OCS Report
MMS 86-0128

Shell Baltimore Rise 93-1 Well

Geological & Operational Summary

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U.S. Department of the Interior
Minerals Management Service
Atlantic OCS Region

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ABSTRACT

The Shell Baltimore Rise 93-1 (OCS-A-0370-1) well is located in the northwest corner of OCS block 93 of protraction diagram NJ 18-9. The well site is about 10 miles south of Baltimore Canyon and 81 miles east-southeast of Ocean City, Maryland. Block 93 was leased to Shell Oil Company during OCS Lease Sale 59 in December 1981 for a bonus bid of $6,188,000. The well was spudded on July 14, 1984, and plugged and abandoned as a dry hole 117 days later on November 7, 1984. Drilling was done by the drillship Discoverer Seven Seas in 5,017 feet of water to a total depth of 17,740 feet. This was the fourth and last well of Shell's Atlantic deepwater drilling program. Shell and partners relinquished the block 93 lease on January 31, 1986.

The primary objective for drilling the well was to test Lower Cretaceous and Upper Jurassic sandstones expected to occur at 10,000 feet and deeper in a large faulted anticline. Although these sandstones were encountered, they were thin, mostly silty, and generally not porous enough to be considered reservoir rocks. Only minor shows of hydrocarbons were encountered.

Tertiary and Quaternary sediments were penetrated from 7,113 to 8,520 feet and include shales, siltstones, and sandstones. Upper Cretaceous limestones, siltstones, and shales occur to 9,150 feet. A thick section of Lower Cretaceous sandstones, limestones, siltstones and shales were encountered to 17,280 feet, with some 2,700 feet of this interval deposited as a large channel-fill feature. Jurassic strata occur to 17,740 feet and consist of siltstones, shales, and thin limestones deposited in primarily nearshore and nonmarine environments. Geochemical analyses indicate that source rocks penetrated by the well tend to be lean in organic material, gas prone, and the well barely entered into the top of the hydrocarbon evolution window.

ABBREVIATIONS

API	American Petroleum Institute
BOP	blowout preventer
C_1, C_2	number of carbon atoms in a hydrocarbon chain structure (methane, ethane, etc.)
FNL	from the north line
FWL	from the west line
HEW	hydrocarbon evolution window
KB	Kelly bushing
L, M, U	late, middle, upper parts of geologic strata
MYBP	million years before the present
OCS	Outer Continental Shelf
ppg	pounds per gallon
ppm	parts per million
R_o	vitrinite reflectance value
SFL	spherically focused log
SP	spontaneous potential
Sw	water saturation of rock
TAI	thermal alteration index
TD	total depth
TIOG	threshold of intense oil generation
TOC	total organic carbon
TTI	time-temperature index
UTM	universal transverse mercator
WD	water depth
WST	well seismic tool
u	micron

INTRODUCTION

A number of large ancient deltas occur off the east coast of the United States and Canada (Amato and Simonis, 1979, Schlee and Jansa, 1981; Libby-French, 1983). Many of these were formed by precursors of present eastern drainage systems such as the Delaware, Hudson, Susquehanna, Potomac, and St. Lawrence rivers. One such delta occurs southeast of Delaware Bay, where seismic data indicates a thick Lower Cretaceous section with river channel deposits, slumps and growth faults. The delta extends to the edge of the continental shelf where it buried or precluded deposition of the Early Cretaceous carbonate platform and reef (Edson, 1987).

Ancient deltas are common throughout the geologic record and they can host very large petroleum accumulations. Thus, sandstones in deltaic deposits are one of the most sought-after exploration targets. Examples of prolific petroleum production from deltas include the Mississippi River delta, both onshore and offshore Louisiana, the Niger River delta of Nigeria, and the Catskill delta of New York and Pennsylvania. Also, discoveries have been made in the last few years in deltaic sandstones in the Scotian Shelf off the east coast of Canada and in the Mackenzie River delta of northern Canada.

The Shell 93-1 well was drilled to test a prospect in this delta in 1984. It was the fourth and final well of the Shell Offshore, Inc. Mid-Atlantic deepwater drilling program. The first three of these wells, the Shell 587-1, 586-1, and 372-1, tested prospects in the carbonate platform and reef. The Shell 93-1 was drilled in 5,070 feet of water about 50 miles southeast of the 587-1 well (fig. 1). Shell established two world deep-water drilling records in this program. The first record was set while drilling the 587-1 well in 6,448 feet of water, but this depth was exceeded by the 372-1 well at 6,952 feet.

Although no commercially significant hydrocarbon shows were encountered, the 93-1 well has provided the only rock samples and electric logs of this ancient delta. Rock units were identified and described by lithologic and petrographic examination, geologic age dates and environments of deposition of rock sequences were obtained from paleontological studies, organic carbon richness, kerogen typing, and thermal maturation data were determined from geochemical measurements, and porosity, water saturation, and seismic velocity calculations were made from well logs. Analyses of this information have significantly advanced the understanding of the geology of this part of the Mid-Atlantic OCS. In addition, considerable data and experience were gained from drilling in very deep water.

This report is based on geologic data provided to the Minerals Management Service by Shell Offshore, Inc., according to offshore petroleum exploration regulations and lease stipulations. The data were released to the public after Shell relinquished the Baltimore Rise NJ 18-9 block 93 lease on January 31, 1986. Interpretations of the data contained in this report are those of the Minerals Management Service and may differ from those of Shell Offshore, Inc. and other company participants in the well.

OPERATIONAL SUMMARY

by

Ray Vincent

The Shell Baltimore Rise 93-1 well is located 81 miles east-southeast of Ocean City, Maryland, in Mid-Atlantic official protraction diagram NJ 18-9 (Baltimore Rise). Block 93 was leased to Shell Oil Company in Lease Sale 59, held on December 8, 1981. Bidding alone, Shell Oil's high bid for this block was $6,188,000. Before the start of drilling operations, Shell Oil assigned 100 percent of its interest to Shell Offshore, Inc. (Shell), who subsequently assigned interests in the lease to two other companies, Amoco Production Company and Murphy Oil USA, Inc. Shell and partners relinquished the block 93 lease on January 31, 1986.

Although seven shows of hydrocarbons were observed while drilling, none were considered significant and no drill stem tests were conducted. The well was plugged and abandoned in accordance with OCS Order No. 3, with a waiver to leave the wellhead and unrecoverable beacons or transponders on the seabed. The location of the well and other pertinent information are given in table 1, and in figures 1 and 2. This was the fourth and final well of Shell's Atlantic deepwater drilling program. The three previous wells (586-1, 587-1, and 372-1) were drilled to test the Cretaceous-Jurassic shelf-edge carbonate trend, whereas the 93-1 tested Lower Cretaceous and Jurassic deltaic sandstones (Edson, 1986, 1987 a,b).

Shell selected Sonat Offshore Drilling, Inc. as the drilling contractor and Sonat used the Discoverer Seven Seas, a self-propelled, dynamically positioned drillship. Built in 1976 by Mitsui Engineering and Shipbuilding Company, Ltd. of Japan, the vessel is equipped with six 3,000-horsepower thrusters for dynamic positioning and is designed to withstand 110-foot waves and 100-knot winds. A unique feature of the vessel is that no mooring system is used to maintain position or station. The vessel classification and certification is: American Bureau of Shipping (ABS) Ice Class 1A, Maltese Cross A1 Maltese Cross AMS circle E circle M mobile drilling unit for unrestricted worldwide ocean use. The drillship meets U.S. Coast Guard standards and is registered under the Panamanian flag. For Shell's Atlantic drilling program, Sonat reinforced the hull and added additional riser capacity for drilling in water depths to 7,500 feet.

The Discoverer Seven Seas was inspected and operations were observed by Minerals Management Service personnel throughout the drilling period to insure compliance with the Department of Interior regulations and orders. Sonat used Davisville, Rhode Island (270 miles northeast of the well's location) as an operational and supply base. For support, Sonat engaged two 190-foot supply vessels to transport the necessary drilling materials and supplies and a standby vessel needed to comply with the regulations. Sonat spudded the well at 0001 hours on July 14, 1984, and reached the well's total depth of 17,740 feet 103 days later on October 24, 1984. However, to complete logging and plugging operations the drillship was on location until November 7, 1984, a total of 117 days.

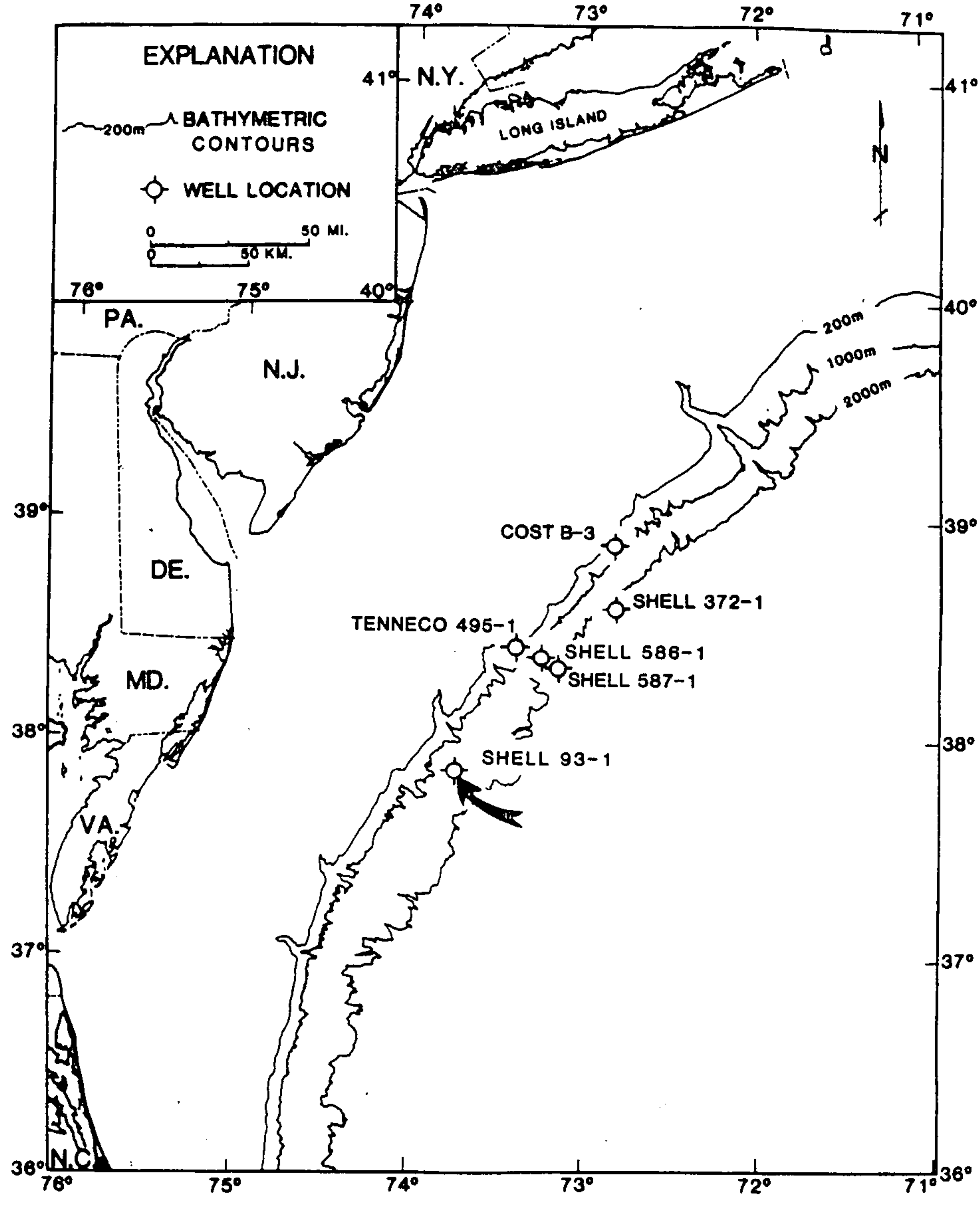


Figure 1.- -Map of a portion of the Mid-Atlantic offshore area showing the location of the Shell 93-1 well and selected other wells.

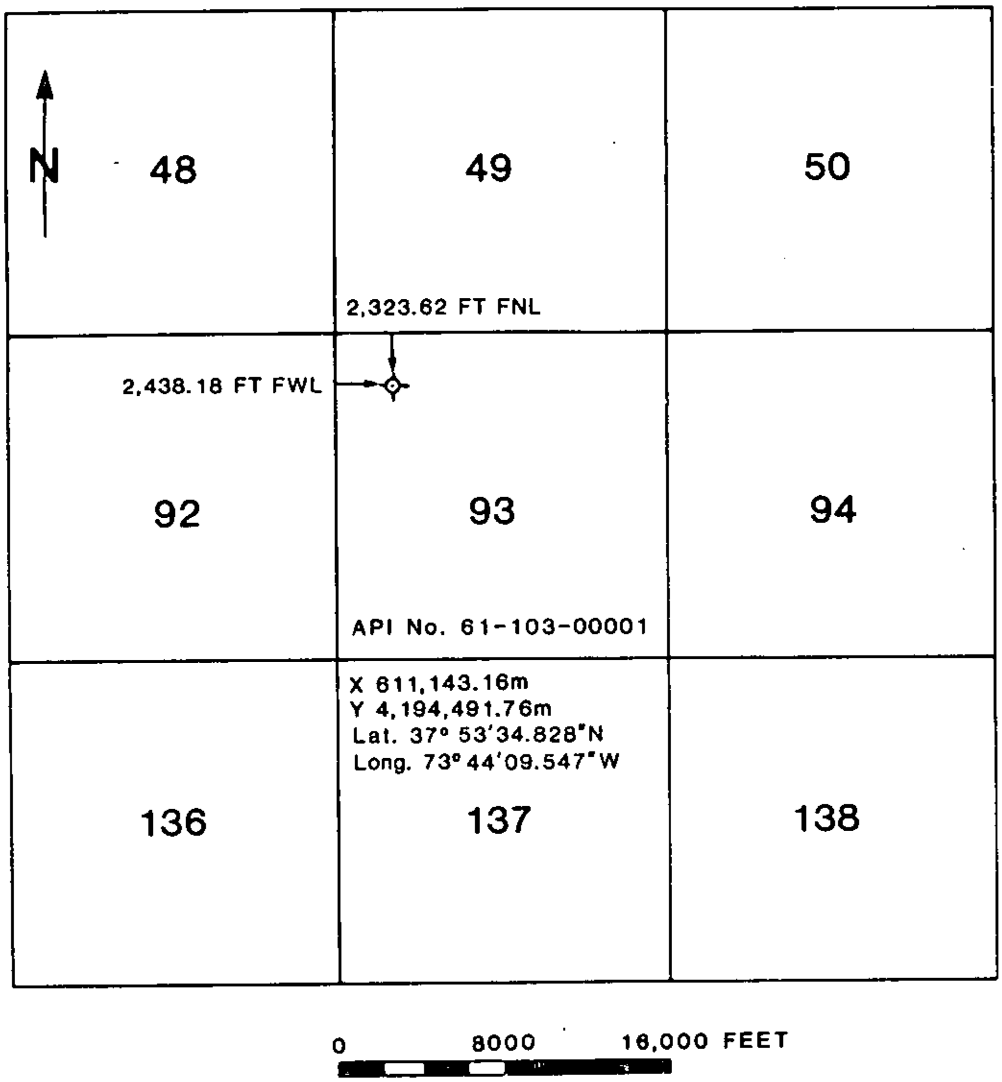


Figure 2.--Plat showing the exact location of the Shell 93-1 well in OCS Protraction Diagram NJ 18-9 (Baltimore Rise).

Table 1.--Pertinent well information for the Shell 93-1 well

Well identification	API No. 61-103-00001
Lease number	OCS-A-0370-1
Protraction diagram	NJ 18-9 (Baltimore Rise)
Actual surface location	UTM Coordinates: X = 611,143.16 m Y = 4,194,491.76 m Latitute: 37°53'34.828"N Longitude: 73°44'09.547"W
Distance from block lines	2,323.62 feet FNL 2,438.18 feet FWL
Hole deviation	5.87° in N118.5° azimuth at 17,645 feet
Initial proposed total depth	15,000 feet
Final proposed total depth	20,000 feet
True vertical depth	17,740 feet
Actual measured depth	17,740 feet
Spud date	July 14, 1984
Completion date	November 7, 1984
Kelly bushing elevation	48 feet above mean sea level
Water depth	5,017 feet below mean sea level
Final well status	Plugged and abandoned

Note: All depths in this report are measured from the kelly bushing unless otherwise indicated.

