LES ENJEUX LIÉS AUX LEVÉS SISMIQUES DANS L'ESTUAIRE ET LE GOLFE DU SAINT-LAURENT

Rapport de Ressources naturelles Canada
présenté à :
la commission du BAPE chargée de l'étude du dossier précité

Questions posées par le BAPE

1. Qu'est-ce que les levés sismiques récents faits par la Commission géologique du Canada dans l'estuaire et le golfe du Saint-Laurent révèlent en matière de potentiel d'hydrocarbures. (lettre du 29 avril de Mme Danielle Dallaire, Coordonnatrice du secrétariat de la commission.

Dans le cadre d'un travail de synthèse en cours sur le potentiel en hydrocarbures du Canada mené par la Commission géologique du Canada (CGC), les régions extra-côtières du golfe et de l'estuaire du Saint-Laurent ont été clairement identifiées comme régions frontières, c'est-à-dire, régions pour lesquelles les données géoscientifiques sont insuffisantes pour en préciser quantitativement le potentiel.

Dans le passé, des quelques forages réalisés dans le golfe, seul un au large de l'Île-du-Prince-Édouard (HB East Point) fut concluant (plus de 5 millions de pi^3 de gaz naturel par jour). D'autres forages (Brion) ont montré des intervalles renfermant des traces d'hydrocarbures. Cependant, ces forages ont été implantés sur la base de données sismiques datant des années 70 et de faible qualité en raison de la présence de nombreux obstacles à la pénétration des ondes sismiques dans le fond marin (effet de rebondissement ou « multiples »).

Les évaluations préliminaires, qui intègrent les connaissances géologiques terrestres en bordure du bassin (Gaspésie, Anticosti, T.-N., N.-B. et N.-É.) avec les données géophysiques terrestres et marines, suggèrent que les parties centre et sud du golfe, soit celles couvrant le bassin sédimentaire carbonifère des Maritimes, ont un potentiel gazier alors que pour la partie nord du golfe et de l'estuaire, les données sont incomplètes et un potentiel pourrait exister pour le pétrole, le gaz ou les deux.

Une campagne récente de sismique pour Corridor Resources sur Old Harry a fait ressortir diverses anomalies de marqueurs sismiques indiquant de façon probable la présence d'hydrocarbures (probablement de gaz) dans la structure. L'industrie a également suggéré la présence d'hydrocarbures par six suintements naturels identifiables sur les images satellites.

Les levés faits par la CGC (sparker-boomer-bulleurs) ont permis de faire avancer le niveau général de connaissances géoscientifiques de la région. Ainsi, les levés au sparker ont permis d'amorcer l'étude des successions quaternaires dans l'estuaire et l'embouchure du golfe. Aucun rapport de gaz n'y est mentionné. Les études au bulleur ont été menées dans l'estuaire et le golfe, en faisant abstraction des levés menés dans le cadre du programme Lithoprobe, lesquels ont documenté essentiellement l'architecture de la partie inférieure de la croûte continentale (hors du domaine économique). Les levés ont permis de fournir les premières données sur la nature du socle rocheux sous le golfe et l'estuaire (limites Grenville, Basses-Terres du Saint-Laurent, Appalaches). Cependant, la faible résolution de ces levés n'a pas permis de reconnaître un potentiel certain pour les hydrocarbures dans le nord du golfe. Pour les parties centre et sud, les levés ont permis de reconnaître la présence de grands diapirs de sel, lesquels constituent souvent des pièges dans des contextes géologiques analogues au golfe du Mexique, sans toutefois localiser des zones d'accumulation d'hydrocarbures certaines ou probables.

Le levé récent de la CGC effectué dans l'estuaire du Saint-Laurent dans le cadre de l'Initiative géoscientifique ciblée (IGC) a été mené en partenariat avec Hydro-Québec et les données sont confidentielles jusqu'en septembre 2004. Si Hydro-Québec autorise la divulgation de certains renseignements, nous pourrons fournir plus de détails sur la campagne de 2003. La campagne a cependant été basée sur les considération suivantes :

- La présence de nombreuses structures de dégazage (pockmarks) sur le plancher marin de l'estuaire est connue par le biais de levés bathymétriques de haute résolution. Ces structures suggèrent que du gaz libre de mouvement est présent dans les sédiments quaternaires.
- Des campagnes sismiques universitaires effectuées avant 2003 suggèrent la présence d'hydrates de gaz dans les épaisses successions quaternaires rencontrées à plus ou moins grande distance de l'embouchure du Saguenay.

Les données universitaires obtenues avant 2003 suggèrent la présence de gaz naturel dans les successions quaternaires de l'estuaire. Cependant, aucune indication sur le potentiel des successions rocheuses sous-jacentes n'est disponible. Il faut également savoir que nous ignorons si le gaz dans les successions quaternaires est biogénique (généré par la dégradation bactérienne de la matière organique récente emmagasinée dans les sédiments quaternaires) ou s'il est thermogénique (généré par la dégradation d'une matière organique ancienne (paléozoïque) dans les successions rocheuses). Les deux scénarios sont supportés par la présence reconnue de gaz naturel dans les successions quaternaires de la région de Trois-Rivières (champ de Pointe-du-Lac surtout thermogénique et réservoir de Yamachiche surtout biogénique).

Réponse préparée par Denis Lavoie, Ph.D., Chercheur scientifique, Commission géologique du Canada, CGC-Québec)

2. Est-ce que la Commission géologique du Canada demande toujours au ministère des Ressources naturelles, de la Faune et des Parcs du Québec des autorisations de réaliser des levés sismiques dans l'estuaire et le golfe du Saint-Laurent? Si oui, depuis quand? (lettre du 6 mai de Mme Danielle Dallaire, Coordonnatrice du secrétariat de la commission)

En ce qui concerne les levés dans le golfe du Saint-Laurent, la CGC en tant qu'agence scientifique ne fait pas d'exploration pétrolière et ne fait donc pas de demande de permis d'exploration à l'Office national de l'Énergie. La CGC est sujette aux règlements de la Loi canadienne sur l 'évaluation environnementale.

En ce qui concerne l'estuaire du Saint-Laurent, les mêmes conditions s'appliquent. De plus, étant donné l'absence de processus formel d'autorisation de tels levés au Québec, la CGC a demandé à l'été 2003 un permis de levé géophysique auprès du MRNFPQ, de façon à faire connaître ses activités prévues au Gouvernement du Québec. Ce permis a été obtenu, pour écarter tout problème d'interruption de travaux, étant donné les échéanciers de travaux très serrés du projet. Nous attirons à nouveau votre attention sur le fait que la CGC ne fait pas de travaux d'exploration pétrolière comme tel et ne requiert pas en ce sens un permis d'exploration pour détenir des droits éventuels d'exploitation. Un avis a aussi été donné car les levés de la CGC sont faits conjointement avec un partenaire, c'est-à-dire une composante de l'Université du Québec (INRS). En raison de ces différents éléments, une demande d'autorisation a aussi été transmise à la Direction des évaluations environnementales du ministère de l'Environnement du Québec, malgré que le gouvernement fédéral n'est pas assujetti à la loi sur la qualité de l'environnement du Québec. Enfin, connaissant les réserves émises par le Ministère des Pêches et Océans concernant les levés sismiques proposés récemment dans le golfe du Saint-Laurent, nous avons sollicité l'autorisation du MPO concernant la Loi sur les pêches et la Politique de gestion de l'habitat du poisson. Cette autorisation a été obtenue.

Selon la politique environnementale de RNCan, il incombe au gestionnaire de centre de responsabilité (GCR) de déterminer si une évaluation environnementale est nécessaire, ainsi que de la réaliser. Le Bureau des affaires environnementales (BAE) de RNCan est responsable de donner des avis et conseils au GCR en matière d'évaluation environnementale. Le BAE ne prend pas de décision en regard des évaluations environnementales, mais peut faire des recommandations aux GCR. Il est conseillé de consulter le MPO directement en ce qui à trait à la Loi sur les pêches et la Loi sur la protection des eaux navigables. Les GCR (chefs de projets ou gestionnaires de programmes) ont accès à un formulaire de détermination préliminaire de l'application de la Loi canadienne sur l'évaluation environnementale (LCÉE) sur l'intranet de RNCan. Les listes d'inclusion et d'exclusion sont accessibles respectivement à : http://www.ceaa.gc.ca/013/incllist_e.htm et http://www.ceaa.gc.ca/013/excllist_e.htm.

Pour les levés sismiques en particulier, l'article 79 (b) du Règlement sur la liste d'inclusion fait en sorte qu'une évaluation environnementale est requise dans le cas de « la prospection sismique marine ou d'eau douce si, au cours de celle-ci, la pression atmosphérique mesurée à une distance d'un mètre de la source peut être supérieure à 275,75 kPa (40 livres par pouce carré) ». Par contre il est possible qu'un autre Ministère fédéral déclenche la LCÉE en vertu d'un autre article du Règlement sur la liste d'inclusion, tel que l'article 43 qui exige une évaluation environnementale si « La détérioration, la destruction ou la perturbation de l'habitat du poisson par des activités concrètes exercées dans un plan d'eau, notamment des opérations de dragage ou de remblayage, qui nécessitent l'autorisation du ministre des Pêches et des Océans prévue au paragraphe 35(2) de la Loi sur les pêches ou l'autorisation prévue dans tout règlement pris par le gouverneur en conseil en application de cette loi. »

3. Quelles sont les prévisions de levés dans le golfe pour la Commission géologique du Canada et les partenaires? (courriel du 27 avril 2004 de Mme Édith Bourque, analyste)

Il n'y a pas de prévisions de levés dans le golfe du Saint-Laurent par la CGC, ou par des partenaires financés par la CGC. Les levés de la CGC de l'été 2004 s'effectueront à l'intérieur d'un polygone dans l'estuaire du Saint-Laurent limité de façon générale entre Tadoussac, les Escoumins, Trois-Pistoles et Rivière-du-Loup. Une carte des levés planifiés par la CGC a déjà été fournie au BAPE et nous la joignons en annexe pour compléter le dossier.

4. Existe-t-il des politiques fédérales sur les exploitations gazières dans le golfe, dans l'Est du Canada? (courriel du 27 avril 2004 de Mme Édith Bourque, analyste)

Les politiques fédérales en cette matière ne relèvent pas de la CGC. Nous vous suggérons de vous référer à M. Michel Chenier, de la Division de la gestion des régions pionnières, de RNCan pour répondre à cette question spécifique.

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En attendant, voici quelques renseignements qui pourront vous être utiles :

L'Office national de l'énergie, et les offices Canada-Nouvelle-Écosse et Canada-Terre-Neuve sont mandatés pour appliquer les lois fédérales qui concernent l'exploitation gazière dans l'Est du Canada. Ces lois sont disponibles à :
http://www.neb-one.gc.ca/ActsRegulations/index_f.htm

Ressources naturelles Canada est responsable de la gestion des terres pionnières du Canada et du golfe du Saint-Laurent. Vous trouverez plus d'information à : http://www2.nrcan.gc.ca/es/erb/prb/francais/View.asp?x=553, dont notamment cet extrait :

« La Direction des ressources pétrolières comprend la Division du pétrole, la Division du gaz naturel et la Division de la gestion des régions pionnières. Ces trois divisions ont ceci

en commun qu'elles ont toutes un mandat les amenant à s'occuper de questions pétrolières.
Les divisions du pétrole et du gaz naturel sont chargées de soutenir l'exploration, le développement, la production, le transport, la valorisation, le raffinage et la vente du gaz naturel, du pétrole et des produits pétroliers sur les marchés intérieurs et étrangers. Cette responsabilité est liée à la politique énergétique fédérale en général.

Ces divisions conseillent aussi le Ministre sur ses obligations réglementaires en vertu de la Loi sur l'Office national de l'énergie, la Loi sur le Bureau de la sécurité des transports, la Loi d'urgence sur les approvisionnements d'énergie et le Secrétariat d'arbitrage des gazoducs.

La Division de la gestion des régions pionnières gère les intérêts pétroliers du gouvernement fédéral dans les régions pionnières du Canada au sud du 60° N. Le mode de gestion des régions extracôtières de l'Est est régi par des accords fédéraux-provinciaux, en vertu desquels les activités extracôtières sont administrées et réglementées par des offices. Dans les régions exclues de ces accords, la Division de la gestion des régions pionnières se charge de l'administration et l'Office national de l'énergie, de la réglementation.

Dans le portefeuille général de la Direction, la Division de la protection des infrastructures énergétiques coordonne les initiatives visant à renforcer les mesures de sécurité et de protection des installations stratégiques de production et de transport de l'énergie du Canada ».

5. Est-il possible de fournir les lignes faites avec des sparker et boomer de la p. 3 de la présentation sur 2 figures différentes? (courriel du 27 avril 2004 de Mme Édith Bourque, analyste)

Ces figures ont été préparées et sont jointes dans le document ci-joint rédigé par M. Russell Parrott. En particulier, la figure 21 a été améliorée pour bien faire ressortir ces différences.

Questions posées par les commissaires lors de la première partie de l'audience publique

6. Les commissaires désirent obtenir une copie du rapport suivant: “Parrott, D.R., 1992, Seismic and acoustic systems for marine surveys used by the Geological Survey of Canada: background information for environmental screening”

Ce document est joint en annexe.

7. D'où provient le graphique fourni à la commission concernant l'intensité sonore des différents levés sismiques et des autres sons importants du domaine marin?

Une grande partie des données provient de références telles que : « Urick - Principles of Underwater Sound » de McGraw Hill. D'autres données proviennent du rapport de 1985 « Effects of Explosives in the Marine Environment », Canada Oil and Gas Lands Administration (COGLA).

7 a) Est-ce que l'échelle est exacte? Elle semble être en PSD - Spectral density plutôt qu'en SPL (Spectral power level). Le PSD est généralement utilisé pour évaluer le bruit de fond, tandis que le SPL est utilisé par l'industrie pour les mesures sismiques.

dB re 1 microPascal**2/Hz est équivalent à dB re 1 microPascal/sqrt(Hz) (dB est calculé comme 10 * dans le premier cas et 20* dans le deuxième.

7 b) Comment les valeurs du niveau sonore du bateau ont-elles été établies?

Comme précédemment démontré. Les légendes ont été améliorées dans le document de R. Parrott en annexe.

7 c) Existe-t-il une formule pour convertir : a) de PSD à SPL dB? b) de lb/po^2 à SPL dB?

Cette question est abordée dans le document de R. Parrott en annexe.

8. Le ministre de RNCan a-t-il une politique concernant l'exploration pétrolière et en particulier l'effet cumulatif des levés sismiques?

Votre question a été transmise à M. Michel Chénier, dont les coordonnées sont données plus haut.

p.j. Carte de localisation des levés planifiés pour 2004 par la CGC
Présentation de Russell Parrot, Géophysicien du milieu marin, CGC-Atlantique

Annexe 1

Geol Survey of Canada
Internal Report.

Draft version.
For discussion only.

Seismic and acoustic systems for marine survey used by the Geological Survey of Canada: background information for environmental screening.

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Siesmic and acoustic systems for marine survey used by the Geological Survey of Canada: background information for environmental screening.

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Executive Summary

Introduction

The Geological Survey of Canada performs marine acoustic and seismic surveys to determine the type, nature, thickness and distribution of seafloor sediments. The equipment used in these surveys produces acoustic signals with a wide range of frequencies and signal levels. An investigation of the acoustic characteristics of these sources has been undertaken in order to satisfy requirements for class assessment, under Environmental Assessment Review Process guidelines, of the impact of this equipment on fish and marine mammals. The objective of this report is to provide background information on the types of acoustic systems used in these surveys, and the characteristics and intensities of the acoustic pulses produced by these systems. This information will be used as part of an internal classification scheme to screen survey activities with respect to their impact on the environment.

