Report of field tests and discussions conducted during visit of E. Ralph at Petty Laboratories, San Antonio, Jan. 24-28, 1963

The experiments conducted at the Petty Laboratories with continuous waves as preported in their "Interim Technical Report No. 1" (Oct. 1, 1962) were encouraging. Signals transmitted from a weak source (a 25 watt speaker) were detected at distances of 10 feet or more at frequencies up to 800 cps. Since then, equipment has been constructed for experimentation with pulsed waves at repetition rates of 5, 10, and 20 cps.

With this and various assessories, including the oscilloscopic detector constructed by G. MacLaughlin, laboratory and field tests were conducted by Art Hasbrook, Andrew Bergquist, and Eliz. Ralph on January 24 and 25th.

First of all, we found out that the synchronization circuits of the MacLaughlin detector were not stable until the amplitude of the pulse to be detected exceeded 30 volts. Therefore, this instrument was set aside, and experiments were continued with the Petty Hewlitt-Packard oscilloscope as a visual detector and recording oscillograph (installed in truck) for permanent records. Both of these, when triggered by the start of the impulse, afforded measures of time delay or, in effect, sonic wave transmission time through the earth.

The results of the experiments with pulsed waves, at first glance, were discouraging. Maximum discernible transmission distance at 600 cps and repetition rate of 20 cps (as determined by reception of a signal distinguishable above noise background) was 6 feet. However, examination of the oscillograph records revealed that a large percentage of the start of the wave, the vital part for pulsed wave reception, was being lost because of the slow response time of filters and other circuit components.

In discussions of this and of future plans on January 28th with W. Harry Mayne, Art Hasbrook, Andrew Bergquist, and Eliz. Ralph, the following steps were outlined:

1) To conduct experiments with a simple step function, etc. in order to adjust circuits for optimum reception of the <u>start</u> of a pulsed wave, and to adjust filters, etc. for maximum reception at 600 cps.
2) To obtain a more powerful speaker and one designed to operate at 600 cps.
3) To experiment with a source with excessive power such as the Edgerton Model 230 Boomer which produces 1000 watts at 1 second repetition rate. (E. Ralph to try to obtain loan of this from Prof. Edgerton at MIT or from Woods Hole Oceanographic Institute).
4) To study the possibility of "enhancement" of the received pulse by magnetic storage -- possibly by the storage of 100 passes.

It was felt that it might be possible to complete the basic "transmitter" experiments within a month, and that then, with more information in hand, a decision could be made as to whether and if so, when, a workable set of equipment could be assembled for trail in Italy and, of course, for finding Sybaris.

I should like to extend my thanks to Mr. Mayne, Mr. Hasbrook, and to Mr. Bergquist for their kind hospitality during my visit in San Antonio, and to mention that the experiments which they have conducted so far are the first (to my knowledge) which have produced some useful information about the behavior of sonic waves at shallow depths. Their testing site with geophones and blocks of concrete planted at various depths and the instruments which have been assembled provide the requisite foundation for the construction of a workable set of equipment.

Elizabeth K. Ralph, Assoc. Dir.
Applied Science for Archaeology
University Museum, Univ. of Pa.
Philadelphia 4, Penna.
February 3, 1963

SONIC ARCHAEOLOGICAL PROBE

Summary of Project work as of

1 July 1963

Initial development concerned basic considerations and determination of necessary field experminents. Preparation included outfitting a truck with the necessary instrumentation for field experiments.

The problems of transducer coupling to earth and the propagation of energy in the earth were first investigated. Results indicated high viscosity oil to be the best coupling medium and propagation measurements at the laboratory indicated an average signal decay of approximately 3 db per foot at 500 cps. The test site was then moved to a location 18 miles south of San Antonio and the 3 db per foot attenuation in earth confirmed by tests of one way travel measurements to calibrated detectors in drilled holes. Attenuation measurements were made in a frequency range of 200 to 1200 cps. The attenuation rate of energy from sources below 800 cps is sufficiently low to encourage the continued investigation of the reflection method for locating relatively small masonry objects near the surface.

A test site with simulated targets was prepared with concrete cylinders 3 feet in diameter and 3 feet thick buried at depths to the top of the cylinder of 7, 11.5 and 24 feet. These targets are available for future tests.

The preceeding tests were performed using continuous wave propagation. A pulse unit was then constructed to be used with either the MacLaughlin DC oscilloscope or conventional oscilloscope. Provision was made for a repetition rate of either 5, 10 or 20 pulses per second with a variable pulse duration at a frequency of 600 cps.

With a pulse power source the underwater speaker (University MM2FUW) proved to have a major resonance of 125 cps and acoustic power less than with continuous wave operation. The speaker was adjusted to a resonance of 600 cps, but resulted in still further reduction in acoustic power output.

A loan of Dr. Edgerton's "Pinger" system was arranged by Miss Ralph, of The University Museum. Resonance of this device was 9 kcps and as expected, severe signal decay occured thru the earth medium. Oil coupling to earth proved superior over water. Maximum detectable seismic energy was at a distance of 3 feet thru the earth. The MacLaughlin exploration system was again tested after a previous failure and indicated comparable results to the equipment initially supplied for the project. Following the work with the "Pinger", a loan of Dr. Edgerton's "1000WS Boomer System" including 2 experimental 500 WS transducers was arranged by Miss Ralph. The "Boomer" produced 3 cycles of a 4 kcps pulse in water. Records indicated lower frequencies than 600 cps predominate and 3 foot resolution was not achieved. The test site was then moved north of San Antonio to check on reflections from larger objects (limestone beds). Records indicate probable reflections at 24 feet and deeper. These results are in agreement with previous work at this site. Dynamite caps were fired in the same position as the "Boomer" transducers. Results were comparable to the "Boomer" with an additional increase in acoustic power output.

According to information received from Italy, the largest buried objects have been walls one meter thick, and it is doubtful that any pavement exists. These tests for larger objects using frequencies below 600 cps were discontinued on the basis that a resolution of 3 feet (or a frequency of approximately 600 cps) definitely is required.

The test site was next moved south of San Antonio. Recordings were made using the "Boomer" transducer and the simulated targets. Different detector arrays and transducer locations were tried in relation to the 24 foot deep target. Possible reflections in the recorded seismic energy were indefinite on the records.

Tests were made using the "1000WS Boomer" transducer and a continuously tuned filter amplifier. Records show a preponderance of energy at a frequency of 350 cps and below. An additional 12 emitter-follower detectors have been constructed and are ready for field use.

Additional tests planned:

1. The evaluation of a Barium Titinate transducer and a 2000 volt pulse power supply at a frequency of 600 cps with variable pulse duration.

2. Possibility of record enchancement using an available Sigma-Flux direct magnetic recording system of the micro head type for the addition of multiple energy pulses. This system to be made available by Petty Geophysical Engineering Company without charge to the project.

3. Possibility of additional record improvement by use of additional filtering at both detectors and amplifiers to removed undesired energy.

The above tests to be made using the existing low power tranducers but a more powerful transducer would be desirable if one can be made available to the project.

Conclusions and recommendations:

Tests to date indicate a high power, discrete frequency (600 cps) acoustic energy souce will be needed for future tests. Use of a signal enhancement technique such as magnetic recording, may also will be required.

A combination of a more powerful source and magnetic recording system appears to offer the best possibilities for a successful archeological exploration system.

If the aforementioned magnetic system is feasible, one of the major needs of the project will be satisfied. If this magnetic system is not satisfactory, then either the construction, or purchase of amagnetic system is necessary at considerable expense.

A transducer resonant at, or near 600 cps and considerably more power is also required. With present information, the most promising transducer is one of 100 watts from Massa Cohu, at a cost of $3200.00. Several of these would probably be required. These transducers can be stacked, or added together for more power. Most of the other manufacturers of sources contacted either have nothing available or their equipment is classified.

If a loan of the equipment needed could be arranged, then the future monetary requirements could be reduced accordingly.

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November 9, 1963

RECOMMENDED EQUIPMENT
FIELD SONIC ARCHAEOLOGICAL PROBE

Quantity	Item	Estimated Cost
1	Truck-2 wheel drive 3/4 ton with light weight cab	$ 3,400.00
1	Drill-Auger type, vehicle mounted	750.00
8	Audio amplifiers-variable filters in 250 to 1000 cps range, 80 db calibrated attenuators, no AGC	5,200.00
1	Photo-paper recorder-minimum chart speed 50 inches per second	4,050.00
1	Magnetic recorder system-custom designed with 6 channel multitrack 100 multiplicity capabilities	15,890.00
23	Acceleration detectors-part of present project	
1	Switching control unit for detectors	
1	Shooting box for dynamite caps	200.00
1	Tektronix type 321 DC Oscilloscope	785.00
1	Hewlett Packard transistorized AC Meter	275.00
1	Hathaway Model N-1 Audio signal generator	310.00
1	Simpson Model 260 Meter	58.60
10	Assorted hand digging tools	50.00
Asstd.	Wire and cables	200.00
Asstd.	Small hand tools, soldering irons, etc.	50.00
	Mechanical Parts Total ---	$31,218.60
	Labor for engineering, assembling, testing, etc. of above	15,870.00
	Salary for technician for three months in Italy	3,000.00
	Labor Total	$18,870.00
1	Edgerton, Germeshausen and Gerier 1000 watt-second "Boomer"	3,500.00
1	3 kw Zeus 115 VAC Portable Power Plant	431.25
1	Truck-2 wheel drive 3/4 ton	2,700.00
		$ 6,631.25
	Grand Total	$56,719.85

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The list of the proposed equipment is attached. The total bid for the equipment is $56,719.85. This bid does not include the cost of transporting the equipment to Italy; the cost of transporting a technician from San Antonio, Texas and return; the technician's expenses while in Italy; nor explosives, recording paper, and magnetic tapes used. The salary for the technician on this trip is included as shown on the equipment list.

ELECTRONICS DIVISION

Petty LABORATORIES, INC.
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Sonic Archaeological Probe

A meeting was held July 9, 1963 to discuss the Sonic Archaeological Probe Project. The meeting was held at the Petty Geophysical Engineering offices in San Antonio. The morning discussion included Mr. F.L. Johnson of Sun Oil Company, the advisor for the project, and Mr. Fred H. Lindall, Mr. Scott Petty, Jr., Mr. Harry Mayne, Mr. Arthur Hasbrook, Mr. Andrew Bergquist and Mr. John Tolk of the Petty Co. The same group with the exception of Mr. Lindall continued the discussion after lunch.

Mr. Johnson opened the meeting by giving a resume of the history of the project. He pointed out the need of a sonic probe or similar device to locate archaeological objects buried 30 feet or more in earth. For this probe to be useful it must be able to reliably define a 3 foot object buried at a depth of about 24 feet. Mr. Johnson voiced the opinion that a 10 foot penetration limit would remove 50% or more of the value of the probe. The device would have greater utility if it were completely portable but a light truck or jeep mounted unit would have practical application. A 600 cycle per second or higher frequency source of sufficient power must be used if a 3 feet definition is to be realized. He further stated that if the problems of obtaining such a source and coupling it to the ground to realize a readable signal from an object at least 24 feet deep is not feasable the project should be abandoned.

Mr. Bergquist presented a short resume of the power sources tried to date including blasting caps, low powered speakers with continuous and pulsed inputs, the Edgerton "Pinger" and "Boomer" and the possibilities of a Barium Titanate transducer now under test. A chart giving measured attenuation rates of energy at different frequencies travelling through earth was discussed with particular interest in the 3 db per foot attenuation rate at 600 cps.

A general discussion was held concerning the problems of transducers, coupling transducers to earth, record help by filtering, and record enhancement by magnetic recording and signal stacking. With signal losses over a two way travel time at 600 cycles of perhaps 200 db the problem is quite great, but Mr. Mayne believes perhaps 40 db improvement could be realized from a special 100 or more head magnetic recording device and about 24 db from improved filtering techniques. The desireable approach would be to realize most or all the improvement in the transducer-coupling device so it was decided to devote the remaining funds in the present project to investigating this part of the system. It was decided to contact Paul Klipsch for consultation on the transducer problem.

The many transducer-coupling arrangements discussed varied from purely mechanical devices such as 600 cycle resonant steel diaphragms and resonant beams mechanically excited to electro-mechanical devices such as the above excited by syncronous off center motors or other electronic means and high powered speaker type devices operating in a fluid. The magnetostrictive devices tried to date were also evaluated. It was decided to continue tests on the barium titanate crystal transducer as a possible discrete 600 cycle power source even though power of the present unit is far too low to approach desired penetration.

Possible mechanical coupling devices varied from heavy plates to expanding metal cylinders buried in holes. The use of vehicle weight was not discounted. Fluid couplers included water, oils, muds and other fluids.

