The Acoustic Manifestations of Marine Hydrocarbon Seeps

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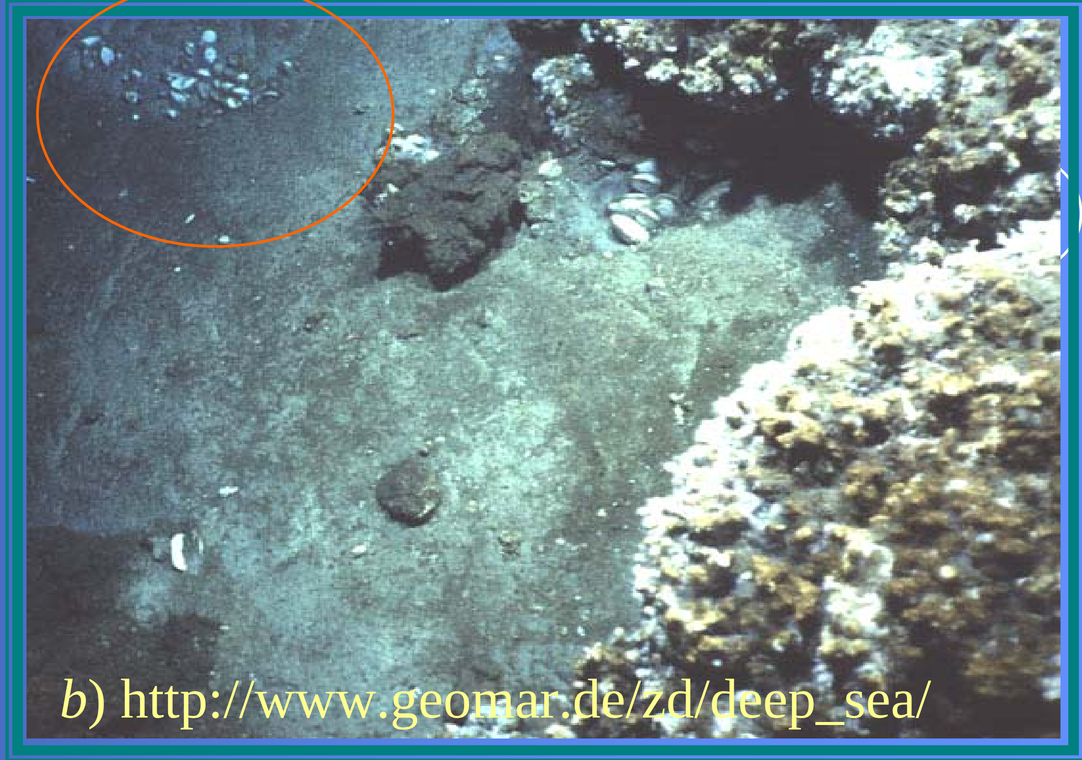
Methane seeps

a) http://www.bubbleology.com



b) http://www.geomar.de/zd/deep_sea/

c) http://www.geomar.de/zd/deep_sea

The modes of a seepage can be rather various: this is periodic emission of the single bubbles forming the emerging chain; bubbles can be thrown out to form a clusters and, at last, it there can be ascending streams from the area in tens square meters.

Interpretation of echo-sounding records of bubble plumes

History of Sonar

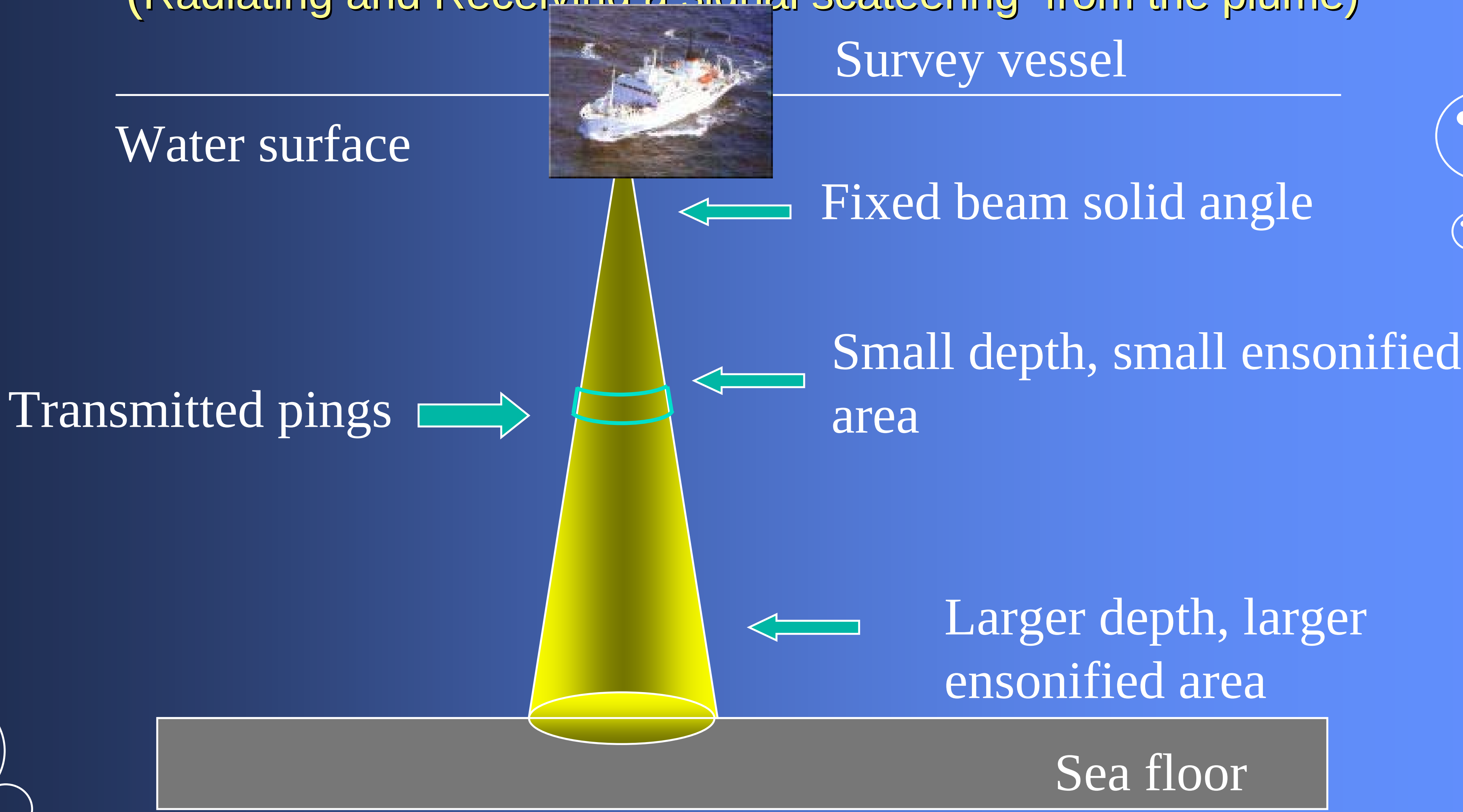
«If you cause your ship to stop, and place the head of a long tube in the water and place the outer extremity to your ear you will hear ships at a great distance from you»

Leonardo da Vinci, 1490.

- SONAR (SOund NAvigation and Ranging)
- Detection, Classification, Localization, Identification
  - Passive: just listen
  - Active: transmit and listen (echolocation)

Active Technique

(Radiating and Receiving a signal scateering from the plume)



Bubble Scattering

The range-gated backscattering intensity measured by sonar provides estimates of the scattering cross section per unit volume. Bubble contribution to the back scattering is defined by

$$M_v(x,y,z) = \int_0^\infty \sigma_s(R,z) f(x,y,z,R)\,dR$$

$$\sigma_s = \frac{4\pi R^2}{\left[(f_R / f)^2 + \delta^2 \right]}$$ – is the bubble scattering cross section

