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The Utilisation of SeaSeep Surveys (a Defense / Hydrography Spin-Off) to Identify and Sample Hydrocarbon Seeps in Offshore Frontier Basins

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Abstract

The goal of SeaSeep exploration is to rapidly and cost effectively evaluate an offshore area for hydrocarbon prospectivity. The tools that are used to do this, multibeam sonar and piston coring – in addition to the more traditional 2D seismic, gravity, magnetics, and heat flow – have been around for decades, yet it is only through recent advances in all aspects of the survey system that data relevant to petroleum systems can now be acquired.

Natural hydrocarbon seepage out of the seafloor can alter the physical and biological characteristics of the sediment-water interface. The presence of seep-related biologic communities and authigenic carbonate or gas hydrate generates anomalously strong backscatter sonar returns in an otherwise monotonous background. Seepage can also lead to local bathymetric highs (mounds, mud volcanoes), and lows (pock marks), and seepage may occur along bathymetrically expressed fault lineaments. The ability to map the seafloor at very high resolution – both bathymetrically and with acoustic backscatter – allows for the identification of anomalous seafloor features that may be related to seepage. To interrogate these potential seep sites, we deploy a standard 6m – 9m piston corer equipped with a Ultra-Short BaseLine (USBL) positioning beacon so that the core can be tracked in three dimensions all the way to the seafloor target.

Through survey design, system calibration, execution, and the proper attention to detail to every aspect of the acquisition system, we are able to image seafloor features on the order of 10-100 meters in lateral dimension, and <5m vertically on the seafloor in up to 3000m of water. Over 1000 sq. km. of quality data can be acquired on a daily basis, with final seafloor maps and mosaics delivered upon the completion of a cruise leg. This allows for rapid integration with existing data, and identification of targets relevant to the petroleum system.

The SeaSeep exploration technique was recently applied to a large frontier basins program offshore Indonesia, acquiring 400,000 sq. km. of multibeam bathymetry and backscatter data, 100,000 line km of gravity/magnetics and 1,188 piston cores, as well as 34,000 line km of new 2D seismic data. The results of a geochemical suite of analyses on the cores showed that 12% contain evidence of migrated liquid petroleum, and 44% contain thermogenic gas. Over 400 isotope pairs, and 20 biomarker (molecular fingerprinting) suites provide insight into the maturity and source of multiple gas and oil petroleum systems. The success of this program significantly impacted the exploration risk through demonstration of source, maturity and migration. The SeaSeep program results, coupled with interpretation of potential leads on the 2D seismic data, allowed BGE to high-grade areas for further exploration, focusing efforts (and money) on the most prospective areas within the larger survey program. Black Gold's recent exploration activities in Indonesia demonstrate the business case for SeaSeep as a cost effective tool for rapid risk reduction in frontier exploration.

Introduction

SeaSeep surveys achieve offshore what many early explorationists achieved onshore: the rapid identification of basins that have hydrocarbon charge and a working petroleum system. The SeaSeep methodology comprises high-resolution multibeam sonar, targeted sea-bottom coring, gravity, magnetics, 2D seismic and hydrocarbon geochemistry data to explore a basin via traditional detection of oil and gas seeps juxtaposed with robust structures. The goal of a SeaSeep program is to rapidly and efficiently delineate and high-grade prospects and prospective areas in previously under-explored basins.

Until recently there have been no means to survey the seafloor beyond the shelf with sufficient accuracy or resolution to image hydrocarbon seeps in a cost-effective manner. The advent and continual improvement of sonar-based mapping techniques, based on declassified US Navy technology and driven by research supported by the US Navy as well as the needs of the hydrographic community, has resulted in publicly available high-resolution seafloor mapping systems. An unexpected consequence of this technology development is a tool ideally suited for identifying hydrocarbon seepage in the marine environment. In this section we will review the evolution of seafloor survey systems, as well as the science that underlies seep identification offshore.
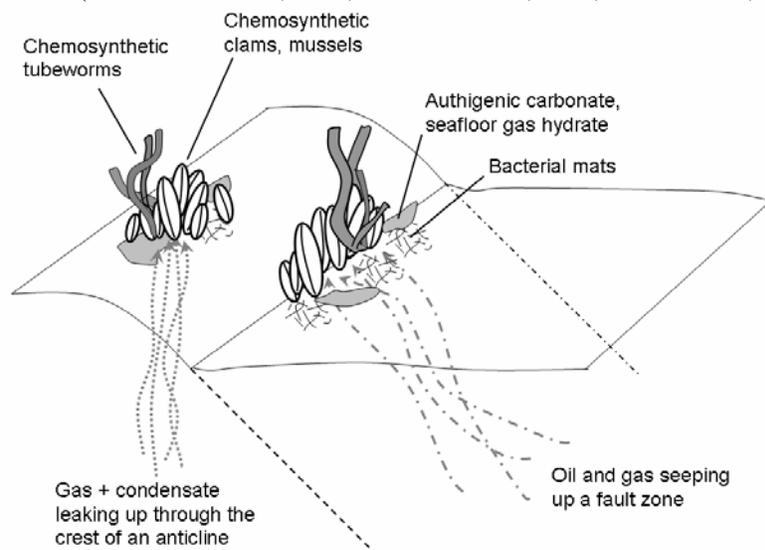
Early Seafloor Mapping:

Seafloor mapping has long been employed for navigation, but until recently, it has not been applied to offshore oil exploration. Whereas most of the world's hydrocarbon provinces were discovered based on onshore seeps, offshore oil seepage was more difficult to 'see' and sample. The technique used to map the seafloor from the time of the Egyptians until the early to mid-20th century was some variation of a weight at the end of a line lowered over the side of the vessel (Mayer, 2006). It wasn't until after the Second World War that a remote sensing technique, using sound waves, became commercially available. These early devices used a piezoelectric transducer to generate a sound pulse (from an applied voltage). The same transducer would receive a reflected sound wave from the seafloor and convert the received pressure signal to voltage. By precisely measuring the time difference, and correcting for the speed of sound in water, each 'ping' could be converted to a depth measurement. These early 'single beam echosounders' used a relatively small transducer or transducer array, which resulted in a very broad (30-60°) beam. Because the transducer measured the time until the first return, which could come from anywhere in the insonified area, the maps created from these systems were biased to the shallowest feature within the beam, and were of relatively low resolution. Still, the maps created in the first few decades after WWII increased the number of soundings in the world's oceans by several orders of magnitude, and found many of the first order features of the world's oceans (for example, the Mid-Atlantic Ridge, which had been discovered by lead-line techniques during the HMS Challenger expedition of 1873 [Thompson, 1878], and mapped during the 1950's using single beam echosounders [Heezen and Tharp, 1954]). At about this time (1947), the oil industry was just beginning to venture offshore following the first successful well out of sight of land, in 4.8m (16') of water in what is now Ship Shoal block 32 in the Gulf of Mexico offshore Louisiana.