The meeting ended on a note of optimism. The problems are great but the solution is certainly within the realm of feasibility.

Petty Laboratories, Inc.
San Antonio, Texas

Experimental Tests With the Edgerton, Germeshausen & Grier "1000 WS Boomer System"

Initial tests were made in a brown sandy-clay soil having an average velocity of 1900 feet per second. Signals were recorded using acceleration type detectors carefully planted in the earth.

Two vertical spreads of detectors were used, with plants in separate holes of 3, 5, 7 and 15 feet depth and arranged on an 18 inch radius about a transducer hole. The other spread had detectors planted in holes of 16, 26 and 31 feet depth. The 500 WS transducer was suspended in the center hole of the spreads, while the 1000 WS transducer was located as close as possible to the detector spreads. The 1000 WS transducer hole was lined with a thin plastic material to prevent loss of the water coupling medium to earth.

The 1000 WS and 500 WS transducers proved to be excellent sources of high sonic power and the sonic signal was detected to a distance of 30 feet through earth. Frequencies below 600 cps largely predominate so apparently the pulse from the transducer is either altered or suffers severe high frequency attenuation through the earth.

In another test detector plants were spaced horizontally at intervals across a concrete target which is 3 feet in diameter and 24 feet deep. The 1000 WS transducer was moved from one hole to another along a line of holes spaced at intervals of 0, 5, 10 and 15 feet, with the "0" hole directly above the target. Detectors were then spaced at one and two foot intervals along this line across the optimum distance for signal reflection from the target.

No definite reflections were recorded with either method. The absence of 600 cps or high frequency energy probably results in no measureable reflection from a target of fractional wavelength.

In order to determine the feasibility of recording seismic signals from larger buried objects, another test site, characterized by chalk and limestone series immediately beneath a thin layer of soil, was chosen. Hard sections are present below 18 feet and hard limestone at forty eight feet. Also, the chalk is a good high frequency medium in comparison with the sandy-clay soil of the initial location. Four transducer holes were dug 6 feet apart along a horizontal line, with holes of two foot depth for detectors drilled on either side of the transducer holes. Records were made using amplifiers with high pass 400 cps, high pass 200 cps and broadband filters. Results indicate possible seismic signal reflections from the 24 foot and deeper limestone beds.

No further work was performed on this site. Information was received, from Miss Ralph, that the largest buried objects of interest have walls no more than one meter thick, with no pavement in association. So, continued experiments to improve results from continuous beds is outside the scope of this project.

Based on results to date, it is thought that a high power discrete frequency source of sonic power is necessary for possible detection of small objects buried in alluvium to depths of 30 feet.

Beth
Ralph

EKR Petty Co. visit 8/20/63
Discussions with Mr. Mayne, Mr Hasbrook, & Mr ?

Funds remaining - approx. $4000, enough to continue thru Sept.

Expts. so far have, at least, furnished some concrete data, a necessary foundation for future development.

Main factors are that 1) transmission is optimum at 600 cps (Higher frequency - attenuation too great, lower, won't see walls less than 1 meter wide). Also, frequency band must be narrow in order to interpret results.

2) Transducer, with crystal at 2000v or with 25w speaker, direct transmission is detected up to 6 ft.

Next ~~month~~ 2-3 weeks to be devoted to design considerations of more powerful transducer.

Possibilities:

1) BaT. crystal, ½ in thick, larger dia., at 25 kv. Gain improvement ~ 40 db

2) Increase dia. to 24 in., a dia. ~ to λ. Gain improvement ~ 20 db.

With 1) & 2) might achieve direct transmission to 20 ft. & might detect a target (see Reflection) at 8 ft.

Other possibility - use large steel plate approx 3' dia. Possibly energized by Boomer or similar device. Steel plate of dimensions such that it resonates at 600 cps. Main problem involved is the damping or elimination of other frequencies

Petty visit, p. 2

With the additional information obtained in the next 2 weeks, Petty Co. will submit proposal for design & construction of a workable transducer & associated components, & cost estimates.

Probable future procedure:

1) Extensive field tests & det'n of limits of penetration & reflection detection
2) Design & construction of improvements, possibly including magnetic tape intensification of reflected signal, and others, in order to reach ultimate goal of detection at 30 ft.

Petty Laboratories, Inc.
San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Summary of Activities

August 1963

Further investigation of methods to produce high power sonic energy in earth were conducted. Various sizes of steel plates were coupled to earth with mud and detectors planted at various depths below the plates. The plates were then pulsed with various weight balls dropped from different heights.

Based on the above tests, a plate one inch thick by thirty inches in diameter was fabricated for tests at the site south of San Antonio. At the 7 foot target location, a detector was buried 2 feet from the surface and directly above the target. A seven foot detector, previously buried directly on the concrete target, was also used. The steel plate was mud coupled to the earth above this location with an additional detector cemented to the plate for an impact, or break time pulse.

Steel balls of weights from 16 grams to 93 grams were dropped from a 3 foot height and recordings made of the seismic signal amplitude. The soil above the target has a velocity of approximately 800 feet per second indicating an unconsolidated condition still exists. Sufficient signal amplitudes were achieved, but of frequencies of less than 600 cps, therefore indication of reflections on the recordings were indefinite.

The steel plate was then moved to a previously undisturbed soil location with detectors buried at seven feet and two feet intervals directly below the plate. Again ball drop tests were made on the plate. An increase in velocity of the soil and also an increase in frequency were recorded.

An attempt was then made to determine the characteristics of the steel plate plant. A driver-detector assembly consisting of calibrated HS-1 detectors was cemented to the plate. The driver detector was driven at various frequencies for the earth plant; then the plate was suspended in air at the laboratory and the driver was again driven at the various frequencies. Results from these tests indicated that insufficient drive power was available to result in a meaningful plant characteristic curve.

Present plans include use of separate ceramic transducers cemented to the steel plate and used to pulse the plate at the discrete frequency of the transducer. A power supply capable of a variable positive voltage from 0 to 16,000 volts will be readied to furnish the high voltage pulse required by the ceramic transducers.

11/14/63

Discussion of Petty Co. Proposal

With Art Hasbrook by telephone:

Andy Bergquist has experimented with large plates, resonant at 600 cps, but even with multiple ceramic crystals & high power source (15kv), one way signal was transmitted only 7 - 8 ft. {There is hope, though, that these plates attached to the Boomer, which is much more powerful, will enable 600 cycle component of the Boomer to be transmitted more efficiently.

Large audio speaker which we sent to Petty Co. has not yet been tried in field, but is expected to put forth much more acoustic power than the original Petty speaker.

Explosive Sources -

Will not put in frequency even as low as 300 cycles unless tuned. Normal components are 30-50 cps.

New Amplifiers -

Much sharper tuning than present amplifier - therefore, will help in eliminating low frequency components which mask the 600 one sought.

(over)

Magnetic Recorder - is expected to enhance returned signal 100 times. This, therefore, will be a great help in detecting ~~a~~ 300 to 600 components if they can be put in ground.

Petty Co. feels that more will be learned by testing over ~~re~~ real archaeological targets than by continued tests over "artificial" concrete blocks in Texas.

Over any target, the critical thing is the velocity contrast between buried feature & surrounding earth.

Plain of Sybaris -

From Linnington's data, velocity of topsoil ~ 1090 ft/sec, with change at 6 ft. deep (water table?) to 7250 ft/sec. in wet clay. In other words, the wet clay may not be very different from the buried walls of rock.

E K Ralph

Jules Rud Coll., Mexico

		B.P. 5568	B.C. 5730
I-3842	Ceramic #1 C = 0.3% 300 grams prior no C Slabs of wall ornaments - back cut off distinct sharp carving	3590 ±100	1750
I-4015	Ceramic #2 C = 0.09% 400 gms - no C	6480 ±100	4725
I-4031	Ceramic #3 C = 0.1%	3060 ± 120	1200

Taylor & Burger Amer. Ant.
v. 33, no. 1968

TL 2750 ± 300 B.C.

Purchased from widow in Mexico

Havegood - New Hampshire

Ralph
ASCA

Petty Laboratories, Inc.
San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Summary of Activities

September 1963

Investigation is continuing in a search for, or development of, a high power sonic source of discrete 600 cps frequency for use as a transducer in the project. Further tests using ceramic transducers to pulse thirty inch diameter plates are planned and equipment is being readied for this purpose.

Eight ceramic transducers have been received and have been polarized at the laboratory. These are to be stacked between an aluminum and steel plate and compression loaded. This arrangement will be surface planted at the test site in brown sandy-clay soil along with acceleration type detectors planted at two and seven foot intervals directly below the plate for signal and frequency comparison with the previously reported ball drop tests on the steel plate.

A laboratory high voltage power supply is available for use to pulse the ceramic transducers for these experiments. Also, a thirty thousand volt pulse power supply has been furnished by The University Museum to the project for these tests.

Another activity during the month was the preparation and mailing of Interim Technical Report No. 2. This report covered the experiments and the results obtained with the Edgerton, Germeshausen and Grier, Inc. "Boomer System". Copies of this report were sent to Dr. Edgerton and the usual addressees.

TR-11 Transducer (High Power Low Frequency Transmitter)

This is a high power transducer approximating an 11" cube and capable of generating 1 kw of underwater acoustic power in the 400 cycle region when arranged in an array such that rho-c loading is achieved. The transducer is an extremely rugged electromagnetic unit which weighs 150 lbs. and will withstand submerged depths up to 3000 ft. DC polarization is required for operating the unit. The impedance of the transducer under normal operating conditions is approximately 100 ohms. This transducer is usable in many types of arrays and baffle systems where extreme high power is desired for low frequency operation such as in long range ocean survelillance.

[Oct. 3, 1961]

Technology

PETTY LABORATORIES, INC.

San Antonio, Texas

RESEARCH AND DEVELOPMENT PROGRAM

FOR

SONIC ARCHAEOLOGICAL PROBE

PETTY LABORATORIES, INC., a Texas corporation, with its office and principal place of business in San Antonio, Texas, herein styled "PETTY", is willing to undertake research and development in the field of sonic and seismic measurements in the earth in an effort to develop a suitable method, instrumentation and interpretational techniques for locating buried archaeological ruins and artifacts, and THE UNIVERSITY MUSEUM, UNIVERSITY OF PENNSYLVANIA, located at Philadelphia, Pennsylvania, herein styled THE UNIVERSITY MUSEUM, wishes to support such research and development, and to that end PETTY and THE UNIVERSITY MUSEUM make and enter into this agreement as follows:

I.

PETTY agrees to conduct research and development work, in its laboratory and at selected field sites, leading to suitable methods and design and construction of instrumentation for use of sonic or seismic measurements in locating buried archaeological ruins, and will carry on such work in an economical and prudent manner consistent with its other normal business activities during the remainder of the present year 1961 and as much of the year 1962 as is required. For the purposes of the present work, the archaeological ruins are defined as buried masonry walls and floors from a few feet to tens of feet in extent and buried under 10 to 30 feet of alluvium. The research and development work contemplated hereunder will be conducted in a logical sequence of phases including a preliminary study to determine the most suitable method of sonic or seismic probing, field experiments for evaluation of that method as to practicability, development and construction of an experimental model of instrumentation required for utilization of that most suitable method, and tests and evaluation of the experimental model at suitable archaeological sites.

THE UNIVERSITY MUSEUM agrees to support that research and development program up to an overall financial limit not to exceed THIRTY TWO THOUSAND TWO HUNDRED DOLLARS ($32,200.00), payable by it on monthly billings from PETTY. Subject to such changes and modifications as may be advisedly determined jointly by PETTY and THE UNIVERSITY MUSEUM, the research and development work as provided for and contemplated hereunder is and shall be under the control, direction and management of PETTY, who specifically undertakes and agrees to conduct and carry on the same in a good faith effort to develop a workable method of sonic or seismic archaeological exploration and to design and construct suitable and usable instrumentation for implementing that method.

II.

In return for support of the research and development program provided hereunder, THE UNIVERSITY MUSEUM shall be entitled to have and receive the following:

(1) A monthly written summary from PETTY showing the general nature of research and development work being conducted and progress made during the preceding month, together with billing for services actually performed during the month in accordance with rates specified in schedule "A" attached.

(2) A written technical report from PETTY following completion of each major phase of the program and describing in detail the research and development activities and results achieved during that phase.

(3) A final report upon completion of the overall program including full details on all research and development work, design and construction of instrumentation and field tests conducted in evaluation of the method and instrumentation.

(4) The final experimental model of the instrumentation as developed and constructed under this program and as utilized in field tests, including complete instructional information as to functioning, operating and interpretational procedures.

