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Seabed fluid flow in the China Seas

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Seabed fluid flow is a widespread and important natural phenomenon in marine environments, which involves complex multi-physics, multi-process and multi-scale processes. The developments in offshore geophysical technology have facilitated the discovery of the widespread emissions of seabed fluids. For an overview on the state-of-the-art seabed fluid flow research and for obtaining a perspective on future research in the China Seas, we reviewed the data, reports, and publications particularly that associated with cold seeps such as pockmarks, seeps, domes, mud volcanoes, and gas hydrates in the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea. This study presents the first report for seabed fluid flow on all China Seas with the basic information required to undertake additional analytical studies of these features. Furthermore, we explore processes responsible for them and their implications. Although the seabed fluid flow is widespread, dynamic, and influential, it is still poorly examined and understood. To understand seabed fluid flow in both time and space, it is important to investigate how and why these seabed fluids form and migrate.

KEYWORDS

China Seas, gas hydrate, methane seep, shallow gas, pockmark, mud volcano, hydrocarbon seepage, marine energy

1 Introduction

Seabed fluid flow encompasses various fluids (liquids and gases) that pass from sediments to seawater (Judd and Hovland, 2009; Zhu et al., 2023). These fluids from dozens of meters to kilometers below the seafloor migrate *via* pathways such as faults, pipes, gas chimneys, and mud diapirs, thus escaping from the seafloor to produce multiple geomorphic features such as pockmarks and mud volcanoes at different scales (Westbrook et al., 2009; Bünz et al., 2012; Brothers et al., 2013; Andreassen et al., 2017; Serie et al., 2020; Yang et al., 2021). Multi-physics (e.g. solid, liquid, and gas), multi-process (e.g. geological, mechanical, and chemical processes) and multi-scale (e.g. pore-scale and region-scale) processes are involved in the seabed fluid flow (Judd and Hovland, 2009). Seabed fluid exchanges at the seabed-seawater boundary are as important as interactions between oceans and atmosphere (Judd and Hovland, 2009). After seeping into seawater, seabed fluid significantly affects the marine environment such as the physical, chemical, and biological nature of seawater. Furthermore, methane emitted from hydrothermal vents, cold seeps, and mud volcanoes in deep oceans can pass *via* the hydrosphere into the atmosphere. Seabed fluid flow is significant for sub-seabed and seabed geological features, marine biological processes, and composition of oceans, involving geosciences, biosciences, chemical, environmental, and ocean sciences. The presence of seabed fluid flow shows hydrocarbon (gas, oil, gas hydrate) generation, migration, accumulation, and the destabilization of seabed structures, which results in geological hazards such as sedimentary collapse and submarine landslide and poses a potential danger to hydrocarbon exploitation and submarine engineering (Jia et al., 2016; Rui et al., 2020; Wang et al., 2020; Zhu et al., 2020; Zhu et al., 2021).

Multiple developments in offshore geophysical technology (Figure 1) over four decades have allowed marine scientists and engineers to determine and map seabed fluid flow. High-resolution seismic profilers, side-can sonar systems, multibeam echo sounders, remotely operated submersibles (ROVs), and autonomous underwater vehicles (AUVs) have enabled wide, rapid, and detailed surveys from coastal seas to deep oceans. These developments facilitate worldwide discoveries of the widespread emissions of water, petroleum fluids, and hydrothermal fluids. To examine the distribution and nature of the seabed fluid flow, reviewing all data, reports, and publications on seabed fluid flow is necessary. However, offshore geophysical technologies and publications have progressed at an incredible rate that it is impossible to include every example. Therefore, this study is limited to the examples of features associated with seabed fluid flow in the China Seas. The literature on hydrothermal vents is extensive, and therefore we focus on "cold" seeps such as pockmarks, seeps, domes, mud volcanoes, and gas hydrates. This study provides the scientific community with the compendium of seabed fluid flow as the base for additional analytical and profound approaches to subsequent investigations.

2 Geological settings of the China Seas

The China Seas, located in the northwestern Pacific Ocean, consist of four parts, the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea (Hu and Wang, 2016). They form an arc from north to south. Figure 2 shows the location map of these China Seas.

The Bohai Sea (Figure 2) is a semi-closed marginal sea in eastern China having a total area of ~77000 km^2 and an average depth of 18 m (Du et al., 2021; Zhang Y et al., 2020; Zhu et al., 2018). Geologically, it belongs to the offshore portion of the Bohai Bay Basin, which is a typical Mesozoic and Cenozoic rifting basin (Hu et al., 2001). Strongly controlled by the Tan-Lu and Zhangjiako-Penglai fault zones (Qi and Yang, 2010; Teng et al., 2010), the Bohai Sea rifts early from the Paleogene and enters the post-rifting thermal subsidence phase from the Neogene with ~7 km of Cenozoic sediments accumulated in sub-basins (Allen et al., 1997; Li et al., 2012; Wang et al., 2014). Neotectonism (tectonic motions after 5.1 Ma) in the Bohai Sea induced multiple faults and traps in the Neogene-Quaternary sequences, thus controlling the tectonic pattern to date (Gong et al., 2010).

The Yellow Sea (Figure 2), embracing an area of ~4.0 × 10^5 km^2, is located on the shallow continental shelf with an average water depth of 44 m (Wang et al., 2014). By a line from the easternmost tip of China's Shandong Peninsula to the western end of North Korea's South Hwanghae Province, the water body is divided into the larger southern and smaller northern yellow seas. The former connects with the Bohai Sea in the Bohai strait and experiences a

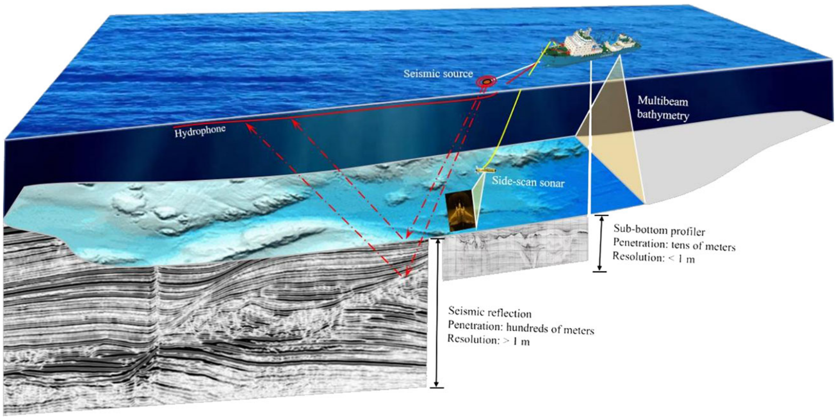

FIGURE 1
Graphic showing geophysical approaches used to identify seabed fluid flows.

