VESIAC Special Report

DEEP-BOREHOLE SEISMIC RESEARCH

Edited by
VESIAC Staff

6050

ACOUSTICS AND SEISMICS LABORATORY
Institute of Science and Technology
THE UNIVERSITY OF MICHIGAN

March 1962

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Acoustics and Seismics Laboratory
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Ann Arbor, Michigan

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Acknowledgments. The VESIAC staff wishes to thank contributors for their cooperation and permission to publish.

Report prepared by Louise Snider.

PREFACE

VESIAC, the VELA Seismic Information Analysis Center, is a facility established at the Institute of Science and Technology of The University of Michigan for the collection, analysis, and dissemination of seismic information. This facility is sponsored by the Advanced Research Projects Agency under the Office of the Secretary of Defense.

The purpose of VESIAC is to analyze the research information related to the VELA UNIFORM Program of Project VELA and to function as a central facility for this information. The facility will serve all authorized recipients of VELA UNIFORM research information by issuing subject bibliographies with abstracts, annotated bibliographies, and special reports as required. In addition, VESIAC will periodically summarize the progress of the research being conducted.

VESIAC is under the technical direction of the Acoustics and Seismics Laboratory of the Institute. In its operation, VESIAC draws upon members of this laboratory and other members of the Institute and University.

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FIGURES

FIGURES (Continued)

FRONTISPIECE: ATTENDEES AT THE SIXTH VELA UNIFORM COORDINATION MEETING.

DEEP-BOREHOLE SEISMIC RESEARCH

ABSTRACT

This document is a compilation of status reports on the deep borehole research program by VELA UNIFORM contractors. The reports were presented at the Sixth VELA UNIFORM Coordination Meeting held at Tulsa, Oklahoma, 9 October 1961. This is not a verbatim record of the proceedings but an edited compilation of those presentations for which speakers furnished written papers or for which meeting notes were available.

Detailed information is presented on instrumentation, seismic measurements, buried arrays, ocean-bottom seismometers, and the United Kingdom borehole program. Diagrams, charts, and other illustrative material is included. Recommendations for future work are given by some authors.

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INTRODUCTION

On 9 October 1961, the Nuclear Test Detection Office of the Advanced Research Projects Agency held its Sixth VELA UNIFORM Coordination Meeting at the facilities of the Jersey Production Research Company in Tulsa, Oklahoma. The purpose of the meeting was to help define the progress and the state of the art of the deep borehole research program. VELA UNIFORM contractors engaged in this program presented highlights of their research. In addition, a representative of the Atomic Energy Authority of the United Kingdom reviewed the British borehole program.

The reports given at the meeting have been compiled in this document. Where written reports were not available, the VESIAC staff has selected excerpts and prepared abstracts from meeting notes.

Some of the reports cite evidence, closely paralleling Rayleigh-wave theory, that the amplitude of seismic noise decreases with depth. It appears that wind-induced seismic noise is attenuated rapidly with depth, and that in deep boreholes the signal-to-noise ratio is considerably improved. However, experimental data show that P-wave amplitudes also decrease with depth, as predicted by theory.

Aside from questions concerning P-wave detection, deep boreholes seem advantageous where the surface area is limited and the terrain rugged. Current findings, though incomplete, indicate that seismic noise and signal recording appear unaffected by the presence of cemented casing in a borehole.

Deep borehole operation, however, gives rise to problems in instrumentation. Several contractors describe the design, fabrication, and testing of seismometers for use in deep boreholes. The advantages of particular types of instruments are reviewed, and problems concerning ancillary equipment, especially cables suitable for long-term use, are discussed.

Improvements in ocean-bottom instrumentation and the use of a nuclear generator for a power supply are described and related to applications in deep borehole work.

The availability of wells for seismic detection research was touched upon in discussions. Limited information on the use of existing boreholes appears in Appendix A.

Suggestions for further areas of study are incorporated in many of the individual papers where the authors, in describing their own research, pointed out other research problems.

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ATTENDANCE LIST FOR SIXTH VELA UNIFORM COORDINATION MEETING[1]

David B. Andrew, Geotechnical Corp., Dallas, Texas
R. A. Arnett, Texas Instruments, Inc., Dallas, Texas
H. O. Banks, Jr., Royal Research Corp., Heywood, California
C. C. Bates, ARPA, Washington, D. C.
Maj. W. J. Best, AFOSR, Washington, D. C.
G. F. Bing, ARPA, Washington, D. C.
R. A. Broding, Century Geophysical Corp., Tulsa, Oklahoma
G. L. Brown, Space-General Corp., Glendale, California
T. W. Caless, University of Michigan, Ann Arbor, Michigan
Eric W. Carpenter, UKAEA, England
D. H. Clements, ARPA, Washington, D. C.
Frank B. Coker, United ElectroDynamics, Inc., Pasadena, California
Paul D. Davis, Jr., Texas Instruments, Inc., Dallas, Texas
Lt. John N. Entzminger, Rome Air Development Center, Rome, New York
E. A. Flinn, United ElectroDynamics, Inc., Pasadena, California
A. F. Gangi, Space-General Corp., Glendale, California
Clark Goodman, Schlumberger, Ltd., Houston, Texas
Capt. Robert A. Gray, AFCRL, Bedford, Massachusetts
J. H. Hamilton, Geotechnical Corp., Dallas, Texas
D. P. Hearn, Century Geophysical Corp., Tulsa, Oklahoma
W. B. Heroy, Jr., Geotechnical Corp., Dallas, Texas
Lynn G. Howell, Humble Oil & Refining Co., Houston, Texas
Bryan Isacks, Lamont Geological Observatory, Palisades, New York
Samuel Katz, Rensselaer Polytechnic Institute, Troy, New York
S. Kaufman, Shell Oil Co., Houston, Texas
Capt. H. W. Leaf, AFOSR, Washington, D. C.
Capt. Notley G. Maddox, AFTAC, Alexandria, Virginia
Robert A. Meek, AFTAC, Washington, D. C.
Ben S. Melton, AFTAC, Alexandria, Virginia
L. M. Mott-Smith, General Geophysical Co., Houston, Texas
William R. Muehlberger, University of Texas, Austin, Texas
L. M. Murphy, USC GS, Washington, D. C.
G. C. Phillips, General Geophysical Co., Houston, Texas
C. F. Romney, AFTAC, Washington, D. C.
Allen M. Rugg, United ElectroDynamics, Inc., Pasadena, California
Ben F. Rummerfield, Century Geophysical Corp., Tulsa, Oklahoma
S. W. Schoellhorn, Seismograph Service Corp., Tulsa, Oklahoma
Norman F. Scott, Esso-Sahara, Algiers
Richard M. Shappee, Geotechnical Corp., Dallas, Texas
D. Silverman, Pan American Petroleum Corp., Tulsa, Oklahoma
Alex Stogryn, Space-General Corp., Glendale, California
P. S. Williams, Jersey Production Research Co., Tulsa, Oklahoma
J. T. Wilson, University of Michigan, Ann Arbor, Michigan
Ted Winston, United ElectroDynamics, Inc., Pasadena, California

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[1] Held at Tulsa, Oklahoma, 9-10 October 1961.

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DEEP-WELL VARIABLE RELUCTANCE SEISMOMETER

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INTRODUCTION

One method of detecting and identifying low-amplitude signals is to place seismometers in deep wells and rely on the attenuation of short period noise with depth to improve the signal-to-noise ratio. This requires a stable instrument that can operate for extended periods in the severe environment encountered in a deep well. Deep-well seismometers can also be installed advantageously at locations which have high surface noise. Figure 3-1 shows the spectrum of the background noise at several locations in the United States. There was a decrease in the short-period noise in the mine at Ogdensburg, New York, where the measurements were made 1850 feet below the surface.

DESIGN REQUIREMENTS

Table I lists the basic requirements for a seismometer which is to operate for extended periods under the conditions encountered in a deep well. In general, it must resist a combination of high pressure, high temperature, and corrosive fluids.

It is expected that the amplitude of the microseismic noise 10,000 feet below the surface will be on the order of 0.1 Å (0.01 mμ). If this proves correct, then the instrumental noise should be equivalent to an earth motion of about 0.01 Å. Calculations of mass based on Brownian motion as the limiting factor (see Reference 1) lead to the selection of 100 kg as the weight of the inertial mass. Tests at Wichita Mountains Seismological Observatory (WMSO) indicate that the amplifier and cable noise (see Figure 3-2) might be one order of magnitude higher; however, these tests are not conclusive. In any event, it appears that a system noise level equivalent to an earth amplitude of less than 0.1 Å (peak to peak) at 1 cps can be achieved.

VARIABLE RELUCTANCE OR MOVING COIL TRANSDUCER

In our opinion, a velocity transducer is the only transducer practical for use in a deep-well seismometer. Two types of velocity transducers warrant consideration. These two types, the moving coil and the variable reluctance, are diagrammed in Figure 3-3. Although it is recognized that the moving coil type transducer has a greater linear operating range and lower inductance than the variable reluctance transducer, the variable reluctance transducer has the advantage of introducing a negative restoring force, which permits the seismometer suspension

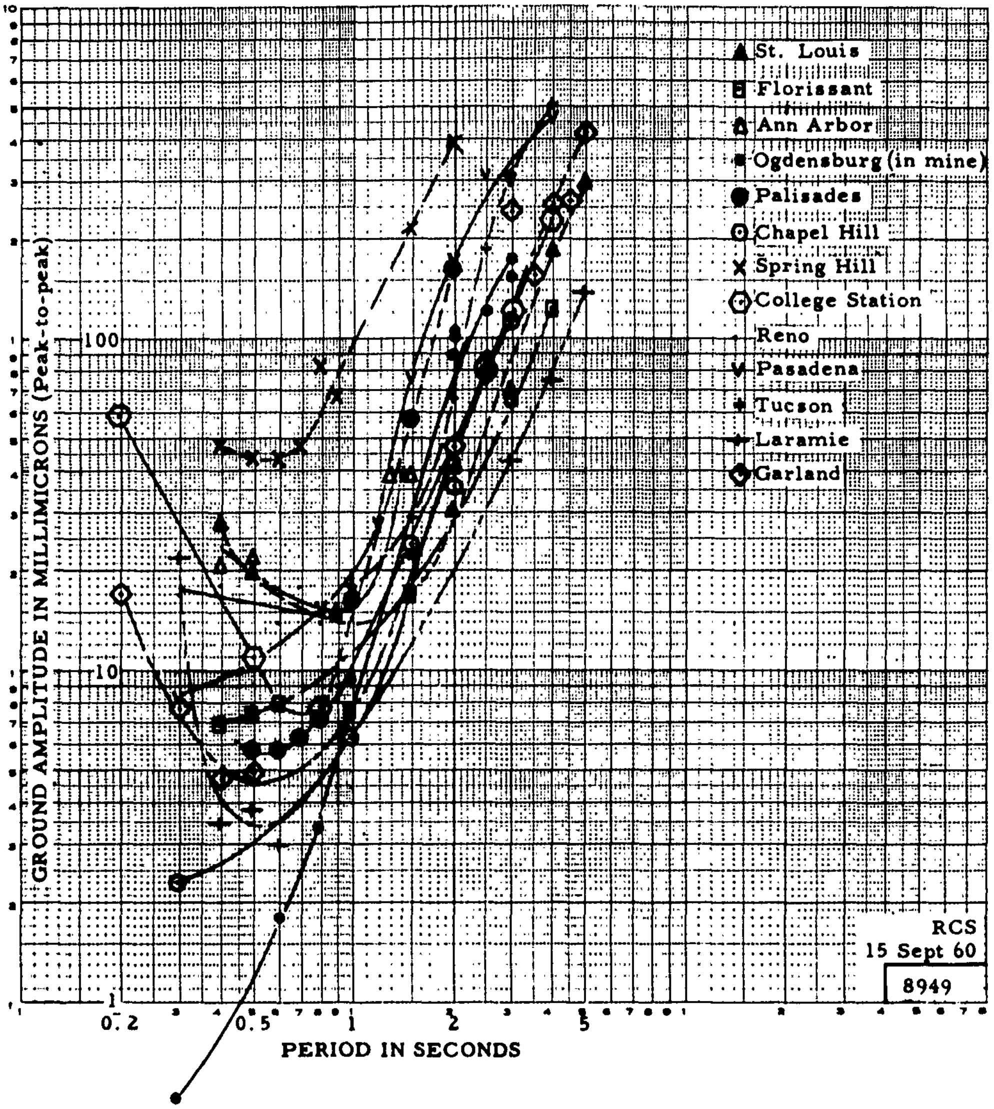

FIGURE 3-1. MICROSEISMIC SPECTRUM OF NIGHTTIME NOISE

system to be over six times stiffer than it would be with the moving coil transducer. Another advantage of the variable reluctance transducer is that the seismometer can be damped with a much smaller magnet than is required for a seismometer with a moving coil transducer. For example, in the variable reluctance transducer used in the deep-well seismometer, the magnet weighs approximately 0.4 lb. Design considerations for a moving coil seismometer with a

TABLE I. DEEP-WELL VERTICAL SEISMOMETER
Requirements for Long-Term Operation

Environment

(a) Depth to 10,000 feet
(b) Pressure to 7500 psi
(c) Temperature to 300° F
(d) Unknown fluids and gases in well, assumed corrosive
(e) Axis of hole inclined to 10°

Design

(a) Instrument noise consistent with sensitivity
(b) Response similar to that of the Benioff
(c) Provisions for down-hole calibration
(d) Provisions for re-centering from surface
(e) Cable and connectors not to be a limiting source of noise

Other Operating Parameters

(a) Seismometer to operate resting on bottom of well or cemented into well
(b) Amplifiers to be at surface
(c) Life in well to be 1 year, minimum
(d) 0.01-Å sensitivity desired

natural frequency of 1 cps dictate that the magnet must have approximately the same weight as the seismometer mass. This means that a seismometer with a 100-kg mass requires 100 kg of magnet to damp the mass. It is recognized that often the magnet itself can be used as the mass, but in this application, where the diameter is limited, it would be very difficult to use a single 100-kg magnet and still retain an efficient magnetic circuit. This means that the transducer must be made in a modular form using several magnets and coils, which complicate the design.

Because it is not clear which type of transducer is most suitable, prototype models of seismometers using both types are under development.

DESCRIPTION OF SEISMOMETER

The objective is to design and construct a simple and rugged seismometer which, when cemented into the well, can drive an amplifier located on the surface. Locating the amplifier on the surface is considered necessary for satisfactory long term operation. Present experience with surface seismographs show that it is feasible to separate the seismometer and amplifier by several miles and still have low system noise.

The characteristics of the deep-well seismometer will be essentially the same as those of the standard Benioff seismometer. Table II shows a comparison of the characteristics of the two instruments.

Figure 3-4 shows a cross section of the seismometer, and Figure 3-5 shows the component parts. The seismometer is 5 inches in diameter and a little over 9 feet long (not including the cable connector), and weighs about 470 lb. Willmore-type "delta rods" are used to constrain the mass to vertical motion. The mass is centered remotely by moving the upper suspension point of the main spring with the motor drive shown in Figure 3-6. Remote calibration is done by an electro-dynamic calibrator.

CABLE

One of the more severe problems anticipated is to develop a long-lasting cable to connect the seismometer to the phototube amplifier. Temperature, pressure, and the corrosive fluids in the well, together with the requirement for high mechanical strength, all make heavy demands on the cable.

TESTS

Figure 3-7 shows the results of the preliminary shaking-table tests of the seismometer. When used in a deep well, the response may have to be altered to provide additional rejection of the 4- to 8-second microseisms. This is necessary because the shorter periods attenuate with depth more rapidly than the longer periods.

A shallow hole approximately 300 feet deep, located at WMSO, will be used for preliminary operational testing and for development of field-handling techniques. The hole drilled in granite is 8 inches in diameter and is uncased. A surface vault, located about 50 feet away, contains a standard Benioff seismometer for control.

For both testing and operation a phototube amplifier will be used to amplify the output of the seismometer, and recordings will be made on a 16-mm multichannel film recorder (Develocorder).

CONCLUSION

Work on the variable reluctance deep-well seismometer is proceeding on schedule, and preliminary results are about as expected. The major problem anticipated is the development of cable which will operate under the conditions in a deep well over a long period of time and produce a minimum of noise.

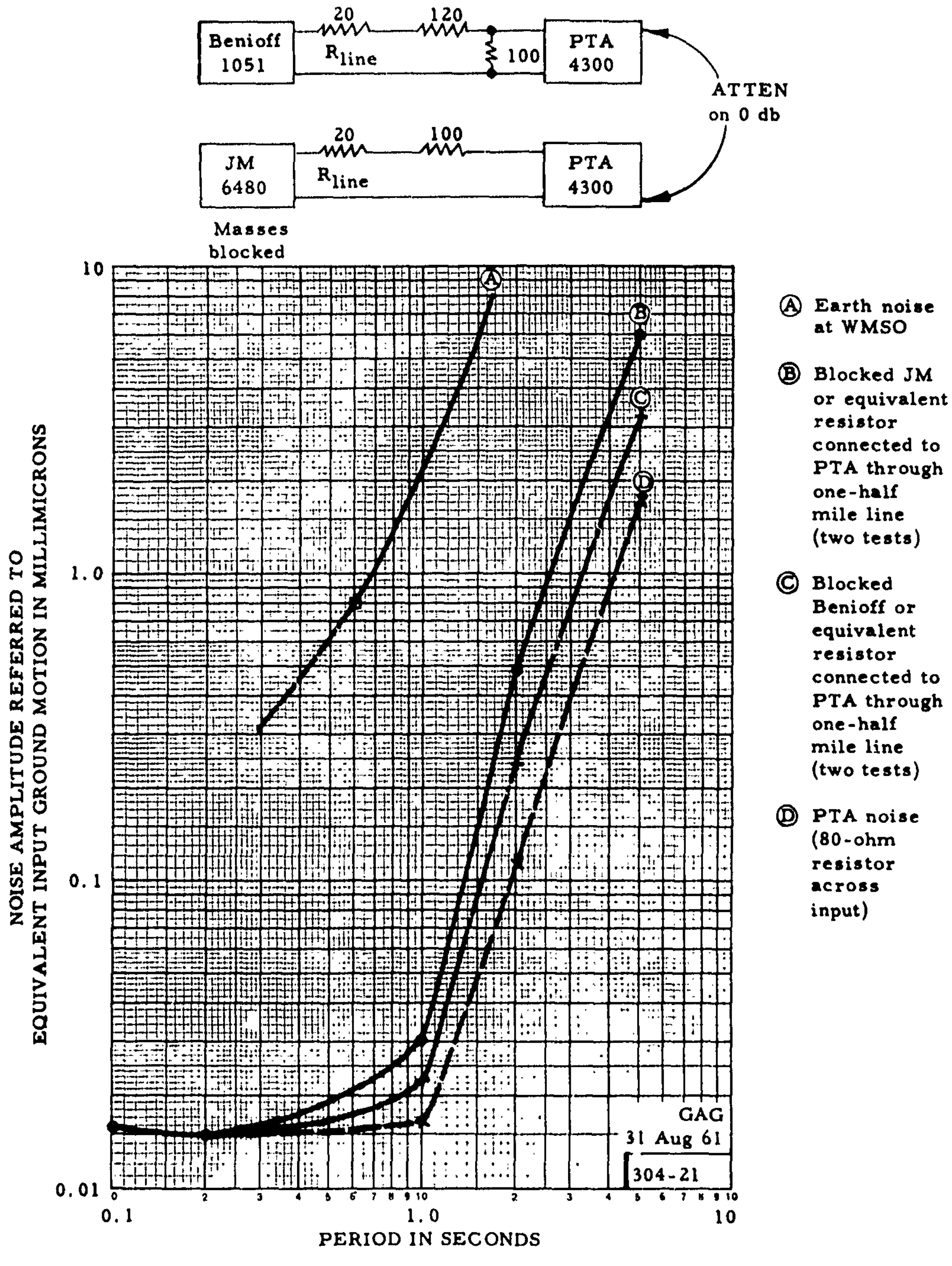

FIGURE 3-2. INSTRUMENT NOISE SPECTRUM

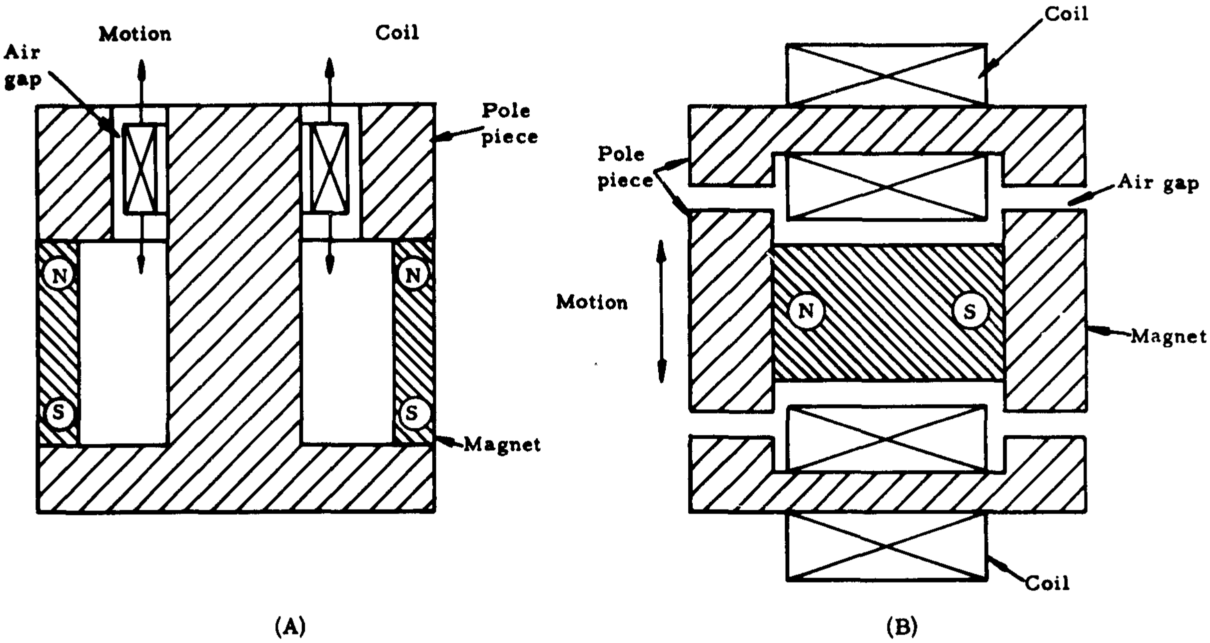

FIGURE 3-3. VELOCITY TRANSDUCERS. (A) Moving coil. (B) Variable reluctance.