$f(x,y,z;R)$ – is the bubble size distribution

$$f_R = \sqrt{\frac{3\gamma P_0 (1 + z/h)}{\rho_w R^2}}$$

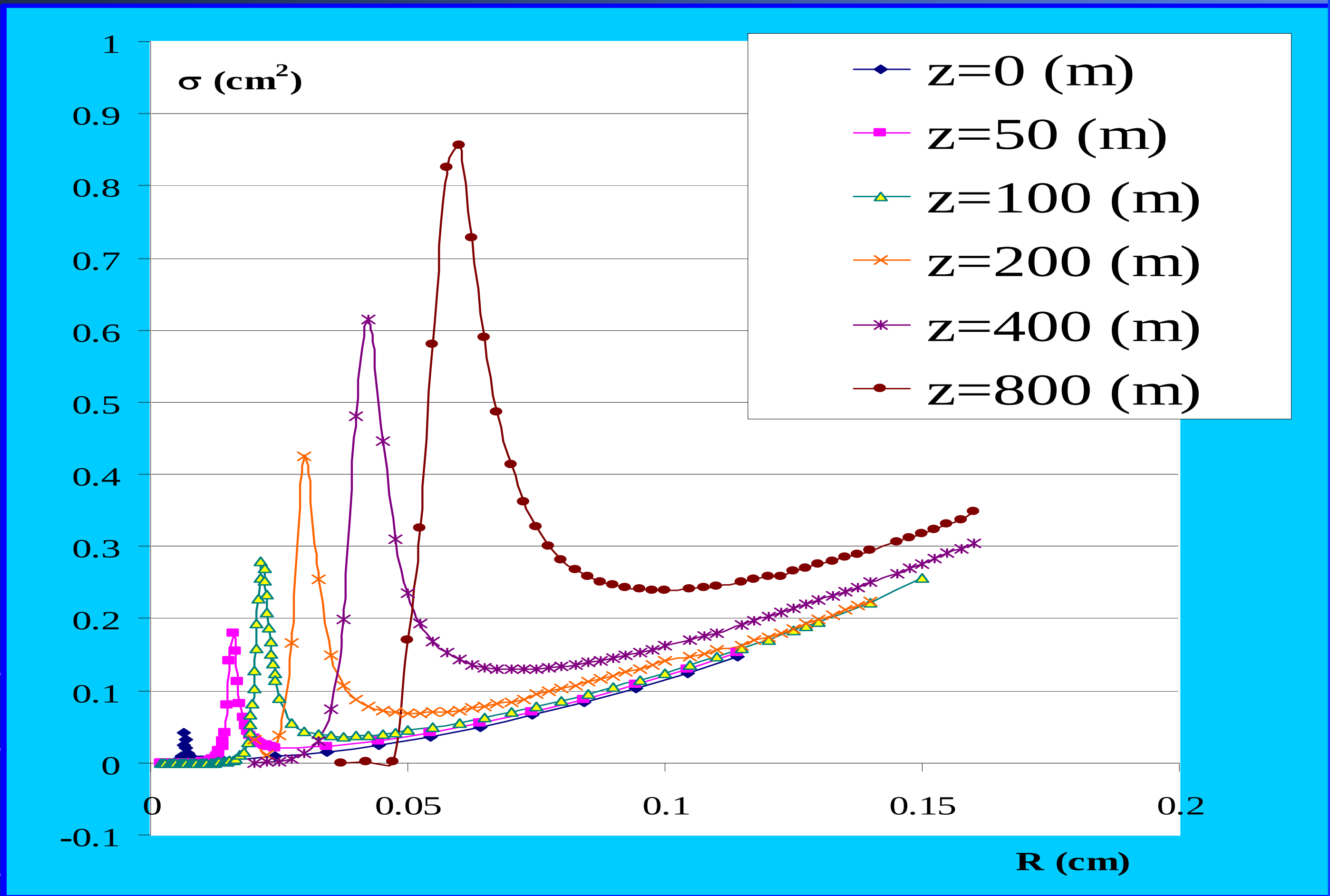
f – is the sound frequency,

f_R – is the natural frequency,

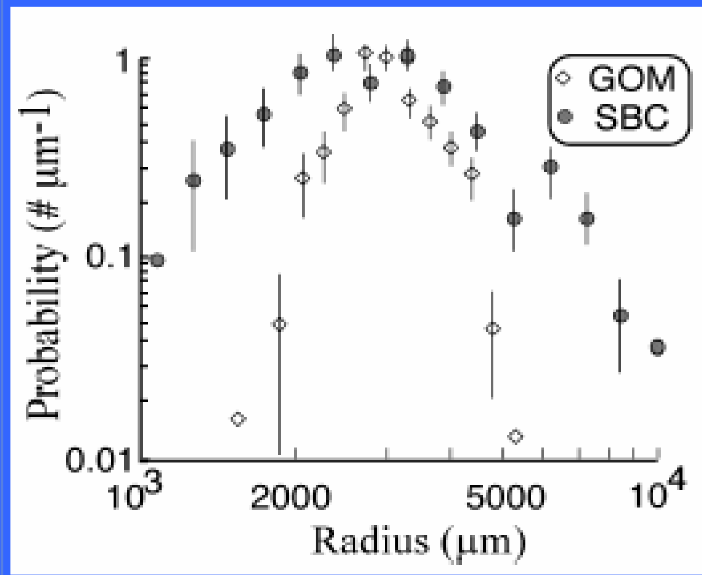
δ – is the damping constant,

h – is the characteristic depth ($h \approx 10$ m).

Scattering cross-section

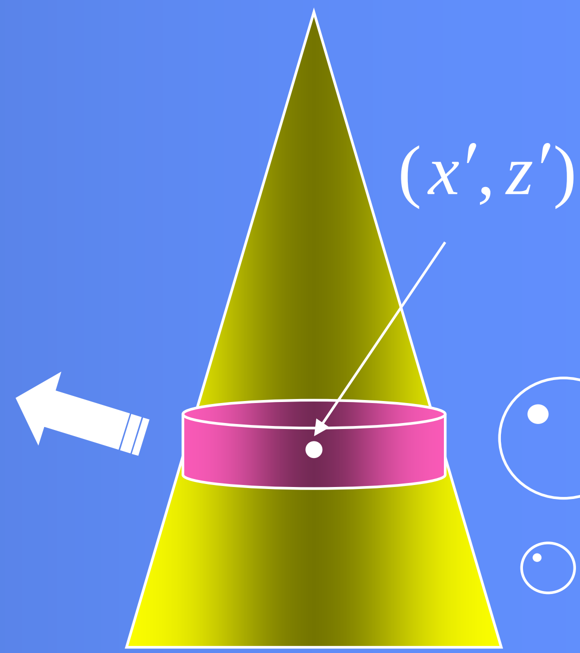


f = 50 kHz



Bubble size distribution for seep in the Gulf of Mexico (GOM) and seep in the Santa Barbara Channel (Leifer, Judd 2002).

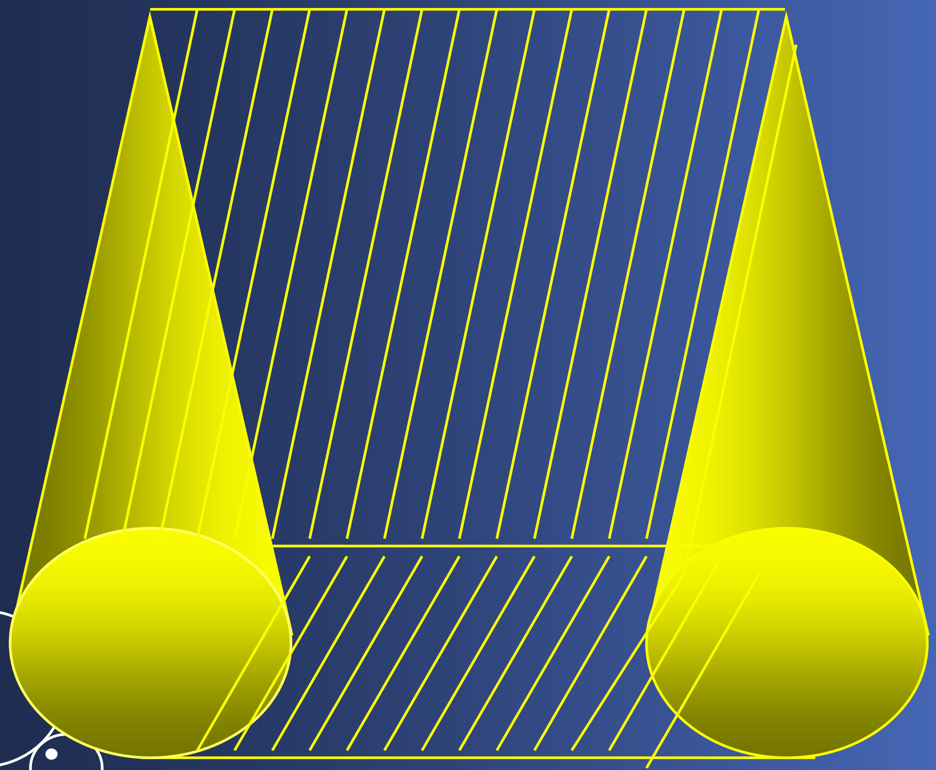
Inverse problem



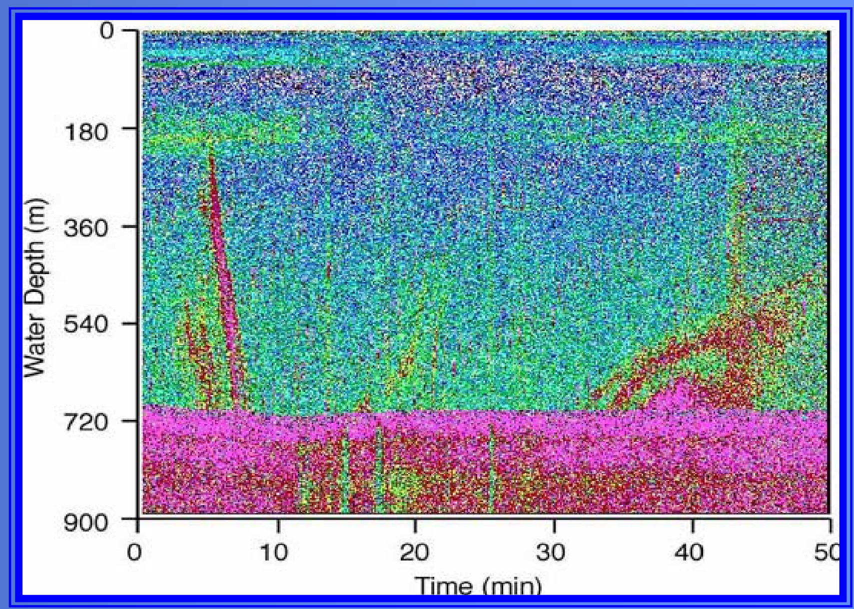
Fredholm integral equation of the first kind

$$\int dR \int_{V(x',z')} dxdydz f(x,y,z;R)\sigma(R,z) = M(x',z')$$

3D ensonified volume



2D record



Sakhalin shelf (KOMEX)