(5) Unlimited licenses for its own use under any and all patents applied for hereunder and the right to use, for itself, without charge, any method, process or system originating out of the research and development program conducted hereunder, without otherwise restricting PETTY'S ownership of all such patents, methods, processes or systems, and their enjoyment, use and exploitation thereof.

(6) The right to consider and evaluate jointly with PETTY, at the conclusion of each phase of the program, the results and findings of that phase and to plan and determine jointly with PETTY any changes or modifications to be made in the following phase or phases.

(7) The right to designate suitable archaeological sites, in the southwestern or western part of the United States, at which field tests of the experimental model of the sonic probe will

be conducted, and to participate in such field tests.

(8) The right and privilege to participate in any continuation, extension or succession of this program as may be carried on by PETTY. In the event a continuation, extension or succession of the research and development program inaugurated hereunder be determined upon and should THE UNIVERSITY MUSEUM not wish to participate therein and fail or refuse to do so, the same may be carried on without participation by THE UNIVERSITY MUSEUM and in such event THE UNIVERSITY MUSEUM shall have no right or interest therein nor in any results achieved therefrom, which limitation shall not restrict rights and interest of THE UNIVERSITY MUSEUM hereunder as are expressly provided above.

EXECUTED this the 3rd day of October 1961

PETTY LABORATORIES, INC.

By W. Harry Mayne
PETTY

ATTEST:

M W Fritz
Secretary

THE UNIVERSITY MUSEUM, UNIVERSITY OF PENNSYLVANIA

By________________________
THE UNIVERSITY MUSEUM

ATTEST:

____
Secretary

Sci Techniques

PETTY LABORATORIES, INC.

San Antonio, Texas

PROPOSED

DEVELOPMENT PROGRAM

SONIC ARCHAEOLOGICAL PROBE

FOR

The University Museum

University of Pennsylvania

PETTY LABORATORIES, INC.

San Antonio, Texas

PROPOSED

DEVELOPMENT PROGRAM

SONIC ARCHAEOLOGICAL PROBE

Summary:

The object of this development program is to provide a sonic probing system suitable for use in exploring and outlining, from the surface of the earth, archaeological ruins and artifacts buried under shallow alluvium. It is understood that such ruins usually are characterized by masonry walls and floors, perhaps some tens or more feet in extent, covered by as much as twenty or thirty feet of deposited material; also, that various artifacts of considerably smaller dimensions are frequently associated with the ruins.

Initially a preliminary study will be made to determine the required characteristics of the system and the most suitable techniques and arrangement of sonic equipment which might provide the desired indications, particularly with respect to depth of penetration and resolution. Next, local field experiments will be undertaken, with available laboratory equipment for the most part, to determine feasibility of the selected arrangement as well as to indicate any special instrumental or operational problems. On the basis of the above work an experimental model of the proposed equipment will be developed and constructed. Field tests will be made on this model to determine actual performance in locating and outlining buried ruins and objects under various sub-

surface conditions. As a result of these tests and evaluation, recommendations will be made as to any necessary modifications or changes in design required in construction of a prototype suitable for production.

Phase I - Preliminary Study

Feasibility of the proposed sonic method appears to depend largely on the amount of penetration and resolution which can be achieved with equipment of size, weight and complexity suited to mobile or portable operations. Therefore this initial phase will be devoted largely to a search and study relating to the system characteristics required to supply the desired indications under typical subsurface conditions, as well as the instrumental and operating limitations. For example, such factors as optimum frequency range, necessary energy levels, propagation problems, coupling means etc. will be covered. In addition to general arrangement of the required instrumentation will be determined.

As a result of this study conclusions will be reached as to the feasibility of the general method and recommendations will be made concerning local field experiments to be carried out in the following phase.

Phase II - Field Experiments

Field experiments will be conducted, in the vicinity of San Antonio, to determine practicability of the proposed method and arrangements. Measurements will be made of the propagation characteristics of a typical subsurface and the effects of buried obstacles will be studied. Various methods of coupling the probe to the earth will be investigated. In this work presently available laboratory equipment will be used insofar as practical; some special components, such as power transducers, may be required.

As a result of this experimental evaluation of the basic system, it will be possible to specify the optimum operating parameters and necessary features for the first model of the equipment.

Phase III - Development and Construction of Experimental Model

Based on the preceding study and field experiments, an experimental model of the equipment, suitable for field tests, will be developed and constructed. Emphasis will be placed primarily on satisfying the basic principles of operation. In brief, the object will be to produce a reliable developmental model which will be satisfactory for extensive field tests of the method.

Considerable development of circuitry and special components will be required, in addition to the design of the overall instrumentation. Certainly the sonic power source or transducer will require special attention. In this model no undue efforts will be made, however, toward features such as extreme miniaturization, very low power requirements and the like.

Phase IV - Field Tests and Evaluation of Experimental Model

Field tests of the experimental model will be conducted at selected sites in the southwestern part of the United States. For these tests the equipment will be installed temporarily in a suitable vehicle with necessary test equipment and accessories for operation in relatively remote areas. In addition to indicating the general performance of the equipment under field conditions, these tests will provide information on special operational and instrumental problems.

At the conclusion of the field tests a comprehensive report will be prepared, including recommendations as to modifications and redesign required for a prototype model of the equipment.

Phase V - Modification and Resdesign for Prototype

In this phase any necessary modifications and redesign will be made in the experimental model so as to result in a prototype suitable for production.

Estimated Time and Cost Schedule

for

DEVELOPMENT PROGRAM

SONIC ARCHAEOLOGICAL PROBE

Phase I - Preliminary Study
Duration: $1\frac{1}{2}$ months @ $1500/month
Estimated Fee $2,250

Phase II - Field Experiments
Duration: 3 months @ $2100/month
Special Equipment: $1000
Estimated Fee $7,300

Phase III - Development and Construction of Experimental Model
Duration: $3\frac{1}{2}$ months @ $2100/month
Equipment and Components: $8000
Estimated Fee $15,350

Phase IV - Field Tests and Evaluation of Experimental Model
Duration: $2\frac{1}{2}$ months @ $2600/month
Vehicle Installation and Mileage: $800
Estimated Fee $7,300

32,200

Phase V - Modification and Redesign for Prototype Model
Duration:) As required in contract
Cost:) extension or continuation.

PETTY LABORATORIES, INC.

San Antonio, Texas

Development of
SONIC ARCHAEOLOGICAL PROBE

Summary of Activities
May-June 1962

Development activities during the past two months have been concentrated primarily on : (1) efforts to provide efficient coupling between the transducer source and the earth; (2) propagation measurements over a wide frequency range and; (3) design and construction of suitable detector-preamplifier assemblies for use in more extensive measurements.

1. Transducer Coupling to Earth

Efficient coupling of the transducer source to the earth has proven to be a considerable problem, as expected, requiring extensive experimental tests. For the initial measurements the transducer has been installed in a hole, about one foot deep, which is lined with a thin plastic material to prevent loss of the coupling fluid and subsequent variations in the coupling conditions.

After some preliminary measurements utilizing water as the medium, it was decided to try other fluids of higher viscosity. A starch mixture, in which the viscosity could be changed over rather wide limits, improved the measured signal from the source by three to five times, depending on the viscosity, frequency and other factors. Due to some lack of control with the starch (which tends to thicken as the water evaporates), the medium recently has been changed to SAE 140 lubricating oil which has a high viscosity, is quite stable and apparently very suitable for the purpose.

On an absolute basis, of course, the coupling efficiency is relatively low due to the limited dimensions of the source and the characteristics of the soil. Since maximum coupling efficiency is a vital factor in providing a useful system with relatively low power, attempts will be made to improve the coupling as the measurements progress.

2. Propagation Measurements

A series of initial measurements was made at the laboratory site where the immediate subsurface is fill consisting of clay mixed with gravel and boulders. As indicated by a relatively few measurements over distance of several feet, the total signal decay (including attenuation and geometrical spreading) averages about 10 db per foot at 500 cps. While these tests were limited to relatively short distances and made under quite high noise levels, information was gained as to the overall instrumental requirements.

Upon completion of the initial tests, work was transferred to a rural site about 18 miles south of San Antonio. The subsurface consists of a very dry sandy clay soil followed by sandy clay and soft clay down to the maximum depth of interest. Sonic velocity to about 30 feet has been determined by previous measurements, in the vicinity, to be about 1900 feet per second.

Measurements have been made thus far in drill holes from the surface down to about nine feet. Using a transducer arrangement with high viscosity fluid in a hole about eighteen inches deep and a continuous-wave input of 30 watts maximum, good signal transmission has been achieved over distances up to about 8 feet. It has been found necessary to use quite narrow bandpass filters to achieve acceptable signal-to-noise ratios. From tests to date, it appears that the same arrangement will provide useful signals down to 10 or 12 feet.

Although the measurements are still in progress, the indicated total signal decay is about 10 db per foot in the foot in the frequency range 500 to 600 cps, for the near-surface materials. As the depth increases it is to be expected that the signal losses will become somewhat less.

Further significant improvements in overall performance could result from use of various signal enchancement techniques in the detection arrangement. In summation, it is probable that all possible approaches must be utilized to provide adequate signal under the power limitations necessitated by portability and economic considerations.

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November 9, 1963

BID PROPOSAL

DEVELOPMENT OF SONIC ARCHAEOLOGICAL PROBE

Experiments to date have yielded information as to the instrumentation necessary for an initial field instrument design for the location of relatively large objects buried at depths to 30 feet. This equipment will also include sufficient frequency selectivity to insure its usefulness as a tool in the location of small objects. Additional experimentation is needed to obtain positive small object resolution but this instrumentation coupled with a suitable transducer or energy source may achieve desired resolution. Experiments at the site using the 200 cycles per second to 1000 cycles per second selective band width filters of the amplifiers will be needed to check this resolution capability.

The Edgerton, Germeshausen and Grier, Inc. 1000 watt-second "Boomer" system and the electric blasting cap are the best energy sources tried but both have a preponderance of low frequency energy. The amplifiers will have filters designed to minimize the masking of high frequency sonic signals by the low frequencies generated by the transducer. The magnetic tape recording equipment is designed to further enhance the reflected sonic signal from buried objects by adding repetitive signals to reinforce the small reflected energy in order to make these reflections recognizable in the random background noise and source hash.

The power supply and equipment used with the "Boomer" is quite large and relatively heavy so an extra vehicle would be needed as a transport if it is used. Light trucks for this use may be leased for $175 per month less gas and oil. The "Boomer" has many disadvantages and would be rather difficult to use in the field but is included in this bid because it is one of the more successful sonic energy sources of the many tested. It is hoped that with these funds a still more successful source, better designed for field use, will be developed. The blasting cap has obvious disadvantages but is a good energy source easy to transport.

The drill proposed is a simple auger type powered by a power takeoff from the vehicle motor. No mechanical pull down features are included in this bid but a design to allow at least 10 foot hole depth is included.

ELECTRONICS DIVISION

Petty Laboratories, Inc.
San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE DEVELOPMENT

Report of Activities

October-November 1962

1. Deeper Detector Spread

A group of four deep detector holes has been drilled around a central driver hole at the test site. These holes, with depths of 16, 21, 26 and 31 feet, will provide for measurements to maximum depths required in the present program. Acceleration detector-preamplifier units have been planted in all of the holes for use in attenuation measurements. Recordings have been made of received signals at all detectors, using continuous-wave output from the driver.

2. Simulated Buried Targets

Three simulated archaeological targets have been constructed at effective depths of 7, 11.5 and 24.3 ft. Holes three feet in diameter were drilled, with a foundation drill, to depths approximately three feet deeper than the desired final depths. Concrete was then poured into the holes to form targets 3 ft. in diameter by 3 ft. thick. After the concrete had hardened, the hole was filled with the excavated material. These prepared targets will be used in reflection tests utilizing primarily pulse transmissions.

3. Tests with Explosive Sources

Brief tests have been made with dynamite caps as sources and a detector planted over the targets to receive possible reflected energy. The resulting recordings are inconclusive due to the poor signal-to-noise ratios.

4. Equipment Preparation

Development work is in progress on a synchronized pulsing arrangement for use with the driver and display oscilloscope. The fundamental frequency will be 640 cycles per second and the pulse duration and repition rate will be adjustable, so as to provide for optimum coverage of different depth intervals and different sonic velocities in the earth.

5. Visit by University Museum Director

During the visit by Dr. Rainey, on November 31, an inspection trip was made to the test site south of San Antonio. Work in progress was discussed and it was agreed that the tests utilizing sonic impulses should proceed in an attempt to detect reflected energy from objects at shallow depths.

ASCA

Petty Laboratories, Inc.

San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Report of Activities

December 1962

Activities during the month have been restricted largely to design and preparation of the equipment for pulse measurements and tests.