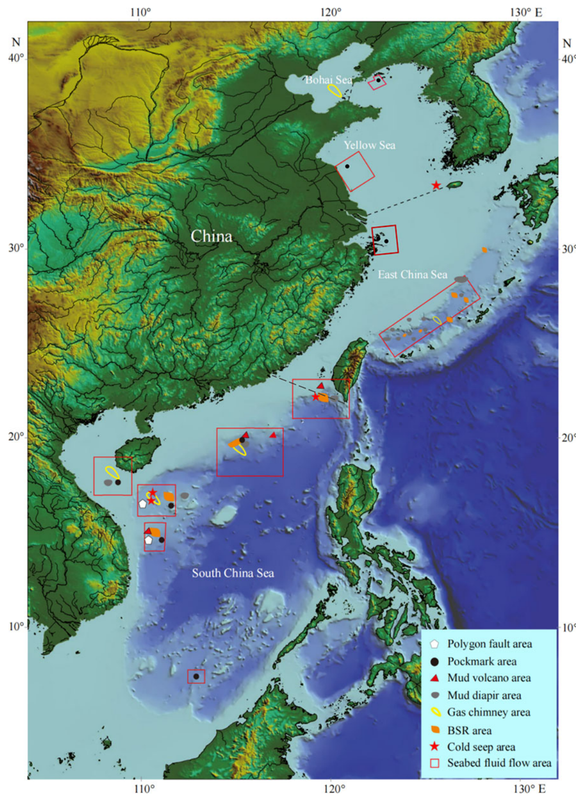

FIGURE 2
Location of these China Seas and the distribution of the fluid escape structures. White pentagon = polygon fault area, black solid circle = pockmark area, red triangle = mud volcano area, gray solid circle = mud diapir area, yellow hollow circle = gas chimney area, orange leaf-shape = bottom-simulating reflector (BSR) area, red star = cold-seep area, and red rectangle = seabed fluid flow area.

major phase of the Paleogene rifting and the initial and Neogene thermal subsidence (He et al., 2007). The latter, however, follows an additional uplift and erosion phase from the late Oligocene to the early Miocene (Yi et al., 2003; Lee, 2010). Here, rifting was confined to localized half-grabens controlled by the Jiaxiang fault with a relatively insignificant thermal subsidence phase (Lee, 2010).

The East China Sea (Figure 2) along the southeastern Chinese continental margin, covering an area of 7.7×10^5 km^2, is composed of the continental shelf with shelf break at water depths of 140–160 m, and the Okinawa trough with an average water depth of 370 m (Wang et al., 2014). The East China Sea continental shelf is featured by NE-striking uplifts and depressions, evolved from the deep Paleogene continental margin rift and has experienced regional open-sea subsidence after the Pliocene (Zhou et al., 1989; Li et al., 2009). However, the Okinawa trough is an active back-arc rifting basin behind the Ryukyu arc, formed by the northwest subduction of the Philippine Sea plate beneath the Eurasian plate (Sibuet et al., 1998). At its early evolution stage, the back-arc rifting is progressive and the syn-rift sedimentation at a rate of 1–2 m/ka has been underway after the late Pleistocene (Tsugaru et al., 1991; Park et al., 1998).

The South China Sea (Figure 2), situated between the western pacific, Eurasian, and Indo-Australian plates, is the largest marginal sea in the western pacific, occupying an area of ~3.5×10^6 km^2 (Wang et al., 2014). The deep-sea basin, continental slope, and continental shelf cover ~15%, 38%, and 47% of the total South China Sea area, respectively; it has an average water depth of 1140 m (Wang et al., 2014). The South China Sea has experienced complex structural and thermal evolution in the Cenozoic (Taylor and Hayes, 1983; Hutchison, 2004). Tectonically, it is characterized by both the northern extensional passive and western strike-slip continental, southern compressive, and eastern active convergent margins (Chen et al., 2015a). Currently, the oceanic crust of the South China Sea is subducting eastward along the Manila trench (Wang et al., 2014).

3 Seabed fluid flow in the Bohai Sea

The highly fluctuating methane in the nearshore areas is attributed to the combined influences of land inputs and *in situ* petroleum contamination. Around the Bohai Sea, the Yellow River water has been reported to contain high methane (Gu et al., 2011). However, the river input of methane is negligible in the central Bohai Sea. Moreover, the tremendous heterogeneity of sea surface methane distributions indicates gas leakage from the seafloor (Zhang et al., 2014a). During the survey periods, the Bohai Sea was a net source of atmospheric methane (Zhang et al., 2014b). The PL19-3 giant oilfield is situated where faulting occurred violently during neotectonism. Oil migrated along the densely distributed faults and charged the PL19-3 structure rapidly. Fluid/oil migration and accumulation triggered by earthquakes are non-continuous and episodic (Zou et al., 2011). The active faults in the neotectonism became passages for oil to migrate from the Paleogene to Neogene (Gong et al., 2004). Charging the shallow Neogene reservoirs was dynamic, probably ongoing, as a combined result of the existence of active source rocks, development of overpressure, and fault reactivation from 5.1 Ma (Hao et al., 2012). Migration modelling without considering the effect of the densely distributed faults describes a good match between petroleum occurrences and predicted preferential petroleum migration pathways and accumulations, indicating that the densely distributed faults in the Neogene sediments do not influence the petroleum enrichment. If the densely distributed faults in the Neogene sediments act as vertical conduits for petroleum migration, most petroleum would have migrated to Quaternary sediments or the seafloor, causing oil dispersion and degradation (Hao et al., 2007).

