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# Microseismic Studies in Tongonan and Southern Negros

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## ABSTRACT

Microseismic monitoring studies, in the Tongonan and Southern Negros geothermal fields, have been used to determine the level of local micro-earthquake activity *during* the development *stages* of these projects. Results indicate that Tongonan is situated within a belt of relatively high micro-seismicity, associated with the Philippine Fault. No correlation could be observed with fluid injection or discharge history. Epicenter studies revealed an even distribution of hypocenters across the fault zone, with depths varying from near-surface to 15 km. In Southern Negros, however, there is *evidence* for induced seismicity in the Puhagan sector, as production/reinjection flow-rates have increased. A recent epicenter study has shown that the hypocenters of these earthquakes are close to existing wells and within the depth range of 1.5 to 3.5 km. P-wave velocity, Poisson's ratio, and 'b'-slopes, for this swarm, have been determined. In addition, pulsed and continuous harmonic tremor is observed at both locations, and a possible source mechanism is discussed.

## INTRODUCTION

The Philippines lies [redacted] an active plate bundary, between two opposing subduction zones. The region is seismically active (Acharya, 1980). In the Visayan Islands, the epicenters of larger earthquakes, as located by the USGS and *P —— networks, are quite well dispersed, but show concentrations along the subducting plates. However, no large shallow *earthquakes* have been recorded in recent years within the immediate vicinity of Tongonan and Southern Negros.

Permanent microseismic monitoring station were established in October 1980, near the administration building in Tongonan, and in February 1982, at OK3 well site, in Southern Negros. They were installed to record *any* changes in microseismicity during the development and-early production phases of these projects. In addition, short term epicenter studies have been conducted in both areas using up *to* five portable seismometers. Reinjection plays a major role in the development of these two hot-water dominated fields, and so injection induced seismicity has always been considered a possibility. In terms of their development history, each of the projects is now close to completion of the commissioning stages of the first 110 MW of installed capacity. In the *case* of *southern* Negros, this has involved on-line production of up to 420 kg/s of steam-water mixture and reinjection of up to 300 [redacted] 160°C fluid, since April 1983. *Similar* mass flow-rates have been involved in Tongonan since 1982. These flow-rates *are* expected to more than double when the power stations come under full load. Small scale production/reinjection tests, involving individual wells or small groups of wells, preceded these commissioning trials, but the fluw-rate of injected fluids did not exceed 100 kg/s.

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## TONGONAN

The histogram of local microseismic activity, recorded at the Admin statim, shows no significant changes with time (fig. 3). The events typically *occur* in swarms or clusters, and the average event rate is 6 per week. Local activity is defined as having an arrival time difference between the primary and secondary waves, (S-P) ≤ 4.5 *seconds.* Given an assumed velocity ratio, Vp/Vs = 1.8 and an average P-wave velocity of 4 km/s, this defines a maximum radius for local activity of about 22 km. The distribution *of* (S-P) times of all recorded events since 1981 (fig. 4), shows a peak at 1 to 4 seconds. This *suggests* that most of the local *events* originate from between about 5 km and 20 km radius. There is a reduction in seismicity within 5 Ian (S-P< 1) of the Admin statim which approximately defines the limit of the Tongonan geothermal field (Upper Mahiao to Mahanagdong.

During *April* and My 1981, and again from September to November 1982, *array* studies were conducted using a total of four *seismometers* (fig. 1) witk station spacings of 2-6 Ian. The 1981 *survey* showed that many of the local events originate from outside the array, to the southeast or northwest, along the Philippine fault zone. However, hypocenters were calculated for 49 *events* near the *array.* They showed a reasonably *even* distribution of epicenters across the fault zone, without *any* clear alignment to known fault traces. Uncertainties were high (residuals of 0.2 seconds) because of noisy records, insufficient velocity information, and difficulties in accurate timing. Hypocenter depths ranged from *a* km to 15 km with an average of 10. One swarm of events which occurred

