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From frozen reservoirs to environmental threats: The dual role of methane hydrates

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ABSTRACT

Growing global energy demands have made methane hydrates an increasingly important subject of research. Considered a potential fuel for the future, they occur in relatively inaccessible polar and marine environments, with the Arctic identified as a critical area due to its vast reserves. However, as climate change progresses, the dissociation of methane hydrates and the resulting release of methane pose a significant risk to our climate system. This paper examines the potential of gas hydrates as a future energy resource alongside the environmental implications of their destabilization. It reviews the current understanding of gas hydrate stability in Arctic and marine environments, the mechanisms of methane release, and the potential impacts on global climate and marine ecosystems. It also briefly discusses historical evidence of methane hydrate dissociation and its role in past climate events, as well as the current state of research and future outlook for responsible development.

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1. Introduction

Gas hydrates, or clathrates, are ice-like solids formed when water molecules trap gas molecules, primarily methane, in a cage-like structure under specific pressure and temperature conditions. These hydrates are abundant in permafrost regions and beneath continental margins, making them a focal point of research due to their potential as a future energy source and their significant environmental implications (Kvenvolden and McMenamin, 1980; Kvenvolden, 1988). The stability of gas hydrates is highly sensitive to environmental changes, such as temperature and pressure, which can lead to their dissociation and the release of methane into the atmosphere.

This review examines the response of oceanic gas hydrate accumulations to temperature changes at the seafloor and assesses the potential for methane release into the ecosystem. While many deposits remain stable under rapid seafloor temperature variations, shallow deposits can undergo rapid dissociation, producing significant carbon fluxes over decades.

While the dissociation of methane hydrates poses notable environmental risks, they are also recognized as a significant untapped energy resource. Extensive reserves have been identified in continental margin sediments worldwide, with major exploration efforts in countries like India and Japan. For example, India's National Gas Hydrate Program (NGHP) expeditions have confirmed substantial hydrate deposits along the eastern and western continental margins and in the Andaman Sea (Collett et al., 2008; Riedel et al., 2010). Similarly, Japan has conducted pioneering offshore hydrate production trials, including the world's first successful offshore methane extraction from hydrate-bearing sediments in the Nankai Trough (Yamamoto et al., 2014).

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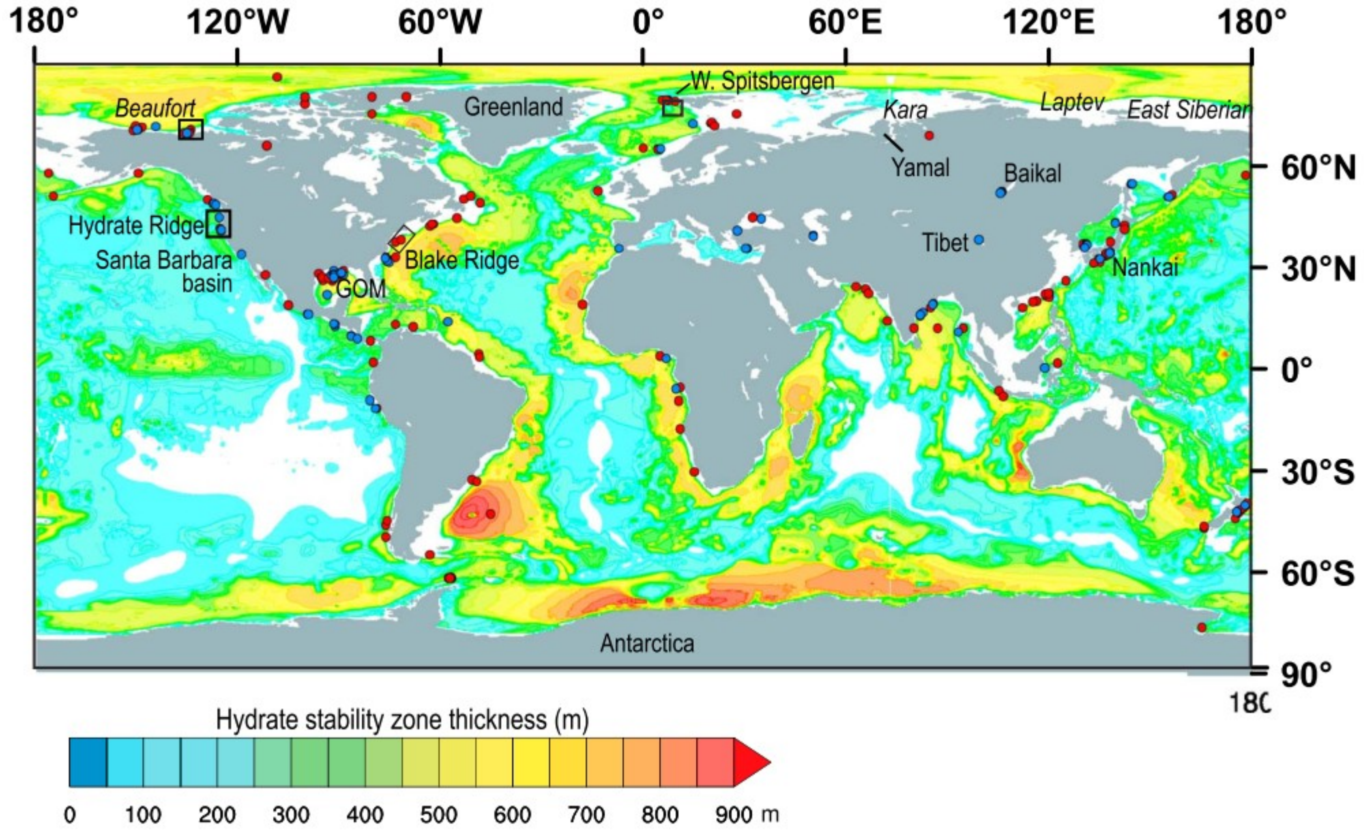