Drilling Program

Sonat's maximum penetration rate of 1,500 feet per day was achieved between the depths of 5,550 and 7,050 feet. Excluding the time required for logging, coring, weather delays and equipment testing, the driller was able to obtain an average penetration rate of 188 feet per day between the depths of 9,700 and 13,650 feet and of 145 feet per day between 13,650 and 17,710 feet. At 17,710 feet, a 30-foot terminal core was taken. Hole deviation above 12,000 feet was 1 degree or less and was 2.9 degrees at 15,475 feet. Below 16,000 feet, hole deviation increased and a survey taken at 17,710 feet recorded a deviation of 6 degrees.

At 5,284 feet, Sonat dropped 165 feet of drill collars, subs, and a drill bit but successfully recovered the equipment from the hole. While drilling at 13,650 feet, the bit locked up, requiring circulation and conditioning of the mud and a trip for a new bit. At 14,076 feet, pump pressure dropped and the surface equipment was checked for leaks; however, none were found. As the drill string was pulled, a hole was found in the drill pipe at 11,898 feet. The problem was corrected, the bit was changed, and drilling resumed. Tight spots in the hole were encountered at 13,928 and 14,450 feet, requiring washing and reaming at both depths. Following this, the drill pipe was raised, the mud circulated and conditioned, and the mud weight increased because of sloughing shales.

After cutting the 30-foot terminal core and reentering the hole for logging, Schlumberger, Ltd. well loggers were unable to pass 14,900 feet with their tools. Over 8 days were required for washing and reaming tight spots, circulating and conditioning the mud, and increasing the mud weight to 12.0 pounds per gallon (ppg) before they could successfully log the well. Figure 3 shows a curve of the daily drilling progress.

Shell ran and set five strings of casing as shown in figure 4. The 48-inch casing was jetted into place and set at 5,073 feet using no cement; the 30-inch casing was set at 5,305 feet with 807 sacks of Class A cement; the 20-inch casing was set at 7,069 feet with 1,330 sacks of Class H cement; the 13 3/8-inch casing was set at 9,662 feet with 1,942 sacks of Class H cement and 665 barrels of mud used to displace the cement; the 9 5/8-inch casing was set at 13,624 feet with 1,330 sacks of Class H cement. Figure 4 also shows the abandonment procedure. An open hole cement plug using Class H cement was placed between 15,220 and 15,520 feet; a 9 5/8-inch cement retainer was set at 13,500 feet and 80 sacks of Class H cement squeezed below the retainer to 13,880 feet. An additional 50 sacks of Class H cement were set on top of the retainer, with the top of the cement plug at 13,355 feet. A top plug was placed between 5,179 and 5,365 feet, using 70 sacks of Class H cement. The mud mat, temporary and permanent guide bases, and any unrecoverable beacons or transponders were left on the ocean floor.

Sonat used seawater as the drilling fluid to 7,113 feet, below which depth they added barite, caustic soda, and bentonite (gel) to the mud system. At 7,135 feet, a modified lignosulfonate was introduced as a dispersant and fluid loss control. At 8,680 feet, Drispac was also added to keep filtration test fluid loss below 10 cc. Generally, mud weights ranged from 9.0 to 9.5 ppg down to 13,200 feet, then increased to 9.7 ppg and to 9.8 ppg at 13,650 feet before Sonat ran the 9 5/8-inch casing. Around 15,400 feet, the mud

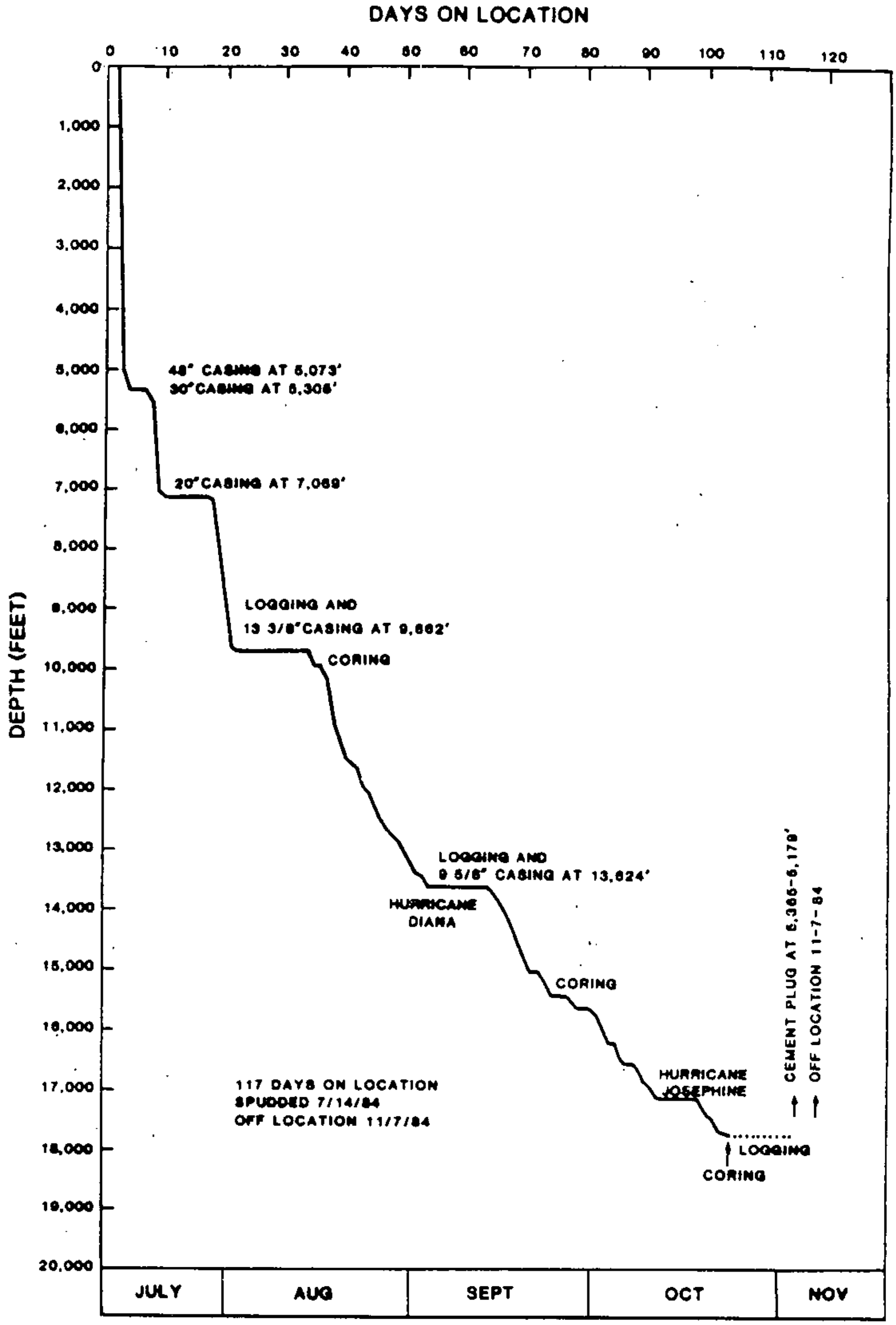


Figure 3.--Graph showing the daily drilling progress for the Shell 93-1 well.

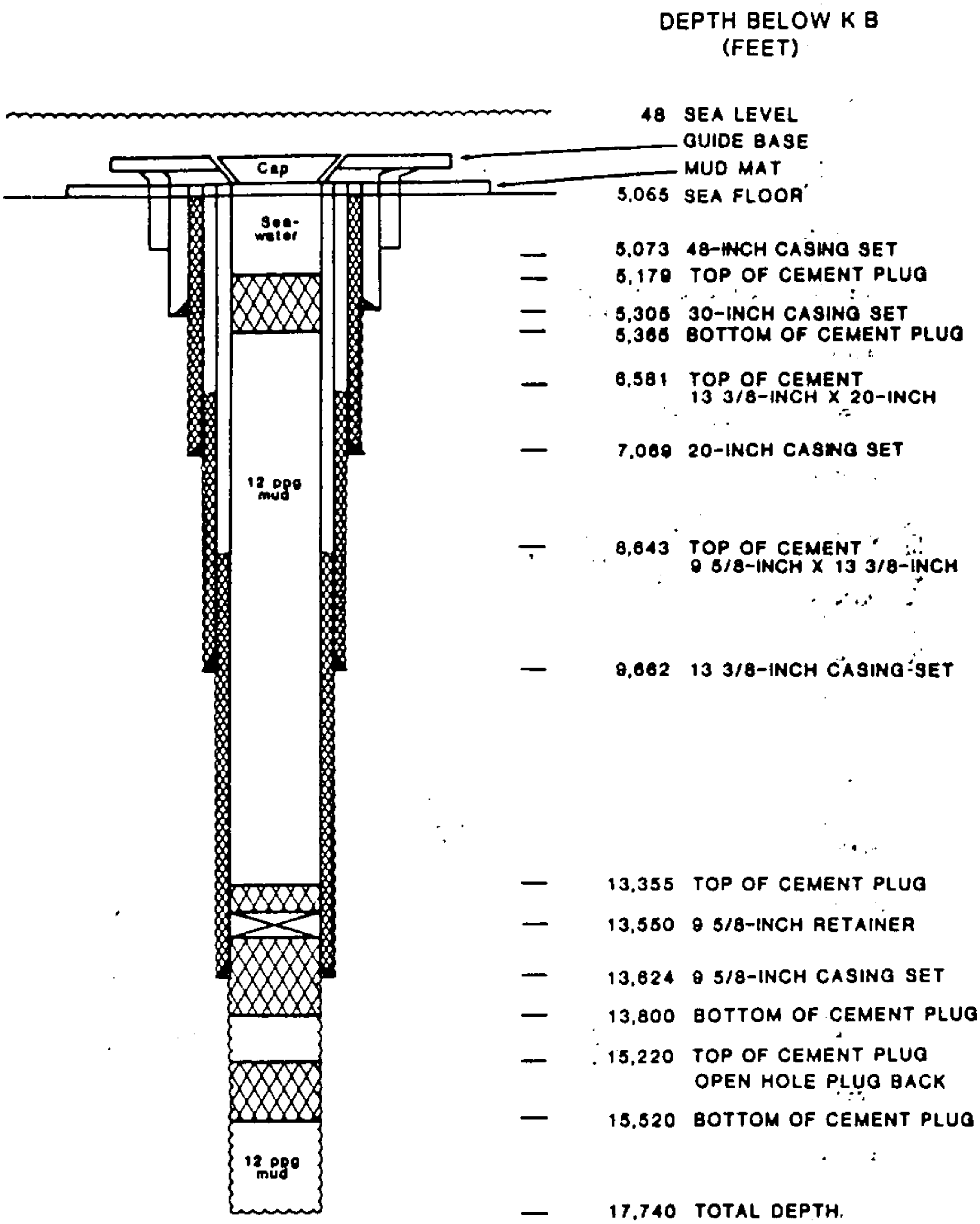


Figure 4.--Schematic diagram showing the casing and cement program for the Shell 93-1 well.

weight was raised to 10.0 ppg and to 10.2 ppg at 16,585 feet to control sloughing shales. At this depth, coarse nut plug was added to the system to reduce the torque on the bit and drill pipe. From 17,100 to 17,633 feet, the mud weight remained at 10.2 ppg after which it was increased to 10.4 ppg. Because of logging difficulties after the hole was completed, extensive hole conditioning and increasing the mud weight to 12.0 ppg were necessary.

Samples and Tests

Both wet and dry samples were collected from 7,113 to 17,740 feet and were provided to the Minerals Management Service for analysis. Cuttings samples were used for lithologic studies, and composites between 7,113 feet and total depth were processed and used for paleontologic examination and interpretations. Thin sections were also prepared from cuttings for selected intervals between 7,113 and 17,740 feet. Shell also provided canned composited drill cuttings from 7,113 feet to total depth for geochemical evaluation.

Shell cut three conventional cores, and pretests were made with Schlumberger's Repeat Formation Tester in the interval between 13,102 and 13,133 feet. The tests indicated low permeability for the interval. The conventional cores were cut from 9,934 to 9,964 feet, 15,406 to 15,419 feet, and 17,710 to 17,740 feet, with good recovery on all cores except core No. 2, which recovered 13 feet from a 30-foot core barrel. Between 7,840 and 13,554 feet, Schlumberger took 90 sidewall cores. Schlumberger ran electric log suites to provide information for stratigraphic correlation, lithologic analysis, and the evaluation of potential hydrocarbon zones (See table 3, p. 49). Exploration Logging, Inc. provided a physical formation log (mud log) from 7,110 to 17,740 feet. No drill stem tests were run.

Weather

Weather was a major factor in interrupting drilling operations on the Shell 93-1 well. In September 1984, Hurricane Diana caused 41 hours of downtime. In October, Hurricane Josephine required Sonat to disconnect and move the drillship off location, stopping drilling operations for 87 hours.

WELL VELOCITY PROFILE

by

Robert E. Johnson

A Schlumberger well seismic tool (WST) was run as a checkshot survey in addition to the sonic log in the Shell 93-1 well. The WST provides a check of the integrated time and establishes a reference time between the beginning of the sonic log and the top of the well. An interval velocity profile plotted from the WST data is shown in figure 5. Velocity data were collected on three separate logging runs: 5,017 to 9,600 feet, 9,600 to 13,500 feet, and 13,500 to 17,000 feet. Between 5,017 feet (sea floor) and 17,700 feet (the deepest data), four intervals were identified on the basis of differences in averaged interval velocities. The average velocities of all four intervals are consistent with terrigenous clastic lithologies, and the higher velocities of intervals III and IV suggest an increasing proportion of carbonates. These four intervals and their inferred lithologies generally agree with the facies units identified in the Lithologic Analysis section of this report and shown in figure 6, pp. 16-19.

Interval I -- This section is identified on the basis of relatively low velocities.

DEPTH RANGE (feet)	5,017-8,300
INTERVAL VELOCITY RANGE (feet/second)	5,805-7,382
AVERAGE INTERVAL VELOCITY (feet/second)	6,215

These velocities suggest clastic lithologies, with shale being the predominant rock type.

Interval II -- This section is identified by slightly higher velocities than those in interval I and a slightly higher range of interval velocity.

DEPTH RANGE (feet)	8,300-9,400
INTERVAL VELOCITY RANGE (feet/second)	6,449-8,328
AVERAGE INTERVAL VELOCITY (feet/second)	7,333

The break at 8,300 feet corresponds well with the Upper Eocene unconformity, which causes a strong reflection in the seismic data. The increased average velocity of this section is consistent with the appearance of a slight amount of carbonate material in these beds.

