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A PARABOLOIDAL SPARKER SEISMIC SOURCE

Abstract. A marine sparker seismic source is presented, in which the electrical discharges take place at the focus of a paraboloidal reflecting surface, in order to obtain a downward-oriented, approximately plane acoustic wavefront. This source, here compared with a traditional sparker-array configuration, gives higher penetration of sea bottom sediments and could be successfully employed in high resolution marine seismic reflection prospecting.

INTRODUCTION

In marine seismic reflection prospecting, the methods generally used to produce acoustic waves can be grouped into four broad categories:

- chemical (Flexotir, Maxipulse, Aquapulse);
- pneumatic and hydraulic (Air or Water Guns, Vaporshoc);
- mechanical (Boomer, Flexishoc);
- electrical (Sparker).

Chemical or explosive sources are the simplest sources for producing compressional waves in the sea, but they entail risks to the operators on board and to the marine environment in general. For this reason, although commonly employed on land, they are now rarely used in offshore activities.

In pneumatic and hydraulic sources, a slug of high-pressure fluid is expelled into the sea. Generally, the fluid is air or water (Air or Water-Guns), but steam is sometimes used (Vaporchoc). Larger volume guns generate a signal richer in low frequencies, while smaller volumes emit a signal richer in high frequencies (Giles and Johnston, 1973). Generally, a "tuned array" is used, in which several guns are spaced at a distance such that the primary pulses interact minimally, but sufficiently close together that the bubbles merge (Ziolkowski, 1971). The result is the bubble period of a single gun having the combined capacity of the individual guns, but with a much larger primary pulse than could be obtained from a single gun of equal capacity (Larner et al., 1982).

In mechanical sources, acoustic waves are produced by a plate vibrating due to an electrical discharge at the sea-surface (Boomer) or by a slug of air at high pressure (Flexishoc).

In electrical sources, the energy is accumulated in capacitors prior to the shot, and then charges from a few thousand to many thousand volts are applied to electrodes towed behind the ship and immersed in the sea water; the electrodes are arranged in particular configurations called "arrays" (Sparker-Array), in order to obtain a cylindrical wavefront, rather than a spherical one, such as that produced by a single pair of electrodes (Knight, 1986).

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In the sparker, electrical discharges occur when the potential difference between two points in the sea-water reaches a particular value, which depends on the physico-chemical properties of the water, and on the nature, form and distance of the electrodes. As the discharge occurs, the rapid ionization of the water produces a high temperature, within a small volume of liquid, which vaporizes the water and creates a gas bubble, followed by its condensation and implosion or explosion.

In this paper we present a new prototype electrical source, which seems to have a better performance than the traditional sources for high resolution marine seismic reflection prospecting.

THE ACOUSTIC RADIATION

The properties of acoustic signals generated by all types of marine energy sources are strongly dependent on the bubble oscillation, which in the case of dynamite and air-guns is associated with an actual bubble in the water. With other types of source, such as electrical and mechanical, where little or no bubble exists, periodic pressure pulses are generated which have characteristics similar to those of bubble oscillations. From this point on, the process of generation is the same whether the source is dynamite, an air gun, or an electric sparker creating a steam or gas bubble in the water.

In order to study the general bubble motion, we start from the scalar wave equation in a rectangular reference frame:

$$\partial^2\phi/\partial x^2+\partial^2\phi/\partial y^2+\partial^2\phi/\partial z^2=(1/c^2)\ \partial^2\phi/\partial t^2, \tag{1}$$

in which ϕ represents the velocity potential, c the speed of sound in water, and x,y,z,t the space coordinates and time.

Eqn. (1) is valid for a homogeneous, linearly compressible fluid with bulk modulus K and density ϱ such that:

$$c^2=K/\varrho,$$

where c is a constant.

For the radiation field around a spherical, oscillating bubble, and assuming that there are only outgoing waves, the solution of eqn. (1) is:

$$\phi=f\ (t_1)\ /r,$$

where $t_1=t-(r-a_0)\ /c$, a_0 is the equilibrium bubble radius, r the distance from the center of the bubble, and f a source dependent function.