A. Narrow beam

Seep Tents Seep (STS): Depth ~ 70 m, area ~ 700 m^2 (Leifer, Clark, 2002)
Sonar survey: 50 kHz (Hornafius *et al*., 1999)

$$\int dRf(z;R)\sigma(R,z) \approx M(z)$$

B. Dominant contribution of the resonant bubbles in the back-scattering

$$f(z,R_r) \approx M_v(z)\left(\int_0^\infty \sigma_s(R)dR\right)^{-1}$$

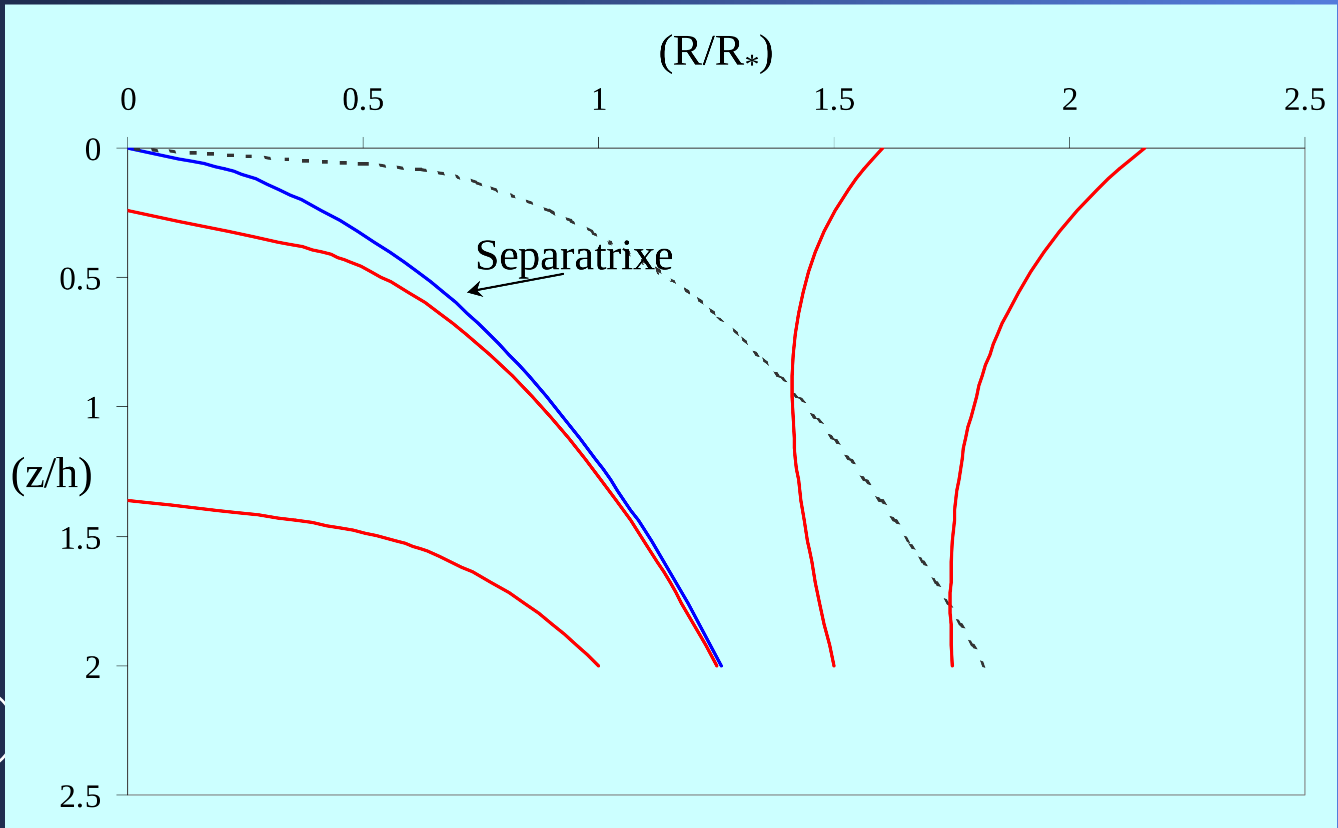
At the sonar frequency *f*, the bubble of the given size $R_r(z) = R_r(0)\sqrt{1+z/h}$ is in resonance with the exciting sound wave at depth *z*.

C. Known kinetics of bubble growth and dissolution

The bubble distribution $f(\mathbf{r},R,t)$ as a function of position r, time t and radius R satisfies a kinetic-type transport equation

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}\left(\frac{dx}{dt}f\right) + \frac{\partial}{\partial y}\left(\frac{dy}{dt}f\right) + \frac{\partial}{\partial z}\left(\frac{dz}{dt}f\right) + \frac{\partial}{\partial R}\left(\frac{dR}{dt}f\right) = 0$$

Bubble rise trajectories in the space of depths and sizes



$$\frac{dz}{dt} = v_B(R)$$ - is the bubble rise velocity as determined by the balance between the buoyancy and drag forces

$$\frac{dR}{dt} = Q(z,R) = $$

$$= \sum_i k_{Bi} \frac{\tilde{R}T}{P_0} \frac{[c_i - (P_{Bi}/H_i)]}{1+(z/h)} - $$

$$- \frac{R}{3} \frac{1}{1+(z/h)} \frac{dz}{hdt}$$

- as the bubble rise, its radius changes due to mass flux and decrease in the hydrostatic pressure.

$$\frac{(R/R_*)^3}{3}[1+(z/h)] - \frac{(z/h)^2}{2} = Const = \frac{(R_0/R_*)^3}{3}[1+(z_0/h)] - \frac{(z_0/h)^2}{2}$$

The solution by the method of characteristics

$$\frac{\partial f}{\partial \tau} = -\frac{1}{L}\frac{\partial Q(R,z)}{\partial R} f, \qquad d\tau = L dt, \qquad L = \left[1 + \left(\frac{dz}{dt}\right)^2 + \left(\frac{dR}{dt}\right)^2\right]^{1/2}$$

$$f(x,y,z(t),R(t),t) = \exp\left(-\int_0^t [\partial Q/\partial R]_{\substack{z=z(t')\\ R=R(t')}} dt'\right) f(x,y,z_0,R_0,0)$$

$$f(H,R_0) = \frac{[1+(H/h)]}{[1+(z/h)]} f(z,R_r) = \frac{[1+(H/h)]}{[1+(z/h)]} M_v(z) \left(\int_0^\infty \sigma_s(R) dR\right)^{-1}$$

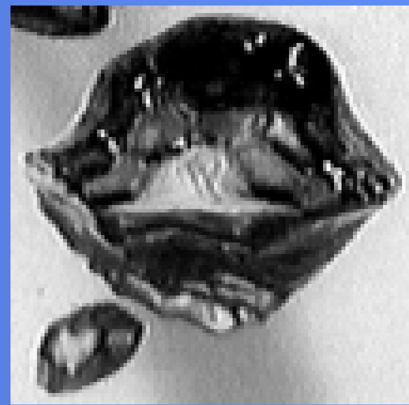
Passive Technique

(Receiving only a signal radiated from the plume)

As gas is pushed out of vent, the surface separating it from the surrounding liquid deforms until opposing points come together and a closed surface is formed.

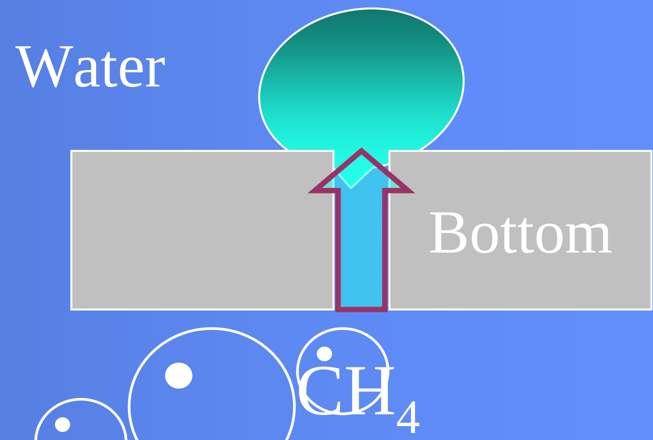
The “birthing wails” of the bubble (Longuet-Higgins, 1990) is due to the transformation of the energy of the distortion modes into the breathing one, corresponding to a volume oscillations.

