OCS Report
MMS 2000-039

SHELL LYDONIA CANYON BLOCK 410 No. 1R WELL

Geological and Operational Summary

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ILLUSTRATIONS

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ABBREVIATIONS

API	--	American Petroleum Institute
bbl	--	barrels
BOP	--	Blow out preventer
CNL	--	Compensated neutron log
CPI	--	Carbon Preference Index
COST	--	Continental Offshore Stratigraphic Test
DST	--	drill stem test
EQMW	--	equivalent mud weight
FDC	--	compensated formation density log
FEL	--	from east line
FNL	--	from north line
FSL	--	from south line
FWL	--	from west line
k	--	permeability
KB	--	kelly bushing
LS	--	limestone
m	--	meter (s)
md	--	millidarcy
MYBP	--	million years before present
OCS	--	Outer Continental Shelf
ppf	--	pounds per foot
ppg	--	pounds per gallon
ppm	--	parts per million
psi	--	pounds per square inch
R_O	--	vitrinite reflectance
SS	--	sandstone
Sw	--	water saturation
TAI	--	thermal alteration index
TD	--	total depth
TIOG	--	threshold of intense oil generation
TOC	--	total organic carbon
UTM	--	Universal Transverse Mercator
ϕ	--	porosity

INTRODUCTION

The Shell Lydonia Canyon (LC) Block 410 No. 1R well was the second to be spudded and third to be completed of the eight industry wildcat wells drilled on Georges Bank. Spudded on July 24, 1981, this is the most seaward of the eight wells. It is about 25 miles southeast of the Continental Offshore Stratigraphic Test (COST) G-2 well and about 150 miles east-southeast of Nantucket Island. The Shell LC Block 410 No. 1R well was drilled by a semi-submersible rig in 381 feet of water at the seaward edge of the continental shelf.

Shell Offshore, Inc., was the designated operator for the well, and the company's drilling target was a Jurassic closure between 12,000 and 16,000 feet inferred from seismic data. Well data showed that these rocks are oolitic limestones of indeterminate age. These carbonates generally have poor porosity with the exception of zones below 14,200 feet, where dolomitization has created some voids. The Shell LC Block 410 No. 1R well bottomed in continental clastics of undetermined age at 15,568 feet. The oldest identified microfossils are Middle Jurassic, Bajocian? to early Bathonian, at 10,340 to 11,420 feet. Shell plugged and abandoned the well as a dry hole on March 31, 1982.

This report relies on geologic and geophysical data provided to the Minerals Management Service (MMS) by Shell, according to Outer Continental Shelf (OCS) regulations and lease stipulations. The data were released to the public after the Shell LC Block 410 Lease No. OCS-A-0218 was relinquished on December 28, 1982. Interpretations of the data contained in this report are those of MMS and may differ from those of Shell. Well depths are relative to kelly bushing (measured depths), unless otherwise stated.

The material contained in this report is from unpublished, undated MMS, internal interpretations. No attempt has been made to provide more recent geologic, geochemical, or geophysical interpretations or data, published or unpublished.

This report is initially released on the Minerals Management Service Internet site **http://www.gomr.mms.gov**, and, together with the other Georges Bank well reports, on a single compact disk (CD). At a later date, additional technical data, including well "electric" logs will be added to the CD.

OPERATIONAL SUMMARY

Taken and adapted from F. Adinolfi, MMS internal report

The Shell Lydonia Canyon (LC) Block 410 No. 1R well is located about 150 miles east-southeast of Nantucket, Massachusetts (figure 1) in North Atlantic Official Protraction Diagram NK 19-12 (Lydonia Canyon). Shell Oil Company and its partners bid $34,733,000 for LC Block 410 in OCS Lease Sale 42, held on December 18, 1979. Before drilling operations started, Shell Oil and Cities Service assigned their entire interests in the lease (OCS-A-0218) to Shell Offshore Inc. The well is located in the northeast quadrant of the lease block (figure 2) in 381 feet of water (453 feet from kelly bushing to mud line). Shell and partners relinquished the lease on December 28, 1982.

Shell Offshore Inc. was designated as the operator for the well, which was drilled by the semisubmersible rig the *Zapata Saratoga*. The rig was inspected and operations were observed by MMS personnel throughout the drilling period to ensure compliance with Department of the Interior regulations and orders.

Data from the well include “electric” logs, a “mud” log, cuttings samples, sidewall cores, and conventional cores. No drill stem tests were performed. These data, along with geologic information and operational reports, were provided to the MMS. The well data and reports failed to confirm the presence of commercial hydrocarbons in this well.

DRILLING PROGRAM

The *Zapata Saratoga* arrived on location July 10, 1981, and the original well was spudded on July 24. Daily drilling progress is shown in figure 3, and well information is presented in table 1. Zapata encountered problems with stuck drill pipe at a depth of 686 feet and cut off the pipe at 632 feet. The hole was spotted to the mud line with 100 sacks of class H cement, and a hole opener, crossover sub, and bit were left in the hole. The rig was skidded 35 feet southeast and a second attempt was made to spud the well, on July 28. Zapata set 30-inch casing at 629 feet and drilled to a total depth of 1,400 feet. On the third of August, 775 feet of 20-inch casing were dropped in the hole. The top of the fish was 100 feet below the mudline. The 30-inch casing was retrieved, but the 20-inch casing was cut 18 feet below the mudline. The hole was then plugged with cement at 115 feet below the mudline and abandoned.

Zapata moved the rig about 40 feet southeast and the Shell LC Block 410 No. 1R (redrill) well was spudded on August 11, 1981. Figure 4 is a casing and abandonment diagram. Total depth (TD) of 15,568 feet was reached in 221 days on March 19, 1982. The well was plugged and abandoned at 12:00 noon on March 31, 1982, and the rig towed to a new location on April 1. It was reported that total exploratory well costs were about $31 million dollars.

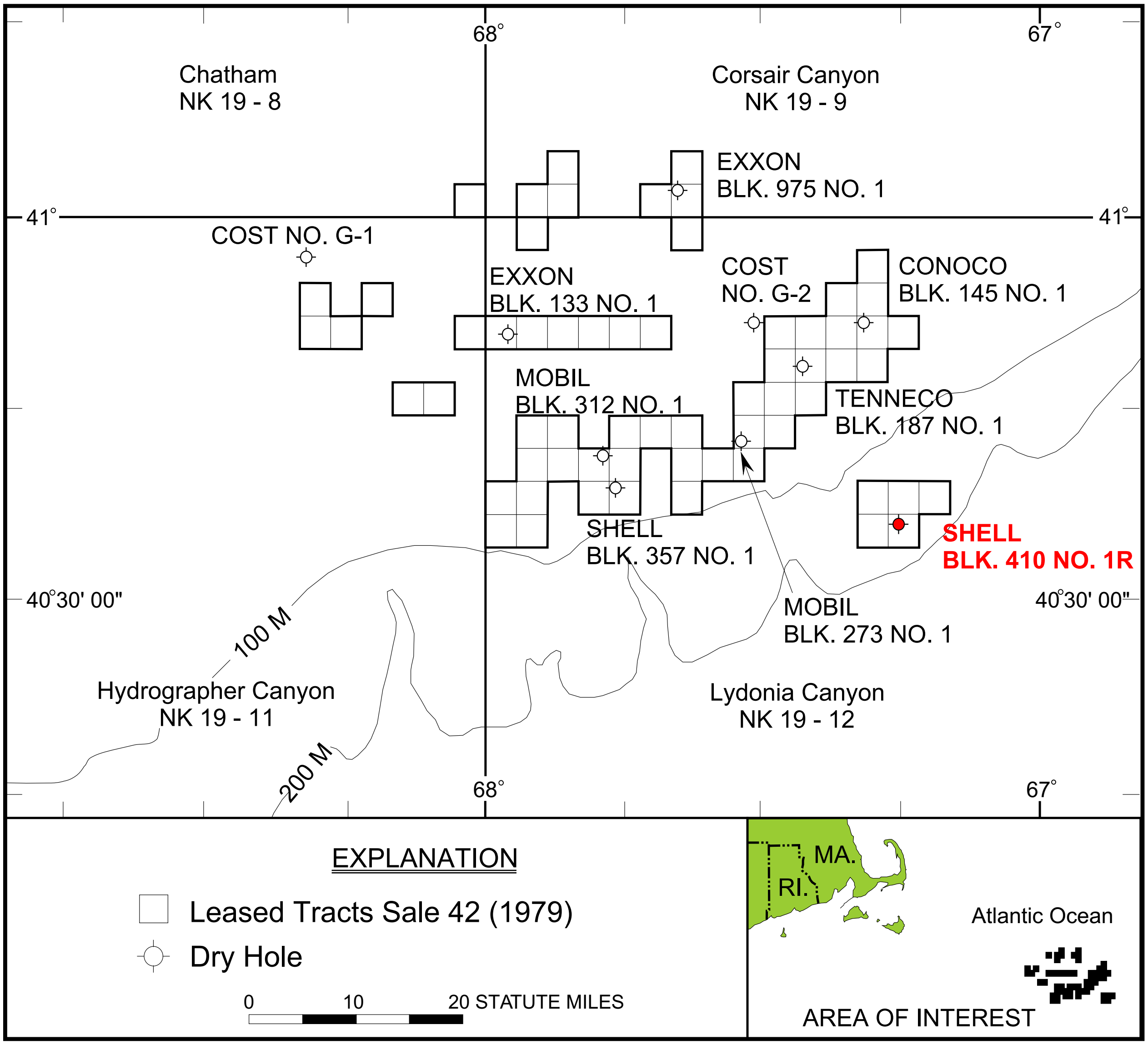

Figure 1. Map of the North Atlantic offshore area showing well locations. The Shell Lydonia Canyon Block 410 No. 1R well is highlighted in red. No. 1R bathymetry is in meters.

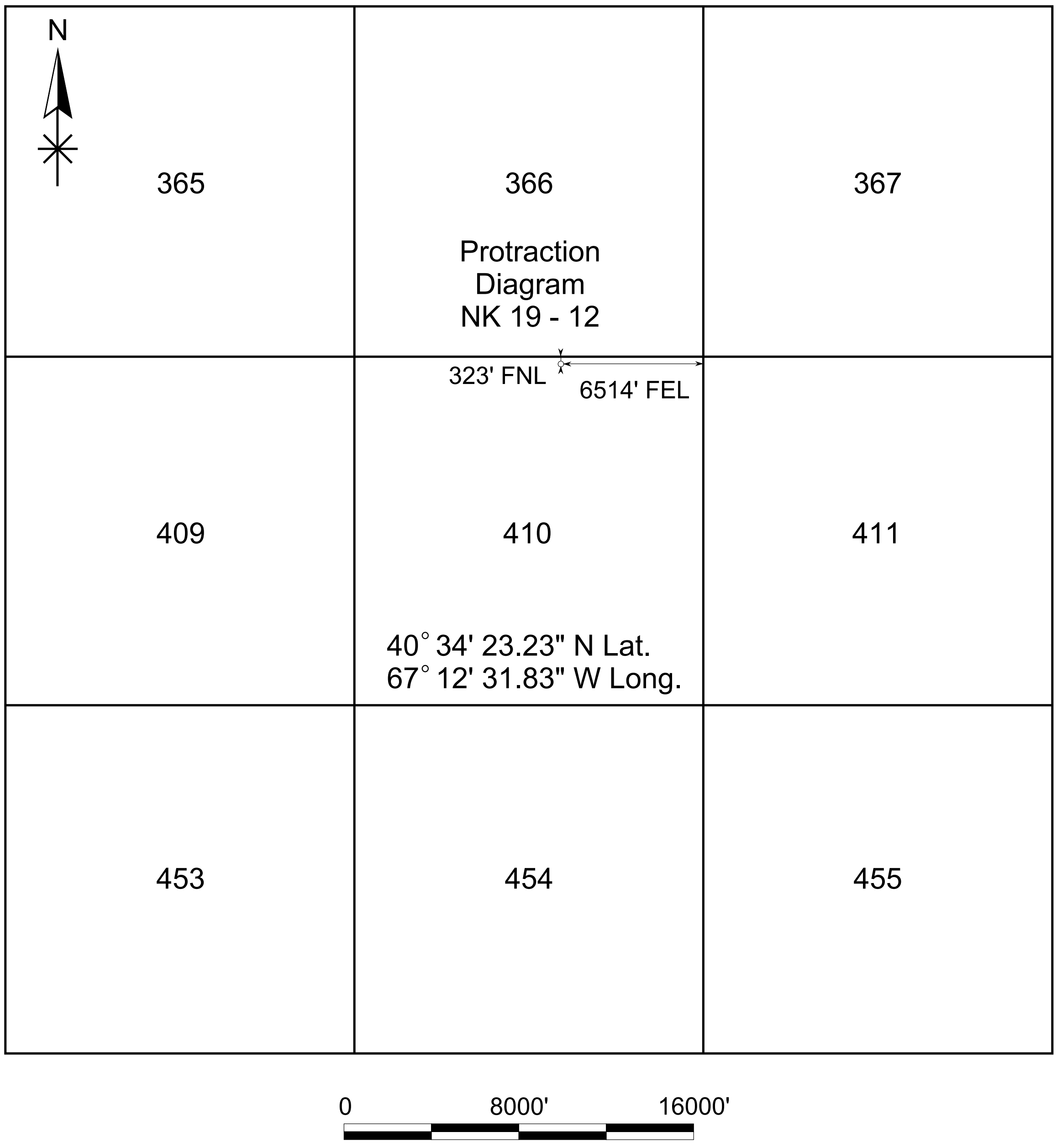

Figure 2. Location plat for the Shell Block 410 No. 1R well on the OCS Lydonia Canyon NK 19-12 protraction diagram.