The particle velocity is extracted from the velocity potential, in a polar reference frame with the origin at the center of the bubble, as follows:

$$u\ (t_1)=\partial\phi/\partial r=-f\ (t_1)\ /r^2-(1/rc)\ \partial f\ (t_1)\ /\partial r. \tag{2}$$

Particle acceleration is obtained by differentiation of equation (2) with respect to time:

$$a\ (t_1)=\partial u\ (t_1)\ /\partial t=-(1/r^2)\ \partial f\ (t_1)\ /\partial t-(1/rc)\ \partial^2 f\ (t_1)\ /\partial r\partial t. \tag{3}$$

Next, we find the pressure from the particle acceleration using Newton's second law and introducing the density ϱ:

$$P\ (t_1)=-\varrho\int a\ (t_1)\ dr=\varrho\int\ (1/r^2)\ \partial f\ (t_1)\ /\partial t dr\ +\varrho\int\ (1/rc)\ \partial^2 f\ (t_1)\ /\partial r\partial t dr=$$

Fig. 1 - The paraboloidal reflector surface.

$$=-(\varrho/r)\ \partial f(t_1)/\partial t+(\varrho/rc)\ \partial f(t_1)/\partial t+(\varrho/c)\int(1/r^2)\ \partial f(t_1)/\partial t dr+const.= \quad (4)$$

$$=-(\varrho/r)\ \partial f(t_1)/\partial t+const.$$

As r tends to infinity, $P(t_1)$ tends to zero. Therefore, the constant of integration in eqn. (4) can be zero and we have the pressure of a spherical wave:

$$P(t_1)=-(\varrho/r)\ \partial f(t_1)/\partial t=-\varrho f'(t_1)/r, \quad (5)$$

where the prime indicates differentiation.

A much-cited paper in the literature on acoustic radiation is Keller and Kolodner (1956). They derived the expression for the particle velocity function and the pressure field around an oscillating bubble using linear elasticity theory. Their expression for the pressure field contains two terms: a $1/r$ term and a $1/r^4$ term. Throughout this paper, we have used an expression for the pressure field which contains only the first term. We will demonstrate that, although this second "afterflow" term does exist, it is absolutely negligible and has no place in linear elasticity theory.

Let us now follow the analysis used by Keller and Kolodner, continuing where we broke off after eqn. (2). They related particle velocity to pressure via Bernoulli's equation:

$$\int\partial P(\varrho)/\varrho=-[\partial\phi/\partial t+(1/2)\ (\partial\phi/\partial r)^2], \quad (6)$$

which they write as:

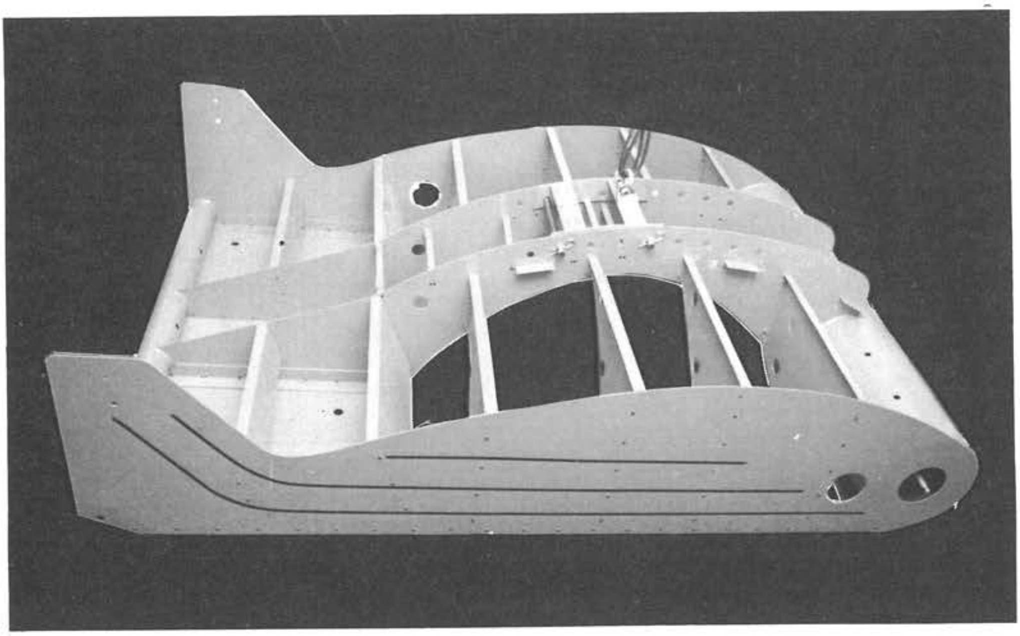

Fig. 2 - Some particulars of the paraboloidal sparker.

$$P\ (r,t) = -\varrho\ [\partial\phi/\partial t + (1/2)\ (\partial\phi/\partial r)^2\ ]. \tag{7}$$

The problem is that the wave equation and Bernoulli's equation are not compatible. The wave equation, with constant speed of sound, is valid for linear elastic fluids, in which the particle velocity is very small. The Bernoulli's equation does not depend upon infinitesimal deformations and is applicable in a much wider sense than the linear wave equation. Thus, there is a problem in reconciling these two equations. The one thing they have in common is that both have been derived using Newton's second law.

