De-Risking Deepwater Exploration: How Seep Hunting Provides Direct Evidence of Charge and Reduces Dry Holes

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Abstract

Hydrocarbon seep hunting has matured into a proven, physics-based method for validating active petroleum systems in deepwater basins, yet most exploration teams still rely primarily on seismic interpretation and legacy workflows. This paper presents an integrated seep and seismic workflow that combines multibeam bathymetry, water column imaging, targeted coring, and geochemical fingerprinting with structural and stratigraphic interpretation to directly confirm charge, migration pathways, and trap effectiveness. This integration materially lowers the probability of dry holes by reducing charge uncertainty and strengthening prospect ranking. Beyond technical de-risking, seep-supported charge confirmation enhances the commercial narrative required to sell prospects internally and during farmouts. For exploration managers operating under heightened scrutiny, seep hunting offers a conservative, data-rich enhancement to traditional workflows, one that improves decision quality without requiring a disruptive departure from established practice.

A seep sampling campaign can mature a basin from a frontier “unknown” area to an established petroleum system in 1 year for about $5 MM USD; whereas conventional exploration with only seismic and wells generally take 10+ years and 100 times the cost.

Keywords

Hydrocarbon seepage; multibeam bathymetry; backscatter; water column imaging; piston coring; geochemistry; petroleum migration; integrated 3D seismic; heat flow surveys; deepwater exploration; charge risk; petroleum systems; prospect bankability.

1 Introduction

Deepwater exploration requires high consequence decisions under uncertainty. Despite advances in seismic imaging and basin modeling, seismic data alone cannot directly confirm whether a petroleum system is actively charging prospects. This limitation forces exploration teams to commit capital based on indirect indicators, contributing to dry holes, inconsistent performance, and avoidable budget exposure. The persistence of seismic only workflows is driven less by technical merit and more by organizational inertia: they are familiar, standardized, and perceived as "safe," even when they leave critical charge questions unanswered.

Hydrocarbon seep hunting provides a direct, empirical method to close this gap. Modern seep hunting campaigns integrate multibeam bathymetry, backscatter, water column imaging, targeted seabed coring, and geochemical analysis to identify active migration pathways and confirm the presence of thermogenic hydrocarbons. When these datasets are integrated with 3D seismic interpretation/fault mapping, trap definition, seal evaluation, and overburden analysis; they create a unified charge model that is both technically robust and operationally defensible. This integration does not replace seismic interpretation; it strengthens it by adding physical evidence where seismic alone cannot.

These datasets also enhance the commercial narrative. Prospects supported by physical evidence of charge are easier to defend internally and more compelling during farmouts, where partners increasingly demand data rich justification. In capital disciplined environments, integrated seep and seismic workflows help exploration managers reduce technical uncertainty, improve budget defensibility, and increase the likelihood of portfolio advancement.

This paper addresses the core hesitation that limits adoption: the perception that seep hunting is "non-standard" and therefore risky to champion. In reality, integrated seep and seismic workflows represent a conservative, risk reducing enhancement to traditional exploration practice. The central question is no longer "Why try something new?" but "Why continue relying on incomplete information when a proven, data rich method can materially reduce both technical and commercial risk?".

2 Geological and Methodological Background

2.1 Hydrocarbon Seepage and Petroleum Systems

Thermogenic hydrocarbon seepage is the most direct surface expression of an active petroleum system. Its occurrence requires mature source rocks, effective migration pathways, and permeable conduits through the overburden. Classic studies (Abrams 1996, 2005) demonstrated that seepage reliably indicates ongoing charge and provides diagnostic geochemical signatures, fluid type, maturity, and oil family that can be correlated to modeled source rock intervals.

Modern biomarker and isotopic frameworks (Dembicki 2022) further refine these correlations, enabling interpreters to distinguish thermogenic from biogenic fluids and to evaluate the maturity and origin of migrating hydrocarbons.

In deepwater settings where well control is sparse, seepage provides rare, empirical evidence that petroleum generation and migration are active today, offering a powerful complement to seismic based charge prediction (Figure 1).