Neotectonic controls the late-stage hydrocarbon accumulation and maintains the sustained dynamic equilibrium where the accumulation amount is greater than the diffusion loss in oil and gas. Seismic sections extensively show active fluid escape in the shallow strata *via* faults and gas chimneys in the Bohai Sea such as the PL19-3 oil field (Figure 3, Gong, 2005). High-resolution seismic sections show densely distributed faults before the late Pleistocene and relatively weak fault activities afterward (Wang et al., 2011). Shallow gas occurs at different depths, and the blowouts threaten platforms, causing serious accidents in several drilling operations (Yang and Qi, 2004). The detection of extensive shallow gas by the regional geological survey (Hou et al., 2016) and its accumulation above these faults in the Laizhou Bay (Du et al., 2007) shows the development of widespread fluid flow in the Bohai Sea. However, the distribution, geological controls, and origin of fluids remain unclear following inadequate detailed geophysical investigation and *in situ* measurement and less investigation in methane flux and its environmental effects. Note that the famous Penglai 19-3 oil-spill accident between June 2011 and August 2011 was induced by fluid escape along faults activated by overpressure water injection in the well, indicating that shallow faults can be activated by overpressure fluid flow or geological activities, thereby providing migration and escape pathways for fluids. Recently, we reveal a complex seabed fluid flow system composed of various seafloor expressions (i.e. mounds and pockmarks) and shallow fluid migration pathways in the central-west Bohai Sea based on an integrated study of side-scan sonar, single- and multi-channel seismic data and magnetic data (Duan et al., 2022).

4 Seabed fluid flow in the Yellow Sea

Cold seeps are widespread in the Yellow Sea, as indicated by lots of evidence, including gas seeps, pockmarks, domes, seafloor faults, and micro-ring depressions. Liu et al. (2013) reported certain micro-ring depressions in the north Yellow Sea at a water depth of 50–55 m. These depressions demonstrate circular and irregular ellipse shapes with a major axis of ~2 km and a shallow groove with a width of 200–300 m wide and a depth of 2 m along the edge (Figure 4). These depressions are interpreted as topography features formed by sub-bottom shallow gas leakage and transformed by bottom current and submarine slumping. However, no simultaneous seismic data confirm the above interpretation, and the formation mechanism for this seepage topography remains unclear. Zhao et al. (2009) reported certain seabed pockmarks and domes in the northern depression of the south Yellow Sea basin (location is unknown), related to fault structures as pathways and sources for the seabed hydrocarbon seepages. This indicates the upward migration of pore fluid in the

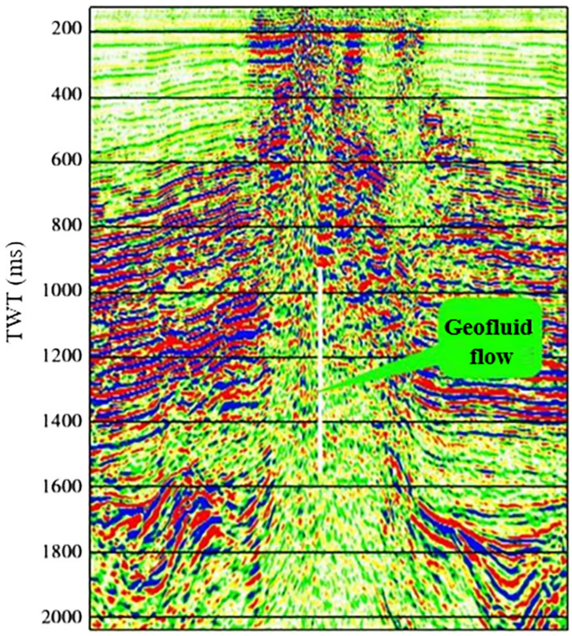

FIGURE 3
PL19-3 oil field in the Bohai bay basin formed in Quaternary and dispersed in the late-stage period of hydrocarbon accumulation (Gong, 2005).

