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SEISMOLOGICAL INVESTIGATION OF CRACK FORMATION IN HYDRAULIC ROCK FRACTURING EXPERIMENTS AND IN NATURAL GEOTHERMAL ENVIRONMENTS

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ABSTRACT

We are developing a variety of new seismological methods for determining the structure of a geothermal energy source region. In one approach, we utilize seismic signals generated in the source region by interpreting them in terms of the parameters of a seismic source model. For example, using a fluid-filled tensile crack driven by excess pressure in fluid as a model of volcanic tremor, we derived formulas which relate seismic observations with model parameters, and applied the formulas successfully to an actual eruption in Kilauea, giving a new insight to the magma transport in a volcano. We continued our theoretical work on the diffraction of seismic waves by a crack and demonstrated that the size and location of a crack can be well determined by particle motion near the crack at various frequencies. We applied the method to Kilauea Iki and found the location of the magma lens in agreement with that estimated by another method.

We carried out an extensive field experiment in Kilauea Iki, with the cooperation of USGS and SANDIA, and revealed interesting properties of the magma reservoir by a multiple use of active, passive, conventional, and unconventional seismic methods. The self-contained, digital event recorder has been developed and successfully tested.

Scope of investigations

We are interested in developing effective seismic exploration methods for determining the structure of geothermal energy source regions, such as a magma reservoir and conduit in a volcano or a hydrofractured crack in a geothermal well.

One approach we have been taking is to determine physical parameters of a geothermal energy source region using seismic signals generated from there. We focused our attention on a model based on a fluid-filled crack under jerky extensions by excess fluid pressure. We completed an initial analysis by means of the finite-difference method for solving dynamic elasticity problems to find a relation between the observed spectrum of seismic signal and the model parameters. The relation was successfully applied to one of the best described case histories of volcanic tremor, which occurred during the October 5-6, 1963 Kilauea eruption. The result shed some new light on the mechanism of magma transport in the volcano. The preliminary result from application to seismic signals observed in a geothermal well also gives a reasonable estimate of the dimension of the hydrofractured crack.

Another approach we have taken is to use an artificial source such as a buried explosion and study the diffracted waves in the near-field and far-field of a structure upon which the primary waves are incident. This method is more reliable than passive ones because the seismic source is at our disposal. We have completed theoretical work on the diffraction of P waves incident upon dry and wet cracks. The result shows a strongly frequency dependent pattern of seismic motion around the crack which, if observed, can be used to determine the orientation and size of the crack. We applied the method to the seismic motion observed on the floor of Kilauea Iki crater due to P waves from a local earthquake outside Iki, and were able to define the location of the magma lens which agreed well with the determination by other methods.

In response to the recommendation of the SANDIA/USGS Magma workshop, March 1975, we planned and carried out an extensive field experiment in Kilauea Iki, with the cooperation of SANDIA and USGS, to test a variety of seismic exploration methods with the magma reservoir known to exist, using explosions and local earthquakes outside Iki as well as seismic events occurring in the crust of the Iki floor. The most important conclusion from this work is that the use of multiple methods (active, passive, conventional and unconventional) is essential for determining the seismic properties of complex structures encountered in exploration of geothermal energy sources.

Another field work was undertaken to apply the coda method (Aki and Chouet, 1975) to Hawaiian earthquakes for the purpose of finding the regional seismic attenuation property in a geothermal region. Comparison of the results with other regions in Japan and California showed an unusual depth dependence of Q under Hawaii; a relatively high Q at the shallow part of the lithosphere and low Q at the deep part.

In order to collect better quality data for both active and passive experiments, we have developed a completely self-contained, digital event-recorder using memory and control circuits. The system includes a precision clock, eliminating the need for a radio time-signal receiver. We have finished testing the function of the system and are going to carry out field work to collect records of volcanic tremor in Hawaii for more detailed study of the magma transport mechanism and those of teleseismic P waves in the Southern Cascade in order to gain experience in data collection for determining the 3-dimensional seismic velocity anomaly by the method of Aki, Christoffersson and Husebye (1976).

The principal investigator spent 10% of the 9 months academic year and 100% of one month in the summer for this project. He planned and carried out the field experiment at Kilauea Iki in March with 4 students, worked later on the interpretation of records obtained during the experiment and finished a paper on the seismic properties of the magma reservoir which was submitted to the Journal of Geophysical Research. He is finishing another paper on the seismic source modeling of volcanic tremor and vibration of a hydro-fractured crack, which will also be submitted to the Journal of Geophysical Research. He supervised M. Fehler's work on computational work on the diffraction problem, B. Chouet's Ph.D. thesis on the coda method, M. Bouchon's work on the synthetic seismogram for the Kilauea Iki refraction experiment, and P. Mattaboni's work on instrument development. He also participated in several panel meetings at LASL and SANDIA on the exploration of magma reservoirs and dry hot rock areas.

Seismic source mechanism of fluid-driven tensile crack: a model for vibration of a hydrofractured crack and volcanic tremor.

A fluid-filled tensile crack driven by the excess pressure ΔP in fluid can generate seismic waves by a succession of jerky extensions, if the fracture strength of rock varies strongly in space. For a crack with half-length ℓ, a jerky extension by $\Delta\ell$ is possible, if the fractional fluctuation ε of strength [critical stress intensity factor] satisfies the following inequality.

$$\frac{\varepsilon^2}{\Delta\ell} > \frac{0.8}{\ell}\left(\frac{P_o}{\Delta P}\right)^2 \quad \ldots \quad (1)$$

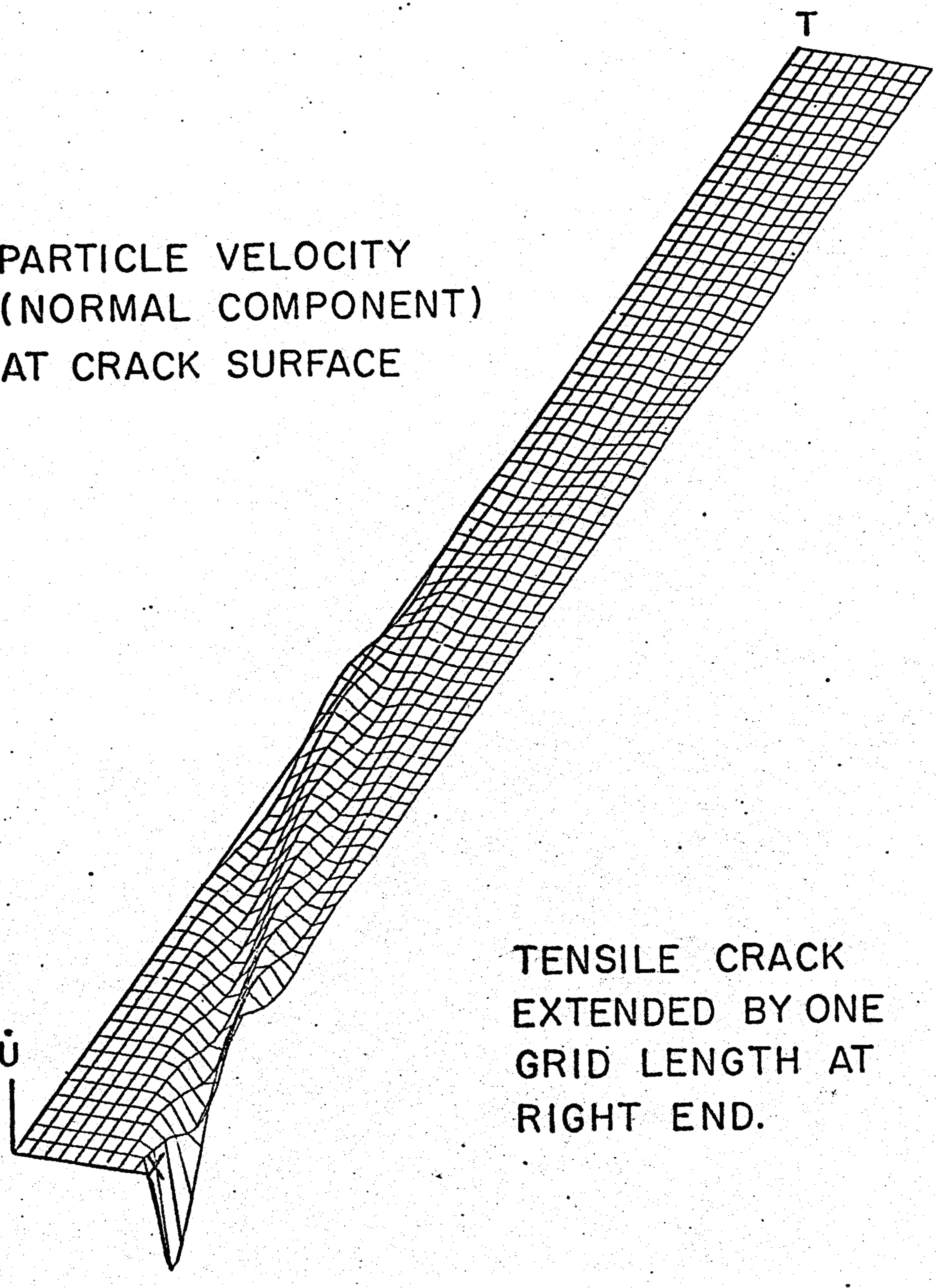
where P_o is the ambient lithostatic pressure.

Suppose that the condition (1) is satisfied and a jerky extension by $\Delta\ell$ occurs at one end of the crack with full length $L = 2\ell$. The particle velocity of the point on the crack surface is computed by a finite-difference method for a dry crack and a wet crack. The results for a dry crack and a wet crack are shown in Fig. 1 and 2 respectively, where the normal component particle velocity is plotted as a function of position x on the crack and time T. The effect of fluid dampens the vibration. The maximum displacement amplitude observed on the crack can be written as

$$V_{max} = C \frac{\Delta\ell\Delta P}{\mu} \quad . . . \quad (2)$$

where μ is rigidity, C is a constant which is about 0.1 for the case of extension at one end.