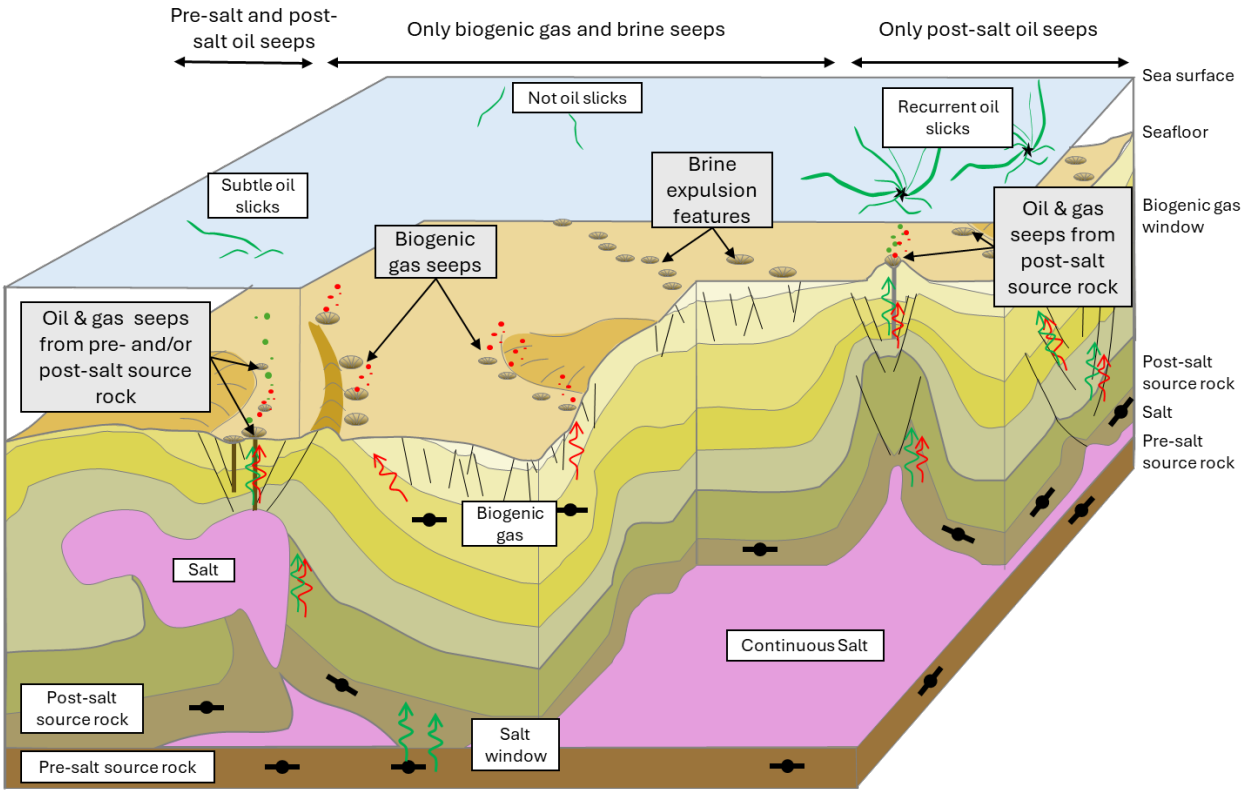

Figure 1. *3D representation of a salt basin with a pre-salt petroleum system, a post-salt petroleum system, and a biogenic gas system with associated seepage in addition to sediment dewatering features at the seafloor. Seeps are not random but controlled by the subsurface fluid sources and migration paths. 3D drawing inspired by Jatiault et al.(2019)*

2.2 Seep Morphology and Large Scale Seep Field Architecture

Seepage is not randomly distributed across the seafloor. High resolution seabed mapping consistently shows that seep fields cluster along geomorphic and structural discontinuities, channel margins, slope breaks, fault scarps, mud diapir provinces, and delta front collapse features (Judd & Hovland 2007; Naudts et al. 2006; Skarke et al. 2014). These patterns reflect the integrated behavior of structural deformation, sedimentary architecture, and overburden permeability.

Large scale surveys in the Gulf of Mexico, U.S. Atlantic margin, Mediterranean, and West Africa demonstrate that seep clusters align with shallow fault networks, buried channel systems, and stratigraphic windows that act as focused migration pathways (Cartwright et al. 2007; Dondurur 2018; Decker et al. 2022; Orange et al. 2023a,b). These relationships provide a predictive framework for anticipating seep distribution and for linking seabed observations to subsurface migration models (Figure 1).

2.3 Overburden Migration Processes

The overburden plays a decisive role in controlling where and how hydrocarbons reach the seabed. Fault networks, stratigraphic discontinuities, overpressure zones, and episodic expulsion events create complex leakage pathways that govern seep distribution (Abrams 1996; Orange et al. 2008). In many deepwater basins, shallow deformation and subtle stratigraphic windows are under-mapped, leading to misinterpretation of seep evidence or missed opportunities to validate charge.

Examples from the Gulf of Mexico illustrate that active seepage often overlies commercial reservoirs, demonstrating that seabed leakage can coexist with effective trap integrity (Hood et al. 2002; Sassen et al. 2001). Interpreting seepage within the context of overburden structure is therefore essential for distinguishing between productive migration pathways and leakage that bypasses reservoir traps.

2.4 Thermal Regime and Petroleum System Activity

The thermal regime governs source rock maturity, hydrocarbon generation, and the likelihood that seepage reflects active versus fossil charge. Heat flow anomalies, particularly those associated with advective fluid movement, provide evidence of ongoing migration and overpressure development (Davies & Clarke 2010; Harris et al. 2017). When integrated with geochemical signatures and overburden structure, thermal data help discriminate between active petroleum systems and background methane fluxes (Orange et al. 2008; Van Rensbergen et al. 2007).

Thermal context is especially important in frontier basins where the timing of generation and migration is uncertain. Elevated heat flow, focused thermal anomalies, and thermogenic geochemical signatures collectively strengthen interpretations of active charge access.

3 Data and Methods

The integrated seep-hunting workflow used in this study combines geomorphology, water-column imaging, geochemistry, heat-flow measurements, and seismic overburden mapping into a unified charge-evaluation framework. The following subsections summarize the operational methods applied to acquire, integrate, and interpret these datasets.

3.1 Multibeam Bathymetry and Backscatter

Multibeam bathymetry (Figure 2a) and acoustic backscatter (Figure 2b) of the seafloor provide the primary spatial framework for identifying seep related geomorphology. High resolution grids and mosaics are used to:

- Map pockmarks, mounds, mud volcanoes, carbonate buildups, and other seep associated features
- Delineate seep provinces and structural or stratigraphic controls
- Prioritize areas for water column imaging and seabed sampling

These datasets establish the initial set of geomorphic targets that guide subsequent phases of the workflow.