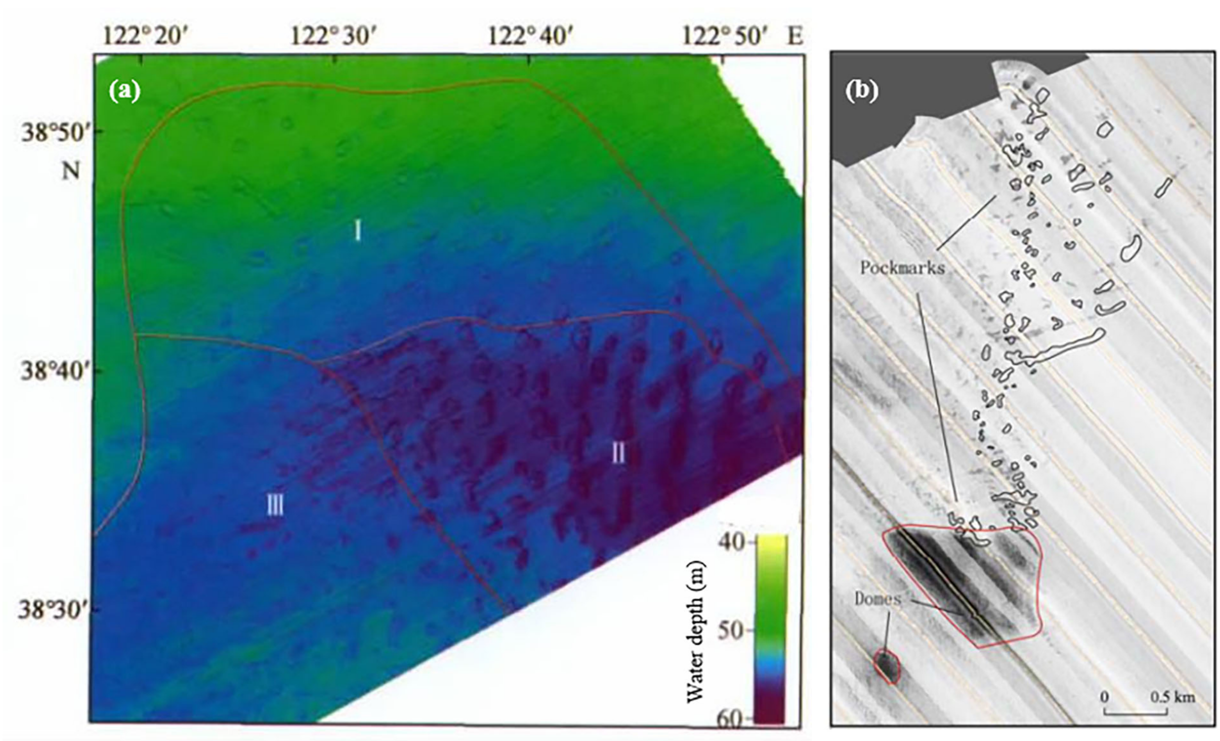

FIGURE 4
Certain geological features on the fluid escape structures in the Yellow Sea. **(A)** Bathymetric map showing the micro-ring depression in the north Yellow Sea (Liu et al., 2013). I) Circular or elliptical micro depressing with a protrusion in the center; II) Elliptical micro depression with depression in the center; III) Curved micro depression. **(B)** Side-scan sonar mosaic image demonstrating domes and pockmarks (Zhao et al., 2009).

deep strata (Figure 4). Jeong et al. (2004) reported a few active gas seepages in the southeastern Yellow Sea. However, geophysical and geochemical observations demonstrate that the gas seepage appears to be explosive to form craters and diapirs, dominant in thermogenic gases, with a smaller amount of biogenic gases. However, seepages in the western Yellow Sea are mostly biogenic with the late Pleistocene peat as the major source. The active cold seeps by acoustic plumes, cloudy turbidity, and point-line-type reflection produce seabed pockmarks and mud domes, as per the occurrence of shallow gas, which is mostly distributed in the buried delta, paleo lacustrine, paleo-fluvial facies, and paleo-tidal channel facies (Gu et al., 2008; Gu et al., 2009; Gu et al., 2006). Kong et al. (2012) compiled a distribution map of marine geohazards with the shallow gas involved as a major factor of marine geohazards. Furthermore, active cold seeps in the central Yellow Sea are speculated to result from fluid escape along faults from the deep. A large collapse crater in the northwestern part of the Subei shoal may be a composite collapse crater resulting from the shallow-faulting-related multipoint eruption of shallow gas, indicating the shallow gas occur in the middle-deep strata (Gu et al., 2009).

5 Seabed fluid flow in the East China Sea

Previous studies demonstrated signs of cold seeps on the continental shelf and slope of the East China Sea. Although shallow gas, pockmarks, small domes, shallow faults, and certain associated gas plumes are extensively reported using geological disaster surveys, the gases are mostly biogenic because of the degradation of organic matter in the shallow sediments of Yangtze Estuary, Hangzhou bay, Xiamen bay, and Zhejiang coast (Jorge et al., 1985; Hu et al., 2012; Liu et al., 2014; Hou et al., 2015; Hu et al., 2016; Figure 5), whereas thermogenic and high pressure as buried several hundreds of meters deep on the vast continental shelf of East China Sea (Yu, 2011; Cui et al., 2013). Previous studies on the Okinawa Trough have demonstrated widespread cold-seep activities. A gas seepage above the acoustic curtain and mud diapir structure (Luan and Qin, 2005; Luan et al., 2008), the authigenic carbonates related to cold seepage (Sun et al., 2015) and intense methane seeps indicated by shallow sulfate-methane interface and abnormal pore water characteristic (Li et al., 2015) show cold seeps are pervasive along the western slope of Okinawa Trough. Roughly circular sediment mounds or mud volcanoes have been mapped for the first time at the shelf edge of the East China Sea. These sediment mounds are associated with large pockmarks. This seepage process is suspected to be very recent, and probably still active (Yin et al., 2003). Then, additional mud volcanoes/diapirs are reported along the western slope of Okinawa Trough. Seismic sections show that gas hydrates, marked by bottom-simulating reflector at the top of mud volcanoes, are observed along with mud diapirs (Xu et al., 2009), fed by the upward fluid along normal faults with a steep dip and slight fault displacement during the formation of mud diapirs (Zhao et al., 2006). Furthermore, bright

