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Hydrocarbon Systems Analysis of the Northern Gulf of Mexico: Delineation of Hydrocarbon Migration Pathways Using Seeps and Seismic Imaging

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ABSTRACT

Widespread oil and gas seepage in the offshore U.S. Gulf of Mexico has allowed the extension of hydrocarbon systems and maturity maps far beyond well control. Analysis of sea-bottom dropcores and imaging of sea-surface slicks have complemented Exxon's integrated, multidisciplinary study of sources, maturation, and migration pathways. Our approach involved development of a regional geologic framework through interpretation of 2-D and 3-D seismic data, identification and mapping of potential source intervals, and delineation of likely migration pathways to reservoirs and seismic-amplitude anomalies. Hydrocarbon compositions from more than 2000 reservoired oils, 600 reservoired natural gases, and 3000 hydrocarbon-bearing, sea-bottom dropcores help constrain such source-rock characteristics as organic-matter type, depositional facies, level of maturation and, to some extent, age. East of the Mississippi River Delta, the complete stratigraphic section is visible on seismic sections, and wells have penetrated deep source intervals. To the west, correlative organic-rich rocks have been sampled onshore and from sheaths overlying salt diapirs offshore. Integration of these data into a regional geologic framework provides a strong basis for hydrocarbon-systems interpretations.

Major offshore hydrocarbon systems are derived from lower Tertiary (centered on Eocene), Upper Cretaceous (centered on Turonian), and Upper Jurassic (centered on Tithonian) source intervals. All Eocene oil types (marine, intermediate, and terrestrial) have been

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tied to source rocks and are consistent with paleofacies distributions for the Eocene deltaic systems. Eocene oils and gases are prevalent on the Texas and Louisiana Shelves and extend both onshore and onto the Texas Slope. Turonian oils have been tied to source rocks offshore (east of the Mississippi River Delta) and onshore (e.g., Tuscaloosa and Giddings trends). Based on seismic-image thinning of the interval and disappearance of diagnostic oils, we interpret a basinward loss of this source type. Elevated-sulfur oils and associated (cogenerated) gases on the upper Gulf of Mexico Slope are interpreted to have originated from a Tithonian source. High-maturity, organic-rich calcareous shales of this age have been penetrated in the eastern Gulf of Mexico, and Tithonian oils occur in Cretaceous reservoirs on the Florida Shelf where the Upper Cretaceous and Tertiary sections are immature. Oxfordian carbonate-sourced oils are common across the northern Gulf basin's rim, and lower-maturity hydrocarbons from this source occur in stains and seeps in the deep central Gulf of Mexico.

Refinements in our understanding of Gulf of Mexico hydrocarbon systems have resulted from this study. They have helped us to improve our exploration methodologies and have provided us with new play concepts.

INTRODUCTION

Continued exploration success in the northern U.S. Gulf of Mexico Basin requires a thorough understanding of all elements of the hydrocarbon systems. To this end, Exxon (now ExxonMobil) has carried out an integrated study to assess sources, maturation, and migration pathways of known and potential hydrocarbon plays in the offshore U.S. Gulf of Mexico. Exxon's multidisciplinary approach has involved development of a regional geologic framework through the interpretation of 2-D and 3-D seismic data, identification and mapping of potential source intervals, and delineation of likely migration pathways. This approach permits evaluation of hydrocarbon migration from mature source intervals to known accumulations and potential reservoirs, as identified by seismic-amplitude anomalies.

The recognition of widespread, and often intense, oil and natural-gas seepage on the Gulf of Mexico Slope has contributed significantly to our understanding of the hydrocarbon systems. As part of this study, we analyzed a large number of sea-bottom dropcores (>5000) and identified surface slicks from remote-sensing data. The sea-bottom dropcores were obtained from existing proprietary dropcore programs, industry consortia, and geotechnical shallow-hazard surveys. Characterization of oils and natural gases in seeps has allowed us to extend our hydrocarbon-family and hydrocarbon-maturity maps far beyond well control. Moreover, abundant seepage documents active hydrocarbon migration on the Gulf of Mexico Slope and provides a means to identify effective migration pathways. Major hydrocarbon accumulations on the slope are commonly associated with intense seepage at the seafloor intersection of the corresponding cross-stratal migration pathways. Thus, seeps provide information that potentially can be used to help rank possible migration pathways to prospects. In addition, the geochemical composition of seep hydrocarbons (as interpreted from biomarkers) can provide important predrilling information about the likely properties of unbiodegraded oils (e.g., API gravity and sulfur content). Oil properties can have a significant impact on production and refinement costs and therefore on product value. By providing advance knowledge about the likely oil properties, seeps can make a major contribution to the economic evaluation of a potential hydrocarbon accumulation.

APPROACH AND GEOLOGIC FRAMEWORK

The sources for oils reservoired in the young Tertiary section of the offshore Gulf of Mexico have been enigmatic in the past, because of a paucity of source-rock penetrations in offshore drilling. Many approaches have been used to infer source intervals. For example, Nunn and Sassen (1986) used maturation modeling to suggest that Cretaceous and lower Tertiary sediments were the probable sources of oils in the offshore Louisiana continental-slope area. Our approach was to focus on an initial study area east of the present-day Mississippi River Delta where the Tertiary section thins and wells have penetrated deep potential source rocks. This area was also selected because the complete stratigraphic section can be imaged on seismic sections, because of only limited interference from shallow salt. To the west, where secondary and even tertiary salt features are abundant in the shallow section, samples of organic-rich rock (dated by microfossils) have been obtained from sheaths overlying salt diapirs. These samples have provided access to source rocks in areas where they typically lie far below current drilling depths. When combined with known, effective source-rock penetrations from the onshore northern Gulf basin and integrated within a regional geologic framework, these data provide a strong basis for source-age interpretations (Wenger et al., 1994).

Geochemical compositions of reservoired and seep hydrocarbons provide a perspective on the regional characteristics and maturity of their respective source rocks. Oil and, to some extent, natural-gas compositions constrain such source-rock characteristics as organic-matter type, clastic versus carbonate facies, elevated versus normal salinity, level of maturation and, to a lesser extent, age. In all, more than 2000 reservoired oils, 600 reservoired natural gases, and 3000 hydrocarbon-bearing seabottom dropcores from the northern Gulf basin have been analyzed. Source-rock ages and the oil types (families) related to each source interval are based on direct comparison of biomarkers to source-rock extracts (e.g., Peters and Moldowan, 1993) as well as inferences drawn from hydrocarbon compositions and constraints of the geologic framework.

To the east of the present-day Mississippi River Delta, source intervals occur at depths between about 16,000 and 35,000 ft (4900–10,700 m) and are generally visible on seismic sections because of only limited interference by small, simple salt bodies above source levels (Figure 1). In contrast, to the west, the source intervals commonly occur at depths between 30,000 and 45,000+ ft (9200–13,700+ m), and seismic visibility is hampered by the presence of multilayered salt sills and/or salt welds with complex geometries formed by sediment loading. Interpretation of hydrocarbon families and source intervals in this more complex setting was guided by extending westward the observations and methodologies developed in the east and north. Most 2-D seismic surveys designed to image common reservoir intervals are generally inadequate to only marginally adequate for imaging deeper source intervals and migration pathways. These data are typically high (60–75) fold, acquired with 4000–4500 m of cable, and recorded to 8 seconds (s). Dramatic improvements in imaging the total hydrocarbon system are provided by a longer cable (6000 m), 3-D versus 2-D acquisition, and longer recording times (15 s). To date, 3-D data collected using a 6000-m cable have provided some of the best resolution (Gross et al., 1995). We used more than 3500 mi^2 (9100 km^2) of 3-D seismic data and 25,000 line-mi (40,250 line-km) of 2-D seismic data within the area east of the Mississippi River Delta, including a 4-mi (6.4-km) grid of 6000-m cable data, recorded to 15 s. A similar amount of seismic data was interpreted to the west of the Mississippi River Delta, on the Louisiana Shelf and Slope and the Texas Slope.

GULF OF MEXICO HYDROCARBON SYSTEMS

Knowledge of the effective source rocks for an area is critical to understanding the overall hydrocarbon system.