The aim of the passive technique is estimating the sizes and numbers of bubbles from the 'ringing' sounds they make when they are formed.

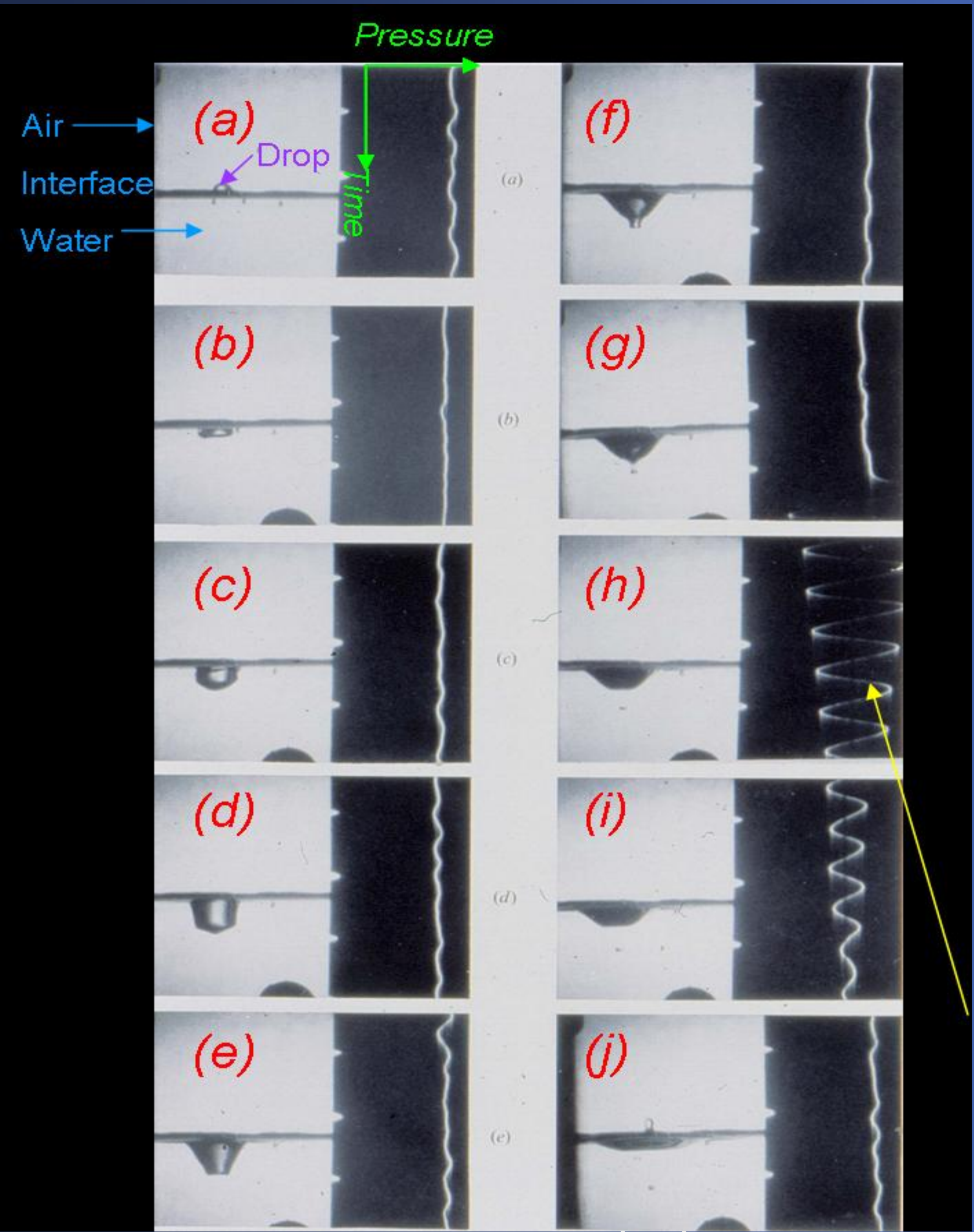


http://www.bubbleology.com

Birthing bubble



The sounds of ringing bubbles



A close analogy can be established between the generation of the noise by rain and birthing bubble. On the screen you see a photograph, taken by H. Pumphrey which shows, on the left high speed photography of a raindrop hitting water and on the right we see an oscilloscope trace of the hydrophone signal, which plots pressure in the horizontal direction and time running down the frame.

The droplet can be seen hitting the water in frame (a). It causes a crater to form up to frame (e). The crater begins to close, and it is not until frame (g) that the hydrophone shows a signal. This is coincident with a bubble being pinched off from the bottom of the crater. It is the bubble pulsation which causes the exponentially decaying sinusoid characteristic of the entrainment, the sound emitted when the bubble

Noise spectrum of gas plume

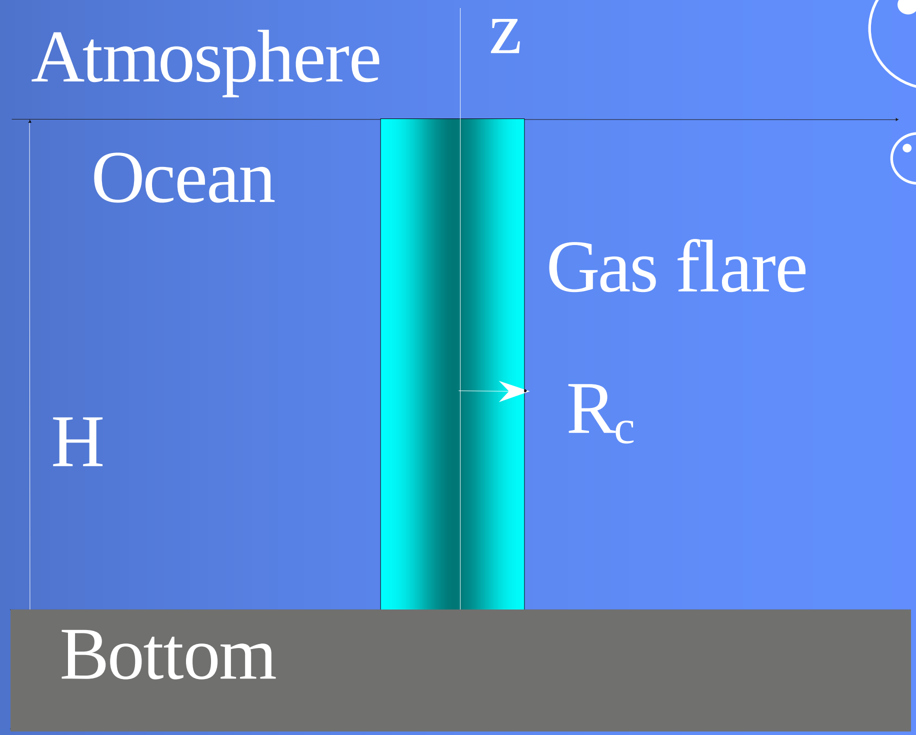
A rising bubble plume forms an effective acoustic waveguide that possesses normal modes.

The sound speed c_m^2 is related to the void fraction, through Wood's equation

$$\frac{1}{c_m^2} = \frac{1}{c^2} + \frac{\beta\rho_0}{P}$$

$$\beta = \frac{4\pi}{3}\int f(R)R^3 dR$$

STS: $\beta \approx 0.01,$ $c_m \approx 100$ m/s



Natural frequencies of gas plume

Explicit expression for the frequencies of these modes have been derived for the bubbly medium in the form of cylinder with radius R_c and length H.

$$\omega_n^* = \frac{2c_m}{R_c}\left|\ln\left(\frac{R_c(\pi n)}{H}\right)\right|^{-1/2}$$

$$P_m(\rho,z) = -\frac{\sin k_m z}{\sin k_m H} + \sum_{n=1}^{\infty} A_n J_0(\rho\mu_n^{(m)})\sin\lambda_n^S z \qquad P(\rho,z) = \sum_{n=1}^{\infty} C_n H_0^{(1)}(\mu_n\rho)\sin\lambda_n z$$

$$s_n \equiv R_c\mu_n \qquad x_n \equiv R_c\mu_n^{(m)} \qquad \lambda_n \equiv \lambda_n^S = \pi n/H \qquad \mu_n = \sqrt{k^2-\lambda_n^2} \qquad \mu_n^{(m)} = \sqrt{k_m^2-(\lambda_n^S)^2}$$

$$A_n = 2b_n\left(J_0(x_n) - \frac{x_n J_1(x_n)H_0^{(1)}(s_n)}{s_n H_1^{(1)}(s_n)}\right)^{-1} \qquad D_n = J_0(x_n) - \frac{x_n J_1(x_n)H_0^{(1)}(s_n)}{s_n H_1^{(1)}(s_n)}$$

To identify the frequencies of the normal modes one should look for the position of the minima of the denominator

