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TITLE FORMATION STRENGTH PARAMETERS FROM ACOUSTIC AND DENSITY LOGS IN EMPLACEMENT HOLES

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ABSTRACT

A new acoustic tool for dry emplacement holes has been built and tested in several emplacement holes. This tool uses a large hammer source and 3 piezo-electric transducers that are independently pressed against the borehole wall. The detectors are 6, 9 and 12 ft from the hammer source. A pure gel is injected between these detectors and the borehole wall to eliminate any air space. The compressional wave travel time and the shear wave travel time are recorded at each detector. The compressional wave velocity (V_p) and the shear wave velocity (V_s) are calculated from the travel time differences between the 3 detectors and their separations of 3 and 6 ft.These velocity values along with the bulk density obtained from the density log are used to calculate the Elastic Constants of Young's Modules, Bulk Modules, Shear Modules and Poisson's Ratio. These elastic moduli compared favorably to some core derived elastic moduli obtained from emplacement hole U19ba. These mechanical rock properties are presently used in phenomenological analysis and seismic verification assessment.

The V_p velocities obtained from the acoustic logs in U19ba and U3mt compared reasonably well with the geophone survey velocities from these emplacement holes. The only major differences occurred in the fracture intervals of I19ba where the fracture intervals were identified with the borehole camera. The geophone velocities were much less than the acoustic velocities in these fractured intervals.

INTRODUCTION

Source region characteristics of underground nuclear explosions and the formation strength parameters in this region are presently being investigated for verification purposes. Calculations of the effects of underground nuclear explosions require reasonable knowledge of the compressional (Vp) and shear (Vs) wave velocities and also the density (D) of the geological materials above the source region. Combining these physical parameters yields the formation strength parameters of Young's modulus, Bulk modulus, Shear modulus and Poisson's ratio and these parameters can be used to characterize the elastic behavior in the linear elastic environment above the source region.

The Vp and Vs/pR (pseudo Rayleigh wave velocity) velocities are calculated from the compressional and shear/pseudo Rayleigh wave travel times that are measured in emplacement holes by the Los Alamos Dry Hole Acoustic Log (LADHAL). A relatively low frequency energy wavelet follows the compressional wavelet and this low frequency wavelet has been identified as a pseudo Rayleigh wave, reflected conical wave or shear normal modes. Theoretical analysis (Biot, 1952, Cheng and Toksoz, 1981, Paillet and White, 1982 and Paillet and Cheng, 1986) describe these waves. An estimate of Vs can be made from the Vs/pR data (Newmark, 1987). Emplacement holes are air filled and uncased and have a diameter of 8 ft (2.44 m) and a depth range of 600 to 3000 ft (185 to 915 m). The LADHAL tool is a full-waveform acoustic-logging device that operates against the borehole wall and has a hammer source and three receivers. The spacing between the hammer impact area and the three receivers is 6 (1.83 m), 9 (2.74 m) and 12 ft (3.66 m) (see Fig 1). Compressional and shear/pseudo Rayleigh wave travel times are measured in each receiver and 3 compressional and 3 shear/pseudo Rayleigh velocities are calculated. These velocities are calculated between the 6 to 9 ft receivers, the 9 to 12 ft receivers and the 6 to 12 ft receivers. The shear/pseudo Rayleigh velocity is converted to shear velocity. The density data are acquired from the gamma-gamma backscatter density log. These data are combined to determine the formation strength or elastic parameters of the linear elastic region above the nuclear explosion source area.

ACOUSTIC SOURCE INVESTIGATION

The standard source for borehole acoustic logging is the piezoelectric source. This source was considered unsuitable for large hole (8 ft, 2.44 m, diameter) acoustic logging at the Nevada Test Site (NTS) because of the low velocity, loosely compacted formations routinely encountered. A higher energy source was desired with the following characteristics:

1) no chemicals, explosives, high pressure or potentially hazardous devices could be used;
2) consistent energy levels;
3) a frequency response suitable for obtaining accurate first break compressional wave speed times in formations with velocity ranges of 2000 to 20000 ft/s (600 - 6000 m/s);
4) sufficient energy so that a receiver could detect the source signal at a distance of 15 ft (4.6m) from the source; and
5) high reliability, low maintenance and low operating costs.

An investigation of possible sources revealed that Southwest Research Institute (SWRI) had developed an arc-discharge source that was used in undersea surveys. This source emitted energy levels that were an order of magnitude larger than piezoelectric transmitters of comparable size. SWRI was contracted to develop a source smaller than the undersea source, using the same principals and suitable for a dry hole environment. SWRI produced an arc-discharge source and the documentation detailing the design, construction and testing of this source. This source was powered at 18.4 ft lbs (25 joules) and compared to a piezoelectric source powered at 0.8 ft lbs (1.1 joules). The two sources were physically about the same size and weight. The signals detected from these two sources showed that the arc-discharge transducer was 13 db larger in received energy than the piezoelectric transducer and the arc-discharge transducer had faster rise times and higher frequency contents than the piezoelectric transducer.
Field testing under actual logging conditions revealed that the SWRI arc-discharge transducer source was still too small for the intended dry hole acoustic use. The power requirements used for the arc-discharge transducer were reasonable considering the logging cable limitations, but to continue to develop electrically powered sources with higher energy outputs would not be feasible. An investigation of mechanical sources was begun.
A weight drop system was investigated. There were concerns about energy requirements to lift the mass, frequency response of the acoustic signal and noise generation from the falling mass. Field testing with a 12 lb (3.5 Kg) sledge hammer established that a signal at 15 ft (4.6 m) could be reasonably detected. Before committing to a falling mass source, an effort was made to compare a high mass, low velocity source to a low mass, high velocity source of equal energy. A .22 caliber Long Rifle pistol bullet has comparable energy to a 12 pound hammer dropped from a height of 3 ft. A .38 caliber pistol bullet which has more energy than either was also compared.
A simple test involved laying out some piezoelectric receivers certain distances from a source target. The source target would be struck by the hammer and the bullets. An oscilloscope pulse was generated as the initial energy (

t_o initial time) arrived at the source target by the source mechanism (hammer or bullets) crushing 2 thin sheets of metal foil separated by a thin sheet of paper, which completed an electric circuit. The energy transmitted to the rock material under the source target (soft soil, sandstone and dolomite) was later received by the piezoelectric detectors. The detected results indicated that very little acoustic energy was transmitted to the rock material by either bullet. Evidently the high frequency energy transmitted into the rock material was quickly attenuated because only a very small response was detected at the receivers. The hammer source transmitted a reasonable amount of energy into the rock material because a large response was detected at the receivers.
The hammer was chosen as the source and other benefits became apparent. These were:
1) the hammer would rebound according to the coefficient of restitution of the rock material;
2) the period of the hammer was long compared to the velocity of the rock material and did not interfere with the recording of the speed of the signal; and
3) the hammer source characteristics adapt to the type of rock material to produce optimum transmission and recording results.
In high velocity, hard rock materials the hammer rebounds are large, very little energy is expended in rock crushing, the hammer energy is transmitted quickly into the rock, and most of the energy transfer is elastic. A low energy but high frequency acoustic signal is transmitted in high velocity, hard rock material. In low velocity, soft rock materials the hammer rebounds are small , most of the hammer energy is absorbed, substantial rock crushing occurs, and low frequency energy is transmitted A high energy but low frequency acoustic signal is transmitted in low velocity, soft rock material. Approximately the same accuracy of wave speed measurement can be made throughout the velocity range of rock material at the NTS using the hammer source.

ACOUSTIC DETECTOR INVESTIGATION

Using the hammer as an acoustic source which provided abundant acoustic energy, canceled the need to develop detectors with ultra-sensitivity. When weaker sources were under consideration, an investigation of piezoelectric receiver characteristics was made, stressing directionality and coupling, to optimize sensitivity and accuracy.

Many laboratory tests were conducted to study receiver responses with a view towards getting an engineering "feel" and recording relative responses to various coupling parameters. The goal was to determine optimum transducer pressure, shape of the transducer/rock interface, effect of air gaps, effect of various membranes, and the effects of adding various types of interface materials.

The laboratory tests contained a piezoelectric transmitter fired with a pulse of adjustable amplitude. Various materials were used to transmit sound, including wood beams (8x6x50 in, 20x15x153 cm), steel plates (1/4 in, 0.64 cm thickness), and rock slabs (sandstone and granite). The receiver was the same as the transmitter. The signals from the receiver were recorded directly on a Nicolet digital scope and stored on disks. A synchronized pulse from the transmitter was used to trigger the oscilloscope and provide a time reference that was used to judge relative response only and not to determine actual travel times through the materials.

The resultant waveforms were studied comparatively and several design factors became apparent. Coupling characteristics could be changed by adding pressure to the transducer to force firmer contact; by adding various fluids, gels, and compounds to the interface between the transmitter and the medium; and by inserting various materials between the transducer and the medium. The various coupling characteristics obtained from tests were:

1. Coupling affected amplitude of the acoustic arrivals and the apparent travel time. As coupling improved, the first arrival was detected earlier (by first break and by peak) by as much as 50 micro-seconds, and the amplitude of the first arrival increased by a factor of 10.

2. Coupling was degraded as the surface area of the contact was reduced.

3. Coupling improved as air was displaced with a pure gel. Compounds, such as Lubraplate, tended to absorb acoustic energy and contribute to attenuation.

4. Improving the coupling of the transmitter transducer was as critical as that of the receivers to improving detected response.

5. The technique of using a fluid filled bag as an interface to couple transducers to dry rock did work, because any material used to contain the fluid and tough enough to withstand borehole rugosity acted as an attenuator.

6. Coupling improved with transducer pressure, up to about 25 lbs (11.4 kg). Beyond that pressure the signal would degrade slightly.

7. If the coupling characteristics of the receiver transducers are not the same, there will be inaccuracies in the time measurements.

8. The effects of poor coupling are more noticeable as the velocity of the medium increases.

9. A membrane or thin plate of any material tested (plastic, rubber, leather, tin, lead, paper, etc) placed in the interface between the transducer and medium would attenuate the signal, but if the membrane or plate was coated on each side with a gel, the effect of the membrane was indistinguishable from an interface containing gel only.

10. The transducer should not be mounted to any support which may act as a vibrating member. The mass of the receiver appears not to be a major factor in improving transmissibility, if contact force can be applied.

11. The amplitude of the first arrival is directly proportional to the amplitude of the voltage pulse firing the transmitter.

The decision to clamp the receivers with about 25 lbs (11.4 kg) of force and to inject a gel into the interface between the transmitter and the borehole wall to displace air were made from these tests.

SWRI was contracted to study the receiver design. They recommended the development of shear polarized piezoelectric transducers and designed, built and tested three transducers. The laboratory tests, conducted under controlled conditions , indicated that these transducers were superior to transducers polarized along the radical axis in sensitivity to signal expected to radiate from the side of the borehole. The pressure wave front radiates vertically along the side of the borehole, and a transducer sensitive to this directional wave would be superior. However, field tests conducted on various exposed rock surface and concrete slabs belied this logic. The standard off-the-shelf radial transducers significantly out-performed the SWRI transducers in all field tests.

TOOL DESCRIPTION AND WAVEFORMS RECORDED

The components of the downhole system are mounted on a carrier of fiberglass construction (see Fig 1). The 18 ft (5.5 m) carrier will log in boreholes from 86 in (2.18 m) to 120 in (3.05 m) in diameter. The carrier was adapted for use as a test bed for acoustic logging research after having served in other downhole testing.

The acoustic energy source is the 12 lb (5.45 kg) hammer mounted at the upper portion of the carrier. The hammer assembly slides on a track, which is acoustically isolated from the carrier, to position the hammer properly for a strike. An accelerometer is mounted on the hammer head provides a trigger source for the oscilloscope. A belt driven potentiometer measures the rotational position of the hammer. The hammer is lifted by a starter motor which kicks the hammer into the raised position where it latches into place, until released by the air pressure actuated latch.

There are three receivers mounted at 6,9 and 12 ft (1.83, 2.74, and 3.66 m) spacings below the hammer impact point. Each of the receivers are mounted on individual rams adjusted to exert 25 lbs (11.4 kg) force. The receiver assembly contains the three rams and the transducer sub-assemblies and provides for acoustic insulation from the carrier. The receiver transducers are each mounted in foam filled cylinders for insulation. There is a faceplate attached to each transducer so that fluid can be pumped into the device to displace the air between the faceplate and the formation. The receiver amplifiers operate in two modes, a high gain setting amplifies the compressional waves for optimum recording and a low gain position allows the entire wavetrain to be recorded with minimum distortion. The high gain mode will saturate later arrivals, and also must be clipped to +/- 0.5 volts to minimize crosstalk effects, since all three signals are transmitted live to the surface in analog form. The low gain position allows signals to be recovered for shear wave picks and general signal analysis (compressional waves are of course present but too weak to pick accurately).

The tool is extended (opened) by hydraulic pressure and retracted (closed) by air pressure. In addition to the rams on the hammer assembly and the three receivers, there are two reaction rams mounted on the opposite side of the carrier. There is an emergency dump valve to dump the hydraulic pressure should there be a failure which prevents closing the tool while downhole. The squirter system forces a gel out of a orifice on the transducer faceplate to fill any gaps between the transducer and the formation. The squirter is operated as an option and the quantity of fluid is a function of the time operated, usually 15 to 30 seconds.

The major components of the downhole system are:
1. hammer assembly;
2. receiver assembly - containing three receivers;
3. electronics - signal, diagnostics and control;
4. hydraulic system;
5. pneumatic system; and
6. squirter system.

The major components of the surface equipment are:

1. Nicolet digital oscilloscope;
2. depth measurement system;
3. control panel;
4. industrial 386 PC computer;
5. DC power supply;and
6. 660 VAC source.

The signals sent from the downhole tool are:

1. the three receiver acoustic waveforms;
2. hammer position;
3. hydraulic pressure;and
4. oscilloscope trigger.

The control signals from the surface are:

1. Extend tool;
2. Retract tool;
3. Release hammer;
4. Lift hammer;
5. Squirt fluid;
6. Emergency dump; and
7. Recording mode (compressional or shear wave).

A typical station record requires about five minutes. The tool is placed into position by the winch operator and is extended for about two minutes. The mode is set for shear wave recording and the hammer is released. The waveforms captured on the Nicolet oscilloscope and are transferred to the PC computer which assigns file names to the data and stores it. The hammer is lifted and the mode switched for compressional wave acquisition. The hammer is released and the data again is transferred to the PC computer. This time the PC computer applies an algorithm to determine arrival times based on first break analysis, calculates travel times and velocities, stores the waveforms on disk, and stores the calculated data in a data file. The operator can override any machine calculations with visual picks and manual inputs. After determining that the data is acceptable, the hammer is lifted, the retraction process is activated, and the carrier is moved to a new location.