Much of the concern about the environmental effects of seismic surveying is a result of early survey techniques which relied on chemical explosives and often resulted in damage to nearby fish. A discussion of the use of chemical explosives is used to present the energy levels involved in these earlier surveys. These are compared with the non-chemical sources used in present marine surveys undertaken by the Geological Survey of Canada.

Technique

Considerable research, mostly on the effects of chemical explosives, has been reported in the literature. It describes characteristics of acoustic/seismic sources, and criteria for estimation of the effect of the acoustic pulse on nearby fish based on the amplitude and energy flux density of the pulse. The effect of chemical sources on fish can be estimated based on the amount and type of explosive, the species, size and maturity of the fish, characteristics of the acoustic pressure pulses and the ambient pressure. Several parameters for the determination of the safe pressure levels and durations have been proposed in the literature. Larsen (1985) reported that pressure pulses with peak pressure greater than or equal to 2.70 x 10^{11} uPa (= 2.70 bars = 40 psi) combined with a rise time and a decay time of the pressure pulse of approximately 1 millisecond or less were hazardous to fish. Sakaguchi et al. (1976) suggested that energy flux densities of 300 joule.m^{-2} and greater were hazardous to fish. Lovlia et al (1966) and Lavergne (1970) calculated a lethal range for chemical explosives by use of the equation

$$R_L = kW_c^{0.5}$$

where R_L = lethal range in metres
W_c = weight of the explosive in kilograms
k = factor (12 to 54 depending on species).

By substituting an expression for the peak pressure, P_{max} (in microPascals), produced by a known weight of chemical explosive it is possible to calculate the lethal range based on the peak pressure P_{max} for chemical explosives

$$R_L = k\ (P_{max}\ /\ 10^{11}\ /\ 532)^{\ 1.327}$$

The lethal range calculated using this technique will be a worst case due to the fast rise and decay times of the pressure pulses produced by chemical explosives. The much slower rise and decay times produced by non-chemical sources will result in less damage to the surrounding environment and a much reduced lethal range.

The foregoing relations have been applied to the non-chemical sources used by the Geological Survey of Canada, and the results are summarized in Table 1. The systems for which detailed information were analyzed include boomers, airguns and airgun arrays, waterguns, and flexichoc. Information on relative source strengths of other systems, such as sparkers, sleeve exploders, etc., was available from various published sources. Characteristics of the outgoing pulses, such as maximum intensity, energy flux, impulse, and rise time were calculated.

Conclusions

From the data presented in Table 1, the system outputs are either entirely within the recommended safe levels or their outputs decline to recommended levels at a distance of a few metres from the source.

Based on the criteria evaluated, it is felt that little or no physical harm will be done to the environment or fish by the sources commonly used by the GSC when used individually or in small arrays. Echo sounders and sidescan sonars, being much less powerful, are not anticipated to pose any threat to marine life. Single airguns up to 185 in^3, waterguns up to 60 in^3 or sparkers do not exceed any of the recommended levels. The array of three guns (40, 80 and 185 in^3) tested did exceed the recommended limits. However a lethal range of only 0.1 m was calculated. The energy flux density was within the recommended level beyond 1.2 metres from the centre of the source.

A large array of 70 airguns (used for deep crustal mapping) exceeded the recommended threshold for both peak pressure and energy flux. However, the lethal range calculated for this array of large airguns was only 1.5-6 metres (depending on fish type, size, etc.).

Greene et al. (1985) in the Overview to the proceedings of the workshop on Effects of Explosives in the Marine Environment state "It has been shown that non-chemical discharges (airguns) have little or no lethal effects on higher marine life such as fish, seabirds and marine mammals.....In general, seismic exploration using modern geophysical methods appears to be of little direct hazard to marine life." Based on the criteria evaluated, the results of this study confirm the conclusions of the 1985 workshop.

Seismic and acoustic systems for marine survey used by the Geological Survey of Canada: background information for environmental screening.

Introduction

The Geological Survey of Canada (GSC) performs marine geophysical surveys to determine the type, nature and distribution of the sediments and bedrock on the seafloor and to investigate the deep crustal structure across continental margins and sedimentary basins. Various seismic and acoustic systems are used in these surveys to provide information on the character of seafloor sediments, and to provide information on the changes in geology that occur with depth below the seafloor.

Due to an increasing awareness of the need to evaluate possible adverse effects of marine acoustic sources on the environment, and in particular, the effect on marine mammals and fish, an investigation of the acoustic characteristics of these sources has been undertaken. The objective of this review is provide background information on the types of acoustic systems used in these surveys, and the characteristics and intensities of the acoustic pulses produced by these systems. This information will be used as part of an internal classification procedure to screen marine geoscience survey activities under the Environmental Assessment Review Process (EARP) requirements and to design surveys to have minimal impact on the environment.

A brief description of systems used by the GSC is presented. Calibration data is given and referenced to standard terms and distances. Factors calculated from calibration data are used to compare the effect of the various acoustic systems used by the GSC to the impact of chemical explosives. Methods for the calculation of a safe zone around the acoustic source are presented and applied.

Survey Equipment

The acoustic equipment used in marine geoscience mapping can be grouped into two general categories: profilers and swath or sidescan sonar systems. Profilers are used to provide information on the character, structure and physical properties of the sediments and bedrock of the seafloor and subsurface. Swath or sidescan sonar equipment provide information on the morphology, character, and bathymetry of the seafloor.

Typically a variety of acoustic systems will be used in a marine geophysical survey. Each acoustic source has different resolution and penetration, depending on the frequency and power of the outgoing pulse, and provides information on different aspects of the geology of the seafloor. Low frequency profiler sources (less than 1 kHz) such as airguns and large sparkers generally have relatively high acoustic output and provide information on the deep structure of the seafloor. They are generally fired at intervals of 1 to 30 seconds. Sub-bottom profilers such as boomers, small sparkers and pingers operate in the 1-10 kHz frequency range and provide detailed information on the top few tens of metres of sediments on the seafloor as well as information on surface roughness. These systems are fired more frequently (.1 - 2 seconds) to provide improved lateral resolution. High frequency sources (greater than 10 kHz) such as echo sounders and sidescan sonars are used to provide information on bathymetry and seafloor morphology. These are fired at periods of .1 - 10 second.

Large airguns and airgun arrays are used to image the deeper crust so that the structure of sedimentary basins and the earth's lithosphere may be defined. These arrays are designed to produce very low frequency (5 - 10 Hz), high energy, output and are fired at intervals that range from 30 seconds to several minutes. Typically the energy output of these arrays is equivalent to the seismic sound sources used by commercial companies in exploration for oil and gas in the offshore.

Figure 1 shows the configuration of a survey vessel involved in a multi-parameter acoustic survey. Some of the systems used are towed in the water column behind the survey vessel, while others are mounted on the vessel. The data from each of these systems is interpreted and integrated to provide a picture of the distribution and nature of sediments on the seafloor and of the configuration of reflectors beneath the seafloor representing the subsurface structure of sedimentary basins and the lithospheric crust.

The need for this variety of survey instruments is in part due to the limited bandwidth and power available from any one source. No one source exists which will provide the resolution and penetration required to allow interpretation of both shallow and deep structure in the seafloor. Sources for a survey are selected on the basis of their resolution and penetration capabilities, and on the requirements of the survey.

Characteristics of a pressure wave

In order to allow discussion and assessment of the effects of a pressure wave, it is necessary to define some parameters. A pressure wave, shown in Figure 2, is characterized by factors such as its peak amplitude, rise and decay time, intensity and energy flux density. In this review, pressures will be expressed in units of microPascals, uPa, (equivalent to a force of 1 micro Newton/m^2; 1 bar = 10^5 Pa = 10^{11} uPa; 1 kg.cm^2 = 98066.5 Pa). The peak pressure, P_{max}, or peak amplitude of the pressure field is the maximum pressure relative to hydrostatic pressure expressed in uPa. The interval from the onset of the rise in pressure to the peak P_{max} defines the rise time. Pressure pulses often exhibit a pseudo-exponential decay from the initial peak pressure. The time it takes for the pressure to fall to 1/e (= 0.37) of the initial peak value is refered to as the time constant.

In order to allow comparison of the wide range of signal amplitudes present in these signals it is standard practice to express the levels of the various quantities as a logarithm of the ratio of the measured pulse relative to a chosen reference value. This results in sound levels being presented as decibels (or dB), and are calculated as

$$\text{Intensity level} = L = 10 \operatorname{Log}_{10}(P/P_{ref})^2$$

$$= 20 \operatorname{Log}_{10}(P/P_{ref}) \qquad ..1$$

where P = pressure of measured wave
P_{ref} = reference pressure

This is a convenient way of handling the wide dynamic range involved in acoustic studies. In the MKS (metre-kilogram-second) system the standard reference for acoustic pressure is the microPascal (uPa). The standard reference range is 1 metre. Amplitude plots presented in this note will be referenced to 1 uPa, and frequency spectra will be presented in dB re $1uPa^2/Hz$. All will be referenced to a range of 1 metre.

The impulse, I, of the wave form is the time integral of the absolute pressure field expressed in uPa.s. It is calculated as

$$I = \int |P| \, dt \qquad ..2$$

where $|P|$ = absolute value of pressure in uPa

The energy flux density, E_f, is the time integral of the energy propagating through a unit area in Joules/m². It is calculated as

$$E_f = 1/\rho_o c_o \int [P\ (t)]^2 \, dt \qquad ..3$$

and ρ_o = mean density of sea water
c_o = speed of sound in water
P = pressure of the shock wave
t = time

Characterization of Seismic Sources

A limiting factor in obtaining an ideal seismic pulse from a marine source is the generation of a bubble pulse, generally as a by-product of the mechanism of sound generation. The bubble can can be produced by such mechanisms as the introduction of compressed air from an airgun, water vapour from a sparker or gas products from chemical explosives. In addition, in the production of the outgoing acoustic pulse, marine sources accelerate water away from or toward the source. If this acceleration is strong enough, the surrounding water will cavitate, forming a bubble. A train of unwanted secondary pulses will be generated after the primary pulse caused by the oscillation of the gaseous bubble in the water. (This expanding air bubble, known as the bubble pulse, generates little pressure, however hydrostatic pressure collapses the bubble, causing an implosion, which generates a pressure wave.) Several oscillations of the bubble can occur. The period, T, of the oscillations are controlled by the source energy, Q, and the depth, D, to the centre of the bubble. The period of these oscillations can be calculated from the Rayleigh-Willis equation (Kramer et al., 1968)

$$T = \frac{0.0448 \quad Q^{1/3}}{(33 + 3.1\ D)^{5/6}} \qquad ..4$$

where Q = energy in Joules
D = depth in metres.

Figure 3 shows the dependence of bubble oscillation period on input energy for a variety of sources used in marine acoustic surveys including airguns, sparkers, and various explosive sources such as dynamite and trinitrotoluene (TNT). A ratio of input energy level of over 100,000:1 is shown. Note that the positions for the various acoustic sources are plotted relative to the input, or total energy available to the source. Various inefficiencies such as conduction losses in cables, generation of heat, etc., result in much lower acoustic output relative to the input energy.

Kramer et al., (1968) also used the diagram as a convenient means of estimating the relative energy and seismic effectiveness of the various types of underwater sources. It is evident that the small airguns, boomers and sparkers used in high resolution surveys occupy the lower end of the plot and that the large airguns (1000 in^3) used in deep penetrating surveys fall in the middle to upper end of the plot. Both the bubble oscillation period and the source strength of the equipment commonly used in surveys performed by the GSC is considerably less than that for chemical explosives of commonly used sizes.

Sources of sound in the ocean

Many natural and manmade events contribute to produce an ambient or background noise in the ocean. These include the effects of wind, waves, rain, shipping and ice, as well as various biological noises. Figure 4 has been compiled from various sources and relates the sound levels of acoustic survey operations to the ambient noise in the deep ocean (from Staal, 1985) and to various biological noises . Spectra from vessels moving slowly in heavy ice and rapidly in open water show considerably higher energy levels than the curves of the general ambient pressure (Peterson, 1981). The levels for various marine mammals are also shown and range up to 220 db for the bottlenose porpoise (Peterson, 1981). Also shown in this figure are the peak spectrum levels for some of the acoustic survey equipment commonly used. The peak pressure at the dominant frequency of each type of sound pulse is plotted for both the acoustic sources and marine mammals. The approximate bandwidth is shown by the width of the bar. It should be noted that Figure 4 contains data which has been calculated by different methods. The ambient noise level spectra show the typical values which can be measured anywhere in the ocean; these values will increase at closed range to the actual source. The levels for acoustic survey systems, such as the airguns, and for the ships and biological noises have been normalized by referencing the values to a standard distance of 1 metre.

Note that the high sound levels produced by some of the marine mammals, such as the bottlenose porpoise, the right whale and the blue whale are similar to those levels produced by some of the survey equipment used by the GSC.

Attenuation of sound with distance

Sound pressure waves undergo both attenuation and spreading losses as they travel through the water column. If the physical dimensions of the acoustic source are small compared to the wavelength of the generated sound (as is the case for most acoustic sources), energy from the source will be radiated equally in all directions. Since the available energy must spread out uniformly over the surface of an expanding sphere the amplitude of the wavefront decreases as $1/R$, and the energy density decreases as $1/R^2$, where R = range from the source. This results in rapid reduction in the signal amplitude and energy density with increasing distance from the source. At a range of 10 m from the source the amplitude is only 1/10 of the amplitude and the energy density is 1/100 of that at a range of 1 metre from the source. Likewise at 100 m the amplitude is 1/100, and the energy density is 1/10,000 of that at 1 m. The signal undergoes further losses as a result of attenuation of the sound in the water column and by interactions with the seabed. This attenuation is highly dependent on the local water and seafloor conditions. Higher frequencies are attenuated more rapidly than lower frequency components.

Chemical Explosives

The output characteristics of chemical explosives have been extensively studied from both theoretically and experimentally (Cole, 1948), and the effect of the output on various species of fish has been documented in the literature. A brief summary of the output characteristics of chemical explosives will be presented to provide a basis for the evaluation of the effects of non-chemical sources.

High explosives such as trinitrotoluene (TNT) have a fast rate of detonation, which produces an extremely rapid rise in pressure. Figure 5a compares the output of a single shot of high explosive, a linear charge consisting of small pellets of high explosive, black powder and a 70 gun array of airguns with a volume of 7900 in^3. Note the extremely rapid rise and decay in pressure associated with the explosives, and the much slower rise times associated with the airgun array. In Figure 5b the output of the 70 gun array is compared to the output of a single 185 in^3 airgun. It is evident that the output levels of the single sources (such as airguns, waterguns, etc.) commonly used by the GSC are considerable less than those associated with chemical sources.

As an example of some of the forces and reaction times involved, Kramer et al. (1968) have illustrated the sequence involved in the detonation of TNT. In the example presented 22.7 kg of TNT with a density of 1.53 gm/cm^3 was cast into a sphere of radius 0.30 m. Detonation was initiated in the centre of the sphere. At the completion of detonation, about 23 microseconds later, pressure at the interface between the explosive and the water reaches 1.4×10^{16} uPa (2,000,000 psi). This results in the compression of the surrounding water, and produces a high intensity shock field which is radiated outward from the source, at a velocity of 4200 $m.s^{-1}$. The velocity of the outgoing shock field is a function of the peak pressure of the field. The high pressures and propagation velocities are quickly attenuated. At a distance of 1.5 m from the centre of the sphere the instantaneous peak pressure has been reduced to 1.1×10^{14} uPa (16,000 psi). The propagation velocity of the shock wave at this range is reduced to 1600 $m.s^{-1}$, which is close to the 1500 $m.s^{-1}$ velocity of normal acoustic pressure waves in seawater. There is a factor of 125 times reduction in the pressure of the shock wave within a distance of 1.5 m.