Spatial correlation of noise

(Produced by bubbles)

$$\left|P_T(\mathbf{r},\omega)\right|^2 = 4\rho_0^2 \dot{n} T (\bar{R}_0 / R_c)^4 \left|(\ddot{R})_\omega\right|^2 \left| \int_0^{2\pi} \int_0^{R_c} d\varphi' \rho' d\rho' G(\omega;\mathbf{r} \mid \rho',\varphi',H) \right|^2 \approx$$

$$\approx \frac{64\pi^2 \rho_0^2 \dot{n} T \dfrac{\bar{R}_0^{\,4} \left|(\ddot{R})_\omega\right|^2}{H^2} K_0^2(k_n \rho) \sin^2\left[\dfrac{\pi z}{H}(n-1/2)\right]}{\left\{1-\dfrac{\omega^2}{\omega_{Rn}^2}\right\}^2 + \left\{4\pi\omega_{nR}^3 R_c^2 \ln\left[\dfrac{R_c \pi (n-1/2)}{H}\right] \displaystyle\int \frac{\delta g(R) R dR}{(\Omega_0^2(R) - \omega_{nR}^2)^2 + 4\delta^2 \omega_{nR}^2}\right\}^2}$$

$\dot{n}_N$ - is the number of bubbles generated per unit time in the vents

$(\ddot{R})_\omega$ - is the Fourier transform of the acceleration of the characteristic bubble $\bar{R}_0$

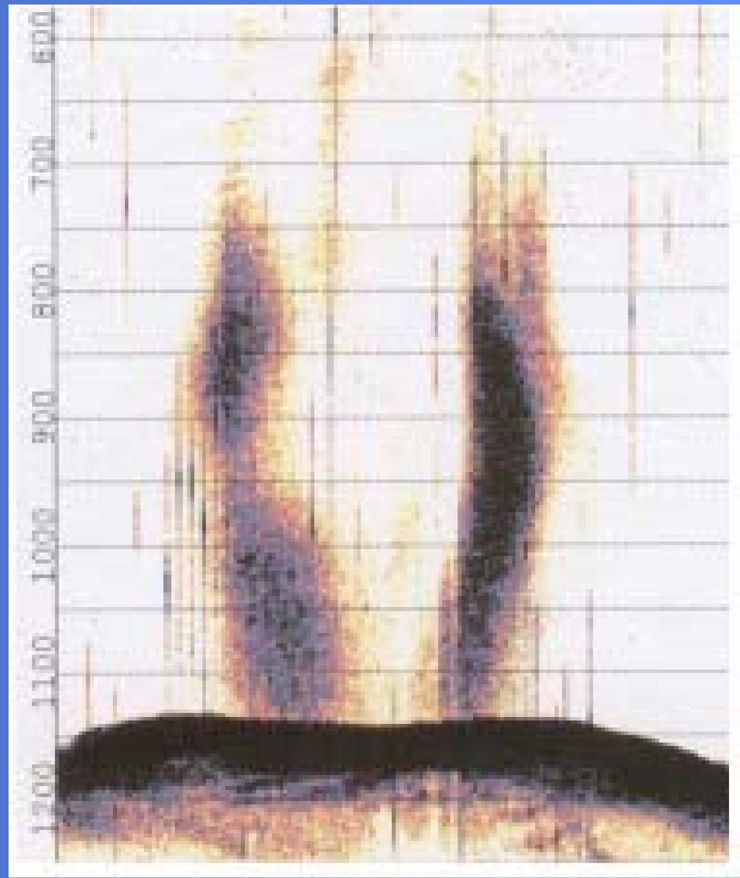
Spatial correlation of noise (Sea surface generated noise)

$$|P_T(\mathbf{r},\omega)|^2 \approx \frac{16\pi^3 Q^2(\omega)\dfrac{R_c^2(n-1/2)^2}{(\omega/c)^2 H^4} K_0^2(k_n\rho)\sin^2\left[\dfrac{\pi z}{H}(n-1/2)\right]}{\left\{1-\dfrac{\omega^2}{\omega_{Rn}^2}\right\}^2 + \left\{4\pi\omega_{nR}^3 R_c^2 \ln\left[\dfrac{R_c\pi(n-1/2)}{H}\right]\displaystyle\int \frac{\delta g(R)RdR}{(\Omega_0^2(R)-\omega_{nR}^2)^2+4\delta^2\omega_{nR}^2}\right\}^2}$$

We use a model of surface generated noise developed by (Kuperman *et al*. 1986, 1987) The random noise sources are represented by correlated monopoles distributed over an infinite plane located below the surface at depth $\tilde{z}$.

Hydrate-shelled bubbles

The persistence of methane gas bubble plumes rising as much as hundreds meters in the water column is remarkable because the ocean is undersaturated in methane, and the bubbles should quickly dissolve. Probable explanation was proposed by Merewether et al. (1985) who inferred that the bubbles were protected by a coating of oil or gas hydrate. The latter was suggested to cause the reduced shrinking rate of methane gas bubbles.



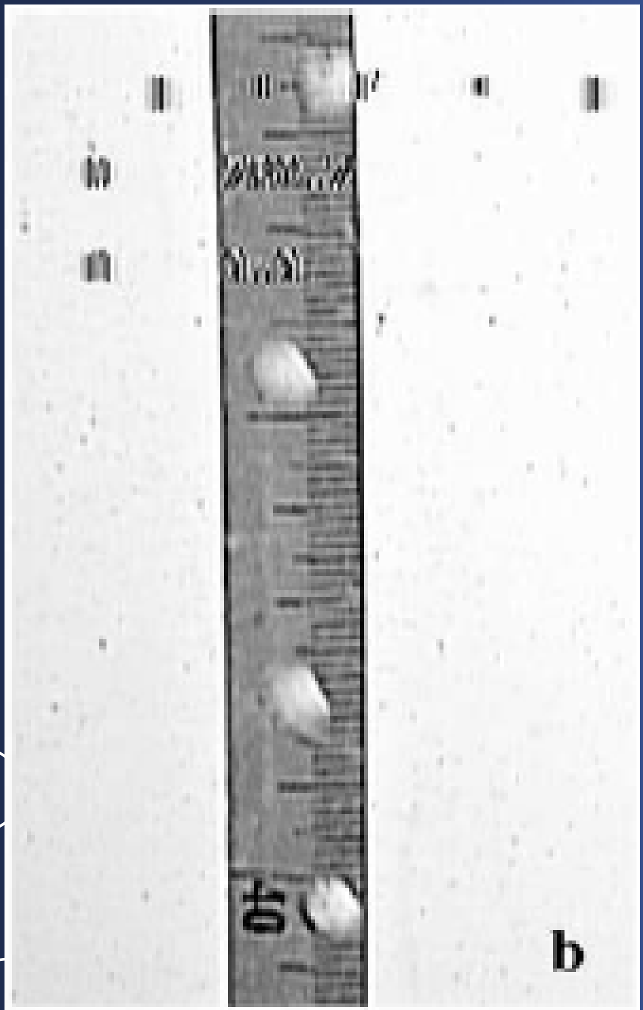
Echographs from the PARASOUND showing the strong backscatter from distinct methane seepages (courtesy of A. Nikolovska).

Gas-Hydrates

Gas hydrate is an ice-like solid that results from the trapping of methane molecules -- the main component of natural gas -- within a lattice-like cage of water molecules. Dubbed the "ice that burns," this substance releases gaseous methane when it melts.

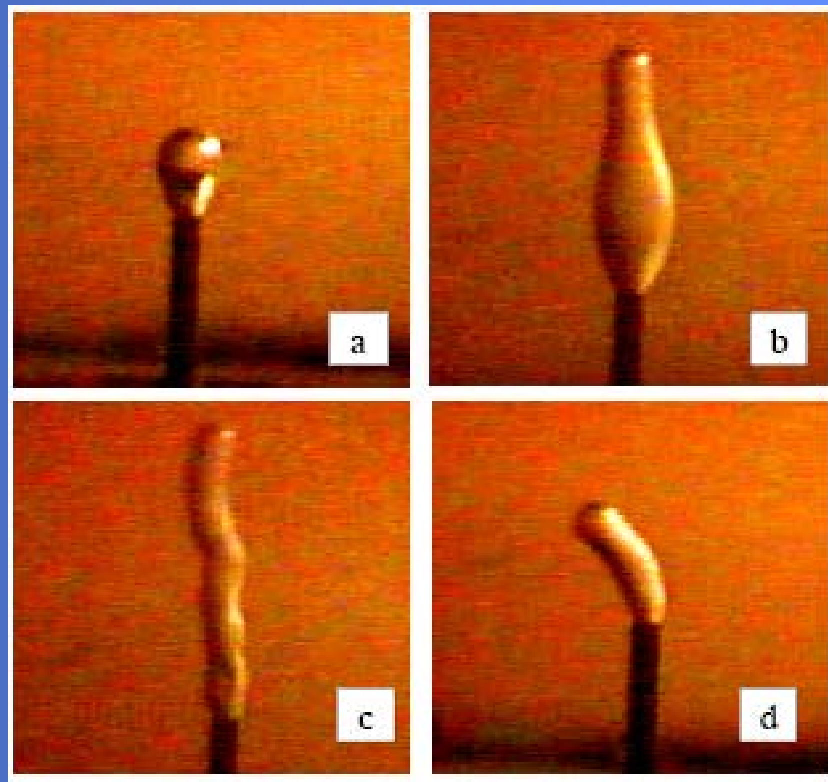
Image courtesy of U.S. Department of Energy

