The Analysis on Marine Controlled-Source Electromagnetic Research Status

Ping Yu\textsuperscript{1,}\textsuperscript{*}, Xianhu Luo\textsuperscript{1, a}, Gongxiang Wang\textsuperscript{1, b}, Ming Deng\textsuperscript{1, c}, Meng Wang\textsuperscript{2, d}, Kai Chen\textsuperscript{2, e}, Jianen Jing\textsuperscript{2, f}, Shuangshuang Cheng\textsuperscript{2, g}

\textsuperscript{1}Guangzhou Marine Geological Survey, Guangzhou 510075, China
\textsuperscript{2}China University of Geosciences (Beijing), Beijing 100083, China

\textsuperscript{*}Corresponding author e-mail: yuping@hydz.cn, a123456@qq.com, b456789@qq.com, cdengming@cugb.edu.cn, dwangmengcugb@qq.com, ek@cugb.edu.cn, fje2008@cugb.edu.cn, g1786487119@qq.com

Abstract. In recent years, exploration and development of marine oil and gas have been gradually turned to deep water area from shallow water area, and the exploration is becoming more and more difficult. Traditional technology can no longer meet the exploration task. However, a newly developed method, marine controlled-source electromagnetic exploration technology, plays an important role in oil and gas exploration. At present, the marine controlled-source electromagnetic exploration technology has developed into a relatively perfect technology system, which has been fully developed in the basic theory, electromagnetic instruments, data processing and interpretation. In the future, marine controlled-source electromagnetic technology will develop towards all directions, high efficiency, high precision, and wide range.

1. Introduction
With the continuous expansion of global energy demand, land resources are gradually decreasing, and the development and utilization of marine resources are attracting more and more attention [1, 2]. In recent years, the exploration and development of marine oil and gas has gradually changed from shallow water to deep water area, and exploration is becoming more and more difficult. So it is necessary to find out more advanced technology to meet the exploration task [3]. The emergence of marine controlled-source electromagnetic (marine CSEM) technology has effectively overcome some difficulties encountered in deep water exploration. What’s more, marine CSEM technology has been more and more applied to deep water oil and gas exploration, which greatly improves the success rate of offshore drilling and effectively reduces the risk of deep sea oil and gas exploration drilling [4-7].

Western countries began to study the marine CSEM technology in 1970s. Cox, Scripps Oceanic Research Institute of California University (SIO), proposed the idea of using horizontal electric dipole method to carry out geo-science exploration in deep water area [8]. In the middle of 2000, the Statoil Research Center, in collaboration with the Southampton University and the Scripps Institute of Oceanography, carried out the first exploration practice of CSEM on the known oil reservoirs in West Africa. The results showed the advantage of the marine controlled-source in evaluating the high resistivity reservoir [9]. SIO and University of Toronto have carried out many experiments on marine CSEM detection [10]. With the rise of marine CSEM technology, several marine CSEM specialization
companies were established (AGO of the US, EMGS of Norway, OHM and MTEM of the United Kingdom [9]. Later, American SIO carried out the investigation of marine CSEM hydrate in the offshore Hydrate Ridge of Oregon and the Santa Cruz basin in southern California [11]. JAMSTAC, Japan, carried out the hydrate investigation in the Japan Sea [12]. And the German BGR conducted the investigation of the hydrates electromagnetic method in the coastal waters of New Zealand [13].

The research on marine controllable source electromagnetic technology started late in China [14]. At the end of the 1990s, a few institutions and researchers had tracked and studied the marine CSEM detection system. The Jilin University took the lead in the magnetotelluric test of the Liaohe River beach [2]. Later, China University of Geosciences (Beijing), Guangzhou Marine Geological Survey, and Bureau of Geophysical Prospecting continued to carry out the research work on marine controlled-source related methods [15, 16], marine equipment[17,18], data acquisition[46], and data processing and interpretation [20]. In recent years, China Geological Survey and China University of Geosciences (Beijing) jointly conducted investigations in the key areas of Dongsha, Shenhu, and southeast Hainan Sea of the South China Sea for finding the hydrate [21].