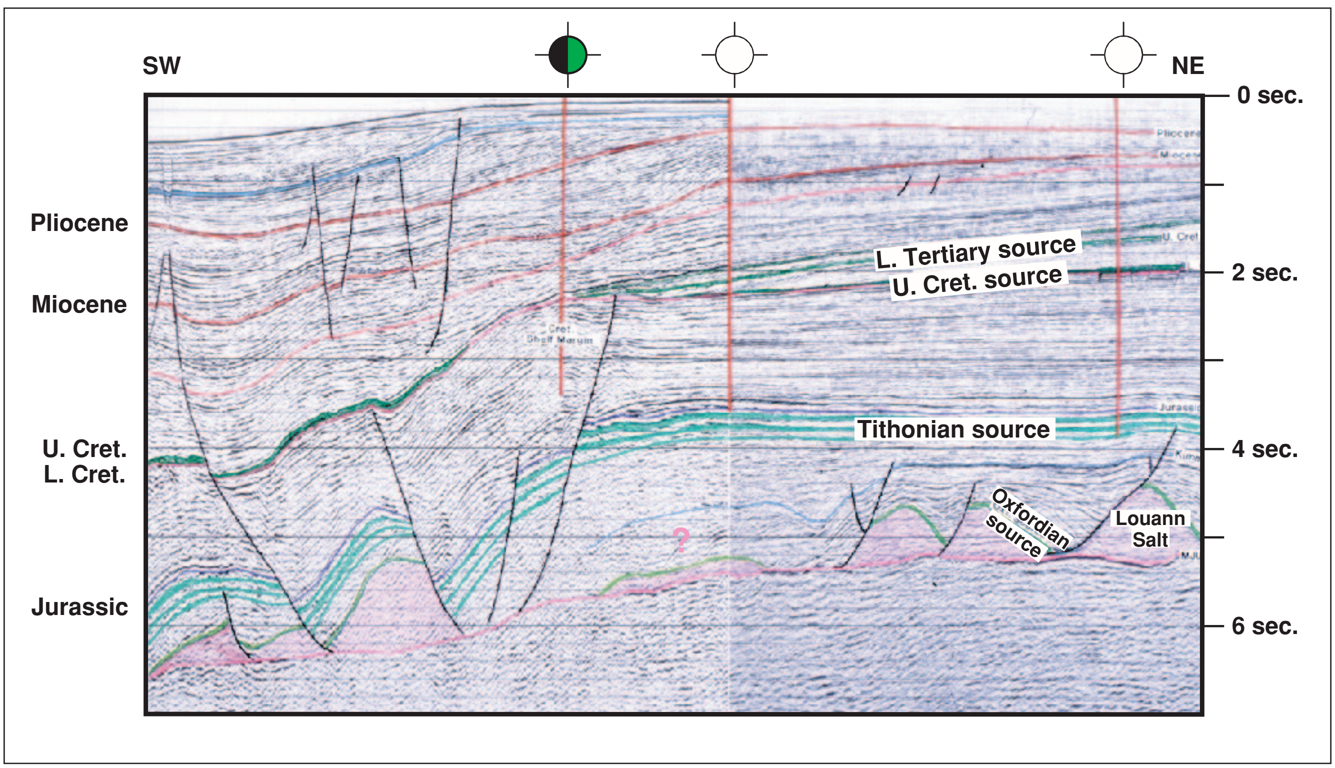

FIGURE 1. Example of a regional seismic line from the eastern Gulf of Mexico that illustrates limited disruption, by salt, of the shallow stratigraphic section. Note that deep wells have penetrated several of the potential source intervals.

Critical source-rock penetrations both offshore and onshore in the northern Gulf of Mexico Basin, when integrated into a regional geologic framework, provide a strong basis for interpreting source age and distribution (Figure 2).

The youngest effective source interval identified in the northern Gulf basin is in lower Tertiary strata, centered on the Eocene (Table 1). No significant Oligocene or younger source rocks have been identified. Oils from the lower Tertiary source have been divided into three subtypes: Tertiary Marine, Tertiary Intermediate, and Tertiary Terrestrial. They reflect a genetically related continuum of hydrocarbons derived from varying mixtures of marine-algal and higher-plant organic matter related to the distribution of shale facies within (or distal to) the Tertiary delta system. Direct correlations to source rocks have been made for all lower Tertiary oil types (McDade et al., 1993). Variations in source-rock character are consistent with the distribution of oil subtypes and with paleofacies of the Eocene deltaic system. Source-rock ties from onshore have been extrapolated to similar oils on the offshore shelf and slope, assuming a corresponding relationship to depositional facies. Organic-rich rocks of Eocene age have been penetrated offshore in sheaths overlying salt diapirs, although the high level of maturity precluded direct rock-oil ties based on geochemical compositions.

Regional differences in the original organic-matter composition of the lower Tertiary source appear to explain much of the variation in the resulting hydrocarbon compositions (distribution of oil versus gas). The marine-source subtype appears to produce a greater proportion of oil, whereas the terrestrial-source subtype appears to be more gas prone. This conclusion contrasts with interpretations in which the prevalence of thermogenic natural gases and gas condensates on the Texas Shelf and onshore has been attributed to higher source maturity (e.g., Thompson et al., 1990).

The next-older source interval identified is in Upper Cretaceous strata, centered on the Turonian. Turonian source rocks are clay-rich shales with dominantly marine organic matter that generates low-sulfur oils (Marine–Low Sulfur–No Tertiary Influence). Direct oil-to-source-rock ties have been made offshore, east of the present Mississippi River Delta, and onshore in the Tuscaloosa trend of Louisiana and Mississippi and the Giddings trend of Texas (see also Wagner et al., 1994). Offshore, we interpret a basinward loss of Turonian source rocks based on seismically displayed thinning of the interval and disappearance of the oil type. In south Texas, a more calcareous (moderate-sulfur) oil type (Calcareous–Undifferentiated Cretaceous) may result, in part from a facies change in the Turonian, although this oil type has also been tied directly to a Lower Cretaceous marine calcareous shale. High-sulfur oils from

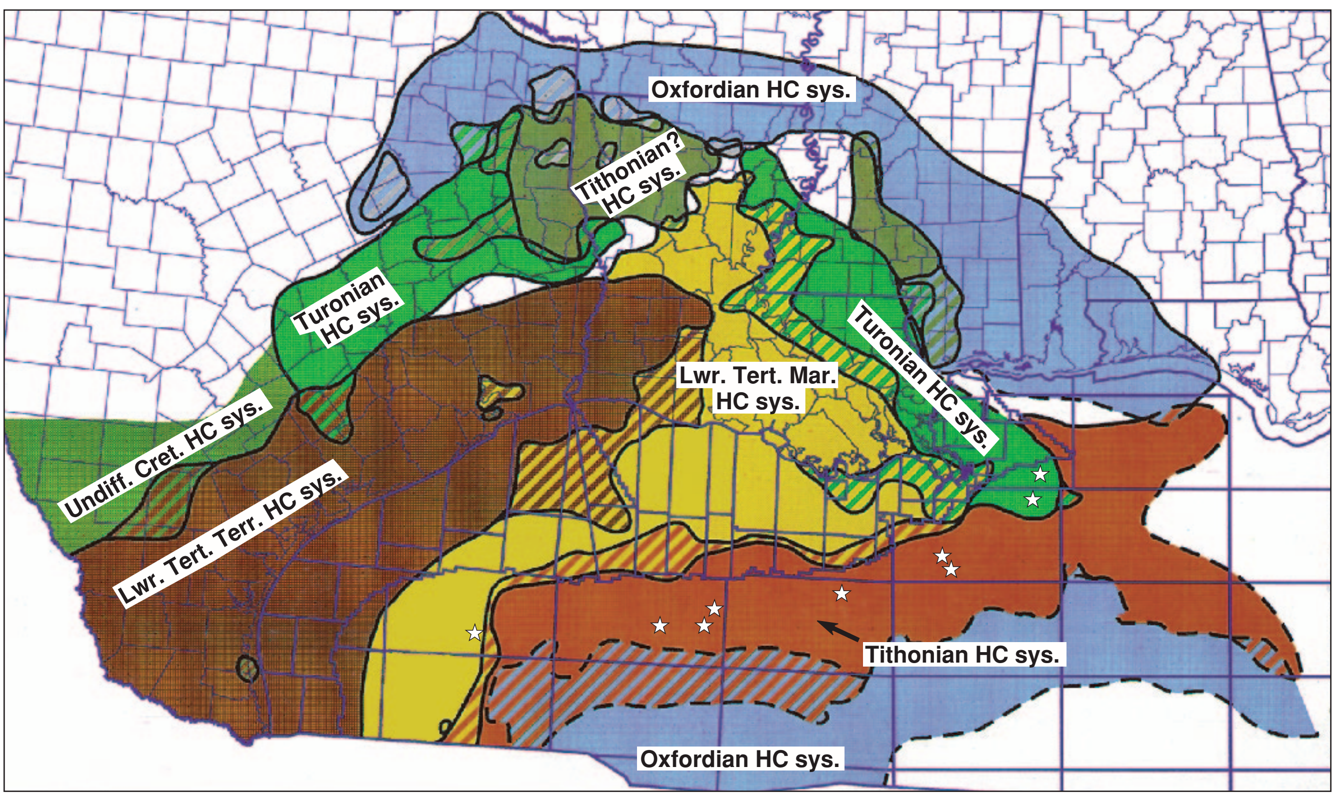

Figure 2. Interpreted hydrocarbon-systems map for the northern Gulf of Mexico Basin. Each hydrocarbon system comprises a family of oils and gases having similar compositions and interpreted to have originated from a common source interval. Stars indicate selected major deep-water discoveries.

Table 1. Northern Gulf of Mexico Basin source intervals (ages), hydrocarbon families, and summary of established rock-oil ties.

