TECHNICAL REPORT NO. 63-15

FINAL REPORT ON TASKS 1a THROUGH 1g (PHASES I AND II) OF PROJECT VT/1139

THE GEOTECHNICAL CORPORATION

3401 SHILOH ROAD GARLAND, TEXAS

GEOTECH

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THE GEOTECHNICAL CORPORATION
3401 Shiloh Road
Garland, Texas

31 January 1963

IDENTIFICATION

AFTAC Project No: VT/1139
Project Title: Deep-Hole Seismometer (Variable-Reluctance Type)
ARPA Order No: 104
ARPA Code No: 8100
Contractor: The Geotechnical Corporation, Garland, Texas
Date of Contract: 22 May 1961 Phase I; 16 April 1962 Phase II
Contract No: AF 33(600)-43369
Contract Expiration Date: 15 October 1962, extended to 31 January 1963, by Supplemental Agreement No. 2
Project Engineer: Richard M. Shappee, Garland, Texas, BR8-8102

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SUMMARY

A deep-well, variable-reluctance-type seismometer was designed in accordance with the general specification of the statement of work. The seismometer was tested in the laboratory, and then in shallow and deep wells. A brief description of the work accomplished under each task of the statement of work is given below, and a copy of the statement of work is included as appendix 1. Specific details are given in the report.

Task 1a - A study of the requirements to be met was undertaken, and the design of a deep-well seismometer was completed.

Task 1b - Two prototype seismometers were assembled and tested.

Task 1c - Components of a complete system were assembled and handling fixtures were fabricated.

Task 1d - Laboratory tests of the deep-well seismometer were completed.

Task 1e - Reduction of laboratory test data was completed.

Task 1f - Preparation and implementation of a field test program was started and completed as Phase II of this contract:

- 1f (1) (a) - Test sites were located and prepared.
- 1f (1) (b) - Special site facilities and services were provided.
- 1f (2) - Assembly and fabrication of seismographs and testing equipment for field use was completed.
- 1f (3) - A testing program was completed.
- 1f (4) - Evaluation of results and reduction and analysis of data were completed, and the recommendations and conclusions were submitted. A copy of the recommendations and conclusions is included as appendix 2 of this report.

Task 1g - Testing was resumed at the Grapevine, Texas, site.

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FINAL REPORT ON TASKS 1a THROUGH 1g (PHASES I AND II) OF PROJECT VT/1139

1. INTRODUCTION

1.1 SCOPE

This report describes the work accomplished on tasks 1a through 1g (Phases I and II) of Project VT/1139 during the period 21 May 1961 through 30 November 1962. A variable-reluctance seismometer suitable for long-term operation in a deep well was designed, constructed, and laboratory tested during Phase I. During Phase II, the seismometer was operated in a deep well near Grapevine, Texas, and in a deep well near Hobart, Oklahoma. The field operations showed that the seismometer meets the design objectives and is satisfactory for use in more extensive field programs.

1.2 AUTHORITY

This work was completed under the direction of the Air Force Technical Applications Center on Project VT/1139, Contract AF 33(600)-43369.

2. DESIGN DEEP-WELL SEISMOMETER, Task 1a

The study phase, which resulted in specifications for material and design for the seismometer, was completed during the first 6 months of the program. After completion of the first prototype, design changes were made to improve the stability and ruggedness of the seismometer. Assembly jigs were constructed to simplify the assembling operation.

2.1 Figure 1 shows the details of the seismometer, and figure 2 shows the completed instrument. Figures 3, 4, 5 and 6 show the general arrangement of the major sub-assemblies of the seismometer. The final design characteristics of the seismometer are given in table 1.

2.2 The centering and locking motor, shown in figure 3, operates on a nominal 24 vdc at 0.08 amp and imparts a motion to the top of the spring of 0.025 inch per minute. This rate was chosen as a compromise between ease of centering the mass, and the length of time required to lock the mass.

2.3 The transducer, shown in figure 4, is of the variable-reluctance type as specified in the statement of work. Magnetic shunts permit adjustment of the flux in the gaps.

2.4 The inertial mass is constrained to vertical motion by the delta rods shown in figure 5. These rods, with a diameter of 0.046 inch, have a combined spring rate of 56 pounds per inch.

2.5 An electrodynamic calibrator is used to permit remote calibration of the seismograph. Three coils, each with a resistance of 1700 ohms, are arranged as shown in figure 6. The frequency of the mechanical output of the calibrator is twice the frequency of the calibrator input because of the inherent frequency-doubling characteristic of this type of calibrator.

2.6 The various sections of the case of the seismometer are sealed by standard O-rings and back-up rings. We have had no failures of the seals.

Table 1
Design Characteristics of the Deep-Well Seismometer, Model 11167

1.	Weight of inertial system	100 kg
2.	Natural, undamped frequency of inertial system only	2.43 cps
3.	Natural, undamped frequency of seismometer, including negative restoring force of transducer	1.0 cps
4.	Resistance of transducer, coils in series (2 coils)	300 ohms
5.	External resistance for 17:1 damping at 20°C	400 ohms
6.	Calibration coil motor constant	130 newton/amp^2
7.	Resistance of calibration coil	5100 ohms
8.	Centering motor input	28 vdc .08 amp dc
9.	Ratio of negative to positive restoring force	.82