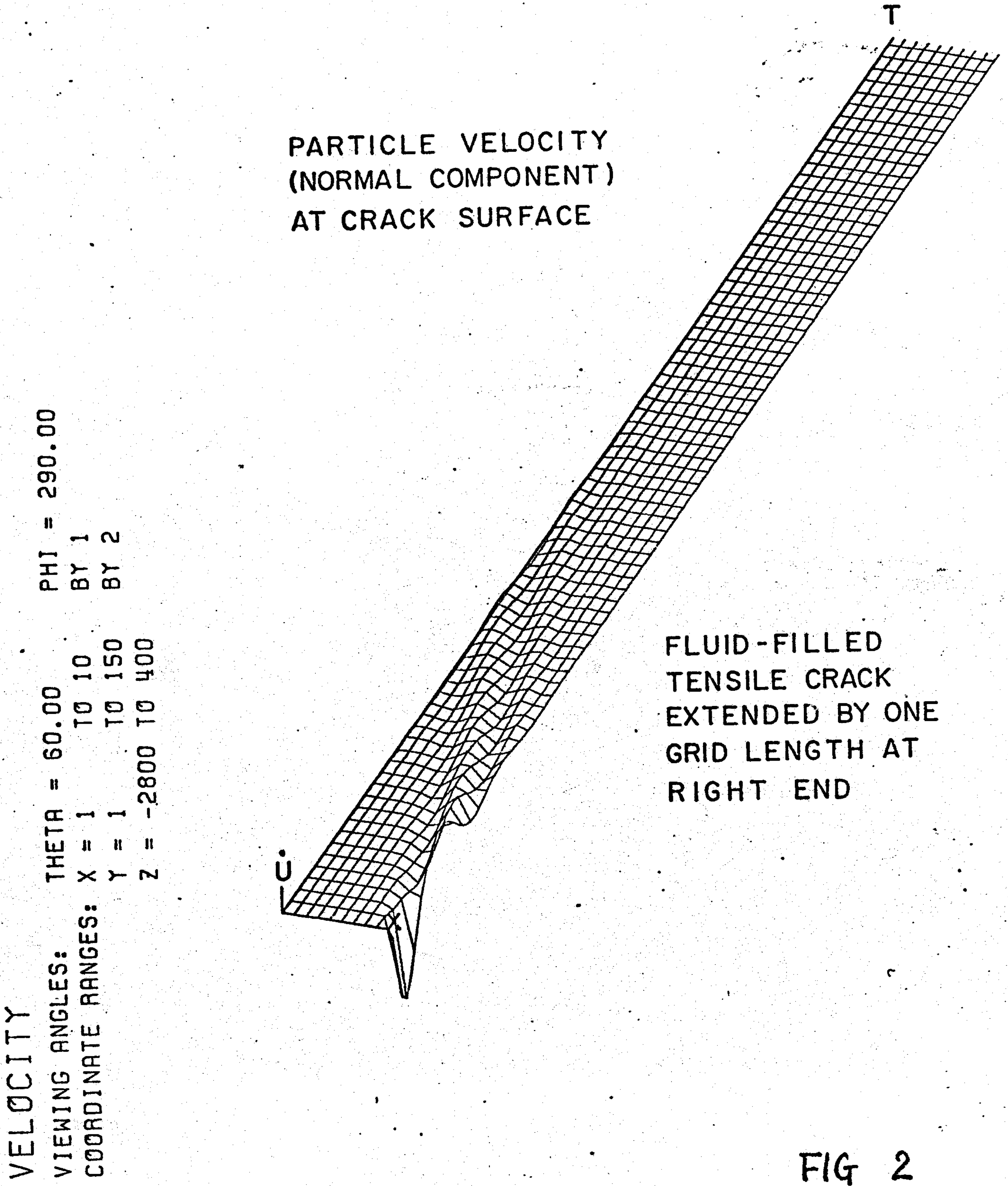
The far-field spectrum radiated to all directions from the jerky crack extension can be seen, at a glance, using the wave-number-frequency spectrum of particle velocity on the crack, as shown in Fig. 3 and 4 respectively for a dry crack and a wet crack. In these diagrams, the profile along $k = \omega\cos\gamma/c$ gives the far-field spectrum of waves with velocity c and radiation direction making an angle γ with the length of the crack. Surprisingly, we find that the main spectral peaks are outside the radiation region for P and S waves. A low-frequency peak present for the dry crack is wiped out in the wet crack. For a wet crack, the near-field is dominated by a peak with frequency about $0.9\ \beta/L$, where β is the shear velocity. The far-field peak for a wet crack occurs between $0.4 \sim 0.8\ \beta/L$ depending



PARTICLE VELOCITY
(NORMAL COMPONENT)
AT CRACK SURFACE

TENSILE CRACK
EXTENDED BY ONE
GRID LENGTH AT
RIGHT END.

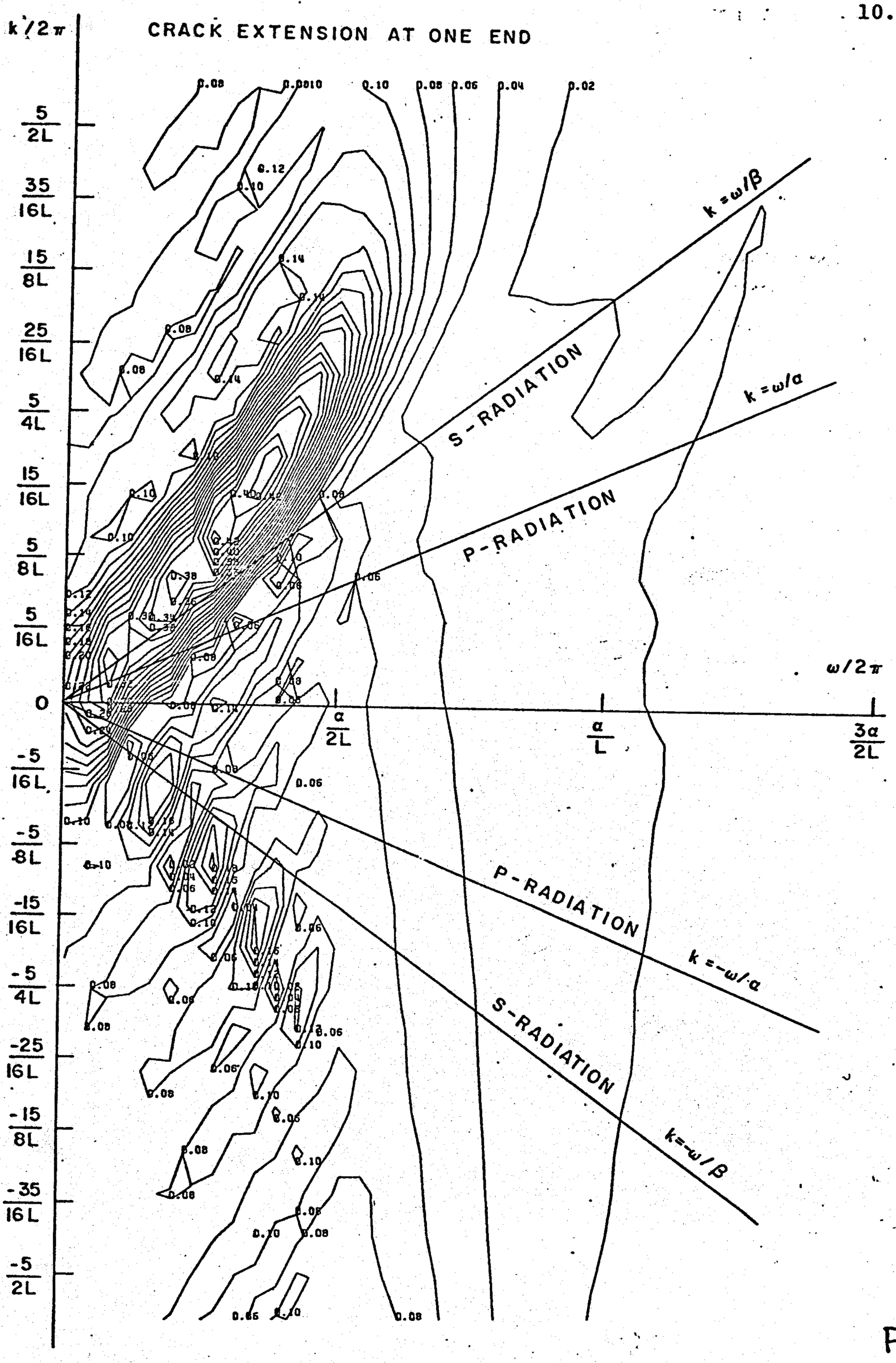
FIG 1



PARTICLE VELOCITY
(NORMAL COMPONENT)
AT CRACK SURFACE

FLUID-FILLED
TENSILE CRACK
EXTENDED BY ONE
GRID LENGTH AT
RIGHT END

FIG 2


CRACK EXTENSION AT ONE END
k/2π
ω/2π
5/2L
35/16L
15/8L
25/16L
5/4L
15/16L
5/8L
5/16L
0
-5/16L
-5/8L
-15/16L
-5/4L
-25/16L
-15/8L
-35/16L
-5/2L
α/2L
α/L
3α/2L
k=ω/β
k=ω/α
k=-ω/α
k=-ω/β
S-RADIATION
P-RADIATION
P-RADIATION
S-RADIATION
0.08
0.0810
0.10
0.08
0.06
0.04
0.02
0.12
0.10
0.14
0.14
0.08
0.08
0.14
0.10
0.10
0.10
0.40
0.42
0.06
0.38
0.36
0.30
0.34
0.38
0.06
0.08
0.06
0.12
0.14
0.16
0.18
0.20
0.08
0.06
0.26
0.24
0.14
0.06
0.08
0.06
0.10
0.08
0.10
0.08
0.06
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0.06
0.08
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0.06
0.10
0.08