Source interval	*Oil types*	*Rock-oil tie*
Lower Tertiary (centered on Eocene)*	Tertiary Marine Tertiary Intermediate Tertiary Terrestrial	Tie with high-maturity core, south Louisiana Multiple-maturity suites (core), south-central Louisiana Offshore Texas (salt sheath)
Upper Cretaceous (centered on Turonian)*	Marine—Low Sulfur—No Tertiary Influence	Direct ties with mature source rocks: Offshore—eastern Gulf of Mexico Onshore—Tuscaloosa trend, Louisiana and Mississippi; Giddings trend, Texas
Lower Cretaceous	Carbonate—Elevated Salinity—Cretaceous	Direct ties with source rocks, South Florida Basin
Undifferentiated Cretaceous		Calcareous—Undifferentiated Cretaceous Production from fractured Lower Cretaceous black shale— south Texas
Uppermost Jurassic (centered on Tithonian)*	Marine—High Sulfur—Jurassic Marine—Moderately High Sulfur—Jurassic Marine—Moderate Sulfur—Jurassic	Inferred tie to postmature, organic-rich calcareous shales—eastern Gulf of Mexico Oils in Lower Cretaceous reservoirs on Florida shelf where Turonian/Eocene is immature
Upper Jurassic (Oxfordian)	Carbonate—Elevated Salinity—Jurassic	Tie to postmature, organic-rich carbonates— Mobile Bay
Triassic (Eagle Mills)	Triassic—Lacustrine	Tie to postmature, organic-rich cores, northeast Texas Paleontology and palynology confirm nonmarine source character

* "Centered on" means that the source is largely contained within, but may not be restricted to, the designated interval.

the Sunniland trend (Carbonate–Elevated Salinity–Lower Cretaceous) of the South Florida Basin are derived from Lower Cretaceous strata, centered on the Aptian.

The source for most reservoired thermogenic hydrocarbons on the Gulf of Mexico Slope is interpreted to be uppermost Jurassic, centered on the Tithonian. Organic-rich calcareous shales of Tithonian age have been penetrated and sampled within wells in the area east of the present Mississippi River Delta. Although the high maturity level of these shales makes geochemical correlation (using biomarkers) with early-mature hydrocarbons on the slope difficult, extrapolation of source character from oils constrains the age of the appropriate facies in the area of occurrence for this oil type. Geographic variations in source facies are probably responsible for differences in sulfur content and associated geochemical parameters (Moderate Sulfur, Moderately High Sulfur, and High-sulfur oil subtypes) of unbiodegraded oils. Oils and stains of these subtypes (distinct from older Oxfordian oils) occur in Cretaceous reservoirs on the Florida Shelf where the Tertiary and Upper Cretaceous sections are immature. Hydrocarbons occurring in many uppermost Jurassic and Lower Cretaceous reservoirs along the onshore northern rim of the Gulf basin, which are geochemically distinct from the two older oil types described below, have also been tentatively ascribed to a Tithonian source (Calcareous–Upper Jurassic or Lower Cretaceous?). These oils have never been encountered in Oxfordian or older reservoirs. The Tithonian has also been reported to be the major source of oils in the Mexican Gulf of Mexico (González-Garciá and Holguin-Quiñones, 1992).

Upper Jurassic (Oxfordian) carbonate-sourced oils (Carbonate–Elevated Salinity–Jurassic oil type) are common across the northern rim of the Gulf basin from northeast Texas to Florida (Oehler, 1984; Wenger et al., 1990). The distinctive geochemical signature of this oil type puts extremely tight constraints on the age of the source facies. Organic-rich, postmature carbonates from Mobile Bay provide a correlative rock tie. Seeps and stains of this oil type in the deep central Gulf confirm a widespread deep basin occurrence of the source interval, assuming minimal changes in facies.

Finally, hydrocarbons from a Triassic lacustrine source have been encountered along the bounding faults of the northern Gulf basin. These hydrocarbon liquids display a strong (and unusual) fermenting bacterial input from the source facies. Although they are postmature where penetrated, paleontologic and palynologic analyses of organic-rich Triassic cores from northeast Texas have confirmed the nonmarine (i.e., the lacustrine) nature of the depositional environment and have provided a basis for correlation with these geochemically unusual liquids (Schumacher and Parker, 1990; James et al., 1993).

The four key source intervals in the offshore Gulf of Mexico (centered on lower Tertiary, Upper Cretaceous, Upper Jurassic–Tithonian, and Upper Jurassic–Oxfordian strata) coincide with second-order transgressions in a sequence-stratigraphic framework (Figure 3). Core and cuttings analyses indicate that source richness can vary considerably within an interval, possibly reflecting local or temporal variations in the environment.

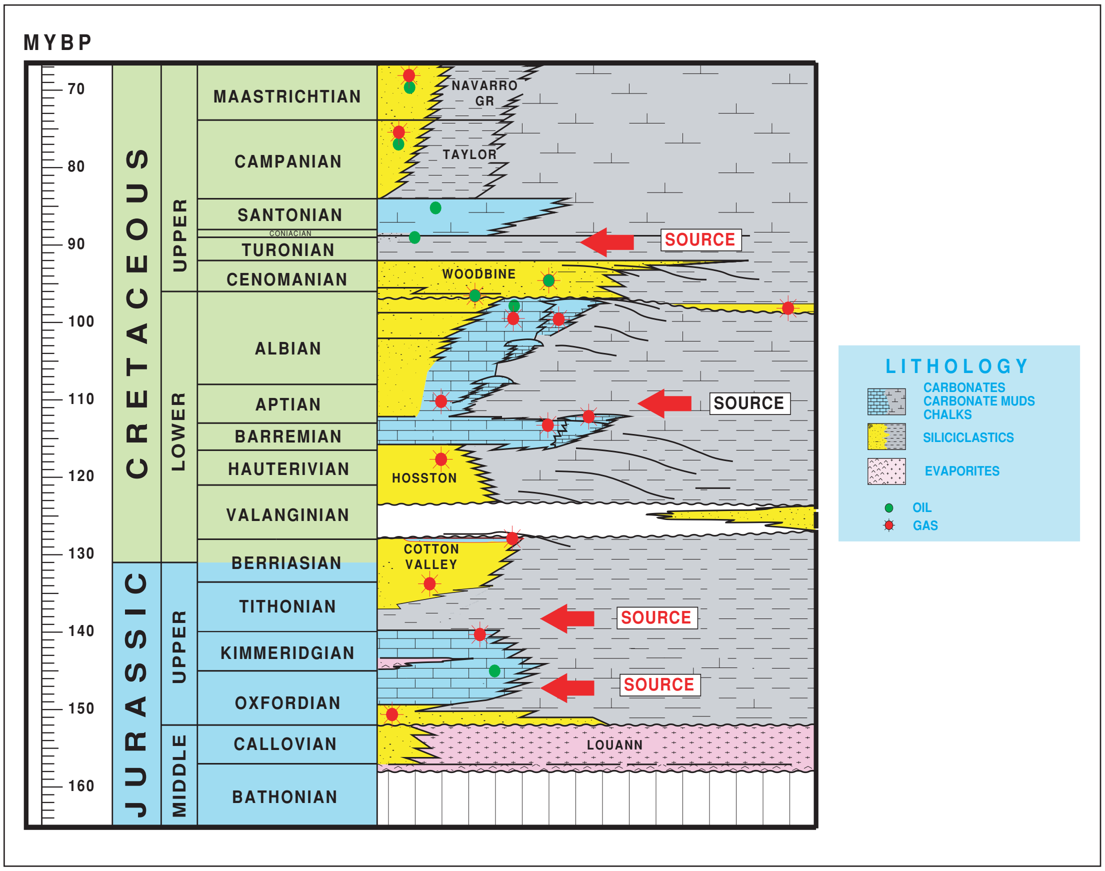

FIGURE 3. Stratigraphic column showing the Mesozoic source intervals (arrows) for the offshore Gulf of Mexico. Note that source intervals coincide with second-order transgressions in a sequence-stratigraphic framework (e.g., Haq et al., 1988).

REMOTE SENSING OF SEA-SURFACE SLICKS

Remote-sensing (satellite) techniques are useful screening tools for identifying potential hydrocarbon seepage in a basin (e.g., MacDonald et al., 1993). Various techniques, such as Landsat Thematic Mapper and Synthetic Aperture Radar, can image hydrocarbon slicks remotely on the sea surface. Hydrocarbons on the sea surface often dampen ripples and reduce the reflectivity of water, making slicks appear as darker patterns on the sea surface. Remote-sensing techniques are often expedient because large offshore areas can be screened rapidly and in a cost-effective manner. Application of multiple techniques and/or multitemporal images raises confidence in the interpretation of authentic natural surface slicks. Abundant natural slicks generally indicate an active hydrocarbon system (e.g., MacGregor, 1993; Kornacki et al., 1994) and may provide some evidence of hydrocarbon charge limits.

Slick distributions provide an initial guide to areas that are candidates for site-specific, sea-bottom sediment coring surveys. Numerous factors can affect both the interpretation of authentic seepage and the location of surface slicks relative to source vents on the sea bottom. These factors include wind velocity and direction, currents, cloud cover, meteorologic conditions, marine vegetation, and anthropogenic pollution. After candidate areas have been identified, the next step is to verify the sea-bottom source of the hydrocarbons. High-resolution 2-D and 3-D seismic data, sometimes complemented by side-scan sonar surveys, are used to identify sea-bottom features from which dropcores can be collected. Potential targets include the surface expressions of deep-cutting faults and diapirs, as well as such other water-bottom features as mounds and pockmarks. Many such water-bottom features in the deep-water Gulf of Mexico contain small quantities of hydrocarbons that have migrated from depth. Dropcores collected over targeted water-bottom features are analyzed for the presence and geochemical characteristics of petroleum hydrocarbons.