Fig. 1. The map illustrates the thickness of the theoretical Gas Hydrate Stability Zone (GHSZ) as calculated by Kretschmer et al. (2015). Known gas hydrate locations are marked with blue circles, while inferred gas hydrate locations are marked with red circles (adapted from Ruppel and Kessler, 2017).

The review also provides insights into gas hydrates under future warming conditions and how and when they could be destabilized, affecting oceanic pH, oxygen levels, and atmospheric methane content. Fig. 1 illustrates the thickness of the proposed Gas Hydrate Stability Zone (GHSZ) as calculated by Kretschmer et al. (2015), with known and inferred gas hydrate locations marked.

The advancements demonstrate the technical feasibility of producing methane from gas hydrates, although challenges remain in ensuring safe, cost-effective, and environmentally responsible extraction. A balanced approach is therefore essential- maximizing the energy potential while mitigating the risks of unintended methane release.

2. Gas Hydrate Stability and Environmental Factors

The stability of gas hydrates in sediments depends on several factors, including changes in bottom water temperature (BWT), geothermal gradient, seabed pressure, composition of the gas, and pore water salinity. The region where hydrates are stable is generally known as the Gas Hydrate Stability Zone (GHSZ). Recent global warming, including a 1 °C rise in ocean temperature, may have influenced gas hydrate stability (Westbrook et al., 2009). Seasonal intermixing of warm and cold water, as well as long-term variations, can lead to the depletion of gas hydrate reservoirs and the subsequent release of greenhouse gases into the ocean.

Initial estimates suggested that as much as 10,000 gigatons of methane carbon may reside in deep ocean sediments and along continental margins, but recent studies have narrowed this range to approximately 500–2,500 gigatons (Boswell and Collett, 2011; Ruppel and Kessler, 2017). In the Arctic Ocean, hydrates are deposited at shallow water depths close to shelf edges, stabilized by year-round cold temperatures. However, the Arctic has warmed considerably in recent decades, and future climate models predict continued warming due to rising global greenhouse gas emissions (IPCC, 2007).

The destabilization of shallow Arctic hydrate deposits has been debated, as it could lead to the release of methane into the water column and atmosphere (Reagan and Moridis, 2007; Kerr, 2010). Several studies have pointed out an increase in methane fluxes from submarine Arctic permafrost and the seafloor (Westbrook et al., 2009; Shakhova et al., 2010).

