Global seafloor gas venting: New insights from paleo-coldseep systems

Zhaojie Cheng,[1,2,3] Zhuangcai Tian,[1,2,3,4,*] Jingxin Wu,[1,2,3] Zhenchao Zhang,[1,2,3] Sicheng Bian,[4] Ming Su,[5] and Xiujun Guo[1,2,3,6,*]

[1]Shandong Provincial Key Laboratory of Marine Engineering Geology and the Environment, Ocean University of China, Qingdao 266100, China
[2]Key Laboratory of Marine Environment and Ecology, Ministry of Education, Ocean University of China, Qingdao 266100, China
[3]College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, China
[4]State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China
[5]School of Marine Sciences, Sun Yat-sen University, Zhuhai 519082, China
[6]Sanya Oceanographic Institution, Ocean University of China, Sanya 572000, China
*Correspondence: zhuangcaitian@ouc.edu.cn (Z.T.); guojunqd@ouc.edu.cn (X.G.)

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Marine sedimentary systems host vast deep carbon reservoirs, comprising solid methane sequestered within gas hydrates and gaseous hydrocarbons trapped as shallow free gas. Seafloor fluid and gas emissions serve as a critical conduit linking these deep reservoirs to the ocean-atmosphere system, exerting a profound influence on the global carbon cycle, marine biogeochemical environments, and sediment stability. Concurrently, rapid advancements in water-column detection, high-resolution geophysics, and in-situ monitoring technologies have significantly enhanced our capacity to identify, characterize, and track these dynamic seepage activities, yet large uncertainties remain regarding the magnitude and variability of oceanic methane release across continental margins.[1]

Current investigations into seafloor gas dynamics have predominantly gravitated toward active cold seep systems.[2] Paleo-cold seep systems refer to relict seep provinces that preserve geological and geochemical signatures of past methane-rich fluid discharge but generally exhibit weaker present-day seep activity compared with modern active seeps. They are commonly recognized by multiple lines of evidence, including authigenic carbonate deposits, seep-associated fossil assemblages, SMTZ-related geochemical anomalies, and preserved subsurface fluid migration pathways revealed by seismic imaging. Growing field observations suggest that paleo-fluid plumbing systems can be reactivated under contemporary environmental forcing, delivering sustained gas emissions from relict seep terrains to the overlying water column.[3] However, the apparent absence of vigorous modern seepage does not necessarily indicate complete termination of fluid circulation, because ancient plumbing systems may remain partially connected to deeper fluid reservoirs.[1] Here, we use "low-intensity fluid activity" to refer to detectable but relatively weak contemporary fluid migration or gas release within paleo-cold seep systems. This term describes a process-based state rather than a quantitative methane flux category.

However, the spatial footprint of seafloor fluid venting may be substantially more pervasive than conventionally assumed. Recent documentation of previously unmapped cold seeps in regions such as the Antarctic Ross Sea suggests that seafloor fluid release may be more widespread than previously recognized.[3] Within this contextual framework, we identified contemporary seafloor gas venting within a relict paleo-cold seep field in the Shenhu area, South China Sea. During multiple dives of the Haiqin ROV conducted in August 2025 along the eastern ridge of Canyon 12 (115°20.051 'E, 19°55.673'N), in-situ visual observations confirmed gas bubble emissions at one site and a small-scale water-column gas plume with a duration of approximately 20 s at another site, both at a water depth of 1,268 m within the paleo-seep provinces (Figure 1). These observations provide direct evidence of active present-day gas release from the seafloor, suggesting that at least a portion of the preserved seep structures remain hydraulically connected to modern subsurface fluid migration pathways.

POTENTIALLY UNDERESTIMATED SEAFLOOR METHANE RELEASE PATHWAYS

A growing body of evidence indicates that novel seafloor gas seepage occurs in regions traditionally presumed to be dormant. For instance, a multitude of previously undocumented methane seeps have been identified along the North Atlantic margin, while newly emerging fluid release sites have concurrently been observed in zones such as the Antarctic Ross Sea and South China Sea,[1,3] suggesting that the spatial footprint of seafloor methane leakage is far more pervasive than currently appreciated. Crucially, our identification of contemporary gas venting within a relict paleo-cold seep provinces suggests that certain systems conventionally categorized as "inactive" may retain connectivity with modern fluid regimes. Although fluid venting within these domains is weaker and less persistent compared with highly active seep systems, their deep plumbing architectures and fluid conduit networks may not be completely disconnected from present-day fluid circulation.[3] This phenomenon strongly implies that the traditional binary classification provides an incomplete description for certain seep systems because fluid activity may persist along a continuum from highly active discharge to weak residual migration.

