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Use of multibeam bathymetry and backscatter to improve seabed geochemical surveys — Part 2: Best practices and case studies in seep hunting for exploration, with an emphasis on Indonesia

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Abstract

The successful sampling of seafloor oil and gas seeps can provide information on source rock, migration, maturation, and charge that can impact exploration decisions. Although 3D seismic data can be interpreted for potential seafloor seeps, multibeam can be acquired over larger areas at lower cost and in a shorter turnaround time, with bathymetry, backscatter, and water column imagery leading to the interpretation of potential seafloor seep targets. The use of multibeam-based exploration early in an exploration project can provide information on the petroleum systems in an area and also areas where no evidence of a petroleum system is present on the seafloor. We have developed case studies of block-specific seep hunting and regional multibeam surveys. For regional surveys, multibeam can be combined with 2D seismic data, ultrashort baseline (USBL)-positioned piston coring, heat flow, high-resolution subbottom profiles, marine gravity and magnetics, and core geochemistry to evaluate exploration potential. The first multibeam-for-exploration survey, with cores acquired for geochemistry, was carried out in 2000 offshore Barbados. Applying a tool used in academia and other industry projects, USBL positioning in real-time in a Geographical Information System (GIS) environment was used to confidently place a core barrel on a seafloor seep target beginning in 2002. In 2003, Unocal acquired the first basin-wide multibeam survey for exploration and demonstrated that multibeam can rapidly interrogate a very large area at a relatively modest cost. Indonesia basin- and regional-scale projects demonstrated the value of multibeam-based exploration through the successful farm-out of exploration blocks with a promotion (in which the farm-in-ee(s) pays a higher percentage of costs than their percentage of equity). We review several examples of seep studies, with an emphasis on Indonesia; target selection philosophy, criteria, and ranking; and target types. Mud volcano and hard substrate sampling can provide information on the subsurface without drilling.

Introduction

In part 1 of this pair of papers (Orange et al., 2023), we review the history of seep science and discuss how a seabed "cold seep" community composed of bivalves and other organisms, authigenic carbonate, and possibly gas hydrate can affect the shape of the seafloor and its acoustic properties. We review the history of multibeam and show how multibeam backscatter can be used to identify potential seep targets either on the seafloor or buried in the shallow subsurface within the reach of a core barrel. One of the significant advantages of multibeam backscatter is that it is quantitative (expressed in units of decibels which is a log scale) where the receive strength is corrected for attenuation, spherical spreading, angle of insonification, etc. We use geographical information system (GIS) to display backscatter with a statistical color palette, with red 2.5 standard deviations above the mean, and blue 2.5 standard deviations below the mean (corresponding to higher and lower than 99.38% of the pixels). Seepage also can lead to water column anomalies (WCAs) that can be imaged by a hull-mounted multibeam system during a survey.

Other geophysical systems and platforms such as towed side scans, remote operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) can be used to survey for seep targets and acquire samples. Deep-towed side scan has a much narrower survey swath width than hull-mounted multibeam, with positional ambiguity due to the challenges of ultrashort baseline (USBL) positioning at low angles and large lay-back distances (USBL uses a ship-mounted transducer and a transponder on the towfish to determine the angle between them and the slant range). AUVs and ROVs can resolve smaller seep targets but cost significantly more

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per day to survey much smaller areas. Hull-mounted multibeam systems can survey a much larger area in a given amount of time than towed packages, ROVs, or AUVs. Over-the-side piston coring can interrogate a much larger area per day much more quickly than ROVs; both can use USBL positioning for precise sampling. In this paper, we will discuss seep hunting with hull-mounted multibeam echosounder (MBES) bathymetry and backscatter as well as 3D seismic data, with USBL-positioned piston cores to interrogate targets. In the predifferential global positioning system (GPS) studies discussed in this paper, commercial satellite navigation systems such as C-Nav (C&C Technologies) and STARFIX (Fugro) were used to improve the positional accuracy, such that the positional uncertainty was smaller than the bathymetric bin size (e.g., 5 m for STARFIX; Dennis, 1987).

Our suggestions and recommendations regarding multibeam seep hunting best practices are based on more than 3 million km^2 of seafloor surveyed, more than 5000 cores acquired and analyzed for geochemistry, and more than 13,000 geochemical analyses; the surveys also include more than 500 heat flow stations and more than 200 Jumbo piston cores (JPCs, with a 20 m core barrel). In each of our projects, the actual geochemical results (successes and failures) have informed subsequent mapping and core target selection programs. We have learned that similar target types behave similarly in the same basin but may behave differently in different basins. In our experience, “best practices” include intentionally locating 5%–10% of the cores on what are interpreted to be “background” features to demonstrate the evidence of absence and to establish a geochemical baseline to better distinguish an anomaly; note that these cores can target geologic features of interest (basin floor fans, mass transport deposits [MTDs], etc.) or may be acquired at heat flow locations to confirm penetrability before deploying the more sensitive (and expensive) heat flow probe. We also favor acquiring 5–10% of the cores in near-offset locations close to the first core to document repeatability or local variance.

We define “success” with coring for geochemistry as a core that yields sufficient oil or gas to unambiguously show their presence.

The projects discussed in this paper include Ghana, Barbados, the Gulf of Mexico (GOM) (USA and Mexican waters), and Indonesia. Seepage is driven by some combination of buoyancy and overpressure. Overpressure can be driven by active plate convergence and accretion or fold-and-thrust belt contraction and also can be driven by rapid sediment accumulation. Barbados and parts of Indonesia are characterized by accretion, whereas parts of the GOM and Indonesia have and have had rapid sediment accumulation. Barbados and Indonesia also have known mud volcanoes (Barbados: on land, Larue and Speed [1984]; offshore, Westbrook and Smith [1983]; Indonesia: on land, Williams et al. [1984] and Barber et al. [1986]; offshore, with mud volcanoes indicating overpressure, Silver et al. [1986]). All of these processes facilitate fluid seepage.

Prior to Indonesia Megasurvey I (IMS-I), many areas offshore had been offered up for exploration yet had received no bids because they were in basins with no previous wells and no known hydrocarbon system (bids at the time required an exploration well and the risk with no known petroleum system was too high to warrant the expense). Furthermore, much of the area surveyed in IMS-I and IMS-II is not characterized by accretion, contraction, or a high sediment accumulation rate. Multibeam was used to identify potential seafloor seep targets in every area surveyed for sampling with the core barrel — the geochemistry of the recovered material showed which areas had an active petroleum system, and, conversely, which did not. The scale of IMS-I (446,141 km^2 and 1321 attempted cores) and IMS-II (505,385 km^2 and 324 attempted cores) guaranteed that hydrocarbon seeps would be successfully identified and sampled in these projects but not that hydrocarbons would be sampled everywhere.

Even in basins with known hydrocarbon seepage, multibeam and USBL-positioned cores significantly improve geochemical success. Multiclient seep hunting programs in the USA and Northern Mexico GOM that used 2D and 3D seismic data to identify seep targets, and piston cores but no USBL positioning, had unambiguous oil in 113 of 3317 cores (3.4%) and proprietary seep hunting programs in the GOM that used 2D and 3D seismic data had confirmed oil in 61 of 1744 cores (3.5%). The GOM multiclient programs that used seismic data to identify targets had 450 of 3317 cores (13.6%) with thermogenic gas or mixed thermogenic and biogenic gas and the GOM proprietary programs recovered thermogenic or mixed thermogenic-biogenic gas in 117 of 1744 cores (6.7%). A multiclient multibeam and piston coring program in the same areas of the GOM recovered unambiguous oil in 124 of 305 cores (40.6%) and thermogenic or mixed thermogenic-biogenic gas in 129 of 305 cores (42.3%). We attribute the significant improvement in geochemical success in the multibeam-guided coring program to the high quality and resolvability of the multibeam, backscatter pixels much smaller than seismic amplitude bin size, the fact that multibeam backscatter insonifies a similar depth via volumetric scatter as the piston core can sample (Orange et al., 2023), and the quality USBL positioning of the cores with an accuracy smaller than the multibeam bathymetric bin size.

In part 1 of this pair of papers, we discussed how multibeam and 3D seismic data can image a possible seafloor target. In Part 2 we discuss best practices and case studies in seep hunting with multibeam and 3D seismic to improve geochemical results and exploration impact. Once the seafloor (and water column) data are interpreted for potential seep targets, the next step is to sample those targets for geochemical analysis.

Seep hunting and USBL positioning of piston cores

Identifying a potential seafloor seep target is one thing, but confidently and successfully sampling it is another. In this section, we will discuss the positioning of sampling equipment in the water column and the seafloor, and we illustrate this approach to seep hunting programs using 3D multichannel seismic data and multibeam. For the first case study, we will focus on Devon's project in the Keta block offshore Ghana. Keta, and all of the other projects discussed in this paper, used piston cores for seafloor sampling. The coring vessel typically acquires a 1 km subbottom profiling (SBP) line over each target prior to deploying the coring rig, and the at-sea team has the authority to adjust the target location based on the SBP data (e.g., to sample diffraction or pockmark imaged in the SBP). Piston cores are lowered slowly through the water column (see Orange et al., 2009, Figure 4) first to approximately 50 m above the seafloor, and, if on target, lowered further to within 1–3 m of the seafloor. The core is lowered the last few meters with the weight triggering the release of the core barrel which then free falls to the seafloor (Bouma, 1969; Woods Hole Oceanographic Institution, 2022). The piston stops when the piston wire goes taught at or just before reaching the seafloor, with the core descending down into the seabed and the stationary piston remaining at the seabed and preventing back pressure. We favor piston cores because of the ability to adjust the position and lower to the target in a controlled fashion, more complete recovery, and less disturbed sediment (Weaver and Schultheiss, 1990), as well as for recovery equal to or greater than a gravity core or a Kasten core (a gravity core assembled of square steel barrels). Piston cores, as opposed to box cores or ROV-deployed push cores, due to their deeper recovery, have a higher probability of sampling below the redox boundary where any hydrocarbons recovered would be less oxidized and less biodegraded (e.g., Orange et al., 2023, their Figure 13). JPCs can be deployed where the objective is much deeper penetration and recovery (several tens of meters; e.g., Szérémέta et al., 2004). Box cores are deployed when the objective is a large volume (0.125–1 m^3) of sediment and near-seafloor material, for example, to recover chemosynthetic fauna. In 2002, Devon funded a project using their existing exploration 3D seismic data over a portion of the Keta block offshore Ghana to identify seafloor seep targets (Figure 1; AOA Geophysics Inc. provided interpretive and client representation services for this project). Both 3D seismic data and multibeam provide information on the shape and acoustic properties of the seafloor (see Orange et al., 2023, this volume for a discussion of the 2 techniques as applied to seep hunting). Seismic data from Keta show the surface expression of pockmarks centered on the tops of ridges oriented downslope (Figure 1a) with interpreted gas chimneys in the subsurface (Figure 1b) that project to the pockmarks; note the integer values of bathymetry from the seismic data yield a "wood grain" texture on the seafloor (Figure 1c). Seafloor extractions of seismic amplitude suggest that numerous pockmarks are characterized by high seismic amplitude, indicating high impedance contrast (Figure 1d; impedance is the product of density and velocity). A ridgetop pockmark with high seismic amplitude within its base (Figure 1d) was targeted for coring (core 50), with a USBL beacon attached to the wire above the core weight (Figure 2c). The first attempt at this location, which USBL positioning data indicate entered the seafloor 5 m from the target in high amplitude, had 1.2 m of mud on the outside of the core liner, a "significantly bent core barrel (Figure 1e) and 30 cm of authigenic carbonate (Figure 1h) and various bivalves of known chemosynthetic affinity (*Solemya* sp., *Mytilid* sp., Figure 1g and 1h and *Calyptogena* sp., Figure 1f)" and a slight petroliferous odor ("kerosene-like"). A second attempt at this target was made, aiming for moderate amplitude approximately 100 m north of the original target (core 50a), yielded 3.8 m of recovery, with "extensive gas parting, distributed authigenic carbonate, and very strong sulfide smell" (Figure 1j).

This project is notable because it is the first industry project of which we are aware of the piston core being tracked through the water column in real-time in a project GIS by USBL positioning (Figure 2); academic institutions used USBL and long baseline (LBL) positioning as far back as the 1970s (Mayer, 1979; E. Franks, personal communication, 2021) and Exxon used LBL positioning for core tracking for geologic and geochemical surveys starting in the 1980s (M. Abrams, personal communication, 2021). Academic projects would identify the latitude and longitude of a feature of interest on bathymetric maps or subbottom profiler data, and then target that location with ROVs or gravity/piston cores via USBL and on-screen guides, tracking the vehicle/core to the target relative to the ship's position in real-time (T. Alves, personal communication, 2022). The idea of tracking the position of something through the ocean in x, y, and z in a GIS in real-time was first proposed at Monterey Bay Aquarium Research Institute (MBARI) in 1995. MBARI declined to fund this project, and so in 1996, with U.S. Navy's Office of Naval Research (ONR) support, MBARI technicians Norman Maher and Gerry Hatcher developed a technique in which the ROV position (in latitude — longitude — depth) was broadcast over a serial cable to a laptop running the project GIS. The ROVs position was logged to a shape file, with the position of the Jason ROV displayed in real-time in the Mariana Forearc with the vehicle track, multibeam bathymetry, and SeaMARC backscatter all shown on the same screen. The ROV pilots eventually came to rely on the real-time GIS to guide the ROV and its clump weight during operations, where the GIS provided the scientists and the pilots with a common reference for communicating dive objectives and options.

For Devon's Keta project, the location of the core (latitude, longitude, and depth) and the vessel (latitude and longitude) were broadcast over the ship's network and viewed and logged in real-time in the GIS project. The vessel's positional accuracy, <5 m, with GPS enhanced by a commercial satellite positioning service, was smaller than the bathymetric bin size (Dennis, 1987). Each core target had a bull's eye surrounding it with 5 m spacing between rings with the vessel and core location and track shown (Figure 2a). Furthermore, the core's position in space was tracked in real-time in a project GIS that included the seafloor bathymetry and amplitude (Figures 1d and 2b) from the 3D seismic seafloor extraction (5 m pixel) to insure that the core barrel interrogated the seafloor target of interest. The deck crew stopped the winch paying out the cable when the core was 50 m above the seafloor; the onboard client representative would give the go-ahead to lower the core when they were confident it was on target. Once the core went in, the winch operator would pay out slack, and the navigator would log 10 good in-bottom positions which typically took approximately 3 min but sometimes took several minutes longer. The small scatter of the in-bottom positions (<5 m; Figure 2a), and the vessel navigation precision <5 m, provide confidence that the core barrel sampled the target of interest (note that the geometry of coring, with the core barrel descending steeply below the vessel, minimizes positional errors due to sound speed velocity/refraction).

The project acquired 52 cores in water depths of 1050–2410 m; seven cores recovered chemosynthetic fauna (13.5%; Figure 1f and 1g) and numerous cores recovered authigenic carbonate (Figure 1h) and showed gas parting (Figure 1j). The goal of the sampling was for sediment to be analyzed for the presence of oil and gas. The recovery of chemosynthetic fauna and authigenic carbonate provides evidence of the cause of the high impedance and direct evidence of seepage and gas (where authigenic carbonate results from the oxidation of methane).