The first step that Keller and Kolodner took in this process of reconciliation was to make the approximation:

$$P\ (r,t)\ /\varrho = \int \partial P\ (\varrho)\ /\varrho \tag{8}$$

implied by their version of Bernoulli's equation. Eqn. (8) is valid only for incompressible fluids, in which the speed of sound must be infinite, and is approximately valid for the linear elastic case. This approximation was never mentioned in their paper and was the source of all future difficulty. When they substituted particle velocity squared into eqn. (7), they derived the following expression for pressure:

$$P\ (r,t)\ /\varrho = -(1/r)\ f'\ (t) - (1/r^4)\ f^2\ (t) - (1/2c)\ [\ (f'^2\ (t)\ /cr^2 + 2f\ (t)\ f'\ (t)\ /r^3\ ], \tag{9}$$

from which they chose to retain the first two terms and drop the last two. They do not examine the relative magnitudes of the terms.

In summary, we draw the following conclusion: since the wave equation and Bernoulli's equation are both based on Newton's second law, the solutions for the pressure wave and particle velocity function must be derivable from each other using Newton's second law, if the solutions are to be consistent. This must be true whatever level of approximation is used.

If linear elasticity theory is used, infinitesimal deformations are implied; that is, the parti-

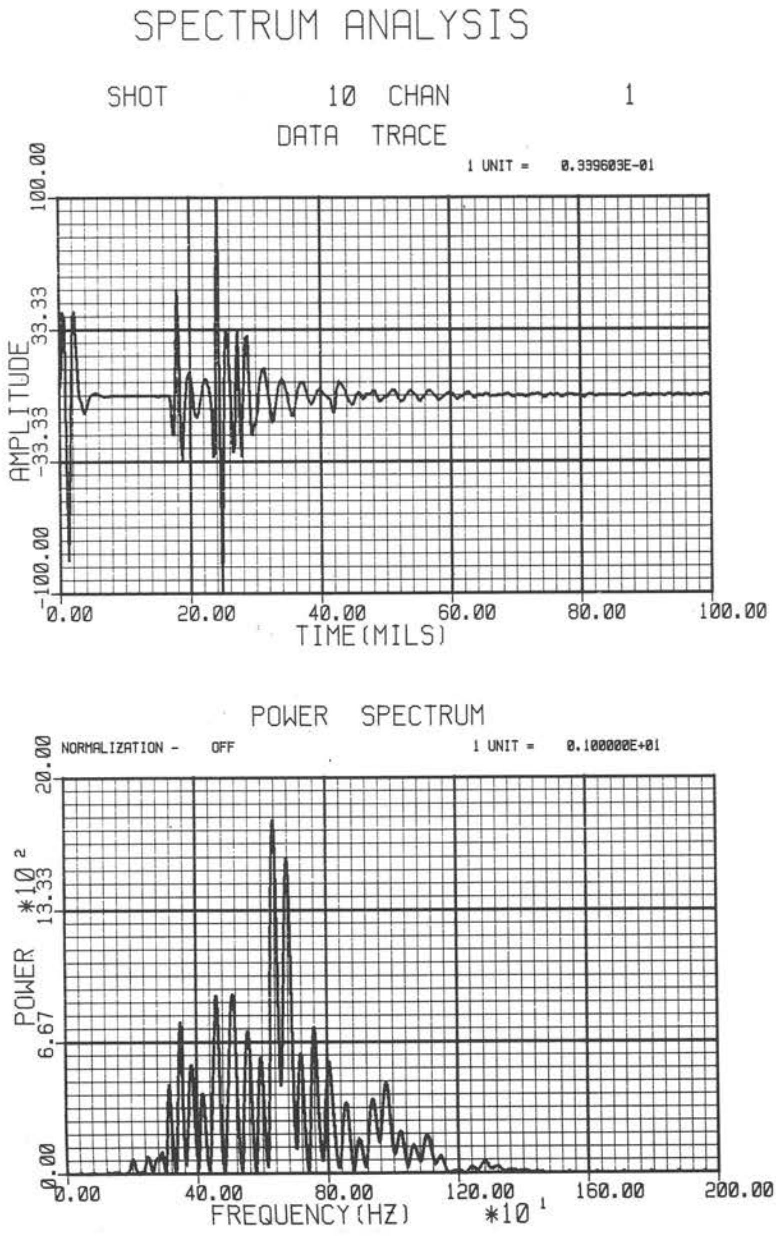

Fig. 3 - Near-field and its spectrum. In the upper graph, the horizontal axis is time in ms, and the vertical is voltage in mV. The first impulse, a few ms after the "time-break", is due to electromagnetic induction. In the lower graph, the horizontal axis is frequency, and the vertical is the power spectrum.

cle velocity is very small compared with the speed of sound. It follows that particle velocity squared is absolutely negligible, and in linear elasticity theory there is no room for the afterflow term (Ziolkowski et al., 1982).

In the same way, if we indicate the pressure of a plane wave with P^*, we have:

$$P^* (t) = \varrho f'(t). \tag{10}$$

From Newton's second law:

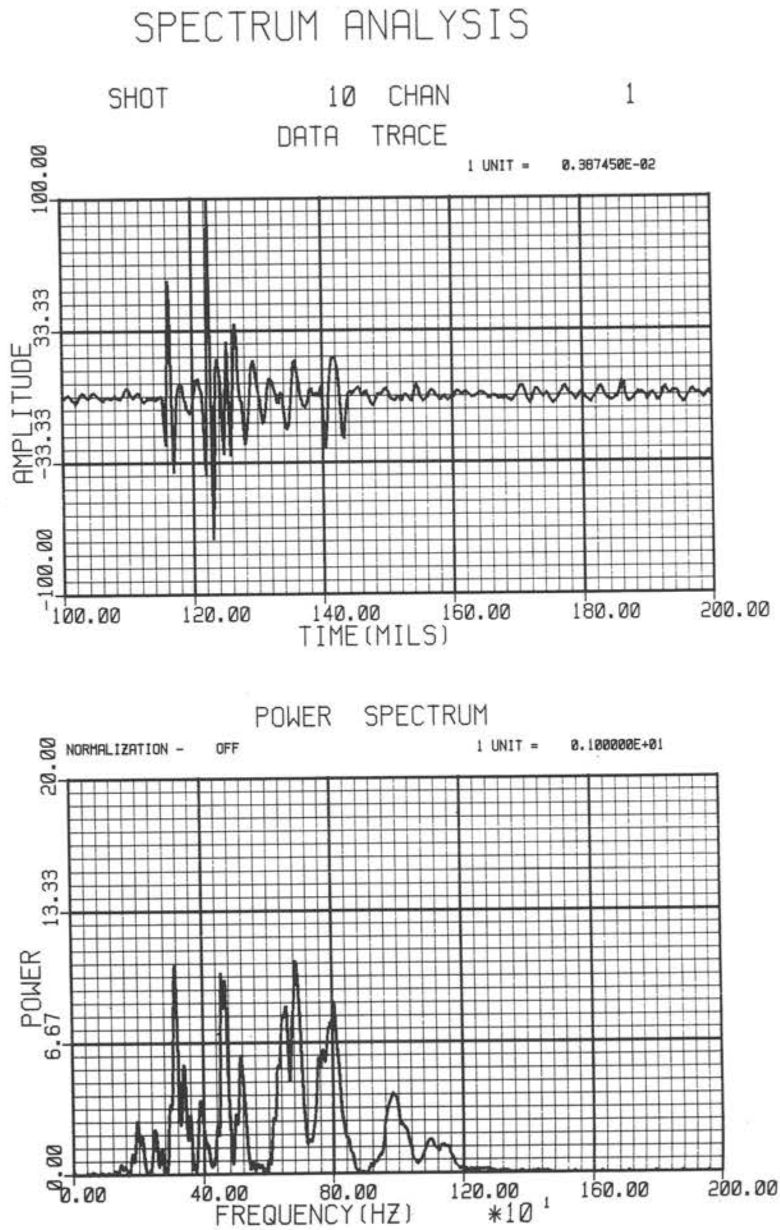

Fig. 4 - Far-field and its spectrum.

$$a\ (r,t) = -(1/\varrho)\ \partial P\ (r,t)\ /\partial r, \tag{11}$$

and substituting eqn. (10) in (11), we obtain the acceleration a^* of a plane wave:

$$a^*\ (t) = (1/c)\ f\ ''\ (t), \tag{12}$$

where the two differentations are done with respect to time and space.