The regimes of hydrate formation



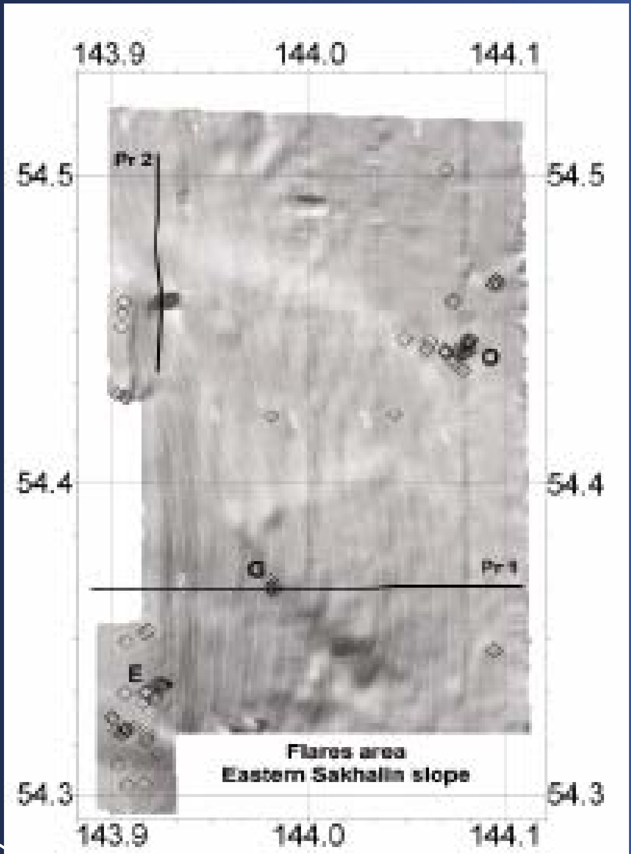
Bubbles of natural gas at the seafloor at 780 m depth (Rehder *et al.*, 2002)

The regimes of hydrate formation on methane bubbles and dynamics of dissolution of such encapsulated bubbles have been the subjects of laboratory, as well as field experiments.



The shape of the methane bubbles growing in water at temperature 275 K and ambient pressure 58 atm (Gumerov & Chahine, 1998).

Hydrocarbon seeps on the Sakhalin slope in the Sea of Okhotsk

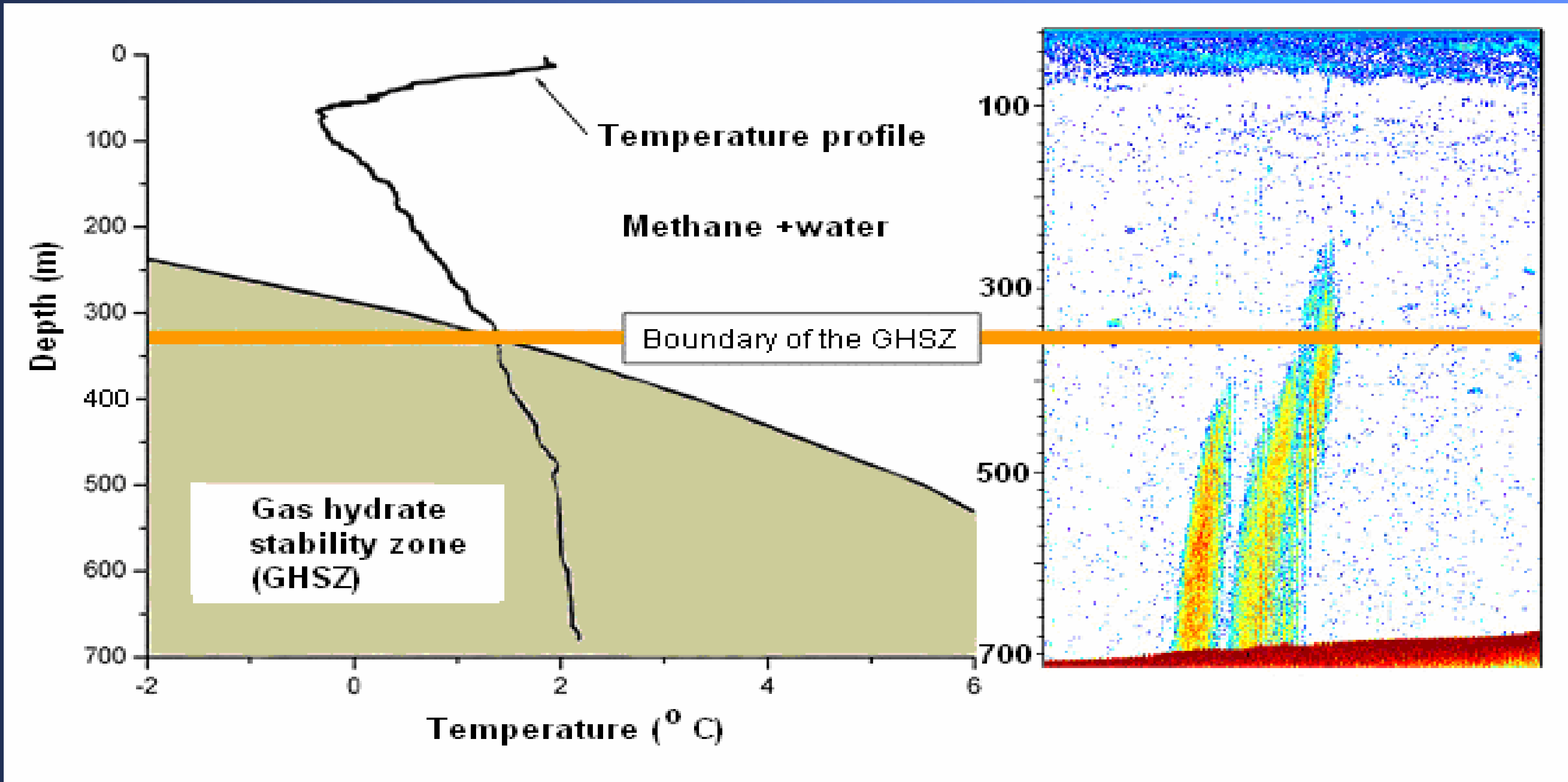


The manifestations of seeps have been actively investigated in different regions of the World Ocean, in particular, on the Sakhalin slope in the Sea of Okhotsk. Within the gas-hydrate stability zone – for high hydrostatic pressures and low temperatures, methane-hydrate ice skins are formed on rising seep bubbles which are typically methane. The objective of the present study was to develop a suitable model describing rheological characteristics of gas-hydrate shell and to analyze acoustic manifestations of such bubbles for the frequency range used in marine field experiments.

Bathymetry of the study area and sites of acoustic surveys Obzhirov – O, Giezelle – G, Erwin – E

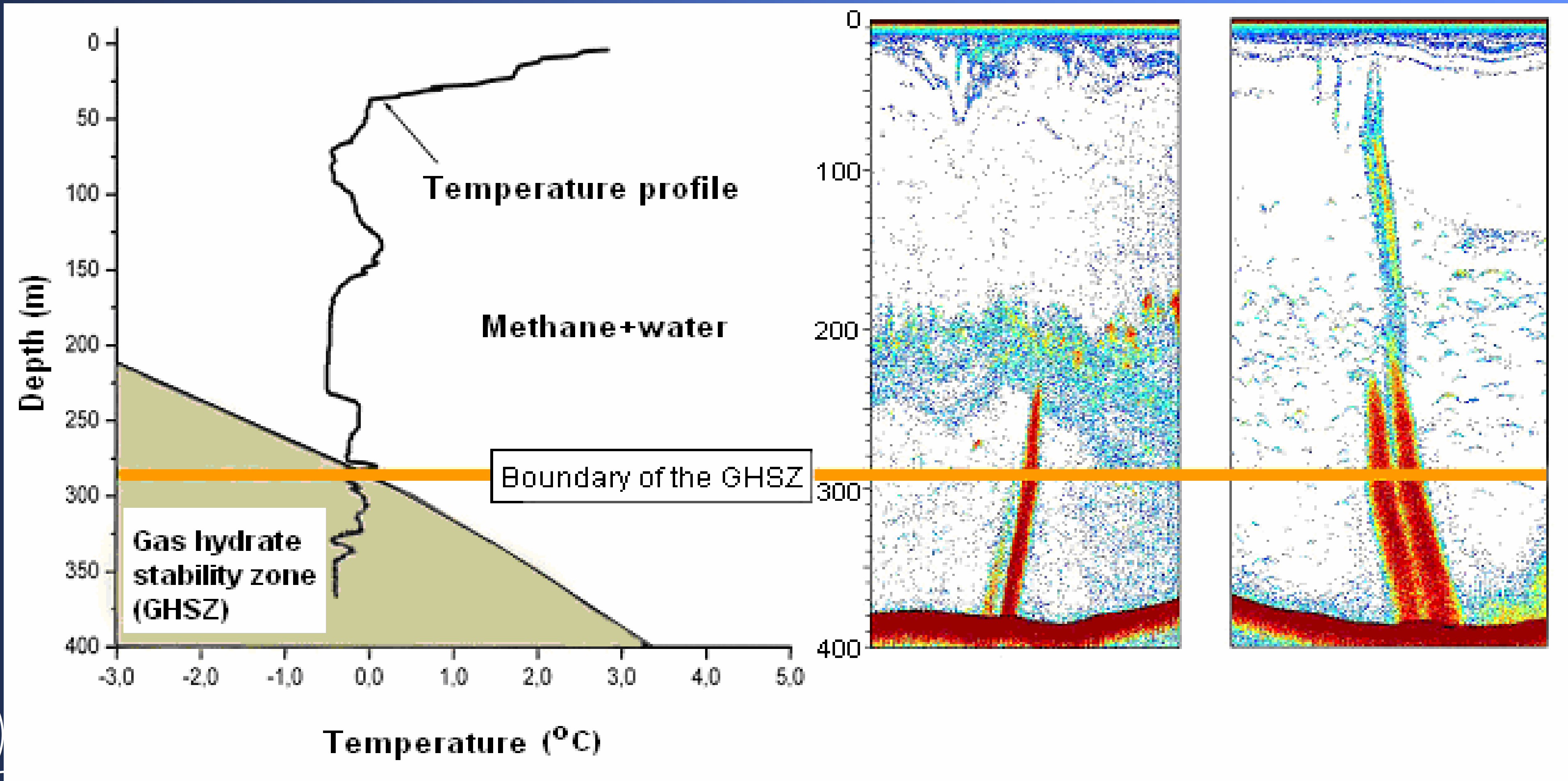
GEOMAR Report 110, Kiel, 2003.

