UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 17

PRELIMINARY REPORT ON SOME FACTORS AFFECTING SHOTPOINT EFFICIENCY*

by

W. H. Jackson** and J. H. Healy**

DENVER, COLORADO

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UNITED STATES
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Technical Letter
Crustal Studies-17
February 10, 1964

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defense
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

TECHNICAL LETTER NUMBER 17

PRELIMINARY REPORT ON SOME FACTORS

AFFECTING SHOTPOINT EFFICIENCY*

by

W. H. Jackson** and J. H. Healy**

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.

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ABSTRACT

A study of first-arrival amplitudes from 6 water shotpoints and 7 drill-hole shotpoints in parts of central and western United States indicate a variation of over 100 to 1 between the best and poorest shotpoints.

Water shotpoints are, in general, superior to drill-hole shotpoints; however, one drill-hole shotpoint produced higher signal amplitudes than more than half of the water shotpoints. Signal amplitudes from drill-hole shotpoints varied by a factor of over 20. Saturated clay shooting medium appears to be the best shooting medium. Amplitudes from water shotpoints varied by a factor of about 10. Signal amplitude increases, in general, with water depth for bottom shots.

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INTRODUCTION

The amplitude of a seismic signal recorded at a distance from a shotpoint is dependent upon a large number of factors including many in the immediate vicinity of the shotpoint. A few of these factors are: size and distribution of the charge, physical properties of the explosive and of the medium enclosing the charge, and the geologic environment of the shotpoint. The success of a seismic experiment involving the recording at distances of several hundred kilometers is determined to a large extent by the selection of shotpoints having the best possible conditions. When operating in a new area there is always an uncertainty as to the efficiency of the shotpoint. In general, detonations in water can be expected to give greater signal amplitudes than in drill holes, but in many parts of the country, such as in the arid regions of south-western United States, lakes and reservoirs are scarce, and are either too shallow to be of practical use or could require expensive fish restocking programs. For these reasons it has been necessary to increase the use of drill-hole shotpoints in recent seismic programs.

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The uncertainties in the selection of efficient drill-hole shotpoints are enormous. This problem is due partly to the lack of specific geologic information, such as ground-water levels, in areas remote enough to allow the detonation of large charges. The more serious uncertainty is that of the effect of the shooting medium and of other variables in the vicinity of the shotpoint on its efficiency.

Some of the variables of both water and drill-hole shotpoints have been studied, but additional work must be done to obtain more conclusive results.

FIELD MEASUREMENTS

Two types of explosives were in common use during the 1961, 1962, and 1963 field seasons. Commercial nitro-carbo-nitrate explosive in 50-pound metal cartridges was used for most water shotpoints, and DuPont "Super Tovex" gel was used in most drill-hole shotpoints. The military explosive "Composition B," cast in 50-pound cans, was used for some of the water shotpoints. In general, large shots were fired in patterns, the size of the individual charges depending upon shotpoint conditions. The minimum charge size for shallow water shotpoints was 150 pounds, and for the average drill hole, 1000 to 2000 pounds. Charges as large as 20,000 pounds were fired for long-distance observations. Recordings were made using seismometers having a natural frequency of 2 cps and an average output of about 2 volts/in/sec when damped to about 50 per cent of critical by the combined impedances of the seismometer cable and system input. Details have been reported on specifications and operation of the recording equipment and on field procedures (Warrick and others, 1961; Jackson and others, 1963).

SHOTPOINT EVALUATION

Until very recently in North America, explosion seismology on a crustal scale depended upon shotpoints in water bodies, upon quarry blasts, nuclear shots, or upon engineering blasts such as the Ripple Rock explosion. In a sense, the location of the area of study was determined by the shotpoint location. It was recognized that quarry blasts using delayed shooting were inefficient sources of seismic energy (Steinhart and Meyer, 1961, p. 181-184), and that the frequency spectra are controlled to a large extent by the size of the individual charges and the delays between each charge rather than by the total shot (Pollack, 1963). In 1958, Richards and Walker (1959) organized a large-scale experiment in Alberta using drill-hole pattern shots totaling 875 pounds per shot, and in 1960, Cram (1961), using 5-hole pattern shots, fired a maximum charge of 3,300 pounds in a crustal study of the Texas Coastal Plain. In 1961 the U. S. Geological Survey initiated a long-range program of seismic-refraction recording in parts of Western and Central United States as a part of VELA UNIFORM. During this year 10 shotpoints were used, 3 of which used drill holes. A total of 74,000 pounds of explosive, ranging from 500 to 10,000 pounds, was fired in drill holes. During the continuation of the program in 1962, approximately

375,000 pounds of explosives was detonated in 13 drill-hole shotpoints. Only 5 shotpoints during this year were in bodies of water. During the 1963 program, 10 of a total of 16 shotpoints used drill holes in which a total of 140,000 pounds of explosives were detonated. The largest single drill-hole shot was 20,000 pounds. During each of the 3 years of work, shooting was done in bodies of water when possible because of the increased shotpoint efficiency and lower cost. During 1962 and 1963 the objectives of the program were shifted from general reconnaissance investigations to studies of specific areas, greatly limiting possible shotpoint locations and requiring a larger percentage of drill-hole shotpoints.