2. The principle of marine CSEM technology

When oil and gas are contained in the pores of the rock, the resistivity will increase to tens of hundreds Ohm, even higher, which leads to great resistivity differences with the surrounding aquifers [22]. The marine CSEM technology determines whether oil or water is contained in the trap by using the huge difference [6, 23].

The commonly used schematic diagram of marine CSEM exploration operation is shown in figure 1. In figure 1, multiple electromagnetic receivers are deposited on the seafloor, and the transmitter drags the horizontal electric dipole source along the expected line near the seafloor 20~60 meters continuously transmitting low frequency (0.01~20 Hz) electromagnetic wave with the current intensity of several hundred to 10,000A [17].

The electromagnetic signals collected by the receiving devices include direct wave, reflected wave and refracted wave. The direct wave attenuates rapidly because of the seawater and the large distance between the transmitter and the receiver, and the reflected wave attenuates rapidly in the low resistivity layer. The refracted wave also has energy attenuation in high resistivity oil reservoirs, but most of them spread along the high resistivity layer. Due to the continuous transmission of energy from the high resistivity layer, the electromagnetic receivers at the seafloor mainly collected refracted wave. This energy can greatly change the current distribution pattern in the whole overlying stratum, making very different from the surrounding rock layer detection structure, so when the seabed layer contains oil and gas, the receivers will receive strong electromagnetic signals. This is the essence of the marine CSEM technology to identify the hydrocarbon reservoir of the seabed.

Figure 1. Schematic diagram of marine CSEM detection method
3. Marine CSEM instrument

The marine environment is much more complicated than the terrestrial environment, so there is no doubt that the marine CSEM prospecting instrument is more complex relatively. The marine CSEM exploration instrument includes electromagnetic signal transmitting system and seafloor electromagnetic signal acquisition system. In addition, there needs accurate positioning, pressure resistance and anti-corrosion instrument, lifting equipment of transmitter and receiver, high strength and quality towing cable and so on [8]. In this paper, we mainly present some electromagnetic signal transmitting systems and seafloor electromagnetic signal acquisition systems.

3.1. Electromagnetic signal transmitting system

The electromagnetic signal transmitting system is mainly composed of a power energy transformer, a depth-control gear and a transmitting electric dipole. The depth-control gear controls the transmitting system to move at a distance of 20-60 meters from the bottom of the sea. The pulse signal is usually a periodic square wave with a frequency between 0.01 Hz and 20 Hz and the peak value of the current between 100 A and 10,000 A.

Since the beginning of 1998, the SIO has developed SUESI 100, SUESI 200 and SUESI 500 transmitters [24]. In 2000, the Southampton marine research center and OHM Company jointly developed the DASI series transmitting systems [25, 26]. WesternGeco and EMGS have also developed the transmitting system for commercial exploration [17]. The mentioned above transmitting systems based on the marine CSEM method are mainly used to explore the oil and gas resources on the seabed, and have achieved meaningful results.

Figures 2 and 3 are transmitting systems developed by OHM and SIO [7], respectively. Figures 4 and 5 are deep-tow marine CSEM transmitter and deployed marine CSEM transmitter [18], respectively, developed jointly by Guangzhou Marine Geological Survey and China University of Geosciences (Beijing). The transmitters are mainly used for the exploration of natural marine hydrates on the seabed. The main performance parameters of the transmitters are listed in tables 1 and 2, respectively.

![Figure 2. The transmitting system used by OHM [7]](image-url)
Figure 3. The transmitting system used by SIO [7]

Figure 4. Towed marine CSEM transmitter [17]

Figure 5. Deployed marine CSEM transmitter [18]