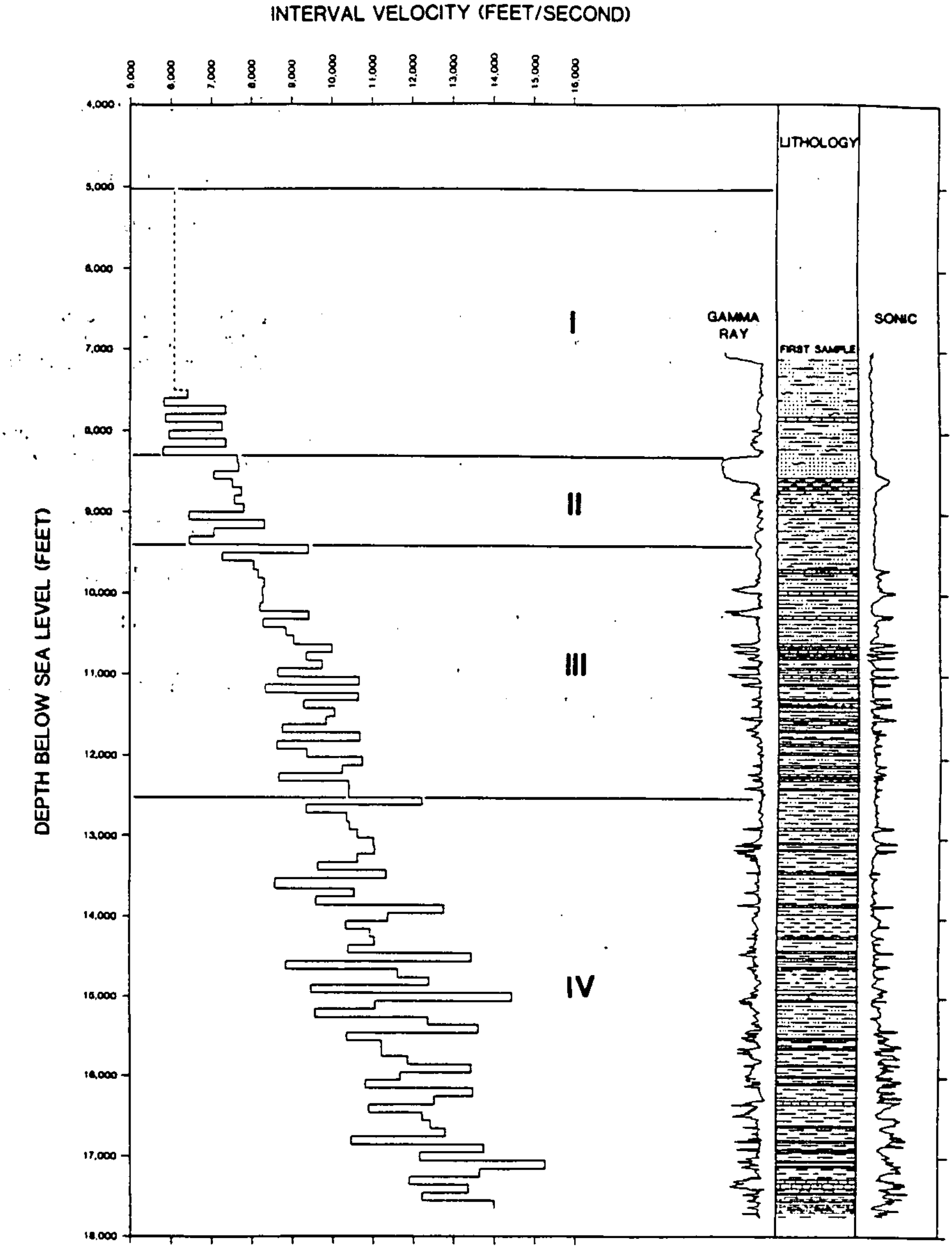


Figure 5.--Interval velocity profile of the Shell 93-1 well. (Profile provides generalized lithologic column with gamma ray and sonic log curves.)

Interval III -- This section is identified on the basis of still higher velocities.

DEPTH RANGE (feet)		9,400-12,522
INTERVAL VELOCITY RANGE	(feet/second)	7,296-10,763
AVERAGE INTERVAL VELOCITY	(feet/second)	9,049

The third interval of the well, though predominantly clastic, contains a higher proportion of carbonate rocks. Variations among the velocities suggest thinly interbedded carbonates among predominantly continental clastic rocks.

Interval IV -- This section is identified on the basis of velocities that are considerably higher than those in interval III and of a much higher range of interval velocity.

DEPTH RANGE (feet)		12,522-17,700
RANGE OF INTERVAL VELOCITY	(feet/second)	8,577-15,271
AVERAGE INTERVAL VELOCITY	(feet/second)	11,662

This interval is essentialy the same as the third, but with much greater variations in the velocities. These variations may indicate thicker and more frequently occurring beds of carbonate rock.

LITHOLOGIC ANALYSIS

by

Anthony C. Giordano

The Shell 93-1 well was drilled to test Lower Cretaceous and Upper Jurassic sandstones in a large faulted anticline. Although these sandstones were encountered, they are thin, very silty, and generally not porous enough to be good reservoir rocks. Geologic data used for this analysis consisted of drill cuttings, electric logs, sidewall and conventional cores, and thin sections. Cuttings were continuously collected from 7,113 to 17,740 feet. Sample quality in the well was fair to very poor. Some sample bags contained mostly additives (cement, spherelite, drilling mud, plastic, fiber, and walnut hulls). Cuttings samples were not collected from the sea floor to 7,113 feet because drill mud was not circulated in the well until that depth. Conventional core and petrographic thin sections of material from 16 sidewall cores and 2 conventional cores were examined by Gary Edson at the offices of Shell Offshore, Inc. Core and thin section descriptions in this report are summarized from the data collected from Shell. Figure 6 shows the lithologic interpretations from the well.

Lithologic Descriptions

7,113 to 8,330 feet

This interval begins with a 30-foot green gray shale of Pleistocene age which contains trace amounts of pyrite and fossil fragments. A 500-foot section of Plio-Pleistocene clear to milky quartz sand follows, which is very fine to coarse grained. Abundant fossil fragments are present and consist of pelecypods, bryozoans, microgastropods, sponge spicules and benthic and planktonic foraminifera. Moderate amounts of glauconite as well as traces of pyrite, feldspar, and mica are associated with the quartz sand. Below 7,600 feet (Miocene), the sediments consist primarily of light gray to gray, soft, noncalcareous, silty, glauconitic shale with glauconite increasing toward the base. Planktonic and benthonic foraminifera are present in this interval as well as trace amounts of pyrite and mica. In the interval 7,835 to 7,880 feet, a 45-foot section of very fine-grained sandstone and thin-bedded micrite is seen with a 345 unit (total gas) hotwire reading of C_1-C_3. In thin section, the limestone exhibits dolomitic alteration. At 8,310 to 8,330 feet, medium-grained quartz sand occurs with abundant glauconite which may indicate an unconformity in which Middle Oligocene sands overly Eocene sediments. No evidence of oil staining or fluorescence was observed in the cuttings from 7,113 to 8,330 feet. Visual porosity of the individual sand units is excellent.

Thin sections from 16 sidewall cores were examined in the interval 7,846 to 8,540 feet. The lithologies are argillaceous, silty, and sandy wackestones with sparse foraminifera and calcareous, silty, and sandy shale. There is good porosity (visually estimated to be 5 to 15 percent) between the mineral grains, but abundant silt causes low apparent permeabilities. Numerous small pieces of organic material and pyrite occur in the thin sections and some of the shale contains foraminifers and calcareous nannofossils. As much as 75 percent

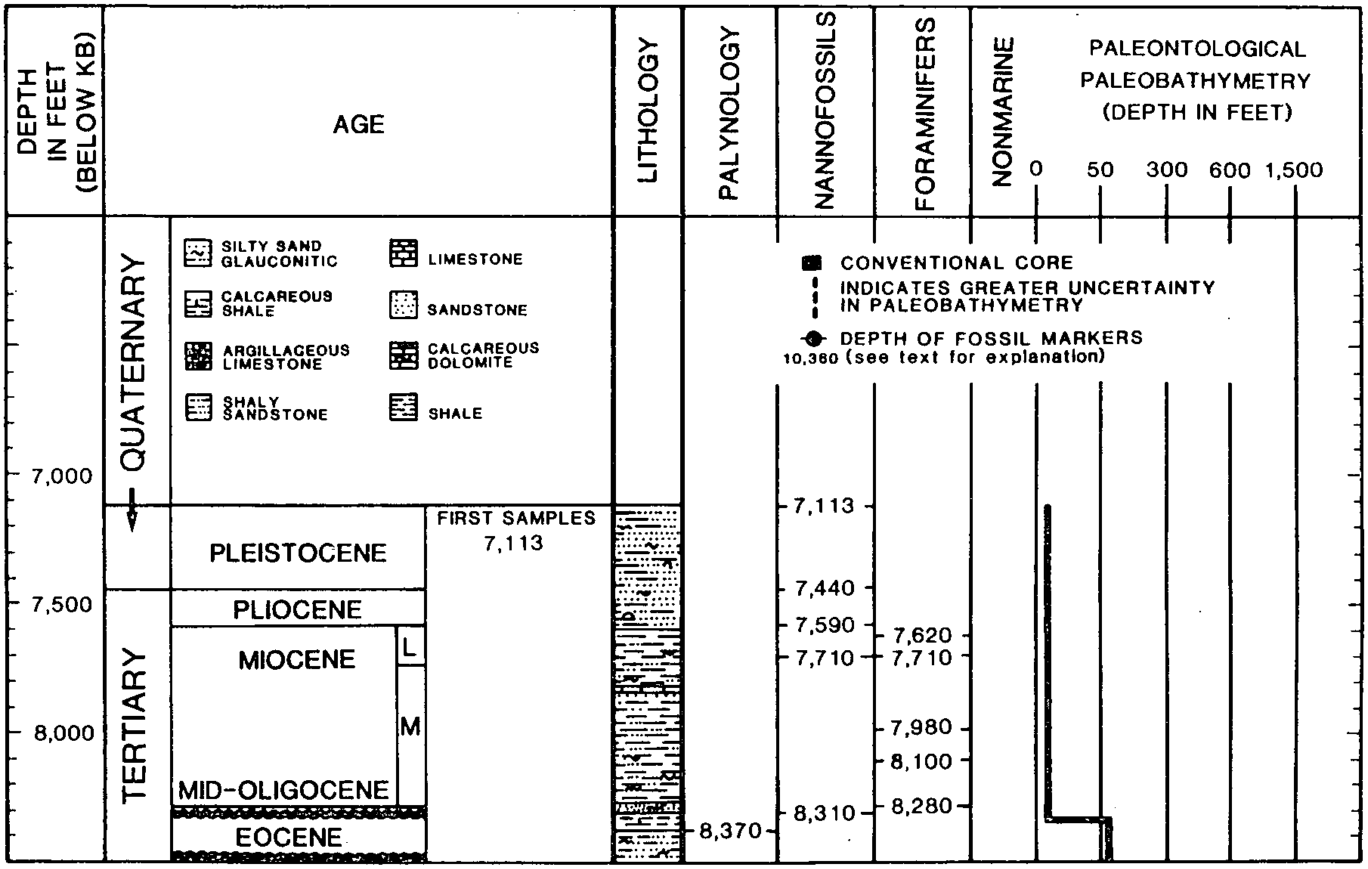


Figure 6.--Lithology biostratigraphy, and paleobathymetry of the Shell 93-1 well (Paleobathymetry becomes gradually less reliable with increasing well depth).

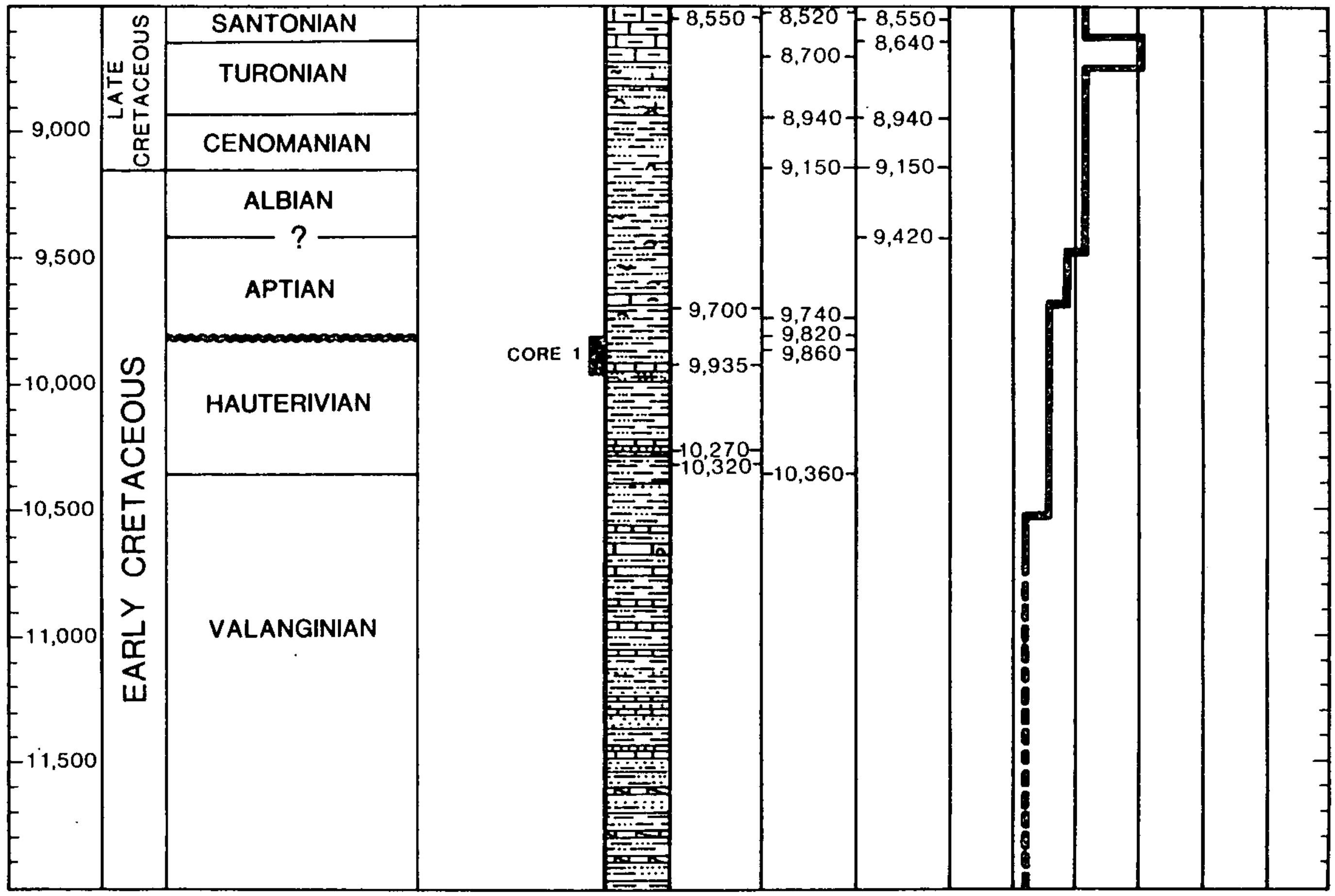


Figure 6.--Lithology biostratigraphy, and paleobathymetry of the Shell 93-1 well, continued.

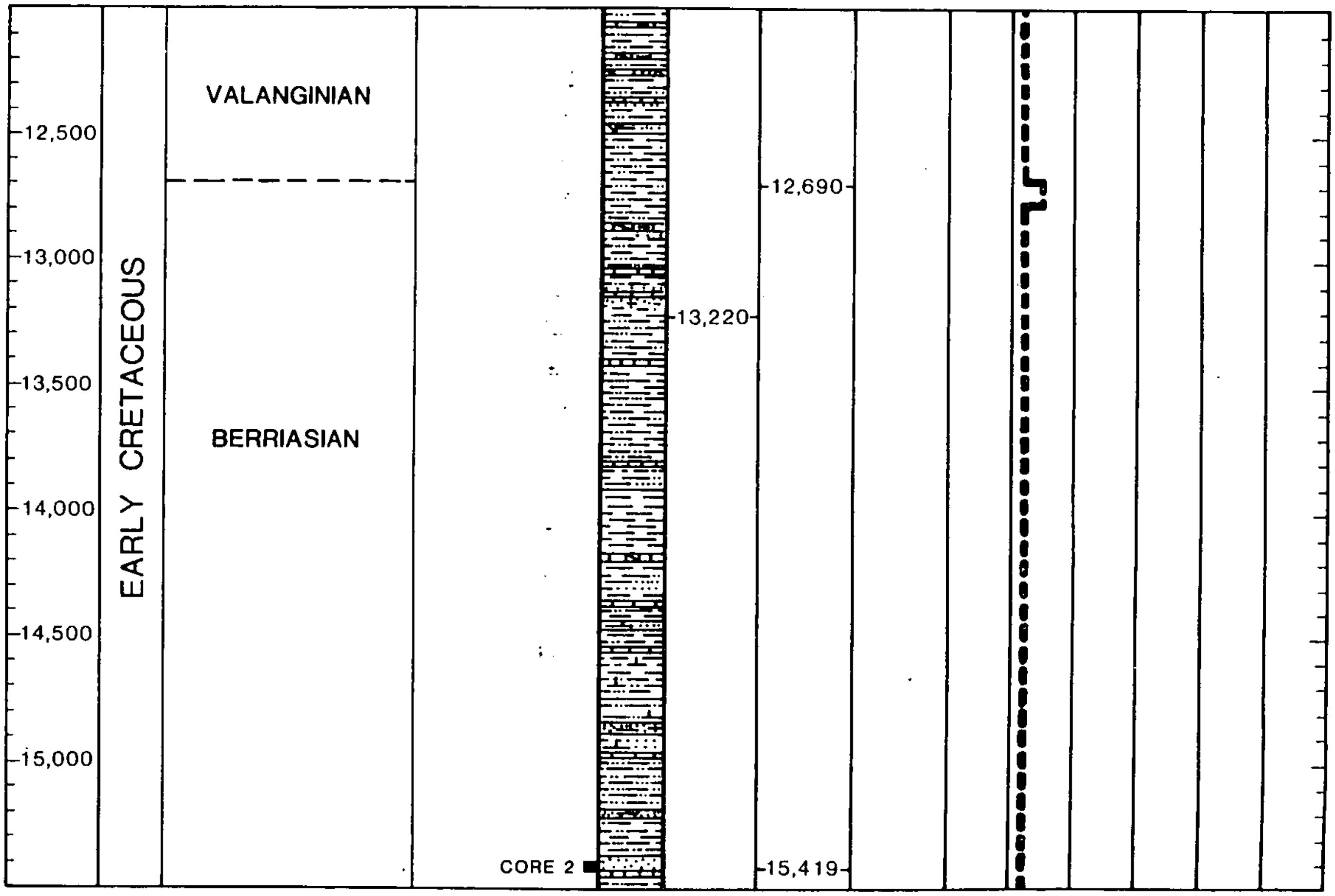


Figure 6.--Lithology biostratigraphy, and paleobathymetry of the Shell 93-1 well, continued.