FIG 3

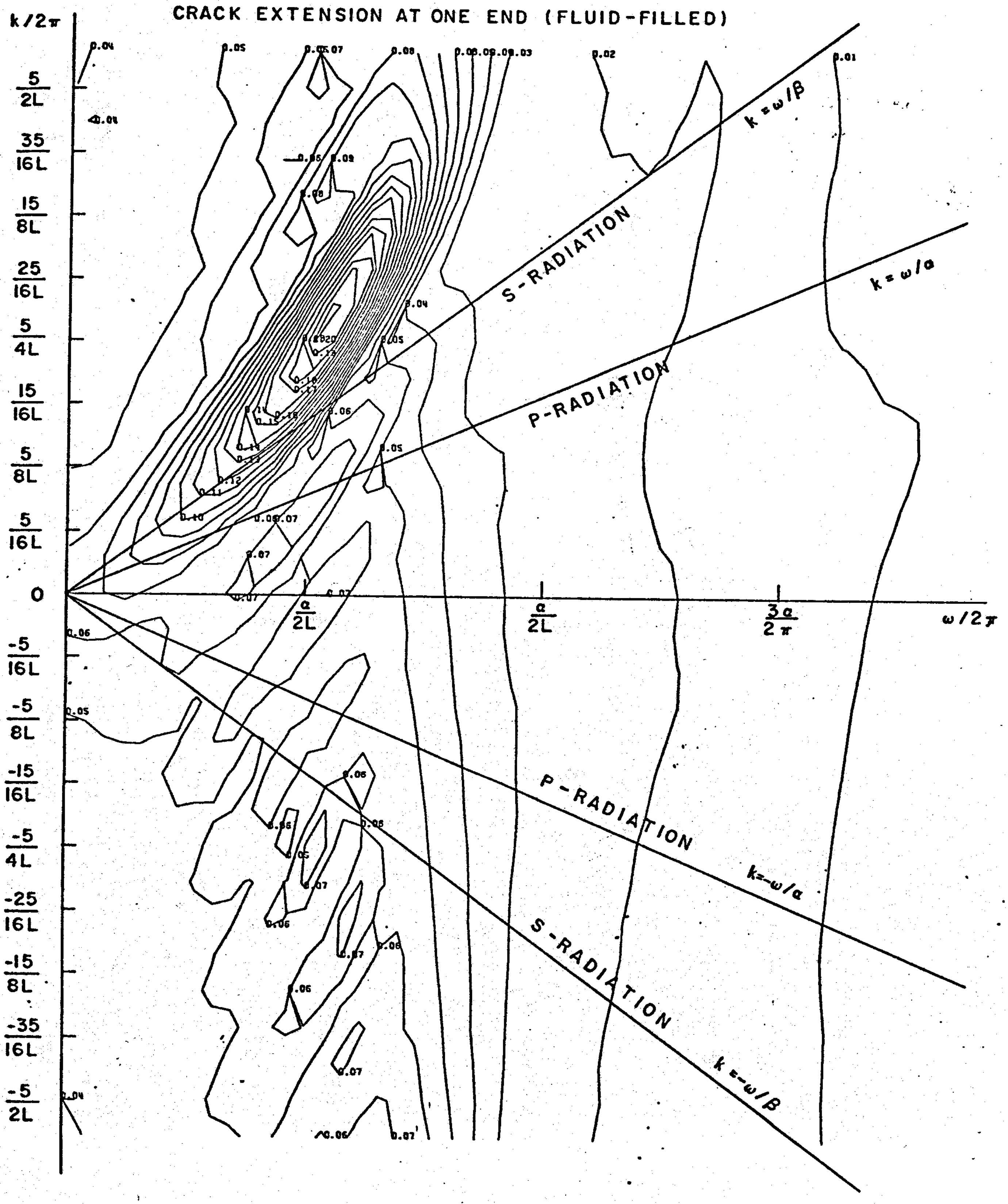

CRACK EXTENSION AT ONE END (FLUID-FILLED)

FIG 4

on radiation direction.

We, then, construct a model of continuous vibration by assuming a randomly occurring jerky extension at a constant rate n per sec. The root-mean-square amplitude of P and S waves can then be expressed as

$$\mathrm{RMS}(U^P) \simeq (4\pi\rho\alpha^3 r_o)^{-1} \frac{(\lambda+2\mu\ \cos^2\theta)}{\mu} C'L\Delta P\Delta S \sqrt{n\Delta f}$$

$$\mathrm{RMS}(U^S) \simeq (4\pi\beta r_o)^{-1} \frac{\sin 2\theta}{\mu} C'L\Delta P\Delta S \sqrt{n\Delta f} \qquad \ldots \qquad (3)$$

where r_o is the distance between source and receiver, α is compressional velocity, C density, λ,μ elastic constants, θ angle between radiation direction and normal to the crack, ΔS, incremental area for each jerky extension, and Δf, bandwidth of recorder. C' is a constant which is about 0.1 for peaks in the frequency range $0.4 \sim 0.8\ \beta/L$ in the case of a wet crack. A similar formula was obtained for surface waves.

We applied the above formulas to the volcanic tremor observations for the October 5-6, 1963 Kilauea eruption described by Shimozuru, et al.(1966) and Moore and Koyanagi (1969). Using the amplitude and spectral peak of volcanic tremor as well as the amount of magma transport estimated from geodetic observations, we arrived at the following mechanism of magma transport. Magma is transported through many cracks with length 1∿2 km undergoing jerky extensions independently. Jerky extensions of these cracks are caused by excess magma pressure around 20 bars at the total rate of one extension per sec. The increment in each extension is about $10^3 m^2$. If the depth of the crack is 1 km, the crack tip advances by 1 m in each extension.

The formulas obtained in this work should be useful for determining the parameters of a hydrofractured crack, if seismic data are available during the period of fluid injection.

Study of diffraction of plane P waves by a finite crack with application to location of a magma lens.

Before an interpretation of seismograms from an active experiment succeeds in determining the size, orientation and location of an underground crack, theoretical problems of the seismic diffraction by a crack must be solved. We have completed the study of diffraction of plane P waves by a finite 2 dimensional dry crack using the finite difference scheme developed by Madariaga (1976). The computer program has been satisfactorily tested against problems with known solutions.

The results are shown in Fig. 5 through Fig. 11 for two different directions of incident waves and various

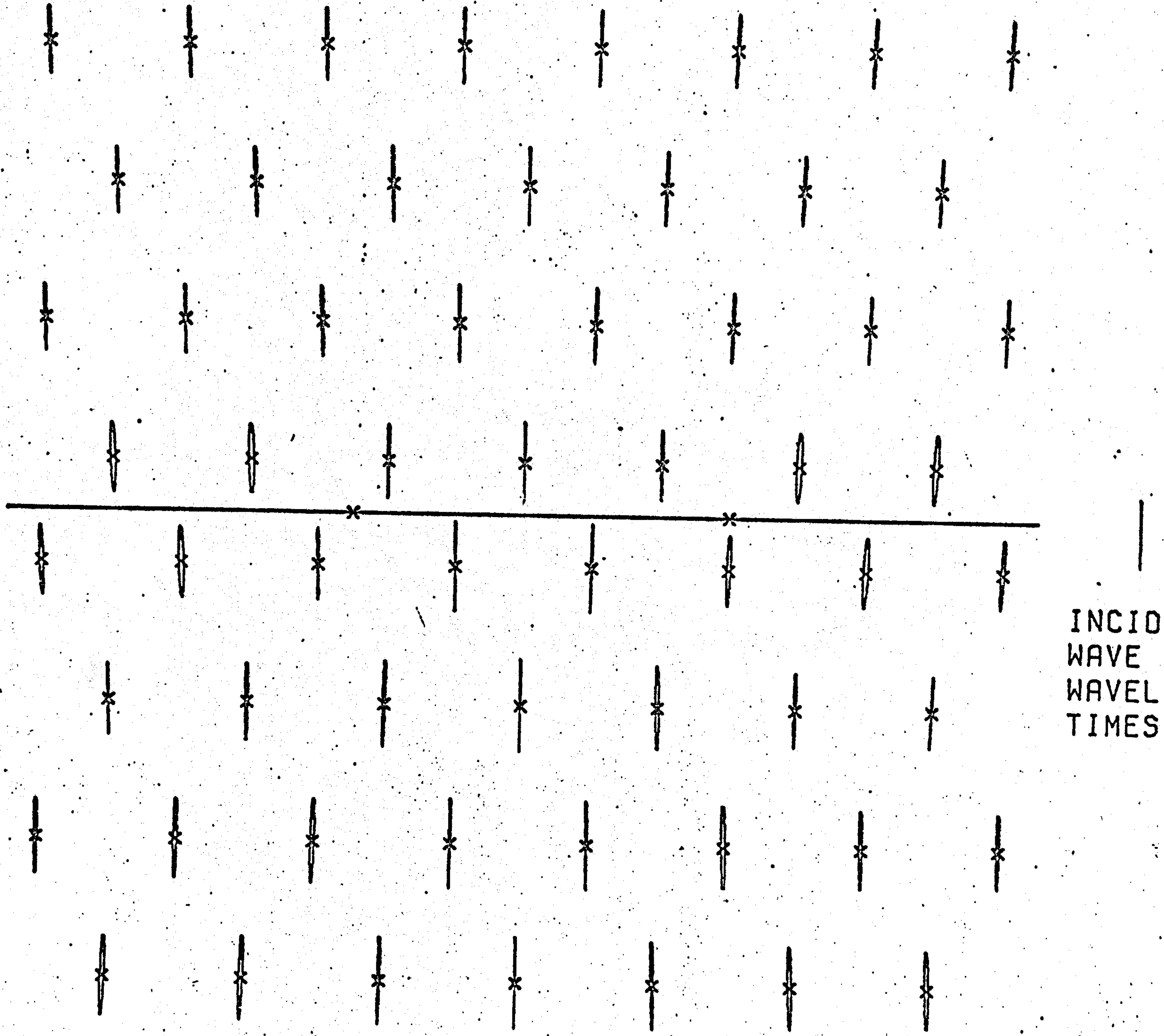
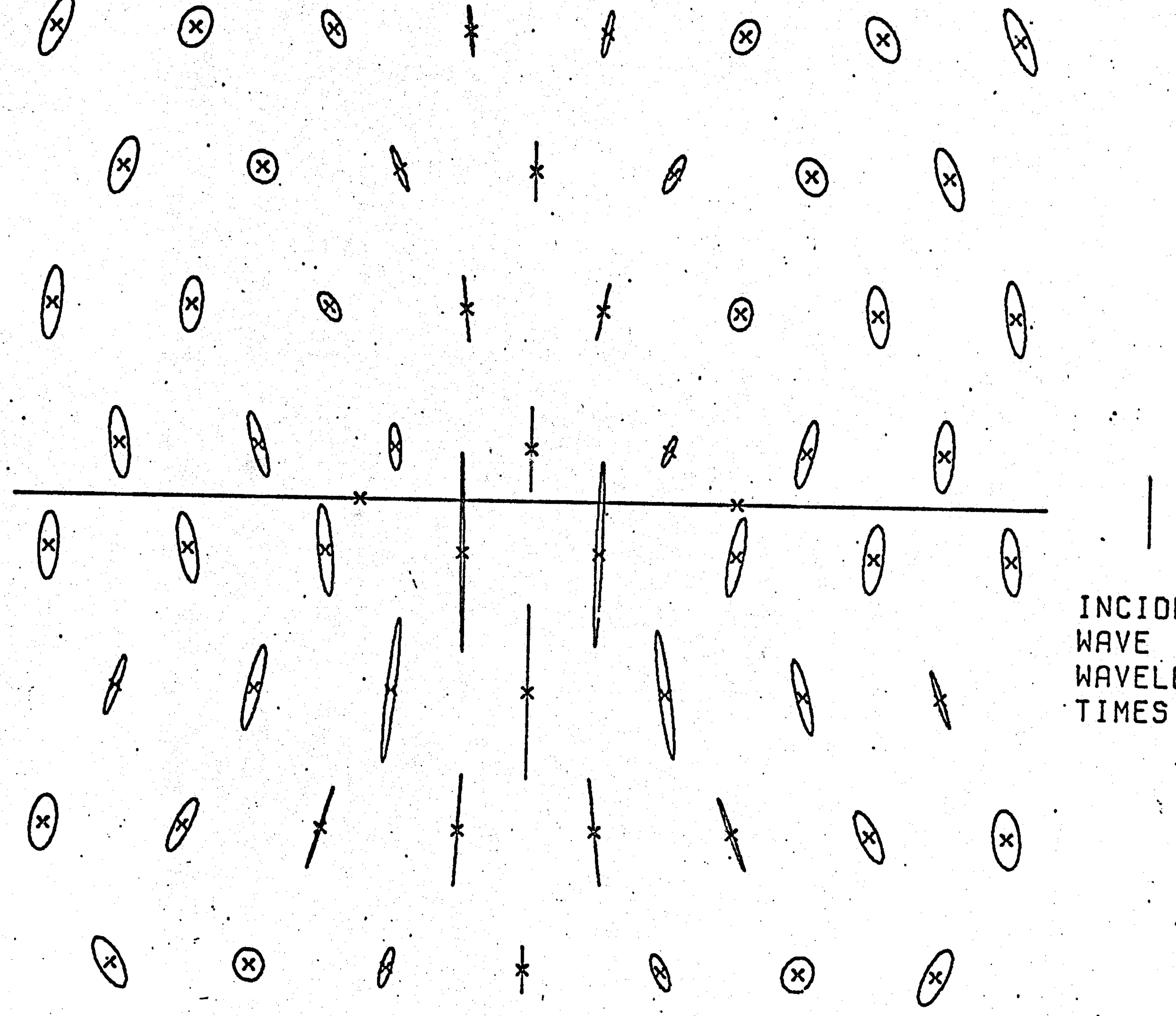