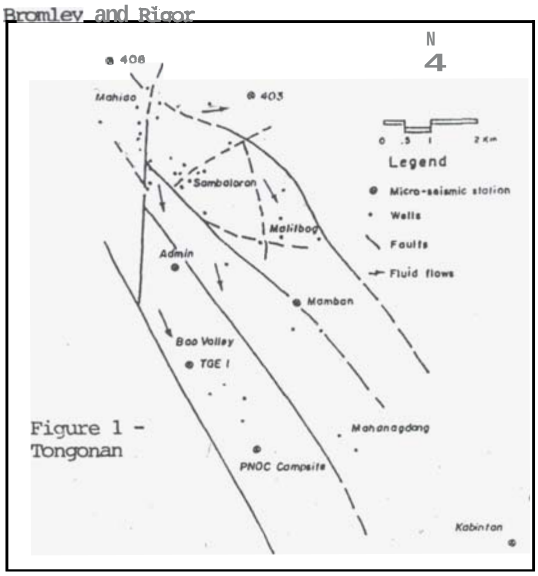



Figure 1 - Tongonan

*during* the array *study* (25th-29th May 1981) showed a clear migration from south-east to north-west. Wadati diagrams of the (S-P) times, as a function of P-wave arrival time, were used to *estimate* velocity ratios (Vp/Vs) which vary significantly from 1.71 to 2.23 (Poisson's ratio = .24 to .37) *suggesting* large lateral variations in fracture density, temperature or degree of saturation. *Similar* large variations in Poisson's ratio have been *observed* in other geothermal areas (e.g. Geysers-Majer, 1979). Strong attenuation was also observed in t h e m and Sambaloran sectors of the field. This is probably a consequence of highly-fractured, water-saturated formations containing pockets of compressible gas and steam.

In summary, the microseismic monitoring at Tongonan has revealed a small localized reduction in seismicity within the reservoir, which *suggests* that aseismic creep processes are absorbing much of the strain along this section of the Philippine fault, while outside the reservoir, frequent swarms of micro-earthquakes are occurring *along the* fault zone at shallow depths. To date, there has been no *change* in local seismicity that *can* be attributed to the production or reinjection of geothermal fluids.

## SOUTHERN NEGROS

Monitoring of the microseismic activity at the OK3 station commenced in March, 1982. For the first *six* months, the event rate for local earthquakes (S-P ≤ 4.5 seconds) was comparatively moderate (fig. 5). Following a swarm of 33 local *events* in October 1982, with (S-P) times of 0.5 to 1.0 ~ e - m the average level of local seismicity increased slightly. Other swarms with similar (S-P) times occurred in January (30 events) and February (185 events). During *this* first 12 month period, separated fluids from two 1.5 MW back-pressure *turbines* at Puhagan, as well as test discharges of *several* production wells, were injected into OK2 and OK12. However, the maximum injection flow-rates were *only 90* kg/s. The distribution of (S-P) times, is shown in figure 7, for this 12 month period. A *large* swarm of 276 *events* with (S-P) = 15 to 18 *seconds* (i.e. at about 100 km radius), which arrived in January, may have originated near the subduction zone southwest of Negros Island. There is also a concentration of local activity with an (S-P) between 0.5 and 1.5 seconds. Given recently estimated velocities from the epicenter study (Vp = 3.7 km/s, and Vp/Vs = 1.8), then these events have probably originated from a zone between 2.3 and 7 km radius from OK3, i.e. within *or* close to the geothermal field.

On May 21, 1983, a substantial swarm of local earthquakes commenced. They all had consistent (S-P) times of 0.5 seconds, as recorded at OK3. The daily event rate for this swarm is shown in figure 12, and compared with the dairy injected flow-rate for separated water into reinjection wells OK12, PN1RD and PN2RD (fig. 11). During *April*, the peak flow-rate was about 150 kg/s, in June it reached 200 kg/s, and in August 300 kg/s ( 26,*000* tonnes/day), as various stages of the 110 MW Palinpinon I power station were commissioned. This swarm of earthquakes has continued now for several months, with more *than* 3000 re-*corded* — concentrated in clusters, and in-*terspersed* with short periods of normal background activity. On several occasions the onset of an *earthquake* cluster occurred within a few hours of a large *step* change of injection flow-rates (e.g. May 21 and *August* 16). Even during April, small clusters of earthquakes followed step increases in the injection flow-rate *on April 4* 13 and 22. On other occasions, clusters also appeared within a