3. Methane Production, Consumption, and Release Mechanisms

Methane on Earth is primarily produced through methanogenesis, occurring in environments such as rice fields, wetlands, animal digestive systems, landfills, and marine and freshwater sediments. It is estimated that about 10–20% of reactive organic carbon buried in soils and sediments is converted to methane through this process (Reeburgh, 2007). Although the oceans—covering about two-thirds of the Earth's surface— generate an estimated 85–300 teragrams (Tg) of methane annually, more than 90% of this methane is consumed through anaerobic oxidation of methane (AOM) within marine sediments, a critical process that regulates the flux of methane reaching the atmosphere. AOM alone accounts for 7–25% of global methane turnover (Hinrichs and Boetius, 2002; Reeburgh, 2007).

Methane can be released from gas hydrates through various pathways, including turbulent diffusion, bubble migration, and advective transport through plant roots (Bastviken et al., 2004; Joyce and Jewell, 2003). According to Joyce and Jewell (2003), turbulent transport is the dominant mechanism in deep-water systems, while bubble release is more significant in shallow waters. Such bubble emissions in marine and freshwater environments can be triggered by factors like dissolved gas super saturation, shear stress from bottom currents, or pressure changes during reservoir drawdown. Additionally, the dissociation of methane hydrates in oceans and deep lakes further contributes to this process (De Batist et al., 2002; Pecher et al., 2001; Suess et al., 1999; Torres et al., 2002; Trehu et al., 1999; Tryon et al., 2002; Van Rensbergen et al., 2002).

The importance of understanding methane bubble transport has grown due to the discovery of numerous methane seep sites worldwide (Greinert et al., 2006; Heeschen et al., 2003; Lewis and Marshall, 1996; MacDonald et al., 2005; Naudts et al., 2006; Paull et al., 1991). Notably, bubbles released within the hydrate stability zone dissolve more slowly than those released above it (Zhang, 2003).

4. Environmental Consequences of Methane Release

The release of methane from gas hydrates has wide-ranging environmental consequences, driven by the complex interplay of pressure, temperature, and geological processes. The stability of gas hydrates in marine deposits depends on specific pressure and temperature conditions, which define the Gas Hydrate Stability Zone (GHSZ). Shifts in the GHSZ due to changes in water temperature can induce hydrate dissociation, leading to methane release (Milkov and Sassen, 2003). Additionally, geological events such as sediment slope failure, sliding, or collapse can significantly accelerate the rate of methane release (Dickens et al., 1995).

4.1. Impact of Ocean Warming on Hydrate Stability

Ocean warming poses a significant threat to gas hydrate stability, particularly in shallow deposits. Arctic regions are especially vulnerable due to pronounced temperature rises and the presence of thicker hydrate deposits, which are more prone to destabilization. To fully understand the consequences of rapid methane release and estimate the quantity of carbon that could reach the atmosphere, a detailed inventory of gas hydrate deposits in these regions is essential. Coupled modelling approaches that integrate dissociation, transport, thermal, and biogeochemical processes are critical for assessing the short-term response of methane-fuelled chemosynthetic communities and providing quantitative estimates of potential carbon release (Milkov and Sassen, 2003).

Studies indicate that gas hydrates are highly sensitive to temperature changes. For instance, an increase in deep ocean temperature of +1 to +5 °C over a century could trigger the dissociation of significant hydrate volumes at depths of around 1,000 meters, with the potential for near-complete exhaustion within a few centuries under sustained warming (Buffett and Archer, 2004). Deep ocean surveys have also revealed evidence of large-scale past fluid releases, underlining the risks of hydrate instability during periods of warming (Kvenvolden et al., 1993; Maslin et al., 2010).

4.2. Ocean Acidification and Hypoxia

Methane, being the primary gas in gas hydrates, has a global warming potential 21 to 23 times greater than that of carbon dioxide (IPCC, 2007). The dissociation of methane hydrates due to rising global temperatures is a major concern, as it can create a strong positive feedback loop, intensifying the effects of anthropogenic emissions. When released into the ocean, methane undergoes microbial aerobic oxidation, converting it to CO_2. This process lowers the pH of seawater, contributing to ocean acidification, and increases biological oxygen demand, which can lead to hypoxic conditions. Both acidification and depleted oxygen levels pose significant threats to marine biodiversity, as many marine organisms are highly sensitive to such environmental changes (Kvenvolden and McMenamin, 1980).