Numerous papers have been published on phases of water shooting (Raitt, 1952; Weston, 1960; Willis, 1963). Others have been published on phases of small explosions in drill holes (Ricker, 1951; Duval and Atchison, 1957; Adams and Swift, 1961), and many on the study of environment in nuclear explosions, for example, Warner and Violet (1959), Werth and others (1962).

Gamburtsev (1952) describes early work by the Russians using pattern shots consisting of a maximum of about 100 pounds loaded in shallow holes. Charge sizes have been increased over the years (Veytsman, 1962) until charges as large as 10 metric tons have been fired in some regions of Russia.

A common means of expressing phase amplitude versus distance is by the equation:

$$A = A_o r^{-n} e^{-ar} \qquad (1)$$

where A is phase amplitude at distance r;

n represents the rate of geometrical spreading, and

a is the coefficient of absorption.

If the period of A does not vary over the range of study, the equation is applicable for A in units of displacement, velocity, or acceleration. Under these circumstances it is common to omit the term involving the coefficient of absorption, a, and to include both geometrical spreading and absorption losses into a single exponent, n:

$$A = A_o \Delta^{-n} \qquad (2)$$

where Δ is the distance.

Using the above equation, the term A_o could be considered as a figure of merit when comparing shotpoints.

First arrival amplitudes of the P_g phase at various azimuths from 5 shotpoints in western United States (Eureka, Fallon, Mountain City, and Lake Mead, Nevada, and Santa Monica Bay, California) were normalized linearily to 2000-pound shot, plotted (Figure 1), and a least-square fit was established for the data. The least-square slope (n, equation 2) for the group was 1.78. The best fit, using the slope determined for the group, was obtained for amplitude data for each azimuth for the 5 shotpoints, and the A_o intercept was computed (Table 1).