SEA-BOTTOM HYDROCARBON SEEPS

The Gulf of Mexico Slope contains widespread areas of oil and gas seepage (Figure 4) that have allowed investigators to extend hydrocarbon-system maps and predictions of hydrocarbon type and properties far beyond well control. The utility of seeps as a tool for interpreting hydrocarbon characteristics and distribution, however, is limited by several factors. First, the hydrocarbons (both oil and gas) in large seeps are often highly biodegraded. Large seeps provide sites for complex chemosynthetic communities that live off seeping oil and natural gas

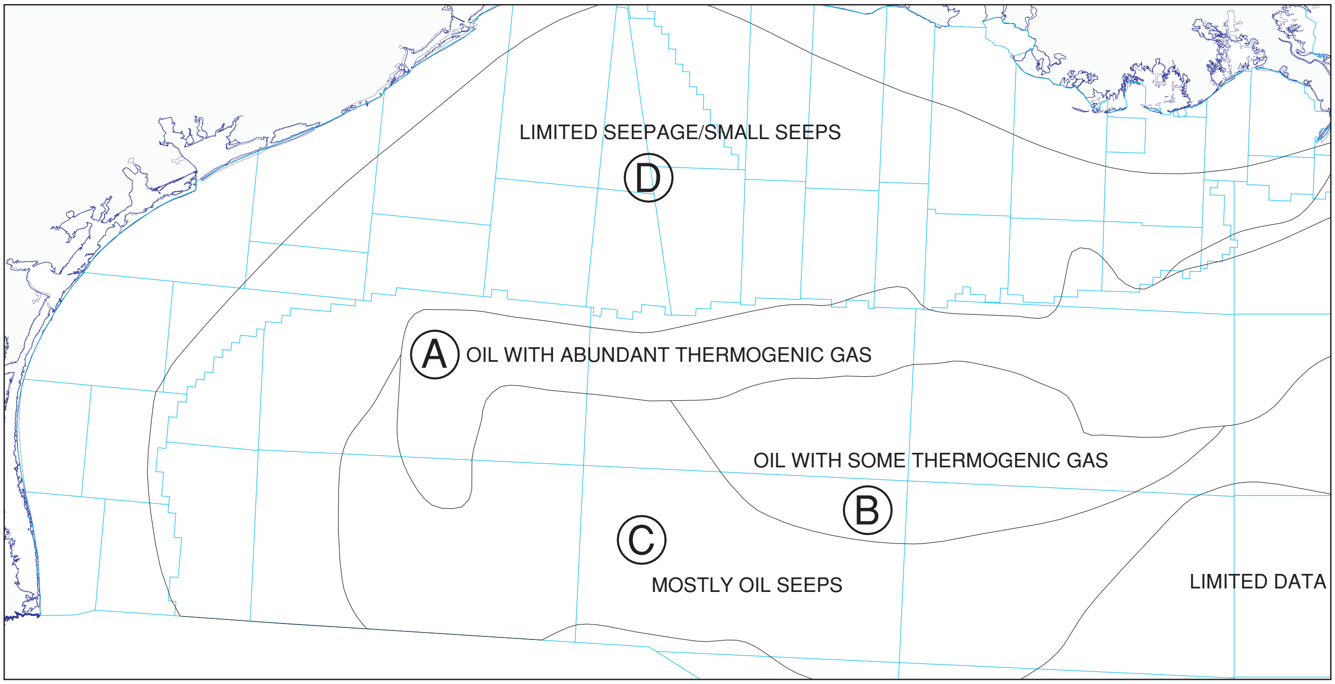

FIGURE 4. Gulf of Mexico regional seep-distribution map based on more than 5200 sea-bottom dropcores plus sea-surface slicks identified on remote-sensing data. (A) Abundant/large oil seeps with prevalent thermogenic gas; (B) abundant/large oil seeps with less thermogenic gas; (C) abundant/large oil seeps with only limited thermogenic gas; and (D) limited hydrocarbon seepage. Within areas A, B, and C, nearly 75% of the sea-bottom dropcores contain moderate or substantial quantities of oil, compared with only about 12% within area D. Within area A, more than 25% of the oil-bearing sea-bottom dropcores also contain substantial quantities of thermogenic (headspace) gas, compared with less than 5% in area C.

(MacDonald et al., 1996). Biodegradation appears to be a rapid process. In laboratory simulations, heavy biodegradation can occur within a few weeks (e.g., Connan, 1984). Interestingly, many large seeps in the Gulf of Mexico appear to be more intensely biodegraded than smaller seeps are, despite the apparently greater influx of fresh hydrocarbons. This difference may result because the greater influx of hydrocarbons associated with large seeps increases the likelihood that a large chemosynthetic community will be established at that site. Second, the abundance and geochemical compositions of petroleum hydrocarbons can be obscured by recent organic-matter components indigenous to the sea-bottom sediments that are extracted along with oil. The biologic signal must be “subtracted” to give the thermogenic signature that provides information on the source and thermal maturity of the seep oil. As illustrated below, both biodegradation and the overprint of recent organic matter can be factored into interpretations of the characteristics of seep oil extracted from sea-bottom sediments.

Figure 5 illustrates the intense hydrocarbon biodegradation that can be encountered in dropcores collected on the Gulf of Mexico Slope. In this particular example, only about 5 ft (1.5 m) of sediments was recovered, although most Gulf of Mexico dropcores recover about 15 ft (4.6 m) of sediment. The limited penetration likely results from an authigenic carbonate hard-ground surface formed in response to hydrocarbon seepage. Canned headspace gas concentrations and whole-extract gas chromatograms (GCs) are shown for three sections sampled from the core. Oil concentrations are evaluated by the maximum fluorescence intensity (MFI) measured on sea-bottom sediment extracts (Brooks et al., 1983, 1986) and by the appearance of whole-extract gas chromatograms. MFIs in this core range from 230,000 to 414,000 using a Perkin-Elmer 650-40 spectrophotometer.

All three samples from the dropcore contained high levels of natural gas and oil, and a pronounced biodegradation profile is evident in both the oil and gas compositions over a depth range of less than 5 ft (1.5 m). Moderate to severe biodegradation of oil and gas has occurred in the upper 2.5 ft (0.8 m) of sediment. The extent of biodegradation is evident by depletion of n-alkanes, large unresolved complex mixture (UCM) humps on the GCs, and preferential removal of C_3 and n-C_4 by microbial biodegradation of gas. Entry or preservation of some fresh, unbiodegraded oil and gas between 4.5 and 5 ft (1.4–1.5 m) is indicated by the unbiodegraded character of the GCs (n-alkanes intact) and the high proportion of n-C_4 to (i-C_4 + n-C_4) in the headspace gas. Figure 6 shows comparative GC and biomarker analyses for the seep and a nearby reservoired oil. Because the reservoired oil is not biodegraded, the deepest (unbiodegraded) sample from the dropcore is used for comparison. Biomarker compositions for the reservoired oil and the seep are comparable, suggesting that the oils belong to the same hydrocarbon family and originated from the same source.

To evaluate the hydrocarbons in sea-bottom sediments, the oil component is extracted with a solvent for analysis. Seeps with limited quantities of hydrocarbons commonly will show an overprint of recent organic components that are extracted by the solvent along with the oil. In large seeps, the signature of recent organic components is usually overwhelmed by high concentrations of oil. For seeps with lesser amounts of oil, the biological signature must be discounted in order to interpret the thermogenic signature correctly. This differentiation is crucial, because only the thermogenic signature provides information on the source and the thermal maturity of the petroleum hydrocarbons. One benefit of interpreting petroleum characteristics from lower-concentration seeps is that the biomarkers typically are less altered by biodegradation, and they better reflect primary petroleum signatures in those "windows" of the analyses where recent organic-matter components do not co-elute and interfere with oil components (Figure 7).