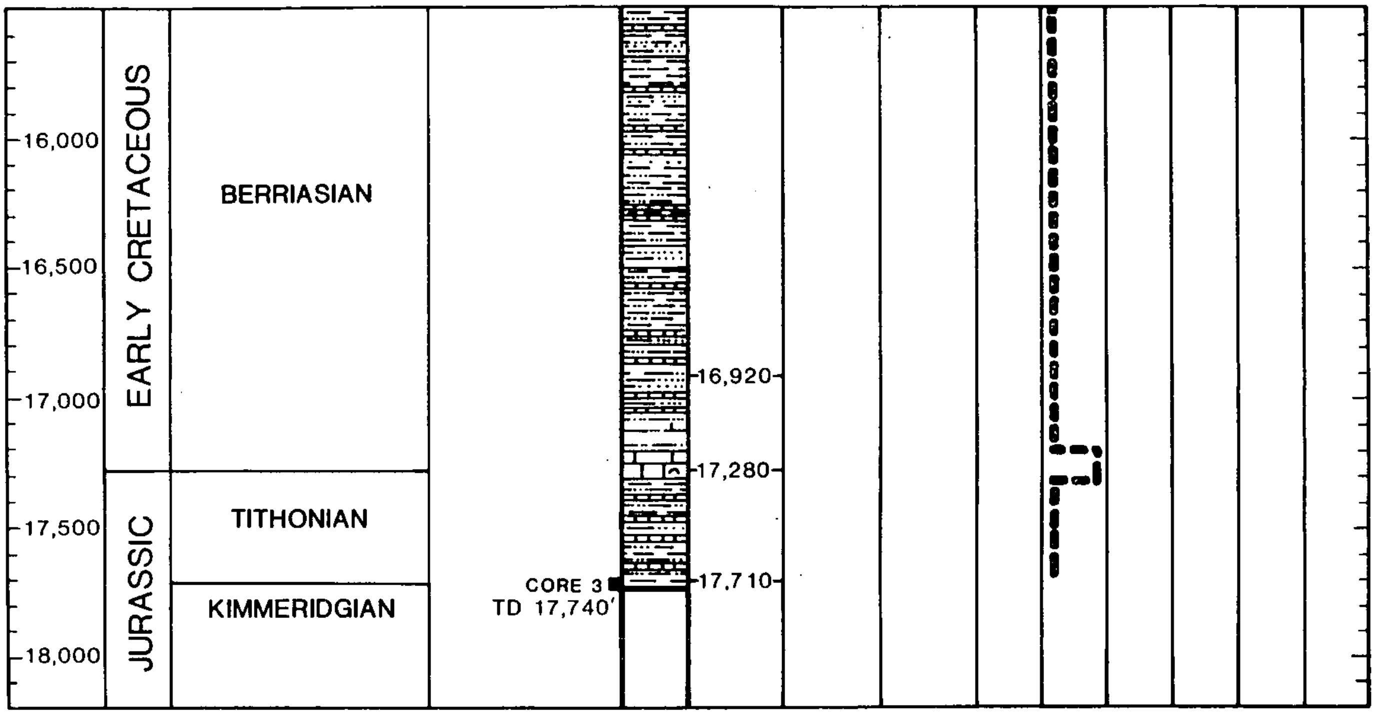


Figure 6.--Lithology biostratigraphy, and paleobathymetry of the Shell 93-1 well, continued.

glauconite grains were noted in a few of the sections along with numerous minute, disseminated, dolomite rhombs.

8,330 to 8,520 feet

This short interval of Eocene age is overlain unconformably by Middle Oligocene sediments and underlain unconformably by Upper Cretaceous (Santonian) sediments. The upper portion of the interval is white to light gray, calcareous clay; the lower portion is unconsolidated, fine- to medium-grained, subrounded, clear quartz sandstone containing glauconite and siltstone. This interval has no evidence of oil staining or fluorescence. Visual porosity in the sand unit is excellent.

8,520 to 9,820 feet

An argillaceous limestone of mostly Santonian age with scattered sponge spicules occurs from 8,520 to 8,720 feet. The remaining sediment to 9,820 feet is Turonian to Aptian and consists primarily of light gray to gray, very soft, noncalcareous to slightly calcareous, cemented siltstone with thin sandstone beds at the top and interbedded shales towards the base. Abundant glauconite and fossil fragments are present with occasional large, subrounded quartz grains and moderate amounts of pyrite. Fossil fragments include planktonic foraminifers, sponge spicules, microgastropods, and *Inoceramus* prisms. At 9,660 feet, a thin white to brown, fossiliferous, slightly oolitic micrite is seen with no visible porosity. This interval contains no evidence of oil staining or fluorescence. Visual porosity is fair to poor in the siltstone interval.

9,820 to 13,580 feet

The sediments in this interval are Lower Cretaceous, ranging in age from Hauterivian to Berriasian. They consist primarily of light gray to gray and brown, very soft to firm, noncalcareous to moderately calcareous to dolomitic siltstone. In places, the siltstone is associated with pyrite; glauconite; some fossil fragments; occasional large, coarse, well-rounded quartz grains; and traces of mica, inertinite, and limestone fragments. Interbedded with the siltstone is light gray to dark gray, very soft to firm, slightly calcareous shale and thin beds of sandstone. The thin-bedded sandstones are white, unconsolidated, fine- to medium-grained, subrounded to subangular, and are moderately well sorted. Calcareous cemented, clear quartz sand occurs in places. Trace amounts of glauconite, pyrite, mica, and fossil fragments occur with the sandstones. Thin-bedded limestones in this interval are readily seen on the dual induction log as high-resistivity and low gamma ray zones. The limestones are primarily grainstones and wackestones that are occasionally chalky. The limestones are partly fossiliferous and pelletal, containing pelecypod and algal fragments. A few oolites are seen with secondary intergranular porosity partly or completely filled with quartz. The limestones in places exhibit alteration to dolomite, and trace amounts of fine-grained "chicken wire" anhydrite are seen in thin section as a replacement of the micritic sediment. This interval contains no evidence of oil staining, but some mineral fluorescence is seen in a few intervals. Visual porosity is fair to good in the thin-bedded limestone intervals and individual sand beds.

Paleontologic and seismic data indicate an unusually thick Lower Cretaceous (Valanginian-Berriasian) section in this well. Seismic data show most of this thickening occurring in the Berriasian section between about 13,000 and 15,000 feet. This thickening is interpreted to be channel-fill deposits associated with a large Lower Cretaceous delta system.

13,580 to 17,740 feet

Siltstone in this interval is light to medium gray, soft to firm, occasionally brittle, slightly to moderately hydrated, and noncalcareous to slightly calcareous. Traces of mica, glauconite, pyrite, and dolomite are associated with the siltstone. The shale is mostly light to dark gray with occasional thin red laminae and varies from soft to moderately hard, brittle, platy, and blocky. It is noncalcareous to slightly calcareous, is hydrated in places, and is associated with very fine sucrosic-textured siltstones with trace amounts of dolomite and limestone. The limestones are thin bedded and distributed sparsely throughout the section. They consist primarily of gray to white mudstones to wackestones with some remobilized calcite filling fractures and some brown silty dolomite.

The interval of 17,250 to 17,320 feet represents one of the thickest limestone intervals in the well. The first Jurassic sediments occur at 17,280 feet near the top of this limestone. The limestones are grainstones and wackestones that are light gray to white with some remobilized calcite filling small vugs. A few thin sandstones are present which are friable, fine-grained to very fine-grained, subrounded to subangular clear quartz and have slight to moderate amounts of calcareous cement. Trace quantities of pyrite, mica, and dolomite are associated with this lithology. Fair to good visible porosity is seen only in the sandstone and grainstone intervals. At 15,400 feet there is an indication of a slight blue-white fluorescence.

Conventional Core No. 1 (9,934 to 9,964 feet)

There was complete recovery for this 30-foot core. This description is based on examination of the core and binocular microscopic examination of core chips. Thin sections were not available. The core consists of friable, light yellowish-brown, sandy to argillaceous, quartzose siltstone that coarsens occasionally to sandstone. Minor amounts of muscovite and inertinite are also present. Porosity and permeability appear to be very good as water soaks into the core immediately. The interval from 9,939 to 9,939.5 feet contains a dense, dark gray, argillaceous limestone unit with abundant fine fossil fragments.

Conventional Core No. 2 (15,406 to 15,419 feet)

There was poor recovery for this core because of core barrel problems. Core No. 2 consists of well-indurated, light gray, very fine-grained sandstone to coarse siltstone with abundant dark gray shale laminae and tan clay clasts. The interval from 15,410.4 to 15,419.1 feet consists of dark gray, silty shale containing tan clay clasts and light gray siltstone clasts. In thin section, the silty shale has abundant quartz silt (about 15 to 20 percent) and very fine sandy laminae, muscovite shreds (about 1 percent) and occasional pyrite grains and organic patches. Abundant clay clasts, several centimeters in length, were also noted.

Conventional Core No. 3 (17,710 to 17,740 feet)

There was good recovery for core No. 3. The predominant lithology of this core interval is dark gray, noncalcareous, silty shale with almost no visible porosity. This interval shows numerous fine laminae in which quartz silt increases in abundance to become siltstone. The rock contains abundant pyrite, less than 1 percent muscovite, and numerous patches of organic material.

PALEONTOLOGY AND BIOSTRATIGRAPHY

by

Harold L. Cousminer, William E. Steinkraus, and Raymond E. Hall

Paleontologic analyses of well cuttings were made of 30-foot composite intervals for both calcareous nannofossils (Steinkraus) and foraminifers (Hall) and of 90-foot composite intervals for palynomorphs (Cousminer). A total of 210 composite samples was examined for nannofossils; 175 for foraminifers; and 129 for palynomorphs. Four sample splits from each core were initially processed and palynologically studied, and 53 additional sample splits were subsequently made to better define the deeper portion of the well. All samples were of poor quality for micropaleontologic analysis, with evidence that cuttings were contaminated by downhole cavings and zones of extensive recycling of organic detritus.

The first samples were obtained at a depth of 7,113 feet after casing had been set at 7,069 feet. The uppermost sample examined from 7,113 feet is in the Pleistocene. Unconformities were detected at 8,310 feet between the Middle Oligocene and Eocene, at 8,520 feet separating the Eocene and Santonian, and at 9,820 feet between the Aptian and Hauterivian.

On the basis of this study, there is paleontologic evidence for an anomalously thick Lower Cretaceous (Valanginian-Berriasian) section. Calcareous nannofossils and palynomorphs indicate that core No. 1 (9,934-9,964 feet) is in the Hauterivian, substantiating previous determinations from cuttings. Core No. 2 (15,406-15,419 feet), over 5,400 feet below core No. 1, contains abundant nannofossils of late Berriasian Age. In the intervening cuttings there is a Berriasian top at 12,690 feet. Samples of cuttings below core No. 2 indicate a Jurassic top (Tithonian) at 17,280 feet. Thus there is a Berriasian section that is about 4,600 feet thick. Late Jurassic dinoflagellates present in core No. 3 (17,710-17,740 feet) range in age from late Kimmeridgian to early Tithonian. Detailed study, based on 53 additional core samples, indicates that these Berriasian fossils exist in core No. 2 (15,406-15,419 feet) and in the section above the core (12,690 feet) to below the core (16,920 feet). These fossils represent a thickened Valanginian-Berriasian section. Seismic profiles, including U.S. Geological Survey's, Line 10, indicate that these thickened deposits follow a southeast linear trend and probably represent rapidly emplaced channel-fill deposits connected with Early Cretaceous drainage in the Baltimore Canyon (fig. 7).

In the initial study, fossils (rare dinoflagellates) ranging in age from Middle to Late Jurassic were found in the deeper part of the well (13,500 to 17,740 feet) and prompted the dating of this section. Detailed study, based on additional core material, indicates that the oldest strata penetrated are Kimmeridgian rocks and that the older fossils are reworked from older strata beneath that penetrated by the well.

Three factors limit the reliability of paleontologic data from offshore Atlantic wells: (1) Most analyses are made from drill cuttings samples, which are often heavily contaminated by cavings from higher in the drill

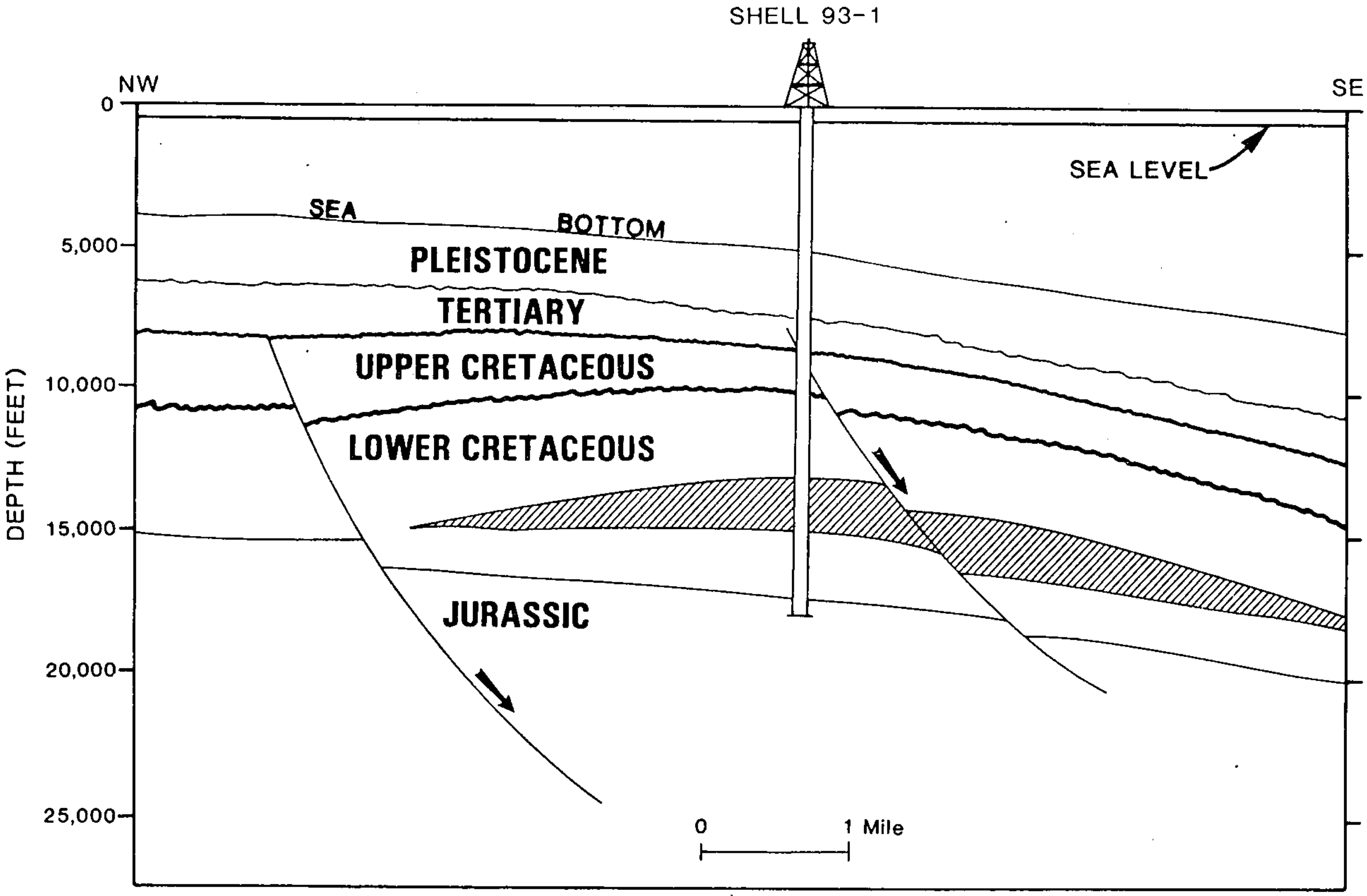


Figure 7.--Schematic dip section through the Shell 93-1 well site showing the relationships of the major geologic units and geologic structures. Shaded area represents the thickened Valanginian-Berriasian section deposited by channels or delta lobes.

hole. For this reason, only "tops," or the uppermost species appearances, are recorded. (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 misdated. (3) Biostratigraphic control is poor in pre-Late Jurassic strata. Calcareous nannofossils and foraminifers are rare to nonexistent. Palynomorphs are more common, but their biostratigraphic distribution is not fully documented with reference to the European stage type localities. The Minerals Management Service has relied on the Jurassic palynostratigraphy of offshore eastern Canada (Bujak and Williams, 1977) because many of their palynomorph marker species also occur in the United States Atlantic offshore subsurface. Although the European stage equivalence of several species is not fully resolved, some species have recently been documented in European type sections (Woollam and Riding, 1983; Riding, 1984; and Davies, 1985).