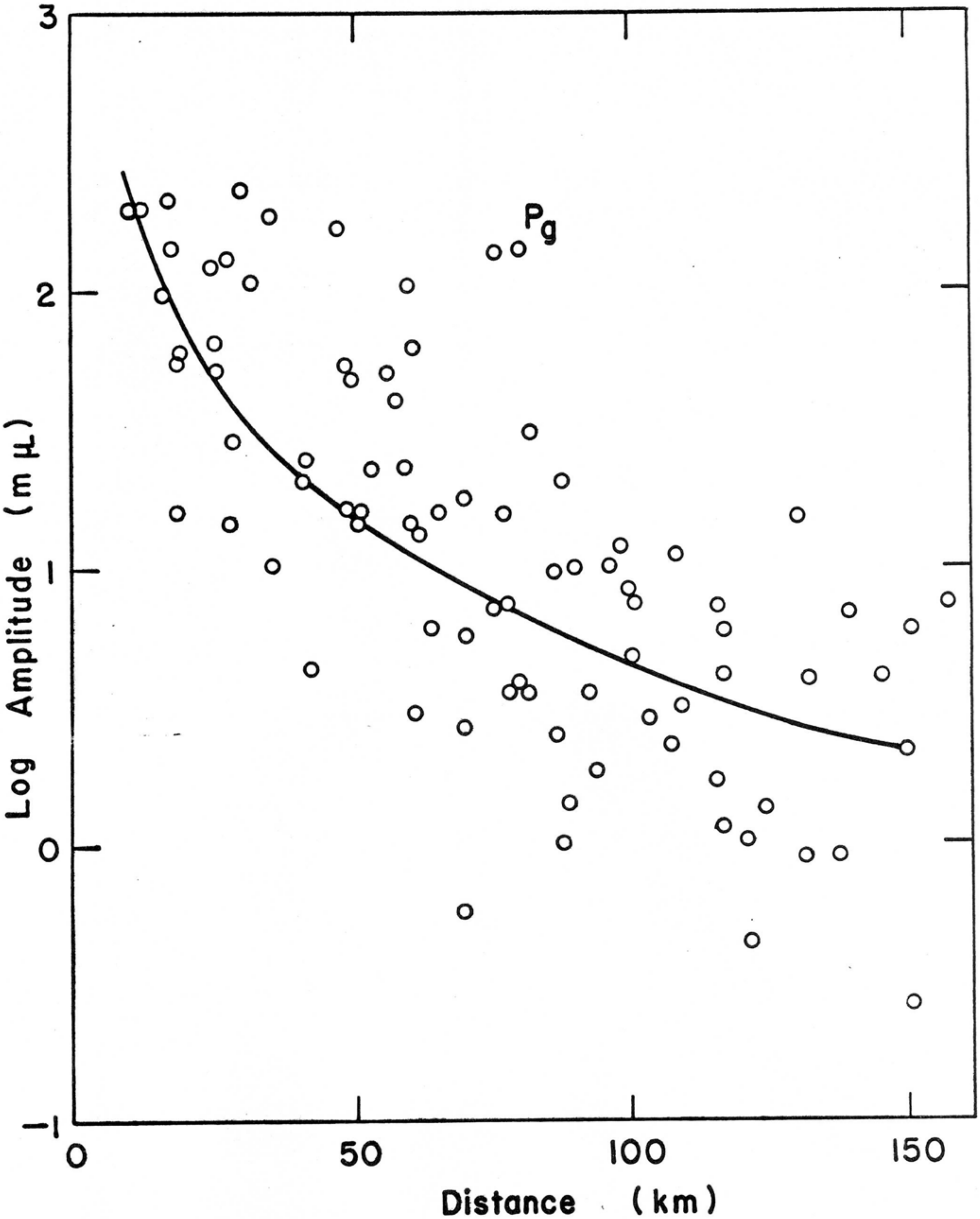

Figure 1.--Amplitude-distance plot of P_g phase for selected shotpoints in western United States, using method of least-squares.

Table 1

Shotpoint	Orientation	A_o Log_{10} intercept	Amp. ratio
Group		4.22	2.8
Eureka, Nev.	toward Fallon	3.77	1
Eureka, Nev.	toward Mt. City	3.85	1.2
Fallon, Nev.	toward Eureka	4.67	8.0
Fallon, Nev.	toward Mono Lake, Calif.	4.76	10.0
Lake Mead, Nev.	toward Mono Lake, Calif.	4.16	2.5
Santa Monica Bay, Calif.	toward Lake Mead, Nev.	4.16	2.5
Mountain City, Nev.	toward Boise, Ida.	4.65	7.6

The units, Log_{10} amplitude in millimicrons, have no physical significance other than it is the extension of the amplitude curve to the 1-kilometer distance. The values do give a parameter for comparing the various amplitudes recorded from each shotpoint of the group. Fallon shotpoint is consistently higher than the average and Eureka is lower. Lake Mead and Santa Monica Bay are about the average. Of interest is the good agreement between A_o intercepts for various azimuths of the same shotpoint.

One disadvantage of the above method is that the attenuation slope of the individual shotpoint may vary considerably from that of the group.

For example, the amplitude-distance curve for the Eureka shotpoint recorded toward Fallon shows a dropoff with distance much greater than the above group average (Figure 2, from Eaton, 1963). Further, this data can not be fitted with single curve describing a simple exponential dropoff. Other inaccuracies may arise when choosing the proper scaling factor for charge size. Over the P_g range from 10 to 160 km the charge size may be increased by a factor of 3 or 4, but, in general, linear scaling of amplitude with charge size has been found to be a reasonable approximation (O'Brien, 1960; Gaskell, 1956).

It is usual field practice, at the conclusion of each day's shooting, for observers to report by radio on the overall quality of his data and to give the peak-to-peak amplitude measured from the first trough to the next peak of the first arrival, in microvolts referred to the output of the seismometer. An amplitude-distance curve, normalized by linear scaling to 2000 pounds, is plotted for the recording line from each shotpoint and is used as a first approximation determination of the relative shotpoint efficiency and, in the case of poor energy output or severe attenuation of amplitude with distance, to make any necessary changes in the recording plan.

Figure 3 is taken from field plots for a number of shotpoints. Data points, which are omitted for the purpose of clarity, show the characteristic scatter. Field plots for 16 drill-hole and water shotpoints in various geologic provinces of Central and Western United States