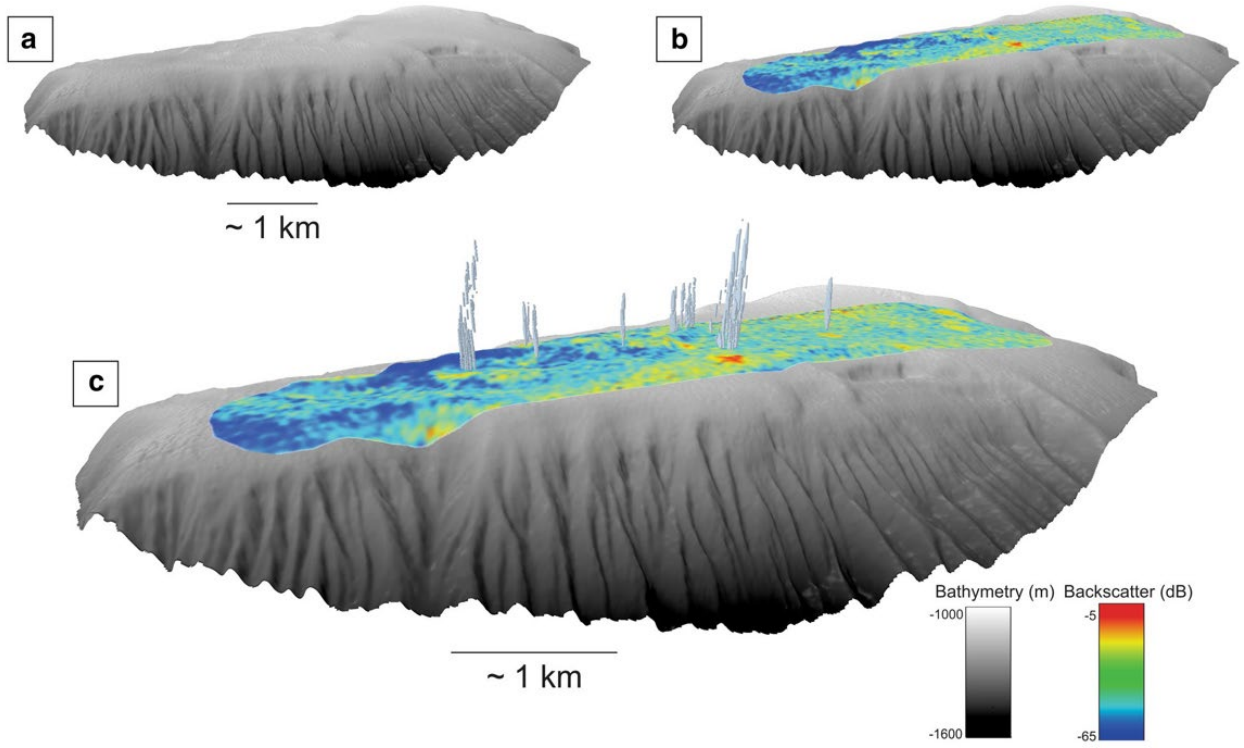

Figure 2. *Image showing how 3 multibeam data types (bathymetry (a), backscatter (b), water column (c)) are integrated to define high confidence candidate areas for targeted sampling (courtesy of Fugro).*

3.2 Water Column Imaging

Water-column imaging (Figure 2c) is part of the multibeam data interpretation focusing on anomalies within the water column. It is used to detect active gas plumes and to rank seep intensity. Operational objectives include:

- Locating active expulsion sites
- Distinguishing persistent thermogenic plumes from background biogenic flux

- Refining the selection of coring targets
- Assessing temporal variability where repeat lines are available

Plume detections are integrated with multibeam geomorphology to focus sampling on the most active and geochemically promising sites.

3.3 Piston Coring and Geochemical Analysis

Targeted piston cores are acquired at geomorphic and plume-supported locations to recover sediments, gases, and pore fluids for laboratory analysis. Figure 3 illustrates a targeted coring plan.

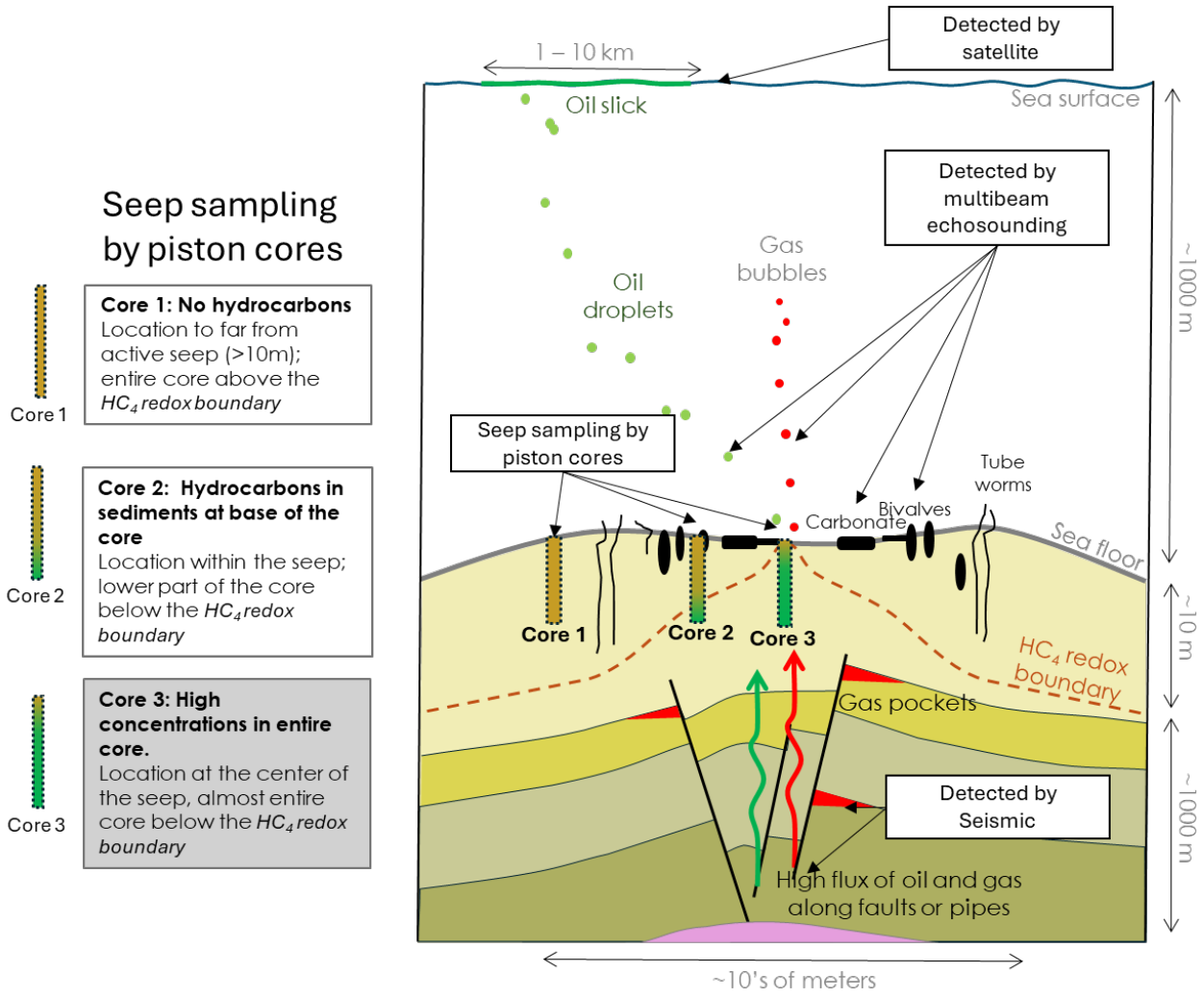

Figure 3. *Cartoon of an active oil and gas seep. The acoustic anomalies at the seafloor and in the water column associated to hydrocarbon seepage are easily detectable by multibeam echosounding. Good quality seep samples require focused sampling near the center of the seep and below the HC_4 redox boundary.*

Seeps are categorized based on geophysical characteristics before piston core locations are planned. Once acquired, core sample geochemical workflows may include:

- Gas composition and gas-wetness measurements
- Biomarker and isotopic fingerprinting
- Fluid-family typing and maturity indicators
- Correlation to modeled or known source intervals

These analyses provide definitive evidence of thermogenic hydrocarbons required to validate active charge and migration pathways (Figure 4).