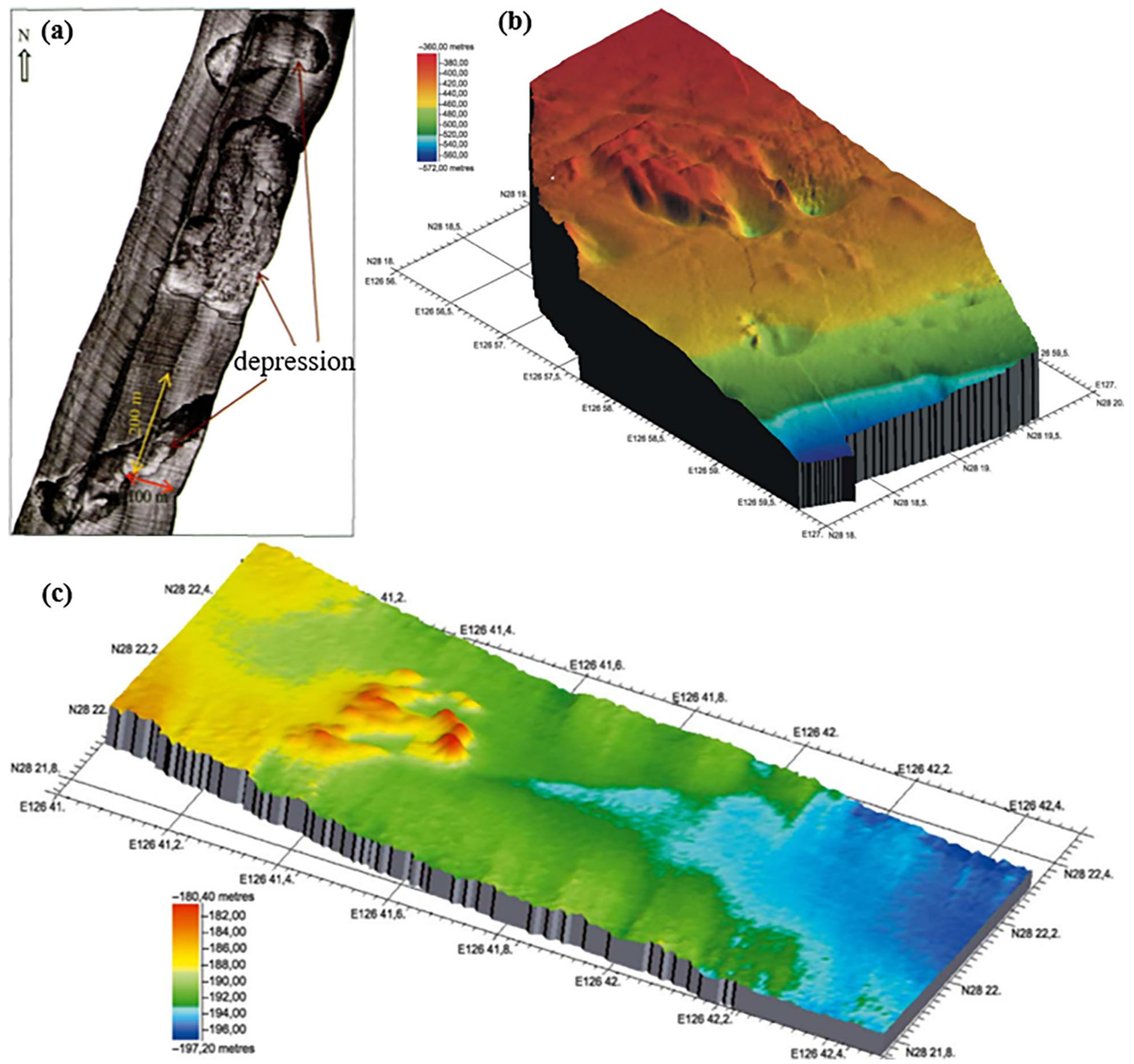

FIGURE 5
Certain geological features on fluid escape structures in the East China Sea. **(A)** Side-scan sonar mosaic image showing the depressions in the Zhoushan area, east of East China Sea (Hou et al., 2015). **(B, C)** Bathymetric map showing sediment depressions and mounds (Yin et al., 2003).

spots, phase reversals, and other acoustic anomalies show that gas and/or fluid escape are important for forming these mud volcanoes (Yin et al., 2003).

Except in mud volcano regions, gas hydrates are widely recognized along the western slope using limited seismic sections (Luan et al., 2006; Luan et al., 2008). In fact, the two regions of methane anomalies in surface sediments reported by Lu et al. (2002) are near two mud volcanoes found four years later. The thermal infrared anomalies before, during, and after earthquakes demonstrate a close relationship with gas hydrate distribution. These indicate that gas hydrates are pervasive in the central and southern Okinawa Troughs (Lu et al., 2002), and cold seeps are closely associated with gas hydrate decomposition. Note that additional investigations demonstrate that cold seeps are extensively spread along the western slope of the Okinawa trough, in the turbidite deposits, which host distinct petrologic composition and sedimentary structures compared with normal marine sediment (Sun et al., 2015). Recently, in a transtensile regime, active gas emissions were reported along the western slope of the mid-Okinawa Trough (Figure 6, Li et al., 2021).

6 Seabed fluid flow in the South China Sea

The South China Sea, one of the largest marginal seas of the west pacific, bears the coldest seeps in China. Tens of possible seep sites have been identified using direct or indirect evidence (Feng D.

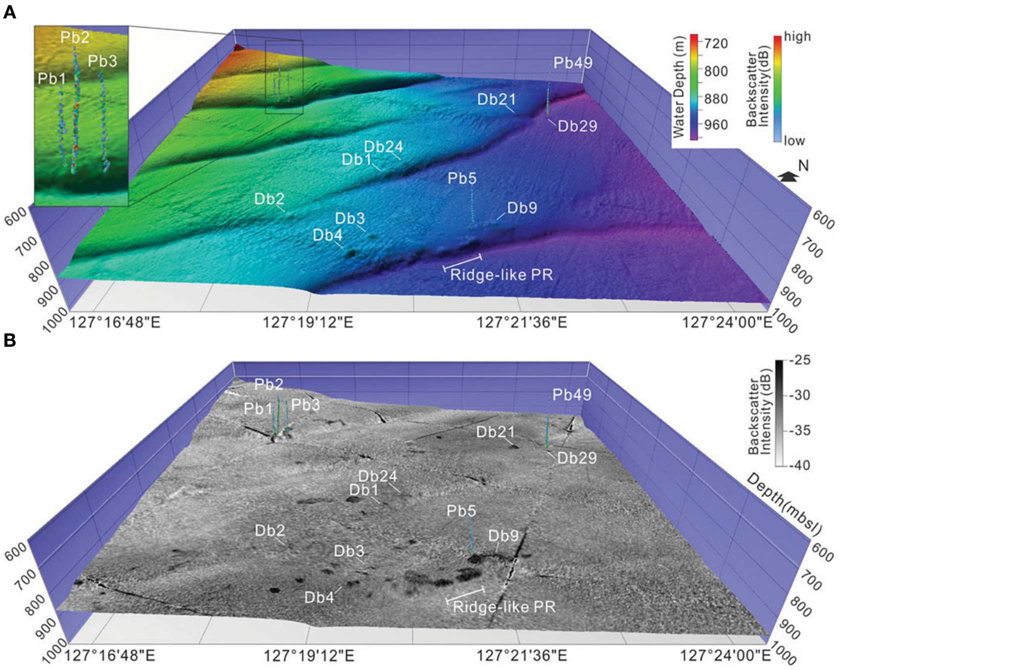

FIGURE 6
(A) 3D view of the bathymetry showing the geometries of positive reliefs and gas plumes. **(B)** 3D view of the map of the backscattering intensities superimposed on the bathymetric one (Li et al., 2021).

et al., 2018). In the South China Sea, focused fluid flows are extremely active. BSRs are reported in Taixinan, Pearl river mouth, and the Qiongdongnan basin, indicating that gas hydrates are extensively distributed in the northern South China Sea (Wang et al., 2018; He et al., 2022; Qian et al., 2022). Moreover, pockmarks have been reported around the South China Sea, including the Pearl river mouth, Qiongdonan, Yinggehai, Zhongjiannan basin, and Nansha region (Chen et al., 2015b; Xiong et al., 2023; Zhang et al., 2020). Furthermore, mud diapirs are reported all over the northern South China Sea and mud volcanoes primarily occur in the Taixinan and Pearl river mouth basins, northeastern South China Sea (Chen et al., 2016; Wan et al., 2019). Except for cold seeps in the Nansha region, others are primarily located on the northern slope of the South China Sea. Active gas seepages are primarily found in the Qiongdongnan basin and Taixinan basin (Wang et al., 2022).