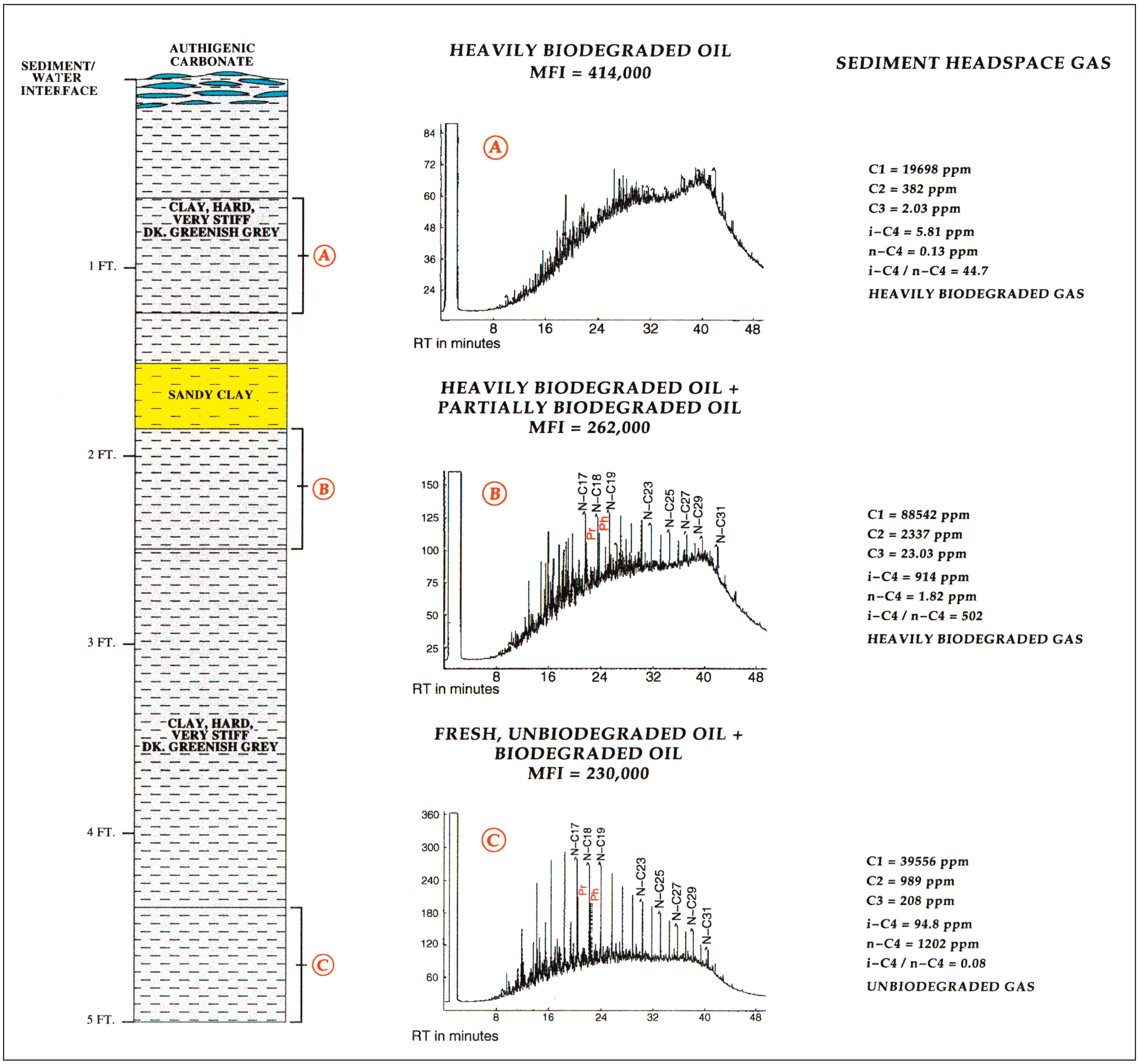

FIGURE 5. Example of a biodegradation profile within a single sea-bottom dropcore from Ewing Banks. Total depth of the core is about 5 ft (1.5 m). Biodegradation is apparent in both the oils (GCs) and the headspace gas. The intensity of biodegradation appears to decrease with depth. MFI = maximum fluorescence intensity, used to evaluate oil concentrations.

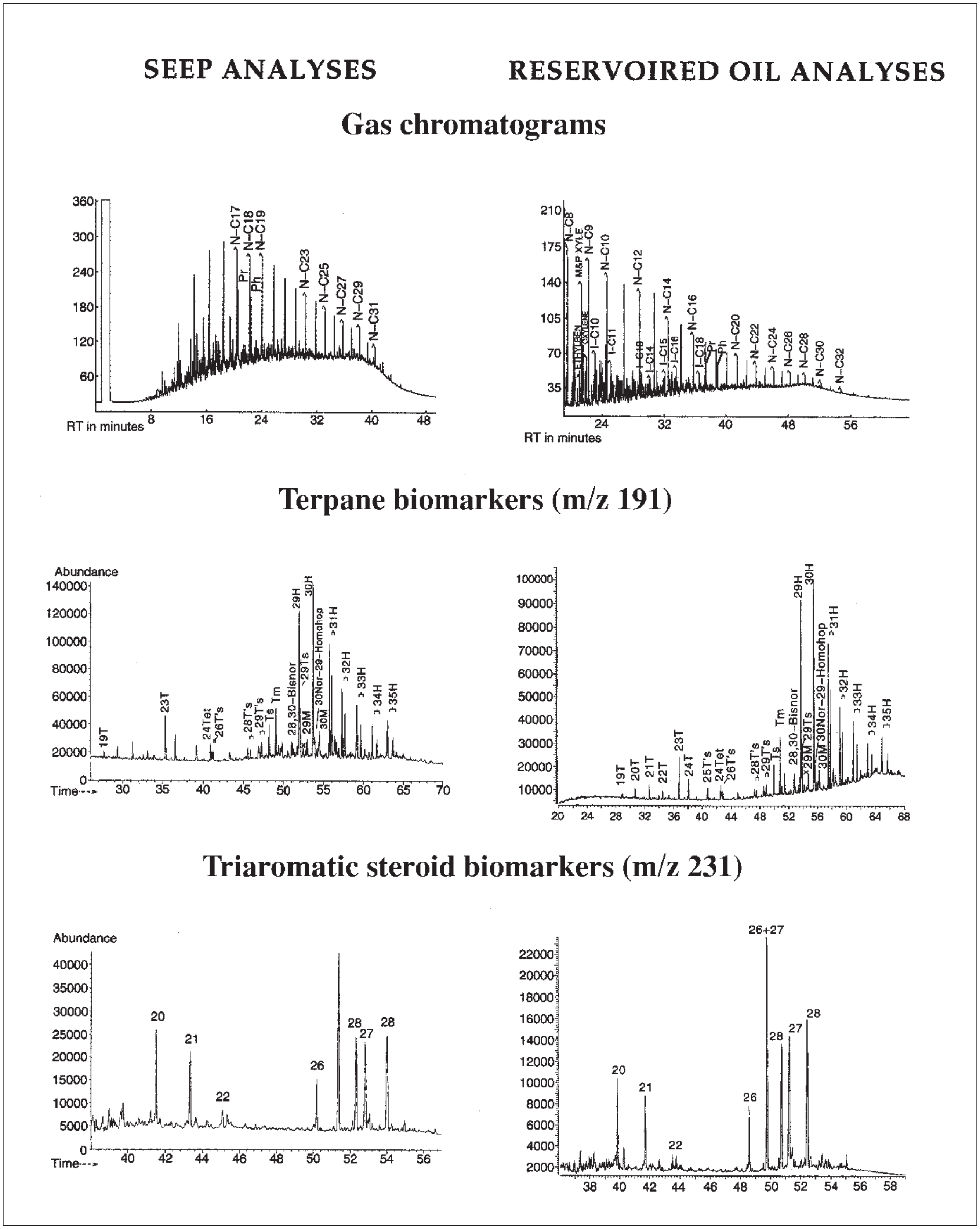

FIGURE 6. Comparison of deepest oil sample from sea-bottom dropcore in Figure 5 with a nearby reservoired oil sample. Although the GC indicates that the seep oil has undergone a markedly higher degree of biodegradation, the more biodegradation-resistant terpane and triaromatic steroid biomarkers are quite similar, indicating that both samples are probably derived from the same source (Tithonian).

Seeps can be used to enhance our understanding of several aspects of the hydrocarbon system, including source maturation and migration timing. On the Gulf of Mexico Slope, many large hydrocarbon accumulations have large seeps at the intersection of the cross-stratal migration pathway with the seafloor. For reasons discussed below, we interpret these large seeps to indicate active, ongoing charge from the source rather than trap failure resulting from inadequate seal or structural deformation subsequent to hydrocarbon emplacement. Other authors, including Nunn and Sassen (1986) and Kornacki et al. (1994), have reached similar conclusions about the derivation of hydrocarbons in seeps. Because seeps appear to indicate active migration from the source, they represent a positive indicator of the potential effectiveness of the associated migration pathways. In contrast, if hydrocarbons in seeps resulted from trap failure without active recharge, then large seeps would likely be associated with underfilled or dry structures.