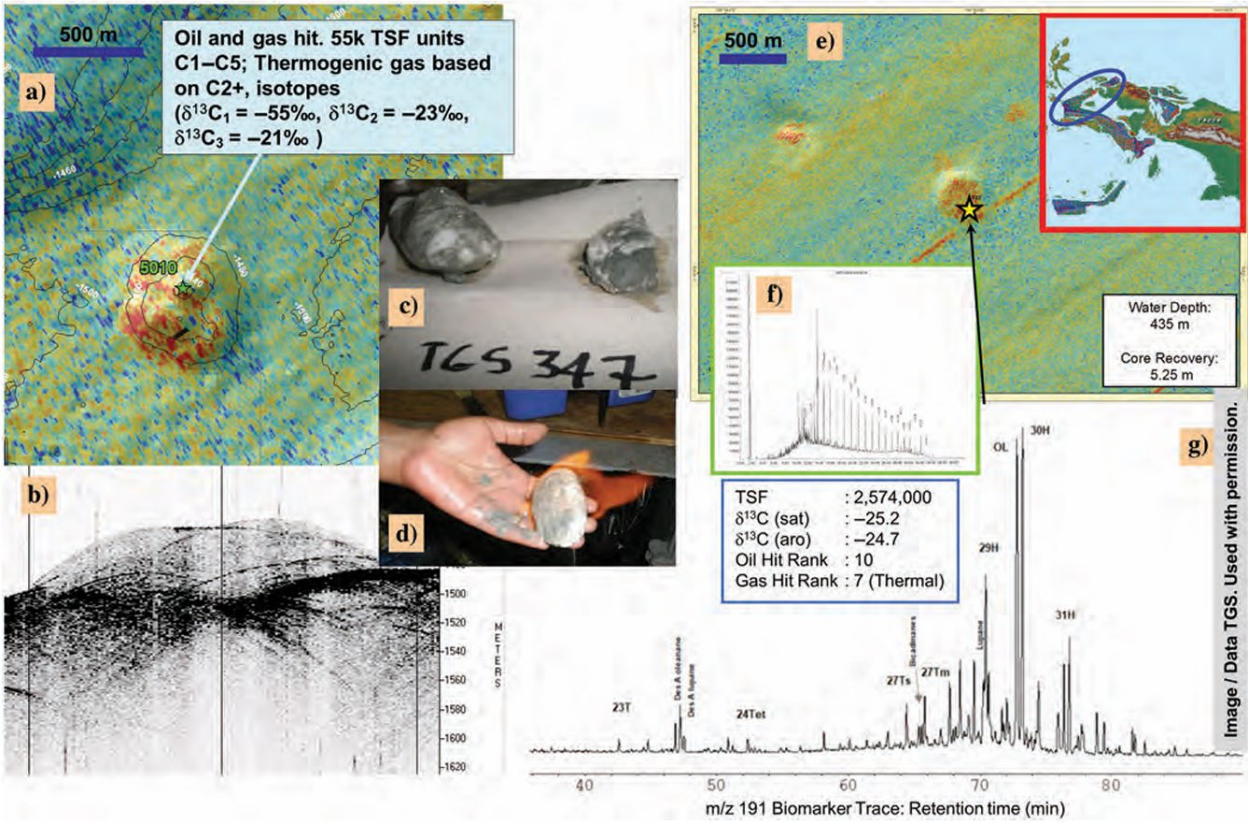

Figure 4. *(a) Moderate to high backscatter irregularly shaped mud volcano in a channel indicates relative geologic youth. This approximately 500 m diameter mud volcano rises 35 m above the channel floor, and (b) SBP data show no internal reflectors. (c) The core, targeting the crest, recovered mud clasts as well as egg-sized clasts of gas hydrate, including from the core catcher. (d) The hydrate ignited indicating that the gas was hydrocarbons (versus pure CO2 hydrate, which would not ignite). (e) Moderate high backscatter mud volcano from the Kofiau area, Misool Strait, Indonesia. (f) The whole extract GC trace indicates the presence of both undegraded (peaks with decreasing height) and degraded (broad hump) oil. (g) Detail of the biomarker trace showing interpreted peaks. Multibeam, SBP, and geochemistry (Reproduced from Orange, D., et al. (2023b)).*

3.4 Heat-Flow Measurements

Heat-flow stations and sediment thermal-property measurements are collected to characterize the local thermal regime and to support interpretations of active versus relict seepage. Operational objectives include:

- Measuring vertical thermal gradients
- Determining sediment conductivity
- Identifying localized thermal anomalies associated with advective flow
- Providing thermal context for geochemical results

Heat-flow data are collocated with coring and geomorphology to strengthen interpretations of ongoing charge access.

3.5 Integrated Petroleum-Systems Analysis

All datasets including geomorphology, plume detections, geochemistry, heat flow, and seismic overburden mapping are synthesized into a unified petroleum-systems interpretation (Figure 1). This integrated analysis is used to:

- Map migration pathways and leakage conduits from available seismic data
- Evaluate charge access and timing
- Assess trap integrity in the context of overburden structure
- Quantify charge risk for prospect ranking
- Provide decision-grade evidence for pre-drill evaluation and farmout narratives

The integration of seabed evidence with seismic interpretation transforms seep hunting from a reconnaissance tool into a rigorous, physics-based workflow for deepwater charge assessment.

4 Regional Context: Published Evidence and Basin-Maturity Framework

Published evidence for seep hunting varies significantly by basin. In some regions, most notably the U.S. Gulf of America/Mexico seepage, subsurface charge, and commercial success are extensively documented in peer-reviewed literature. In others, published data confirm active seepage, but does not yet quantify exploration impact. This section therefore distinguishes between published examples and exploration opportunities, organized by basin maturity.

4.1 Published examples

Gulf of America – offshore USA provides a well-documented analog for frontier settings. Basin-scale multibeam mapping and seabed sampling have identified thousands of seep features

and recovered numerous thermogenic hydrocarbon samples from seeps (MacDonald et al. 1993; Roberts & Carney 1997; Hood et al. 2002). These studies demonstrate that:

- Thermogenic hydrocarbon seepage correlates with mature source intervals and active migration pathways
- Seep clusters align with structural and stratigraphic conduits
- Seeps may occur directly above producing fields without impacting trap integrity (Sassen et al. 2001)
- Modern multibeam and geochemistry datasets refining migration pathways (Decker et al. 2022; Orange et al. 2023)

Kwanza and Lower Congo Basin - offshore Angola have been heartlands for petroleum production offshore Africa since the discovery of the Girasol field in 1996. Serie et al (2015) published an integrated study involving integrated analysis of 3D seismic, seabed geochemistry, and satellite-based surface slick data from the deep-water Kwanza Basin. They document:

- The widespread occurrence of past and present fluid flow associated with dewatering processes and hydrocarbon migration
- Differentiate dewatering features from biogenic gas seeps and thermogenic hydrocarbon seeps
- Evidence from seep samples for the presence of a mature petroleum source rock from post-salt marine origin, which corresponds to the nature of the producing fields.

