J. Geophys. 41, 463–474, 1975

Explosions in Shallow Water for Deep Seismic Sounding Experiments

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Abstract. The basic importance of underwater explosions as efficient seismic sources is due to secondary source effects, i.e. gas bubble pulsation and signal reverberation within the water, and optimum shot conditions can be defined for the case of constructive interference of both effects. In shallow water, where secondary source effect conditions are not satisfied, seismic signals are determined by the low-frequency part of the primary source signal. For very small shot depths the observed seismic signal reduction can be avoided by the use of distributed charges, which is shown to be a general means to increase the seismic source efficiency. General conditions of shot planning for deep seismic sounding experiments in deep, medium and shallow water are given, together with several examples, showing the applicability of explosions in shallow water for seismic purposes.

Key words: Underwater explosions – Deep seismic sounding – Effective shot conditions.

1. Introduction

One of the main problems of deep seismic sounding experiments is the generation of suitable seismic signals. For technical, financial and seismic reasons underwater explosions are normally preferred to underground explosions. Some advantages are: better practicability, no drilling, possibility of signal manipulation, better seismic efficiency, smaller risk of direct damages and reproducibility.

On the other hand, there is not everywhere suitable water available for this purpose or, sometimes, there are only small and shallow lakes and rivers in the region of interest. So the question arises about the necessary conditions for such waters to be suitable for efficient seismic signal generation.

With underwater explosions a general scheme for the shot-planning procedure of deep seismic sounding experiments may be compiled as shown in Fig. 1.

2. Optimum Source Conditions

It is a wellknown fact in explosion seismology, verified by theoretical calculations as well as by experimental data, that the basic importance of underwater explosions

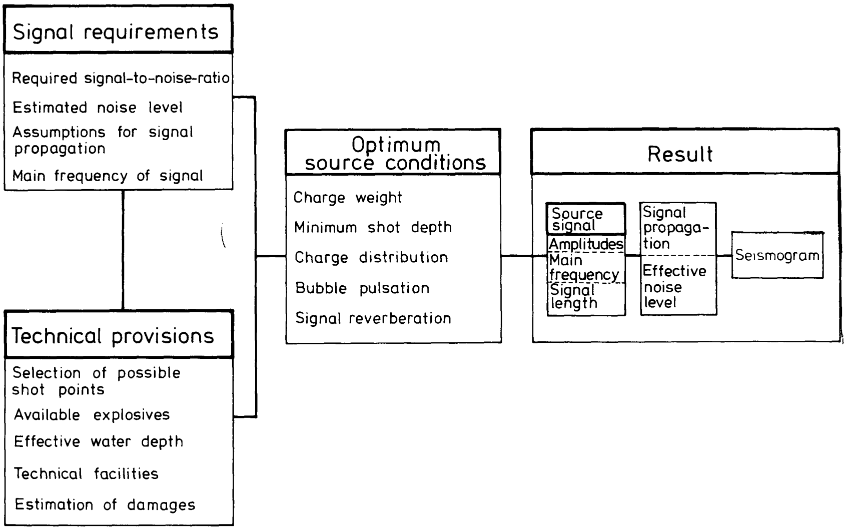

Fig. 1. Scheme for the planning procedure with underwater explosions

for seismic purposes, characterized by the relatively good efficiency in the low-frequency band of seismic signals, is mainly due to secondary source effects: gas bubble pulsation and signal reverberation within the water.[1] With these two effects it is possible, by appropriate choice of explosion conditions, to increase the seismically interesting low-frequency amplitudes of the source spectrum considerably. Further seismic signal enhancement is achieved with source conditions where constructive interference between the two effects occurs, determined by the equality of bubble pulse period and the appropriate reverberation period in the range of seismic periods; these conditions are sometimes referred to as optimum ones (*e.g.* Fuchs *et al.*, 1972; Wielandt, 1972).

Therefore, the first objective of every shot planning has to be the investigation, whether or not these optimum source conditions are possible.