Several lines of evidence support the interpretation that pervasive seepage on the Gulf of Mexico Slope results from active hydrocarbon generation and ongoing charge from the source. First, the apparent volume of seeping hydrocarbons appears to preclude the possibility that generation occurred in the past and that hydrocarbons are currently leaking out of known or unidentified deep

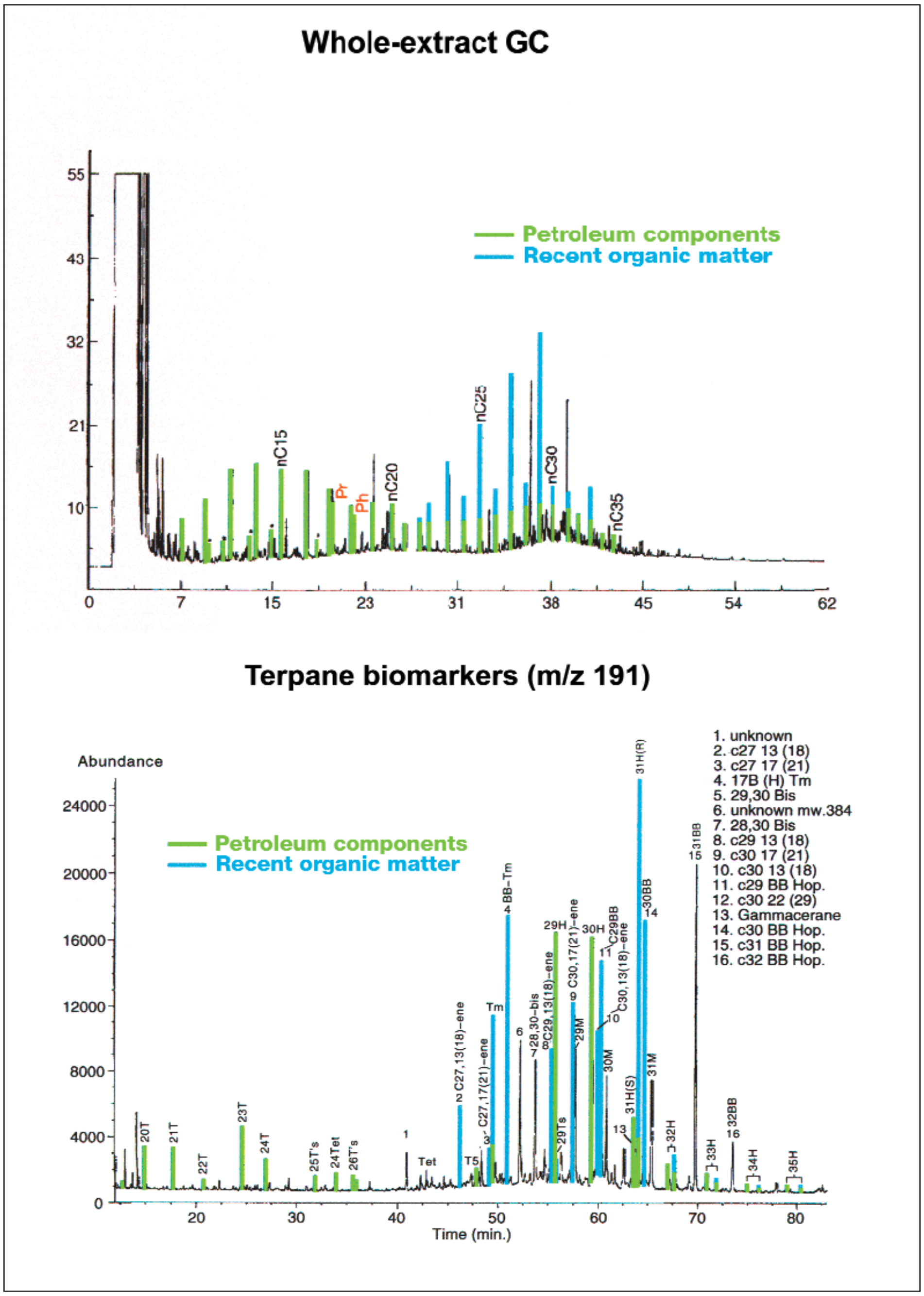

FIGURE 7. Whole-oil gas chromatogram and terpane biomarker (m/z 191) scan of a sea-bottom sediment extract from offshore Florida containing the signature of carbonate-sourced oil (peaks highlighted in green) overprinted with recent organic matter (peaks highlighted in blue). Interpretations of source family and hydrocarbon maturity for the petroleum can be made in "windows" in which the interference by recent organic matter is limited.

reservoirs. For example, MacDonald et al. (1993) estimated that the volume of hydrocarbons in surface slicks exceeds 120,000 barrels (bbl) of oil per year. This estimate is conservative in that it includes only oil from seeps large enough to create surface slicks that can be identified using remote-sensing techniques. Lawrence and Anderson (1993) estimated the ultimate potential of the deep-water Gulf of Mexico to be between 8 billion and 10 billion bbl of oil equivalent (BBOE). Without recharge, continuous seepage of 120,000 bbl of oil per year would deplete this entire volume in less than 100,000 years. Second, large seeps can occur on migration pathways with no known or inferred (from seismic-amplitude anomalies) hydrocarbon accumulations at depth. Third, Exxon has documented examples where the reservoired hydrocarbons in a field are biodegraded, while seeps associated with the same migration pathway contain fresh oil. The interpretation of ongoing generation is interesting, given that seeps are abundant in areas where the source intervals are currently buried to depths of 30,000 ft (9 km) or more below mud line. Because it is an area of active generation and migration of early-mature oils, the Gulf of Mexico Slope affords a rare opportunity to calibrate maturation modeling methods.

Natural seeps contain varying mixtures of oil, thermogenic natural gas, and biogenic gas. Because the gas components are neither likely to be retained at the seafloor for an extended period of time nor transported away from the migration pathway and redistributed in sediments, we interpret an abundance of thermogenic natural gas to indicate active migration at the specific site of the dropcore. In contrast, modest amounts of oil imply hydrocarbon migration in the general area of the dropcore. Seep compositions document that both oils and natural gases are migrating simultaneously within individual pathways. Because both products are available, the hydrocarbon type contained within any particular trap (oil versus gas) appears to be controlled by local factors of hydrocarbon charge or retention in the reservoir. The composition of hydrocarbons in a seep (oil versus gas), therefore, cannot generally be used to predict whether a particular trap on the associated migration pathway will contain oil or gas. Biogenic gas in seeps is identified by large components of isotopically light (–60 to –80‰ d^{13}C) methane (e.g., Rice, 1993). Much of the biogenic methane associated with seeps is probably formed at the seafloor by biodegradation of oil or from indigenous organic matter in recent sediments. Consequently, the presence of biogenic gas in a seep cannot be used as an indicator of the likely products trapped at depth.

A small dropcore program was designed to evaluate the use of seeps as direct indicators of the extent of a field (Figure 8). A grid of 41 dropcores was extended from presumed background, across the seismic-amplitude anomalies of a major discovery on the eastern Gulf of Mexico Slope, and across the interpreted migration pathway. Background MFI values were recorded in dropcores represented along the right and upper parts of the figure. Substantially higher MFI values were recorded near salt features and faults associated with the likely cross-stratal migration conduit. Fluorescence intensity generally decreases from right to left, away from cross-stratal migration pathways. Anomalously high values over the field but away from the principal cross-stratal migration conduit may suggest migration of oil through seismically unresolvable pathways. However, the distribution of MFI values across the grid in this example does not appear to closely define the limits of the hydrocarbon accumulation as defined by the seismic-amplitude anomaly.

MIGRATION PATHWAY EVALUATION

An understanding of source intervals, coupled with the ability to image known and potential hydrocarbon accumulations (from seismic-amplitude anomalies), facilitates the evaluation of potential migration pathways within a basin. Most known fields and discoveries in the offshore Gulf of Mexico require cross-stratal migration to move hydrocarbons from known, deep source intervals to young Tertiary reservoirs. The two most likely mechanisms for creating cross-stratal conduits are salt move-

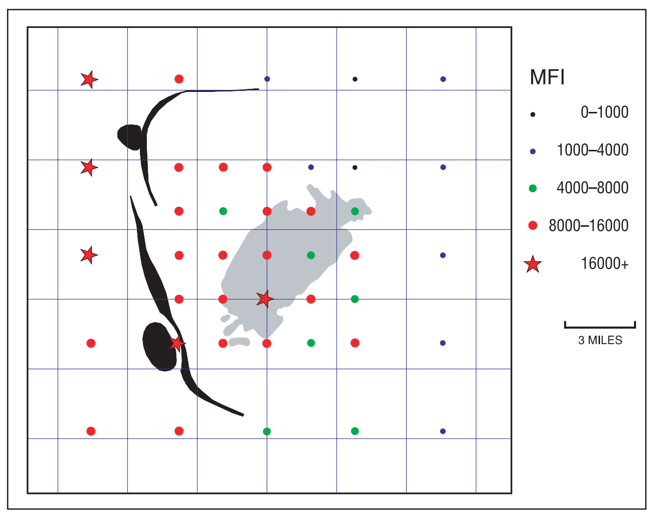

Figure 8. Sea-bottom dropcore grid within Viosca Knoll, designed to evaluate the utility of seeps for defining the limit of field extent as indicated by seismic-amplitude anomalies (shaded area). Although the MFI values over the amplitude anomaly appear to be somewhat higher than for dropcores near the right and upper limits of the grid, these data do not provide the capability to closely constrain the limits of the anomaly. Some of the largest MFI values are from dropcores collected near the intersection of the cross-stratal migration pathway with the seafloor.

ment and faulting. To be effective, potential migration pathways must intersect both the deep source intervals and the young reservoir levels. In some areas, modern seismic data allow the entire inferred migration pathway to be imaged. In cases where migration pathways extend to the seafloor, sea-bottom hydrocarbon occurrences and surface slicks can be used to document active migration.