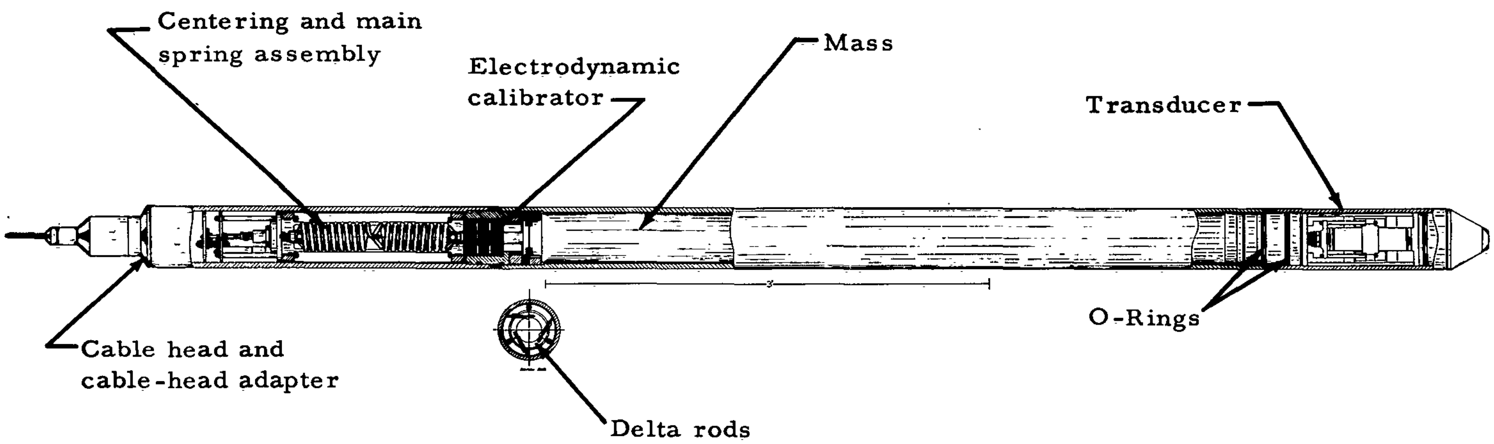

Figure 1. Deep-Well Seismometer, Model 11167, variable-reluctance type

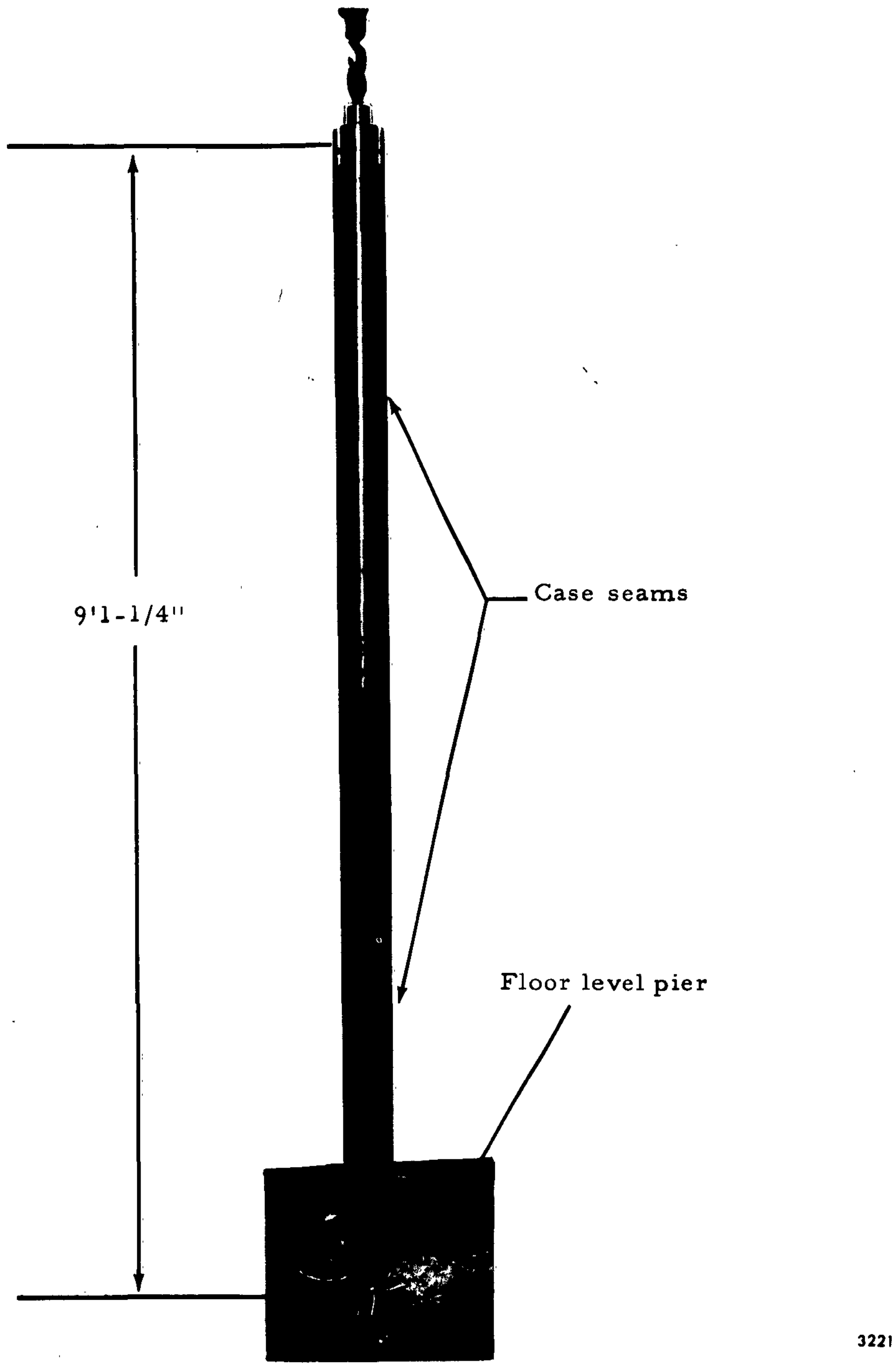

Figure 2. Deep-well seismometer

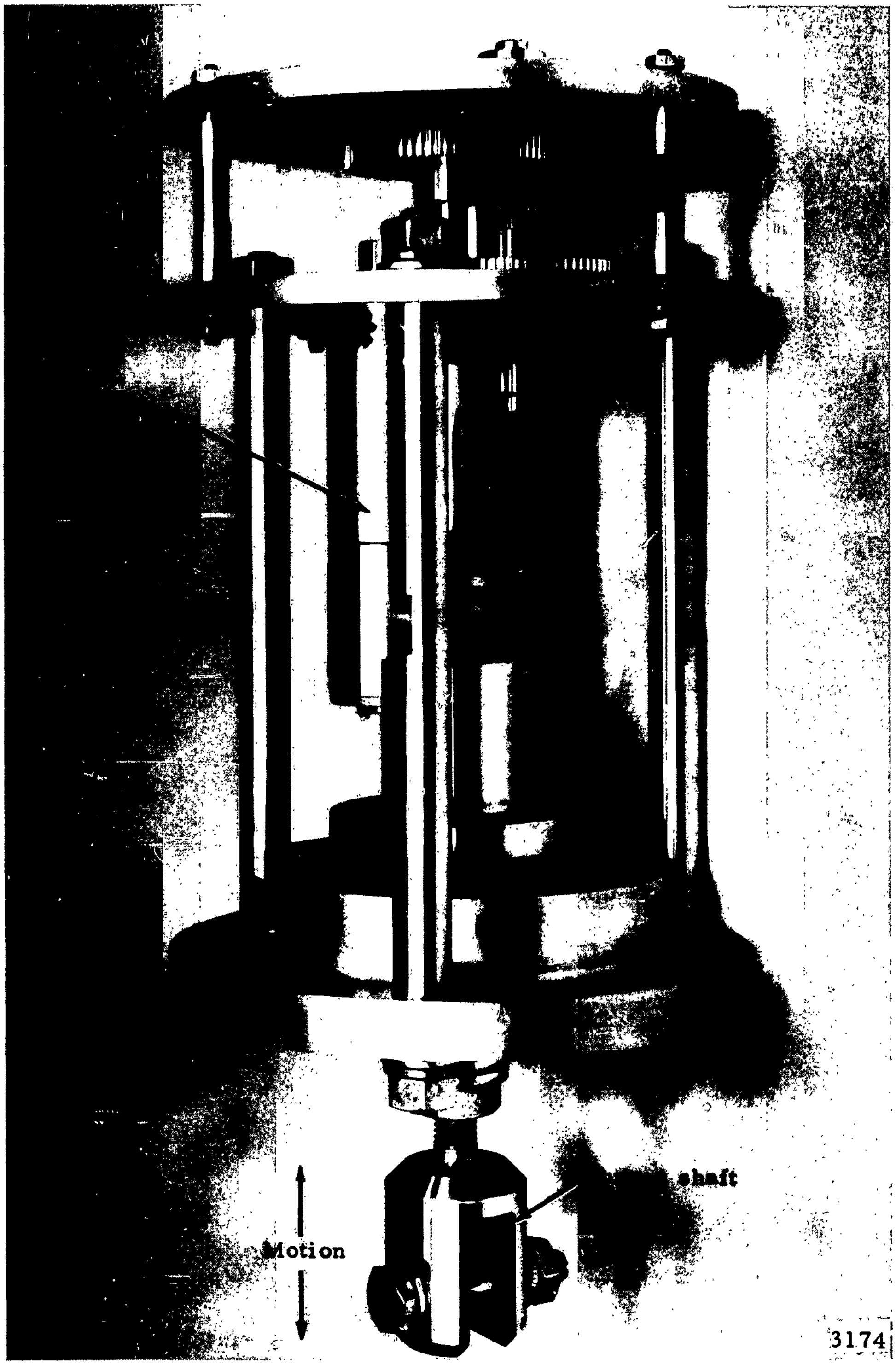

Figure 3. Mass-positioning device

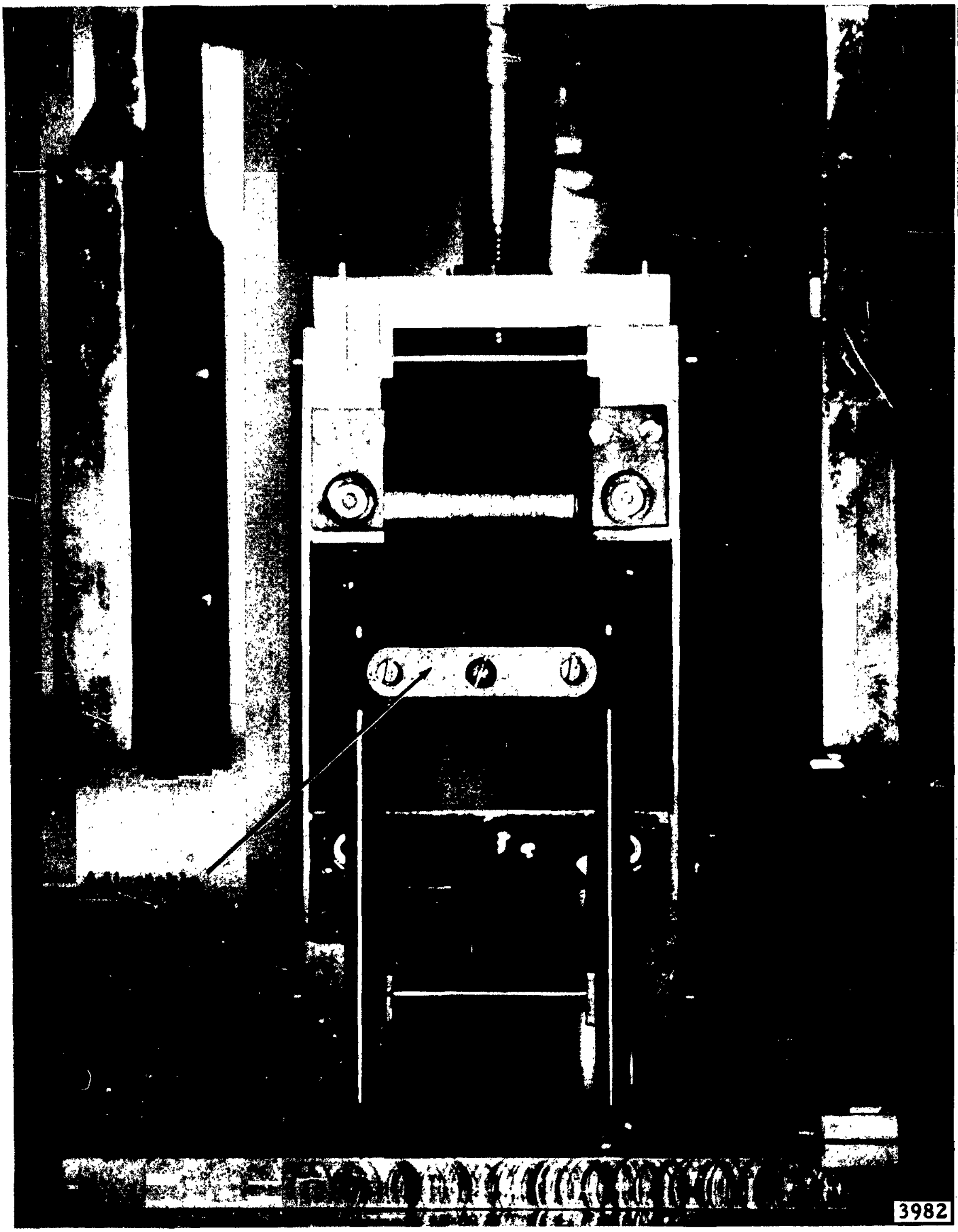

Figure 4. Deep-well transducer mounted on Benioff seismometer

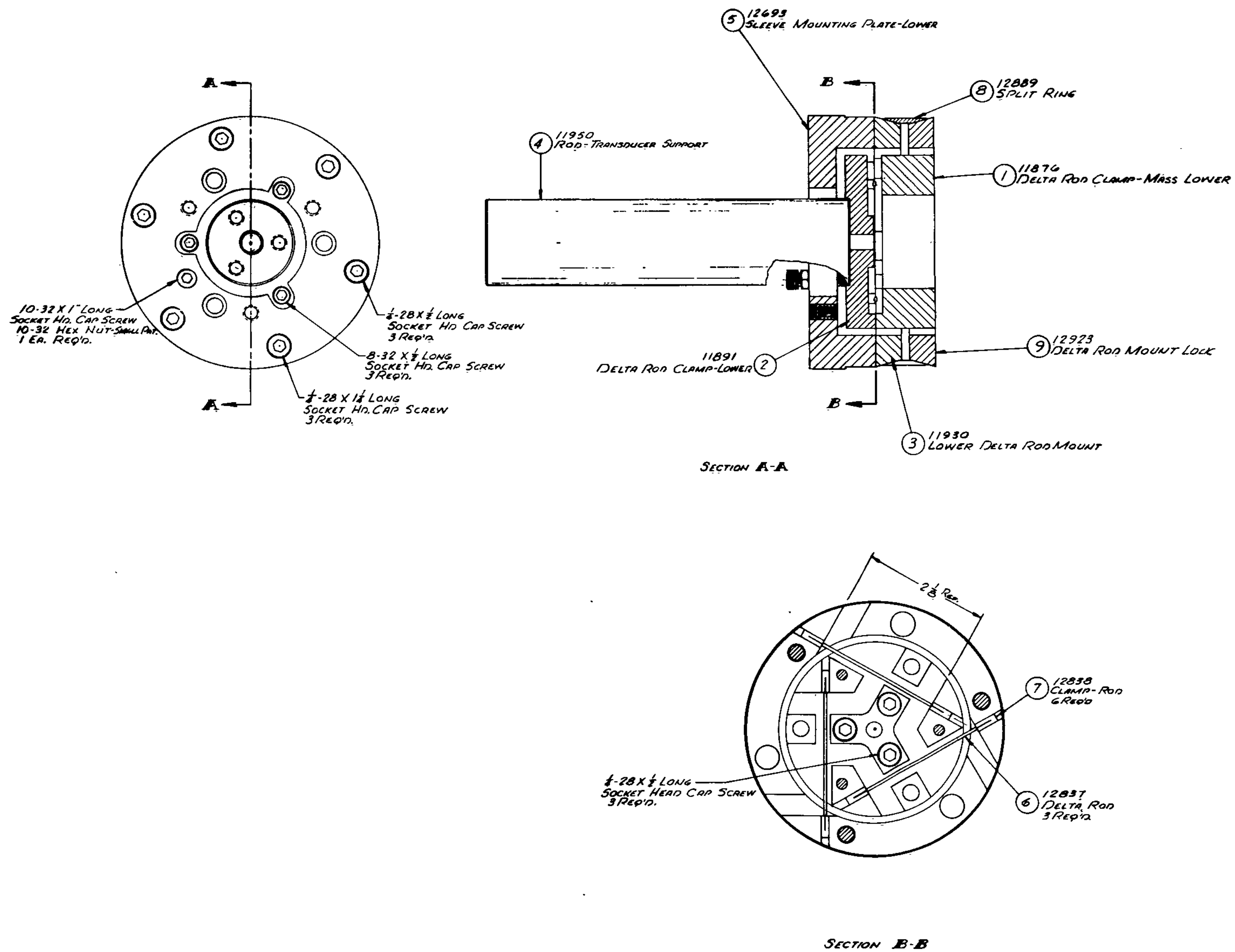

Figure 5. Delta rod arrangement

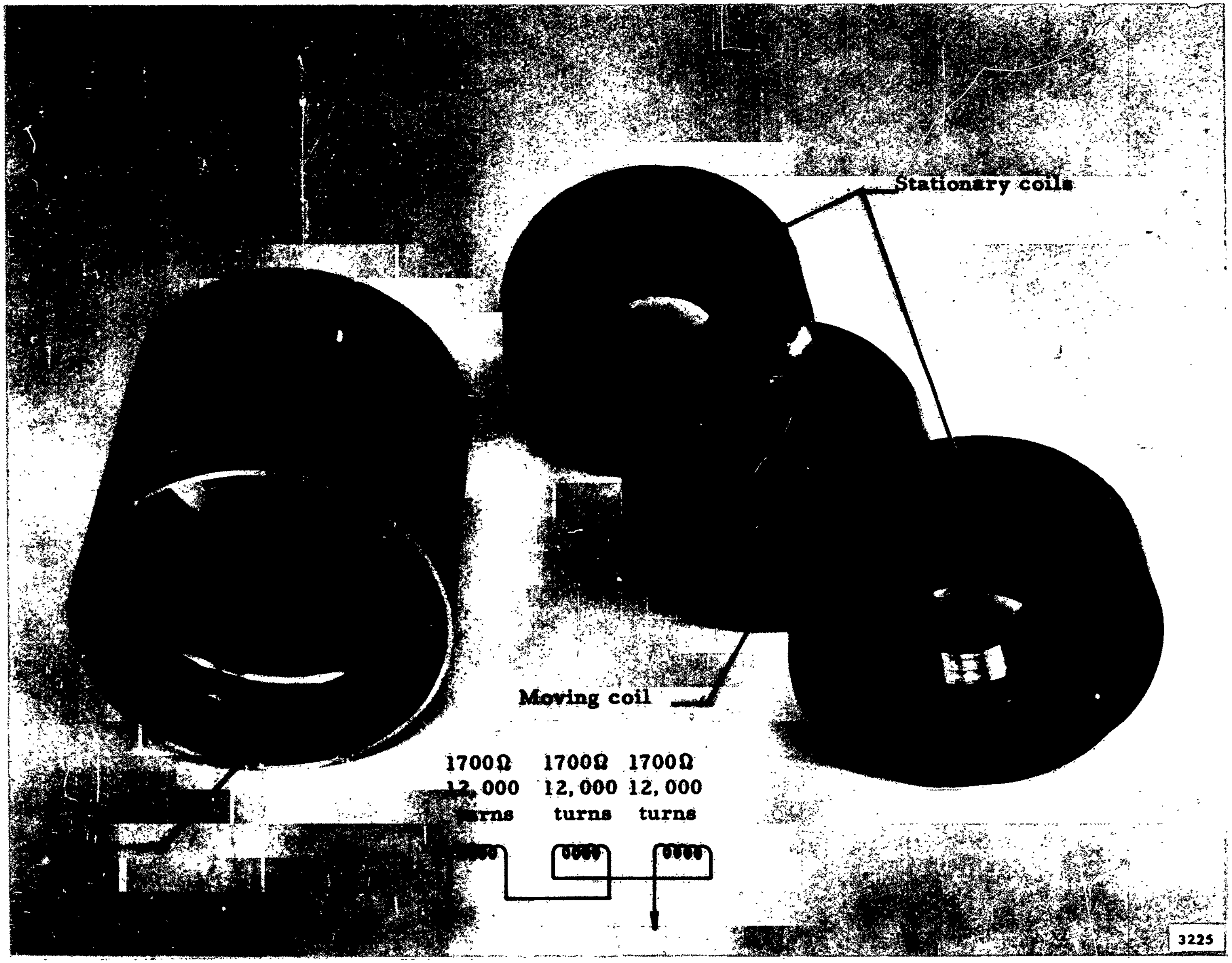

Figure 6. Electrodynamic calibrator, deep-well seismometer

3. CONSTRUCT PROTOTYPE, Task 1b

A second prototype seismometer was constructed using the improved design changes made on the first seismometer. These design changes greatly improved the stability and ruggedness of the seismometer.

4. ASSEMBLE SYSTEM, Task 1c

All necessary equipment needed to operate the system was procured. This included Phototube Amplifiers, Geotech Model 4300, Centering Motor Control, Geotech Model 12345, calibration-control panel, cables, connectors, and handling equipment.

5. LABORATORY TESTS, Task 1d

Shake table and calibration coil tests of the seismometer were completed. Figure 7 shows the shake table and calibration coil responses of the seismometer compared to LRSM and WMSO response curves for Benioff systems. In order to determine the performance of the seismometer at elevated temperature, the instrument was operated in a temperature chamber. The instrument had a natural undamped frequency of 1.01 cps at room temperature. When raised to a temperature of 220°F, the natural frequency increased to 1.10 cps or about a 9 percent increase. The free-period decay of the seismometer, which is an indication of the internal damping of the mass system, was unchanged at elevated temperatures.

Pressure tests were performed at 2500 psi, 4500 psi, and 7500 psi at Schlumberger Well Surveying Corporation in Houston, Texas. Because of the high noise level, an accurate measurement was difficult, but it was estimated that the free period changed less than 5 percent.

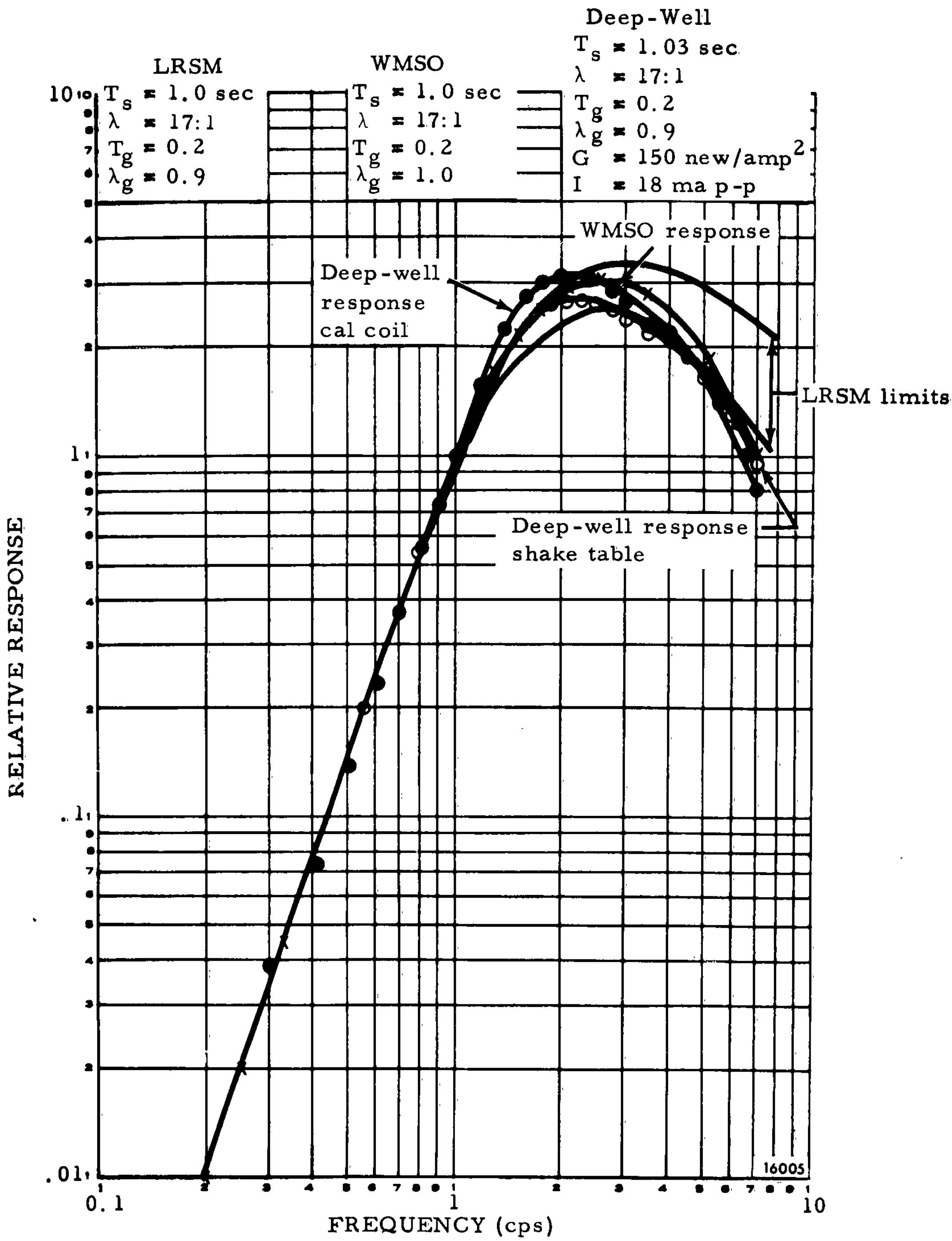

Figure 7. Shake table and calibration coil response of deep-well system compared to response of LRSM and WMSO systems. Curves normalized at 1 cps

The design requirements to be met and the test data and instrument characteristics are summarized below.

Design requirements:	Test or instrument characteristics:
Mass greater than 100 kg	103 kg
Instrument natural undamped frequency 1 cps	1 cps
Instrument noise consistent with ambient noise expected	Thermal agitation noise equivalent to an earth motion of 0.05 Å (calculated)
Rugged design	Can be transported fully assembled
Operate at expected well temperature	Tested to 250°F in temperature jacket
Operate at 7500 psi external	Tested to 7500 psi at Schlumberger facilities
Cylindrical construction, 5-inch maximum diameter	5-inch diameter x 107-inches long
Corrosion resistant	Alloy steel case, hard chrome O-ring seat and threads
Operate in linear range when tilted up to 10°	Proved by shake table tests and calibration coil tests

A 500-ft cable and header were purchased for preliminary tests in a shallow well. Both header and cable were found to be adequate for shallow well operation where pressure and temperature were not extreme. The first prototype seismometer was installed in a 350-ft cased well at the Garland plant. After 1 week of operation, the seismometer was raised to the surface and installed in the 220-ft uncased hole at WMSO. At both sites a surface Benioff was used for comparison. Figures 8 and 9 are events recorded at each well.

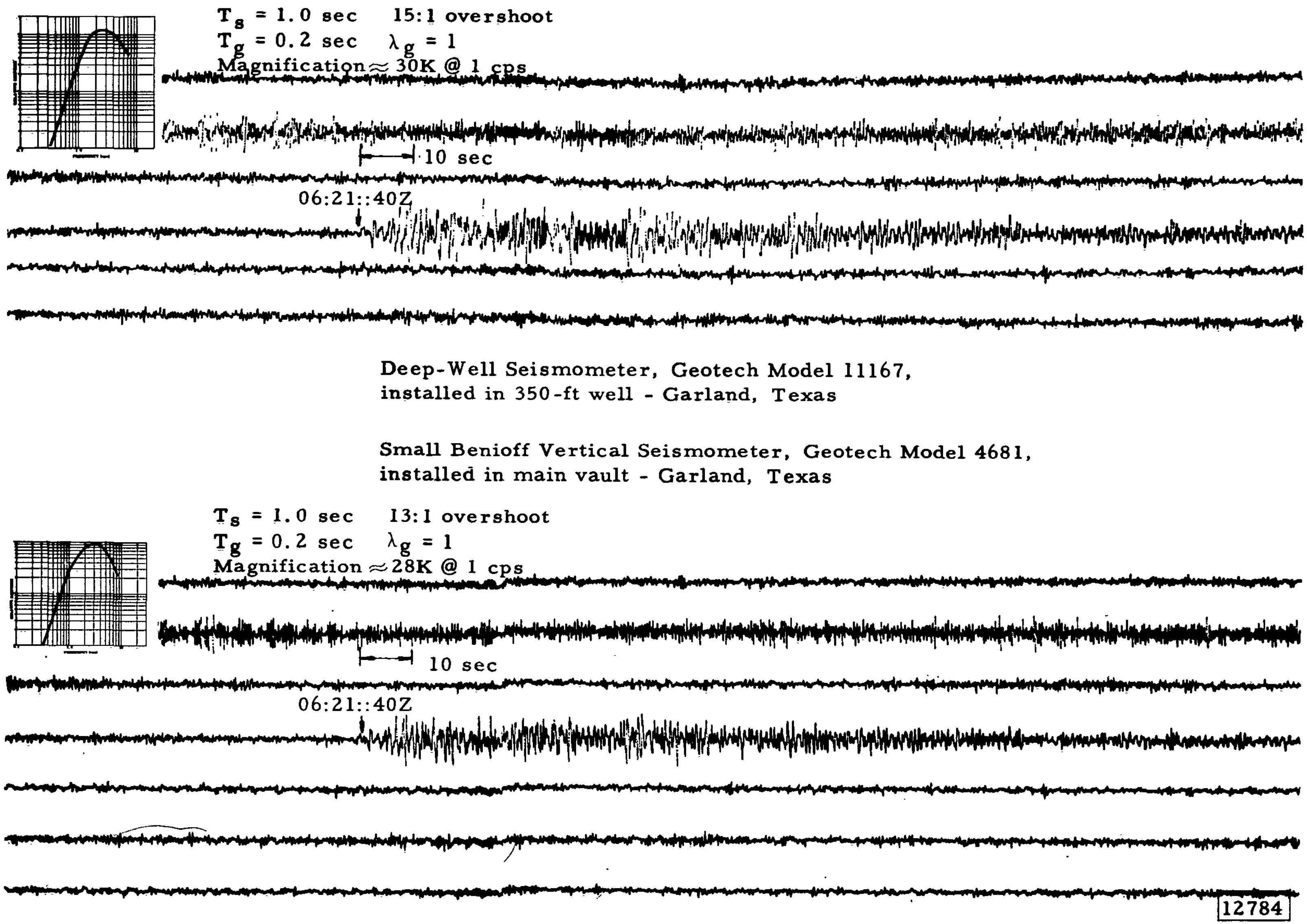

Figure 8. Comparison of records of event recorded from surface instrument and deep-well instrument