The following section presents the findings of the paleontologic analyses for the well. Depths indicated are from the top of each sample interval. The age dates, index fossil depths, and depositional environments are also summarized in figure 6, pp. 16-19.

Cenozoic

Quaternary

Pleistocene (7,113-7,440 feet)

Calcareous nanofossil marker species of Pleistocene age were identified at 7,113 feet and include *Pseudoemiliania lacunosa* and *Geophyrocapsa oceanica*.

Tertiary

Pliocene (7,440-7,590 feet)

The nannofossils *Discoaster pentaradiatus* (7,440 feet) and *Discoaster surculus* (7,470 feet) both are Pliocene marker species.

Late Miocene (7,590-7,710 feet)

Microfossils of late Miocene age include the nannofossils *Discoaster quinqueramus* (7,590 feet) and *Discoaster brouweri* (7,620 feet) and the foraminifer *Globorotalia siakensis* (7,620 feet).

Middle Miocene (7,710-8,100 feet)

Discoaster kugleri was recovered from 7,710 feet and the planktonic foraminifer *Globorotalia fohsi fohsi* from 7,980 feet; both indicate middle Miocene age.

Early Miocene (8,100-8,280 feet)

The planktonic foraminifer Globigerinoides primordius marks the top of the Lower Miocene (N4) at 8,100 feet.

Middle Oligocene (8,280-8,310 feet)

The middle Oligocene planktonic foraminifer Turborotalia opima was recovered from 8,280 feet.

Eocene (8,310-8,520 feet)

The nannofossil Discoaster barbadiensis is from 8,310 feet; the dinoflagellate Leptodinium maculatum is from 8,370 feet, and the planktonic foraminifers Globorotalia wilcoxensis and Globorotalia quetra (8,340 feet) all have Eocene restricted ranges. The longer ranging dinoflagellate Cordosphaeridium inodes (Early Paleocene-Late Oligocene) was also recovered from 8,370 feet.

Mesozoic

Late Cretaceous

Eocene-Cretaceous boundary

No Paleocene paleontologic markers were found in the samples examined. Eocene strata appear to rest directly on Santonian rocks, separated by a major unconformity.

Santonian (8,520-8,640 feet)

The calcareous nannofossil marker Marthasterites furcatus occurs at 8,520 feet indicating the top of the Santonian at this depth. The planktonic foraminifer Dicarinella concavata has a Santonian top and is accompanied by the dinoflagellate Chatangiella sp. aff. victoriensis at 8,550 feet, also indicating the Santonian stage at this depth.

Turonian (8,640-8,940 feet)

Turonian nannofossil markers include Radiolithus planus (8,700 feet) and Corollithion achylosum (8,880 feet). Planktonic foraminifers of Turonian age include Praeglobotruncana aumalensis, Proglobotruncana stephani (both from 8,640 feet) and Hedbergella simplex from 8,730 feet.

Cenomanian (8,940-9,150 feet)

The Cenomanian nannofossil Corollithion kennedyi and planktonic foraminifers Rotalipora cushmani and Rotalipora deekei were recovered at 8,940 feet.

Early Cretaceous

Albian (9,150-9,420 feet)

Albian nannofossils include Braarudosphaera africana (9,150 feet) and Braarudosphaera stenorhetha (9,240 feet). The planktonic foraminifer Ticinella roberti was also found at 9,150 feet.

Middle Aptian (9,420-9,820 feet)

The mid-Aptian benthonic foraminifer Lenticulina nodosa was recovered at 9,420 feet. Additional Aptian markers include John Bebout's (1981) spore markers Cyathidites sp. 10 (121) and Auritalinasporites deltaformis (123) from 9,700 feet. Nannofossil species ranging into the Aptian include Nannoconus "ashqeloni" (9,750 feet) and Micrantholithus obtusus from 9,780 feet.

No Barremian microfossil species were identified.

Hauterivian (9,820-10,320 feet)

The Hauterivian top is indicated by the nannofossil Nannoconus steinmanni at 9,820 feet. Additional support for the Hauterivian age of this interval are Bebout's (1981) spore species Trilobosporites sp. 1 (132) and Trilobosporites sp. 2 (133) from 9,935 feet. Core sample splits at 9,956-9,957 feet and 9,962-9,963 feet both contain specimens of Ctenidodinium elegantulum, Cribroperidinium septimentum, and Muderongia crucis. All of these have Hauterivian-Berriasian ranges, but are most common in the Scotian Shelf-Grand Banks Ctenidodinium elegantulum palynozone of Hauterivian age (Bujak and Williams, 1978). Subsequent study of an additional 20 core sample splits from core No. 1 yielded specimens of Nannoconus colomi and Microrhabdulus bollii, which by range overlap indicate a Late Hauterivian age (see fig. 8a, p. 28).

Valanginian (10,320-10,400 feet)

Oligosphaeridium perforatum, a Hauterivian-Valanginian dinoflagellate marker, first appears at 10,320 feet. Tubodiscus verenae, a nannofossil species restricted to the Valanginian, occurs at 10,360 feet.

Valanginian-Berriasian (10,400-12,690 feet)

The dinoflagellates Muderongia simplex (Hauterivian-Berriasian) and Polystephanephorus sarjeantii (Berriasian) were recovered from 10,400 feet indicating a stratigraphic position that may be proximal to the Valanginian-Berriasian contact zone.

Bebout's (1981) palynomorph spore markers Gleichenidites sp. 2 (137) and Reticulatisporites spinosum do not have a known post-Berriasian range. These species are recorded from 10,960 feet. Another sample at 11,200 feet carries Bebout's palynomorph markers Trilobosporites domitus (134) and forma 22 (141), as well as the foraminifers Lenticulina saxonica and Lenticulina bifurcella. Bebout's spore markers do not have a post-Berriasian range, while the foraminifers have an overlapping Valanginian range. The palynomorph species from 12,400 to 12,690 feet may be reworked in the Valanginian, accounting in part for the greatly expanded Berriasian.

Berriasian (12,690-16,920 feet)

The nannofossil Polycostella senaria, used to identify the top of the Berriasian, was noted at 12,690 feet, and the dinoflagellate Occisucysta evitti, another upper Berriasian marker, was noted at 13,220 feet. No calcareous nannofossils or foraminifers considered to have age-restricted significance were recovered in cuttings below 12,690 feet. Eight additional sample splits from core No. 2 (15,406-15,419 feet) indicate an upper Berriasian age range (see fig. 8b). Both Polycostella senaria and Nannoconus bronnimanni have an uppermost Berriasian range and have their uppermost occurrence in the base of core No. 2 (15,419 feet). Nannoconus colomi, Cruciellipsis cuvillieri, Nannoconus bermudezi, and Nannoconus steinmanni do not range below the Berriasian and occur throughout the core. Cyclagelosphaera deflandrei (15,418 and 15,419 feet) does not range above the mid-Valanginian.

Restudy of palynology slides from cuttings also resulted in identifying the dinoflagellate species Occisucysta evitti from 16,920 feet. In the Mid-Atlantic wells, this species usually occurs well below the top occurrence of the Berriasian marker species Polycostella senaria.

Jurassic

Tithonian (17,280 feet)

The dinoflagellate species Ctenidodinium panneum was identified at 17,280 feet during restudy of palynology slides. Ctenidodinium panneum does not occur in rocks younger than Tithonian.

Kimmeridgian (17,710-17,735 feet)

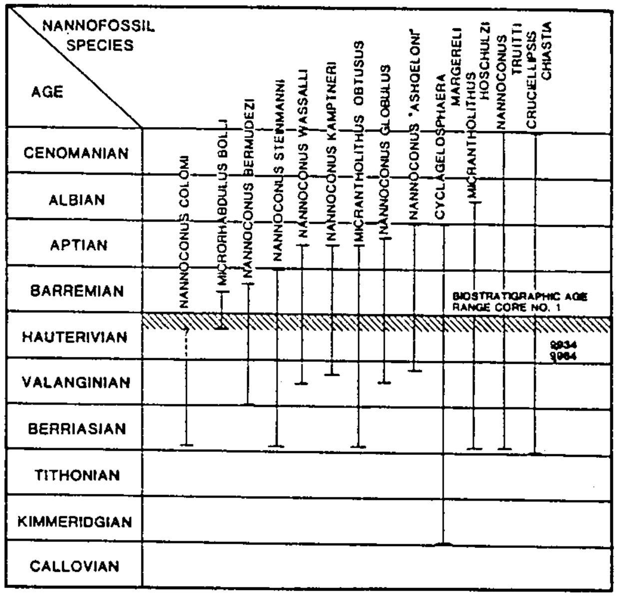
The dinoflagellate species Ctenidodinium panneum, Muderongia sp. A, Gonyaulacysta longicornis, and Senoniasphaera jurassica were recorded in many of the core sample splits from 17,710 to 17,735 feet. Senoniasphaera jurassica is an early Tithonian marker, while Ctenidodinium panneum does not occur in rocks older than late Kimmeridgian (see fig. 9, p. 31, and Davey, 1979)

Discussion of Results

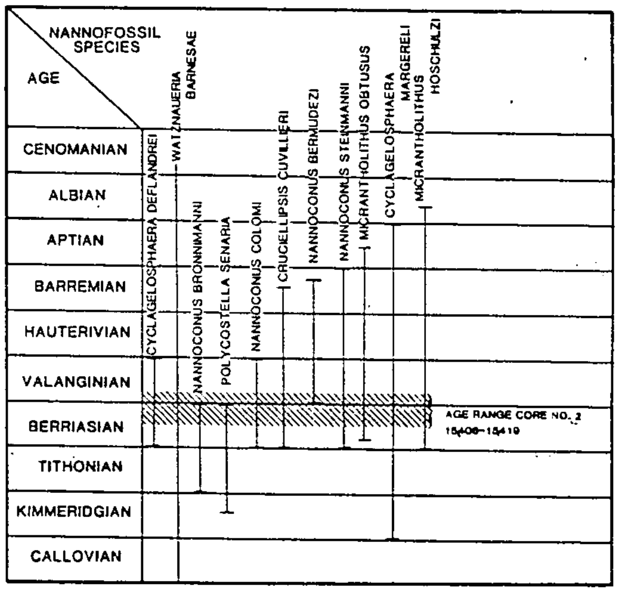
The results of the paleontologic study of the Shell 93-1 well indicate that an extremely thickened Berriasian-Valanginian section is present. Although the range chart of nannofossil species found in samples of core No. 1 (9,934-9,964 feet) includes many long-ranging species (fig. 8a), Microrhabdulus bollii does not range above the Hauterivian and Nannoconus colomi does not range above the early Hauterivian (Steinkraus, 1983). Both these species are present in several samples of core No. 1 and support the Hauterivian age determination of this interval on the basis of paleontologic study of cuttings. The occurrence of the nannofossil species Polycostella senaria in cuttings from 12,690 feet indicates late Berriasian age, and the dinoflagellate species Occisucysta evitti from

13,220 feet supports this age assignment since its uppermost appearance is below Polycostella senaria. However, reappearance of Polycostella senaria in the base of core No. 2 (sample from 15,419 feet), along with Nannoconus bronnimanni, indicates another Berriasian top some 2,700 feet below the first top as shown in figure 8b.

The reappearance of Occisucysta evittii in cuttings from 16,920 feet and deeper and the Jurassic top seen below in cuttings at 17,280 feet together support this conclusion. This is in turn reinforced by the appearance in core No. 3 (17,710-17,740 feet) of Ctenidodinium panneum, Muderongia sp. A, Gonyaulacysta longicornis, and Senoniasphaera jurassica, all of which are restricted in range to Upper Kimmeridgian-Lower Tithonian (see fig. 9, p. 31) This greatly thickened Valanginian-Berriasian section corresponds with a lowering in sea level (Vail and others, 1977) that increased the rate of clastic sedimentation in Baltimore Canyon during this time and that hosted the thick channel-fill deposits of reworked Lower Cretaceous sediments. It is also possible that the section may have been additionally thickened by faulting (see fig. 7, p. 24). Seismic data indicate growth fault activity in the vicinity of the well, but resolution is too poor to interpret the amount of offset represented by these structures. Deposition of this thick clastic wedge in Early Cretaceous time may have restricted development of the southern extension of the offshore carbonate shelf-edge trend present to the northeast.



(a) Biostratigraphic age range of core no. 1



(b) Biostratigraphic age range of core no. 2

Figure 8.--Ranges of calcareous nannofossils identified in core Nos. 1 and 2, Shell 93-1 well.

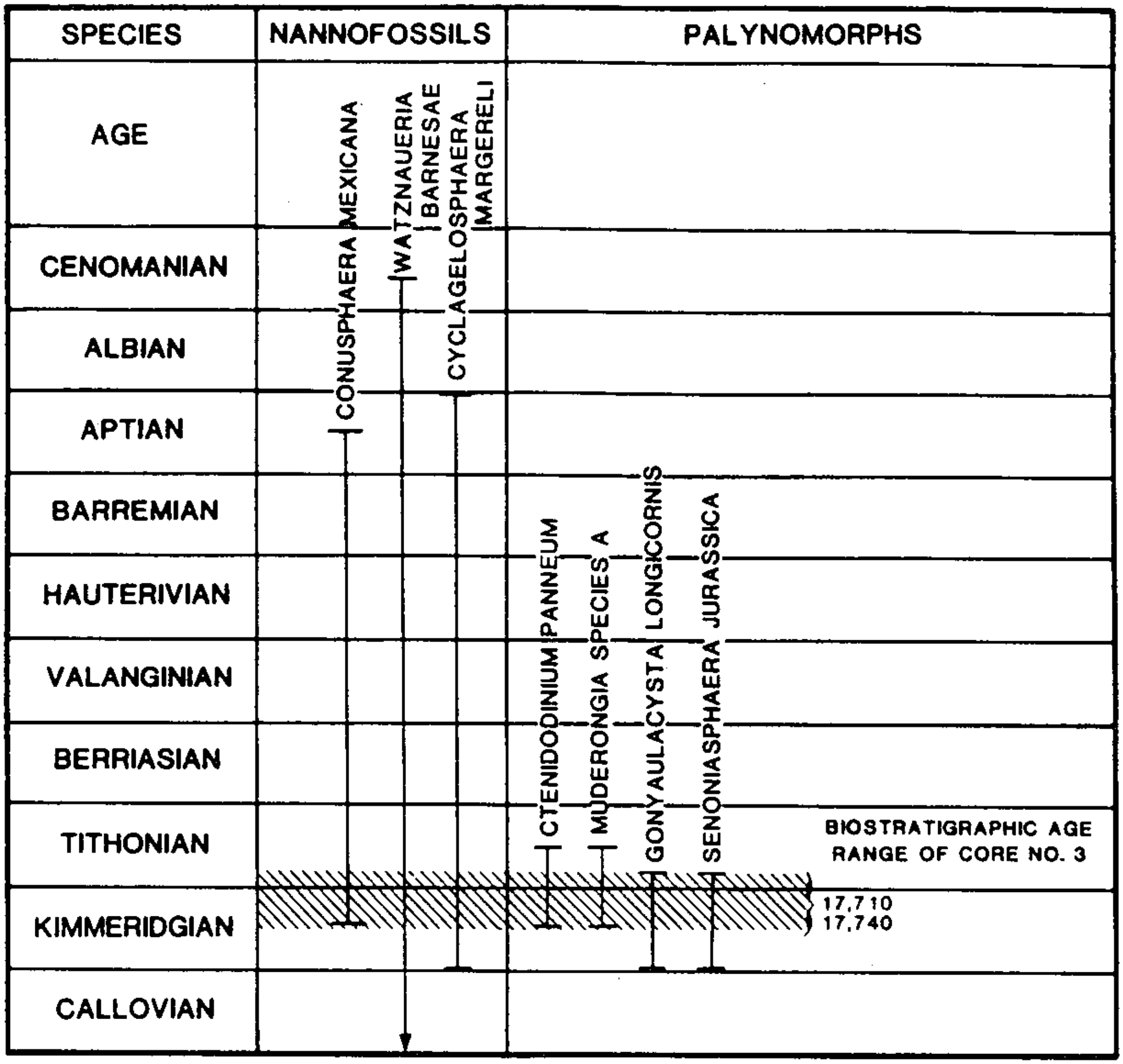


Figure 9.--Ranges of calcareous nannofossils and palynomorphs identified in core No. 3, Shell 93-1 well.