Table 1. Main performance parameters table of towed CSEM transmitter

| Name                          | Parameters                                    |
|-------------------------------|-----------------------------------------------|
| Transmission waveform         | Single frequency or multi frequency rectangular waves |
| Transmission frequency        | 0.01-10 Hz                                    |
| The stability of transmission frequency | 10-8 s/s                                      |
| Maximum transmission current  | 250 A                                         |
| Transmission dipole length    | 150 m                                         |
| Transmission dipole moment    | 37.5 kA·m                                     |
| Depth rating                  | 4000 m                                        |
**Table 2. Main performance parameters table of deployed CSEM transmitter**

| Name                        | Parameters                                      |
|-----------------------------|-------------------------------------------------|
| Transmission waveform       | Single frequency or multi frequency rectangular waves |
| Transmission frequency      | 0.01-20 Hz                                      |
| The stability of transmission frequency | 10-8 s/s                                       |
| Maximum transmission current| 150 A                                           |
| Transmission dipole length  | 10 m                                            |
| Transmission dipole moment  | 1500 Aꞏm                                        |
| Channel of current          | 2                                               |
| Transmission direction      | Horizontal orthogonal direction (X and Y)        |
| Effective range of video monitoring | 0~5 m                                        |
| Location mode               | Ultra short base line                           |
| Seabed height measurement range | 0~300 m                                    |
| Range and accuracy of pitching measurement | ±90°,±1°                               |
| Range and accuracy of rolling measurement | ±180°,±1°                           |
| Range and accuracy of azimuth measurement | 0~360°,±1°                                 |
| Power and signal transmission channel | 10000 m optical-electrical composite cable |
| Remote communication rate   | 115,200 bit/s                                   |
| Depth rating                | 4000 m                                          |

3.2. **Electromagnetic signal acquisition system**

The seafloor electromagnetic acquisition system is a kind of the highly integrated marine equipment [19, 20], which consists of electric field sensors, magnetic field sensors, the data recording system, the positioning system, the sound control system, floating balls and cement blocks. The acquisition system has 4~6 channels, receiving 4~6 channels of electromagnetic field signals, namely, Ex, Ey, Hx, Hy, Ez and Hz. Every collection station is free to sink from the ship to the bottom of the sea and is precisely positioned through the sonic ultra-short baseline communication device [14, 19, and 29]. After the acquisition, release commands are sent to the receivers to separate the floating balls which contain the collecting systems from the cement blocks. And the floating balls float out of the sea, realizing the recycle for collected data [19, 29, and 30].

Figures 6 and 7 are electromagnetic signal receivers used by SIO and EMGS, respectively. Figure 8 is a submarine electromagnetic field instrument developed by Chongqing Geological Instrument Co., Ltd., with a small low frequency flux gate sensor and a filled electric sensor, which can be used for submarine MT and artificial magnetotelluric sounding. The main performance parameters are shown in table 3.

Figure 9 is a submarine electromagnetic receiver developed jointly by Guangzhou Marine Geological Survey and China University of Geosciences (Beijing). The main performance parameters are shown in table 4.
Figure 6. The acquisition system used by SIO [31]

Figure 7. The acquisition system used by EMGS [7]

Figure 8. Seafloor electromagnetic field instrument
Table 3. Main performance parameter table of seafloor electromagnetic field instrument

| Name                     | Parameters                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| Channels                 | 5 (Ex, Ey, Ez, Hx, Hy)                                                      |
| Frequency range          | 1000 s ~ 500 Hz                                                             |
| Background noise         | Electric field: 1nV / sqrt(Hz) @ 1 Hz                                      |
|                          | Magnetic field: 6pT / sqrt(Hz) @ 1 Hz                                       |
| Dynamic range            | E-field: 110 dB; M-field: 90 dB                                             |
| Continuous working time  | 2 months                                                                    |
| Maximum recovery cycle   | 4 months                                                                    |
| Depth rating             | 6000 m                                                                       |

Figure 9. Seafloor electromagnetic receiver

Table 4. Main performance parameters table of seafloor electromagnetic receiver

| Name                     | Parameters                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| Channels                 | 6 (Ex, Ey, Ez, Hx, Hy, temp)                                                |
| Frequency range          | 3000s-320 Hz                                                                |
| Background noise         | E-field: 0.1 nV/m/rt(Hz) @ 1 Hz                                             |
|                          | M-field: 0.1 pT/rt(Hz) @ 1 Hz                                               |
| Dynamic range            | E-field: 120 dB; M-field: 100 dB                                            |
| Time drift               | 1-5 ms/day                                                                  |
| Continuous working time  | >60 days                                                                    |
| Depth rating             | 6000 m                                                                       |
| Release mechanism        | Acoustic releaser and electric corrosion fusing mechanism                   |