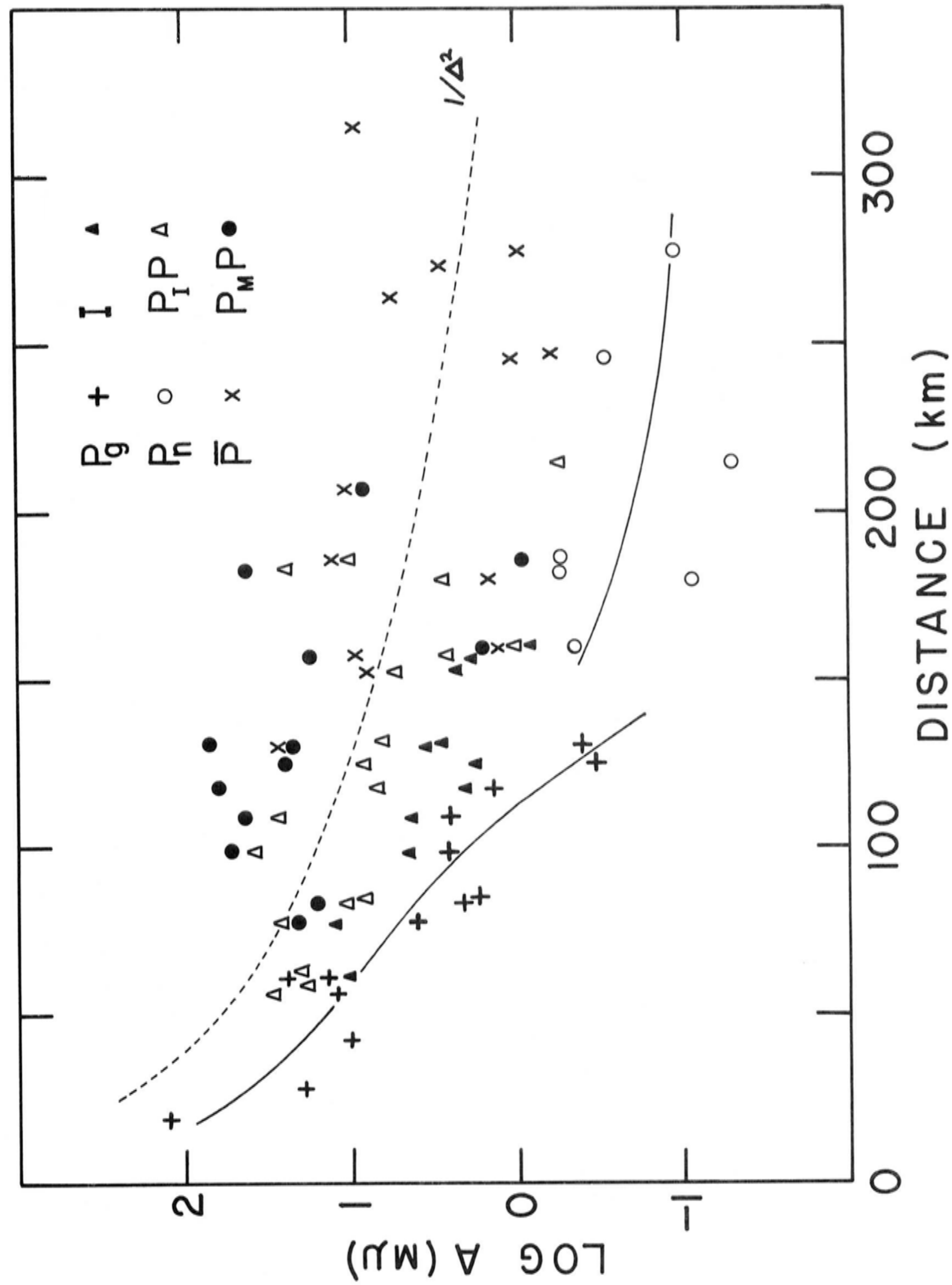

Figure 2.--Amplitude vs distance: Eureka to Fallon. Log A is plotted vs distance (km), where A is the ground displacement (1/2 peak to trough) expressed in millimicrons. The solid curves were drawn by inspection through P_g and P_n. The dashed line is a reference line showing the law $A \propto \frac{1}{\Delta^2}$, where Δ is distance (from Eaton, 1963).