Although single beam systems were capable of mapping the large scale topography under the world's oceans, they were not capable of mapping or identifying natural seeps that could serve as evidence of hydrocarbon prospectivity. To do so would require advances in both science and technology.

Chemically-based Lifeforms and Seafloor Seeps:

In 1977 oceanographers discovered life forms where the base of the food chain is chemical energy ("chemosynthesis", as opposed to photosynthesis) at hydrothermal vents in the Galapagos Rift (Lonsdale, 1977). The recognition that mega-fauna could live off chemical energy at these so-called "Black Smoker" hot vents provided the scientific basis for recognizing that similar mega-fauna (clams and tube worms) could be living off chemical energy offshore Oregon (Kulm et al., 1986; Suess et al., 1985) and in the Gulf of Mexico (Kennicutt et al., 1985). These "cold seeps" (**Figure 1**) derived their chemical energy from hydrogen sulfide and methane (Oregon), or from hydrocarbons and methane (Gulf of Mexico). In the decade following the discovery of these unusual benthic communities, researchers found that they were associated with anomalous bathymetric features and anomalous seafloor acoustic character (Hovland and Judd, 1988; Le Pichon et al., 1990; Roberts et al., 1990).

Figure 1: Schematic diagram of seafloor seeps. Fluids (including gas and/or liquid hydrocarbons) can migrate to the surface along conduits such as fault zones, or may percolate through the section, for example at the crest of an anticline. Where fluid expulsions reaches the seafloor, it can support chemosynthetic communities. The fluid seepage, and the seep communities, can alter the shape and acoustic properties of the seafloor.

Imaging Seafloor Seeps with Advances in Seafloor Mapping:

   Submersible (MacDonald et al., 1989) and ROV (Orange et al., 1999) surveys documented that the scale of active seepage at the seafloor was on the order of tens of meters, to perhaps 100m. For hull-mounted mapping systems to be capable of imaging such features required advances in sonar array technology that would increase the resolution of the system by decreasing the size of the area insonified on the seafloor. This was done by employing arrays of transducers that would either transmit or receive acoustic energy that would be narrow in the direction perpendicular to the array. Specifically, a transmit array parallel to the ship's keel transmits a fan-shaped (focused) beam of acoustic energy that would be narrow in the along-ship direction. The receive array, perpendicular to the ship's keel, would 'listen' for returning energy from a narrow acoustic window parallel to the ship's keel. The intersection of these two narrow fan shaped features – the transmit beam and the listening window – is one 'beam' of acoustic energy (**Figure 2**). By breaking the receive array into discrete sub-sections, and employing signal processing techniques to 'listen' in a range of directions (through phase shifting), the receive array is able to detect incoming acoustic energy from discrete fan-shaped acoustic windows at a range of take-off angles athwartship, and in this way is able to detect multiple beams of acoustic return energy for each transmit pulse. This technology, referred to as "multibeam" or "multibeam sonar", was developed in the 1960s and 1970s for the U.S. Navy, and became commercially available after declassification in the late 1970s. The earliest multibeam systems used twelve beams spread across a 45° swath, and, combined with automated contouring software, allowed for mapping of broad swaths of the seafloor. Over the last three decades, multibeam arrays, pushed by the demands of hydrographers and scientists, evolved so that they now can have hundreds of narrow beams, each 1° or smaller across (so that each beam insonifies a small area of seafloor), spread across a 150° swath or more (e.g: **Figure 3**). Such seafloor mapping systems are now capable of imaging natural hydrocarbon seep features relevant to petroleum exploration, and moreover, can do so at survey speeds of ~18.5 km/hr (10 knots), in water depths up to 4000m deep, with a daily survey coverage of 1000 sq. km. or more.
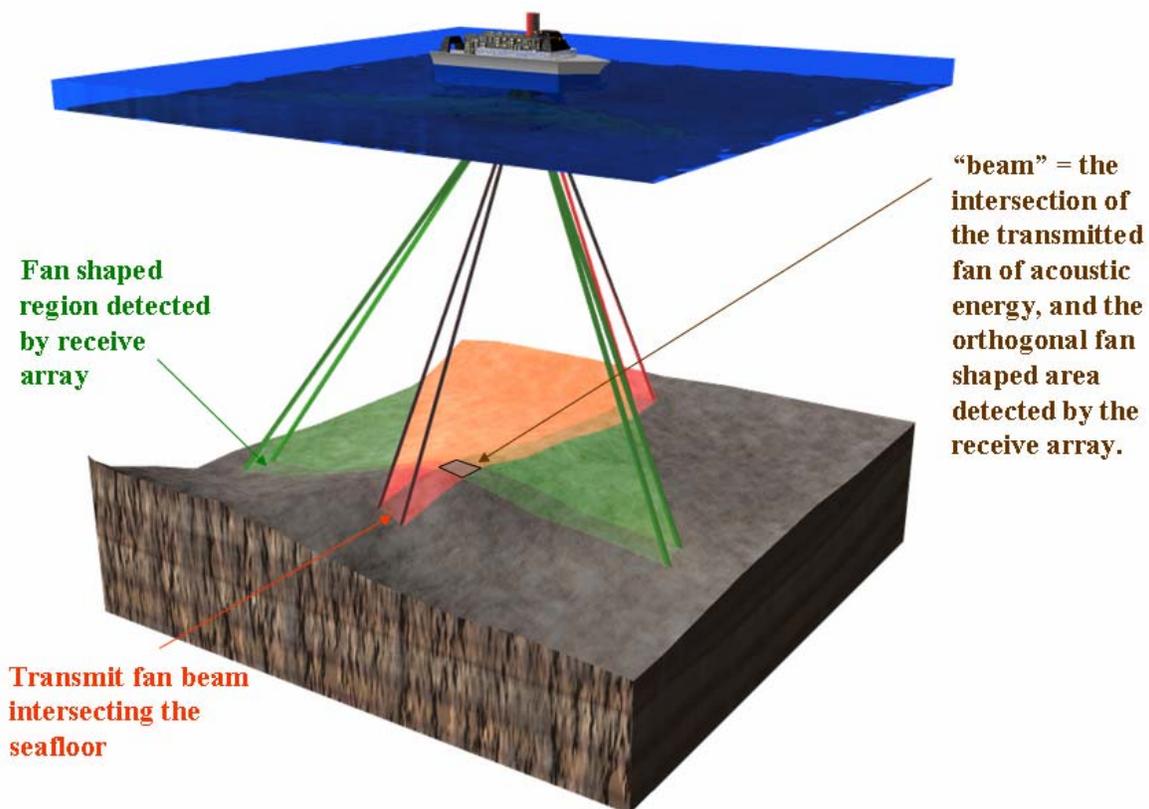