TABLE II. COMPARISON BETWEEN CHARACTERISTICS OF BENIOFF SEISMOMETER AND DEEP-WELL SEISMOMETER

	Deep Well	Benioff
Natural Period (seconds)	1.0	1.0
Weight Inertial Mass (pounds)	220	237
Length of Each Air Gap (inches)	0.091	0.078
Flux Density in Gap (gauss)	900	750
Spring Rate of System (lb/in.)	22.55	24.2
Spring Rate of Main Spring (lb/in.)	95	95
Spring Rate of Centering Rods (lb/in.)	50 to 55	54
Spring Rate of Transducer (lb/in.)	-120 to 125	-124.8
Ratio of Negative to Positive Spring Rate	0.81 to 0.85	0.83

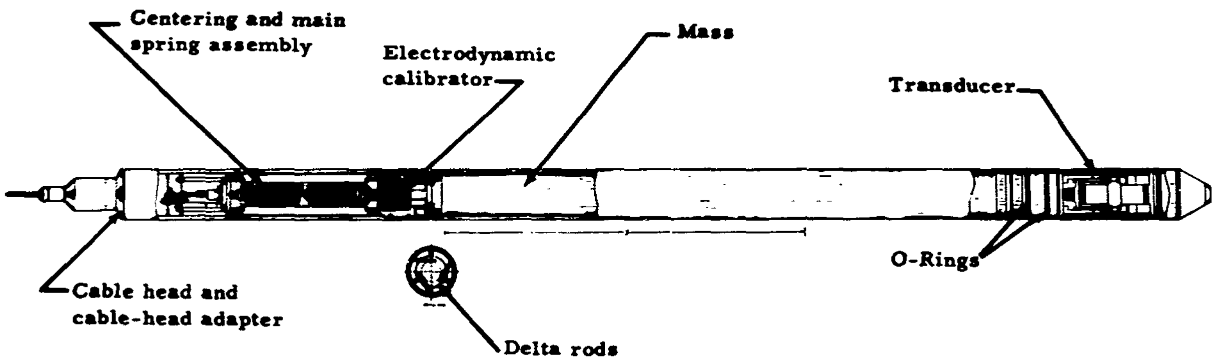

FIGURE 3-4. DEEP-WELL SEISMOMETER, MODEL 11167, VARIABLE-RELUCTANCE TYPE

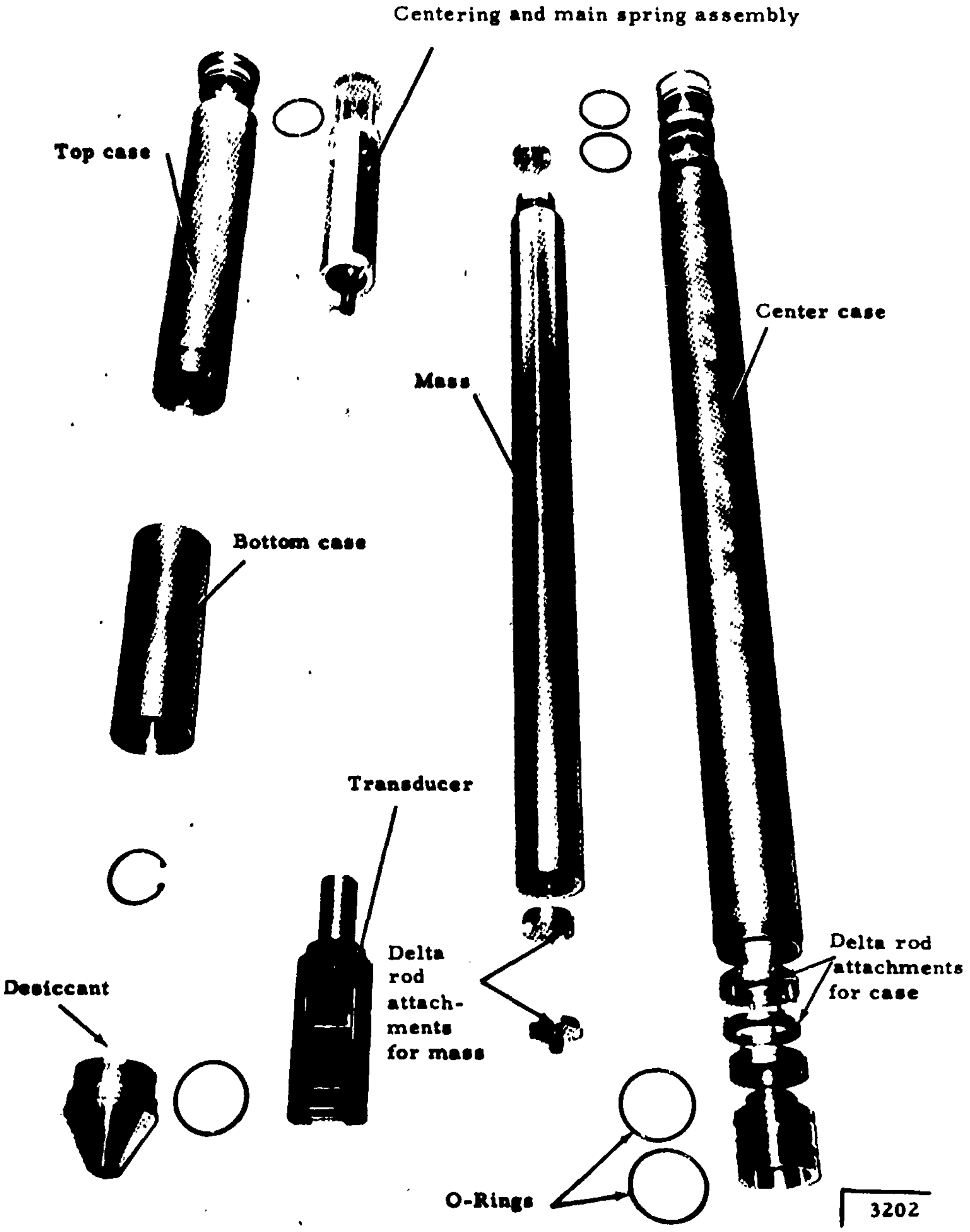

FIGURE 3-5. MAJOR COMPONENTS OF DEEP-WELL SEISMOMETER

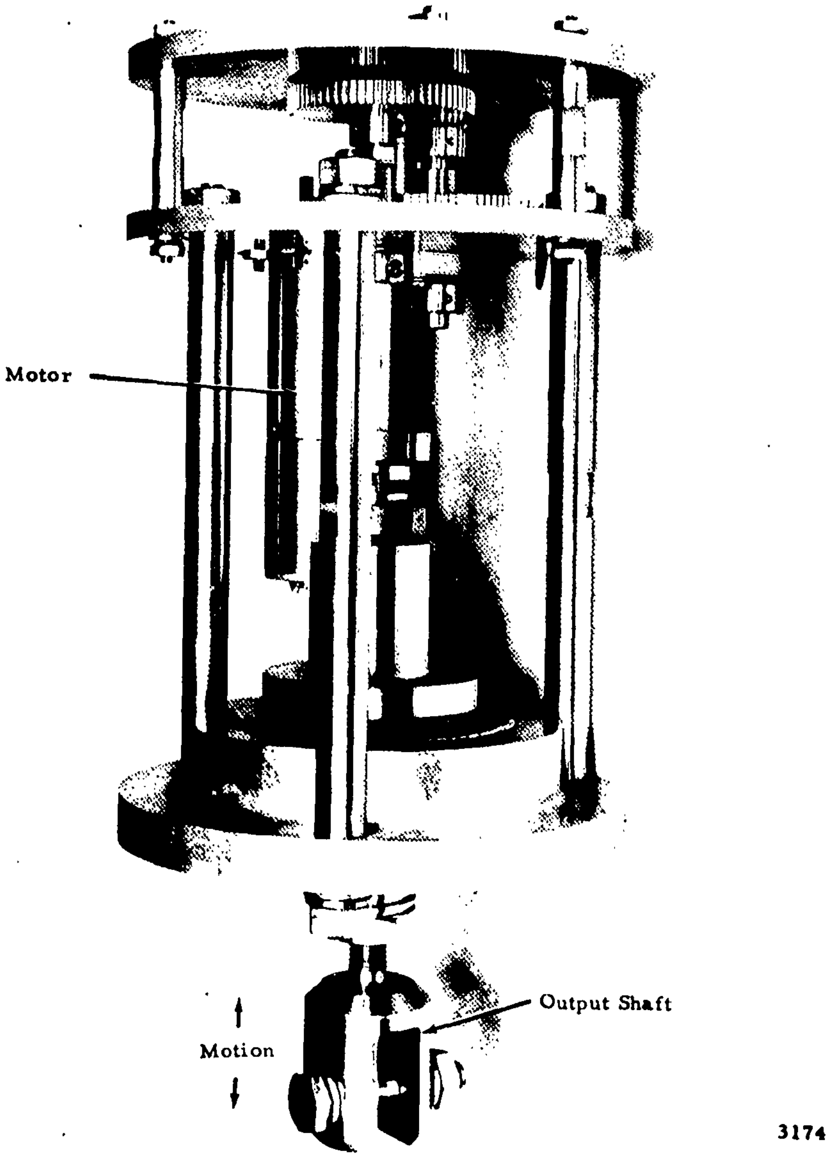

FIGURE 3-6. MASS-POSITIONING DEVICE

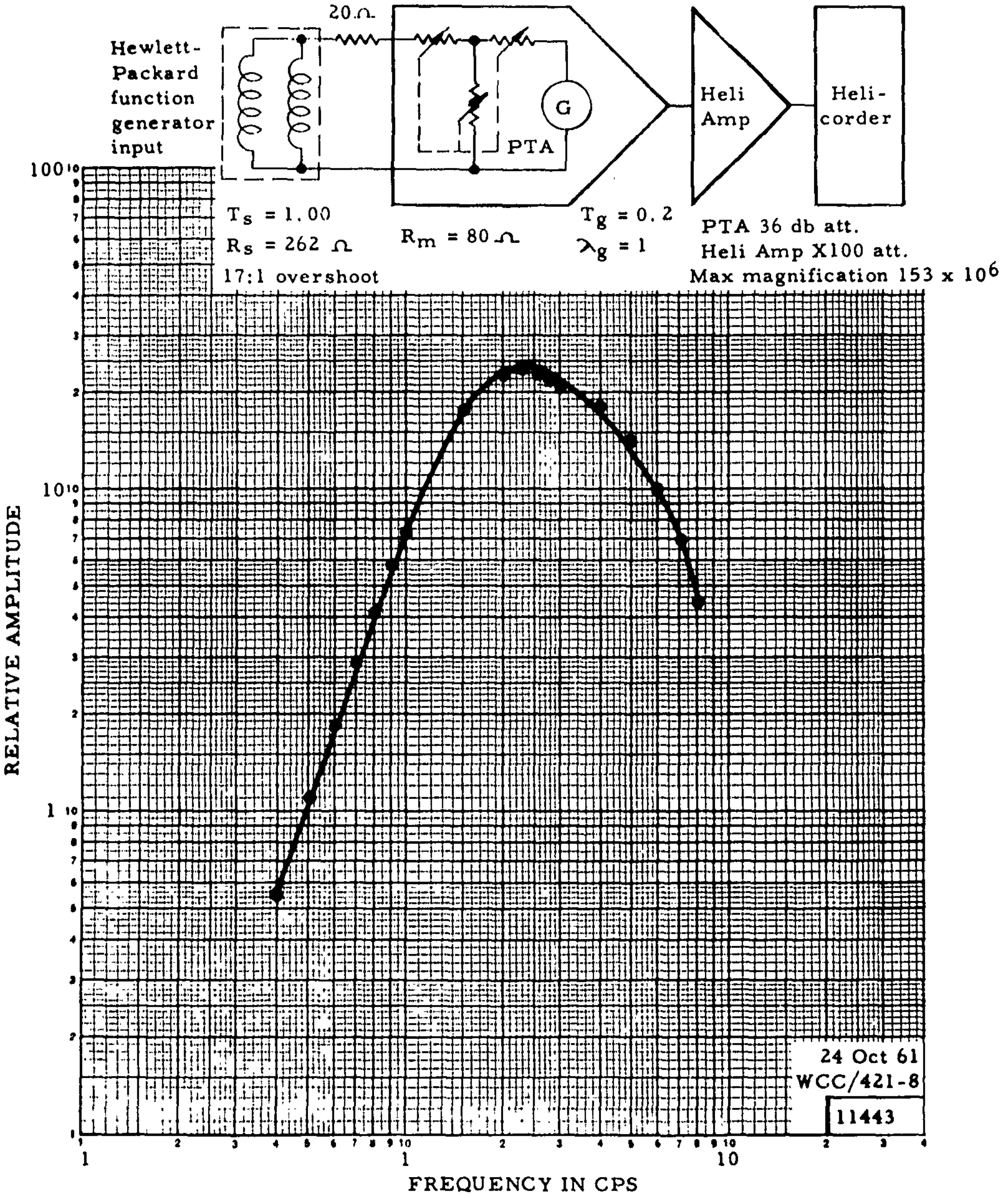

FIGURE 3-7. FREQUENCY-RESPONSE CURVE OF DEEP-WELL SEISMOMETER, VARIABLE-RELUCTANCE TYPE

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DEEP-WELL MODULAR MOVING-COIL INERTIAL SEISMOMETER

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At the conclusion of its "Initial Deep-Well Program,"[2] United ElectroDynamics, Inc., recommended the development of a modular, deep-well, inertial seismometer embodying the following concepts:

(a) It should be a completely passive, earth-powered unit for simplicity and reliability.
(b) It should be of modular design to obtain high reliability through redundancy.
(c) It should be expendable, to offset the hazards of deep-well operation.
(d) It should be rugged and field-worthy.
(e) It should feature remote calibration to insure extended life at depth.

The seismometer must be capable of operating at depths down to 10,000 feet in well mud at temperatures approaching 300°F. The operating pressure will be near 5500 psi, but the case design pressure will be 7500 psi and the seal design pressures will be 10,000 psi for reliability. The seismometer must have an od (outside diameter) of no more than 5 inches, and must be designed to operate tilted as much as 10° from vertical.

It was desired that earth noise rather than instrument performance be the limiting factor in the design of the unit. The results of the initial UED deep-well program indicated that earth noise attenuates with depth, as shown in Figure 4-1. Extrapolating this finding to 10,000 feet indicates that the 1.5 $m\mu$ peak-to-peak surface noise measured at Payson, Arizona, will attenuate to about 0.1 $m\mu$ (1Å) peak-to-peak. This dimension, being a representative noise level at an extremely quiet area, was therefore adopted as the design-noise level of the seismometer.

For signal power considerations, it appears desirable to imitate the Benioff seismometer with its 100-kg seismic mass. To extrude this as one solid mass into a pressure case of 5 inches od would prove rather unwieldy. To facilitate the design and to gain extra reliability, it was decided to divide the mass into a number of conveniently sized modules. Mechanical coupling of these modules was investigated, but discarded as far too complex. Electrical summing of the outputs was considered more appealing because of its extreme simplicity, and was therefore adopted.

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[2] Project T/741, Contract AF 33(600)-35516.

The magnitude of the thermal agitation of these smaller masses was next investigated. As shown in Figure 4-2, the incoherent thermal noise amplitudes of each individual module are summed as the square root of the sum of the squares, coherent earth noise, which must now be considered the signal into the seismometer, is summed directly. The amplitude signal-to-noise ratio of the summed output of the seismometer can be shown to be improved over that of a single signal module by the square root of the number of modules (as is common with surface arrays). Assuming 5 modules, a desired summed amplitude signal-to-noise ratio of 25, and an earth noise of 1 Å, the thermal noise amplitude of each individual mass must not exceed 0.0995 Å.

Wolfe (see Reference 2) has shown that thermal agitation decreases as the mass is increased. At 500°K (which is higher than expected in the well) and at 1 cps (the nominal center frequency of the Benioff seismometer which we desire to imitate), it can be seen that a 20-kg mass will have a noise amplitude of approximately 0.08 Å, well below the 0.0995-Å target.

Flexures are employed to guide the mass in a seismometer. Wire flexures are often used because they add so little to the spring rate of the system. However, since they cannot support compressive loads, they will change the natural frequency of the seismometer as it is tilted from the vertical. For this reason they are unsatisfactory for use in deep-well seismometers.

Willmore flexures overcome this difficulty, but they are rather stiff. From Figure 4-3 it may be seen that to support a 3-lb end load (the load on each flexure when the seismometer is tipped 20°) the minimum spring rate will be 0.6 lb/in. per flexure. Six flexures will therefore contribute 3.6 lb/in. to the spring-mass system.

A spring-mass system with a 20-kg mass and a natural frequency of 1 cps will require a system spring-rate of 4.5 lb/in. Subtracting the 3.6-lb/in. contribution of the Willmore flexures leaves only 0.9 lb/in. for the seismic spring. As shown in Figure 4-4, the surge frequency of this spring will range from about 0.2 to 10 cps, depending upon the stress levels in the spring. These frequencies are within the bandpass of the instrument and cannot be tolerated.

To correct this difficulty, the levered spring-mass system diagrammed in Figure 4-5 was investigated. The seismic spring is attached to a spider which in turn is attached by a flexure to levered Willmore flexures at the top of the seismic mass. Since the spring rate can be increased by the square of the lever ratio, a 12.5-lb/in. spring will produce the desired 0.5-lb/in. spring rate, using a 5 to 1 lever ratio. This spring will have a surge frequency of 50 cps with a rather low 50,000 psi stress level. Low stress levels are desirable to reduce creep.

Two types of passive transducers were considered, moving coil and variable reluctance. A moving coil transducer is relatively insensitive to mass position, so that a mass positioning device may not be needed. A solid iron path may be used in its magnetic circuit, as the flux is essentially constant. Variations in magnetic flux with time and temperature will not affect the natural frequency of a spring-mass system, and its dynamic range is very wide. However, if moving magnets are used to reduce the size of the seismometer, the mass may be difficult to dampen.

In contrast, a variable reluctance unit is easy to damp, and it contributes a negative spring rate which allows the use of stiffer, stronger flexures. It is, however, very sensitive to mass position, which is affected by temperature and by aging of the magnets. Therefore a moving coil transducer has been chosen.

A schematic illustration of a deep-well seismometer module is shown in Figure 4-6. The seismic spring is attached to the mass through a levered flexure system. The lower flexures will be of the straight Willmore type. The mass will be composed of the transducer magnets, which move relative to the coils mounted to the case of the instrument. The mass lock motor is used to position the mass, and to lock it when the seismometer is transported or while it is being lowered or removed from the borehole. It is also used to position the mass. An electromagnetic coil is employed to calibrate the seismometer.

Equipment which can simulate the conditions at the bottom of a 17,000-foot well will be used to test the seismometer. A 150-foot well will be used for testing equipment and procedures for field handling.

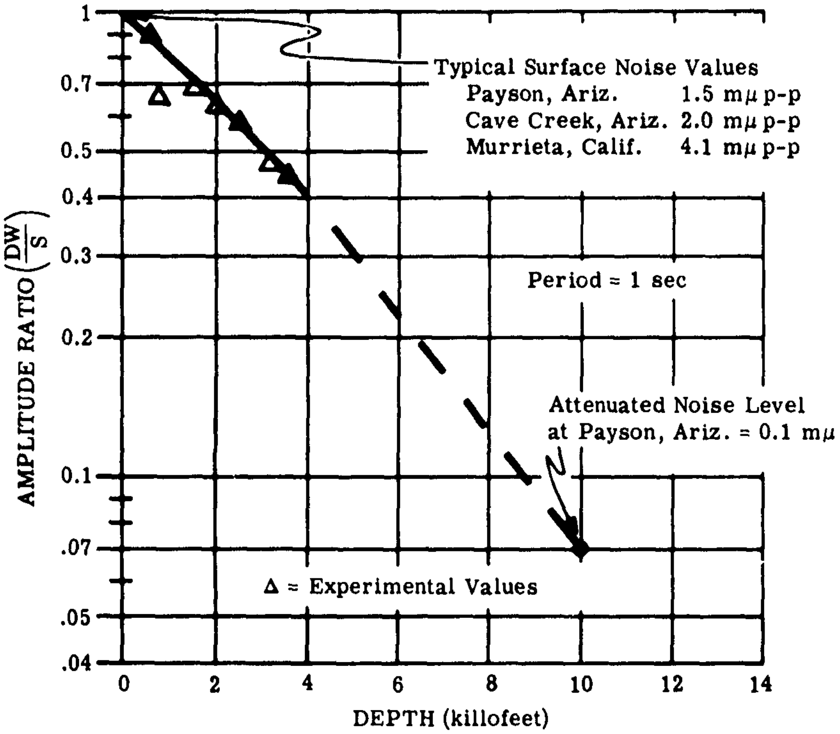
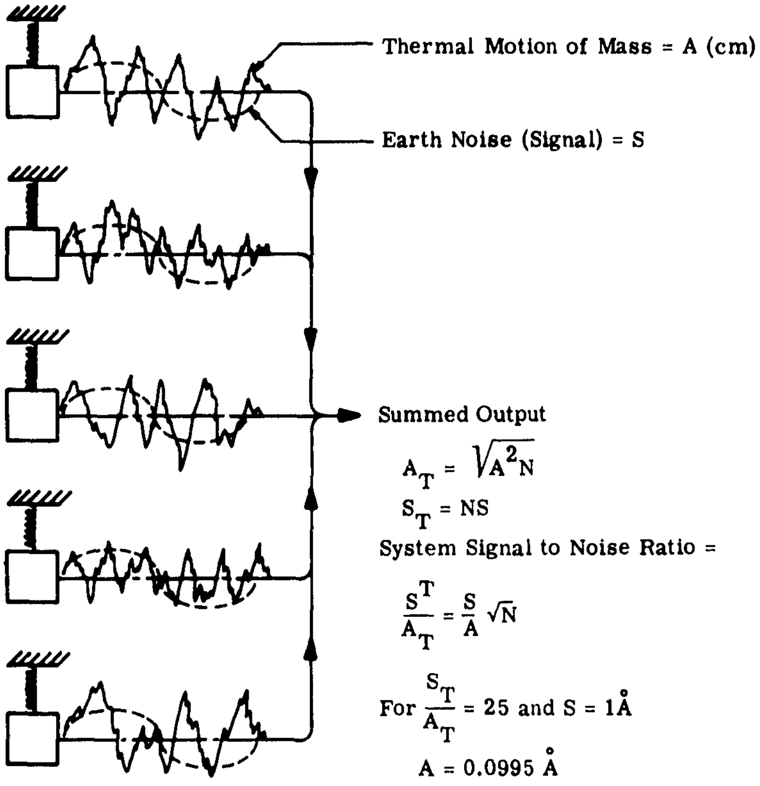