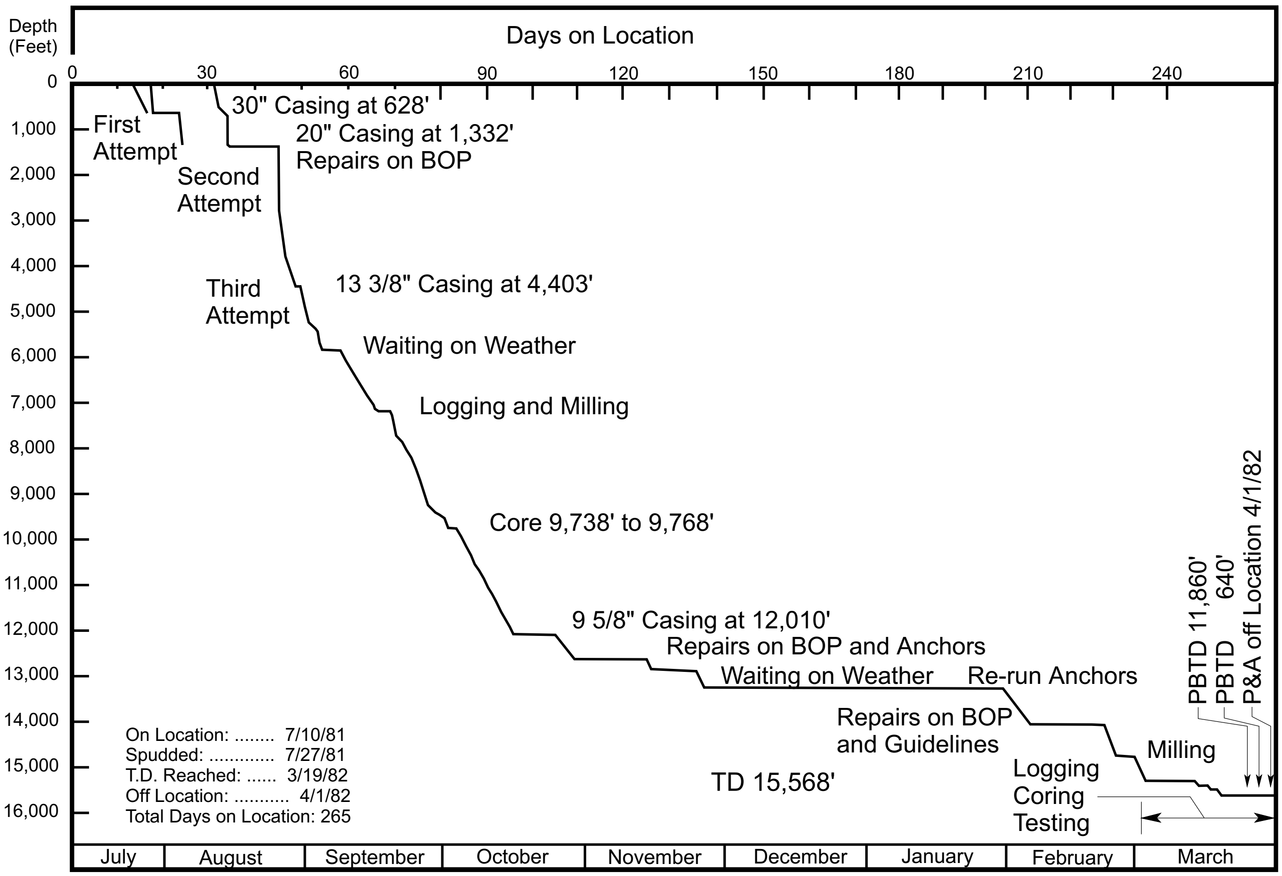

Figure 3. Daily drilling progress for the Shell Lydonia Canyon Block 410 No. 1R well.

Table 1. Well statistics

Well identification:	API No. 61-040-00003 Lease No. OCS-A-0218
Surface location:	Lydonia Canyon NK 19-12 LC Block 410 323 feet FNL 6,514 feet FEL Latitude: 40^{O} 34' 23.23" N Longitude: 67^{O} 12' 31.83" W UTM coordinates: X = 651,615m Y = 4,492,702m
Bottomhole location:	67 feet N 54^{O} W of surface location
Proposed total depth:	17,000
True vertical depth:	15,556
Measured depth:	15,568
Kelly bushing elevation:	72 feet
Water depth:	381 feet
Spud date:	
First attempt:	July 24, 1981
Redrill:	August 11, 1981
Reached TD:	March 19, 1982
Moved off site:	April 1, 1982
Final well status:	Plugged and abandoned

Note: All well depths indicated in this report are measured from the kelly bushing, unless otherwise indicated. Mean sea level is the datum for the water depth.

The surface hole was drilled and the 30-inch casing was set at 628 feet and cemented with 1,200 sacks of class H cement. The 20-inch casing was set at 1,332 feet and cemented with 1,150 sacks of class H cement. After approximately 10 days were spent in repairing the blowout preventer, Zapata continued with a 17 1/2-inch bit to 4,455 feet and 13 3/8-inch casing was run and cemented at 4,403 feet with 3,780 cubic feet of class H cement. Zapata drilled ahead using 12 1/4-inch bits, until an early September storm slowed operations for about four days.

A show was encountered during the drilling of a sandstone-shale sequence from 6,805 to 6,850 feet. Eight units total gas were recorded on the mud log. The 12 1/4-inch hole was continued to 12,060 feet, pausing routinely for well surveys, logging, coring, and testing the blowout preventer. Approximately two days were lost milling junk in the hole. After logging and setting 9 5/8-inch casing at 12,010 feet with 1,940 sacks of class H cement, the blowout preventer was tested and Zapata drilled ahead to 12,578 feet.

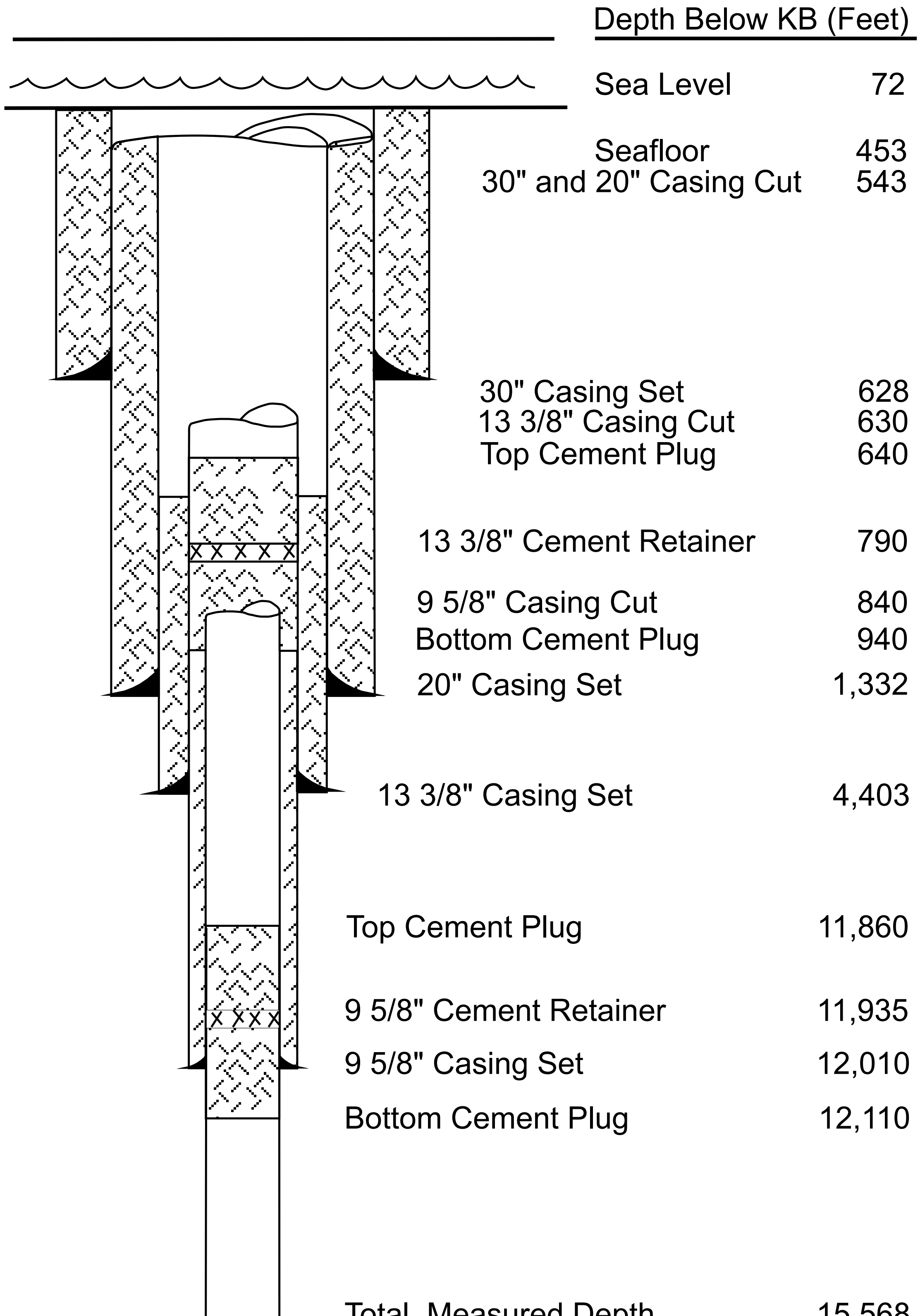

Figure 4. Casing diagram for the Shell Lydonia Canyon Block 410 No. 1R well.

At this point, Shell experienced numerous operational problems. Repairs on the blowout preventer stack were delayed while Zapata waited on parts and retrieved a broken anchor chain. After the hole was drilled to 12,769 feet, the No. 6 anchor chain broke again in rough seas. Zapata drilled to 13,122 feet and a 50-knot wind broke the Nos. 2 and 3 anchor chains and the No. 4 guideline. Rough seas and wind delayed the drilling through December 1981 and January 1982. All eight anchor lines were replaced and, beginning January 30, 1982, drilling continued for six days to 13,981 feet. A leaking hydraulic hose in the blowout preventer stack, re-establishing guidelines, and waiting on weather delayed drilling another 14 days in February. After the milling operations on junk (bit cones) in the hole and more bad weather, a 12-foot core was cut (15,229 to 15,241 feet), and Schlumberger logged the well. Zapata then drilled ahead and reached total depth (TD) of 15,568 feet on March 19, 1982. At total depth, Schlumberger again logged the well and ran pressure tests.

Zapata used five 17 1/2-inch bits, seventeen 12 1/4-inch bits, and eighteen 8 1/2-inch bits to drill the well. Drilling rates varied considerably, but averaged about 10 feet per hour through limestone below 5,700 feet and sometimes exceeded 400 feet per hour through sandstones and clay above 5,700 feet. Maximum penetration rate was 1,358 feet per day, which occurred from 1,445 feet to 2,803 feet (figure 3). Maximum borehole deviation from vertical is 3 1/2 degrees.

The well was spudded with seawater spud mud from the mudline (453 feet) to a depth of 1,400 feet. Shell carried a mud weight of 8.9 pounds per gallon (ppg) with a viscosity of above 100 seconds. At 1,400 feet, the mud was gelled with freshwater and conditioned to a mud weight of 10.3 ppg with a viscosity of 80 seconds. The same mud system was used for surface casing hole to 4,403 feet. Fluid loss was adjusted as required for seepage control with Drispac.

Mud weight in this section ranged from 8.9 to 9.4 ppg with a viscosity between 40 and 46 seconds. In the 12 1/4-inch hole from 4,403 to 12,060 feet, Shell ran a nondispersed saltwater/freshwater system with Drispac and maintained a mud weight of 9.3 ppg with a viscosity between 40 and 53 seconds. Below 12,060 feet a lightly treated lignosulfonate system (a more inhibitive mud with higher temperature stability) was required. Mud weight ranged from 9.3 to 9.8 ppg with a viscosity between 37 and 45 seconds to a depth of 13,122 feet, when drilling was suspended on November 27, 1981. Drilling continued on January 25, 1982, and mud weight ranged from 9.5 to 9.9 ppg, with a viscosity between 43 and 57 seconds down to total depth. Mud pH averaged 11.5, but fluctuated between 10.0 and 12.0. Chloride concentrations began at 7,300 parts per million (ppm); increased to 18,000 ppm between 4,000 and 5,500 feet; and decreased to 3,400 ppm at 13,981 feet. Chloride concentrations increased to 7,500 ppm at total depth.

Figure 4 also shows the abandonment procedure. No open-hole cement plugs were required. A 9 5/8-inch cement retainer was set at 11,935 feet and tested to 1,000 psi. Twenty barrels of cement were squeezed below the retainer to 12,110 feet and an additional five barrels were set on top, with the top of the cement plug at 11,860 feet. The plug was tested to 1,000 psi and the 9 5/8-inch casing was cut and pulled from 840 feet. A 13 3/8-inch cement retainer was set at 790 feet and tested to 1,000 psi. Fourteen barrels of cement were squeezed below the retainer to 940 feet and an additional 22 barrels were set on top, with the top of the cement plug at 640 feet. The 13 3/8-inch casing was cut and pulled from 630 feet. After pulling the risers and the BOP stack, the 30-inch and 20-inch casings were cut and pulled from 543 feet. Anchors and piggybacks were pulled and the rig was released on March 31, 1982.