In our study area, migration pathways with the fewest segments (individual faults or salt/sediment interfaces) and the greatest disruption between source and reservoir levels appear to be the most effective. Consequently, collapsed salt stocks appear to provide more effective migration conduits than faults do, in areas where both features are present. Vertical salt movement from the Middle Jurassic Louann Salt (autochthonous salt) to allochthonous salt sills within the Tertiary section provides a strong disruption of the overlying sources and younger strata. The disruption appears to be enhanced when the salt stock pinches off from the mother salt, and the surrounding strata collapse as the salt evacuates. Figure 9 illustrates several potential as well as some unlikely migration pathways on the eastern Gulf of Mexico Slope. Notice how the salt stock on the right part of the seismic line penetrates all potential source intervals and provides a strong focus of hydrocarbons into the cross-stratal conduit. Several seismic-amplitude anomalies shallower in the section appear to connect to this pathway extending below the shallow salt. The large fault on the lower left part of the seismic line also cuts the potential source intervals, but the dip of the source on the downthrown side of the fault appears to provide less migration focus into the cross-stratal conduit in this 2-D view. A somewhat smaller seismic-amplitude anomaly connects to the conduit shallower in the section. Many other shallow faults on this part of the line do not intersect the source intervals and thus would have limited potential as effective migration conduits.

In many areas of the Gulf of Mexico, the source intervals cannot be imaged on seismic sections, making it difficult to evaluate the viability of potential migration pathways. Fortunately, many of the potential migration pathways reach the seafloor and can be evaluated for direct evidence of hydrocarbon migration. Even so, the relationship between seafloor hydrocarbon indicators and hydrocarbon accumulations at depth is complex. Most large hydrocarbon accumulations on the Gulf of Mexico Slope have large seeps at or near the intersection of the cross-stratal migration conduit with the seafloor. However, some migration pathways with large seeps at the seafloor do not have known or inferred hydrocarbon accumulations at depth. Thus, a large seep at the seafloor would be considered a positive indicator of hydrocarbon migration, thereby reducing the risk for an associated seismic-amplitude anomaly, but it would not be considered a definitive indicator of a hydrocarbon accumulation.

Figure 10 illustrates the interpreted migration pathway for a major discovery on the Gulf of Mexico Slope. The interpreted collapsed salt stock is labeled "salt-ascension zone" under the salt body. The collapsed salt stock appears to be the main conduit connecting the uppermost Jurassic (Tithonian) source interval to Miocene reservoirs. Figure 11 shows high-resolution, shallow seismic data across a seafloor mound near the intersection of the cross-

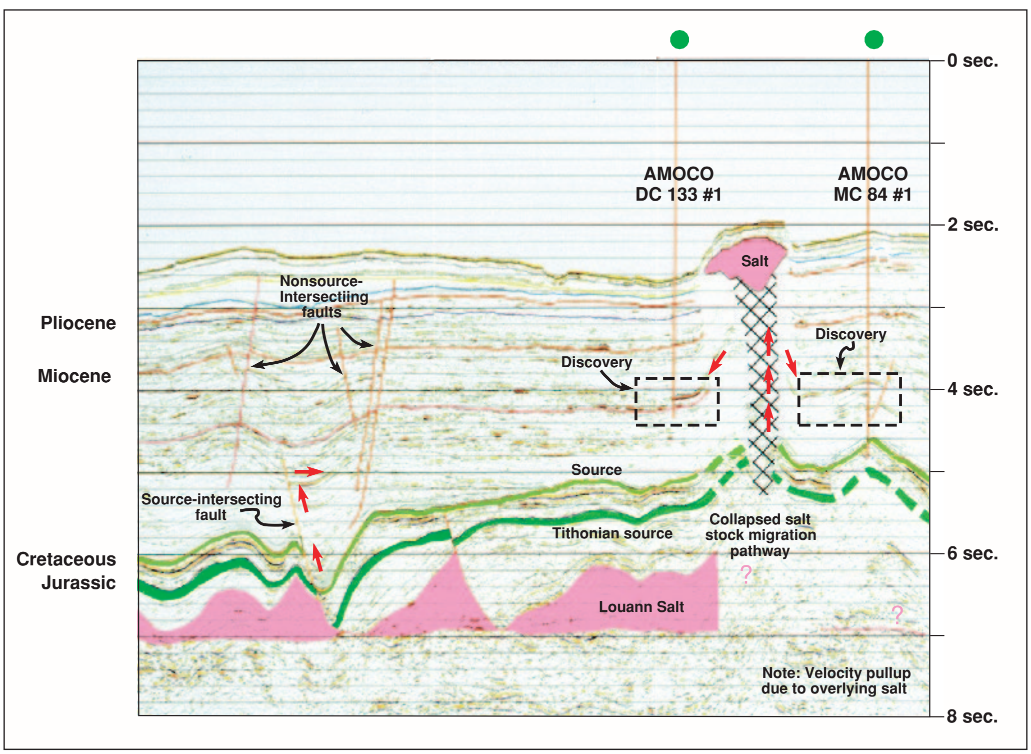

FIGURE 9. Example of a seismic line showing the source intervals and several potential hydrocarbon migration pathways (compliments of Veritas Marine Services).

stratal migration conduit with the sea bottom. The seafloor mound is 200+ ft (60+ m) high and more than 8000 ft (2500 m) wide. MFI values exceeding 2.5 million indicate that the mound is a site of substantial oil and gas seepage. The mound likely supports a chemosynthetic biological community that lives off seeping oil and gas far below the photic zone. A wipeout zone is present on the seismic line under the mound, probably the result of large amounts of migrating gas. Oil collected in sea-bottom dropcores from the intense seep over the migration pathway was geochemically analyzed prior to drilling the discovery well. Geochemical characteristics reflecting source depositional environment, facies, and level of maturity, as interpreted from the seep analysis, allowed successful prediction of API gravity and sulfur content of the oil in the reservoir prior to drilling the discovery well. This prediction was especially significant because biomarker analysis of the seep suggested that the oil would have a high sulfur content (2–3% S), whereas earlier calculations had used the more highly valued "south Louisiana sweet" benchmark in economic models. Figure 12 shows a representative example of oils eventually discovered at this prospect, compared with the seep analysis. Oils in the stacked reservoirs were unbiodegraded, and most had API gravities in the upper 20° range and sulfur contents from near 2% to almost 3%. Although the seep GC is heavily biodegraded, the biomarkers in the seep are unaltered and are virtually identical to the reservoired oil. This example illustrates the potential value of geochemically characterizing seeps as a basis for predicting expected hydrocarbon properties before drilling. Such information is valuable in both prospect-specific and regional frontier contexts.

CONCLUSIONS

An integrated-study approach to understanding regional source distribution, hydrocarbon maturation levels, and effective migration pathways in the deep-water Gulf of Mexico has resulted in development of new play concepts and has helped to improve Exxon's exploration strategies.

Major offshore hydrocarbon systems are derived from lower Tertiary (centered on Eocene), Upper Cretaceous (centered on Turonian), and Upper Jurassic (centered on Tithonian) source intervals. Regional variations in source facies result in subfamilies within these hydrocarbon systems. Oxfordian carbonate-sourced oils are common across the northern Gulf basin rim, and lower-maturity hydrocarbons from this source are found in stains and seeps in the deep central Gulf of Mexico.

Satellite-based tools for seep detection have proved useful for screening large tracts of offshore acreage for evidence of active hydrocarbon systems in a cost-effective manner. Piston-core sampling of features imaged on the seafloor has provided samples of oil that have been characterized geochemically. These samples allow hydrocarbon-systems maps and prediction of hydrocarbon properties to be extended far beyond well control.