FIG 5



INCIDENT
WAVE
WAVELENGTH = 4.65
TIMES CRACKLENGTH

FIG 6

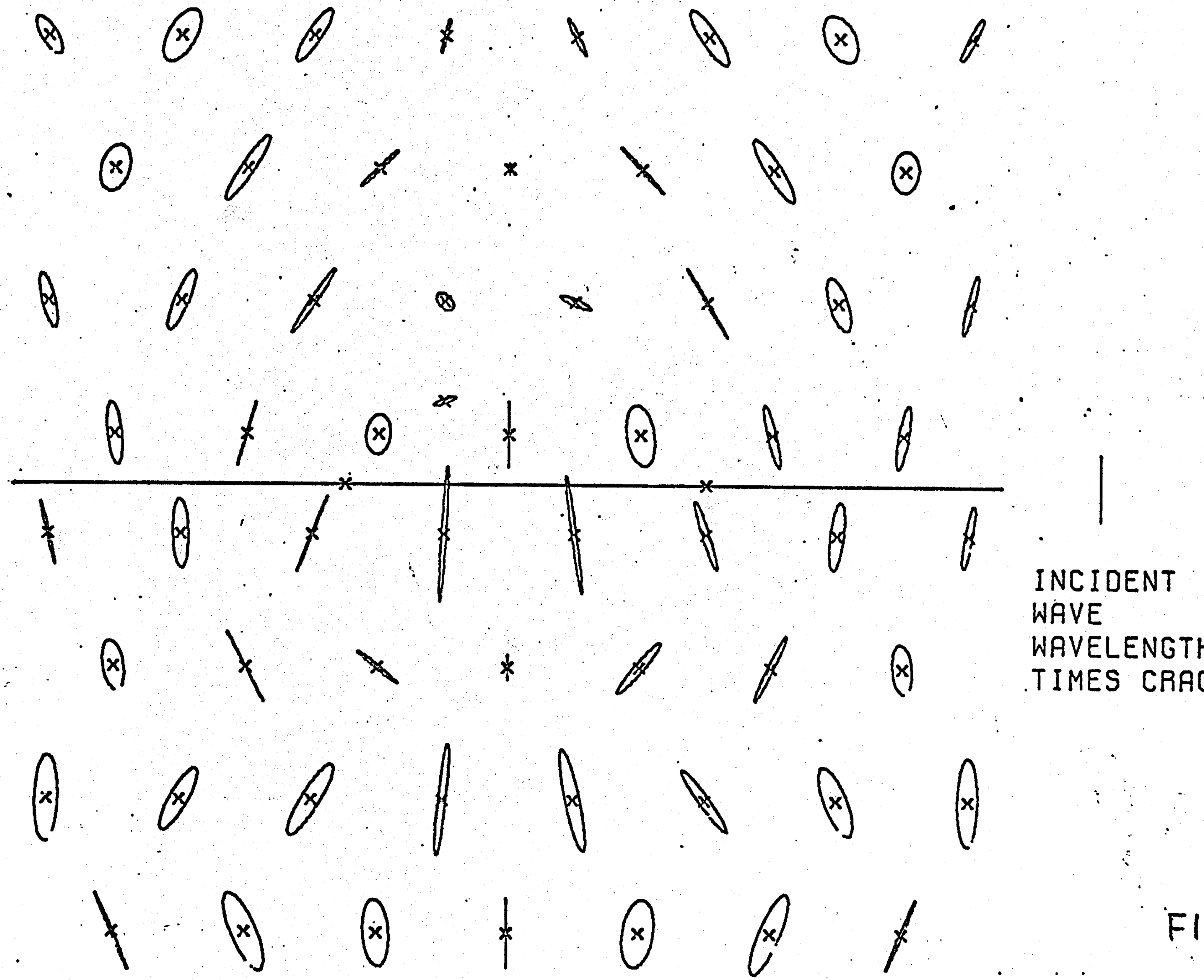


FIG 7

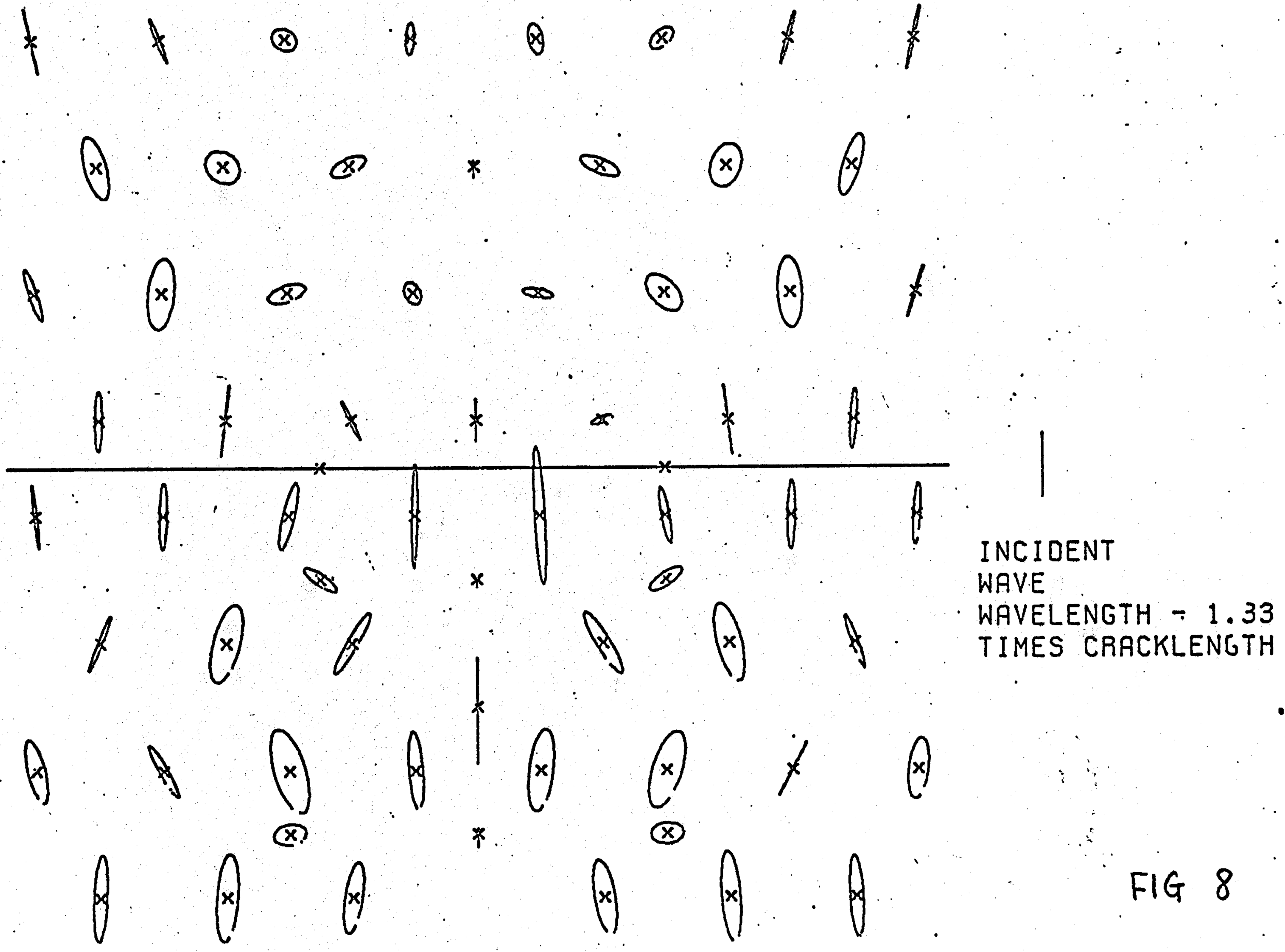