Current estimations of the global benthic methane flux rely almost exclusively on data compiled from modern active cold seeps. Previous synthesis estimated that global cold seeps release an annual methane flux equivalent to approximately 20 Tg C, predicated on the baseline assumption that tens of thousands of active systems checker the global continental slopes.[5] However, recent in-situ observations by the Chinese Academy of Sciences reveal that methane fluxes across active seep fields in the South China Sea are three orders of magnitude higher than traditionally assumed;[2] scaling this up to a global slope baseline yields an updated active seep methane flux of up to 126 Tg C,[2] demonstrating that the active-seep budget component is critically undervalued. Consequently, if similar low-intensity fluid activity occurs across a wider range of paleo-cold seep provinces, current estimates of the global benthic methane budget may underestimate methane release pathways associated with these traditionally overlooked systems.

IMPLICATIONS FOR THE GLOBAL MARINE CARBON CYCLE

By identifying contemporary gas venting within relict paleo-cold seep provinces, this study suggests that methane-bearing fluid migration and potential methane release may occur beyond the confines of modern, highly active seep systems. Beyond these conventional active focal points, a subset of paleo-seep regions systematically retains low-intensity fluid activity, thereby expanding the recognized spatial footprint of seafloor methane leakage. Because current estimations of global benthic methane flux are heavily predicated on identified active seep systems, these potential low-intensity methane release pathways associated with historical paleo-cold seep fields remain insufficiently constrained in existing marine carbon cycle assessments.

IMPLICATIONS FOR MARINE GEOHAZARDS

The low-intensity fluid activity within paleo-cold seep systems may exert a sustained influence on the stability of the submarine geological environment. Such continuous but weak fluid migration does not necessarily trigger immediate failure; instead, over geological timescales, it may progressively modify sediment properties by increasing pore-fluid pressure, promoting gas accumulation, altering effective stress conditions, and weakening shallow sediments. In gas hydrate-bearing regions, even subtle but persistent fluid migration can fundamentally influence shallow gas distribution, pore-fluid pressure regimes, and the internal structure of sediments. These long-term fluid dynamic processes may gradually induce sediment weakening, the accumulation of excess pore pressure, and ultimately contribute to submarine instability and shear failure. Therefore, paleo-cold seep provinces that have tradi-