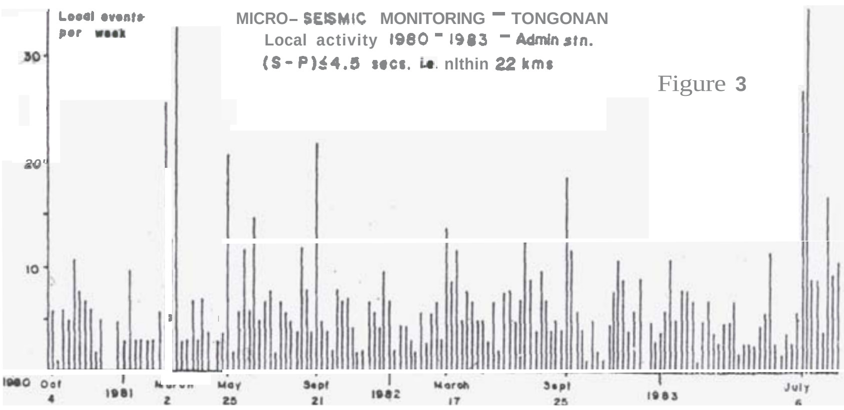



Figure 3

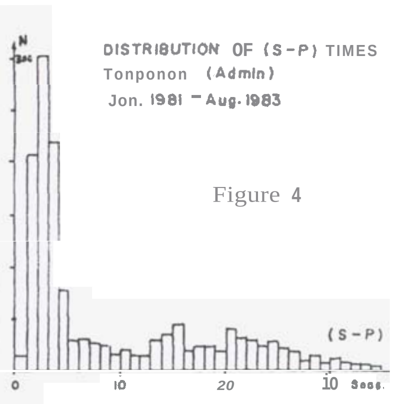



Figure 4

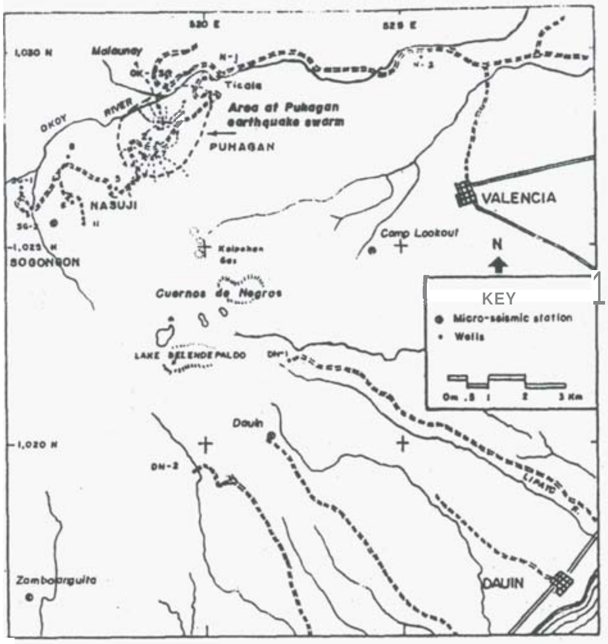



Figure 2 Southern Negros

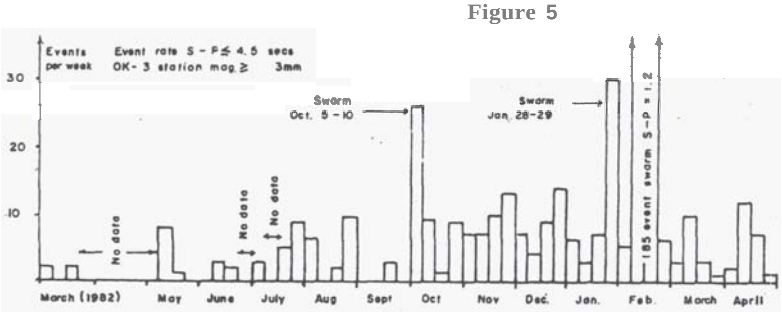
day of injection rate increases, for example on June 34 and August 23.

In June, four additional seismometers were installed (fig. 2), to conduct an epicenter study. Blasting at the OK5 quarry site, involving 80 kg of dynamite, was detected by all 5 stations and a t/d plot (fig. 9) revealed a P-wave velocity of 3.7 km/s with no evidence of a layered velocity structure.