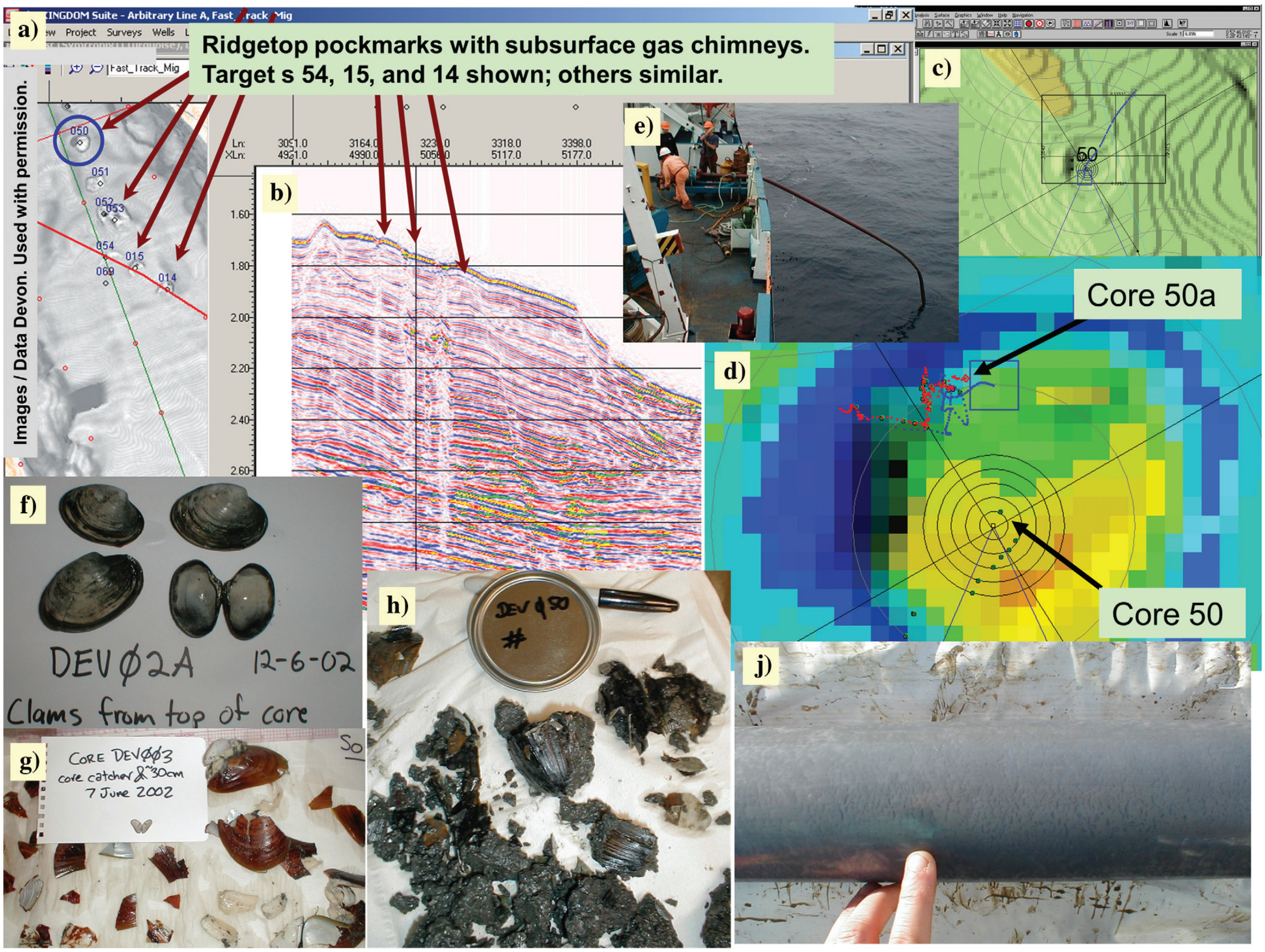
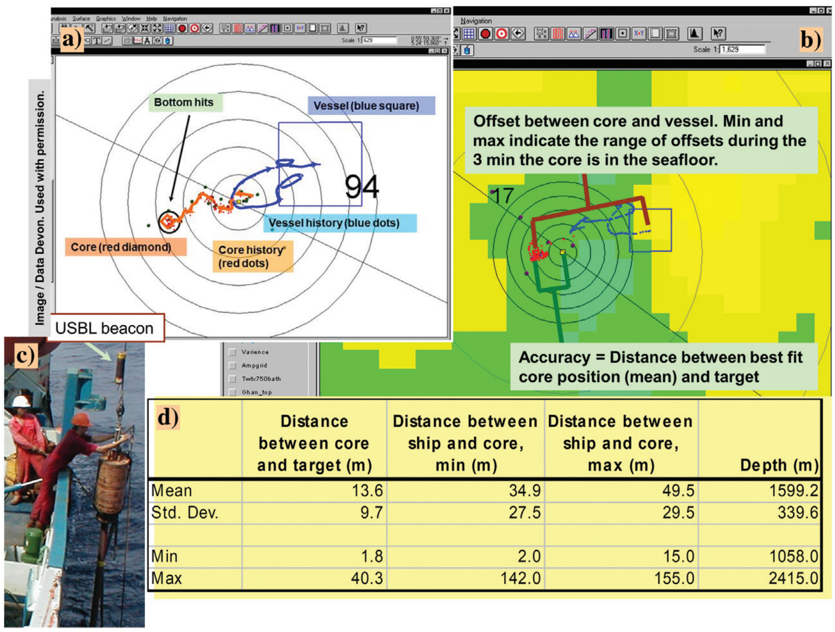


Figure 1. Exploration 3D seismic data over the Keta block, offshore Ghana, showed (b) subsurface gas chimneys projecting to (a) seafloor pockmarks on the centers of ridgetops (ridges oriented downslope; the map view image is approximately 2 km across). (c) Seafloor extraction converted to bathymetry, where the integer format of bathymetry resulted in a "wood-grain" texture. (d) Seismic amplitude (warmer colors = higher amplitude), draped on shaded-relief bathymetry showed that pockmarks were associated with high amplitude seafloor. Core 50 targeted the high-amplitude center of a pockmark (yellow to orange) and resulted in a (e) bent core barrel that yielded (h) 30 cm of authigenic carbonate and chemosynthetic shell hash; other cores in the program recovered (f) *Calyptogena* sp. chemosynthetic clams and (g) *Mytilid* sp. mussels. A second attempt at target 50, adjusted approximately 100 m north to low-to-moderate backscatter on the pockmark rim, (d) 50a, yielded (j) 3.8 m of recovery with extensive gas parting, authigenic carbonate, and a strong sulfide smell. Multibeam and coring data acquired by Devon, shown with permission.

Because the objective was sediment for geochemical analysis and chemosynthetic communities were not expected, video-guided grab sampling, which might be used for sampling chemosynthetic fauna, was not available. The ability to track the core through the water column and, more importantly, to know its location in the seafloor in the context of the bathymetry and seismic amplitude in real-time, gave the at-sea team confidence that they had interrogated each target. The core was allowed to remain in the seabed for a minimum of 3 min in order for the USBL beacon to settle and provide several quality fixes; the mean and standard deviation of each in-bottom position was determined, with the minimum distance of the vessel to the core, and the maximum distance, logged. Each in-bottom position was then evaluated for accuracy (the distance between the core and the target) and offset (the distance between the core and the vessel; Figure 2d). The core accuracy, the mean distance between the core and its intended target, was 13.6 m (0.85% of the mean water depth of 1599 m; the contractual obligation was 25 m; Figure 2d), with a standard deviation of 9.7 m (the high-amplitude targets were typically >50 m in diameter [e.g., Figure 1d], so this accuracy was acceptable, whereas greater accuracy would have required more time, and thus more money). The mean distance between the core on the seafloor and the ship (the offset) was 42 m, with a standard deviation of 28 m — the maximum distance of the core on the seafloor from the ship was 142 m; clearly, the core does not go "straight down" from the vessel! The mean position of the core in the seafloor 42 m from the vessel in 1599 m (Figure 2d) equals a take-off angle of 1.5° from straight down, minimizing the positional distortion due to refraction in the water column due to variations in sound velocity.

In 2003, Unocal contracted the first multibeam seep hunting program to use USBL positioning of piston cores to sample interpreted seafloor hydrocarbon seeps (Decker et al., 2004a); AOA Geophysics Inc. provided technical specification, client representation, and interpretive services for this project using Gardline and their EM120 12 kHz and USBL equipped vessel "*Ocean Endeavour*" for the multibeam, coring, and heat flow operations. The use of USBL allowed precision coring to be within 0.5% of the water depth. The targets identified using MBES are on the order of 10–100 m across, with many target areas extending across 1000 m of the seafloor. Practically, this means that in water depths of 2000 m, a target of 10 m in diameter could be reasonably reliably acquired, whereas targets of 100 m in diameter could be easily acquired at any water depth. At many features, such as faults and fold crests, the anomalous backscatter extends more than 100 m along strike but is only 10–20 m across. The "tolerance" of the actual coring location is therefore different depending on the core location relative to the strike of the anomalous backscatter, with a much larger distance off target allowed along strike than across.

Operationally, the core should be lowered over the side with the vessel directly above the target and oriented into the wind and sea. The winch operator and the bridge should have displays showing the core position in the GIS relative to the target. The bridge can then adjust the vessel's position to move the core barrel at depth if it is going too far off target with regular communication with the winch operator and the at-sea seep team. Because the position of the core relative to the target is important, as opposed to the position of the vessel, deft vessel handling by the captain and mates is far more important than dynamic positioning.



d)	Distance between core and target (m)	Distance between ship and core, min (m)	Distance between ship and core, max (m)	Depth (m)
Mean	13.6	34.9	49.5	1599.2
Std. Dev.	9.7	27.5	29.5	339.6
Min	1.8	2.0	15.0	1058.0
Max	40.3	142.0	155.0	2415.0

Figure 2. Tracking the core through the water column, and into the seafloor, with USBL positioning (the core is tracked back up through the water column during recovery, minimizing the chance for "two-blocking"). (a) Vessel position shown in the blue square, with the track of the vessel positions shown in blue dots. The core position shown in the red diamond, with the track of core positions shown in red dots. The bull's eye is centered on the target, with 5 m rings shown. (b) The vessel and core are tracked in real-time in a project GIS, with the target and seafloor amplitude shown; shaded relief can be shown as well (see Figure 1d); (c) the USBL beacon can be clamped to the wire above the core weight, or attached to the fins of the core weight, depending on the coring contractor's preference; and (d) a minimum of 3 min of USBL positions (10 good fixes) are obtained once the core is in the seafloor, with the mean and standard deviation for each in-bottom fix determined as well as the minimum and maximum distance of the vessel to the core while it is in the bottom. The core's in-bottom distance from the target (accuracy) and the distance to the vessel (offset) can be evaluated for each core. Coring data acquired by Devon, shown with permission.

Mega-survey seep hunting and basin-wide exploration

The Unocal MBES seep survey in 2003 covered three noncontiguous production sharing contract (PSC) blocks in the Makassar Straits, and the results were very successful and game changing in every regard (Decker et al., 2004a). We discuss the Unocal program here because the authors are intimately familiar with it and its impact, whereas we have less visibility of the geochemical results or exploration impact of proprietary surveys acquired by other companies. Key elements of the Unocal program relevant to best practices that were not typically available to exploration teams at the time included:

- Continuous site-survey-resolution bathymetric map of the sea bottom showing accurate surface fold geometries and fault traces imaged using just 2D seismic data.
- Map of all possible oil and gas seeps on the sea bottom greater than approximately 10 m in diameter.
- Backscatter showing the depositional architecture of the basin including submarine fans, channels, lobes, slumps, MTDs, and sediment waves (Decker et al., 2004b).
- Ability to core any seep target seen on MBES data using USBL-positioned piston cores.
- Ability to sample features for geologic studies including sands from depositional features for petrology and detrital zircon dating, muds for biostratigraphy, and paleogeography. JPCs, up to 20 m in length, as opposed to the standard 6 m surface geochemical exploration (SGE) cores, allow interrogation of sediment accumulation rates.
- Ability to acquire heat flow probes cotargeted with jumbo cores to provide basin-scale thermal data critical for basin modeling.
- Acquisition of water column data (velocity, conductivity, temperature, and depth) in many locations and over time to better understand data variability in the survey area.

Multibeam exploration was such a successful tool for reducing risk in offshore exploration in new basins that the Unocal seep team pushed for additional surveys in the region, particularly in open acreage. Unfortunately, collecting proprietary data in open acreage was not allowed by any of the governments in Southeast Asia at that time.

What multibeam-based exploration had in common with regional 2D multichannel seismic data was an ability to interrogate a very large area at a relatively modest cost. In contrast to the regional 2D seismic data, however, multibeam allowed the acquisition of 100% seafloor bathymetry and backscatter for target identification and later sampling. The application of multibeam-based exploration at such a large scale and at a modest cost and accelerated timeline (coring could follow multibeam by days or weeks) is what allowed for rapid value creation in exploration. The ready application of regional multibeam-based exploration at scale (>350 km^2 per day at vessel speeds of 16.7 km/h [9 knots]) and on a quick timeline represents a best practice for evaluating prospectivity in frontier acreage.

In 2003 and 2004, Kerr-McGee acquired a 22,000 km^2 regional survey offshore Northwest Africa including MBES, USBL-positioned piston coring, gravity, magnetics, and 2D multichannel seismic data, all acquired with the same vessel. This project used the "*Fugro Meridian*" equipped with a 30 kHz EM300 1° × 1° multibeam, a 4.5 km towed streamer, and a 3100 in^3 combined generator/injector (GI) and generator (G) gun source. The primary line direction was downslope. Multibeam lines were acquired at 8 knots (15 km/h) at a fixed 2.5 km spacing, and every fourth line (10 km spacing) was acquired at 4 knots (7.5 km/h) with both multibeam and 2D seismic data. Strike lines were acquired at 4 knots (7.5 km/h) with both multibeam and 2D seismic data. Because multichannel seismic acquisition is more sensitive to weather and sea state than multibeam, when the weather came up the vessel was able to acquire the multibeam lines until the weather subsided, at which point the vessel would loop back acquiring all of the multibeam + 2D lines. The survey began in December and was completed by June with less than 9% client-billable downtime. Although the 4.5 km streamer was not long enough for amplitude variation with offset analysis at the depth of interpreted reservoirs, the system provided seismic penetration deep enough to image and interpret leads. Multibeam data and seismic brute stacks were interpreted on the vessel for target selection. Following the demobilization of the streamer and seismic source, the vessel returned to the survey area for USBL-positioned piston coring of seafloor targets.

We favor one USBL-positioned core per target, with an option for a reduced-price (50%) add-on core on a target if the at-sea team is not satisfied with the recovery in the first attempt, or if they want to try again on a different part of the feature. Contractually, this decision has to be made while the vessel is still in the area (typically within 15–30 min of the core recovery) with no additional SBP required over the adjusted target. Other companies prefer multiple cores on each target for their coring (for arguments in favor of multiple cores per target, especially in the absence of USBL positioning, see Dembicki, 2017). USBL positioning adds a minor (<10%) cost to piston coring, with minimal impact on the overall core acquisition rate once the captain and mates are comfortable with tracking the core to the target with USBL.