Post-job processing requires reviewing many (30%) of the automatic picks for compressional wave velocities by examining the waveforms previously recorded and modifying the data file. The waveforms are also graded as to the quality of the first arrival and this information is included in the data file. When first breaks are not well defined, other methods might be used, such as peak detection or determining consistent points at some level above the baseline. The shear wave travel times must then be picked and processed to determine the shear velocities.. Finally the data are plotted and presented.

Experience has shown that the first strike of the hammer is not the optimum for measuring compressional wave arrivals because of energy expended in rock-crushing. Second and subsequent blows yield superior results because the first break has a faster rise time and is better defined.

Signal integrity is largely dependent on preventing electrical or mechanical noise from distorting the waveforms as they are recorded. The source assembly was acoustically isolated from the carrier by pneumatic shock absorbers, and was designed to free fall as noise. The trigger synchronized signal is processed downhole to go high and stay high for 10 ms so it will not interfere with signal integrity. The diagnostic signals, hammer position and hydraulic pressure, are brought to zero during this interval. The hammer position indicator is used to record rebounds. With further study, there may be useful information gleaned from such data.

Examples of various waveforms recorded at a depth of 130 ft (39.6m) in emplacement hole u19bg are exhibited in Figs 2 through 7. The compressional velocity at this depth is approximately 3000 ft/s (915 m/s). The compressional waveforms of P 130-1,-2 and -3 show good development and the first breaks are easily identified. The closet waveform is P 130-1 which is 6 ft (1.83 m) from the source and the furthermost waveform is P 130-2 which is 12 ft(3.66 m) from the source while P 139-3 is 9 ft (2.74 M) from the source. A Fourier transform of these data (see Fig 8) shows a frequency peak at approximately 500 Hz. The shear/pseudo Rayleigh waveforms for these same detectors, S 130-1, -2 1nd -3, are well developed for all detectors and easily identified. A Fourier transform of this data (see Fig 8) shows a frequency peak of 200 Hz.
Examples of additional waveforms recorded at a depth of 600 ft (182.9m) in U19bg where the compressional velocity is approximately 10000 ft/s (3048 m/s) are seen in Figs 9 through 14. Again the compressional waveforms are well developed for all detectors (P 600-1 is 6 ft (1.83 m)from source, P 600-3 is 9 ft (2.74 m) from source and P 600-2 is 12 ft (3.66 m)from source) and the first breaks are easy to identify. The frequency responses of this data shown in Fig 15 have a frequency peak at approximately 1500 Hz. The far detector, P 600-2, exhibits a double peak and a frequency content range of 750 to 1500 Hz. The shear/pseudo Rayleigh waveforms are generally well developed. The pseudo Rayleigh wave of the far detector, S 600-2, is not as well developed as the others because this detector is probably not well coupled to borehole wall. The frequency responses of this data are shown in Fig 15 where a double peak of 900 and 1600 Hz is seen for the near detectors and the frequency response of (900 to 1350 Hz is seen for the far detector. Poor coupling of this detector probably accounts for its slightly different response. From these examples, a high frequency

compressional wave is seen followed by lower frequency wave that has been identified previously as a surface wave and not a shear wave.

Newmark (1987) using Biot's (1952) derived expressions for the phase and group velocities of axial-symmetric surface waves along a borehole showed that in an air filled emplacement hole with a diameter of 2.44 m, the pseudo-Rayleigh velocity needed a small correction to convert this velocity to shear velocity. The pseudo-Rayleigh velocity was multiplied by a factor that varied from 1.04 to 1.14 as Poisson's ratio varied from 0.0 to 0.5. Using a multiplier factor of 1.09 (this factor corresponds to a Poisson's ratio of 0.25) to correct the pseudo-Rayleigh velocity to shear velocity only introduces a-+ 4% variation in the resulting estimate of the shear velocity for a range in Poisson's' ratio of 0.0-0.5. It was also shown from laboratory measurements and refraction surveys (Constantino and Bonner, 1980 and Carroll, 1986) that Poisson's ratio varied from 0.2 to 0.4 for the NTS tuffs in areas 19 and 20. If Poisson's ratio is in this range than the uncertainty in the estimate of the shear velocity due to the uncertainty in Poisson's ratio is only -+ 2%. All of the pseudo-Raleigh velocities were increased by a factor of 1.09 and called shear velocities.

VELOCITY RESULTS

A comparison of acoustic and geophone compressional velocity was made in 4 emplacement holes of U3mt, U19az, U19ba, and U19bg. Also the bulk density from gamma-gamma backscatter and gravity tools ,the stratigraphy, and the fractures located by camera are compared to these velocities. A routine geophone survey is accomplished with an air gun source at the surface near the hole while a geophone is hydraulically clamped at 50 ft (15.24 m) spacing downhole. The results of these comparisons can be seen in Fig 16 through 19.

The character of the bulk density curves and the acoustic compressional velocity compare reasonably well in emplacement hole U3mt shown in Fig 16.. Dense thin layers shown by the gamma-gamma density probe are seen as high velocity layers by the acoustic probe. These layers are basalt flows or welded tuff units which have higher velocities and densities. The geophone compressional velocities do not have the same pattern as the acoustic compressional velocities in these thin high velocity layers. The radius of investigation is too large and velocity properties are averaged over larger intervals. The acoustic compressional velocities generally agree reasonably well with the geophone compressional velocities away from these thin high velocity layers. The same pattern is seen in Fig

17 through 19 between the bulk density the acoustic compressional velocity. Fractures that were observed in the camera log are also shown. These fractures are generally vertical cooling fractures. Dense intervals occur in these fractured units and the acoustic compressional velocity increases also in these units. The geophone compressional velocity generally does not correspond to these intervals because the geophone technique has a larger radius of investigation and averages the high velocity intervals with the normal velocities. Also the fractured intervals appear not to greatly influence the geophone compressional velocities even though there may be some attenuation of these compressional velocities.

No ultrasonic core p-wave information to compare with acoustic or geophone p-wave information.

Generally no shear wave information is obtained from the geophone surveys. At the present time no ultrasonic core s-wave information is available to compare to the acoustic s-wave data.

The comparison of the compressional and shear velocities and the formation strength parameters or the elastic moduli for three emplacement holes (U3mt, U19ba and U19bg) are shown in Figs 20 through 25. The compressional and shear velocities of each emplacement hole outline the zones of both weak and competent rock. Poisson's ratio is generally between 0.2 to 0.4 for holes U19ba and U19bg which are drilled in volcanic tuffs and basalts. Poisson's ratio is less than 0.2 in hole U3mt which is drilled in Quaternary alluvium and in part less competent tuffs. Also the elastic moduli of shear modulus, Young's modulus and bulk modulus are shown. Competent rock layers are outlined by these elastic parameters and weak units or intervals are also seen.

Presently no comparison can be made of core elastic constants and log derived elastic constants.

CONCLUSIONS

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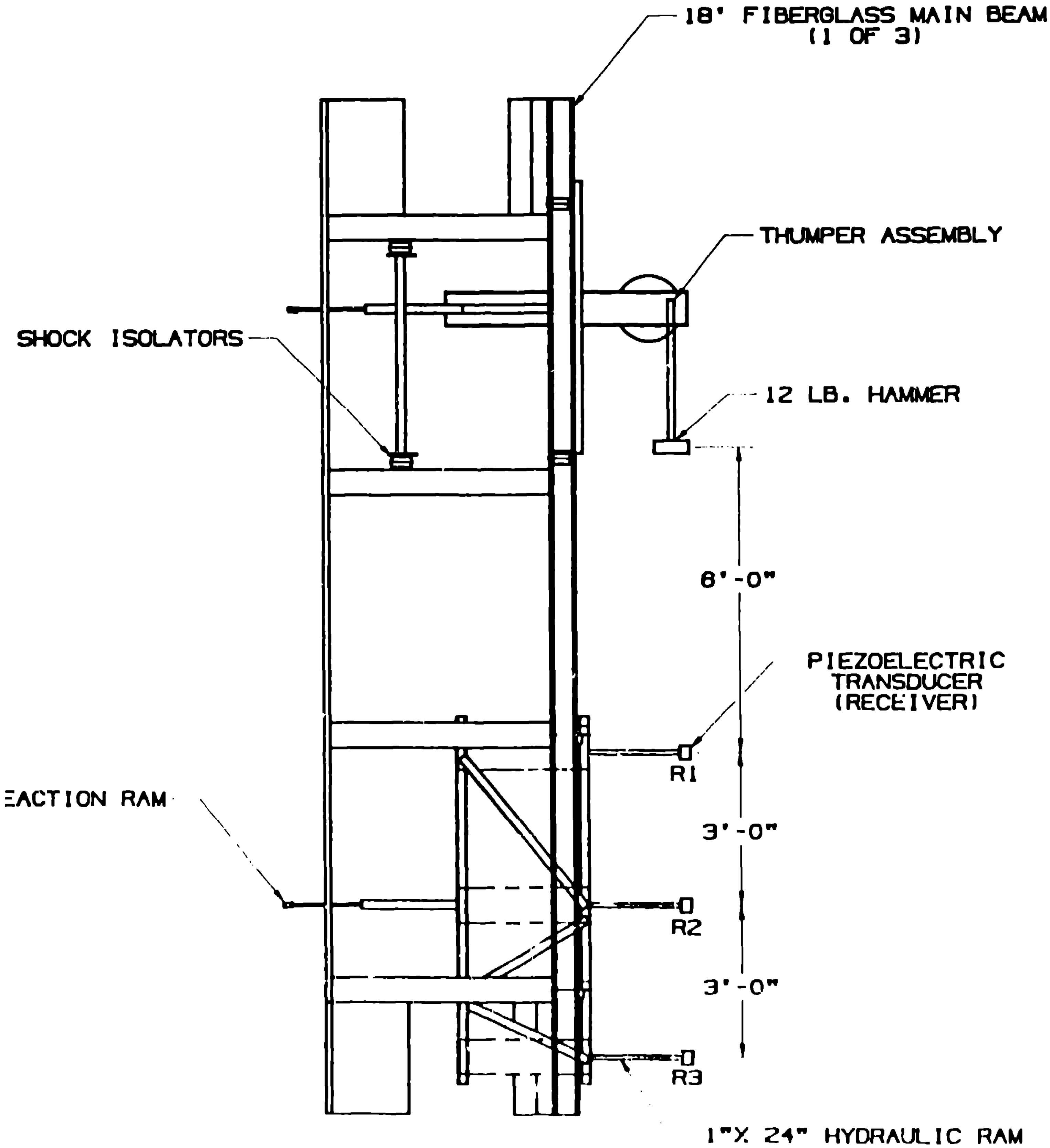
B.H.S. ACOUSTIC THUMPER (BHSAT) ASSEMBLY



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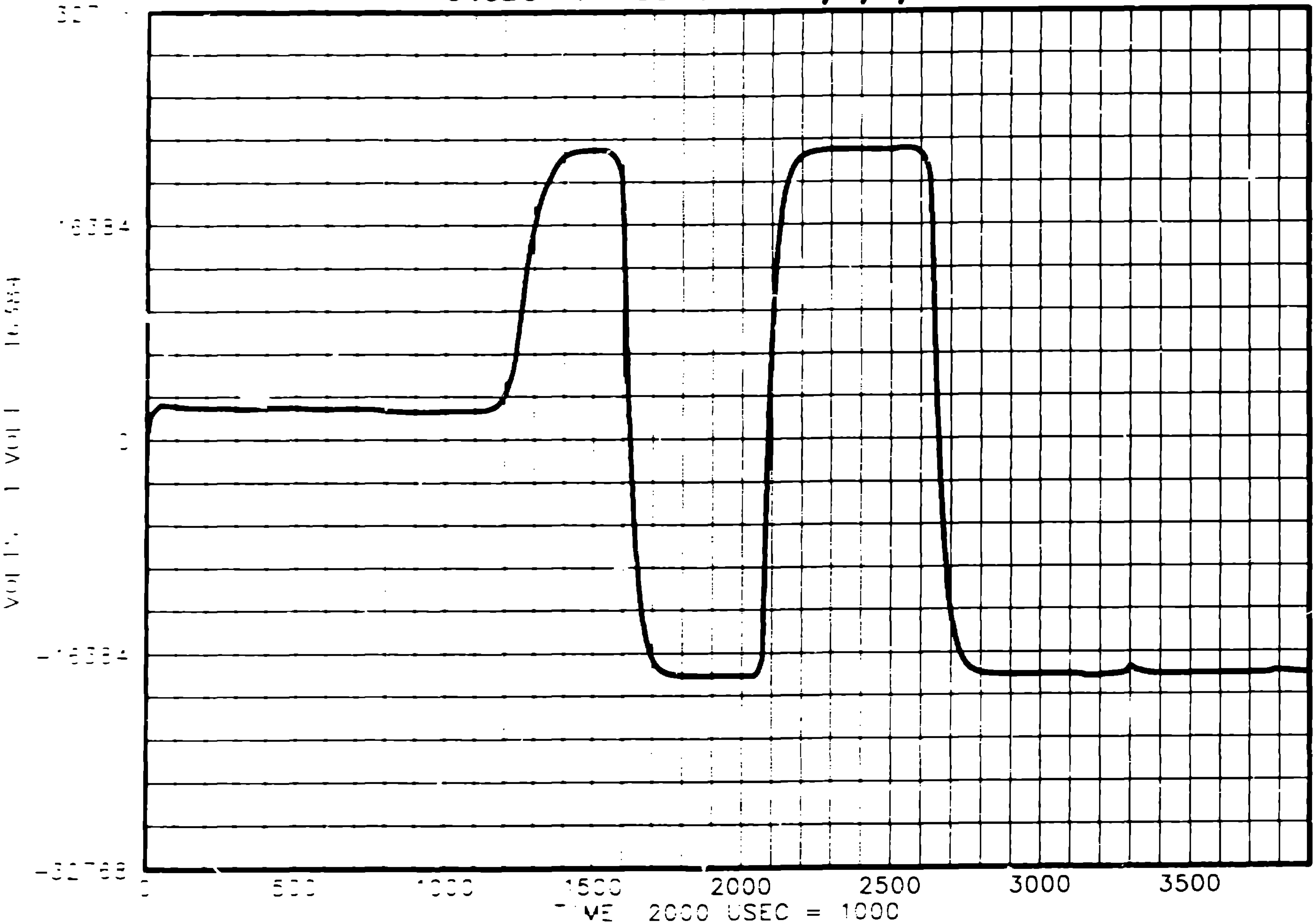