Associated with the explosion is the generation of a large expanding bubble of gas. The bubble continues to grow past the equilibrium point at the ambient pressure due to the momentum of the expanding gases and to the water being forced away from the shock wave, and creates a partial vacuum. For the example cited, Kramer et al., (1968) calculated a maximum bubble volume of about 390 m^3. At some point the ambient pressure in the water column overcomes the momentum of the bubble and the bubble collapses. The bubble decreases in size, with increasing speed, which results in water accelerating back in towards the centre of the explosion to create an implosion. The bubble is then compressed so that the pressure within is greater than the ambient pressure and the bubble again expands. The expansion and contraction of the bubble will continue for several cycles, though with decreasing energy and intensity. The oscillation of the bubble leads to the propagation of bubble pressure pulses following the primary pulse through the water column. The rates at which these bubble oscillations occur have been extensively studied and are a function of the energy involved in the explosion and the ambient pressure.

The relationship between the bubble period and the energy involved in the generation of underwater explosions provides a means of comparing the output energy of some of the various systems used in marine geophysics. The Rayleigh-Willis formula (Eqn. 4) is used to calculate the period of the oscillations and to compare the output energy of various sources.

The results of theoretical and experimental research into the characteristics of the shock wave generated by high explosives has been presented in detail by Cole (1948). Formulas for the calculation of the peak pressure, time constant, and impulse of the wave relative to the size of the charge and the range provides a quick means of estimating the source characteristics of a chemical explosive. Lavergne (1970) summarized the earlier work and transcribed the equations into metric units. Baxter (1985), in order to calculate the lethal range of a chemical explosive, also presented the same equations but in a slightly different fashion. In order to facilitate comparison between the various acoustic sources to be evaluated in this review the equations for the calculation of peak pressure, time constant, impulse and energy flux density of a chemical explosive are presented below.

The peak pressure P_{max} generated by a charge of TNT is calculated as

$$P_{max} = [532 \; (W^{1/3} / R)^{1.13}] * 10^{11} \qquad ..5$$

where P_{max} = peak pressure expressed in uPa
W = Weight of the charge in kilograms
R = range from the source in metres

The time constant t_c of the pressure wave is the exponential rate of decay of the pressure pulse from its peak value to a value of 1/e = 0.37 of the peak and is calculated as

$$t_c = [0.13 \; W^{1/3} \; (W^{1/3} /R)^{-0.22}] \; 10^3 \qquad ..6$$

where t_c = time constant in seconds.

The intensity I of the pressure wave is calculated as

$$I = [58\ W^{1/3}\ (W^{1/3}\ /R)^{0.89}\ ]\ 10^{14} \qquad ..7$$

where I = impulse expressed in uPa.s

The energy flux density E_f of the pressure wave is calculated as

$$E_f = [82100\ W^{1/3}\ (W^{1/3}\ /\ R)^{2.05}\ ] \qquad ..8$$

where E_f = energy flux density expressed in Joules/m^2)

Use of low velocity explosives and linear charges

Early work in marine exploration seismology relied heavily upon high velocity explosives. It was soon recognized that the steep wave front, and high amplitudes of explosions from these high velocity explosives were lethal to fish with swim bladders. Tests were conducted on a variety of explosives and black powder was found to have a very low fish kill but gave a useable seismic record, although large amounts (41 kg) were required for each shot.

Jakasky and Jakasky (1956) reported that, in 1953, during monitoring of seismic surveys, 2,065,240 kg of black powder were shot (using 41 kg shots) resulting in a total fish kill of 2,057 fish. Black powder has a much slower detonation rate than a high explosive such as TNT (1050 m.s^{-1} vs 7800 m.s^{-1}) which results in a much slower rise time and lower amplitude for the pressure pulse (Fig. 5a). The much reduced harmful effect on fish is attributed to this slower rise time and lower amplitude for the pressure pulse.

Effect on Fish

Many studies have been performed on the use of explosives in the marine environment to determine the effect on various fish and sea mammals (Wright, in prep; O'Keefe, 1985; Lovlia et al.,1966; Lavergne, 1970; Yelverton, 1975; Baxter, 1985). High peak pressure (P_{max}), rapid rise and decay time of the pressure to below ambient hydrostatic pressure are the properties of underwater explosions which are most damaging to fish. Fish with swim bladders are generally affected by these factors, resulting in death due to rupture and hemorrhage of the swim bladder and adjacent organs.

Results of recent studies have been reported by Wright (in prep) and O'Keefe (1985) which indicate that the negative pressure associated with explosions is the prime cause of damage to the swim bladder. Blood and fragments of the swim bladder were reported in the abdominal cavity, suggesting that the swim bladder had exploded under the reduced pressure produced by an oscillation of the gas bubble or by a reflection of the shock wave at the air/water interface. (Reflections at the interface inverts the phase of the acoustic pulses so that the positive pressure peak becomes a negative pressure peak in the reflected wave).

Techniques for determining the effects of explosions have been developed based upon the following controlling factors:

- size - Lovlia et al (1966), Lavergne (1970), and Yelverton (1975) demonstrated that mortality due to an explosion was directly related to the weight of an exposed fish, with smaller fish being more susceptible to injury.
- species - different species were found to have varying susceptibilities depending on their shape and internal structure. Wright (in prep) reports that laterally compressed species (such as clupeids - the herring family) are more susceptible to damage due to their high surface area to volume ratio.
- water depth - Baxter (1985) reported that damage to fish with swim bladders was related to oscillations of the swim bladder. Since the oscillation of a bubble is a function of depth, for a fish of a given size the damage would increase with depth to a fairly shallow critical depth (ideally less than 5 m), and decrease for depths greater than the critical depth.

Calculation of Lethal Range and Effect on Fish

The lethal range for an explosion is the range at which a percentage of test organisms will be killed outright. Several techniques have been suggested in the literature for the calculation of the zone of damage or lethal range of an explosive for which 50 percent of the fish present at that range will be killed. They are based on factors such as the rise time of the pressure pulse, the amplitude, intensity and energy flux density of the pressure pulse.

Simple criterion for calculation of the lethal range of an chemical explosion based on the weight of the charge have been developed by several workers. Lovlia et al (1966) and Lavergne (1970) proposed use of the equation

$$R_L = kW_c^{0.5} \quad ..9$$

where R_L = range in metres at which 50 % of the fish will be killed
W_c = weight of the explosive in kilograms
k = factor (12 to 54 depending on species).

MacLennan (1977) derived a similar expression:

$$R_L = 15.47\ W_c^{0.4959} \quad ..10$$

It is possible to relate the lethal range of a source to its peak pressure by combination of equation 5 and 9. Equation 5 is rearranged to calculate the equivalent weight of a charge required to produce a peak pressure of P_{max} at a range of D m from the source.

$$W_c = D^3 \left(P_{max} / 532\right)^{3/1.13} \qquad ..11$$

Substituting for W_c in equation 8 and calculating for a reference distance of D = 1 m, with P_m expressed in uPa, yields

$$R_L = k \left(P_{max} / 10^{11} / 532\right)^{1.327} \qquad ..12$$

This equation will be used as one of the parameters in the calculation of the lethal range for the non-chemical sources in use by the GSC. The lethal range calculated using this technique will be a worst case due to the fast rise and decay times on the pressure pulses produced by chemical explosives. The much slower rise and decay times produced by non-chemical sources will result in less damage to the surrounding environment.

Sakaguchi et al. (1976) suggested that the peak pressure alone is not a reliable indicator of the level of damage. Explosions having the same peak pressure can have different rise times and peak pressure durations. They suggested that an energy flux density was highly correlated with fish damage. Energy flux densities of 300 joule.m^{-2} and greater were found to be harmful to fish.

Baxter (1985) and Baxter et al., (1982) concluded, on the basis of data sets from other investigators, that energy flux density had the highest correlation to explosion damage over most of the water column. The model does not account for reflections from the sea floor or sea surface but does consider the negative portion (or below ambient pressure) of the pressure wave. Several parameters were presented for the calculation of fish kill based on the energy flux density and the impulse. These parameters account for the ambient pressure, P_a, and size of the fish. The fish kill probability parameter, Pr_{fke}, based on energy flux was calculated as

$$Pr_{fke} = \text{Log}\left[\, E_f / (P_a * W_f^{1/3})\right] \qquad ..13$$

It is used under conditions where the water depth is greater than a critical depth (ideally greater than 5.0 m). For shallow water a fish kill probability parameter, Pr_{fki}, based on the impulse was found to be more representative. It is calculated as

$$Pr_{fki} = \text{Log}\left[\, I / (P_a * W_f^{1/3})\right] \qquad ..14$$

Yelverton et al. (1975) suggested that the impulse, is correlated to the degree of damage to fish. His calculation of the impulse considered the effect of the surface reflection of the source pulse and was calculated as

$$I = \int_{t_o}^{t_c} |P| \, dt \qquad ..15$$

and t_o = time of first arrival
t_c = time to arrival of surface reflection
$|P|$ = absolute value of pressure
t = time

Larsen (1985) reported on the results of a literature survey into the mortality of fish exposed to all types of existing seismic energy sources. The most vulnerable adult fish have swim bladders, an "oval" shape, and were positioned perpendicular to the impulse. The findings of the study were that mortality of the most sensitive of adult marine organisms occurs when two criteria are met simultaneously. These are

1. peak pressure greater than or equal to 2.72×10^{11} uPa (2.72 bars = 40 psi)
2. a rise time and a decay time of approximately 1 millisecond or less

As can be seen from the variety of methods for calculation of the effect of pressure waves on fish, there is still uncertainty in the best method for the calculation of a danger zone around a seismic source. In order to determine the impact of these various techniques on the lethal range of the systems studied, results will be presented for a variety of the techniques.

Data Sources

Acoustic signature data for the non-chemical sources evaluated in this study have been obtained from a variety of sources. Detailed information on the source characteristics of single airguns, small airgun arrays, waterguns and flexichoc was obtained from reports on calibration trials of these equipment during 1985 (Quinn and Vigier, 1985 and Racca and Scrimger, 1986). In these tests, a variety of sources were calibrated at firing depths ranging from 0.5 to 10 metres. Information on the peak pressure, frequency distribution, pulse width, etc. were presented. The raw data from the calibration was also used (Quinn and Vigier, 1985) and additional parameters such as the impulse and energy flux density were calculated. The peak pressure produced by the seismic sources and a comparison of the pulse characteristics at a depth of 5 metres, as calculated by Quinn and Vigier (1985), are shown in Tables 2 and 3.

Information on additional sources was obtained from overviews of seismic systems by Lugg (1979), Kramer et al (1968) as well as texts by McQuillan et al., (1980), Trabant (1984) and Le Tirant (1979). These references provide detailed descriptions of the various sources and techniques used in marine surveys. Very brief descriptions of the systems evaluated in this report are included here. For further details on these and other sources the reader should consult the above references.

Information on the characteristics of some sources have also been obtained from various company brochures, information sheets, technical reference manuals, and directly from the manufacturer.

Discussion of characteristics of commonly used survey gear

Airguns

Airguns are the primary tool used to provide information on the character and structure of earth materials. An airgun produces an acoustic pulse through the rapid release of high pressure air (1400-2100 kpa = 2000-3000 psi). Air is stored in a chamber and released over a period of a few milliseconds by the opening of an electrically controlled solenoid. Airguns are typically towed behind the survey vessel at depths of 0.5 to 20 m.

Airguns generally have the lowest frequency content, and the highest output power of the acoustic systems used in surveys run by the GSC. Airguns range in size from 16.4 cm^3 (1 in^3) to 32800 cm^3 (2000 in^3). Airguns can be used either singly or combined into arrays. Through suitable timing of the firing of different size guns it is possible to increase the energy in the primary pulse and to reduce the effects of unwanted bubble pulses.

Fig. 6 a)-b) shows the source signatures for a variety of airgun sizes and combinations of airguns. The smaller airguns have lower amplitude output and a shorter duration pulse. As the size of the airgun chamber is increased the duration and amplitude of the pulse also increases. Characteristics such as peak pressure, impulse and energy flux density have been calculated as part of this study (Table 1), and through earlier calibration work (Quinn and Vigier, 1985) (Tables 2 and 3).

When combined into arrays the outputs of the various guns add to generate a more powerful pulse. Tables 1-3 show the effect of combining a variety of airguns into small arrays. An increase in the output can be observed.

When three guns (40, 80, 185 in^3) were combined into an array the output (Fig. 6b and Tables 2 and 3) was seen to exceed the recommended peak pressure of $2.72 * 10^{11}$ uPa. A lethal range of 0.1 metres was calculated for this pressure. The energy flux density of 441.3 J/m^2 is also seen to exceed the recommended threshold of 300 J/m^2. As presented in an earlier section the energy of an acoustic wave decays as a function of the square of the distance. A threshold level of 300 J/m^2 will occur at $(441.3/300)^{1/2} = 1.22$ metres from the source.

For some of the deep crustal studies performed at the GSC a large airgun array (7900 in^3) consisting of 70 airguns ranging in size from 20 to 141 in^3 is used. The total length of the array is about 17.8 m. The farfield signature of this array is shown in Figure 5b) and compared to the output signature of chemical explosives. Note that while the peak pressures produced by this array in the far field are quite high (72 and -102 * 10^{11} uPa), the rise time for the positive portion of the pulse is 5 ms. As shown in Figures 5a) and b), this is considerably slower than the rapid rise time produced by chemical explosives. Due to the large areal extent of the array, the pressure near the array will be dependent on the configuration of the array. It is expected that the near field pressures will be considerably lower than that experienced in the far field. Based on Equation 12, the lethal range for this array is calculated as 1.5 - 6 m depending on fish size and species. The energy flux density criterion of 300 Joules/m^2 is satisifed 15 metres from the source.

Referring to the Rayleigh-Willis diagram of Figure 3, a single airgun with displacements of 3030 cm^3 (185 in^3) has the same potential energy as about 70 grams of dynamite detonated at a depth of 9 m, while a 82 cm^3 (5 in^3) airgun has potential energy equivalent to about 2 grams of dynamite. Note however that the airguns produce pulses with much slower rise and decay time than would be produced by explosives. From Table 1 the peak pressure and energy flux density of single airguns less than 3030 cm^3 (185 in^3) are well below the recommended thresholds.

Sparkers

Sparkers are used in a variety of surveys and can be configured to provide a wide range of output power and frequencies. Sparkers generate acoustic energy by electrical discharges in sea water, and operate in a fashion similar to a spark plug. Energy is stored in capacitor banks, which are triggered to discharge through spark tip arrays towed in the water. The discharge boils the water in the immediate vicinity of the spark tip to create an expanding bubble. The resulting output pulse contains a wide range of frequencies depending on the size of the power unit and on the configuration of the spark tip. Sparkers are typically towed behind the survey vessel at depths ranging from 0.5 m to 200 m or more.

A wide variety of sparker configurations and input power are available. Commonly input power is on the order of about 100-200 Joules for high frequency, high resolution systems used to profile the top few tens of metres of the seafloor to 16 kJoule for deeper penetrating sources used for multi-channel surveys where penetrations of 1 kilometer or more are desired. By reference to the Rayleigh-Willis curve of Figure 3 the potential energy for the larger sparkers (16 kJ) is about equivalent to the energy of a 164 cm^3 (10 in^3) airgun. Note that the reference energy levels are for the input energy. Inefficiencies in the production of acoustic energy result in output energies 10-100 times smaller than the input energy.