A post-abandonment well site survey was conducted in April 1982, using sidescan sonar. The data revealed numerous anchor-impact craters and drag scars across the study area, as well as five sonar targets that may represent possible debris lost during operations and abandoned on the seafloor.

SAMPLES AND TESTS

Cutting samples were collected from 790 to 15,568 feet in the well, and aliquots were provided for analysis. Dry samples were provided from 790 to 3,410 feet as 30-foot composited samples and as 10-foot composited samples below 3,410 feet. Cutting samples were used for lithologic studies and processed for paleontologic examination and interpretations. Thin sections were also prepared from cuttings for selected intervals below 9,700 feet. Canned composited wet drill cuttings were also provided by Shell for geochemical analyses.

Shell cut two conventional cores, and pretests were made with Schlumberger's Repeat Formation Tester from 13,273 to 15,000 feet at 17 intervals. One cubic centimeter of condensate was collected at 14,071 feet. According to Shell, the condensate probably came from the tool itself. No other fluids were detected. The conventional cores were cut from 9,738 to 9,767 feet and from 15,229 to 15,241 feet, with good recovery on both cores. Between the depths of 13,060 and 15,484 feet, Shell attempted 59 sidewall cores and recovered 45 samples. Core Laboratories, Inc. made lithologic descriptions of the samples and analyzed 26 samples for porosity and permeability.

Schlumberger Ltd. ran "electric" log suites to provide information for stratigraphic correlation, lithologic analysis, and the evaluation of potential hydrocarbon-bearing zones (see **Formation Evaluation** chapter). Exploration Logging, Inc. provided a physical formation "mud" log from 781 to 15,568 feet. No drill stem tests were run

A final directional survey was completed from a measured depth of 15,568 feet by Sperry-Sun, Inc. of Harvey, Louisiana. True vertical depth is 15,556 feet and the bottomhole location is 67 feet from the surface location along a N 54^{O} W line.

WELL VELOCITY PROFILE

Schlumberger, Ltd. Wireline Testing ran a velocity checkshot survey between 4,378 and 15,128 feet in the Shell LC Block 410 No. 1R well. All depths cited are subsea. The checkshot data, together with that for the other nine wells drilled on Georges Bank, were given to Velocity Databank, Inc. at their request after all leases had been relinquished or had expired. Velocity Databank calculated interval, average, and RMS velocities, plotted time-depth curves, and tabulated the data. Tables 2a and 2b present well depth, two-way travel time, and the calculated velocities for the Shell LC Block 410 No. 1R well. Figures 5 and 6 show interval velocity, average velocity, and RMS velocity, as well as averaged interval velocity, plotted against depth and against two-way travel time, respectively.

Table 2a. Well velocity data

Depth (feet)	Two-way Travel Time (seconds)	Interval Velocity (feet/sec.)	Average Velocity (feet/sec.)	RMS Velocity (feet/sec.)
4,378	1.202	7,284	7,284	7,284
5,128	1.346	10,416	7,619	7,680
5,628	1.444	10,204	7,795	7,877
6,128	1.520	13,157	8,063	8,222
6,728	1.610	13,333	8,357	8,588
7,103	1.672	12,096	8,496	8,743
7,778	1.776	12,980	8,759	9,046
8,958	1.948	13,720	9,197	9,551
9,478	2.026	13,333	9,356	9,724
9,828	2.068	16,666	9,504	9,914
10,448	2,136	18,235	9,782	10,283
10,848	2.184	16,666	9,934	10,465
11,378	2.242	18,275	10,149	10,739
11,928	2.300	18,965	10,372	11,022
12,028	2.312	16,666	10,404	11,059
12,128	2.322	20,000	10,446	11,113
12,228	2.332	20,000	10,487	11,166
12,328	2.344	16,666	10,518	11,201
12,428	2.352	25,000	10,568	11,276
12,528	2.364	16,666	10,598	11,310
12,628	2.380	12,499	10,611	11,319
12,728	2.386	33,334	10,668	11,427
12,828	2.394	24,999	10,716	11,499
12,928	2.406	16,666	10,746	11,531
13,028	2.416	20,000	10,784	11,579
13,228	2.436	19,999	10,860	11,673
13,328	2.448	16,666	10,888	11,702
13,428	2.456	24,999	10,934	11,770

Continued

Table 2a. Well velocity data --*continued*

Depth (feet)	Two-way Travel Time (seconds)	Interval Velocity (feet/sec.)	Average Velocity (feet/sec.)	RMS Velocity (feet/sec.)
13,528	2.464	25,000	10,980	11,837
13,648	2.480	14,999	11,006	11,860
13,728	2.486	26,666	11,044	11,918
13,828	2.496	20,000	11.080	11,961
13,928	2.508	16,666	11,106	11,988
14,028	2.516	24,999	11,151	12,052
14,128	2.524	25,000	11,194	12,115
14,178	2.530	16,666	11,207	12,127
14,328	2.544	21,428	11,264	12,198
14,378	2.550	16,666	11,276	12,210
14,528	2.564	21,428	11,332	12,280
14,628	2.576	16,666	11,357	12,304
14,728	2.586	20,000	11,390	12,343
14,828	2.594	24,999	11,432	12,402
14,928	2.604	20,000	11,465	12,440
15,028	2.616	16,666	11,489	12,462
15,128	2.622	33,333	11,539	12,550

Table 2b. Well velocity data averaged below 12,000 feet

Average Depth (feet)	Average Two-Way Travel Time* (seconds)	Average Interval Velocity* (feet/second)
12,178	2.3275	18,333.00
12,278	2.3375	20,416.50
12,378	2.3480	19,583.00
12,478	2.3600	17,707.75
12,578	2.3705	21,874.75
12,678	2.3810	21,874.50
12,778	2.3915	21,874.50
12,878	2.4005	23,749.75
12,978	2.4130	20,416.00
13,078	2.4265	18,332.75
13,178	2.4390	20,416.00
13,378	2.4510	21,666.00
13,478	2.4620	20,416.00
13,578	2.4715	22,916.00
13,678	2.4815	21,666.25
13,798	2.4925	19,582.75
13,878	2.5015	22,082.75
13,978	2.5110	21,666.25
14,078	2.5195	20,832.75

Continued

Table 2b. Well velocity data averaged--*continued*

Average Depth (feet)	Average Two-Way Travel Time* (seconds)	Average Interval Velocity* (feet/second)
14,178	2.5285	22,023.25
14,278	2.5370	19,940.00
14,328	2.5470	19,047.00
14,478	2.5585	19,047.00
14,528	2.5690	18,690.00
14,678	2.5800	20,773.25
14,778	2.5900	20,416.25
14,878	2.6000	20,416.25
14,978	2.6090	23,749.50

*Running averages of data, $\frac{n_1 + \ldots + n_4}{4}$; $\frac{n_2 + \ldots + n_5}{4}$; etc

The interval velocity range below 12,000 feet (and below 2.3 seconds, two-way travel time) is anomalous in magnitude (12,499 to 33,334feet per second) and in the repetition of particular values (e.g., 16,666, 20,000, and 25,000 feet per second). However, the average velocities and RMS velocities appear reasonable, owing to the small influence of each successive interval, compared to that of the overlying rock, sediment, and water column.

Figures 5 and 6 also show the interval velocity differences smoothed below 12,000 feet, and below 2.3 seconds, by taking a running average of four data points at a time. The averaged data are also shown in table 2b. This procedure yields a more reasonable velocity profile and may be more true to the general reliability of the data in representing the interval of 12,000 feet to total depth.

A lithologic column is also shown in figure 5, and four velocity intervals are indicated, which generally correlate with lithologic intervals penetrated by the well:

Table 3. Well velocity intervals

Interval	Depth range (feet)	Interval Velocity Range (feet/second)	Average Interval Velocity (feet/second)
I	0-4,600	7,284	7,284
II	4,600-9,600	10,204-13,720	12,405
III	9,600-12,000	16,666-18,965	17,761
IV	12,000-15,128	18,333-23,750*	20,697*

* Averaged data.

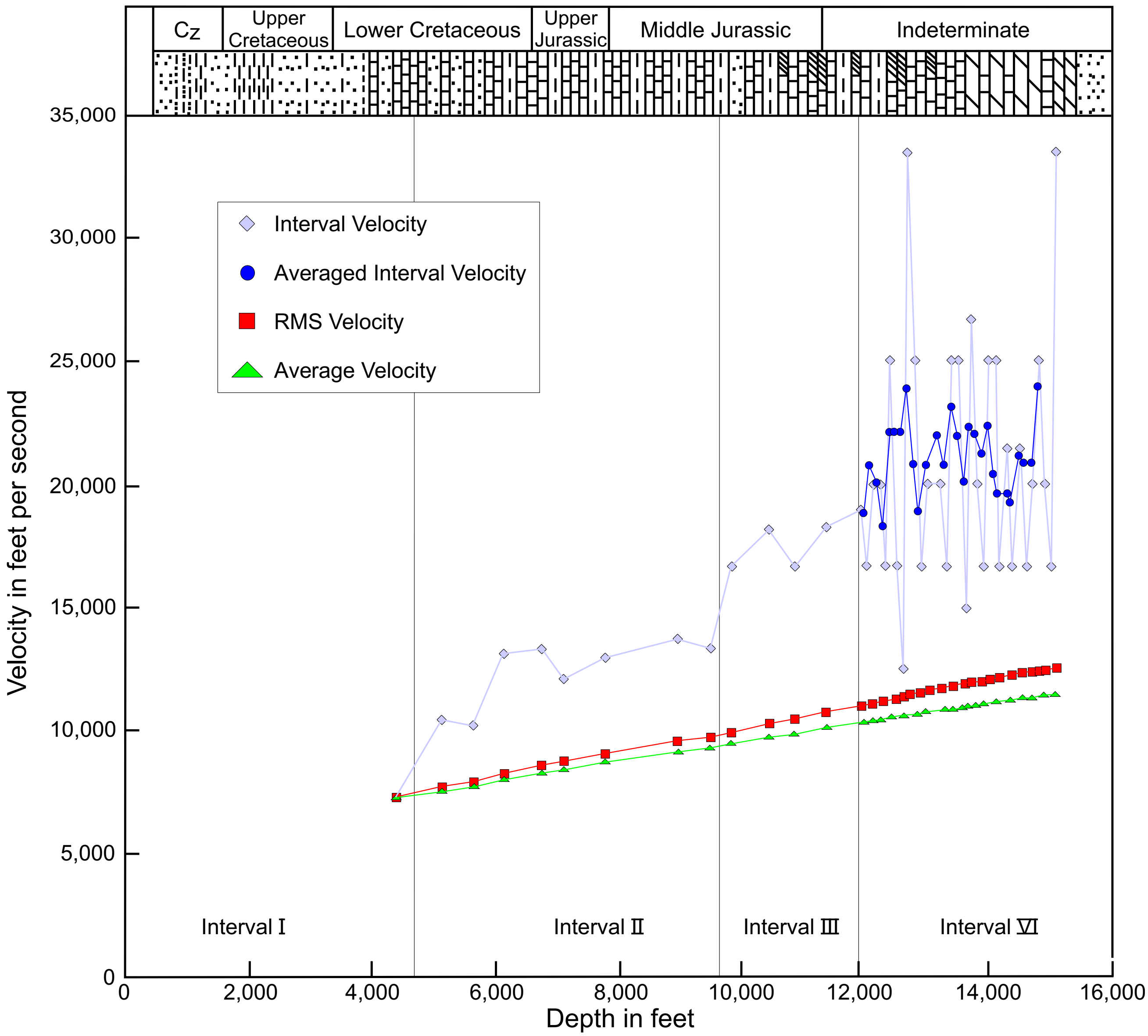

Figure 5. Well velocity profile for the Shell Lydonia Canyon Block 410 No. 1R well, plotted against depth, with biostratigraphic ages and generalized lithologies. Intervals and averaged interval velocities are explained in text.