The cold seeps and Jiulong methane reefs were discovered in the South China Sea in 2004 during the Sino-German cooperative investigation in the northeast Dongsha and Taixinan basin (Chen et al., 2005). In the Jiulong methane reef area, the chemoherm edifices and methane-derived carbonates are widespread (Suess, 2005; Han et al., 2008). Field observations and laboratory studies of these carbonates demonstrate multiple microbial structures preserved around and embedded in these carbonates, which supports the anoxic oxidation of methane in their formation (Han et al., 2008; Shi et al., 2014). Other active cold seeps were identified using high-resolution seismic images at the southern summit of the Taiwan ridge, southwest Taiwan in 2008 (Liu et al., 2008; Hsu et al., 2018). ROVs and deep submergence vehicles were used to explore the region in the subsequent years (Feng and Chen, 2015; Feng et al., 2015; Zhang et al., 2017). During the exploration, methane gas hydrates were discovered on the seabed surface of the Taiwan ridge and the exposed hydrates were attached to the inner wall of seeps (Figure 7, Zhang et al., 2017). Multibeam water column data show gas plumes and the possible existence of gas hydrates in the Taixinan basin (Chen et al., 2019). Furthermore, mud volcanoes and authigenic carbonate nodules were discovered in southwest Dongsha (Tong et al., 2013; Yan et al., 2017). Carbonates from southwest Dongsha have relatively high mineral contents and low $^{87}Sr/^{86}Sr$ ratios compared with those from northeast Dongsha, indicating a deeper source of seepage fluids (Tong et al., 2013; Feng D. et al., 2018).

Another important seabed fluid flow region is located in the Shenhu area, which witnessed both China's first gas hydrate drilling in 2007 and offshore gas hydrate production test in 2017. Fluid flow features are widespread; the high-resolution 3D seismic data demonstrate abundant acoustic anomalies, indicating the occurrence of shallow gas. Sun et al. (2012) discovered 45 mud diapirs and 4 isolated mud volcanoes; however, only one mud volcano was exposed on the seafloor with the conduit visible in the seismic profile. Chen et al. (2016) identified 164 gas chimneys, 5 mud diapirs or volcanoes, and 9 pockmarks from the results of high-resolution 3D seismic investigations. Carbonates from the Shenhu area are categorized into two: pipes and crusts; the extremely negative $\delta^{13}C$ value of these carbonates indicates that the primary carbon source in the Shenhu seeps is biogenic methane (Tong et al., 2013). From the results of the multibeam survey, Zhu et al. (2019) reported multiple suspected gas plumes; however, no active cold seeps have been reported with direct and solid evidence in the Shenhu area.