The period T_B of the first bubble pulsation is given by

$$T_B = C W^{1/3}/(h+10)^{5/6} \qquad W = \text{charge weight}, \quad h = \text{shot depth}$$

with $C \approx 2.1$ [s $m^{5/6}$ $kg^{-1/3}$] for TNT and similar explosives (Cole, 1948).

In some cases multiple bubble pulsations have to be taken into account too, with period variations due to energy radiation and vertical displacement of the pulsating gas bubble (Burkhardt, 1964). Mostly, however, it is only the first pulsation, which contributes significantly to the seismic source signal.

[1] A third secondary effect of underwater explosions in bounded media such as lakes in homogeneous surroundings is the frequently observed occurrence of resonance effects within the further surroundings of the source. This effect is also observed with some underground explosions (Burkhardt and Vees, 1974b). It should be mentioned, that even neglecting the secondary effects, underwater explosions are still more effective for seismic signal generation than underground explosions in rocks, due to the different shear strength of the surrounding medium (Wielandt, 1972).

The effective reverberation period depends on the geometry of existing boundaries, such as water surface, sea bottom, lateral boundaries, on the boundary conditions and on the location of the source with respect to the boundaries.

For suspended charges in deep water with shot depth h smaller than water depth H, *e.g.* for underwater explosions at sea with no contributing lateral boundaries, there are two periods due to surface reflections

$T_{h_n} = 4h/(2n-1)\,c_w$ (surface-source reflection)

and

$T_{H_n} = 4H/(2n-1)\,c_w$ (surface-ground reverberation)

$n = 1, 2, \ldots;$

c_w = velocity of compression wave in water.