A pulsing unit is being designed and built for use with either the MacLaughlin unit or a conventional oscilloscope. Provision is being made for a repetition rate of either 5, 10 or 20 pulses per second. A pulse duration control is provided for selection of from $\frac{1}{2}$ to 2 cycles of 640 cps waveform for excitation of the transducer; additional pulse length can be provided readily if desirable. The basic 640 cycle signal may be obtained either from an internal oscillator or from an external signal generator.

Inquiries have been made to a number of manufacturers of sonic transducers for information on higher power units suitable for use in this frequency range. It is hoped to locate a unit capable of supplying sonic pulses, into fluid, of hundreds of watts of peak power at 640 cycles and with suitable transient response.

ASCA
Lab.

Petty Laboratories, Inc.

San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Report of Activities

January 1963

A sonic probe pulse unit was completed and tested. Results of use of pulsed power to driver, or underwater speaker, indicate that maximum power is considerably reduced from steady state, or continous wave operation. Horizontally spaced detectors and driver of one foot depth from surface were used in field testing. Information from recordings of the detected signal indicate a resonant frequency of 125 cps with a small 640 cps pulse component for the underwater speaker diaphragm. This speaker resonance was not apparent from previous continuous wave operation.

During the latter period of January, Miss Elizabeth K. Ralph brought the MacLaughlin oscilloscope and detector to San Antonio for testing and application to the field experiments.

In testing the MacLaughlin equipment it was found that the device was evidently not functioning properly. As covered in Miss Ralph's report of work, the MacLaughlin oscilloscope required an excessively large minimum detected pulse of 30 volts. Further test were then conducted using a Hewlitt-Packard 130B oscilloscope and Petty detection equipment. As mentioned previously a large part of the energy detected from the driver was at a frequency of 125 cps.

A discussion of future plans included the use of a "Boomer, developed by Dr. Edgerton of M.I.T., for use as a driver capable of 1000 watts of power with resonance about 600 cps.

Miss Ralph contacted Dr. Edgerton before leaving and he had no "Boomer" available, but was forwarding a "Pinger" resonant at 9000 cps for evaluation in a week or two.

Immediate plans are for work on filtering of detection equipment and altering resonant frequency of driver, pending arrival of "Pinger" from Dr. Edgerton.

Petty Laboratories, Inc.
San Antonio, Texas

ASCA

SONIC ARCHAEOLOGICAL PROBE

Summary of Activities

February 1963

Several methods for altering resonant 125 cps of frequency of driver, or underwater speaker, diaphragm were tried. The most successful was the application of a reversable cement to the outer edge of the diaphragm to "stiffen" it. Resonant frequency could be altered to 600 cps and higher without power deterioration.

Inquiries were sent to various sources for information concerning higher power drivers resonant around 600 cps. The replies were as follows: negative from General Instrument Corp (Harris); Massa-Cohu has a TR-11 transducer capable of 100 watts of acoustic power; and University Loudspeakers, Inc. had no higher power units available, but would be happy to engage their Laboratory in this work.

The Edgerton "Ping" transducer and power supply, resonant at 9 kcs, was received on the 18 of February. The "Pinger" required a 200 volt positive pulse trigger so additional circuitry was added to the Sonic Probe Pulse Unit to furnish this output. Attenuation measurements with the "Pinger" indicated severe signal decay at 9 kcs through a typical earth medium. Maximum detectable energy was 3 feet with the "Pinger" coupled to earth with SAE 250 weight oil. Coupling of energy from "Pinger" to earth with water and oil tried, with the latter proving the superior coupling medium. Tests with the repaired MacLaughlin oscilloscope and detector indicated comparable results as presented above.

Dr. Rainey and Miss Ralph visited the laboratory on the 25th of February and discussed present status of project and possible use of equipment in Italy this coming season. Various exploration plans were discussed and driver-detector spread arrangement was proposed based upon satisfactory preformance of the Edgerton "Boomer" as a sonic power source. Also discussed, was the possible use of magnetic recording equipment for signal enchancement as a future requirement for detection, if "Boomer" power source is not adequate.

Miss Ralph called Dr. Edgerton and explained the results of testing the "Pinger", she also sent a written report of this work along with a copy of the Petty report titled "Propagation Measurements In Typical Earth" to him. Dr. Edgerton promised to send a "Boomer" sonic device to San Antonio on or about the 4th of March.

Petty Laboratories, Inc.

San Antonio, Texas

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SONIC ARCHAEOLOGICAL PROBE

Report of Activities

March 1963

A control unit was constructed with provision for 12 detectors with separate batteries. The truck wiring was modified for multiple spread detector arrangement.

On the 11th of March, the "Boomer" power supplies and transducers arrived, furnished thru the courtesy of Dr. H.E. Edgerton of Edgerton, Germeshausen and Grier, Inc. Included were two 500 watt experimental and one 1000 watt transducers.

Holes were dug as near as practical to the shallow and deep vertical detector arrays for the 1000 watt transducer. Previous driver holes in centers of the detector arrays were used for the smaller 500 watt transducers. Driver holes were lined with thin plastic material to prevent loss of coupling fluid.

Transducers were tried with both shallow and deep vertical detector arrays and the seismic energy recorded. The records indicate lower frequencies than 600 cps are produced.

Dynamite caps were also fired in water filled center driver hole with the detector array. Recordings of the seismic energy were very similar to those produced by the "Boomer" transducers.

The "Boomer" system is an excellent source of high power acoustic energy, but the results so far indicate seismic signals of much lower frequencies than 600 cps. Apparently the initial pulse of the "Boomer" transducer in water is either altered or suffers high frequency attenuation in the earth medium. Previous results of impulsed continous wave seismic recording indicates a gradual build-up of 600 cps energy thru about 3 or 4 cycles. A pulse of discrete frequency is desirable in the region of 600 cycles.

Further work is in progress using horizontal spreads of detectors spaced along the optimum angle with the "Boomer" transducer to attempt to obtain reflections from a concrete target 3 feet in diameter and 25 feet deep. Detectors and transducer moving along an axis over the target will be tried.

ASCA

Petty Laboratories, Inc.

San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Report of Activities

April 1963

The months acitivies concerned experiments with the Edgerton, Germeshausen and Grier, "1000 WS Boomer System."

In one Method, horizontal detector arrays were spaced at intervals across a 3 foot diameter concrete target 24 feet deep. The 1000 Watt Second "Boomer" transducer was moved from one hole to another with these holes spaced 5 feet apart across the target. Recordings were made using detectors planted 2 feet deep on either side of the transducer location.

In another experiment, the 1000 Watt Second transducer was spaced along a line at 5, 10 and 15 feet intervals from a point directly above the 24 feet deep target. Detectors were then spaced along this line, across the optimum distance for reflection, at one and two foot intervals.

No definite reflections were obtained from the target with either method. The loss of higher frequencies thru either attenuation, alteration, or both by the earth medium probably results in no measurable reflection with a target of fractional wave length.

In order to determine the feasibility of recording reflections from larger buried objects, a test site was chosen approximately 10 miles northwest of San Antonio. This site has Austin chalk mixed with surface soil thru several feet of the surface. Limestone beds are at depths from 20 to 48 feet deep with the remainder of brown clay. The Austin chalk is a good high frequency medium as compared to the sandy clay of the test site south of San Antonio.

Four transducer holes were dug 6 feet apart along a horizontal line with 2 foot deep detector holes on either side of each transducer hole.

Recordings were taken at each transducer position with filter settings of high-pass 400 cps, high-pass 200 cps and broad-band amplifiers. Records indicate possible reflections from the 24 foot and deeper limestone beds.

According to information received from Italy, the largest buried objects have been walls about one meter across with no pavement in association. Therefore orders of higher resolution for detection of the buried objects are necessary for the sonic archaeological probe. Further work will continue based on using another type of transducer.

Petty Laboratories, Inc.

San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Report of Activities

May 1963

Additional tests with the Edgerton, Germeshausen and Grier, "1000 WS Boomer System" were conducted at the test site south of San Antonio.

The 1000 watt second transducer was placed in a one foot deep plastic lined hole with a thin mud mixture. This was an attempt to improve the coupling to the earth medium. Also the plastic liner was removed from the transducer hole and then the hole was filled and kept full of water while the transducer was in operation. Neither experiment resulted in any appreciable improvement in results as compared to those previously taken.

Recordings were made with a continuously tuned filtered amplifier and these records indicated the preponderance of energy was at 350 cps and lower frequencies.

Dynamite caps were substituted for the transducer in the water filled hole with a cap suspended at the approximate location at the transducer plate. Recordings were made at filter settings of high-pass 400 cps, high-pass 200 cps and broad-band amplifier. Results indicated an increase in acoustic energy produced, but of frequencies very similar to that produced by the "Boomer" system.

Dr. Edgerton's "1000 WS Boomer System" was returned to him on 23 May 1963, as he requested, with appreciative thanks for the loan of his equipment.

A Barium Titanate type transducer is now available for evaluation and a suitable power supply is being developed for this unit.

Petty Laboratories, Inc.
San Antonio, Texas

SONIC ARCHAEOLOGICAL PROBE

Summary of Activities

June-July 1963

Tests were conducted with a ceramic transducer, using a previously tested underwater speaker as a reference for comparison. A 2000 volt rms power source of 600 cps discrete frequency was constructed to drive the transducer which had a resonant frequency of 6000 cps.

The transducer was tested with a vertical spread of detectors planted at depths of 3, 5 and 7 feet. Detector holes were drilled on an 18 inch radius around the transducer hole of 1 foot depth. The transducer was pulsed with 2 to 4 cycles of a cycle per second waveform.

In the first test the ceramic transducer was cemented to the bottom of the hole with thick mud. Records of the signal output of the transducer were taken with the detectors at distances of 2.5, 4.3 and 6 feet. The maximum distance for useful signal amplitude was 4.3 feet.

In the second test the ceramic transducer was suspended at different levels in an oil-filled hole. A maximum signal through the earth was recorded when the transducer was against the bottom of the hole. The maximum distance for useful signal amplitude was 4.3 feet, with approximately 3 db signal increase in comparison with the tests using mud coupling. Next the underwater speaker was placed on the bottom of the oil-filled driver hole and a signal to a distance of 6 feet was recorded. The gain in signal output, using the speaker versus the ceramic transducer, was approximately 20 db at a distance of 4.3 feet.

The sonic signal amplitude of the speaker was encouraging; therefore, a hole was dug directly above the 7 foot concrete target, with a detector planted directly on top of the target and other detectors planted on an 18 inch radius around the drive hole. Backfill material in the hole above the target is unconsolidated, as velocity measurements for the signal at 7 feet were less than the normal velocity of this soil. Possibility of reflections exists on the records, but reflection quality must be improved for definite identification of buried objects.

Three detectors were planted around the 7 foot deep target and detectors connected in parallel in an attempt to phase out noise or unwanted signals. No improvement of reflected signal was indicated.

On 9 July 1963, a meeting was held in San Antonio with Mr. F.L. Johnson of Sun Oil Company to discuss the present status and future progress of the sonic probe program. It was decided that a transducer of considerably higher power of discrete frequency is necessary for any future tests.

Mr. Paul Klipsch has been engaged as a consultant to the program to suggest methods of producing high sonic powers. Also, inquiries are being made of various sources to determine the possibility of high power drivers adaptable to piston operation in a fluid coupling medium.

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Summary of Activities

Transducer for the Archaeological Probe

July 1963

I. Object

The object of this development program is to provide a sonic probing or exploration system capable of locating, from the surface of the earth, archaeological ruins and objects buried under shallow (up to thirty feet) alluvium. Location of stone and masonry artifacts having a minimum dimension of three feet, as well as larger ruins of considerable horizontal extent, is desired.

II. Initial Attenuation Tests

a. Detectors

Detectors used are of the acceleration type using a barium titanate ceramic crystals with a counterweight and an emitter-follower preamplifier integrated in a single case and powered from a surface battery.

b. Transducer to Earth Coupling Investigations

Efficient coupling of the transducer to the earth has proven to be and is a considerable problem

Transducer holes have been dug to a depth of one foot to reduce surface soil losses and to diameter to fit the transducer. The holes have been lined with a thin plastic to prevent the loss of the coupling fluid. Initially water was used as a medium, then fluids of higher viscosity to increase the coupling efficiency. A water-starch mixture, with which the viscosity could be changed over wide limits, improved the measured signal from the transducer source by three to five times. Because of lack of control over aging of the starch mixture, the coupling medium was changed to SAE 140 wt. oil and then to SAE 250 wt. oil. The SAE 250 wt. oil was the heaviest obtainable locally, and is quite stable. This oil provided a repeatable coupling medium for transducer tests.