This enabled the computation of hypo-centers using a single-layer velocity model in an iterating computer program, "HYPO". When the arrival time data from the quarry blast was entered, the computed hypocenter was less than 0.2 km from its true location. A selection of well-recorded events, from the swarm, was then run through the program. The computed epicenters all lie within the Puhagan area. Depths are within the range -0.7 to -2.5 km (reduced level). Residuals are generally quite low (< 0.1 seconds), but the epicenter locations are sensitive to the velocity chosen. Since the OK5 calibration blast was at 1 km elevation, it may not give reliable velocities for depths below about -1 km, so it is quite possible that the P-waves from these Puhagan events are travelling at velocities greater than 3.7 km/s. In many instances, changing the velocity from 3.7 to 5 km/s, for example, moves the epicenter about 2 km. For this reason, it is not possible, at present, to locate hypocenters with sufficient confidence to be able to ascribe them to particular wells or faults. However, they all lie close to the producing and reinjecting wells at Puhagan. Further work is planned to refine the velocity model and determine the hypocenters with better precision. To assist in velocity modelling other physical properties of subsurface formations can be used. For example, within the Okoy geothermal field there is little contrast in average density between formations (2.7 to 2.75), suggesting that velocities are relatively uniform. However, a few cores below -2 km show variable, but higher, densities, averaging 2.9 gm/cc. Using an empirically derived formula relating density and velocity: $\Delta V$(km/s) = 3 x $\Delta D$ (gm/cc) (Birch's law), this suggests a small increase in velocity below this depth. Another empirically derived formula relating resistivity and velocity may also be useful: $V = 906\ (Z\ R)^{1/6}$. Choosing depth (Z) of 1 km and resistivity (R) of 5 $\Omega$ m, from sounding interpretations in the area, this results in a comparable velocity of 3.7 km/s. The Dauin area, to the

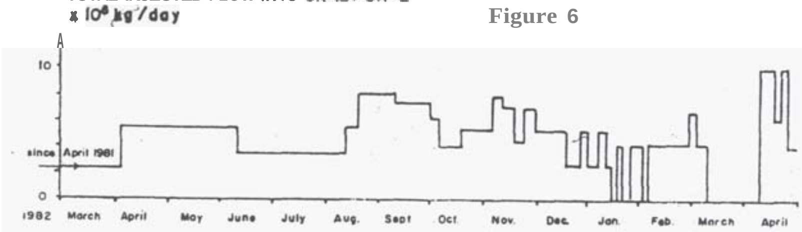
MICRO-SEISMIC MONITORING SNGP

Figure 5



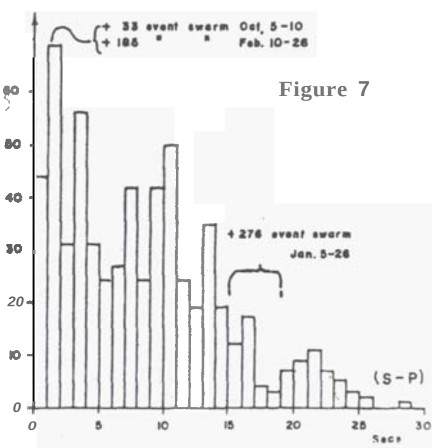

TOTAL INJECTED FLOW INTO OK-12 / OK-2
x 10⁶ kg/day

Figure 6




DISTRIBUTION OF (S-P) TIMES
March 1982 - March 1983

Figure 7



south, has lower average density (2.55) suggesting a slight reduction in velocity. Further information to assist velocity modelling will result f— a program of acoustic velocity measurements of core samples.

An attempt has been made to calculate the b-slope for this Puhagan earthquake swarm from the log frequency/magnitude relationship of Gutenburg and Richter: Log N = a-bM. Magnitudes were estimated from the coda lengths of 2832 earthquakes (durations in seconds) using the relationship: M = 1.8 logT - 1 (Raleigh et al) from the injection induced earthquake swarm at Rangely, Colorado. Different authors use widely varying Magnitude/coda length relationships so it is planned to refine this equation using a set of USGS and PAGASA earthquake magnitudes of commonly recorded larger events. However, the frequency/magnitude plot, shown in figure 8, reveals an excellent straight line fit for magnitudes between 0.5 and 2.0. These 6 points on the histogram have been fitted by least squares linear regression to a line, With equation: log N = 3.21-1.27M, and a regression coefficient of 0.999. using the "maximum likelihood method" of calculation (Aki 1965), the bslope for all events greater than magnitude 0.5, is 1.42. Another equation relating magnitude to coda length is one used by Majer (1979) in The Geysers geothermal field, and also for swarms on the San Andreas fault: M = 2 logT - 0.87. When this is applied to the Puhagan swarm, the b value frun maximum likelihood estimate becomes 1.27. Worldwide values of 'b' for tectonic earthquake swarms usually vary between 0.6 and 0.8. High temperature geothermal areas and active volcanoes generally have much higher b valueg for example: the *Geysers* (1.2), Iceland's volcanic eruptions (3), Cerro Prieto geothermal field (1.25). Previous examples of injection-induced seismicity in non-geothermal areas (at Rangely, and Denver, Colorado) have b values typical of normal tectonic swarms (0.6 to 0.9).

