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Résumé de l'article

Dans le cas des systèmes sismiquesde profilage sismique de haute résolu-tion utilisés en milieu marin, les niveauxd'énergie d'impulsion et les variationsd'impédance sont faibles, les bandespassantes requises sont larges, les tauxd'atténuation des signaux sont élevéset, la source sismique, les capteurs etla géométrie de leur disposition sont desfacteurs aussi importants dans la déf-inition du profil que ne l'est la configura-tion géologique du milieu sondé. Aussi,avant que la géophysique ne puisseprétendre jouer un rôle plus importantdans l'évaluation des paramètres envi-ronnementaux des milieux marins, desressources qui s'y trouvent et des défisqu'ils posent au génie, il faudra d'abordaméliorer la résolution, la quantificationet la fiabilité de la cueillette, du traite-ment et des modes de représentationdes données des levés sismiques de haute résolution. Le présent article traitedes quatre grandes catégories de tech-nologies d'impulsion (forme d'onde con-trôlée, masses d'eau accélérées, explo-sion, et implosion) et de la géométriede la disposition des capteurs et passeen revue l'histoire des tendances enmatière de levé et de technologie desoutien des levés sismiques de réflexionde haute résolution en milieu marin.

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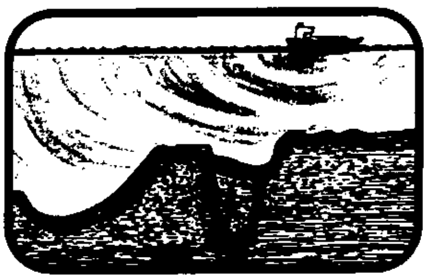

Environmental Marine Geoscience 1. Status and Trends of Marine High-Resolution Seismic Reflection Profiling: Data Acquistion

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We usually find oil in new places with old ideas. Sometimes we find oil in an old place with a new idea, but we seldom find much oil in an old place with an old idea. Several times in the past we have thought that we were running out of oil, whereas, actually we were only running out of ideas (the late Parke Dickey, Professor Emeritus, University of Tulsa)

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SUMMARY
For marine high-resolution seismic reflection profiling systems, source energy is low, impedance changes are small, wide bandwiths are required, signal attenuation is high, and the seismic source, receiver and geometry are as critical to the resulting profile image as is the subsurface geology. For geophysics to play a larger role in offshore environmental, resource and engineering assessment there is a need for improvements in resolution, quantification and consistency in the collection, processing and display of marine high-resolution seismic reflection data. This paper reviews the four broad categories of source technologies (controlled waveform, accelerating water mass, explosive and implosive), receiver geometric considerations, and discusses evolving survey and technological trends in support of marine high-resolution seismic reflection surveying.

RÉSUMÉ
Dans le cas des systèmes sismiques de profilage sismique de haute résolution utilisés en milieu marin, les niveaux d'énergie d'impulsion et les variations d'impédance sont faibles, les bandes passantes requises sont larges, les taux d'atténuation des signaux sont élevés et, la source sismique, les capteurs et la géométrie de leur disposition sont des facteurs aussi importants dans la définition du profil que ne l'est la configuration géologique du milieu sondé. Aussi, avant que la géophysique ne puisse prétendre jouer un rôle plus important dans l'évaluation des paramètres environnementaux des milieux marins, des ressources qui s'y trouvent et des défis qu'ils posent au génie, il faudra d'abord améliorer la résolution, la quantification et la fiabilité de la cueillette, du traitement et des modes de représentation des données des levés sismiques de haute résolution. Le présent article traite des quatre grandes catégories de technologies d'impulsion (forme d'onde contrôlée, masses d'eau accélérées, explosion, et implosion) et de la géométrie de la disposition des capteurs et passe en revue l'histoire des tendances en matière de levé et de technologie de soutien des levés sismiques de réflexion de haute résolution en milieu marin.

INTRODUCTION
High-resolution marine seismic reflection techniques have been used extensively in the last 20-30 years for Quaternary mapping, seafloor process investigations, engineering applications, exploration for aggregates and placers, and habitat studies (see for example King and Fader, 1976; Ardus, 1980). The demands of high-resolution seismic reflection data are distinct from traditional oil exploration seismic reflection techniques. There are, therefore, distinct differences in acquisition system sources and receivers, and in the processing and display of data. This paper reviews elementary theory of seismic reflection in the context of high resolution, and summarizes the various types of equipment presently available. It also discusses evolving survey and development ideas and trends in the technology in support of marine high-resolution subbottom reflection surveying.

REVIEW: REFLECTION THEORY
For thorough discussion about theory on the behaviour of sound in the marine environment, see such texts as Urick (1982, 1983) or Brekhovskikh and Godin (1990). For texts more specific to seismic reflection, see Claerbout (1985), Yilmaz and Doherty (1987), or Helbig and Treitel (1997). Brouwer and Helbig (1998) provide a text more suitable to high-resolution seismic reflec-

tion practice, including a discussion on digital acquisition. It is focussed on land-based seismic work, however. A brief review is provided herein.

Seismic reflection is the reflection of sound at a boundary between two media with different acoustic impedances (an impedance contrast). In almost all cases of single-channel, high-resolution profiling, the reflection of sound occurs at near-normal incidence and an echo series is produced, representing changes in acoustic impedance through the sediment column. Acoustic impedance is the product of two physical properties of the media: acoustic compressional velocity and bulk density. The plane wave reflection coefficient (μ_o) from a smooth surface is the ratio of the amplitude (pressure) of the reflected to the normal incident wave, and is given by:

$$\mu_o = \frac{I_2 - I_1}{I_2 + I_1} = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1} \qquad (1)$$

where I = acoustic impedance, V = compressional-wave sound speed, ρ is the bulk density, and subscripts relate to the two media on either side of the impedance boundary. The energy reflected from an impedance boundary and back to a detector is proportional to the amplitude of the sound impulse produced by the source and the magnitude of the impedance contrast (the absolute value of the reflection coefficient). In high-resolution seismic reflection the reflection coefficient can be affected significantly by scattering due to boundary surface roughness (see Urick, 1982). This effect is shown in Equation 2.

$$\mu = \mu_o \exp\left(\frac{-4\pi h \sin\theta}{\lambda}\right)^2 = \mu_o e^{-R^2} \qquad (2)$$

where μ_o is the reflection coefficient that would exist if the surface were smooth (as shown in equation 1), and μ is the reflection coefficient from the rough bottom. The exponential factor is the effect of surface roughness, where R is the Rayleigh parameter.

Energy not reflected or scattered will be transmitted through the boundary and into the lower layer. The amount of energy reflected is independent of the sign of the reflection coefficient, but the waveform will be phase-reversed for a negative impedance contrast when I_2 is less than I_1. In marine seismic work, the upper layer is invariably water, which supports the seismic sources and detectors, with the underlying sediments forming a complex layered situation. Detection of reflected waves at the receiver depends upon the source impulse amplitude, receiver geometry and sensitivity, transmission and other energy-loss processes such as scattering and absorption, the amplitudes in the reflection coefficient series represented by the sediment column, and the ambient noise level at the detector.

In a given medium, the visco-elastic loss processes associated with absorption have a dependence on range and the frequency of the propagating wavefront, approximately of the form

$$P_r = \frac{P_o e^{-\alpha_k fr}}{r} \qquad (3)$$

Where P_r is the pressure amplitude received at a distance r (two-way) from the source with a reference pressure P_o at a distance, say 1 m, α_k is the absorption coefficient for a particular material in nepers/m/Hz and fr is the received frequency. The term $e^{-\alpha_k fr}$ represents the absorption losses and the term $1/r$ represents attenuation in amplitude due to spherical spreading processes. Spherical spreading is affected by roughness as well. From a smooth bottom (a reflector), the component of transmission loss due to spreading is $20\log(2r)$. When the bottom is rough (a scatterer) the spreading loss becomes $20\log(r^2)$.

Equation 3 indicates that high-frequency sound will suffer higher energy losses, resulting in smaller echo amplitudes at the detector. In high-resolution marine seismic profiling, relatively small impedance changes within sediment bodies are normal, and high frequencies with broad bandwidths are sought from relatively low-energy sources. In addition, the scale of surface roughness can be of the same order as the resolution required, so scattering can be a significant component of the signal. These physical constraints result in a significant difference between high-resolution seismic reflection practice and the deeper- and lower-resolution seismic reflection work more typical of the oil exploration industry.

From a systems viewpoint, a seismic trace or signature is the result of the convolution of the Earth's reflection coefficient series with the sound source, incorporating the effects of various loss processes and noise as discussed above. Convolution in the time domain is a mathematical process equivalent to multiplication in the frequency domain. Any frequencies absent from the source, therefore, are absent from the resulting seismic trace. The source of sound, therefore, is as important in determining the character of the seismic profile as is the Earth's reflection coefficient series. The ideal sound source to accurately image the Earth's reflection coefficient series is a zero-phase delta function, which is an impulse at time zero yielding power at all frequencies in the frequency domain. This function is physically impossible to achieve in practice, but most seismic sources approximate it by attempting to create a sharp pressure impulse in the time domain, which is equivalent to emitting energy over a broad frequency spectrum. The alternative approach is to emit a long time-domain signal with broad-band frequency characteristics, such as Chirp or vibrator-type sources. In these cases, the signal has to be post-processed to "collapse" the long time-domain signature.

HIGH-RESOLUTION SEISMIC REFLECTION SOURCES

In selecting a seismic source, there is a trade-off between penetration, which demands lower frequencies, and resolution, which requires greater bandwidths (including higher frequencies). In addition, the detector has to be sensitive to all frequencies generated by the source. Since the ambient or background noise level is a function of bandwidth of the detector, higher resolution typically means higher levels of noise at the receiver. This "in-band" noise will tend to mask the desired echoes from the target sediments. This need to recognize detailed coherent echoes in the presence of high noise levels also distinguishes high-resolution seismic reflection work.

One way to minimize noise is to design a detecting system with directional properties. Another is to configure and operate the various components of the system in a manner that will minimize the generation of certain types of noise. Not all high-resolution marine seismic techniques will be discussed; however, four categories of sources will be presented, along with their respective advantages and disadvantages, followed by a short discussion of receivers. Particular emphasis will be placed on state-of-the-art systems. Verbeek and McGee (1995) present a thorough technical presentation of a number of seismic systems for marine high-resolution reflection surveying.

All acoustic sources used in marine seismic profiling have to convert stored energy into motion of the surrounding water mass. This motion, which manifests itself as a pressure wave, propagates outward from the source and is subjected to the physical laws of reflection, absorption, diffraction, refraction and scattering in the host media. There are four broad categories of marine seismic sources for high-resolution studies in common use today: 1) controlled waveform, 2) accelerating water mass, 3) implosive and 4) explosive.

