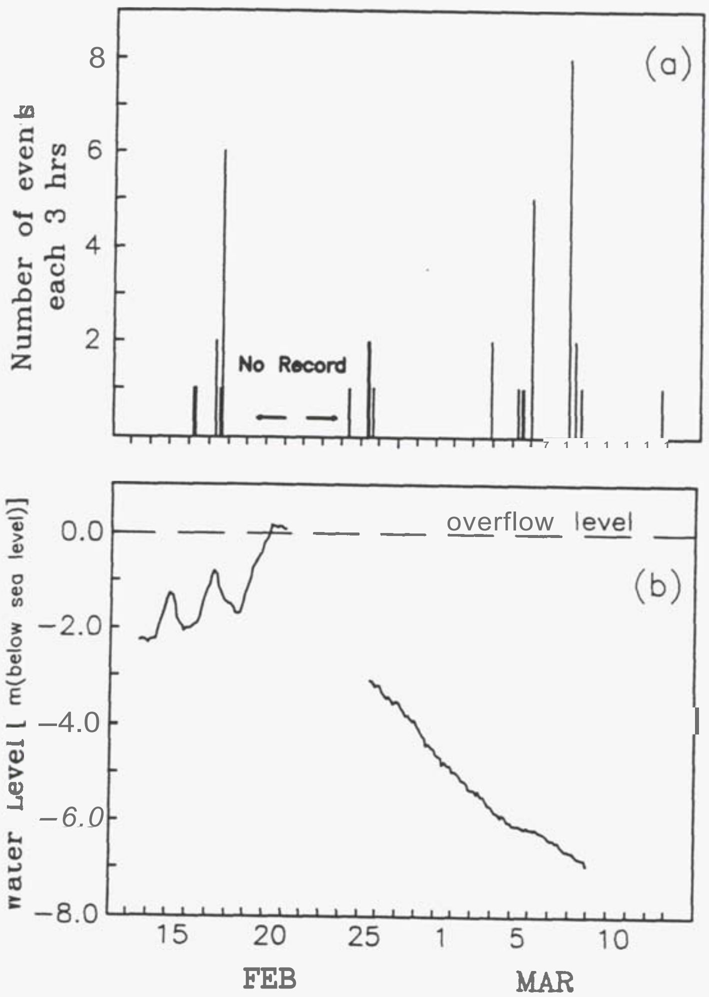

Figure 7. (a)Plot of number of microearthquakes (at 3 hours interval) with short S-P intervals (<1 sec) and (b) water level of Inferno Crater Lake during the survey period.

6.0 CONCLUSIONS

During the 29 dy survey a total of 52 microearthquakes were recorded of which 38 were classified as near events. All events had a magnitude less than 1.8 and a characteristic dominant frequency within the range 10-20 Hz. No strong acoustic noise and no relationship between seismic features and water level change at the lake were obtained. Continuous seismic recording in Inferno Crater Lake is needed to determine whether seismic noise associated with cyclic water level changes is still present.

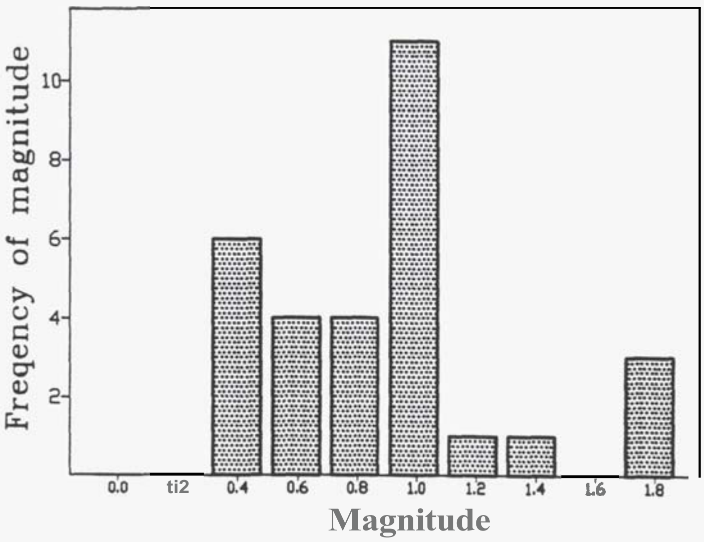

Figure 8. Frequency distribution of magnitudes for short S-P time earthquakes.

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