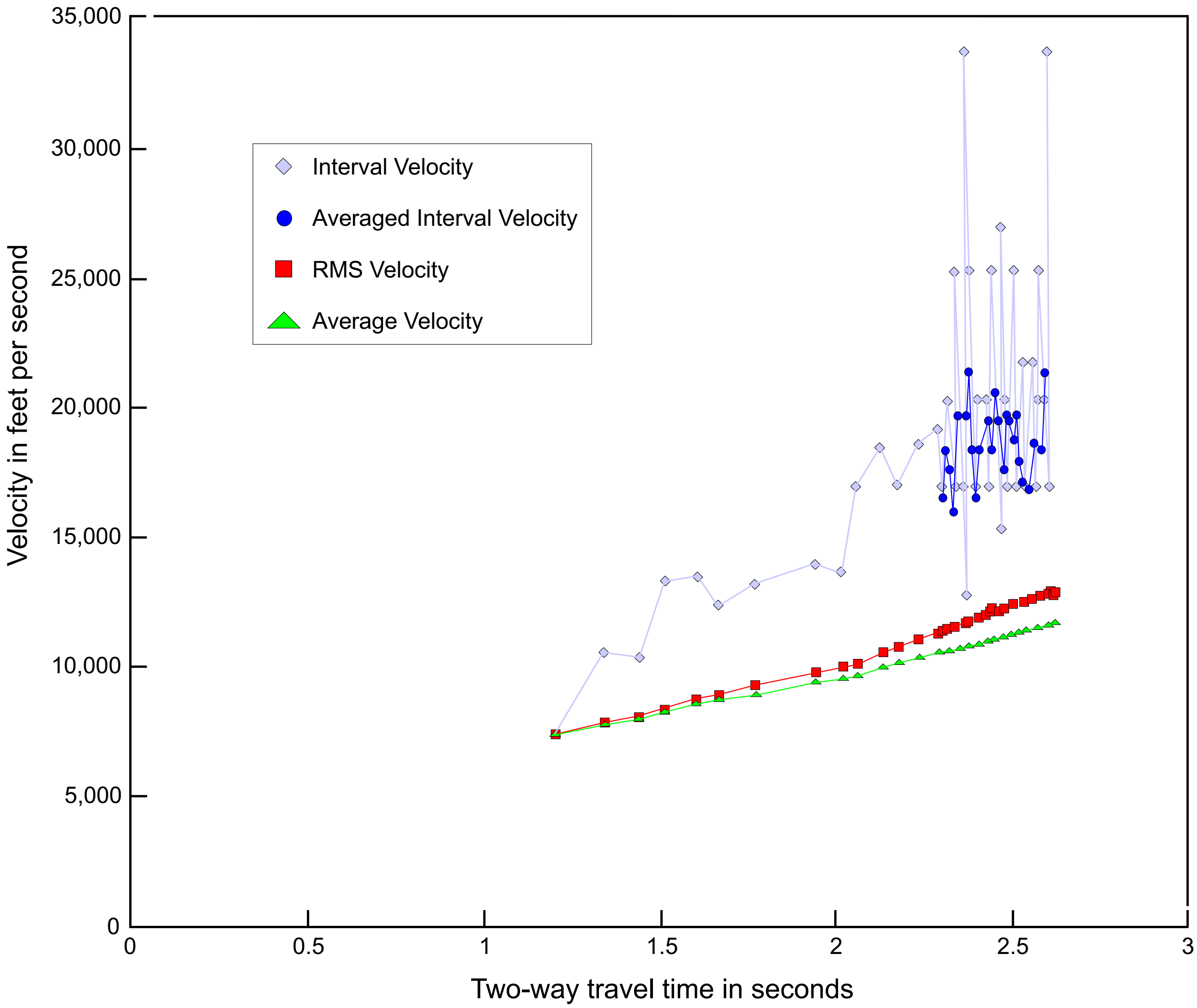

Figure 6. Well velocity profile for the Shell Lydonia Canyon Block 410 No. 1R well, plotted against two-way travel time. Averaged interval velocities explained in text.

Interval I This interval has limited practical value because it is very large and is represented by a single data point. The interval velocity of 7,284 feet per second is for the entire section from the ocean surface to the depth of 4,378 feet. Interval I contains Cenozoic and Upper and Lower Cretaceous mixed lithologies and has low to moderate interval velocities.

Interval II This interval is identified on the basis of moderate interval velocities, averaging about 12,405 feet per second. Included are Lower Cretaceous and Upper and Middle Jurassic mixed lithologies with an increasing proportion of limestone with depth.

Interval III This interval has interval velocities averaging about 17,761 feet per second and contains mostly Middle Jurassic limestones with some siliciclastic interbeds and anhydrite.

Interval IV This is the interval of the anomalous interval velocity data. However, the calculated average velocity of 20,697 feet per second agrees with checkshot data from the same depth range in neighboring wells. The rocks are limestone, dolomite, and anhydrite, with minor siliciclastic interbeds.

LITHOLOGIC INTERPRETATION

Taken and adapted from A. C. Giordano, MMS internal report

Samples were collected at 30-foot intervals from 790 feet to 3,410 feet and 10-foot intervals to total depth, 15,568 feet in the Shell LC Block 410 No. 1R well. Sample quality ranged from fair to good, based on amounts of cavings and degree of washing. Additional lithologic control was provided by two conventional cores, at 9,738 to 9,767 feet and 15,229 to 15,241 feet, and descriptions of 45 successful sidewall cores by Core Laboratories, Inc.

The lithologic descriptions of this report are interpretations derived mainly from examination of drill cuttings, supplemented by viewing thin sections. Depths of lithologic boundaries are adjusted with reference to “electric” and “mud” logs. All depths are from kelly bushing. Rocks penetrated are divided into gross lithologic-stratigraphic units, and a lithologic column appears as figure 7.

LITHOLOGIC DESCRIPTION

From 790 to 1,520 feet, the section consists of sandy pebble conglomerate with minor clay and glauconite. A mixed assemblage of pelecypods, sponge spicules, and planktonic and benthonic foraminifera is present throughout the interval. The sand grains are clear and light gray to pinkish red, fine to coarse in texture, and angular. Metamorphic rock fragments, reworked sedimentary clasts, abundant pyrite, and traces of coal are also present. The clay is gray to greenish gray, unconsolidated, sticky, and calcareous.

From 1,520 to 1,700 feet, the section consists of subrounded-to-rounded, frosted sand grains, sandstone fragments, and abundant pyrite. From 1,640 to 1,700 feet, glauconitic sand marks an unconformity between the Eocene and the Upper Cretaceous.

Between 1,700 to 2,510 feet, the section consists of medium-to-very dark-gray, sticky clay, becoming calcareous with depth. Occasional glauconite and pyrite grains are also present.

Between 2,510 and 4,070 feet, the section consists of sandstone, siltstone, limestone, and clay. The sandstone is clear to white, soft, friable, medium grained, subrounded, poorly sorted, and calcareous. The siltstone is calcareous with poor porosity and contains traces of glauconite, pyrite, and lignite. The limestone is white to gray, coarse grained, firm, and slightly oolitic, with blocky to angular fragments. The clay is light to medium gray, moderately sticky, and calcareous, with abundant glauconite and fossil fragments.

From 4,070 to 5,650 feet, the section consists of limestone, shale, and sandstone. The limestone is gray to white and contains abundant spherical or flat oolites and pellets with variable amounts of intrapartical and interpartical porosity. Dolomite crusting is seen at the top of limestone intervals and is attributed to groundwater penetration. The shale is medium to dark gray, platy, variably calcareous, and has earthy luster. The sandstone is composed of clear, fine- to-coarse grains, fines upward, and is

Figure 7. Columnar chart of the lithology, biostratigraphy, and paleobathymetry of the Shell Lydonia Canyon Block 410 No. 1R well. Lithologic interpretations from examination of cuttings; lithologic breaks picked from well logs. Within columns, depths refer to uppermost occurrence of index fossils listed in Biostratigraphy chapter. Stage tops based on paleontology. Biostratigraphy and bathymetric interpretations become less reliable with increasing depth.

unconsolidated to consolidated, poorly sorted, and variably calcareous.

The interval from 5,650 to 9,750 feet consists of interbedded limestone and shales. The limestone is white to brown to gray, oolitic and slightly sandy, and exhibits little or no visible interpartical or intrapartical porosity. The shale is light to dark gray, soft to firm, calcareous, and slightly silty with traces of pyrite.

From 9,750 to 9,920 feet, the section consists of a white, fine- to-very fine, poorly sorted, relatively unconsolidated, calcareous sandstone with clear to frosted, subangular to subrounded grains. There is no visible porosity. Present also are traces of pyrite and lignite.

From 9,920 to 14,220 feet, the section consists of limestone and interbedded shales. The limestone is white to brown to medium gray, massive, microcrystalline, and oolitic or pelletal or oncolitic. Interpartical porosity is mostly filled with sparry calcite, but some interpartical porosity exists in sucrosic limestone. A trace of chicken-wire-to-bladed anhydrite is observed as a replacement of some micritic limestone. The shale is dark gray.

From 14,220 to 15,160 feet, the section consists of limestone and dolomite. The limestone is white to light brown, microcyrystalline, finely sucrosic, and nonporous. The dolomite is light gray to brown, medium to coarse, and sucrosic. Coarse replacement dolomite (euhedral, rhombic crystals) exhibits intercrystalline porosity and is a replacement of micritic limestone, perhaps through freshwater leaching.

From 15,160 to 15,568 feet (TD), the section consists of sandstone, red siltstone, anhydrite, and schist. The sandstone is white to red, fine to medium, and silica cemented with subrounded to subangular grains. Fragments of pyrite and hematite are also present.

RESERVOIR POTENTIAL

Analyses of rock cuttings, core data, and well logs (see **Formation Evaluation** chapter) indicate that the best reservoir characteristics are associated with clastic rocks above 5,650 feet. Porosities average 32 percent, based on log analysis, but these rocks are thermally immature. From 5,650 feet to 9,550 feet, interbedded carbonates and shales have moderate to poor reservoir potential and are still thermally immature. From 9,550 to 14,220 feet, the limestone is massive, dense, and tight with slight dolomitization. Log analysis indicates 15 percent average porosity in the best zones above 9,888 feet and 8 to 9 percent in the most porous zones below this depth. In general, however, microscopic sample examination reveals poor porosity among these alternating carbonate and shale sequences. Anhydrite beds below 11,250 feet have no measurable porosity. Borderline thermal maturity is not reached until 13,300 feet, according to MMS optical thermal maturation studies (see **Kerogen analysis** chapter). From 14,220 to 15,120 feet, freshwater leaching occurred, resulting in a dolomitized zone with secondary porosity. From 15,200 feet to total depth, the clastic sediments are tightly cemented by silica and exhibit no visible porosity.

BIOSTRATIGRAPHY

Taken and adapted from W. E. Steinkraus, H. L. Cousminer, and C. E. Fry, MMS internal report

The biostratigraphic and paleoenvironmental interpretations of the Shell LC Block 410 No. 1R well are based on foraminifera, spores, pollen, dinoflagellates, and calcareous nannofossils from well-cutting samples (figure 7). This report includes the results of three separate investigations by the paleontological staff of the Atlantic OCS office of the MMS.

Foraminiferal analyses were based on 112 samples at 30-foot intervals collected from 790 to 4,130 feet. Palynological studies were made from 160 slides prepared from composited 90-foot intervals from 1,200 to 15,560 feet. Nannofossil studies were made from the examination of 212 slides representing 30-foot intervals from 770 to 7,130 feet. No core samples were used. Well depths are relative to kelly bushing.

Two factors limit the reliability of the paleontologic data. (1) Analyses are made from drill cuttings, which are often heavily contaminated by cavings from higher in the drill hole. For this reason, only “tops,” or the uppermost (last) appearances of species, are used. (2) Reworked, older fossil assemblages and individual specimens are commonly reincorporated in detrital sedimentary rocks. These fossils must be recognized so that intervals are not dated older than they really are. In addition, in U. S. offshore Atlantic wells, biostratigraphic control is poor in pre-Late Jurassic strata. Calcareous nannofossils and foraminifera are sparse. Palynomorphs are more common, but their biostratigraphic distribution is not fully documented with reference to the European type-stage localities.

This investigation relies on the Jurassic palynostratigraphy of offshore eastern Canada (Bujak and Williams, 1977) because many of their palynomorph marker species are also present in the U. S. offshore Atlantic subsurface. Although the European stage equivalence of many species is not fully resolved, several species have recently been documented in European type-sections (Woollam and Riding, 1983; Riding, 1984; Davies, 1985).

CENOZOIC

TERTIARY

No samples above 790 are available. The age of the interval between 790 and 1,050 feet is indeterminate because no age-diagnostic fossils were recognized.

Miocene (1,050-1,520 feet)

The highest occurrence of the nannofossil species Coccolithus miopelagicus at 1,050 feet indicates a Miocene age for this interval. Pollen species were recovered at 1,200 feet, including Pinus, Picea, Tsuga, and Carya. The depositional environment is characterized by shallow-water benthonic foraminiferal species, including Cibicides, Nonionella, Gyroidina, Anomalina, Siphonina, Uvigerina, Dentalina, Lenticulina, Bulimina, Pseuodoglandulina, and Lagena. Microgastropods were observed in this interval. The nannoflora is very sparse. An inner shelf (0-50 feet) environment of deposition is interpreted for the interval 1,050 to 1,200 feet. Foraminiferal evidence indicates middle shelf (50 to 300 feet) from 1,200 to 1,670 feet.

Early Oligocene (1,520-1,580 feet)

The highest occurrence of the nannofossil species Reticulofenestra umbilica and Chiasmolithus oarmaruensis indicates an Early Oligocene age for this interval.

Late Eocene (1,580-1,640 feet)

The entire Eocene section is characterized by sparse nannoflora. A Late Eocene age was determined by the joint occurrence of Discoaster saipanensis, which extends no higher than the top of the Eocene, and Istmolithus recurvus, which ranges from the Late Eocene to the base of the Oligocene.

Middle Eocene (1,640-1,670 feet)

Rare specimens of Mesozoic nannofossils in this interval represent reworked species. A Middle Eocene age for this interval is based on the planktonic foraminifer Globigerina primitiva.

MESOZOIC

CRETACEOUS

Late Cretaceous

Campanian (1,670-1,700 feet)

A Campanian age for this interval is based on the highest occurrence of the palynomorph Lejeunia hyalina, the foraminifer Globotruncana linneiana, and the nannofossil Gartnerago obliquum. Other palynomorph species recovered from this interval include Hystrichsphaeropsis ovum, Deflandrea echinoidea, and Hystrichokolpoma ferox. An inner shelf environment of deposition is indicated.

Santonian (1,700-2,270 feet)

The highest occurrence of the nannofossil species Marthasterites furcatus at 1,700 feet indicates a Santonian age for this interval. The planktonic foraminifer Globotruncana renzi was recovered at 1,730 feet. A significant nannofloral assemblage was noted in the lower part of the Santonian interval from 2,150 to 2,270 feet. The foraminifera and nannoflora suggest deposition in a shallow marine, inner shelf environment of deposition from the Campanian through Santonian interval.