Figure 2: Diagram demonstrating multibeam geometry. The transmit array, oriented parallel to the keel (the long axis of the ship), transmits a fan-shaped beam that is narrow in the along-track direction. The receive array, oriented perpendicular to the keel (athwartship) employs a sub-set of the transducers in order to detect incoming acoustic energy from a fan-shaped area that is narrow in the across-track direction. The area in common between these two fan-shaped regions is the area of the seafloor that is both insonified by the transmit ping, and detected by the receiver. This constitutes one "beam". By sub-dividing the receive array into many sub-sets, and employing signal processing techniques, a single transmit pulse can insonify many such beams on the seafloor, with the beams from a single ping spread across a single swath of the seafloor.

transmit array housing

receive array housing

Transducer array housing

Figure 3: Hydrographic survey vessel, in dry dock, being fitted out with a new multibeam array. The array housing shown is the receiver array, and is 3m long, oriented athrwartship. Only a portion of the transmit array, which in this case is 6m long, is shown. This array, a Kongsberg-Simrad EM120, transmits at a center frequency of 12kHz, and is capable of a transmitting a 1° wide fan beam across track, and detecting a 2° wide fan beam along track. The intersection of the two defines this systems as a 1° x 2° system.

Bathymetry alone, however, only provides part of the picture. The manifestations of seafloor seepage, both biological and chemical/precipitate, alter the acoustic properties of the seafloor. The presence of shells, authigenic carbonate, and gas hydrate can increase the impedance (acoustic velocity x density) of the mudline as well as the roughness (roughness, in this case, defined as a function of the wavelength of acoustic energy). Both the impedance and the roughness of the seafloor affect the strength of the acoustic energy that is returned to the multibeam system – which is referred to as 'backscatter' energy. Backscatter is also sensitive to the volumetric scatter that occurs below the sediment-water interface, so that if the seafloor is both smooth and soft, the backscatter energy will be increased by hard or irregular objects buried below the mudline (Gardner et al., 1991). Modern multibeam systems can acquire backscatter information from the seabed at a scale much smaller than an individual beam footprint, and can correct this backscatter for attenuation, spherical spreading, angle of insonification, etc., such that the data are delivered in quantitative units (decibels), as opposed to a qualitative arbitrary scale.

Most systems only allow one 'ping' to be in the water at any given time, though, so that for example, in 2000m of water on a typical survey, the time between a ping being sent and received may be 5 seconds or longer. Because of this, the precise location as well as orientation in three dimensions (pitch, roll, heading, heave) needs to be known for each element in the transmit array for the time when the ping is sent out, and for each element in the receive array for the time when the acoustic energy returns. This can be achieved through a combination of differential GPS and very accurate motion reference units (MRUs), which are the final elements that allow for very high resolution multibeam data to be acquired. Note that the highest quality instrumentation alone is not sufficient for producing quality data – each system needs to be mounted correctly, and then surveyed in to typically much higher tolerances than the manufacturer requires.

Sampling Seafloor Seeps:

By applying the same advances in positioning (dGPS) and transducer orientation (MRU) to improving Ultra-Short BaseLine (USBL) navigation systems for tracking the positioning of objects in the water column, we are able to follow a piston core from the surface to the seafloor with a very high degree of accuracy (<1%, to perhaps 0.5%, of water depth). This gives us confidence that we can 'hit' any target we can 'see' in order to obtain a sample from a feature that we can analyze for hydrocarbon seepage. The same vessel that is used to core the seafloor can also be used to lower a surface heat flow probe (e.g: Christoffel and Calhaem, 1969; Von Herzen and Anderson, 1972). Such probes can measure the geothermal gradient, and by applying and then monitoring the decay of a heat pulse, be used to calculate the thermal conductivity of the probed section. These can be combined to calculate the heat flow, which can provide valuable information for later basin modeling and petroleum systems analysis.

To sample features of interest we deploy a piston core. The routine core length is 6m, although long cores of 9m, or shorter cores of 3m, may be acquired. Long cores are used for a more lengthy stratigraphic sampling section in benign and normally consolidated regimes, whereas shorter cores can be acquired in an area of anticipated very hard or overconsolidated seafloor. Prior to coring, a USBL beacon is attached to the core unit, either on the body of the core weight itself, or clamped to the wire directly above the core trigger. The USBL beacon is tracked by a 'big head' transducer on the surface vessel (the larger head allows for a narrower beam, and a tighter angular discrimination for the slant range calculation that locates the beacon in the water column). By combining a quality USBL solution with highly accurate vessel positioning (dGPS) and transducer orientation (MRU), the beacon's position in the water column can be constrained to less than 1% of water depth, and in practice, on the order of 0.5%.