FIGURE 4-1. SURFACE NOISE ATTENUATION WITH DEPTH



$$A_T = \sqrt{A^2 N}$$

$$S_T = NS$$

System Signal to Noise Ratio =

$$\frac{S^T}{A_T} = \frac{S}{A}\sqrt{N}$$

For $\frac{S_T}{A_T} = 25$ and $S = 1\text{Å}$

$$A = 0.0995\ \text{Å}$$

FIGURE 4-2. THERMAL NOISE LEVEL LIMIT

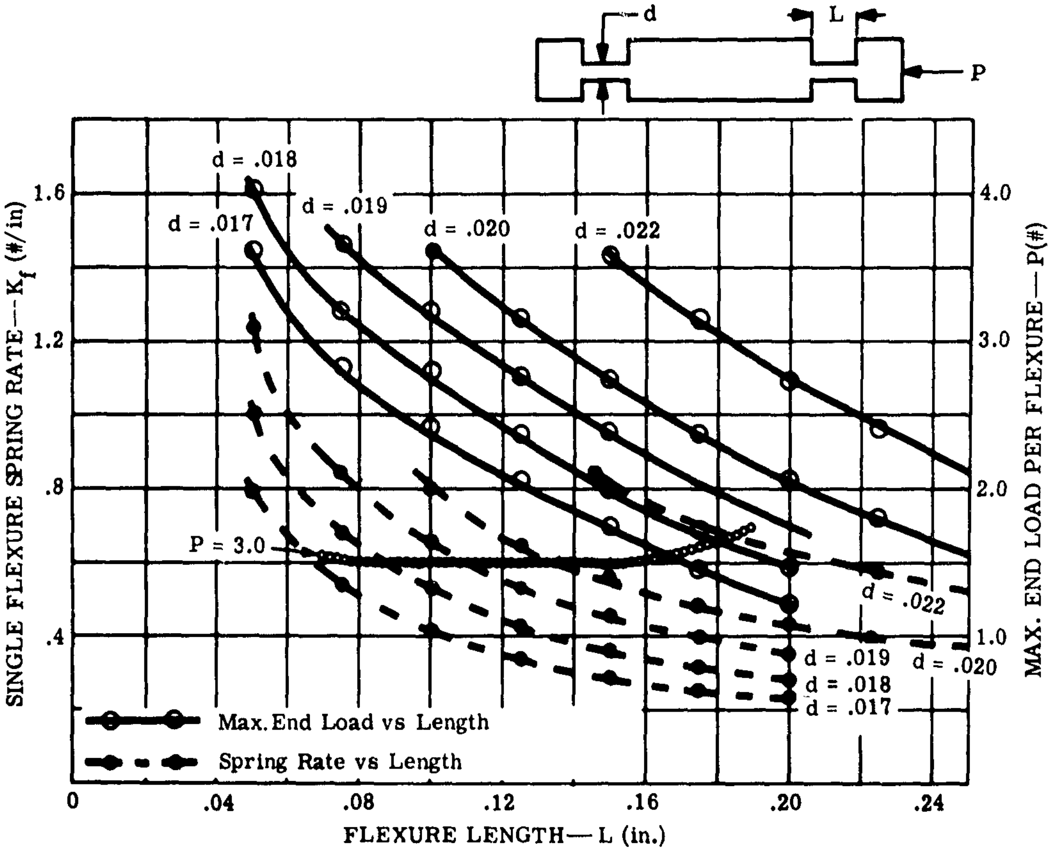


FIGURE 4-3. WILLMORE FLEXURE DATA

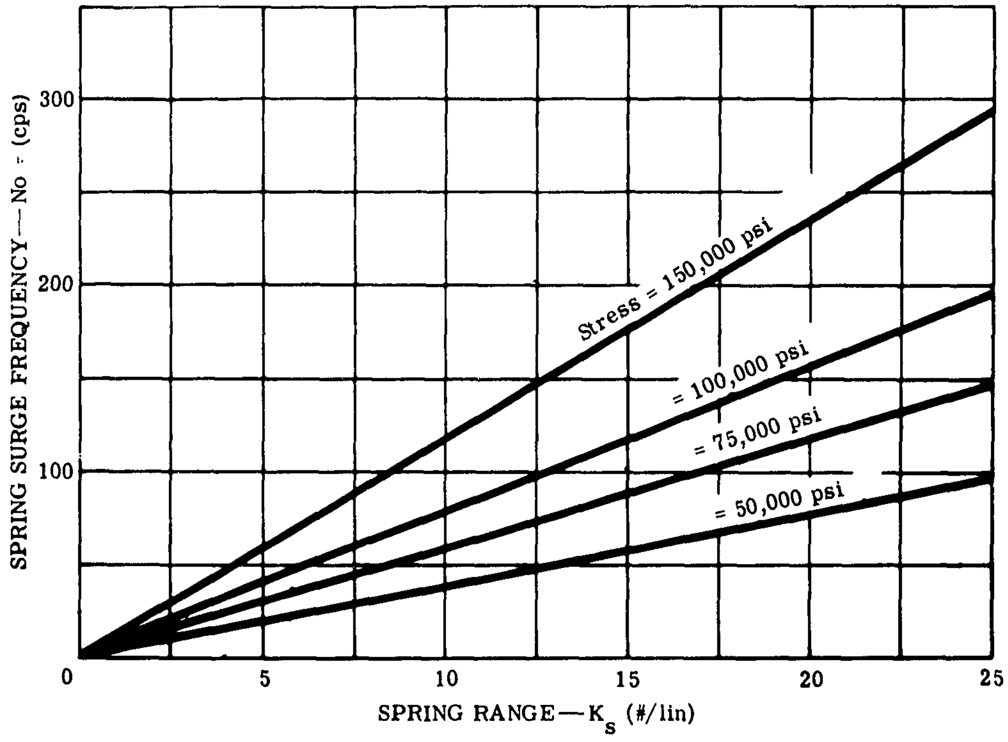


FIGURE 4-4. SURGE FREQENCY VS. COIL SPRING RATE FOR VARIOUS STRESS LEVELS

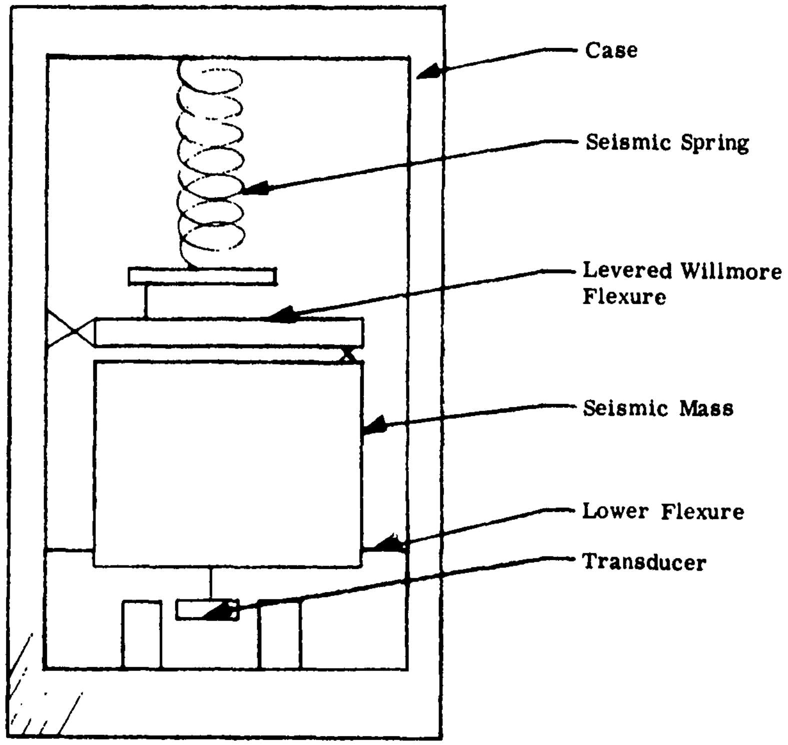


FIGURE 4-5. INERTIAL SEISMOMETER WITH A LEVERED SPRING SYSTEM

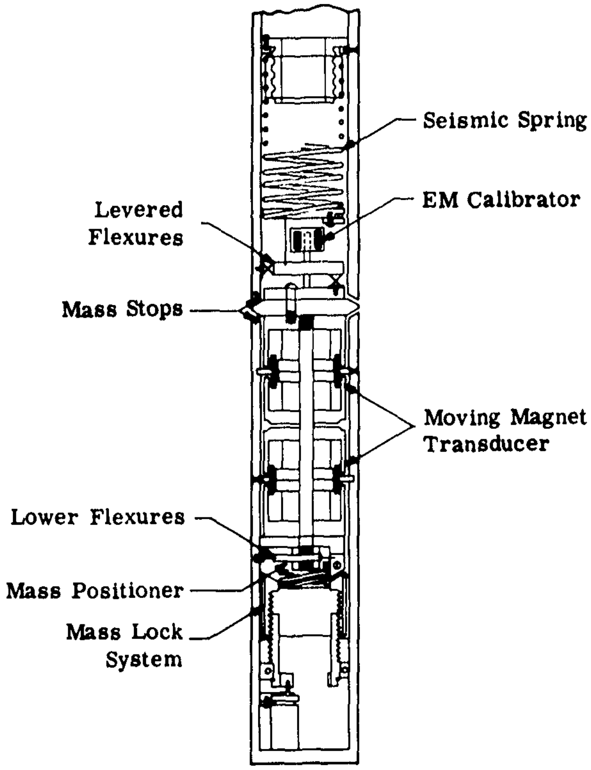


FIGURE 4-6. DEEP-WELL SEISMOMETER MODULE

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EVALUATION OF A PRESSURE DETECTOR AS A DEEP-WELL SEISMOMETER[3]

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OBJECT

The object of this study is to evaluate the use of a pressure sensor as a seismic detector for deep-borehole detection of underground nuclear explosions.

GENERAL

In the procedures for determining travel time from surface shots to a borehole detector in velocity surveys of oil wells, pressure detectors have proved superior to inertial detectors. The pressure detectors commonly used employ a diaphragm-operated reluctance sensor which makes the signal output proportional to the rate of change of pressure. Recent experiments with ceramic sensors of the lead-zirconate titanate type have shown that at frequencies of 100 cps or more their sensitivity is equal to or greater than that of the best reluctance sensors. With these new ceramic sensors it is possible to make the pressure-vs.-frequency response flat down to 1 cps. Figure 5-1 compares the response of a ceramic detector to that of a detector using a reluctance sensor; a surface charge of only 2.5 lb was exploded, and readings were taken at 10,000 feet. The figure shows that at low frequencies the ceramic elements have relatively greater output than the reluctance pressure detectors.

This study discusses the modifications made on a deep-borehole pressure detector of the lead-zirconate titanate type in an attempt to achieve response down to 1 cps. Also, it compares noise measurements made by the modified detector, a surface Benioff seismometer, and a borehole inertial detector.

RESULTS

(1) The goal of achieving a pressure resolution of 0.02 dyne/cm^2 was not reached. The usable sensitivity was limited by a noise-level equivalent to 0.113 dyne/cm^2 pressure signal, resulting from a higher peak-to-peak noise level than expected, and a slightly lower transducer output.

(2) In-hole measurements showed that for all tests background noise was well above the limiting input resistor noise. There is some question whether the noise is self-generated in

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[3] Report No. P-4-61-2, prepared for Air Force Cambridge Research Laboratories under Contract AF 19(604)-8454, 23 August 1961, and sponsored by the Advanced Research Projects Agency under Project VELA UNIFORM.

the transducer when pressure is applied, or is actual borehole noise. Transducer manufacturers have suggested that noise may be generated when domains of stress in the ceramic relax under pressure. They could supply no actual figures for this.

(3) In order to reduce surface noise and ambient-pressure fluctuations, it was necessary to clamp the supporting cable and pressure-seal the casing head.

(4) There was no major change in noise level with depth.

(5) Comparison of background measurements made by a short-period surface Benioff to those made by the borehole detector gave no evidence of correlation.

(6) Background measurements made by the borehole detector were compared to those made by a 1-cps inertial responsive detector in a nearby borehole at the same depth. Only poor evidence of correlation on strong signals appeared.

(7) Recordings of shot events indicate that wall-clamped inertial transducers are superior to others, undoubtedly because of the better coupling coefficient which results from the use of a velocity-responsive system with a relatively high frequency pulse.

(8) The results of these tests are not conclusive. They strongly suggest the use of a pressure detector in which the sensor is not a ceramic, to determine whether the in-hole noise is seismic or self-generated.

INSTRUMENTATION

Transducer Element. The ceramic element used is 4 inches long and 3 inches in diameter; the wall is 1/4 inch thick. The simplified mounting used is shown in Figure 5-2. This is the mounting used in the tests recorded in Figure 5-1. It has been successfully used to depths on the order of 18,000 feet.

Both fluid and air were tested as backing for the element. It was found that air backing, though it presents a structural design problem for deep-borehole surveys, results in a greater output per unit of pressure change.

Computed Sensitivity. The open-circuit voltage output per unit of hydrostatic pressure, for a radial polarized tube with exposed ends, was calculated in accordance with the derivation by Langivin (Reference 3). For the above ceramic element the open-circuit voltage is calculated to be 37.4×10^{-6} v/dyne/cm^2.

Borehole Amplifier. To make use of the voltage calculated above, a high-input impedance amplifier with low inherent noise is necessary. An amplifier using an electrometer tube input and a transistor amplifier was tested, but proved to have a noise level above the input resistor noise. Therefore an amplifier using only vacuum tubes was built; it is diagrammed in Figure 5-3. A 60-cps rejection filter is included in the amplifier, because a-c pickup at the impedances and voltages involved makes it very difficult to measure noise in the laboratory. The electrical response of the preamplifier is shown in Figure 5-4.

Surface Amplifier. The signals from the borehole preamplifier were transmitted over two cable conductors to a special high-gain, low-noise amplifier equipped with filters and suitable for driving a recording oscillograph. This amplifier is shown schematically in Figure 5-5, and the overall electrical response at the different filter positions is shown in Figure 5-6. The only transformer in the system is the special-input transformer. Input noise level at the first-stage grid is on the order of 2 μv. Since the total gain through the preamplifier and the logging cable is 30, signals from the preamplifier will override any noise level in the surface amplifier system.

SYSTEM CALIBRATION

Pressure Calibration. The absolute pressure sensitivity of the seismometer is calibrated by the following method. A small reciprocating piston with a variable-speed drive provides a near-sinusoidal pressure pulse to the transducer via the water jacket surrounding the transducer. As the piston moves, it displaces air in the cylinder and thus exerts pressure on the water column. A 0.1-inch change in water level, equivalent to a pressure change of 250 dyne/cm^2, is used throughout the calibration tests. A pressure change of this magnitude produces a signal well above the level of normal atmospheric pressure change and room noise. Pump speed in the range of 1-4 cps is used in calibration.

For the sake of accurate in-hole pressure determination, the entire instrument system was calibrated. Because of pump limitations, complete frequency-response tests could not be made, but through the range of 1-4 cps the response followed the electrical-system response closely.

Electrical Calibration. To calibrate the system electrically, a signal was injected into the input of the preamplifier in place of the transducer. The sensitivity of the system was found equal to 10 μv/in. of trace movement. For a fluid-backed transducer with a trace deflection of 0.72 in./dyne/cm^2 and 10 μv/in., the output is

$$1 \text{ dyne/cm}^2 = 7.2\ \mu\text{v peak to peak}$$

Tests made with an air-backed transducer gave an output of 32 μv/dyne/cm^2, which checks well with the computed sensitivity. The deep hole tests were made with a fluid-backed transducer, the other tests with an air-backed transducer.

Noise Level. To determine the noise level, the transducer was suspended in the test stand exactly as in the pressure tests, except that the pump system was not operated. A peak-to-peak trace deflection as low as 0.12 inch was recorded with an attenuator setting of 10 db. This is equivalent to 0.36 inch with no attenuation. Using a voltage sensitivity of 10 μv/inch, as previously measured, gives

$$\text{peak-to-peak noise} = 3.6\ \mu v$$

When pressure sensitivity is 32 μv/dyne/cm^2, the noise is equivalent to

$$\frac{3.6}{32} = 0.113\ \text{dyne/cm}^2$$

To verify that the noise recorded was thermal noise, and was not caused by unshielded pressure fluctuations, the thermal noise was calculated and measured.

Thermal Noise Calculation. Noise generated by thermal agitation in the input grid resistor can be estimated from the relation

$$E^2 = 4KTR(f_2 - f_1)$$

where E = rms voltage

K = Boltzmann's constant = 1.374 x 10^{-23} joules/$^{\circ}$K

T = absolute temperature, $^{\circ}$K

R = input resistor

$(f_2 - f_1)$ = frequency range

For a frequency range of 1-10 cps at 300°K and an input resistor of 20 megohms, a voltage of 1.72 μv rms (or 4.8 μv peak to peak, making a sine-wave approximation) is calculated. Reducing the bandwidth to 1-4 cps would reduce the rms noise to 1.6 μv peak to peak. A voltage of 6 μv peak to peak was recorded for this bandwidth after the transducer was removed. Thus the system noise level was on the order of that calculated for the input resistor. Tests showed that the noise level is lowered by the square root of the value of the grid resistor, verifying that the noise level is limited by the input resistor.

COMPARISON WITH BENIOFF RESPONSE

For a reference or comparative signal, a 1-cps Benioff Seismometer, Type 4681, was mounted on a concrete table firmly embedded in the earth—approximately 50 feet from the well-casing head for the laboratory well tests, and on a concrete platform for the Dowell well tests.[4] Typically, the system operated at a magnification of 12,030 times, so that 1 mm of trace deflection is equivalent to 83 mμ of movement. (The relatively high-frequency [4.5 cps] galvanometer

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[4] See section on Dowell Test Well.

used gave rise to high-frequency noise which limited the magnification.) At this relatively low magnification the noise level gave a good background deflection. The overall response was very similar to that recorded on the subsurface detector.

A separate Benioff recording was made on a dual-channel oscillograph at chart speeds on the order of 1/3 ips. This allowed good resolution of wave forms up to 10 cps and a direct comparison between the surface and subsurface signals. However, since the recording galvanometer in the dual-channel oscillograph had a natural frequency of 30 cps, the Benioff exhibited a much higher frequency response than the subsurface detector, which was always used with a filter cutoff of 4 cps. Further, the Benioff has better high-frequency response because it is velocity sensitive, whereas the borehole detector has linear response vs. frequency.

NOISE MEASUREMENTS

Laboratory Test Borehole. Initial measurements were made in a 1320-foot laboratory test borehole. The noise level in the borehole was very high, on the order of 200 dyne/cm^2 pressure equivalent. This noise was traced to movement of the logging cable on which the detector was suspended. By clamping the cable at the borehole head so that the cable was supported by the casing and was slack above the clamp, the noise level was reduced to approximately 84 dyne/cm^2 pressure equivalent. However, it was still much too high. In an effort to determine whether it was generated in the transducer, a test was made in the borehole with the transducer disconnected but the rest of the system operating. A noise level equivalent to 0.5 dyne/cm^2 was measured at all levels. Thus it was shown that the hole noise with the transducer on is real, and the input resistor noise level is not limiting the pressure resolution. The measurements checked with the laboratory measurements, indicating that the presence of the cable in the hole did not increase the noise.

The noise recorded by the deep-hole seismometer was found to arise from diverse causes. Atmospheric pressure changes were reflected through the liquid column to the detector; however, the resultant noise was greatly reduced by capping the casing head. Also, derrick movement produced considerable noise, enough to be controlling; in the quietest weather a noise level of 2 dyne/cm^2 pressure equivalent was measured. And the seismometer, at 1320 feet, detected any surface activity near the well head. It appears that the seismic energy was traveling by earth conduction to the casing head, from the cable clamp to the cable, and along the cable to the seismometer.

Efforts to achieve correlation in the recordings made by the deephole seismometer and the Benioff met many problems. There was no correlation between their recordings of random noise. Both systems easily detected large signals, such as those generated by dropping a weight or jumping on the ground; but since the signals traveled different paths for different distances, the two recordings were very different. Quarry blasts were recorded, but no records suitable for comparison were obtained. A set of two recordings is shown in Figure 5-7. The high gain setting resulted in excessive background deflection which, with the blast signal, saturated the recording amplifier.

Dowell Test Well. Further measurements were made at the Dowell test well, located in an area of high seismic noise. Again it was found necessary to minimize cable and atmospheric pressure noise by clamping the cable and pressure capping the well casing. The Benioff seismometer was placed near the well site, and records for comparison were made on a multichannel oscillograph. Again there was no correlation between the two recordings of background noise. Tests made during day and night were compared. The high noise level and lack of correlation led to the conclusion that, if any correlation is to be achieved, detectors must be in nearly identical environments.

Jersey Test Wells. Tests were then conducted in cooperation with the Jersey Laboratories, using test wells and their borehole inertial detector. Noise checks were made at levels of 250 to 2000 feet, with the pressure detector in a cased borehole and the Jersey wall-clamping inertial detector in an uncased borehole. The two recordings showed little or no correlation. The electrical systems responded similarly, but the Jersey detector is velocity sensitive, whereas the Century detector is pressure sensitive.

Next, seismic pulses were made by dropping weights. The pressure detector obtained clearly defined pulses, but the character of these pulses suggested strong tube waves generated as a result of conduction to the water column by the casing. Figure 5-8 shows weight-drop pulses.

Seismic pulses were then generated by small chemical explosions 6000 feet from the detection point. These pulses showed up plainly on the records of the inertial detector but were masked by a background build-up coincident with the arrival of the pulse. Surface inertial detection of these pulses was poor compared to in-hole detection. When the positions of the detectors were reversed, so that the pressure detector was in the open hole and the inertial in the cased hole, the noise again built up at the arrival of the pulse. The inertial element failed to operate in this test, so that the comparison was not complete.

RESULTS

Reliable calibrations of absolute pressure sensitivity have been made possible by the development of the air-piston water-jacket technique. Previously, we had no means for obtaining an absolute pressure sensitivity check. Therefore, estimates of the performance of the higher-frequency well seismometers used in velocity surveying were based only on calculation. Since the resistor noise level was higher than calculated and the pressure-voltage sensitivity was slightly lower than calculated, the laboratory measurements showed a pressure signal resolution of 0.113 dyne/cm^2. In the borehole the minimum noise level was approximately 0.5 dyne/cm^2. The cause of this difference was found to be microphonism in the subsurface preamplifier. By insulating the well detector from mechanical contact with the casing, this difference in noise levels was reduced to approximately 0.2 dyne/cm^2 equivalent.

In all measurements the transducer's signal output in the borehole was well above grid resistor noise. Therefore, it was assumed that the measured noise was caused by true pressure signals, rather than being self-generated. However, since correlation records were so poor, other possible noise sources were considered. It has been suggested that the most likely source of a self-generated noise, other than the grid resistor, is the ceramic detector, in which the domains of stress may relax under pressure. This suggestion has not yet been verified.

Because of the relatively high sensitivity of the system it was found necessary to quiet the well phone by clamping the supporting logging cable to the casing head and pressure sealing the casing head. The recordings made in the three sets of tests showed no major change in noise level with depth to approximately 3000 feet. This might suggest that the noise being measured was not the earth-noise background. However, since we have no evidence of other noise sources, it must be assumed to be earth-generated noise.

Records made with a surface Benioff detector failed to correlate with background noise recorded by the subsurface detector. It was reasoned that resemblance was not likely, since surface waves were being compared to in-hole noise. Further, the differences in the responses of the two systems would make a direct correlation difficult.

Comparisons using an in-hole seismometer at the same depth also failed to correlate the background noise, except that there was some evidence of primary noise frequencies on the order of 2 cps. Frequencies in this range could be generated by tube waves, the so-called "organ pipe" effect. Evidence of such waves also appeared in recordings of pulses generated by weight drops and explosions. Study of this mode and of ways to eliminate it, is needed. There may be encouragement in the fact that the tube-wave phenomenon has not been noticeable in conventional well-survey measurements, an explanation for which may be that the low-frequency cutoff (20 cps) of recording systems used in well-surveying does not allow the long-period tube waves to interfere. A solution may be reached by using acoustic plugs in the borehole, at short intervals, so that the tube-wave resonance is outside the seismic spectrum.

The results of the field tests using small explosions for seismic pulses do not merit complete confidence because the pressure detector did not excel in performance as it did in the well-survey tests. We were unable to use test holes long enough to confirm the results. Therefore, the superiority of a clamped inertial detector cannot be conclusively stated until further verified.