Best practices in multibeam seep hunting for exploration — Case study: IMS-I

In 2006, following the acquisition of Unocal by Chevron, the Unocal seep team and several of the exploration team left to form a new company, Black Gold Energy (BGE), to use MBES seep surveys and coring to evaluate unexplored frontier basins in Indonesia with a multibeam-based exploration approach. TGS, with BGE providing technical guidance, conducted a 446,141 km^2 multiclient IMS-I in 10 offshore basins in Indonesia; AOA Geophysics Inc., who had provided consulting services to Unocal in the 2003 program, contributed seep hunting expertise (see Orange et al., 2009, Figure 1 for the multibeam survey areas and 2D seismic lines). Because the data were not proprietary to any particular company, it was allowed and even encouraged by the Indonesian government to facilitate further exploration in previously unbid areas. SeaSeep™, the combination of traditional exploration tools (2D seismic data, gravity, and magnetics) with less traditional exploration tools (MBES bathymetry and backscatter, USBL-positioned piston coring, heat flow, high-resolution subbottom profiler, and geochemistry) was used to quickly and inexpensively evaluate unexplored basins. Of the 1182 cores acquired for geochemistry, 566 yielded gas and/or oil (47.9%; Orange et al., 2008). Companies that purchased a license to the multiclient data were able to select, bid on, and acquire the best blocks in the best basins and leverage the successful recovery of hydrocarbons in and around those blocks to farm them out at a promote (wherein the farm-in-ee(s) pay a premium for their participating interest — paying a higher percentage of all costs than they receive {also known as "carried interest"} and paying that same higher percentage of all costs already spent {"sunk costs"}).

The relevance of the Indonesia Megasurvey to best practices in multibeam seep hunting is illustrated by the farm-in companies, as it demonstrates the financial value of successful multibeam seep hunting toward exploration. Most modern oil and gas exploration companies evaluate opportunities through a quantitative risk approach, in which the probabilities of source rock, maturation, migration, charge, reservoir, seal, and all at the right times are evaluated (Rose, 2001). The lower the risk of one or more of these items in an exploration block, the more a company may be willing to pay for an opportunity to explore that block. The successful recovery of sufficient oil and/or thermogenic gas and geochemical analysis from a multibeam-identified seafloor seep target can definitively prove the presence of source rock, maturation, and migration, and it can thus materially reduce exploration risk; geochemical success cannot prove an economic oil and/or gas field resides at depth, only the presence of these components of a petroleum system. Because successful recovery of hydrocarbons reduces risk, companies may be willing to pay a larger percentage of the exploration costs (including already spent sunk costs) than they receive. As an example, a company might farm-in to an exploration block by agreeing to pay 90% of all sunk and future costs to receive 50% of the proceeds from any future production. The original block holder could then farm out another portion of their remaining stake in the block at a promotion, for example, selling 25% to a company willing to pay 40%, to be completely carried (e.g., all sunk costs and costs going forward covered by the farm-in-ee companies). Not only does multibeam-based exploration materially reduce exploration risk but also it can do so in a very short timeframe (months) due to the rapid turnaround of multibeam acquisition through target identification, coring, and geochemistry. Companies also can use the multibeam for geohazard analysis and preselect anchor locations for a drilling rig. In a successful case, the multibeam data can be used to identify viable pipeline and flowline routes ahead of a site survey. Therefore, multibeam data are useful over the life of an exploration and development project (a feature one major oil company refers to as "life-of-field").

Companies use multibeam-based exploration to prove whether a petroleum system exists, even if it does not fit their preconceived ideas. Parts of eastern Indonesia in the Indonesia Megasurveys, and the ultradeepwater GOM, were viewed as nonprospective due to their being interpreted as oceanic crust with a lack of source rocks. The successful recovery of oil and gas in these previously written-off areas in both projects definitively proves that these preconceived notions were incorrect, and multiple major and supermajor oil companies subsequently farmed into exploration blocks.

Multibeam data are interpreted within typically a month of the completion of each multibeam leg, with potential seep targets identified and prioritized. Targets are cored with USBL-positioned cores. Once on deck, the core liner is extracted for visual inspection for any features potentially related to hydrocarbon seepage (gas hydrate, gas parting, oil staining, and chemosynthetic fauna; we recommend using clear core liners which allow inspection; see Orange et al. [2009], Figures 10 [chemosynthetic fauna recovered in a piston core] and 12 [gas hydrate]; note that such features may indicate hydrocarbons but would not indicate thermogenic versus biogenic gas or differentiate between fresh versus biodegraded oil). Three 20 cm subsections are taken from each core for further analysis at the laboratory (e.g., Table 1, Sample sub-sectioning strategy for geochemical cores, Bernard et al., 2008). Each subsection was analyzed for interstitial gases, gas chromatography-mass spectroscopy (GCMS) for C14–C34, and total scanning fluorescence (TSF) (this suite is referred to as the "SGE"; Cameron et al., 1999). The geochemical results, which can differentiate between thermogenic versus biogenic gas and differentiate between fresh versus biodegraded oil, are what materially impact exploration risk (but again, the geochemistry of a seafloor seep cannot predict reservoir, seal, volume, or commerciality). If present in sufficiently high concentration, hydrocarbons in the core can be further analyzed (biomarkers, diamondoids, and isotopes) for source rock maturity, age, and facies (Cole et al., 2001). Because preliminary geochemical results are delivered approximately 1 month after the core subsections arrive in the laboratory, the financial impacts of multibeam-based risk reduction can be extremely quick relative to more traditional exploration approaches (multiple months versus many years).

Following TGS's IMS-I, GeoData Ventures (GDV) acquired the multiclient IMS-II. Companies that licensed the megasurvey data were able to high grade their block-by-block exploration results because of the multibeam and geochemistry data, thereby reducing cost and risk, and helping to inform their final decisions on block bids, additional seismic data (two dimensions and three dimensions) and, ultimately, drilling.

Following the success of the Indonesia Megasurveys, TGS expanded multiclient seep hunting to basins worldwide. The first program, with Fugro acquiring multibeam and TDI-Brooks carrying out piston coring, heat flow, and geochemical analyses, was in the GOM (Mexico, "Gigante" and U.S. "Otos" and the two international portions in between) with 917,904 km^2 of MBES data, 1402 cores for geochemistry, 145 JPCs, and 145 heat flow stations, plus gravity, magnetics, and 2D seismic data (Figure 3). More recently, regional multiclient seep surveys have been acquired offshore Brazil, Senegal, Guinea Bissau, The Gambia, Guinea, and Nigeria. The relevance of these regional surveys to best practices in multibeam seep hunting is that they demonstrate the upside value of multibeam and seep geochemistry to multiclient geophysical data packages. All of these surveys were acquired as multiclient projects, where any company can purchase a license to the data.

The IMS-I (2006–2008) relied heavily on a scientific workflow from the technical teams on the vessels and onshore. For its time, this survey demonstrated a significant increase in what was defined as a success rate in Orange et al. (2008) and Bernard et al. (2008): 11.9% of all analyzed samples contained evidence of migrated liquid petroleum compared with the globally estimated average recovery rate of migrated liquid petroleum from previous surveys of <5% of samples in frontier basins, and 46.0% contained unambiguous evidence of thermogenic gas compared with the globally estimated average recovery rate from previous surveys of approximately 25% (Bernard et al., 2008; Orange et al., 2008). This is statistically significant because of the very large size of this survey (446,141 km^2 multibeam, 1321 cores, and 1182 of the seep targeting geochemical cores yielding sufficient recovery for analysis) and that it was conducted over multiple different basins and geologic settings. Of the 1182 cores analyzed for geochemistry, 426 cores yielded gas but no oil (36.0%; 147 of the 426 gas cores were classified as biogenic based on the lack of C3 and above, or by the isotopic value of the C1 [and C2] and 279 of the 426 cores were classified as thermogenic, or mixed biogenic-thermogenic, gas), 41 cores yielded oil but no gas (3.5%), and 99 cores (8.4%) yielded oil and gas; 566 of the 1182 cores analyzed (47.9%) resulted in an unambiguous hydrocarbon hit (Orange et al., 2008); and 616 cores (52.1%) yielded a background response, with neither gas nor oil. This is an increase in the success rate as defined previously by 2.4 times and 1.8 times the previous collated and published global surface geochemistry data sets for gas and oil chemistry, respectively; we attribute some of this increase in success to Indonesia having accretion and areas of rapid sediment accumulation, processes that drive seepage although, as discussed previously, hydrocarbons were successfully recovered from basins that had been written off as oceanic crust, or nonprospective. The two defining lessons from this survey were the reliance on high-quality multibeam data and the reliance on engaged and experienced technical teams on the vessel and onshore making the interpretations.

Less successful multibeam-for-exploration projects have resulted from acquisitions where the petroleum system was nonexistent, or where high vessel acoustic noise significantly and negatively impacted the multibeam data, especially the backscatter.

Surveys where the multibeam data were excellent and fit-for-purpose, but where coring yielded no hydrocarbons, constitute "exploration failure, but commercial success" if the operator makes commercial decisions based on the coring results. The exploration may have failed due to the lack of a sampled petro-

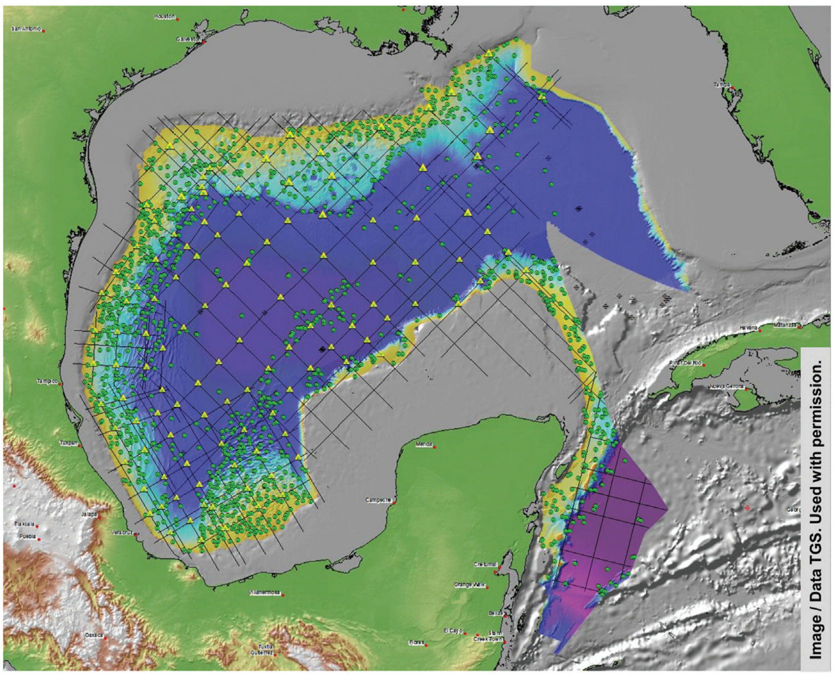


Figure 3. The GOM, showing the extent of the TGS multiclient Gigante (Mexico) and Otos (USA) multibeam surveys (shaded-relief bathymetry; artificial sun from the northwest; total area surveyed = 918,000 km^2). The green dots represent the USBL-positioned 6 m piston cores (n = 1548 drops, with 1402 analyzed for geochemistry). The yellow triangles show the locations of 20 m JPCs and heat flow stations (both n = 145). The black lines show regional 2D multichannel seismic lines. Additional 2D lines in the U.S. GOM (3.2 km × 3.2 km, or better), the Mexican shelf and slope (5.0 km × 5.0 km, or better), Mexican deep water (5.5 km × 7.5 km or 22.5 km × 22.5 km), and Mexican Caribbean (24 km × 24 km), not shown. Multibeam data courtesy of TGS, used with permission.

leum system, but this could be viewed as a commercial success if the operator spends the least amount of money required to fulfill their commitment. The Sangkerang PSC, in the Makassar Strait of Indonesia, is an example of this (Decker et al., 2004a). In contrast to the two other blocks mapped and sampled in this program, Sangkerang had no indications of hydrocarbons in 109 samples from 33 cores; furthermore, the heat flow data acquired during the coring program indicated that the mapped source horizon was not in the hydrocarbon generating window. A PSC commitment well, Lombosang 1, was drilled to the shallowest depth possible that would fulfill the operator's drilling commitment (and therefore at the least cost) and sample the source facies. The well contained no hydrocarbons, confirming the lack of charge in this block, and was plugged and abandoned (Decker et al., 2004a).

Seep target identification and core target selection

Target selection philosophy and criteria

The goal of the MBES mapping is to identify anomalous features on the sea bottom. Of particular interest are features thought to be caused by or associated with hydrocarbon seepage to the sea bottom. Targets for coring are selected by the following process.

The at-sea technical team, generally three people during mapping operations, reviews data acquired and processed on a daily basis. They interpret the geologic context and select features of interest, including potential core targets, and report those interpretations to the shore-based operations and interpretation team in their daily reports. Given the unknown nature of a field area before a survey, and the potential for complex geology and new or unusual features, we strongly recommend trained, expert, and experienced geoscientists on board the mapping and coring vessels; trainees are encouraged so that they gain real world experience with experienced geoscientists. Trained geoscientists can recognize unusual features and can bring them to the attention of the shore-based team, whereas a surveyor without geoscience experience may not realize that a feature is either new or unusual, or potentially related to the petroleum system. The client's shore-based technical teams should maintain a close line of communication with the at-sea technical teams.

These interpretation teams work with processed bathymetry and backscatter grids using GIS mapping packages. All grids are loaded into the project GIS, with bathymetry augmented by hillshade and used to create derivative slope and aspect maps. The backscatter is loaded on a line-by-line basis as well as merged regional grids, often displayed with shaded relief. The line-by-line backscatter allows a more thorough interrogation of areas of overlap which can be obscured when grids are merged.

At the end of each survey leg, MBES data and interpretations are delivered to the shore-based operations and interpretation team, typically on an external hard drive. The hard drive should include a relative-path GIS project (for "plug and play" ability), all of the subbottom profiler data in native format as well as SEG-Y, a subbottom project in a seismic viewer and interpretation package, multibeam data in raw format, and WCA data.

Whereas the at-sea team typically reviews each day's acquisition for features of interest, line-by-line, the shore-based team has the benefit of beginning with a large area of coverage allowing for a better understanding of regional trends defined by seismic data, onshore mapping, gravity, and magnetics. Instead of viewing the data as a set of lines, starting with a complete grid of 30 days of acquisition provides context which only increases as subsequent survey legs are appended. This allows interpretation from a more geologic perspective as opposed to an acquisition perspective. Grids are observed at scales ranging from 1:1,000,000 up to 1:1000. For seepage features, reconnaissance interpretation is favorable at approximately 1:24,000 allowing viewing of approximately 9 km × 9 km on a large format monitor; in areas with lower, slower, or more widely distributed seepage a more detailed approach may be warranted. Any feature of interest at 1:24,000 is then reviewed at 1:1000 or 1:2000 scale for discrete target selection. At 1:1000 scale, the 5 m backscatter pixels are clearly visible allowing targets to be placed precisely either within high backscatter features or along edges of high to low backscatter transition; because of the steep lateral geochemical gradient at most seeps and our experience acquiring multiple cores on and near numerous targets, we believe that "meters matter" when it comes to target selection.