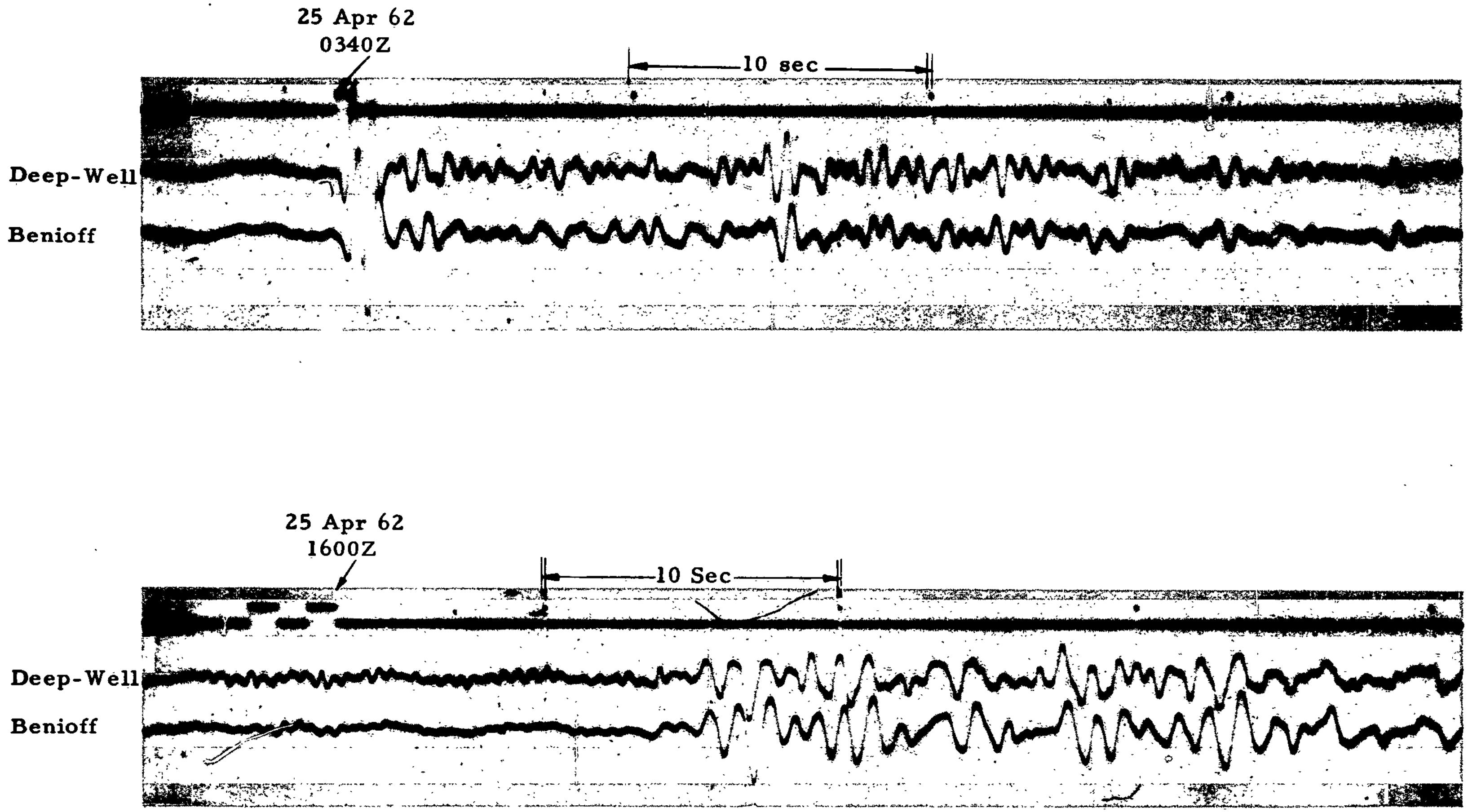

Figure 9. Develocorder record of deep-well seismometer and large Benioff seismometer at WMSO. Magnification $\approx$ 490K @ 1 cps.

6. DATA REDUCTION, Task 1e

As might be expected, no measurable signal-to-noise ratio improvement was noted in the shallow-well test. Acoustical waves in the well at WMSO were frequently observed on the records in the form of high frequency "ringing" as shown in figure 10. This ringing may have occurred in the well at Garland but could not be detected because of the low system magnification.

7. PREPARATION AND IMPLEMENTATION OF A FIELD TEST, Task 1f

7.1 INVESTIGATE AVAILABLE WELLS AND WELL SITES, Task 1f (1) (a)

Investigation revealed that two wells, the Trigg No. 1 near Grapevine, Texas, and the Prater No. 1 near Hobart, Oklahoma, were suitable for the field test program. Lease arrangements were completed, the wells were cased with 7-in casing, and derricks were erected over the wells. A 75-ft shallow well was drilled and cased at the Grapevine site for surface comparison and a 512-ft well was available for this purpose at the Hobart site. Sixty-foot A-frames were erected over the shallow wells, all-weather roads were built, and recording vans from the VT/074 program were moved to each site.

7.2 SPECIAL SITE FACILITIES AND SERVICES, Task 1f (1) (b)

Lease arrangements were made with Schlumberger Well Surveying Corporation for a winch truck, cable, and other equipment necessary for field operation. This equipment was delivered when the field test program began. Figures 11 and 12 show the layout of the two sites. Figure 13 shows the general location of the van and wells at the Grapevine site.

7.3 ASSEMBLE AND FABRICATE SEISMOGRAPHIC AND TESTING EQUIPMENT, Task 1f (2)

A third deep-well seismometer was built and a Phototube Amplifier, Geotech Model 4300, was ordered and received. The necessary operating equipment

Figure 10. Develocorder record of high frequency (≈ 2 cps) ringing recorded from deep-well seismometer in uncased shallow well at WMSO. Magnifications $\approx 490K$ at 1 cps. Recorded on 25 April 1962

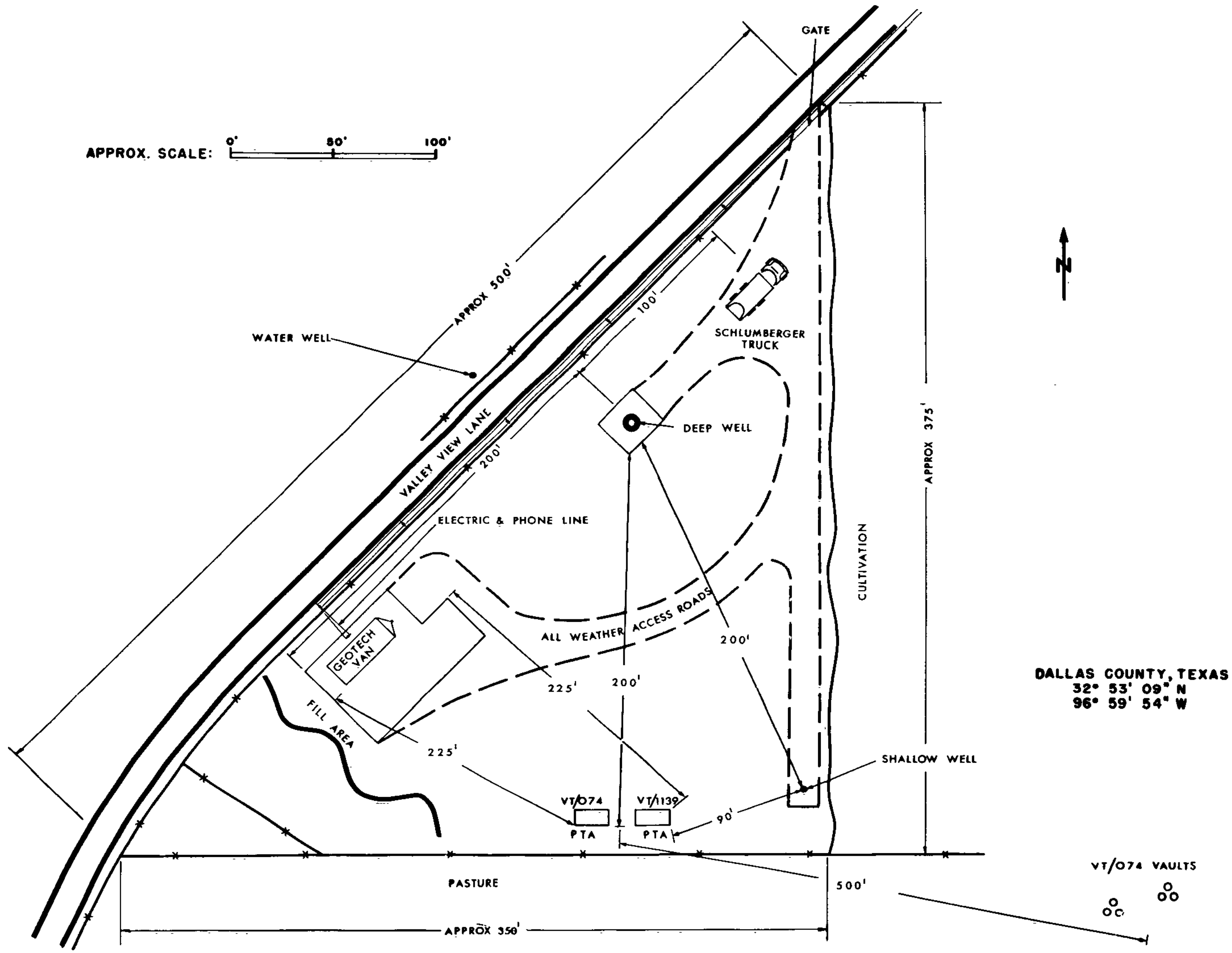

Figure 11. Trigg No. 1 deep-well site

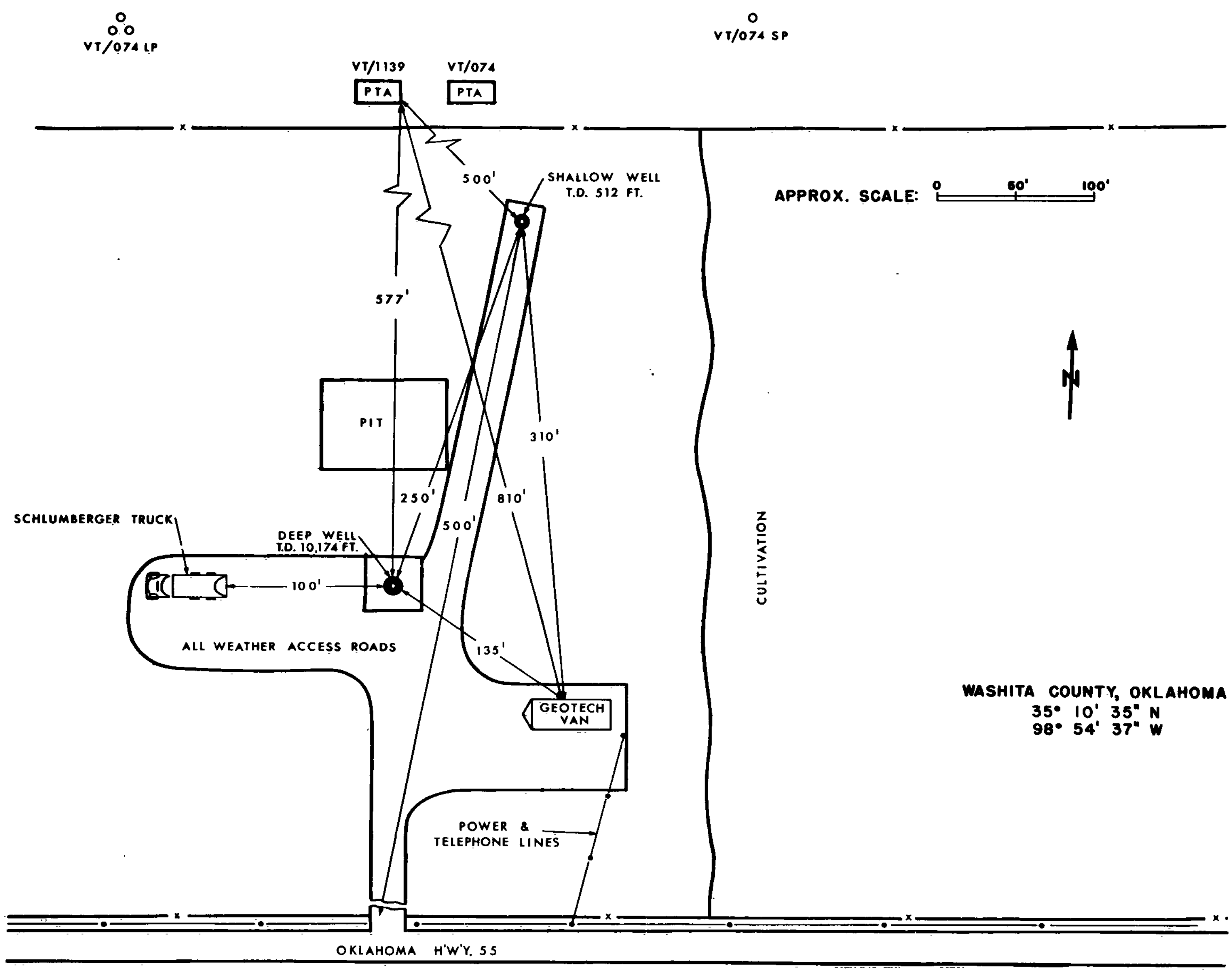

Figure 12. Prater No. 1 deep-well site

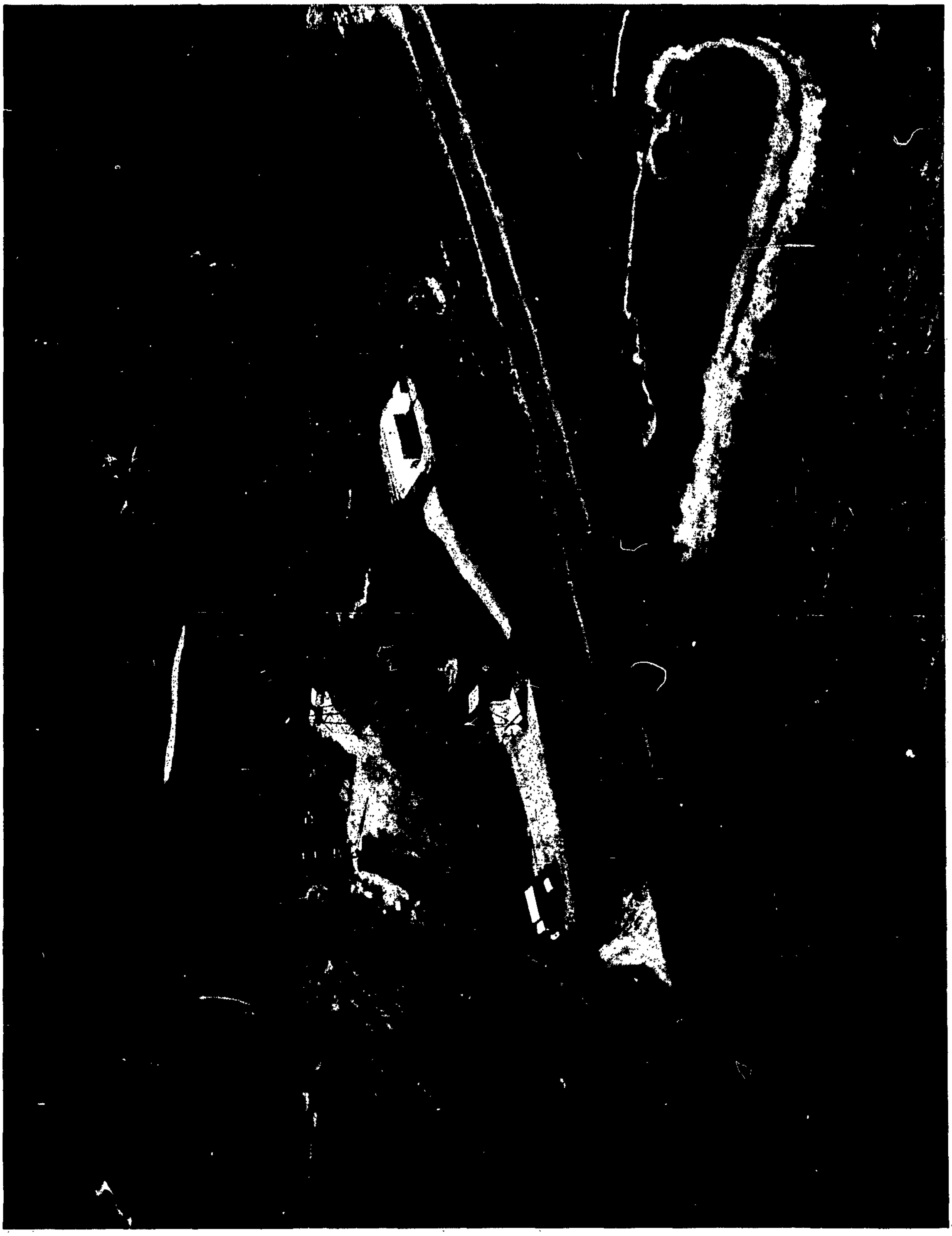

Figure 13. Location of equipment at Grapevine site

such as specialized controls, panels, and cables necessary for field testing were constructed under Phase I of this program. An on-site shop facility, shown in figure 14, was ordered and received. This facility contains all necessary equipment needed for service and maintenance of the deep-well seismograph.