FIG 8

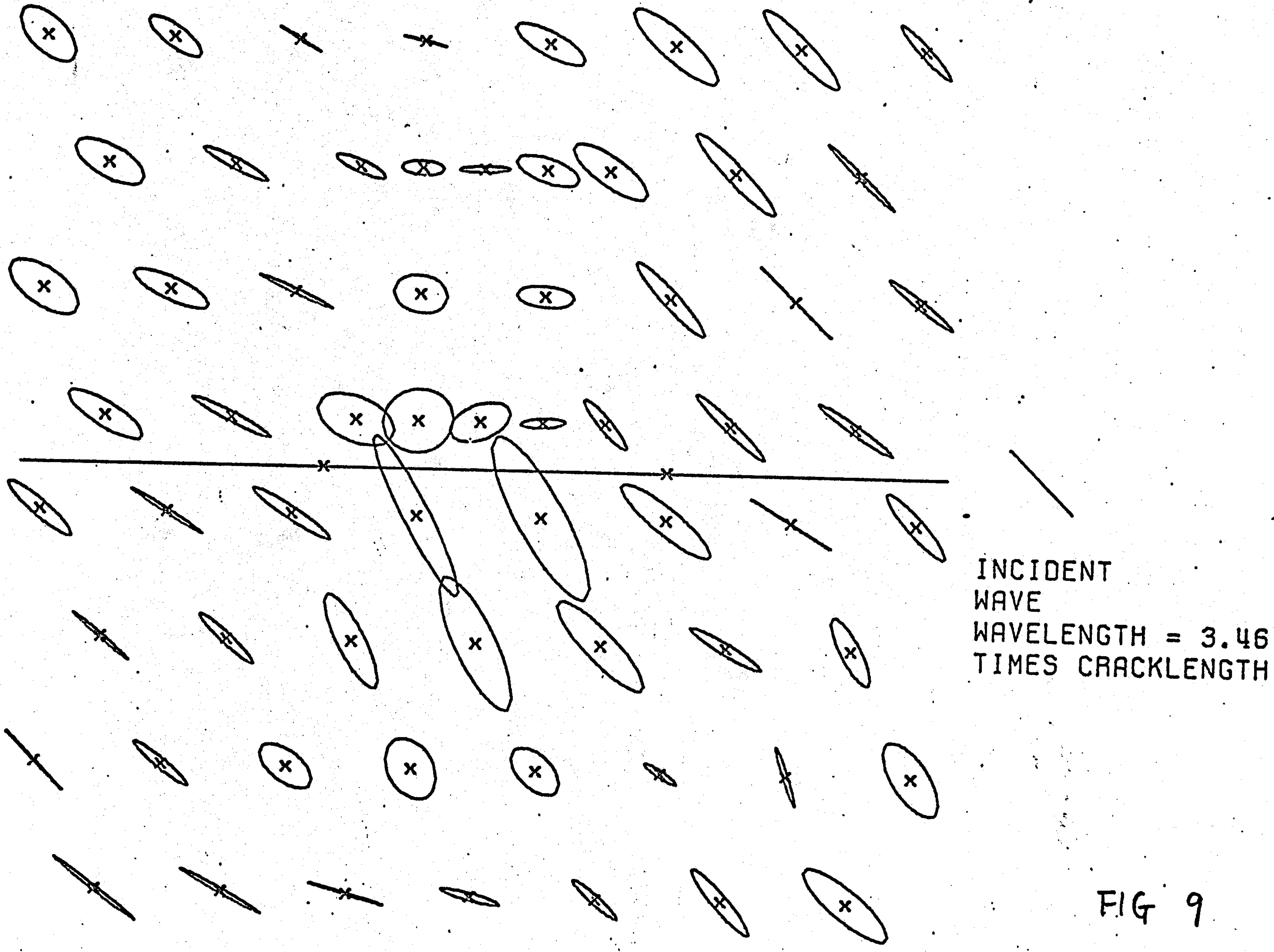
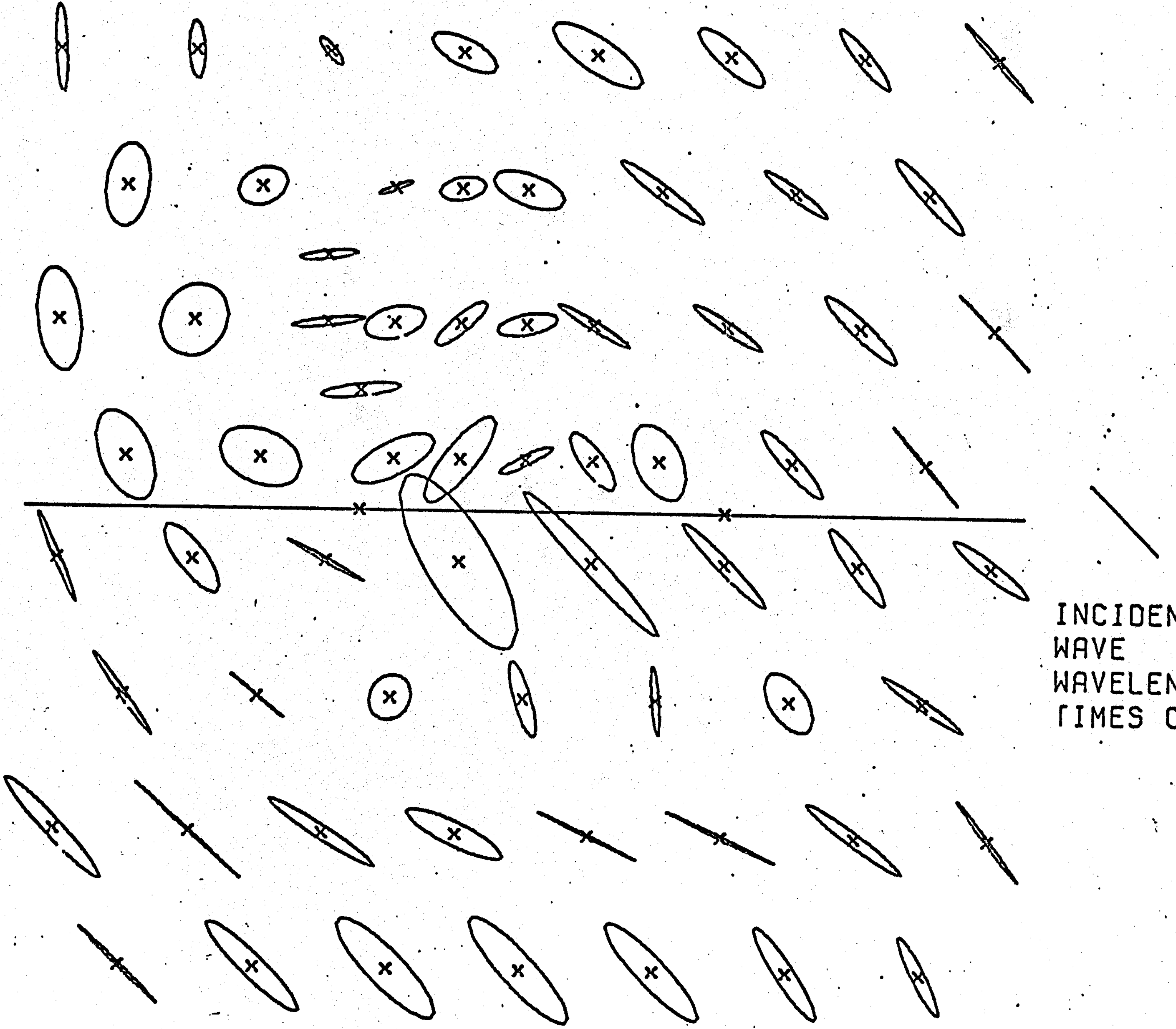
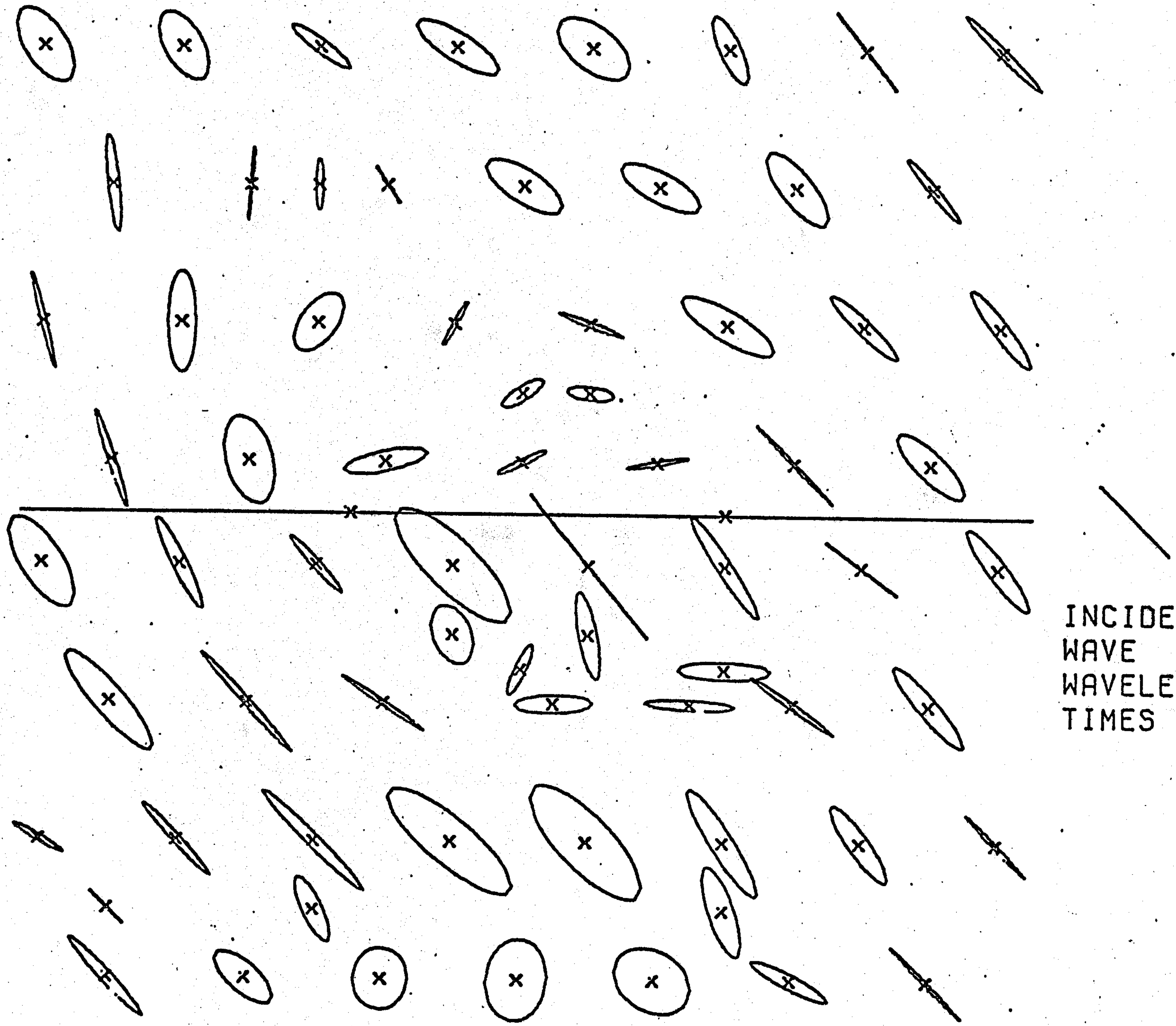