FIGURE 5-1. COMPARISON OF MODIFIED MODEL "C" PRESSURE DETECTOR WITH STANDARD WELL PRESSURE SEISMOMETER

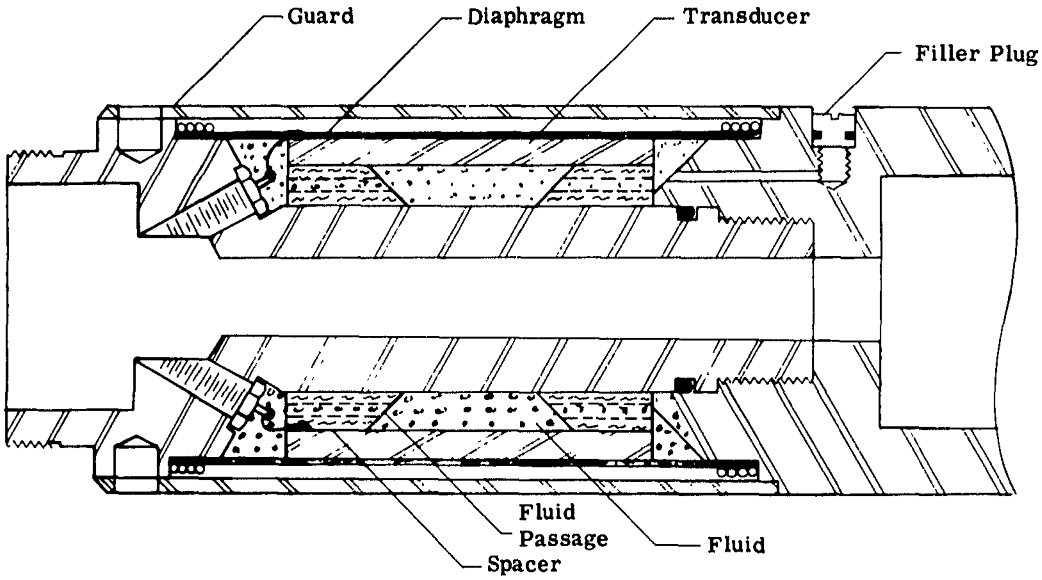

FIGURE 5-2. TRANSDUCER MOUNTING

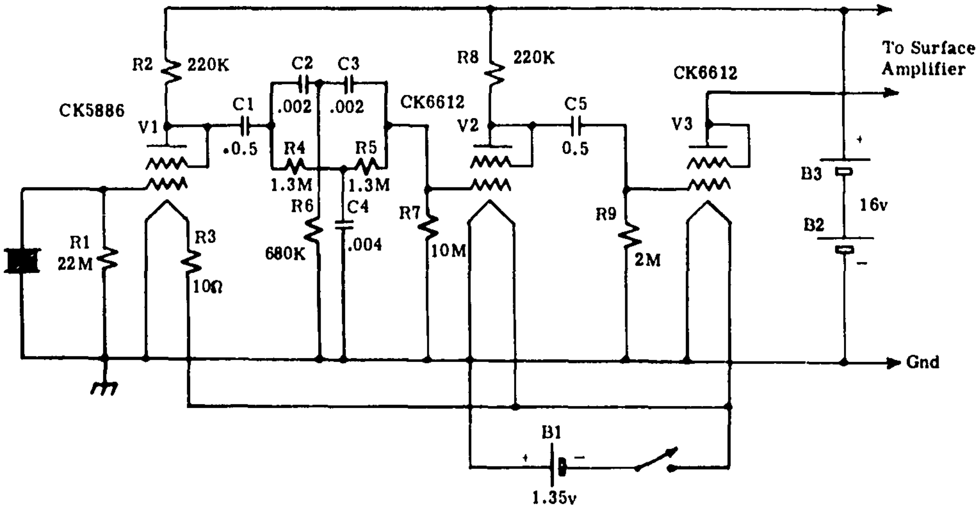

FIGURE 5-3. SUBSURFACE PREAMPLIFIER CIRCUIT DIAGRAM

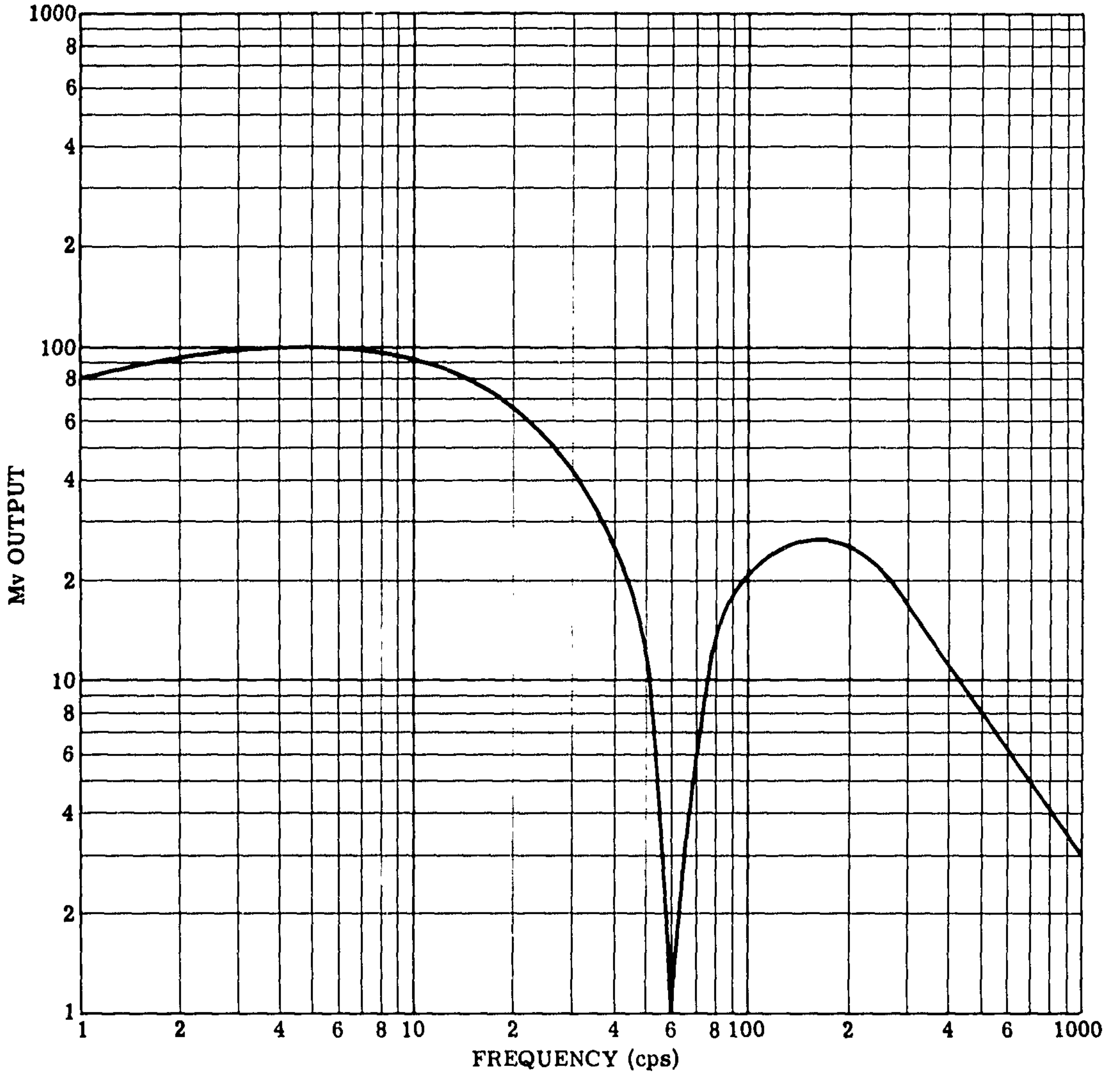

FIGURE 5-4. SUBSURFACE PREAMPLIFIER OVERALL RESPONSE

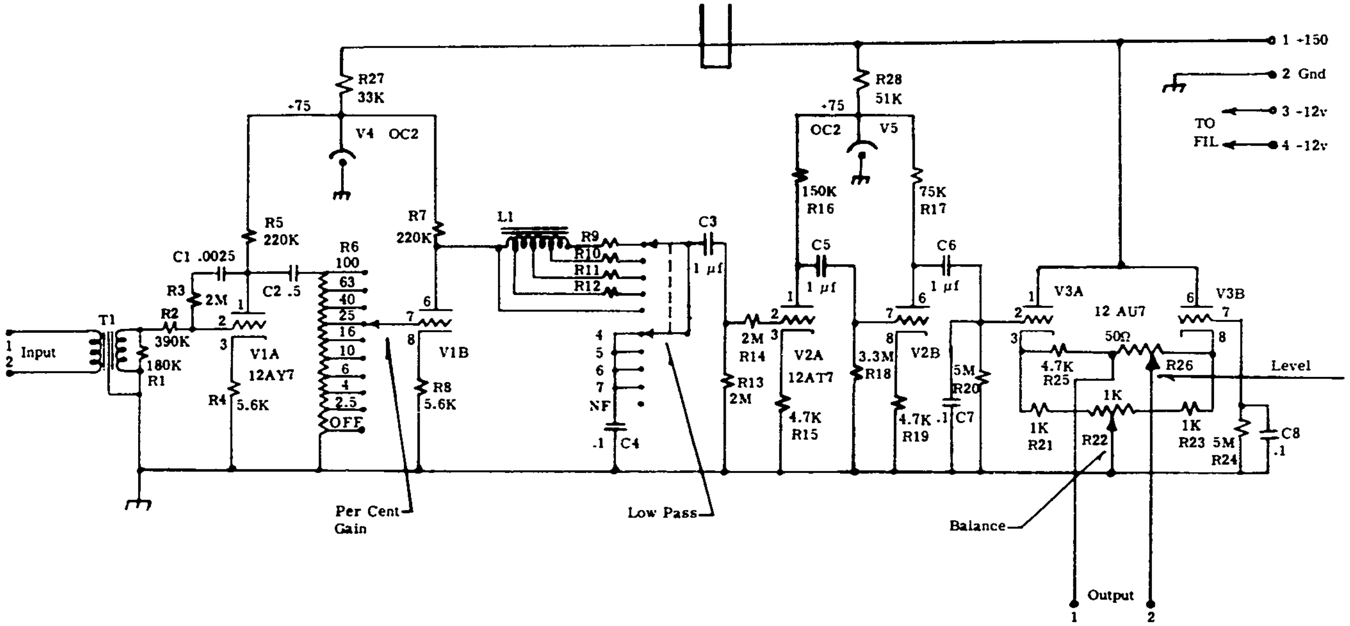

FIGURE 5-5. SURFACE AMPLIFIER SCHEMATIC

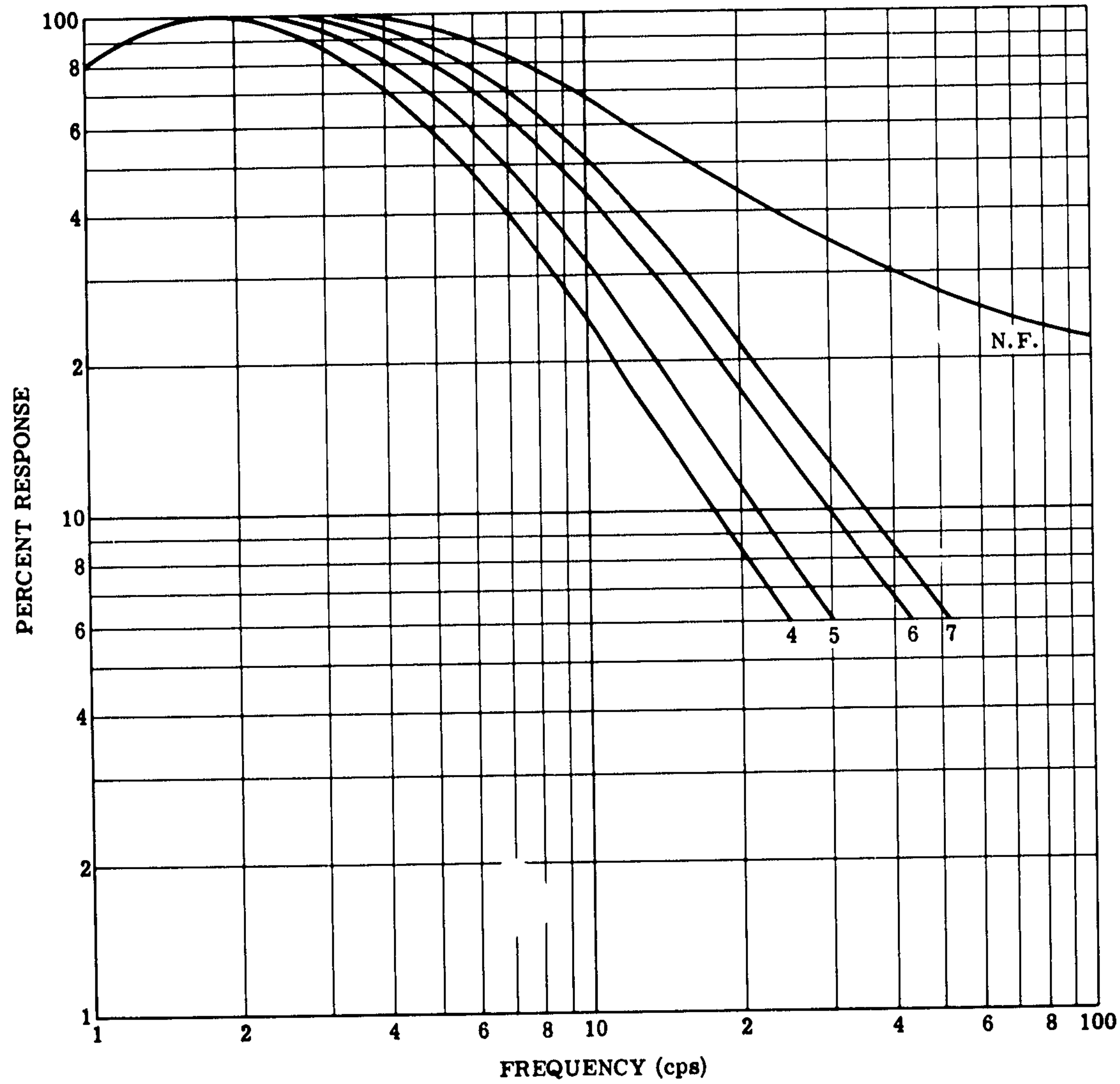

FIGURE 5-6. SURFACE AMPLIFIER FILTER RESPONSE

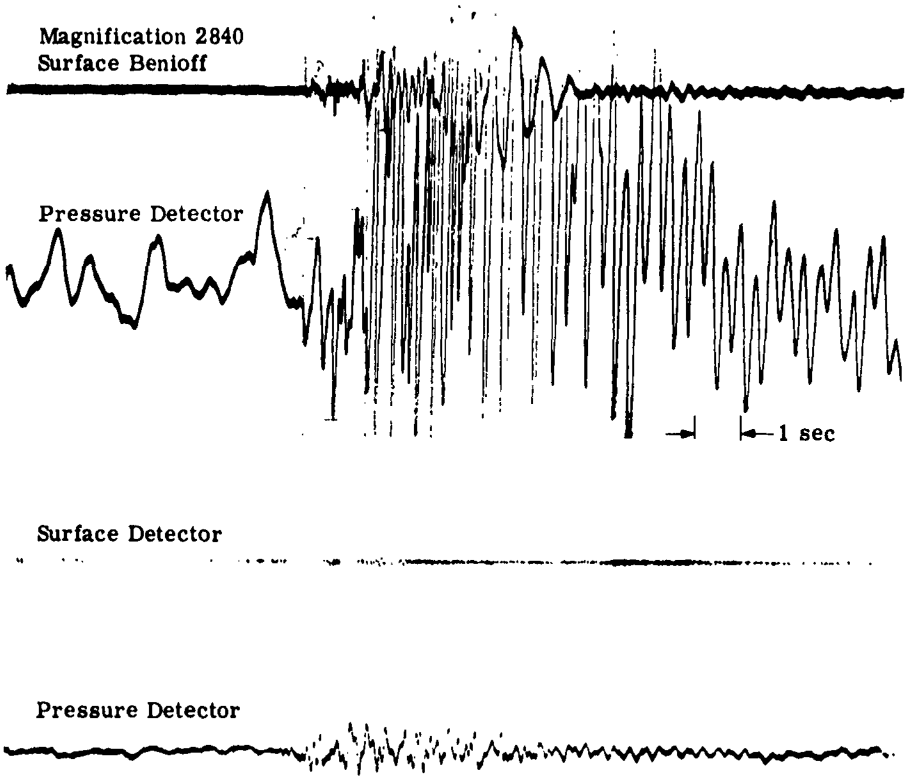

FIGURE 5-7. QUARRY BLASTING RECORDINGS

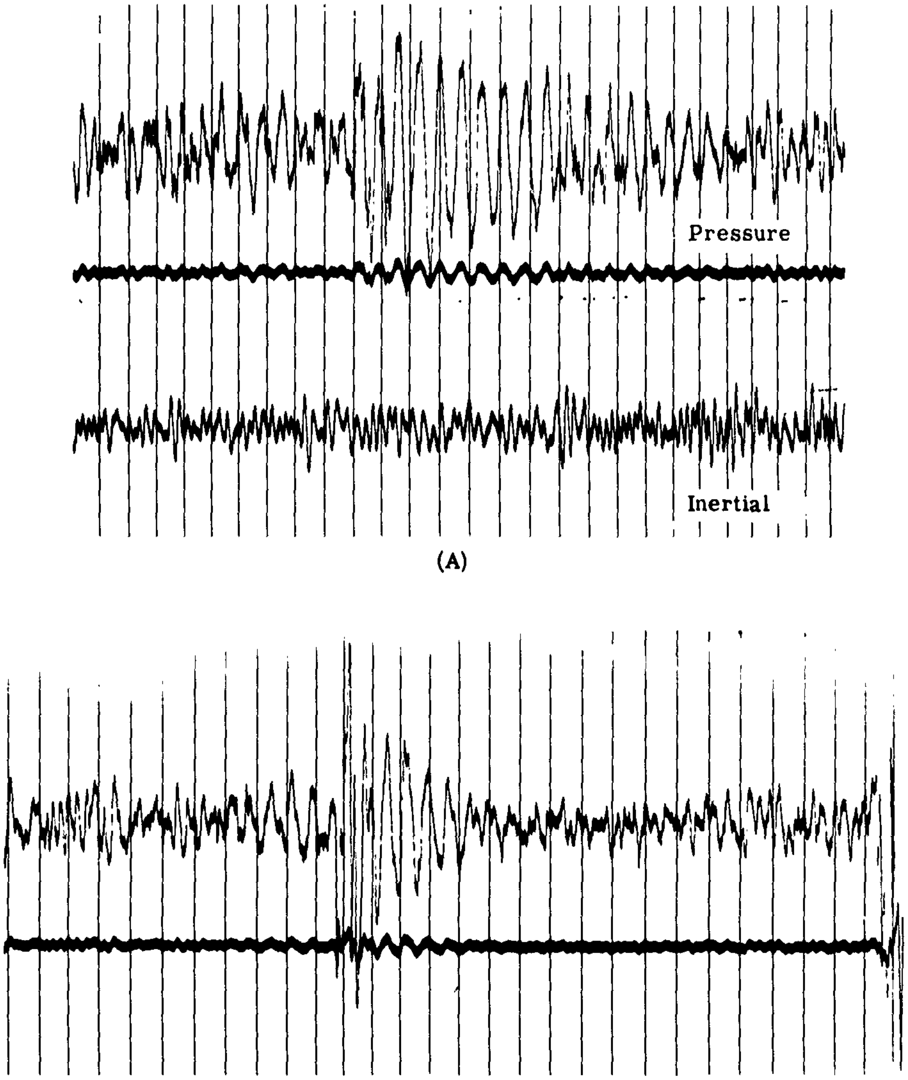

FIGURE 5-8. 100-POUND WEIGHT-DROP SIGNAL. (A) Seismometer 500 feet deep. (B) Seismometer 1000 feet deep.

6

SEISMIC MEASUREMENTS IN DEEP BOREHOLES

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The Jersey Production Research Company has been studying the suitability of cased wells for deep-hole seismic detection.[6] The study is divided into two phases:

Phase I

(1) Study problems of interferences, if any, and their reduction
(2) Compare reception in 2500-foot cased and uncased holes

Phase II

(1) Provide and evaluate equipment in 10,000-foot cased hole
(2) Receive and analyze noise and signals in 10,000-foot hole

The advantages of usable cased holes include ease of equipment planting and retrieval, greater latitude in equipment design, control of fluid environment, and consequent reduction of the corrosion problems encountered in open holes.

The preliminary study of Phase I was relatively brief. There was good evidence from previous work that cemented casing did not perceptibly distort arrivals from the dynamite shots used in reflection prospecting. Since these arrivals tend to be in the neighborhood of 50 cps, we were reasonably sure that signals of lower frequencies and, consequently, longer wavelengths would not be affected at all (conversely, signal reception in uncemented casing was usually poor). A second consideration was the transmission of surface noise down the hole. Transmission through the steel casing, if it is cemented, seems unlikely. The well known cement log relies on the rapid loss of energy from the steal to the bonding cement. As for noise transmission by fluid, a review of the subject indicated that in all probability only the so-called "speaking tube" mode in the fluid could be of importance. However, experience indicated that this normally has little effect on locked-in inertial geophones. A design was worked out whereby gas sacks could be inserted in the fluid for tube-wave attenuation, if needed. It was found that the fluid usually could be removed. We therefore felt justified in proceeding with the second part of Phase I, comparing reception in a pair of 2500-foot holes.

For cased and uncased hole comparisons, we chose a location near Leonard, Oklahoma, about 20 miles from Tulsa. There were several reasons for this choice. Work on another project had

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[6] Under AFCRL Contract AF 19(604)-8346.

indicated that surface noise at this site was comparatively low; the solid underlying rock structure improved the chances for stability at an open hole; and finally, the site was fairly close to the laboratory, and we were already occupying it for the company's Geophysical Observatory.

Conditions at the site are shown in Figure 6-1. The smoothed velocity log shows several breaks, with an interval velocity of about 19,000 fps at the bottoms of the holes. This considerable stratification affects the variation of noise with depth. The geologic section shows old, well consolidated materials. The basement rock is at about 3800 feet, but the 19,000 fps dolomite is physically a good approximation to it.

The two holes are 300 feet apart on an east-west line, drilled to 2530 feet, with usable depths of 2450 feet. The open hole was drilled to approximately 8 inches, had 150 feet of surface pipe, and was left filled with fresh, 9-pound, 80-second viscosity water-gel mud. The cased hole was

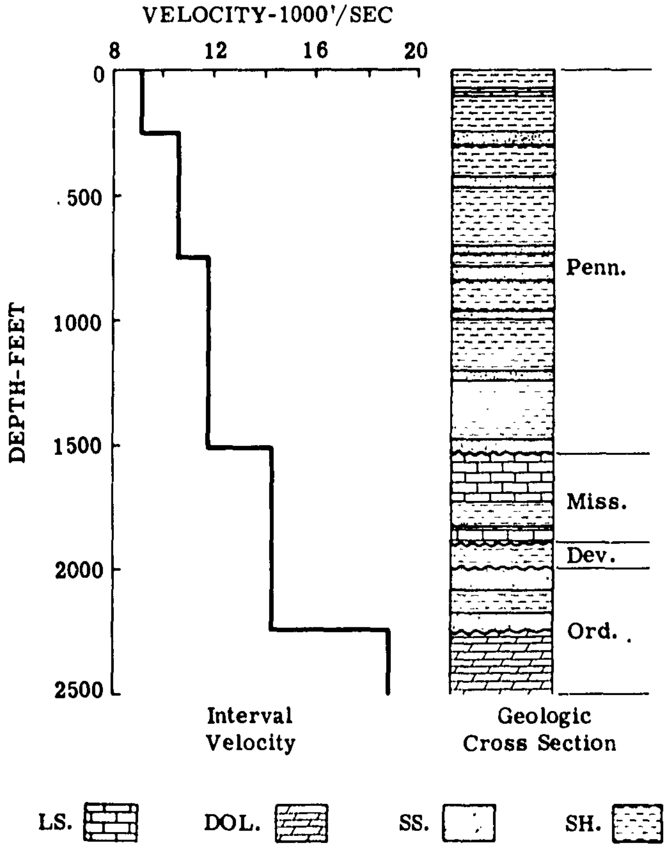

FIGURE 6-1. SUBSURFACE CONDITIONS AT SITE

drilled to 9 inches; was cased with 7-inch, 23-pound casing, fully cemented from bottom to top; had 60 feet of surface pipe; and was filled with the same mud as the open hole. The cement bond was checked with a commercial cement log. The holes were logged with gamma ray-neutron, sonic-caliper, and electrical logs. Adequate deviation control was maintained for both holes. A geophone was placed in each hole and at the surface.

The geophones were modifications of a design we had used for several years. The movement is of the reluctance type with a natural frequency of 1 cps, oil damped to 0.7 critical, and with a sensitivity of 0.9 v/cm/sec. The sensitivity was slightly less than anticipated, but proved reasonably satisfactory. The preamplifiers were of vacuum tube type, 3-stage, with local batteries for plate supply and filaments supplied from the surface. The preamplifiers were flat to below 1 cps and had a voltage gain of about 330. The input noise level was about 0.2 μv rms for a bandwidth of 1-10 cps. This noise level was probably not entirely constant. Each of the two down-hole geophones was provided with a lock-in unit consisting of a remotely extensible arm so that if it is caught on a casing joint, the geophone is held firmly against the side of the hole by its own weight. The cables were of standard type; each had six conductors and a sheath, and a satisfactorily low electrical leakage level. Wind noise plugs were used at the casing heads.

The surface amplifiers had also been used in earlier work. They were resistance-coupled, with no transformers anywhere, and flat to below 1 cps. The filters were 5-, 10-, and 20-cps commercial low-pass types, with attenuations above their cut-offs of about 18 db/octave. The camera was a reflection seismograph unit modified for this application to a paper speed of 2 in./sec. Paper storage capacity was four minutes, though one minute was the usual length of record.

The overall system noise appeared to depend on the preamplifiers. For their input noise of 0.2 μv rms and the movement sensitivity of 0.9 v/cm/sec, the equivalent earth amplitude at 4 cps was about 1.25 Å zero to peak. The typical observed frequency with the 5 cps filter was 4.0 cps. In velocity amplitude, the system noise was about 6.4 mμ/sec peak to peak. These noise figures are for the 10 cps filters; figures for the others vary with bandwidth. This level of system noise proved to be low enough most of the time, although on occasion it may have contributed to lapses in correlation observed between the holes.

With the above equipment, a number of records of natural and man-made noise and of explosive events, for various hole depths and filters, were taken. Figure 6-2 shows several sections of a natural noise record made with both in-hole geophones placed at 550 feet and using 5 cps filters. For the indicated sensitivity setting, the noise amplitude is around 6 Å at 4 cps. The hole-to-hole agreement could be called good, but not perfect. There is some evidence of

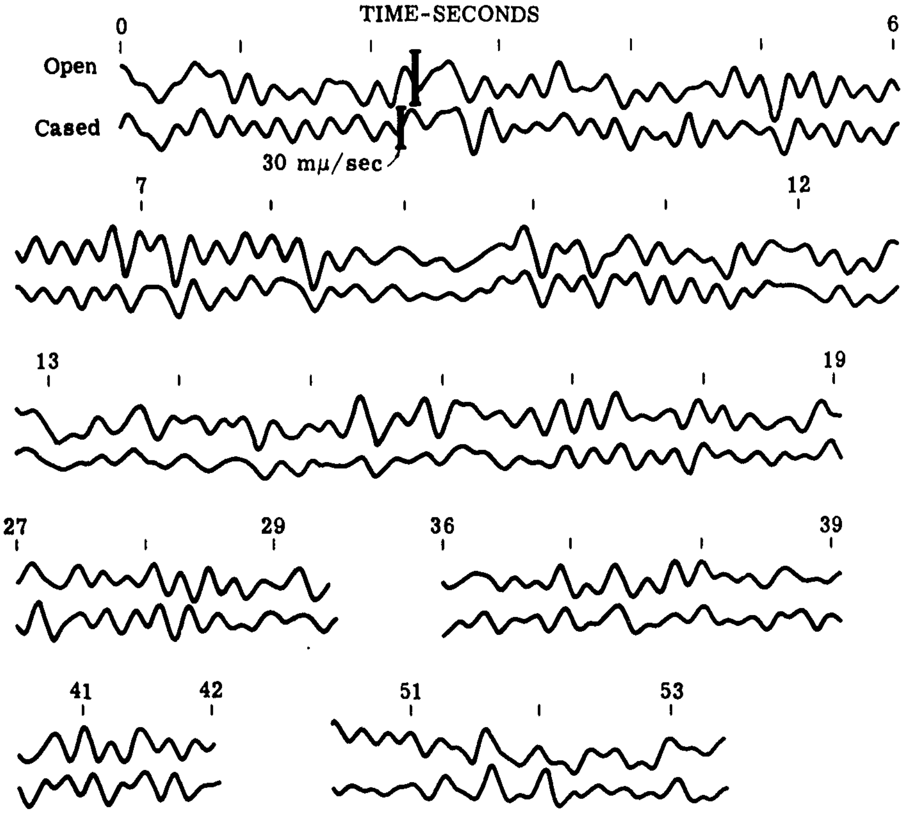

FIGURE 6-2. NOISE RECORD: 550 FEET, 5-CPS FILTER

"step-out" from lower-velocity, near-surface waves and the 300-foot hole separation. Possibly a little system noise was contributing also, since its amplitude was nominally about 1/10 of the trace amplitude for this filter. In this and subsequent figures, it will be noted that the cased-hole trace has no anomalous characteristics distinct from those for the open hole.

A similar record was obtained with the geophones placed at 1025 feet. However, the observed noise level is slightly higher in amplitude and lower in frequency than in the preceding example. The correlation between traces was very good.

At the maximum depth of 2450 feet, the amplitude of the natural noise was relatively low: around 4-6 Å at 4 cps. The correlation between holes is still good, although the higher-frequency inflections sometimes fail to track.

Figure 6-3 shows a comparison between natural noise at the surface and that at various deeper levels. The 5-cps filter was used. On the top three traces, records made at the sur-

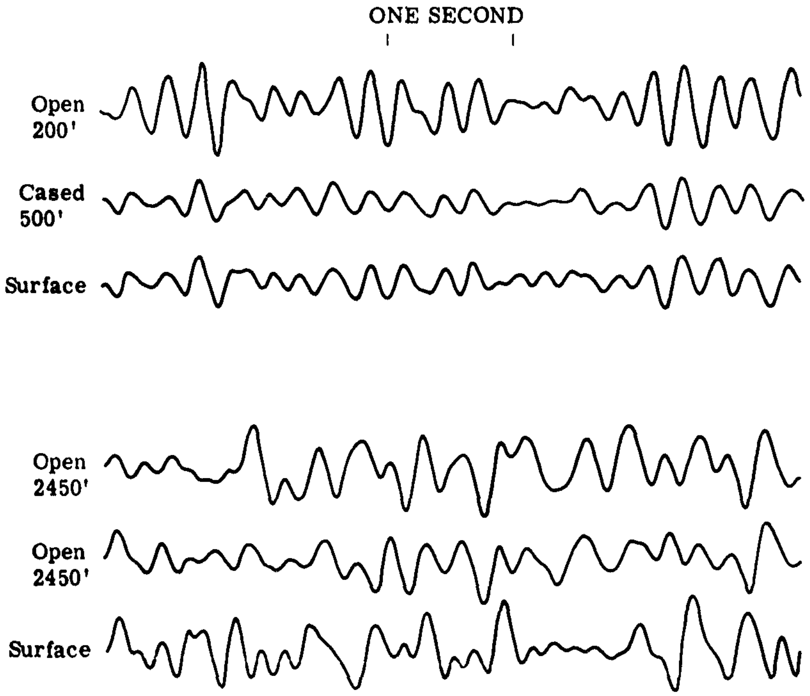

FIGURE 6-3. SURFACE-SUBSURFACE NOISE COMPARISONS

face, at 200 feet, and at 500 feet showed good agreement, which is not surprising for these frequencies. However, on the bottom three traces, the surface motion shows virtually no relation to that at 2450 feet. Again, however, records for the cased and open holes usually agree. The surface-subsurface disagreement shown is probably due to the frequency band employed, stratification of the section, or both. This type of disagreement will be seen again in later examples. Note that our noise frequencies are far from the 6-second microseism peak and probably come from various sources within a relatively few miles. For the equipment sensitivities used, the 0- to 2450-foot noise amplitude ratio is about 3-1/2. However, in view of the nature of the section and the absence of surface-subsurface correlation, this number has little significance, especially with regard to the attenuation of any particular wave type.