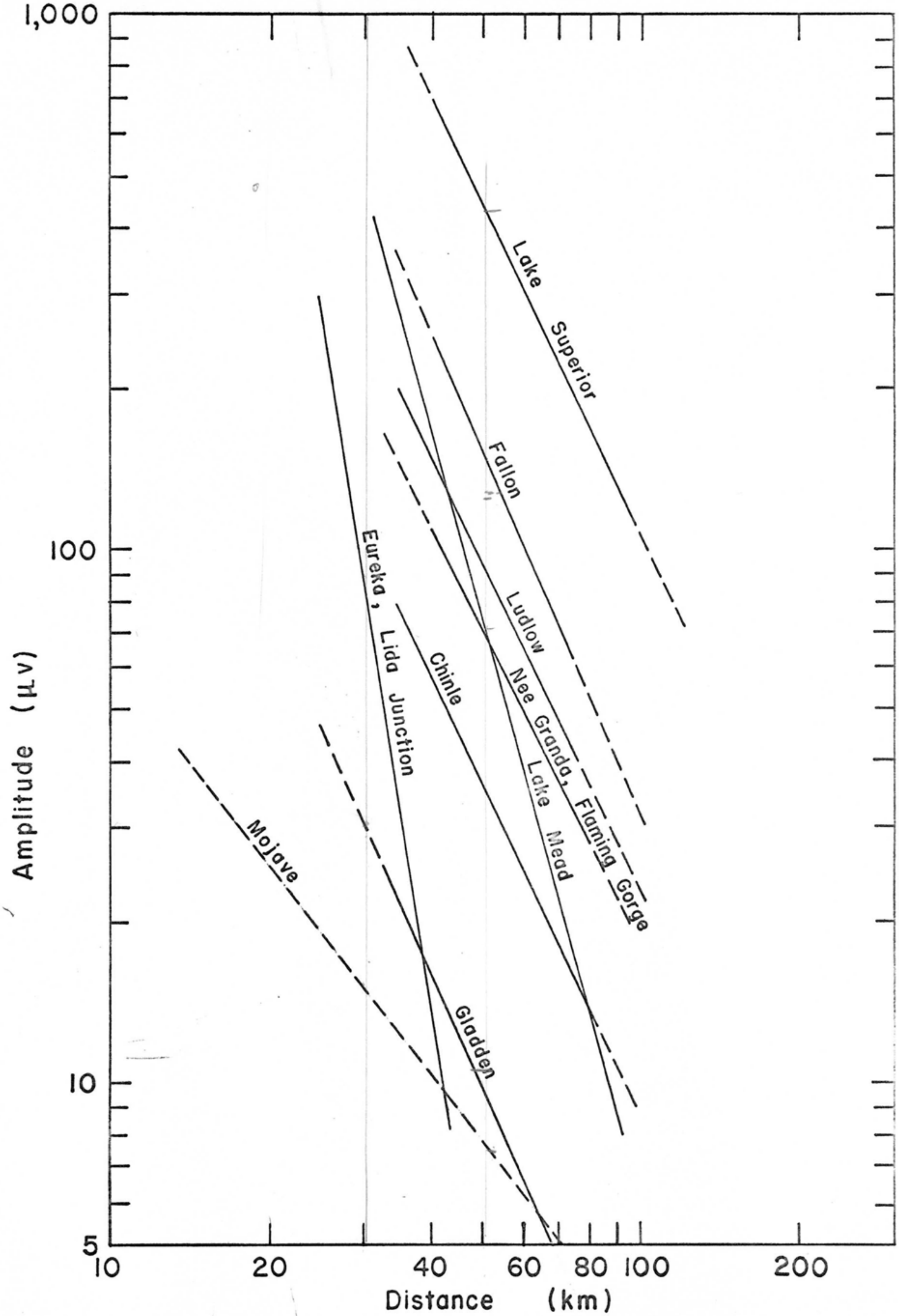

Figure 3--Amplitude-distance curves for selected drill-hole and water shotpoints in central and western United States.

were studied in an effort to obtain a common parameter that could be used in evaluating shotpoint efficiency. In general, first motion could be detected at distances less than 80 km. At distances less than 40 km there were doubts in some cases that the first arrival was P_g. Essentially a great part of the data obtained over the 40 to 80 km range was with 2000-pound shots. Much of the data in the 40 to 80 km range fits an inverse-square dropoff. Exceptions are Lida Junction, Nevada, Eureka, Nevada, Chinle, Arizona, and Lake Mead, Nevada (Figure 3).

Within this range, interval velocities of the refracted arrivals are near 6 km/sec, the velocity associated with P_g. Using the amplitudes measured at the center point of this range (60 km) as a common parameter, Table 2 lists the shotpoints in order of peak-to-peak signal amplitude as measured from the first trough to the next peak. Data that would not fit the inverse-square dropoff were not included in this evaluation.

Table 2 indicates an amplitude ratio of about 100 to 1 between Lake Superior, Wisconsin and Minnesota, which is considered the best of the group, and the Hanksville, Utah, shotpoint, the poorest. In terms of particle velocity, and assuming linear scaling, 100 pounds of explosive was required at Hanksville for each pound at Lake Superior for the same amplitude. Amplitude ratio between the best (Ludlow, Calif.) and the poorest drill hole shotpoint (Hanksville)

Table 2.

Shotpoint	Location	Type	Recording Direction	Amplitude (Microvolts)
Lake Superior	Minn., Wisc.	lake	west	310
Fallon	Nevada	lake	west	110
Ludlow	Calif.	drill hole	west	70
Ste. Genevieve	Mo.	river	north	60
Flaming Gorge	Utah	reservoir	north	50
Nee Granda	Colo.	reservoir	west	50
Mono Lake	Calif.	lake	west	32
Mountain City	Utah	drill hole	north	30
Delta	Utah	drill hole	west	25
Dribble	Miss.	drill hole	north, south	15
Gladden	Mo.	drill hole	east	7
Mojave	Calif.	drill hole	east	6
Hanksville	Utah	drill hole	south	3
Eureka	Nevada	drill hole	west	
Lida Junction	Nevada	drill hole	north	
Chinle	Arizona	drill hole	north	

was over 20, while the water shotpoints range through a factor of about 10. Other observers have reported similar amplitude ratios. Burkhardt (1963), in firing small charges, observed a 20:1 energy ratio for underwater to underground explosions, and Gaskell (1956) reports an improvement of 4 to 1 for water as compared to drill-hole shotpoints.