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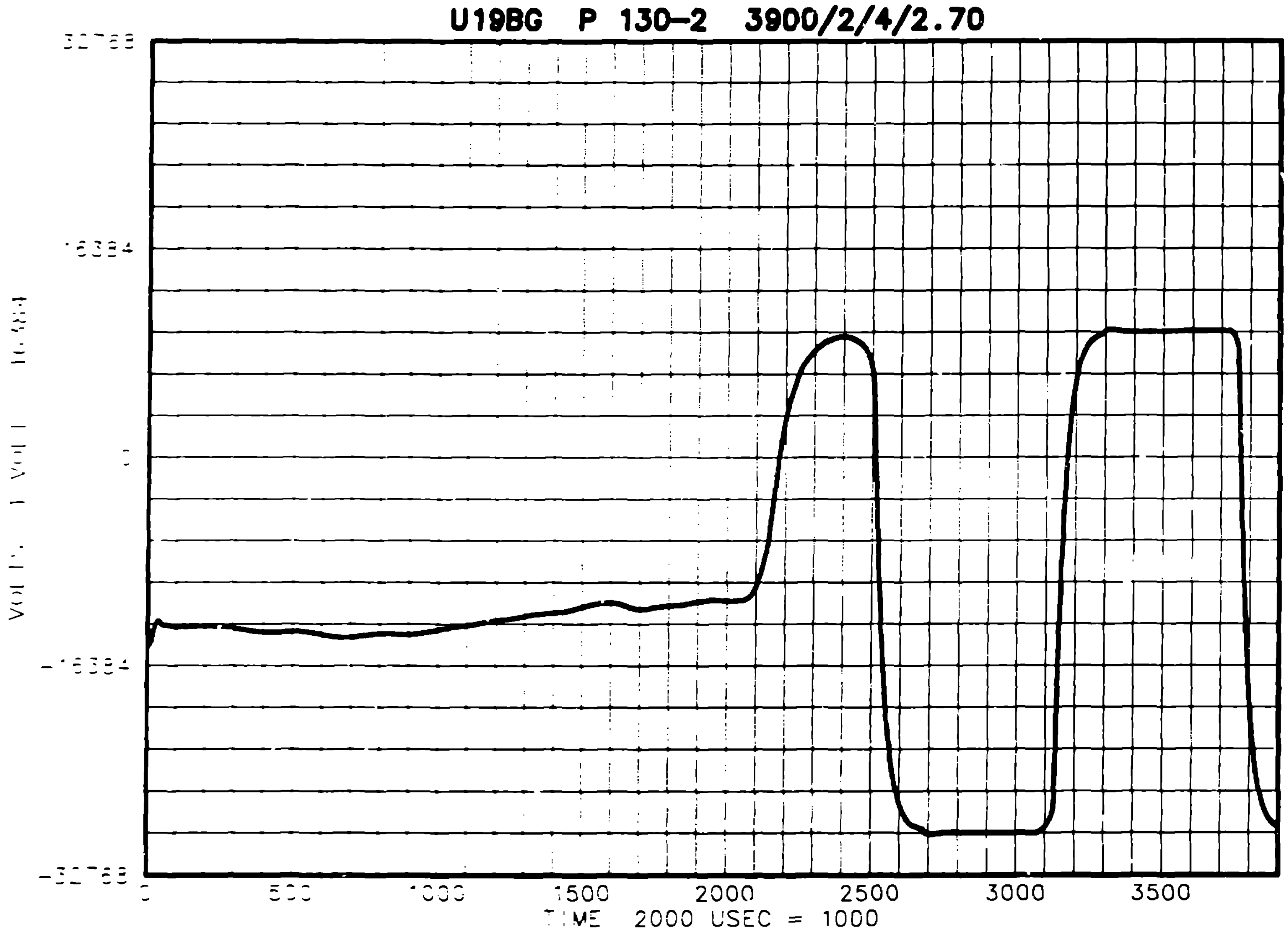
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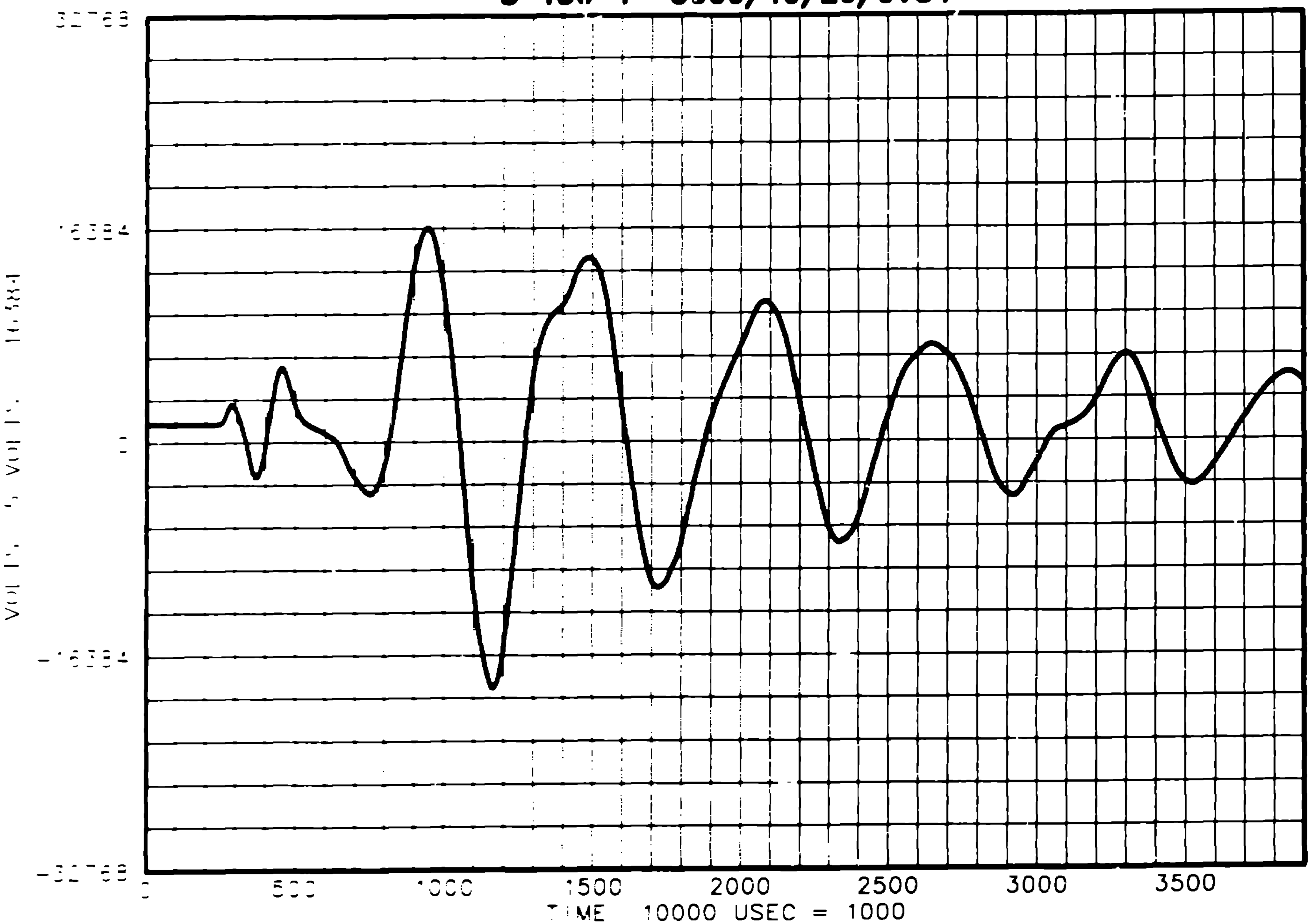

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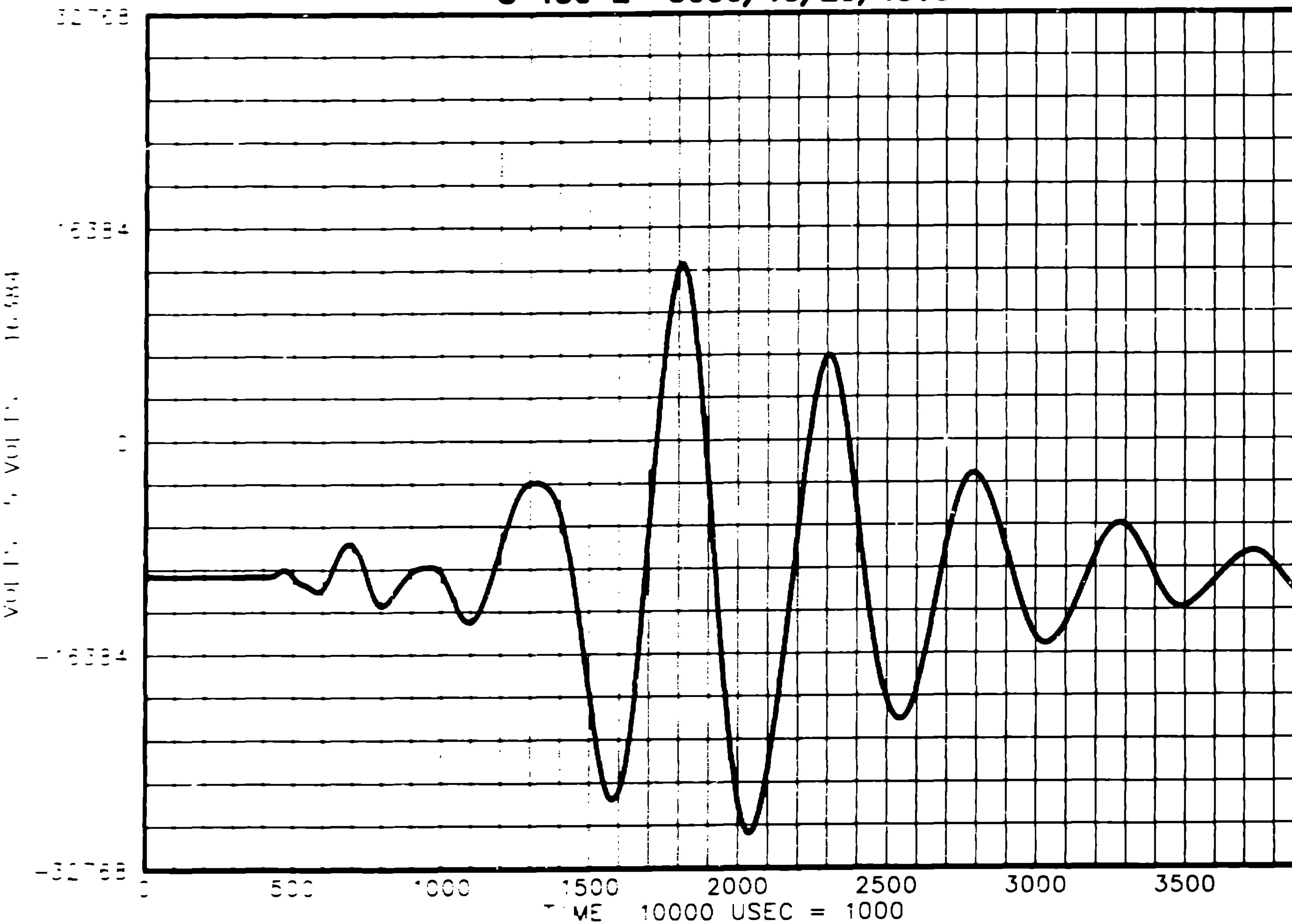

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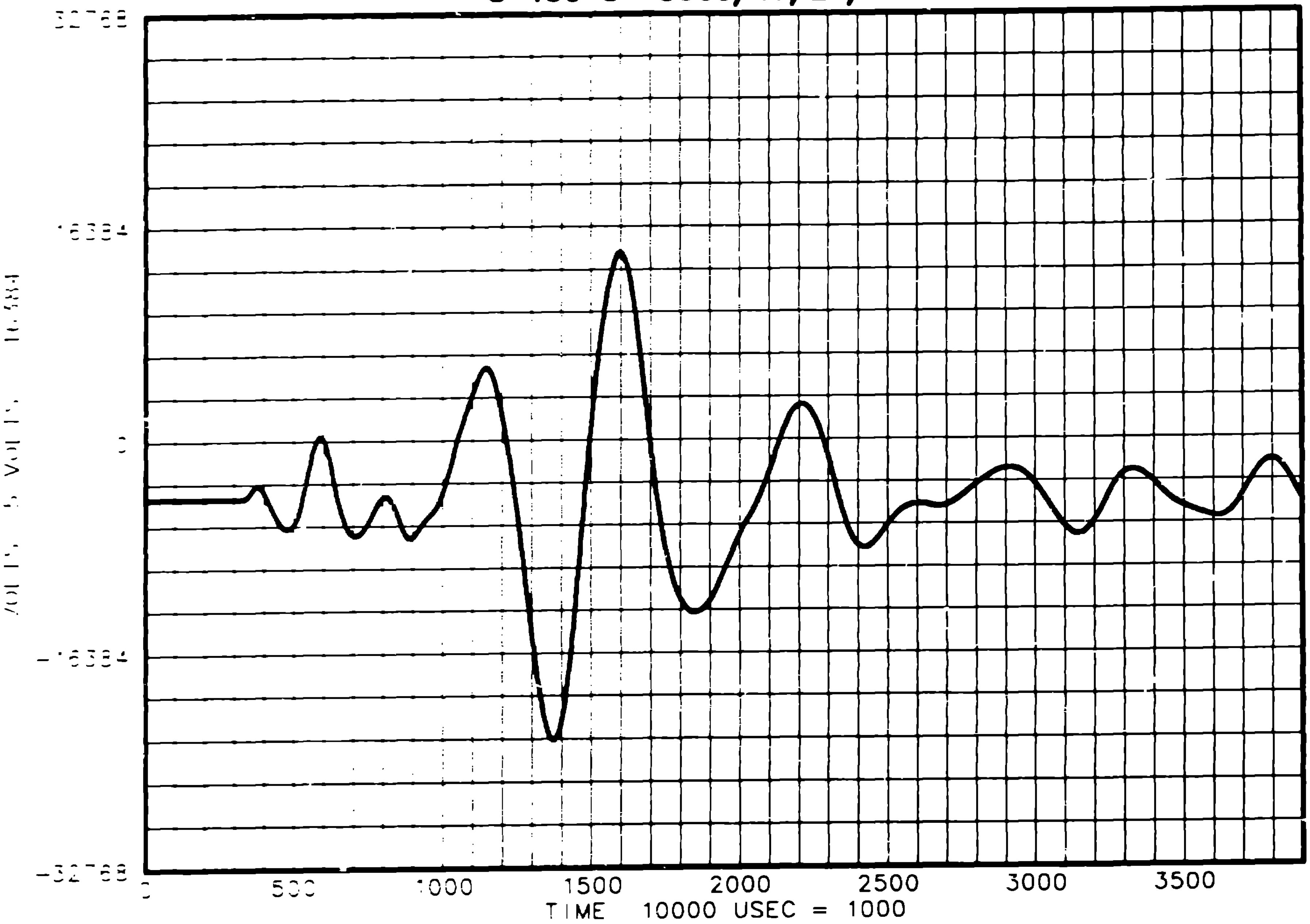

