Geophysical Methods for Studying Gas Release from Seabed

Subjects: Geochemistry & Geophysics
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Marine geophysical methods are of particular importance in the comprehensive study of the process of gas seepage from the seabed. Their use allows for solving a wide range of problems related to the detection, mapping, quantification, and monitoring, as well as the study of upper and deeper geological roots of gas emission and their relationship with tectonic processes.

marine geophysics | gas seeps | arctic seas | multibeam sonar | sub-bottom profiler | single-beam echo sounder | ocean-bottom seismographs | continuous seismoacoustic profiling | time-domain electromagnetic imaging

1. Introduction

Areas of active gas release from marine sediments are common in many seas including arctic regions. Taking into account the fact that development of offshore oil and gas fields and sea routes is intensive, as well as the development of the corresponding coastal and marine infrastructure, the study of marine geohazards is becoming a very urgent scientific and practical task. Gas streams released from the sea bottom generally weaken the structure and natural stability of bottom sediments and serve as a potential source of natural risks during the construction and operation of underwater structures, such as pipelines, oil platforms, etc [1].

2. Hydro- and Seismoacoustic Instruments

Three acoustic instruments are used to obtain data on the structure of the uppermost sediment deposits, the seafloor morphology, and the water column above: SES-2000 Standard sub-bottom profiler (SBP), WASSP WMB-3250 multibeam echo sounder and Simrad EK15 single-beam echo sounder. Their main application is to detect gas bubbles in the water column. High-resolution sub-bottom profiling was also used for the choice of definitive station points for deep coring. The continuous seismic profiling (CSP) system Geont-shelf, is additionally used in order to investigate the geological roots of gas flares in the upper part of the soil profile at sub-bottom depths up to several hundred meters.

2.1. WASSP WMB-3250 Multibeam System

Multibeam echo sounder WASSP WMB-3250 (manufactured by WASSP Limited, Auckland, New Zealand) is the system of bathymetry and water column data acquisition for water depths 2–200 m. The multibeam system consists of a transceiver BTxR, a WASSP processor, and a transducer. Real-time heading, attitude, and position are provided to the WMB-3250 by an integrated satellite compass and positioning system. The basic technical characteristics of the WASSP multibeam system are given in **Table 1**.

Table 1. Main technical characteristics of the WASSP WMB-3250 multibeam system.

Parameter	Value
Frequency	160 kHz
Beam width	224 beams equidistant spacing over 120° port/starboard swath
Seafloor coverage	Up to 3.4 × depth
TX rate	Automatic ping rate, determined by depth. Max ping rate 40 Hz.
Output power	Up to 1 kW
Depth range	2–200 m
Depth resolution	7.5 cm
Transducer dimensions	33–17–10 cm

2.2. SES-2000 Standard Sub-Bottom Profiler

The SES-2000 Standard narrow-beam parametric sub-bottom profiler (manufactured by Innomar Technologie GmbH, Rostock, Germany) (**Table 2**) is a two-channel acoustic system consisting of three main elements: an SBP transducer, a topside unit, and a positioning system sensor. The transducer emits two high-power and high-frequency nonlinear signals with frequencies near 100 kHz. In accordance with the laws of nonlinear acoustics, difference-frequency signals are formed in the water column, which are then used.

Table 2. Main technical characteristics of the sub-bottom profiler SES-2000 Standard.

Parameter	Value
Primary frequencies	approx. 100 kHz (band 95–110 kHz)
Secondary low frequencies	4–15 kHz
Pulse width	0.07–0.8 ms
Pulse rate	Up to 30/s
Power consumption	Up to 1 KW
Beam width	±1.8°
Water depth range	1–500 m
Penetration	Up to 50 m
Layer resolution	Up to 5 cm

The main advantage of the generated difference-frequency signals is their narrow radiation pattern, the almost complete absence of side lobes, and good penetration of the low-frequency channel into sediments. At the same time, the high-frequency channel is used as an echo sounder for bathymetric surveys. Depending on the signal frequency ratio, the low-frequency profiling pulse can have a frequency from 4 to 15 kHz.

2.3. Simrad EK15 Single-Beam Echo Sounder

The Simrad EK15 scientific single-beam echo sounder is used to study the water column and the seabed at depths from 1 to 200 m. It is designed to provide information on volumetric sound backscatter levels from acoustic anomalies in the water column. Due to its small dimensions and low power consumption, this model allows performing research in hard-to-reach places (shallow lagoons, rivers, and lakes). The basic technical characteristics of the Simrad EK15 echo sounder are given in **Table 3**.