Analyzing Cores for Hydrocarbons - Geochemistry:

Anomalous seafloor targets interpreted to be potential seafloor seep sites are interrogated with navigated piston cores. When the core is recovered at the surface, the clear plastic tube containing the core material is extracted from the piston core and visually examined by the client representative and the contractor's shift supervisor. If any features indicative of hydrocarbons are observed (for example, gas hydrate, gas parting, or oil staining), that part of the core would be nominated for sub-sampling. In the absence of such features, three 20cm sections of the core were typically sub-sampled from the core. Geochemical samples were separated by 1m sections of undisturbed sections for later CAT (computed axial tomography) scanning. Following geochemical sub-sampling, all of the remaining core sections were capped and stored vertically for later studies (including sedimentology, paleontology, mineralogy, and seep biology). Samples to be dried and extracted were extruded directly into labeled plastic bags by inverting each bag inside-out and sampling about one-third of each 20 cm section length. Another one-third of each section was used to sample for interstitial gases. After these sections of interstitial-gas core sample were placed into a 500 mL can, 165 mL of clean, degassed seawater with bactericide was added. The can was quickly purged with nitrogen gas to remove atmospheric gases before sealing. All samples were frozen at -20° C. Every effort was made to minimize the time between core retrieval, sample processing, and frozen sample storage. The remaining one third of each sub-section was bagged and retained as an archive / replicate sample, which was retained on the ship until confirmation that the first set had been received by the geochemistry laboratory.

Geochemical analyses include: (1) total scanning fluorescence (TSF) spectra from bagged sediment sections using dried-sediment solvent extraction, (2) gas chromatography for the C_{15+} hydrocarbon concentrations in the same sediment extracts, and (3) head-space gas analysis of the interstitial light hydrocarbon gas (C_1-C_5) concentrations from separately canned sediment sections using wet-sediment gas partitioning and gas chromatography. From these analyses, screening indicators of migrated liquid and gaseous thermogenic hydrocarbons were developed and used to qualify cores and distinguish them from defined background thresholds for the study area. Sediment samples canned for interstitial gas measurements, each representing one section of a core acquired at a site of interest, were qualified for the unambiguous presence of migrated thermogenic gases (Bernard et al., 2008) through flame inozation (for a more detailed discussion of the extraction and analysis techniques, refer to Bernard et al., 2008).

Survey Design:

Multibeam systems come in many different variations, and the optimal configuration for a given survey will depend on the water depth and the desired resolution. The transmitted and received beam width (in degrees) of each beam in a multibeam system is governed by the length of the respective transducer array (in # of wavelengths). Longer arrays achieve a narrower beam width at a given frequency; for any given frequency, an array 50 wavelengths long can achieve a 1° beam width. A 200 kHz system, with a wavelength of 7.5mm, requires a 38cm long array to achieve a 1° beamwidth. A 12 kHz system, with a wavelength of 12.5 cm, requires a 6.3m array. A lower frequency system requires a much larger vessel to carry the long array necessary to get a narrow beam width – which translates fairly directly into a higher day rate for shiptime.

Higher frequences have higher theoretical resolution than lower frequency (Hughes Clarke, 2006). High frequencies (e.g., 200 Hz and above) cannot be used to image water depths much deeper than the continental shelf, however, because acoustic energy absorption in the water column increases at approximately the square of the frequency, so that a 200 kHz system will

suffer approx. 60 db/km of absorption, whereas a 12 kHz system will have on the order of 5 db/km absorption (at similar temperatures and salinities; Francois and Garrison, 1982).

The maximum water depth of interest in a particular survey will govern the maximum useable frequency. For surveys in water depths within the interest of today's deepwater petroleum exploration, e.g.: 3000m or less, a 12 kHz 1° x 2° system will be capable of acquiring data over wide swaths of seafloor – for example, 14.8km with a $\pm$68° system. A higher frequency (e.g.: 30 kHz) system may be capable of imaging the seafloor, but due to the higher attenuation it may not be capable of survey swaths greater than 1 or 2km. In these water depths, a 12 kHz system operated over such a large swath with have a ping rate of 15 seconds, or 77m along track at 5.15 m/s (10 knots), and each individual beam will be insonifying a relatively large area (52m x 105m directly below the vessel ('nadir'), to 140 x 750m at a take-off angle of 68°!). In order to improve the resolution of a multibeam survey with such a system, we force all of the beams to insonify a fixed swath, for example 2km each on port and starboard, thereby decreasing the beam-to-beam centerpoint spacing across track, and because the maximum slant range is less, increasing the ping repetition rate and therefore the beam-to-beam centerpoint spacing along track.

Multibeam surveys are typically conducted with a sail line parallel to isobaths. This allows the survey operator to map a relatively consistent swath of seafloor with a fixed angular survey width. As the water depths get shallower, the swath decreases in width, and the beam centerpoint spacings decrease. Although this, in theory, produces the highest achievable resolution in any given water depth, in practice the data are gridded with the grid cell size governed by the largest centerpoint spacing in the survey area.

We employ a different survey strategy, where, in water depths greater than about 400m, we acquire fixed swath width lines with a survey sail line direction decoupled from the orientation of the isobaths. This allows us, for example, to utilize a sail line direction that minimizes weather downtime by surveying oblique to the swell and wave directions (surveying into the weather can lead to excessive hull slamming which creates bubble – cavitation – sweep down below the transducer array and decreased sonar performance). Although the beam size decreases with decreasing water depth, we maintain consistent beam-to-beam centerpoint spacing by fixing the system into an equi-distant beam spacing mode, thus allowing consistent gridding across a field area which may have a wide range of water depths. Quantitative backscatter is also critical to SeaSeep exploration, and we typically generate backscatter mosaics of sub-sampled beam footprints such that the backscatter pixel size is significantly smaller than the bathymetric bin size, and much smaller than an individual beam footprint. **Figure 4** shows an example of a seafloor anticline that shows an area of very high backscatter that is otherwise not evident on the bathymetric data.