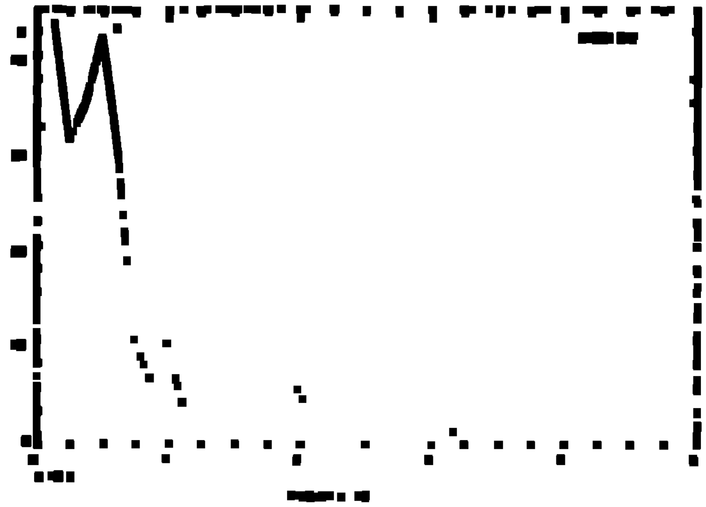

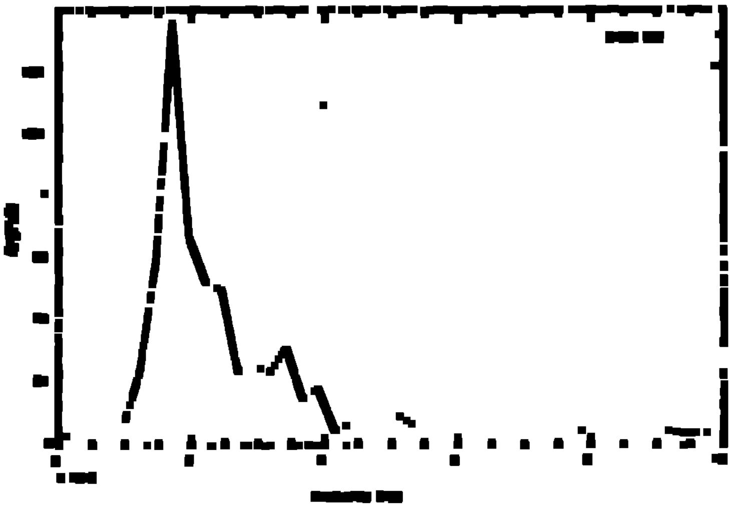

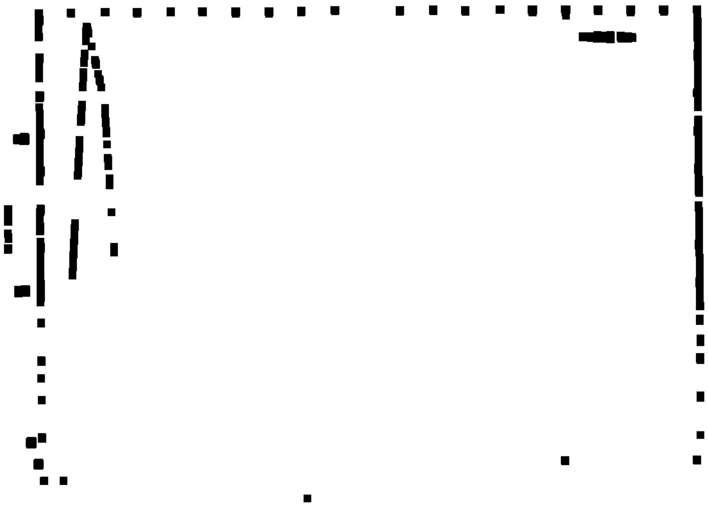

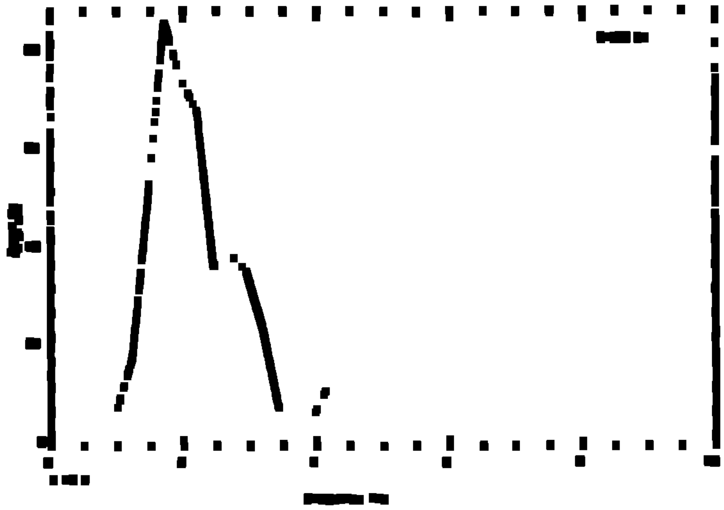

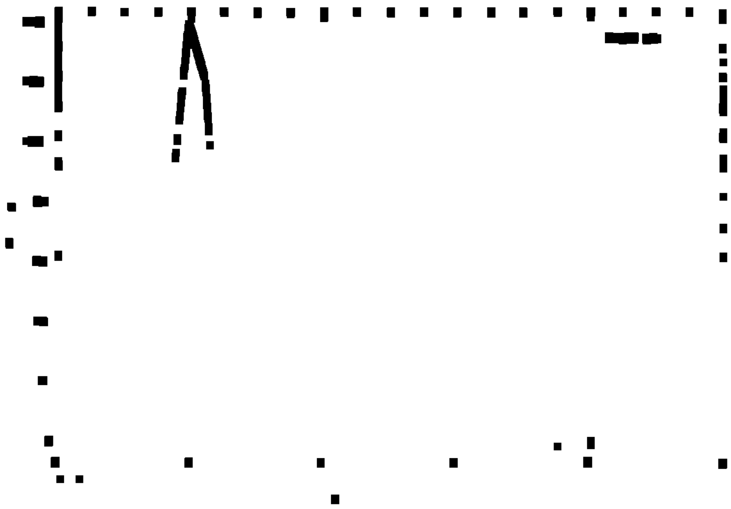

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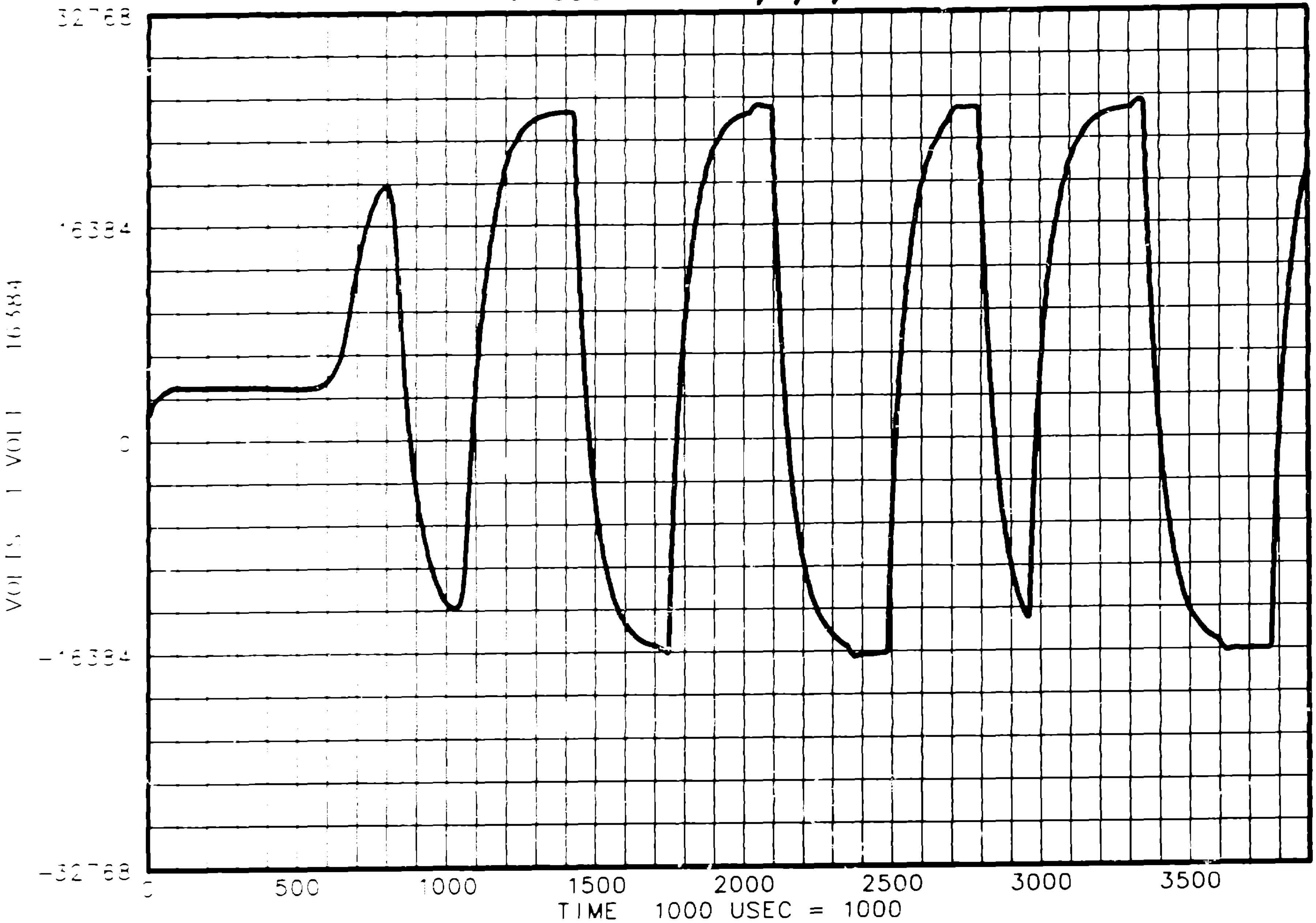

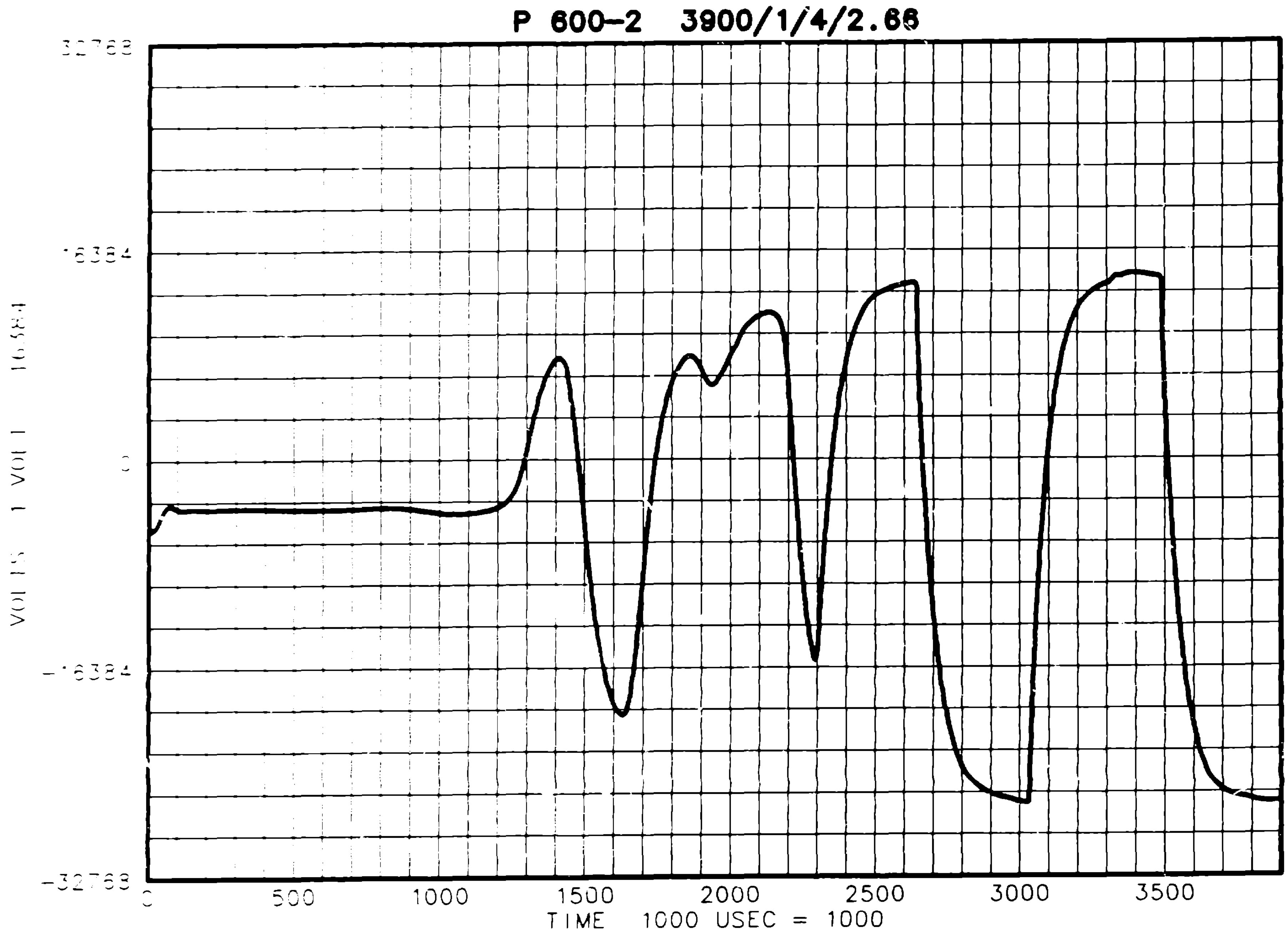
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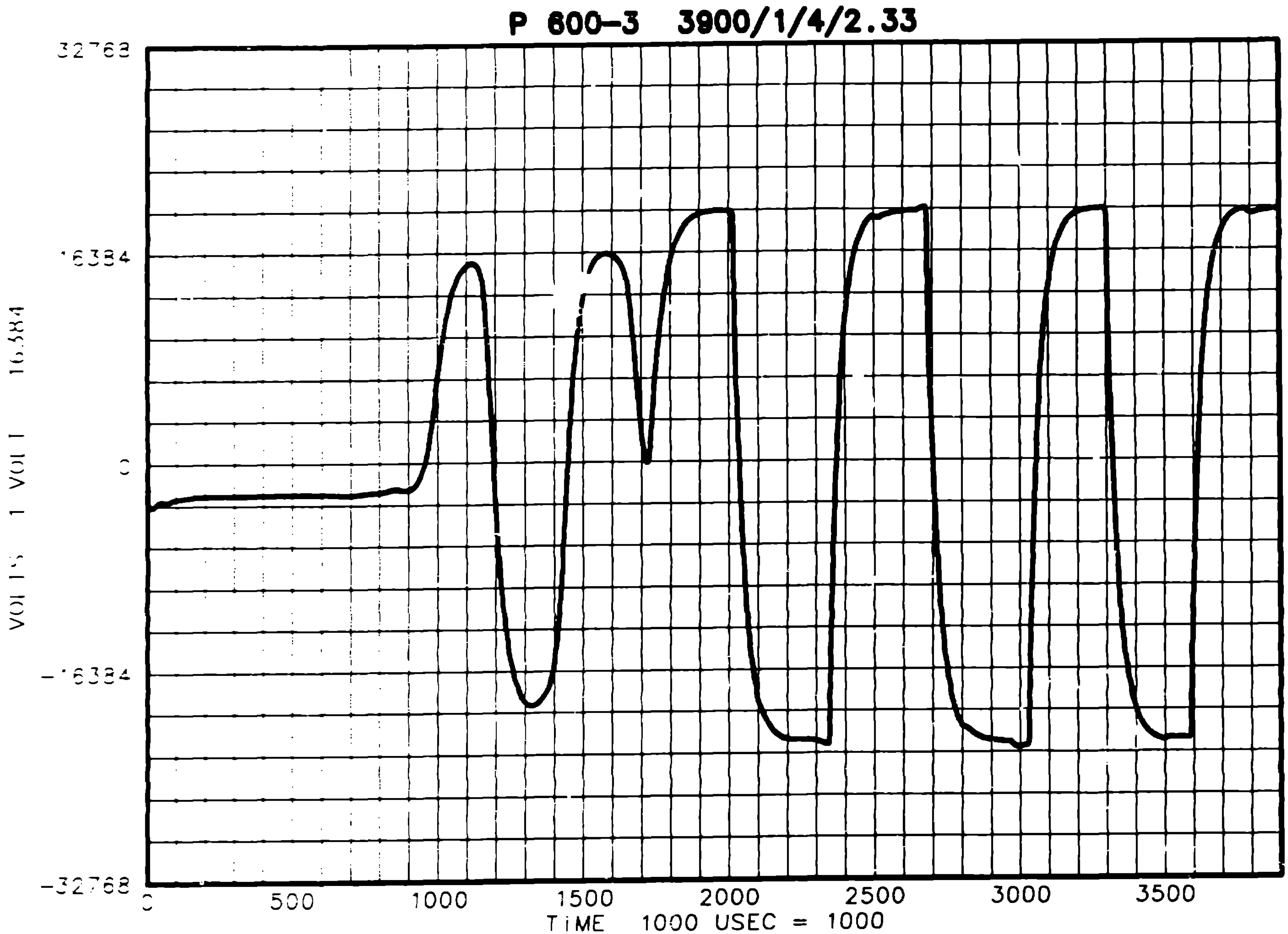