Each potential core target is described in terms of geomorphology, backscatter character, position relative to regional trends, and position relative to other data sets such as seismic data, subbottom profile data, gravity, and synthetic aperture radar (SAR) — these are descriptive characteristics that do not connote interpretation; the interpreter also may add comments regarding their geologic interpretation of the target (e.g., a surficial indication of faulting or folding, headscarp, etc., or surficial features tied to seismic interpretation). In addition to these characteristics, the interpreter quantifies each target with a number signifying their personal interpretation regarding the probability that the targeted feature is hydrocarbon-seepage related or a geologic anomaly of some sort. The interpreter also provides a quantitative ranking capturing their opinion that the target should be included in the final core acquisition program. Both quantitative factors are adjusted iteratively dependent on the ongoing regional analysis and as the interpreter gains experience with each basin and with subsequent basins.

Background cores in addition to seep target cores

Background piston cores are cores taken intentionally off target to determine the regional baseline geochemistry. It is essential to establish a base level to understand the magnitude of any anomaly in each basin; using the same 6 m piston coring rig that is used to sample seep targets insures that background cores will have a similar depth of recovery for geochemical analysis (more than 5 m). Some basins, especially those with extensive and voluminous natural hydrocarbon seepage, such as the GOM and the Caspian Sea, have a higher level of background hydrocarbons in cores unrelated to seepage (referred to as the "haze"; J. Zumberge, personal communication, 2017). Using the same piston coring rig for background cores is relatively quick and inexpensive, as it avoids rerigging over-the-side equipment (e.g., swapping between the grab sampler and piston core). In addition to providing valuable information on the geochemical baseline in an area, piston cores that are acquired off seep targets can yield important data on the geology of a basin including sediment accumulation rates and recent geologic history.

We recommend that background piston cores be acquired somewhat evenly spaced across the basin at 2D seismic line intersections (or on a 3D seismic grid). The locations should be in areas of relatively flat bathymetry and benign sea bottom conditions (uniform low or moderate backscatter), away from faults, seep targets, MTDs, etc. Background cores are sampled and analyzed geochemically exactly the same way as cores taken on seep targets. A subset of 2D seismic line intersections where background cores are acquired makes an excellent grid of sites for heat flow stations. The 2D seismic data can be interpreted for basin modeling of the heat flow (Figure 3).

The heat flow probe also may use USBL for positional confirmation, where the background core recovery minimizes the risk of bent or damaged heat flow probes when the probe is deployed into stiff or hard seafloor.

If available, we recommend the use of JPCs at as many background core locations as the project can afford. JPCs provide a significantly deeper depth of interrogation and, in areas with high sedimentation accumulation rates, can penetrate through the nearly universal Holocene drape and obtain samples below the last glacial maximum.

Background cores can be returned to the laboratory for additional analyses. In our typical program, we log the whole core using a GeoTek MultiSensor Core Logger at 1 cm resolution. Measurements include gamma ray, density, P-wave velocity, resistivity, magnetic susceptibility, 2D X-radiographs (or full high-resolution computed tomography [CT] scan), X-ray fluorescence [XRF], ultra-violet [UV] and visible linescan photography, and color spectrum. Cores are then sampled for biostratigraphy, sedimentology, petrology, grain size, age dating, sedimentation rates, etc. Because the process of piston coring may disturb the sediment water interface, care has to be taken (through a variety of means) to depth register the top of the core. Analyses of piston cores may allow the acoustic properties of the sea bottom, in particular, the backscatter data to be tied to physical properties.

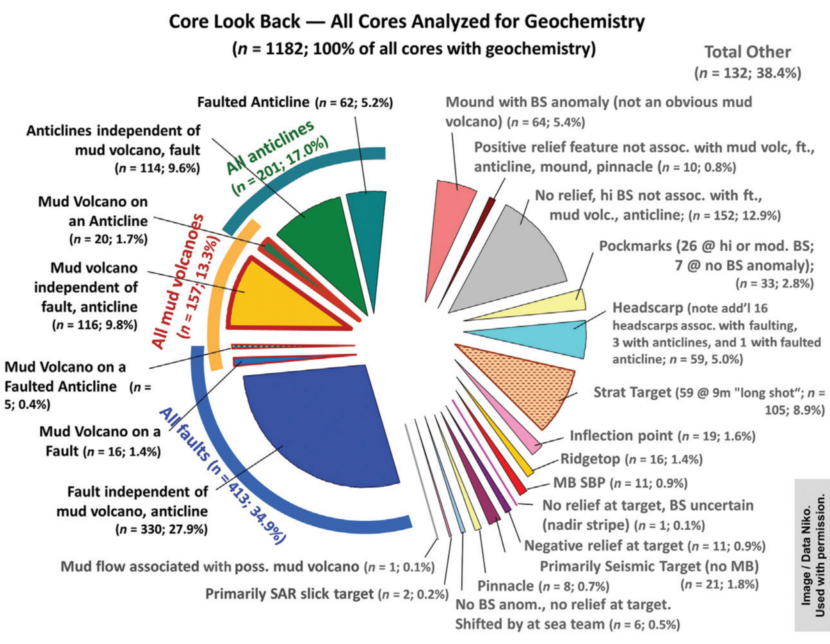


Figure 4. Pie chart indicating the types of targets interrogated in IMS-I. TGS analyzed 1182 cores for geochemistry in the 446,000 km^2 surveyed. Each target was characterized descriptively (mound, lineation, etc.) and genetically (fault, mud volcano, etc.); cores also were flagged that were associated with subsurface information (seismic or subbottom profiler) and whether they could be tied to SAR slicks. Each geochemical subsample was in turn quantitatively ranked for gas, oil, and CO_2 (for each, 0 = none, 1 = weak, 10 = strongest). A comprehensive look back was then carried out evaluating target type and geochemical success (or lack thereof). Here, 663 of the 1182 sections analyzed (56.1%) were associated with some combination of faults, mud volcanoes, and anticlines. Coring look back by Niko Resources, used with permission.

Seep target types and target selection and the prioritization process

Figure 4 shows all of the target types sampled during the IMS-I project (n = 1182); the size of each pie slice is relative to the number of targets of this type interrogated. The most common target types were associated with faulting (n = 413, 34.9%), anticlines (n = 201, 17.0%), or mud volcanoes (n = 157, 13.3%; for examples of the seafloor faults imaged in IMS-I, see Teas et al., 2009). Following the delivery of the geochemistry, BGE carried out an extensive "look back" to evaluate aspects such as which type of targets yielded the strongest oil hits or were most likely to be associated with gas hits, or hydrate (where a "hit" is unambiguous geochemical evidence of oil or thermogenic/mixed gas). Each oil and gas hit was given a quantitative rank of 1 (a hit, but weak) to 10 (strongest), with a number determined separately for oil, gas, and CO_2. Oil seep ranking was based on the solvent extraction of seafloor cores using TSF and high-resolution gas chromatography (C15 + GC). A scale was defined from 1 (weak) to 10 (strong) using quantitative parameters and visual interpretation of gas chromatograms. All samples with a score of one or above showed positive evidence for oil seepage. The lowest rank samples had TSF > 25,000 units and gas chromatograms with identifiable oil peaks above a recent organic matter (ROM) background. The highest rank samples had TSF > 1,000,000 units with a complete oil signature and virtually no ROM. GCMS of biomarkers also was used in the selected samples to confirm the ranking. Gas seeps were ranked from 1 to 10 using the headspace gas concentrations of C1–C5 components (ppm). A further qualifier was applied to identify thermogenic, mixed, and biogenic gases using δ13C carbon isotopes for methane and ethane together with C1/C2+ ratios. Each target also was evaluated for description (bathymetric low, bathymetric high, lineation, inflection point, etc.) and interpretation (surficial anticline, fault, mud volcano, etc.). With a comprehensive look back, for example, 34.9% of cores associated with faulting could be evaluated to determine the % of overall gas, oil, and CO_2 hits that occurred on faults versus the overall % of hits. In this way, target types that yielded above-average geochemical success were differentiated from those that yielded below-average geochemical success, as well as which targets were more or less oil prone, gas prone, hydrate prone, and CO_2 prone.

Ideally, each area is reviewed independently by at least two interpreters and with the interpretation from the at-sea team hidden. This approach allows multiple objective interpretations without bias from other workers. This goal is not always met due to personnel and time constraints but has been particularly valuable in large regional programs. For readily identifiable features, each independent interpreter generally identifies the feature, however, the precise placement of core targets often varies. This allows for iterative collaboration in determining the final proposed core target locations. Each interpreter, once completing their own analysis, reviews the other interpretations, and provides their qualitative factors for hydrocarbon quality and priority for inclusion in the final core acquisition program. Figure 5a shows an area from an actual program with potential core target locations indicated and symbolized according to an interpreter's quantitative ranking for hydrocarbon probability. In most surveyed basins, many more features are identified than can be included in a final core program due to cost and timing constraints. Only a fraction of the potential targets were able to be cored and many higher quality core locations were omitted from the final program. Culling targets is an iterative process involving multiple interpreters of the MBES data as well as corroborative data such as seismic data or SAR. Figure 5b shows the variety of geochemical signatures (triangle colors) and strength (triangle size) on the subset of cores actually acquired within the area of Figure 5a. This indicates the areal variation in the strength of the geochemical anomaly and the different oil and/or gas signatures (oil families, thermogenic gas, etc.). We can observe a distinct geographic variation in the resulting geochemistry allowing the definition of trends. The presence of different oil families in an area can indicate multiple source horizons charging the petroleum system and increase an area's attractiveness for further evaluation and prospect maturation (3D seismic data) prior to bidding or drilling a well.

The shore-based operations and interpretation team is responsible for selecting and ranking potential core targets. There is no "cookbook" or automated ranking system that can be applied to a new basin. Rather, an understanding of the regional tectonics, the geologic history of a region, its stratigraphy, and nearby petroleum

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b)

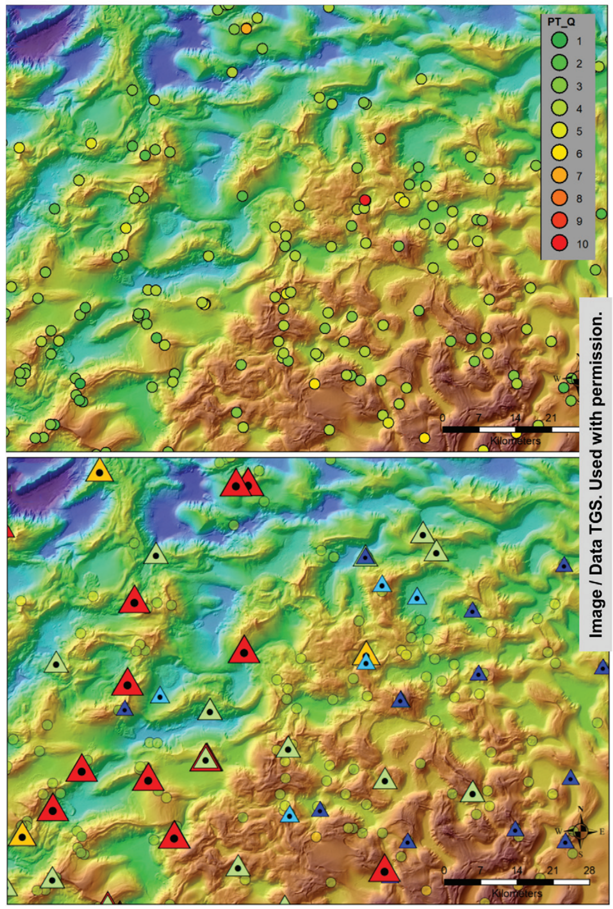

Figure 5. (a) Shaded-relief bathymetric map showing locations of potential core targets selected by the interpretation team color-coded by one interpreter for qualitative indication of the likelihood of the target being related to hydrocarbon seepage. Lower numbers = higher interpreted quality. Each interpreter evaluates all of the targets individually without visibility of the others' ranking. Each interpreter also evaluates the probability that a given target should be in the final ranking, with one being a higher probability. In areas with many very high-quality targets, we will demote the probability of many of them, while promoting lower-quality targets in areas with fewer quality targets. (b) Shaded-relief bathymetric map showing the variety of geochemical signatures (triangle color and size) on the subset of cores actually acquired within the area shown in (a). Triangle size scales with the strength of the geochemical anomaly; colors represent different oil and/or gas signatures (oil families, thermogenic gas, etc.). Note that the red geochemical family has the strongest hits, but that hit strength alone would only give part of the information in the area. For example, the presence of different oil families in an area can indicate multiple source horizons charging the petroleum system. Multibeam data courtesy of TGS, used with permission.

systems must all be incorporated by the interpreters into their approach to a basin. The ranking is based on two philosophies, quality of the seep target and regional distribution needed to cover the entire survey with targets regardless of the target quality:

I) Quality: How likely are the seabed features related to oil or gas seepage on a global or universal basis — on a 1–10 scale with one being the highest rank (we apologize for any confusion caused by this being the opposite of the geochemical strength ranking discussed previously; the scales were developed separately by two different geoscientists):

    1) Definitely seep-related: Several typical hydrocarbon seep-related characteristics include WCAs/gas plumes, high backscatter, circular with concentric rings or flow appearance, and topographic relief, either positive or negative.
    2) Very likely seep-related: Characteristics similar to one but missing one or two indicative characteristics.
    3) Probably seep-related: Generally having only one or two typical hydrocarbon seep characteristics.
    4) Possibly seep-related: Arguably possessing at least one of the high probability seep characteristics but lacking perfect clarity.
    5) Unknown: These features are equally likely to be seep-related or due to some other geologic feature such as outcrop and slide block.
    6) Uncertain but probably not seep-related: Feature likely related to nonseep geologic phenomena but lacking perfect clarity such that it could arguably be seep-related.
    7) Possibly a geologic feature unrelated to seepage: No definitive seep-related features and generally a clear geologic cause.
    8) Probably a geologic feature with a low probability of seepage: A clear geologic causation can be described for the feature.
    9) Very likely a geologic feature and very unlikely to be seep-related: Typically, several features in the same vicinity that show similar characteristics that form a probable geologic trend or individual characteristics of a known geologic feature.
    10) Definitely a geologic feature and highly unlikely to be related to seepage: Clearly a reef, outcrop, turbidite fan, fold trend, etc. Also assigned to a target clearly not associated with any type of anomaly; background locations.

II) Regional distribution: How important to the program is it to obtain a core and geochemistry at a particular location, also on a 1–10 scale: The goal of this ranking (1 = highest priority, 10 = lowest) is to obtain a broad and somewhat even geographic distribution and to core a variety of target types.

It is important that each target be ranked individually but with similar criteria applied to other targets. Targets with similar quality rankings generally cluster in subregions of the survey area. There may be a cluster of highly ranked mud volcanoes, for example, in a small area or trend (e.g., Silver et al., 1986). Core geochemistry from these features almost always produces the same or similar geochemical results. For this reason, we favor selecting only a few samples from these high-quality trends, and, instead of coring more high-quality targets in these areas, coring possibly lower-quality targets in areas away from such trends to spread the target distribution and increase the variety of target types. Overall, spreading the distribution and core types provides a better regional understanding of an area's prospectivity (e.g., Figure 5b). It is of course very important that the high-quality trends are sufficiently sampled but having real-time geochemical results from the vessel can provide assurance of this, allowing the coring budget to be spread out over a greater distribution to better interrogate regional trends. In an area with only low-quality targets, acquiring some anyway would, if they yielded no evidence of hydrocarbons, provide evidence of absence. Failing to acquire any cores in this area would result in an absence of evidence.