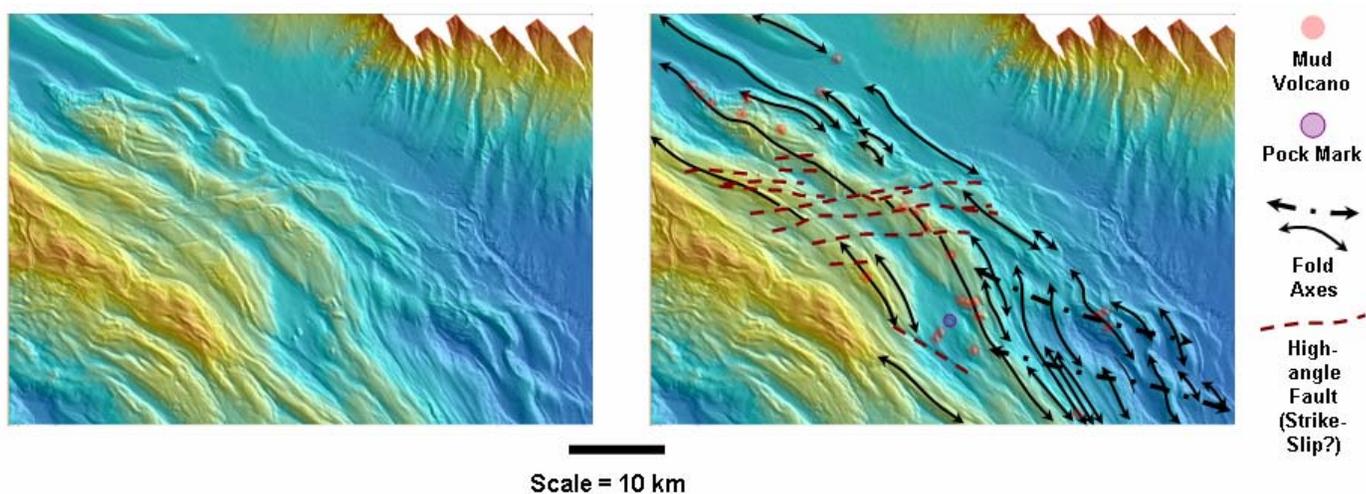**Shaded Relief Bathymetry**   **Backscatter on Shaded Relief Bathymetry**
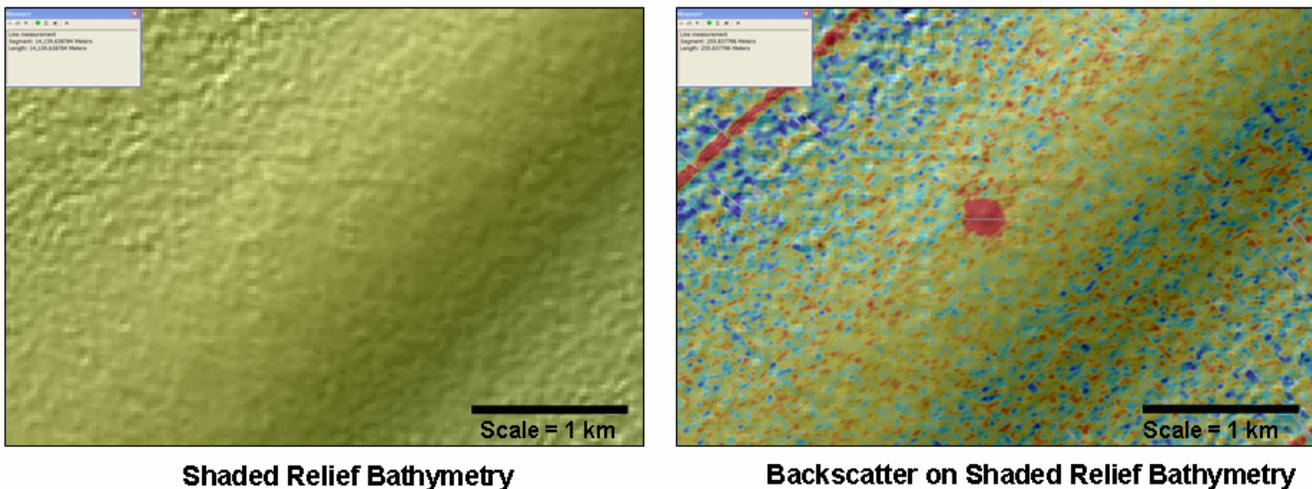
Figure 4: Shaded-relief multibeam bathymetry (left; artificial sun from the northwest) and co-located multibeam backscatter draped on shaded relief bathymetry (right; high backscatter = hotter colors) on a NE-SW trending anticline with a relatively smooth surface. The backscatter, however, shows that on the crest of the anticline there is an area of very high backscatter ~200m in diameter (water depth at the anticlinal crest = 1350m). This example demonstrates that quality backscatter, co-located with quality bathymetry, is critical in helping to identify potential seafloor seep targets. Geochemical analysis from this core target yielded thermogenic gas.

In water depths shallower than 400m, the maximum swath width will be governed by the maximum survey array width (in degrees), so that the cost of surveying a given area of seafloor increases significantly (a survey in 100m of water, with lines spaced every 500m, will be 7x as expensive as a survey in 500m of water, where the lines can be spaced every 3.5km).

Identifying, Prioritizing, and Sampling Features of Interest:

The result of a multibeam survey will be a high-resolution 100% map of seafloor bathymetry and backscatter. Sub-bottom profiler data (high frequency (3.5 – 9kHz), medium beam, ~30°) showing the sub-seafloor acoustic character to ~100ms sub-bottom are acquired along every sail line, as well as gravity and magnetics data. All of these survey data are integrated with available 2D seismic data, as well as satellite-based gravity and magnetics, and satellite Synthetic Aperture Radar (SAR) to assess the basic geology of each survey area (basin architecture, tectonic fabric and character, depocenters, etc.). The data are further used to create a model of the petroleum system which provides the framework for seafloor sampling.