Boomers

Boomers are a common survey tool for use in high resolution surveys where penetrations of several tens of metres are required. A boomer consists of a bank of capacitors which are used to store electrical energy, and a metal plate held close to an induction coil by a rubber diaphragm or springs. An acoustic pulse results when electrical discharge of the capacitor through the induction coil produces eddy currents and repel the nearby metal plate. The acceleration of the plate produces a short duration pulse, with a large frequency content. The relatively large size of the metal plate used in the boomer results in the output being directional. The majority of the output acoustic energy, especially the high frequency component, is radiated in a cone of about 60° directly below the boomer. Acoustic levels are much reduced outside this cone. Boomers can be deployed at the sea surface on a catamaran or towed near the seafloor.

Boomers are generally run with input power in the range of .1 - .5 kJoules. As can be seen by referring to the Rayleigh-Willis diagram (Figure 3) boomers have a low potential energy compared to the majority of systems. In fact the systems used by the GSC typically are operated with input energies of 200-500 joules and would be plotted off the low end of the scale. Note that the reference energy levels are for the input energy. Inefficiencies in the production of acoustic energy from boomers result in output energies 10-100 times smaller than the input energy. Boomers appear to present no hazard to the environment.

Waterguns

Waterguns employ the same basic principles of operation as an airgun, except that they rapidly expel a fixed volume of water rather than a volume of high pressure air. The outward moving slug of water forms a cavitation pocket that implodes to create a sharp acoustic pulse, with no bubble pulse associated. Water guns can be used either individually or in arrays.

The acoustic output from a watergun is generally larger than for a comparable sized airgun. As shown in Table 1 the peak intensity and energy flux density are $2.5 * 10^{11}$ uPa, and 61.9 J/m^2 respectively for a 60 in^3 unit and $3.6 * 10^{11}$ uPa, and 170.4 J/m^2 respectively for a 160 in^3 unit. The energy flux is well within recommended standards. The peak pressure output by the larger unit is seen to exceed the recommended level of $2.72 * 10^{11}$ uPa, however the lethal range calculated for this output is 0.07 metres.

Flexichoc

The flexichoc system consists of a flexible envelope surrounding a pair of rigid circular plates. The volume enclosed is enlarged to its maximum volume by increasing oil pressure, until the plates are locked by a set of jointed legs. Pressure is then reversed to lower the pressure inside the source. When the locking mechanism is released the hydrostatic pressure on the walls of the housing force the plates together, creating an implosion.

The pressure pulse produced by this system is shown in Figure 7. As shown in Tables 1-3 the peak intensity and energy flux density are $3.4 * 10^{11}$ uPa and 71.8 J/m^2 respectively. The peak pressure is seen to exceed the recommended level of $2.72 * 10^{11}$ uPa. Based on Equation 12 a lethal range of 0.06 metres was calculated.

Echo Sounders

Echo sounders are generally mounted on the survey ship and are used to provide information on the amount of water below a ship. They operate at frequencies ranging from 3 - 4 k Hz to over 500 kHz, with a repetition rate ranging from .1 sec or less to several seconds in deep water. Most of the echo sounders have very low output power and would plot off the low end of the scale in Figure 3.

Sidescan Sonar

Sidescan sonar provides information on the morphology of the seafloor on both sides of the ships track. High frequency (6.5 - 500 kHz) sound pulses are transmitted in a narrow fan-shaped beam. The sound is reflected off irregularities in the seafloor and reflected back to the towfish. The sound pulses produced by these systems are usually of short duration (0.1-12 msec) and have low power levels.

Conclusions

The results of this study confirm the recommendations and conclusions of the 1985 Workshop (Greene et al., 1985). The seismic sources used by the Geological Survey of Canada have been shown to have relatively low output levels. When used individually, none of the sources (airguns, small watergun, flexichoc, sparkers, boomers) exceeded recommended thresholds for the energy flux density. Echo sounders and sidescan sonars are not anticipated to pose a threat to marine life.

Small arrays of airguns did not exceed the recommended thresholds. An array of 40, 80 and 180 in^3 airguns resulted in a considerable increase in the peak pressure, and energy flux density was obtained and the threshold for both peak pressure and energy flux were exceeded. A lethal range of 0.1 metres was calculated for the array of larger guns.

It is felt that little or no physical harm will be done to the environment or on nearby fish by the sources when used individually or in small arrays. The larger array of guns tested did exceed the recommended limits, with a lethal range of 1.5 to 6 metres from the source.

The results of this review agree with the results of the 1985 workshop on the effects of explosives used in the marine environment. "In general, seismic exploration using modern geophysical methods appears to be of little direct hazard to marine life." (Greene et al. 1985)

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Figure 1. Survey vessel equipped for a multi-parameter acoustic survey. Note that some of the gear is mounted directly on the vessel, some is towed at the water surface and some is towed below the sea surface.

Figure 2. Stylized pressure pulse showing the peak pressure, pulse width, rise time and bubble oscillation period.

Figure 3. Rayleigh-Willis diagram for representing energy source systems. Plotted for a depth of 9 m. The sources are plotted at the equivalent input energy. For many of the sources inefficiencies in the production of sound result in output energies far less than the input. Note that the amount of 60% dynamite required to produce an equivalent input energy is plotted across the top of the diagram.

Figure 4. Comparison of average ambient noise spectrum levels versus frequency with biological noise and acoustic systems. This figure contains data which has been calculated by different methods. The ambient noise level spectra show the typical values which can be measured anywhere in the ocean; these values will increase at closed range to the actual source. The levels for acoustic survey systems, such as the airguns, and for the ships and biological noises have been normalized by referencing the values to a standard distance of 1 metre.

Figure 5 a). Pressure time curves for different chemical explosives and a 70 airgun array (with a volume of about 7900 in^3). Note the slow rise time of the airgun array when compared to the 40% gelatin and multipulse charge. Only the initial portion of the pulse shape for the airgun array is shown; the complete pulse is shown in Figure 5b). (Modified after Jakasky and Jakasky, 1956).

Figure 5 b). Pressure time curves for 3 airgun array composed of a 40, 80 and 185 in^3 airguns.

Figure 6 a) Pressure time curve for single 5 in^3, 40 in^3, 185 in^3 airguns

Figure 6 b) Pressure time curves for the 70 airgun array shown in 5a) and a single 185 in^3 airgun

Figure 7. Pressure time curve for a flexichoc system.

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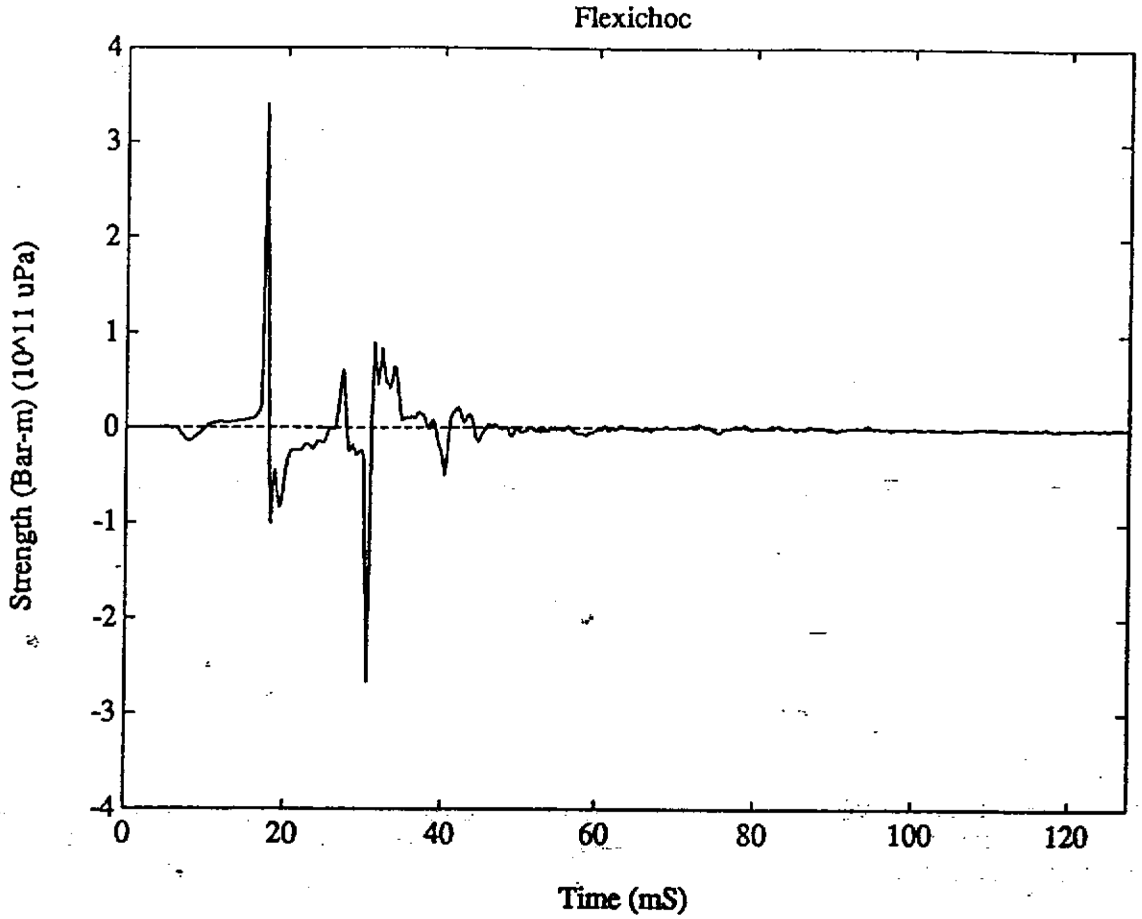

Figure 7. Pressure time curve for a flexichoc system.

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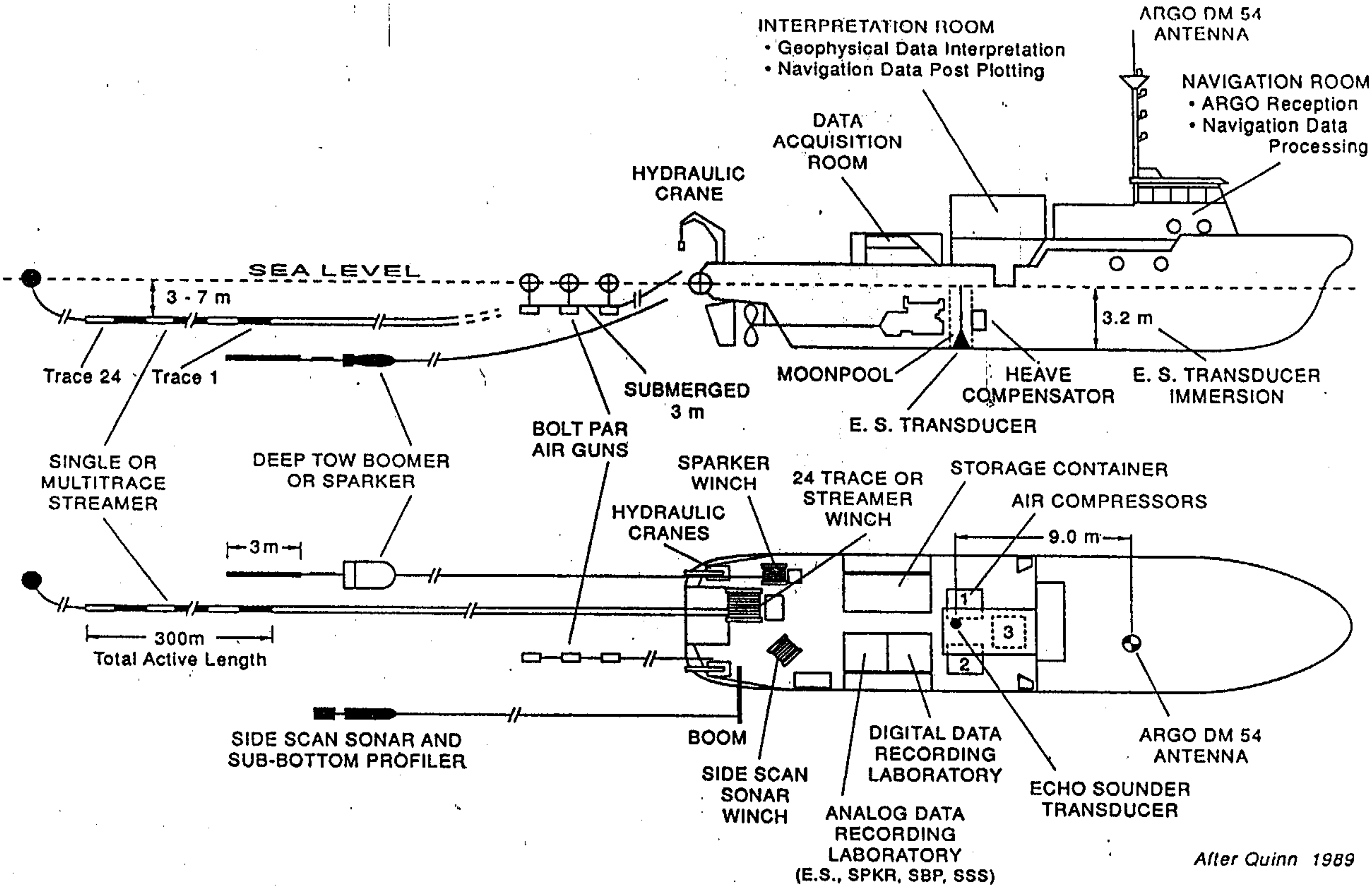
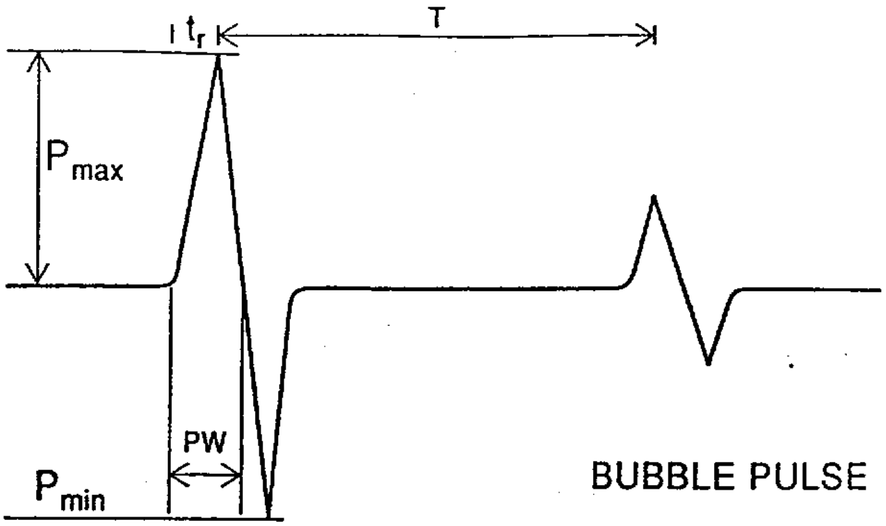


Figure 1. Survey vessel equipped for a multi-parameter acoustic survey. Note that some of the gear is mounted directly on the vessel, some is towed at the water surface and some is



P_{max}	PEAK POSITIVE PRESSURE OF THE PRIMARY PULSE (SOURCE STRENGTH)
P_{min}	PEAK NEGATIVE PRESSURE OF THE PRIMARY PULSE
PW	PRIMARY PULSE WIDTH
t_r	RISE TIME OF PRIMARY PULSE
T	BUBBLE OSCILLATION PERIOD

Figure 2. Stylized pressure pulse showing the peak pressure, pulse width, rise time and bubble oscillation period.