7.4 FIELD TEST, Task 1f (3)

The field test program began 1 June 1962. Recordings were made at Grapevine, Texas, during the periods 5 June 1962 through 12 August 1962 and 30 October 1962 through 30 November 1962. Recordings were made at Hobart from 16 August 1962 through 18 October 1962.

Electrical leakage in the leased cable and connectors prohibited continuous operation of the seismometer in the deep well. Figures 1 and 2, appendix 2, show the operational time at Grapevine and Hobart. It should be noted that an identical instrument operated in the shallow well at each site (75 ft at Grapevine, 512 ft at Hobart) without failure.

With the approval of the Project Officer, a hole lock was designed and built to permit operation in the well at selected depths in order to measure signal-to-noise improvement as a function of depth. Operation with the hole lock started on 28 September 1962 at Hobart. The operational time at each selected depth is listed below.

Time interval	Depths of operation at Hobart in feet
28-30 September	493
30 September	9766
2- 3 October	8452
3- 6 October	7474
6- 8 October	6498
8-10 October	5591
10-11 October	4520
11-12 October	3792
12-16 October	2769
16-18 October	1702

The instruments were raised to the surface and the operations were moved to Grapevine on 19 October 1962.

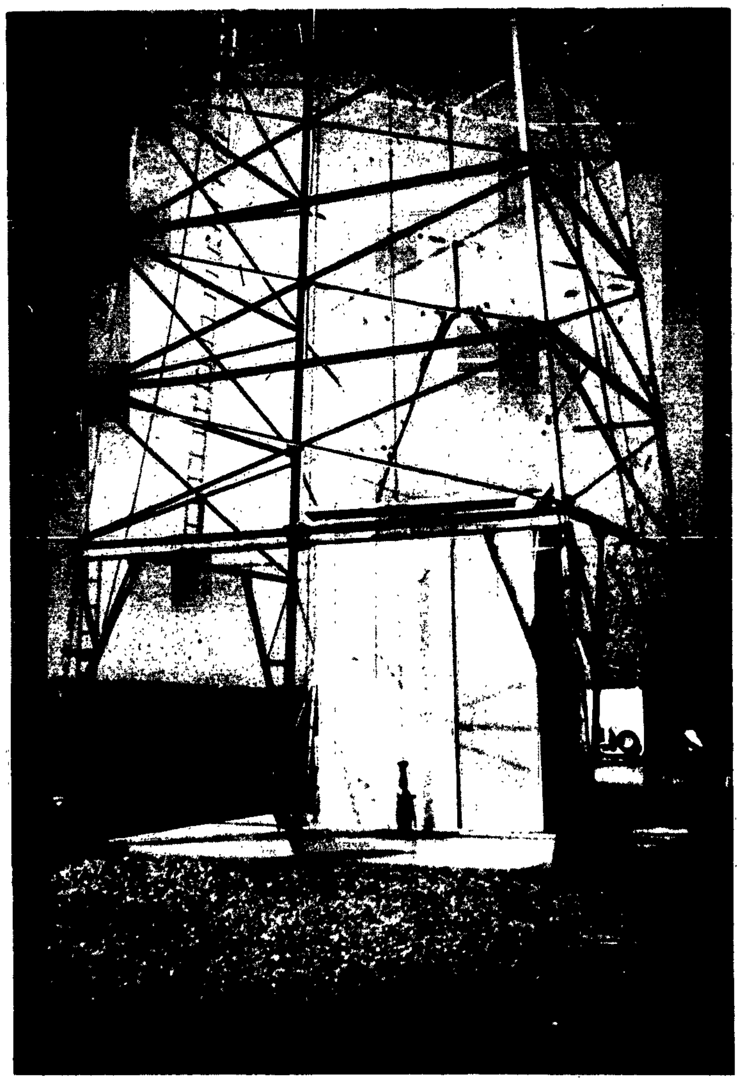

Figure 14. On site service facility

7.5 REDUCTION AND ANALYSIS OF DATA, Task 1f (a)

The records produced during this work have been analyzed to show the performance characteristics of the seismometer and, to a lesser degree, some of the characteristics of the two wells in which the seismometer was tested. The results of the analysis are given in appendix 2.

8. CONTINUE TESTING AT GRAPEVINE SITE, Task 1g

Testing was resumed at the Grapevine site on 26 October 1962. Preliminary measurements were made of signal-to-noise improvement and p-wave amplitude reduction as a function of depth. Because of the high surface noise, few signals were recorded that could be used for this work. It is probable that comparisons between signals recorded at various depth and signals recorded from a deep-well seismometer in a well of intermediate depth will permit the work to be completed.

9. CONCLUSIONS

9.1 The seismometer meets all the requirements of the statement of work and is capable of long-term operation in wells 10,000 to 12,000 feet deep.

9.2 The standard Schlumberger well-logging cable and connector operated continuously from 15 August 1962 until the end of the test program at the Hobart site, a period of about 45 days. The electrical leakage was above 2 megohms when it was removed from the well and it is likely that the cable could have operated for a much longer period. Because of the cable troubles encountered earlier in the program, the results described above may not be indicative of future performance.

9.3 The noise level of the complete seismograph system with the seismometer at the bottom of a 10,000-ft well and with the seismometer mass locked is equivalent to an earth motion of about 0.1 mμ (peak-to-peak) at 1 cps. The inherent noise level of the seismometer (thermal agitation noise) is lower than this; however, no direct measurement has been made of this noise.

10. RECOMMENDATIONS

10.1 We recommend that the deep-well variable-reluctance seismometer developed and tested in tasks 1a through 1f be used in a field measurement program to:

a. Investigate geological and other factors which influence the signal-to-noise improvement obtained by operating seismometers in deep wells.

b. Measure and study the physical characteristics of deep wells in order to determine methods of emplacing seismometers to optimize the detection of small signals.

c. Compare signal-detection capability with that of a surface array by making an installation in a well near a permanent seismic station.

10.2 We recommend that the data accumulated in the field measurement program be processed to permit comparison between observations and theoretical studies to evaluate the effects of geology, environment, and emplacement technique on signal-to-noise improvement.

APPENDIX 1 to TECHNICAL REPORT NO. 63-15

WORK STATEMENT, PHASES I & II, PROJECT VT/1139

APPENDIX 1 to TECHNICAL REPORT NO. 63-15

WORK STATEMENT, PHASES I & II, PROJECT VT/1139

1. TASKS

a. Conduct studies on the expected properties and characteristics desired for deep-well inertial variable-reluctance seismometer designs.

b. Construct prototype instruments based on specifications which result from the design study. In addition to other critieria to be established as work progresses, the ultimate design shall include these features:

(1) Possess a large mass, on the order of 100 kg, combined with a strong magnetic circuit so that the need for a preamplifier in the seismometer is eliminated. Natural frequency shall center around 1 cps.

(2) An inherent sensor element noise sufficiently low to take advantage of the low ambient noise values (approximately 0.01 Å displacement) expected in a deep hole.

(3) A relatively constant electrical response characteristic when subjected to the high temperatures and ambient case pressures to be expected while operating in deep holes 10,000 to 12,000 feet below the surface. The instrument must be very rugged and the materials used shall resist corrosive action by chemical agents at expected operating depths and temperatures.

(4) The instrument case shall be of tubular (long cylindrical) construction with an outside diameter not exceeding 5 inches.

(5) The device shall continue to operate within its linear range even though tilted as much as 10^{o} from the vertical.

c. Assemble all of the additional components, amplifiers, recorders, connectors, cables, etc., required to complete a recording seismograph for conducting laboratory testing.

d. Perform laboratory tests which simulate actual field conditions expected. During the course of testing, observe and record system sensitivities, instrument and system noise effects, frequency response, and other electrical and mechanical phenomena connected with operation in deep wells.

e. Perform data reduction and analysis using laboratory test information and present conclusions on the operations. From this, make recommendations concerning the application of this particular instrumentation to deep-well seismology, to include identifiable parameters based on theoretical and actual findings and operational restrictions.

f. After a suitable series of laboratory tests are completed, prepare and implement a field testing program. This program will incorporate the following provisions:

(1) The contractor will locate, prepare and operate a deep-well test site containing a bore hole of approximately 10,000 feet depth and suitable for instrument testing.

(a) Legal and site preparation arrangements will be completed by about 1 June 1962 to accommodate a field testing period of four months duration. Sites selected will be subject to Government approval prior to any firm legal commitment by the contractor.

(b) Special site facilities and services for similar testing being performed under AFTAC Project VT/1139 should be furnished as a part of this work requirement. Examples are a derrick over the bore hole having sufficient height and clearance, and mud mixing, storage and pumping facilities.

(2) Assemble and fabricate as required all seismographic and test equipment necessary to support field measurements. This includes such items as cable and handling equipment, specialized controls and panels, etc. A complete seismic station will be furnished from AFTAC Project VT/074 for surface instrumentation and recording of data in support of this project.

(3) After about two months of data collection, the field test unit will be relocated at a second test site near Tulsa, Oklahoma. Approximately two months of comparison testing will be accomplished in medium depth cased and uncased bore holes; therefore, two deep-well seismometers will be required.

Reference paragraph f (1) above, the management task assigned will be retained while another contractor occupies the deep-well testing facility.

(4) The prototype instruments will receive performance evaluation and testing under various environmental conditions to depths of 10, 000 feet or more. From the data obtained, reduction and analysis will be accomplished to determine precise instrument characteristics. Conclusions and recommendations will be submitted not later than 15 October 1962.

g. Upon completion of instrument performance measurements at the Oklahoma deep-well test site, the field unit will return to Grapevine, Texas, to obtain additional data pertaining to the attenuation of earth noise with changes in depth. An instrument hole clamping device will be used. This data will be analyzed and compared with predictions of the theoretical behavior of signal and noise in a complex layered geologic media.

2. REPORTS

a. Monthly letter-type progress reports, in twelve (12) copies, summarizing work through the 25th of the month, shall be dispatched to AFTAC by the end of each month. Topics shall include technical status, major accomplishments, problems encountered, future plans and any action required by AFTAC. Illustrations and photographs shall be included as applicable. In addition, the monthly report submitted for the reporting period occurring six (6) months prior to the schedule contract termination date shall contain specific statements concerning requirements and justifications for extension, modification or expiration of work and changes in cost estimates which are anticipated by the Contractor. The heading of each report shall contain the following information:

AFTAC Project No.
Project Title
ARPA Order No. 104
ARPA Project Code No. 8100
Name of Contractor
Date of Contract

Amount of Contract
Contract Number
Contract Expiration Date
Project Scientist or Engineer's Name and Phone Number

b. A list of suggested milestones shall be dispatched to AFTAC, in twelve (12) copies, within twenty (20) days after the date of receipt by the Contractor of an executed copy of this contract. (Milestones are defined as points of accomplishments which present significant progress when completed.) For a given milestone, the list shall include the completion date and a brief description, when necessary, to define specifically the accomplishment to be attained. Upon approval of milestones information, copies of SD Form 350 will be made available for use in reporting progress against the milestone schedule. The SD Form 350 shall be attached to the monthly report.

c. Special reports of major events shall be forwarded by telephone, telegraph, or separate letter as they occur during the life of the contract and shall be included in the following monthly reports. Specific items shall include (but shall not be restricted to) program delays, program breakthroughs and new inventions or techniques.

d. A semiannual technical summary report, in twenty (20) copies, covering work performed during each six (6) month period shall be submitted to AFTAC within fifteen (15) days after the close of each reporting period, except that the first report shall cover the work performed through the last day of the fifth month following the month in which the Contractor received an executed copy of the contract. These reports shall present a concise and factual discussion of the technical findings and accomplishments of the reporting period. The heading of the report shall contain the heading information indicated in paragraph 2.a, above.

e. A final technical report, in fifty (50) copies, shall be submitted within sixty (60) days following completion of the work. The heading of the report shall contain the information indicated in paragraph 2.a, above, and the report itself shall include all of the pertinent information covered in the semiannual reports described above.

f. Special reports, as requested by the AFTAC Project Officer, may be required upon completion of various portions of the work.

3. TECHNICAL DOCUMENTS

The Contractor shall furnish the following documents concurrently with the final technical report:

a. Technical manuals on the installation, calibration and operation of all technical equipment specified in paragraph (3) above.

b. Two (2) sets of reproducible engineering drawings and specifications and one (1) set of prints for any changes or modifications in standard operational equipment and instruments and for any new equipment designed.

4. MISCELLANY

All technical reports and documents shall be forwarded to:

Headquarters USAF (AFTAC/TD-1)
Washington 25, D.C.

APPENDIX 2 to TECHNICAL REPORT NO. 63-15

RECOMMENDATIONS AND CONCLUSIONS, PHASE II, VT/1139

THE GEOTECHNICAL CORPORATION
3401 SHILOH ROAD
P. O. BOX 28277 • DALLAS 28, TEXAS • PHONE BR 8-8102
GARLAND, TEXAS
15 October 1962

HQ USAF (AFTAC/TD-1)
Washington 25, D. C.

Attention: Major Robert A. Meek

Subject: Recommendations and Conclusions, Phase II, VT/1139

Identification: AFTAC Project No: VT/1139
Project Title: Deep-Hole Seismometer (Variable-reluctance type)
ARPA Order No: 104
ARPA Project Code No: 8100
Contractor: The Geotechnical Corporation, Garland, Texas
Date of Contract: 22 May 1961, Phase I; 16 April 1962, Phase II
Amount of Contract: $327,813.00
Contract No: AF 33(600)-43369
Contract Expiration Date: 15 October 1962
Project Engineer: Richard M. Shappee, BR8-8102, Garland, Texas

Gentlemen:

1. INTRODUCTION

1.1 This report presents conclusions and recommendations resulting from the work accomplished on Project VT/1139 during the period 16 April 1962 thru 15 October 1962 and is submitted in compliance with task 1f(4) of Amendment No. 1 of that project.

1.2 The work to date has been accomplished in two phases. Phase I, the development and laboratory testing of a variable-reluctance deep-well seismometer, was completed on 23 May 1962. Phase II, the field evaluation of the seismometer in two deep wells, was completed on 15 October 1962. Sections 2 and 3 of this report summarize the work on these two phases.

2. PHASE I SUMMARY

The design of the deep-well variable-reluctance seismometer was completed during Phase I. The seismometers used in the field test program, Phase II, were completed and tested prior to the start of the field test program, and it was not necessary to alter the instruments nor to make design changes during Phase II. The results of the tests performed in Phase I are summarized below.

Design requirement	Instrument characteristic or test
Mass greater than 100 kg	103 kg
Natural frequency 1 cps	1 cps
Sensor noise consistent with ambient noise expected	Thermal agitation noise equivalent to an earth motion of 0.05 A (calculated)
Rugged design	Can be transported fully assembled
Operate at 7500 psi external	Tested at Schlumberger facility to 7500 psi
Operate at temperatures to be expected in well	Tested in temperature jacket to 250° F.
Cylindrical construction, 5" max diameter	5" dia x 107" long
Corrosion resistant	Alloy steel case, hard chrome "O" ring seats and threads
Operate within linear range when tilted up 10°	Tested on shake table and with internal calibrator
Simulate field test	Operated in 375' well at Garland and 220' well at Wichita Mountains Seismological Observatory. Performed laboratory shake table tests.

3. PHASE II SUMMARY

3.1 Five specific tasks were to be accomplished under Phase II:

Task 1f(1a) - Locate, prepare, and operate two deep-well sites.

Task 1f(1b) - Provide special site facilities and services.

Task 1f(2) - Assemble and fabricate all seismographic and test equipment.

Task 1f(3) - Deep well test program.

Task 1f(4) - Evaluation, data reduction, and analysis.

The sites and facilities covered by task 1f(1a) and task 1f(1b) were ready on schedule, although additional work was accomplished at the well sites during the test program to repair roads damaged by heavy rains, to replace fences taken down during site preparations, and to provide other minor maintenance of the sites as required.

The assembly and fabrication of the seismographic and test equipment called for under task 1f(2) was also completed on schedule, and the deep well tests, task 1f(3), started on 1 June 1962. The evaluation, reduction, and analysis of data, task 1f(4), was accomplished concurrently with the field test program. The following paragraphs summarize the field tests.

3.2 The deep-well variable-reluctance seismometer was operated at the bottom of the 10,150-foot well at Grapevine, Texas, from 4 June 1962 to 12 August 1962. The instrumentation was then transported to Hobart, Oklahoma, and operated at the bottom of a 10,160-foot well thru 30 September. From 1 October until 15 October 1962, the seismometer was operated while clamped to the well casing at various depths. The instrumentation functioned satisfactorily throughout all test periods. It was raised to the surface only when the cable or connector failed.

An identical instrument was operated in a shallow well (75 feet at Grapevine, 512 feet at Hobart) for the same periods of time as above. The shallow-well instrument functioned throughout each test period and was not raised to the surface. Attached to this report as Appendix A are typical events recorded at each site, with copies of the Wichita Mountains Seismological Observatory record of the same event.

3.3 The leakage resistance of the cable conductors to ground was measured at intervals during the test program as shown in figures 1 and 2. Also shown are the intervals where recording was interrupted while the cable or connector was repaired. Note that the seismometer was operated continuously at the Hobart, Oklahoma, site except during the installation of the hole-lock mechanism.

3.4 The responses of the seismographs were measured on 70 different days. All responses fell within the limits of figure 3. For comparison, a response curve obtained with the deep-well transducer attached to the mass of a Benioff seismometer is shown in figure 4. The impedance of the transducer was measured in the frequency range of 0.6 to 10 cps as shown in figure 5, and may be seen to lie between the Benioff C- and D-type coil configurations. The critical damping resistance (CDR) of the deep-well seismometer also lies between the CDR of the C and D Benioff coil configurations.

3.5 In anticipation that a broader bandpass might be desirable, a frequency test was performed using a 10-cps galvanometer and a 20-cps filter, as shown in figure 6. This galvanometer and filter combination should be tried in future field work.