PALEOENVIRONMENTAL ANALYSIS

by

Raymond E. Hall, William E. Steinkraus, Harold L. Cousminer, and Anthony C. Giordano

In the following interpretation of the depositional settings, depths of lithologic boundaries are adjusted to depths recorded on the electric logs. The environmental descriptions are interpretations derived mainly from foraminiferal assemblages and examination of cuttings and petrographic thin sections. The determination of a particular depositional setting is based on the occurrence of various lithologic indicators (shale, oolites, anhydrite, etc.) and the distribution and abundance of marine and nonmarine fauna. Foraminiferal assemblages are generally sparse, and show evidence of extensive caving downhole. The paleoenvironmental curve shown in figure 6, pp. 16-19, is based primarily on foraminiferal data.

The sediments from 7,113 to 7,620 feet consist of terrigenous clastic detritus and fossil fragments including pelecypods, bryozoans, microgastropods, sponge spicules, and benthonic and planktonic foraminifers. This sedimentation indicates reworked periglacial clastic deposits of Pleistocene-Pliocene age. Miocene through Middle Oligocene sediments from 7,620 to 8,310 feet are primarily gray, soft, noncalcareous siltstone, which indicates a shallow, inner shelf environment in water up to 50 feet deep. Specimens of *Elphidium*, *Cibicides*, and *Quinqueloculina* recovered in this interval and an increased diversity of the calcareous nannoplankton indicate shallow, inner neritic waters. From 8,310 to 8,330 feet, an unconsolidated quartz sand with a glauconite break marks an unconformable surface between Middle Oligocene and overlying Eocene sediments. The presence of glauconite indicates a low rate of deposition in a shelf environment in water up to 50 feet deep.

The interval from 8,330 to 8,520 feet consists of Eocene rocks, which unconformably overlie Santonian sediments. This interval is defined paleontologically as well as lithologically. The upper portion of the interval consists of calcareous clay and the lower portion is quartz sandstone. The inferred environment of deposition is in shelf water no deeper than 50 feet. A Santonian, argillaceous limestone occurs from 8,520 to 8,700 feet and appears to have been deposited in a deeper water (up to 300 feet deep) shelf environment on the basis of the increased abundance and diversity of the foraminifer and calcareous nannofossil assemblages. The Tertiary-Cretaceous boundary, which is within a world wide transgressive sequence, is represented here amid rising sea level and a deeper water environment.

A marked increase in planktonic foraminifer species, the presence of the benthonic foraminifer *Tritaxia*, and the occurrence of glauconite in the interval all substantiate the deepwater environment. From 8,700 to 9,820 feet the sediments are Turonian to Aptian and consist primarily of siltstone with fossil fragments,including planktonic foraminifers, sponge spicules, microgastropods, and Inoceramus prisms. The environment of deposition in this interval gradually changes to shallower water (less than 50 feet of water at 9,500 feet). This shallowing is seen in nearby wells and in the Mid-Atlantic in general. The fossil assemblage, which is diverse and abundant at the top of the section, becomes sporadic towards the base of the section.

A major unconformity occurs at 9,820 feet in which Aptian rocks overlie Hauterivian sediments. The section from 9,820 to 13,580 feet contains mostly siltstone and shale with thin beds of limestone and sandstone. The limestones that are associated with thin quartz sandstones may represent cyclic sedimentation in slightly deeper water in which nearshore terrigenous detritus alternates with limestone interbeds. Subsequent groundwater leaching by freshwater partly dolomitized some of the limestones.

An increase in benthic species, lack of planktonics, and the presence of Trocholina in the interval from 9,600 to 10,600 feet indicate shallow-water conditions (less than 50 feet deep) for this interval. Below 9,860 feet, foraminifers are extensively weathered and much reduced in number. Foraminifers are rare from 10,700 feet to total depth and include Trocholina spp. and other very shallow, brackish-water benthonics. Lithologic data indicate a probable restricted marine, nearshore environment. A grainstone occurring at 17,250-17,320 feet may indicate a minor transgression. Some of the red shales and siltstones below 10,000 feet, though, were probably deposited in nonmarine depositional environments.

The thickened Valanginian-Berriasian section (12,690 to 16,920 feet), which is interpreted to have been deposited as channel-fill or delta lobe features, further supports nonmarine to nearshore marine depositional environments in the Lower Cretaceous section. (See Lithologic Analysis and Paleontology and Biostratigraphy sections of this report.) The presence of abundant siltstone, fine-grained sandstone, red shale, glauconite, and oxidized pyrite provides additional evidence for this interpretation.

PETROLEUM GEOCHEMISTRY

by

Robert E. Miller, David M. Schultz, Harry E. Lerch, Paul C. Bowker,

and Dennis T. Ligon

The quality of the organic richness of a source rock and its ability to provide petroleum hydrocarbons may be indicated by (1) a minimum amount of total organic carbon (0.7 to 1.0 weight percent for argillaceous rocks) (2) pyrolytic oil yields greater than 0.2 to 0.3 percent, and (3) solvent extractable hydrocarbon concentrations in excess of 100 to 500 ppm. It is significant to note that the weight percent of total organic carbon required to provide or constitute an excellent, good, or poor source rock is not as well defined for fine-grained, medium to dark gray limestone and dolomites. The amorphous nature of the organic matter derived from hydrogen-rich marine algal substances in dark gray carbonates may provide the potential to generate more hydrocarbons than shales with the equivalent amounts of total organic matter. As a consequence, medium- to fine-grained, dark gray to dull brown limestones and dolomites with a total organic carbon as low as 0.3 percent may have sufficient richness to be classified as source rocks (Hunt, 1967).

The definitions, concepts, and terminology used in this report are those established by Vassoyevich and others (1970), Dow (1977), Tissot and Welte (1978), Hunt (1974, 1978, 1979), Miller and others (1979, 1980, 1982), Momper (1978), Walper and Miller (1983), and Waples (1980).

Analytical Methods and Procedures

The Minerals Management Service Petroleum Geochemistry Laboratory analyzed 24 well cuttings samples and 3 conventional core samples for their C_{15+} characteristics and 68 gas samples from well depths of 7,170 feet to 17,735 feet. The unwashed cuttings samples were first analyzed by the "head-space" procedure to determine the concentration of the C_1 to C_5 light hydrocarbons present in the sealed one-quart cans delivered to the laboratory. Following the "head-space" analysis, each selected individual cuttings-sample can was opened and the drilling mud removed from each rock fragment by carefully washing the rock chips under running water through a Tyler 100-mesh (150 micron) screen. The washed rock chips were then air dried. Each cuttings sample was hand picked to remove the solid contaminants composed of metal fragments, rubber, plastic, fibers, walnut husks, and various morphological forms of solid to semisolid hydrocarbons. The samples were then described by light-optical binocular methods and divided into aliquots for detailed gasoline-range hydrocarbon analysis, total organic carbon analyses, Soxhlet solvent extraction and liquid column chromatography, and high-resolution glass capillary gas chromatographic analyses of the saturated paraffin-napthene hydrocarbon fractions.

Results and Discussion

Source Rock Quality and Type

The source rock potential of the Shell 93-1 well is shown in figure 10. This plot of the total organic carbon (weight percent) depicts the richness or quality of the organic carbon present in the stratigraphic units penetrated during the drilling of the well. The Tertiary shales (7,440 to 8,370 feet) have total organic carbon values that range from 0.45 to a maximum of 1.50 weight percent. Such values are in the fair to good range for argillaceous source beds. The Upper Cretaceous shales (8,520 to 9,150 feet) are characterized by total organic carbon values that range from 0.50 to 0.80 weight percent and are considered to be in the moderately fair category for source rocks. The Lower Cretaceous shales and sands (9,150 to 17,280 feet) have total organic carbon values that range from 0.70 to 1.35 weight percent. These values are within the fair to good range. The total extractable hydrocarbons (ppm), extractable paraffin-naphthene, aromatic hydrocarbons, nitrogen-sulfer-oxygen, and total extractable fractions (50-300 ppm) for the section from 8,520 to 12,690 feet are in the poor to fair source rock quality range.

The Upper Jurassic section, from 17,280 to 17,735 feet, contains extractable hydrocarbons that range from 50 to 250 ppm. These extractable hydrocarbon concentration values are within the fair to good range and are believed to be the result of the onset of hydrocarbon generation beginning at a well depth of about 16,500 feet. The cutting samples from the 8,000 to 11,000 feet section are believed to be influenced by mud additives. Below 11,000 feet the cuttings samples are believed to be free from mud additive effects, and the source rock quantity and quality values are believed to be consistent and realistic assessments.

Types of Organic Matter

Organic geochemical elemental analyses of the Cretaceous ground whole-rock samples show that the predominant form of organic matter is of the hydrogen-lean, gas-prone variety. The hydrogen to carbon ratios of the Cretaceous shales range from 0.30 to 0.50. The Jurassic section from 17,280 to 17,735 feet contains organic matter with a hydrogen to carbon ratio that varies from 0.35 to 0.40, indicating the presence of hydrogen-deficient, gas-prone kerogens. These data indicate that the predominant kind of organic matter present in both the Cretaceous and Upper Jurassic shales is of the terrestrial variety. The hydrogen to carbon ratio molecular geochemical signature for the predominant kerogen types identified is consistent with the light optical descriptions of the solid organic matter types (see the Kerogen Analysis section of this report).

Thermal Maturity

The hydrocarbon evolution window (HEW) for liquids and condensates is based on the temperature sensitivity of the ratio of the paraffin-napthene $C_{15}+$ hydrocarbon to total organic carbon plotted as a function of the geothermal gradient. This ratio is susceptible to mud additive or other hydrocarbon contamination of the cuttings samples. However, in the Shell

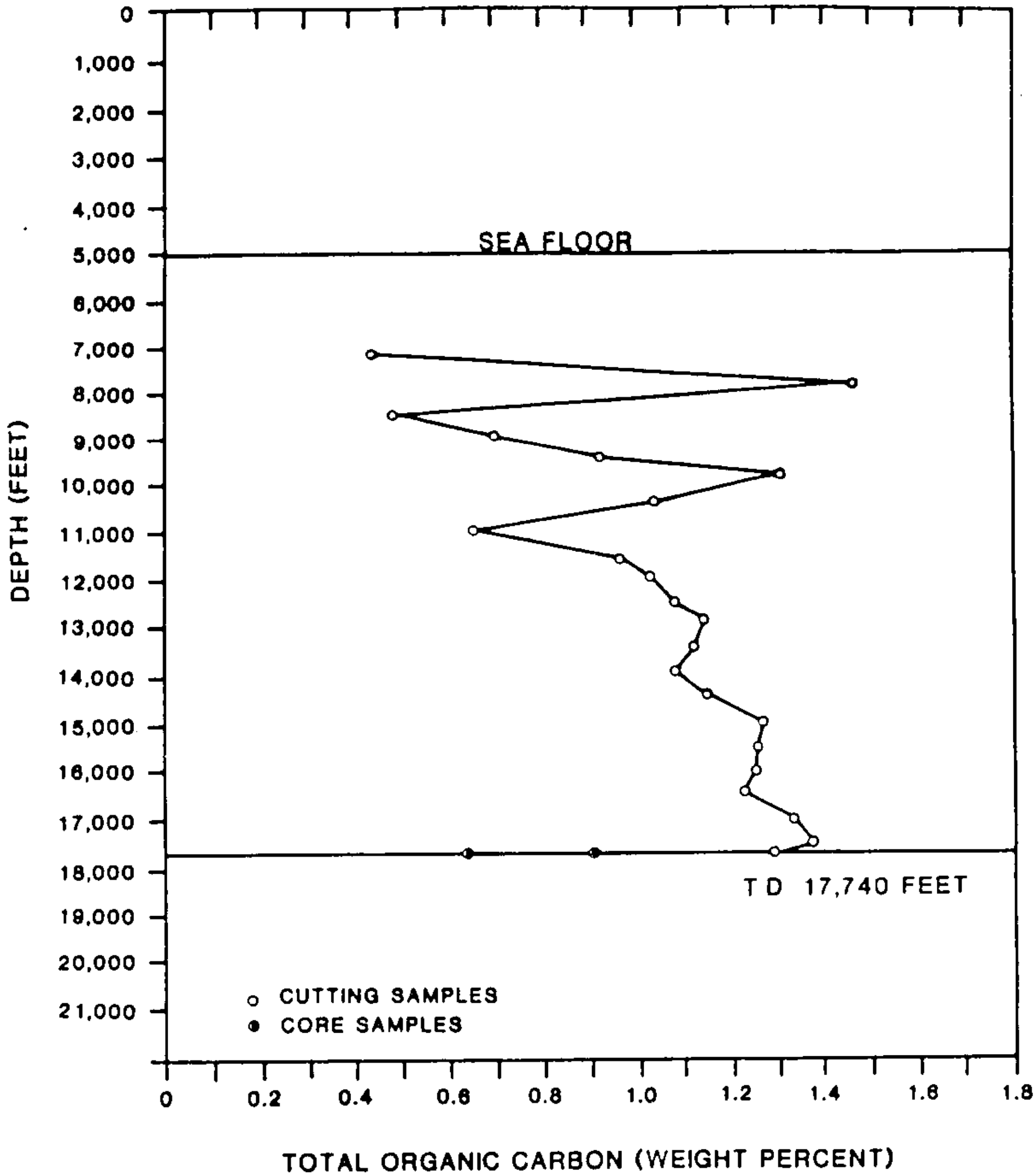


Figure 10.--Graph showing total organic carbon content of rocks in the Shell 93-1 well.

Table 2.--Ranges of C_1-C_4 concentrations and gas wetness values for the Shell 93-1 well

[Values are based on averages of triplicate analyses.]

Depth Interval (feet)	C_1-C_4 (ppm)	Gas Wetness (%)
6,000-6,500	3,000	- - -
6,500-7,000	14,000-19,400	1
7,000-7,500	20,000-43,600	2
7,500-8,000	19,300-38,500	2-4
8,000-8,500	0-500	1-2
8,500-9,000	0-4,000	4-6
9,000-9,500	2,000-13,000	2-4
9,500-10,000	500-1,000	3-5
10,000-10,500	250-4,000	2-28
10,500-11,000	250-3,000	3-5
11,000-11,500	1,500-10,000	2-12
11,500-12,000	0-10,000	11-45
12,000-12,500	200-600	18
12,500-13,000	750-4,000	5-18
13,000-13,500	200-500	18-38
13,500-14,000	0-500	18-48
14,000-14,500	500-1,000	25-32
14,500-15,000	500-2,000	38-58
15,000-15,500	1,000-3,600	54-60
15,500-16,000	4,400-8,500	55-80
16,500-17,000	5,800	65-72
17,000-17,500	5,800	66-72
17,500-17,735	6,600	58

93-1 well, the mud additive contamination factor was minimal. The ratio of the saturated paraffin-naphthene to total organic carbon when plotted against the geothermal gradient (0.98°F/100 feet) indicates that the threshold of intense oil generation (TIOG) begins at a well depth of about 16,500 feet or a burial depth of about 11,500 feet (fig. 11). On the basis of a geothermal gradient of 0.98°F/100 feet, the theoretical TIOG is consistent with the experimental saturated paraffin-napthene total organic carbon (TOC) ratio. Theoretical peak liquid generation is predicted to occur at a burial depth of about 12,000 to 13,000 feet. Comparison of the theoretical depth limits for the HEW with the actual thermal liquid maturity window depth limits established by molecular geochemical ratios confirms that the principal zone of oil formation was approached but not completely penetrated in the Shell 93-1 well (fig. 11). This interpretation is consistent with the molecular geochemical thermal maturation parameters and TAI values of 2.8 observed at a depth of 17,190 feet.