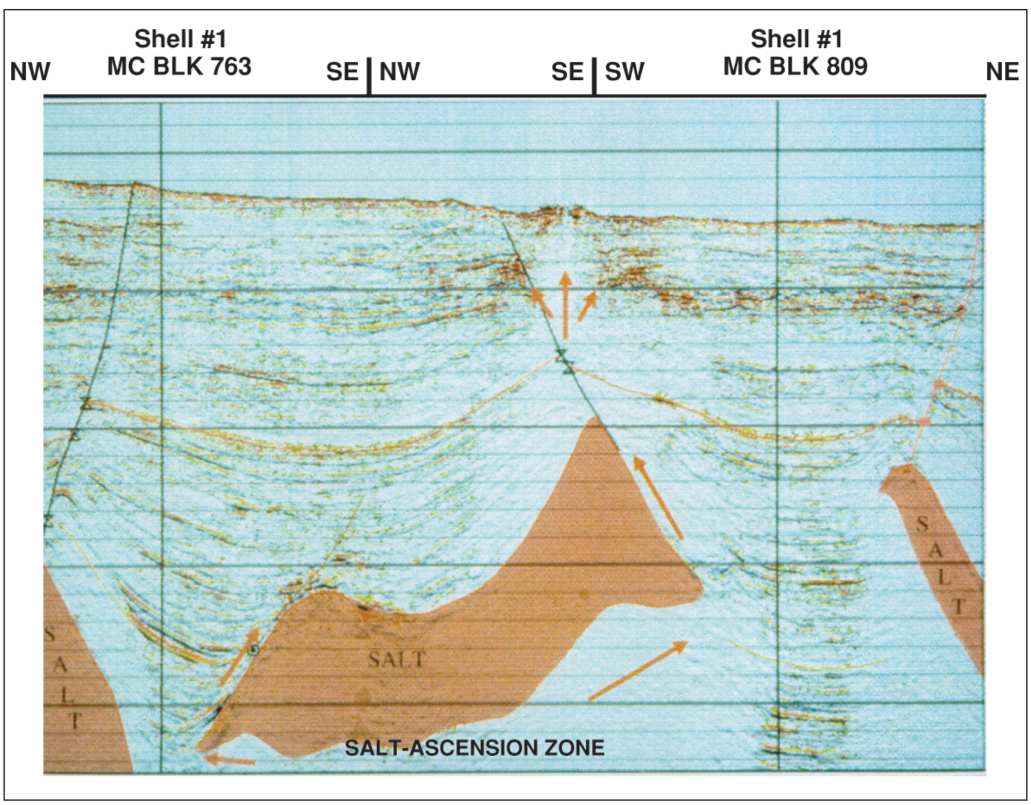

FIGURE 10. Example of a seismic line showing the interpreted cross-stratal migration pathway to a large discovery in the southern Mississippi Canyon. Hydrocarbon migration is interpreted to occur up the collapsed salt stock, then near the salt/sediment interface, and finally up small faults to the seafloor.

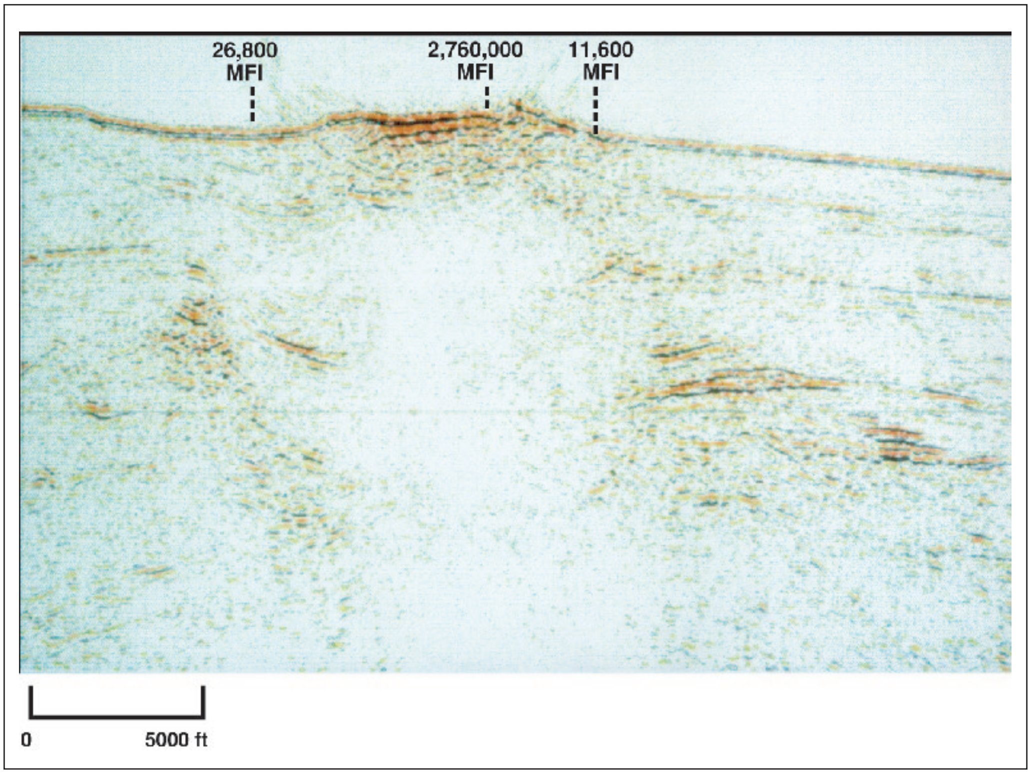

Figure 11. Example of a seismic line showing a close-up of a seafloor mound interpreted to represent a chemosynthetic community over the cross-stratal migration pathway illustrated in Figure 10. MFI values from nearby dropcores are projected onto the line.

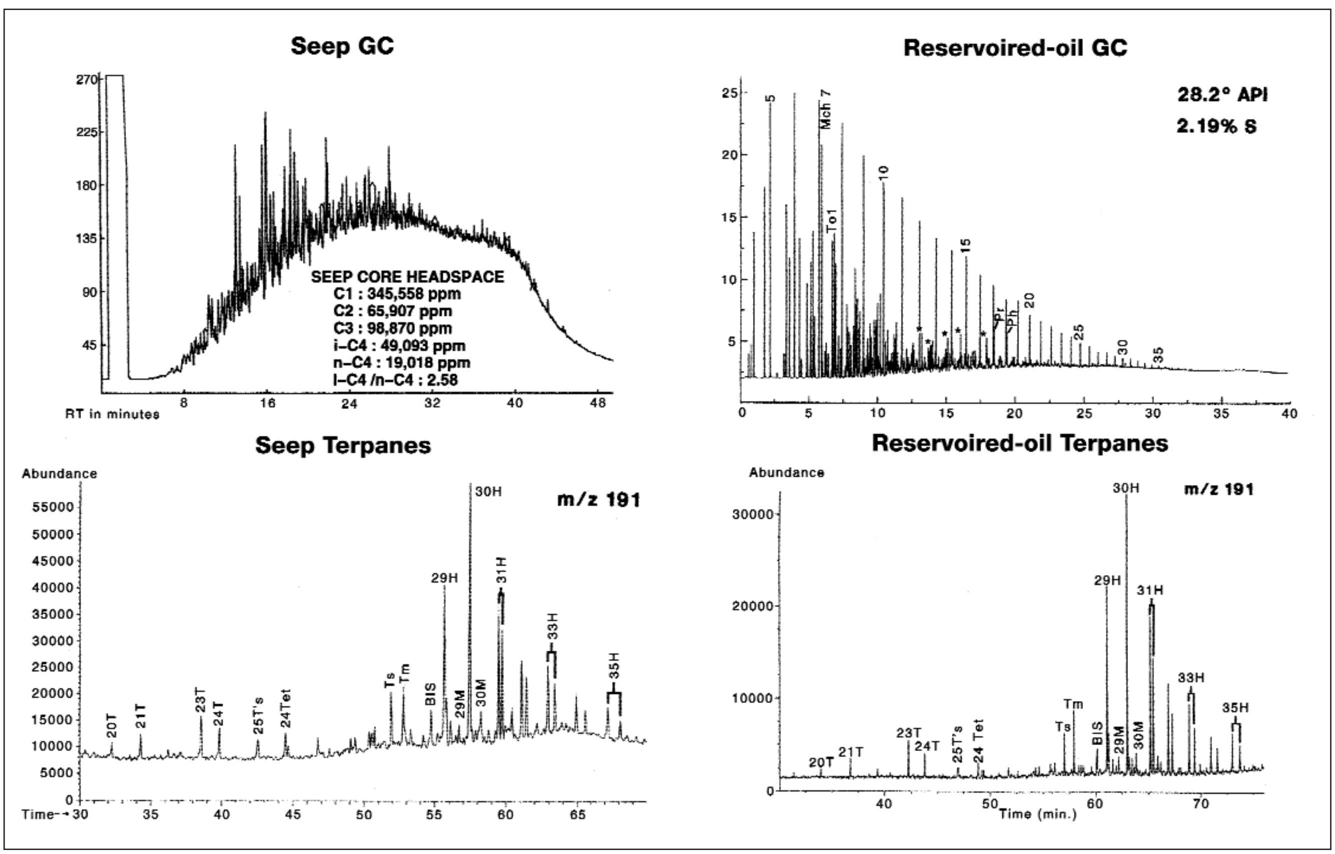

Figure 12. Comparison of a seep oil with the oil from a nearby discovery. Although the oil in the seep is heavily biodegraded and the reservoired oil is not, the strong similarity of terpane biomarkers suggests that both oils derive from a common source.

Analysis of many sea-bottom sediments by such high-resolution techniques as GC/MS and GC/MS/MS has allowed us to place samples within a regional interpretive framework. This framework has enabled us to understand complex signatures that included heavily biodegraded petroleum compounds and the overprint of recent organic matter. The regional framework has allowed estimation of likely characteristics of reservoired oils over virtually the entire offshore Gulf of Mexico.

Integration of seep data with geophysical imaging of source rocks and potential migration pathways, such as diapiric salt and major faults, has improved our understanding of effective migration pathways. This understanding can be used to risk the migration pathways associated with amplitude anomalies, which may represent hydrocarbon accumulations, or any other trap. Potential pathways that provide the greatest disruption and fewest segments between source and reservoir levels (e.g., salt diapirs) appear to provide the most effective migration conduits. The collection of dropcores and analysis of seeps have been major contributors to our current understanding of hydrocarbon migration on the Gulf of Mexico Slope.

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