In summary, then, the monitoring and epicenter studies at Southern Negros have *shown* a significant correlation between the onset of a large swarm of earthquakes in the Puhagan *area,* and major increases in production/reinjection flow-rates during power station commissioning. A P-wave velocity of 3.7 km/s has been determined fran surface blasting, and a velocity ratio Vp/Vs of 1.8, from Wadati diagrams which implies a Poisson's ratio of 0.27. Prior to this swarm, a background level of 5 events/week with (S-P) ≤ 4.5 seconds was recorded, which is similar to Tongonan, but a much larger percentage of the earthquake activity originated

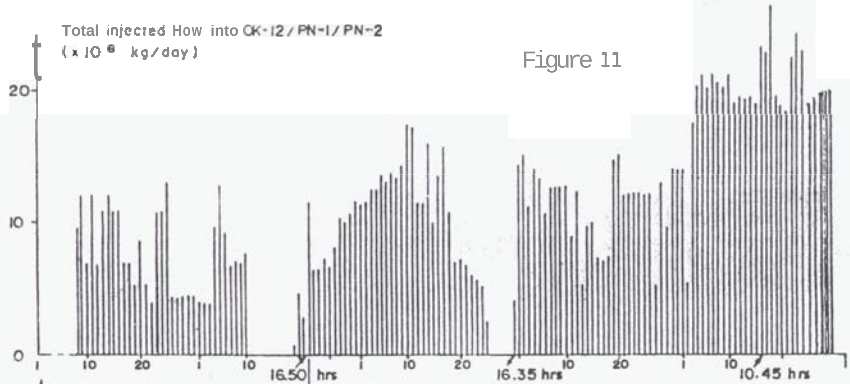



Figure 11

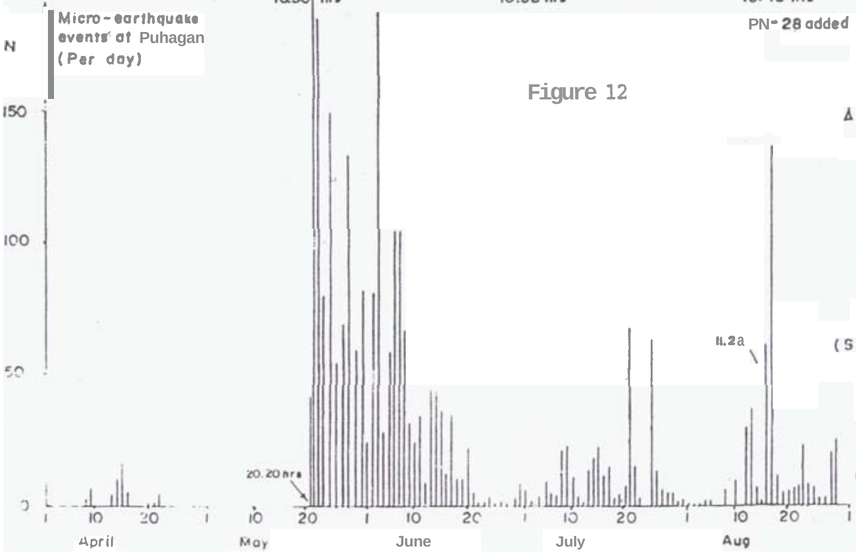



Figure 12

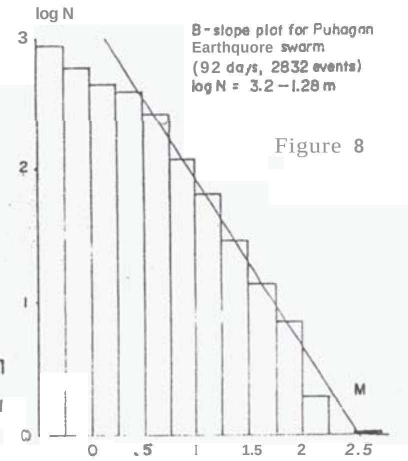



Figure 8

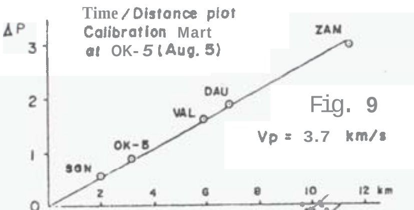



Fig. 9

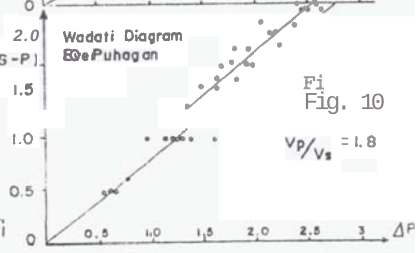



Fig. 10

fmn within the geothermal field. The high b-value for the Puhagan induced swarm suggests a low strength/low stress/high temperature formation. Possible mechanisms for the induced earthquakes include: (a) increased pore pressure along fractures in the reinjection area, which reduces effective normal stress across faults, and therefore frictional forces, and triggers failure; (b) gradual thermal contraction of rocks by cooler reinjection fluids, (or possibly by pressure/temperature drawdown around producing wells feeding from localized 2-phase zones), that opens fractures and also reduces the effective normal stress across them. Differential temperatures in excess of 100°C can be expected in the reinjection area, and up to 60° temperature drawdown has been measured in sane Puhagan wells under test production &-tions (although not in those wells initially supplying the power station). The preferred explanation is a combination of the two mechanisms, resulting from injection of separated fluids.