4.3. Arctic Vulnerability: A Hotspot for Hydrate Destabilization

The Arctic is particularly susceptible to hydrate destabilization due to its rapidly warming climate and the widespread presence of shallow, thick gas hydrate deposits. Several factors contribute to this heightened vulnerability which include,

4.3.1. Rapid Warming Trends

The Arctic is warming at more than twice the global average rate, a phenomenon known as Arctic amplification. This accelerated warming is driving significant changes in both atmospheric and oceanic temperatures, directly impacting the stability of gas hydrates (IPCC, 2021). Shallow hydrate deposits in the Arctic, often found at depths of less than 500 meters, are highly sensitive to even modest temperature increases. Because they are already near the threshold of stability, further warming makes these deposits especially prone to dissociation.

4.3.2. Thick Hydrate Deposits and Observed Emissions

The Arctic holds some of the thickest and most extensive gas hydrate reserves on Earth, particularly along its continental shelves and slopes. These deposits are stabilized by persistent cold conditions, but this balance is being disrupted as Arctic waters warm. For example, the East Siberian Arctic Shelf (ESAS), one of the largest continental shelves in the world stores vast quantities of shallow methane hydrates that are increasingly unstable. Recent observations have documented methane plumes and widespread bubble seeps in this region, highlighting the scale of potential emissions (Shakhova et al., 2014). Studies show that shallow Arctic and sub-Arctic water bodies, including northern lakes, are already releasing significant methane, partially offsetting terrestrial carbon sink of the region.

4.3.3. Permafrost Thaw and Subsea Instability

Extensive subsea permafrost across the Arctic acts as a seal over hydrate-bearing sediments. As this permafrost thaws under rising temperatures, it loses its ability to contain these hydrates, leading to increased methane release. Additionally, the warming of sediments can trigger slope failures and landslides, further destabilizing hydrate deposits and accelerating methane release (Reagan and Moridis, 2007).

4.3.4. Feedback Loops and Climate Impacts

Methane released from Arctic hydrates can enter the atmosphere, where it acts as a potent greenhouse gas, contributing to further warming. This creates a positive feedback loop, where warming leads to more methane release, which in turn exacerbates global warming. Even if methane is oxidized to CO_2 in the water column, it contributes to ocean acidification and hypoxia, with cascading effects on marine ecosystems (Kvenvolden and McMenamin, 1980). Fig. 2 illustrates the dynamics of methane hydrates and the distribution of methane across various physiographic provinces, especially the Arctic shelf.

5. Historical Evidence of Methane Hydrate Dissociation

Historical evidence suggests that the dissociation of methane hydrates has played a significant role in past climate events. The positive-feedback mechanism has been proposed as a significant contributor to rapid and significant climate changes in the late Quaternary period (Kennett et al., 2000).

The Clathrate Gun Hypothesis proposes that past increases in water temperatures near the seafloor may have induced large-scale dissociation, with the methane spike and isotopic anomalies reflected in polar ice cores and in benthic foraminifera (Kennett et al., 2002). This hypothesis has been challenged by other interpretations of the paleoclimatic data (Nisbet, 2002; Sowers, 2006). However, the dissociation