Coupling efficiency is relatively low due to the limited dimensions of the transducer diaphragm and characteristics of the soil impedance versus coupling fluid and transducer.

c. Driver Units Tested

1. University PAHF Model 100 watt (30 watts applied) driver unit had too small a diaphragm and required an air column between fluid and diaphragm. This greatly increased the impedance mismatch to fluid.

2. Under Water Speaker

University underwater speaker MM2FUW of 25 watts power was chosen because of a larger diaphragm. This speaker has a hemispherical plastic piston about 2½ inches in diameter and the piston is driven directly by the voice coil which is cemented in place. This speaker worked relatively satisfactorily and provided minimum detectable signal to 30 feet, one way travel, using a sharp filtered amplifier to improve the signal to noise ratio, and a pulsed continuous wave of 600 cps.

3. Pulse Tests of Transducer Sources

Since ultimate use of a pulse reflection arrangement was intended, circuitry was devised for pulsing the MM2FUW underwater speaker. Initial tests indicated major resonance at 125 cps in the fluid media. Modifications were made (by stiffening the diaphragm surround) so as to raise the resonant frequency to 600 cps; however, these changes resulted in considerable loss of maximum permissable power.

Limited attempts were then made to obtain reflected signals from shallow concrete targets, but no recognizable return signals were noted and the tests were not carried to a definite conclusion.

Arrangements were made next, through the University Museum, for a loan from Dr. Harold Edgerton of a 9 kc magnetostrictive sonar "pinger" transducer and a 1000 watt-second sonar "boomer" transducer which operates on the principle of electromagnetic repulsion.

Tests made with the "pinger" in the usual oil coupling medium to earth resulted in a two-way detectable signal only to a depth of about 3 feet. Evidently the earth attenuation at 9 kc is excessive.

Tests next were made using the 1000 watt-second "boomer" in a water-filled hole. The rated impulse of the transducer in water is 3 or 4 cycles of 4 kc frequency; however, the recorded wave when coupled through earth shows energy predominantly below 350 cps. This wave form of less than 350 cps was readily detected to a depth of 30 feet, with a very good signal to noise ratio (about ± 10 db).

In reflection tests utilizing the "boomer" over a concrete target 3 feet in diameter and 24 feet deep, in a sandy clay subsurface, indications of reflected energy were indefinite. There were, however, some indications of return signals (in the form of phase changes etc.) at about the proper elapsed travel times.

Additional tests were made with the "boomer" in a chalk subsurface underlain by limestone beds 23 to 50 feet deep. The predominant recorded frequencies again were below 350 cps, but there were rather definite indications of shallow reflections.

It is concluded that the "boomer" is an excellent source of high power acoustic energy, but the resulting seismic frequencies are much lower than the desired 600 cps. If the "boomer" could be redesigned to furnish 3 or 4 cycles of discrete 600 cps energy, it would appear to have excellent possibilities as a high power controllable source.

Tests presently are being conducted on a ceramic transducer (barium titanate?), about 5-½" diameter by ½" thick, with a loaded resonance of 6 kc. The unit is being driven by a pulse of variable duration and 600 cps basic frequency. Results thus far indicate measureable one-way signals to a depth of five feet when the transducer is coupled to earth through a stiff mud medium. An amplifier with a sharply tuned 600 cps filter was used in the detection arrangement.

4. Other Suggested Transducers

Various types of mechanically driven sources have been considered, with the primary objectives of producing quite large amounts of acoustic power with relatively simple equipment. These include arrangements as:

(1) a steel drum head in which the head is struck mechanically and the resulting vibrations coupled to the earth through a fluid medium;

(2) a resonant pipe or rod which is struck mechanically so as to produce large amplitude vibrations in a fluid-filled hole;

(3) various eccentric flywheel types of vibrators using synchronous motors to obtain the basic frequency and clutching to furnish an impulse of chosen duration; and

(4) a spring-mounted 600 cps mechanically resonant plate system which is struck with a hammer to produce large amplitude vibrations which are coupled to the earth (F.L. Johnson). It should be noted that all of these mechanical systems are relatively uncontrollable as to pulse length etc.; thus they are suitable only for rough determinations of possible energy transmission at 600 cps.

Other suggested sonic power sources have included special electromagnetic moving coil arrangements to drive a solid metal piston which in turn drives the fluid medium. Various other types well-known in the literature have been considered also; for example, the 2 kw Fessenden oscillator much used by Evison in his earth investigations (Proc. Physical Soc. vol. 64, Part A, #376 B; also, New Zealand Journal of Science and Tech.

vol. 35, Sect. B, July 1953; Geophysics V. XXI, p. 939-959; Geophy. Prospect v. 5, no. 4, p. 381-392). The high power generator devised by St. Clair, for use at 10 kc., also offers possibilities (Review Scient. Instruments, May 1941).

5. Conclusions

Measurements to date indicate that a higher power source of discrete frequency (600 cps) acoustic energy will be needed to definitely determine the possibility of obtaining pulse reflections from small objects at the 30 foot depth. Possibilities of conserving the radiated energy by beaming should be investigated. Possible improvements in the transducer-earth coupling arrangement should be investigated carefully.

Use of a signal enhancement technique such as magnetic recording may be required in the measurements work.

COMMON REFLECTION POINT HORIZONTAL DATA STACKING TECHNIQUES

W. HARRY MAYNE

ABSTRACT

Techniques are described whereby multiple coverage of the subsurface is recorded. Detector spreads and shotpoints are arranged so that the channels representing common depth points are recorded with appreciably different horizontal distances between the shotpoints and detector stations. The channels which have a common reflection point are combined, or stacked, after appropriate corrections for angularity, and travel time to datum have been applied.

Reflections which follow the assumed travel paths are greatly enhanced, and other events are reduced.

Methods for attenuating multiple reflections with respect to primaries are discussed in considerable detail.

Typical field comparisons between conventional and stacked traverses are shown to illustrate the degree of improvement which can be obtained in the signal to noise ratio.

General considerations applicable to field usage, and the geographic range of field experience are summarized.

COMMON REFLECTION POINT HORIZONTAL DATA STACKING TECHNIQUES *

W. HARRY MAYNE

INTRODUCTION

Improvements in the signal to noise ratio of seismic signals has been a continuing project with geophysicists for many years. As certain problems have yielded to solution, new ones have been encountered. From Klipsch (1936), Rieber (1936), Poulter (1950), Woods (1953). Reynolds (1954), Parr (1955) to Graebner (1960), various techniques have been described to utilize the noise attenuation properties of multi-element arrays.

Applications of these and related techniques, either singly, or in combination, have produced solutions to many difficult problems. As the multiplicity is increased to cope with still more difficult situations, however, we are eventually confronted with an inherent limitation. As the arrays become larger and larger, the subsurface area which is averaged increases correspondingly. In practice the summation or integration of reflection arrivals from a subsurface area theoretically as great as ten acres may result from pattern dimensions of less than 700

* Presented at the 31st Annual SEG Meeting, Denver, November 8, 1961.

ft. This, of course, tends to obscure the very detail which is being sought. The multiple-coverage, common-reflection point technique was devised to provide a practical means of increasing multiplicity without this limitation.

DESCRIPTION OF THE METHOD

Multiple coverage of the same subsurface with different shot and detector positions has been suggested for several purposes. Green (1938) advocated multiple paths centered about a common depth point to eliminate the effect of dip on velocity determinations.

This writer (1956) proposed that the information associated with a given reflection point, but recorded with a multiplicity of shotpoint and geophone locations, be combined algebraically after applying appropriate time corrections. Thus, if the reflected signals received along the several paths are adjusted for coincidence, their resultant sum will be proportional to the number of signals. Perturbations following other than the postulated ray paths will not be coincident, and hence will be degraded relative to the reflections. For random incidence the average theoretical enhancement will be proportional to the square root of the number of signals. This is analogous to pattern performance. Since, however, the source and receiving points have been selected so that the reflection point is common to all paths, the limitations of conventional pattern techniques no longer apply. The horizontal spacing between source and receiver is restricted only by the following considerations.

1. The greatest distance which will permit coincidence adjustments of the requisite accuracy. The probable error in the postulated stepout increases with distance and must be kept small with respect to the reflection period.

2. The greatest distance over which the reflected signals persist with adequate similarity.

Magnetic tape recording equipment, Loper and Pittman (1954), has become readily available, and has made the necessary summation processes convenient and economical.

FIGURE 1 illustrates one simple field procedure for obtaining multiple coverage of the subsurface. This 24 detector station arrangement has the unique property of recording data from a specific reflection point on the same channel throughout a sequence of 12 shots. The multiplicity, i. e. the number of available paths which have a common reflection point, is 12 or one-half the number of stations in the spread. Note that the progressive variation in horizontal distance between the shotpoint and detector for the end stations is 22 intervals. Thus summation of the number one channels of the 12 shots is equivalent to a 12 element array with a total length of more than one-half mile if typical station intervals are used. This is, of course, many times longer than would be permissible with conventional techniques, and thus provides effective attenuation of events with extremely great apparent wave lengths. Each of the shots recorded in this manner will require a different moveout correction program, but summation can be made without channel transposition.

ALTERNATE ARRANGEMENTS

It is possible to develop the desired multiple coverage in a variety of ways. In the following examples, 24 detector station spreads will be used. If a standard split spread configuration is preferred, the arrangement of FIGURE 2 can be used. In this example both the spread and shotpoint are advanced two intervals so that a symmetrical setup is maintained. The depth points corresponding to each shot have been indicated by the dots underneath the setup. It is seen that channels from a total of 12 shotpoints must be used to obtain the full multiplicity of six.

The table of FIGURE 3 shows the channels recorded from each shotpoint which are used to compose the 24 depth points under Shotpoint 7.

In each of the previous examples only one shot is made into each instrument spread. FIGURE 4 illustrates a sequence which also yields six fold multiplicity using three shots per spread, but allows the spread to be moved six stations ahead each time. FIGURE 5 shows the corresponding channel composition schedule.

The preceding examples point the way to the general expression for the multiplicity of any particular progression. Thus if:

M = path multiplicity (as previously defined)

N = number of detector stations in the spread

n = number of stations by which the spread is advanced

S = number of shot positions for each spread

the following expression will define the multiplicity for any sequence.

$$M = NS/2n$$

FIGURE 6 illustrates a third arrangement which develops six fold multiplicity. This is similar to the sequence of FIGURE 2 since the shot location and spread are both advanced two stations, and only a single shot per spread is taken. The shot is located at the end of the spread thus changing the geometry of the common reflection point paths. FIGURE 7 shows the channel composition schedule. This type of arrangement is particularly efficient in attenuating multiple reflections.

MULTIPLE REFLECTIONS

Powerful evidence confirming the existence of multiple reflections was presented by Ellsworth, Sloat et al (1948). Later experience has indicated that occurrence of this insidious form of "noise" is dangerously common.

The common-reflection point technique can be an excellent tool in reducing multiple reflections even though they defy exact analysis. FIGURE 8 illustrates a rather typical example. A hypothetical velocity function of 6000 + .2Z has been assumed. An objective of major interest is postulated at a depth of 8,960 ft and vertical two way time of 2.300 sec. The second order reflection (simple multiple) from a shallow reflector at 3,710 ft would also have a total travel time of about 2.300 sec. The relative strength of the two reflections will, of course, depend on the respective reflective indices, and the reflective index of the transition boundary where the near surface reflection occurs. Since the travel path of the multiple is confined to a low velocity zone, it will exhibit the stepout shown by the upper curve of FIGURE 8. The deep primary reflection will follow the stepout shown by the middle curve. The lower curve shows the difference in stepout between the two events. Hence if a number of channels with different shotpoint to detector distances are combined so that the primaries are in coincidence, the multiples will be out of phase as indicated by the lower curve. For example, suppose we combine five paths, and the multiple has a period of 0.035 sec. Attenuation behaviour will be the same as a five unit pattern array. Hence we must have a minimum of 0.035/5 or 0.007 sec difference in stepout between the successive paths, or a total of 0.028 sec between the extremes if adequate attenuation is to be obtained. The estimated distances required to establish the necessary differences are indicated in FIGURE 8 by the circled points numbered one through five on the lower curve. Note that the distance to the fifth or fartherest channel in this example is 4,500 ft. Shorter distances will seriously reduce the attenuation and should not be considered. Longer distances will not seriously affect the attenuation, but become increasingly unwieldy. Obviously paths with a common reflection point must be used if excessive subsurface averaging is to be avoided. Of equal importance is the fact that the amount and direction of dip of either reflector is not significant if common-reflection point geometry is applicable.