4. Data processing and interpretation of marine CSEM

In order to analyze and explain the information of the seabed more accurately, the data processing and interpretation of the marine controllable source electromagnetic detection plays an important role [32]. This paper mainly introduces the following aspects.
4.1. Directional correction
In the process of marine CSEM detection, the flow of sea water, the change of the seabed topography, and the artificial factors, will lead to a certain deviation between the positions of the transmitter and receivers and the expected effect [33]. In order to solve these problems, an azimuth recorder is installed on the submarine electromagnetic receiver. After the data collection is finished, the azimuth recorder is recovered to the deck. The azimuth and horizontal state of the electromagnetic field sensor can be recorded from the azimuth data. In the process of data processing, the marine CSEM data can be observed on the basis of the elliptical polarization parameters [4, 33].

4.2. Noise treatment
Because of the high conductivity of sea water, the sea is equivalent to a low pass filter, which makes the high frequency electromagnetic wave signal seriously attenuate and cannot reach the bottom of the sea [33]. As a result of the data processing, the natural and human noise of the high frequency section can be ignored, and the main active noises include the ocean current, the natural electromagnetic field activity, and the dipole antenna vibration, the noises from the internal electrode and the amplifier, and the environmental impact [32]. The classification of marine controlled source noise sources is listed in table 5.

| Noise source classification | Description |
|-----------------------------|-------------|
| Natural electromagnetic field noise (<1 Hz) | A conductor is moving in an electric field to produce a voltage |
| Ocean ocean current noise (<1 Hz) | Low frequency noise produced by natural electromagnetic field |
| Ambient noise | High or high resistance objects close to the receiver to produce noise |
| Internal noise of the receiver (>1 Hz) | High or high resistance objects close to the receiver to produce noise |
| Dipole disturbing noise (>1 Hz) | Noise generated by dipole antenna disturbance |

The methods to improve the signal noise ratio (SNR) of data in CSEM data processing include frequency domain amplitude superposition, time-varying smoothing filtering, time-varying bilateral filtering, noise estimation, and wavelet correction.

In the method of the frequency domain amplitude superposition, the more the superimposed windows, the lower the data noise level [32].

The time-varying smoothing filter is a de-noising method which is based on the smooth filtering method to segment and deal the marine CSEM signal response with low SNR. As the SNR ratio gradually decreases, the smoothing radius of smoothing filter is gradually increased to suppress noise [34].

The time-varying bilateral filtering method is based on the traditional bilateral filtering, according to the characteristics that the SNR of the marine CSEM signal response with the change of the distance between the transmitter and receivers, to segment the marine CSEM data with low SNR. With the gradual reduction of the SNR, the smoothing radius, the spatial distance standard deviation parameter, and the numerical similarity standard deviation parameter of bilateral filter increase gradually in order to reduce marine CSEM noise [34].

The noise estimation method is to improve SNR of marine CSEM data by filtering active frequency noise [35].
The wavelet correction method, based on the characteristics of the transmitting wave and wavelet base, selects the best wavelet base and studies the best decomposition layer number, and using the approximate sequence corresponding to the decomposition layer number to estimate and remove noise from sea water disturbance [36].

4.3. Suppression of air wave
When a horizontal electric dipole is used as a transmitting source in shallow water, the air wave propagating along the air-sea interface will completely cover up the useful signals returned from the high resistivity reservoir. The air wave seriously affects the application of the marine CSEM. At present, a lot of researchers have studied the suppression of air wave. We just list several methods here, such as subtracting the background model response [37], direct reduction of air wave method [38], separation of upstream and downward wave [39], separation of TE and TM waves [40], weighted subtraction method [41], the observation data to the frequency derivation method [41, 42], and the MT impedance stripping side [41], low frequency data subtracting high frequency data method [43], modified normalization method [44], time domain filtering method and so on [45].