The near-field radiation may be defined as the region in which the first term on the right hand side of eqn. (3) dominates close to the source, while the second term represents the far-field (Parkes and Hatton, 1986).

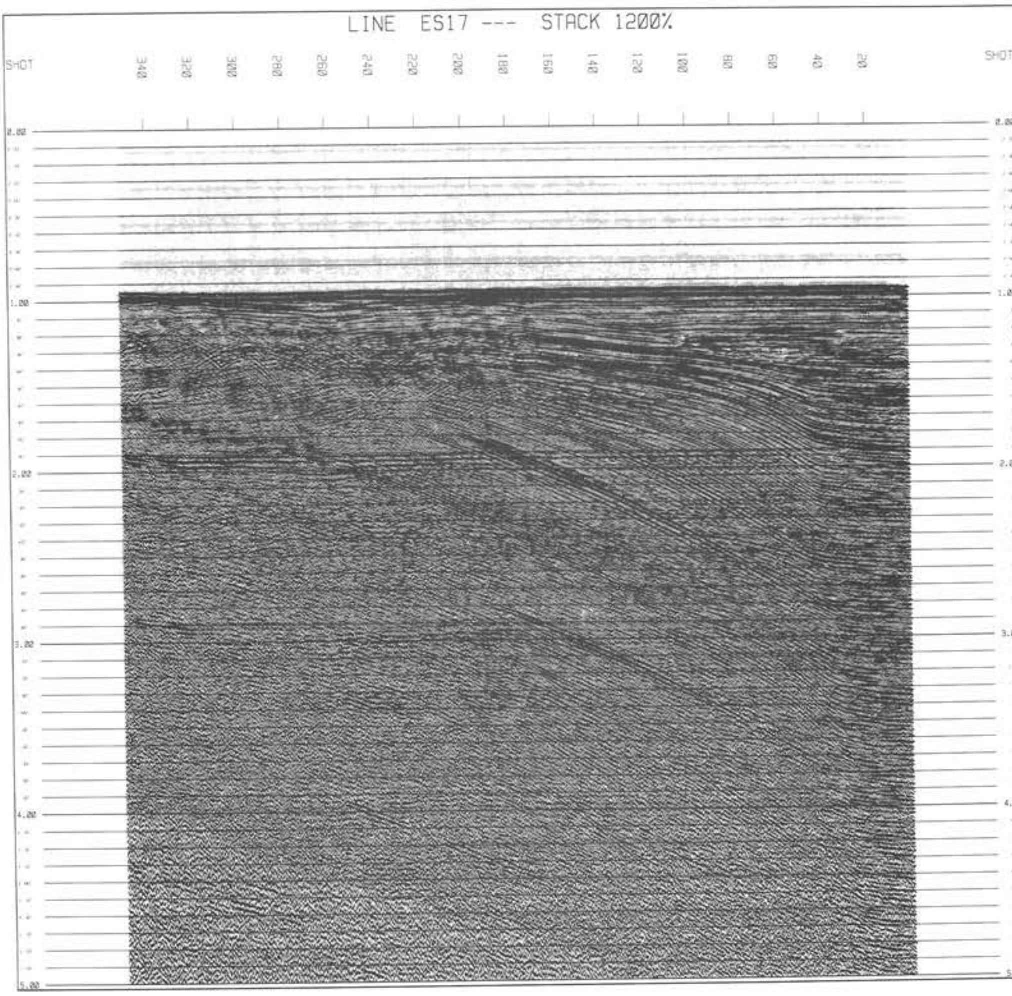

Fig. 5 - Seismic reflection profile recorded in the Tyrrhenian Sea using the paraboloidal source. The horizontal axis shows the shots, and the vertical the two-way-time in seconds.

In the case of a spherical wave, the signature shape is dependent on the distance of the point source, because the acceleration is the sum of two terms that depend on the distance although differently.

For the plane wave of eqn. (12), no difference between the near and the far-field exists. Thus the signature preserves its shape during propagation. This property can improve the deterministic deconvolution of seismic reflection data (Alessandrini and Gasperini, 1989).

THE PARABOLOIDAL SPARKER

In this sparker, the electrical discharge occurs at the focus of a paraboloidal reflector surface, in order to obtain an approximately plane wavefront for high frequency waves (Gasperini, 1987; Cannelli et al., 1988).