This published evidence shows how seep hunting can rapidly establish the presence of an active petroleum system in areas with limited well control. It demonstrates that seepage reflects effective charge access rather than trap failure and provides a robust analog for other new exploration basins.

4.2 Opportunities in Frontier basins - Establishing First-Order Charge Presence

Frontier basins lack well control and often have untested petroleum systems. In these settings, seep hunting provides the earliest empirical evidence of active charge.

- **Venezuela - Trinidad - Barbados Ultra-Deepwater**

  A high-potential but underexplored frontier basin (Figure 5). Published slick-detection studies (Garcia et al. 2020) and regional petroleum-system analyses (Galeota et al. 2019) confirm active hydrocarbon migration along the slope and basin floor. The structural transition between the Caribbean accretionary prism and the South American passive margin creates numerous potential leakage pathways. Although no basin-scale multibeam or coring survey

has been published, the geological context strongly favors thermogenic seepage, making the region an ideal candidate for seep-supported charge validation.

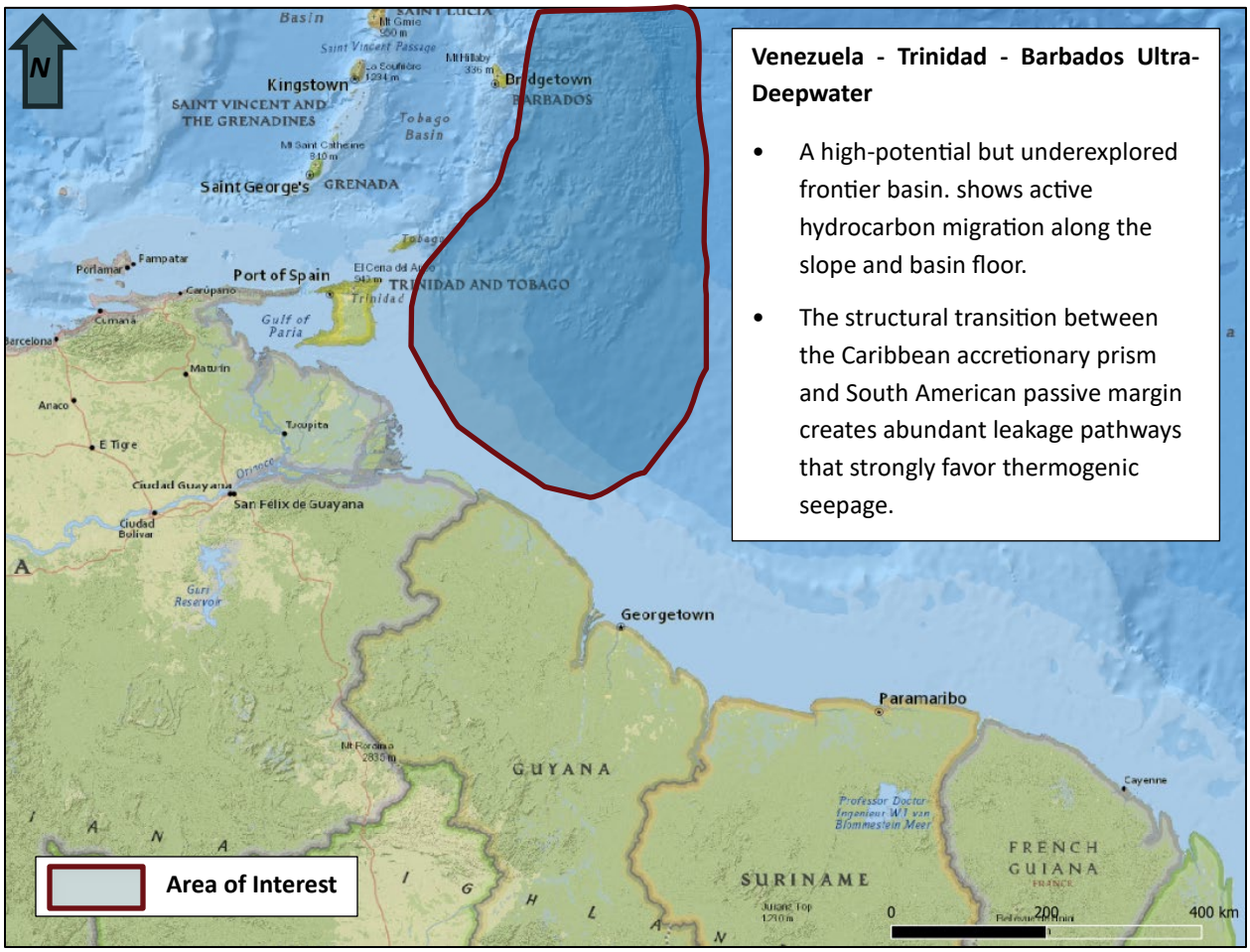

Figure 5. *Venezuela - Trinidad - Barbados Ultra-Deepwater Seep Hunting Opportunities*

- **Eastern Gulf of America (U.S. & Cuba Sectors)**

  Remains largely unexplored due to regulatory constraints, yet the petroleum-system fundamentals mirror the central and western Gulf where seepage is prolific. Seep hunting could provide early confirmation of charge access in this under-sampled region (Figure 6).