4.4. Spectral analysis, normalization and geometric structure
The source of the marine CSEM technology is in dynamic change, so it is necessary to calculate the time and position of the source accurately in the process of data pre-treatment so as to provide a good result for the next data simulation [33]. The basic data pre-processing includes spectral analysis, normalization and geometric structure [33, 46].

(1) Spectrum analysis. For the spectrum analysis. We classify time series data and name a corresponding time label for each level. Fast fourier transform can be performed on each level of time series. However, because the transmission source needs to transmit a few pre-selected frequencies, we usually use the least square method to calculate the amplitude and phase of these frequencies effectively [33].

(2) Normalization. First, the received signals need to be corrected and normalized. The correction includes correction of clock drift and correction of amplifier response. Normalization includes normalization of antenna length and normalization of Analog / Digital (A/D) conversion factor. We need to correct the distance of the transmitting source and the spectrum of the transmitting waveform to implement the normalization of the transmitting signals [33].

(3) Geometric structure. The electromagnetic field signal, transmitting current and navigation data collected by the receiver are separately recorded, and these data are related to the GPS clock. Normalized data and navigation data are used to structure the geometric position of the transmitter and the receiver by adjusting their respective clocks [33].

4.5. Data interpretation
At present, using Magnitude Value Offset (MVO) curve to display oil and gas anomalies is the most widely used interpretation method of CSEM data in frequency domain [46]. The MVO curve is the curve of the electromagnetic field response amplitude received at a measuring line by the receivers within the range of the seabed detection, as shown in figure 10. The graph shows the MVO curve with / without a high resistivity reservoir, in which the dotted line shows the curve of the seabed without anomalous body, and the solid line shows the curve when the seabed contains an anomalous body. In addition, we can see that when the offset is too small or too large, the two curves are close to coincided. From this curve, we can also see that the marine CSEM detection is helpful to determine whether the trap contains abnormal bodies, and is able to ascertain the boundary of the anomalous body, which is better than the seismic exploration technology.
5. Application of marine CSEM

5.1. Application of marine CSEM in oil and gas exploration
In the middle of year 2000, the Statoil Research Center, in collaboration with the Southampton University and SIO, carried out the first experiment using marine CSEM method to find oil on the known oil reservoir in West Africa. The electromagnetic receivers used in the experiment include LEMURs of Southampton University and ELFs of SIO, and the broadband MT/CSEM receiving equipment of the SIO. The transmitter is DASI of the University of Southampton. The transmission dipole moment is 16 kA·m and the working frequencies are 0.25 Hz and 1 Hz. The receivers use an ultra-short baseline (SSBL) navigation system. The experimental results clearly show the sensitivity of electromagnetic response to oil and gas reservoirs, and strengthen the confidence of Statoil and other oil and gas companies in marine CSEM research.

At the beginning of 2002, ExxonMobil used the British research ship RRS Charles Darwin and the DASI transmitter of the University of Southampton in the West African sea area to carry out marine CSEM exploration [47].

In 2004, MTEM Company carried out an experiment on the exploration of oil and gas reservoirs by the land-based time domain multichannel transient electromagnetic method in France and got a clear image [48, 49] of the oil and gas reservoirs. This method can also be applied to the sea. During the years of 2010-2012, Petroleos Mexicanos completed 12 thousand square kilometers of three-dimensional marine CSEM exploration in Mexico Bay, the main purpose of which is to evaluate whether the three-dimensional seismic structural targets contain oil or seawater. Practice shows that the development of marine CSEM exploration before deep-sea drilling is of great significance in reducing drilling risk.

5.2. Application of marine CSEM in natural gas hydrate
Recently, SIO has carried out a number of experiments using marine CSEM method to detect gas hydrates in the western United States and the Gulf of Mexico. The test results show that it is feasible to use marine CSEM method to detect gas hydrate.