It should be added that in the whole set of natural noise records, the down-hole traces did not always agree as well as in the records shown. The periods of poor correlation tended to be associated with lower amplitudes, higher frequencies, or both. Under these conditions a certain lack of tracking is to be expected, because of the 300-foot hole operation and the probably random arrival direction and short-wave length of some of the possible waves. For example, at mid-range depth a 5 cps shear-wave length will be only about 1200 feet. Higher than average system noise also was possible.

Figure 6-4 is a record made at 1500 feet of the noise from a train passing a mile or two away. As is usual when the signal is large and unidirectional, the hole-to-hole correlation was excellent.

Figure 6-5 is a recording from a near-surface dynamite shot 6000 feet away at about 45° to the line between the holes. The surface trace is compared with the two in-hole geophones at 570 feet for each of the three filters. Relative channel sensitivities within each filter group are shown. It will be noted that the subsurface traces agree very well for all filters, but especially for the 5-cps cutoff. The surface traces agree better for the 5-cps filter than for the 10 and 20.

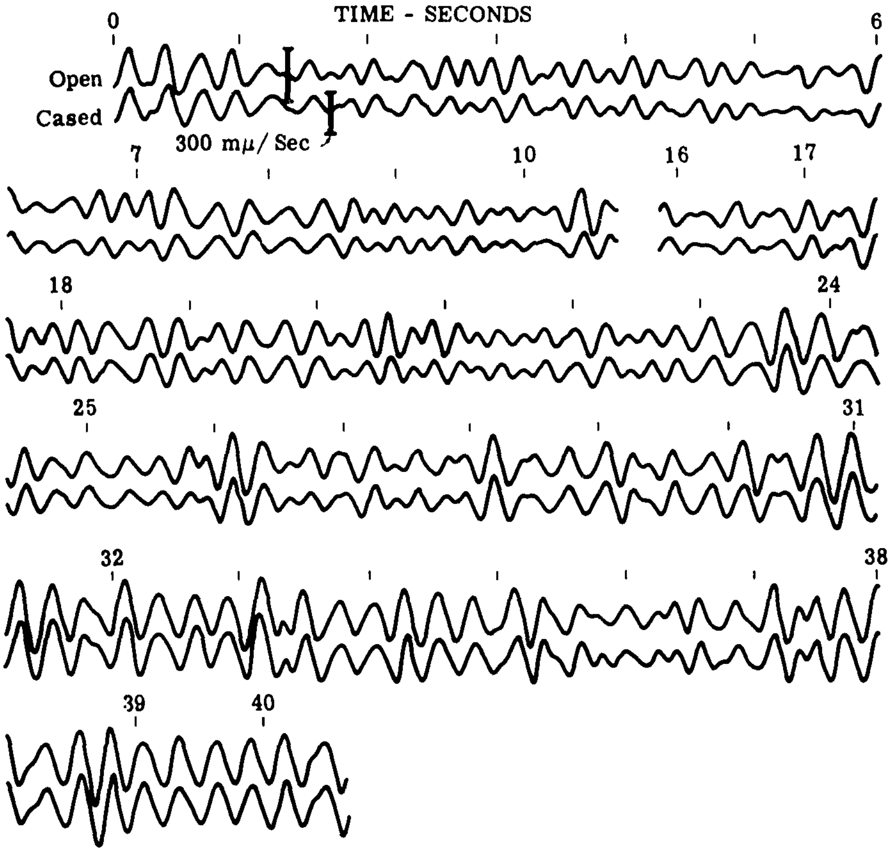

FIGURE 6-4. RECORD OF PASSING TRAIN: 1500 FEET, 5-CPS FILTER

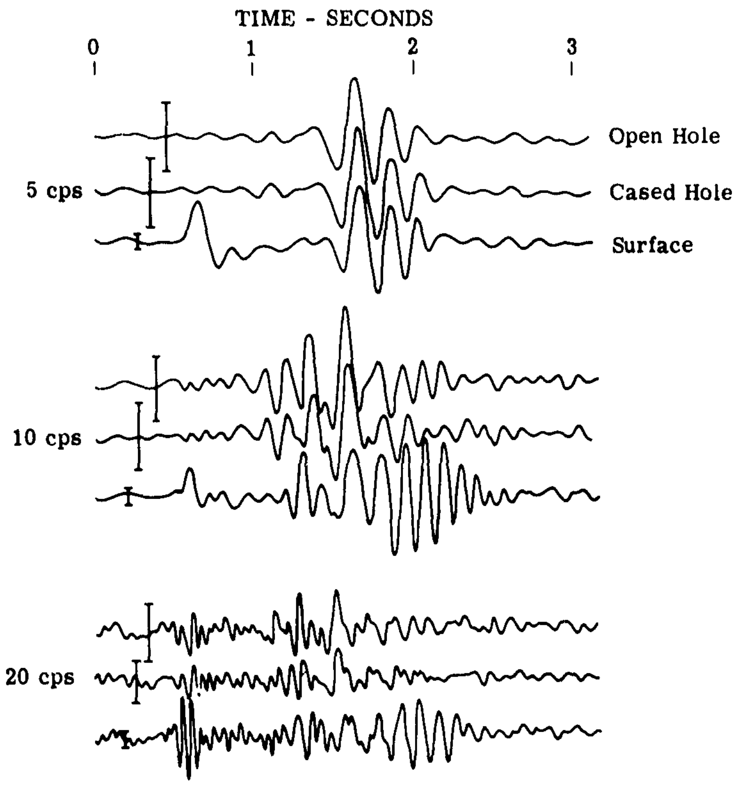

FIGURE 6-5. DYNAMITE SHOTS, 570 FEET

Figure 6-6 shows similar comparisons, except that the deep-hole geophones are at 2360 feet. The hole-to-hole agreement is again excellent, but the surface trace is different from the deep-hole traces for all filters. The deep-hole traces show a probable shear-wave arrival, especially evident for the 5- and 10-cps filters. On the 20-cps filter, the first arrivals are reversed from surface to subsurface.

To summarize Phase I, we attempted to demonstrate whether cemented casing in a hole affected seismic noise and signal recording in any way. We used a nearby uncased hole as a reference. It was found that the presence of the casing neither distorted the signals nor contributed noise. This conclusion is based on:

(1) The high degree of correlation between traces, especially when the recorded energy was above background noise and largely unidirectional.

(2) The general character and amplitude agreement between holes when cycle-to-cycle correlation was imperfect.

(3) The absence of any frequency, periodicity, or other peculiarity in the cased-hole trace.

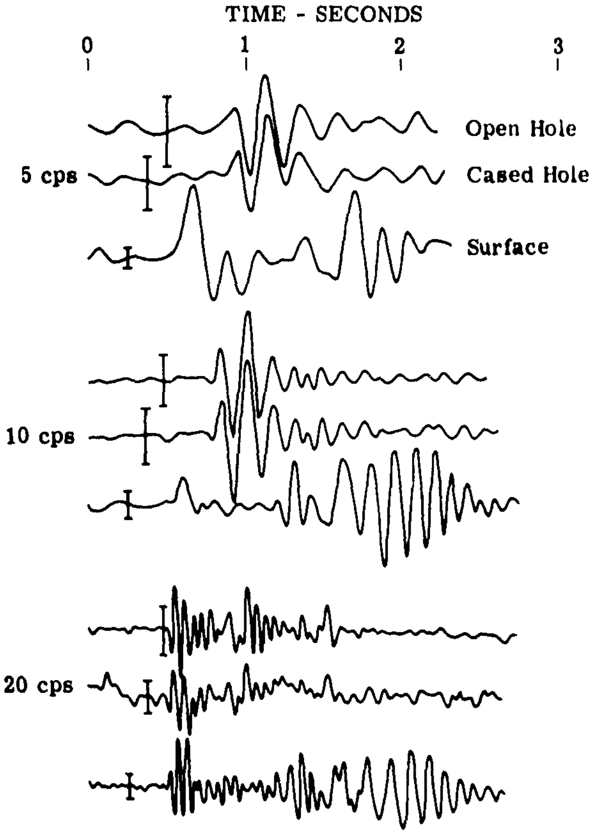

FIGURE 6-6. DYNAMITE SHOTS, 2360 FEET

The work in Phase I also helped develop our techniques for use in Phase II and provided two test holes for use in future measurements (the uncased hole was still open in October 1961).

The experiment did not produce good information on down-hole attenuation of noise, improvement of signal-to-noise ratio, or changes in dominant frequency. Further data analysis will include the computation of correlation coefficients, using digitized data and some frequency analysis.

On the basis of the results of Phase I, we are proceeding on Phase II with considerable assurance that it will be profitable.

We will work in a well called the No. 1 Prater, about 40 miles northwest of the Wichita Mountains Seismological Observatory at Ft. Sill, Oklahoma, which has been prepared for our use. Figure 6-7 shows the characteristics of the hole and a schematic of the instrumentation to be used. The hole is made less than ideal by the long section of uncemented 9 5/8-inch pipe,

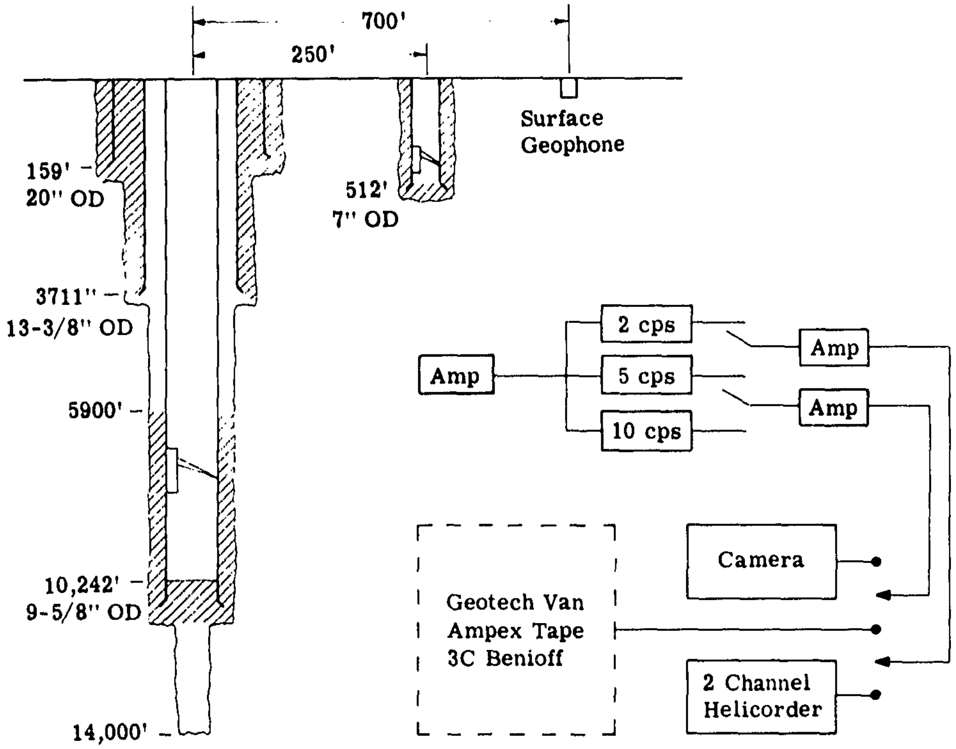

FIGURE 6-7. PHASE II HOLE AND INSTRUMENTS

ut recording should be satisfactory from a few hundred feet below the cement top at 5900 feet, down to the plug at 10,242 feet. We will again use three geophones: one in the deep hole, one in a 500-foot hole, and one at the surface. The geophone at 500 feet is provided to give near-surface information generally free of wind and other surface noise. The geophones are similar to those used in Phase I except that they will have new 1-cps moving-coil detector elements with sensitivity as high as 50 v/cm/sec. Built-in calibration has also been added, and Schlumberger cable will be used. The three surface amplifiers are new, but similar to those in Phase I. The 20 cps filter setting will be replaced with a filter setting of 2 cps. The camera is the one used in Phase I, with a 3-channel Helicorder added. It is expected that the system noise will be caused by the Brownian movement of the 1300-gram geophone coils, and should be equivalent to 0.1-0.2 Å at 1 cps with the 2-cps filter. However, this is based on an older theory for thermal noise (Wolf, 1942), and the true noise level may be somewhat different. In addition, a recording van and crew supplied by The Geotechnical Corporation will be at the location, and we will normally have use of six of their magnetic-tape channels. They will also set up and record with a 3-component Benioff seismometer.

The program will include equipment check-out, possible refraction shots for location evaluation, determination of casing effects, surface and subsurface noise measurements, and recording of distance events as feasible. Tests of casing effects will be indirect, in the absence of a comparison hole, and we will rely heavily on Phase I results. Data analysis will include comparison with other stations including the local Benioff installation.

7

SEISMIC INSTRUMENTATION IN A BOREHOLE OF INTERMEDIATE DEPTH

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A borehole has been drilled at the new Botanical Gardens of The University of Michigan. The borehole is 1208 feet deep to the top of a cement plug in the bottom. It is cased to bedrock at about 200 feet with an 11 1/2-inch casing and from top to bottom with an 8-inch casing. The casing is fully cemented.

The borehole is dry (it was earlier reported to be partly filled with water) and is being prepared to receive 3-component Hall-Sears 2-cps geophones. Current plans call for filling the borehole with dry nitrogen to maintain low humidity and a noncorrosive atmosphere.

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SIGNAL-TO-NOISE RATIO FOR A BURIED ARRAY IN A NUMBER OF ENVIRONMENTS

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We are considering boreholes of from fifty to a few hundred feet deep that could be drilled with shot-hole-type portable drilling equipment. Our plan is to improve seismic detection by use of seismometers placed in boreholes to form a horizontal array, and to try to improve the signal-to-noise ratio by this well known array technique used in exploration geophysics. This technique cancels out a large amount of horizontally arriving energy, but still retains sensitivity to vertically arriving energy.

Since we believe that the standard of comparison for any detection system in the Benioff range is the Benioff instrument, we plan to compare a system composed of a multiple array of small geophones in boreholes with a single Benioff instrument. This system will probably cost about the same as a single Benioff instrument, and it may have a better signal-to-noise ratio.

Some of the possible advantages of using small seismometers in boreholes are:

(1) Portability: The instruments can be transported to various sites very cheaply and quickly.

(2) Low cost: The instruments are relatively inexpensive since they are small and mass-produced.

(3) Ruggedness: They will withstand considerable abuse and they require no special leveling techniques.

(4) Geophysical advantages: The signal-to-noise ratio should be improved in two ways. First, in a large multiple array of these instruments, the ratio of the signal to the noise due to incoherent noise sources at the detectors should be improved according to the square root of the number of detectors. Second, energy arriving vertically on a horizontal array of geophones would be in phase whereas energy arriving horizontally, if the distance between the seismometers is properly chosen, can be largely canceled out by the use of some reasonable passband.

Other advantages of such a system for a future unmanned detection station are:

(1) The cased borehole forms a thermally isolated and well protected environment for a seismometer.

(2) Instruments in boreholes encounter reduced surface noises.

(3) If an organization develops techniques for seismometer recording in boreholes, it may be able in the future to conduct research on measuring body-wave properties of signals in the earth. This could eventually lead to research on three-dimensional measurements at each point throughout some volume within the earth.

The system I will describe involves the use of a field station consisting of a Benioff instrument with its conventional galvanometer and photo cell amplifier, and a surface array of Hall-Sears 2-cps seismometers connected in a series-parallel arrangement to feed an electronic amplifier. The amplifier will have an equivalent noise input of .02 μv in the passband of about 1-10 cps. For future analyses the signals will be recorded on magnetic tape by a Helicorder, and on film. All this equipment will be carried in a trailer.

The Hall-Sears instrument has a sensitivity of approximately one v/in./sec velocity at a frequency of about two cps, which gives a sensitivity to displacements at that frequency of about 0.2-0.3 Å. Although this is not the ultimate sensitivity one might desire in very deep and quiet holes, it is still well below usual ground-noise signals.

We propose to use this equipment in a circular array, with a Benioff instrument in the center. The Benioff would be placed in the vault in a way to ensure the quietest conditions possible. With seven seismometers in this circular array and one at the center, by the Benioff, we will have three seismometers recording in almost any horizontal direction. The recording trailer would be placed nearby and would contain all the equipment except the seismometers and the shielded cables running to the various instruments.

The first step in setting up the station at a particular site would be to make noise measurements with individual Hall-Sears instruments and the individual Benioff instrument. Then we would fire a few shots; make some measurements; determine the various velocities of Rayleigh waves, pressure waves, and shear waves in this area; analyze the frequency spectrum of the noise; and then, on the basis of this information, adjust the size of the array to optimize the sensitivity of the signal to the noise, where we interpret noise as horizontally traveling energy. At the same time, noise measurements would be made by seismometers placed at various depths.

Similar measurements of noise, made with low-cycle instrumentation by our company, have at times disclosed striking improvements in the recording of background earth motion by installations only 50 or 75 feet deep. By this I mean noise reduction by factors of 2 or 3.

The design of the individual arrangement could be determined by local conditions (terrain, plant life, sea effects). These factors would affect the determination of the size of the array and the depth of the holes. The station, once designed and optimized for this location, would be run for a short time, perhaps a week or several months. After examining a number of such installations placed in various conditions of terrain and geology, we would analyze all of the data and reach whatever conclusions seem warranted.

9

THE AWRE BOREHOLE PROGRAM

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CHARACTERISTICS OF SIGNALS AT DEPTH AND ON THE SURFACE

It is generally considered that microseismic noise consists mainly of surface waves whose amplitude decreases approximately exponentially with depth. If this postulate is accepted, then signal-to-noise ratio can be increased by placing a detector deep underground. Typically a factor of 10 would be gained at 3 cps for a depth of 4000 feet. If, however, the signal and noise are present in different proportions at the surface and at depth, it is possible to increase this factor by doing some arithmetic with the records.

For simplicity, consider a signal traveling vertically upwards to the surface. Let its value at the surface be a(t); then at a depth H the signal is

$$(a/2)(t + \tau) + (a/2)(t - \tau)$$

where $\tau = H/c$, c being the velocity of the signal. Let the noise at the surface be F(t), having frequency components whose amplitude is $A(\omega)$. Then the noise at depth can be regarded as G(t), whose frequency components are $A(\omega)/b(\omega)$, where $b(\omega)$ is the ratio of amplitudes of the surface wave at the surface and at the depth H for the frequency ω.

If a filter having an attenuation $b(\omega)$ at the frequency ω now operates on the signal recorded at the surface, we get

$$a(t) + F(t) \xrightarrow{\text{filter}} [a(t)_{\text{mod}}] + G(t)$$

where $a(t)_{\text{mod}}$ is the result of filtering a(t). Subtracting this modified signal from the signal at depth, we are left with

$$(a/2)(t + \tau) + (a/2)(t - \tau) - [a(t)_{\text{mod}}]$$

the net signal being a true representation of a(t) until $t = \tau$.

FILTER REQUIREMENTS

A peculiar feature of the filtering action which increasing depth has on surface waves is that it produces no phase shift. If an electrical filter is used, it is impossible to operate on the surface record without producing a phase shift in the frequency-dependent attenuation, but this problem can be solved by

(1) Passing the surface record through a filter whose amplitude-frequency characteristic matches that of surface waves at depth.

(2) Applying to the signal obtained at depth a phase shift which matches the phase shift produced in the filter.

(3) Subtracting the signal produced by the first operation from that produced by the second.

Two methods for achieving stages 1 and 2 are proposed:

(I) The filter is designed to have a linear phase shift which is then matched by a time delay introduced into the depth record, the time delay being conveniently produced by a tape loop. This method gives no phase distortion of the original P-wave signal.

(II) A simple resistance-capacitance circuit is used for the filter, and the phase response it introduces is matched by a similar phase shift at constant amplitude in the second channel. This method is capable of good noise cancellation, but will cause some distortion of the P-wave signal.

MODEL INSTRUMENTATION

To test the methods, a series of two-dimensional model experiments has been carried out at Foulness by Mr. F. Key. The basic model consists of a sheet of perspex 1/16 x 48 x 12 inches. A transmitter at the surface generates a burst of white noise, about 750 μsec in duration, and a "buried" source transmits a 10 μsec pulse. The detectors are placed two thirds of the way along the model, the one at depth being one inch below the surface (corresponding to about 1600 feet full scale). (See Figure 9-1).

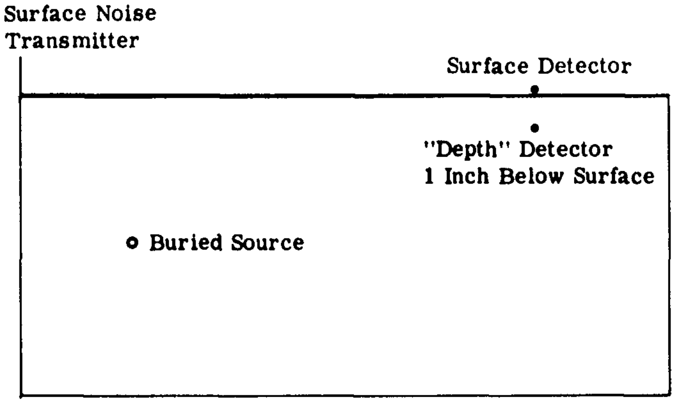

FIGURE 9-1. PERSPEX MODEL

The transmitted signals are timed so that the P wave from the buried source arrives at the detectors about half-way through the burst of surface waves from the noise source. The first experiment with this model used an approximation to Method I. The filter was a 3-stage RC circuit whose attenuation characteristics are given in Figure 9-2(A) in which the corresponding Rayleigh-wave attenuation is shown dotted. The direction of the noise source being known, the time delay was easily effected by placing the depth detector about 3/4 inch further from the source than the surface detector. The phase response of the RC filter is shown in Figure 9-2(B); it can be seen that there are errors of $\pm 50^{\circ}$ relative to a straight-line response. This response can be improved slightly by adding a constant-amplitude phase-shift circuit (which will be described later), as is also shown in Figure 9-2(B). By using more filter elements a better approximation to a linear phase shift can be obtained.

Method II requires the simplest associated instrumentation. The constant-amplitude phase-shift circuit is shown in Figure 9-3 with its phase response.

R_{L_1} and R_{L_2} are equal anode and cathode loads, provided that the output impedance at the anode is small compared with R, and that the output at the junction of R and C is given by

$$\frac{V_0}{V_1} = \frac{\omega^2\tau^2 - 1}{\omega^2\tau^2 + 1} + j\left(\frac{2\tau}{\omega^2\tau^2 + 1}\right)$$

where $\tau = RC$, it follows that $\left|\frac{V_0}{V_1}\right| = 1$, and $\phi = \tan^{-1} \frac{2\tau}{\omega^2\tau^2 - 1}$.

By combining two of these circuits in series, one having a time constant 14 times the other, it is possible to get a close fit between the resultant phase shift and that of the 3-stage RC filter. Figure 9-4 shows a comparison between these two phase responses. The disadvantage of this method is the effect of the phase shift on the desired P-wave signal. To illustrate the distortion involved, a signal which has been passed through the phase-shift network is compared with the original signal in Figure 9-5.

MODEL RESULTS

A series of records taken on the model using Method II are shown in Figure 9-6. The records, which are self-explanatory, clearly show the improvement possible. The phase inversion of the combined signal can be ignored.

A second experiment, using noise only, was undertaken to illustrate the basic property of the surface waves. In the experiment the "noise" consisted of a burst of pure sine waves, and the ratio of the canceled signal (D_2 phase shifted - D_1 filtered) to both the surface signal D_1 and the depth signal D_2 is plotted against frequency in Figure 9-7. The improvement in the signal at depth varies from 10 at the low frequencies to 2 at the high frequencies, and averages out to an overall factor of 15 compared to the signal recorded by the surface detector. The ratio of signals at the surface and at depth, also shown, agrees well with the theoretical curve. The "scatter" is believed mainly due to slight differences in the frequency response of the two detectors, and we feel that it is this factor which limits the noise cancellation possible on the model.

Perhaps a more convincing illustration of the technique is shown in Figure 9-8. The surface and depth records given in this figure were taken from a report by United ElectroDynamics on a deep-well seismic program. The records have been combined according to Method II, the filter for the surface record being a simple 3-stage RC circuit giving the Rayleigh-wave attenuation for a homogeneous medium.