The shore-based interpretation team integrates their targets with the at-sea team's targets into a set of recommended targets within the core budget for that leg and provides this list to either their colleagues and partners (if they are funding the acquisition) or the primary acquisition company and their clients along with the MBES data and a plug and play GIS. Colleagues, partners, and/or clients provide feedback and their target nominations to the interpretation team for further iteration and eventually final consensus before providing the list of targets to the coring acquisition contractor.

An important factor in target generation and through the iteration toward a final core program is the concept that seep hunters gain experience regarding target type viability and relation to seepage as the operations and groundtruthing continue and as geochemical results come in. It is especially important to consider many different types of seafloor features and broad geographic coverage. It is easy to become focused on high-quality targets to the exclusion of less confident features. However, experience over several decades has convinced us that a more thorough geochemical data set is achieved by the inclusion of a variety of target types over broad areas.

Hydrocarbon seep targets

Hydrocarbons can reach the seafloor in several ways (Hovland and Judd, 1988; Judd and Hovland, 2007; Abrams, 2020): with mud volcanoes or through the subsurface with mud diapirism (via the shear fabric/fracture permeability along the margins of the mud diapir; Orange, 1990), flow along permeable pathways (either stratigraphic or fault related), or vertically driven by buoyancy (potentially related to gas-phase bubbles in the migrating gas which can result in seismic features such as "smearing" [acoustic turbidity], "wipe-out" [acoustic masking or blanking], enhanced reflections, and bright spots; Judd and Hovland, 2007). Mud diapirism involves a volume of fluidized sediments along with water, oil, and gas buoyantly rising through the overburden and expelled at the surface creating mounds. Hydrocarbons also migrate along permeable paths due to the buoyancy force and are resisted by capillary forces. The migration follows a weakest-link pathway tending to create point source expulsion features when escaping to the surface. The visual observations from ROVs (Eel River Basin; also L. Mayer, personal communication, 2021) show that individual seep point sources tend to be on the scale of centimeters, with the region of active seepage (as evidenced by live chemosynthetic communities) having dimensions of tens to hundreds of meters with dense clusters of seep organisms and other seep features (bacterial mats and dark sediment) at the surface (e.g., Mayer et al., 1988; Suess et al., 1998; Orange et al., 1999a). Diffusion of hydrocarbons would not create morphologic features and would not result in point source expulsion and would therefore be difficult to detect based on remote sensing, as distinct anomalies are not formed, however, this type of transmission of hydrocarbons also is generally minor (Abrams, 2020).

Hydrocarbon seepage is expressed on the seafloor in several primary ways, including: as bathymetric mounds of expelled sediments in mud diapir-related mud volcanoes (Figure 6), as pockmark depressions related to forceful expulsion of gas or hydrate dissociation, as chemosynthetic seep communities, and as plumes of bubbles observed within the water column (note that two or more of these can occur on the same feature). Occasionally, hydrocarbons also will flow outward from seep points such as mud volcanoes (Figure 6b) like lava flows from a volcano (see Decker et al., 2022, their Figure 7; note that mud volcanoes may be the surface expression of subsurface diapirs, Figure 6f). In basins with active salt tectonics, hydrocarbons can be entrained in salt diapirism as well or may migrate along the flanks of salt diapirs or walls. Each of the modes of seepage can be observed using quality MBES bathymetry and backscatter and detailed interpretation; with more than 100 ROV dives on seeps and the surrounding seafloor in the Monterey Bay and the Eel River Basin, no seeps were observed away from bathymetric and/or backscatter anomalies interpreted to be related to seepage (all seeps were associated with bathymetric and/or backscatter anomalies; Orange et al., 2002).

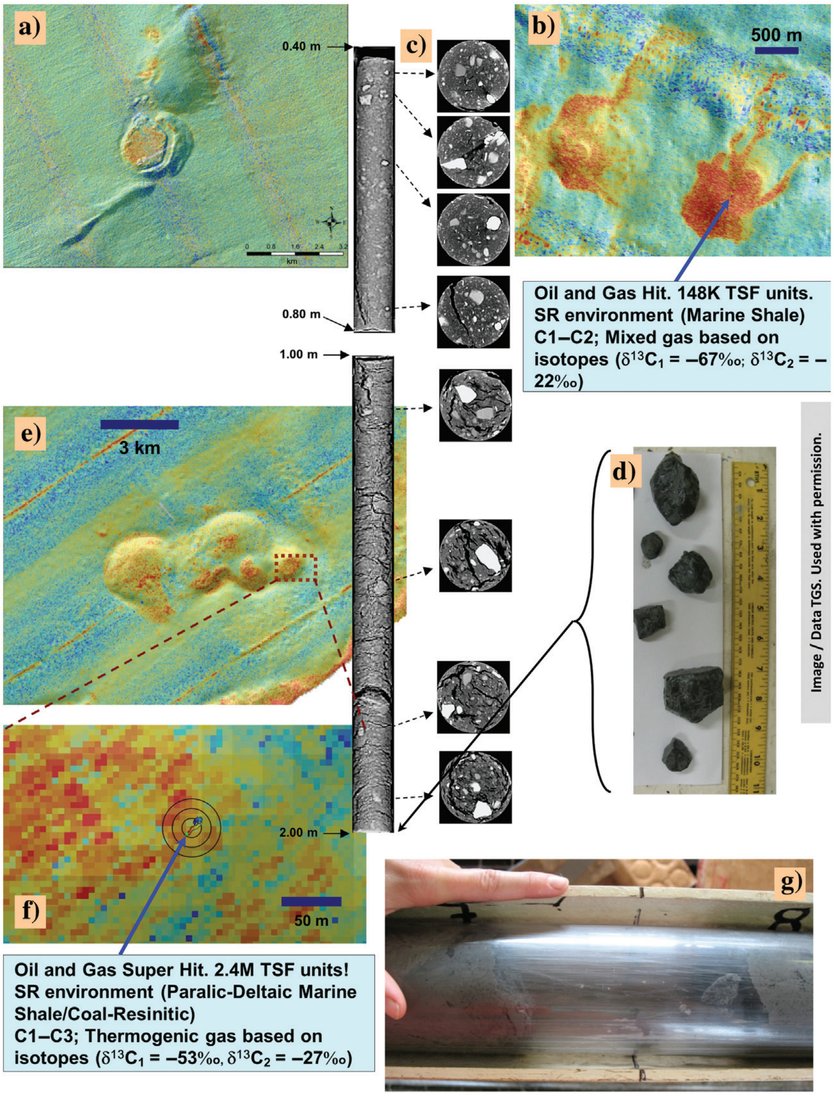

Figure 6. (a) Shaded-relief backscatter map of a large mud volcano (GIS backscatter displayed with a statistical color palette, with the red 2.5 standard deviations above the mean, and the blue 2.5 standard deviations below the mean, corresponding to high backscatter higher than 99.38% of the pixels, and low backscatter lower than 99.38% of the pixels). This rough circular approximately 1.5 km in diameter relatively flat-topped mud volcano rises 25 m (the northwestern edge) to 125 m (eastern) above the surrounding seafloor. High backscatter indicates a rough or hard surface or internal complexity in the near subsurface. (b) Backscatter draped on a mud volcano from the Seram Trough, Indonesia. Geochemical analysis of the core yielded oil (biomarkers indicate a marine shale source) and gas, with mixed gas based on isotopes. (c) A CT scan of the core (after removal of the 20 cm sections for geochemistry) and selected sections showed abundant clasts with variable density. (d) A photograph of the pebbles removed from the core catcher. (e) Composite mud volcano imaged in the Misool Strait, eastern Indonesia. (f) The backscatter suggested an annular ring, interpreted to be due to enhanced fluid migration along the fracture permeability that characterizes the flanks of subsurface diapirs or diatremes (Orange, 1990; Brown and Orange, 1993). (g) The core targeting the high backscatter ring showed significant gas parting and yielded an oil and gas super hit; note biomarkers and gas isotopes indicated a paralic-deltaic marine shale/coal-resinitic source (Noble et al., 2009). Multibeam data are shown in a, b, and e, and are used with the permission of TGS. The CT scans, 6C, are used with the permission of Niko Resources.

Mud volcanoes typically form broad flat-topped mounds due to the expulsion of low-viscosity mud to the surface (Figure 6a), to more peak morphology if the viscosity is higher (Figure 6b). We use slope maps to differentiate between mud volcanoes and igneous volcanoes: mud volcanoes rarely show flank slopes in excess of 20°, with slopes more than 30° extremely rare. Mud volcanoes also commonly have high backscatter, either across the entire mud volcano (Figure 6a) or associated with areas of active expulsion and mud flows away from the mud volcano (Figure 6b). Figure 6e shows a composite mud volcano comprised of five individual mud volcanoes. Figure 6f shows the crest of the eastern-most mud volcano in the complex, where the backscatter suggests an annular ring; we interpreted this to be due to fluid expulsion associated with enhanced fluid migration along the fracture permeability that characterizes the flanks of subsurface diapirs or diatremes (Orange, 1990; Brown and Orange, 1993). The core targeting the high backscatter ring showed extensive gas parting through the core liner on deck (Figure 6g) and yielded an oil and gas super hit (rank 10: extremely high TSF, "reservoir-quality" chromatograms, very high gas concentrations); biomarkers indicated a paralic-deltaic marine shale/coal-resinitic source (Noble et al., 2009); and C1–C3 plus gas isotopes indicated a thermogenic source (gas rank 5).

In IMS-I, approximately 35% of the 1182 cores acquired for geochemistry were CT scanned. The CT scan of the core acquired on the mud volcano in Figure 6b is shown in Figure 6c (the CT scan was conducted following the removal of the 20 cm sections for geochemical analysis). The CT scan shows abundant clasts with variable density; these clasts would increase the volumetric scatter below the seafloor and may be the dominant source of the high multibeam backscatter in addition to seafloor seep communities. Figure 6d shows a photograph of the pebbles removed from the core catcher. This mud volcano was included in Orange et al. (2009, 2010) prior to a further "mud volcano study" across the Indonesian archipelago (studies of onshore mud volcanoes in Indonesia showed that they brought blocks and clasts to the surface from deeper stratigraphic levels [Barber et al., 1986] demonstrating their usefulness in providing the age and sedimentary facies of subsurface formations; Staffini et al. [1993]; for an early application to submarine mud volcanoes, see Sautkin et al. [2003]). The range of clasts recovered from mud volcanoes and the range of densities in a single core from a mud volcano indicate that the mud volcanoes entrained material from the wall rock from a wide range of depths during their ascent through the subsurface. Cores were analyzed similarly to well cuttings; the biostratigraphy of this core is shown in Figure 7 (B. Morley, personal communication, 2012, 2013) and indicates Late Triassic to Late Jurassic nannofossils as well as Early Oligocene, Middle Miocene, and Paleocene nannofossils. Microfossil assemblages were interpreted for the depositional environment. Clasts also were analyzed for vitrinite reflectance, heavy mineral analysis, and sedimentology. Individual clasts also were examined in thin section for petrography and porosity. Zircon dating of clasts also was used to determine the presence and limit of Australia-affinity crust in Central and Eastern Indonesia (Decker et al., 2017).

TDI-Brooks reengineered the piston core assembly to be used in much the same way that a rock hammer is used in field work to obtain hand samples from outcrops for further analysis (Kullman et al. [2017]; note that the reengineering goes beyond the JPC weight assembly on a 6 m core barrel that Chris Moser and colleagues at Oregon State University developed for increased sample length in hard-to-core material; MGL12-08 [2012]). A significant advantage of a piston core "hard substrate" sampler is that it can be tracked to the target with USBL, insuring the sample attempt of the unit of interest, in contrast to a dredge, which would accumulate samples over a transect with uncertain sample locations (with uncertainty due to the length of the dredge transect and the large layback distance if USBL positioned). In the IMS-I Banggai Sula survey area offshore eastern Sulawesi, Orange et al. (2010) show a multichannel seismic line with a high impedance unit daylighting in a submarine canyon where multibeam shows the unit to have high backscatter. The core recovered abundant angular rock fragments in several sections of similar density (based on CT scans; see Orange et al., 2010). Subsequent thin section and micropaleontologic analysis showed that the rock is Miocene limestone interpreted to be the New Guinea Limestone that forms the reservoir for numerous oil and gas fields in the area (e.g., Miocene carbonates of the Tomori Formation and the Minahaki Formation, Sonoro-Toili PSC, where reefal facies limestones contain excellent porosity and permeability; Hasanusi et al., 2004).

The "hard substrate sampler" was used during GDVs IMS-II to gain information on the units present in survey areas without a well penetration. Figure 8a shows a multichannel seismic line across the leading edge of the Banda Arc thrust sheet and the Kai Ridge; cores targeting seeps in the allochthonous thrust yielded Mesozoic oil (no Oleanane; see Noble et al., 2009) and thermogenic and mixed thermogenic-biogenic gas, whereas cores acquired in the autochthonous Adi Trough, Kumawa Basin, and the Aru Trough yielded Miocene Klasafet-type oils and thermogenic and mixed thermogenic-biogenic gas. A key question was whether the Plover Formation, the prolific reservoir in Northwest Australia, was present in the area. The multibeam data showed a high backscatter unit with an apparent south dip on the east face of the Kai Ridge (Figure 8b) which could be tied to seismic data, and which TDI targeted with a hard substrate coring rig. The core yielded 1.2 m of recovery and included angular clasts that filled the core liner (Figure 8c). The at-sea team described the core as containing "pebble-size rocks that are either a well-cemented sandstone or metamorphic quartzite (Figure 8d and 8e). It was pale gray with dark flecks. In a hand lens view, most of the grains were quartz that was rounded to subangular with some flakes of biotite and an occasional dark grain of something else, possibly a plagioclase." (A photo from the coring vessel taken through a hand lens is shown in Figure 8f; these photos were emailed to shore the day after the core was acquired.) Petrographic analysis (Figure 8g; Core Lab, personal communication, 2013) of the core found "a medium to coarse grained, moderately well-sorted sandstone classified as a quartzarenite and composed mostly of quartz (Q). Syntaxial overgrowths (Qo) have commonly developed on quartz grains. Minor authigenic kaolinite (K) occurs in intergranular pores and as a replacement for grains. Visible porosity is good and is mainly of intergranular pores (IP; 9.6%) with subordinate secondary pores (SP; 6.8%)." Permeability was measured between 429 and 501 mD (n = 3). Micropaleontologic analysis yielded a significant number of Middle to Early Jurassic, Bajocian — Toarcian nannofossils. The sandstone was interpreted to be the Jurassic Plover Formation equivalent based on petrography and microfossils, with good porosity and permeability. The crest of this bathymetric feature is planar (Figure 8b), dips gently to the northwest with water depths ranging from approximately 950 to 1100 m, and is characterized by high backscatter. This feature was interpreted to be a southeast-facing drowned reef. Hard substrate cores acquired on the high backscatter crest of this bathymetric feature recovered Miocene limestone.