3.6 The natural frequency of the seismometer was found to increase when it was installed at the bottom of a deep well. This increase in natural frequency is caused by shunting of the magnetic field by the casing of the well and is not due to temperature or pressure effects on the mechanical system. This was verified by operating the seismometer at the well bottom with a very low magnet charge, thus providing negligible negative restoring force due to the magnetic effect. Figure 7 shows the free period decay at the surface and at the well bottom with the weak magnet charge. The residual damping for each case is also shown. No change in natural frequency was noted between operation at the surface and at the well bottom under this condition. Since there was no fundamental trouble with the mechanical system due to pressure or temperature, the magnetic charge was set high to compensate for shunting effects when the instrument was placed in the well casing. Figure 8 shows the decay of the free period at the well bottom with a normal magnet charge.

3.7 Using multiple level recording, the dynamic range of the system is about 70 db. The seismograph has not "clipped" on any signal to date. Figure 9 illustrates its response to a large amplitude signal. Even though the high gain trace has been deflected off of the film, the 1/10 gain trace shows no evidence of clipping. Another example may be seen in the lower portion of figure 7, where 1/100, 1/10, and full-gain records of large amplitude show no clipping.

3.8 "Cross-feed" of the calibration signal directly into the data circuit is about 60 db below the output signal of the seismometer when being calibrated. Also, because an electrodynamic calibrator is used, the signal which is cross-fed into the data circuit is one-half the frequency of the output signal of the seismometer. The cross-feed was determined by locking the seismometer mass while at the bottom of the well, increasing the gain of the amplifying circuits by 18 db and then driving the calibration coil with the normal calibration signal. Figure 10 shows that the signal that is cross-fed into the data circuit has an amplitude of about 0.5 mm and is the same frequency as the calibration signal. The fact that the cross-fed signal has the same frequency as the calibration signal indicates that the mass of the seismometer was securely locked during the test. When the mass is unlocked and the magnification of the seismograph is returned to the operating setting, the signal due to calibration is about 70 mm and is twice the frequency of the calibration signal. Thus the signal resulting from calibration is more than 60 db larger than the cross-fed signal and does not introduce a significant error in calibration.

3.9 Figure 11 shows the recorded output of the complete system with the seismometer mass locked and the amplifying system set to an equivalent magnification of 4×10^6 at 1 cps. The background represents an equivalent earth motion of less than 0.1 millimicron (peak-to-peak) at 1 cps. It should be noted that the inherent noise level of the seismometer is much lower than 0.1 millimicron.

3.10 Authorization of the Project Officer was received to design a hole lock to permit operation in the well at selected depths in order to measure

signal-to-noise improvement as a function of depth. Operation with the hole lock was started on 30 September. The results of this work are not included in this report, but will be given in detail in subsequent monthly reports and the final report. At the time of this report, the hole lock has been used at the depths given below.

Date	Depth (in feet)
30 September-2 October	9766
2-3 October	8458
3-6 October	7474
6-8 October	6498
8-10 October	5591
10-11 October	4524
11-12 October	3792
12-15 October	2769
15-18 October	1702

3.11 During operations in the deep well, various types of well noise have been recorded. In general, the noise is one of two types: either isolated pulses of multiple bursts. Use of the hole lock at Hobart has eliminated the single pulses, suggesting that settling of the seismometer in the bottom of the well might have been a source of this type of noise. Locking of the seismometer to the casing by use of the hole lock has reduced the multiple bursts but not eliminated them. The multiple burst type of noise is only partially understood. One possible source could be stress in the casing which is relieved as a function of time, resulting in casing motion. Another possibility is that gas pressure builds up until it exceeds some hydrostatic force, and then is abruptly relieved. The cause of this type of noise, as shown in figure 12, requires further investigation.

4. CONCLUSIONS

4.1 The seismometer meets all the requirements of the statement of work and is capable of long-term unattended operation in wells 10,000 to 12,000 feet deep.

4.2 The standard Schlumberger well-logging cable and connector operated continuously from 15 August until the end of the test program, a period of about 45 days. The electrical leakage was above 2 megohms when it was removed from the well and it is likely that the cable could have operated for a much longer period. Because of the cable troubles encountered earlier in the program, the results described above may not be indicative of future performance.

4.3 The noise level of the complete seismograph system with the seismometer at the bottom of a 10,000-foot well and with the seismometer mass locked is equivalent to an earth motion of about 0.1 millimicron (peak-to-peak) at 1 cps. The inherent noise level of the seismometer (thermal agitation noise) is lower than this; however, no direct measurement has been made of this noise.

4.4 The cross-feed from the calibration circuit into the data circuit is down by 60 db.

4.5 After stabilization, the magnification of the seismograph remained within ± 5% and the frequency response remained within the limits shown in figure 3.

4.6 The bandpass of the seismograph can be increased by the use of a higher frequency galvanometer in the phototube amplifier.

4.7 The mechanism that locks the seismometer to the well casing has proved to be very reliable. Locking the seismometer to the well casing at a point above the bottom of the well reduces spurious noises on the record.

4.8 The fully assembled seismometer and a tripod for over-the-well servicing can be transported in a station wagon.

5. RECOMMENDATIONS

Detailed recommendations for future work were transmitted to the Project Officer on 15 September 1962. The proposed future work (Proposal P-135) was divided into six task, as follows:

a. Investigation and cataloging of wells and sites for wells that would be suitable for use in a program to measure signal-to-noise ratio as a function of depth and geology and to obtain data leading to the determination of the usefulness of deep-well seismographs as compared to surface instrumentation.

b. Systems engineering directed toward improving methods for preparing wells for the installation of deep-well seismometers, improving instrumentation, and improving methods of installing and operating the instrumentation.

c. Detailed field measurements at approximately ten representative deep-well sites.

d. Telemetering of data from as many as three unattended deep-well sites to determine long-term capability and reliability of remote deep-well seismographs.

e. Reduction and analysis of seismographic recordings to compare theoretical and measured signal-to-noise ratios, to determine signal and noise characteristics and spectrum, and to estimate the capability and reliability of deep-well seismographs as compared with surface arrays of seismographs.

f. Preparation of a preliminary handbook of deep-well seismology to provide data on the criteria for site selection, requirements for drilling and preparation of wells, requirements for the equipment and installation of deep-well instrumentation, specification of surface instrumentation, calibration procedures, and operation and maintenance procedures.

Yours very truly,

THE GEOTECHNICAL CORPORATION

Richard M. Shappee

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Senior Engineer

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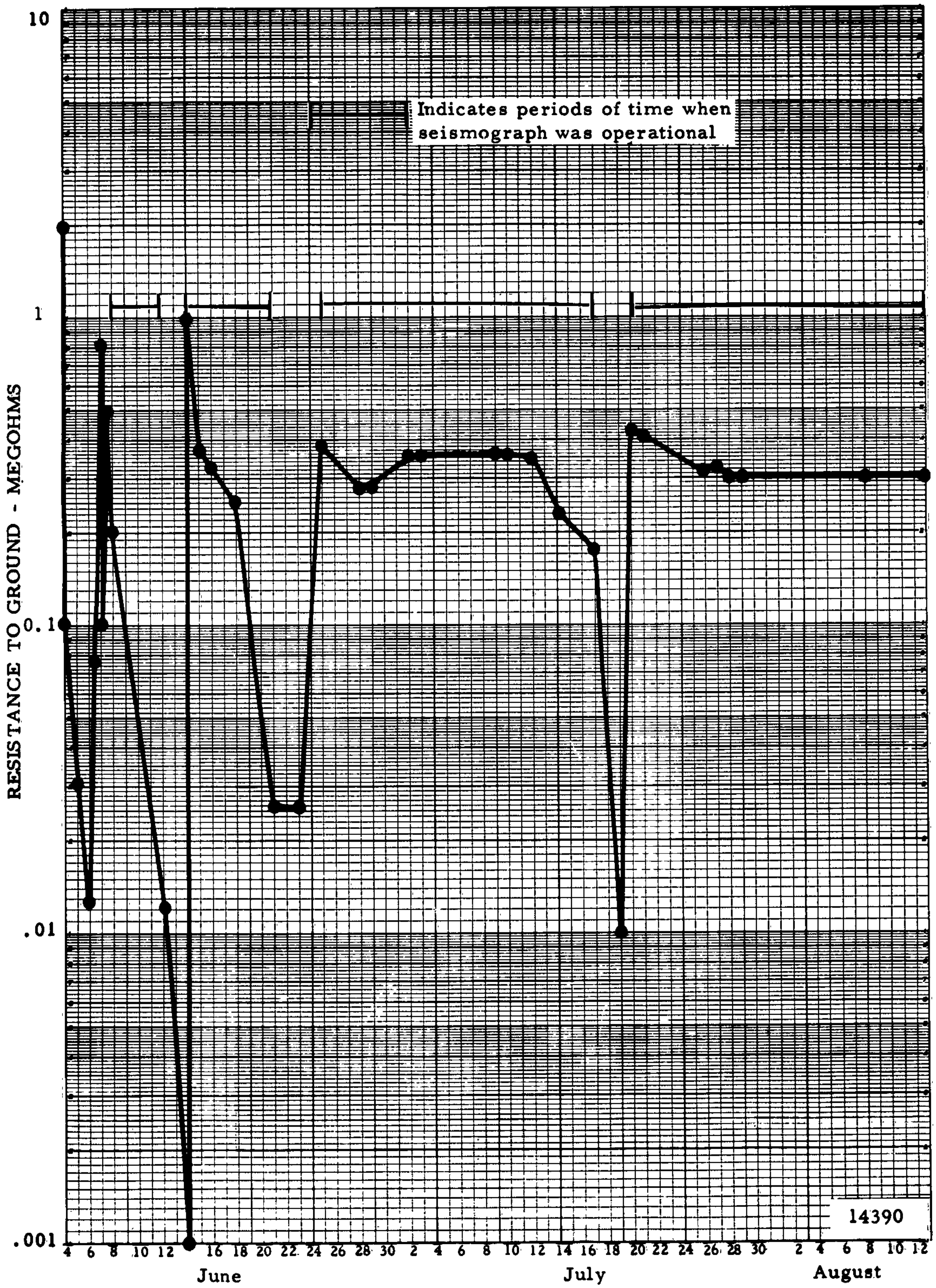


Figure 1. Electrical resistance, data line to ground, deep-well seismometer, Grapevine, Texas

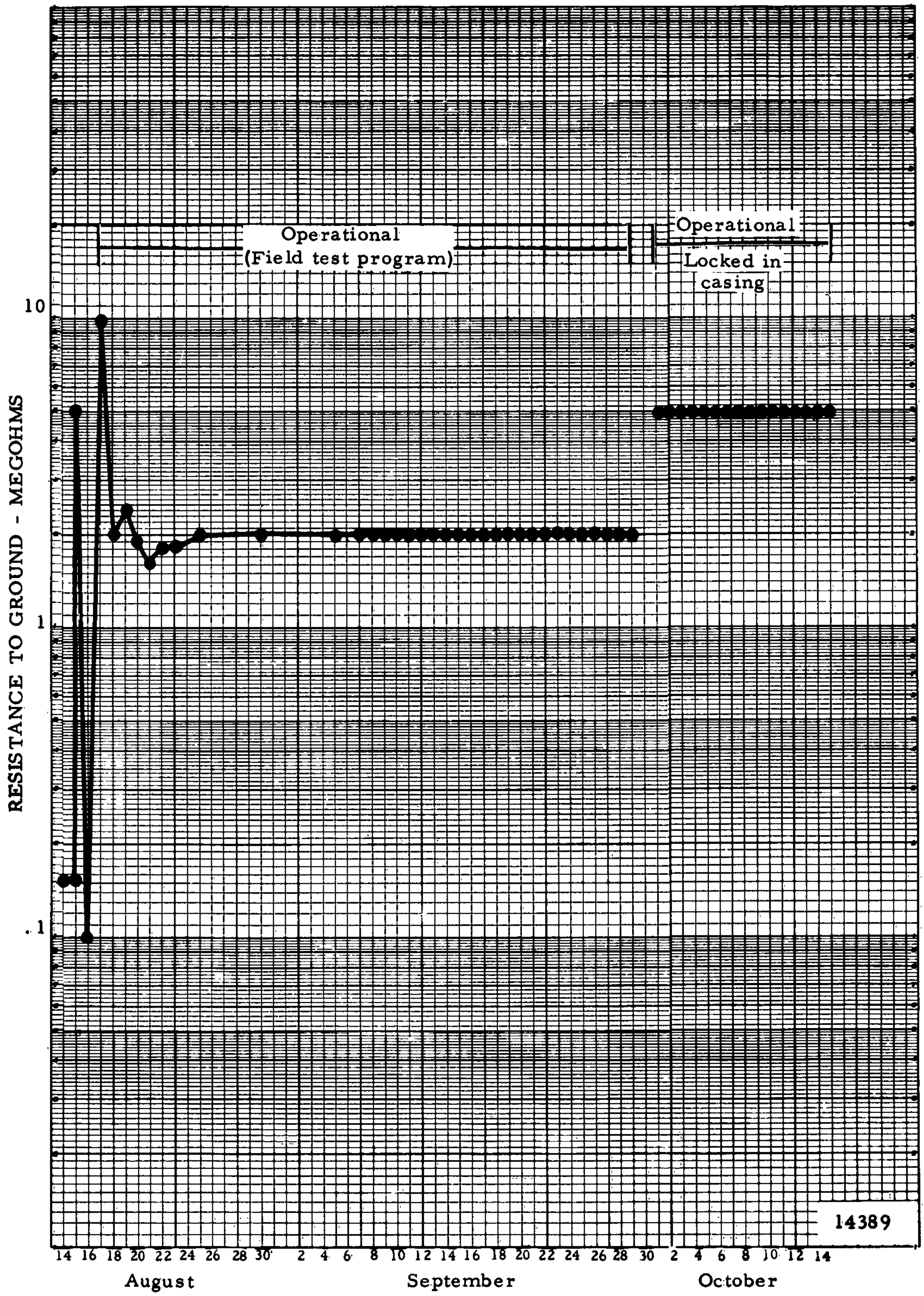


Figure 2. Electrical resistance, data line to ground, deep-well seismometer, Hobart, Oklahoma