SEISMOMETER DESIGN

Frequency Considerations. Even when the noise subtracting method is used, the improvement available is proportional to the depth of the second detector. This depth is limited primarily by economic considerations, but for a fixed depth the improvement increases with frequency. The question naturally arises, what are the amplitude-frequency spectra of both the signal and the noise?

There is some evidence from the Hardtack series that waves having significant energy in the range 2-6 cps are transmitted to distances of the order of 1000 km. Moreover, the explosions were in a relatively soft medium, and it is unlikely that explosions in other media would result in seismogram frequencies lower than this.

Theoretical estimates of first-motion signal-to-noise spectra to be expected from typical events are shown in Figure 9-9. These are based on the published Hardtack records, the estimates given by Oliver for typical noise conditions, and some elementary calculations on signals from a decoupled device in a spherical cavity. These figures suggest that frequencies up to several cycles per second can carry significant Pn energy. It was therefore decided, as a preliminary step, to work in the range 1.5 - 10 cps in boreholes 1000 to 1600 feet deep, which are available in the United Kingdom for test purposes.

Mechanical Details. At the outset, a moving-coil electromagnetic detector was preferred, because of its inherent stability, to the somewhat more sensitive powered transducers. The basic layout, shown in Figure 9-10, is essentially a two-coil assembly suspended by prestressed leaf springs of the type used in the Willmore seismometer. The open-circuit sensitivity can be expressed as

$$Q_0 = 0.12 \sqrt{R} \text{ v/cm/sec}$$

where R is the coil resistance in ohms. Under operating conditions the coil is shunted with a resistance S, and the voltage across S is measured, thus giving an effective sensitivity

$$Q_e = \frac{0.12S}{R + S} \sqrt{R} \text{ v/cm/sec}$$

At first sight it would appear that the optimum condition is to have both R and S large, but the ultimate sensitivity is limited by thermal motion which is roughly proportional to the square root of the seismometer mass. Alternatively, for a given coil geometry and damping factor, it turns out that the thermal limit is proportional to $\sqrt{S}$.[6]

In the prototype, which has the dimensions shown in Table III, the mass is about 2.5 kg. When a brass former is used, a damping factor of 0.7 is obtained when S = 4R. This gives a sensitivity of

$$Q_e = 0.1 \sqrt{R} \text{ v/cm/sec}$$

If we can obtain amplifiers whose noise level is less than the thermal noise for a resistance of 4R, then it will be possible to opitmize the sensitivity-to-noise ratio by using a mass of 6 kg with a copper former (or a self-supporting coil) and a damping resistance equal to R, in which case

$$Q_e = 0.06 \sqrt{R}$$

with a net gain in signal-to-noise ratio by a factor of 1.2. At present one of our main concerns is to obtain amplifiers with low input noise, our best amplifiers being (1) a transistor amplifier requiring an input impedance of 500 ohms and having a noise level = 0.2 μ v (peak to peak) and (2) a high impedance valve amplifier with a noise level equal to 2 μ v (peak to

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[6] $$\overline{V_N^2} = 2/\pi \, (kTRw)$$

where $\overline{V_N^2}$ is the mean-square voltage across a resistance R in the frequency band of width ω

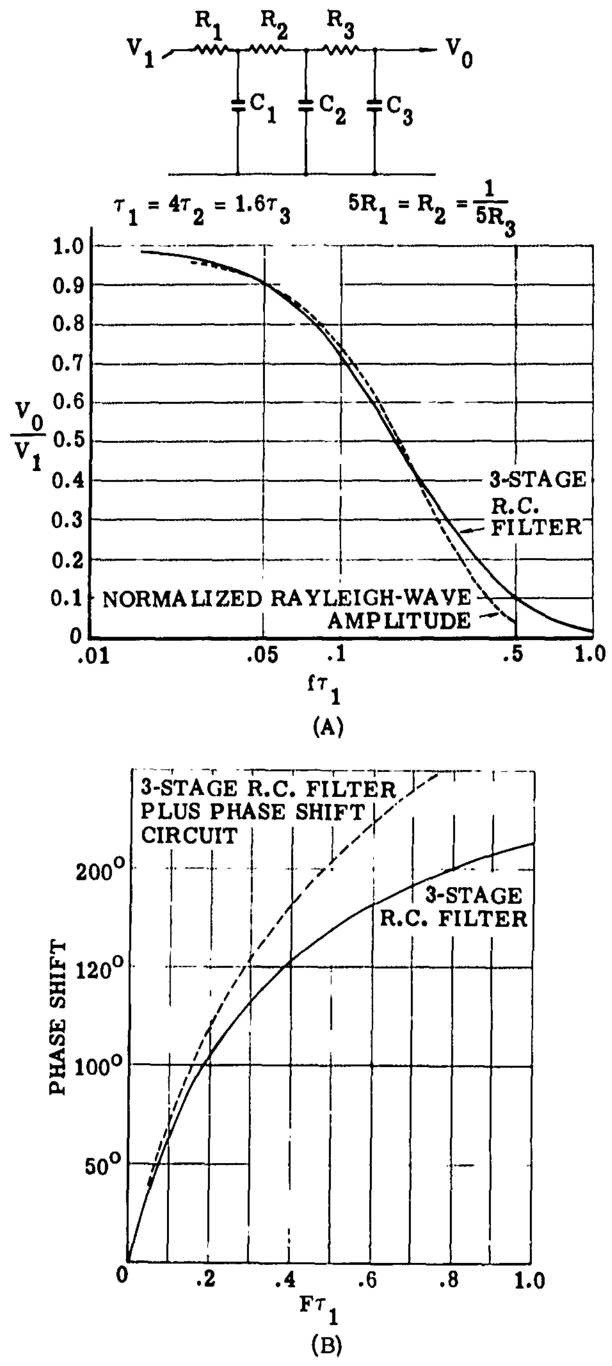
k is the Boltzmann constant

T is the temperature

Taking a 10-cycle bandwidth, $\overline{V}_N(\text{rms}) = 4 \times 10^{-10} \sqrt{R}$ volts.

peak). The highest impedance coils we can reasonably wind give R = 0.4 MΩ, so that the ratio of signal to noise is theoretically about three to one in favor of the valve amplifier.

By using N detectors in series we can obtain an improvement of $\sqrt{N}$ in signal-to-noise ratio with the transistor amplifier, and possibly somewhat more with the valve amplifier, depending on the noise levels. Although we have started trials using only one transducer, we have plans for using (if necessary) up to ten seismometers in series.



(A)

(B)

FIGURE 9-2. 3-STAGE RC FILTER. (A) Response of filter compared with theoretical Rayleigh-wave attenuation. (B) Phase response, showing nonlinearity.

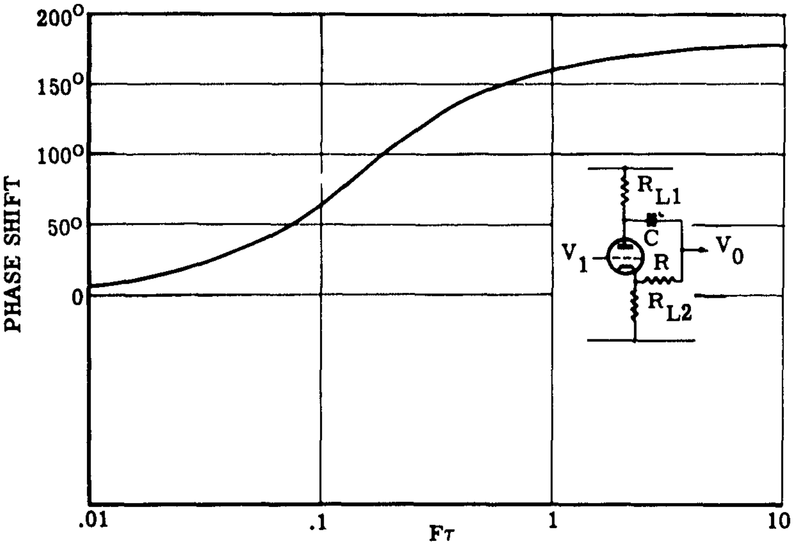


FIGURE 9-3. RESPONSE OF CONSTANT-AMPLITUDE PHASE-SHIFT CIRCUIT

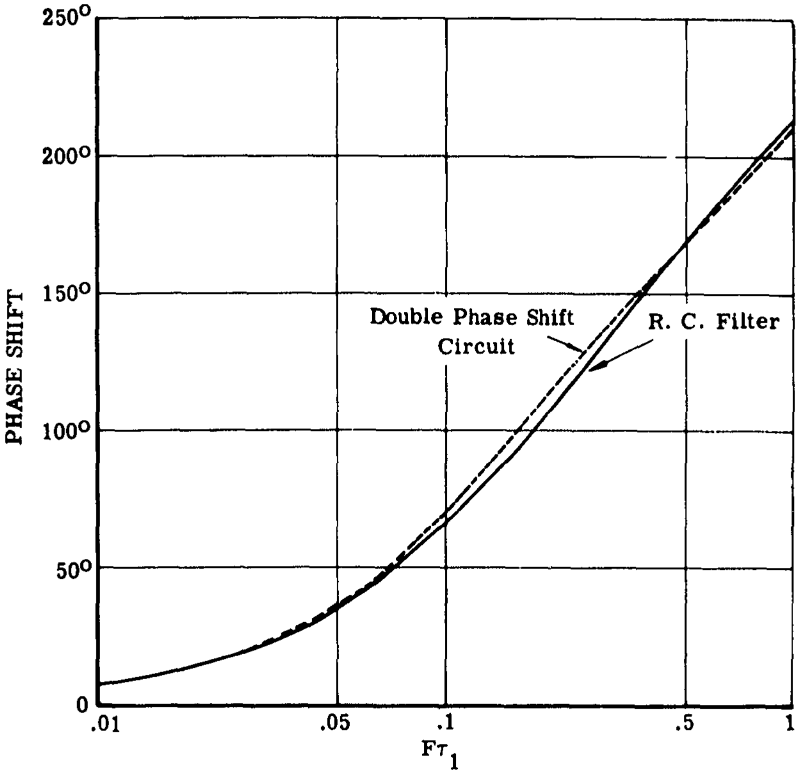


FIGURE 9-4. COMPARISON OF PHASE SHIFT OF 3-STAGE RC FILTER AND TWO CONSTANT-AMPLITUDE PHASE-SHIFT CIRCUITS.

$\left[\tau_{1(\text{Filter})} = \tau_{1(\text{Phase Shift})} = 14\tau_{2(\text{Phase Shift})}\right]$

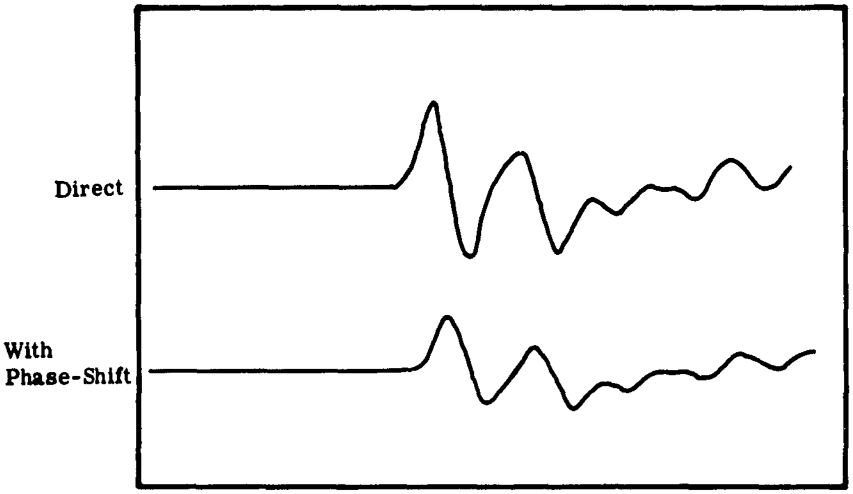


FIGURE 9-5. EFFECT OF PHASE-SHIFT CIRCUITS ON P-WAVE SIGNAL FROM DETECTOR AT DEPTH

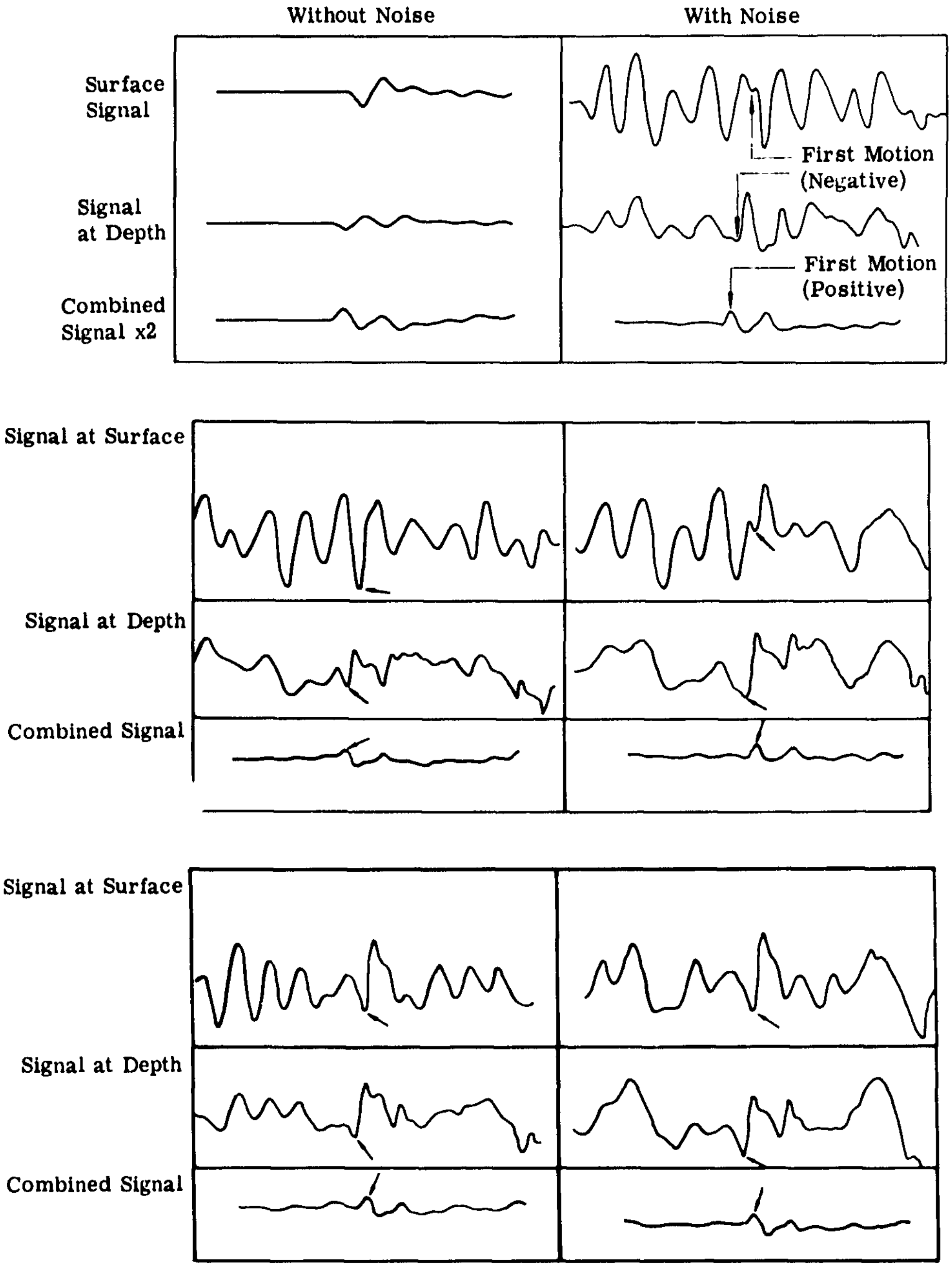


FIGURE 9-6. MODEL SEISMOGRAMS

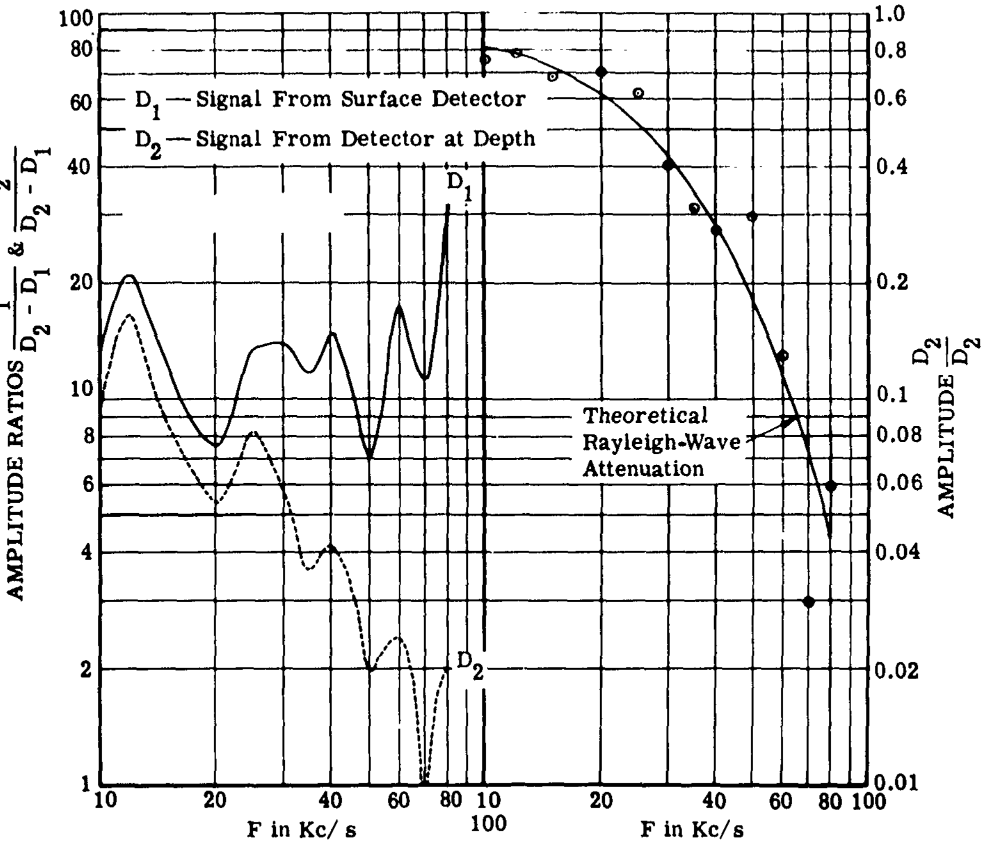


FIGURE 9-7. MODEL RESULTS OF NOISE-CANCELING CIRCUITS

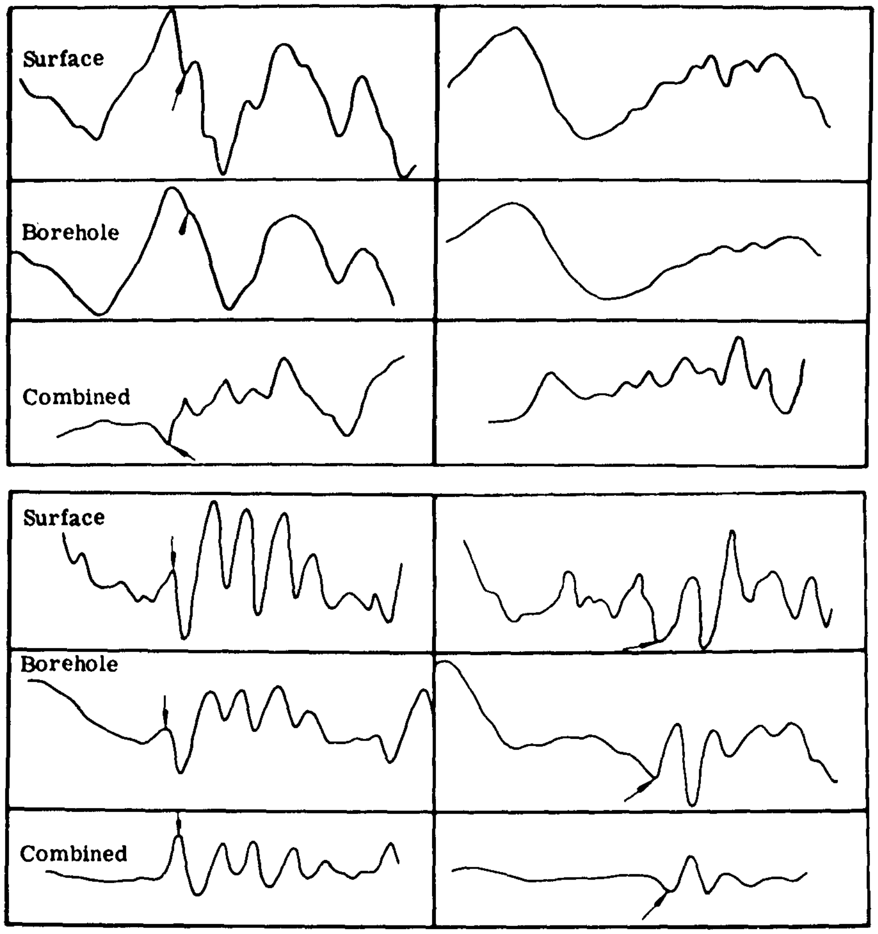


FIGURE 9-8. EARTHQUAKE RECORDS

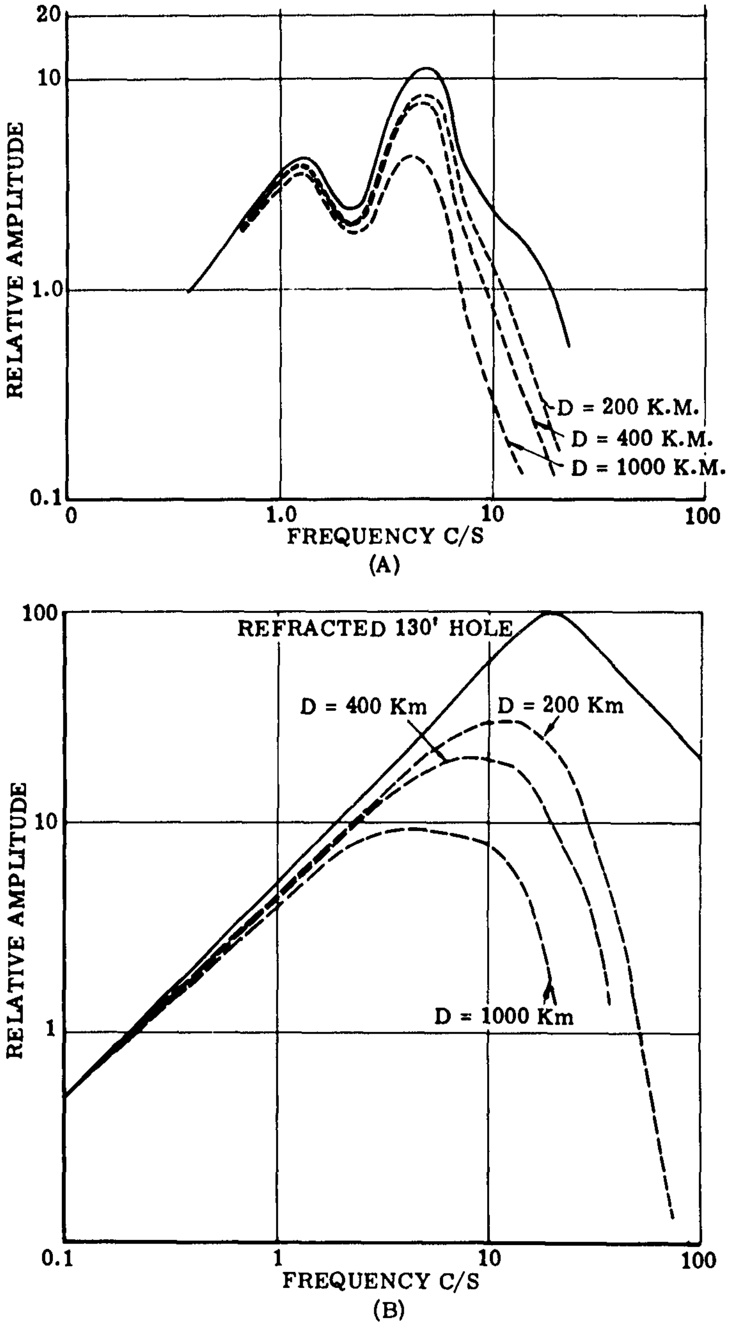


FIGURE 9-9. SIGNAL-TO-NOISE RATIO. (A) For 1-kt explosion in tuff. (B) For refracted arrival from 130-foot cavity in salt.