Controlled Waveform (Sonar)

Sonar transducers have been in common use for nearly 4 decades in marine geological studies (Hersey *et al.*, 1963; VanReenan, 1964; King, 1967; Damuth, 1980). Urick (1983) provides a thorough discussion of sonar technology. This category includes systems ranging from high-frequency bathymetric echo sounders to the modern Chirp profiler. These systems operate on the principle that an electric field applied to the piezo-electric material forming the transducer results in a mechanical strain proportional to the electric field strength. If the frequency of the applied field is close to a mechanical resonant mode, then the electrical energy can be very efficiently changed into vibrational motion, which is easily coupled to the surrounding water. This process is reversible such that a pressure signature applied to the transducer produces an electrical analog of the incident waveform. The 3.5 kHz subbottom profiler (Fig. 1), for example, has been a mainstay of high-resolution reflection profiling for decades. These systems can be mounted within the hull of a ship or can be towed in a separate vehicle. There are few alternatives for deep-water profiling (>1500 m water), because of the inherent strength of these transducers.

The conventional sonar signal consists of several cycles of a sine wave, the frequency depending upon the resonant frequency of the piezo-electric crystal (Figs. 1B, C). Frequencies of operation for subbottom studies are typically in the range of 20 Hz to 20 kHz. The maximum amount of acoustic power that can be generated by a transducer is limited by the cavitation effect: the formation of bubbles on the face of the projector (Urick, 1983). These bubbles form by the rupture of water caused by the negative pressures of the generated sound field. Table 1 summarizes some of the characteristics of sonar transducers.

There have been modifications to the standard sonar technology to address some of the limitations presented in Table 1. The parametric sounder, such as the Krupp-Atlas Parasound system (Grant and Schreiber, 1990; Speiss and Villinger, 1990; Rostek *et al.*, 1991) (Fig.

Table 1 Summary of sonar transducers as high-resolution seismic reflection sources.

Advantages	Limitations
• ease of use and low maintenance	• narrow bandwidth (except Chirp)
• high repeatability and efficiency	• no phase information
• deep-tow capability	• low power and high frequency limits penetration in hard sediments
• functional in deep water	• long pulse length limits resolving power
	• moderate source pattern directivity

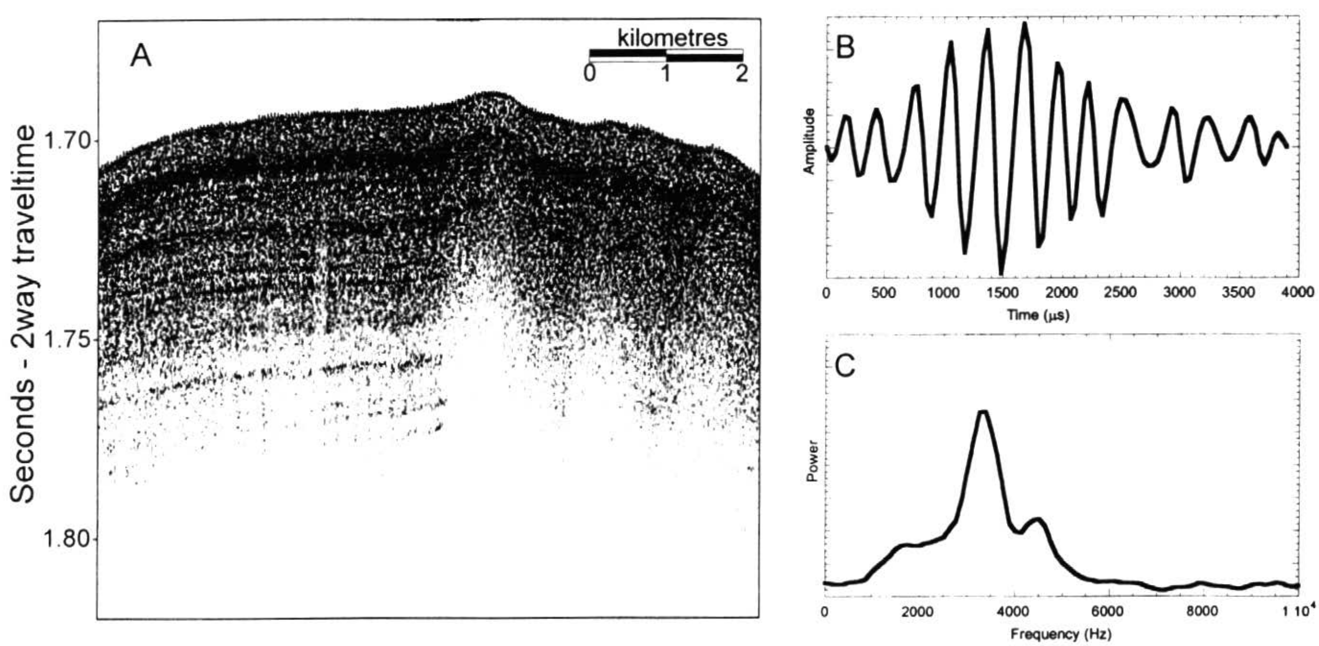


Figure 1 (**A**) 3.5 kHz profile from a hull mounted transducer system in 1250 m water depth, showing 60 m of subbottom penetration. (**B**) 3.5 kHz source signature of the system used in this profile, with associated frequency spectrum (**C**), showing a peak frequency of 3.2 kHz and a very narrow bandwidth.

2), emits two signals of different frequencies simultaneously. The interference of these two signals generates a secondary frequency equal to their difference. This secondary frequency is generated only in the main part of the beam, where the highest energy levels occur. A low-frequency, very narrow beam transmission, virtually free of side-lobes, is produced as a result. This parametric effect gives high directionality and low-frequency operation (lower propagation losses) from a physically small transducer. The Parasound system is operated with a fixed primary frequency of 18 kHz and a second operator-selectable primary frequency, generating a secondary frequency between 2.5 kHz and 5.5 kHz. The narrow beam angle, however, provides difficulty for imaging slopes, and the signal bandwidth is very small.

The Chirp sonar is the latest advance in sonar technology for subbottom profiling (Schock *et al.,* 1989; Schock and LeBlanc, 1990). It transmits selectable frequency modulated (FM) pulses, in essence "sweeping" through a range of frequencies, anywhere between about 400 Hz and 20 kHz. The sweep gives the source function a wide bandwidth, but also a long pulse length (Fig. 3). To achieve the theoretical temporal resolution predicted by the inverse of the bandwidth, the FM pulse is compressed using a digital compression filter, analogous to a match filter or a spiking deconvolution, and, in essence, removing the long wave length of the source signal (Quinn *et al.,* 1998). This processing achieves significant signal-to-noise improvement over conventional sonar systems and restores phase information. The application of the Chirp to high-resolution seismic reflection surveying would not be possible were it not for digital sampling of the received waveform, and subsequent processing (see Bull *et al.,* 1998 and Quinn *et al.,* 1998 for processing of Chirp data).

Accelerating Water Mass

A number of systems using rapid water mass displacement are in common usage for seismic reflection surveying. These include electro-dynamic sources known as "boomers" (Edgerton and Hayward, 1964; Hutchins *et al.,* 1976; Simpkin and Davis, 1993) and pneumatic sources such as air and sleeve

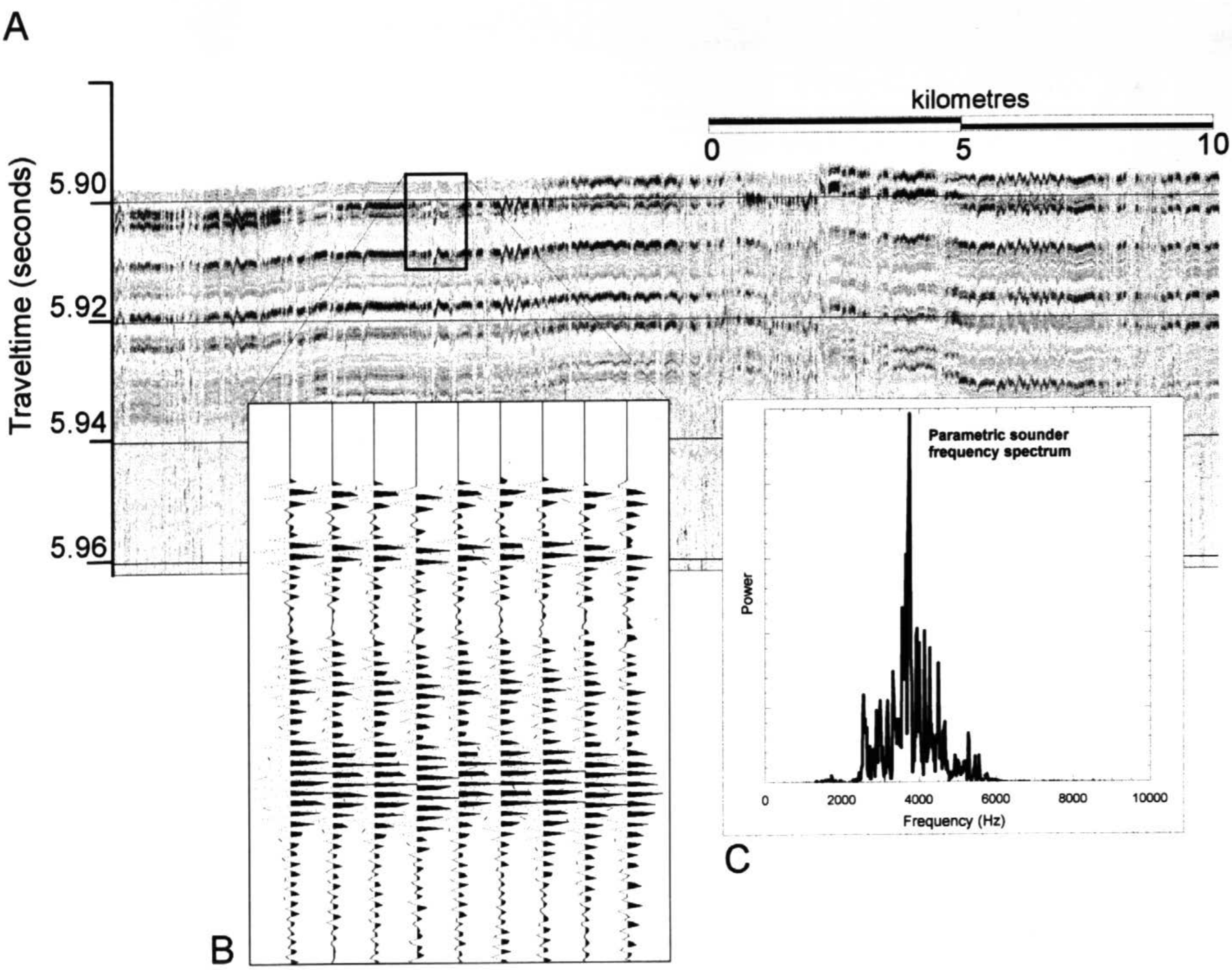


Figure 2 Parametric sounder (Krupp-Atlas Parasound) record from the Amundsen Basin in 4400 m water depth with subbottom penetration of greater than 40 m, while breaking ice. Since there is no phase information, sonar data are generally plotted as the envelope of the amplitude (the inverse transform of the square of positive frequencies), as shown in (**A**). Compare this record with (**B**) an amplitude trace display plot, as seismic data typically are shown. Frequency analyses (**C**) show these data are very narrow band, centered at about 3.9 kHz.