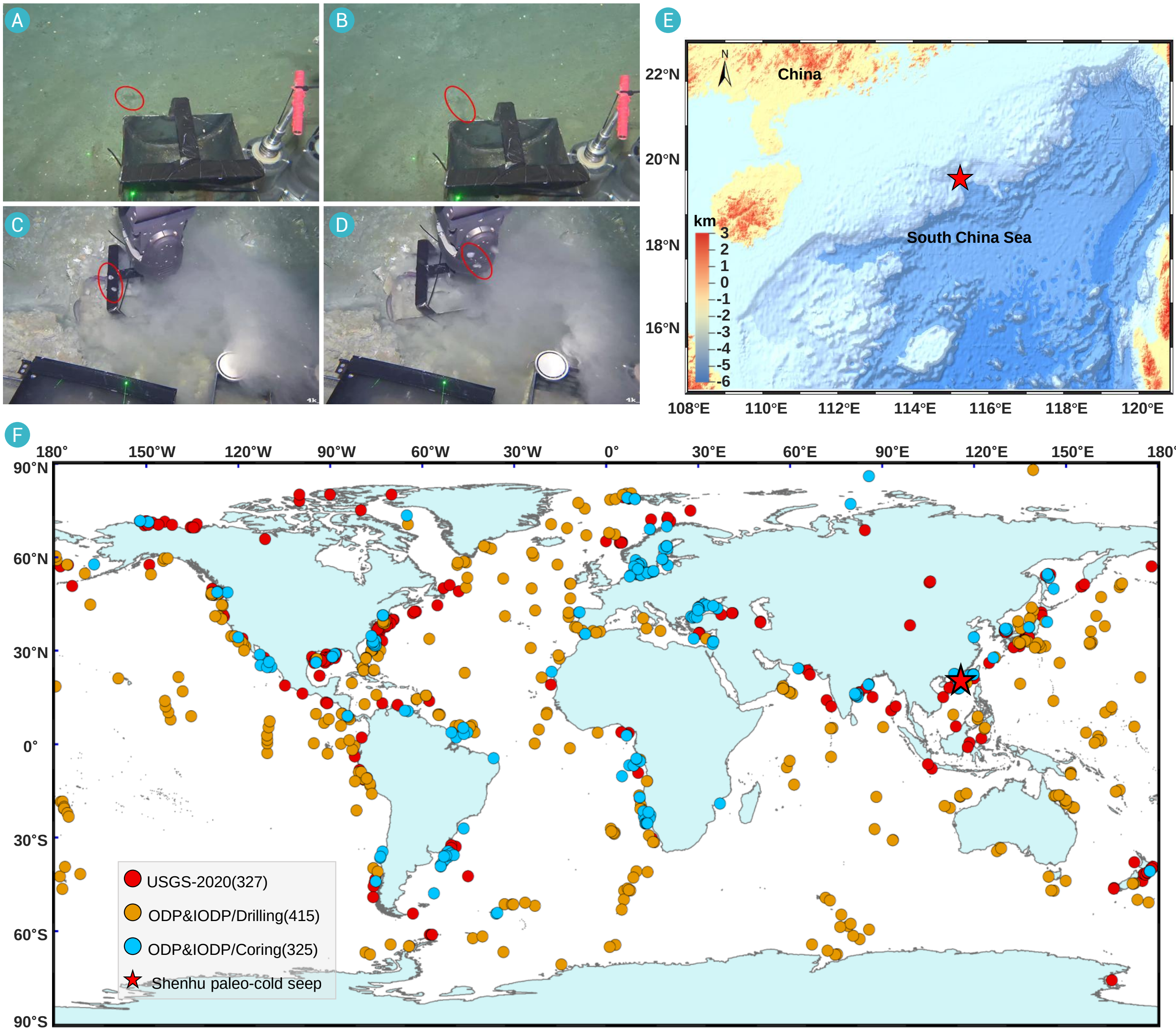

Figure 1. In-situ ROV observations, local bathymetry and global distribution of cold-seep sites (A–D) Seafloor fluid activity within the paleo-cold seep system of the Shenhu area, South China Sea. (A–B) Water-column plumes; (C–D) bubble seepage. (E) Bathymetric and geomorphologic map showing the location of Shenhu paleo-cold seep in the South China Sea. Submarine topography dataset (CSTR:13452.11.2.11.162.3.00079.1) is supported by the National Marine Science Data Center, National Science and Technology Infrastructure of China (https://mds.nmdis.org.cn). (F) Global distribution of documented marine methane seepage sites compiled from multiple data sources. Different colors indicate different data sources.[4] The Shenhu paleo-cold seep province investigated in this study is marked by a star. Made with Natural Earth. Free vector and raster map data were obtained from https://www.naturalearthdata.com.

tionally been regarded as completely "dormant" may possess previously overlooked, long-term cumulative geohazard potential, which warrants systematic investigation.

CONCLUSIONS

The documentation of contemporary gas venting within a relict paleo-cold seep provinces indicates that some systems conventionally categorized as "inactive" may retain connectivity with modern seafloor fluid dynamics. Our findings reveal that marine methane release pathways may extend beyond traditionally recognized active seep configurations; rather, the low-intensity gas emanation within historical paleo-seep domains constitutes an integral, yet previously overlooked, component of the broader seafloor emission architecture. Consequently, this study challenges the traditional, binary "active-inactive" dichotomy, showcasing that such conventional taxonomies may underestimate transitional states between active seep systems and apparently inactive paleo-seep provinces. Ultimately, these observations highlight the need to consider paleo-cold seep provinces as potential components of marine methane cycling and motivate further investigations into their spatial distribution and quantitative contribution.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

All authors declare no conflicts of interest.