Water shotpoints

From past experience, water shotpoints have been more efficient than drill-hole shotpoints. The increased efficiency is probably related to the manner of energy transfer in the immediate region of the explosion. Coupling is more uniform in water shooting than in drill holes, and there are fewer complications in determining maximum charge sizes for a given depth for a contained water shot than for a drill hole.

Although there appears, with one exception (Mono Lake, Table 3) to be a direct correlation between water depth and amplitude for the water shotpoints, other complicating factors such as thickness of the sedimentary layer, bottom type, charge size and distribution, etc., may be of importance in determining the efficiency of these shotpoints.

Table 3.--Water Shotpoints

Shotpoint	Amplitude, μV	P_g Intercept, sec	Water Depth, ft	Bottom
Lake Superior	310	0.8	>100	Precambrian rocks
Fallon	110	1.6	80	unconsol. sed.
Ste. Genevieve	60	0.1	27	sed. rocks
Flaming Gorge	50	0.5	23	sed. rocks
Nee Granda	50	0.7	23	unconsol. sed.
Mono Lake	32	1.4	50	unconsol. clastic rocks

Veytsman (1962) observed an improvement of about 4 in the Ukranian crystalline shield area as compared with the Transcarpathian flexure where the sedimentary section is between 7 and 8 km thick. Energy from the Lake Superior shotpoint, in the southern extremity of the Canadian Shield, is about 6 times that received from the Nee Granda Reservoir in the Great Plains, where the sedimentary section is over 2 km thick. However, the sedimentary section in the Fallon area may be comparable in thickness to that of the Mono Lake area, yet the energy from Fallon was over 3 times that recorded from Mono Lake, suggesting that factors other then the thickness of the sedimentary section may have a greater affect on shotpoint efficiency.

The sequence of events taking place during underwater explosions has been established and described in detail by Cole (1948). Following the detonation of the explosive, a shock wave of high amplitude and velocity is radiated into the water. When the shock wave reaches the water surface, it is reflected as a tension wave forming a region of cavitation which may result in a dome of broken water or spray (Figure 4). Simultaneously, the gas bubble is expanding and contracting and migrating upward toward the surface. The most spectacular surface feature is at the moment the gas bubble breaks the surface and forms a plume of water (Figure 5). The oscillations of the gas bubble result in "bubble pulses," a source of compressional energy. Bubble-pulse period depends upon charge size and water depth; but even for small charges on the bottom of shotpoints such as Flaming Gorge, several pulses should have occurred but were too weak to have an appreciable effect on the recorded data.

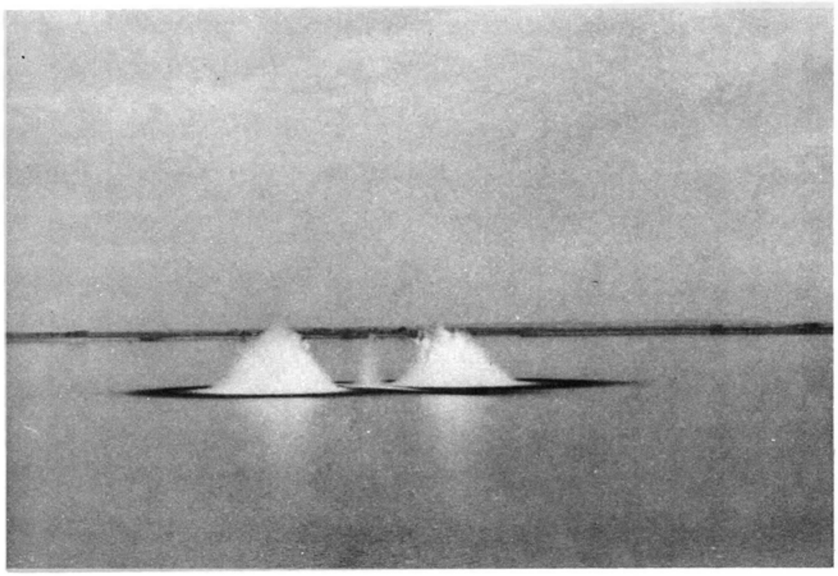

Figure 4.--Spray domes from shot "American Falls No. 1", consisting of two 1,000-pound charges detonated on the floor of the American Falls Reservoir near Pocatello, Idaho. Water depth was 62 feet.