guns (Giles, 1968; Parkes and Hatton, 1986). The boomer produces a pressure pulse, which at long range mirrors the acceleration history of a moving circular metal piston. When electrical energy stored in a capacitor is discharged through a flat coil positioned immediately behind the piston, induced electrical currents oppose the coil current, producing repulsive forces to drive the piston and coil rapidly apart. This piston movement produces a very stable pressure signature. Stored energy in the range of 100-1000 Joules can be absorbed with existing boomers, and peak pressures on the order of 1 bar-metre with a pulse duration of 100-200 s can be obtained. Table 2 and Figure 4 summarize some of the characteristics of the boomer. The boomer ranks as one of the best impulse-type sources for high-resolution seismic reflection studies (see, for example, Darling, 1999). The boomer source signatures shown as insets in Figures 4 and 7 demonstrate significant energy spanning a broad frequency bandwidth. This bandwidth can be of critical importance, as shown by Marlow *et al.* (1996) in a comparison of boomer and Chirp profiles.

The most common sources of the water mass acceleration technique for medium and deep penetration are those which use compressed air as a storage medium (see Kramer *et al.*, 1968, Giles, 1968; Ziolkowski *et al.*, 1982; Parkes and Hatton, 1986; Racca and Scrimger, 1986; Quinn *et al.*, 1988). Air guns and their most recent derivatives, sleeve guns and GI guns, explosively release a volume of compressed air into the surrounding water. Plots of these pneumatic source signatures typically show a strong bubble pulse following the primary pulse (Fig. 5B). The bubble pulse is a "source" of sound generated by the oscillating expansion and collapse of air under hydrostatic pressure after it has been released and during its ascent to the sea surface. The amplitude of the bubble pulse increases with the volume of the air released and the tow depth of

Table 2 Summary of boomers as high-resolution seismic profiling sources.

Advantages	Limitations
• high repeatability	• limited deep-tow capability
• high peak frequencies and large bandwidth	• high voltage, high current
• high output levels relative to sonar	• physical size constrained by boomer plates
• some directivity	• low efficiency

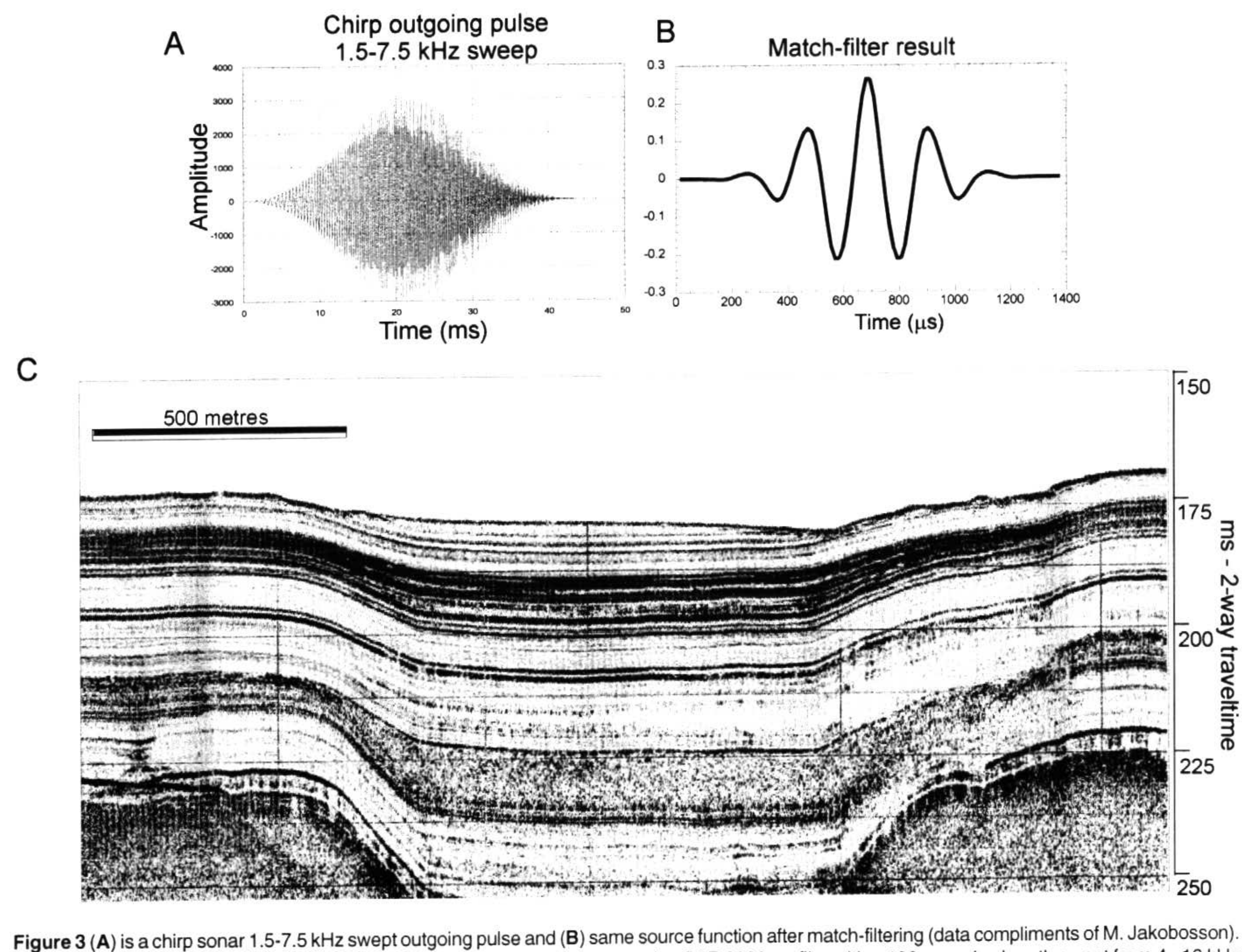


Figure 3 (**A**) is a chirp sonar 1.5-7.5 kHz swept outgoing pulse and (**B**) same source function after match-filtering (data compliments of M. Jakobosson). (**C**) is an example of a chirp profile from Lake Huron collected with a Datasonics CAP 6000 profiler with a 100 ms pulse length swept from 4 - 10 kHz (image courtesy of L. Mayer).

the gun. The period of oscillation is described by the Rayleigh-Willis formula (Kramer *et al.*, 1968):

$$T=1.14\rho^{0.5}(KQ)^{0.333}(d+33)^{-0.833} \quad (4)$$

where T is the bubble oscillation period in seconds, ρ is the density of the surrounding fluid, Q is the potential energy of the expanded bubble, K is a constant whose value depends on the units chosen to express Q, and d is the depth of the center of the bubble in the fluid.

The energy contained in the bubble pulse can cause subsidiary notches in the amplitude spectra of a signature (Fig. 5B). The frequencies affected depend upon the period of oscillation, as described in equation 4. It creates a bubble pulse "multiple" in the seismic record as well (Fig. 5C), which interferes with the primary trace and, thereby, can affect the ability to interpret the seismic section. The bubble pulse can be reduced and overall signal enhanced by the use of an array of guns triggered simultaneously or pene-simultaneously (see for example, Giles and Johnston, 1973; Safar, 1976; Nooteboom, 1978; Mosher *et al.*, 1998). This technique generally yields a broader-frequency spectrum, higher-signal amplitude and, typically, a more repeatable source (see Fig. 5).

The air guns used in high-resolution profiling are similar to those used in conventional exploration seismic reflection work except that they are considerably smaller, involving as little as 16.4 cm^3 (1 in^3) of air at 7000 kPa (~1000 psi). For achieving deeper penetration compared to boomer and sonar systems, and acquiring signal in the presence of high noise, the air gun source is excellent, but care must be taken in its deployment, operational configuration, and tuning to optimize the source signature. Table 3 and Figure 5 summarize some of the characteristics of air guns and resulting data.

Implosive Sources

Implosive sources are those that use the implosion of a bubble or vacuum to create an impulsive pressure wave. The Flexichoc, mini-Flexichoc and Vaporchoc are such systems, operating on the implosion of a gas or vapour bubble (Games, 1988; Cholet *et al.*, 1979; Manin, 1979; Quinn *et al.*, 1988). A more recent development is the water gun, which is available in a variety of sizes for shallow- and medium-depth targets (Hutchinson and Detrick, 1984; Racca and Scrimger, 1986; Lugg and Brummitt, 1986; Tree *et al.*, 1986; Quinn *et al.*, 1988). This system uses a compressed volume of air to accelerate a closed piston, which then projects a slug