Table 3. Main technical characteristics of the Simrad EK15 Single-Beam Echo Sounder.

Parameter	Value
Operational frequency	200 kHz
Typical depth range	200 m
Ping rate	up to 40 Hz
Pulse durations	80 to 1240 μs
Data rate	1.6 Mbps
Maximum number in use	15
Output power	45 W
Raw data	EK60 format
Maximum installation depth	600 m
Beamwidth	26°

This system is based on a small, sealed single-beam transceiver antenna and a data processing system. The operating frequency of this device is 200 kHz, which allows for getting a high-resolution in depth. Data obtained during the reception of the reflected acoustic signal is collected and accumulated using Simrad EK15 software.

2.4. Continuous Seismic Profiling System

The continuous seismic profiling (CSP) system Geont-shelf includes the SPES-600 energy source, the PSA-1 seismic recorder, a towed hydrophone streamer, and a seismic source (sparker). Sparker is a marine seismic source, which generates an acoustic signal by discharging an electrical pulse. The sparker produces a highly repeatable broadband signal, suitable for any type of high-resolution seismic surveys with vertical resolution up to

30 cm for geohazard assessment, detailed stratigraphic studies, etc. The frequency composition of the emitted signal can be controlled by the number of tip levels and energy per electrode involved in the pulse generation. The main technical characteristics of the CSP system Geont-Shelf are given in **Table 4**.

Table 4. Main technical characteristics of the continuous seismic profiling system.

Parameter	Value
Seismic recorder PSA-1	
Frequency range	60–1200 Hz
Dynamic range	120 dB
Gain ratio	1 to 1000
SPES-600 energy source	
Maximum voltage	5 kV
Operating energy	5–600 J
Towed streamer	
Number of channels	1 to 32
Interval between channels	2 m

3. Time-Domain Electromagnetic (TDEM) Imaging System

Time-domain (or Transient) electromagnetics (TDEM or TEM) is a controlled-source EM geophysical method using measured electromagnetic decay response to image the subsurface resistivity [2][3], which can be used in both onshore and marine environments [4]. The key concept of this technique implies the excitation of a primary electromagnetic field using a square wave-form current transmitted into a dipole or loop antenna, followed by measuring the secondary EM field arising in the conducting medium due to EM induction (Faraday's Law). Depending on the receiver type, TDEM data have the form of transient response either in terms of voltage (measured by dipole) or magnetic field change rate (if measured by loop). The measured transient process, also referred to as response or decay curve, is a function of time passed after the current is cut off, and the shape of this curve plotted in log-log scale reflects the subsurface resistivity structure (the depth-resistivity profile in the simplest case of 1-D resistivity model). The time variable plays the role of a sounding parameter that controls the depth of field propagation, where earlier time corresponds to a shallower depth, while the later time corresponds to a greater depth. Offshore TDEM operations employ towed dipole-dipole arrays, in which electric current pulses are transmitted via the line, providing galvanic contact between the seawater and the electrodes placed at the ends of the source dipole. The received signal is a voltage measured between two other electrodes, towed behind the transmitter line. Both lines can be submerged or float on the water's surface.

In terms of electrical hardware, the acquisition system includes a five-channel receiver (Tells-3E) with 32-bit ADC that is employed for voltage recording, both from the towed receiver dipole and transmitter output and Forpost 105 kW transmitter providing a maximum voltage of 260 V and square waveform current up to 400 A. Steel and brass electrodes were used to provide galvanic contact between the dipoles and seawater.

During the survey, the voltages are recorded in continuous TDEM acquisition mode, with individual responses (stations) collected every 4 s (having 1 ms sampling rate) within a 2 s interval following another 2 s current transmission phase. Depending on the vessel speed (4–10 knots), the station spacing varies from 13 to 50 m. Practically, the transmitted current value (pulse amplitude) is between 170 and 200 A and is continuously recorded along with voltage measurements with the same sampling rate.