The molecular gases examined in the Shell 93-1 well cuttings samples were the C_1 to C_4 (methane through butane) "head space" components and the C_4 to C_7 (butane through heptane) detailed gasoline range species. The average concentration of the total methane through butane molecular species (ppm) was very low, generally about 1,000 ppm for the entire stratigraphic section. Exceptions to this are samples from 7,000 to 9,000 feet where the total concentrations ranged from about 19,000 ppm to 43,000 ppm. The shallow gas occurrence is believed to be primarily due to biogenic methane. The highest gas wetness (85 percent)--which is defined by the ratio of the ethane, propane and butane components to methane in a unit volume of gas--was found to occur at a sediment burial depth of 10,000 to 12,000 feet. The presence of trace amounts of the higher homologs from C_4 to C_7 suggests that petrogenic thermal generation processes are active at greater burial depths. However, the low concentrations (500-1,500 ppm) raises concern with regard to the quality of the source rocks (table 2). The trends of the isopentane-to-pentane and normal butane-to-isobutane ratios indicate that thermal maturation processes are active at burial depths greater than 11,000 to 13,000 feet, as indicated by the increase in the percentage of the permanent gases. The low concentrations, however, of the C_4 to C_7 gasoline range hydrocarbons strongly suggest the existence of a relatively low thermal history. The presence of a predominantly terrestrial gas-prone organic matter for both the Lower Cretaceous and Upper Jurassic units, coupled with a low geothermal history, implies a low generation potential.

Time-Temperature Burial Model

The time-temperature burial model relationships for the Shell 93-1 well (fig. 12) are based on stratigraphic tops and thicknesses defined in the Paleontology and Biostratigraphy section of this report and on a geothermal gradient of 0.98°F/100 feet determined from well bore temperatures (see Geothermal Gradient section, p. 43) with an assumed initial temperature of 65°F. This gradient is similar to the Shell 586-1 well. The gradient is assumed to have been relatively constant for the past 150 million years. The chemical kinetics concept predicts that the thermal generation of hydrocarbons (principal zone of oil formation) occurs between the temperatures of 60°C and 150°C (Tissot and Welte, 1978). From the model, it is implied that the Upper Jurassic in the Shell 93-1 well has a time-temperature index (TTI) of 8.901. This value would indicate that the onset for oil and gas

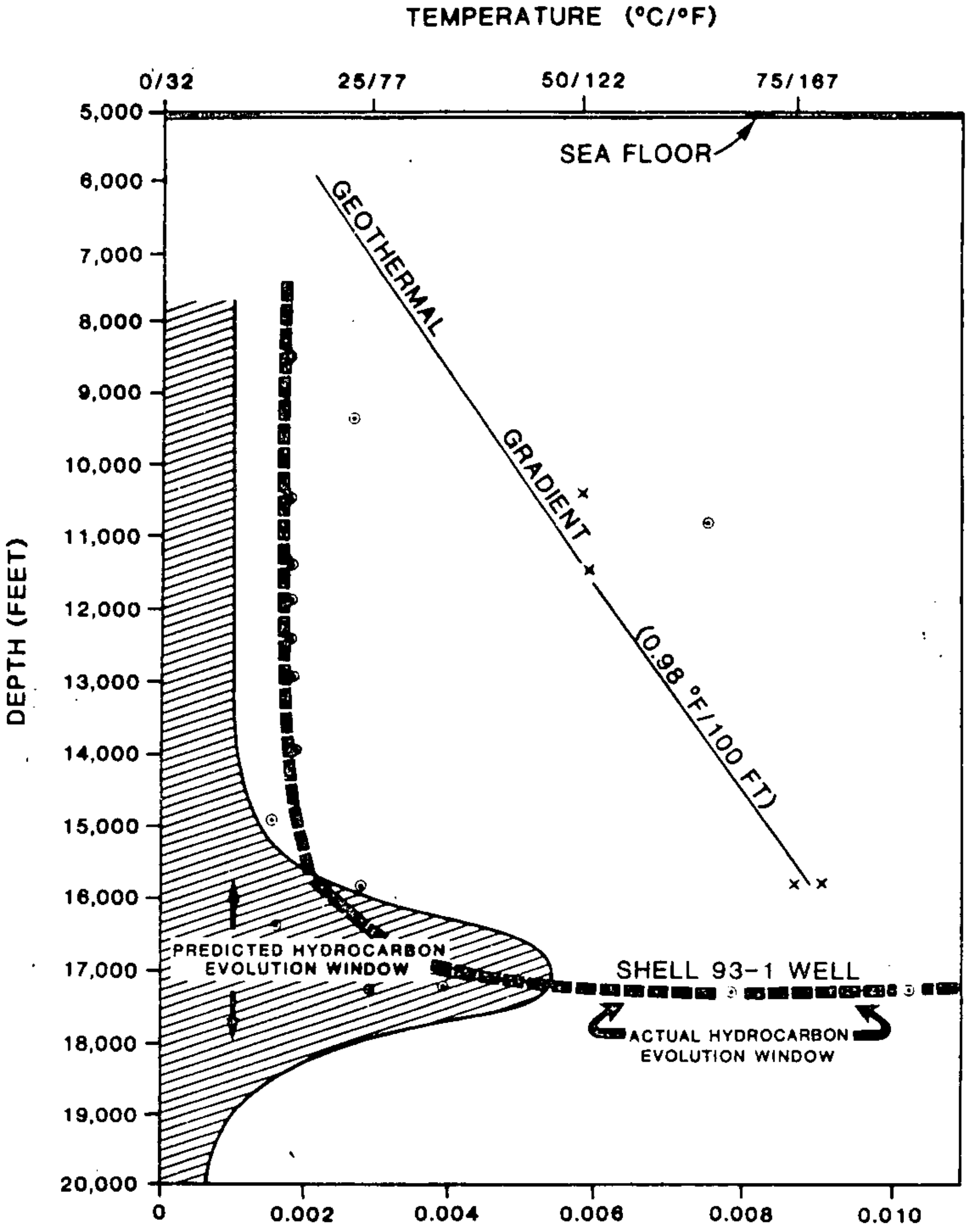


Figure 11.--Predicted and actual hydrocarbon evolution windows and geothermal gradient for the Shell 93-1 well.

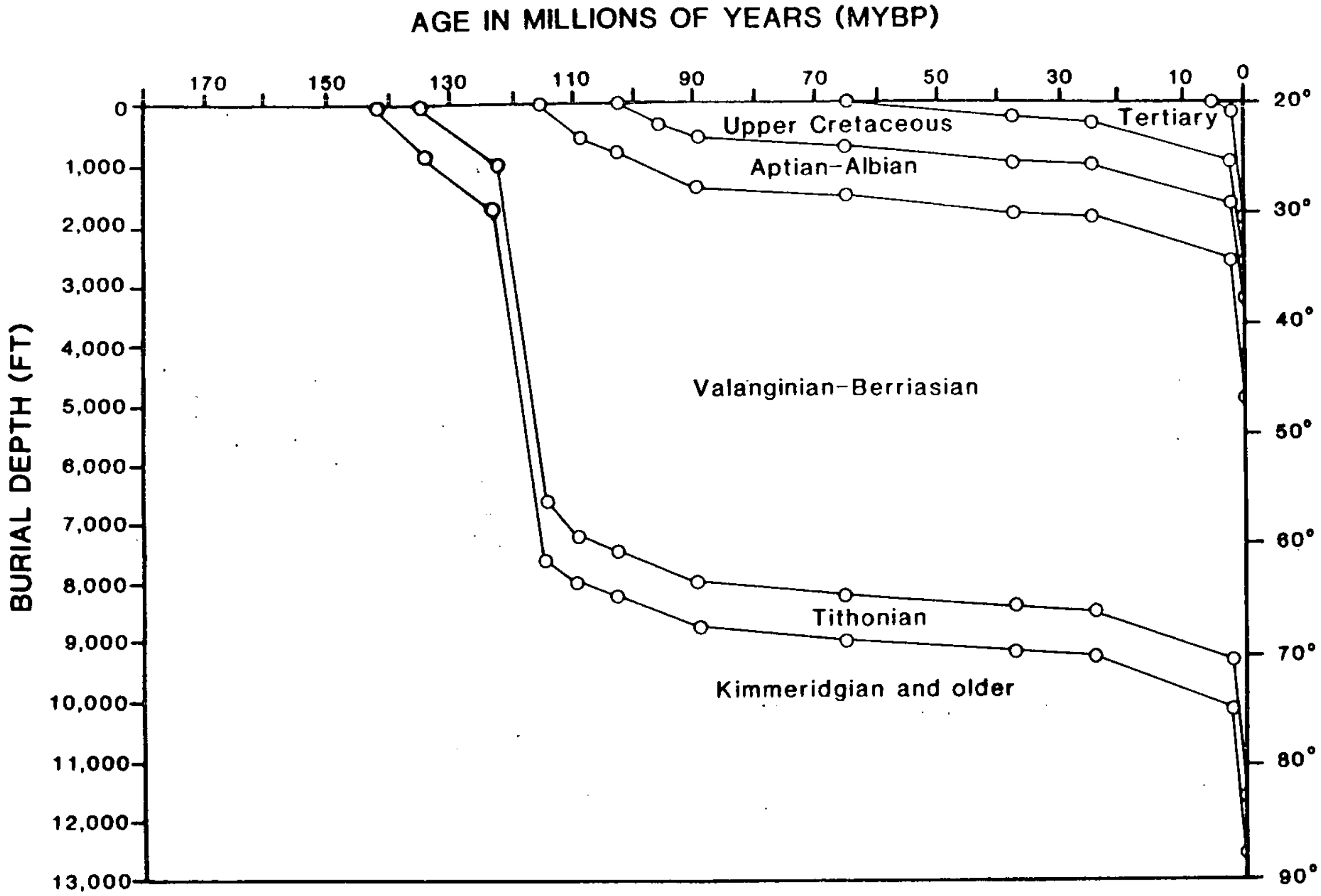


Figure 12.--Time-temperature burial profile for the Shell 93-1 well.

generation has not been reached. The burial model is believed to be influenced by reworked sediments that affect the stratigraphic tops and, hence, could influence the TTI relationships. For the younger, overlying stratigraphic section, however, the time-temperature burial history is clearly inadequate to have generated significant liquids or gases.

GEOTHERMAL GRADIENT

by

Charles E. Fry

Subsurface temperatures recorded in the process of logging a well can be used to estimate the ancient geothermal gradient of a sedimentary basin. Individual temperature logs were not run for the Shell 93-1 well so thermometer readings taken from the electric logs are the only subsurface temperature data. The time between drilling and logging a well is minimized so that thermal equilibrium with the undisturbed formation fluids is usually not established. Consequently, formation temperatures are generally underestimated (Tissot and Welte, 1978).

Bottomhole temperatures were recorded on four electric logs (induction SFL-sonic, continuous dipmeter, simultaneous compensated neutron-litho density, and natural gamma ray spectrometry) at three depths (8,317 feet, 13,640 feet, and 17,740 feet). The temperatures recorded were plotted against the time expired since circulation was stopped (fig. 13). Maximum temperatures, recorded at 8,317 feet (104°F) and 13,640 feet (149°F), were both taken after circulation had stopped for at least 6 hours. The maximum temperature, recorded at 17,740 feet (174°F), was taken after only 10.25 hours after circulation had stopped. The estimated temperature at this depth 28 hours after circulation ceased (thermal equilibrium) is 189°F.

A temperature gradient of 0.98°F/100 feet is calculated using a weighted average of the temperature gradients for the separate intervals between the logging depths and a surface temperature of 65°F. This gradient is somewhat lower than the gradients for other Mid-Atlantic shelf wells, which averaged about 1.2°F/100 feet, but about the same as the gradients calculated for the Shell 586-1, 587-1, and 372-1 wells which were drilled on the slope. Explanations for the lower gradient are (1) the more seaward position of the wedge of sediments penetrated in the Shell 93-1 well relative to the transition crust indicated by the East Coast Magnetic Anomaly (ECMA) and thus a possible lower heat flow; (2) well logging errors in determining the borehole temperatures; (3) possible lower temperatures caused by the circulation of formation fluids removing heat. The increased distance and thickness of the stratigraphic section penetrated in the Shell 93-1 well relative to the transition crust indicated by the ECMA appears to be the most likely reason for the lower gradient.

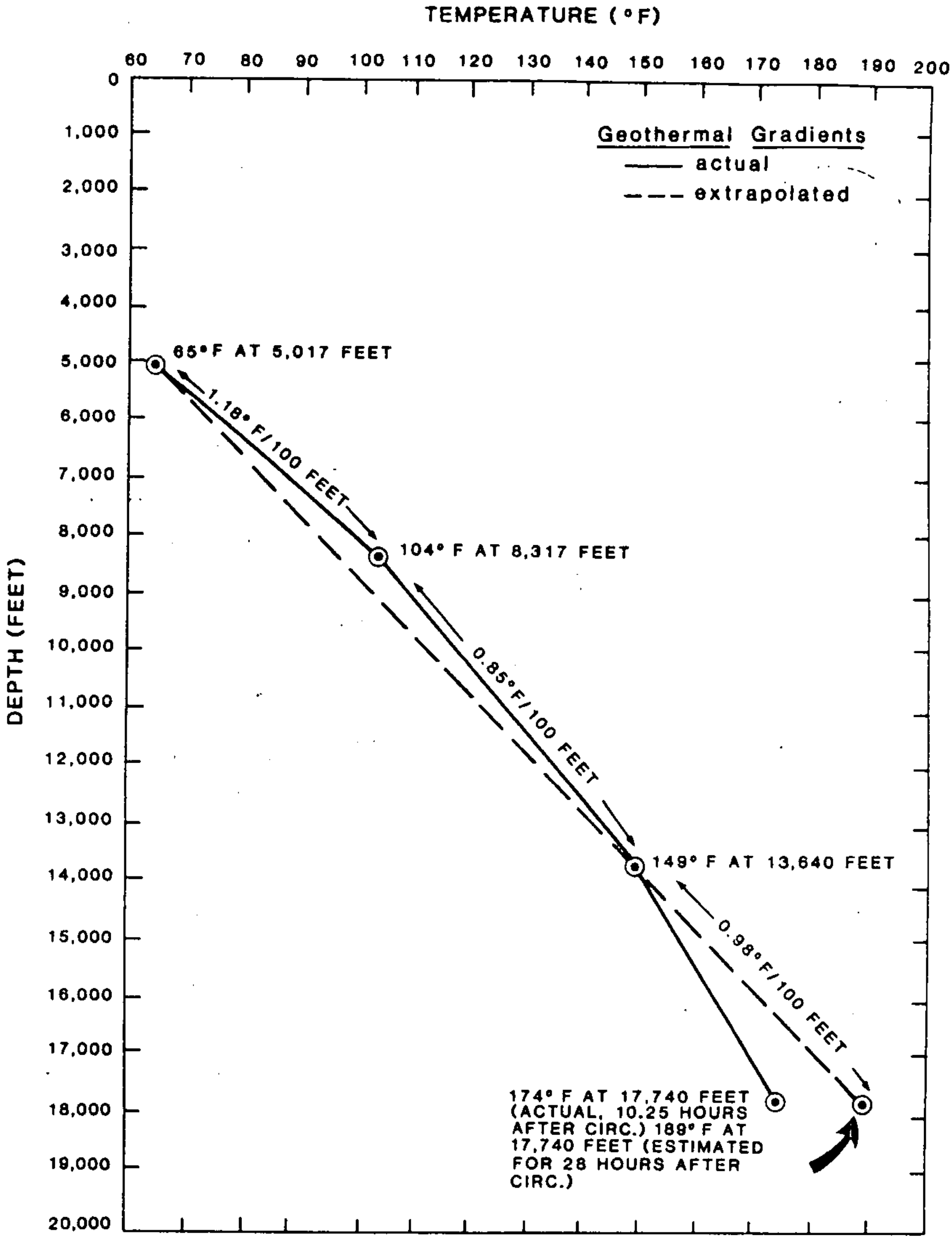


Figure 13.--Graph of temperature measurements for the Shell 93-1 well.

KEROGEN ANALYSIS

by

Charles E. Fry

Kerogen and palynology slides were analyzed to determine the type and thermal rank of the kerogen contained in the cuttings and core samples of the Shell 93-1 well. For this analysis, the insoluble organic material dispersed in sedimentary rock is classified as four major types: Algal, organic material of marine origin, either recognizable algae or its unstructured remains; Herbaceous, leafy portion of terrestrial plants, also including spores and pollen; Woody, plant detritus with a lignified fibrous texture; and Coaly, black opaque material considered to be chemically inert (adapted from Bayliss, 1980; Hunt, 1979). Estimates are made of the percentage of each of these types contained on the kerogen and palynology slides. Algal- and marine-derived kerogen have the best potential for oil and gas generation, depending on temperature and burial conditions. The more structured terrestrial kerogen has less oil generation potential, but can generate gas hydrocarbons at higher temperatures (Tissot and Welte, 1978).