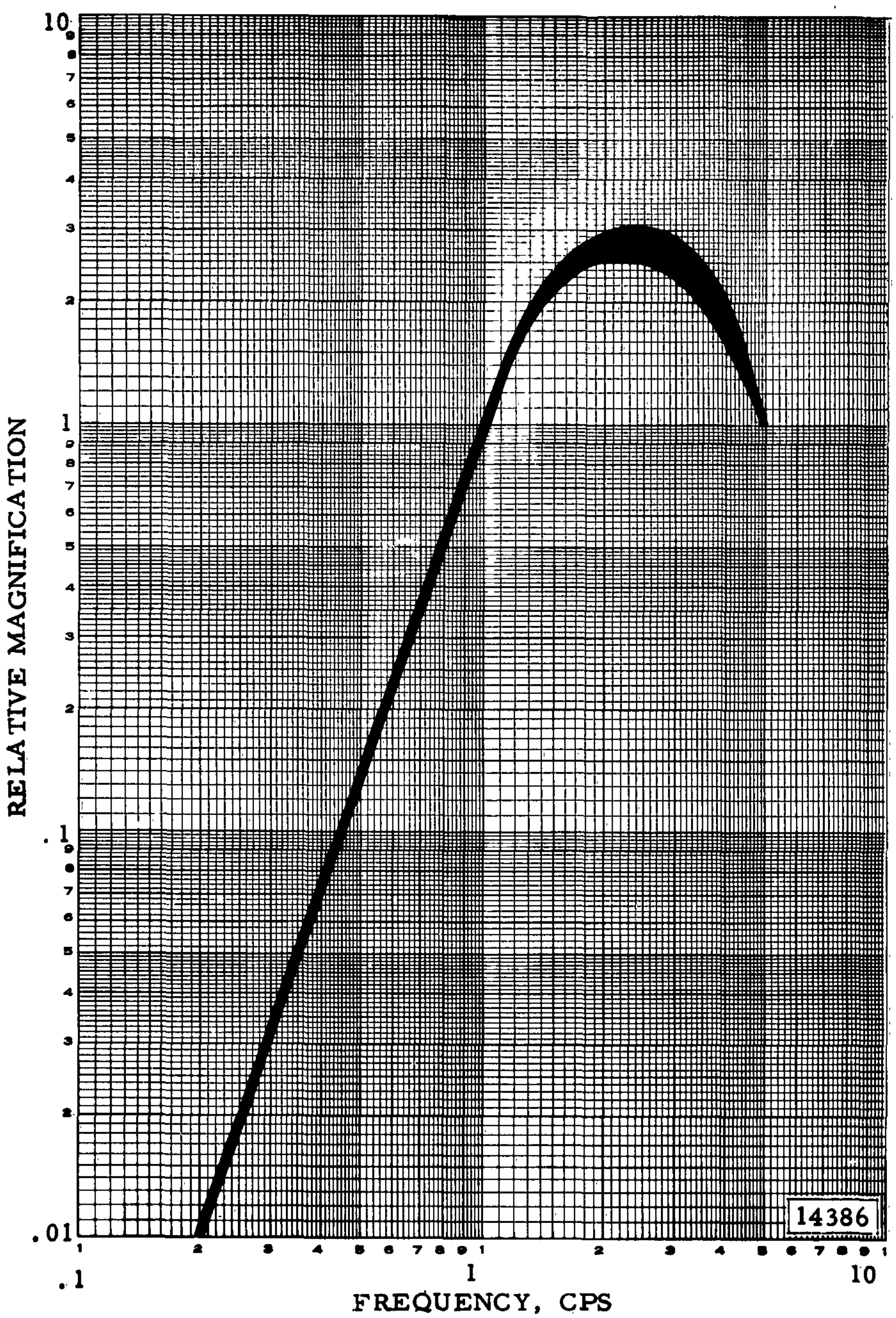


Figure 3. Measured limits of response for deep-well seismograph

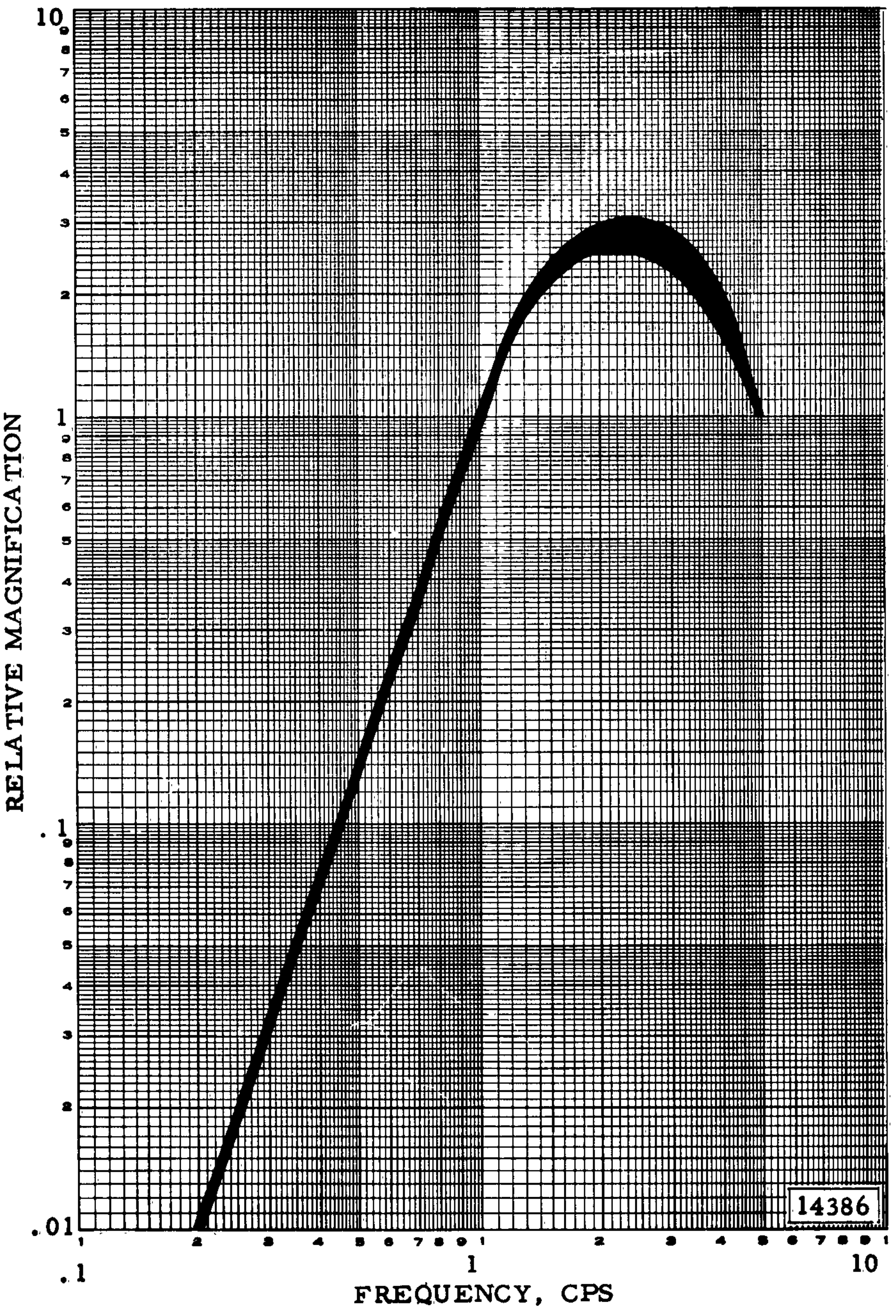


Figure 3. Measured limits of response for deep-well seismograph

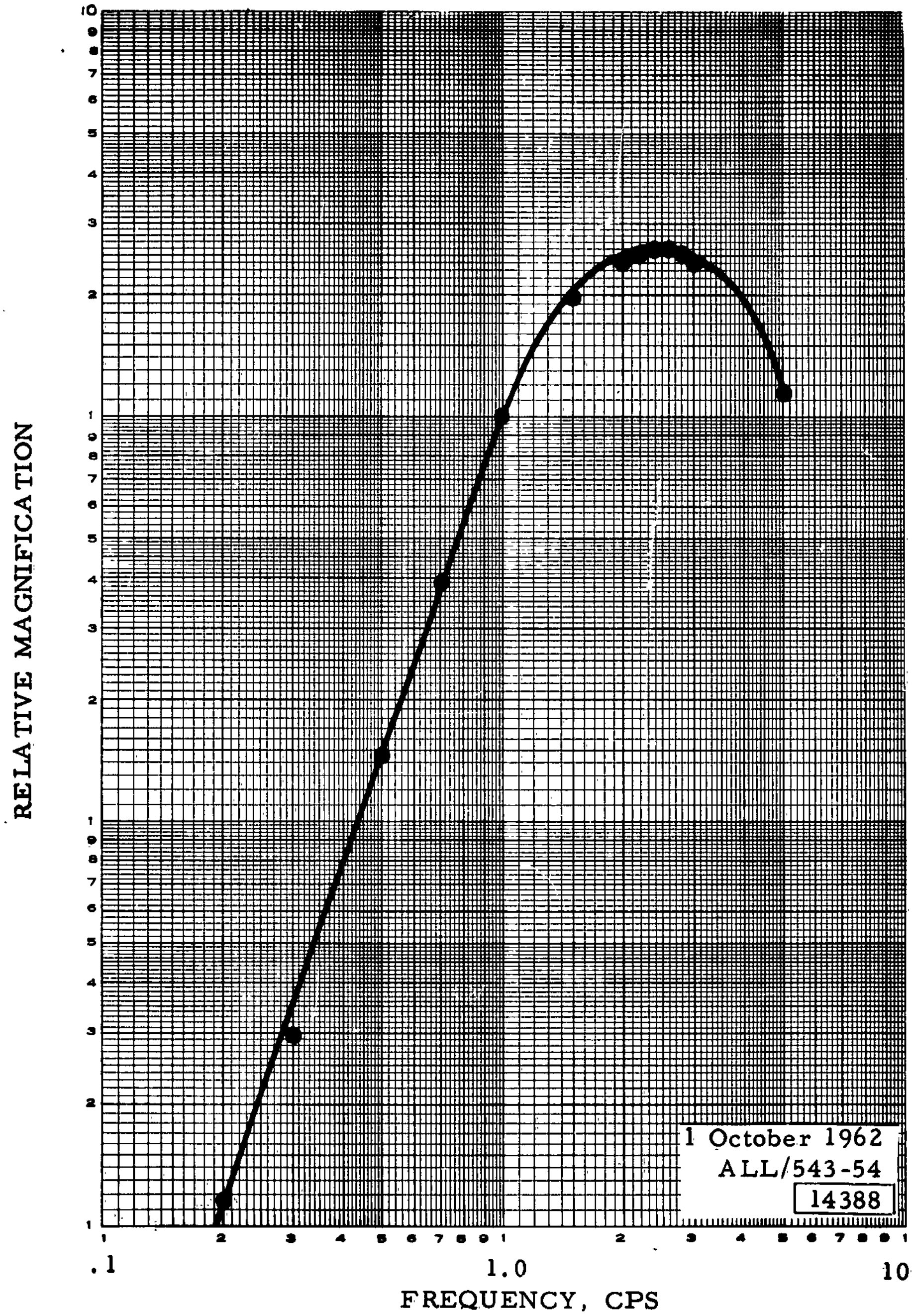


Figure 4. Response of deep-well transducer mounted on Benioff seismometer (obtained with remote calibrator) using 4300 PTA with 5 cps galvo and 6824-1 10-cps filter. Free period = .99 cps. Damp ratio ≈ 17/1

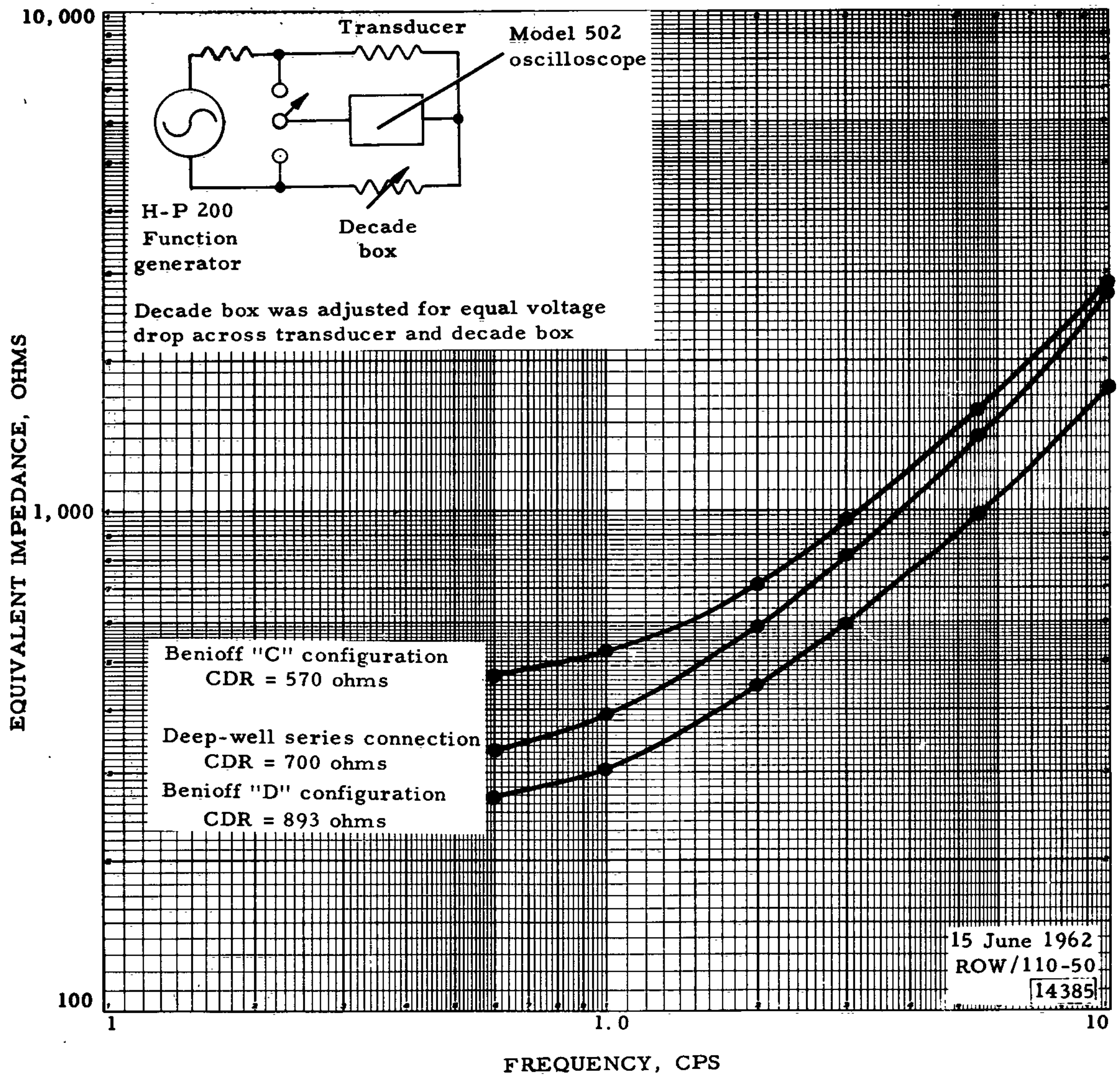


Figure 5. Equivalent impedance vs. frequency, deep-well and Benioff transducers (mass blocked)

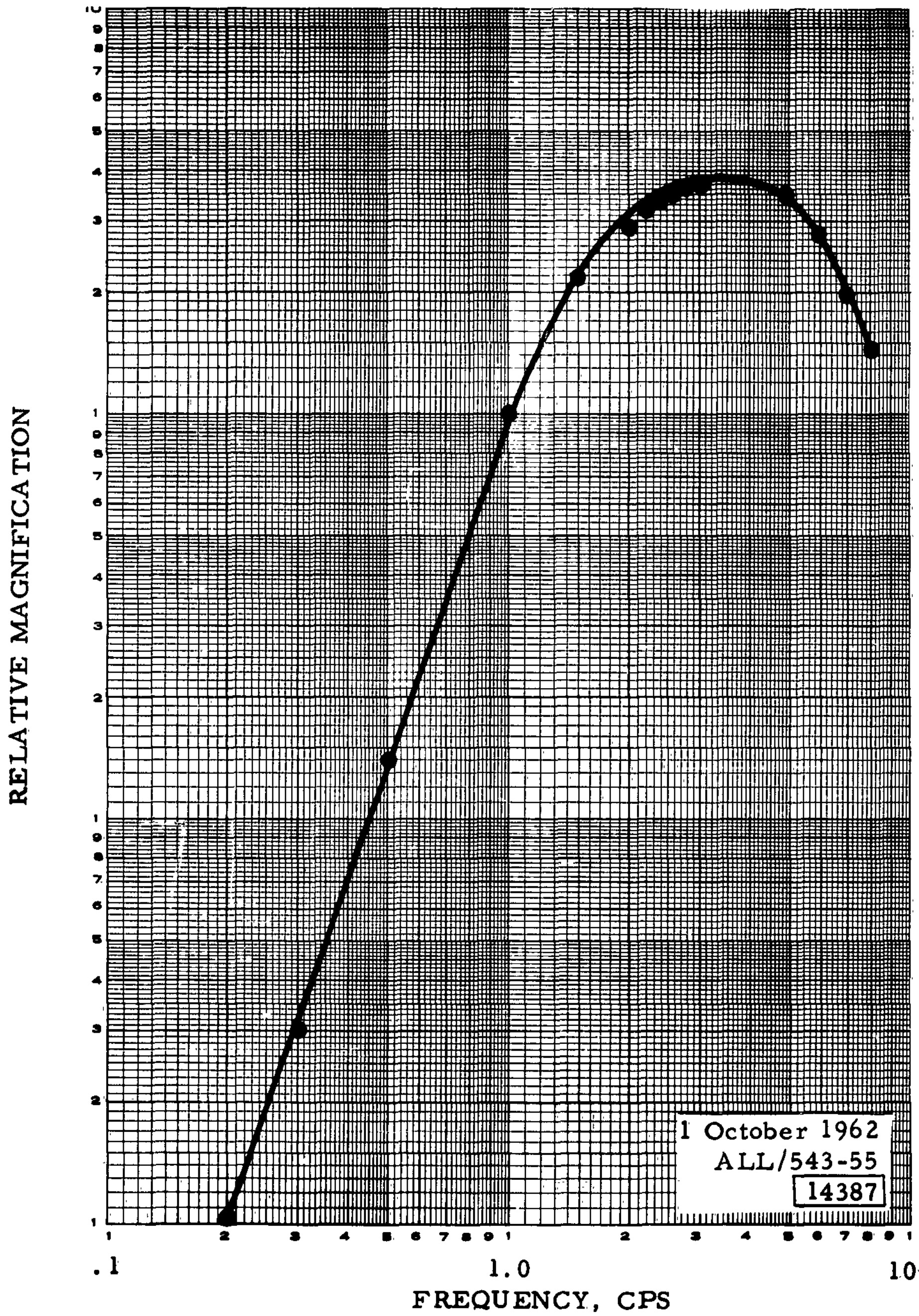
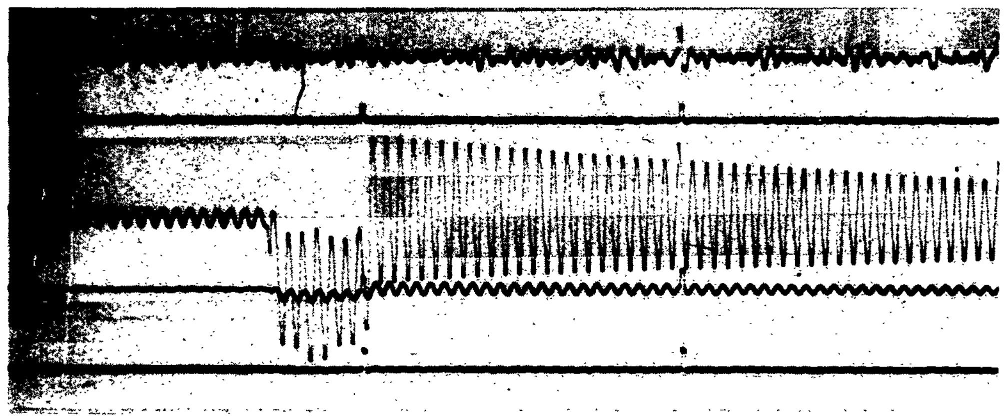
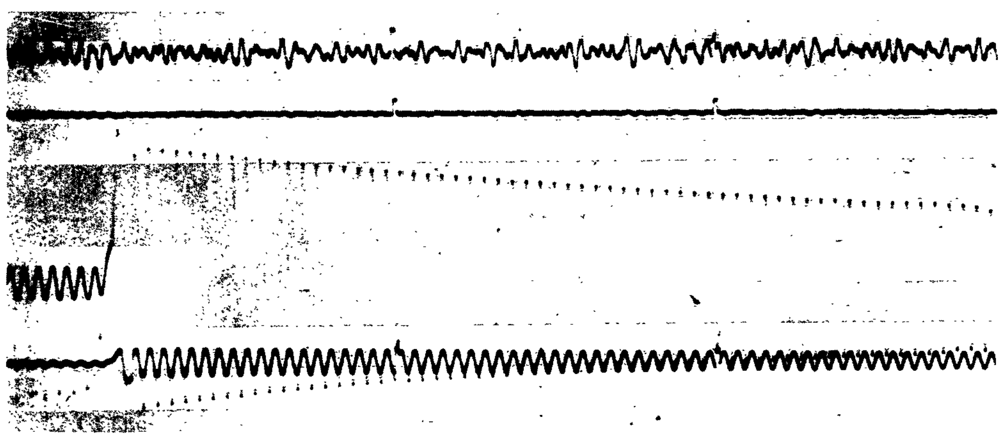