Although many of these Puhagan earthquakes have been felt locally (intensity 3 to 4 on the Modified Mercalli scale), the maximum magnitude detected to date is only about 2.6 (Richter scale), and return periods estimated fran extrapolation of the b-slope plot (with all its assumptions) are 18 years for magnitude 4, and 325 years for magnitude 5. This suggests that, even if the present high level of microseismic activity is maintained, assuming that there is no change to the b-value, thentheriskof a large magnitude earthquake, occurring within the lifetime of the plant (25 years), remains law. With the source-sink configuration of production and reinjection, and a net mass loss fran the system (the steam fraction going to the turbine), high pore pressures should be restricted to a small zone in the reinjection area, with perhaps a gradual pressure dissipation alcng the natural outflow path to the north-east. The present hydrological model for the reservoir suggests that this natural outflow path has been well traversed by geothermal fluids in the past (producing low resistivity, and a séries of hot springs down the Okoy Valley). These fluids have probably weakened the rock by hydrothermal alteration and reduced its capacity to store stress. Therefore earthquake swarms migrating down the outflow path will probably display the same high b-value in their frequency-magnitude distribution. As long as injection is main ——— therefore, there is no reason at present to believe that the relative frequency of earthquakes will change. However, in one case of injection induced seisnicity into a non-geothermal reservoir (Healy et al, 1968), a significant reduction in b-value (to 0.6) occurred after cessation of injection, which resulted in several large earthquakes of magnitude about 5. For this reason, it will be important to monitor the magnitude-frequency distribution of the Puhagan earthquakes to observe any trends with time.

## HARMONIC TREMOR

Several seismometers installed in Tongonan, and at OK3 in southern Negros, have recorded intermittent harmonic tremor with frequencies between 1.6 and 6 hz. These tremors arrive as individual pulses, regular streams of pulses, or continuous vibrations, with amplitudes up to 10 mm (amplification of 28,000), and are characterized by their emergent arrival, regular frequency, and smooth envelopes (fig. 13). Other noise sources such as wind vibrations (for example during a typhoon), passing vehicles, radio transmissions, bulldozers and footsteps, can easily be distinguished from the tremor.