Figure 9a shows a moderate to high backscatter irregular mound-shaped mud volcano in a downslope channel; the mud volcano postdates channel formation, indicating its relative geologic youth. The subbottom profile (Figure 9b) shows the mound geometry, diffractions, and lack of internal reflectors. The piston core targeting the crest of this mud volcano recovered 2.67 m, with mudstone fragments, gas parting, and several egg-sized pieces of gas hydrate, including in the core catcher (Figure 9c). The gas hydrate ignited (Figure 9d), indicating that it was a hydrocarbon gas hydrate (versus a CO_2 hydrate which we have sampled in other projects, but which are rarely encountered); when ignited, the hydrate dissociates, with the water ice melting to cold water where the gas in the clathrate cages ignites as an upward-directed flame. Geochemical analysis of this core indicated an oil hit (rank 3), with thermogenic gas indicated by C1–C5 concentrations and isotopes (rank 4).

Multibeam data imaged approximately 350 m diameter flat topped mud volcano in the Kofiau area of the Misool Straits (Figure 9e; Noble et al., 2009). Geochemical analysis from the 5.25 m piston core recovery indicates an undegraded oil, degraded oil residue (plus biomarkers; oil rank 10), and thermogenic gas (C1–C5, isotopes C1–C5; gas rank 7). The presence of undegraded and degraded oil as shown in the whole extract gas chromatography trace (the light green outline, Figure 9f) indicates episodic fluid expulsion. Noble et al. (2009) interpret the isotopic signature of the oil and the m/z 191 biomarker trace (horizontal axis = retention time in minutes; Figure 9g) to indicate a marine shale source rock with detrital land plant organic matter of

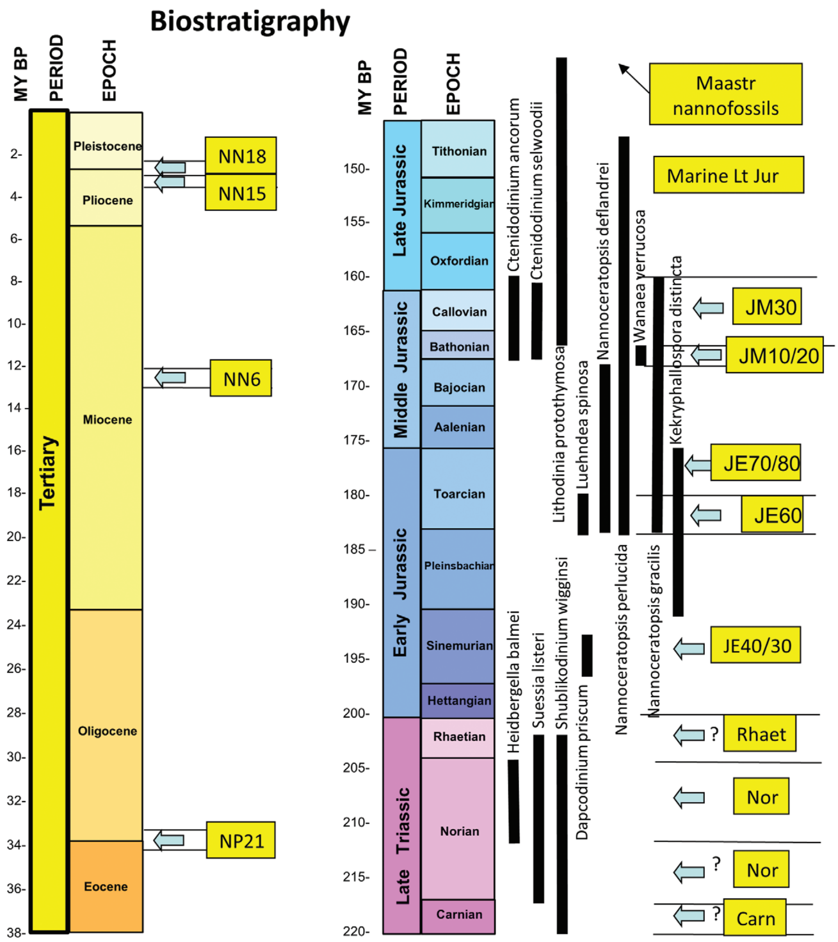

Figure 7. Biostratigraphic analysis of the core acquired on the mud volcano shown in Figure 6b (B. Morley, personal communication, 2012–2013; see Morley et al. [2021]; Cenozoic nannofossil zones after Martini [1971]; Mesozoic biostratigraphic zonation scheme developed using the same methods as Morley et al. [2021] from first principles using the entire Irian database as a data source). The CT scan indicated clasts with variable density and was used to guide the subsampling of the core. Clasts were analyzed individually for biostratigraphy; microfossils labeled with vertical text, and associated age ranges indicated by the thick black bar. Yellow boxes indicate interpreted ages. Note extensive Mesozoic microfossils, absent early Tertiary (except for Maastrichtian) but some Oligocene, Miocene, and Pliocene fauna. Microfossil assemblages also were interpreted for depositional environment. Cores also were analyzed for vitrinite reflectance, heavy mineral analysis, and sedimentology. Core biostratigraphy courtesy of Niko Resources, used with permission.

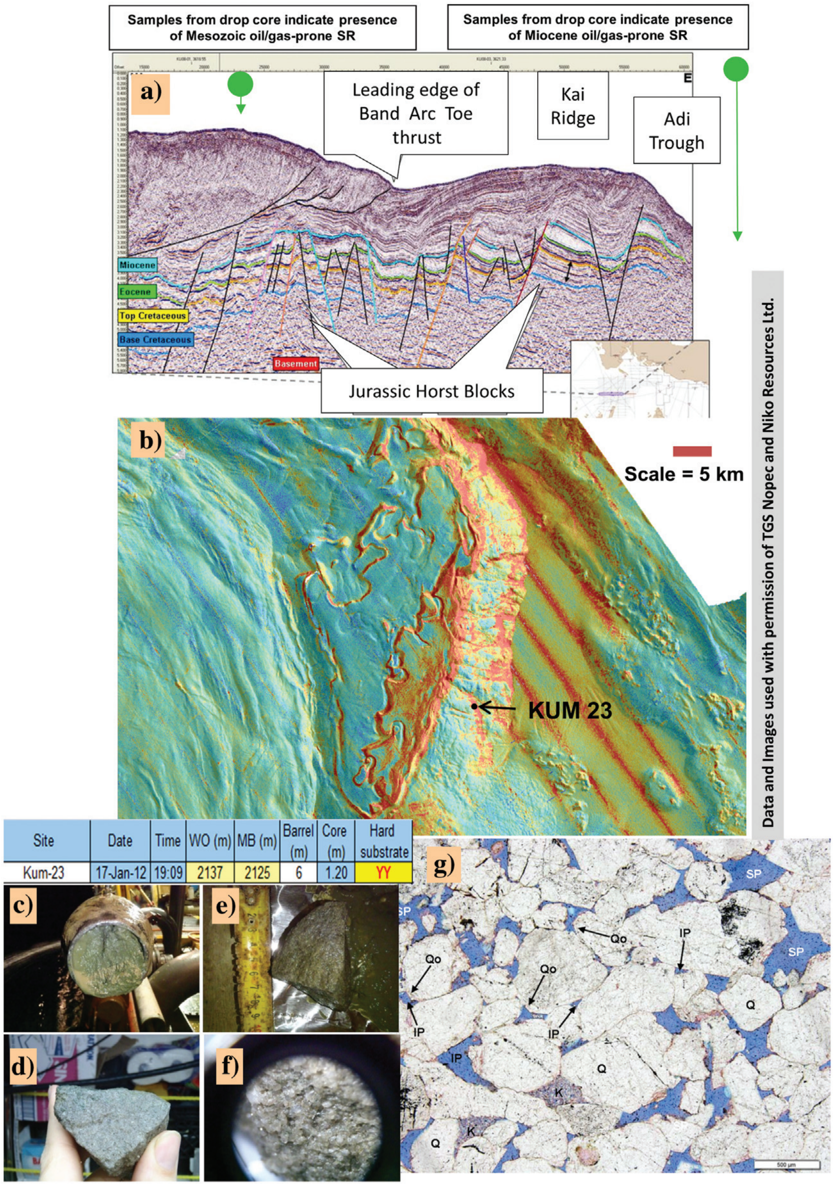

Figure 8. Montage illustrating the application of "hard substrate sampling" to exploration prospectivity. (a) Multichannel seismic line across the Banda Arc thrust sheet and the Kai Ridge north of Kai Besar island. Seep targets in the thrust wedge yielded Mesozoic oil and mixed thermogenic/biogenic gas, whereas seep targets in the Adi Trough yielded Miocene Mesozoic oil and mixed thermogenic/biogenic gas. Note the interpreted Jurassic horst blocks. (b) The Jurassic section was interpreted to crop out on the east face of the Kai Ridge with an apparent south dip in multibeam high backscatter. Core KUM 23 targeted one interpreted outcrop. (c) The core rig modified for hard substrate sampling yielded 1.2 m of recovery and included angular clasts, including some that filled the core liner that (d and e) the at-sea team described as "pebble-size rocks that are either a well-cemented sandstone or metamorphic quartzite". (f) In the hand lens view, "most of the grains were rounded to subangular quartz." (g) Petrographic analysis (Core Lab, personal communication, 2013) found "a medium to coarse-grained, moderately well-sorted sandstone classified as a quartzarenite and composed mostly of quartz (Q)" with syntaxial overgrowths (Qo) and minor authigenic kaolinite (K) in intergranular pores and as replacement of grains. See text for porosity and permeability. Micropaleontologic analysis yielded Middle to Early Jurassic, Bajocian — Toarcian, nannofossils. Based on the petrography and microfossils, the sandstone was interpreted to be the Jurassic Plover Formation equivalent, a prolific reservoir in Northwest Australia. (a) Multichannel seismic data and (b) multibeam are used with permission of TGS and core analysis courtesy of Niko Resources, used with permission.

an Early to Middle Pliocene age. Noble et al. (2009) compare the geochemistry with known production in Indonesia and show that this core yielded "Klasafet" type oil, which is the oil produced in the Selawati trend of oil fields 55 km southeast of this mud volcano (Satyana, 2009); two wells drilled in the area encountered gas at depth similar to the seafloor seeps but no oil (Noble et al., 2016). The lack of oil at the target horizons was attributed to "migration lag" where the oil migration front has not reached the targeted stratigraphic level in a vertically drained basin, whereas mud volcanoes do (Noble et al., 2016). Judd and Hovland (2007) discuss three discoveries, Cognac, Canterill, and Estrella, where seeps directly lead to exploration success.

During IMS-I, TGS acquired two samples on an approximately 700 m diameter mud volcano that rises approximately 100 m above the surrounding relatively flat seafloor in the southern Seram Trough (Kumawa Basin; Adhitama et al., 2017) in eastern Indonesia (mud volcano shaded relief, Figure 10a, and backscatter, Figure 10b; IMS-I core locations shown by green text boxes in Figure 10c). The mud volcano shows very high backscatter over most, but not all, of the positive relief, a low backscatter crater offset from the crest, and surrounding low backscatter seafloor. The first core (TGS_AruMV-1) near the very high backscatter crest recovered 4.86 m and had visible oil staining. The at-sea team elected to acquire a second core (TGS_AruMV-2) on the mud volcano, 145 m southeast, sampling the moderate backscatter crater edge at the edge of the high backscatter (Figure 10c). Geochemical analysis of TGS_AruMV-1 yielded a maximum TSF of 20,696,000 units, C1–C5 (including 13 ppm C5), C1–C4 isotopes, and sufficient hydrocarbons for biomarkers. TGS_AruMV-2 yielded a maximum TSF of 27,125 units, C1–C5 (including 7.5 ppm C5), C1–C3 isotopes, and not enough hydrocarbons for biomarkers. TGS_AruMV-1 was classified as an oil super hit (rank 10) and moderate gas hit (rank 5, thermogenic). TGS_AruMV-2 was classified as a very weak oil hit (rank 1) and moderate gas hit (rank 5, mixed thermogenic and biogenic). The question was raised: how close to an oil super hit do you need to be to get a strong oil hit?

To answer this question GDV, as part of IMS-II, acquired 16 cores at this mud volcano: seven on the very high backscatter on the mud volcano (the pink text boxes, Figure 10c), four on the low-to-moderate backscatter on the mud volcano (the orange text boxes), two near (20 and 40 m) the edge of the high backscatter mud volcano (the yellow text boxes), and three cores 100, 200, and 400 m from the mud volcano in the low backscatter surrounding the seafloor (the gray text boxes). Here, six of the seven cores into the very high backscatter on the mud volcano yielded very strong oil hits (the bold text boxes, Figure 10c, five rank 10 and the other rank 7) with TSF > 1 million units, strong thermogenic gas (C2+ and isotopes), biomarkers, and diamondoids. One of the seven cores in the high backscatter yielded no oil or gas. None of the other nine cores were classified as super oil hits no matter how close to the high backscatter they were. Of the four cores into low to moderate backscatter on the mud volcano, three had weak to moderate oil, two had weak mixed gas, one had moderate thermogenic gas (hydrate, C1–C5, isotopes), and one yielded no oil or gas. Neither of the cores 20 and 40 m from the high backscatter base of the mud volcano had oil or gas. For the background cores away from the mud volcano, one had weak mixed gas and two of the three had a weak oil signature (based on 40–50,000 max TSF units and chromatograms); we hypothesize that the transport of dilute mud volcano material away from the bathymetric high may be the source of this weak oil signature. The detailed study of the Aru Mud Volcano clearly shows that if oil is the objective, it matters whether you are in high backscatter, and meters matter if you are away from high backscatter. In a follow-up to the Aru Mud Volcano study, TGS, as part of the Gigante megasurvey in the Mexican GOM, revisited an oil super hit acquired in April 2016. The area was of interest due to repeat SAR slicks, with two repeat slicks having origin points 290 and 815 m away from this moderate to high backscatter mound on a ridge flank at a water depth of 940 m (Figure 11a and 11b). The initial core recovered 4.94 m, and the at-sea team described the core as "Greenish Gray Clay, H_2S odor, (stronger down core) with gas parting and oil staining." The geochemistry revealed an oil and gas super hit (184 million maximum TSF units),