Coniacian (2,270-2,390 feet)

The top of the Coniacian is based on the highest occurrence of the foraminifer species Globotruncana imbricata. This species is restricted to the Turonian-Coniacian ages. A middle shelf environment of deposition is indicated through the Cenomanian.

Turonian (2,390-2,660 feet)

The Turonian is based on the highest occurrence of the dinoflagellate species Surculosphaeridium longifurcatum at 2,390 feet. The planktonic foraminifer Globotruncana helvetica was recovered at 2,510 feet. The nannofossil species Corollithion achylosum and Lithastrinus floralis were identified at 2,540 feet.

Cenomanian (2,660-2,810 feet)

The top of Cenomanian stage at 2,660 feet is based on the planktonic foraminifera Rotalipora cushmani and R. greenhornensis. The nannofossil Corollithion kennedyi was recovered at 2,690 feet. A rich nannofossil assemblage is present in the Cenomanian and the lower part of the Turonian (2,540-2,810 feet).

Early Cretaceous

Albian (2,810-3,200 feet)

The Albian is based on the highest occurrence of the planktonic foraminifer Rotalipora ticinensis. The dinoflagellate species Spinidinium vestitum, recovered from 3,110 feet, supports an Albian age. The Albian section is characterized by abundant planktonic foraminiferal assemblages. An inner shelf environment of deposition is indicated from Hauterivian through Albian.

Aptian (3,200-4,460 feet)

The top of the Aptian is based on the highest occurrence of the dinoflagellate Apteodinium conjunctum at 3,200 feet. The presence of Astrocysta cretacea at 3,470 feet supports the age for this interval. The nannofossil species Cyclagelospharea margerili has its highest occurrence at 3,770 feet and Nannoconus globulus is present at 4,070 feet. Foraminifer species of known stratigraphic significance are rare below the Albian section.

Barremian (4,460-5,270 feet)

The dinoflagellate species Pseudoceratium pelliferum and Tenua anaphrissa, identified at 4,460 feet, are not known to occur in post-Barremian strata.

Hauterivian (5,270-5,810 feet)

The top of the Hauterivian has been placed at 5,270 feet, on the basis of Bebout's Trilobosporites sp. 133 and the dinocyst Kleithriasphaeridium corrugatum. According to Bebout (1981), Trilobosporites sp. 133 does not range above this stage in the Mid-Atlantic. Muderongia simplex and Canningia cf. C. reticulata are also present.

Valanginian (5,810-6,080 feet)

The Valanginian section is characterized by the dinoflagellate species Oligosphaeidium perforatum (asterigerum) at 5,810 feet. The nannofossil indicator Cruciellipsis cuvillieri, which may range above this stage, was also found in this interval. A middle shelf environment of deposition was interpreted from the Middle Jurassic through the Valanginian on the basis mainly of the palynomorph assemblages.

Berriasian (6,080-6,650 feet)

The top of the Berriasian is placed at 6,080 feet on the basis of the nannofossil Polycostella senaria. This species does not range above the Berriasian. Palynomorph index species were identified at 6,350 feet, including the dinocyst Occisucysta evittii and the spore species Bebout sp. 139, 140, and Reticulatisporites simireticulatus.

JURASSIC

Late Jurassic

Tithonian (6,650-7,010 feet)

The top of the Tithonian section is based on the highest occurrence of the dinoflagellate Ctenidodinium panneum at 6,650 feet. Gonyaulacysta cladophora is also present in this interval.

Kimmeridgian (7,010-7,730 feet)

The Kimmeridgian top is based on the dinocyst species Gonyaulacysta longicornis and Gonyaulacysta sp. "A" at 7,010 feet.

Oxfordian (7,730-7,910 feet)

An Oxfordian age for this interval is based on the palynomorph Surculosphaeridium vestitum at 7,730 feet, which does not range above the Oxfordian. Gonyaulacysta jurassica, Meiourgonyaulax pila, and M. staffinensis were also present.

Middle Jurassic

Callovian (7,910-8,630 feet)

The top of this age at 7,910 feet is based on the highest occurrence of the dinocyst Valensiella vermiculata. Other longer-ranging palynomorphs include Adnatosphaeridium aemulum and A. caullyeri.

Bathonian (8,630-10,340) feet)

The top of this stage is based on the dinoflagellate Gonyaulacysta filapicata at 8,630 feet. Other species recovered in the interval include Ctenidodinium ornatum and C. pachyderma.

Bajocian? to early Bathonian (10,340-11,420 feet)

Gonyaulacysta filapicata is present throughout this interval. No evidence is available for Triassic or Early Jurassic deposits in this well. The interval from 11,420 feet to total depth (15,568 feet) is barren and, therefore, the age is indeterminate.

FORMATION EVALUATION

Taken and adapted from R. Nichols, MMS internal report

Schlumberger Ltd. ran the following geophysical "electric" logs in the Shell LC Block 410 No. 1R well to provide information for stratigraphic correlation and for evaluation of formation fluids, porosity, and lithology:

Table 4. Well logs

Log Type	Depth Interval (feet below KB)
DISFL/Sonic (dual induction spherically focused log/sonic)	627-15,564
FDC/GR (compensated formation density/gamma ray)	627-1,399 and 12,018-15,564
CNL/FDC (compensated neutron log/compensated formation density)	627-15,564

Exploration Logging Inc. provided a formation evaluation "mud" log, which includes a rate of penetration curve, sample description, and graphic presentation of any hydrocarbon shows encountered (629 to 15,568 feet).

The electric logs, together with the "mud" log and other available data, were analyzed in detail to determine the thickness of potential reservoirs, average porosities, and feet of hydrocarbons present. Reservoir rocks with porosities less than 5 percent were not included. A combination of logs was used in the analysis, but a detailed lithologic and reservoir property determination from samples, conventional cores, and sidewall cores is necessary to substantiate the following estimates as shown in table 5.

Table 5. Well log interpretation summary

Series	Depth Interval (Feet)	Potential Reservoir[1] (feet)	Avg ϕ	SW%	Feet of Hydrocarbon
LK	4,668-5,625	315	32	NC*	NC
	5,827-5,966	72	13	NC	NC[2]
MJ	9,747-9,888	81	15	NC	NC
	11,040-11,106	57	8	NC	NC
	13,058-13,068	10	9	NC	NC
	13,068-15,561	--	--	NC	NC

*Not calculated

[1]Generally in beds > 10 feet thick and $\phi > 5\%$

[2]Carbonate, thinly bedded

The electric logs were of acceptable quality. However, the SP was very spiky from 4,450 to 15,561 feet and the CNL/FDC repeat section from 12,100 to 12,300 does not compare favorably to the final log.

SIDEWALL CORES

Fifty-nine sidewall cores were attempted in the well and 45 were successful and are summarized in table 6.

Table 6. Sidewall core analysis summary

Depth Interval (feet)	Lithology	Porosity Range (%)	Permeability Range (md)
13,060-13,900	Limestone	5.2-14.9	<0.1-2.9
14,046-14,800	Limestone	8.9-15.3	<0.1-4.6
14,848-15,090	Limestone	4.4-11.5	<0.1-1.1
15,236-15,385	Siltstone	7.2-19.3	<0.1-7.2

CONVENTIONAL CORES

Two conventional cores were taken in this well, No. 1 at 9,738 to 9,767 feet and No. 2 at 15,229 to 15,241 feet. The conventional core properties are described in table 7. Core No. 1 compares favorably with the porosities calculated from the sonic log, especially in the interval 9,746 to 9,762 feet. However, the core porosities do not compare well with the density or neutron porosities. Core porosity values are substantially lower than those from the density log, particularly in the interval 9,746 to 9,762 feet.

Table 7. Conventional cores

Core No.	Depth Interval (feet)	Lithology	Porosity Range (%)	Permeability Range (md)
1	9,738-9,767	SS[1]	3.1-13.6	<0.1-26.5
2	15,229-15,241	SS[1]	1.0-2.6	0.031-0.21

[1]Lithology and mud sample description and from photographs

SIGNIFICANT SHOWS

As summarized in table 8, there were no significant shows of hydrocarbon encountered in this well. No tests of any zone were made.

Table 8. Hydrocarbon shows

Depth (Feet)	Drilling Break	Sample Description (Mud Log)	Total Gas bk. grd.		Chromatograph	Cuttings Gas	Conventional Cores	Sidewall Cores	Well Log Interpretation	Test
4,300 - 4,500	-	LS, no vis. ϕ, some w. sl tr brn stn, brt / yel-wht flu, vy sl creme-wht cut	0	0	-	-	-	-	$\phi \cong 16\%$	-
6,800 - 6,980	-	SS, no vis. ϕ no stn, dull yel flu, no cut	0	10	$C_{l, 2,3,}$	3	-	-	$\phi \cong 11\%$	-
9,738 - 9,767	-	SS, vy calc, no vis. ϕ , dull yel flu, occ lt brn stn, no cut	0	0	-	-	Core #1 K= <.1 -26.5md ϕ =3.1 - 13.6%	-	$\phi \cong 5\%$	-
13,200 - 13,850	-	LS, pr ϕ , tr minl flu, no cut. @13,550 - occ dul-br yel minl flu, sl crush cut @13,850-occ dull-br yel minl flu, sl crush cut	0	2	-	2	-	LS, shly, K= < .1 - .8md ϕ =5.8 - 12%	$\phi \leqq 5\%$	-
14,800 - 15,000	-	Dol. xln, tr intergr ϕ @14,850 @14,975	 0 0	 5 5	 $C_{l, 2, 3,}$ $C_{l, 2, 3, 4}$	 - 2	-	LS, shly K=<0.1 - 3.0md ϕ=4.4 - 13.5%	$\phi \leqq 5\%$	-
15,229 - 15,241	-	SS and siltstn, tr anhydrite, no flu, no cut	0	0	-	-	Core #2 K =0.031 - 0.21 md ϕ =1.0 - 2.6%	Silt, vy shly, K=<0.1 - 0.8md ϕ=5.8 - 12.0%	$\phi \leqq 5\%$	-

GEOTHERMAL GRADIENT

Figure 8 shows bottomhole temperatures for seven logging runs in the Shell LC Block 410 No. 1R well plotted against depth. A temperature of 60 ^{o}F is assumed at the seafloor at an indicated depth of 453feet (381-foot water depth plus 72-foot kelly bushing elevation). Shown also is a straight-line graph between the seafloor and total-depth temperatures in order to represent an overall geothermal gradient for the well, which is 1.25 ^{O}F/100 ft. Calculated geothermal gradients for all Georges Bank wells range from 1.06 to 1.40 ^{O}F/100 ft.

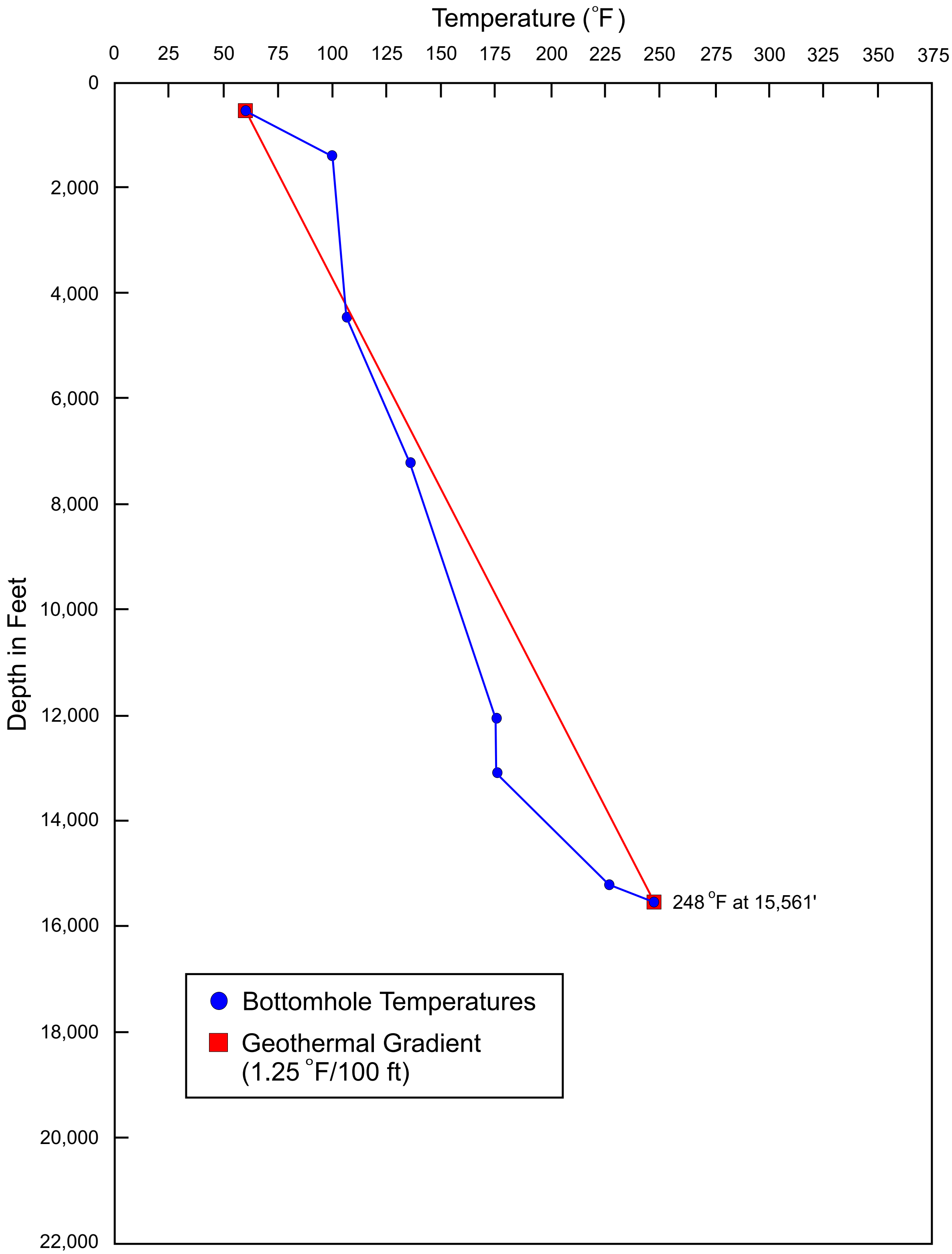

Figure 8. Well temperatures and geothermal gradient for the Shell Lydonia Canyon Block 410 No. 1R well. Well temperatures from bottomhole temperatures of logging runs. Geothermal gradient based on bottomhole temperature of deepest logging run.