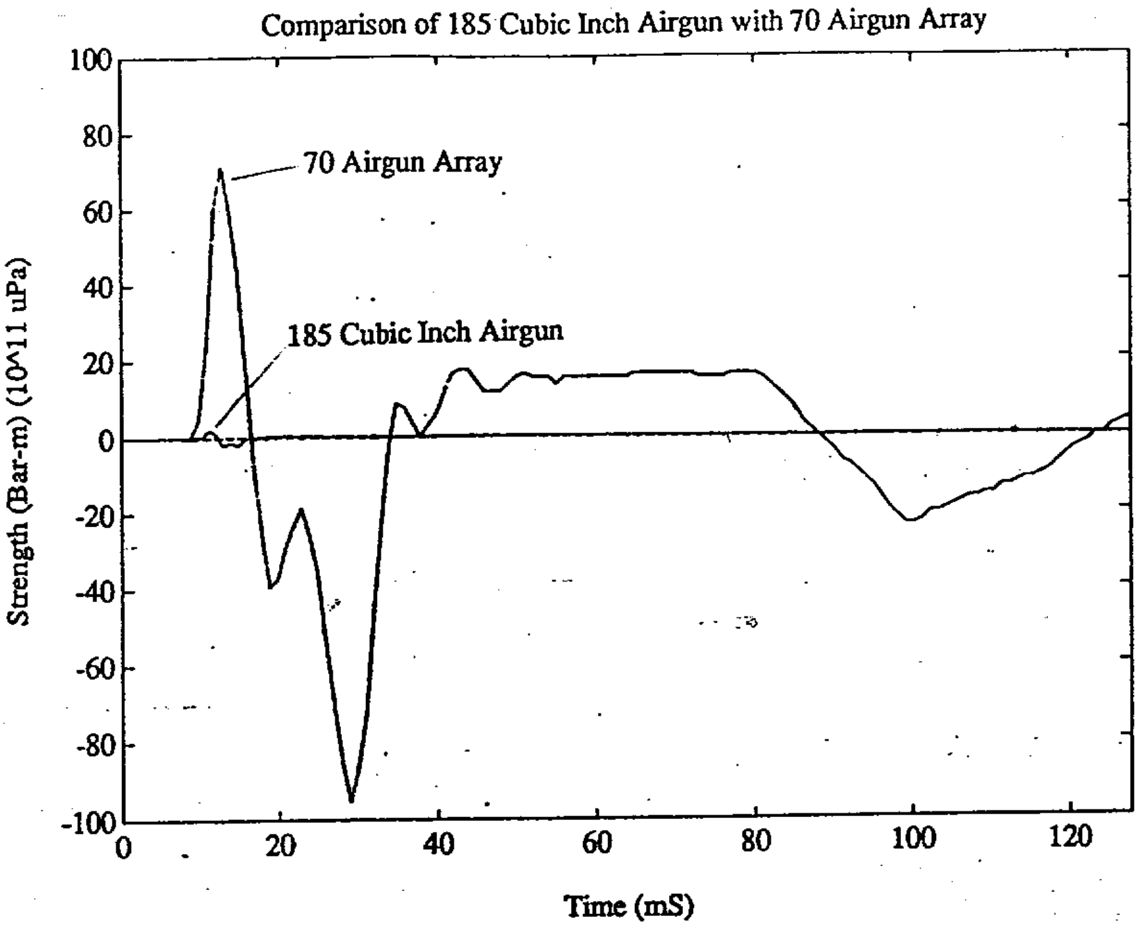


Figure 5 b). Pressure time curves for the 70 airgun array shown in 5a) and a single 185 in³ airgun.

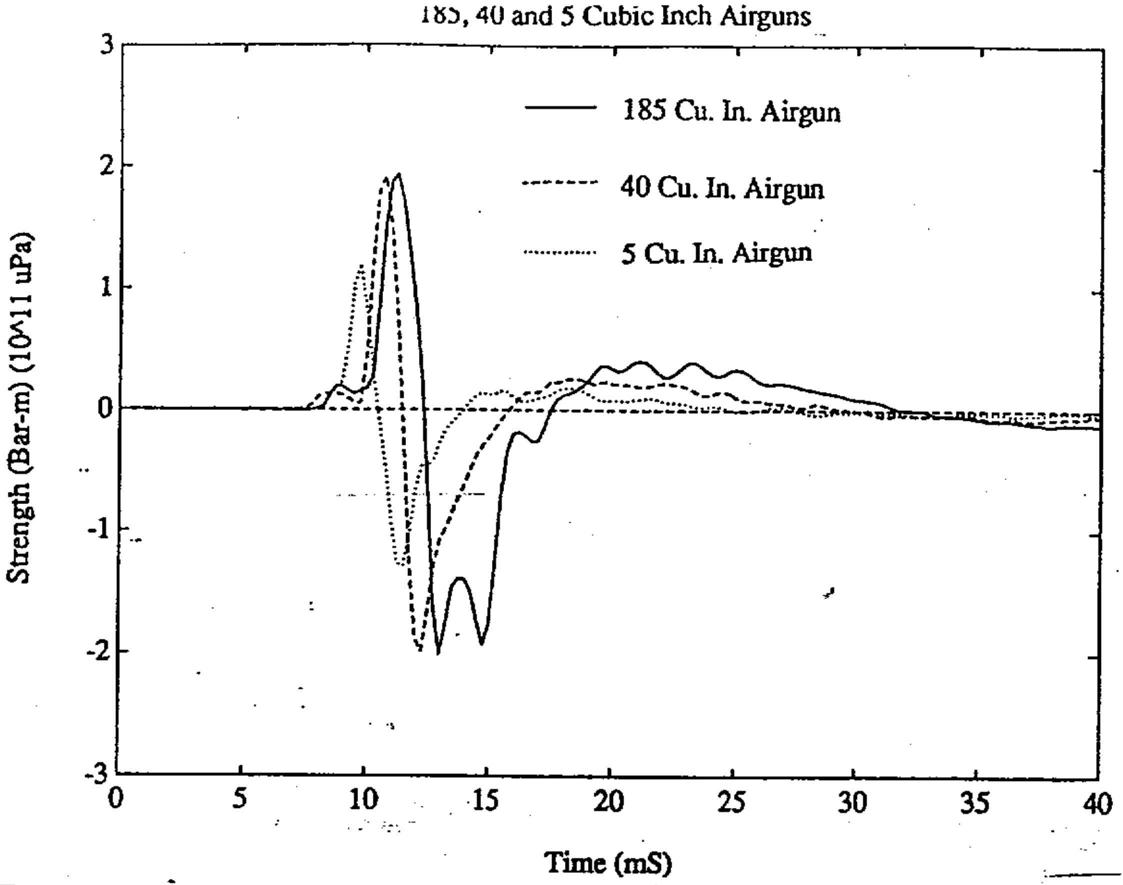


Figure 6 a) Pressure time curve for single 5 in³, 40 in³, 185 in³ airguns

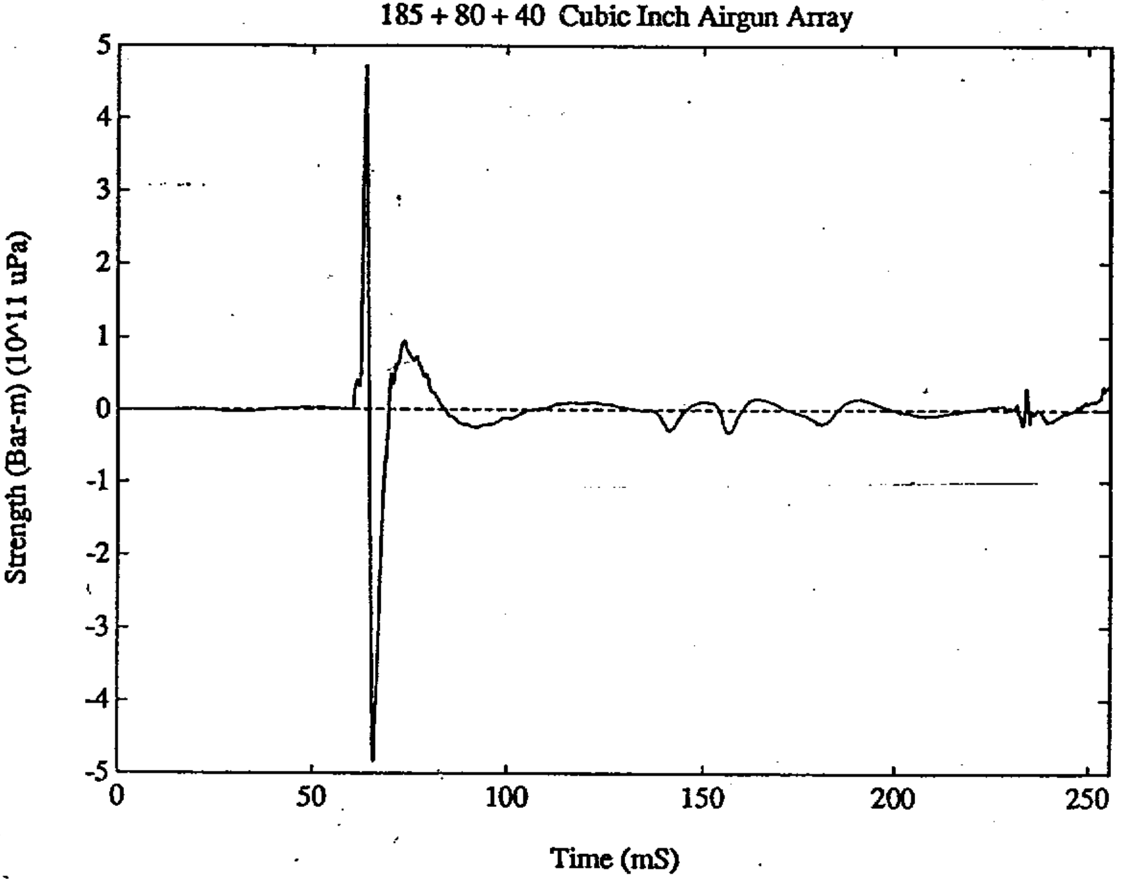


Figure 6 b) Pressure time curves for the 70 airgun array shown in 5a) and a single 185 in³ airgun

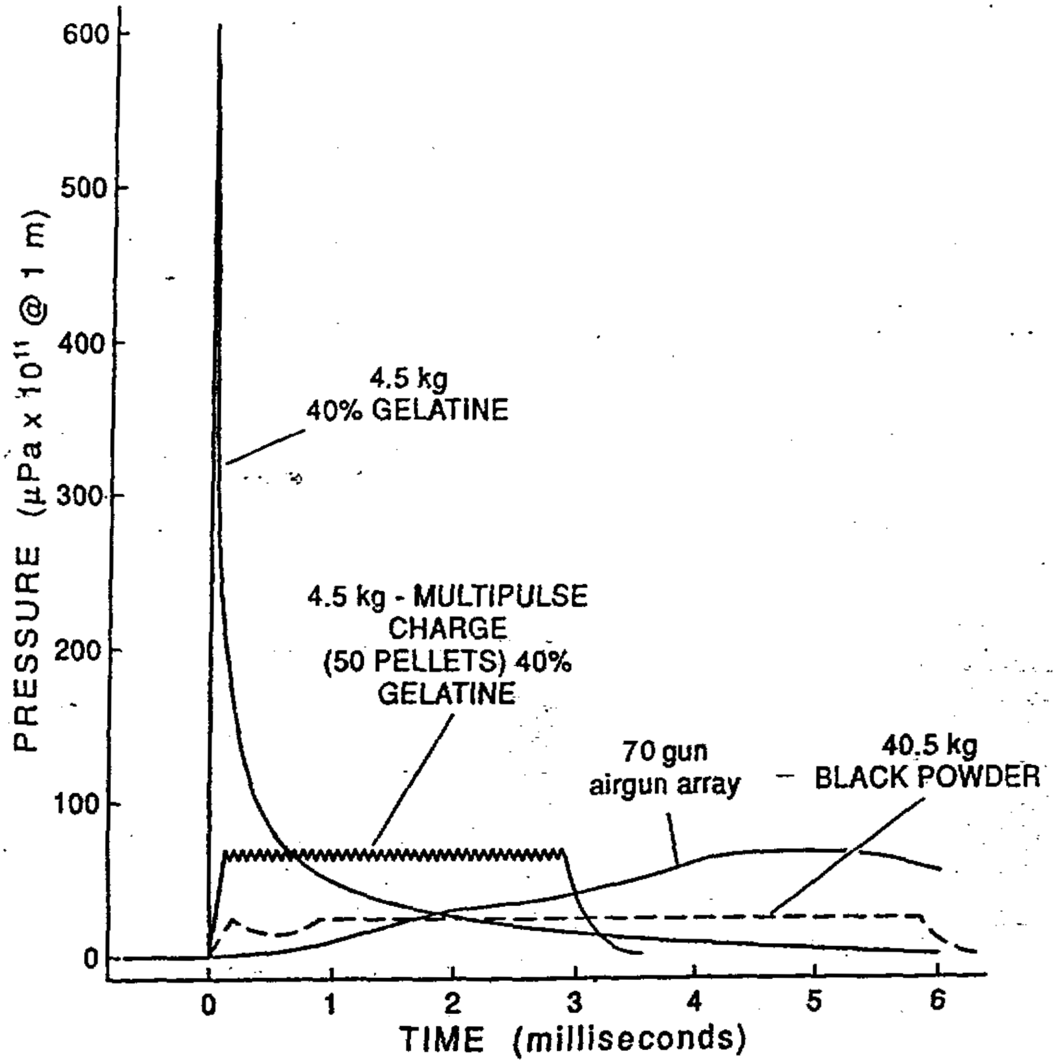


Figure 5 a). Pressure time curves for different chemical explosives and a 70 airgun array (with a volume of about 7900 in^3). Note the slow rise time of the airgun array when compared to the 40% gelatin and multipulse charge. Only the initial portion of the pulse shape for the airgun array is shown; the complete pulse is shown in Figure 5b). (Modified after Jakasky and Jakasky, 1956).