Anomalous bathymetric and backscatter features are identified on the multibeam data, and where possible, tied to the subsurface architecture using seismic data. Individual targets are described based upon their observed features (relief, backscatter, lineations, seafloor structural culminations, etc.), and interpreted based upon their geomorphic character (faults, folds, mud volcanoes, slump headscarps, etc.; **Figure 5**). Targets are graded by each interpreter based upon perceived quality (e.g.: potential to be a geochemical 'hit'). In any given survey area the number of potential targets typically greatly exceeds the available time and budget for coring work in that area, so that targets need to be prioritized.
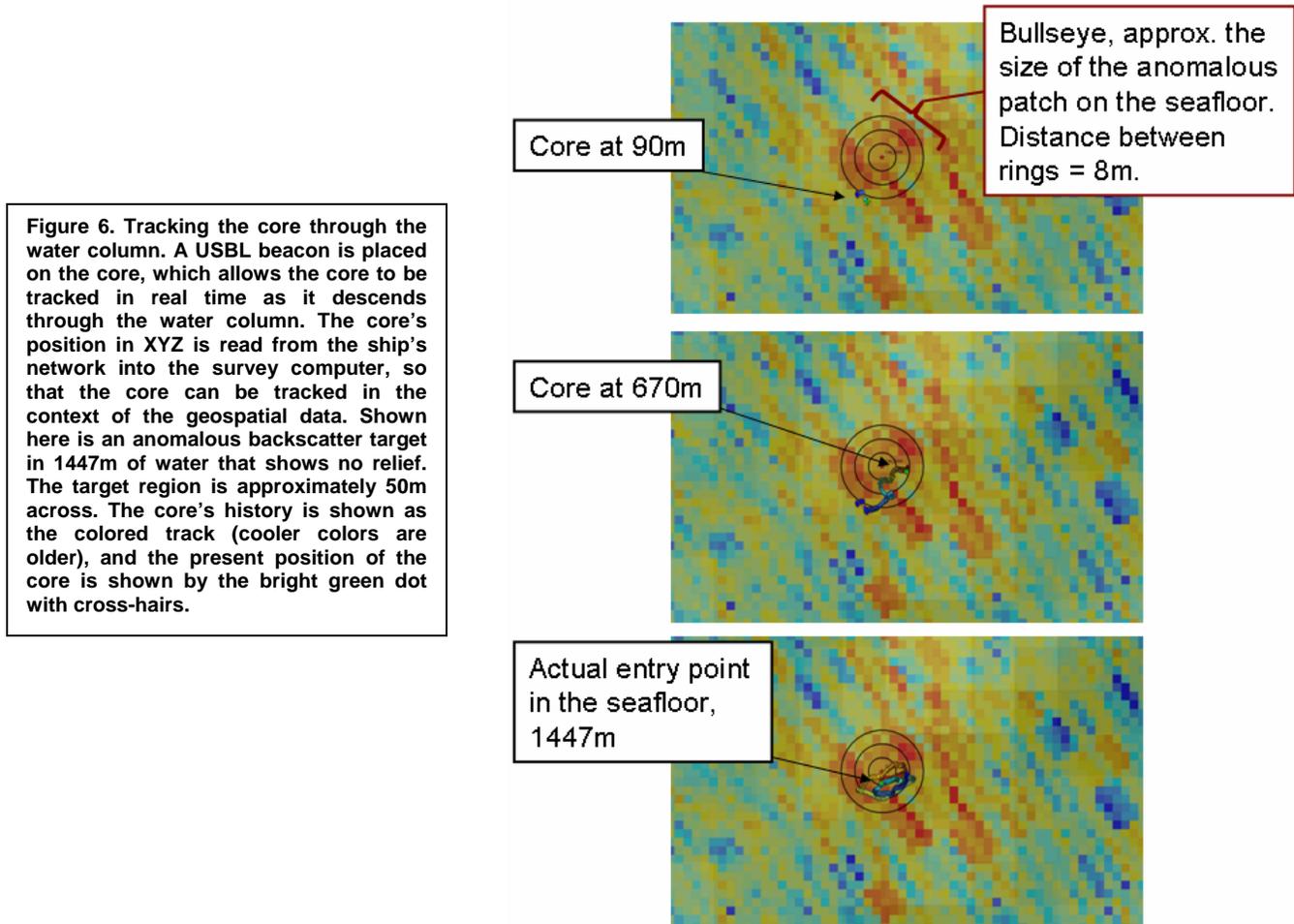

Scale = 10 km

Figure 5: Shaded-relief multibeam bathymetry (artificial sun from the northeast) showing both exceptional structural detail as well as a range of target types. Targets can be identified first based on bathymetry or backscatter, and cross-referenced with the other data set for signs of geologic youth (sharp inflection points in bathymetry) and anomalous seafloor acoustic character (anomalous backscatter). Typically, many more targets are identified in an area than can be cored given time and budget constraints. Targets are prioritized, and spread throughout the survey area. See text for details.

Our strategy is to spread targets spatially, so that all parts of a survey area are interrogated (if one area comes back with no geochemical 'hits', this then provides evidence of absence). Cores are also placed over known leads, or on possible leak points that might interrogate specific leads. We also favor distributing core targets among various target types, even though this may mean that the some of the most highly rated features in a block (for example, mud volcanoes) go untested. The total number of cores in a block will likely be constrained by budget. The challenge for the geoscience team then is to come up with a set of cores that adequately tests the hydrocarbon prospectivity of a block in terms of spatial distribution and target type. Note that we also favor acquiring cores in benign parts of a survey area for background, and that these locations are also where we favor acquiring surface heat flow data (acquired on the same acquisition program as the coring).

The at-sea team utilizes the high resolution multibeam bathymetry and backscatter data during the coring program. The position of the beacon in X, Y, and Z, is broadcast in real time over the ship's network to be read by the survey computer and plotted in the survey GIS in the context of all available geospatial data (**Figure 6**). In this way, the at-sea team can track the core's position relative to the target, and can inform the acquisition contractor as to whether the core is on- or off-target (targets may not be uniform in all dimensions; faults, for example, may have a high tolerance in two directions, but a low tolerance off the fault trend). The typical mode of operation is to track the core's position, and lower it in the water column until it is approximately 50m off the bottom. If the core location is outside of tolerance for that target, the core is held in this position while the vessel maneuvers on the surface and the core, with some lag time, responds until it is in an acceptable location for lowering to the seafloor. In our experience, distances of 20m or less can impact the geochemical success of a core, and so we work closely with our at-sea team to make sure that we are hitting our features of interest. The at-sea team,

though, is gaining experience with every core as to whether a particular target type is problematic relative to recovery, and so they may modify the coring strategy on the fly for all subsequent cores of a particular type in a basin. The goal is not to get the longest recovery possible – the goal is to get meaningful cores that can provide geochemical evidence of seepage, and thus impact the hydrocarbon prospectivity of a basin.

Figure 6. Tracking the core through the water column. A USBL beacon is placed on the core, which allows the core to be tracked in real time as it descends through the water column. The core's position in XYZ is read from the ship's network into the survey computer, so that the core can be tracked in the context of the geospatial data. Shown here is an anomalous backscatter target in 1447m of water that shows no relief. The target region is approximately 50m across. The core's history is shown as the colored track (cooler colors are older), and the present position of the core is shown by the bright green dot with cross-hairs.