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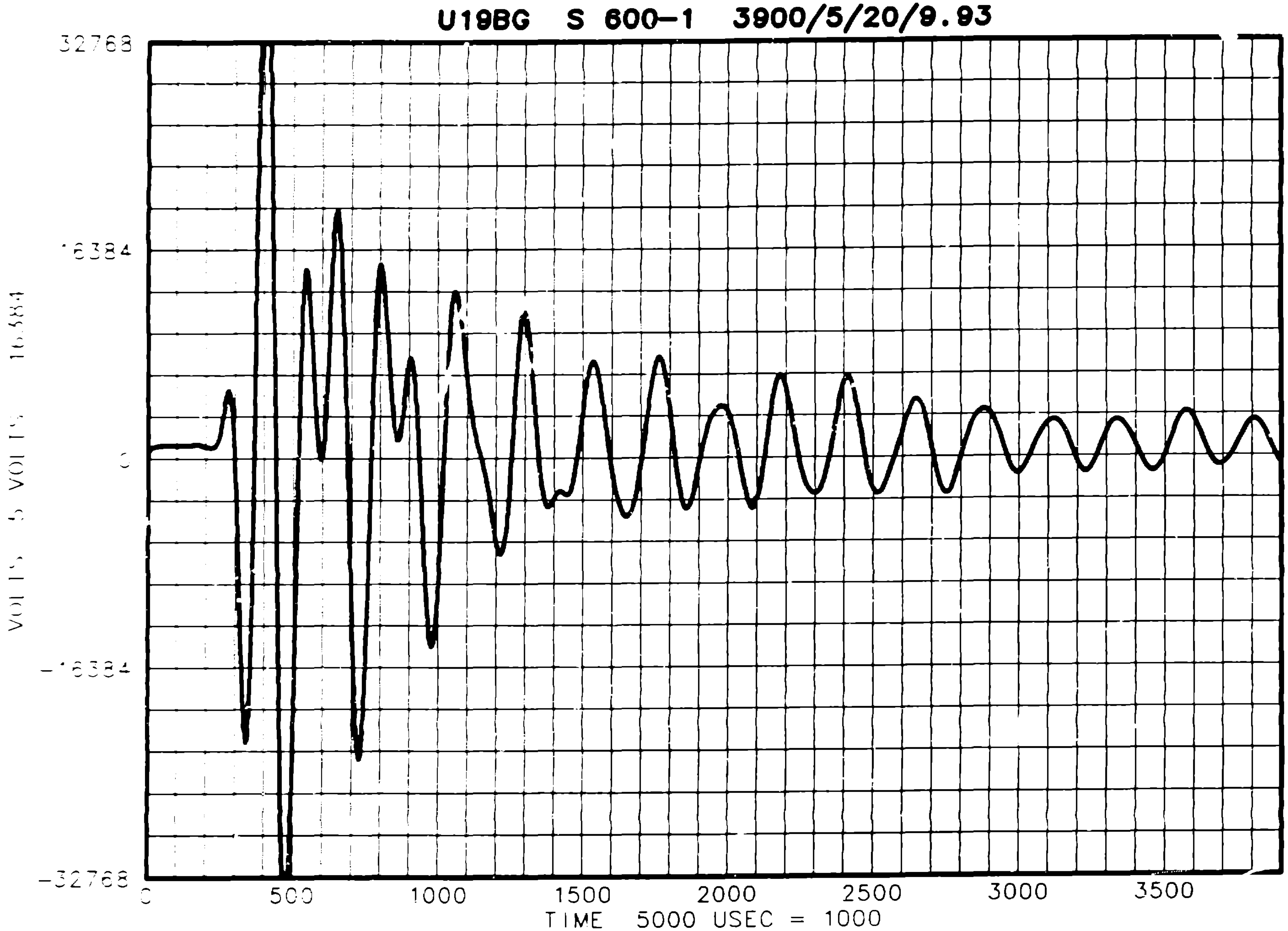
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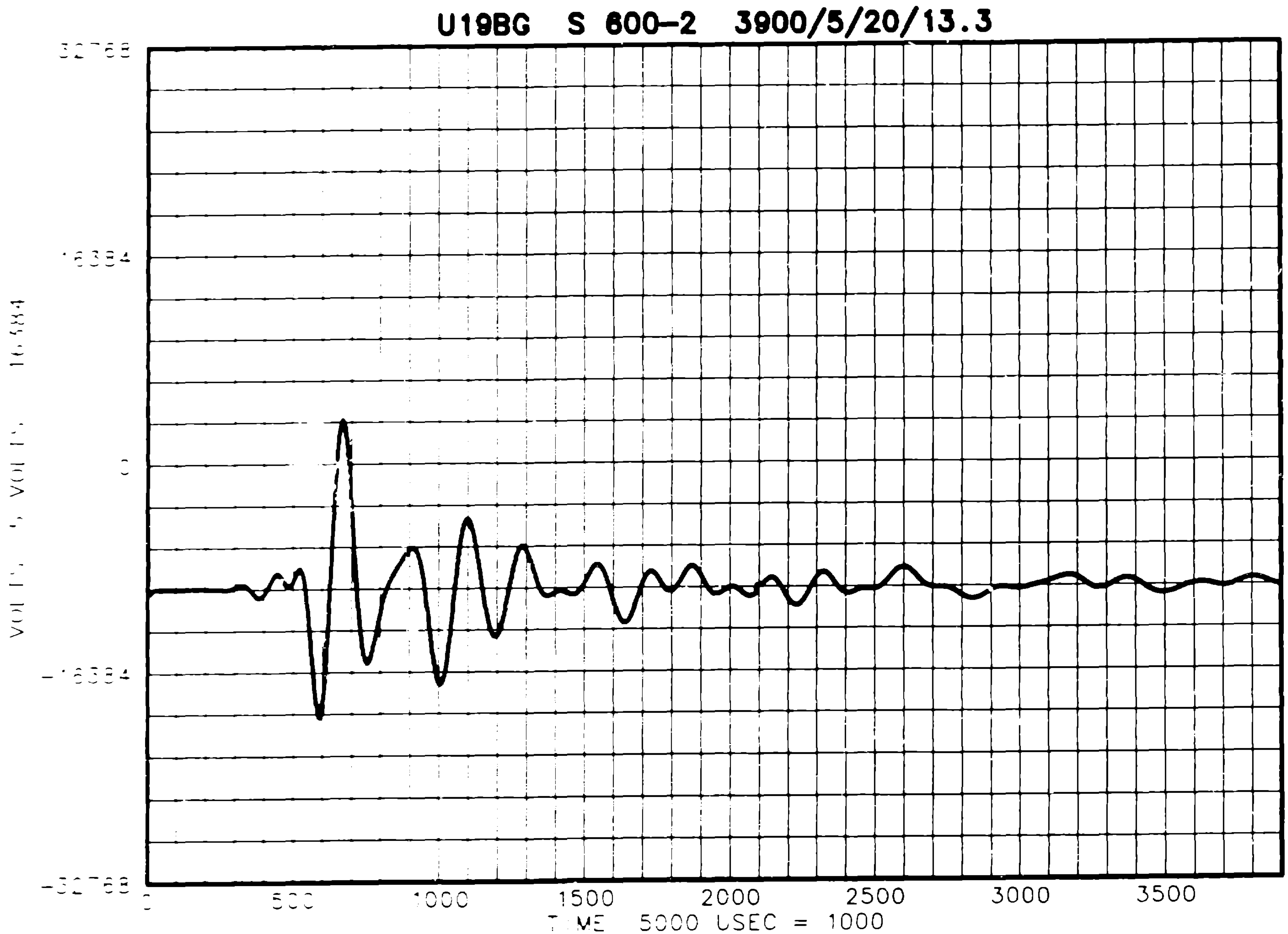
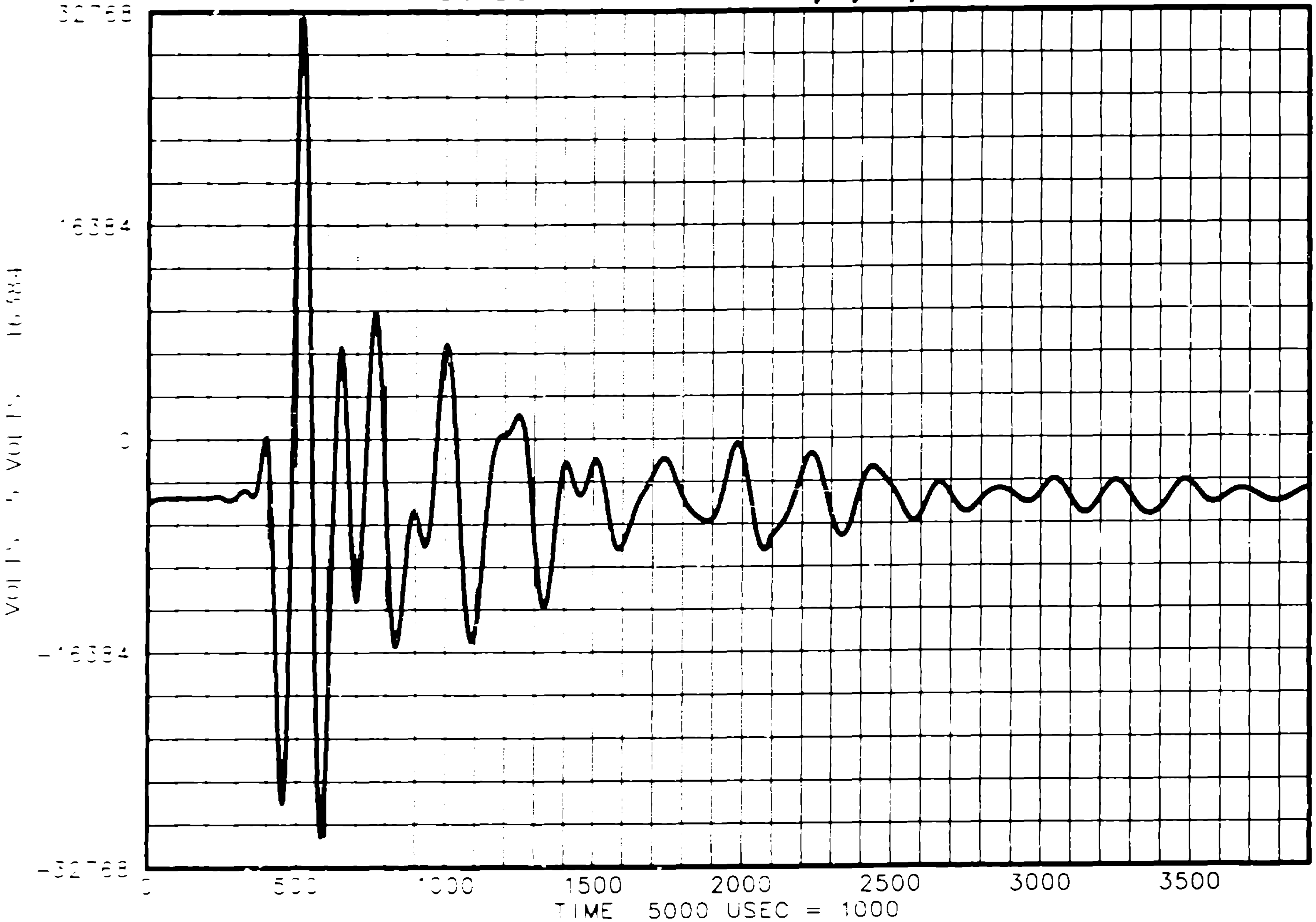
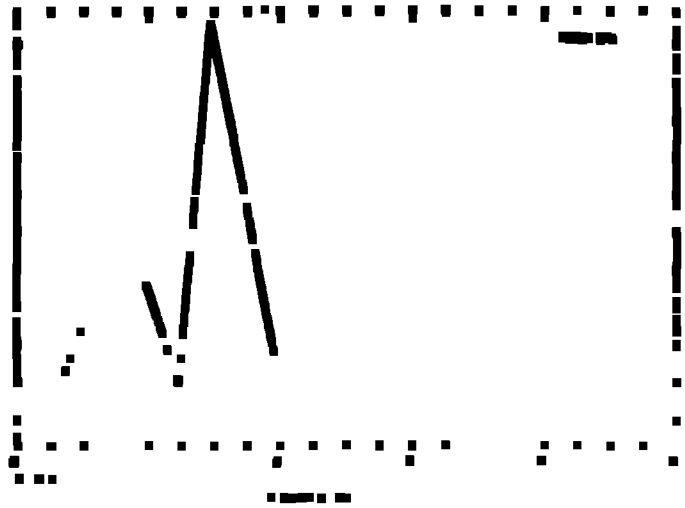
3500
TIME 5000 USEC = 1000