FIG 9



INCIDENT
WAVE
WAVELENGTH = 2.27
TIMES CRACKLENGTH

FIG 10



INCIDENT
WAVE
WAVELENGTH = 1.69
TIMES CRACKLENGTH

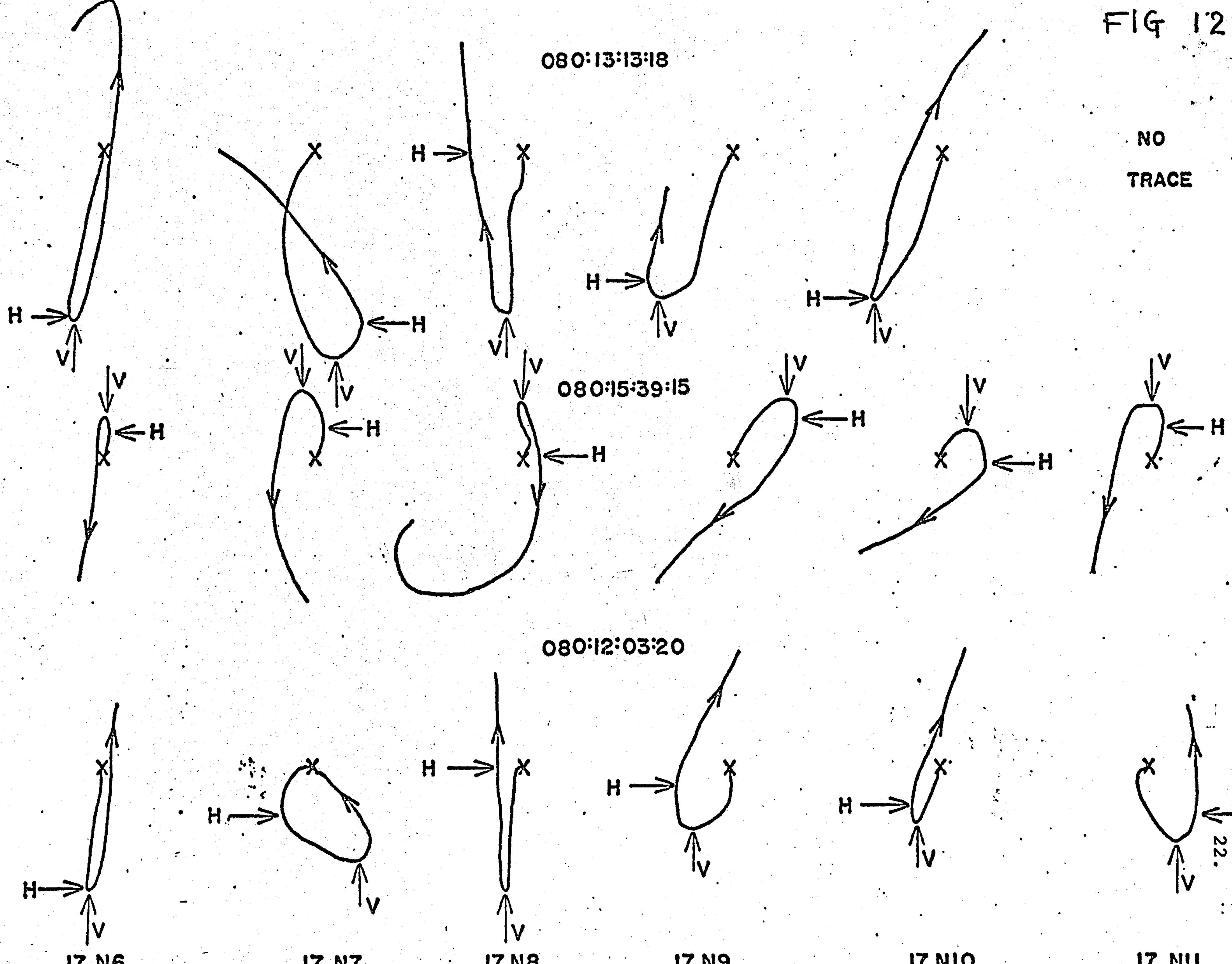
FIG 11

incident wave-lengths. The direction of incident wave, and the particle motion in the absence of the crack is indicated on the right of each figure. These figures show the total particle motion at points surrounding the crack. The crack is located between two crosses in the horizontal line at the center of each figure.

It is found that the crack has little effect on particle motion for incident waves with wave-lengths greater than 10 times the crack-length. For wave lengths less than 5 times the crack length we see a complex diffraction pattern. The amplitude and phase of both components of motion are affected by the crack. For wave-lengths less than two times the crack length there is a region of reduced amplitude (shadow zone) behind the crack. The relative phase of two components of particle motion varies rapidly with position inside the shadow zone.

The results of theoretical calculation are used to locate the edge of a magma lens in Kilauea Iki crater. Fig. 12 shows the particle motion observed at sites 17N6 through 17N11 (see Fig. 13 for map of stations) due to P waves from three local earthquakes outside Iki. We found that the ratio of vertical to horizontal displacement amplitude and the direction of rotation of particle motion vary along the array in such a way as expected from our theoretical result if

FIG 12


080:13:13:18
NO TRACE
080:15:39:15
080:12:03:20
H
V
X
17 N6
17 N7
17 N8
17 N9
17 N10
17 N11

there is a crack tip located near 17N9. This location agrees with the boundary between an area with high activity of small seismic events presumably caused by cooling of magma and an area with very little seismicity, presumably completely frozen.

We are currently extending the computation to the case of wet cracks. These results should be useful for defining a hydrofractured crack if the data from active experiments are available. This is the best way to define the crack in case no seismic events were occurring around the crack such as used by J. Albright (1976) in mapping the LASL geothermal crack. M. Fehler, a graduate student who did the calculation of diffraction problem, has been spending most of the summer at LASL working on the seismic data from LASL geothermal wells.

Seismic properties of a shallow magma reservoir in Kilauea Iki by active and passive experiments.

Since the paper on this subject is submitted to the Journal of Geophysical Research and a preprint copy was forwarded to the Contracts Management Office, we shall here briefly summarize the main results.

Eruptions in Kilauea volcano, Hawaii produced accessible, stagnant lava ponds in several pit craters, which provide an excellent laboratory for studying the mechanisms by which lavas cool, crystallize, and differentiate.

No systematic geophysical studies have, however, yet been made of the internal structure of these lava ponds. Kilauea Iki, in particular, is known to have a magma body under the crust as confirmed by recent drilling conducted by the U. S. Geological Survey. It also offers an unprecedented opportunity for testing any geophysical method for exploring a magma chamber in the earth. We undertook a seismic experiment with Kilauea Iki as a part of a comprehensive geophysical experiment being organized in response to the recommendation of the SANDIA-USGS magma workshop, March 6, 1975.