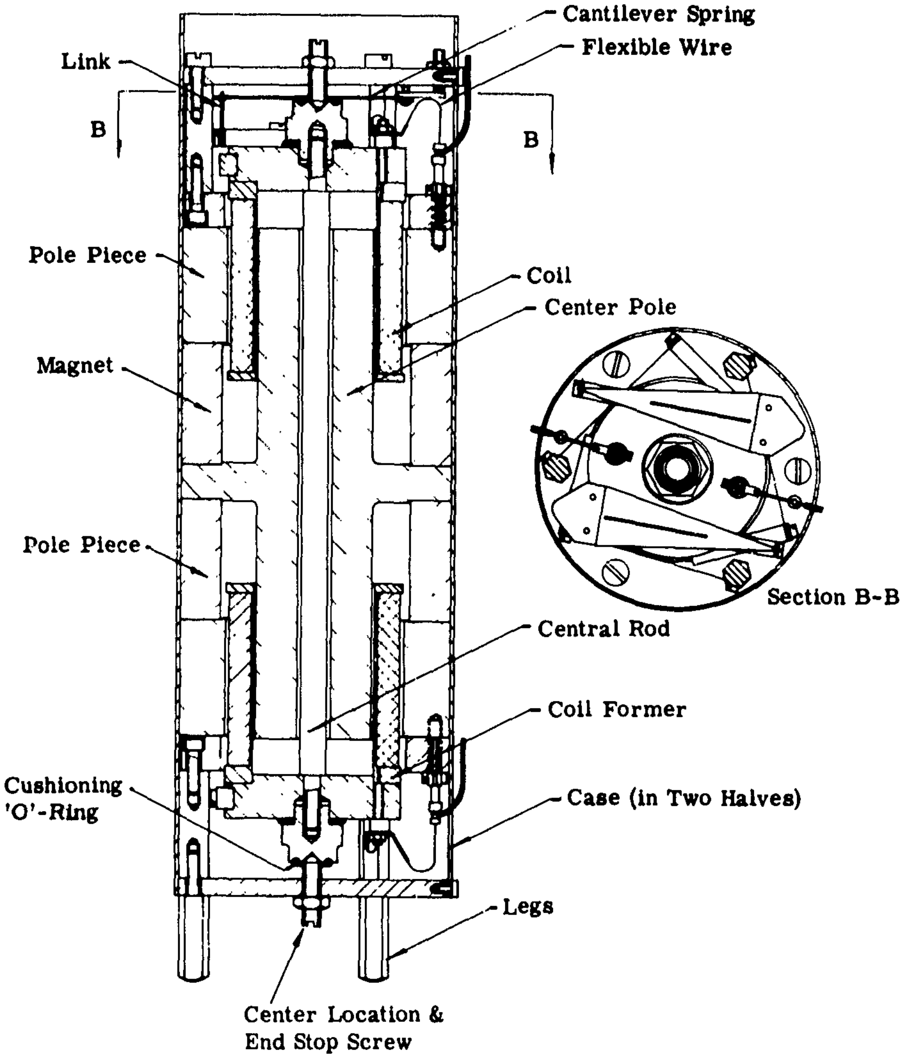


FIGURE 9-10. BOREHOLE SEISMOMETER UNIT

TABLE III. PROTOTYPE DETECTOR SPECIFICATIONS

Seismometer Dimensions

Physical dimensions: 5 inches od x 16 feet long (approximate)

Weight per cell: 28 lb (approximate)

Weight of outer tube: 240 lb

Weight of whole seismometer: (10 cells): 600 lb (approximate)

Maximum working depth: 6000 feet (borehole assumed flooded)

Cable breaking strain: 4 1/2 tons (provisional)

Cable make-up 4-7/0.0076 screened, 12-7/0.0076 PVC (provisional)

Weight of moving parts: 5.5 lb (each unit)

Natural frequency: 1.8 cps (prototype)

High-Impedance Coil (2 per cell)

Number of turns: 139,000

Size of wire: 0.002 inch diameter (No. 47 SWG)

Resistance: 200 KΩ (approximate)

Former length: 6.35 cm (2 1/2 inches)

Low-Impedance Coil (2 per cell)

Number of turns: 5460

Size of Wire: 0.0108 inch diameter (No. 32 SWG)

Resistance: 275 KΩ (approximate)

Magnet field gap: 1.17 cm

Magnet field depth: 4.25 cm

Strength of field: 1860 lines per cm^2

Center pole piece diameter: 4.25 cm

Outer pole piece diameter: 6.6 cm

10

POTENTIAL APPLICATION OF OCEAN-BOTTOM INSTRUMENTATION TO DEEP-HOLE SEISMOMETRY

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Three successful tests[7] of a telemetering ocean-bottom seismograph have been made. In all three the seismograph was resting on the ocean bottom or planted in the sediments, and sent its information to the surface by a frequency-modulated supersonic beam. The use of cables connecting the instrument to the recording ship was avoided so that background noise would not be increased by the shaking of a long cable. These first tests were designed to help determine what frequencies should be recorded, at what levels, and what method is best for transmitting the earth's vibration in these frequencies to the recording instrument at the surface. Neither the instrument used nor the method was the optimum for obtaining all of the seismological data from the ocean bottom, but the results have demonstrated the feasibility of ocean-bottom seismographs and have helped to determine the criteria for the more complicated instruments and methods of transmission which will ultimately make up a world-wide system. Data from such a system are expected to settle the question of the origin and propagation of microseisms and provide detailed information about the sedimentary layer and about the earth's crust and upper mantle; and, most important of all, they may greatly increase the radius over which a single station can monitor small earthquakes or explosions. This will materially increase our ability to investigate the seismicity of the entire earth and also to monitor nuclear explosions.

The telemetering systems were tested at several localities: off Bermuda in about 5000 meters during the fall of 1959 and 1960, in the Gulf of Mexico at a depth of 3800 meters during January 1961, and off the Argentine coast at a depth of 5600 meters during June 1961. The basic unit employed for these tests was a 2-cps Hall-Sears HS 10 geophone operating at about 0.5 critical damping.

The signal from the geophone is amplified and used to drive a variable-inductance element which controls variations in frequency of the oscillator about a mean of 12 kc. The frequency-modulated output of the oscillator is amplified to deliver about 1 watt of power to the transducer.

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[7] This report is a summary of the paper by Mr. John Ewing and Dr. W. Maurice Ewing, "A Telemetering Ocean-Bottom Seismograph" J. Geophys. Res., Vol.66, No. 11, Nov. 1961 pp. 3863-3878.

The transducer is small free-flooding magnetostrictive unit, whose transmitting response is about 10 to 14 kc. The ocean-bottom unit is completely transistorized. Its power supply is a battery, estimated to provide for seven to eight days of continuous operation.

The telemetered acoustic signal is received on shipboard by a standard UQN-1 echo-sounder transducer, which is tuned broadly to 12 kc and provided with a bandwidth of about 2 kc. It has a beam width (between 10-db points) of about 45°. An amplifier covering the band from 10 to 14 kc is used to amplify the signal from the transducer and to pass it into the FM demodulator (a commercial frequency meter). The output of the demodulator is filtered, amplified, and recorded on a pen recorder and on magnetic tape.

Several methods of launching the seismograph were used. At first a coring assembly was rigged with a geophone inside the case of a coring pipe, and the electronic assembly was mounted above the weight. This is a standard ocean bottom piston coring unit which is triggered about five meters above the bottom and drives the whole assembly into the sediment.

A second, lighter assembly was used in later tests. It had the geophone mounted on a cartwheel base and placed as a trigger weight. When the geophone was seated, the electronic package was released and allowed to fall free and seat itself separately, and the cable used to lower the assembly was disconnected.

In a later method, the seismograph unit was simply allowed to fall free from the surface. It struck the bottom at about 8 meters per second without damage to any of the components.

The last method, used near Argentina, again used the coring rig. The geophone and the electronic mechanism were placed in a single unit and suspended 20 meters below the coring weight and release mechanism. The trigger weight was suspended 10 meters below the release mechanism, i.e., 10 meters above the seismograph unit. This arrangement allowed the unit to be placed on the bottom and test monitored before the cable was actually released. If it performed satisfactorily, the wire was lowered further and the trigger weight touched bottom and released the cable, which could then be withdrawn.

Except for the method of placement on the ocean floor, the units described have been very similar functionally. The differences have been in minor details of electronic circuitry, power supplies, or detector sensitivity. Each has used a short-period vertical seismometer modulating a 12-kc carrier frequency. In the earlier part of the work, the transducer on the monitoring ship was rigidly attached to the hull, and the only indication of the direction toward the seismometer was obtained by correlating the variation in carrier intensity with the roll of the ship. Later, provision was made for training and tilting the transducer in any desired direction, and the problem of maintaining contact with the seismometer was greatly simplified.

Five refraction lines were successfully shot using bottom detectors off Bermuda and in the Gulf of Mexico at depths of about 15,600 and 12,000 feet. Preliminary results of data analysis gave useful measurements of P- and S-wave velocities in the crust and upper mantle, and showed interesting variations in the amount of energy propagated along each refraction path which indicate appreciable differences in interface characteristics from one area to the other. We recorded very good mantle shear waves in several tests, which is rather unusual in deep sea work. Body waves from an earthquake having a magnitude of 6 to 6.25 and an epicenter 2800 km away, near the Panama-Colombia border, were recorded. The sharpness and distinctness of several of the recorded phases indicated a good signal-to-noise ratio on the sea floor. Determination of background noise levels was very difficult because of a lack of complete experimental control. However, approximate calibrations in noise analysis, which will be available in the near future, do give some valuable information.

The choice of an FM telemetering system permitted a calibration of the entire system which would be independent of the losses in the telemetering length. The geophones were calibrated in the laboratory by the Willmore-Bridge method, and standard electronic calibrations were run in the laboratory and on shipboard, at temperatures from 27° to 0° C, before the units were placed in operation. The curves run from about 2 to 10 cps.

The Bermuda data indicate a peak in the ground noise spectrum of the same order of magnitude—about 10 microns amplitude—and the same period as the peak given in Oliver and Brune's continental ground noise curves. But there are indications that the noise at both the long period and short period sides falls off around six seconds faster than Oliver's waves indicate.

Future experiments will include lowering a 3-component pendulum type system which would give noise data in the period spectrum above 10 seconds.

The systems described here have many obvious and serious disadvantages. A principal one is that they were never intended to serve for long and continuous monitoring. For such purposes, the system might incorporate a cable connected to shore or extended far enough along the bottom to transmit signals without introducing mechanical noise caused by shaking. Another method would be to store the data on either magnetic tape or film for a minimum of one month. Upon command from a monitoring vessel, the accumulated data could be delivered either by accelerated telemetering playback or by transport of the record to the surface. Both these systems are being investigated with the view of installing permanent or semipermanent stations.

Power for such a system is a very serious problem. The most promising source we have come across is a nuclear generator.

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The newest, most ambitious and exotic use of isotopes is in isotopic power.[8] The cesium 137 generator being built for Lamont is the fourth of its kind. It differs from its predecessors in application, longevity of its fuel, and cost. It is designed for use in an undersea seismometer station. The fuel has a half-life of about 26.7 years and currently costs about one dollar per curie.

A diagram of the generator follows in Figure 10-1.

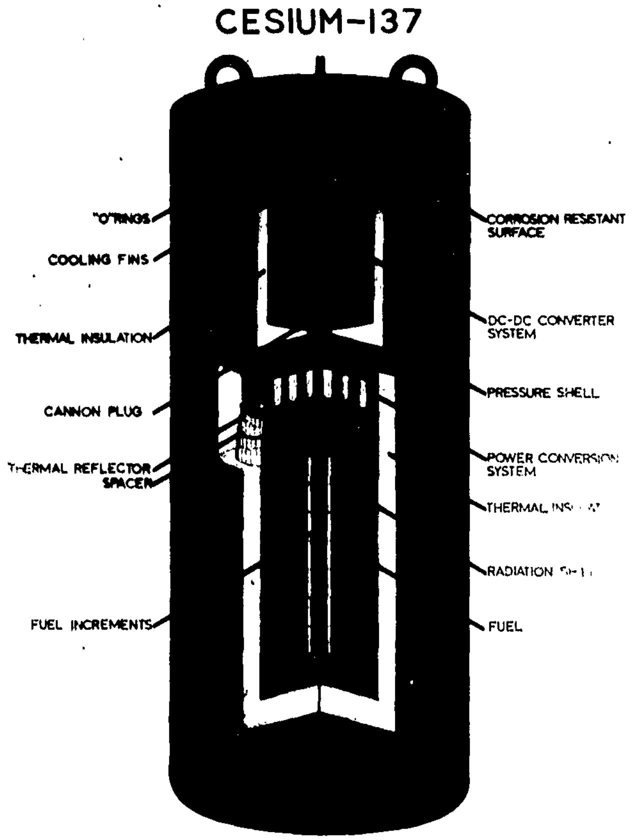

FIGURE 10-1. THERMOELECTRIC 5-WATT GENERATOR FOR DEEP-SEA APPLICATION

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[8] A transcript of this presentation, entitled "Nuclear Generator for an Ocean-Bottom Instrument," was not available. This abstract is intended simply to acquaint the reader with the subject matter.

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As part of a research program to study the seismic characteristics of the ocean bottom, Texas Instruments, under Contract AF 19(604)-8368, has recently completed the development of an automatic marine seismic measuring and recording instrument. Certain restrictions had to be placed on the specifications of the seismometer and the amplifier in order to achieve high sensitivity for seismic signals in an instrument of practical size which was to be placed on the ocean floor. These restrictions precluded the use of conventional land-type seismic sensors and amplifiers. The seismometers had to be as small as practical, yet respond to earth movements of a fraction of a millimicron at frequencies as low as 1 cps with sufficient signal voltage output to allow amplification to a level suitable for recording. This made it desirable to increase the sensitivity of a seismometer of a given size by using a low-noise, high-input impedance amplifier, if one could be made available. The sensor development phase of the program therefore included parallel design effort on a relatively high impedance seismometer and a supplementary amplifier. The seismometer which was developed is described first, and then the low-noise, low-frequency amplifier. These components of the marine seismograph are of greatest interest for possible deep-well application.

The ocean-bottom seismic instrument requires a three-component seismometer. The horizontal units are identical to the vertical unit except that the latter, which is the more applicable to down-hole work, uses a spring in compression with an 8.1 to 1 lever arm to support an equivalent mass of 97.2 lb. The actual mass is then 97.2/8.1 = 12 lb. This seismometer is basically a "moving coil" velocity sensor consisting of a spring-suspended coil moving in a magnetic field. Its natural frequency is 1 cps. The working stresses in the spring system are chosen high enough to place surge frequencies out of the operating-frequency spectrum, and the stretch is reversed into the more easily handled compression mode.

The seismometer used in the ocean-bottom instrument has a coil impedance of 12,000 ohms. The corresponding sensitivity is about 450 v/m/sec when a damping factor of 0.6 is applied via a 12,000-ohm damping resistor tied across the coil. The thermal noise of the resulting 6000-ohm source over a 10-cps band and at room temperature is less than 0.04 μv. An earth movement of 0.1 mμ peak to peak at 1 cps will give an output of 0.1 μv rms, considerably above the input noise voltage of the amplifier used. Because the input impedance of the amplifier is much higher than this, the overall noise figure of the system could be improved still more by increasing the coil resistance, which would increase the output signal level correspondingly. However, the value chosen gives the desired sensitivity without requiring the use of extremely fine-wire coils, which are inherently difficult to wind.

Other pertinent specifications of the seismometer are:

Weight: 46 lb
Diameter: 4 1/2 inches
Length: 19 7/8 inches
Operating depth: 10,000 feet
Allowable tilt from vertical: ± 5 degrees

As noted above, in order to achieve the desired sensitivities with relatively small 1-cps seismometers, it is necessary to have an extremely low-noise seismic signal amplifier, one whose internal noise level is 0.1 μv or even less. Conventional vacuum tube or transistor amplifiers have much higher than tolerable self-generated input noise voltages in the 1- to 10-cps frequency band because of the so-called 1/f characteristic, i.e., the voltage of the internally generated noise varies inversely with frequency.

Other features the amplifier must have to meet the requirements of the marine seismic instrument are:

(1) High input impedance, allowing the use of a relatively high impedance seismometer for increased sensitivity without the need for a bulky step-up transformer.
(2) Small size, ruggedness, and insensitivity to orientation, made necessary by the very nature of the problem of planting a seismic instrument on the bottom of the ocean.
(3) Low power drain, necessary for long-period operation in the smallest practical instrument package.

The three-section low-noise amplifier developed under the contract for the marine seismic instrument has all of the above features. The first section, the input low-level "preamplifier" section, uses low-frequency reactance amplifier circuit principles based on an invention of Dr. J. R. Biard of Texas Instruments' Semi-Conductor Division. Basically, the circuit is a double sideband up-converter (or modulator) in which a band of low signal frequencies is used to modulate an rf carrier frequency. The nonlinear element used to support modulation is the junction capacitance of the reverse-biased diodes. This is illustrated in Figure 10-2, which shows a typical diode capacitance waveform resulting from application of a sinusoidal voltage. Note the rather large second harmonic component of the time-varying capacitance.

Refer to Figure 10-3 for the schematic diagram. The junction capacitances of the matched diodes D_1 and D_2 are modulated by the rf pump voltage applied through transformer T_1. The diodes are reverse-biased by batteries E_{01} and E_{02}; since low-leakage silicon diodes are used

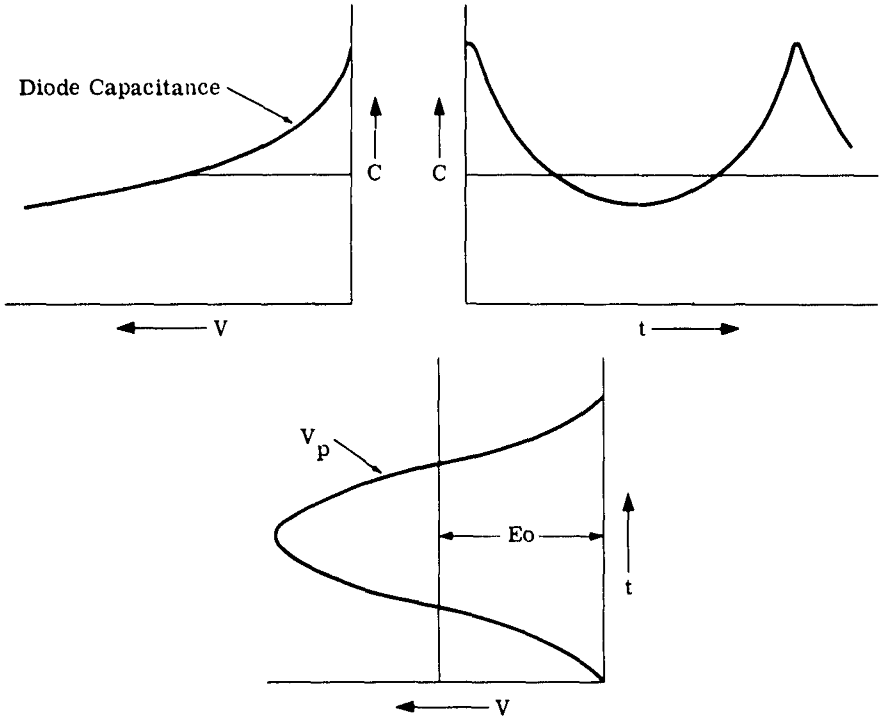


FIGURE 10-2. TYPICAL DIODE CAPACITANCE WAVEFORM FROM APPLICATION OF A SINUSOIDAL VOLTAGE

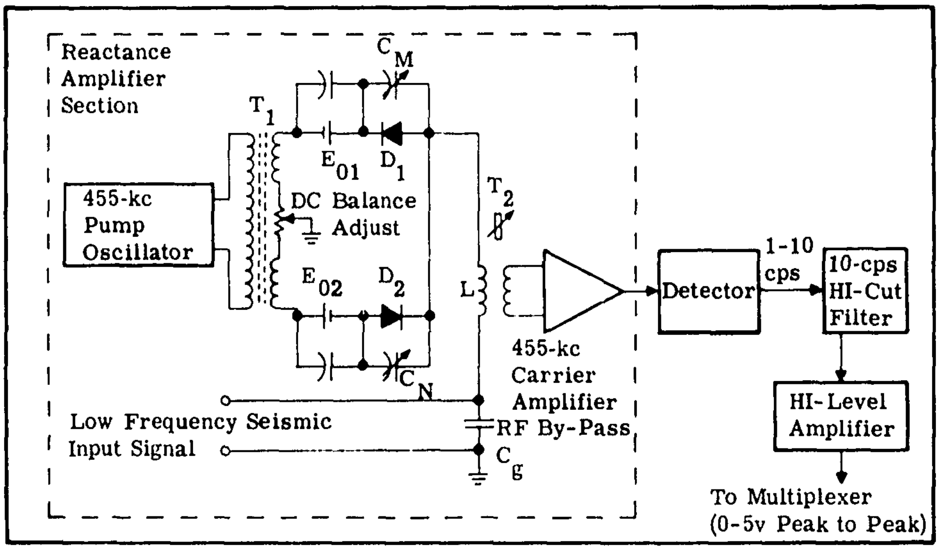


FIGURE 10-3. SCHEMATIC DIAGRAM OF REACTANCE AMPLIFIER SECTION

in the circuit, the battery life should be essentially the same as shelf life. The trimmer capacitors C_n and C_m are used to compensate for mismatch in the diodes and to provide a controlled imbalance in the bridge composed of the secondary windings of T_1, D_1, and D_2. This capacitive imbalance provides a constant amplitude signal which has the proper phase to serve as an AM carrier for the sidebands resulting from the application of a seismic input signal at e_a. Bridge imbalance is normally adjusted to give a carrier signal of sufficient amplitude to allow modulation by the seismic signal over at least a 60-db dynamic range without over-modulation. For example, a 455-kc carrier of 100 μv can handle seismic signals from 0.1 to 100 μv. Gain is adjusted by proper detuning of the tank circuit to a stable operating point slightly off 455-kc peak resonance. Voltage gain is usually adjusted to a value between 10 and 30.

The low-level input signal to be amplified is supplied to the diodes through the inductor L, which has a very low impedance at signal frequency. The capacitor C_g bypasses the signal source at pump frequency and prevents the output signal from returning to the input. The output tank, consisting of L, the indicated trimmer capacitors, and the average capacitance of the diodes, is normally tuned to near pump frequency.

The AM output signal of the reactance amplifier is further amplified by the tuned amplifier and converted back to signal frequency in the full-wave detector at the output.

All components of the reactance amplifier must be extremely stable and of the highest quality. For example, the pump oscillator must be several orders of magnitude more stable in amplitude than normally required. Any minute variation in the applied pump signal level will appear as noise modulation in the output of the amplifier. Stability is achieved by regulating the supply voltage carefully and by providing negative feedback to the crystal-controlled transistor pump oscillator.

The capacitor diodes, D_1 and D_2, not only must be well matched over the capacity swing due to the pump signal, but must be specially selected for low leakage and identical operating characteristics over a wide range of temperatures.

The reactance amplifier and the carrier amplifier have a flat frequency response from below 1 cps to several hundred cps.

The second section of the seismic amplifier is the 455-kc carrier amplifier, which amplifies the pump frequency modulated by the seismic signal. It is a simple tuned amplifier. However, its noise figure (input noise resistance) must be kept as low as possible. The equivalent input noise resistance of the low-level reactance stage previously discussed is directly proportional to the input noise resistance of the carrier amplifier, because this latter resistance is reflected back into the reactance circuit. Also, the modulated signal carrier is still at a relatively low level when it enters the input stage of the carrier amplifier; consequently, the input stage noise must be kept low to preclude the possibility of injecting additional circuit noise on top of the signal.

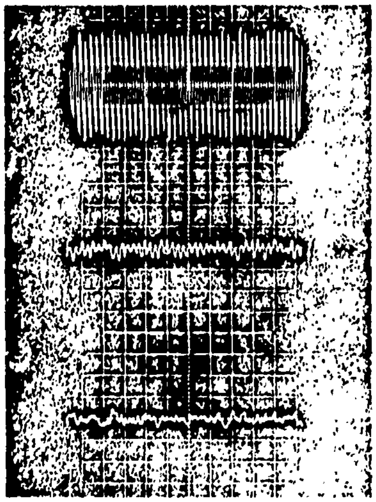
Low noise and high gain can be achieved by the use of recently developed low-noise rf transistors. The overall voltage gain of the carrier amplifier is normally adjusted to about 60 db.

Figure 10-4 illustrates the low noise characteristics of the reactance amplifier and the carrier amplifier. The signals shown were detected at the output of the carrier amplifier. The input noise level of the amplifier is well below 0.1 μv rms, and a seismic signal of 0.1 μv rms is readily discernible.

In the marine seismic application, an active RC-transistor "high-cut" filter, to eliminate frequencies above 10 cps, follows the carrier amplifier.

The third and final section of the seismic signal amplifier uses an extremely stable high-level amplifier, composed of two transistorized stages, a "difference pair" amplifier stage at the input, and a complementary emitter-follower stage at the output.

Overall voltage gain of the seismic signal amplifier is normally set at 250,000. With the input attenuator set at 0, this will allow a minimum seismic signal of 0.1 μv rms to be amplified to 25 mv rms, or about 70 mv peak-to-peak.



Output with 1.0 Microvolt rms, 7 cps Input

Output with 0.1 Microvolt rms, 7 cps Input

Noise Level of Amplifier (No Signal Input)

FIGURE 10-4. OSCILLOSCOPE PATTERNS OF REACTANCE AMPLIFIER OUTPUTS. Bandwidth: 0.2 to 10 cps, filter at output of amplifier.

The present amplifier is designed to operate stably at temperatures between 32° F and 120° F. A complete seismic amplifier, including pump, reactance stage, carrier, active filter, and high level amplifier, consumes a total power of only 0.25 watt from a plus and minus 12-volt d-c supply.