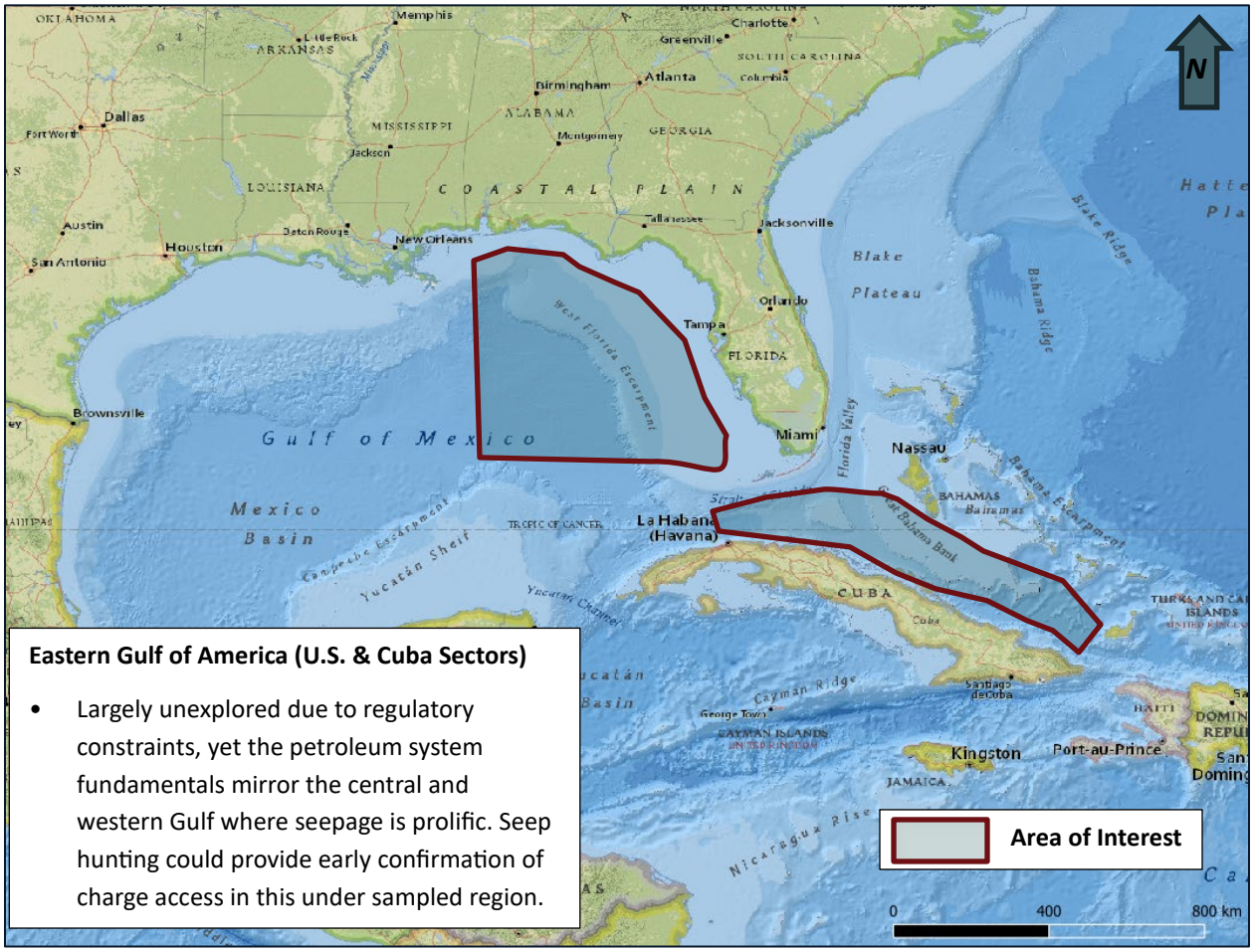

Figure 6. *Eastern Gulf of America (U.S. & Cuba Sectors) Seep Hunting Opportunities*

- **Deepwater Brazil (Pelotas, Potiguar to Foz do Amazonas basins**)

  The conjugate margin to West Africa prolific petroleum systems but vastly underexplored (Figure 7). Seep hunting can quickly test the presence of a prolific mature petroleum system along the margin.

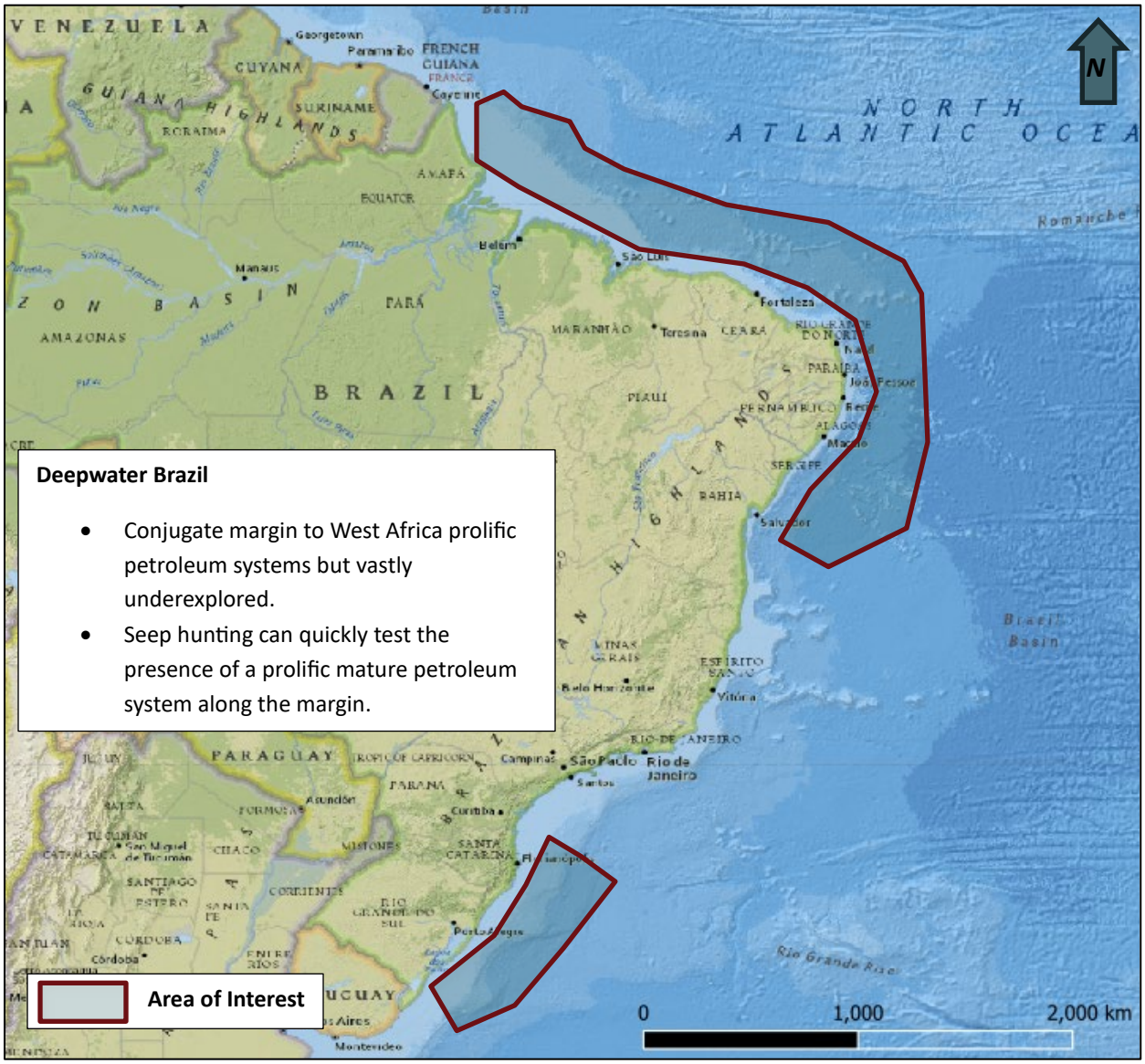

Figure 7. *Deepwater Brazil Seep Hunting Opportunities*

4.3 Opportunities in Emerging Basins - Validating Early Charge Models and Migration Pathways

Emerging basins (Figure 8) have initial discoveries or promising seismic indicators but still face uncertainty around charge access and migration efficiency. Seep hunting can rapidly characterize the type and the extent of the petroleum system to accelerate exploration activity.