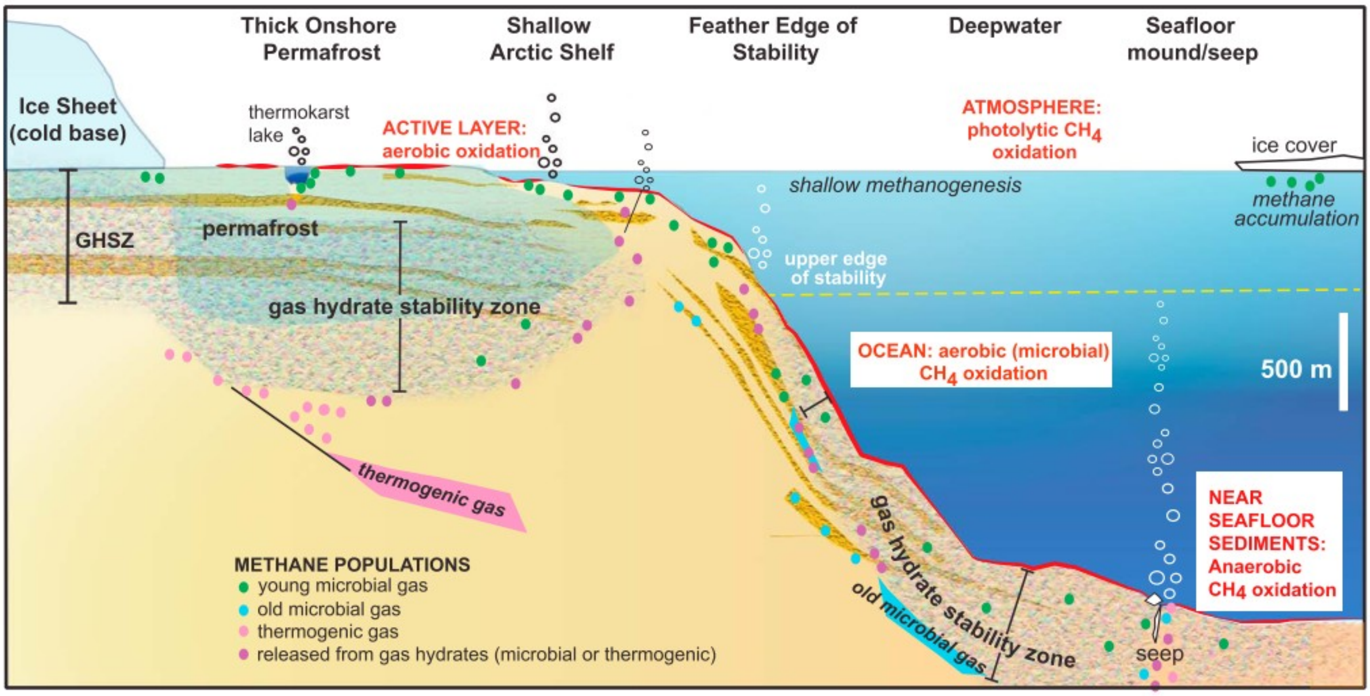

Fig. 2. The schematic illustrates the dynamics of methane hydrates and the distribution of methane across various physiographic provinces, as detailed by Ruppel (2011) and Ruppel and Kessler (2017). The most climate-sensitive hydrates are associated with i) *Thawing Subsea Permafrost*: Beneath Arctic Ocean shelves that were unglaciated at the Last Glacial Maximum (LGM) and ii) *Dissociating Gas Hydrates*: On upper continental slopes.

of methane hydrates remains a plausible explanation for rapid climate changes observed in the geological record.

6. Current State of Research and Future Outlook

Significant gaps still exist in our understanding of the dynamic response of oceanic hydrates to changes in ocean temperature and the resulting gas and aqueous transport through benthic sediments into the water column. Hydrates found in the deep ocean are stable due to pressures well above and temperatures well below those defining the hydrate phase boundary (Brothers et al., 2013; Plaza-Faverola et al., 2015; Ruppel, 2011; Skarke et al., 2014). Even if deep ocean temperatures were to increase by several degrees, which is larger than anticipated in any global warming scenario over the multi century scale and comparable to the difference between the Last Glacial Maximum (LGM) and the present (Adkins et al., 2002), the ambient hydrostatic pressure regime means that gas hydrates in the shallow part of the sedimentary section at these locations would generally remain stable (Reagan and Moridis, 2008; Ruppel, 2011).

Despite the fact that methane hydrates are potentially an enormous energy source and a factor in global warming, the magnitude of global methane hydrate occurrences and their geographical distribution and depth profile are very uncertain (Boswell, 2007; Shinu and Lasitha, 2015). Further development of advanced seismic techniques, extended drilling programs, and improved inventory modelling are needed to reduce uncertainty. Shakhova et al. (2010) invoked anomalous shallow gas hydrates beneath the East Siberian Arctic shelf as a potential CH_4 source, but the origin and existence of these hydrate deposits remain controversial and require further examination.

Circum-Arctic Ocean continental shelves have long been presumed as a source of atmospheric CH_4 emissions (Kvenvolden et al., 1993). Recent studies have focused on the Siberian shelves, where annual atmospheric CH_4 emissions are estimated to be up to 17 Tg CH_4 when ebullitive and diffusive fluxes are combined (Shakhova et al., 2014). However, Thornton et al. (2016) described a continuous shipboard survey of CH_4 concentrations in the atmosphere and near-surface waters in much of this same area, concluding that outburst does not substantially contribute to the sea-air CH_4 flux, which they calculate to be less than

2.9 Tg yr-1 CH_4. They also note that some of the previously reported atmospheric CH_4 concentrations on the East Siberian Arctic shelf may be unrealistic.