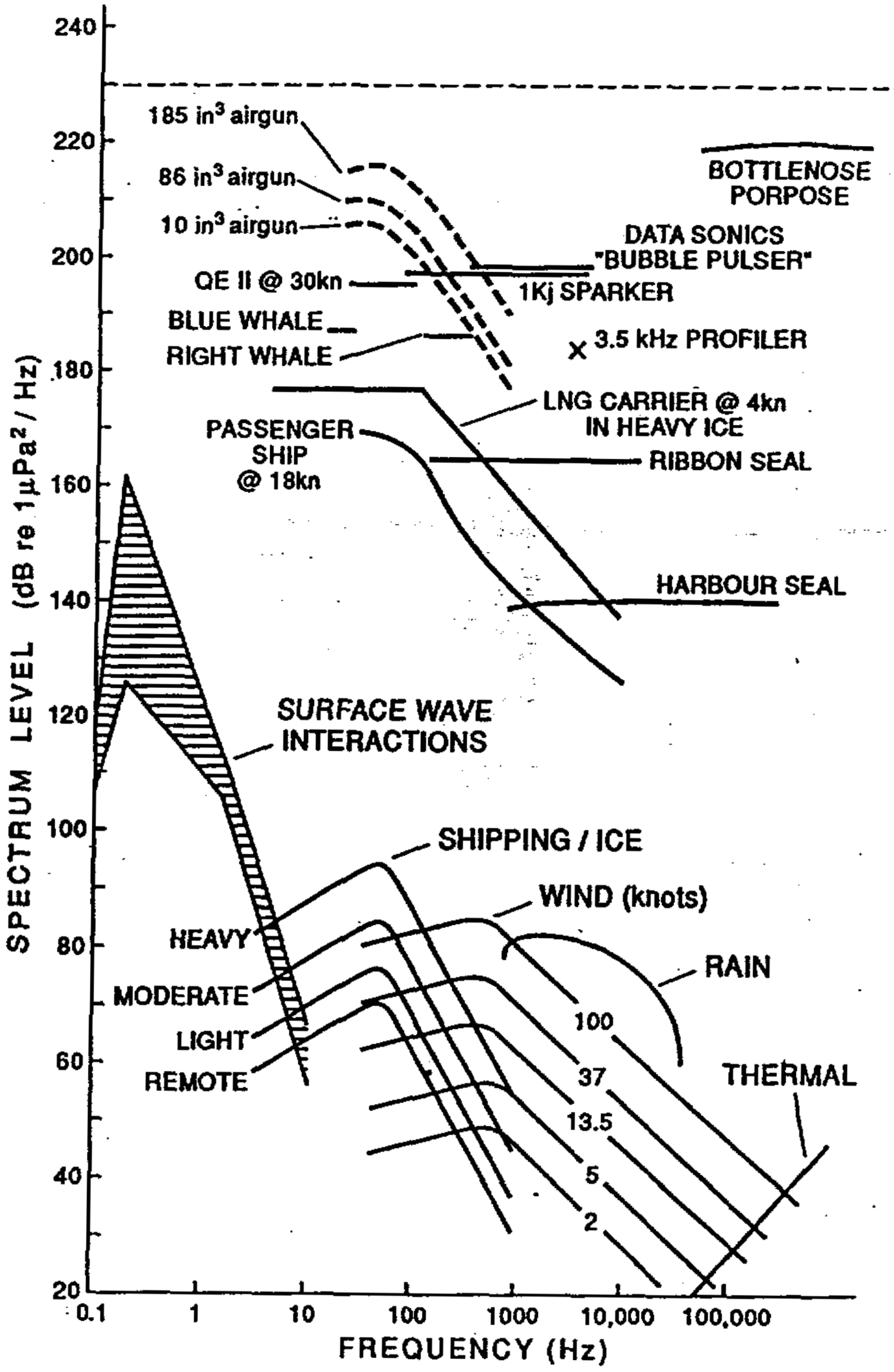


Figure 4. Comparison of average ambient noise spectrum levels versus frequency with biological noise and acoustic systems. This figure contains data which has been calculated by different methods. The ambient noise level spectra show the typical values which can be measured anywhere in the ocean; these values will increase at closed range to the actual source. The levels for acoustic survey systems, such as the airguns, and for the ships and biological noises have been the values to a standard distance

	Source	Pmax	Pmin	E-flux	Flux	Lethal Range (m)	
Name	Depth - m	P-P uPa/e11 = bars			Range - m	k=12	k=54
Airgun 5 in	1.0	1.2	1.3	21.4	0.267	0.004	0.018
Airgun 10 in	0.5	1.4	1.1	18.1	0.246	0.005	0.021
Airgun 40	1.0	1.9	2.0	55.1	0.429	0.007	0.033
Airgun 80	1.0	2.1	2.2	71.3	0.488	0.008	0.037
Airgun 185 WSK	1.0	2.0	2.0	85.8	0.535	0.007	0.033
Flexichoc 50	8.0	3.4	2.7	71.8	0.489	0.015	0.066
Watergun 60	2.0	1.8	2.5	61.9	0.454	0.010	0.044
Watergun 160	2.0	3.0	3.6	170.4	0.754	0.016	0.071
Arrays							
Airguns 10 -10	1.0	2.0	2.4	60.8	0.450	0.009	0.042
Airguns 5-10-10	1.0	2.6	3.0	109.7	0.605	0.012	0.056
Airguns 40-80-185	1.0	4.7	4.8	441.3	1.213	0.023	0.104
Airguns - large array		74.0	102.0	67341	14.982	1.341	6.033

Table 1. Characteristics of the acoustic systems evaluated in this review. Shown are the peak positive pressure (Pmax) and peak negative pressure (Pmin) the energy flux density in Joules/m², the range ant which the energy flux density had decayed to the safe level of 300 Joules/m² and the lethal range in metres. Lethal range is calculated from the peak pressure and is dependent on the fish size, type and maturity. Ranges are shown for values of k =12 and k = 54, to show the effect on highly sensitive and less sensitive fish.

SOURCE • COMPARISONS AT 5 m. DEPTH

Source / arameter	1 FHC 50	2 60 cu. in.WG	3 160 cu. in.WG	4 LAG	5 40 cu. in.AG	6 80 cu. in.AG	7 200 WSK AG	8 2x10 cu. in.AG	9 5+10 cu. in.AG	10 5+2x10 cu.in	11 2x10 cu. AG+WSK	12 5+10cu. in.AG + WSK	13 5 cu. in.AG	14 10 cu. in.AG	15 10 cu. AG+W
trength Bar-m *	2.1 ± 0.2	1.9 ± 0.6	2.7 ± 0.9	5.3	2.0	2.3	2.1	1.9	1.7	2.6	1.2	1.6	1.2	1.4	0.9
ulse Width ms	1.5	1.5	1.5	4.7	4.5	4.5	4.5	2.8	3.2.	3.0	3.5	2.8	2.5	3.0	3.0
ominant Frequency Hz	60	60	60	50	40	30	45	50	50	50	50	35	40	40	30
requency Band At 20 dB HZ	15-110	10-125	10-125	10-125	10-150	10-120	10-120	10-120	10-120	10-120	10-120	10-250	10-120	10-100	10-13

1. Miniflexichoc FHC 50
2. 60 cu.in watergun
3. 160 cu.in watergun
4. Large airgun array (40 cu.in + 80 cu.in + 200 cu.in with wave - shape - kit)
5. 40 cu.in airgun
6. 80 cu.in airgun
7. 200 cu. in airgun with wave - shape - kit
8. 2 x 10 cu.in airguns (coalesced)
9. 1 x 5 cu.in airgun separated 1 m from 1 x 10 cu. in airgun
10. 1 x 5 cu.in airgun separated 1 m from 2 coalesced - 10 cu.in airguns
11. 2 x 10 cu.in airguns coalesced (one has wave - shape - kit)
12. 1 x 5 cu.in airgun separated 1 m from 1 x 10 cu.in airgun with wave - shape - kit
13. 1 x 5 cu.in airgun
14. 1 x 10 cu.in airgun
15. 1 x 10 cu.in airgun with wave - shape - kit

Table 3. Comparison of source characteristics for systems deployed at a depth of 5 metres. The peak pressure (in uPa * 10^{11} = bar @ 1 m), the width of the positive portion of the pulse (in ms), the dominant or centre frequency of the pulse and the bandwidth of the systems are shown. After Quinn and Vigier, 1985.

STRENGTHS OF SEISMIC SOURCES

BAR@ 1 M

Source)epth m)	1 FHC 50	2 60 cu. in.WG	3 160 cu. in.WG	4 LAG	5 40 cu. in.AG	6 80 cu. in.AG	7 200 WSK AG	8 2x10 cu. in.AG	9 5+10 cu. in.AG	10 5+2x10 cu.in	11 2x10 cu. AG+WSK	12 5+10cu. in.AG + WSK	13 5 cu. in.AG	14 10 cu. in.AG	15 10 AG
0.5								1.763	1.475	2.55			1.099	1.386	
1	1.592	*	2.048	4.720	1.812	2.071	1.960	2.037	1.695	2.008	*	1.928	1.201	*	0.84
2	1.640	1.798	2.975	5.387	1.952	2.374	2.137								
3	1.012	1.704	3.276	5.953	1.958	2.428	2.103	2.003	1.865	2.729			1.227	1.510	
4	2.324	2.499	3.670	5.207	2.055	2.266	2.139								
5	2.649	2.238	2.457	5.295	*	2.302	2.115	1.956	1.753	2.889	1.207	1.662	1.242	1.477	0.89
6	2.957	2.123	3.572	5.450	1.968	2.210	2.103								
7	2.907	2.503	2.784	4.920	2.065	2.279	2.128								
8	3.401	2.255	*	5.603	2.076	2.299	2.098								
9	2.938	2.007	2.800	*	2.031	2.327	2.139								
10	*	1.735	3.353	4.291	2.066	2.329	2.110								

* Not recoverable

1. Miniflexichoc FHC 50
2. 60 cu.in watergun
3. 160 cu.in watergun
4. Large airgun array (40 cu.in + 80 cu.in + 200 cu.in with wave - shape - kit)
5. 40 cu.in airgun
6. 80 cu.in airgun
7. 200 cu. in airgun with wave - shape - kit
8. 2 x 10 cu.in airguns (coalesced)
9. 1 x 5 cu.in airgun separated 1 m from 1 x 10 cu. in airgun
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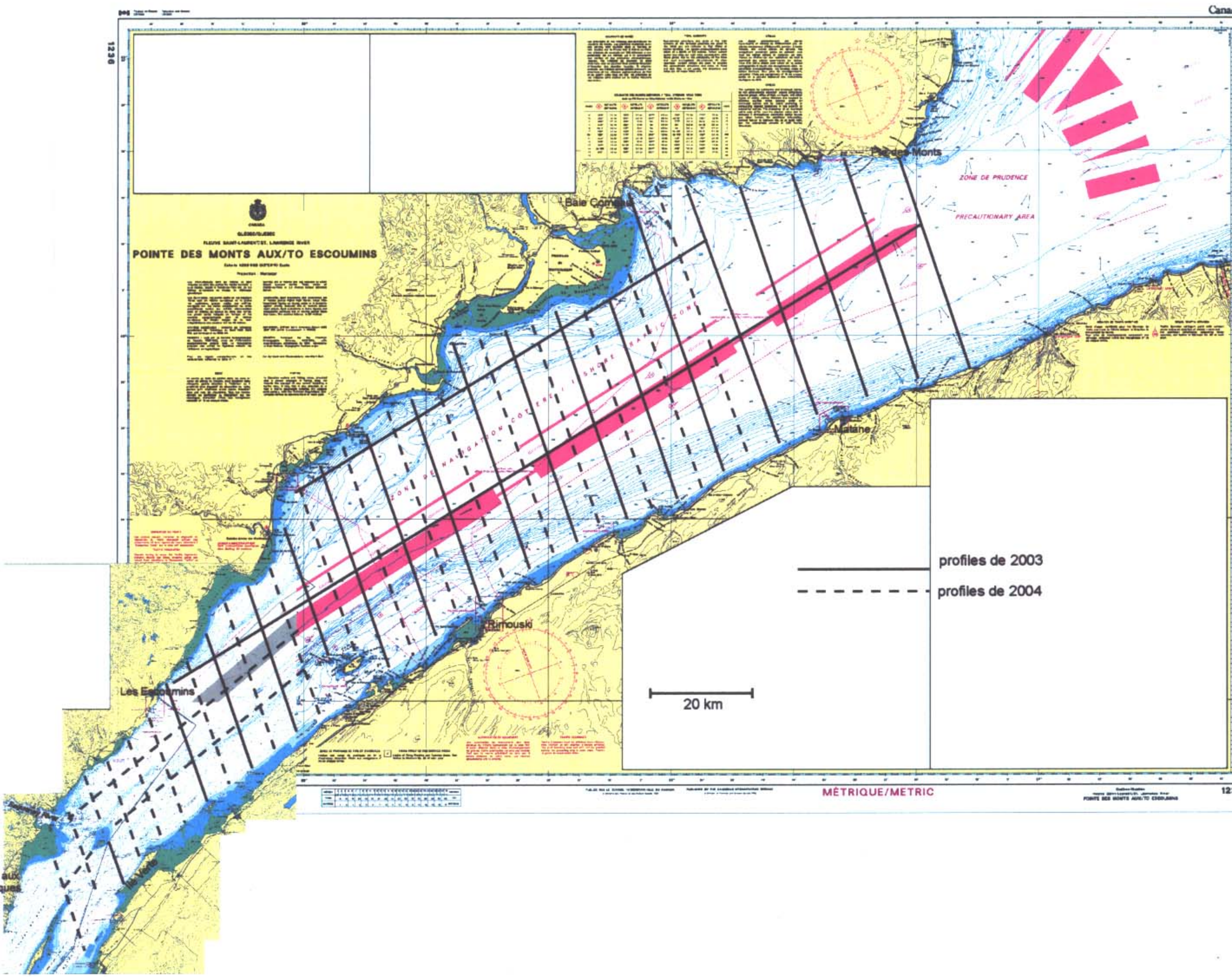
11. 2 x 10 cu.in airguns coalesced (one has wave - shape - kit)
12. 1 x 5 cu.in airgun separated 1 m from 1 x 10 cu.in airgun with wave - shape - kit
13. 1 x 5 cu.in airgun
14. 1 x 10 cu.in airgun
15. 1 x 10 cu.in airgun with wave - shape - kit

+ bar-m = 10^{11} μPa

Table 2. Strengths of seismic sources showing the peak pressure produced for sources deployed at depths ranging from 0.5 to 10 metres. Values are expressed in uPa * 10^{11} = bar @ 1 m. After Quinn and Vigier, 1985.

Annexe 2

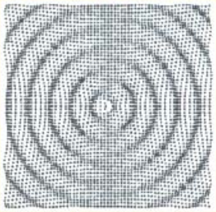

POINTE DES MONTS AUX/TO ESCOUMINS
Pointe-des-Monts
Baie Comeau
Matane
Rimouski
Les Escoumins
Cap aux Basques
ZONE DE PRUDENCE
PRECAUTIONARY AREA
ZONE DE NAVIGATION CÔTIÈRE / INSHORE TRAFFIC ZONE
profiles de 2003
profiles de 2004
20 km
MÉTRIQUE/METRIC

Sound in water

Pressure wave

Shear wave

Monopole source

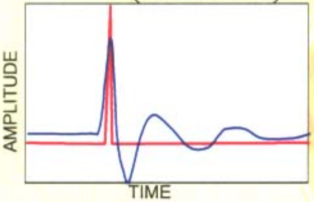


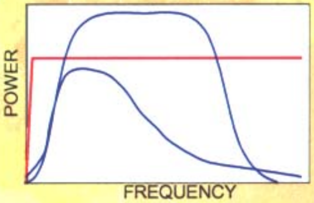
Dipole source

Seismic principles

Seismic resolution requires broadband frequencies

Seismic penetration requires power (S/N ratio)





Marine Seismic Reflection Source Technology

Controlled Waveform (SONAR) = Chirp, Parasound, 3.5 subbmottom. low power, high resolution, shallow sub-bottom

Boomers = accelerated water mass, rapid expansion of boomer plate. low power, high resolution, shallow sub-bottom

Explosive = Sparker. low-med power, high to moderate resolution, shallow to deep sub-bottom

Implosive = water gun (collapse of vacuum), medium power, medium resolution, moderate sub-bottom depths

Vibrator = complex waveform, moderate power spread over long time span (non-impulsive), moderate resolution, moderate sub-bottom depths

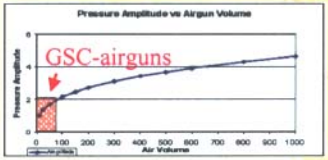
Pneumatic = air guns, sleeve guns, GI guns. release of compressed air release.