- **Guyana - Suriname Margin** is an emerging prolific petroleum system that keeps generating new discoveries. The full extent and the lateral variability of the petroleum system along the margin is not known. ExxonMobil technical releases confirm positive geochemical results from targeted coring and possible seepage areas and migration features have been documented on the Demerara plateau as well as towards the Barbados accretionary prism.
- **Orange Basin - offshore Namibia** has been an focus area for exploration since the Graff and Venus discoveries in 2022, with billion-dollar investments in wells and 3D seismic. Numerous plays and source rocks seem to co-exist but the petroleum systems remain poorly understood (Sorkhabi 2025). 3D seismic interpretation indicates numerous migration paths and possible seeps.
- **Liberia - Sierra Leone - Ghana** margin remains underexplored, and while no basin-scale seep surveys have been published, the structural and stratigraphic framework is favorable for long-distance migration. Seep hunting offers a low-cost, high-impact method to determine whether deepwater charge is active before committing to large seismic programs or early drilling.

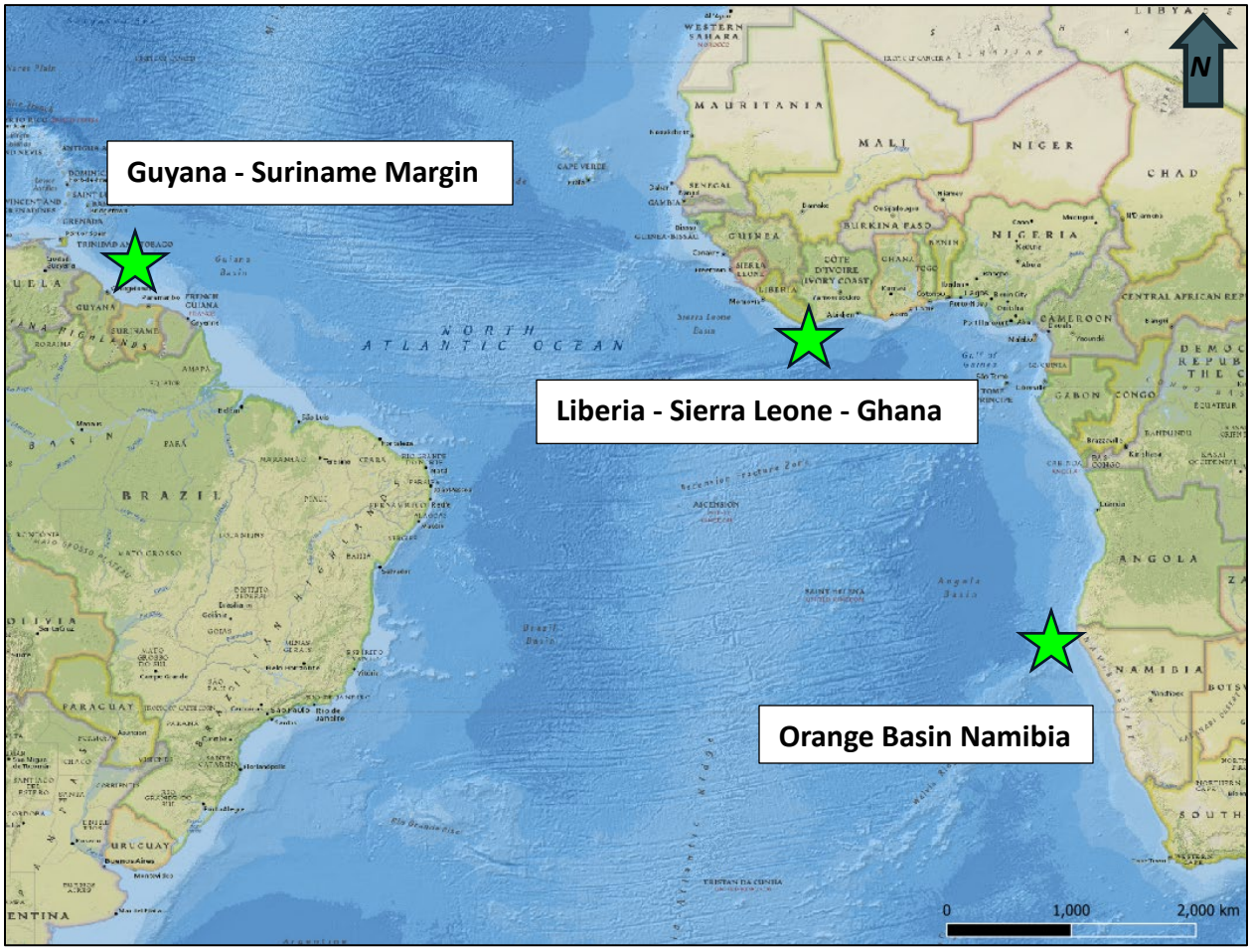

Figure 8. *Emerging Basins Opportunities Map - Emerging basins have initial discoveries or promising seismic indicators but still face uncertainty around charge access and migration efficiency. Seep hunting can rapidly characterize the type and the extent of the petroleum system to accelerate exploration activity.*

4.4 Opportunities in Heartland Basins - Refining Charge Models and Boosting Declining Production in Mature Petroleum Provinces

Mature basins require new discoveries to maintain petroleum production. Seep hunting can help by trap-scale charge prediction for higher risks traps; and by finding additional petroleum systems in deeper water or deeper stratigraphy.