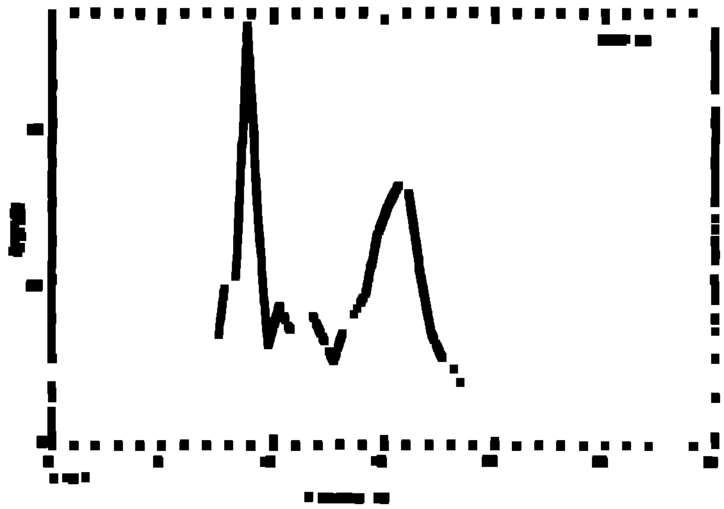


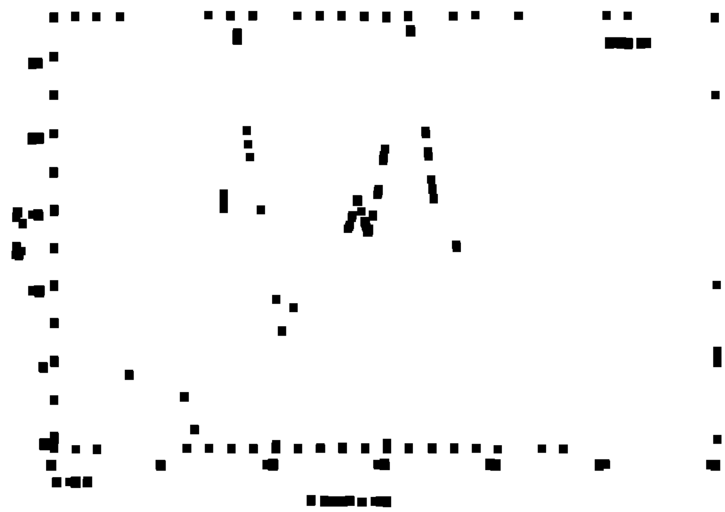
U19BG S 600-2 3900/5/20/13.3
32768
16384
0
-16384
-32768
0
500
1000
1500
2000
2500
3000
3500
TIME 5000 USEC = 1000

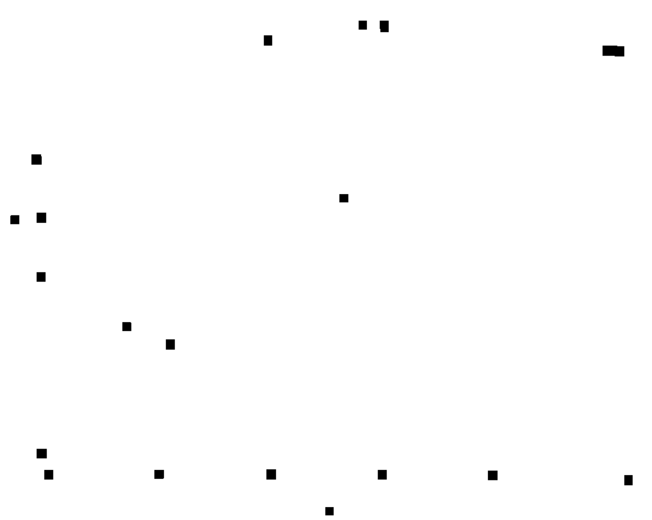
U19BG S 600-3 3900/5/20/11.66

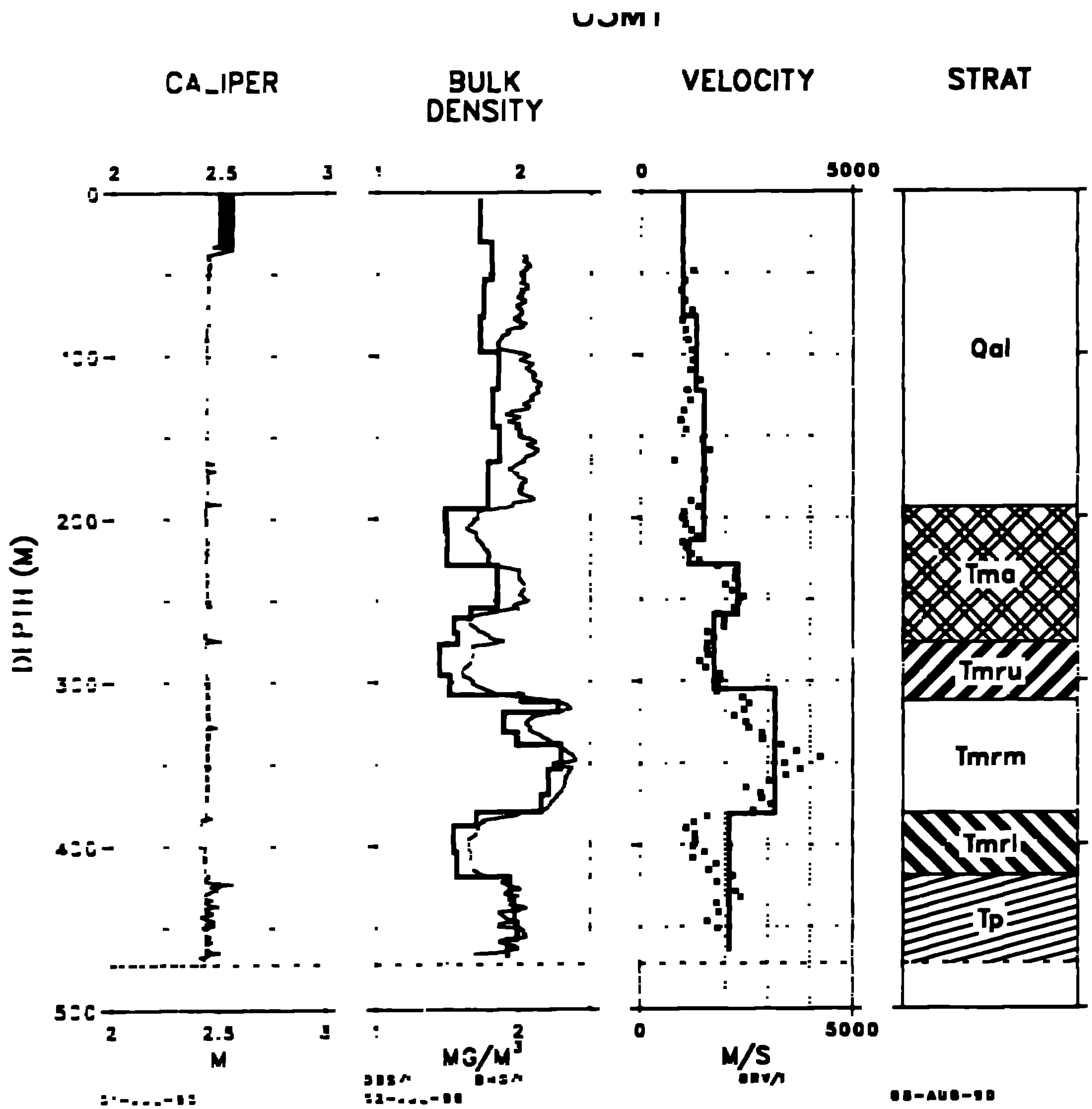








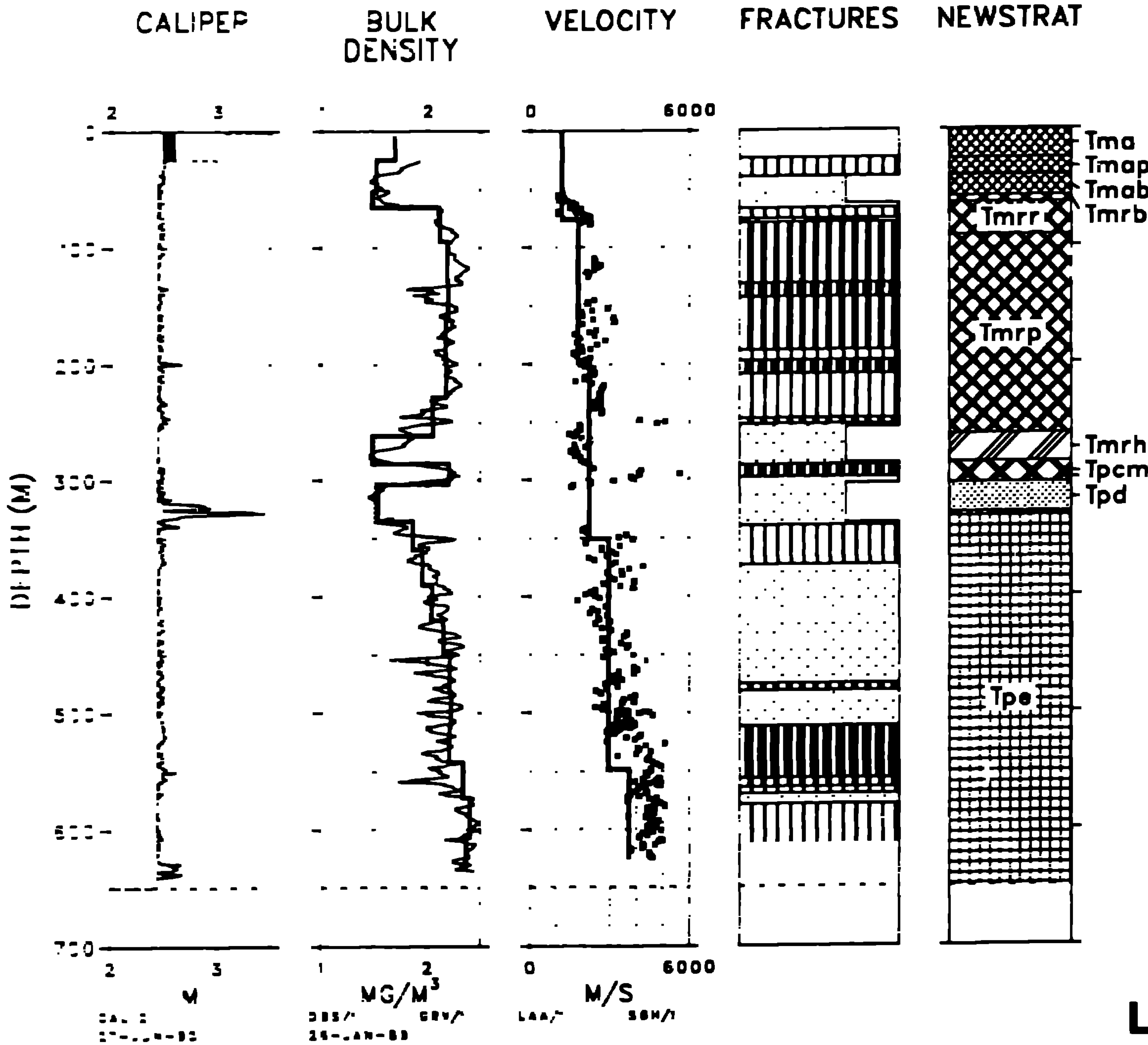




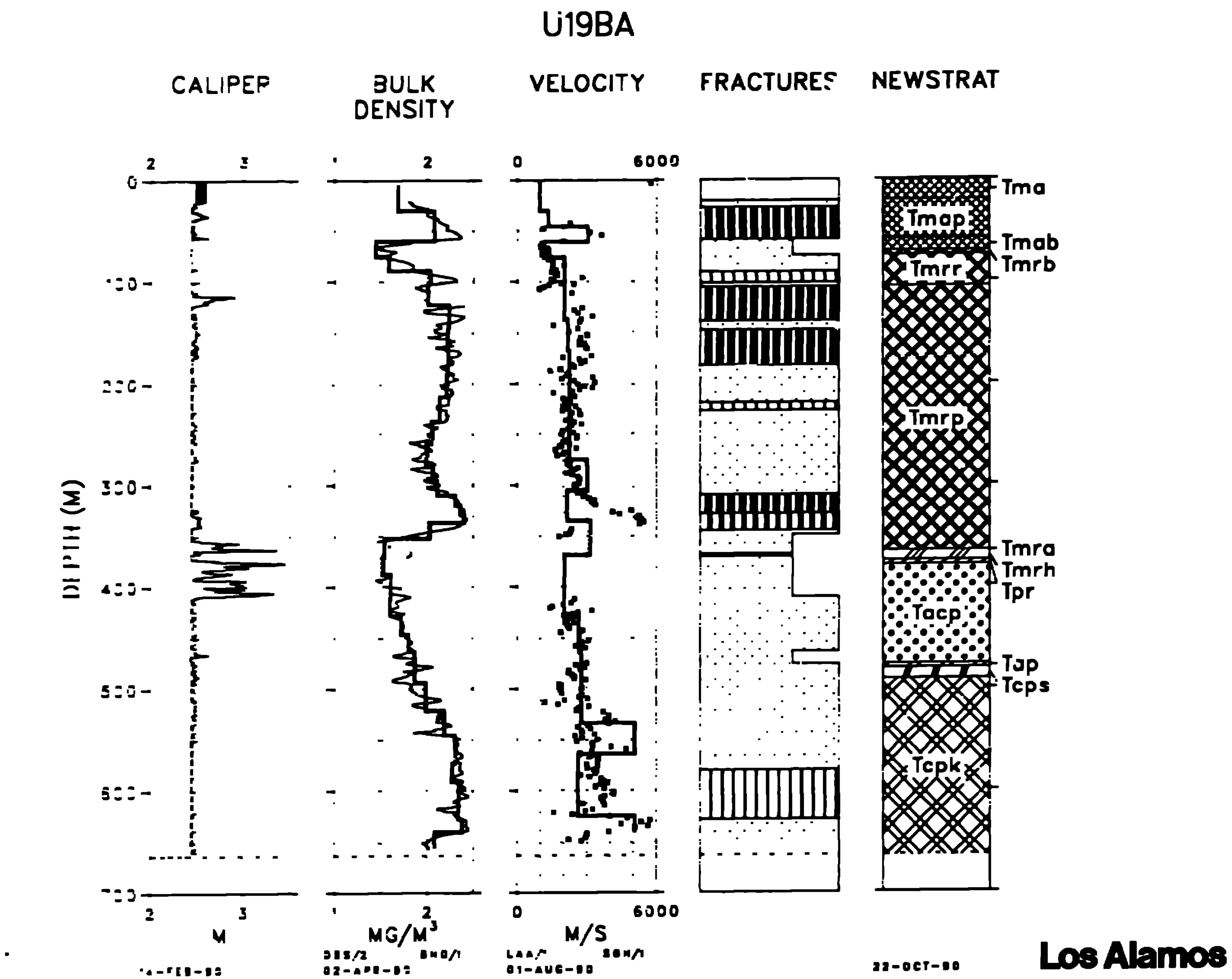
CALIPER
BULK DENSITY
VELOCITY
STRAT
DEPTH (M)
Qal
Tma
Tmru
Tmrm
Tmrl
Tp
M
MG/M³
M/S