Upon recovery from the seafloor, each core is visually inspected for possible evidence of hydrocarbon seepage. In our programs, we have observed visible oil, gas hydrate, and gas parting, all of which provide direct evidence of hydrocarbons. We have also recovered many cores with chemosynthetic fauna (clams, mussels, tubeworms), which may also indicate seafloor seepage of hydrocarbon-rich fluids.

Results:

SeaSeep surveys in water depths deeper than 400m can acquire over 1000 sq. km. of data per day, with complete survey blocks delivered at the completion of each port call. The SeaSeep portion of the Indonesia Frontier Basins (IFB) program (**Figure 7**) utilized 2 multibeam vessels, each equipped with a 191 beam, 1° x 2° beam, 12 kHz multibeam system as well as a higher frequency (95 kHz) system capable of mapping the upper slope and shelf. Both vessels were put through extensive sea trials and calibration in order to tune each component of the system to its utmost capability, with the end result that the overall system performed far beyond the manufacturer's specification. A combination of standard patch test techniques (Wheaton, 1988; Herlihy et al., 1989) and the 'reference surface' calibration approach (Hughes Clarke, 1993; Hughes Clarke and Godin, 1993), was employed along with our own calibration and trouble-shooting routines. The IFB used one coring vessel, which also acquired heat flow data. The IFB was carried out by TGS-NOPEC, with BGE providing planning and technical oversight of the SeaSeep portions of the program. The program mapped over 400,000 sq. km. in unprecedented detail in less than a year. The coring vessel began acquisition approximately five months after the first multibeam vessel began acquiring data, and acquired 1182 cores for geochemical analysis; the last core was acquired 15 months after the multibeam program began, with the final geochemistry analysis summary delivered one month after that. The proof of success is geochemistry, and cores acquired by TGS-NOPEC as part of the Indonesia Frontier Basins Project successfully sampled oil, condensate and gas throughout the areas surveyed.
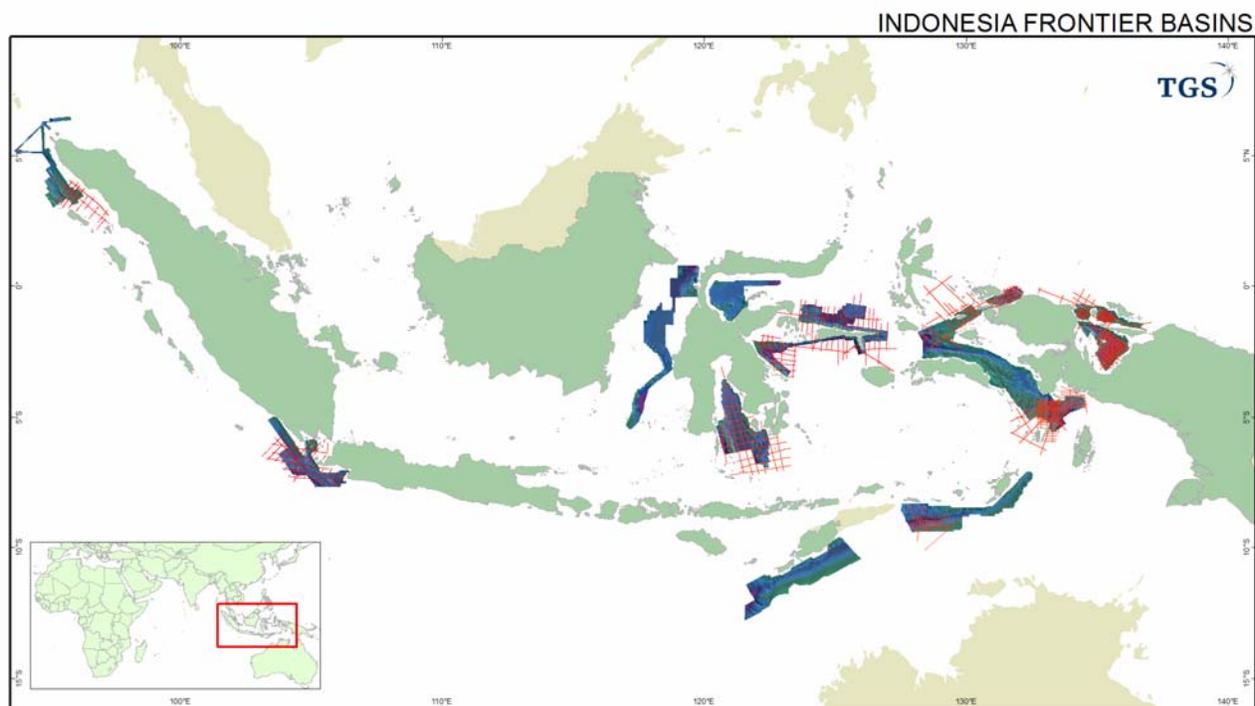
Figure 7: Location map of the Indonesia Fontier Basins mega-survey, showing new 2D seismic acquisition (red lines) and SeaSeep™ multibeam survey areas (shaded as a function of water depth, with deeper water darker blue).

Sediment extracts of this study, each representing one section of a core acquired at a site of interest, were qualified for the unambiguous presence of migrated liquid petroleum (thermogenic) hydrocarbons (Bernard et al., 2008). Using these screening criteria, 140 of the 1182 cores (12%) exhibited unambiguous evidence of liquid petroleum hydrocarbons. A large number of the analyses yielded very high total scanning fluorescence values (**Figures 8, 9**), and upon examination, showed chromatograms clearly indicative of fresh (non-biodegraded) oil. Upon further analysis of these samples, 20 have yielded biomarker (molecular fingerprinting) suites providing insight into the maturity and source of multiple gas and oil petroleum systems. The overall high percentage of oil seep hits, and the quality of the hydrocarbons sampled at the seafloor, are unusual for frontier SeaSeep surveys (compare the 12% success for the IFB to to about 8% on average globally, and <5% on average in frontier basins), and attests to the potential of the region as well as to the quality of the targets selected.