The amplifiers described are developmental models, specifically designed to meet the packaging and operating requirements of an ocean-bottom seismograph instrument. Such a device would be capable of stable operation in a wide range of environments, and would be ruggedly packaged for easy placement, adjustment, and operation.

11

USE OF WATER-LEVEL DETECTORS IN SHALLOW AND DEEP WELLS[9]

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INTRODUCTION

The objective of this program is to study how earthquakes and explosions affect the water level in open wells and the pressure in closed wells. Work has proceeded in three directions, dictated in part by the types of wells currently available. First, a sensitive water-level detector has been designed and built, and is in operation in one well. As the water level fluctuates, the detector measures the changes in electrical resistance between two parallel wires. A second system, using a sensitive differential-pressure sensor, is being designed and constructed for use on a well which has a static pressure at the surface of about 10 psi. A third system, consisting of a hydrophone with lead zirconate elements and a broad frequency response from 0.02 to 20 cps, is under design and construction for use in a deep well. The first two systems will be described in detail, following a review of some of the general considerations which determine the response of a well used as part of a seismic transducer.

GENERAL CONSIDERATIONS

As a first approximation, we consider a well tapping an aquifer with a total volume V_0 and a shape with linear dimensions that are small compared to the wavelength of the incident elastic waves. We take the particle displacement in plane compressional waves to be

$$\underline{a} = a_0 \sin (\vec{k}\,\vec{d}) - \omega t)$$

where a_0 is the peak displacement,

$\vec{k}$ is the wave vector ($|k| = 2\pi/\lambda$, λ the wavelength)

$\vec{d}$ is the normal to the wavefront from the origin of the coordinate system.

For a wave incident on the free surface at an angle and propagating normal to the y-axis, the amplitude variation with depth z is given by

$$2 \cos (kz \cos \theta) \cos (kx - wt)$$

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[9] Semi-Annual Technical Report No. 1, prepared for Air Force Cambridge Research Laboratories under Contract AF 19(604)-8376, 15 October 1961, and sponsored by the Advanced Research Projects Agency under Project VELA UNIFORM.

The strain produced by this wave is proportional to the space gradient of a, and its maximum value is $a_0 k \cos \theta$. The change in volume produced by this peak strain is

$$a_0 k V_0 \cos \theta$$

In an uncapped well, the volume fluctuations of the aquifer ΔV produce oscillations of the water surface $\Delta h = \Delta V/\pi r^2$, where r is the radius of the well which taps the aquifer. The magnification of the well, M, may be defined as the ratio of the peak water-level fluctuation to the peak particle displacement, and from the above relations

$$M = \frac{\Delta h}{a_0} = \frac{2V_0}{\lambda r^2} \tag{1}$$

To utilize Equation 1, an estimate of V_0 may be made from earth-tide data. Typical water-level fluctuations produced by earth tides in Saratoga Well No. Sa-529 are 2.5 cm. With r = 10 cm, $\lambda \sim (2)\,10^7$ cm (one-half the earth's circumference), $a_0 \sim 30$ cm, and $\Delta h \sim 2.5$ cm, the total aquifer volume required to produce the observed water-level oscillations is $V_0 \sim (8.3)\,10^3\ m^3 = (20.2m)^3$. This volume is to be regarded as an apparent or equivalent volume, active at the long periods of strain produced by tidal forces. Its value will be a function of the period of the disturbance and the porosity and permeability of the aquifer. If one assumes the same value of V_0 to hold at a period of 1 second, in a formation with compressional-wave velocity of 4 km/sec, the well magnification equals 415. Under these conditions a particle displacement a_0 of 0.1 μ results in a water-level fluctuation $\Delta h \simeq 0.042$ mm. The estimated resolution of the water-level detection system to be described is on the order of 0.05 mm. (We ignore here the effects of doubling of particle displacement at the free surface, the motion of the well wall, and diffraction.) A well having a smaller radius and tapping an aquifer of larger volume would afford a larger magnification.

In a capped well, the normal components of motion of the aquifer walls produce pressure fluctuations in the aquifer, according to the bulk modulus of the water, given by

$$K = (1/\rho_0)(dp/dv) = V_0(dp/dv)$$

where ρ_0 = initial density
v = specific volume
p = pressure

The peak pressure fluctuation produced by the assumed wave may be shown with the above relations to be

$$\Delta p = 2\pi a_0 K/\lambda = (14.1)\,10^{10}\, a_0/\lambda$$

in cgs units. With $a_0 = 0.1\ \mu$ and $\lambda = (4)10^5$ cm, $\Delta p = 3.5$ dyne/cm^2. The estimated resolution of the differential pressure system under development is 0.8 dyne/cm^2, corresponding to particle displacements of the order of 0.025 μ.

WATER LEVEL RECORDING SYSTEM

The recording equipment, which is now operating, consists of the water level probe energized by regulated 60-cycle a-c current, and a viewing resistor whose output is rectified by a full-wave rectifier and filtered by a series of double RC filters providing a 3-db frequency cut-off of about 10 cps. The output is d-c coupled to a low-sensitivity (1:10), low-speed (1 in./hr) Rustrak recorder which records the slow fluctuations of the well, including tidal fluctuations. It is a-c coupled to a high-sensitivity (10:1), high-speed (30 mm/min) Helicorder. A high-pass RC filter reduces the response below 20 seconds, and a twin-T network designed for 6 seconds attenuates microseisms, which have appeared on our early records.

The water-level probe measures the change in resistance between two partially submerged, parallel platinum wires as the water level fluctuates. The wires are 2 inches apart and 0.020 inch in diameter. If R_w is the resistance of the water, R_v that of the viewing resistor, and R_1 that of the connecting wires and transformer (Figure 11-1), then the signal voltage V_s for an applied voltage V_0 is $V_s = V_0 R_v/(R_w + R_1 + R_v)$. The water resistance is inversely proportional to the depth of immersion of the wires h: $R_w = b/h$, where the constant b is a function of the diameter of the wires and the separation between them.

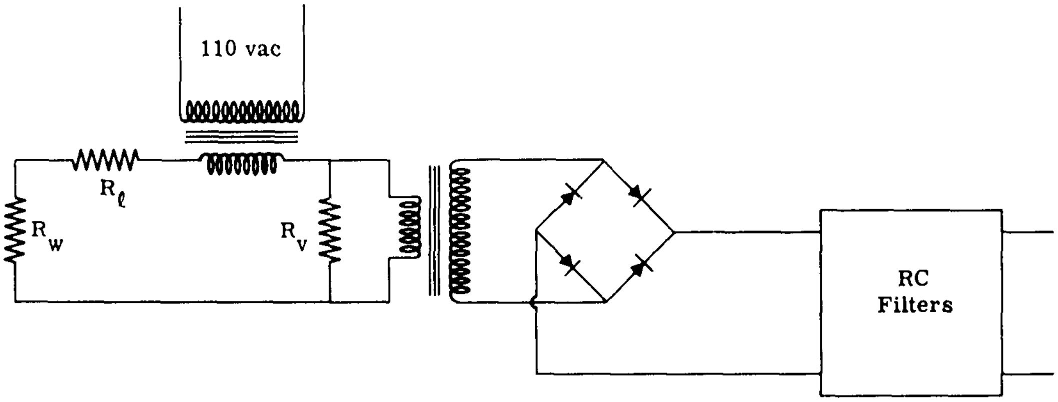

FIGURE 11-1. WATER-LEVEL SENSING CIRCUIT

Hence, $V_s = V_0R_v/[b/h + (R_1 + R_v)]$. When the water resistance is large compared with the circuit resistances, $b/h > (R_1 + R_v)$, and the signal voltage becomes directly proportional to the water level, $V_s = V_0h\, R_v/b$. The water resistance is in the neighborhood of 1000 ohms, depending on the actual water depth. The viewing resistor, which provides a linear response under these conditions, has a resistance of 50 ohms or less.

DIFFERENTIAL PRESSURE SENSOR

Two wells have been located which are over 800 feet deep and from which there is a constant flow of water at the surface. In one of these the static surface pressure is 10 psi. The differential pressure sensor, designed and partly built will be completed and installed in this well during the next quarter. It consists (Figure 11-2) of a branched pipe leading through needle and shut-off valves to a Decker differential pressure sensor,[10] capable of resolving a pressure differential of 0.8 dyne/cm^2. This corresponds to particle displacement on the order of 0.025 μ

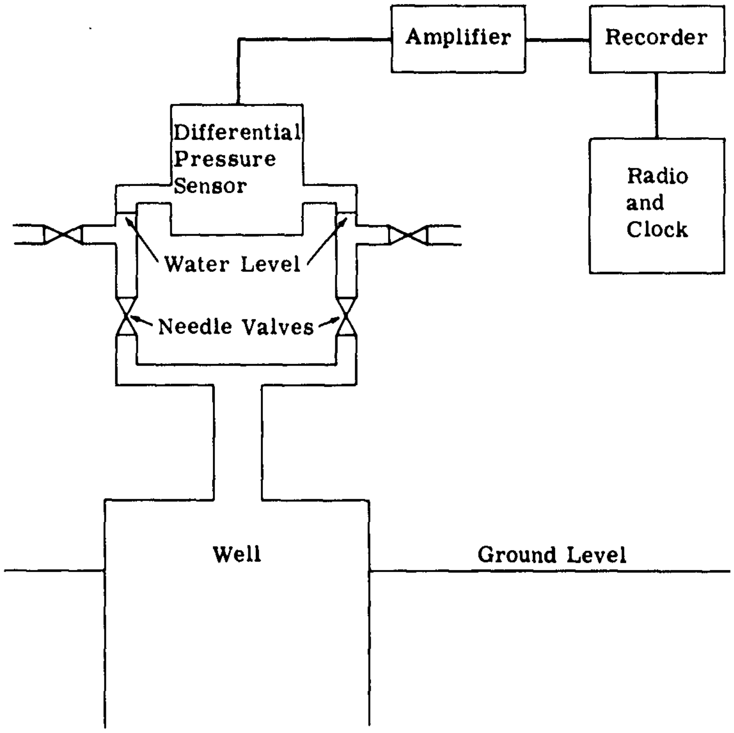

FIGURE 11-2. DIFFERENTIAL PRESSURE SENSOR

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[10] Micro-Differential Pressure Meter, The Decker Corporation, 45 Monument Road, Bala-Cynwyd, Pennsylvania.

for the example given above. The valve system will permit ready control of the frequency response of the overall system.

RELATED DATA FROM NEARBY WELLS

The Saratoga Well (Sa-529) is located about a quarter-mile from the well in which the present equipment has been installed. The response of the well to earthquakes during 1958 was plotted (Figure 11-3) from data[11] obtained from a conventional water-level recorder used by hydrologists.[12] One earthquake with a magnitude of 6, detected at a distance of about 1300 km, gave a peak-to-peak deflection of about one inch. Data for Long Island Well Q-64 shows a peak-to-peak deflection of about 1/4 inch from an earthquake of a magnitude of 6.75 at a distance of 9000 km.

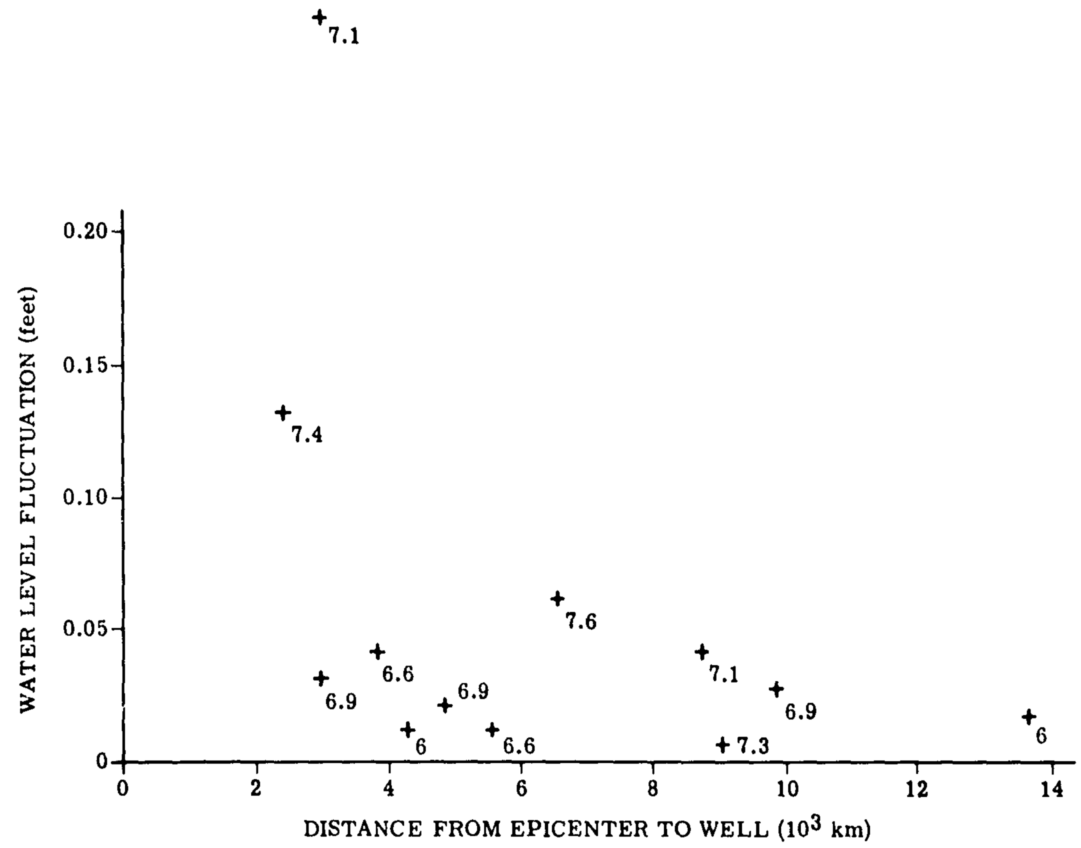

FIGURE 11-3. EARTHQUAKES RECORDED IN SARATOGA WELL SA-529 DURING 1958

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[11] Data obtained from U. S. Earthquakes, 1958, Coast and Geodetic Survey.

[12] Leupold and Stevens Instruments, 4445 N.E. Glisan St., Portland 13, Oregon.

12

GEOLOGIC INVESTIGATION OF THE BURIED CRUST OF NORTH AMERICA

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The initial investigation of the buried crust of North America began in 1952 with Peter T. Flawn's study of the subsurface Precambrian basement of Texas and southeastern New Mexico. This project was sponsored by the Texas Bureau of Economic Geology, and many oil companies cooperated by furnishing samples and cores from wells penetrating to the Precambrian. The results of this study are summarized in "The Basement Rocks of Texas," published in 1956 by the Texas Bureau of Economic Geology.

The report aroused considerable interest among the cooperating oil companies and prompted them to extend the study to other regions. Oil companies were interested in the rocks beneath their oil- and gas-producing formations because it was recognized that the framework of the sedimentary basins, and therefore the deposits within them, are strongly influenced by the structures of the older rocks. The types of rocks in the basement control the kinds of folds and faults that can develop in the overlying sedimentary rocks. Thus, these ancient features could furnish a base for further oil and gas exploration and a better understanding of regional geologic development.

Flawn next began a study of the concealed Ouachita system from Mississippi to Mexico under the same sponsorship as the earlier study. The results of this work are summarized in a forthcoming publication, "The Ouachita System," which should be available from the Texas Bureau of Economic Geology by the end of 1961. In addition to the petrographic studies and the compilation of maps of the buried Ouachita System made by Flawn, X-ray studies of the clay minerals were made by Charles E. Weaver, and regional syntheses were made [illegible] illip B. King of the U. S. Geological Survey. August Goldstein studied the buried part of the Ouachita belt east of the outcrops in the Ouachita Mountains. This latter project began in 1955 and is now being completed.

In 1956, the Research Committee of the American Association of Petroleum Geologists (AAPG) established the Basement Rocks Projects Committee, with Peter T. Flawn as director, to assemble information on basement wells of the United States, Canada, and Mexico between latitudes 24° and 60° north. The project was supported by funds of the Research Committee of the AAPG, and in 1958 the Standard Oil Company of New Jersey gave $20,000 to support the Committee's work. At the present time the Committee has completed a map of North America which shows (1) all basement wells with a code number, (2) the exposed basement rocks differentiated by age and gross lithology, and (3) a structural contour map of the basement surface. The map will be published soon by the U. S. Geological Survey. An accompanying text which tabulates all pertinent and available well information will be published by the AAPG.

Upon being named Director of the Texas Bureau of Economic Geology, Dr. Flawn resigned his position with the Basement Rock project, and I was asked to direct the next stage. Under the terms of our grant from ARPA, we expect in the next two years to take the assembled material, study the samples and cores, and compile a geologic map of the buried basement of North America. Simultaneously, the U. S. Geological Survey has offered to compile a map of the exposed basement, so that the two combined efforts will result in a comprehensive map that shows the basement of North America to the extent of our present knowledge.

The thousands of deep borings which penetrated the crystalline crust and were recorded on the recently completed well map are represented by rock samples and cores capable of yielding significant petrographic and radiometric data. One of our major efforts will be the detailed petrographic analysis of these samples and cores. Selected samples will be analyzed radiometrically to determine their geologic ages and provide information on continental development through time. Many of the boreholes have been surveyed by "in-the-hole" logging devices to obtain data on temperature gradients, electrical and radioactive responses, and sonic velocity of the crustal rocks and the overlying sedimentary strata. Where possible, a selection of unsurveyed holes will be similarly investigated. Quantities of seismic, gravimetric, and magnetic data gathered in academic and industrial investigations are also available. In addition, a hundred years of surface mapping and analysis have produced a moderate amount of information on the exposed crystalline crust, although the amount of available information varies greatly from one area to another. The trends and patterns established by these outcrop studies can be applied by projection and extrapolation to the study of buried crustal rocks.

The resulting map will present the first systematic assembly of such data and will, for the first time, permit a firmly based analysis and interpretation of North American geology in terms of the history and three-dimensional geometry of such major geologic features as orogenic belts, igneous and metamorphic provinces, and major fracture systems. Extrapolation and projection of observed trends would assist in interpreting the crustal nature of the continental shelves. Integration with current oceanographic studies would make possible a better understanding of the relationship between the continental and the oceanic crust. Downward projection of geometric and compositional attributes observed at the curst's surface would have an important bearing on studies of the character of the deeper crust and upper mantle. Besides having the fundamental scientific value of increasing knowledge, the proposed investigation of the buried crust of North America would contribute immeasurably to an assessment of the compositional and structural anisotropy of the crust and its effects on the transmission of seismic energy, to a better understanding of seismic wave trains and their interpretation for the detection of nuclear blasts, and to the development of "hard" communication systems. The study would lend itself to integration with specific investigations in the field of seismology such as those recently proposed by Griggs and Press (Reference 4).

Generation of new data other than that arising from materials at hand is not contemplated in the present program. It is apparent, however, that certain fields of investigation have not been carried far enough to be related specifically to the study, and these will be postponed to a later phase. Maps prepared in this second phase of the expanded project will reveal areas in which adequate data on the buried crust are not available. These data can be filled in by more drilling. A large number of deep boreholes which approach but do not penetrate the crystalline crust have been drilled in the exploration for oil and gas. Many of these boreholes are in a condition that would permit re-entry and deeper drilling, a procedure that takes advantage of the thousands of feet of rock already drilled and the millions of dollars already spent. In other areas, the investigation cannot be completed without drilling new boreholes from the surface to the rocks in the buried crust. This is all work for the future, beyond the scope of the current project. However, when the project is expanded, it is anticipated that industry cooperation through the AAPG will permit the maximum economy in any deep drilling found necessary.

The project currently being sponsored by ARPA will have as a free consulting panel the 15 members of the Basement Rocks Committee of the Research Committee of the AAPG. They will maintain liaison between this investigation and those industrial and academic scientists who can contribute to the project. The accumulated files at The University of Texas, which represent the greatest single concentration of data on the buried crystalline crust of North America, will be available.

13

MODEL EXPERIMENTS FOR ELECTROMAGNETIC PROPAGATION FROM AN UNDERGROUND SOURCE

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The modeling program described is part of a study to determine the feasibility of detecting electromagnetic signals which might be generated by an underground nuclear burst and to determine whether the signals, if detected, can be correctly identified.

It is well known that a nuclear explosion above the surface of the earth produces extremely large field strength and propagates signals which travel around the earth many times. We believe that an underground nuclear explosion might also produce electromagnetic signals of some magnitude. The signal then propagates to a receiver which may be on or below the surface of the earth. The problems are: (1) Can we detect the signal? (2) Can we recognize it if we detect it? and (3) What are the best operating conditions for detecting and recognizing the signal?

To answer these questions requires knowledge of the electromagnetic properties of the earth, but information in this field is scarce. However, there are reasons to believe that the conductivity of the rock decreases markedly with depth, particularly if there is a basement at a depth to which one can sink a well. The conductivity in this basement material might be about 10^{-8} mhos per meter. There is also some possibility that the conductivity will again increase at a still greater depth. This depth is not known, but perhaps at the depth of the Moho there would be some sort of phase transition of the rock, accompanied by a marked increase in conductivity.

In any case, there is the possibility of propagation through the earth, either in bedrock or in low-conducting layers, and of channeling effects to allow propagation over large distances. In general, the conductivity of the overburden of the earth runs to about 10^{-2} mhos per meter, so that there is a marked difference between the electromagnetic impedance of the material near the surface and that of the material at greater depths.

Detection at depth seems to offer great advantages. First, electromagnetic noise, most of which would be generated on the surface by lightning strikes and various man-made sources, decays exponentially with depth just as Rayleigh waves do; therefore one would have quiet conditions in which to detect signals. Second, the low-conductivity layer, if it exists, would considerably lessen the attenuation which the signal would undergo if allowed to propagate through highly conductive material. Third, the attenuation of the waves propagating to and along the surface is highly dependent upon frequency, so that a signal received on the surface will have lost much detail; but attenuation of the electromagnetic waves propagating directly through a low-conductivity layer in the earth may very possibly not depend on frequency above a few hundred cps, so that detail would be retained, and signature recognition might be possible.

Since there are enormous difficulties in attempting to solve these problems theoretically, modeling has been used. The results obtained so far are based on a simple earth model consisting of a low-conductivity duct model, depths on the order of 35 km, and a highly conductive material above and beneath the duct.

Physically, the model consists of a salt-water solution, whose conductivity can be adjusted to desired values for each experiment, with an aluminum plate above and below which acts essentially as an infinitely conducting material above and below the waveguide.

In order to determine the validity of the model, a problem was constructed which could be solved theoretically. This problem, which postulates a one-dimensional wave guide with infinitely conducting boundaries, has been solved by a number of people. The theoretical and experimental results agreed very closely.

We are currently engaged in obtaining more significant data from a model consisting of a low-conductivity duct, with a material of high but finite conductivity above the duct to simulate the upper crust of the earth, and a high-conductivity material below the duct to simulate the deep earth.

Appendix

AVAILABILITY OF WELLS FOR DETECTION RESEARCH[13]

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Department of Geology
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A number of wells, especially in granite or metamorphic rock, are available in central New York and Pennsylvania. This region is probably the most active one east of the Mississippi in oil and gas research: each month drilling is terminated on about twelve wells, of depths ranging from 1000 to 10,000 feet. Most of these are cut through competent limestones, sandstones, and shales, and some penetrate to within a few hundred feet of the Precambrian surface. They will probably stand up without casing for years.

About half the completed wells are unavailable for seismic research because they are producing — mostly gas. Of those remaining, most of which are likely to be available, about half are shallower than 5000 feet, most of the rest are around 7000 feet, and a few reach 10,000 feet. One well is planned for a depth of 15,000 feet.

The following economic considerations are of importance. The state laws of New York and Pennsylvania require that dry holes, i.e., nonproductive ones, be plugged and capped as soon as feasible after drilling is completed, to prevent pollution of ground water and of oil and gas reservoirs. Plugging costs about $2500, if the rig is in place. The cost of opening up a plugged well would be additional and would depend very much on the condition of the hole. In general it is better to work with wells that have not been plugged. The cost of keeping a relatively small drill rig on site but inactive is $200 to $400 per day, and for a large rig, about $700 per day.

In view of these circumstances, we feel that the most economical course is to keep track of the deeper wells as they near completion and be ready to insert the detection equipment as soon as the well is available. The companies which we have contacted have been glad to cooperate. In return for permission to use a well for seismic detection for as long as necessary, one could assume the costs of plugging and capping the well after the detection equipment is withdrawn.

Detailed weekly reports of all well-drilling activity in the Pennsylvania, New York, Ohio, and West Virginia areas, including location, depth, and ownership, are available from H. & R. Scouting Service, Box 312, Coudersport, Pennsylvania.

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[13] Excerpt from a letter to Mr. A. M. Rugg, Jr., of United ElectroDynamics, Inc., 17 November 1961.

REFERENCES

1. C. J. Byrne, "Instrument Noise in Seismometers," Bull. Seism. Soc. Am., January 1961, Vol. 51, No. 1, pp. 69-84.
2. Alfred Wolfe, "The Limiting Sensitivity of Seismic Detectors," Geophysics, April 1942, Vol. VII, p. 115.
3. R. A. Langivin "The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes," J. Acoust. Soc. Am., May 1954, Vol. 26, No. 3, pp. 421-427.
4. D. T. Griggs and F. Press, "Probing the Earth with Nuclear Explosions," J. Geophys. Res., January 1961, Vol. 66, p. 237.

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