Los Alamos

UI9AZ

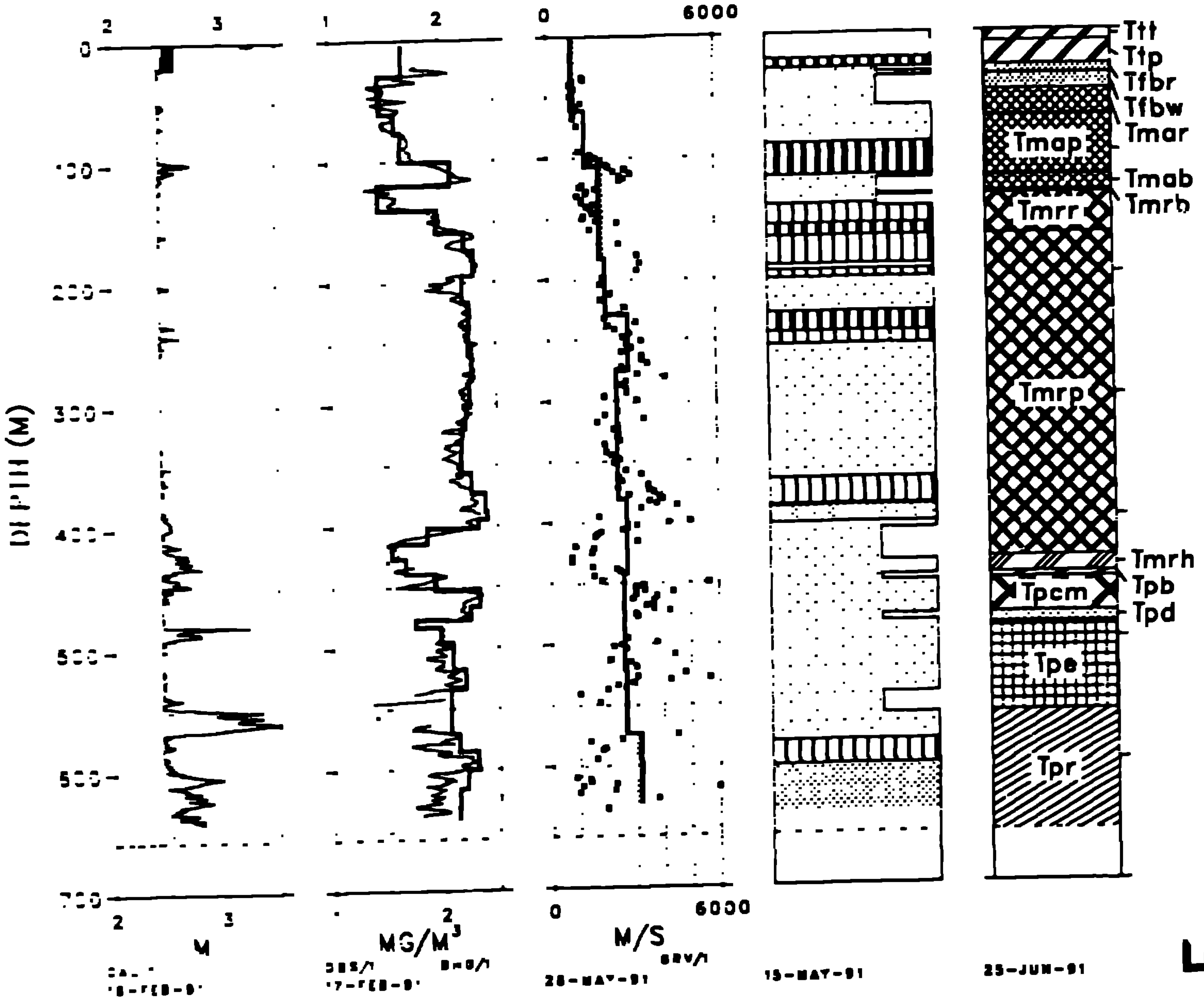


Los Alamos

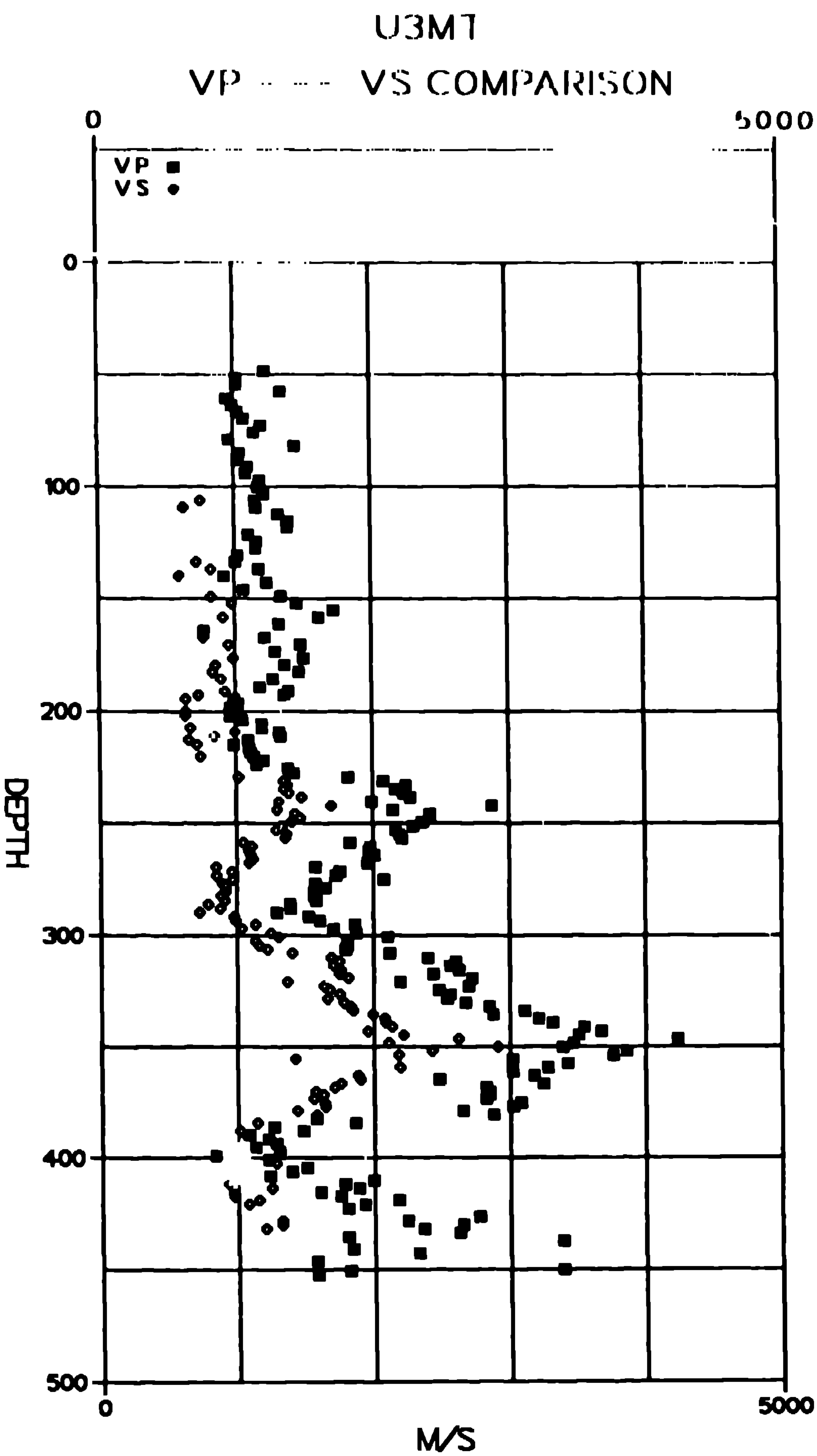


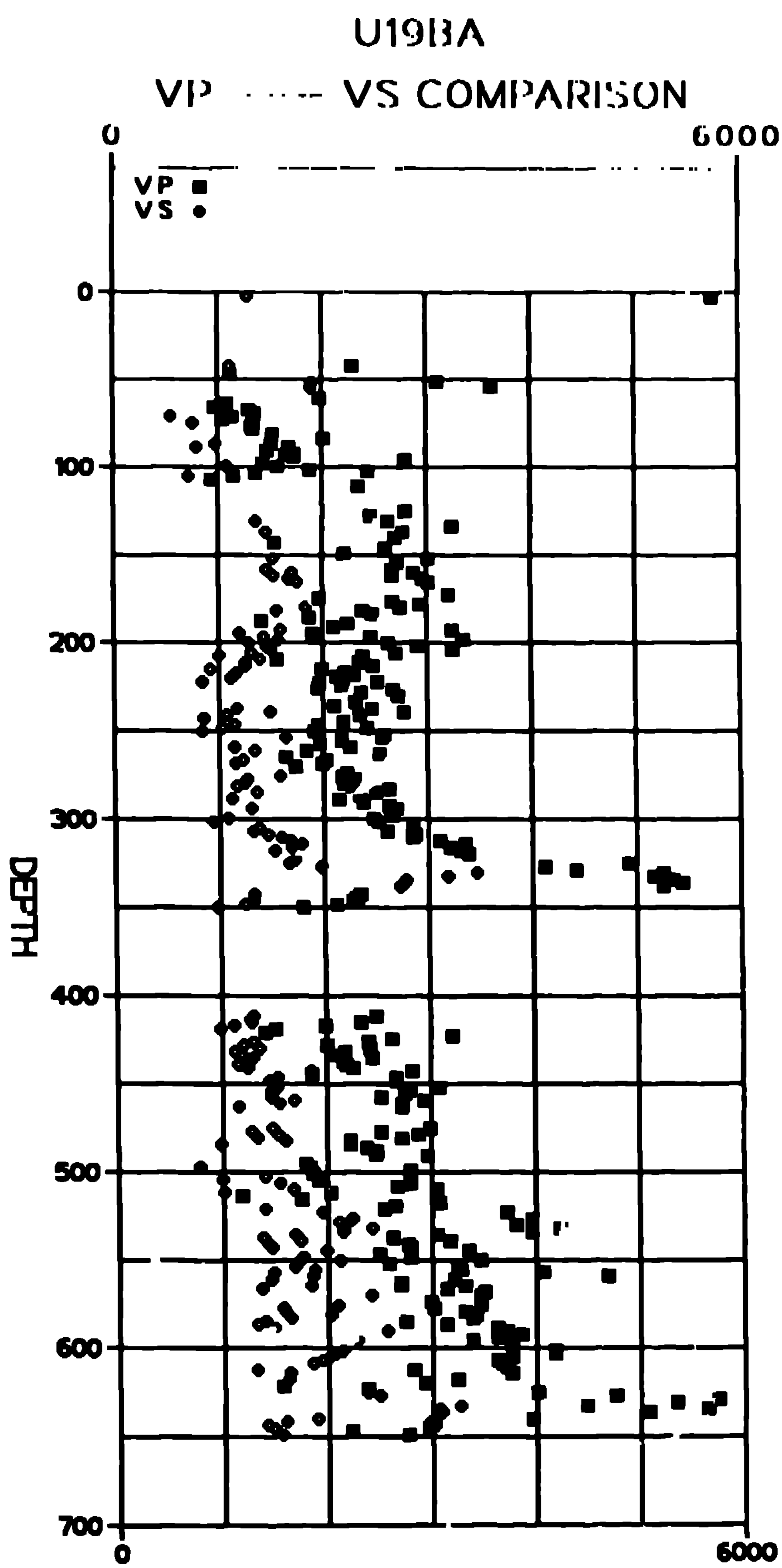
U19BA
CALIPER
BULK DENSITY
VELOCITY
FRACTURES
NEWSTRAT
DEPTH (M)
M
MG/M³
M/S
0
6000
Tma
Tmap
Tmab
Tmrr
Tmrb
Tmrp
Tmra
Tmrh
Tpr
Tacp
Tap
Tcps
Tcpk
22-OCT-90
Los Alamos