Headspace gas analyses of the interstitial gases in the cores yielded 525 of the 1182 cores (44%) that exhibited unambiguous evidence of thermogenic gas, including many with pristine, unfractionated reservoir gases (Bernard et al., 2008). This is an unusually high percentage of gas seep shows for frontier SeaSeep surveys (compared to about 25% on average), and, again, attests to the potential of the region as well as to the quality of the targets selected. Thermogenic gas shows typically outnumber the oil shows in a prospective regional study, apparently due to the higher mobility of the gases during migration (Bernard et al., 2008).

Figure 8: Unresolved Complex Mixture (UCM, generally associated with extracts that contain oil) vs. Total Scanning Fluorescence (TSF, a semi-quantitative analytical technique using UV light to cause trace quantities of chemical compounds in samples to fluoresce). Samples in the upper-right quadrant are typically significant oil "hits", whereas less prolific 'seep' hits, although still significant as hydrocarbon hits, have a lower UCM and TSF. A comparison of the IFB data to Angola and Nigeria graphically shows the quality of the IFB oil seep 'hits' (after Bernard et al., 2008).
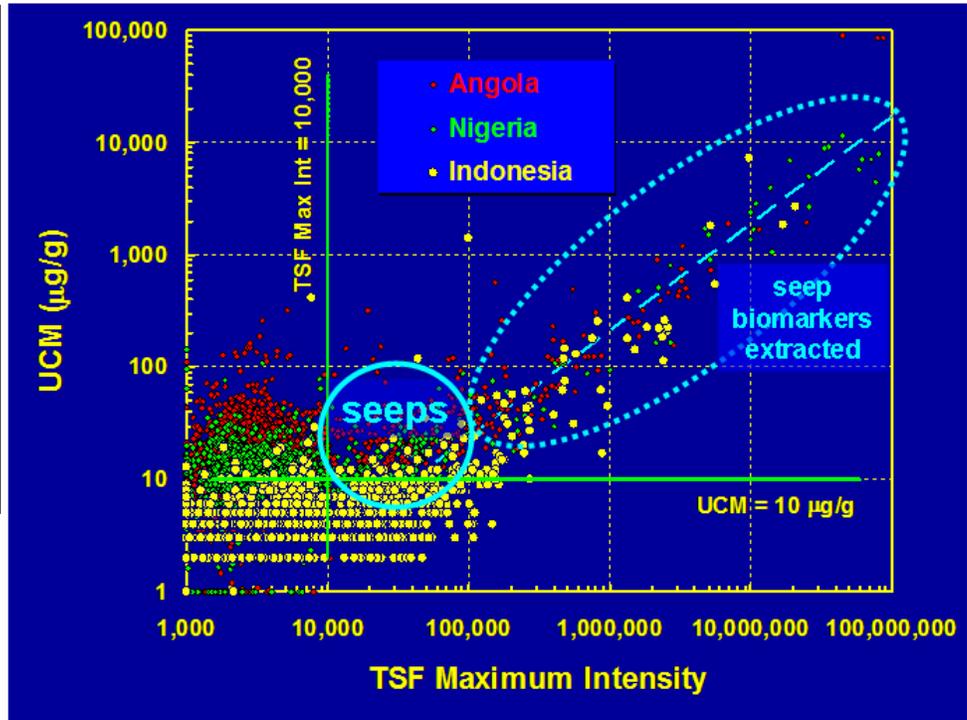
Figure 9: Geochemical "hit" breakdown of all cores that showed geochemical evidence of oil or thermogenic gas. A total of 3122 geochemical analyses were analyzed from 1182 cores. The chart shown is for cores, so that many cores have more than one sub-section analyzed for geochemical anomalies.
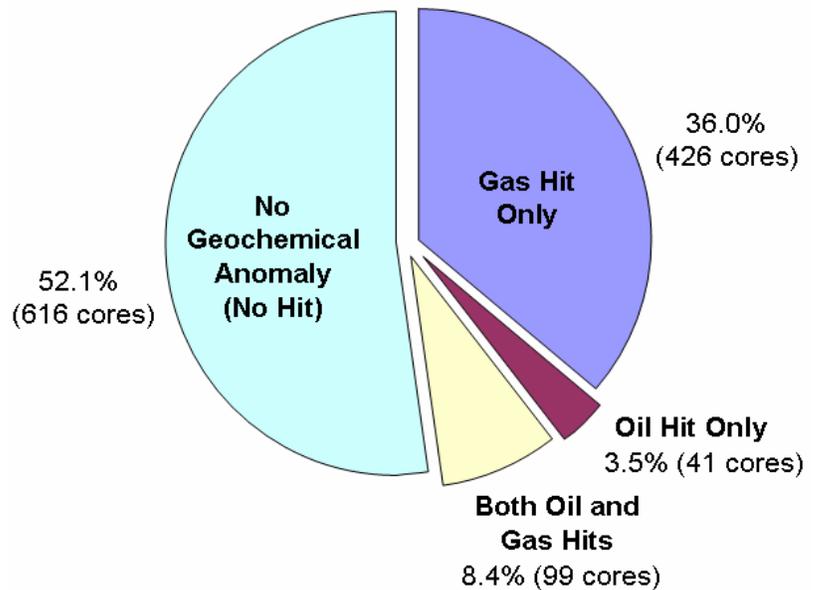
Significance – Cost-Effective and Rapid Risk Reduction:

Combined with more traditional data sets such as 2D seismic, gravity and magnetics, multibeam surveys and follow-up navigated coring applied in a SeaSeep approach can be used to lower the risk for exploration by providing information on source, maturity and migration. In the recent Indonesia frontier basins program, we have demonstrated that a well-planned and well-executed SeaSeep survey can successfully identify and sample oil and gas seeps in frontier basins.

The Indonesia Frontier Basin SeaSeep program interrogated 400,000 sq. km. of frontier basin in 15 months, from the first multibeam ping to the last core acquired. Geochemical data were available for evaluation, and interpretation of prospectivity, within 30 days of the completion of each coring leg. By integrating the resultant geochemistry, including the distribution, strength and composition of hydrocarbon 'hits', with the 2D seismic, multibeam, gravity and magnetics, the program was able to dramatically increase the amount and quality of petroleum system information in each of the basins surveyed. Specifically, the oil and gas data were used to define source (or, in some cases, multiple sources!) and constrain maturity.

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