In May 2012, Guangzhou Marine Geological Survey and China University of Geosciences (Beijing), firstly used high and new technologies such as remotely operated vehicle (ROV), CSEM to obtain a number of evidences related to gas hydrate, including cold spring methane leakage activities clear images, authigenic carbonate rock, and biological samples [50]. At the same time, we had
successfully used the independent research and development of the marine CSEM technical equipment to carry out the hydrate investigation and tests, and found the high resistivity anomaly zone which may be caused by the gas hydrate. The experiment results provide very favorable data for the drilling selection.

6. Summary and expectation
Marine CSEM technology plays an irreplaceable role in marine prospecting. This technology can not only be applied to the exploration of offshore oil and gas, but also is one of the effective methods for exploring the gas hydrate. At present, the development and application of marine CSEM technology have been very mature in the world, and China also attaches great importance to the development of marine industry. It has been put forward that the strategic idea of improving the ability of marine resources development and speeding up the construction of marine power. And related departments and units have also accelerated the research and application of marine CSEM technology. Remarkable achievements have been made in major projects of "key technologies for exploration and development of marine gas hydrates" set up by China Ministry of Science and Technology. Guangzhou Marine Geological Survey of the China Geological Survey, working with China University of Geosciences (Beijing), Jilin University, Central South University, China Ship Heavy Industry 710, Beijing University of Technology Institute, and the Qingdao HI Sun Marine Equipment Co., Ltd, applied for the project of “deep sea dual ship towed marine electromagnetic exploration system”. The project was approved by the state key research and development program "key technologies and equipment for deep sea". We believe that with more support and investment putting into the field of marine exploration technology.

Acknowledgments
This work was supported in part by the Key Technologies R&D Program under Grant 2016YFC0303100, in part by the Natural Science Foundation of China under Grant 41504138 and Grant 61531001.

References
[1] W. B. Wei, M. Deng, Z. H. Wen, ET a1, Experimental study of marine magnetotellurics in southern Huanghai [J, Chinese J. Geophys. (In Chinese). 2009, 52 (3), pp. 740-749.
[2] S. J. Yang, Y. C. Y. Hu, H. X. Song, J. X. Gao, An overview of marine controlled source electromagnetic detection syste [J]. Product and Technology:Automatic System, 2018, P118-120.
[3] W. N. Tian, A brief analysis of marine controlled source electromagnetic exploration technology and prospect [J], Science and Technology Outlook. 2016, 26(15), pp. 93.
[4] Y. G. Li, S. M. Duan, Study on electromagnetic data preprocessing method of marine controllable source[J], PERIODICAL OF OCEAN UNIVERSITY OF CHINA. 2014, 44(10), pp. 106-112.
[5] K. J. Xu, R. L. Du, Z. Liu, Inversion of one dimensional combined reservoir parameters of controlled source electromagnetic and seismic sea [J], Oil Geophysical Prospecting. 2016, 51(1), pp. 197-203.
[6] J. C. Ding, J. S. Shen, B. Weng, J. M. Zhang, Marine controlled source electromagnetic exploration technology and its development trend[C], 2015 Geophysical technology symposium, and 2015.
[7] W. B. Sun and Z. X. He, Marine controlled-source electromagnetic exploration techniques and instruments, EGP. 2010, 20 (1) pp. 51-56.
[8] J. S. Shen, X. H. Chen, Development and Enlightenment of controlled source electromagnetic prospecting (CSEM) in offshore oil and gas exploration [J], Oil Geophysical Prospecting. 2009, 44(1), pp. 119-127.
[9] Z. X. He, W. B. Sun, Y. T. Wang, Application status of western marine controlled source electromagnetic technology[C]. The twenty-second annual meeting of the Chinese Geophysical Society, Chengdu, Sichuan, China, 2006.

[10] J. S. He, L. Z. Bao, The situation and progress of marine electromagnetic method research [J]. Progress in Geophysics, 1999, 14(1), P7-39.

[11] K. A. Weitemeyer, S. C. Constable, K. W. Key, et al, First results from a marine controlled-source electromagnetic survey to detect gas hydrates offshore Oregon [J]. Geophysics Research Letter, 2006, 33(3):L03304

[12] T. N. Goto, T. Kasaya, H. Machiyama, et al, A marine deep-towed DC resistivity survey in a methane hydrate area, Japan Sea [J]. Exploration Geophysics, 2008, 39(1) P52-59.