Relationship between the height of the acoustic backscatter images and the upper boundary of the gas hydrate stability zone



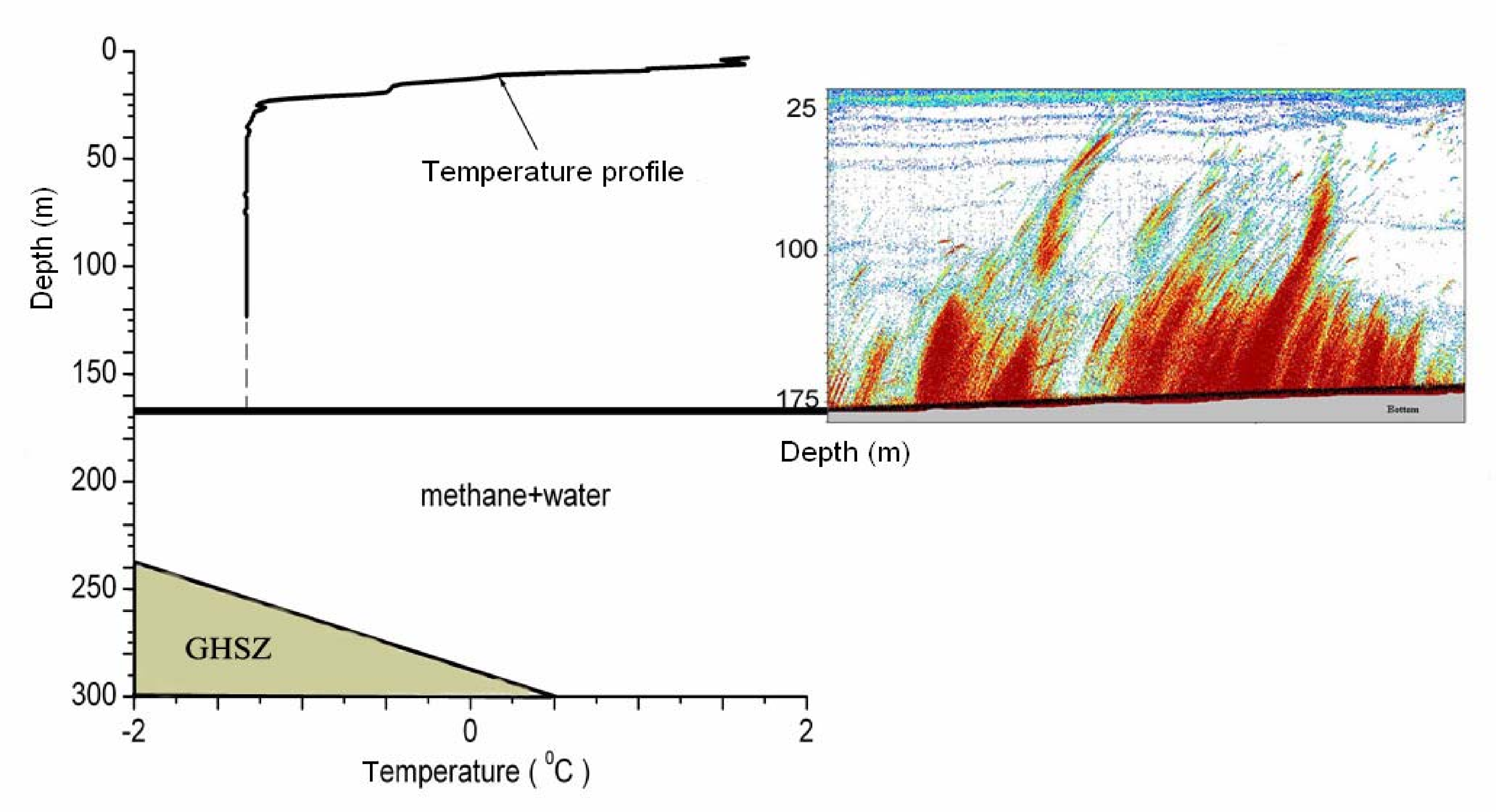
Obzhirov seepage (echo sounding records courtesy of A. Salomatin)

Relationship between the height of the acoustic backscatter images and the upper boundary of the gas hydrate stability zone



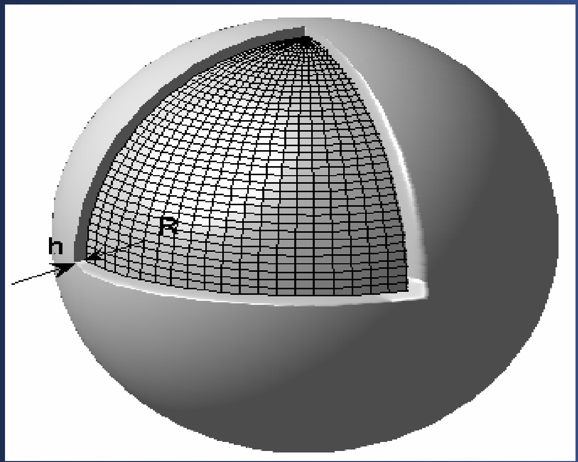
Giezelle seepage (echosounding records courtesy of A. Salomatin)

Relationship between the height of the acoustic backscatter images and the upper boundary of the gas hydrate stability zone



Erwin seepage (echosounding records courtesy of A. Salomatin)

Rheological model of hydrate shell



The methane bubble with radius R covered by gas-hydrate shell of thickness h.

To characterize the rheological properties of the hydrate shell the specific models (Maksimov & Sosedko, 2005) have been proposed .

$$\Omega_0^2 = \left(3\gamma P_0 + 12\mu \frac{h}{R}\frac{1}{1+4\mu/3K}\right)\left(\rho_L R^2\right)^{-1}$$

- is the natural frequency of the hydrate encapsulated bubble;

$$f_0 = -R\frac{\omega^2}{\omega^2 - \Omega_0^2(1-ik_L R)}$$

- is the scattering amplitude;

P_∞ is the equilibrium gas pressure in the bubble;

γ is the ratio of specific heats; μ, K are the elastic modulus of the shell;

ρ_0 is the liquid density.

In derivation of these equation, we assumed that the behavior of the gas core is polytropic. For the hydrate shells, the elastic modulus of which are very close to ones of the common ice ($K \approx 7.5\cdot 10^9$ Pa, $\mu \approx 3.5\cdot 10^9$ Pa), the correction factor $(1+4\mu/3K)$ to the model of the rubber like shell should be accounted