KEROGEN ANALYSIS

Taken and adapted from C. E. Fry and H. L. Cousminer, MMS internal report

Kerogen types and thermal maturation levels were determined by microscopic examination of kerogen slides and palynology slides made from cutting samples from the Shell LC Block 410 No. 1R well. Vitrinite-reflectance data are included in a geochemical report submitted by Shell Offshore, Inc. Cuttings samples were also analyzed for total organic carbon (TOC) by R. E. Miller and others (see **Petroleum Geochemistry** chapter). Well depths cited here are relative to kelly bushing.

In this analysis, organic material is classified as one of four major types: algal-amorphous, organic material of marine origin, either recognizable algae or the unstructured remains of algal material; herbaceous, leafy portions of plants, including spores and pollen; woody, plant detritus with a lignified, ribbed structure; coaly, black opaque material, thought to be chemically inert. Visual estimates are made for the percentage of each type, relative to the total abundance of kerogen, contained in each of the slides. Algal material is generally considered the best source for oil; more structured terrestrial kerogen is primarily a gas source.

Thermal maturity of the organic material is estimated by comparing the color of various palynomorphs contained in the kerogen slides to the thermal alteration index (TAI) scale taken from Jones and Edison (1978). Measuring the exact amount of light reflected from a piece of vitrinite (a humic coal maceral commonly disseminated in sedimentary rocks) provides additional maturation data that can be compared to TAI determinations. Relationships among various maturity indicators are shown in figure 9.

Kerogen type and thermal alteration rank are used with total organic carbon abundances to evaluate whether sediments in a well are prospective as petroleum source rocks.

KEROGEN TYPE

Figure 10 shows the MMS kerogen-type analysis for the Shell LC Block 410 No. 1R well. Algal-amorphous kerogen is most abundant at five depths: 1,300 feet (10 percent), 3,300 (5 percent), 4,800 (25 percent), 5,900 (30 percent), and 10,700 (5 percent). Below 7,000 feet, samples are dominated by terrestrial kerogens (herbaceous, woody, and coaly). From 7,000 to 11,400 feet, herbaceous kerogen averages about 30 percent, decreasing to 20 percent below 11,400 feet. A lens of oxidized and decomposed herbaceous material appears at 12,100 feet. Woody and coaly kerogens together dominate most of the stratigraphic section penetrated by the well, especially from 1,800 to 3,500 feet, 6,100 to 7,000 feet, and below 12,500 feet, where they account for more than 75 percent of the organic matter present.

MATURITY

Judging thermal maturity from cuttings must be done with great care to ensure that the material being analyzed is indigenous to the level sampled. Caved or reworked material or sample contamination will give false indications of maturity. Oxidation in

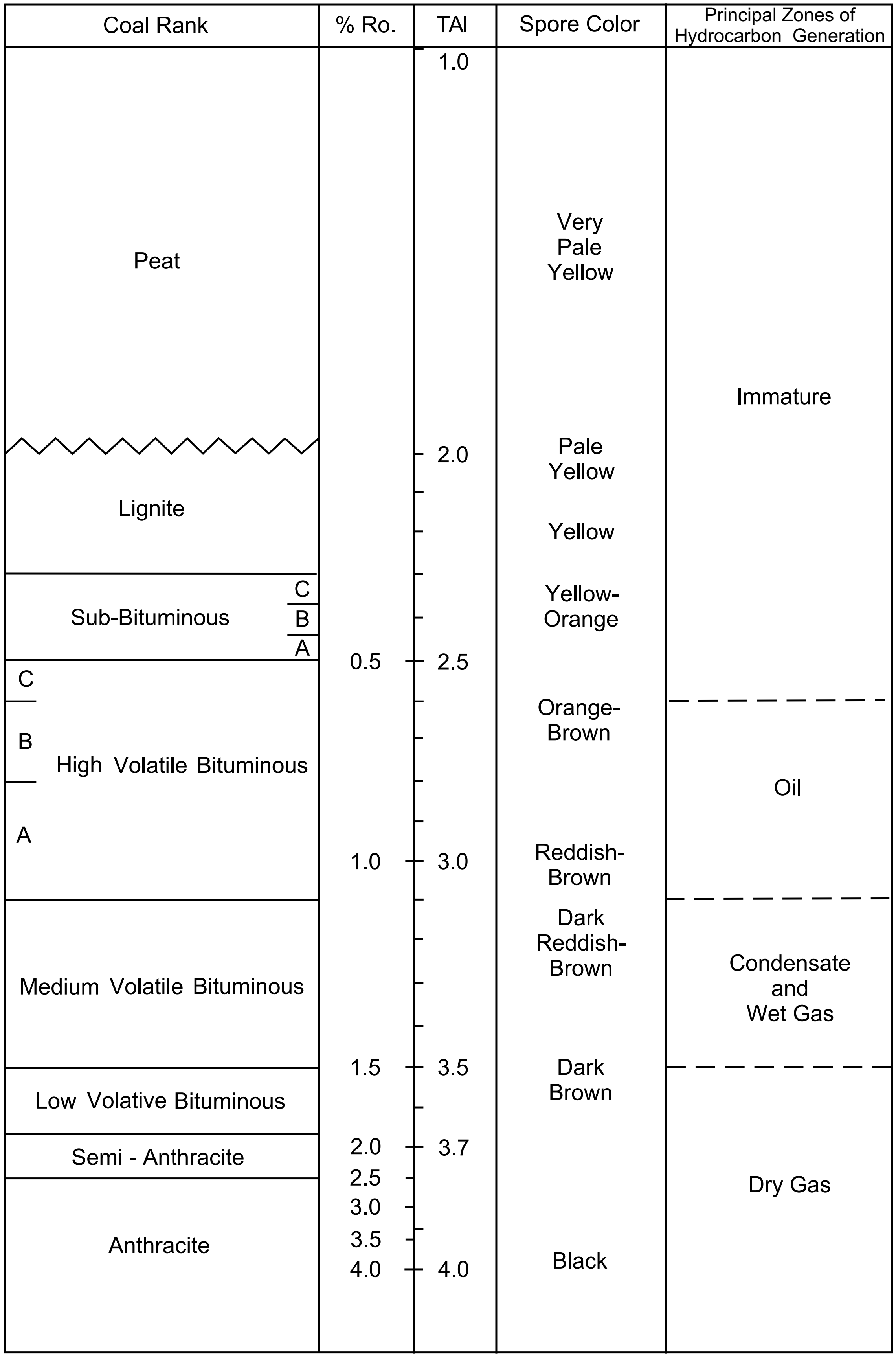

Figure 9. Relationships among coal rank, percent R_o, TAI, spore color, and thermal zones of hydrocarbon generation (after Jones and Edison, 1978).

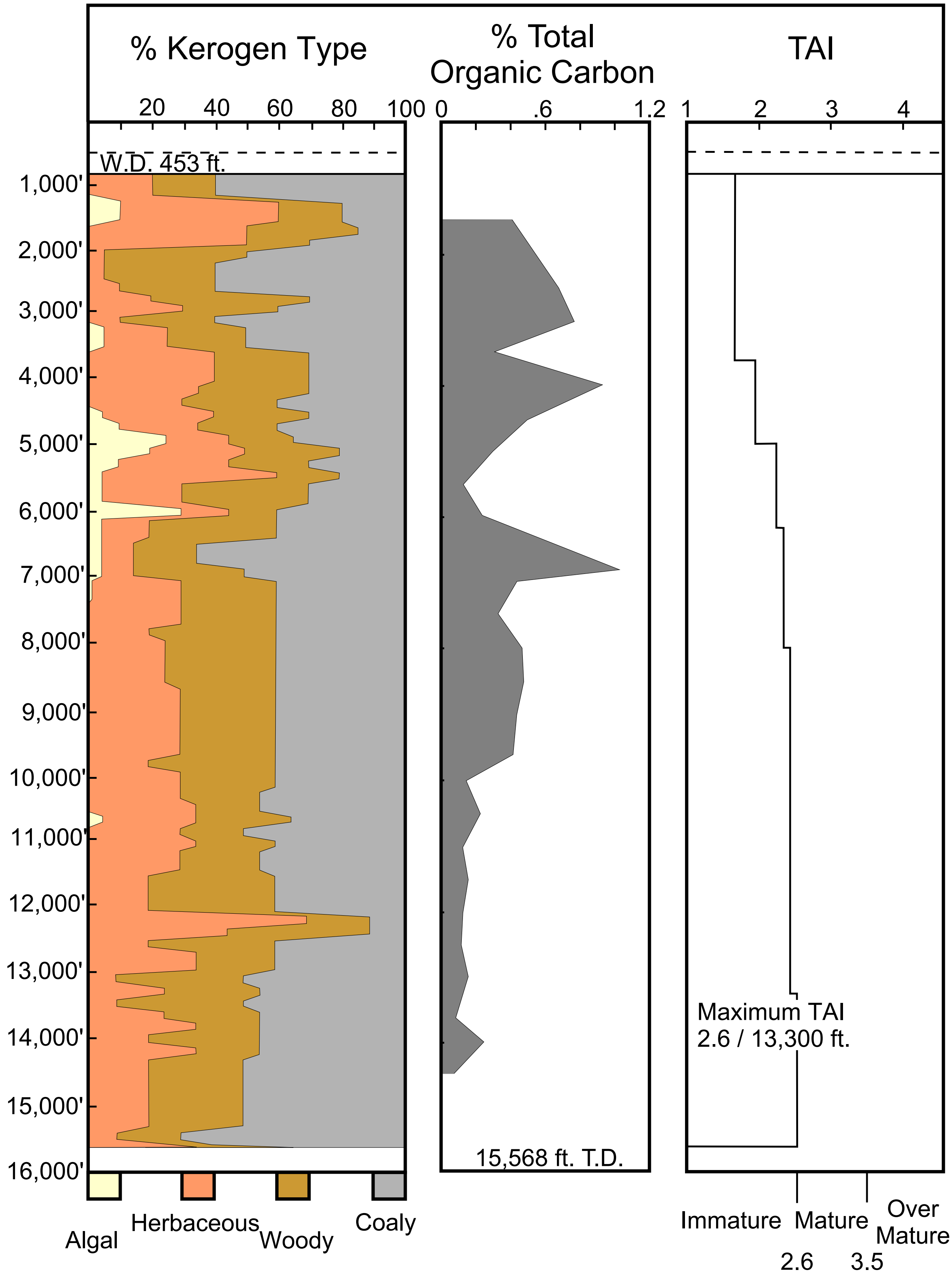

Figure 10. Graph of kerogen types, total organic carbon, and organic thermal maturity for the Shell Lydonia Canyon Block 410 No. 1R well.

a high-energy environment of deposition can also alter the appearance of organic material. Two methods were used to determine organic thermal maturity in this well: vitrinite reflectance and visual estimation of TAI. These methods serve as a check on one another and should generally agree. However, in this case, the Shell vitrinite reflectance data and the TAI estimation done by MMS personnel do not match. The vitrinite reflectance data indicate sufficient thermal maturity to generate hydrocarbons at 9,000 feet and peak generation at approximately at 13,000 feet. However, TAI does not show maturity until 13,300 feet, and even then the colors are borderline (2.6 TAI) (figure 10). The exact method and material Shell used to generate the vitrinite reflectance data are unknown, with only the results presented in their report. For the MMS TAI analysis, in as many cases as possible, the palynomorphs used for visual color determination were fossil markers to ensure the material analyzed was indigenous. However, molecular geochemical analysis (see **Petroleum Geochemistry** chapter) by MMS suggests thermal maturity/depth relationships in closer agreement with Shell's vitrinite analysis.

TOTAL ORGANIC CARBON

Sedimentary organic material must be present in sufficient quantity if rocks are to be considered potential hydrocarbon sources. In general, shales in which total organic carbon is less than 0.5 percent are not prospective source rocks. TOC measurements were taken from the well between 1,300 and 14,500 feet (table 9, figure 10). The interval from 1,460 to 6,780 feet ranges from poor to good with three samples having 0.77, 0.93, and 1.03 percent, respectively. From 6,980 to 9,600 feet, most samples are between 0.4 and 0.5 percent TOC, which is marginal at best. From 10,000 feet to total depth, TOC abundance is 0.25 percent or less, insufficient to generate hydrocarbons.