[13] K. Schwalenberg, M. Haeckel, J. Poort, et al, Evaluation of gas hydrate deposits in an active seep area using marine controlled source electromagnetics: Result from Opouawe Bank, Hikurangi Margin, New Zealand. Marine Geology, 2010, 272(1-4), P79-88.

[14] M. Deng, W. B. Wei, Y. Sheng, et al, Several theoretical points and instrument technology of magnetotelluric data acquisition in deep water [J]. Chinese Journal of Geophysics, 2013, 56(11):3610-3618, doi: 10.6038/cjg20131102.

[15] C. X. Yu, Research on data processing of marine controlled source electromagnetic method [D]. China University of Geosciences (Beijing), 2010.

[16] Q. H. Zhang, Study on electromagnetic response of marine controlled source electromagnetic method [D]. China University of Geosciences (Beijing), 2011.

[17] M. Wang, H. Q. Zhang, Z. L. Wu, et al, Marine controlled source electromagnetic launch system for natural gas hydrate resource exploration. Chinese Journal of Geophysics, 2013, 56(11):3708-3717, doi: 10.6038/cjg20131112.

[18] M. Wang, M. Deng, Z. L. Wu, et al, New type deployed marine controlled source electromagnetic transmitter system and its exoeriment application[J]. Chinese Journal of Geophysics, 2017, 60(11):4253-4261, doi: 10.6038/cjg20171113.

[19] M. Deng, W. B. Wei, H. D. Tan, et al, Seafloor magnetotelluric data collector[J], Chinese Journal of Geophysics, 2003, 46(2), P217-223.

[20] K. Chen, J. E. Jing, Q. X. Zhao, et al, Ocean bottom EM receiver and application for gas-hydrate detection[J]. Chinese Journal of Geophysics, 2013, 60(11):4262-4272, doi: 10.6038/cjg20171114.

[21] J. E. Jing, Z. L. Wu, M. Deng, et al, Experiment of marine controlled-source electromagnetic detection in a gas hydrate prospective region of the South China Sea. Chinese Journal of Geophysics (in Chinese), 2016, 59(7), P1564-1572, doi: 10.6038/cjg20160721.

[22] Z. X. He, W. B. Sun, F. S. Kong, X. F. Wang, Marine electromagnetic metho. Oil Geophysical Prospecting, 2006, 08, 41(4) P451-457.

[23] X. Q. Hu, B. Li, T. Huang, Y. B. Zhang, Offshore Controlled-Source Electromagnetic Methods[J]. OFFSHORE OIL, 2012, 32(3), P13-17.

[24] S. Constable, Marine electromagnetic methods-a new tool for offshore exploration [J]. The Leading Edge, 25(4) : 438-444, 2006.

[25] L. MacGregor, M Sinha, Use of marine controlled-source electromagnetic sounding for sub-basalt exploration [J]. Geophysical Prospecting, 48(6) : 1091-1106, 2000.

[26] L. M. MacGregor, M. Sinha, S. Constable, Electrical resistivity structure of the Valu Fa Ridge, Lau Basin, from marine controlled-source electromagnetic sounding[J]. Geophysical Journal International, 146(1): 217-236, 2001.

[27] K. Chen, W. B. Wei, M. Deng, et al, Low noise E-field acquisition technology for MCSEM receiver [J]. Progress in Geophysics (in Chinese), 30(4):1864-1869, doi: 10.6038/pg20150447.
[28] Sheng Yan, Deng Ming, Wei Wenbo, Ke Shengbian, Marine electromagnetic detection technology developmental status and feasibility of gas hydrate explodation[J]. Chinese Journal of Engineering Geophysics, 2012, 9(2), P127-133, doi: 10.3969/j. issn. 1672-7940. 2012.02.001.

[29] M. Deng, Q. S. Zhang, K. L. Qiu, L. L. Wang, Technique problems in marine geoelectrical field prospecting. Instrument Technique and Sensor. 2004, No.9, P48-50.