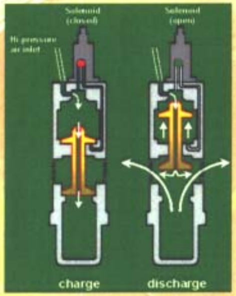
Seismic Reflection Source Technology

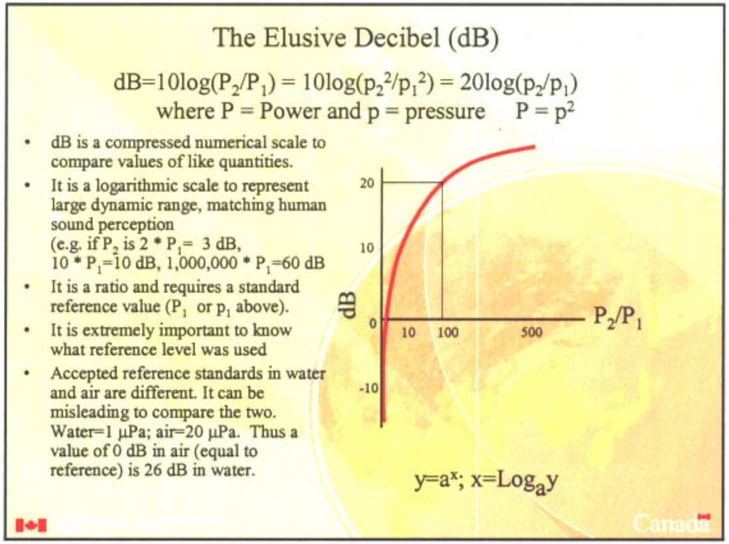
Pneumatic = rapid release of compressed air (airguns)

range of sizes from 1-2000 in^3 volumes, and pressure is variable but typically between 1600 and 2000 psi, thus range of power outputs, depth of penetration and resolution

GSC-A typically uses pneumatic sources with 5-40 in^3 volume chambers = very small to small sources (Pressure ~ $Volume^{1/3}$)







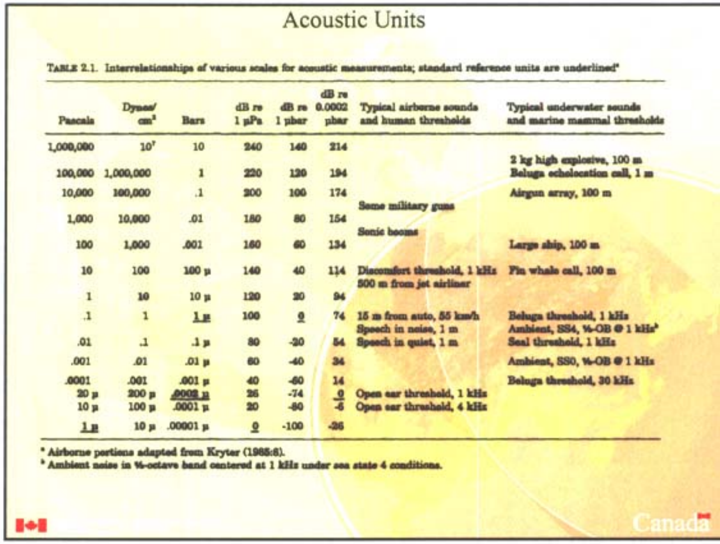
The Elusive Decibel (dB)

$$dB=10\log(P_2/P_1) = 10\log(p_2^2/p_1^2) = 20\log(p_2/p_1)$$

where P = Power and p = pressure $P = p^2$

- dB is a compressed numerical scale to compare values of like quantities.
- It is a logarithmic scale to represent large dynamic range, matching human sound perception
  (e.g. if P_2 is 2 * P_1= 3 dB,
  10 * P_1=10 dB, 1,000,000 * P_1=60 dB
- It is a ratio and requires a standard reference value (P_1 or p_1 above).
- It is extremely important to know what reference level was used
- Accepted reference standards in water and air are different. It can be misleading to compare the two. Water=1 µPa; air=20 µPa. Thus a value of 0 dB in air (equal to reference) is 26 dB in water.

$y=a^x$; $x=\mathrm{Log}_a y$



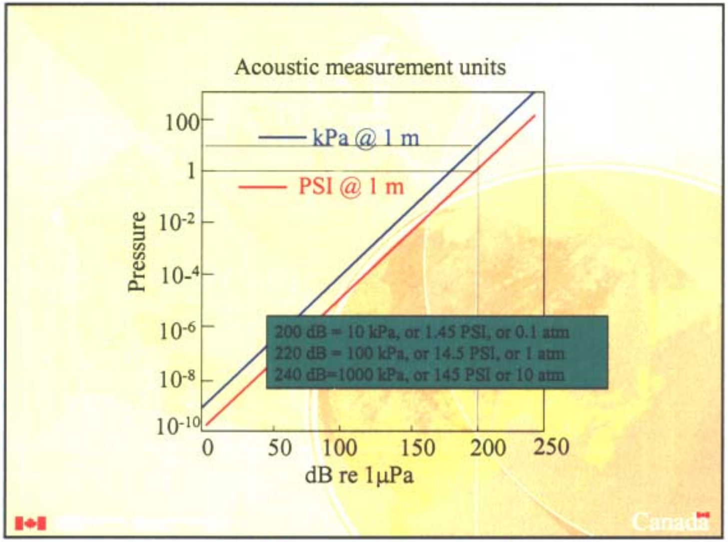
Acoustic Units

TABLE 2.1. Interrelationships of various scales for acoustic measurements; standard reference units are underlined[a]

Pascals	Dynes/cm^2	Bars	dB re 1 µPa	dB re 1 µbar	dB re 0.0002 µbar	Typical airborne sounds and human thresholds	Typical underwater sounds and marine mammal thresholds
1,000,000	10^7	10	240	140	214		
							2 kg high explosive, 100 m
100,000	1,000,000	1	220	120	194		Beluga echolocation call, 1 m
10,000	100,000	.1	200	100	174		Airgun array, 100 m
						Some military guns	
1,000	10,000	.01	180	80	154		
						Sonic booms	
100	1,000	.001	160	60	134		Large ship, 100 m
10	100	100 µ	140	40	114	Discomfort threshold, 1 kHz 500 m from jet airliner	Fin whale call, 100 m
1	10	10 µ	120	20	94		
.1	1	1 µ	100	0	74	15 m from auto, 55 km/h Speech in noise, 1 m	Beluga threshold, 1 kHz Ambient, SS4, ⅓-OB @ 1 kHz[b]
.01	.1	.1 µ	80	-20	54	Speech in quiet, 1 m	Seal threshold, 1 kHz
.001	.01	.01 µ	60	-40	34		Ambient, SS0, ⅓-OB @ 1 kHz
.0001	.001	.001 µ	40	-60	14		Beluga threshold, 30 kHz
20 µ	200 µ	.0002 µ	26	-74	0	Open ear threshold, 1 kHz	
10 µ	100 µ	.0001 µ	20	-80	-6	Open ear threshold, 4 kHz	
1 µ	10 µ	.00001 µ	0	-100	-26		

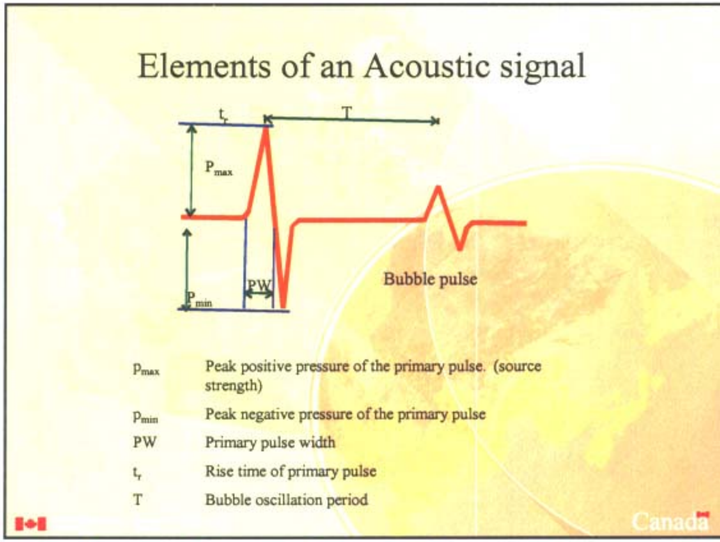
[a] Airborne portions adapted from Kryter (1985:6).

[b] Ambient noise in ⅓-octave band centered at 1 kHz under sea state 4 conditions.



Acoustic measurement units

200 dB = 10 kPa, or 1.45 PSI, or 0.1 atm
220 dB = 100 kPa, or 14.5 PSI, or 1 atm
240 dB=1000 kPa, or 145 PSI or 10 atm



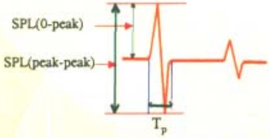
Elements of an Acoustic signal

p_{max}	Peak positive pressure of the primary pulse. (source strength)
p_{min}	Peak negative pressure of the primary pulse
PW	Primary pulse width
t_r	Rise time of primary pulse
T	Bubble oscillation period

Units of Measure

SPL (Sound Pressure Level)

– shows the peak pressure in a pulse



Positive peak pressure of 3.2×10^{11} µPa-m (3.2 bar-m) is said to have a SPL (**0-peak**) of

$$20\log[(3.2 \times 10^{11})/1] = 230 \text{ dB//1µPa@ 1 m}$$

SPL (**peak-peak**) of 236 dB//1µPa@ 1 m

Note that pulse width (T_p) is not a factor in the calculation, thus peak pressure is not a good indicator of the duration of acoustic energy release

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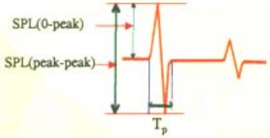
Units of Measure



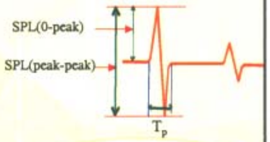
The root mean square (rms) energy is calculated over pulse duration T_p

$$\mathrm{SPL}_{\mathrm{RMS}} = 20\log_{10}\left(\sqrt{\frac{1}{Tp}\int_{Tp} p(t)^2\,dt}\right)$$

where *T* is the time interval containing the total pulse energy.

- it still doesn't reflect accurately the duration of acoustic energy release, e.g. high frequency high resolution sources and large (low frequency) sources provide similar numbers due to averaging over the pulse width.

Units of Measure



SEL (Sound Exposure Level) – accounts for the rate of energy release

you modify the rms values with the following adjustment:

$$\mathrm{SEL}_{\mathrm{RMS}} = 20\log_{10}\left(\sqrt{\frac{1}{Tp}\int_{Tp} p(t)^2\,dt}\right) - 10\log Tp/1 \text{ dB}$$

Tp is the primary (+ve and –ve) pulse duration and the "1" means that the measurement is averaged over 1 second, as opposed to the pulse duration.

e.g. 25 ms pulse, adjustment is 10 log (0.025) /1= -16 dB

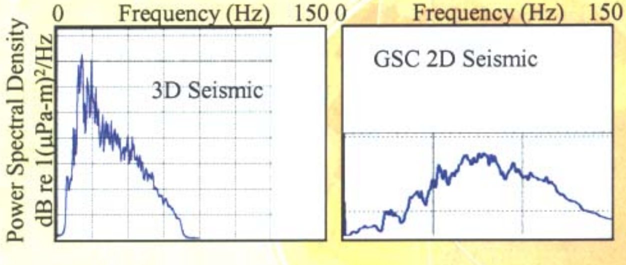
	Boomer	Airgun	Difference Factor
SPL(0-peak)	214 dB	230 dB	6
SPL(peak-peak)	220 dB	236 dB	6
SEL	220-49=171	236-27=209	79

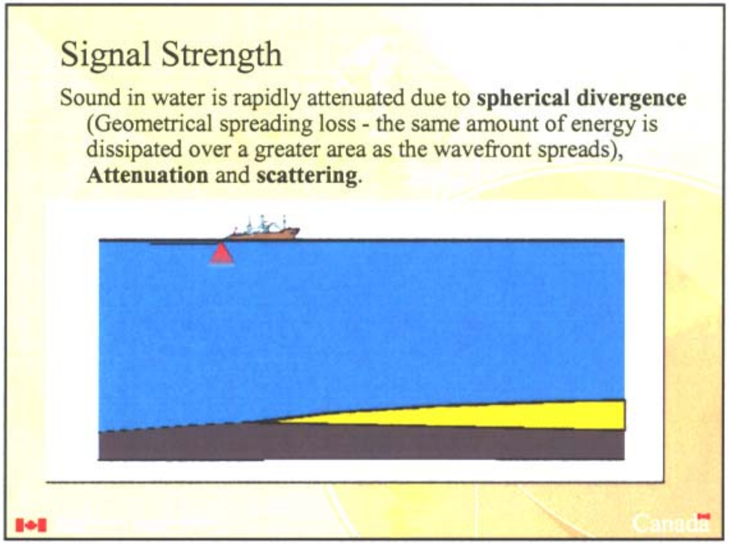
Units of Measure

Sound Spectra/Power Spectral Density

The energy distribution as a function of frequency, better reflects how a signal "sounds".

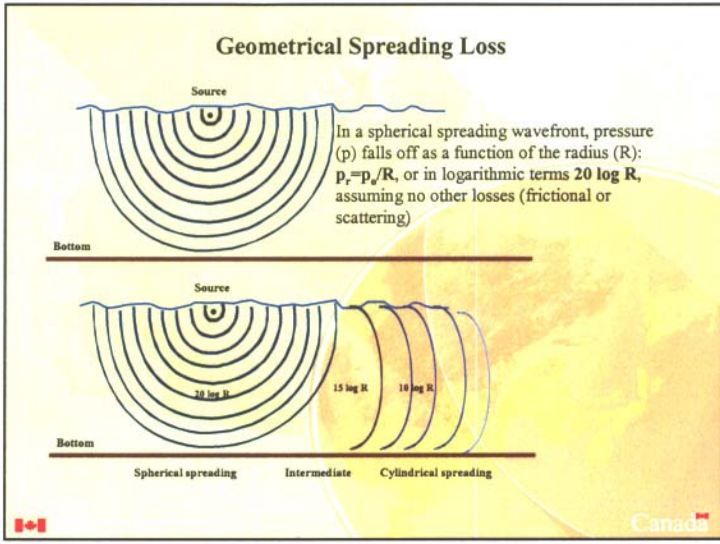
Represented as power per unit frequency vs frequency,
or in terms of pressure: mean square pressure per unit frequency.





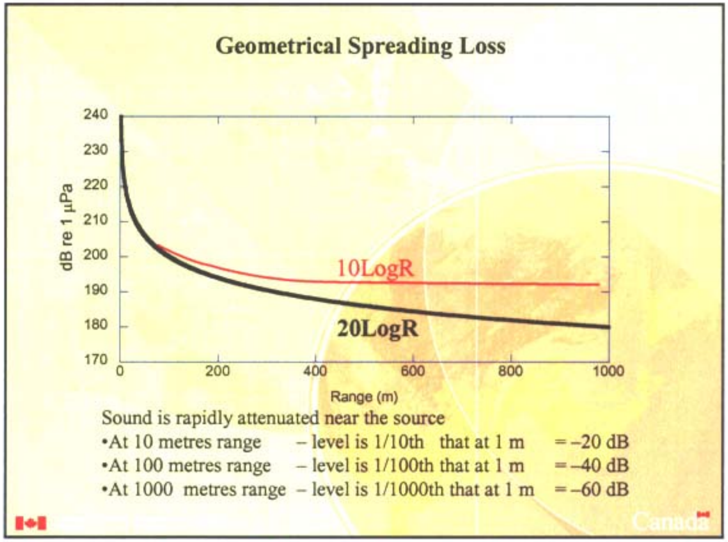
Signal Strength

Sound in water is rapidly attenuated due to **spherical divergence** (Geometrical spreading loss - the same amount of energy is dissipated over a greater area as the wavefront spreads), **Attenuation** and **scattering**.