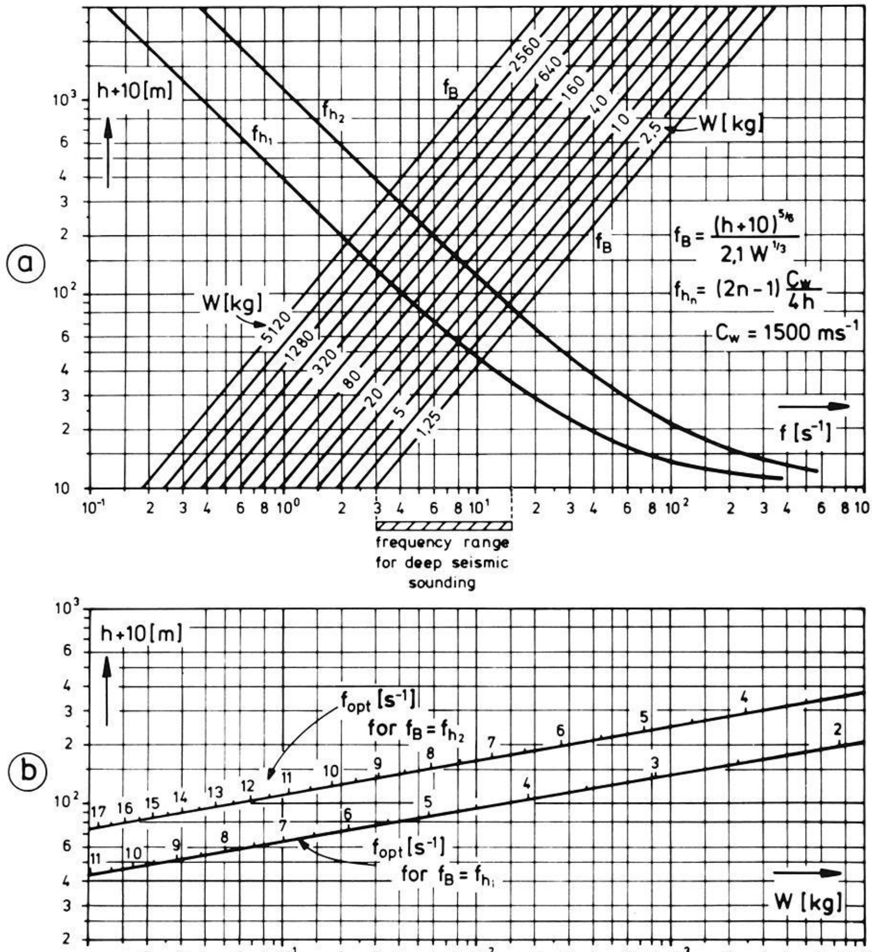

Fig. 2a and b. Optimal source conditions for underwater explosions. (a) Bubble pulse frequency f_B with parameter charge weight W, fundamental frequency f_{h_1} of surface reverberation and its first harmonic f_{h_2} as a function of shot depth h. (b) Optimal frequency f_{opt} as a function of charge weight W and shot depth h for the frequencies f_{h_1} and f_{h_2}

Then, optimal seismic source conditions occur, when

$$T_B = T_{h_n} \quad \text{or} \quad T_B = T_{H_n},$$

giving constructive interference between bubble pulse period and surface reverberation period, with n equal 1 or 2 or sometimes even 3 (Bancroft, 1966).

The only factors involved are charge weight W and shot depth h or water depth H, respectively.

The relationship between bubble pulse frequency $f_B = 1/T_B$, fundamental frequency $f_{h_1} = 1/T_{h_1}$, its first harmonic f_{h_2}, charge weight W and shot depth h is shown in Fig. 2a. The points of intersections of the two families of curves mark the optimum seismic source conditions, indicating the achievable range of appropriate pairs of charge weight and shot depth.

Fig. 2b shows the resulting optimum frequency f_{opt} as a function of shot depth and charge weight in the seismic range. With charges ranging from 1 to 10^4 kg, optimum shot depths vary between 35 m and 350 m and optimum frequencies between 17 Hz and 2 Hz for $n = 1$ and 2.

So, except for explosions at sea with sufficient water depths, optimum source conditions are normally not possible for underwater explosions in shallow water, e.g. lakes, rivers etc., which are frequently used as seismic sources for crustal investigations. In these cases underwater explosions may still be superior to underground explosions, provided that careful consideration is given to the various other factors which can influence the seismic source efficiency (see footnote p. 464). Remembering the fact, that an important contribution to the low-frequency part of the source spectrum comes from the secondary effects, the separate contributions of bubble pulsation and surface reflections have to be investigated in the frequency range for deep seismic sounding, 3 to 15 Hz approx. (Fig. 2a).

For the bubble pulsation the minimum shot depth is ca. 25 m ($W = 30$ kg, $f = 3$ Hz), this depth increasing with increasing charge weight and increasing frequency.

For the surface-source reflections there is the same minimum shot depth ($f_{h_1} = 15$ Hz) with frequency decreasing for increasing depth. The same is true for the surface-ground reverberation with regard to the water depth.

3. Explosions in Shallow Water

(a) No-Bubble Pulse Condition

If the available shot depth is smaller than this minimum depth, the secondary effects no longer improve the seismic signal, they may even tend to disturb the seismogram. In this case, in order to prevent the gas bubble from pulsating, the shot depth must be smaller than a critical depth h_c, resulting in a blowout of the bubble.

A reasonable estimation of this critical depth is given by the condition, that h_c must be equal to the maximum radius a_m of the spherical bubble during pulsation.