Figure 6. Response of deep-well transducer mounted on Benioff seismometer (obtained with remote calibrator) using 4300 PTA with 10 cps galvo and 6824-7 20-cps filter. Free period = .99 cps. Damp ratio ≈ 17/1



19 July 1962 on surface. Damping ≈ .00283; T_s = .435 second



20 July 1962 at 10,150 feet. Damping ≈ .00238; T_s = .435 second

Figure 7. Free period of deep-well seismometer with weak magnet charge, at surface and at 10,150 feet

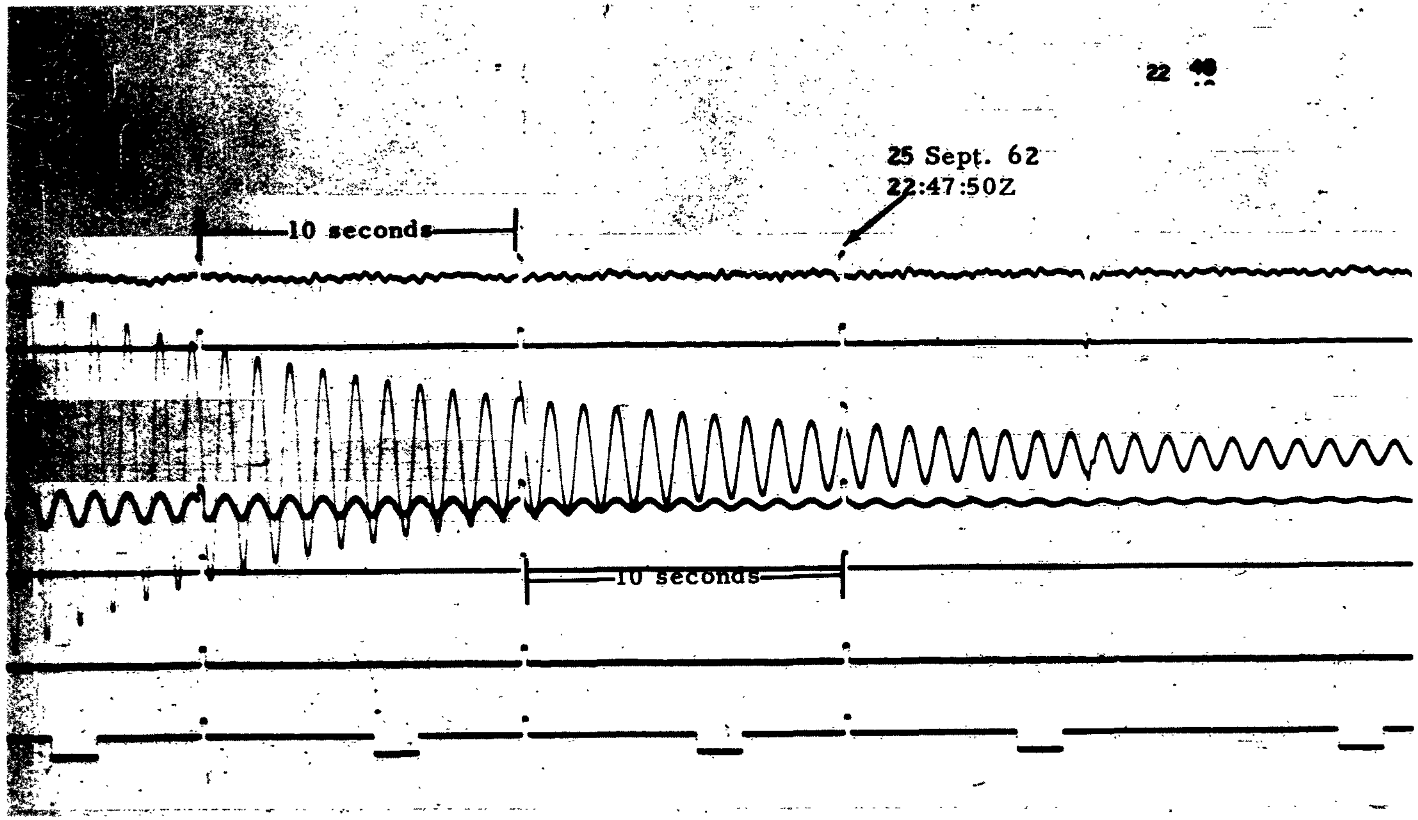


Figure 8. Develocorder record showing free period decay of the deep-well seismometer in the 10,160' well at Hobart, Oklahoma
T_s = 1.014 seconds. Damping = .012

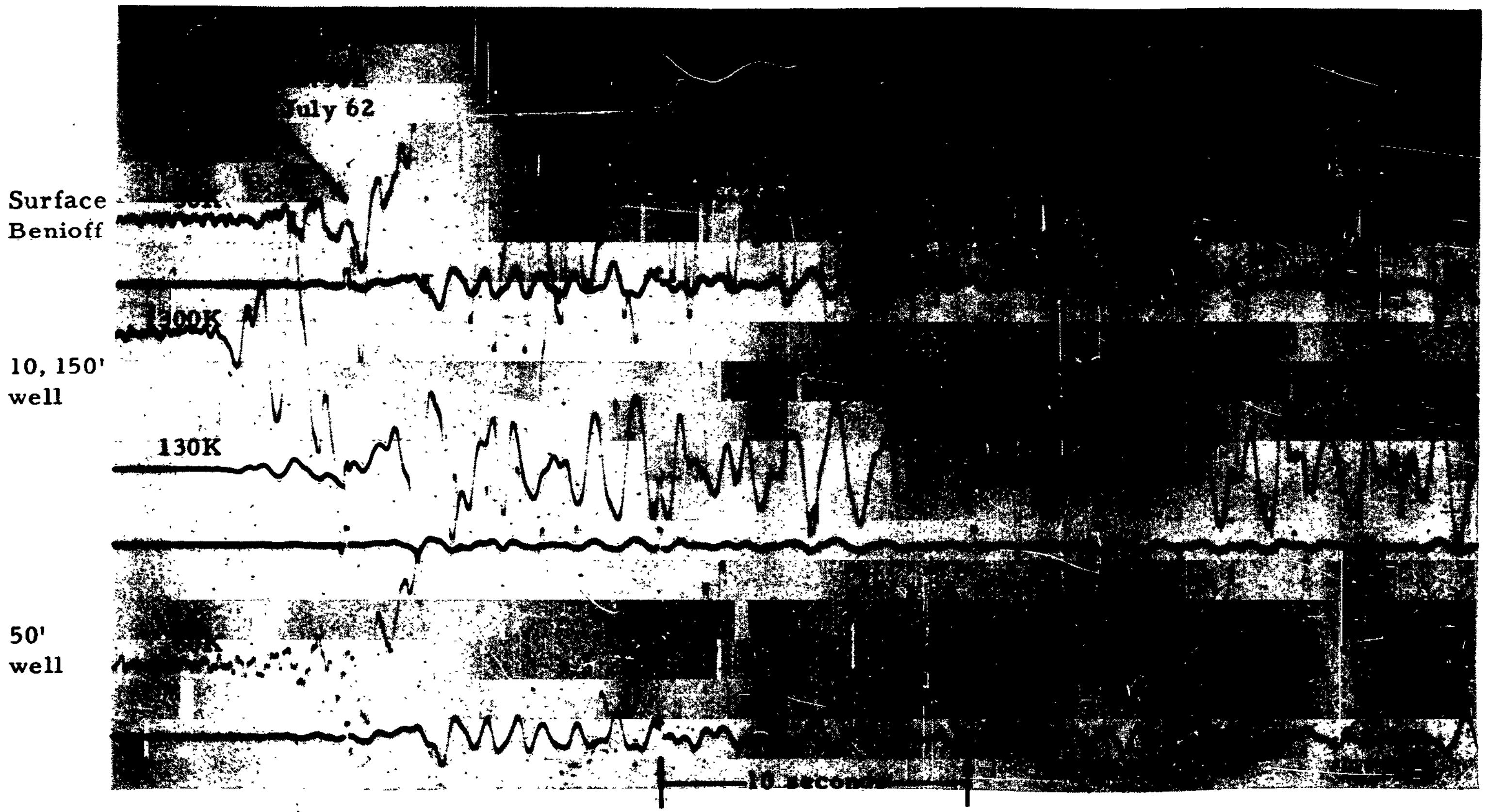


Figure 9. Large signal response, deep-well, shallow-well and surface Benioff instruments at Grapevine, Texas. Magnifications at 1 cps, 10X view.

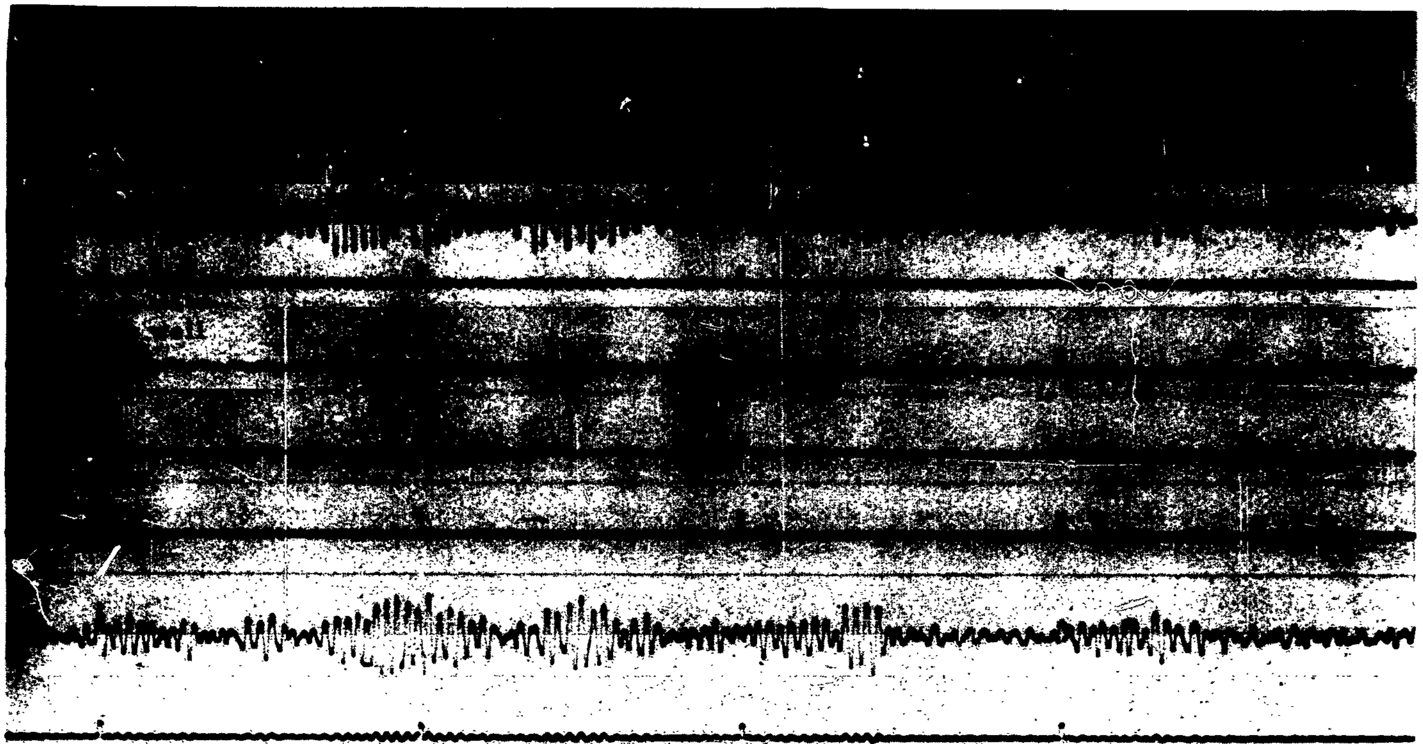


Figure 10. Cross-feed from calibration circuit to deep-well data line. Magnification approximately 4×10^6, 1 cps.

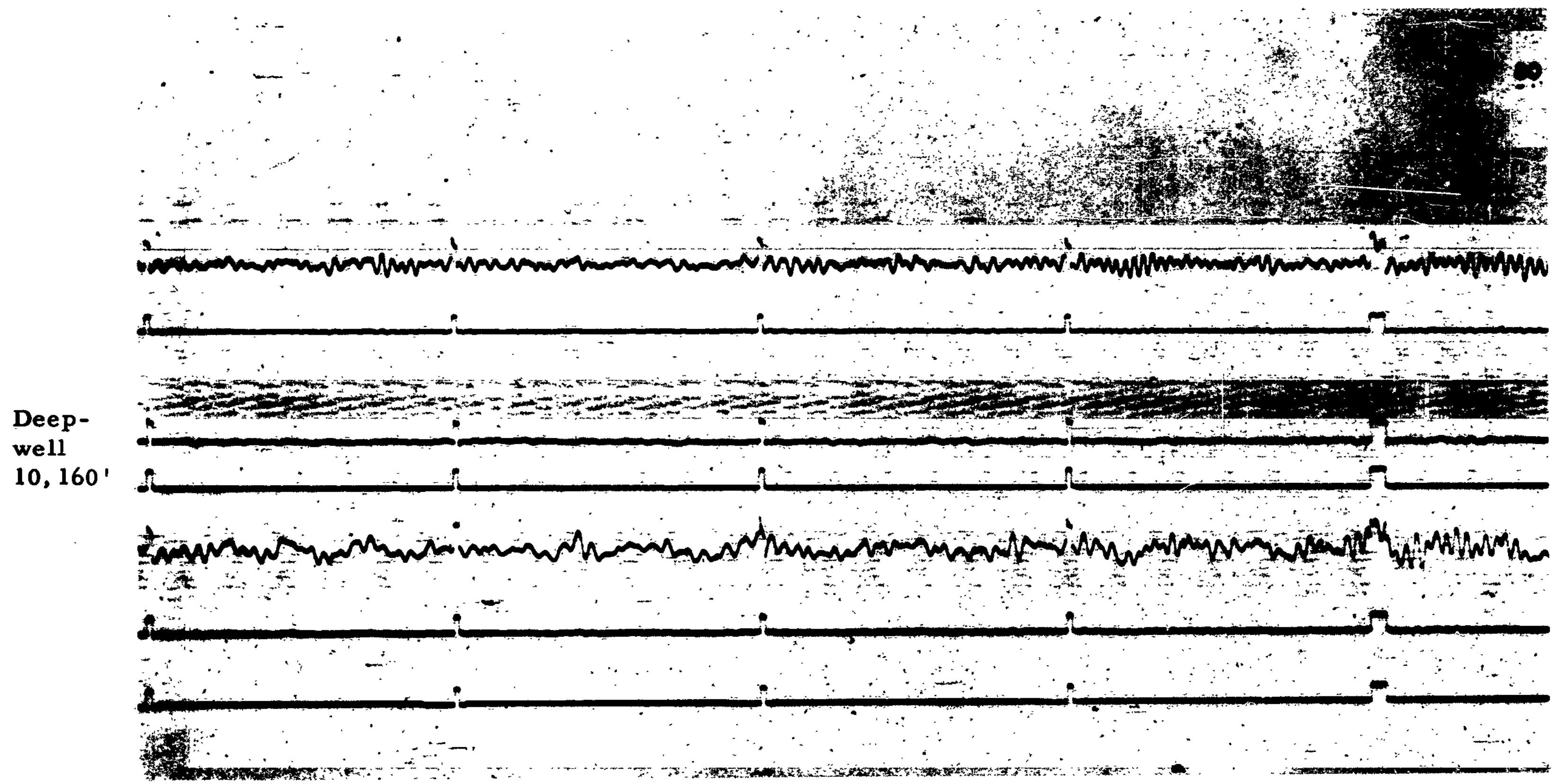


Figure 11. Background noise of deep-well seismograph at Hobart, Oklahoma, with mass locked and all attenuators at zero attenuation. Magnification 4 x 10^6 at 10X view, 1 cps