4. Ocean-Bottom Seismographs (OBS)

The two OBS models MPSSR (abbreviation from Russian: sea bottom station for seismoacoustic exploration) and Typhoon developed by the Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS) are suitable for a wide range of tasks, including seismological monitoring, active and passive seismics, and high-resolution seismoacoustic investigations. The basic parameters are presented in **Table 5**. Both models are equipped with three-component MET seismometers: CME-4311 type (0.0167–50 Hz) in the MPSSR station and CME-3311 type (1–50 Hz) in the Typhoon station (R-sensors, Moscow, Russia [5]). The hydrophone 5007 m used has a frequency range of 0.04–2500 Hz. The MPSSR is also equipped with SV-10 and two SH-10 classic electromechanical geophones, with a frequency range of 10–250 Hz (analogy of GS-20DX), placed in a gimbal [6][7].

Table 5. Main technical characteristics of the non-self-popup OBSs.

Parameter	Value
MPSSR	
Sensors	three-component seismometer CME-3311, three-component geophone SH/SV-10, hydrophone 5007 m
Frequency Band (CME-4311)	0.0167–50 Hz
Sensitivity (CME-4311)	2000 V/(m/s)
Frequency Band (SH/SV-10)	10–250 Hz
Sensitivity (SH/SV-10)	28 V/(m/s)
Frequency Band (5007 m)	0.04–2500 Hz
Sensitivity (5007 m)	7.2 ± 0.5 mV/Pa
Maximum depth	3000 m
Sample rates, Hz	20, 25, 40, 50, 80, 100, 160, 200, 400, 800
Time synchronization	GPS interface
Temperature stability of the quartz generator	$\pm 5 \times 10^{-9}$
Memory	SD card up to 64 Gb

Parameter	Value
Typhoon	
Sensors	three-component seismometer CME-3311, hydrophone 5007 m
Frequency Band (CME-3311)	1–50 Hz
Sensitivity (CME-3311)	2000 V/(m/s)
Frequency Band (5007 m)	0.04–2500 Hz
Sensitivity (5007 m)	7.2 ± 0.5 mV/Pa
Maximum depth	2000 m
Sample rates, Hz	20, 25, 40, 50, 80, 100, 160, 200, 400, 800
Time synchronization	GPS interface
Temperature stability of the quartz generator	$\pm 5 \times 10^{-9}$
Memory	SD card up to 64 Gb

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Unlike the MPSSR and Typhoon models described above, the GNS and GNS-C models are used for scientific applications of the IO RAS in deep waters (up to 6000 m) [6][8]. It was developed by the IP Ilinskiy A.D. and IO RAS. The GNS employs the SM-6 electro-dynamic sensors, and GNS-C employs 120 s MET sensor CME-4111 (R-sensors, Russia, [5]). These OBSs are self-pop-up with water depths ranging up to 6000 m and are suitable for studying deep structures, down to the middle mantle by active and passive seismic methods and also for earthquake seismology. The design of the GNS and GNS-C models differ mainly by size. The general characteristics are shown in **Table 6**.

Table 6. Main technical characteristics of the self-popup OBSs.

Parameter	Value
GNS	
Sensors	three-component seismometer SM-6, hydrophone HTI-94-SSQ
Natural frequency (SM-6)	4.5 Hz
Sensitivity (SM-6)	28.8 V/(m/s)
Frequency Band (HTI-94-SSQ)	2–30,000 Hz
Sensitivity (HTI-94-SSQ)	12.6 V/Bar (without preamp)
Maximum depth	6000 m
Sample rates, Hz	62.5, 125, 250, 500, 1000, 2000, 4000
Time synchronization	GPS interface
Temperature stability of the quartz generator	$\pm 5 \times 10^{-9}$
Memory	SD card up to 128 Gb
GNS-C	
Sensors	three-component seismometer CME-4111, hydrophone EDBOE RAS

Parameter	Value
Frequency Band (CME-4111)	0.0083–50 Hz
Sensitivity (CME-4111)	4000 V/(m/s)
Frequency Band (hydrophone)	0.067–30,000 Hz
Sensitivity (hydrophone)	200 V/bar
Maximum depth	6000 m
Sample rates, Hz	62.5, 125, 250, 500, 1000, 2000, 4000
Time synchronization	GPS interface
Temperature stability of the quartz generator	$\pm 5 \times 10^{-9}$
Memory	SD card up to 128 Gb

5. Conclusion

The described marine geophysical methods are effective and of particular importance for solving most problems related to the detection, mapping, quantification, and monitoring of underwater gas release from the bottom sediments, as well as the study of upper and deeper geological roots of gas emission and their relationship with tectonic processes. In addition, geophysical surveys have a significant performance advantage compared to any contact methods.

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