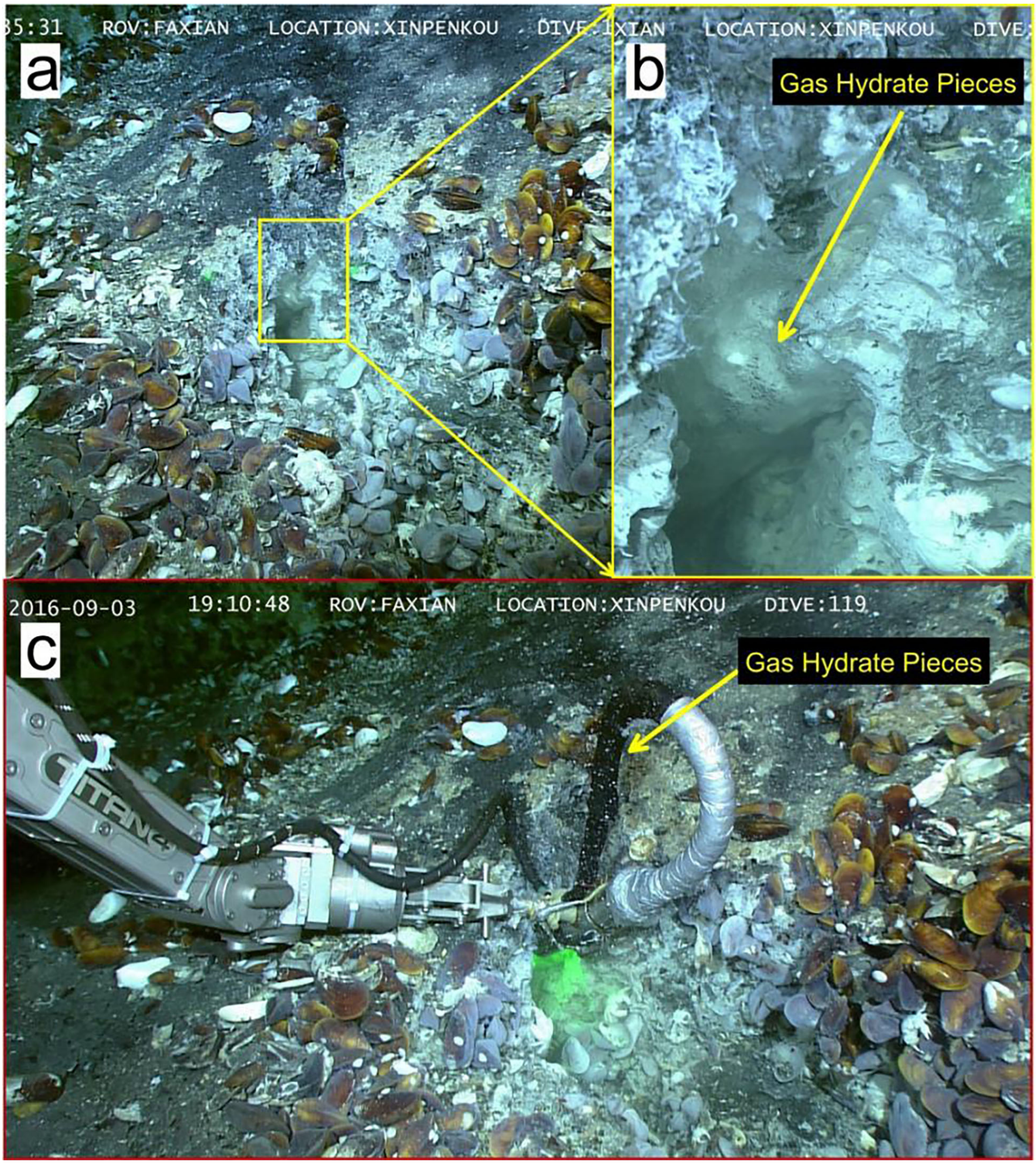

FIGURE 7
Raman observations of gas hydrates exposed on the seafloor. **(A)** The exposed hydrate inside the channel of a cold seep vent surrounded by lush chemosynthetic communities. **(B)** A close-up view of the exposed hydrate attached to the inner wall of the channel. **(C)** The release of small pieces of gas hydrate from the vent (Zhang et al., 2017).

Fluid escape features are developed in Zhongjiannan and adjacent Qiongdongnan basins. Using 2D seismic data and multibeam bathymetry data, Sun et al. (2013) identified three focused fluid escape features, mud volcanoes, pipes, and associated pockmarks, in the Zhongjiannan basin. When fed by gas-rich plumbing systems, mud volcanoes are either isolated or in groups. Chen et al. (2015b) first reported newly discovered crescent pockmarks and pockmark strings in the northern Zhongjiannan basin and discussed the geological and oceanographic controls on these seabed fluid escape structures (Chen et al., 2018). Using the reaction transport model, Luo et al. (2015) suggested that the fluid seepage at the pockmark ceased 39 kyr ago, corresponding to a relative sea-level high-stand and gas hydrate stabilization. Another important progress occurred when active cold and Haima seeps were discovered using ROV in 2015 and 2016 in the Qiongdongnan basin. Geophysical data were used to outline migration pathways for fluid and gas to the seabed. Furthermore, gas hydrates were recovered in sediments at ~4 m below the seafloor at Haima seep sites (Liang et al., 2017). Recently, a new and active cold seep was reported ~50 km northeast of the Haima cold seeps (Figure 8, Geng et al., 2021). All these prove the ongoing gas seepage activities at this newly discovered cold seep.

From the interpretations of geophysical data, Liu et al. (2021) hypothesized an evolutionary model developing the gas hydrate system and gas seepage at the Haima cold seeps (Figure 9). In addition to these results, thermogenic gas in the Qiongdongnan basin migrating from the deep reservoir through the gas hydrate stability zone along deep faults and gas chimneys forms active cold seeps. The results provide insight in the relationship between seafloor cold seeps and deep hydrocarbon generation and migration. Furthermore, they have important implications for hydrocarbon exploration in the Qiongdongnan basin of the northwestern South China Sea (Geng et al., 2021). Feng D. et al. (2018) quantitated the contribution of cold seep fluids to the bottom-water carbon reservoir of the South China Sea, which help to understand the dynamics and the environmental impact of hydrocarbon seep.

In addition to the northern slope of the South China Sea, a few possible cold seeps are indicated in the southern South China Sea, e.g., methane seepage is inferred from the porewater geochemistry of shallow sediments in the Beikang basin (Feng J. et al., 2018). Zhang K et al. (2020) reported 125 pockmarks close to the Andu seamount in the southern margin of the South China Sea. To date, cold seeps remain poorly investigated in the southern South China Sea.

7 Summaries and conclusions

It is remarkable how common seabed fluid flow is in the China seas, from every seabed environment from coastal waters down to the deep oceans. Given the larger scale and quantity, seabed fluid flows are widespread in the continental margins of the East China Sea (e.g. the Okinawa Trough) and the South China Sea (e.g. the Pearl River Mouth Basin). In the Bohai Sea, seabed fluid flows are also found in the hydrocarbon enrichment basins, such as the Bohai bay basin. In comparison, levels of scale and quantity are low in the Yellow Sea and the East Sea shelf basin.

Previous investigation works on the seabed fluid flow over the last three to four decades have led to significant progresses in our understanding of this geological phenomenon. However, the field investigations on seabed fluid flow are severely insufficient in the Bohai Sea, the Yellow Sea, and the East China Sea shelf basin. In addition, more comprehensive and detailed investigations are required in the Okinawa Trough and the South China Sea for the sake of the gas hydrates and hydrocarbons.

The distribution, feature and origin of the seabed fluid flow are controlled by various geological, biological and oceanographic factors in the China seas. In sedimentary basins the most significant fluids are hydrocarbons, particularly methane, formed by thermogenic or biogenic processes within the sediments. Therefore, seabed fluid escape structures (e.g. pockmarks, seeps, domes, mud diapirs, gas chimneys, and mud volcanoes) are usually associated with deep marine hydrocarbons or shallow gas hydrates. In order to understand the nature of these seabed fluid escape structures in both time and space, it is essential to appreciate how