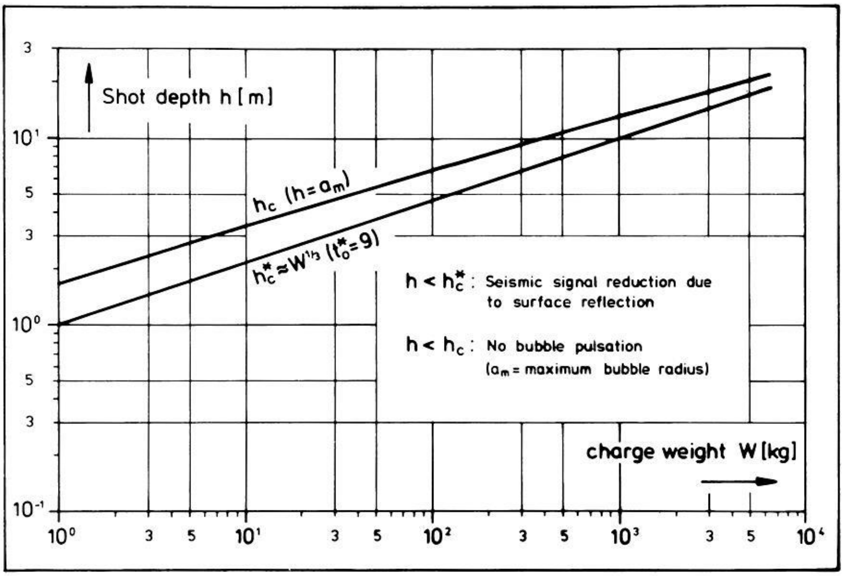

Fig. 3. Critical shot depths h_c and h_c^* for underwater explosions

In good approximation a_m is given by

$$a_m = 3.7(W/(h+10))^{1/3} \text{ [m]} \qquad W = \text{charge weight [kg]}, \quad h = \text{shot depth [m]}$$

neglecting bubble migration and boundary effects (Cole, 1948).

So, with freely suspended charges in shot depths $h < h_c = a_m$ there are no bubble pulses and the resulting seismic signals are determined only by the primary source signal (Fig. 3).

For explosions on the bottom in shallow water additional boundary forces are acting and influence the bubble expansion. In these cases the above no-bubble-condition is necessarily only a rough estimation.

(b) Minimum Shot Depth

For shallow water explosions, experiments show an influence of shot depth on seismic amplitudes, with amplitudes rapidly decreasing with the charge approaching the surface. This points out, that the main cause for this amplitude reduction is a surface effect. Due to the large pressure amplitudes, associated with an underwater explosion, the boundary conditions at the free surface will be very complicated with non-linear effects such as e.g. cavitation and spray dome. Besides these effects there is a cut-off effect for the radiated pressure wave due to the surface reflection, with the reasonable assumption, that normal water cannot sustain any tensional forces (Cole, 1948). For the primary positive pressure wave, which can be approximated by an exponentially decaying time function with a charge dependent time constant (for quantitative results with small explosives, *see* Keller, 1970), this cut-off effect leads to a reduction of the corresponding low-frequency spectral amplitudes.

Now, the distant seismic signals (e.g. particle velocity) depend on the low-frequency part of the pressure field in the water. So, a reduction of the low-frequency spectral amplitudes of the pressure wave will also lead to a reduction of the resulting seismic amplitudes.

As a minimum condition for effective seismic radiation of an underwater explosion source we require, that the cut-off effect of surface reflection must not occur before the decay of the primary pressure wave.

With

$$t_0^* = 2h/\Theta\, c_w \approx 9\, h/W^{1/3}$$

(h in metres, W in kg, Θ = time constant of exponentially decaying pressure wave) the minimum condition is given by the requirement, that the delay $2h/c_w$ of the surface reflection must be appreciably larger than the time constant Θ of the pressure wave, i.e. $t_0^* \gg 1$. This yields a charge dependent critical minimum shot depth h_c^*, with seismic amplitudes rapidly decreasing with smaller depths (Fig. 3).

The numerical value for t_0^* in Fig. 3 has been chosen in order to give approximate agreement with experimental evidence during the Afar experiments, where distributed charges of 20 to 60 kg in water depths of 3 metres yielded satisfactory seismic long range signals (see Fig. 6).

The rather large value for t_0^* indicates, that the cut-off effect is not the only factor involved in reducing seismic amplitudes, but that the above mentioned surface effects have to be taken into account too.