As we have seen, during the propagation of a plane wave, no geometrical spreading occurs, in contrast to the spherical wavefront produced by a single pair of sparker electrodes or by a "Sparker-Array" configuration.

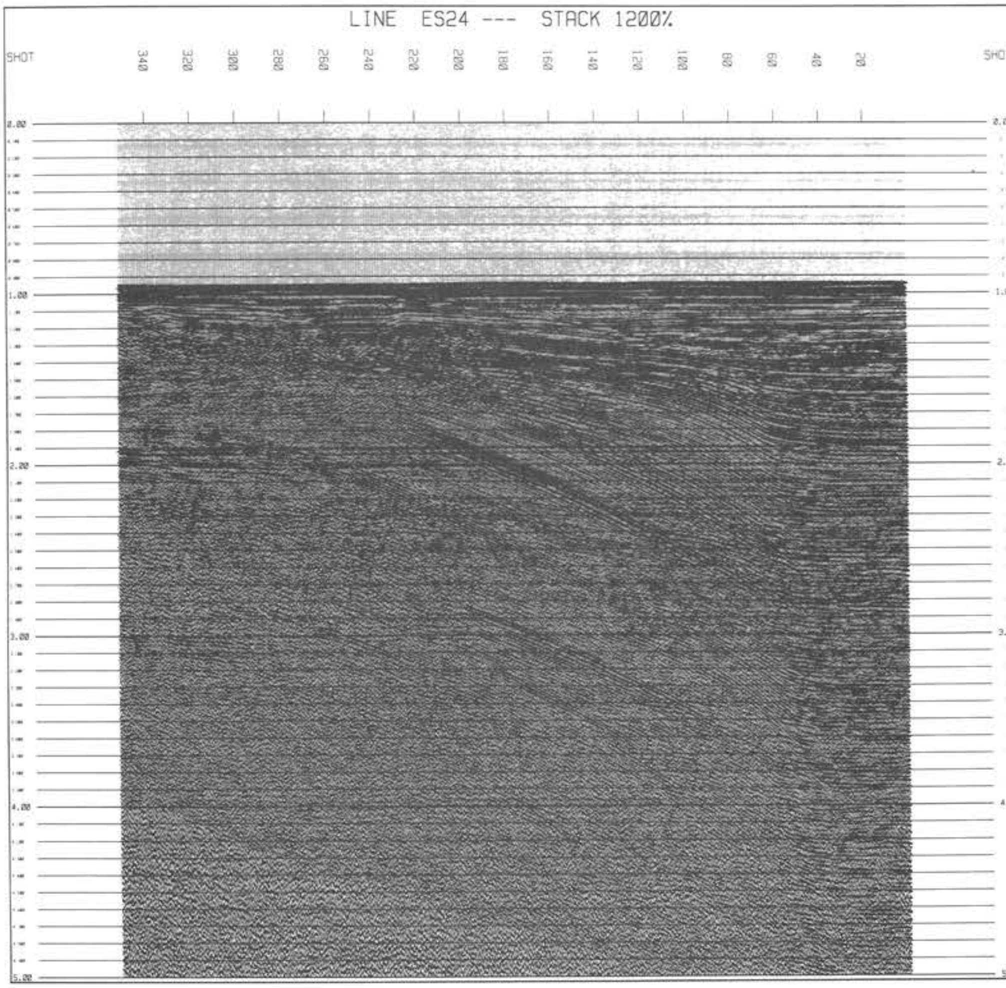

Fig. 6 - The same profile as in Fig. 5 obtained using a traditional "Sparker-Array" configuration.

We have constructed a 30 cm focal length paraboloidal surface, with an aperture of 150 cm (Fig. 1), and mounted on a towed structure, as shown in Fig. 2. The dimensions of this structure are 240x150x70 cm, for a total weight of about 300 kg.

The near-field and its spectrum are presented in Fig. 3, while the far-field of this source and the power spectrum are shown in Fig. 4. The energy emitted is 1kJ, the pass band filter ranges between 320-720 Hz and the hydrophone sensibility is 1 V/bar. It can be seen that the difference in amplitude between the far-field and near-field is insignificant, while the two power spectra are quite different.