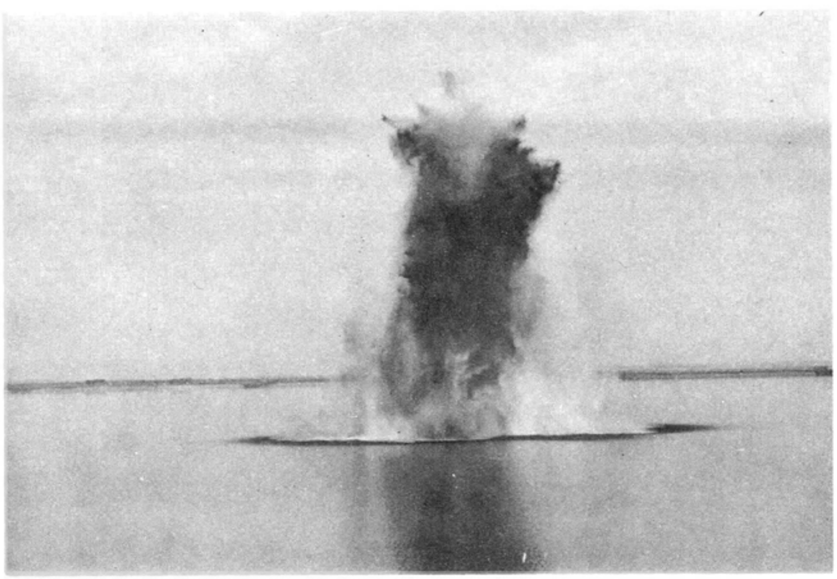

Figure 5.--Water plume from shot "American Falls No. 1".

Pattern shooting was used at the shallow-water shotpoints, and the charge size versus depth relationships were designed to reduce the air blast of the gas bubble when breaking the water surface. Maximum charge size for a given depth was established at Nee Granda Reservoir and extended to greater depths (Figure 6), assuming that maximum charge size may be increased with the cube root of the depth. This assumption was found to be reasonable and the curve was tested to a maximum of 2000 pounds at about 47 feet.

Drill-hole shotpoints

The seven drill-hole shotpoints listed in Table 2 are retabulated according to signal amplitude in Table 4, which includes additional data on these shotpoints. As with water shotpoints, no single factor appears to be outstanding in controlling good or poor shotpoint efficiency.

The shooting medium for three of the best shotpoints, Ludlow, Delta, Utah, and Dribble (Tatum Dome area, near Hattiesburg, Miss.), was saturated clay. The velocity of the clay, as determined by detailed measurements, increased from 1.4 km/sec at Ludlow to 2.0 km/sec at Dribble, suggesting an inverse correlation between amplitude and medium velocity (Kisslinger and Gupta, 1963). The Mountain City shotpoint was in a highly faulted complex region. Drilling logs show the shooting medium to be clay in parts of the area, basalt flows in others, and possible granite in the remainder, so the shooting medium is in question. Charges were placed below the water table for all shots at Mountain City.