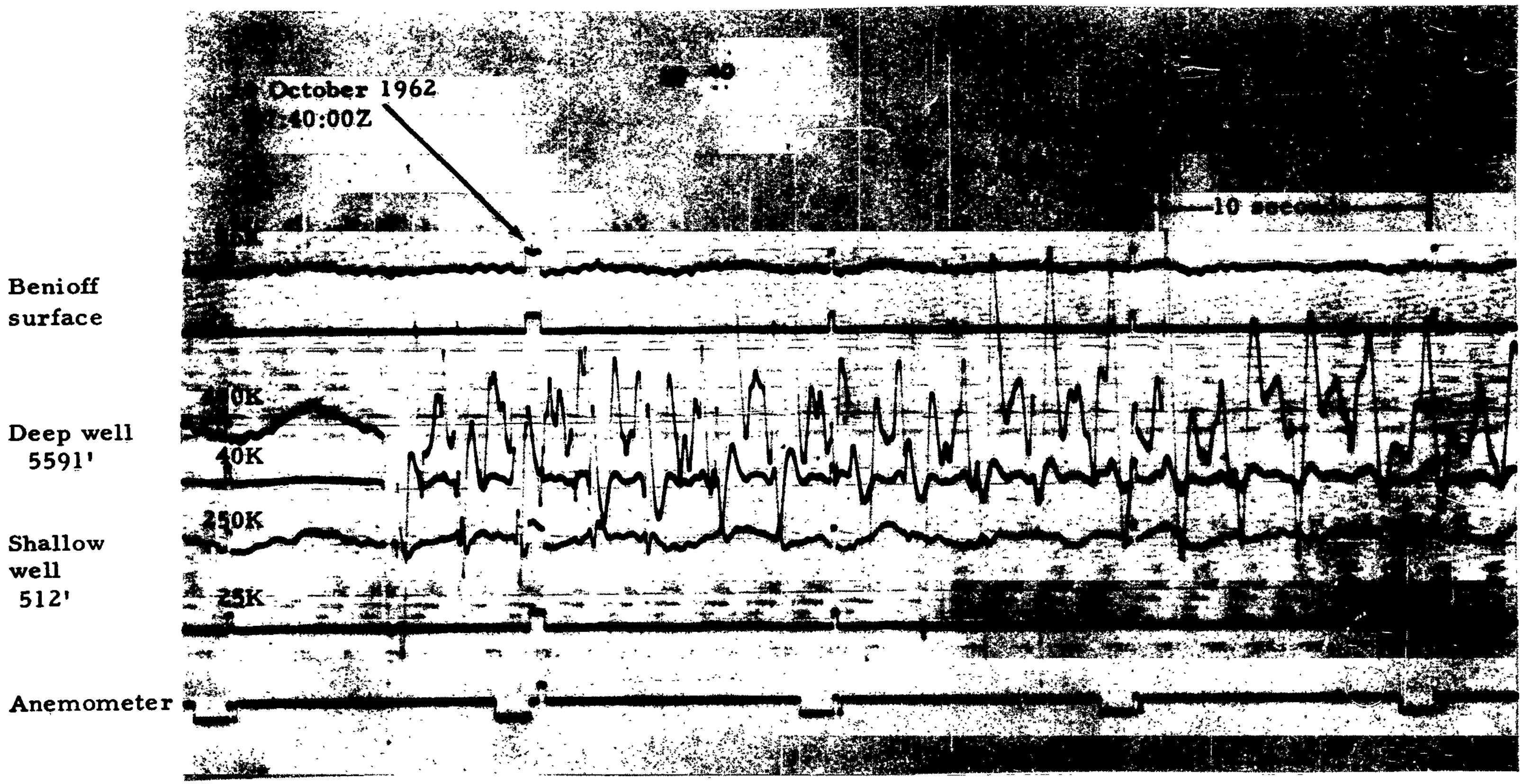
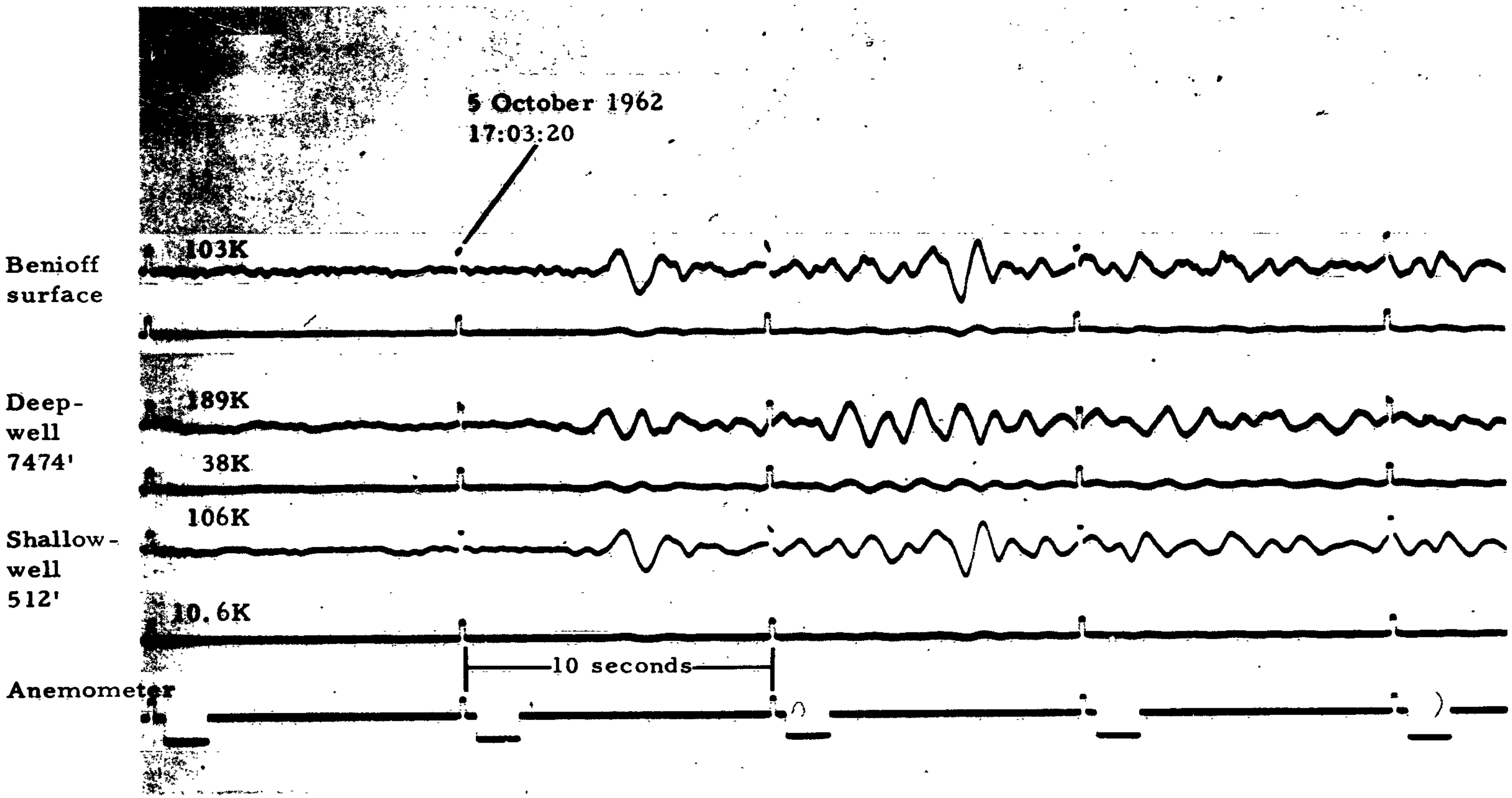


Figure 12. Example of sustained noise burst recorded from deep-well seismometer locked in casing at 5591 feet, Hobart, Oklahoma

APPENDIX A

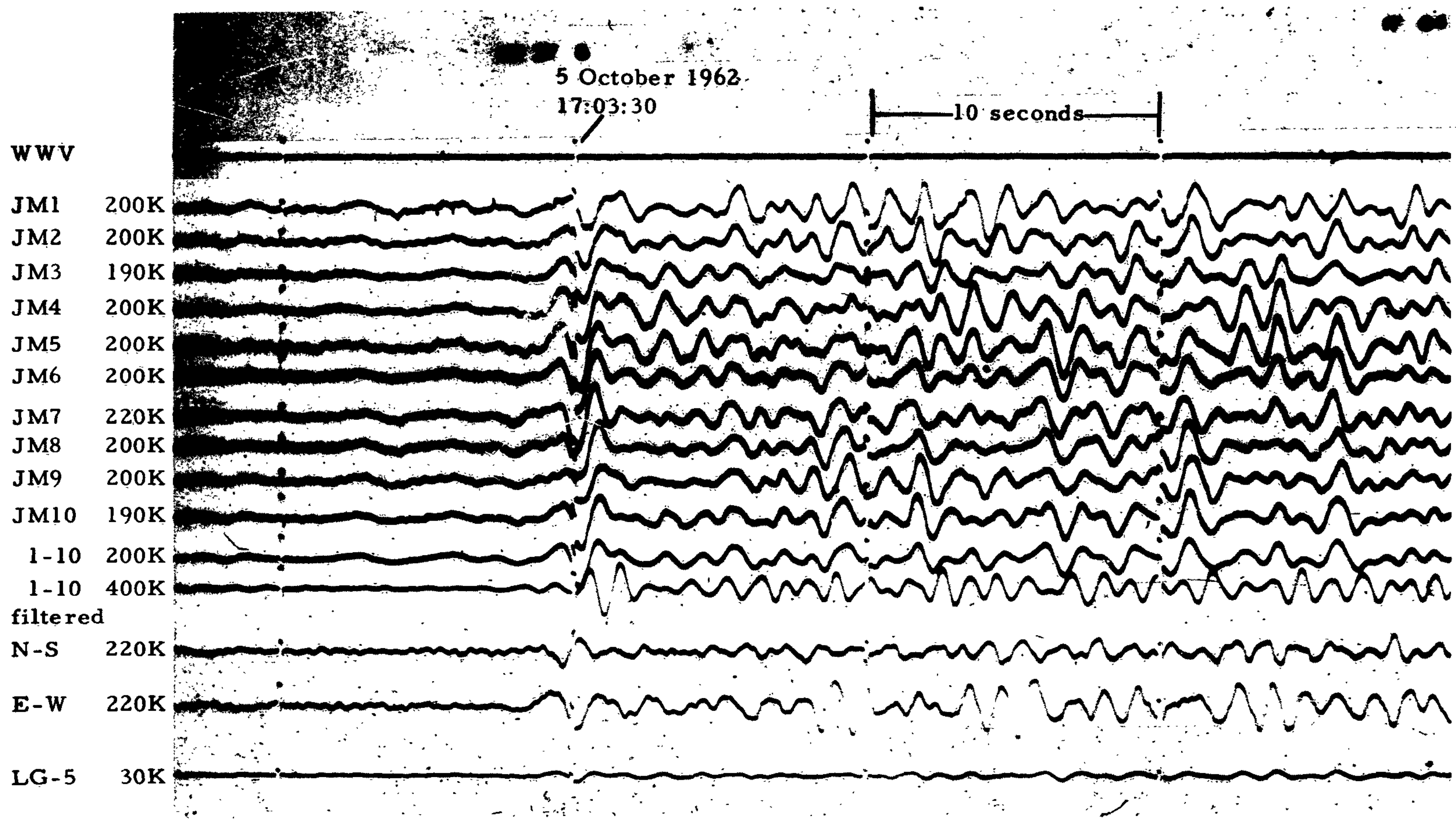
to

Recommendations and Conclusions, Phase II, VT/1139



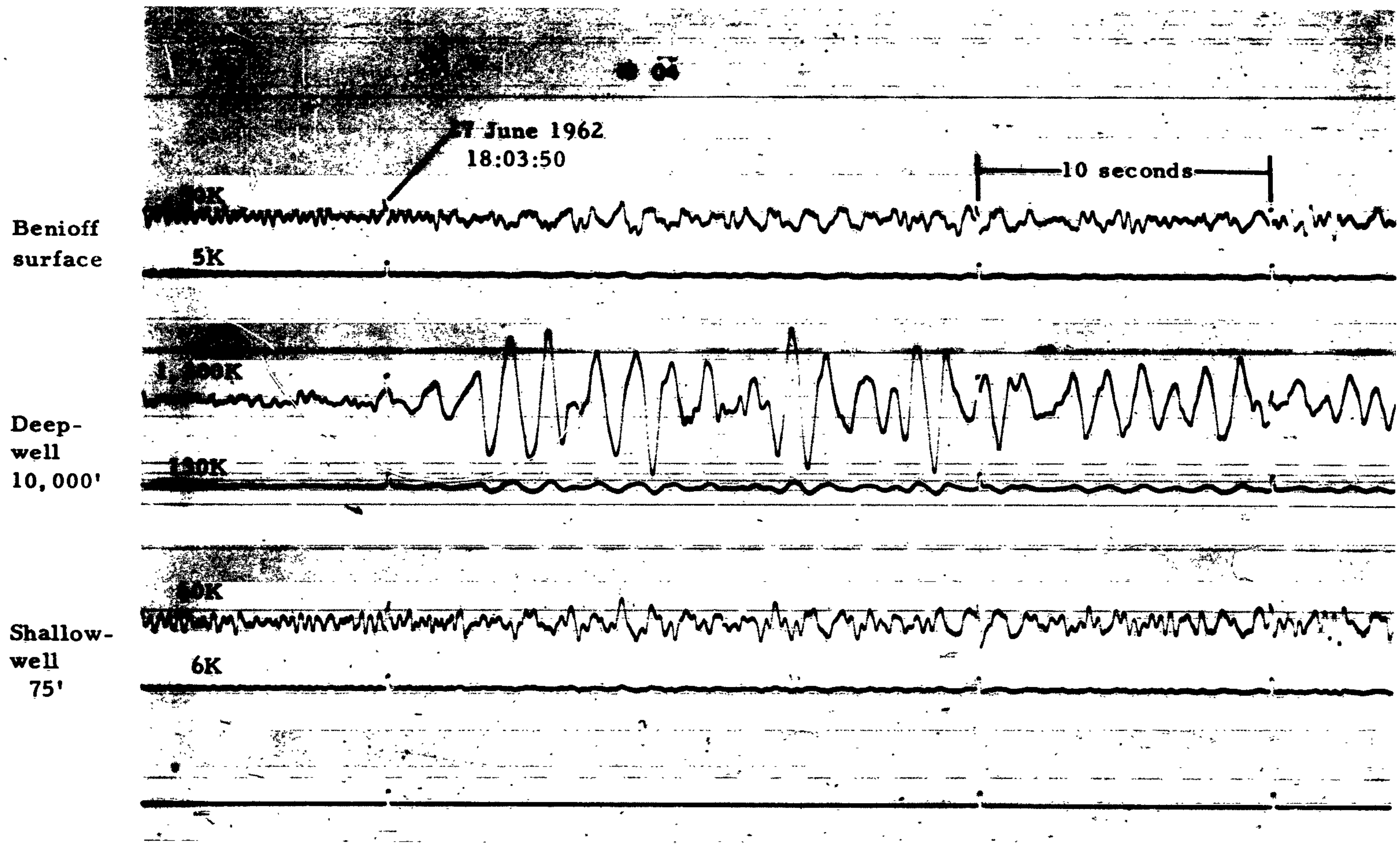
Develocorder record of small Benioff, deep-well and shallow-well seismometers at Hobart, Oklahoma. Magnification at 1 cps, 10X view. Distance - 1569 km; time correction 0.0.

10-62-48

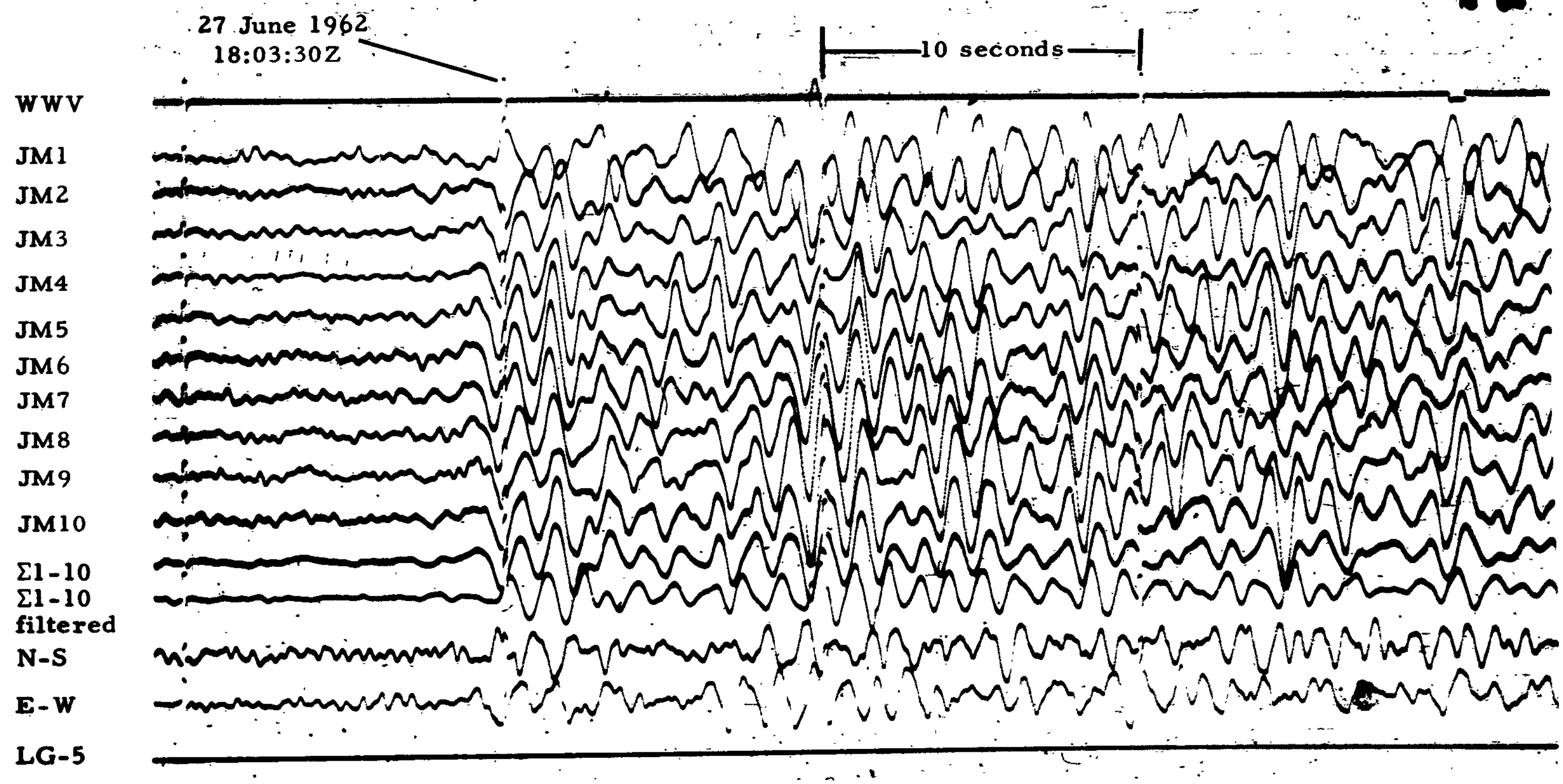


Develocorder record of JM array at WMSO. Magnification at 1 cps, 10X view. Distance 1569 km.

10-62-49



Develocorder record of large Benioff, deep-well, and shallow-well seismometers; distance = 1812.3 km. Time correction = 0.00.



Develocorder record of JM seismometer array at Wichita Mountains Seismological Observatory.
Magnification ≈ 500K at 1 cps, X10 view. Distance ≈ 1650 km.

10-62-50