Geometrical Spreading Loss

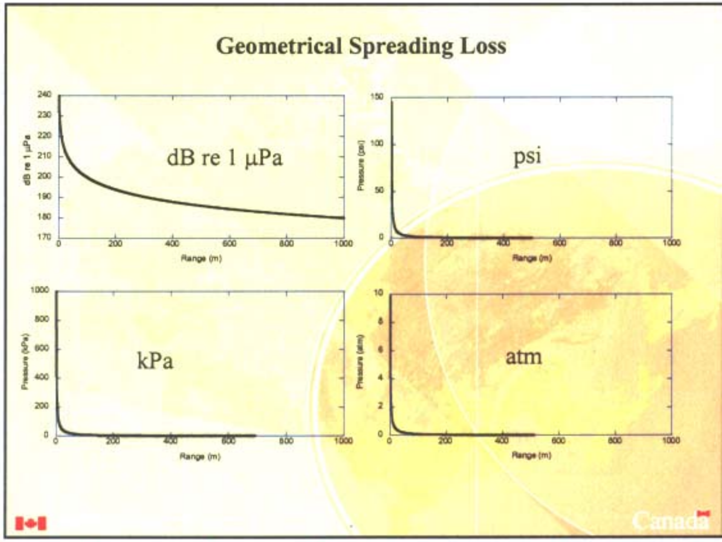
In a spherical spreading wavefront, pressure (p) falls off as a function of the radius (R): **$p_r=p_o/R$**, or in logarithmic terms **20 log R**, assuming no other losses (frictional or scattering)



Geometrical Spreading Loss

Sound is rapidly attenuated near the source

- At 10 metres range – level is 1/10th that at 1 m = –20 dB
- At 100 metres range – level is 1/100th that at 1 m = –40 dB
- At 1000 metres range – level is 1/1000th that at 1 m = –60 dB



Geometrical Spreading Loss

Attenuation Losses

- Seawater is a dissipative medium, it absorbs part of the energy of the transmitted wave, which is dissipated through viscosity or chemical reactions.
- The local amplitude decrease is proportional to the amplitude itself, the acoustic pressure then decreases exponentially with distance.
- Attenuation depends strongly on the propagation medium and frequency.
- It is often the most limiting factor in acoustic propagration.

$$p(R,t) = p_0\exp(-\gamma R)\frac{\exp(2j\pi f_0(t-R/c))}{R}$$

Expressed as dB/km

p=presure
γ = attenuation coefficient
f=frequency
R=radius
c=celerity/velocity
t=time

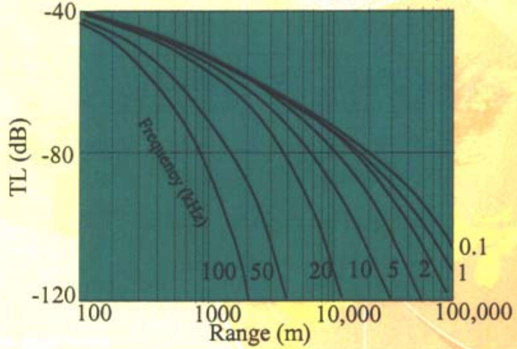
Attenuation Losses

γ = attenuation coefficient, is a function of the properties of the propagation medium, including depth, temperature and chemical composition

Total transmission losses, including geometrical spreading and attenuation

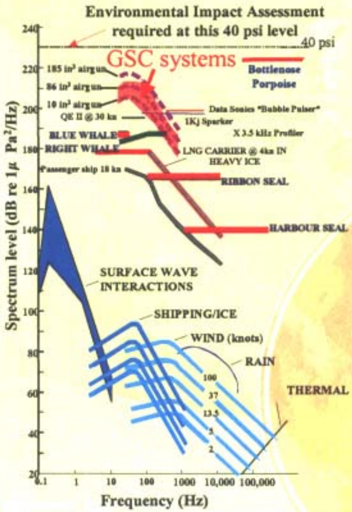
$= -20\log R - \alpha R$

Note how the higher frequencies are attenuated faster



Other sources of signal loss:

- Scattering and absorption due to bubbles
- Multiple path interference
- Sea surface interference
- Velocity structure and inhomogeneties in the water column
- Transmission into the sediment column



Comparative sound levels

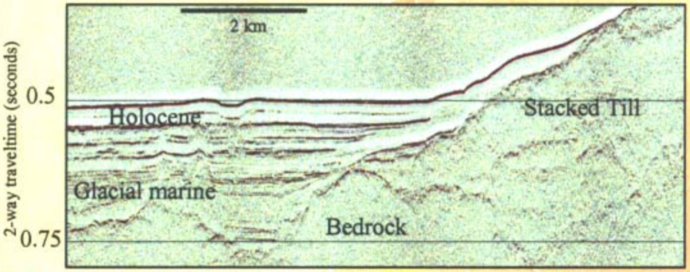
Comparative sound levels showing environmental noise, shipping traffic, some marine mammals and survey equipment used by the Geological Survey of Canada

Note that the sound levels produced by large vessels and some marine mammals are similar to those produced by survey equipment used by the GSC.

Each GSC system is compared to standards in national guidelines and an environmental assessment is performed if required by the guidelines

GSC Seismic Applications (examples)

- **Quaternary Geology: depth to bedrock, till, glacial-marine, Holocene**
- Sea Level Change: paleogeography
- Sediment Transport: pipeline and submarine cables
- Geohazards: shallow gas, faulting, submarine landsliding



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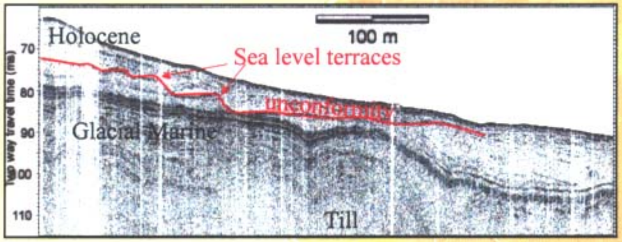

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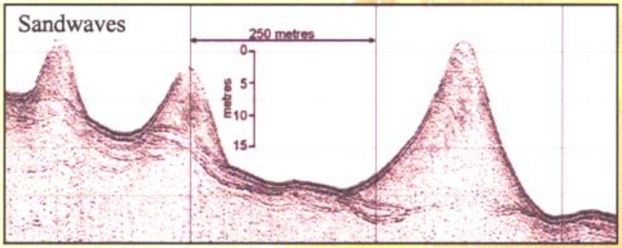

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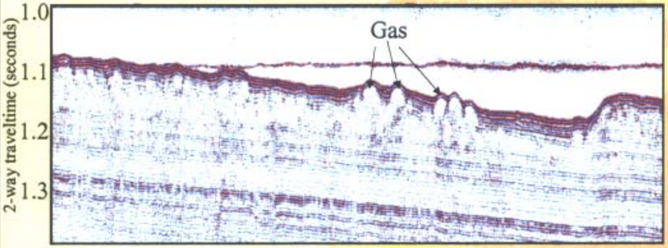
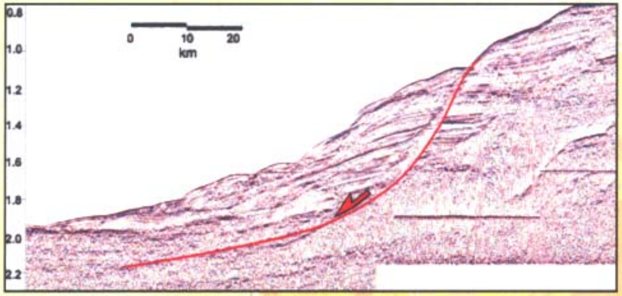


Submarine landslides



Mitigation Measures

1. Small seismic sources

means less acoustic energy and higher frequencies; these signals suffer greater amplitude attenuation due to spherical divergence, frictional losses and scattering, and thus have fewer environmental implications

2. Avoidance, shut-down and short duration

Areas of concentrations of marine mammals are avoided. Systems are shut down with observance of marine mammals in close proximity. Nature of our surveys implies we rarely concentrate within a specific area; our work is regional, thus our presence is of short duration

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Mitigation Measures (cont'd)

3. Survey design and escape

   As necessary, we design programs to survey out of embayments allowing escapement.

4. Softstart

   Seismic sources are "ramped up" in output power to allow escapement..

5. Observers

   Mammal observers are employed when surveying with larger arrays. All observations to date have shown avoidance as the principal impact

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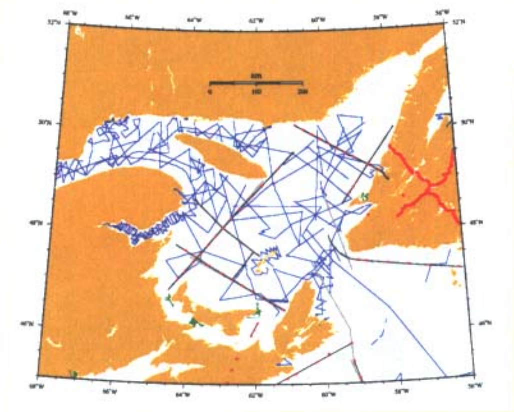
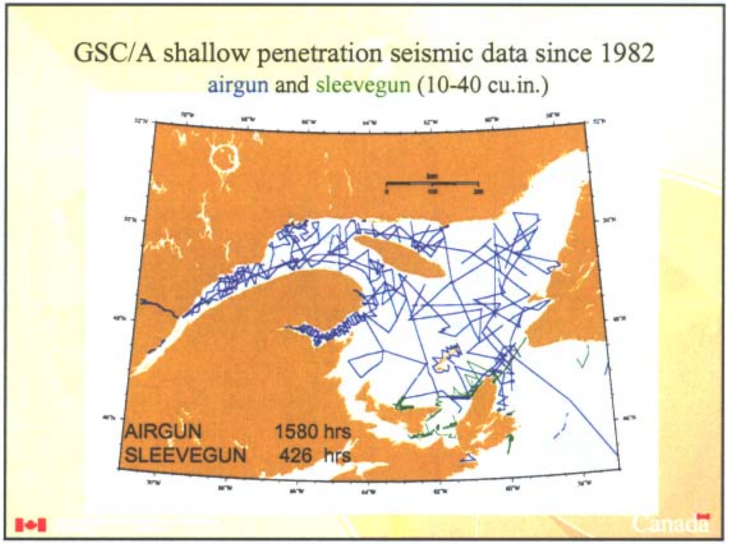
GSC/A pneumatic, boomer, multichannel and refraction seismic data since 1982

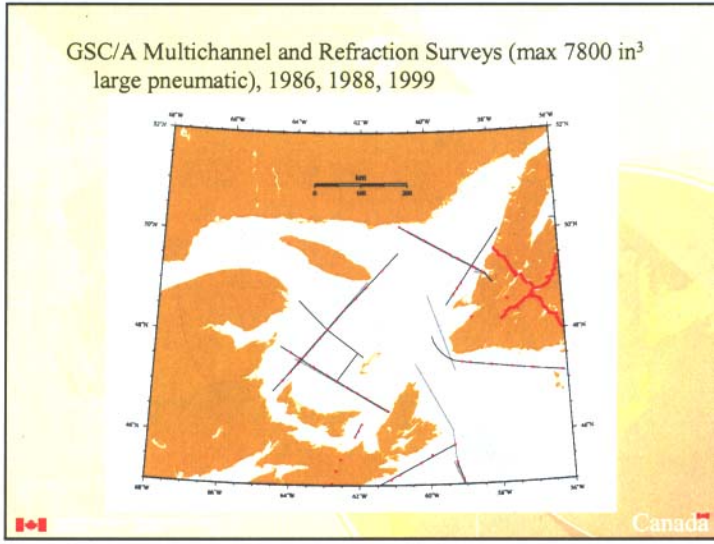




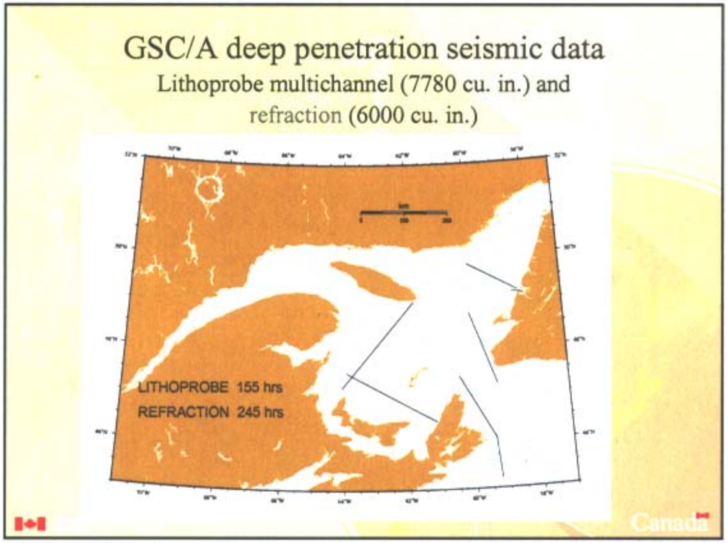
GSC/A shallow penetration seismic data since 1982

airgun and sleevegun (10-40 cu.in.)

AIRGUN	1580 hrs
SLEEVEGUN	426 hrs



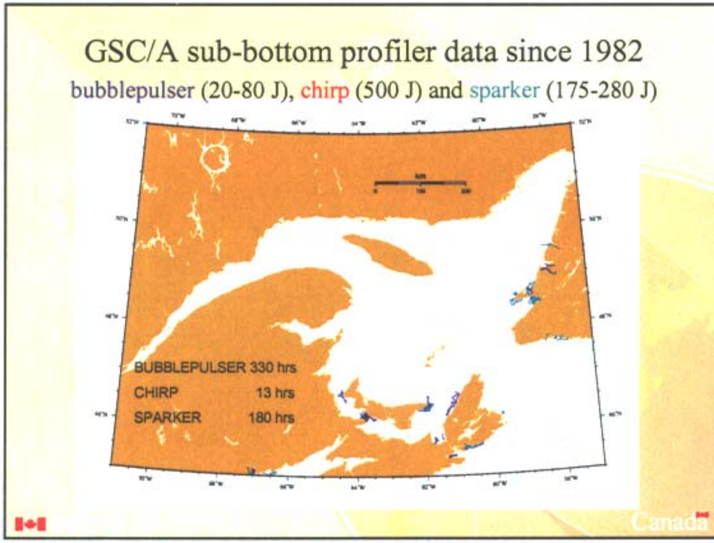
GSC/A Multichannel and Refraction Surveys (max 7800 in^3 large pneumatic), 1986, 1988, 1999



GSC/A deep penetration seismic data

Lithoprobe multichannel (7780 cu. in.) and refraction (6000 cu. in.)

LITHOPROBE	155 hrs
REFRACTION	245 hrs



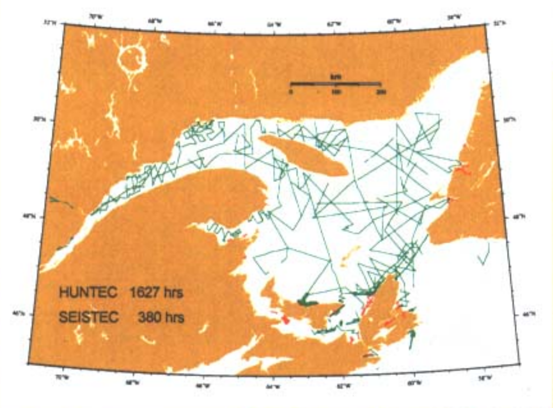
GSC/A sub-bottom profiler data since 1982

bubblepulser (20-80 J), chirp (500 J) and sparker (175-280 J)

BUBBLEPULSER	330 hrs
CHIRP	13 hrs
SPARKER	180 hrs

GSC/A boomer sub-bottom profiler data since 1982

(SEISTEC and HUNTEC)



Seismic Reflection Surveying Movie