A preliminary experiment made in August 1975 by B. Chouet revealed a high activity of seismic events occurring beneath the floor of Iki. A seismograph located near the center of the lake recorded about one hundred events per hour. In March 1976, both active and passive experiments were carried out using 13 seismic channels with various combinations of vertical and horizontal seismographs. In the active experiment, in addition to the usual P-refraction survey, we studied the propagation of SH and Love waves. The map of shot points and seismograph sites is given in Fig. 13. In the passive experiment, we studied not only the events occurring within the Iki crater, but also seismic signals propagated through the magma body from the earthquakes outside Iki. Fortunately, the outside seismicity was high enough for such an experiment

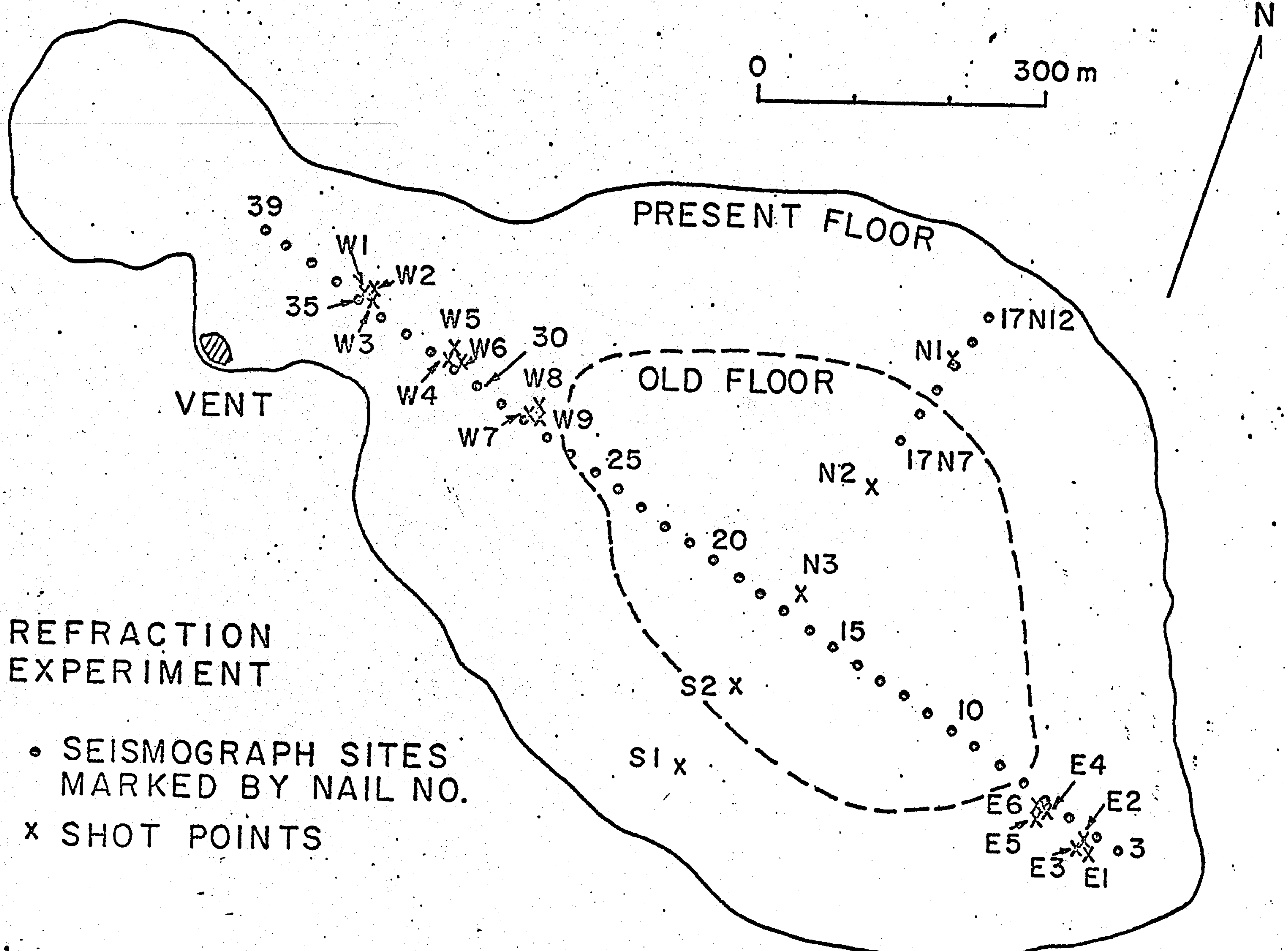

N
0
300 m
PRESENT FLOOR
OLD FLOOR
VENT
39
W1
W2
35
W3
W5
W6
30
W4
W8
W7
W9
25
20
N3
15
S2
10
S1
17N12
N1
17N7
N2
E4
E2
E6
E5
E3
E1
3
REFRACTION EXPERIMENT
∘ SEISMOGRAPH SITES MARKED BY NAIL NO.
x SHOT POINTS

FIG 13

particularly because of the activity following the Kalapana earthquake (M=7.2) of November 29, 1975.

The results obtained are very intriguing. Both P wave travel time and Love wave dispersion data require a low velocity body under the crust of Iki. The interpretation of P wave observation was made by a new exact synthesis method for a layered medium recently developed by M. Bouchon. The lateral extent of this low velocity body agrees well with the area of high activity of seismic events in the crust. The most surprising observation is 9 Hz SH waves clearly recorded at the center of Iki's floor from an outside earthquake. This may be explained by the Bingham body theory of Shaw et al. (1968) who found a finite yield strength for magma in the Makaopuhi lava lake by an in-situ viscosity measurement. The stress associated with our seismic signal is comparable to the yield strength measured by them. As suggested by Shaw et al., vesicles (bubbles) in magma may be responsible for the non-Newtonian behavior. The presence of vesicles also reduces the compressibility of magma drastically, and helps to explain the extremely low P-velocity under the crust of Iki inferred from the refraction data. From the dispersion of Love waves, we find, for a given thickness of magma lens, the apparent shear velocity and consequently the apparent viscosity of magma. Then, the transmission of 9 Hz S-waves imposes an additional constraint on the relation between the thickness and viscosity. From Love and S-wave data, we infer a rather thin (less than 10 meters) magma lens with viscosity around 10^7 poise and corresponding shear velocity about 0.2 km/sec. The presence of vesicles of a few volume percent in the melt can reduce the apparent bulk modulus to as low as the apparent rigidity inferred from the Love and S-wave data. The P-velocity of about 0.3 km/sec is possible in the melt of apparent viscosity 10^7 poise with 5% vesicles. The observed refraction data further require the P-velocity in the lower crust to be about 0.9 km/sec. Such a low velocity may be possible if the cracks in the lower crust are kept open by pressurized gas or water vapor trapped by the overlying magma lens. Because of gas pressure in the crack, the cracked solid behaves as if it were at zero effective pressure. In fact, we found the P-velocity around 0.9 km/sec at the top of the upper crust in the most severely cracked part of Iki.

Our experiment demonstrates the importance of multiple approaches in seismic studies of a complex structure like a partially frozen lava lake. The seismic events within Iki gave the most detailed information on the lateral extent of the magma lens. The dispersion of Love waves played an important role in defining the low velocity body because we could not use high-frequency body waves which suffered strong attenuation and scattering in the severely cracked crust. The SH waves from an earthquake outside Iki provided important information on the physical property of the magma body. All these results point out that the study of such a complex structure requires both active and passive seismic experiments using conventional and unconventional techniques.

Development and testing of self-contained digital event-recorder.

In the revised proposal dated 15 December, 1975, we stated that we planned to complete 4 seismograph systems and the playback system before the summer, and carry out the testing during the summer. We have completed one seismograph system and the playback system as shown in Fig. 14 and 15. Fig. 14 shows the seismometer and preamplifier in the left front, and the upper part of the tape recorder and electronics assembly is exposed from a waterproof container. In the field, the container is buried in the ground, and the maintenance check is made in the half-exposed setting by the use of a suitcase packed playback unit shown on the right of Fig. 14. It contains digital playback electronics, a strip chart recorder, a master clock and other elements for checking the operation of a seismograph system.

Fig. 15 shows the exposed interior of the event-recorder. It contains the tape recorder, precision oscillator, amplifier,