Therefore, due to its approximate nature, this condition does not necessarily mean, that seismic signals would not further increase with increasing shot depth but only determines a minimum condition, which must be satisfied for efficient seismic signal generation.

(c) Distributed Charges

For deep seismic sounding experiments with explosion generated signals the necessary charge weights are, according to experiences, in the order of several hundreds of kilograms. So, for shallow water conditions, the total charge weight has to be divided in such a way, that every single charge is fully effective in the above mentioned sense.

Furthermore, in contrast to explosions with concentrated charges, where, neglecting secondary source- and lateral boundary-effects, seismic amplitudes scale with (charge weight)$^{2/3}$, approximately (Burkhardt, 1964; Vees, 1965), we have different scaling laws for distributed charges. It is known from shockwave measurements, that in the range of linear acoustical behaviour of the pressure wave, i.e. for distances r with $r > r_x \approx 20\, kW^{1/3}$ approximately, ($k \approx 5 \cdot 10^{-2}\,\mathrm{m\,kg^{-1/3}}$) (Cole, 1948), the resulting pressure field from distributed charges is the sum of all contributing single charge pressures.

Let $W_\Sigma = n\, W_s$, where W_s = weight of single charge, n = number of charges with weight W_s. W_Σ = total charge weight.

Then the spectral amplitudes of the resulting pressure wave in the range of seismic frequencies are scaling with charge weight as

$$|P(\omega)|_n \sim n\, W_s^{2/3}$$

ω = frequency

provided that the distances Δx between the charges are complying with the condition

$$\Delta x \geqq 2 r_x \approx 2\, W_s^{1/3}$$

(W_s in kg, Δx in metres).

In order that the gas bubbles from single charges are pulsating with a period, determined by W_s, the necessary minimum distance between the charges must be

$$\Delta x_B \gg 2 a_m \approx 7.4\,(W_s/(h+10))^{1/3};$$

(W_s in kg, Δx_B and h in meteres),

which gives

$$\delta = \frac{\Delta x}{\Delta x_B} = \frac{(h+10)^{1/3}}{3.7} \lesseqgtr 1 \quad \text{for } h \lesseqgtr 40\,[\mathrm{m}].$$

For W_s = const we have

$$|P(\omega)|_n \sim n \qquad \text{or } |P(\omega)|_n \sim W_\Sigma^1.$$

For W_Σ = const we have for the ratio of spectral amplitudes of concentrated charges with

$$|P(\omega)|_c \sim (n\, W_s)^{2/3}$$

and distributed charges, the result

$$\frac{|P(\omega)|_n}{|P(\omega)|_c} = n^{1/3}$$

yielding an increasing amplitude with increasing distribution of the charge W_Σ.

If

$$W_{\Sigma_1} = n_1\, W_{s_1} \quad \text{and} \quad W_{\Sigma_2} = n_2\, W_{s_2},$$

the ratio of resulting spectral amplitudes is given by

$$\frac{|P(\omega)|_{n_1}}{|P(\omega)|_{n_2}} = \frac{n_1}{n_2}\left(\frac{W_{s_1}}{W_{s_2}}\right)^{2/3}.$$

Experimental verifications (within 10% approx.) of these relationships have been achieved with controlled investigations during deep seismic sounding experiments in various regions, *e.g.* Lago Bianco-experiments in the Alps (Vees, 1965) and Afar-experiments (Burkhardt and Vees, 1974a) where explosions with distributed charges were carried out in shallow lakes and rivers in shot depths as small as 2 to 3 meters and where effects from lateral boundaries were small.