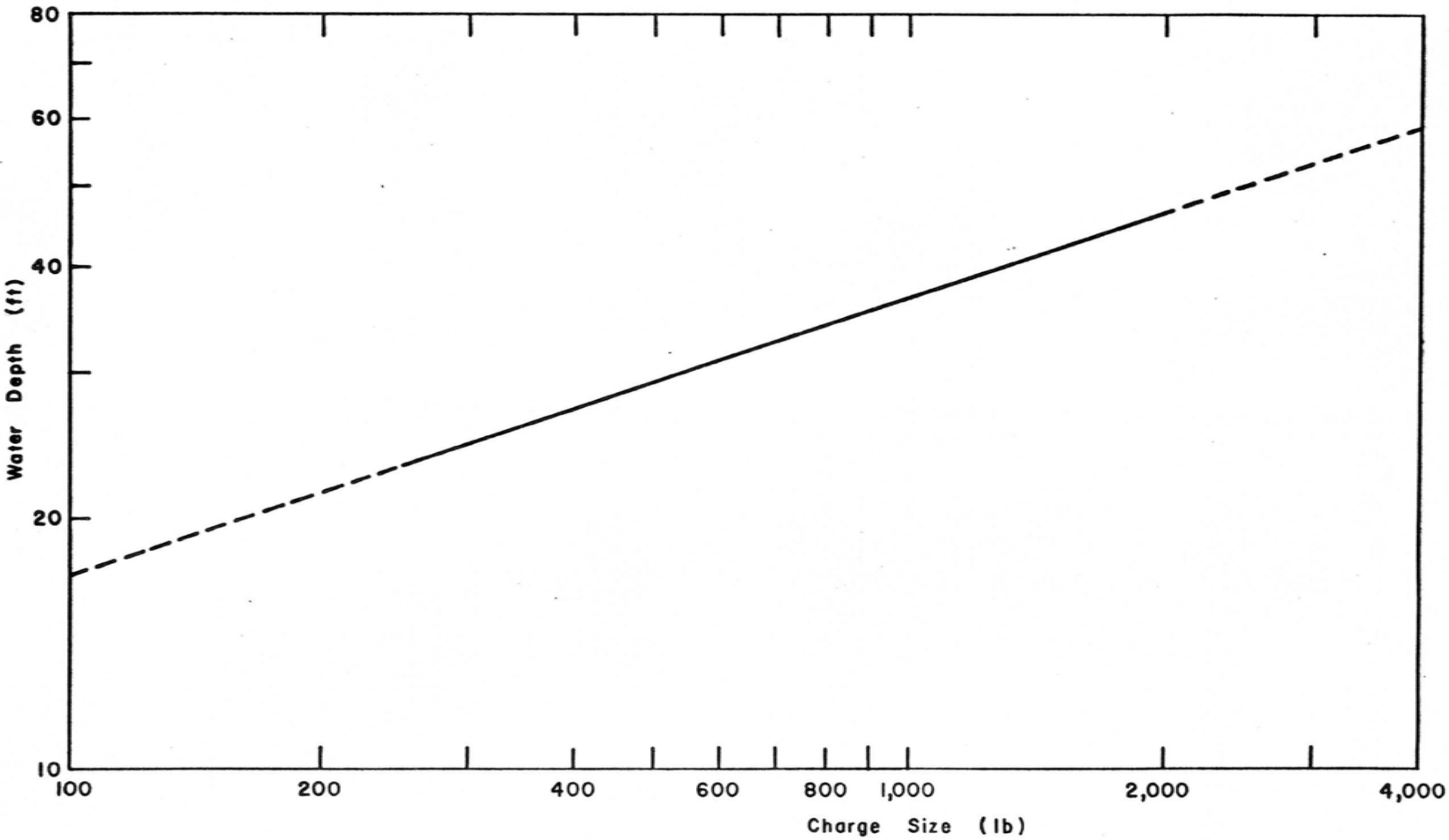

Figure 6.--Maximum charge size versus water depth for explosives fired on lake and river bottoms.

Shotpoint	Signal Amp. (μV)	Shooting Medium	Medium Velocity V_1 km/sec / V_2 km/sec	P_g Intercept (sec.)	Period of 1st Arrival at 60 km (sec.)	First Arrival Period (sec.)	First Arrival Dist. (km)	Charge Size (lb.)
Ludlow	70	clay	1.4/2.7	0.8	0.12	0.070 0.120	3 14	4,000 "
Mtn. City	30	basalt, clay, granite	2.9/5.3	0.1	0.11	0.065	7	4,000
Delta	25	clay	1.9/5.2	0.1	0.12	0.040 0.050	2	250 "
Dribble	15	clay	2.0	2.5	0.13	0.100	3	1,000
Gladden	7	dolomite limestone		0.1				
Mojave	6	decomposed granite	3.2/4.2	0.7	0.11	0.075	6	4,200
Hanksville	3	shale	2.0/4.5	1.1	0.12	0.065 0.090	2 10	2,000 "

Table 4.--Drill-hole Shotpoints

The thickness of the sedimentary section, as indicated by the 5 km/sec (or greater) intercept, does not appear to be greatly important in reducing the recorded amplitudes. This agrees in general with observations from the water shotpoints.

Taking the duration of the first pulse as the half period, the period of the first arrival at about 60 km from all shotpoints of this group is between 0.11 and 0.13 seconds. There appears to be no overall relation between this period and the shotpoint efficiency, or shooting medium. Periods of near-in observations may have little significance because they were not all made of constant charge sizes at constant distances; however, there appears to be no large difference in periods between good and poor shotpoints or between contrasting media such as clay and hard rock from near-in observations.

Some shotpoints drilled in hard rock (Gladden, Mo., for example) appear to have a much lower signal amplitude than those in clay. This is in agreement with the model studies of Kisslinger and Gupta (1963).

The mismatch in characteristic impedances between explosive and medium (Nichols, 1962) is apparently not serious in the case of a clay shooting medium. Further, the impedance of dolomite at the Gladden shotpoint (about 40-lb-sec/in^3) probably most nearly matches that of the explosive (about 32-lb-sec/in^3), yet Gladden is considered a relatively poor shotpoint.

SUMMARY

Based on first-arrival amplitudes from 6 water shotpoints and 7 drill-hole shotpoints in parts of central and western United States, the following observations have been made:

1. Water shotpoints are, in general, more efficient than drill-hole shotpoints. For the group of shotpoints studied, the signal amplitude ratio between the best water shotpoint and the poorest drill-hole shotpoint was over 100 to 1.

2. The variation in efficiency of drill-hole shotpoints is about twice that of water shotpoints. Extremes in efficiency for drill-hole shotpoints was over 20, while water shotpoints ranged by a factor of about 10.

3. Water shotpoints are not always superior to drill-hole shotpoints; one drill-hole shotpoint was superior to more than half of the water shotpoints.

4. Signal amplitude from water shotpoints increases, in general, with depth. The Lake Superior shotpoint in the Canadian Shield area produced about 6 times more energy than the Nee Granda shotpoint in the Great Plains of Colorado.

5. The shooting medium for drill-hole shotpoints appears to be the controlling factor; saturated clay appears, in general, to be superior to hard rock.

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