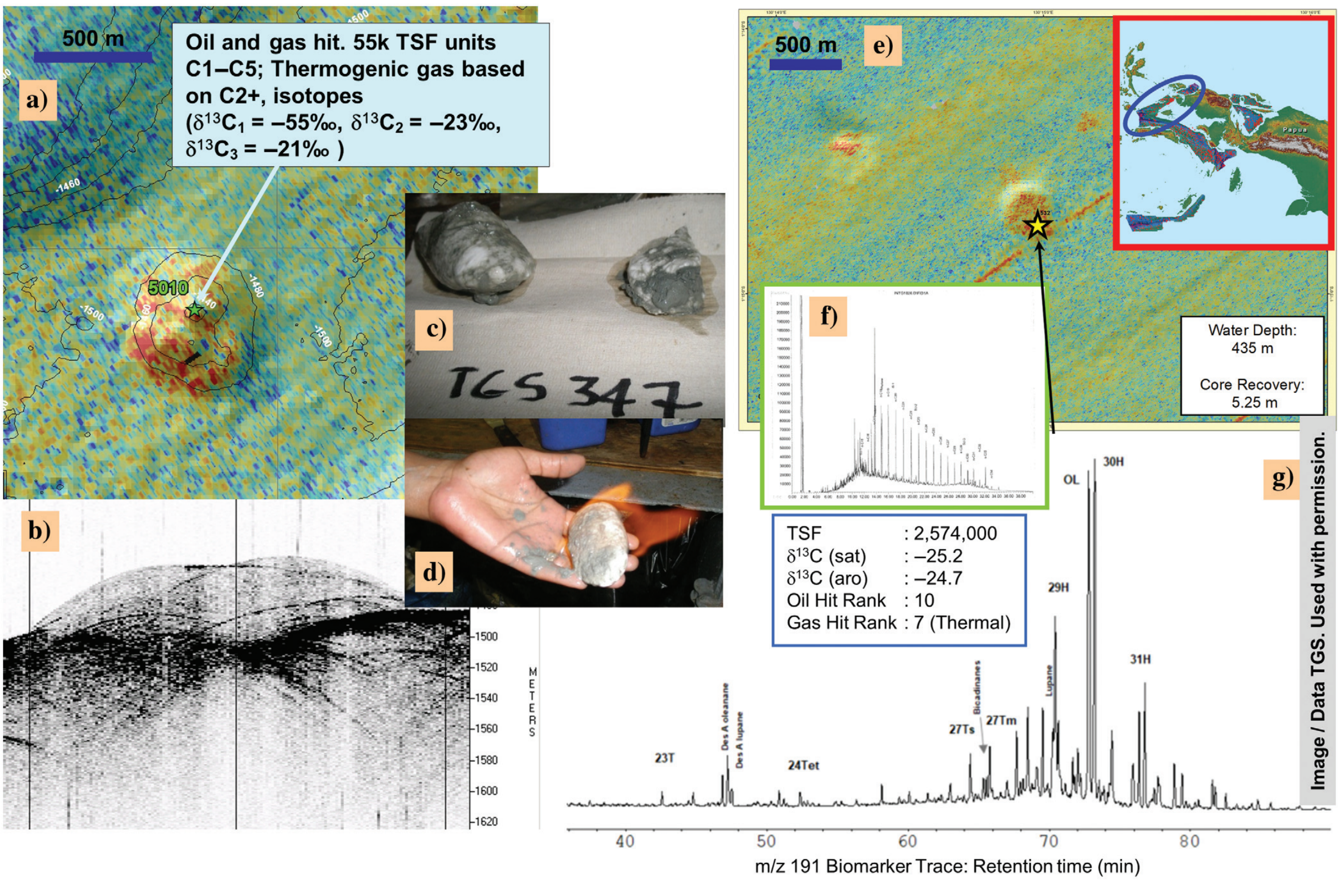

Figure 9. (a) Moderate to high backscatter irregularly shaped mud volcano in a channel indicates relative geologic youth. This approximately 500 m diameter mud volcano rises 35 m above the channel floor, and (b) SBP data show no internal reflectors. (c) The core, targeting the crest, recovered mud clasts 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 CO_2 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 courtesy of TGS, used with permission.

with sufficient biomarkers for interpreting source rock age, environment, maturity, and family (this is the northeastern core location annotated in Figure 11c).

With the geochemistry results in hand, TGS had an opportunity to revisit this site in mid-July 2016, three months after the initial coring. TGS acquired a core in the high backscatter, 72 m from the first attempt (Figure 11c), and 27 m from the edge of the high backscatter. A second core was acquired 62 m northwest in the background backscatter 35 m from the high backscatter, and a third core a further 101 m northwest, 136 m from the high backscatter (Figure 11c). The follow-up core in the high backscatter is another oil and gas super hit, with 314 million maximum TSF units and sufficient oil for a full biomarker interpretation (identical to the first core). Both of the cores into the nearby background low backscatter had no visual indicators of hydrocarbons, with geochemistry indicating elevated TSF but no gas. Only 62 m separates the high backscatter super hit from the background backscatter core, again indicating that meters matter.

Pockmarks can form due to the rapid expulsion of gas which causes sediment to be ejected into the water column and dispersed (Hovland and Judd, 1988); pockmarks also can form by repeated events such as hydrate formation and dissolution (Taleb et al., 2020). The resulting depression forms a discrete circular feature. These will be buried or degraded over time and the detailed morphology of the depression may be related to the activity of expulsion (Figure 12a). Figure 12b shows three ridgetop pockmarks with varying backscatter and morphology; detail shown in Figure 12c. The northeast pockmark, which showed significantly higher backscatter but a more subtle depression, was targeted for coring. This core recovered 4.75 m of sediments containing rock fragments and oil staining in all sections of the core. Geochemical analysis indicated an oil and gas hit; biomarkers provided information on source rock age, environment, and biodegradation. Gas data (C1–C4 concentrations and light methane isotopes) suggested mixed thermogenic and biogenic gas.

Slump headscarps also provide useful targets for hydrocarbon seepage. Once a slump forms, the base of the slump head scarp provides a topographic inflection point that allows overpressured fluids to focus seepage (because the ocean is at a constant head everywhere and the concave upward headscarp base is a constant head surface; Orange and Breen, 1992; Orange et al., 1994). Headless slumps, indicative of retrogressive failure via seepage-induced spring sapping, are particularly attractive seep targets (Orange and Breen, 1992; Orange et al., 1994, 2003, 2004). TGS targeted 59 headscarps in the IMS-I program independent of faulting or anticlines, an additional 16 headscarps associated with faulting, three with anticlines, and one with a faulted anticline (for a total of 79 cores, or 6.7%; Figure 4), Decker et al. (2022, their Figure 19) show a headless slump on the flank of an anticline with the high backscatter successfully sampled for hydrocarbons.

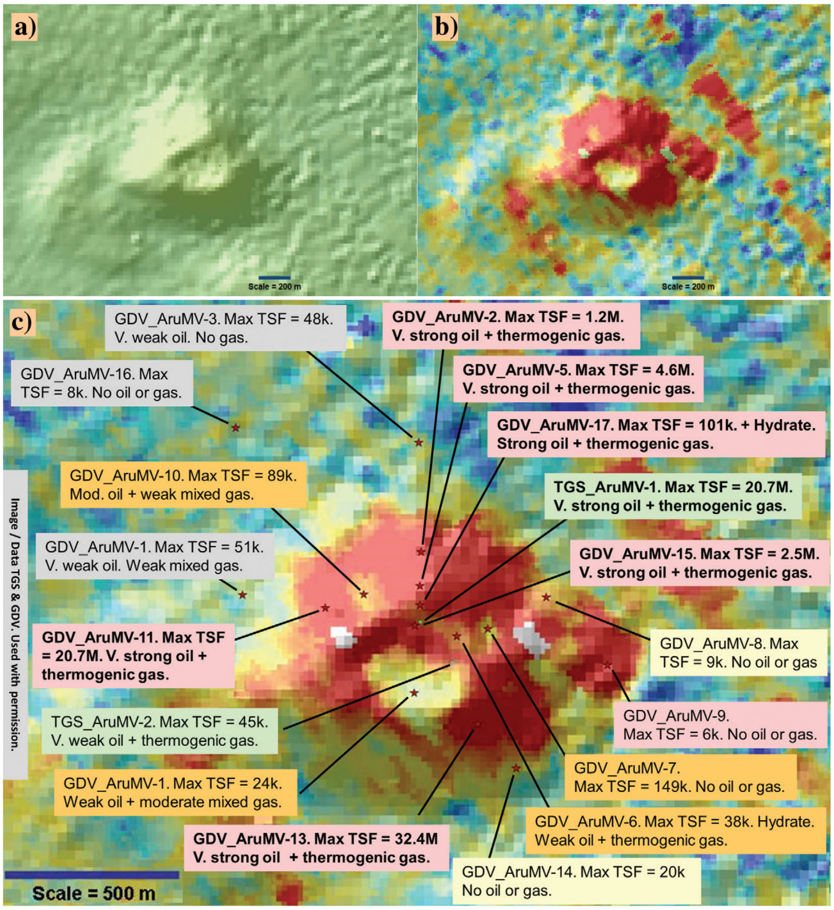

Figure 10. (a) Shaded relief and (b) backscatter draped on shaded relief of approximately 700 m diameter mud volcano that rises approximately 100 m above the surrounding relatively flat seafloor, Kumawa Basin, with (c) the location and geochemical results of all cores acquired. Two cores acquired in IMS-1 (the green text boxes) had very different results, with the high backscatter crest an oil super hit (TGS_AruMV-1) versus the weak oil + thermogenic gas at the edge of the moderate backscatter crater (TGS_AruMV-2). To evaluate how close a core has to be to qualify as an oil super hit, GDV acquired 16 cores on and near this mud volcano. Cores into high backscatter (n = 7) shown in the pink boxes (bold = oil super hit; five of seven). Cores on the mud volcano but in moderate to low backscatter (n = 4) shown in tan boxes; 1 moderate oil + weak mixed gas, 2 weak oil + thermogenic gas, and 1 no oil or gas. Cores 20 and 40 m from the high backscatter mud volcano edge (n = 2) in yellow boxes had neither oil nor gas. Cores 100, 200, and 400 m from the mud volcano shown in the gray boxes; the 100 and 200 m cores had very weak oil and weak or no gas, where the 400 m core had no oil or gas. All super oil hits with biomarkers were in high backscatter on the mud volcano. Data courtesy of TGS and GDV, used with permission.

Seepage can occur without impacting the morphology of the seafloor, with the manifestations of seepage (clam shells, authigenic carbonate, and gas hydrate) increasing the hardness and roughness of material on the seafloor, or buried in the shallow subsurface, where the manifestations of seepage increase the volumetric scatter. Seepage with no bathymetric signature may be due to low flux or seep growth similar to the rate of sediment accumulation. We refer to these features as "high backscatter, no relief," and in the IMS-I 12.9% of the cored features fit this description (Figure 4), where the high backscatter/no relief was not associated with interpreted faulting, mud volcanism, anticlinal crests, etc. Due to the roughness and hardness of the components of seep communities and seep precipitates, relative to the soft mud that typically surrounds these features in deep waters dominated by hemipelagic deposition, they tend to have a high backscatter in MBES data. The manifestations of seepage will, as long as they cover an extent that can be imaged, impact the backscatter and appear as discrete backscatter patches, often circular or semicircular due to point source expulsion, without associated positive or negative relief, and with diffuse, as opposed to sharp, edges (Figure 13).

Seep sampling

The objective is not just taking a core, it is getting the right sample at the right location. Navigating the core to the target accurately using the aforementioned USBL beacon greatly improves the accuracy and precision of sampling. Seeps often are point sources and they have steep lateral chemical gradients and therefore slight offsets in the targeting and sampling can lead to missing the target by tens to hundreds of meters and can result in inconclusive results (Abrams, 1996; Mottl et al., 2003). It is important that the sampling is performed by geoscientists who understand the risks of geochemical contamination and sample loss from degassing during slow sampling at surface pressure and temperature conditions. Furthermore, having experienced geoscientists allows geologic indicators such as authigenic minerals, seep fauna, gas hydrates, gas expansion, etc. to be identified in the recovered cores and preserved for further analysis. Some cores may have very short recoveries because seeps often are associated with hardgrounds, and there need to be members of the core acquisition team who can identify when a seep has potentially been groundtruthed by a core and recommend resampling at that location (but offset tens to hundreds of meters) to ensure an adequate sample is acquired. The second attempt location should be selected by the at-sea team based on their interpretation of the multibeam and subbottom profile line, as the time required for the onshore team to understand the situation and the proposed reacquisition would cost more money (time) than the cost to acquire the second core.

The sampling should be just as data driven as the interpretations, and groundtruthing by doing simple geochemical analyses on the vessel to screen for hydrocarbons is an effective tool for ensuring confidence in

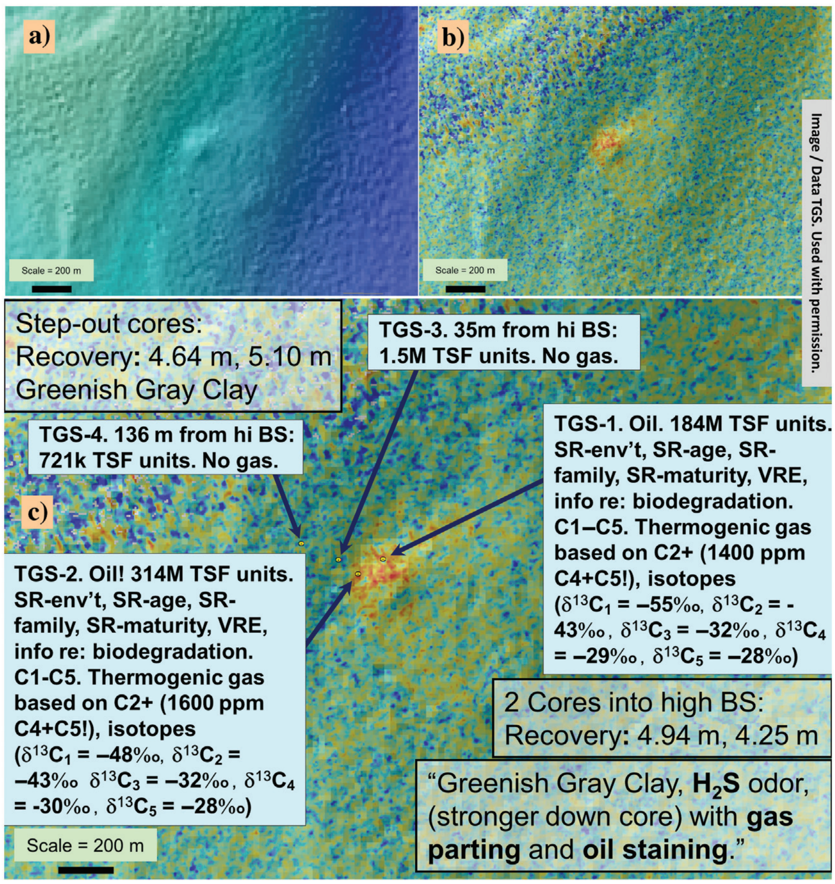

Figure 11. (a) Shaded-relief bathymetry and (b) backscatter draped on shaded relief of the approximately 250 m diameter high backscatter mound on the flank of a ridge with surrounding low to moderate backscatter seafloor, Mexican GOM. The proximity of this feature to two repeat SAR slicks elevated its quality ranking and its probability of core ranking. (c) The first core, TGS-1, located on the high backscatter mound, had visible gas parting and oil staining. Geochemical analyses indicate an oil and gas super hit, with C1–C5 isotopes and sufficient hydrocarbons for a full biomarker interpretation. TGS returned to the area 3 months later, providing an opportunity to evaluate how close to this high backscatter feature you need to be to get a robust oil hit. TGS acquired a follow-up core in the high backscatter 72 m WSW of the first core (TGS-2), where geochemistry revealed an even stronger TSF hit, C1–C5 isotopes, and sufficient hydrocarbons for an identical biomarker interpretation to the first. Two cores into the regional low backscatter (TGS-3 and TGS-4) had no visual indicators of hydrocarbons, with geochemistry indicating elevated TSF but no gas. With only 62 m separating the high backscatter super hit from the background backscatter core, meters matter. Image/data courtesy of TGS, used with permission.

the final results and being able to optimize target selection while in the field. Simple analyses done on the vessel can include extracting the organic matter from the sample and quantifying the n-alkanes and acyclic isoprenoids in a gas chromatograph (Bendoraitis et al., 1962; Short et al., 2007; Logan et al., 2009) as well as measuring the fluorescence of aromatic hydrocarbons using fluorescence spectroscopy (Brooks et al., 1986a; Barwise and Hay, 1996; Bjorøy and Ferriday, 2002, 2010). Another simple screening geochemical analysis important to understanding hydrocarbon geochemistry is measuring the light hydrocarbon gases (e.g., methane to pentane as well as carbon dioxide) using a flame ionization detector and thermal conductivity detector gas chromatography (Bernard et al., 1976, 2008; Brooks et al., 1986b). Analyzed at sea, these data may allow geochemists to infer information such as thermal maturity, source, biodegradation, and diagenesis of extracted organic matter, and thermogenic versus biogenic nature of the gases (Bjorøy and Ferriday, 2002; Wenger and Isaksen, 2002; Abrams, 2005, 2017, 2020; Abrams and Dahdah, 2011). These data often are referred to as screening analyses because they allow the geochemist to decide if more samples should be made from similar seafloor trends/features as well as to select the highest-value samples for more advanced analytical work at shore-based laboratories after the sampling portion of operations is complete (Peters and Moldowan, 1993; Piggott and Abrams, 1996; Dembicki, 2010, 2013, 2017).