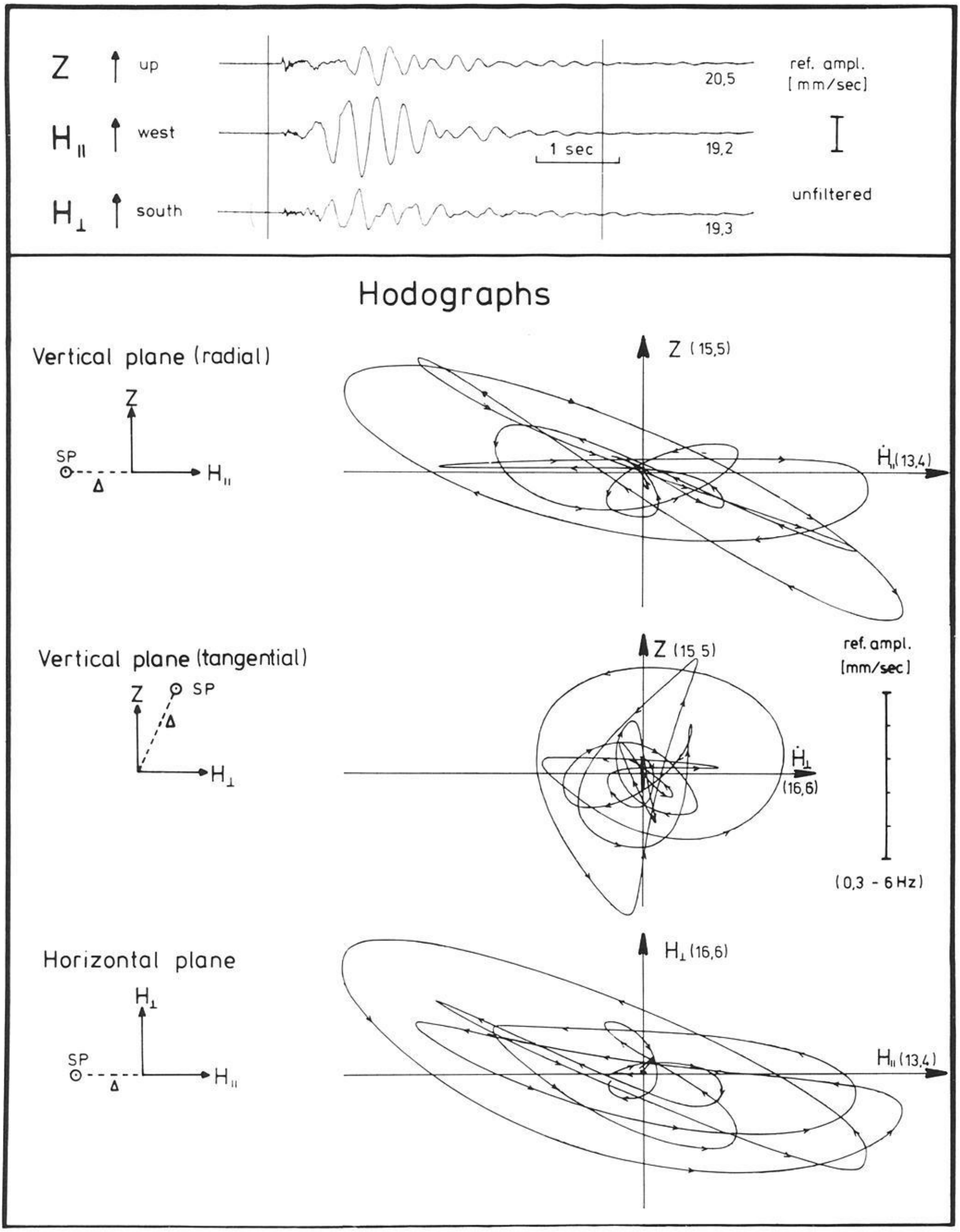

Fig. 4. Three-component seismic measurements (velocity transducer) near the source for shot point Green Lake/Ethiopia. Recording distance 300 m; charge weight $W = 10 \times 30$ kg; shot depth $h = 28$ m (bottom)