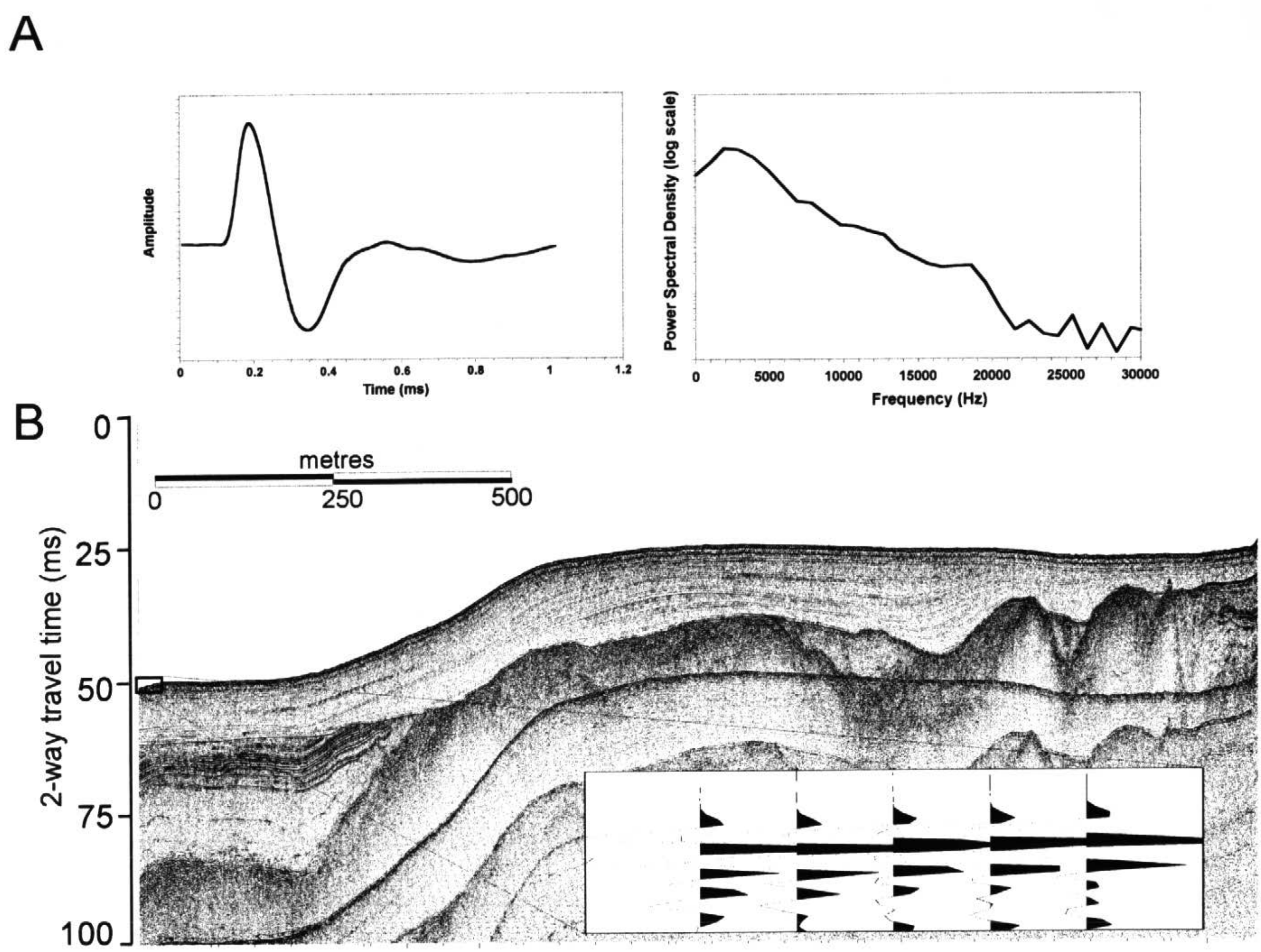


Figure 4 (**A**) IKB-Seistec™ boomer source function with frequency spectrum for 280 Joule output setting, and (**B**) an example Seistec profile from the Gulf Islands, BC. The boomer source shows good shot to shot repeatability (as shown in the inset), relatively high energy levels, and an even distribution of energy throughout the spectrum of 500-20,000 Hz, resulting in an acceptable combination of resolution and subbottom penetration.

of water at high speed into the surrounding water mass. The cavity produced in the wake of this slug is, in fact, a near vacuum, which implodes and produces a signature with a sharp pressure rise and acceptable broadband characteristics. A low-frequency, low-amplitude precursor is produced by initial acceleration and retardation of both the piston and water mass, however. The water gun's operation and suitability is similar to that of the air gun's (Table 3), typically with a slightly broader frequency spectrum (Fig. 6).

Explosive Sources

Explosive sources include dynamite, blasting caps, and gas exploders (*e.g.*, Cole, 1948; Richard and Pieuchot, 1956; Godfrey *et al.*, 1968). The most common explosive source for high-resolution marine surveying, however, is the sparker (Edelmann, 1968; Cassand and

Table 3 Summary of airgun technology as a high-resolution seismic reflection source.

Advantages	Limitations
• high energy output	• very limited deep-tow capability
• broadband in the lower frequencies	• no directivity
• in common use (accessible and familiar technology)	• regular maintenance required
	• bubble pulse interference

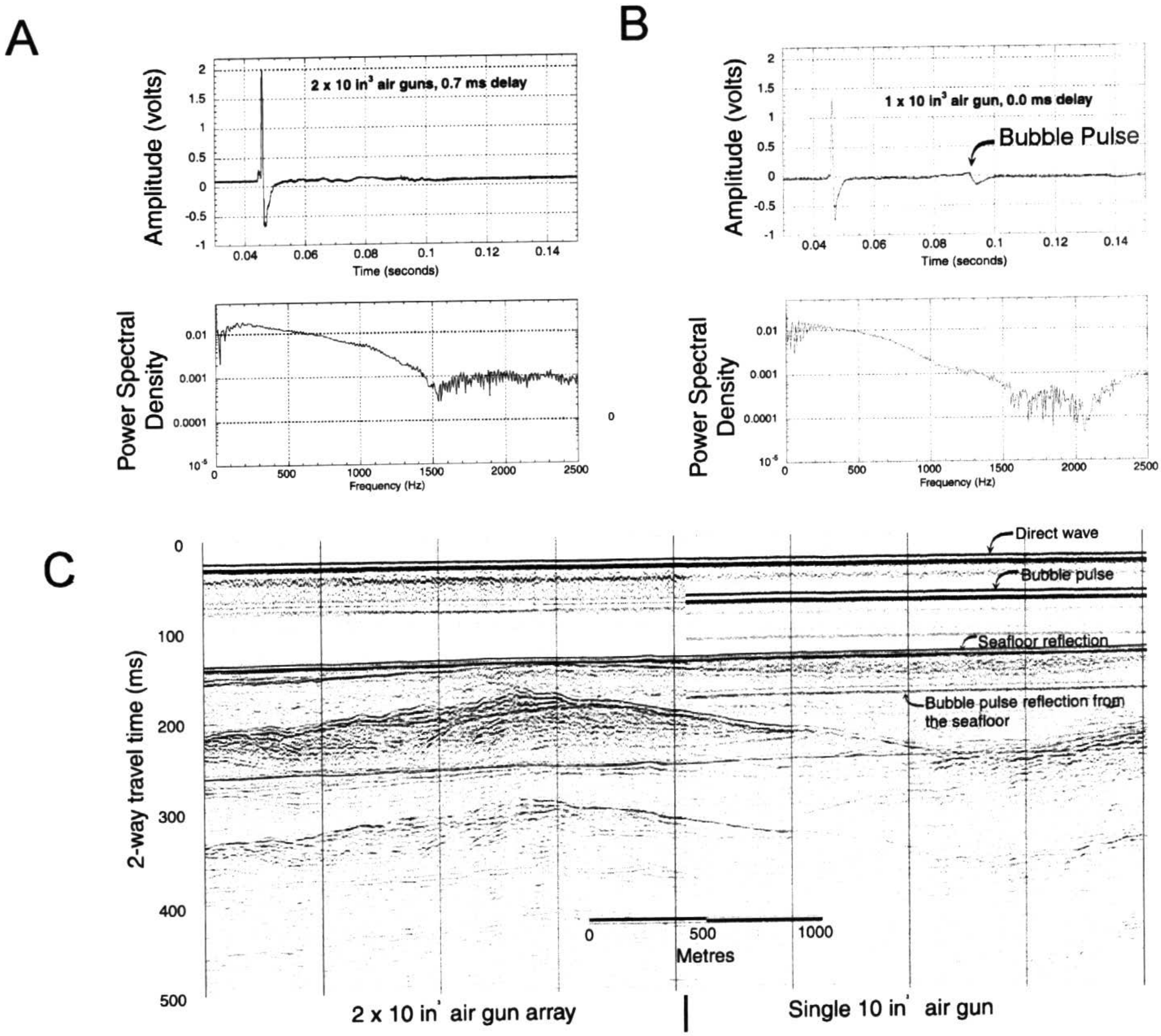


Figure 5 (**A**) shows a source function for a 2 x 10 in³ tuned airgun array compared with (**B**), a single 10 in³ airgun source function. (**C**) is an example profile in the eastern Strait of Juan de Fuca resulting from first, the two gun array shown in A, then the single 10 in³ airgun. Note the lower energy levels (lower gain) in the second part of the profile and the predominance of the bubble pulse.

Lavergne, 1970; Bidgood, 1974). It was one of the first marine seismic sources, and the technique is still useful for high-resolution or deeper seismic investigations at relatively low cost. The sparker generates a steam bubble by discharging electrical energy through a point electrode surrounded by a conducting fluid, *i.e.,* salt water. The rapid expansion of the steam bubble generates a nearly ideal positive pressure impulse. Input energies range from 100 Joules to 30 kJoules. Unfortunately, the bubble expands until it exceeds equilibrium ambient pressure and then collapses to produce a second high-pressure bubble, similar to the bubble oscillations of pneumatic sources discussed above. This process continues, with multiple bubbles being produced, until all energy is dissipated. This oscillation increases the duration of the source signature, causes destructive interference in frequencies of interest (notching), and is variable, affecting the repeatability of the source (Fig. 7). As in the case of arrays of air guns, the use of multiple-tip sparkers can attenuate the bubble effect through interaction of multiple bubbles. A multiple electrode arrangement can also increase the peak pressure (Cassand and Lavergne, 1970). Table 4 and Figure 7 show some of the characteristics of a sparker-based profiler.

HIGH-RESOLUTION SEISMIC REFLECTION RECEIVERS

For sonar systems, the same piezoelectric crystal or crystals act as both transmitter and receiver. In the other systems discussed, the detector used for marine seismic profiling primarily consists of pressure-sensitive piezoelectric elements called hydrophones, which produce an output voltage proportional to the change in amplitude of the surrounding pressure field (see Urick, 1983; Helbig and Treitel, 1997 for the physical principles and design of hydrophones). These detectors are normally enclosed in a flexible watertight tube (streamer) and towed some distance away from the source and off to one side of the survey vessel, where low noise conditions are more likely to exist. The output from a streamer is influenced by many other sound "sources," which tend to mask the desired echoes from the sediment column. These unwanted noise "sources" include the direct acoustic wave from the sound source itself and many natural and man-made generators of noise, including weather-induced waves, ocean waves, towing noise, ship and machinery noise, turbulence, bubbles and remotely generated noises such as shipping traffic and potentially other seismic operations.