CONCLUSIONS

Using the more optimistic option of Shell's vitrinite reflectance assessment, rocks above 9,000 feet in the Shell LC Block 410 No. 1R well are not thermally mature for hydrocarbon generation and, using the MMS TAI assessment, rocks above 13,000 feet are immature. Only a few hundred feet of sedimentary rock immediately below 9,000 feet approach sufficient organic richness for hydrocarbon generation. Rocks below 13,000 feet are entirely too lean to produce any hydrocarbons. Using Shell's more optimistic thermal maturity interpretation, about 600 feet of section, from 9,000 to 9,600 feet, is marginally thermally mature and approaches marginal organic richness. On the basis of the TOC data and the MMS thermal profile of the Shell LC Block 410 No. 1R well, there is no well interval that can be considered effective source rock

Table 9. Total organic carbon analysis

Depth	%TOC
1,460	0.41
2,480	0.68
2,990	0.77
3,470	0.31
3,950	0.93
4,500	0.50
5,000	0.30
5,500	0.13
5,980	0.24
6,780	1.03
6,980	0.44
7,490	0.33
8,000	0.47

Depth	%TOC
8,500	0.48
9,000	0.44
9,600	0.42
10,000	0.15
10,500	0.23
11,000	0.13
11,490	0.16
12,000	0.13
12,500	0.12
12,990	0.16
13,630	0.09
14,000	0.25
14,490	0.08

PETROLEUM GEOCHEMISTRY

Taken and adapted from R. E. Miller, H. E. Lerch, D. K. Owings, D. T. Ligon, W. Walker, C. Fry, D. M. Schultz, and H. Cousminer, MMS internal report

INTRODUCTION

Purpose And Scope

The objectives of this geochemical study are to assess source-rock potential, thermal maturity, and types of organic matter encountered in the Shell LC Block 410 No. 1R well and to compare these characteristics to those of equivalent stratigraphic units in the Georges Bank COST G-1 and G-2 wells.

Concepts And Terminology

The basic principles and terminology in this report were established by Vassoyevich and others (1969), Dow (1977), Tissot and Welte (1978), and Hunt (1974, 1978, 1979). Terminology to define source-rock richness, maturity, and potential follow these principles and interpretive concepts used by Claypool and others (1977) and Miller and others (1979, 1980, 1982). Briefly, the organic richness of a source bed and its potential to generate petroleum hydrocarbons may be indicated by (1) a minimum amount of total organic carbon (TOC) (0.7 to 1.0 weight percent for shales) and (2) solvent-extractable hydrocarbon concentrations considerably greater than 100 ppm. The total organic carbon required to constitute an excellent, good, or poor source bed is not as well defined for fine-grained, medium- to dark-gray limestones and dolomites (Miller and others, 1982). Hunt (1979) states that “Because of the amorphous nature of the organic matter derived from hydrogen-rich marine algae, dark-gray carbonates may have the potential to generate more hydrocarbons than shales with equivalent amounts of total organic matter.” Thus, limestones and dolomites with as little as 0.3 weight percent organic carbon may be considered to be potential source rocks (Hunt, 1967). This classification does not apply to limestones containing primarily allochthonous, terriginous herbaceous, woody, and coaly kerogens.

Thermally immature potential source rocks are defined here as sedimentary rocks that contain an abundance of organic matter that, when subjected to thermal heating (pyrolysis), are capable of generating petroleum hydrocarbons. However, these rocks have not been thermally altered by natural reactions to yield a significant amount of petroleum. A source rock is defined as mature, or effective, when thermochemical processes have converted the indigenous extractable hydrocarbons to petroleum, and when extractable hydrocarbons are present with concentrations of about 1 to 2 percent of the total organic carbon.

Geochemical Methods And Procedures

Geochemical analyses for C_{15}+ heavy hydrocarbons are run on washed cuttings samples greater than 10 - 20 Tyler mesh size. Composite samples having a minimum weight of 40 grams are used to ensure that sufficient rock material is available to give reliable results. Each sample is examined under a binocular microscope, the lithology is described, and foreign substances such as plastic, rubber, walnut husks, iron filings, and mica are removed. Composite samples are ground to finer than 60 mesh and aliquots are set aside for total-organic-carbon determinations.

Procedures for solvent-extraction liquid-column chromatography and gas-chromatography for C_{15}+ liquid-hydrocarbon analyses used by the MMS Petroleum Geochemistry Group may be summarized as follows. Soxhlet-solvent extraction in chloroform is followed by removal of free sulfur by passing the extract over a column of activated copper. The sulfur-free extract is separated into paraffin-naphthenes, aromatics, and nitrogen-sulfur-oxygen (NSO) compounds using elution-column chromatography (gravimetrics) on silica gel. The saturated paraffin-naphthene fractions are analyzed both quantitatively and qualitatively on Perkin Elmer Sigma 2B and 3920 gas chromatographs, respectively. The Carbon Preference Index (CPI) calculations were modified from Hunt (1974):

$$\text{CPI}= \frac{\dfrac{(\%n\text{-}C_{25} + \%n\text{-}C_{27} + \%n\text{-}C_{29} + \%n\text{-}C_{31})}{(\%n\text{-}C_{24} + \%n\text{-}C_{26} + \%n\text{-}C_{28} + \%n\text{-}C_{30})} + \dfrac{(\%n\text{-}C_{25} + \%n\text{-}C_{27} + \%n\text{-}C_{29} + \%n\text{-}C_{31})}{(\%n\text{-}C_{26} + \%n\text{-}C_{28} + \%n\text{-}C_{30} + \%n\text{-}C_{32})}}{2}$$

Total organic carbon (TOC) is a basic measure of the organic richness of a potential source rock. Triplicate organic-carbon analyses are performed on dried, weighed aliquots of carbonate-free residue produced by leaching with hot, 6-normal hydrochloric acid approximately 0.07 oz of ground sample smaller than 60 mesh. The samples are combusted in a Perkin Elmer model 240 carbon, hydrogen and, nitrogen analyzer.

Kerogen Analysis Methodology

Organic petrology, to determine organic material types and maturation state, was done by microscopic examination of kerogen and palynology slides (see **Kerogen Analysis** chapter).

RESULTS AND DISCUSSION

Source-Rock Richness and Quality

Upper Cretaceous rocks of the Shell LC Block 410 No. 1R well from 1,670 to 2,810 feet have total organic carbon values in the 0.7 weight percent range (table 9). Total extractable hydrocarbons for these rocks are in the poor to fair range (161 ppm) (table 10), so the Upper Cretaceous is not considered to be a viable exploration target. Lower Cretaceous strata from 2,810 to 6,650 feet have total organic carbon values that average 0.50 weight percent, which is minimal for petroleum hydrocarbon generation. Extractable hydrocarbons average 239 ppm, which suggests, according to Philippi (1957) and Hunt (1979), only fair source rock quality.

Table 10. Molecular geochemical analysis results

Sample Interval (Feet)	Total Saponifiable Gravimetric / Sediment Weight (ppm)	Paraffin-naphthene / Sediment Weight (ppm)	Aromatic / Sediment Weight (ppm)	Eluted N.S.O. / Sediment Weight (ppm)	Total Organic Carbon (%)	Total Organic Carbon (mg/g)	Total Hydrocarbon / Total Organic Carbon (%)	Total Saponifiable Gravimetric / Total Organic Carbon (mg/g)	Paraffin-naphthene / Aromatic	Total Hydrocarbon / Total Saponifiable Gravimetric	Total Hydrocarbon (ppm)	Paraffin-naphthene / Total Saponifiable Gravimetric	C.P.I. A	C.P.I. B	Pristane / Phytane	Pristane / n-C_{17}	Pristane / n-C_{18}	Pristane + Phytane / n-Alkane
2,330 - 2,600	300.0	136.0	25.0	154.0	0.68	6.8	2.4	44.1	5.4	0.54	161.0	0.45	1.05	1.03*	1.86	0.43	0.41	0.14
3,410 - 3,560	235.0	98.5	24.0	119.5	0.31	3.1	4.0	75.8	4.1	0.52	122.5	0.42	1.11	1.23*	1.89	0.52	0.43	0.15
4,480 - 4,530	849.1	396.5	67.8	299.6	0.50	5.0	9.3	169.8	5.9	0.55	464.4	0.47	2.49	1.75*	1.61	0.41	0.44	0.11
5,470 - 5,530	263.0	116.5	21.0	164.0	0.13	1.3	10.6	202.3	5.6	0.52	137.5	0.44	1.03	1.61*	1.87	0.58	0.43	0.16
6,700 - 6,940[a]	435.1	190.8	42.7	211.4	1.03	10.3	2.3	42.3	4.5	0.54	233.5	0.44	1.07	0.91*	2.02	0.48	0.41	0.16
7,450 - 7,530	235.2	127.2	21.3	67.3	0.33	3.3	4.5	71.3	6.0	0.63	148.5	0.54	1.04	1.46*	2.08	0.53	0.42	0.14
8,460 - 8,550	205.9	84.4	15.1	142.9	0.48	4.8	2.1	42.9	5.6	0.48	99.5	0.41	0.98	0.74*	2.10	0.52	0.42	0.22
9,560 - 9,650	240.5	93.5	34.5	177.5	0.42	4.2	3.1	57.3	2.7	0.53	128.0	0.39	0.97	1.65	2.10	0.49	0.41	0.20
10,470 -10,540	240.8	87.2	23.7	132.5	0.23	2.3	4.8	104.7	3.7	0.46	110.8	0.36	0.97	0.90*	2.04	0.51	0.43	0.16
10,970 -11,040	217.4	64.2	10.5	92.0	0.13	1.3	5.7	167.2	6.1	0.34	74.6	0.30	1.07	1.15	1.96	0.48	0.43	0.12
11,460 -11,540	182.6	62.2	7.5	147.3	0.16	1.6	4.4	114.1	8.3	0.38	69.7	0.34	1.10	0.97*	2.08	0.62	0.40	0.25
11,970 -12,050	185.6	64.5	30.8	102.7	0.13	1.3	7.3	142.8	2.1	0.51	95.3	0.35	1.06	0.94*	1.79	0.65	0.42	0.15
12,450 -12,650[b]	585.0	312.5	31.5	216.5	0.12	1.2	28.7	487.5	9.9	0.59	344.0	0.53	0.89	0.83*	1.89	0.63	0.43	0.18
12,960 -13,040	197.5	93.1	17.3	130.2	0.16	1.6	6.9	123.5	5.4	0.56	110.4	0.47	0.99	1.22*	1.90	0.59	0.42	0.17
13,630 -13,640	122.3	34.9	7.6	117.7	0.09	0.9	4.7	124.8	4.6	0.38	42.5	0.31	1.20	0.78*	2.22	0.36	0.32	0.09
13,980 -14,030	298.4	176.7	30.2	116.3	0.25	2.5	8.3	119.4	5.9	0.69	206.9	0.59	0.99	0.87*	2.09	0.37	0.38	0.11
14,440 -14,510	85.8	31.8	4.4	101.7	0.08	0.8	4.5	107.2	7.3	0.42	36.2	0.37	1.04	1.09	2.19	0.53	0.37	0.11

[a] excludes 6,810 - 6,820

[b] excludes 12,570 - 12,580

* unresolved peaks not included in ratio

Jurassic sediments range from 6,650 feet to at least 11,420 feet. Below this, the rock units could not be conclusively dated because of the lack of diagnostic index fossils (see **Biostratigraphy** chapter). For the purpose of source-rock characterization, rock units from 11,420 feet to total well depth of 15,568 feet will be included with the Jurassic. The average total organic carbon for this interval is 0.14 weight percent (table 9). The average extractable hydrocarbon for this interval is only 130 ppm (table 10). These source-rock richness parameters suggest that the concentration of organic matter in Jurassic strata penetrated by the well is in the poor range.

In predominantly carbonate or calcareous shale potential source beds, the degree of preservation of organic matter is critical in assessing hydrocarbon source potential. During the Late Jurassic, a strongly oxidizing environment may have affected organic matter deposited in the Georges Bank Basin. The isoprenoid hydrocarbon ratio of pristane-to-phytane ranges from 1.79 to 2.22 (table 10), which is consistent with oxidizing environments. If low sedimentation rates existed within the basin near the Shell LC Block 410 No. 1R well, these conditions would favor the destruction rather than preservation of organic matter and may explain, in part, why the total organic carbon values are poor. The organic richness of time-equivalent rocks in the COST G-1 well is slightly better than in the Shell LC Block 410 No. 1R well.

Thermal Maturity

The two optical methods used to determine thermal alteration for kerogen, vitrinite reflectance done by Shell (figure 11) and thermal alteration index (TAI) (figure 10) by Minerals Management Service, do not agree. Differences such as these are not uncommon and can be caused by sample caving, reworking, oxidation, sample contamination, or the lack of an indigenous vitrinite population in a carbonate section.

The vitrinite reflectance data indicate that kerogen has reached sufficient thermal maturity to generate hydrocarbons at 9,000 feet with peak generation occurring at approximately 13,000 feet (figure 11). TAI data do not show maturation until 13,300 feet, and even then the TAI values are borderline.

The concept of a thermal maturation window for hydrocarbon generation was first suggested by Larskaya and Zhabrev (1964). These authors observed that the generation of hydrocarbons from shales increases logarithmically with depth of burial and higher temperature. The same increase in hydrocarbon generation with depth in other sedimentary basins was observed in Philippi (1965), Louis and Tissot (1967), and Albrecht (1970). Vassoevich and others(1969) described the generation zone as the principal phase of oil formation or oil window. Connan (1974) defined the depth at which the first significant hydrocarbon generation occurs as the “threshold of intense oil generation” (TIOG).