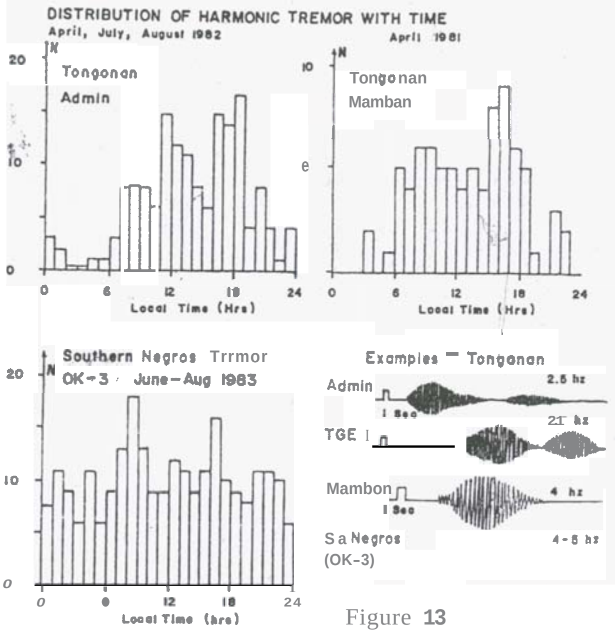



Figure 13

In Tongonan, the tremors were first detected in January 1981, and have been a regular feature of the Admin statim seismograms. Here, the frequency is consistent, at 2.5 ± 0.1 hz, and a histogram of the hourly distribution of their occurrence shows a strong correlation with daylight hours, which suggests that a significant proportion of the tremor is somehow stimulated by cultural sources. However, sane tremor episodes occur late at night and on non-working days when normal background cultural mise, with more variable frequency and amplitude, is negligible. Similar behaviour was observed at the TGE1 statim (2.15 km fran Admin in the Bao Valley). The same frequency (2.5 hz) and similar amplitudes were observed, but the arrival times of individual pulses were not consistent at the two stations. This suggests that the tremor source is localized and it's amplitude attenuates rapidly with distance. But the same type of mechanism appears to be responsible for the tremor at both sites. A high speed seismograph, installed at Mamban, which was relatively free from cultural noise, recorded harmonic tremor mainly during daylight hours with a frequency of 4 to 5 hz. At Well 403, in the Mahiao sector, which is also a quiet site, harmonic tremors with frequencies of 1.6, 2.5, and 6 hz were occasionally recorded at irregular intervals. Tremor was also observed at the project campsite, with a frequency of 4 to 5 hz, but not at Well 408 or Kabintan.

In Southern Negros, OK3 is the only station that has detected harmonic tremor. It was first observed in February 1983, but became more frequent from June. The frequencies vary from 3 to 5 hz and form pulses, chains of pulses, or continuous tremor for several hours. The histogram of occurrence time shows no significant correlation with daylight hours. Amplitudes vary, but the tremors are not observed at nearby stations, where Puhagan earthquakes with similar amplitudes (at OK3), are well recorded. This also suggests that the tremor source is very local, and attenuation is rapid.

A postulated mechanism for this phenomenon of localized harmonic tremor is the pressure driven outflow of geothermal fluids through near-surface fractures. Aki (1981) has described a mechanism for deep tremor observed at Hawaii, in terms of vibration of a crack, filled with magma, driven by excess magmatic pressure. In his stationary type model, the liquid filled cracks are constrained at lock points, which open under pressure and set off vibrations with a resonant frequency related to the length of the crack, and the acoustic velocity of the fluid medium. High frequency vibrations (25 hz to 15 hz) caused by fluid injection have also been observed during hydraulic fracturing experiments for the hot dry project in Los Alamos (Potter and Dennis 1974). It was suggested that the decreasing frequency related to an increasing length of the stimulated fracture. If this postulated mechanism is valid, the length of the constrained resonating fracture can be calculated using $2L = V.T$ where T is the period of oscillation, and V is the acoustic velocity in water (1.3 km/s at 200°C). Fracture lengths of 100 to 250 m are indicated. If the moving fluid is at temperatures close to the boiling point, then pressure changes during the vibration could induce periodic flashing and sudden expansion, which would contribute substantially to the amplitude of the resulting seismic tremor.

In Tongonan, geochemical evidence supports hydrological models that postulate large sub-surface outflows of geothermal fluid (Lovelock, 1982). Recent hydrothermal eruptions in the Bao Valley, near TGE1, convincingly demonstrate that this fluid (near the surface) is at temperatures close to boiling point for depth. A wide network of faults connects the Mahiao and Bao Valleys (fig. 1), and so a dynamic model of fluid movement along these structures, stimulating localized episodes of harmonic tremor, appears reasonable. However, the observed correlation of occurrence time with daylight hours, introduces some doubt into this explanation. At OK3, in Southern Negros, the tremor episodes are suggested to be related to the over-pressuring of the reinjection area with large volumes of fluid which may be forcing higher sub-surface flow-rates down the natural outflow path of the Okoy Valley, and thereby stimulating harmonic tremor within localized fractures.

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