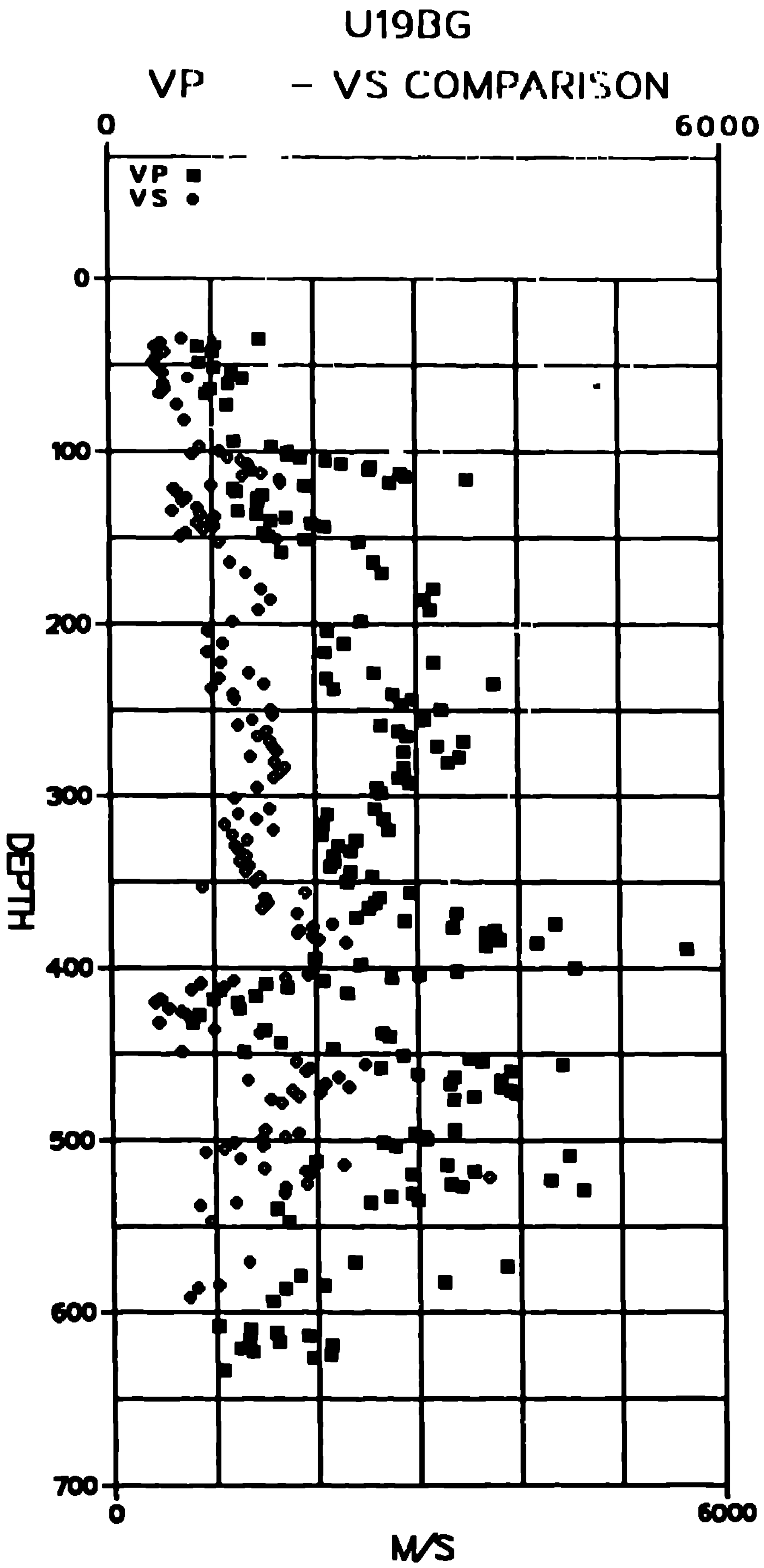
U19BG

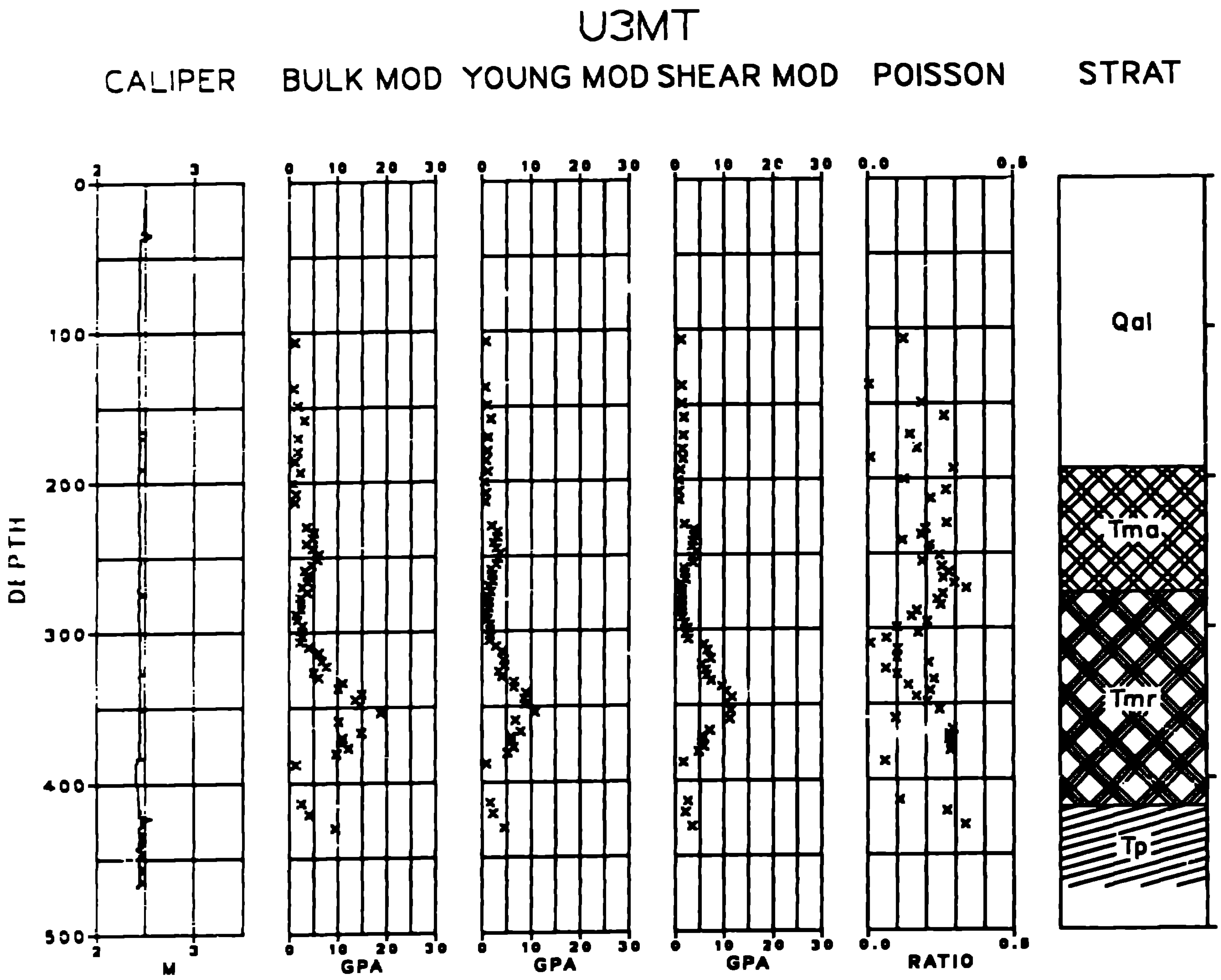


Los Alamos

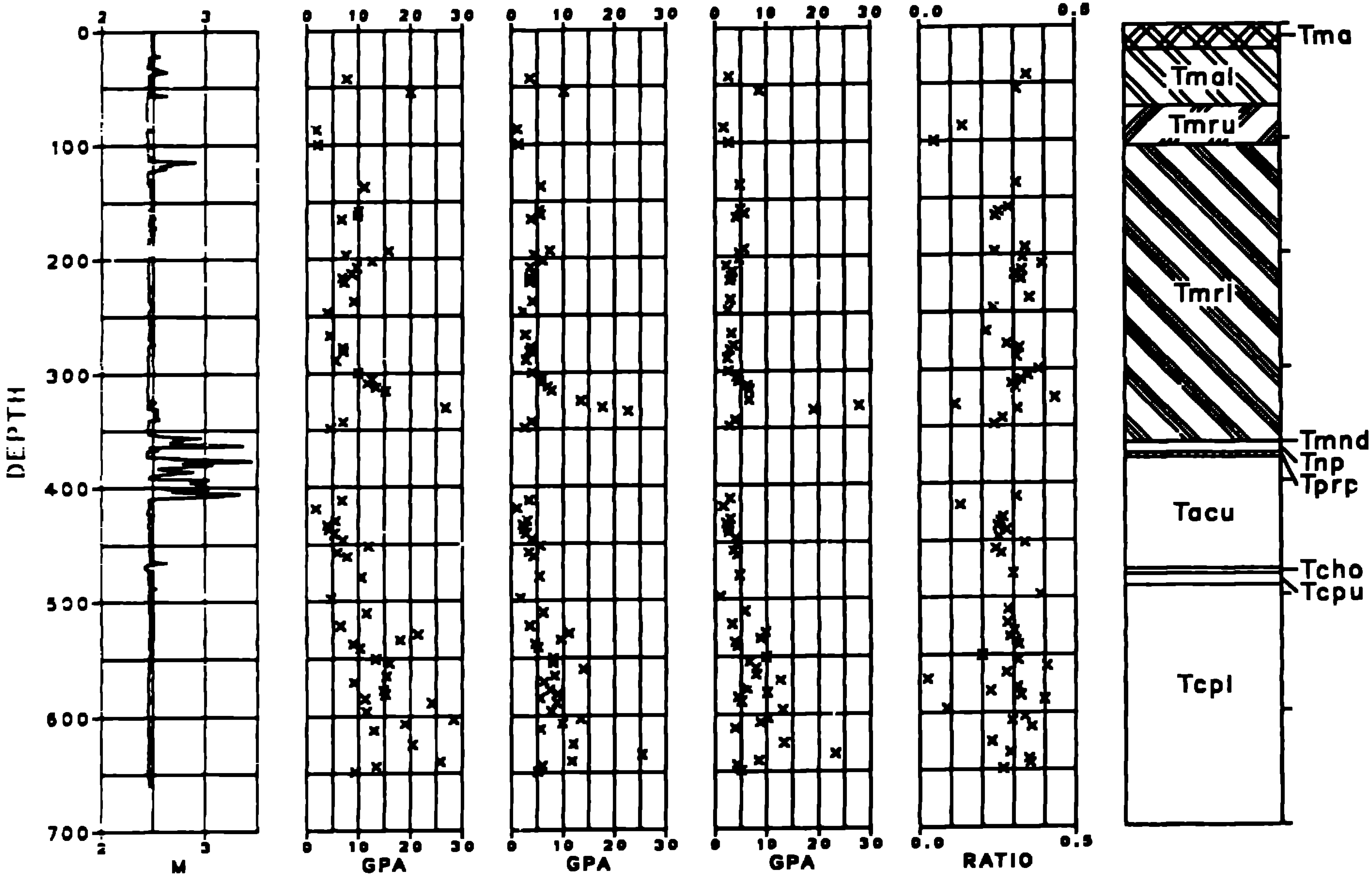

U3MT
VP - - - VS COMPARISON
VP
VS
0
5000
0
100
200
300
400
500
DEPTH
M/S


U19BA
VP ---- VS COMPARISON
0
6000
VP
VS
0
100
200
300
400
500
600
700
DEPTH
0
6000
M/S

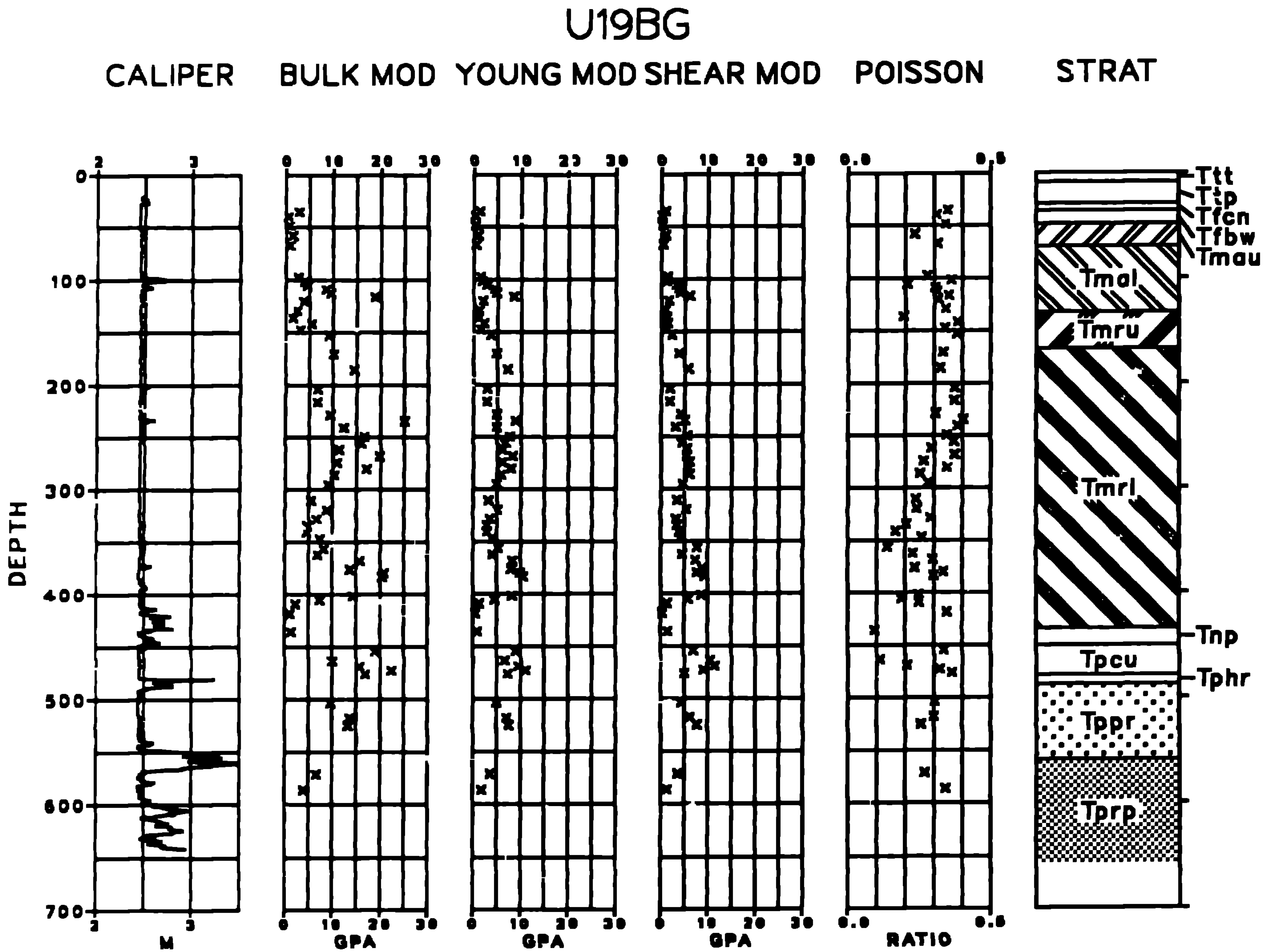

U19BG
VP - VS COMPARISON
0
6000
VP
VS
DEPTH
0
100
200
300
400
500
600
700
0
6000
M/S


U3MT
CALIPER
BULK MOD
YOUNG MOD
SHEAR MOD
POISSON
STRAT
DEPTH
M
GPA
GPA
GPA
RATIO
Qal
Tma
Tmr
Tp

U19BA



CALPIER
BULK MOD
YOUNG MOD
SHEAR MOD
POISSON
STRAT
DEPTH
0
100
200
300
400
500
600
700
2
3
M
0
10
20
30
GPA
0.0
0.5
RATIO
Tma
Tmal
Tmru
Tmrl
Tmnd
Tnp
Tprp
Tacu
Tcho
Tcpu
Tcpl


U19BG
CALIPER
BULK MOD
YOUNG MOD
SHEAR MOD
POISSON
STRAT
DEPTH
M
GPA
GPA
GPA
RATIO
Ttt
Tip
Tfcn
Tfbw
Tmau
Tmal
Tmru
Tmrl
Tnp
Tpcu
Tphr
Tppr
Tprp