One problem is apparent from FIGURE 8. Since the differential stepout versus distance curve is not linear, the distances are non-uniform. Suppose that data are to be recorded using the spread arrangement of FIGURE 6. If the required 0.028 sec stepout is developed between a station 1 and a station 21 (FIGURE 7), our station interval should be 4500/21 or approximately 215 ft. FIGURE 9 shows the comparison between the theoretical stepout desired, and the actual values obtained. These approximations yield better than 4.5 to 1 theoretical improvement in the primary to multiple ratio, assuming sinusoidal waves. There is so little stepout difference between the nearest channels (1 thru 4) and their next corresponding common reflection point channels (5 thru 8) that better attenuation is obtained if channels 5 thru 8 are omitted. Use of all six channels reduces the corresponding ratio to 2.5 to 1.

The common reflection point technique is also advantageous when inverted polarity mixing is used to attenuate multiple reflections. This form of skip mixing is effected by first adjusting the multiples to time coincidence. After adjustment the polarity of one channel is reversed, and it is then combined with any normal polarity channel having similar wave form and amplitude.

Attenuation of the multiple reflection will be limited only by the degree of wave form identity between the two signals, and the precision of the phase and amplitude adjustments.

Destructive interference will also attenuate the primary reflections unless they happen to be approximately one-half cycle out of phase on the channels which are combined. This means that the differential stepout between the multiple and the primary reflections must be one-half the period of the primary reflections, and the resultant primary reflection pulse will be broadened by one-half cycle. Thus for a primary reflection period of 0.035 seconds, FIGURE 8 indicates that channels separated by a spread distance of approximately 3,500 feet must be selected to avoid attenuation of the primary reflection. Although fortuitous dip relations might permit combination of channels closer together, this illustrates the order of subsurface averaging which will probably occur.

This excessive subsurface averaging will be avoided if common reflection point channels which possess the proper difference in stepout are used. The multiple reflection will be attenuated as before, but use of the common reflection point technique will eliminate subsurface averaging and also make the process independent of the dips involved.

DATA COMPARISONS

FIGURE 10 illustrates a conventional traverse in the Powder River Basin of Wyoming compared to the same traverse with 12 fold multiplicity. Shot pattern, geophone arrangement and playback settings were identical.

FIGURES 11 and 12 show a similar comparison in Southern Oklahoma.

FIELD EXPERIENCE

Considerable field experience in a wide variety of terrain has been accumulated. While experience has varied somewhat from place to place, certain common considerations have become apparent.

1. Filter: Because of improved attenuation of "ground roll" and other extraneous low frequency noise, wider band filters can generally be used. They are preferable because reflection character and apparent damping are improved, and the required correction precision is somewhat reduced.

2. Spreads should be as long as practicable. Not only are they more efficient from a production standpoint, but data quality is enhanced. Detector stations should be at least 220 ft apart, and 440 ft is desirable if conditions permit. The longer spreads are much less vulnerable to multiple reflections, and complement the multiplicity obtainable with conventional pattern arrays.

3. The most effective shot and detector patterns permitted by economic considerations should be employed. The added multiplicity available with this technique should be used as a supplement to normal good practice and not in substitution therefore.

4. Preliminary traverses in an area should be recorded with

greater multiplicity than may be necessary. Test processing can then be performed to select the most economical arrangement.

5. Corrections for moveout, weathering, and elevation must be accurately determined and precisely applied. Careful editing of corrections, and deletion of obviously poor data can be of great benefit.

6. Approximately the same daily production can be maintained using this method as would be attained with conventional operations.

CONCLUSION

The common reflection-point, horizontal data stacking technique has added a new order of magnitude to the usable dimensions of multi-path pattern array geometry. Signal to noise ratios have been enhanced well beyond the saturation point of conventional pattern methods. Field effectiveness has been demonstrated in Mississippi, South Louisiana, the deep Frio and Wilcox trends of the Texas Gulf Coast, the Delaware and Palo Duro Basins of Texas, the thrust areas of Southern Oklahoma, the Powder River Basin of Wyoming and Montana, and Colombia, South America.

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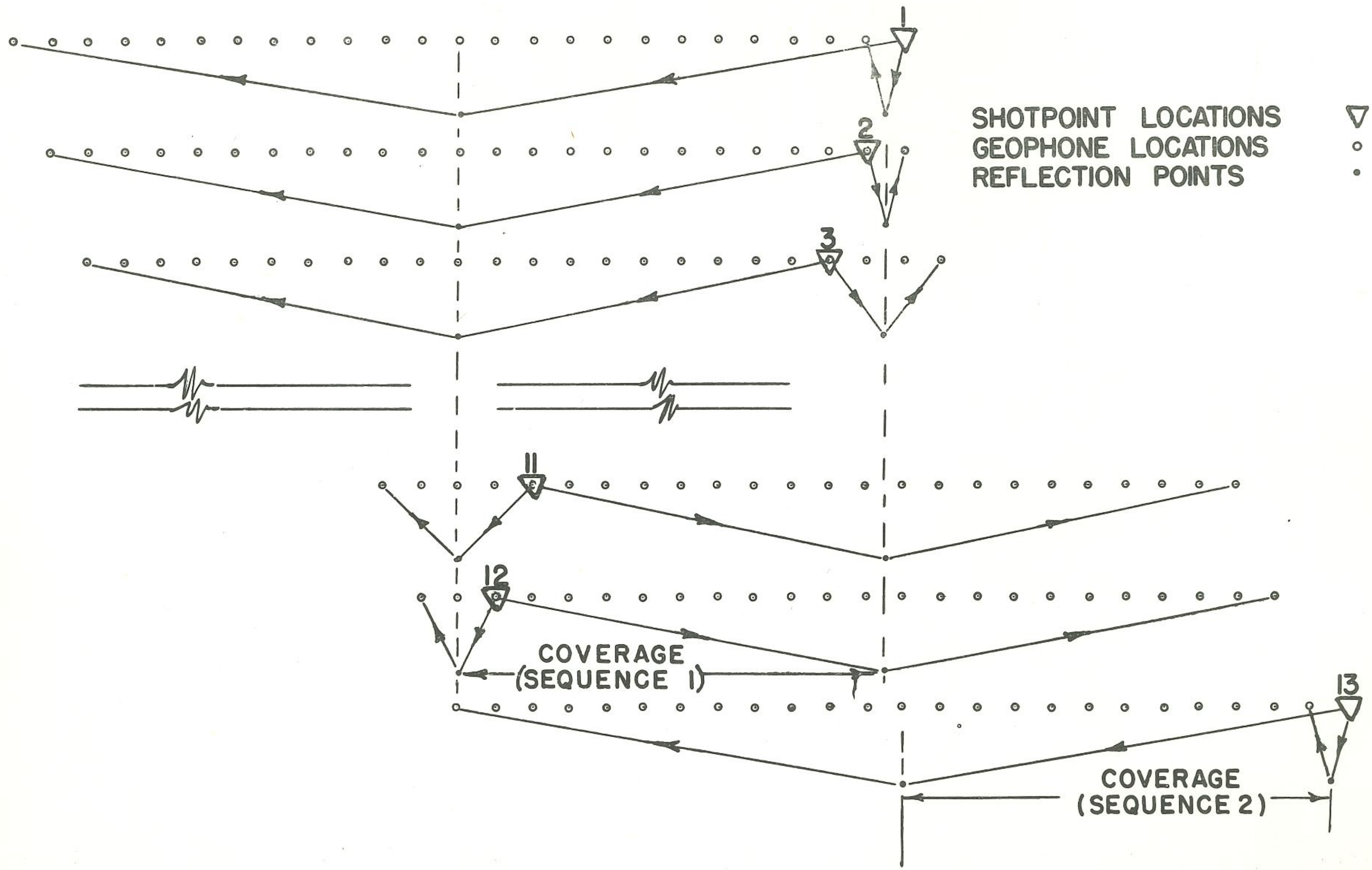

FIG. 1. Common channel spread sequence giving 12 fold multiplicity. Detector spread advances one station, shotpoint backs up one station for a total of 12 recordings. Common depth points are recorded on the same channel throughout each sequence of 12 recordings.

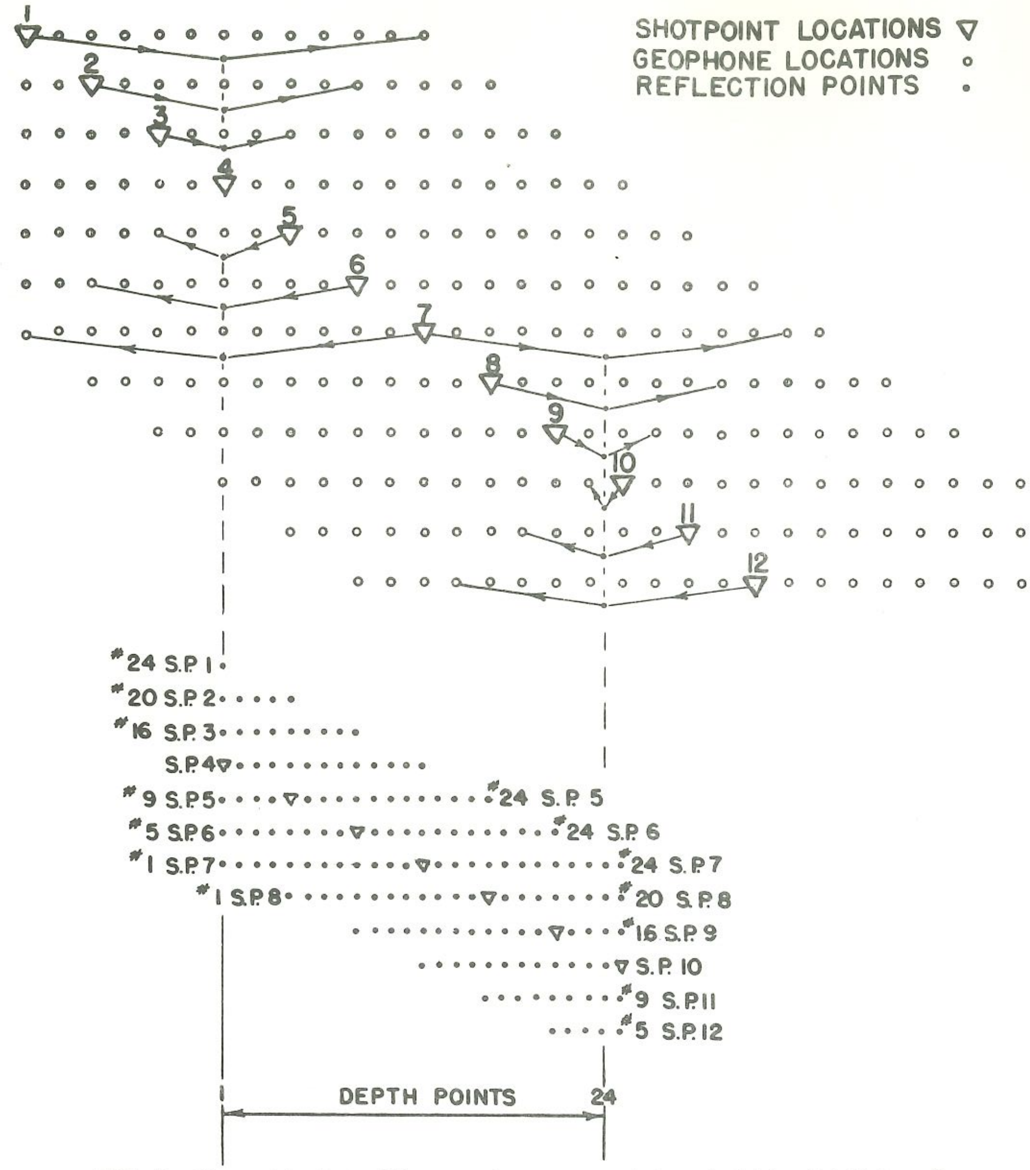

FIG. 2. Symmetrical straddle spread sequence giving six fold multiplicity. Detector spread and shotpoint are advanced together by two stations for successive recordings.

S. P. NO.	DEPTH POINT NO. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	24																							
2	20	21	22	23	24																			
3	16	17	18	19	20	21	22	23	24															
4	-	13	14	15	16	17	18	19	20	21	22	23	24											
5	9	10	11	12	-	13	14	15	16	17	18	19	20	21	22	23	24							
6	5	6	7	8	9	10	11	12	-	13	14	15	16	17	18	19	20	21	22	23	24			
7	1	2	3	4	5	6	7	8	9	10	11	12	-	13	14	15	16	17	18	19	20	21	22	23
8					1	2	3	4	5	6	7	8	9	10	11	12	-	13	14	15	16	17	18	19
9									1	2	3	4	5	6	7	8	9	10	11	12	-	13	14	15
10													1	2	3	4	5	6	7	8	9	10	11	12
11																	1	2	3	4	5	6	7	8
12																					1	2	3	4

FIG. 3. Table illustrating the channel combination schedule for data recorded using the spread sequence of Figure 2. Depth points of the stacked resultant are composed of the channels included in each vertical column, as recorded from the indicated shotpoints. Depth points of the stacked resultant correspond to those recorded on channels one thru 12 of shotpoint 7 respectively. Stacked depth point 13 is under Shotpoint 7, and stacked depth points 14 thru 24 correspond to those recorded on channels 13 thru 23 of Shotpoint 7 respectively.