The use of acceleration-cancelling hydrophones can reduce certain forms of motion-induced noise but the primary method of noise reduction is to add directionality to the streamer by using an array of detectors suitably spaced where their individual outputs are

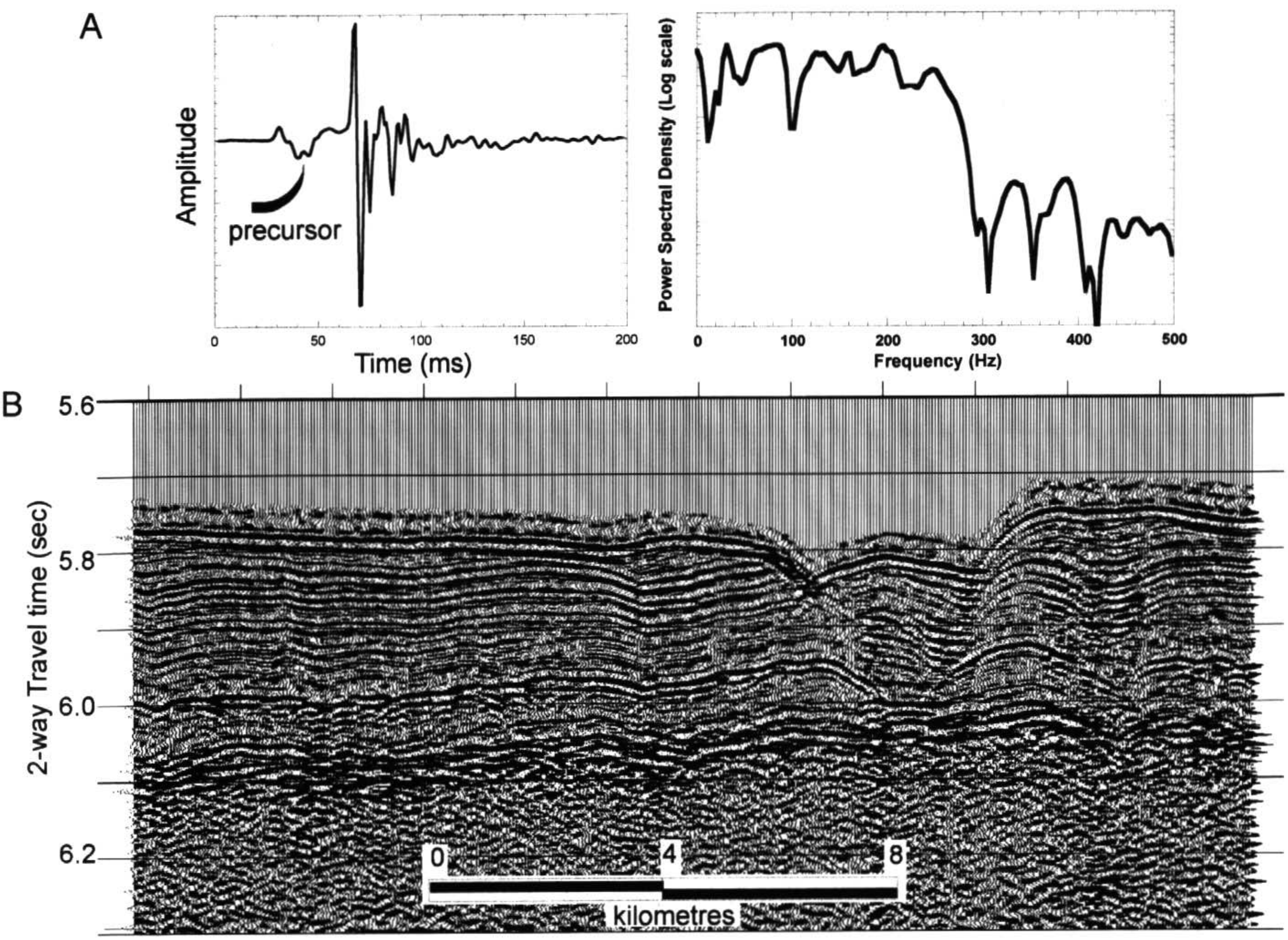


Figure 6 (**A**) shows the source function and power spectrum of an 80 in^3 water gun (implosive source). The water gun yields a sharp pulse with a characteristic precursor. (**B**) is a sample water gun profile from the western equatorial Pacific.

Table 4 Summary of sparker sources for high-resolution seismic profiling.

Advantages	**Limitations**
• high energy output	• poor repeatability
• broadband with relatively high frequencies possible	• limited directivity
• moderate deep-tow capability	• long pulse length with bubble pulse
• cost effective, convenient and reliable source	

summed (Windisch and Ewing, 1967; Knott *et al.*, 1975). The principle works in two ways. 1) For random, non-coherent noises, averaging will take place and noise will be reduced by a factor of $N^{1/2}$, where N is the number of active elements. If the signals observed by the individual detectors are in-phase, the summed amplitude will be N times that from a single detector, while signal amplitudes from random noise or out-of-phase noise should again cancel. 2) If the array is towed horizontally, then the acoustic field from the seafloor sediment will be in-phase, while received signals from other directions will tend to cancel. The design of multi-element arrays, however, is complex, and together with certain operational parameters, must match the source characteristics to achieve the best results for a particular geologic setting. There are four critical factors to consider: 1) hydrophone spacing, 2) tow depth, 3) array length with respect to water depth, and 4) source-receiver geometry.

The spacing of the individual hydrophone elements in an array is governed by Nyquist sampling theory (Nyquist, 1928). To avoid aliasing (the construction of artificial low frequencies; Shannon, 1949) there must be at least two hydrophones per wavelength of the highest frequency of interest in order to appropriately sample the waveform. In normal incidence reflection, if the hydrophone spacing is 1 m, then

$$f = \frac{c}{2\lambda} = \frac{1500\,m/s}{2 x 1 m} = 750\,Hz \quad (5)$$

where c is the speed of sound in water and λ is wavelength, in this case the hydrophone spacing.

The maximum frequency that can be sampled with this spacing is 750 Hz.

The hydrophones in a group must be in phase in order to add constructively. This requirement means that the difference in travel distance of the seismic signal between the nearest and farthest hydrophone in a group must be smaller than a quarter of a wavelength of the signal. The relation between the maximum array length (L), water depth (D), source-receiver offset (X) and minimum wavelength (λ) can be expressed as

$$L = -X \pm \frac{1}{2}\sqrt{4X^2 + \lambda^2/4 + 2\lambda\sqrt{4D^2 + X^2}} \quad (6)$$

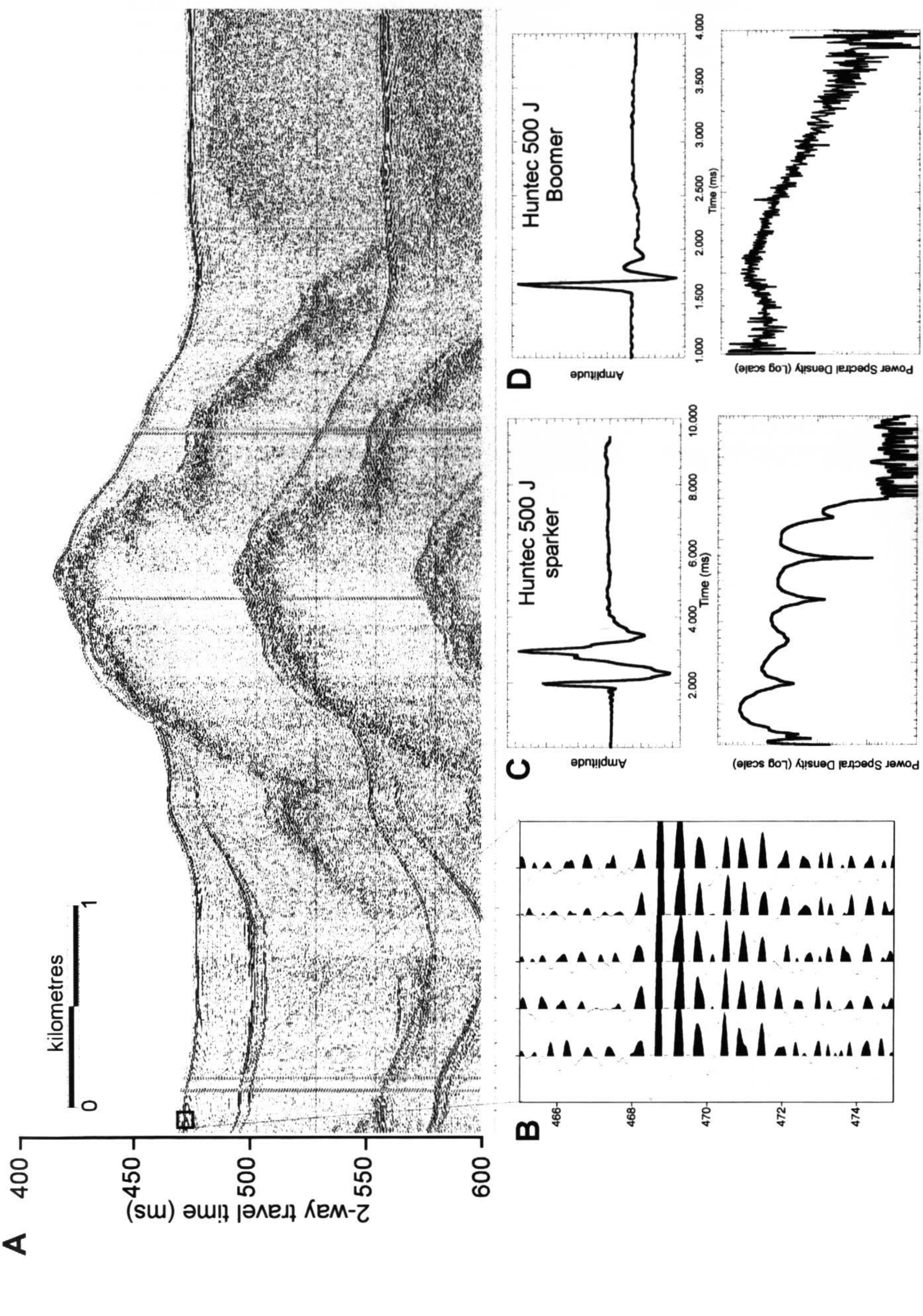
Equation 6, solutions for which are demonstrated in Figure 8, shows that shorter array lengths are required for higher frequencies, shallower water depths, and increasing source-receiver offset.

Tow depth is critical to the frequency characteristics of the received signal as well. A returning echo is received by the hydrophone, but the pressure wave also passes the hydrophone and is reflected from the sea surface back to the hydrophone. If the depth to the hydrophone from the sea surface is more than one-quarter of a wavelength of the highest frequency of interest, then destructive interference will occur between the reflected and the incoming wavelet. An alternative is to tow the hydrophone deep enough so that the sea-surface reflected wave does not reach the hydrophone within the data window of interest (*e.g.*, Hutchins *et al.*, 1976, 1985; Robb *et al.*, 1981; Purdy and Gove, 1982; Bowen, 1984).

A number of recent developments in high-resolution seismic reflection receivers have attempted to make streamers more versatile so they can be used in a variety of water depths and with a variety of seismic sources. The "nested array" is a single streamer with two or more "nests" of hydrophones of different spacing and active lengths. These nests, or groups, can be recorded separately and later, during processing, be summed. Recording the groups separately gives the potential to use a shorter group for the near-surface reflections where high resolution is desired, and to add in the signals of the outside groups for deeper penetration, which results in an improved signal-to-noise (S/N) ratio. If the water is deep enough, the signals of several groups can be summed in the amplifier before recording. More complex streamers can be designed such that the "nests" can be dynamically assigned through software control, in order to optimize the array for many situations.