[30] M. Deng, S. L. Hou, G. F. Wang, K. L. Qiu, Y. Z. Xiong, Q. S. Zhang, The Development of seafloor prospecting instrument in China. Progress in Exploration Geophysics. 2004, 27(4), P241-245.

[31] https://scripps.ucsd.edu/news/photo-week-bound-bottom.

[32] N. Liu, Typical preprocessing and several de noising methods for marine controlled source electromagnetic data [D]. Jilin University, 2015, 06.

[33] J. S. He, Principles of marine electromagnetic method [M]. Higher Education Press, 2012.

[34] N. Liu, C. Liu, Y. Liu, Marine controlled-source electromagnetic data de-noising method based on time-varying Bilateral Filtering [J]. Global Geology, 2015, 03, 34(1), P232-239.

[35] X. Lin, W. B. Wei, J. E. Jing, et al, Study on improving MCSEM signal-to-noise ratio [J]. Progress in Geophysics, 2009, 06, 24(3), P1047-1050, DIO:10.3969/J.ISSN. 1004-2903. 2009.03.032.

[36] Y. Li, S. Q. Jiang, Y. Y. Wang, et al, A wavelet correction method for the seawater turbulence noise in marine controlled-source electromagnetic data [J]. Geophysical Prospecting for Petroleum, 2016, 09, 55(5), P657-663.

[37] X. Lu, L. J. Srnka, J. J. Carazzone, Method for removing air wave effect from offshore frequency domain controlled-source electromagnetic data. US, WO2005/010560[P]. 2005-02-03.

[38] J. Nordskag, L. Amundsen, Asymptotic airwave modeling for marine controlled source electromagnetic surveying [J]. Geophysics, 2007, 72(6):F249-F255.

[39] P. M. Van den Berg, A. Abubakar, T. Habashy, Removing sea surface-related electromagnetic fields in performing an electromagnetic survey. US, WO/2008/054888[P]. 2008-09-30.

[40] L. O. Løseth, L. Amundsen, Removal of air-response by weighting inline and broadside CSEM/SBL data[C]. 77th Annual International Meeting. SanAntonio:SEG, 2007:529-533.

[41] J. P. Chen, D. L. Alumbaugh, Three Methods for Mitigating Airwaves in Shallow Water Marine Controlled-Source Electromagnetic Data [J]. Geophysics, 2011, 76 (2):F89-F99.

[42] F. A. Maaø, A. K. Nguyen, Enhanced Subsurface Response for Marine CSEM Surveying [J]. Geophysics, 2010, 75 (3):A7-A10.

[43] M. Wirianto, W. A. Mulder, E. C. Slob, Exploiting the Airwave for Time-Lapse Reservoir Monitoring with CSEM on Land [J]. Geophysics, 2011, 76(3):A15-A19.

[44] R. Mittet, Normalized Amplitude Ratios for Frequency-Domain CSEM in Very Shallow Water [J]. First Break, 2008, 26 (11):47-54.

[45] C. C. Yin, Y. H. Liu, A. H. Weng, et al, Research on Marine Controled-Source Electromagnetic Method Airwave [J]. Journal of Jinlin University (Earth Science Edition), 2012, 09, 42(5), P1506-1520.

[46] H. L. Ma, Data processing and interpretation of marine controlled source electromagnetic survey [D]. Chengdu University of Technology, 2013, 05.

[47] S. Ellingsrud, T. Eidesmo, S. Johansen, et al, Remote sensing of hydrocarbon layers by seabed logging (SBL): Results from a cruise offshore Angola [J]. THE LEADING EDGE, 2002.

[48] W. David, B. A. Hobbs, Z. Anton, MTEM Demonstration survey in France [J]. 2004.

[49] Z. Anton, B. A. Hobbs, W. David, Multitransient electromagnetic demonstration survey in France. GEOPHYSICS, 2007, 72(4): F197-F209.

[50] Redrilling the South China Sea "flammable ice" - focusing on China's marine gas hydrate exploration process. Land and resource, 2012, 08.