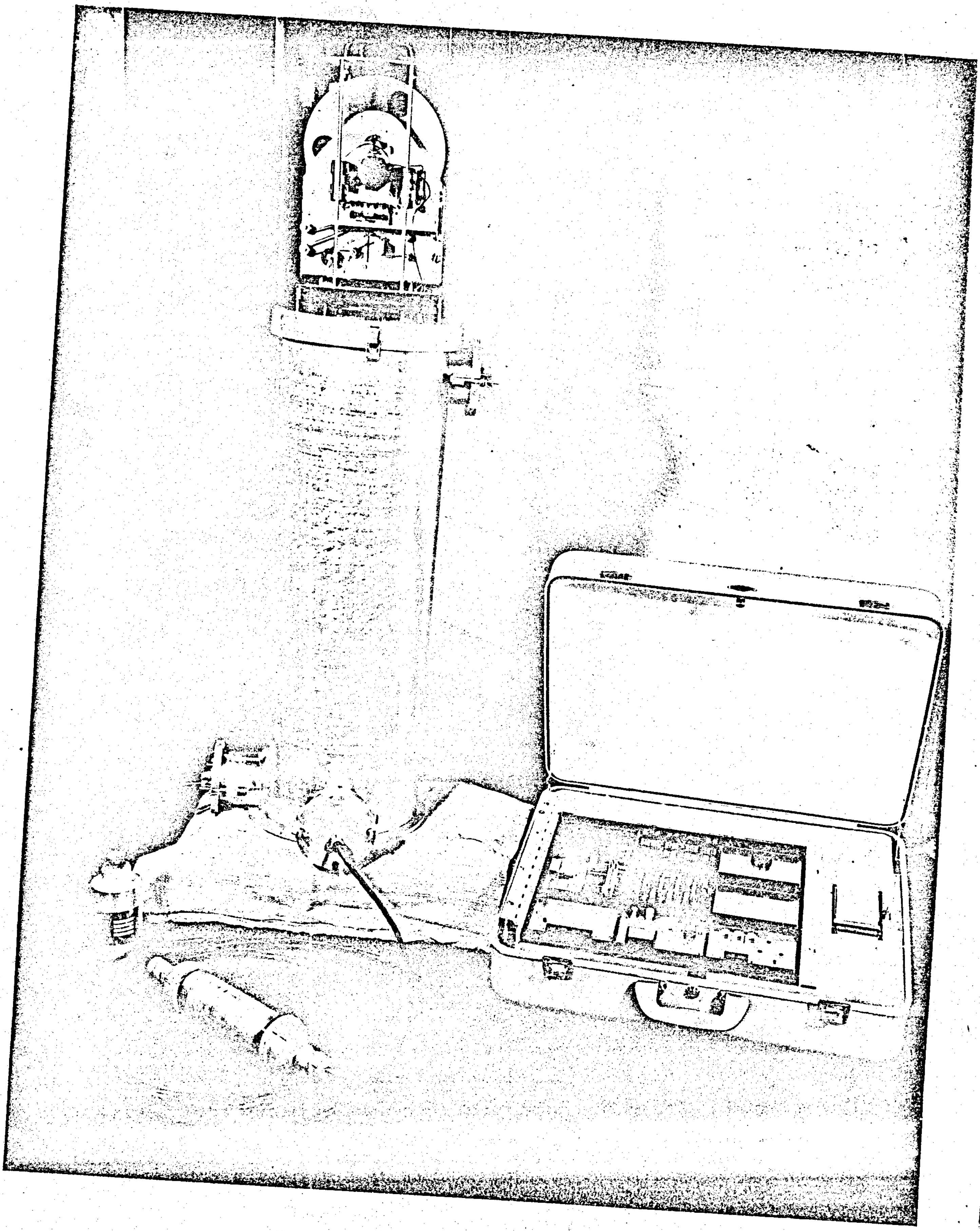


FIG 14

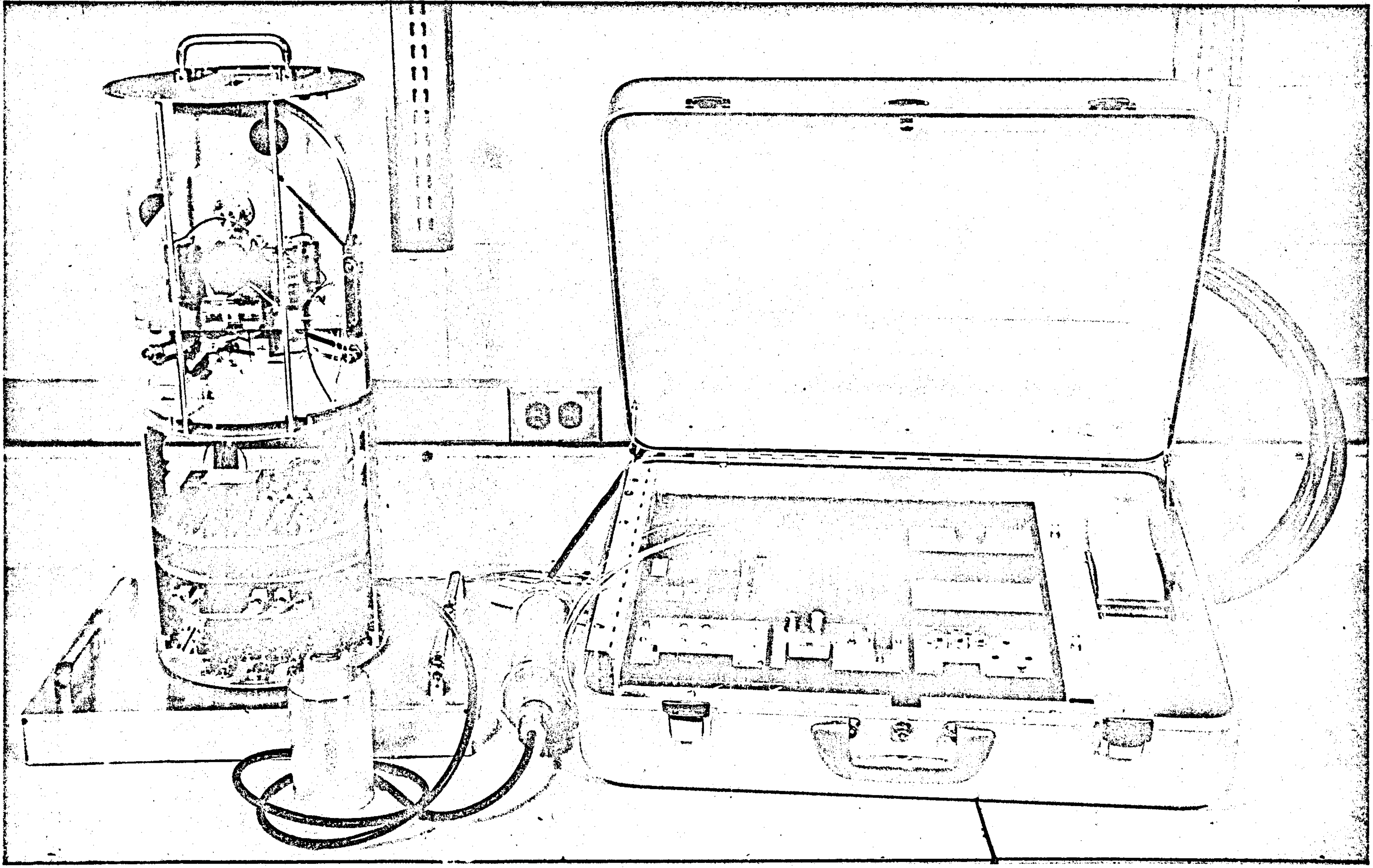
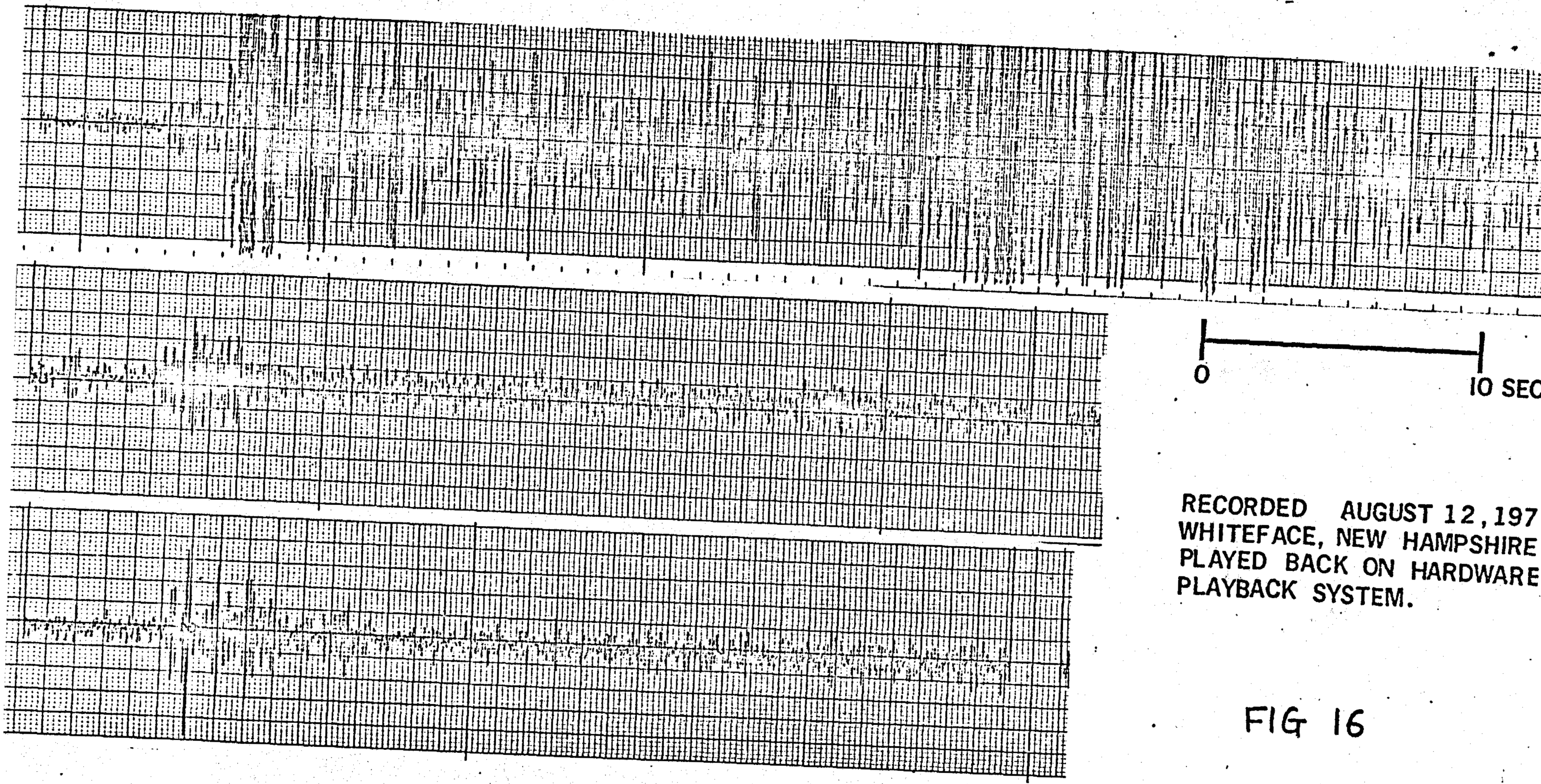


FIG 15

A to D converter, digital memory and control circuit.

We have tested the system successfully at our Wallace Geophysical Observatory. Fig. 16 shows sample records of seismic events (presumably quarry blasts) obtained by the system.

We are going to carry out field experiments to collect volcanic tremor data from Hawaii and teleseismic P wave data from Cascade before the end of this year. Unfortunately, because of unexpected delays in delivery of certain items, the completion of the planned additional three seismograph systems will be near the end of this year, so that the field experiments during the current year will be done with one system. Since the purpose of the field experiment during the current year is primarily to test the functioning of the event-recorder, the reduced number of seismographs does not seriously impair our original plan.



RECORDED AUGUST 12,197
WHITEFACE, NEW HAMPSHIRE
PLAYED BACK ON HARDWARE
PLAYBACK SYSTEM.

FIG 16

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