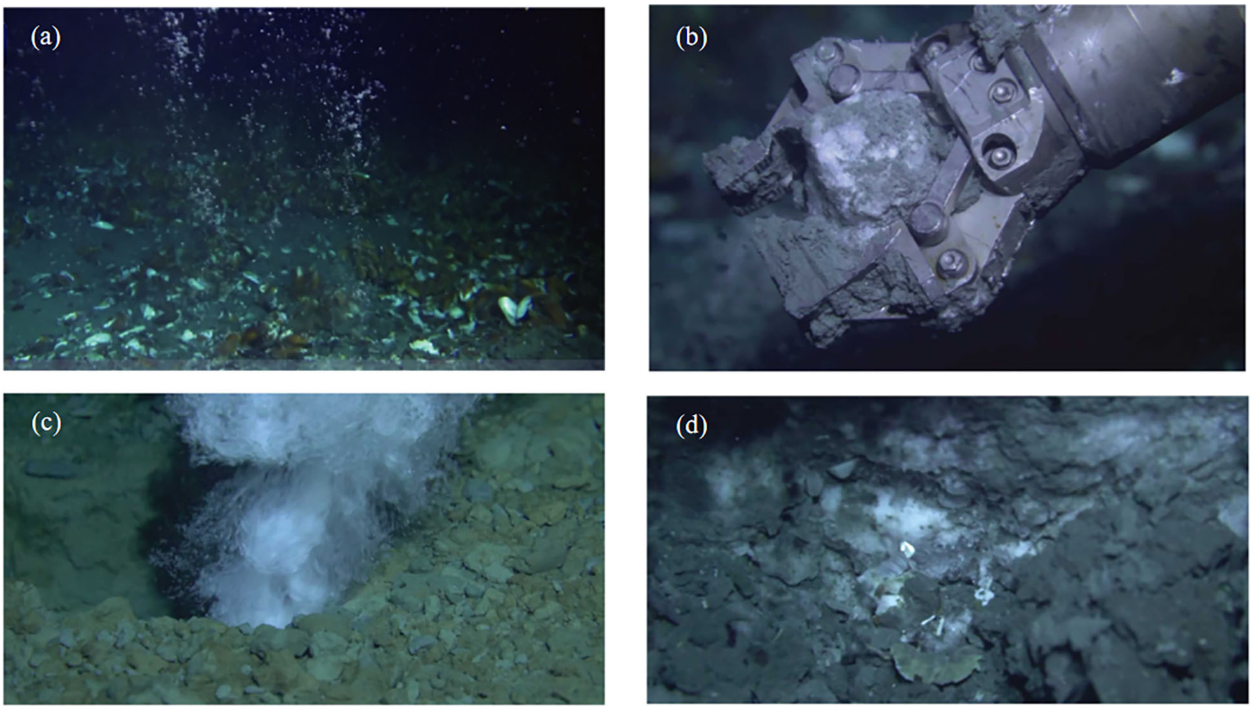

FIGURE 8
Seafloor observations of gas seepages **(A, C)** and near-surface gas hydrates **(B, D)** (Geng et al., 2021).

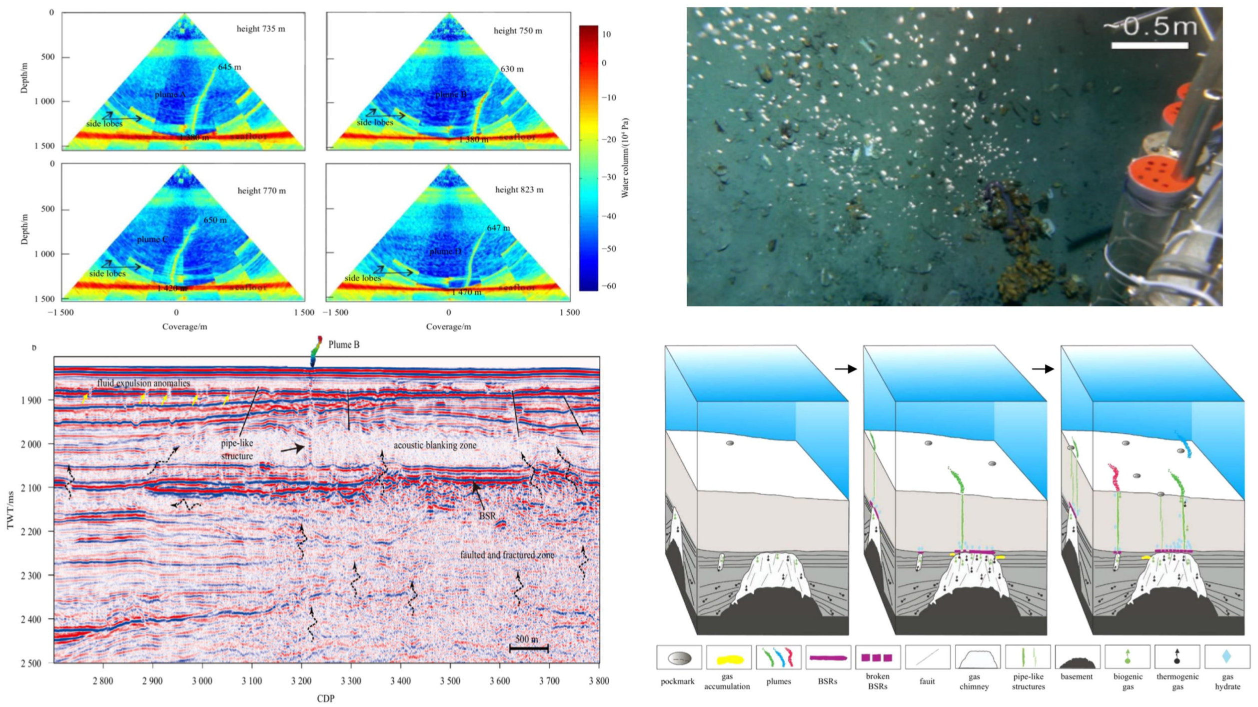

FIGURE 9
Seabed fluid flow at the Haima cold seeps and the evolutionary model associated with the hydrate (Feng et al., 2020; Geng et al., 2021).

and why these seabed fluids form and migrate.Indeed, the seabed fluid flow is clearly a dynamic process and it is determined by a function of endogenic (e.g. seabed hydrocarbon) and exogenous (e.g. marine dynamic conditions) factors.

In essence, seabed fluid flow is a geological process. Further, it may affect marine ecology, ocean biogeochemistry, and even the atmosphere and global carbon cycle. Though these processes may be significant not only to today's climate, but also to global climate change over geological timescales, they are still poorly understood. Considering the widespread, dynamic, and influential feature of seabed fluid flow, more attention should be given to the future study on the seabed fluid flow.

Author contributions

CZ, MD, and JC wrote, edited and revised the text and figures. All authors contributed to the text and figures. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author MD was employed by Hainan Branch of CNOOC Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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