- **Deepwater Delta Systems: Niger delta, Nile delta, Baram delta** Deepwater extensions of deltaic petroleum systems, such as Egypt, the Niger Delta, and Brunei contain proven source kitchens that extend into deeper water where well control is sparse. Published seep-mapping in these regions is limited, but the geological context makes them strong candidates for seep-supported charge calibration.
- **Pre-salt systems in salt basins: Angola, Gulf of America**. Initial petroleum production in salt basins often is post-salt as the pre-salt systems are difficult and expensive to image and to

drill. Focused seep hunting can provide evidence of working pre-salt petroleum systems. An example is the Campos and Santos basin offshore Brazil where known seeps document pre-salt petroleum systems.

- **Biogenic gas provinces overlying thermogenic petroleum systems: offshore Columbia, Deepwater Trinidad.** Biogenic gas provinces often occur together with deeper thermogenic systems, e.g offshore Trinidad, Niger delta, Egypt. Drilling results often only target biogenic gas reservoirs, but seeps have a different plumbing system and can provide evidence of an additional thermogenic petroleum system that has not been recognized in standard exploration results.

5 Implications for Deepwater Exploration and Charge-Risk Reduction

The integration of seep hunting into deepwater exploration workflows has material implications for both technical decision-making and commercial outcomes. Across basin types (frontier, emerging, and heartland) the published evidence demonstrates that seabed seepage provides direct, empirical confirmation of active petroleum systems and improves the reliability of charge assessment in ways that seismic data alone cannot. These implications fall into three primary domains: Technical Implications; Portfolio Implications; and Commercial Implications.

5.1 Technical Implications: Reducing Charge Uncertainty Across Basin Maturity Levels

The physics-based foundation outlined in Section 2 and the published regional evidence summarized in Section 4 collectively show that seep hunting provides a unique form of information: direct observation of active hydrocarbon migration. This has several technical consequences:

- **Frontier basins:** Seep hunting can determine whether a petroleum system is active before large seismic investments or early exploration wells, reducing the probability of committing capital to basins with no charge access.
- **Emerging basins:** Thermogenic seepage provides independent calibration of early migration models, improving pre-drill predictions of charge access and fluid phase.
- **Heartland basins:** In mature settings, seep hunting refines trap-scale charge models, but can also help to boost declining production through finding additional petroleum systems overlooked in the traditional exploration results

In all cases, seep hunting reduces reliance on indirect indicators and strengthens the geological basis for prospect evaluation.

5.2 Portfolio Implications: Improving Prospect Ranking and Capital Allocation

Charge risk remains one of the largest contributors to dry holes in deepwater exploration. By providing direct evidence of active petroleum systems, seep hunting improves the fidelity of prospect ranking and portfolio optimization:

- Prospects supported by thermogenic seepage move upward in ranking due to reduced charge uncertainty.
- Prospects in areas with no seepage should not be downgraded solely on that basis; however, when the absence of seepage coincides with a dearth of structural or stratigraphic migration pathways, the combined evidence can justify deprioritizing those locations early in the portfolio cycle.
- Basin-scale seep maps help identify migration fairways and charge shadows, enabling more accurate play-level risk assessments.

These improvements translate into more efficient capital allocation, fewer high-risk wells, and a more resilient exploration portfolio.

5.3 Commercial Implications: Enhancing Internal and External Prospect Narratives

In capital-disciplined environments, exploration managers must justify drilling decisions to internal stakeholders and potential farm-in partners. Seep-supported charge confirmation strengthens these narratives in several ways:

- Physical evidence of charge is more compelling than model-based predictions alone.
- Published analogs, particularly from the U.S. Gulf of America, provide a credible scientific foundation for seep-supported workflows.
- Thermogenic geochemical signatures offer a level of specificity (fluid family, maturity, source correlation) that directly supports valuation and farmout discussions.
- Basin-scale seep datasets demonstrate that the exploration team has reduced uncertainty using all available empirical tools.

As a result, prospects supported by seep data are easier to defend, more attractive to partners, and more likely to advance through internal gatekeeping processes.

5.4 Summary of Strategic Implications: A Conservative Enhancement to Standard Workflows

A recurring barrier to adoption is the perception that seep hunting is “non-standard” or operationally disruptive. The evidence presented in this paper demonstrates the opposite:

- Seep hunting does not replace seismic interpretation; it strengthens it.
- It is a conservative, data-rich enhancement to existing workflows, not a departure from them.

- It aligns with the industry's increasing emphasis on empirical validation, risk reduction, and capital discipline.
- It provides decision-grade evidence at a fraction of the cost of a deepwater exploration well.
- The presence of seepage does not indicate a failed trap; seepage commonly overlies productive reservoirs and reflects active migration rather than trap breach.

In this context, the question for exploration teams is not whether seep hunting is innovative, but whether continuing to rely on incomplete information is defensible.

6 Conclusions

6.1 Overall Implication: A Scalable, Physics-Based Method for Reducing Dry Holes

Across basin types, seep hunting consistently improves the quality of charge assessment by providing direct evidence of active petroleum systems. Published examples, from the U.S. Gulf of America/Mexico, and Angola Kwanza Basin demonstrate that seepage correlates with mature source intervals, active migration pathways, and, in many cases, producing reservoirs.

While the magnitude of impact varies by basin maturity, the underlying implication is consistent:

Seep hunting is a scalable, physics-based method that reduces charge uncertainty and materially lowers the probability of dry holes in deepwater exploration.

This makes it not only a technical enhancement but a strategic tool for improving exploration performance.

Across basin-maturity levels, the implications are consistent:

- **Frontier basins:** Seep hunting establishes whether a petroleum system is active before major capital is committed.
- **Emerging basins:** Thermogenic seepage validates early charge models and reduces uncertainty in areas with limited well control.
- **Heartland basins:** Seep hunting refines trap-scale charge predictions, supports deepwater extensions of proven plays, or can help in the discovery of additional petroleum systems to boost declining production

These outcomes directly address one of the most persistent sources of dry holes in deepwater exploration: uncertainty in charge access. By providing direct evidence of active migration, seep hunting improves prospect ranking, strengthens portfolio decisions, and enhances the commercial defensibility of exploration programs. Importantly, seep hunting does not replace seismic interpretation; it reinforces it by adding empirical constraints where seismic data are inherently indirect.

In an era of heightened capital discipline and increasing scrutiny of exploration decisions, integrated seep-and-seismic workflows represent a conservative, data-rich enhancement to standard practice. They reduce uncertainty, improve decision quality, and provide exploration managers with a more defensible basis for advancing prospects. The question is no longer whether seep hunting is innovative, but whether exploration programs can justify relying on incomplete information when a proven, scalable method exists to materially reduce charge risk.

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