The central challenge remains determining how much CH_4 is being released to the ocean and atmosphere on regional to global scales due directly or indirectly to hydrate dissociation. Given the substantial differences between top-down and bottom-up estimates of atmospheric CH_4 emissions, delineating the small component that might be attributable to gas hydrates will be a challenge for decades (Kirschke et al., 2013).

7. Mitigation and Adaptation Strategies

Given the dual role of methane hydrates as a promising energy resource and a potential climate hazard, effective mitigation and adaptation strategies are essential to ensure responsible development and minimize environmental risks.

Controlled Extraction. Advanced extraction methods such as depressurization and CO_2-CH_4 swapping can reduce the risk of uncontrolled dissociation. For example, Japan's Nankai Trough trials have demonstrated the feasibility of controlled depressurization to extract methane safely (Yamamoto et al., 2014).

Monitoring Systems. Continuous monitoring of hydrate-rich regions, especially in the Arctic and continental margins, is crucial. Seabed observatories equipped with sensors for pressure, temperature, and gas flux can provide early warnings of destabilization (Ruppel and Kessler, 2017).

Carbon Capture Integration. Linking methane production with carbon capture and storage (CCS) can help offset greenhouse gas emissions. CO_2 injection into depleted hydrate reservoirs has been proposed as a method to both store CO_2 and stabilize the remaining hydrates (Boswell and Collett, 2011).

Improved Climate Models. Enhanced climate models that include hydrate feedbacks can help predict future methane emissions and inform policy decisions.

Marine Conservation. Identifying and designating hydrate-rich areas with high ecological value as **protected zones** can help reduce the impact of exploration activities on marine biodiversity.

Emergency Response Planning. Developing coordinated emergency response protocols for accidental large-scale releases such as submarine landslides or rapid permafrost thaw is vital for risk preparedness.

Diversifying the Energy Mix. Investments in renewables can reduce the urgency to exploit gas hydrates aggressively, buying time to develop safer extraction technologies.

International Collaboration. Collaborative projects provide valuable data and technological insights, demonstrating the benefits of shared research and best practice development.

Developing and enforcing strict regulatory frameworks is necessary to ensure safe drilling and production operations, particularly in ecologically sensitive regions like the Arctic and deep water margins.

8. Conclusion

Gas hydrates hold significant promise as an unconventional energy resource at a time of growing global energy demand. However, they also present serious environmental challenges that require careful consideration. The potential dissociation of methane hydrates could release large quantities of methane amplifying global warming through positive feedback loops. Such releases may also contribute to ocean acidification, reduce oxygen levels, and disrupt marine ecosystems in complex ways that remain only partially understood.

Historical evidence indicates that large-scale hydrate breakdowns have contributed to abrupt climate shifts in the past. Today, the risk of destabilization remains relevant as ocean temperatures continue to rise. Nevertheless, promising pilot projects such as National Gas Hydrate Program of India and Japan's offshore production trials demonstrate that, with advanced technology and strong safeguards, gas hydrates can potentially be tapped.

Natural processes like anaerobic methane oxidation help moderate methane release from the seabed, but these processes may not be sufficient to counteract additional risks posed by warming seas or large-scale production. While some studies suggest that catastrophic methane releases to the atmosphere are unlikely in the near term (USGS, 2023; Ruppel and Kessler, 2017), local impacts on seafloor stability, benthic habitats, and regional ocean chemistry still require close monitoring and proactive management.

Key knowledge gaps persist. Precise quantification of global hydrate reserves, a clearer understanding of destabilization thresholds under different warming scenarios, and better predictions of regional variability are urgently needed. There is also a need for improved technologies for safe extraction, such as CO_2–CH_4 exchange, controlled depressurization, and real-time monitoring systems that can detect early signs of hydrate destabilization.

Future research must be interdisciplinary, combining geophysics, oceanography, climate science, engineering, and policy studies to address the complex challenges and opportunities that gas hydrates present. International collaboration, transparent data sharing, and robust environmental frameworks will be vital to ensure that gas hydrate development, if pursued, aligns with climate goals and ocean sustainability. A balanced, precautionary approach integrating smart mitigation, adaptive strategies, and global cooperation offers the best path forward to harness the potential of gas hydrates while safeguarding climate stability and marine ecosystems.

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Conflict of Interest

The authors declare that there are no known conflicts of interest associated with this publication. No significant financial support was received that could have influenced the outcome of this work.

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