In Fig. 5, a seismic profile obtained with this source is presented. Fig. 6 shows the same profile recorded by a "Sparker-Array" from Teledyne at the same energy of 20 kJ. The lines were obtained across the depocentral axis of the Paola Basin in the Tyrrhenian sea. An evident improvement in penetration depth with the paraboloidal source compared to the Sparker-Array can be noted. The deep reclector around 4-5 s two-way-time (near the left lower corner) is clearly recorded in Fig. 5 only.

Fig. 7 illustrates a seismic line recorded in the northern Adriatic sea by the paraboloidal source, and Fig. 8 shows the same line recorded at the same energy with the sparker-array source. The receiving streamer, made by Teledyne, employed 24 channels (formed by 20 hy-

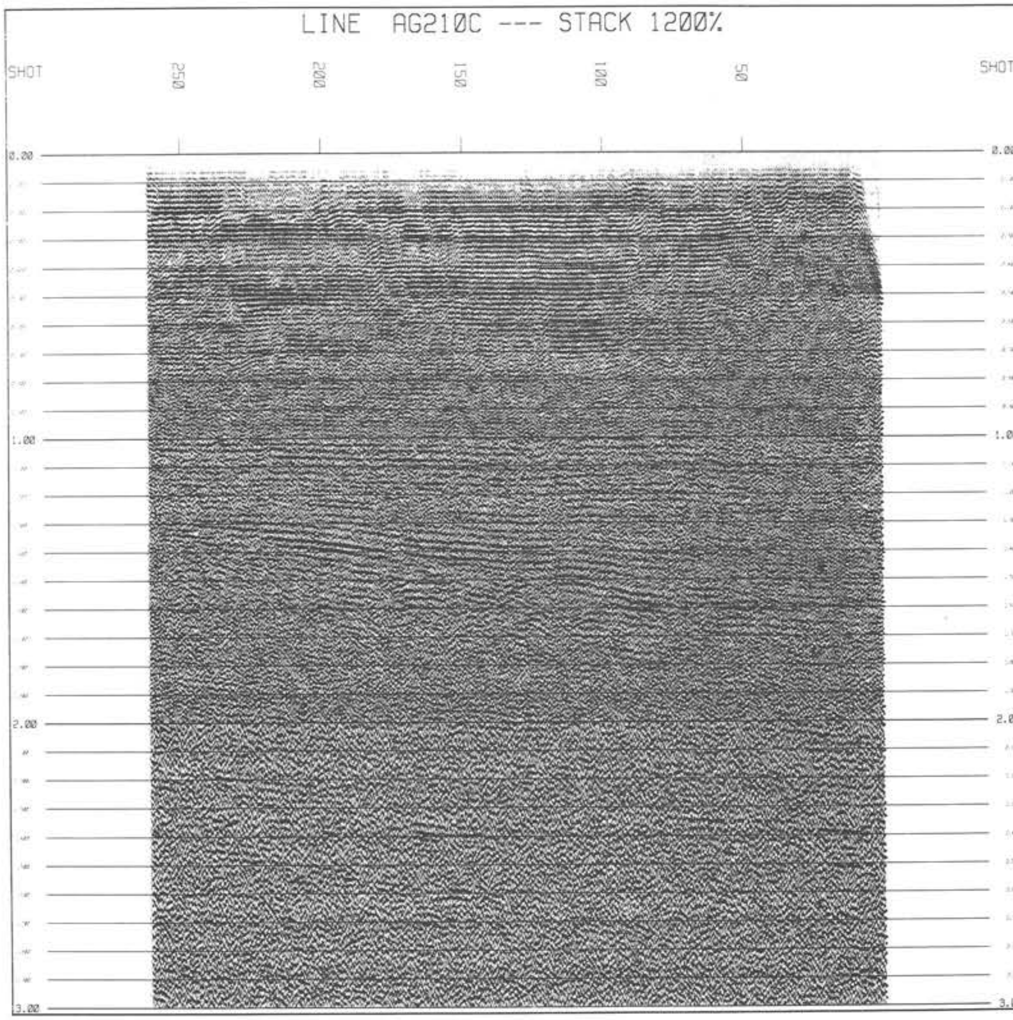

Fig. 7 - Seismic reflection profile recorded in the northern Adriatic Sea using the paraboloidal source.

drophones each) spaced 25 m apart. The shot interval was 25 m, allowing a coverage of 1200%. Seismic source and nearest channel were spaced of 150 m apart.

Digital acquisition was done with a Geometrics ES2420 seismograph, with a sampling rate of 1 ms, a record length of 5 s and an anti-alias filter of 180 Hz. Gain recovery and resampling to 2 ms were done before processing.