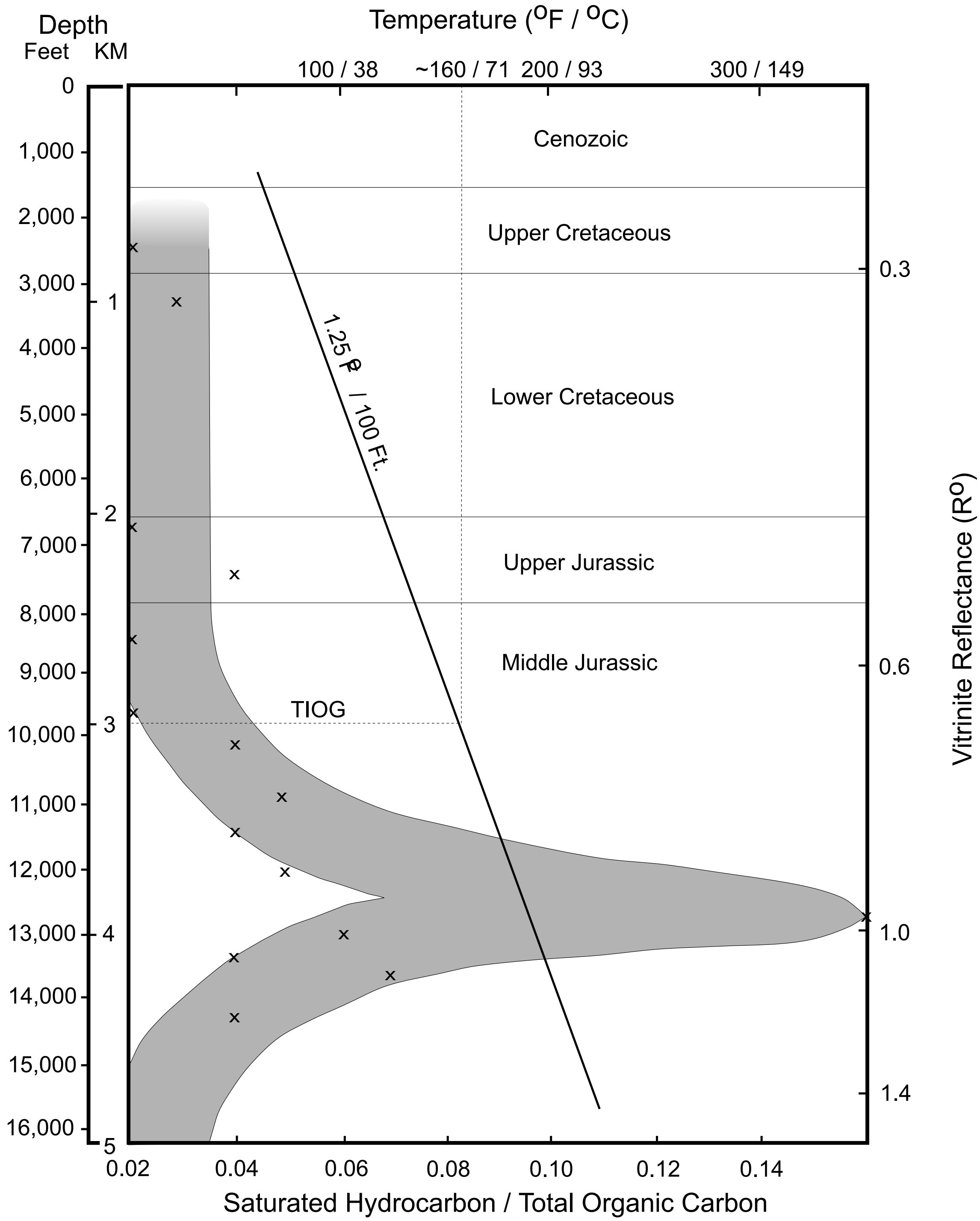

Figure 11. Hydrocarbon evolution window, geothermal gradient, and vitrinite reflectance values plotted against well depth for the Shell Lydonia Canyon Block 410 No. 1R well. Vitrinite reflectance data from Shell.

The petroleum window, described in the preceding paragraph, is applied to the Shell LC Block 410 No. 1R well in figure 11, which presents a plot of the ratio of the concentration of saturated paraffin-naphthene hydrocarbons to total-organic carbon as a function of well depth. The illustration also shows the present geothermal gradient of 1.25 ^{O}F/100 ft. This hydrocarbon evolution curve shows that the TIOG begins at approximately 9,800 feet at a temperature of 160 ^{O}F. Peak thermal evolution occurs between 12,792 and 13,776 feet. The transition phase from mature oil to condensates would be expected below about 14,760 feet.

The hydrocarbon evolution window for this well, determined by molecular geochemical means, is in closer agreement with Shell's vitrinite reflectance data than the MMS TAI results. Further, the molecular geochemical-based hydrocarbon evolution window for the well is in close agreement with the windows for the COST G-1 and G-2 wells. However, in both COST wells the vitrinite and TAI data indicate a much shallower zone of thermal organic maturity than the molecular geochemical data (Miller and others, 1982). Because of the low organic content and poor kerogen preservation in the Shell LC Block 410 No. 1R well, the accuracy of conventional organic petrologic techniques is limited.

Time-Temperature Burial Model

The burial model for the sedimentary units of the Shell LC Block 410 No. 1R well (figure 12) is based on biostratigraphic determinations of the MMS paleontological staff (figure 7) and the Cretaceous and Jurassic time scale of Van Hinte (1976a and 1976b). The burial model for this well is similar to those of the COST G-1, G-2, and the other exploratory wells on Georges Bank. The oldest rocks identified in the Shell well are Middle Jurassic Bajocian ?- early Bathonian. Below 11,420 feet, the section is indeterminate, owing to absence of age-diagnostic fossils. Based on well temperatures, the identified early Bathonian strata are barely into the present-day zone of borderline thermal maturity for petroleum generation. Peak generation, at about 13,000 feet, is in the indeterminate interval of the lowermost 4,148 feet of the well.

The burial history curve for the Shell LC Block 410 No. 1R well shows decreasing subsidence and sediment loading through geologic time. The Triassic-Early Jurassic rifting stage, shown in diagrams for other Georges Bank wells, is not seen here because of the indeterminate section. Rapid Middle Jurassic subsidence is shown in the Bathonian, decreasing slightly through the rest of the Jurassic and through the Early Cretaceous, including the Aptian age. Finally, a Late Cretaceous-Cenozoic quiet period has even less subsidence, which has continued to the present. For other Georges Bank wells, on the basis of the present-day geothermal gradient, Upper Triassic and perhaps lower Lower Jurassic sediments became thermally mature for petroleum generation 60 to 70 million years ago. Rocks of these ages were not identified in the Shell LC Block 410 No. 1R well. However, the lower part of the indeterminate-age section should have

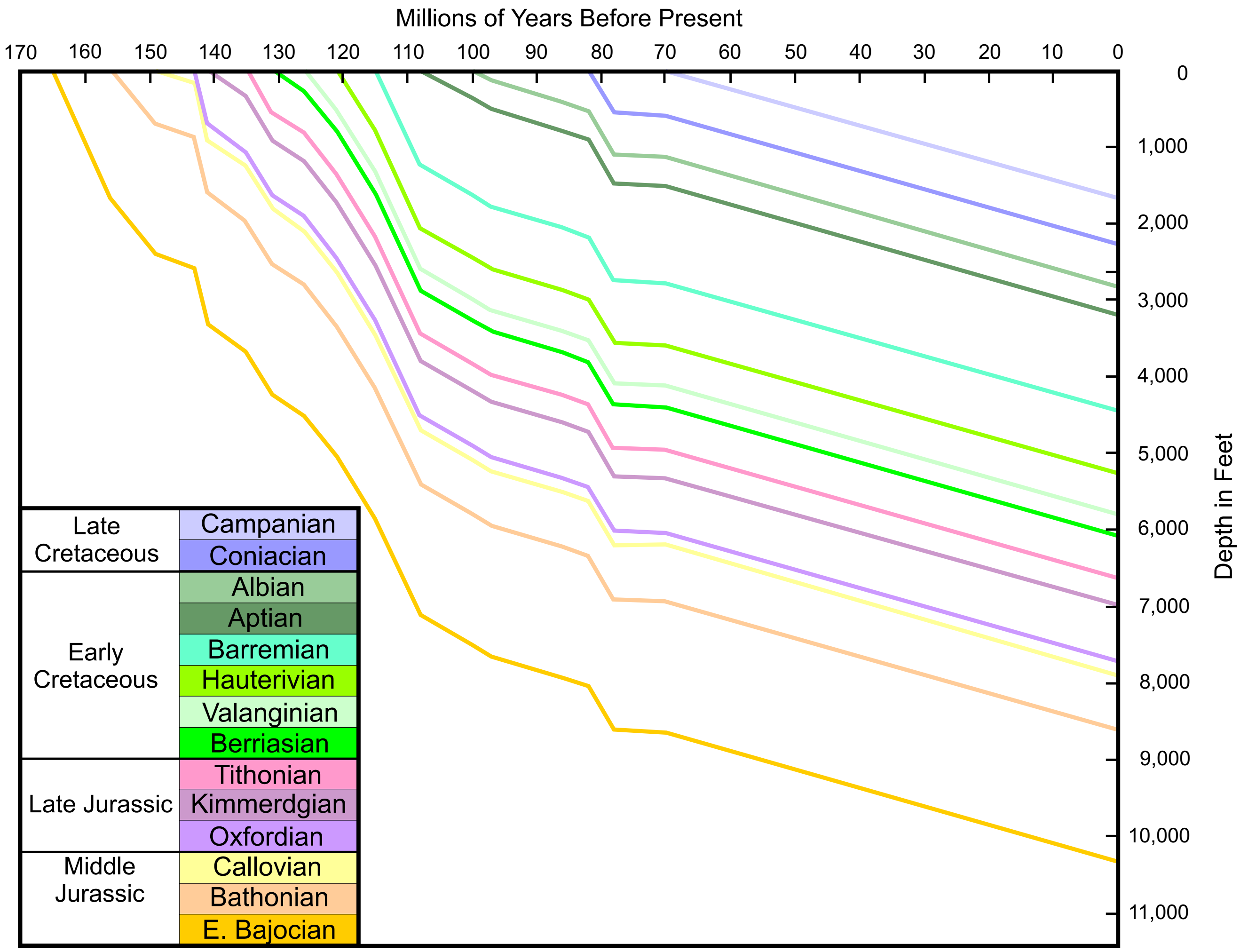

Figure 12. Burial diagram for the Shell Lydonia Canyon Block 410 No. 1R well.

become thermally mature in the last 60 to 70 million years. However, these rocks are organically very lean.

CONCLUSIONS

Samples to a depth of 8,500 feet contain intervals where algal-amorphous kerogens are present. Below 7,000 feet, however, terrestrial Type-III kerogens predominate.

Total organic carbon data suggest that organic richness is poor for Upper Jurassic and deeper rocks. Comparison with source-rock quality of the COST G-1 and G-2 wells indicates slightly higher values in the COST wells for rocks of equivalent time-stratigraphic ranges.

Thermal-maturity profiles generated by vitrinite-reflectance and molecular-geochemical data indicate that the threshold of intense oil generation begins at a depth near 9,800 feet. Below this depth kerogens are mature enough to generate hydrocarbons; however, the organic richness of the shales and carbonates is low to the point of being nonprospective.

Thermal maturation determinations based on the concept of hydrocarbon evolution as a function of increasing temperature and burial time, and measured by the ratio of saturated hydrocarbons-to-total organic carbon, show that peak hydrocarbon generation occurs between 12,792 and 13,776 feet. The transition from oil to wet gas and condensates will most likely occur below about 14,760 feet.

COMPANY-SUBMITTED DATA

Data and reports were submitted by Shell Offshore, Inc., to MMS when the Shell Lydonia Canyon Block No. 1R well was drilled, as required by Federal regulations and lease stipulations. Items of general geological, geophysical, and engineering usefulness are listed below. Items not listed include routine required submittals, such as the Exploration Plan, Application for Permit to Drill, and daily drilling reports, and detailed operations information, such as drilling pressure and temperature data logs. Well "electric" logs are listed in the **Formation Evaluation** chapter. Listed and unlisted company reports and data are available through the Public Information Unit, Minerals Management Service, Gulf of Mexico OCS Region, 1201 Elmwood Park Boulevard, New Orleans, Louisiana 70123-2394; telephone (504)736-2519 or 1-800-200-GULF, FAX (504)736-2620. Well logs are available on microfilm from the National Geophysical Data Center, 325 Broadway Street, Boulder CO 80303-3337, attn. Ms Robin Warnken; telephone (303) 497-6338, FAX (303)497-6513; e-mail rwarnken@NGDC.NOAA.GOV.

At a later date, additional original technical data, including well logs, will be added to the compact disk (CD) version of the Georges Bank well reports. The CD will be available from the Gulf of Mexico OCS Region Public Information Unit.

SELECTED COMPANY-SUBMITTED DATA

Velocity survey computation (well velocity and well seismic tool data), Schlumberger Ltd., Wireline Testing, Houston TX, undated.

Physical formation ("mud") log, Exploration Logging of U.S.A., Inc., undated.

Core analysis (sidewall core), Core Laboratories, Inc., Dallas TX, undated.

Core analysis data (porosity, permeability, and grain density, cores 1 and 2), Shell development Co., Petrophysical Services Laboratory (PSL), 10/12/81, core 1, 04/22/81, core 2.

Photographs, cores 1 and 2, PSL, 10/81, core 1, date unknown for core 2.

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