Peculiarities of scattering by encapsulated bubbles

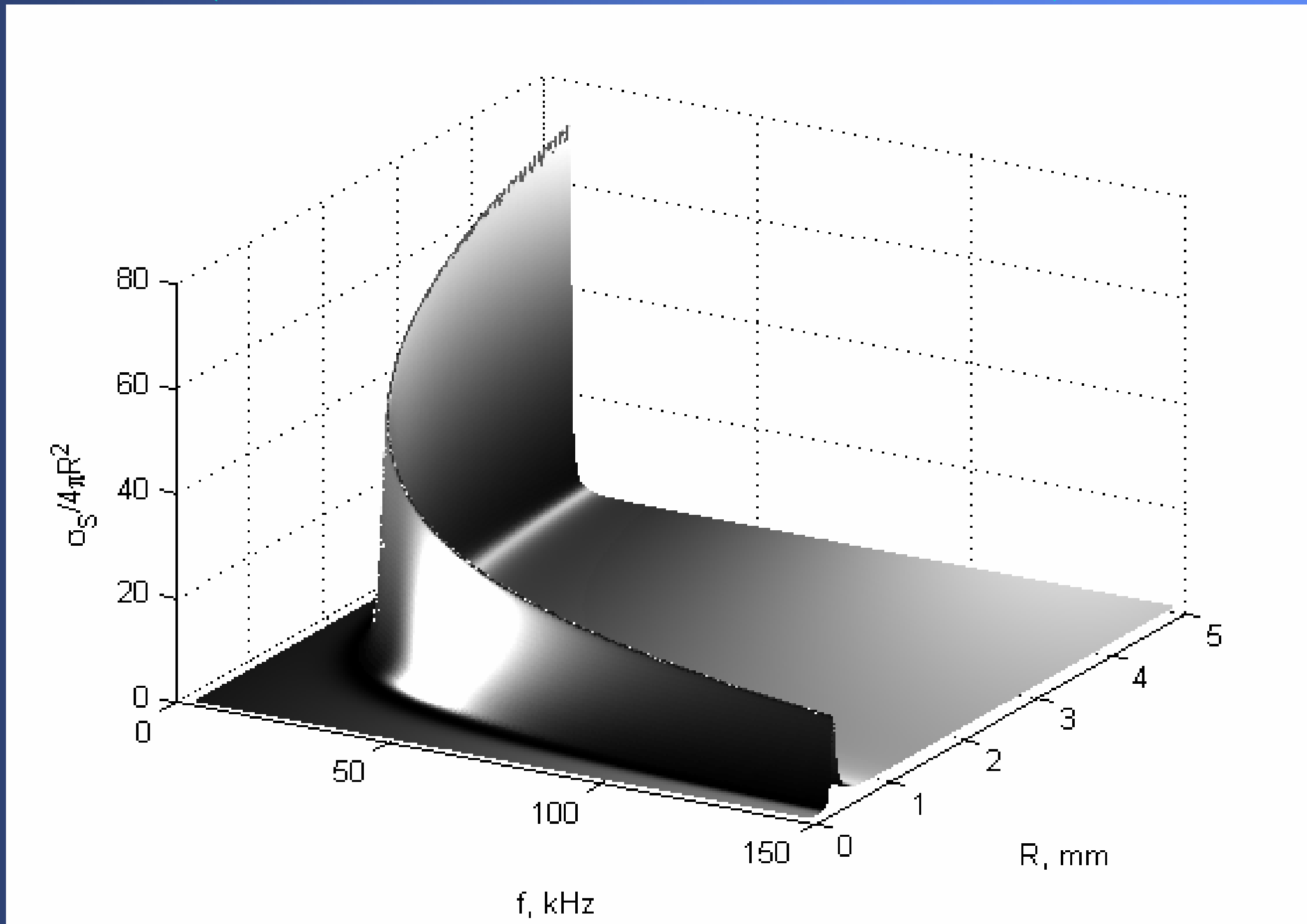
$$\sigma_S = 4\pi R^2 \Omega^4 \left[\left(1-\Omega^2\right)^2 + (\omega R / c_L)^2 \right]^{-1}, \qquad \Omega = \omega / \Omega_0 .$$

- In considering scattering from encapsulated bubble we did not account dissipative effects in liquid, shell and gas. This approximation is justified, since the zone of stability for gas-hydrates is located at depths in hundreds meters and high hydrostatic pressure in tens atmospheres provides that the dominant mechanism of losses near the resonance , where they should only be accounted, is the radiation damping. This type of losses has been accounted in derivation of the current equation.
- Another peculiarity, that distinguishes cardinally the behavior of the scattering amplitude from one for the conditions of the laboratory experiments with contrast agents, is the high equilibrium pressure in the bubble, which is near hydrostatic and varies with the depth.

$$P_h(z) = P_h(0)(1 + z/H), \qquad P_h(0) \approx 10^5 \text{ Pa}, \qquad H \approx 10 \text{ m}$$

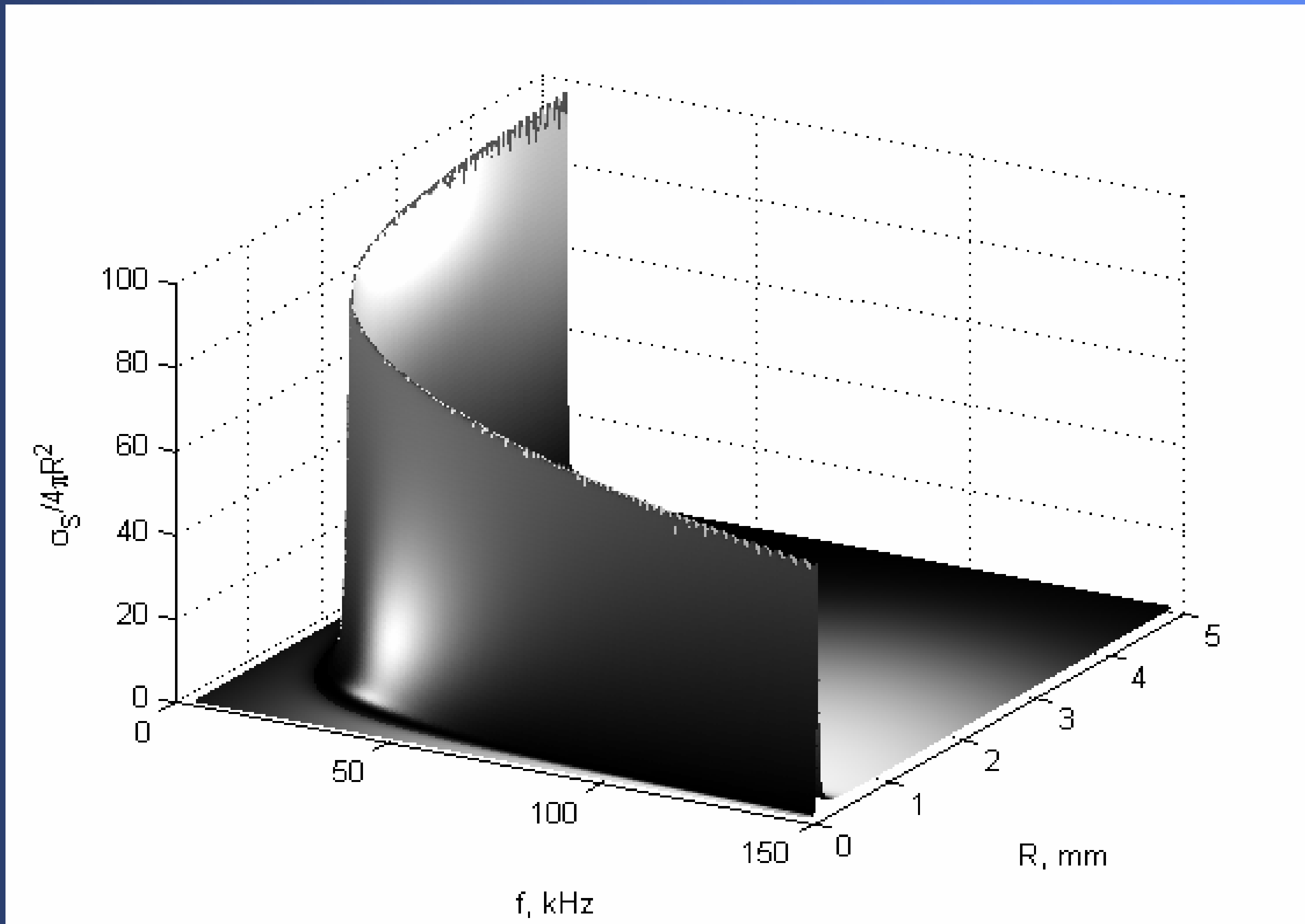
The peak values of the scattering cross sections, corresponding to the resonance condition $\Omega = \omega/\Omega_0 \approx 1$, do not follow the curve for the free bubbles at atmospheric pressure, but markedly deviate from this dependence.

Scattering cross-section (thin shelled bubble)



- The variation of scattering cross-section normalized on the bubble area $\sigma_S/4\pi R^2$, with driving frequency $f=\omega/2\pi$ (in kHz) and bubble radius R (in mm)
- at the depth 500 m for the shell thickness $h=2$ μm, the bulk modulus and the shear modulus were taken to be $K=7.5\cdot10^9$ Pa, $\mu=3.5\cdot10^9$ Pa

Scattering cross-section (thick shelled bubble)



The variation of scattering cross-section normalized on the bubble area $\sigma_S / 4\pi R^2$, with driving frequency $f = \omega / 2\pi$ (in kHz) and bubble radius R (in mm) at the depth 500 m for the shell thickness $h = 25$ μm, and the shear modulus $\mu = 20$ MPa.

Conclusions

- The inverse problem of evaluation of parameters of gas vents on the base of the data of echo-sounding can be solved in the number of limiting cases.
- A passive method for diagnostics of gas vents has been proposed. A rising bubble plume forms an effective acoustics waveguide. The spatial distribution of low-frequency noise near the seeps is quite inhomogeneous and has a mode-like structure.
- To find correlations between the upper boundary of the gas flare and the predicted depth of the gas hydrate stability, the model of hydrate coating has been derived. Based on this model bubble scattering cross section has been calculated and the method for diagnostics of these hydrate-shelled bubbles has been proposed.