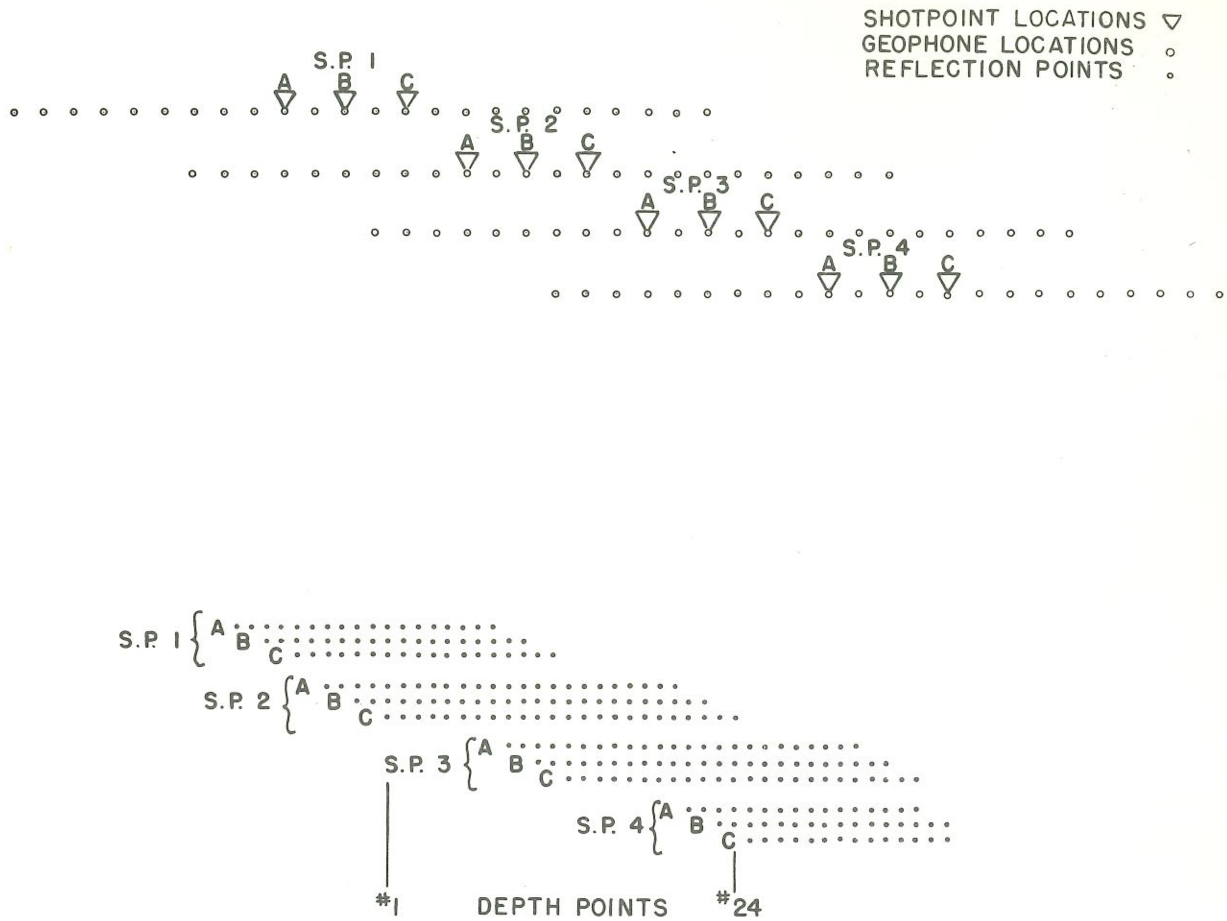

FIG. 4. Non-symmetrical spread sequence which gives six fold multiplicity using three shotpoint locations for each detector spread. The detector spread is advanced six stations forward after each sequence of three recordings Shotpoints spaced two intervals apart.

S. P. NO.		DEPTH POINT NO.																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	A	17	18	19	20	21	22	23	24																
	B	15	16	17	18	19	20	21	22	23	24														
	C	13	14	15	16	17	18	19	20	21	22	23	24												
2	A	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24				
	B	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
	C	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
3	A									1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	B											1	2	3	4	5	6	7	8	9	10	11	12	13	14
	C													1	2	3	4	5	6	7	8	9	10	11	12
4	A																					1	2	3	4
	B																							1	2
	C																								

FIG. 5. Table illustrating the channel combination schedule for data recorded using the spread sequence of Figure 4. Depth points represented by the stacked data are the same as those recorded from Shotpoint 2 C.

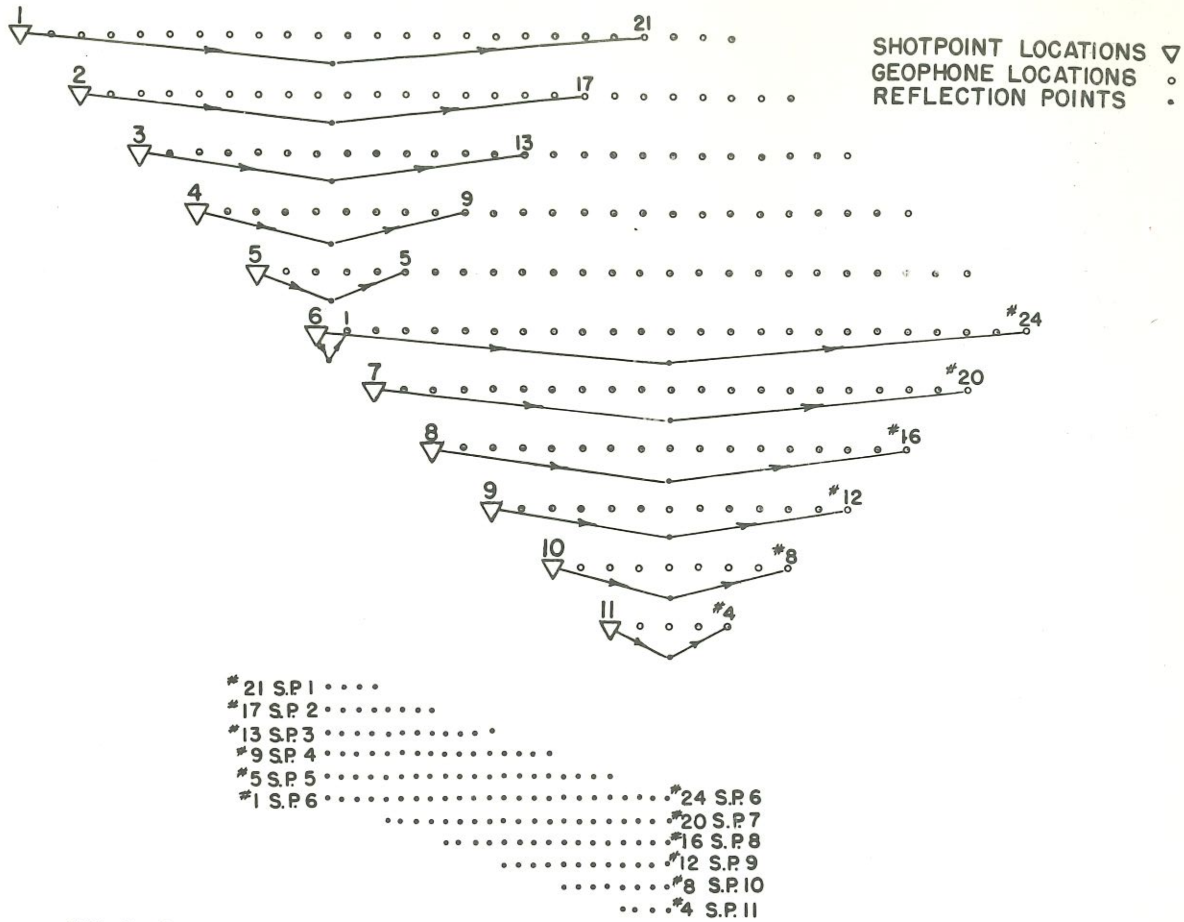

FIG. 6. Single-ended spread sequence giving six fold multiplicity. Shotpoint and spread advanced together by two stations between successive recordings. Similar arrangements with the shotpoint at one end of the spread are preferred for use in attenuating multiple reflections.

S. P.	DEPTH POINT NO.																						
NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	21	22	23	24																				
2	17	18	19	20	21	22	23	24																
3	13	14	15	16	17	18	19	20	21	22	23	24												
4	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24								
5	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20								
6	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
7					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
8									1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
9													1	2	3	4	5	6	7	8	9	10	11	12
10																	1	2	3	4	5	6	7	8
11																					1	2	3	4

FIG. 7. Table illustrating the channel combination schedule for data recorded using the spread sequence of Figure 6. Depth points represented by the stacked data are the same as those recorded from Shotpoint 6.

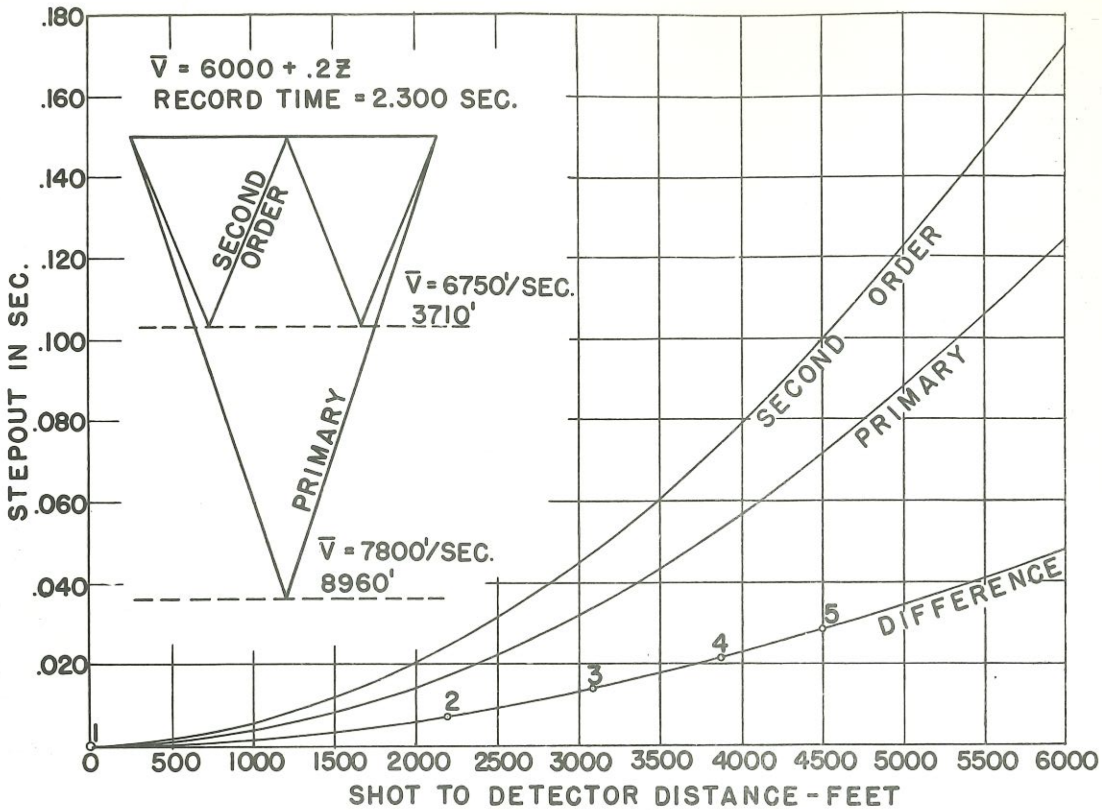

FIG. 8. Stepout as a function of shotpoint to detector distance for a primary reflection and a multiple with the same total travel time. Assumed velocity function is typical of the Gulf Coast of Texas. The lower curve represents the difference in stepout between the multiple and the primary at each distance. The circled points numbered one thru five on the lower curve show the distance at which channels should be recorded to obtain infinite theoretical attenuation of a multiple with a period of 0.035 sec. Corrections for the moveout of the primary would be applied, and the five channels combined to produce a single resultant.