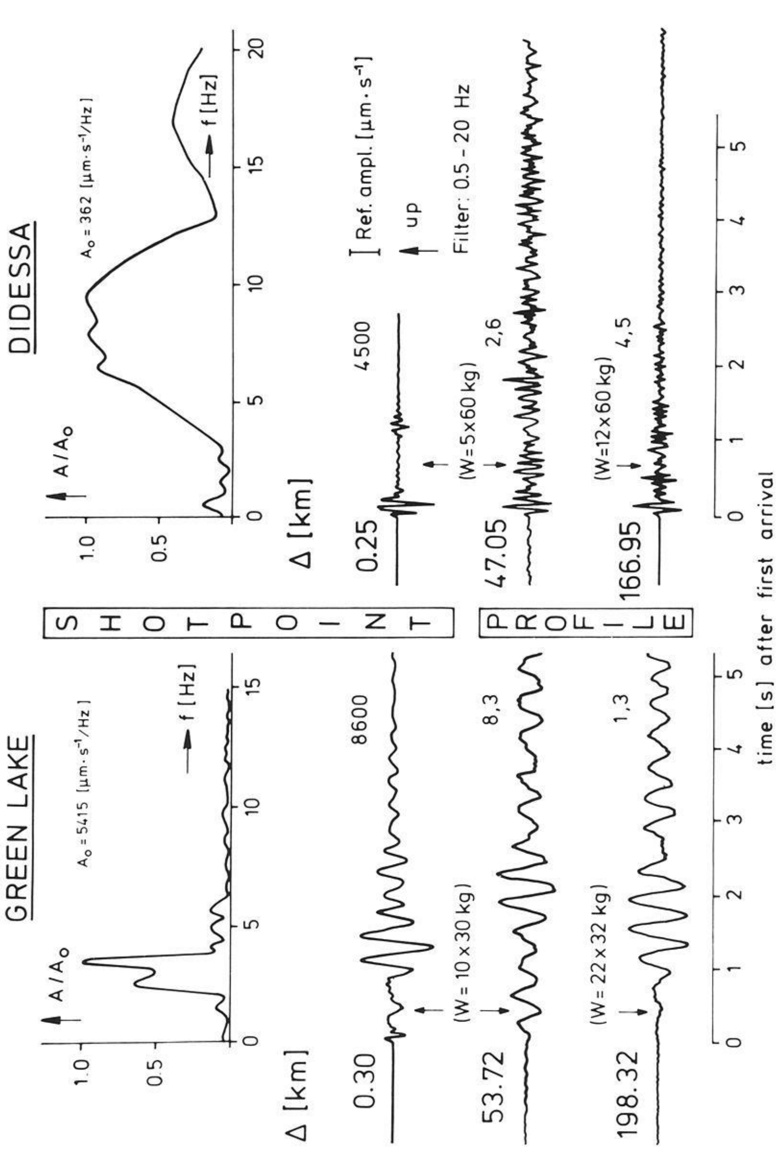

Fig. 5. Vertical components of close-by seismic records for two shot points with corresponding frequency spectra in comparison with vertical components of profile seismograms. Shot point Green Lake: see Fig. 5. Shot point Didessa: River in Ethiopia, water depth 12 metres approx. (After Burkhardt and Vees, 1947a)

4. Some Examples of Seismic Source Signals

During the deep seismic sounding experiments in the Afar region of Ethiopia in 1972 (Berckhemer, 1974; Burkhardt and Vees, 1974a) close-by seismic control measurements were carried out, which can be used as additional information for the interpretation of distant profile records.

The following examples are to demonstrate the applicability of shallow water explosions for such experiments.