The data were deconvolved (operator 200 ms with gap 20 ms), stacked and time-variant filtered with three windows: 30-70 Hz, 25-60 Hz and 20-50 Hz.

CONCLUSIONS

The first two categories of seismic sources (chemical and pneumatic) are extensively used in conventional marine seismic prospecting for oil. They characteristically generate low frequency deep penetrating seismic waves and therefore mainly detect large scale geological structures (tectonic traps).

The future trend in marine seismic exploration is oriented towards the utilization of high resolution sources with the aim of identifying more subtle, mainly stratigraphic oil traps.

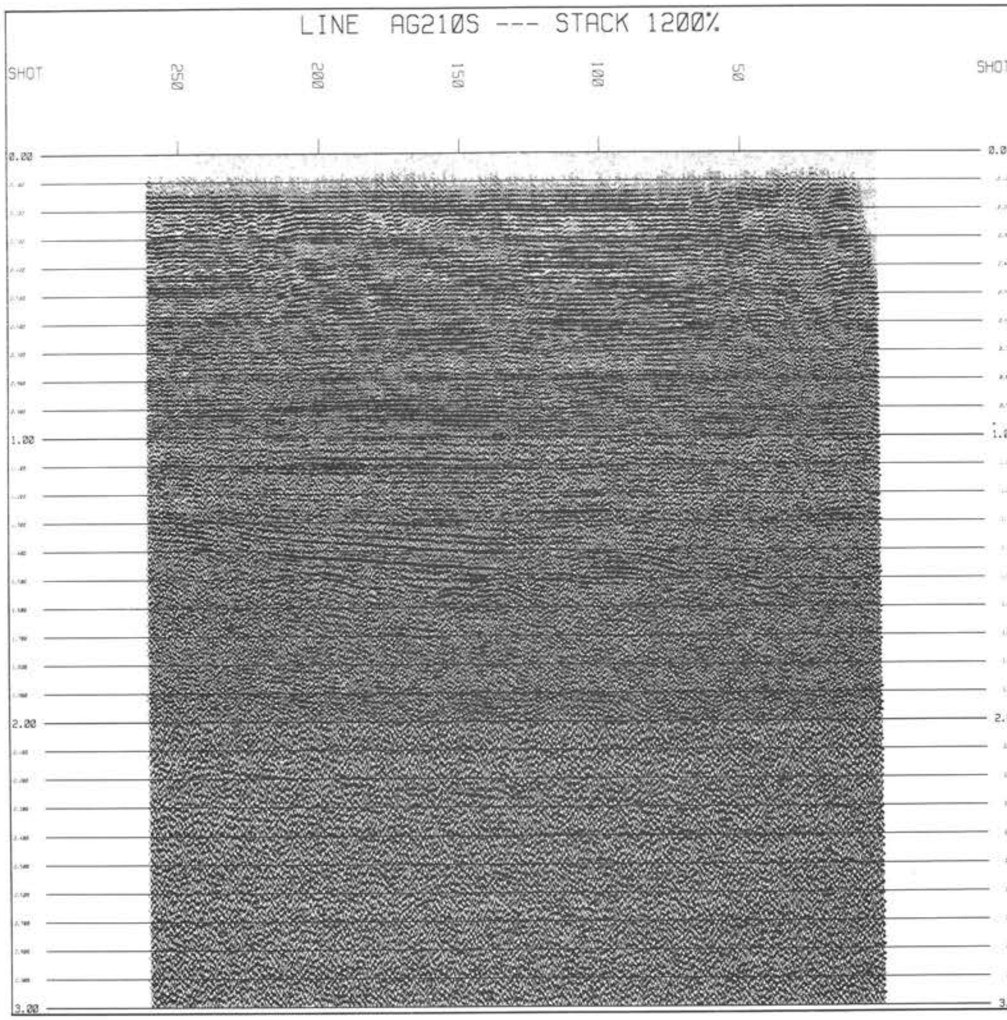

Fig. 8 - The same profile as in Fig. 7 obtained using a "Sparker-Array" source.

The type of sparker source described here seems to show an improvement in terms of depth penetration, while having the same high degree of resolution typical of electrical sources.

From this preliminary test, it is confirmed that this prototype electro-acoustic transducer provides an improved penetration of sedimentary sequences, and images reflectors at greater depths than those obtained by traditional sparker-array configurations at the same energy.

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