Access to preliminary geochemistry, even if relatively simple analyses used for a cursory understanding of the hydrocarbon system, allows the shore-based and shipboard science team to be able to make potentially project-saving decisions based on real geochemical data while the vessel is still operational, rather than receiving the data after the survey vessel has already demobilized. Although the geochemical analyses during the coring program can provide valuable information that can inform the ongoing sampling efforts, we recognize that it may not be practical due to the cost or analytical equipment/personnel constraints.

Exploration impact of IMS-I and IMS-II

Joint studies provide one avenue to pursue exploration in Indonesia (Khaqim, 2015). In granting joint studies, the goal of the Government of Indonesia is to ultimately increase exploration activity, with the aim of licensing PSC blocks and the eventual discovery and production of oil and/or gas fields. The joint study process involves an industry sponsor and an Indonesian university who together evaluate the hydrocarbon prospectivity of an area. Most joint studies involve the reprocessing and reinterpretation of existing data. With the Indonesia Megasurveys, the industry sponsors underwrote the acquisition of new data: multibeam, USBL-positioned cores, heat flow, 2D multichannel seismic data, geochemistry, gravity, and magnetics. Following the completion of a joint study, the industry sponsor can indicate to the government the areas that they are not interested in exploring. The Government of Indonesia may offer the remaining area (approximately 5000 km^2) through the "Direct Award" process, where the industry sponsor of a joint study has a Right-of-First-Refusal to match the winning bid. All the other acreage may be offered as exploration blocks through the Open Tender process in the same, or any future, bid round. Companies that purchased the multiclient IMS-I and IMS-II data had, or would have, a competitive advantage in pursuing a direct aware or open tender block, in that they would have information on the petroleum systems in the survey area of the block(s) on offer (or the lack thereof), including what systems are active where, which are oil prone, which gas prone,

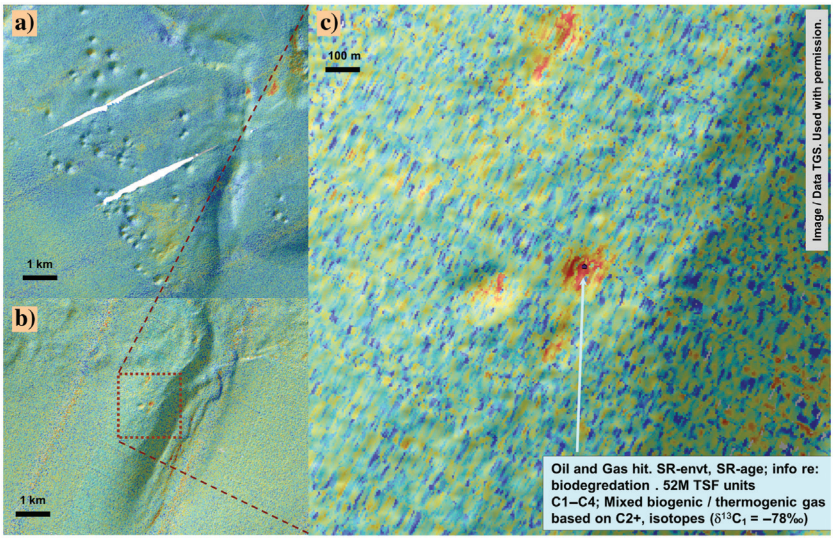

Figure 12. Pockmarks are localized approximately circular depressions on the seafloor (Hovland and Judd, 1988). (a) Shaded-relief backscatter map of a field of pockmarks. Individual pocks are typically on a scale of 100 m in diameter. Note the variety of form here with some pockmarks having rounded margins and others sharper; sharper edges may indicate relative geologic youth. Some pockmarks have moderate to high backscatter associated, whereas others do not. The depths of pockmarks in this image range from 20 to 60 m (60 m deep pockmarks are generally larger than 100 m in diameter). (b) Multibeam data from the Mexico GOM Gigante project image a cluster of pockmarks on a ridge top. Detailed multibeam of the cluster (detail outlined in [b], shown in [c]) showed three pockmarks, with one showing subtle and rounded topography and moderate backscatter (southeast), one showing moderate backscatter but sharper relief (W), and one showing much higher backscatter but a more subtle depression (northeast), which we selected for coring. Geochemical analysis indicated an oil and gas hit, with detailed information on source rock age and environment from biomarker analysis, and a mixed biogenic and thermogenic gas as indicated by C1–C4 and light C1 isotopes. Multibeam data and geochemistry courtesy of TGS, used with permission.

which are overmature, and which may be undermature (e.g., due to low heat flow).

Underwritten by the joint study holders, TGS acquired the IMS-I, and GDVs acquired IMS-II; both were acquired as multiclient surveys. Together they included 951,528 km^2 of multibeam, 1450 cores for geochemistry, 3886 sections for geochemical SGE analysis, 97 heat flow stations, and 42,777 line km of new 2D multi-channel seismic, gravity, and magnetics data. As of April 2022, 34 PSC blocks have been successfully bid on and secured in the IMS-I and IMS-II survey areas, including 24 by Black Gold/Niko (two of which were farmed into after the IMS data were interpreted) and 10 others by major oil and gas companies. BGE/Niko's partners included Marathon, ExxonMobil, Repsol, Statoil, ENI, Baruna Nusantara Energy, and Hess. Niko and partners underwrote the acquisition of 17,081 km^2 of new 3D MCS. A total of 14 wells have been drilled in the 34 PSCs, including two side-track wells. Of the nine wells that we are aware of, all but one encountered hydrocarbons at a significant depth below the seafloor consistent with the hydrocarbons sampled by the core barrel and analyzed as part of IMS-I and IMS-II (e.g., Noble et al., 2016); none encountered commercial quantities of hydrocarbons. Most of the wells drilled to date are new field wildcats, and the first wells drilled in each of the subbasins or blocks. With the hydrocarbons encountered at depth and knowledge gained from these first penetrations, we look forward to discoveries in the IMS-I and IMS-II acreage.

Using industry-average costs for 2D and 3D seismic data and drilling, we estimate cumulative exploration expenditure in the IMS-I and IMS-II survey areas by the companies that licensed the data in excess of US $1.5 billion.

Summary and conclusions

Hydrocarbon seepage out of the seafloor can impact the morphology and/or the acoustic properties of the

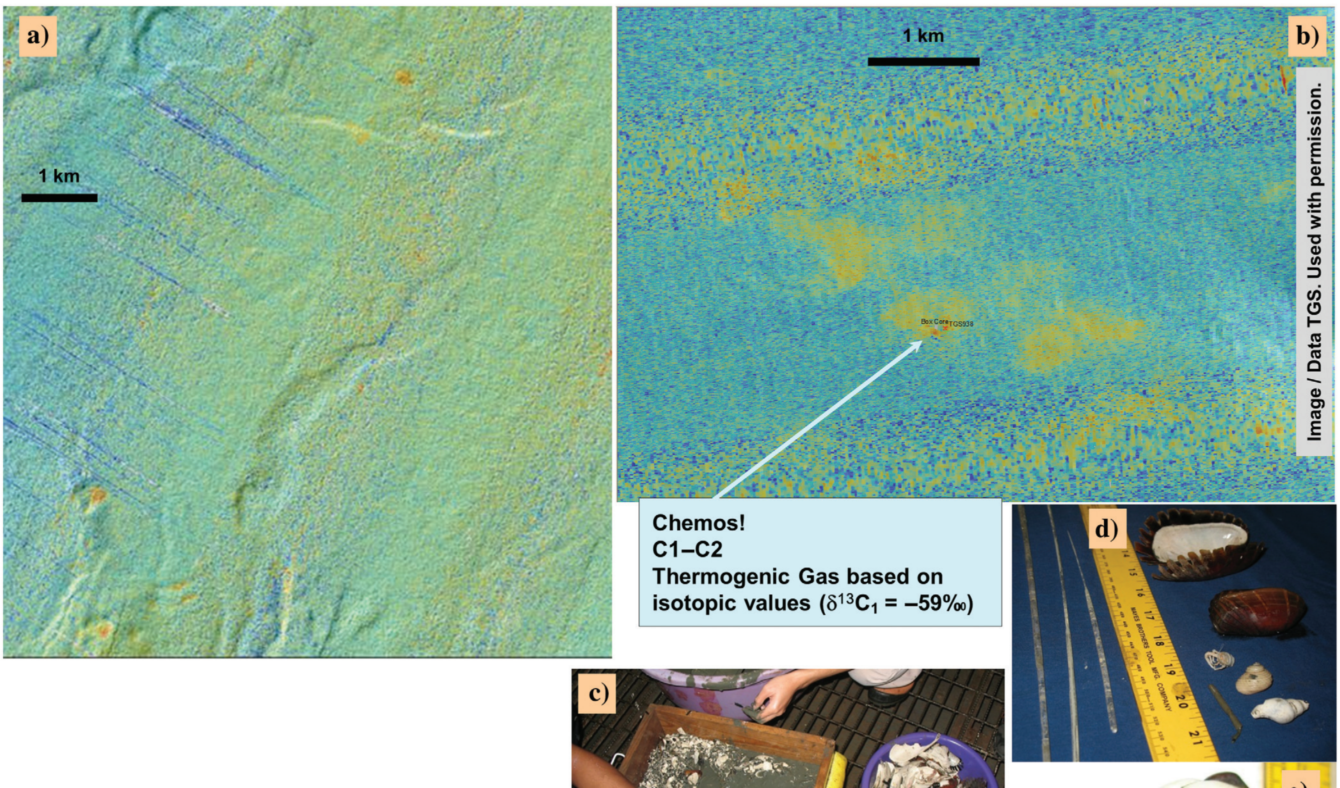

Figure 13. No-relief, high backscatter features on the seafloor. (a) Shaded-relief backscatter map of a typical low-relief seafloor with several high backscatter patches. Isolated semicircular patches here are approximately 100 m in diameter. (b) East of Sulawesi, Indonesia, 12 kHz EM122 data imaged moderately high backscatter patches several hundred to approximately 800 m across × 400 m. A USBL-positioned core recovered chemosynthetic fauna. Because there were few known cold seeps in this region, BGE followed up with an USBL-positioned box core which was sieved (c) for recovery of fauna (d), including a *Solemya* sp. (e) chemosynthetic bivalve. Geochemical analysis of the piston core material yielded gas (anomalous C1-C2) and thermogenic methane based on isotopes. Multibeam data and geochemistry courtesy of TGS, used with permission.

seafloor. Both 3D seismic data and multibeam can image potential seep features. The first coring program for exploration with USBL-positioned cores in a real-time GIS was carried out on interpreted seep targets in 2002; coring in a real-time GIS allows the at-sea team to understand the core position relative to the target anomaly and to make decisions that insure that the core interrogates the target of interest. This project, on Devon's Keta block offshore Ghana, clearly showed that the cores do not go straight down from the vessel and that they could be placed with confidence on target. The first multiblock multibeam program with USBL-positioned cores was carried out in 2003; this also was the first basin-wide multibeam exploration program, carried out by Unocal in the Makassar Straits of Indonesia. This project demonstrated that a regional exploration project could be carried out at a relatively low cost with a rapid turnaround of geochemistry with unambiguous evidence of oil and gas. In 2006, TGS initiated the multiclient IMS-I program that combined multibeam-based seep hunting, 2D seismic data, gravity, magnetics, heat flow, coring, and geochemistry to interrogate 446,141 km^2 offshore Indonesia. Of the 1182 acquired cores for geochemistry, 566 cores (47.9%) yielded unambiguous evidence of gas and/or oil. With evidence of hydrocarbon source, maturation, migration, and charge, all of which reduce exploration risk, early license holders such as BGE secured nine exploration blocks and farmed-out percentages of each block to partners who paid more than they received (a "promote"). The farmins at a promote, with farmin-ees paying their percentages of already spent "sunk" costs, demonstrate the financial value of multibeam-based exploration. The Indonesia Megasurvey targeted many different target types — every target was assessed with a probability of geochemical success, and the likelihood that it should be acquired, in the core prioritization process. We recommend sampling a range of target types, spread throughout an exploration area as well as 5%–10% background cores to provide a geochemical baseline for each survey area. Once the geochemical results are received, we recommend a comprehensive look back at geochemical results versus target type to inform future seep hunting programs.

CT scans of cores targeting mud volcanoes showed clasts with significant variations in density. This led to a "mud volcano study" of clasts which represent material encountered on each mud volcano's ascent to the surface to within the reach of a core barrel. Micropaleontologic analyses of these mud volcano cores provide valuable information on the subsurface without drilling. The piston core was repurposed and reengineered to acquire cores on seafloor outcrops interpreted based on multichannel seismic and multibeam data. These hard substrate samples were analyzed in the same way that an outcrop hand sample could be analyzed, with information on petrography, micropaleontology, vitrinite reflectance, heavy minerals, zircon dating, porosity, permeability, etc. used to interpret the geologic formations encountered in an exploration block without drilling. This geologic information, and the geochemical evidence of hydrocarbons, added value to the exploration of each survey block.

Hull-mounted multibeam, with a 15 or 25 m bathymetric bin size and a 3 or 5 m backscatter pixel independent of water depth, can identify small (25 m diameter) potential seep targets. With vessel positional accuracy of 5 m or better using differential GPS augmented by commercial positioning systems, and with USBL accuracy of better than 0.5% of water depth, meters matter in terms of coring for geochemical success.

IMS-I and IMS-II achieved the goals set out for the programs: surveying 951,528 km^2 of the seafloor, acquiring 1450 cores for geochemical analysis, and providing information on the presence and absence of hydrocarbons in Indonesia's frontier basins. The Government of Indonesia awarded 34 PSC blocks in the surveyed areas. Industry lease holders then acquired 17,081 km^2 of 3D MCS and drilled a total of 14 wells. The block awards, 3D seismic data, and drilling all demonstrate the exploration impact of multibeam-based exploration with a cumulative exploration expenditure postmegasurvey greater than US$1.5 billion. Although none of the wells drilled to date have encountered commercial accumulations of hydrocarbons, the hydrocarbons encountered at depth and the knowledge gained from the wells improve the chances that follow-on wells will ultimately lead to commercial discoveries and production. Multibeam, to identify potential seafloor hydrocarbon seep targets, and USBL-positioned piston cores, to confidently hit them, provide exploration-relevant data with a rapid turnaround time and in a cost-effective manner.

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Data and materials availability

Data associated with this research are confidential and cannot be released.

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