STATION NO.	DISTANCE	ACTUAL STEPOUT	STEPOUT FOR OPTIMUM ATTENUATION
1	215		0
5	1070		
9	1925	.006	.007
13	2785	.011	.014
17	3640	.019	.021
21	4500	.028	.028

ACTUAL ATTENUATION OF 5 CHANNEL SUMMATION > 4.5 TO 1

FIG. 9. Table comparing the actual stepout differences obtained with the desired theoretical optimum values when the spread arrangement of Figure 6 is adapted to the example shown in Figure 8. The detector spacing is chosen to provide the desired overall difference in stepout between the nearest and the fartherest common-reflection point channels recorded. More attenuation can be obtained by using only five channels as shown, since there is so little difference in stepout between channels one and five. Station interval is 215 ft.

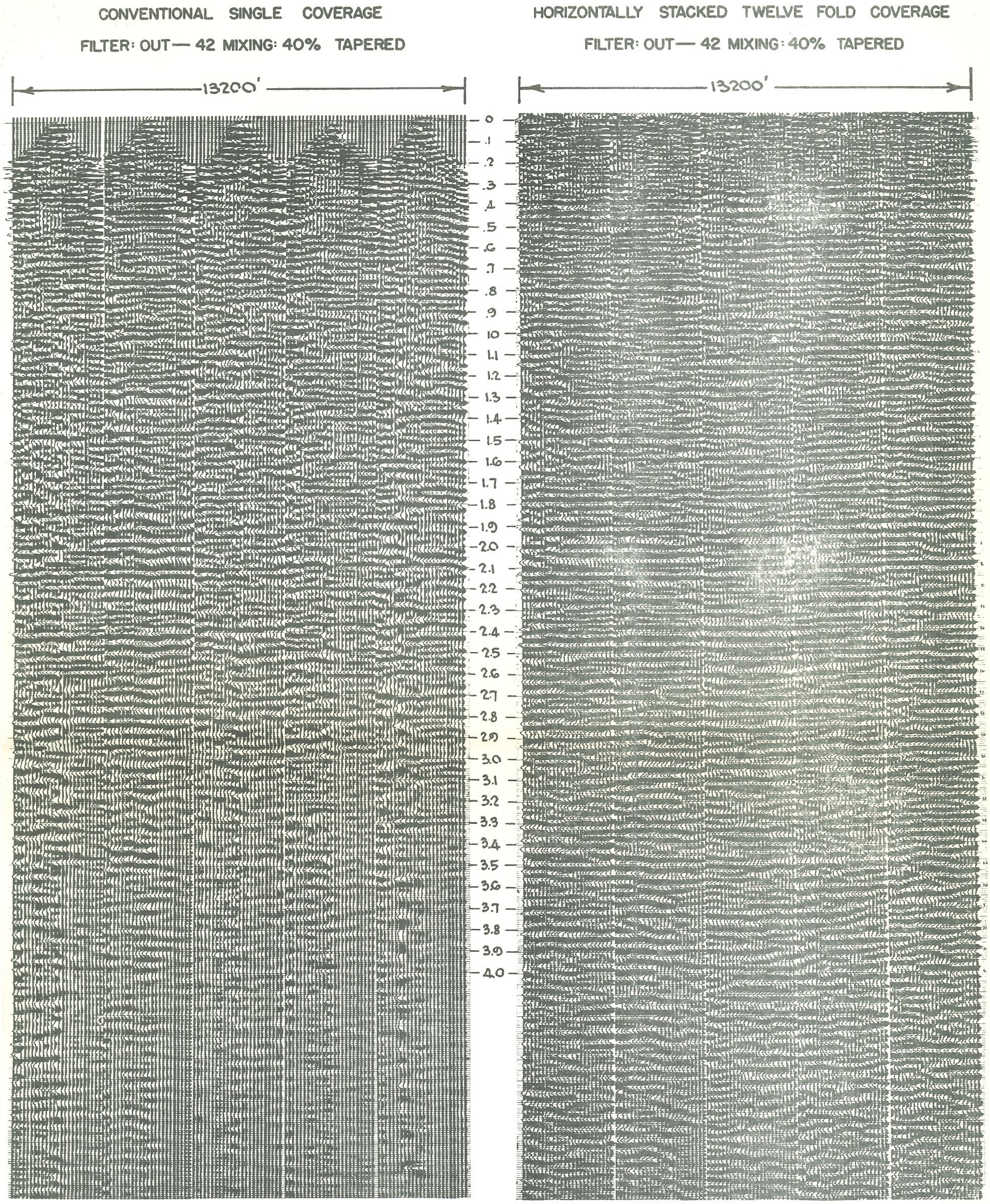

FIG. 10. Comparison of the same traverse recorded with conventional single coverage and stacked 12-fold multiplicity in the Powder River Basin of Wyoming. Shot and detector patterns, and playback settings were identical for both sections.

SOUTHERN OKLAHOMA
CONVENTIONAL COVERAGE

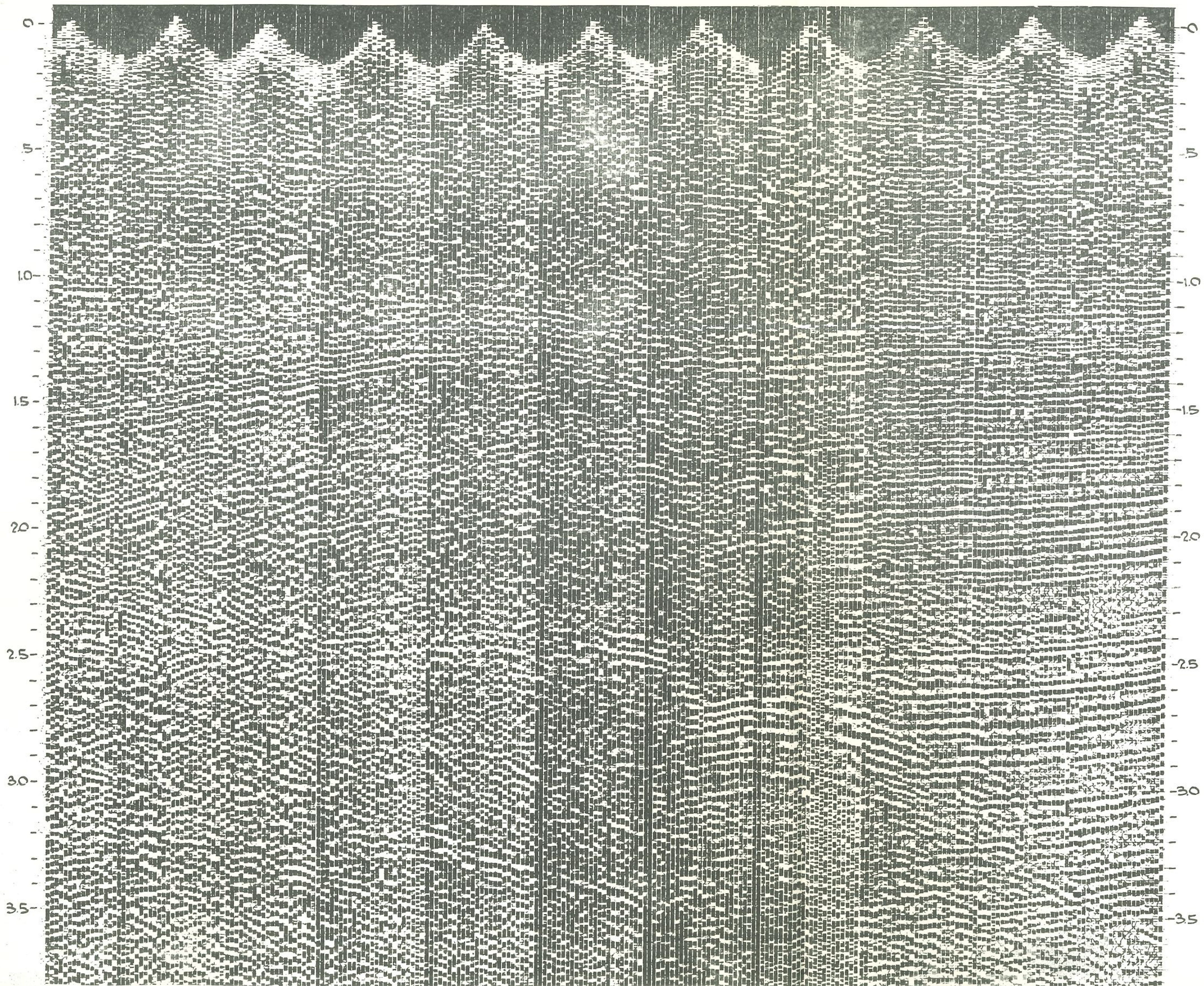

FIG. 11. Conventional single coverage traverse recorded in Southern Oklahoma indicating highly complicated geological conditions. Shot and detector patterns, and playback settings are identical with those used for Figure 12.

SOUTHERN OKLAHOMA
HORIZONTAL 12 FOLD COVERAGE

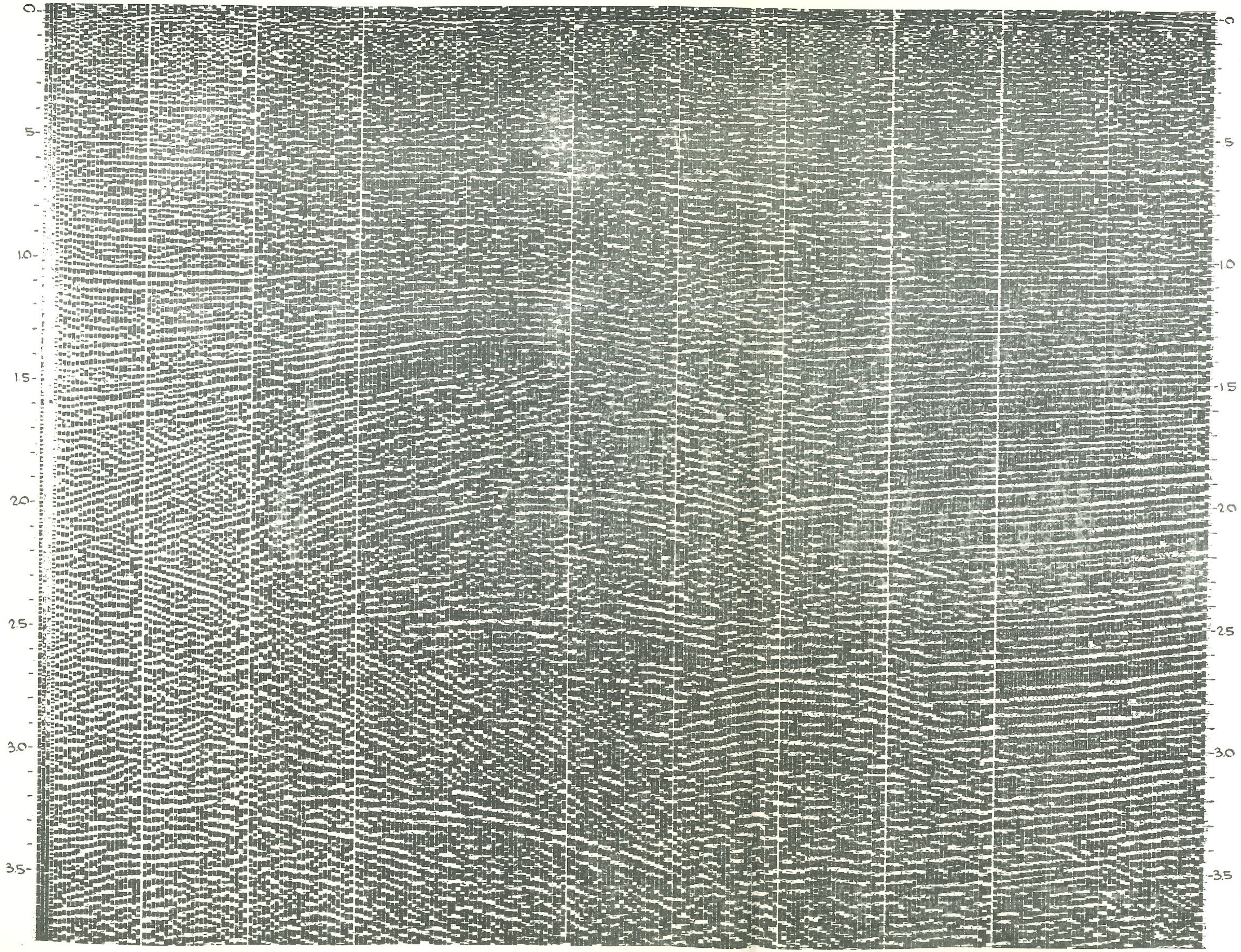

FIG. 12. Same traverse as Figure 11 using stacked 12-fold multiplicity. All field and playback parameters identical with those used in obtaining Figure 11.