A further development in high-resolution seismic streamers, the use of multi-channel arrays, has been adapted from the seismic exploration industry (see texts on seismic processing, such as Claerbout, 1985; Yilmaz and Doherty,1987; Helbig and Treitel, 1997). Many hydrophone channels with equal spacing in a linear array yield redundancy of sampling at any one particular point of the sea floor through successive shots centred on that point. This redundancy, through the process of common midpoint stacking, allows for a dramatic increase in the S/N ratio with the potential for observing deeper targets. A byproduct of this technique is subbottom velocity (speed of propagation) information from the sediment column. The technique, however, dramatically increases the amount of post-processing required and can actually result in a decrease in S/N if great care is not taken. The final results may show great improvements in record quality (Fig. 9) but invariably, heavily processed data will have a lower spectral bandwidth, hence lower resolution when compared to an equivalent single-channel record. Multi-channel techniques

Figure 7 (facing page) (**A**) is a profile in the Strait of Georgia, BC, acquired with a Huntec 500 Joule sparker system. (**B**) shows detail of several traces, showing reasonable shot-to-shot similarity but with some start time delays (examine the fourth trace from the left in **B**) which are typical of sparker systems, i.e. it is difficult to control precisely the ignition time of the spark. (**C**) shows the sparker source function in the time and frequency domains. There is usable energy up to 6000 Hz but with significant spectral nulls, *i.e.*, the power is not evenly distributed among all frequencies, as compared with the Huntec boomer source shown in (**D**), for example. This notching is a result of destructive interference caused by the strong bubble pulse. The boomer shows power at much higher frequencies than the sparker, but less power at the low frequencies.


A
2-way travel time (ms)
400
450
500
550
600
kilometres
0
1
B
466
468
470
472
474
C
Huntec 500 J sparker
Amplitude
Time (ms)
Power Spectral Density (Log scale)
Frequency (Hz)
D
Huntec 500 J Boomer
Amplitude
Time (ms)
Power Spectral Density (Log scale)
Frequency (Hz)

also demand that the source and streamer positions be known very accurately (within a small part of a wavelength), which again is not always practical for very high-resolution reflection profiling.

A number of profiling systems that employ a fixed geometry with minimal source-receiver offsets have been used over the years in deep-tow configurations. In sonars, the piezo-electric elements are reversible and can transmit as well as receive acoustic signals. This mono-static arrangement offers a fixed geometry with zero offset and directionality at higher frequencies. The Huntec Deep Tow Seismic (DTS) system, which can be towed to depths of up to

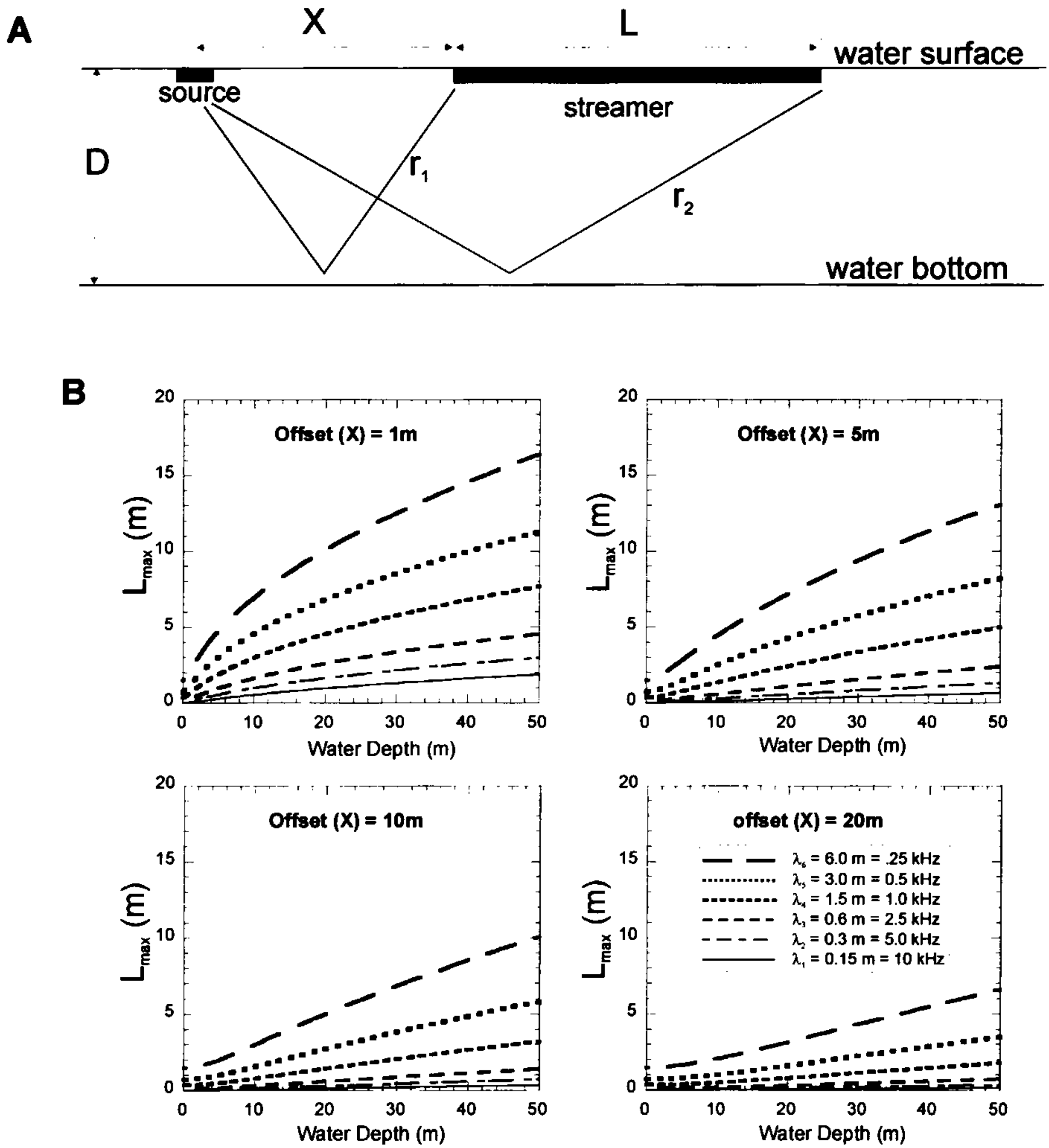


Figure 8 (**A**) Schematic of commonly used source-receiver geometry. (**B**) Relationship between water depth (D), source-receiver offset (X), minimum wavelength (λ_i) or highest frequency of interest and maximum array length (L_{max}) for source-receiver geometry as shown in **A**, and described in equation 6. Modified from Verbeek and McGee (1995).

500 m, incorporates a pressure-compensated boomer source and both a single-element hydrophone mounted beneath the boomer plate and a short streamer towed behind (McKeown, 1975; Hutchins *et al.*, 1976). This dual-channel arrangement optimizes resolution and penetration performance in deep water.

The IKB-Seistec™ profiler employs a "line-in-cone" array adjacent to the boomer plate (Simpkin and Davis, 1993; Mosher and Law, 1996). In this case, a short hydrophone with a number of closely spaced elements is mounted axially within the cone. The arrangement provides some noise reduction in summation of the signal, while the vertical mounting keeps the acoustic aperture small. The cone reflector provides further directional properties to the system, reducing side echoes and direct interference from the source. This configuration is optimized for very shallow-water profiling.

HIGH-RESOLUTION SEISMIC REFLECTION DIGITAL ACQUISITION

As a result of the reduction in cost and increase in speed of computers and analogue-to-digital converters, digital acquisition of high-resolution seismic reflection data is commonplace today. Often, however, digitization is used primarily as a data storage mechanism and little attention is paid to the consequences of inappropriately sampled data. McGee (1995) and Brouwer and Helbig (1998) provide valuable discussions on the digitization of high-resolution seismic reflection signals. A brief review of digital sampling is provided below.

Digital sampling requires the discretization of a continuous time series (seismic signal) such that the time series can be recreated without loss of detail. In signal digitization, there are two critical parameters affecting this accuracy: 1) digital resolution and 2) sample rate. Digital resolution is the number of bits comprising each digital sample. It affects the level of accuracy with which a sample of amplitude can be represented, and is generally referred to as the dynamic range of a system. The range of amplitudes (gains) expected from a seismic system must "fit" within the range of values possible of the data format type, and yet the value must represent accurately the amplitude of the signal relative to other amplitudes within