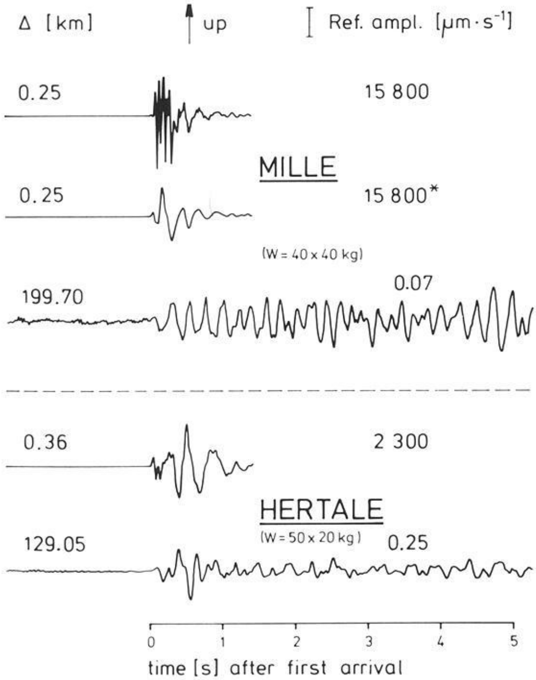

Fig. 6. Vertical components of close-by seismic records for two shot points in comparison with vertical components of profile seismograms (Afar-experiments 1972). Shot point Mille: Awash river, water depth 3 metres max. Shot point Hertale: Lake, water depth 3 metres approx. Filter settings 0,5–20 Hz. (*0,5–8 Hz)

Fig. 4 shows a three-component seismogram and the corresponding hodographs of a near-by station for the shot point Green Lake. This shot point is a crater lake in the Highlands of Ethiopia with nearly radially symmetric shape, steep side walls and a maximum depth of 25 to 28 m. The effective diameter in this depth amounts to ca. 450 m, surface diameter is approximately 800 m. The total charge weight used was divided in 10 single charges of 30 kg, which were fired on the bottom of the lake in a mutual distance of 15 m. Corresponding bubble pulse frequency of the single charges is 3.3 s^{-1}, which clearly dominates the seismograms. Due to the relative large shot depth multiple bubble pulses occur. From the hodographs it is seen, that this low-frequency part of the signal is of a radially horizontal type of motion. This fact, together with the high energy content of the signal and shape and size of the lake, led to the interpretation, that there is a constructive interference between bubble pulses and successive radial reflections within the lake with frequency $f_r = c_w/l$, where l = effective diameter of the lake. Inserting our numerical values, we get $f_r \approx 3.3$ s^{-1}. Due to this secondary source effect we have a very effective shear-wave source with a main frequency of 3 s^{-1} (see also Fig. 5).

Figs. 5 and 6 show comparisons between close-by control seismograms and distant profile records for some shotpoints and profiles of the Afar experiments.

There is a good correspondence between respective close-by and distant signals, stressing the importance of the control measurements (Burkhardt and Vees, 1974a).

In all cases distributed charges were used because of the small available water depths. So, these examples also clearly illustrate the fact, that explosions in shallow water can be used as efficient seismic sources for long range seismic experiments, provided that the considerations given above with respect to the mechanisms of signal generation are taken into account.

5. Summary and Conclusions

1. Underwater explosions are known as efficient sources of seismic energy for deep seismic sounding experiments.

2. The basic importance of underwater explosions for seismic purposes is mainly due to secondary source effects, i.e. gas bubble pulsation and signal reverberation within the water. Optimum shot conditions occur with constructive interference of these two effects, requiring minimum water depths (35 metres approximately in the range of seismic relevant charge weights and frequencies).

3. For smaller water depths the separate contributions of the secondary source effects can be utilized to increase the seismic efficiency.

4. In shallow water conditions, where no secondary source effects occur and where the seismic signal is determined only by the low-frequency part of the primary source signal, there is a charge dependent, critical minimum shot depth due to a cut-off effect of the source signal by the surface reflection.

5. With the use of distributed charges this disadvantage can be avoided and so even explosions in shallow water can be used as efficient seismic sources. Moreover, this charge division turns out to be a general means to increase the seismic source efficiency.

6. Several examples from different experiments demonstrate the applicability of explosions in shallow water for deep seismic soundings.

Acknowledgements. The financial support of the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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Received July 25, 1974; Revised Version March 24, 1975