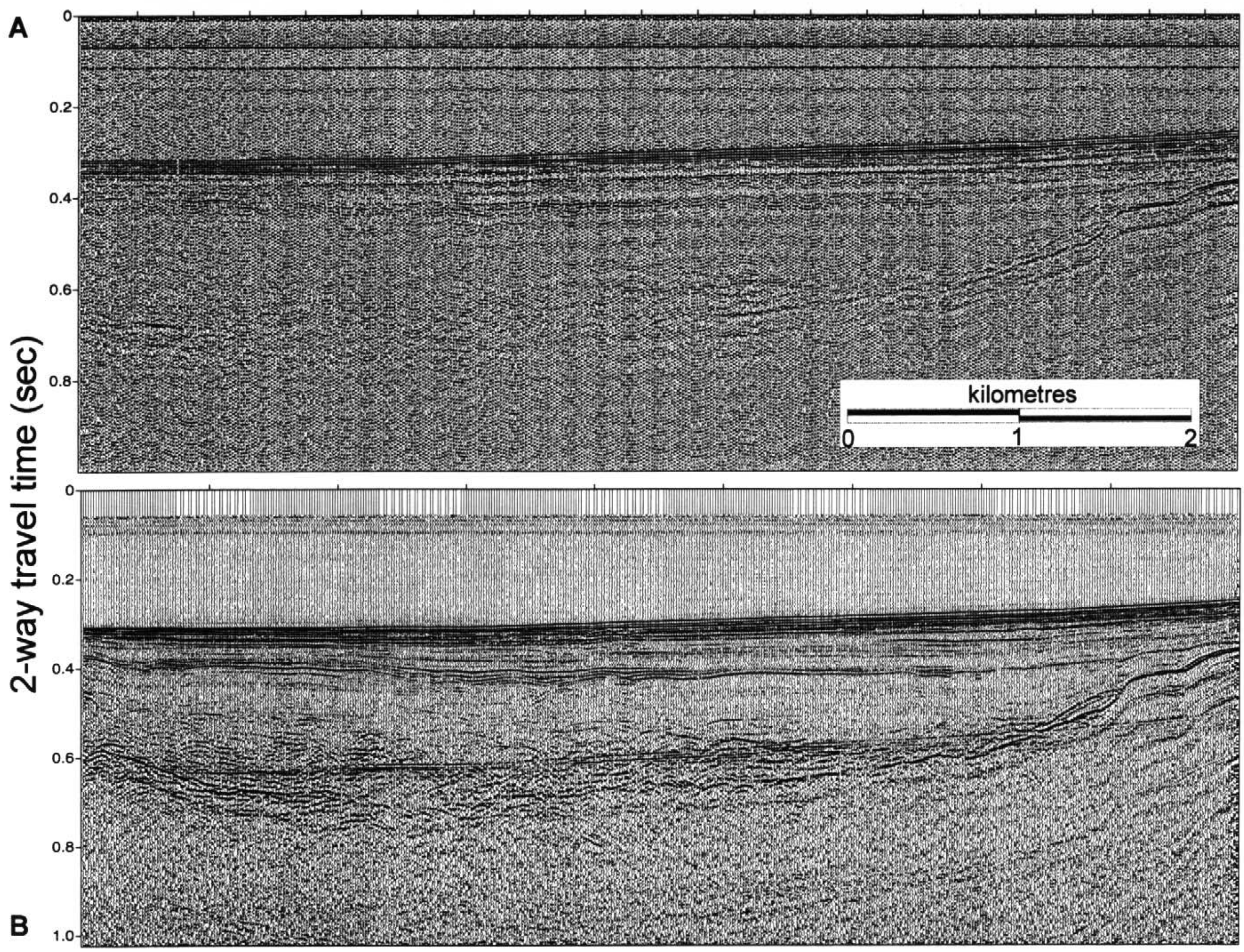


Figure 9 A 10 in^3 airgun profile from Saanich Inlet, BC: (**A**) is a single channel profile extracted from the multichannel array, and (**B**) is the 6-fold stacked record from the 24-channel array. There is abundant coherent noise on the single channel record, the result of a faulty digitizing board. The stacked section (**B**) highlights the improvements that can be achieved in the signal-to-noise ratio through move-out and stacking in multichannel array processing.

the seismic trace. For example, if the signal is to be acquired as short integer data, then each sample requires 8 bits, and the digitized value must lie between -16,384 and +16,383. If the data are acquired as long integers, there are 16 bits available, and the range of values must lie between -32,768 and 32,767. The cost of more bits per data point is longer acquisition times, and the requirement of larger storage capacity and longer processing time.

The relevant point to seismic acquisition is that the amplitude gains of the received signals must be adjusted to fit within the range of values provided by the bit-resolution of the data type. Any analogue signal outside the range will be "clipped" and thus be unrecoverable. On the other hand, severe gain dampening will reduce the dynamic range of the signal, and hence the true variability within the signal will be lost. Low-cut filters should be applied to reduce high-amplitude, low-frequency noise that could occupy a significant portion of the digital converter's dynamic range, and thereby restrict the range remaining available for the seismic signal.

Seismic signal sampling theory, in large part, has been governed by the pioneering work of Nyquist (1928) and Shannon (1949). Shannon's theorem states that if a function contains no frequencies higher than W, it is completely determined by giving its ordinates at a series of points spaced $1/2W$ seconds apart. This theorem indicates that a waveform can be described by a minimum of two samples per cycle (as shown in equation 5, above). This sampling frequency is referred to as the nyquist frequency and is given by $|f|=1/2d$, where d is the sample interval (*e.g.*, if a sample interval is 4 ms, the nyquist frequency is 1/(2*.004) = 125 Hz). If a signal has frequencies above the nyquist, these frequencies will be folded into lower frequencies, causing the data to be aliased. For example, if an original signal contains frequencies of 150 Hz, and the data are sampled at a nyquist frequency of 125 Hz, the 150 Hz data will be "folded" into the 100 Hz band (125-(150-125) = 100 Hz). To prevent aliasing, the signal should be pre-conditioned before discretization in order to eliminate frequencies higher than those that are to be sampled. This can be accomplished with a high-cut or anti-aliasing filter.

A mathematical contradiction is encountered when trying to avoid aliasing of seismic signals. Seismic signals are causal, *i.e.*, they are zero prior to their onsets, and are finite in length. Shannon's theorem applies to signals that are non-causal and that are limited in frequency. It is not possible for a non-zero function to be both limited in time and limited in frequency. This contradiction can lead to some confusion as to the choice of appropriate anti-aliasing filters and sample rates for a given seismic system. McGee (1995) provides in-depth discussion of this dilemma. The choice of the filter must be a compromise between resolution and data volume. In addition, any filtering has side effects on data quality. Suffice to say, in the interest of subsequent digital processing, the anti-alias filter must be set high enough that the resolution provided by the seismic source is not seriously degraded. When setting sampling parameters, it is safe to assume that oversampling will not jeopardize data quality, but inadequately sampled data can never be recovered.

SUMMARY AND FUTURE DEVELOPMENTS

As marine high-resolution seismic reflection profiling plays a more prominent role in environmental and engineering assessments and in resource exploration, there is a need for improvement in resolution, quantification of seismic data and, in turn, consistency in collection and post-processing. Aside from the Chirp sonar, there have been few recent developments of seismic source technology for marine high-resolution profiling. The IKB-Seistec™ profiler, nested arrays, and multichannel arrays are examples of adaptations of receivers to improve high-resolution profiling. Careful attention in specifying the type of source, receiver, their geometrical arrangement, and the operational conditions to match the target sediments and survey requirements can dramatically improve results. The onset of signal digital acquisition requires the appropriate use of sampling parameters in order to accurately record all the required information that is contained within the signal, without aliasing the data. Digital acquisition can lead to many types of signal and image processing to improve record quality and layer resolution, but will not compensate for poor data collected by an ill-configured survey. Real-time data processing, as with match filtering of Chirp data, can improve data quality without adding to the effort level. Real-time processing can be readily adapted to all the systems described if the signals are digital.

Canadian companies have led the world during the last 25 years in the development of the technology to acquire high-quality, high-resolution seismic reflection data, with systems such as the Huntec DTS (Hutchins *et al.*, 1976; King and Fader, 1976), NSRF deep towed sparker (Bidgood, 1974), Seabed II (Hutchins *et al.*, 1985) and more recently the IKB-Seistec™ profiler (Simpkin and Davis, 1993). Some of the best subbottom imagery in the published literature comes from Canadian marine geologic practitioners as a result (see, for example King and Fader, 1986; Praeg *et al.*, 1986, 1992; Bornhold and Prior, 1990; Todd and Lewis, 1993; Syvitski, 1993; Mosher and Law, 1996; Davies *et al.*, 1997; Todd *et al.*, 1997; Todd *et al.*, in press). These systems are still at the forefront in terms of data quality, and have great potential for further development, but have lacked investment in recent years compared with sonar profiling and more recent multibeam hydrographic systems. Re-engineering of the boomer technology and appropriate receivers, combined with real-time signal digitization and processing could further improve data quality and at the same time make these complex systems easier to operate.

In addition to the data collection technology, the approach to surveying needs to take advantage of digital data acquisition, processing, and geo-referenced imagery. Concepts of digital sampling must be applied not only to the seismic signal but to the survey strategy as well. In this way, resulting data and interpretations of the data can be used effectively in a GIS environment.

Three feasible goals to improve marine high-resolution seismic reflection data quality include: 1) the collection of digital data with real-time processing and mapping, 2) the collection of true multi-channel high-resolution reflection data, and 3) the acquisition of true 3-D high-resolution data, as is the standard today for lower-resolution data for the oil exploration industry, and not pseudo-3-D with close line spacing (*e.g.*, Davies and Austin, 1997),

The greatest limitation to multi-channel and 3-D surveying is accurate positioning of the source and receivers in both vertical and horizontal planes. Their positions not only need to be known, they need to be controlled to within a fraction of the wavelength of the highest frequency of interest. Ocean swell and currents can be sufficient to disrupt the necessary geometry. The technology does exist at present, however, to overcome some of these obstacles. Swath bathymetry mapping, for instance, employs a sophisticated combination of differential GPS and inertial navigation systems to accurately position the acoustic beams on the sea floor. A similar array of position and motion sensors could be employed to control the source and receivers in high-resolution reflection profiling to achieve greater positioning resolution albeit at great monetary cost. A merging of the swath/multibeam, 3-D seismic exploration, and high-resolution subbottom technologies would, therefore, greatly enhance our ability to image the shallow subsurface.

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REFERENCES

Ardus, D.A., ed., 1980, Offshore Site Investigation: Graham and Trotman Publishers, London, 291 p.

Bidgood, D.E.T., 1974, A deep-towed sea bottom profiling system: Oceans 74, IEEE Conference, Proceedings, Halifax, NS, v. 2, p. 96-107.

Bornhold, B.D. and Prior, D.B., 1990, Morphology and sedimentary processes on the subaqueous Noeick River delta, British Columbia, Canada: International Association of Sedimentologists, Special Publications, v. 10, p. 169-181.

Bowen, A.N., 1984, A high-resolution seismic profiling system using a deep-towed horizontal hydrophone streamer: Marine Geophysical Researches, v. 6, p. 275-293.

Brouwer, J. and Helbig, K., 1998, Shallow High-Resolution Reflection Seismics, Handbook of Geophysical Exploration, v. 19: Elsevier Science Ltd., Amsterdam, 391 p.

Brekhovskikh, L.M. and Godin, O.A., 1990, Acoustics of Layered Media I: Springer-Verlag, New York, 240 p.

Bull, J.M., Quinn, R. and Dix, J.K., 1998, Reflection coefficient calculation from marine high resolution seismic reflection (Chirp) data and application to an archeological case study: Marine Geophysical Researches, v. 20, p. 1-11.

Cassand, J. and Lavergne. M., 1970, Etinceleurs multi-electrodes à haute résolution: Geophysical Prospecting, v. 18, p. 380-388.

Cholet, J., Grau, G., Magneville, P. and Rialan, J., 1979, The Flexichoc implosion source; a system for offshore seismic prospection by means of extended source arrays, *in* New Technologies for Exploration and Exploitation of Oil and Gas Resources: Graham and Trotman, London, UK, p. 805-834.

Claerbout, J.F., 1985, Imaging the Earth's Interior: Blackwell Scientific Publications, Boston, 398 p.

Cole, R.H., 1948, Underwater Explosions: Princeton University Press, Princeton, NJ.

Damuth, J.E., 1980, Use of high-frequency (3.5-12 kHz) echograms in the study of near bottom sedimentation processes in the deep-sea, review: Marine Geology, v. 38, p. 51-75.

Darling, A., 1999, There's more to life than Chirp: International Ocean Systems Design, May/June issue, p. 19-20.

Davies, T.A. and Austin, J.A. Jr., 1997, High-resolution 3D seismic reflection and coring techniques applied to late Quaternary deposits on the New Jersey shelf: Marine Geology, v. 143, p. 137-149.

Davies, T.A., Bell, T., Cooper, A.K., Josenhans, H., Ployak, L., Solheim, A., Stoker, M.S. and Stravers, J.A. , 1997, Glaciated Continental Margins: An Atlas of Acoustic Images: Chapman & Hall, London, 315 p.

Edelmann, H., 1968, An underwater sound source with higher seismic efficiency: Geophysical Prospecting, v. 16, p. 474-490.

Edgerton, H.F. and Hayward, E.C., 1964, The Boomer sonar source for seismic profiling: Journal of Geophysical Research, v. 69, p. 3033-3042.

Games, K.P., 1988, Flexichoc FHC50 seismic source: First Break, v. 6, p. 254-260.

Giles B.F., 1968, Pneumatic acoustic energy source: Geophysical Prospecting, v. 16, p. 21-53.

Giles, B.F. and Johnston, R.C., 1973, System approach to air-gun array design: Geophysical Prospecting, v. 21, p. 77-101.

Godfrey, L.M., Stewart, J.D. and Schweiger, F., 1968, Application of dinoseis in Canada: Geophysics, v. 33, p. 65-77.

Grant, J.A. and Schreiber, R., 1990, Modern swath sounding and sub-bottom profiling technology for research applications: The Atlas Hydrosweep and Parasound Systems: Marine Geophysical Researches, v. 12, p. 9-21.

Helbig, K. and Treitel, S., 1997, Seismic Exploration on CDRom: Elsevier Science Ltd, London.

Hersey, J.B., Knott, S.T., Caulfield, D.D., Edgerton, H.E. and Hays, E.E., 1963, Adaptation of sonar techniques for exploring the sediments and crust of the earth beneath the ocean: Radio and Electronic Engineer, v. 26, p. 245-250.

Hutchins, R.W., McKeown, D.L. and King, L.H., 1976, A deep-tow high resolution seismic system for continental shelf mapping: Geoscience Canada, v. 3, p. 95-100.

Hutchins, R.W., Dodds, J. and Fader, G., 1985, Seabed II: High resolution acoustic seabed surveys of the deep ocean, *in* Advances In Underwater Technology and Offshore Engineering, v.3, Offshore Site Investigation: Graham and Trotman Ltd., p. 69-83.

Hutchinson, D.R. and Detrick, R.S., Jr., 1984, Watergun versus air gun: a comparison: Marine Geophysical Researches, v. 6, p. 295-310.

King, L.H., 1967, Use of conventional echo-sounder and textural analysis in delineating sedimentary facies–Scotian Shelf: Canadian Journal of Earth Sciences, v. 4, p. 691-708.

King, L.H. and Fader, G.B.J., 1976, Application of the Huntec deep tow high-resolution seismic system to surficial and bedrock studies: Grand Banks of Newfoundland: Geological Survey of Canada, Report of Activities, Part C, Paper 76-1C, p. 5-7.

King, L.H. and Fader, G.B.J., 1986, Wisconsinan glaciation of the Atlantic continental shelf of southeast Canada: Geological Survey of Canada Bulletin 363, 72 p.

Knott, S.T., Hess, F.R. and Nowak, R.T., 1975, Uniformly-sensitive line hydrophones: Woods Hole Oceanographic Institute, Technical Report 02543, Woods Hole, MA, 20 p.

Kramer F.S., Peterson R.A. and Walter W.C., 1968, Seismic energy sources 1968 handbook: Bendix United Geophysical Corporation, 57 p.

Lugg, R.D. and Brummitt, J.G., 1986, The P400 watergun source in the quest for improved resolution at all depths: Geophysical Prospecting, v. 34, p. 665-685.

Manin, M., 1979, An attempt to control the frequency spectrum transmitted during the implosion generated by a steam gun in offshore seismics (Vaporchoc), *in* New Technologies For Exploration And Exploitation Of Oil And Gas Resources: Graham and Trotman, London, UK, p. 3-11.

Marlow, M.S., Hart, P.E., Carlson, P.R., Childs, J.R., Mann, D.M., Anima, R.J. and Kayen, R.E., 1996, Misinterpretation of lateral acoustic variations on high-resolution seismic reflection profiles as fault offsets of Holocene bay mud beneath the southern part of San Francisco Bay, California: Marine and Petroleum Geology, v. 13, p. 341-348.

McGee, T.M., 1995, High-resolution marine reflection profiling for engineering and environmental purposes. Part B: Digitizing analogue seismic signals: Journal of Applied Geophysics, v. 33, p. 287-296.

McKeown, D.L., 1975, Evaluation of the Huntec (70) Hydrosonde Deep Tow Seismic System: Bedford Institute of Oceanography, Report B1-R-75-4, Dartmouth, NS, 115 p.

Mosher, D.C. and Law, L.K., 1996, Application of concurrent marine electromagnetic and marine seismic high resolution profiling, British Columbia, Canada: Journal of Engineering and Environmental Geophysics, v. 1, p. 215-228.

Mosher, D.C., MacDonald, R., Hewitt, A.T. and Hill, W.T., 1998, Small airgun arrays for high resolution geophysical surveying: Geological Survey of Canada, Current Research, 1998D, p. 43-50.

Nooteboom, J.J., 1978, Signature and amplitude of linear air-gun arrays: Geophysical Prospecting, v. 26, p. 194-201.

Nyquist, H., 1928, Certain topics in telegraph transmission theory: American Institute of Electrical Engineering Transactions, April, p. 617-644.

Parkes, G. and Hatton, L., 1986, The Marine Seismic Source: D. Reidel Publishing Co., Dordrecht, 114 p.

Praeg, D., D'anglejan, B. and Syvitski, J.P.M., 1992, Seismostratigraphy of the middle St. Lawrence estuary: a Late Quaternary glacial marine to estuarine depositional/ errosional Record: Géographie physique et Quaternaire, v. 46, p. 133-150.

Praeg, D.B., Maclean, B., Hardy, I.A. and Mudie, P.J., 1986, Quaternary geology of the southeast Baffin Island continental shelf: Geological Survey of Canada, Paper 85-14, 38 p.

Purdy, G.M. and Gove, L.A., 1982, Reflection profiling in the deep ocean using a near bottom hydrophone: Marine Geophysical Researches, v. 5, p. 301-314.

Quinn, F.J., Vigier, L., Poley, D.F. and Simpkin, P.G., 1988, Evaluation/Calibration of Marine Sources for High Resolution Seismic Studies: Geological Survey of Canada, Open File 1520, 178 p.

Quinn, R., Bull, J.M. and Dix, J.K., 1998, Optimal processing of marine high-resolution seismic reflection (Chirp) data: Marine Geophysical Researches, v. 20, p. 13-20.

Racca, R.G. and Scrimger, J.A., 1986, Underwater acoustic source characteristics of air and water guns:Canadian Department of National Defence, Defense Research Establishment Pacific, Contract No. 06SB 97708-5-7055, unpublished report, 213 p.

Richard, H. and Pieuchot, M., 1956, Seismic efficiency of explosives: Geophysical Prospecting, v. 4, p. 167-180.

Robb, J.M., Sylwester, R.E. and Penton, R., 1981, Simplified method of deep-tow seismic profiling: Geo-Marine-Letters. v. 1, p. 65-67.

Rostek, F., Spiess, V. and Bleil, U., 1991, Parasound echosounding; comparison of analogue and digital echosounder records and physical properties of sediments from the equatorial South Atlantic: Marine Geology, v. 99, p. 1-18.

Safar, M.H., 1976, Efficient design of air-gun arrays: Geophysical Prospecting, v. 24, p. 773-787.

Shannon, C.E., 1949, Communication in the presence of noise: Proceedings of the Institute for Radio Electronics, v. 37, p. 10-21.

Schock, S.G., LeBlanc, L.R. and Mayer, L.A., 1989, Chirp subbottom profiler for quantitative sediment analysis: Geophysics, v. 54, p. 445-450.

Schock, S.G. and LeBlanc, L.R., 1990, Chirp Sonar: new technology for subbottom profiling: Sea Technology, v. 31, p. 35-43.

Simpkin, P.G. and Davis, A., 1993, For seismic profiling in very shallow water, a novel receiver: Sea Technology, September, 1993, p. 21-28.

Speiss, V. and Villinger, H., 1990, Digital sedimentechography with the new Parasound echosounder system: Eos, Transactions, v. 71, p. 1408.

Syvitski, J.P.M., 1993, Glaciomarine environments in Canada: an overview: Canadian Journal of Earth Sciences, v. 30, p. 354-371.

Todd, B.J. and Lewis, C.F.M., 1993, A reconnaissance geophysical survey of the kawartha lakes and Lake Simcoe, Ontario: Géographie physique et Quaternaire, v. 7, p. 313-323.

Todd, B.J., Lewis, C.F.M., Nielsen, E., Thorleifson, L.H., Bezys, R.K. and Weber, W., 1997, Lake Winnipeg: geological setting and sediment seismostratigraphy: Journal of Paleolimnology, v. 19, p. 215-244.

Todd, B.J., Fader, G.B.J., Courtney, R.C. and Pickrill, R.A., 1999, Quaternary geology and surficial sediment processes, Browns Bank, Scotian Shelf, based on multibeam bathymetry: Marine Geology, in press.

Tree, E.L., Lugg, R.D. and Brummitt, J.G., 1986, Why waterguns?: Geophysical Prospecting, v. 34, p. 302-329.

Urick, R.J., 1982, Sound Propagation in the Sea: Peninsula Publishing, Los Altos, CA, 212 p.

Urick, R.J., 1983, Principles of Underwater Sound: McGraw-Hill Book Company, New York, 423 p.

VanReenan, E.D., 1964, Subsurface exploration by sonar seismic systems, *in* Symposium of Soil Exploration, Atlantic City. NJ, 1963: American Society for the Testing of Materials, Special Technical Publication.

Verbeek, N.H. and McGee, T.M., 1995, Characteristics of high-resolution marine reflection profiling sources: Journal of Applied Geophysics, v. 33, p. 251-269.

Windisch, C.C. and Ewing, J.I., 1967, Some towed line hydrophone arrays for seismic reflection profiling: Lamont Geological Observatory of Columbia University, Technical Report , Palisades NY, 34 p.

Yilmaz, O. and Doherty, S.M., eds., 1987, Seismic Data Processing: Society of Exploration Geophysicists, Tulsa, OK, 526 p.

Ziolkowski A., Parkes G., Hatton L. and Haugland T., 1982, The signature of an air gun array: Geophysics, v. 47, p. 1413-1421.

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