The maturity of the organic material was estimated by comparing the color of various palynomorphs included on the kerogen and palynology slides to a thermal alteration index (TAI) scale (Jones and Edison, 1978). The colors displayed by the organic matter indicate the degree to which the kerogen has been thermally altered (Staplin, 1969). The kerogen type and thermal alteration data complement geochemical analyses in determining whether or not sediments encountered in a well are potential petroleum source rocks. The relationships between TAI, coal rank, and hydrocarbon generation are summarized in figure 14.

Kerogen Type

Samples were not collected from the uppermost 2,096 feet (5,017 feet to 7,113 feet) in the Shell 93-1 well. Quaternary and Tertiary samples (7,113 feet to 8,520 feet) display a moderate to dominantly marine kerogen distribution: 30 to 55 percent algal kerogen, 25 to 35 percent herbaceous, 20 to 30 percent woody and 5 to 10 percent coaly. Figure 15 shows the kerogen type percentages and the TAI for the Shell 93-1 well.

Upper Cretaceous samples (8,520 feet to 9,150 feet) also have a moderately marine distribution: 35 percent algal kerogen, 20 percent herbaceous, 35 percent woody, and 10 percent coaly. The Albian and Aptian sections of the Lower Cretaceous (9,150 feet to 9,820 feet) represent an irregular transition from the moderately marine kerogen population observed in the Upper Cretaceous to a mainly terrestrial distribution. Neocomian samples (9,820 feet to 13,580 feet) continue this terrestrial trend: trace to 5 percent algal kerogen, 20 to 35 percent herbaceous, 35 to 40 percent woody, and 30 to 40 percent coaly. The herbaceous, woody, and coaly kerogen types are evenly distributed in the samples from the interval 13,580 feet to 17,740 feet. Algal kerogen, though observed in every sample, is only present in trace amounts.

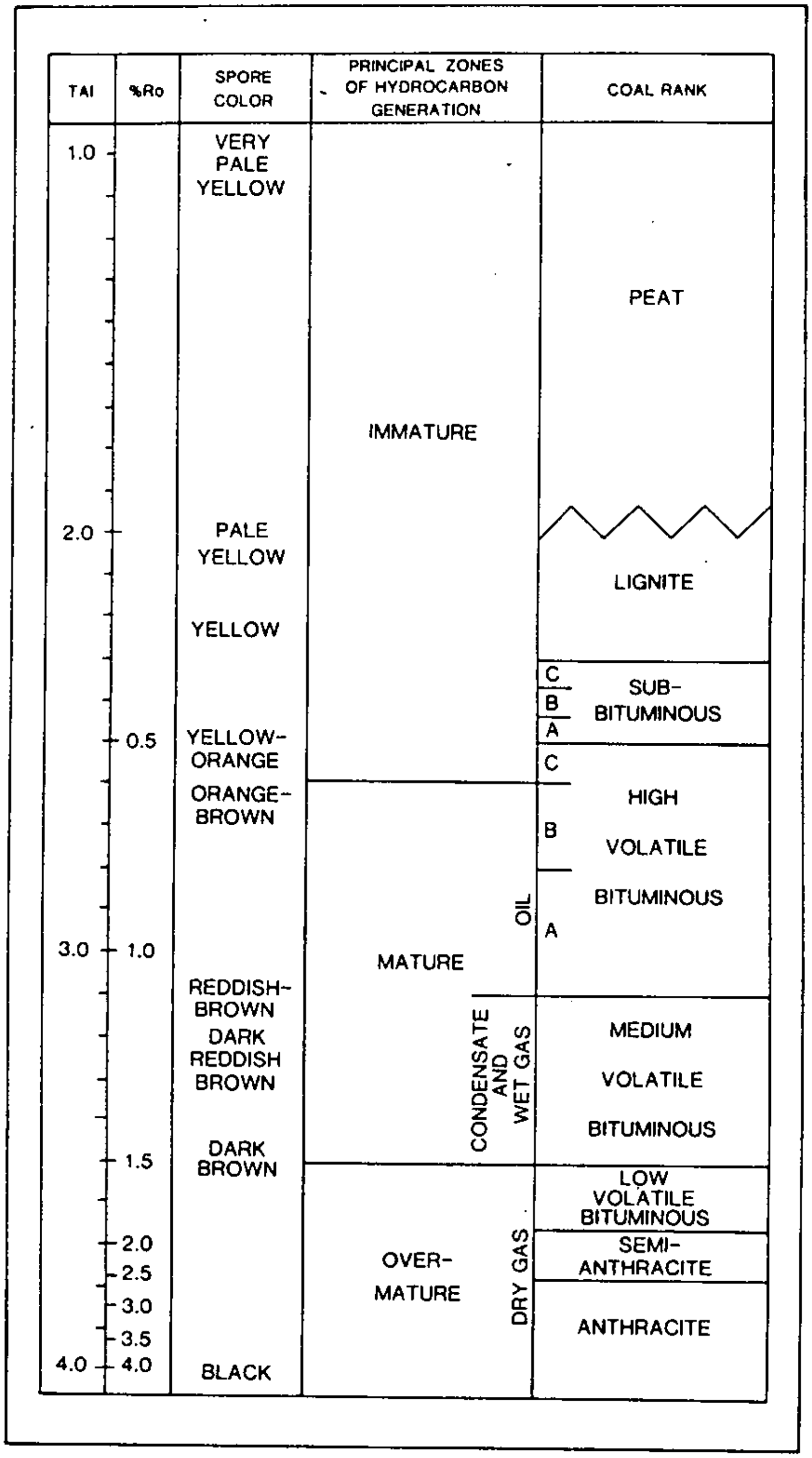


Figure 14.--Relationships among TAI, %Ro, spore color, hydrocarbon generation, and coal rank (after Jones and Edison, 1978).

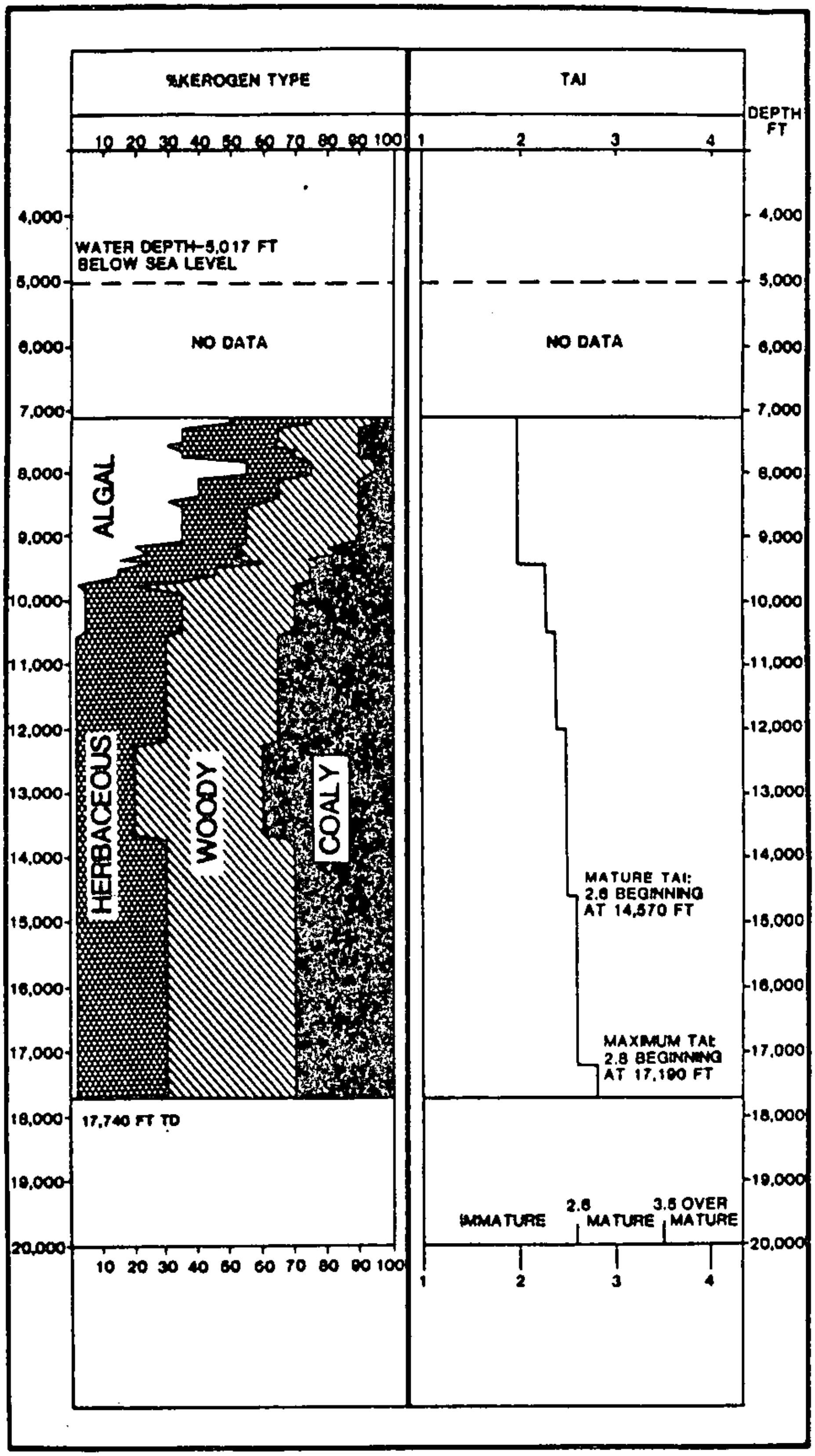


Figure 15.--Kerogen analysis and thermal maturity for the Shell 93-1 well.

In summary, the Tertiary and Upper Cretaceous sections of this well contain significant amounts of marine, oil-prone kerogen. Lower Cretaceous and Jurassic samples contain traces of algal material, but are dominated by the terrestrial kerogen types.

Maturity

Judging thermal maturity from well cuttings must be done with great care to insure that the material being analyzed is indigenous to the level sampled. Caved or reworked material both give false indications of maturity. Oxidation caused by a high energy depositional environment can also alter the appearance of kerogen. TAI values for this well were recorded using palynomorphs considered to be in place.

The thermal maturity of the kerogen analyzed from the Shell 93-1 well was estimated by visual observation of palynomorph color (fig. 15). Amber-brown dinoflagellates were observed in the 14,570 foot sample. This color corresponds to a TAI value of 2.6 which represents borderline maturity. The 17,190 foot sample contains dinoflagellates with a dark orange-brown hue (2.8 TAI). This color indicates a level of alteration just below peak maturity. No other color changes were observed below this sample.

Conclusion

The Tertiary and Upper Cretaceous sections of the Shell 93-1 well contain significant amounts of marine, oil-prone kerogen. A TAI value of 2.0 indicates that this material is immature and would be unlikely to generate notable hydrocarbons by catagenesis. Mature palynomorphs are first observed in the 14,570 foot sample. Darker colored forms occur in the 17,190 foot sample (Berriasian). Although geochemical analyses best define the actual onset of intense hydrocarbon generation, the organic material contained at and below 14,570 feet appears to be mature. The mainly terrestrial kerogen found in the Lower Cretaceous and Jurassic sections of this well is associated with the generation of gas hydrocarbons.

FORMATION EVALUATION

by

Renny R. Nichols

Schlumberger Limited ran the following logs in the Shell 93-1 well (table 3) to provide information for stratigraphic correlation and for evaluation of formation fluids, porosity, and lithology.

Table 3.--Well logs for Shell 93-1 well

Log Type	Depth Interval (feet)
Dual Induction-Spherically Focused with Sonic Log (DISFL)	7,054-17,740
Dual Induction Tool/Long-Spaced Sonic/Gamma Ray Log	9,660-17,740
Lithodensity Tool/Compensated Neutron Tool	9,660-13,627
Natural Gamma Spectroscopy Tool	7,054-13,640
High-Resolution Dipmeter	9,662-13,640
Repeat Formation Tester	7,054-13,132

Exploration Logging, Inc., provided a Formation Evaluation Log ("mud log") which included a rate-of-penetration curve, sample descriptions, and a graphic presentation of any hydrocarbon shows encountered (7,110 to 17,740 feet). In addition, a Drilling Data Pressure Log (7,110 to 17,740 feet), a Pressure Evaluation Log (7,110 to 17,740 feet), and a Temperature Data Log (7,110 to 17,740 feet) were run. Also, the Downhole Logging While Drilling technology was used on this well from 5,350 to 17,694 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 thickness of hydrocarbon-bearing zones, if any. Reservoir rocks with porosities of less than 5 percent were disregarded. A combination of logs was used in the analysis, and detailed lithologic and reservoir property determinations from samples, conventional cores, and sidewall cores were used to substantiate the following estimates listed in table 4.

Table 4.--Well log interpretations (summary)

Depth Interval (feet)	Potential Reservoir (feet)[a]	Porosity (%)	Average Saturation (%)	Thickness of Hydrocarbon Zone (feet)[b]
7,167-7,200	37	35+	70	0
7,248-7,323	75	35+	73	0
7,332-7,510	174	35+	75	0
7,844-7,852	8	35	83	0
8,305-8,318	13	35	75	0
8,570-8,577	7	35	73	0
9,928-9,965	33	29	67	0
10,540-10,553	10	11	71	0
10,723-10,748	8	10	83	0
11,062-11,080	12	10	83	0
11,574-11,598	24	17	88	0
13,097-13,109	12(?)	11	90	0
13,120-13,124	4	9	100	0
15,402-15,413	11	[c] 19(?)	[c] 45(?)	?
15,422-15,430	8	[d] 30(?)	[d] 46(?)	?
17,046-17,058	12	6	100	0
17,262-17,290	12	12(?)	57	0
17,312-17,320	8	6	71	0
17,710-17,740	30	[e] (?)		

a - Generally in beds > 10 feet thick and porosity > 5%.
b - Generally in beds > 10 feet thick, porosity > 5%, and S_W < 50%.
c - Log porosity appears too high, rate of penetration = 10 ft/hr to 30 ft/hr, Core No. 2 (15,406 to 15,419 feet) appears to be hard, dense limestone with very little porosity. Consequently the water saturation is probably too low.
d - Log porosity appears to be too high. Consequently, the water saturation is probably too low. Rate of penetration is approx. 8 ft/hr.
e - Lowest porosity log information commenced above the core No. 3 interval (17,710 to 17,740 feet).

Most of the electric logs were of good quality; however, some difficulties were encountered. A significant baseline shift of the spontaneous potential (SP) curve occurs at 9,000 feet. The last two runs of the DISFL Log have virtually featureless SP curves between 9,660 and 17,730 feet, and there appears to be cycle skipping on the Long-Spaced Sonic Log in the intervals 14,090 to 14,314, 14,816 to 14,846, and 14,970 to 15,036 feet. A caliper curve was not run from 13,628 to 17,730 feet. The sonic log readings are high and seem to be indicating substantial porosity over much of this section in contrast to the cuttings descriptions. This porosity suggests an enlarged borehole with inaccurate sonic log responses. The final logging run was postponed a number of times for clean out trips, washing/reaming, and cleaning/conditioning activities.

Dipmeter

Results of the dipmeter survey were recorded on an arrow plot from 9,662 to 13,640 feet. Possible structural or stratigraphic anomalies may be present at 10,220, 10,280, 10,350, 10,660, 11,280, 11,420, 11,540, 11,580, 11,980, 12,380, 12,450, 12,640, 12,710, 12,880, and 13,020 feet. A summary of the dipmeter analysis is listed in table 5.

Table 5.--Dip direction and magnitude from dipmeter analysis

Interval (feet)	Predominant Direction	Magnitude (degrees)
9,662-10,220	northwest	1-10
10,220-10,360	variable	1-13
10,360-11,440	northwest	1-13
11,440-11,800	south	1-31
11,800-12,060	northwest	1-30
12,060-12,640	northwest	1-18
12,640-12,710	northwest	1-5
12,710-12,820	south	1-9
12,820-13,280	southwest	1-17
13,280-13,624	west	1-33

Shows And Tests

Table 6 lists all shows of hydrocarbon encountered in this well. None of the shows encountered has been judged to be significant. No drill stem tests were run in this well.

Table 6.--Comparison of log and core analyses, Shell 93-1 well

Depth Interval (feet)	Drilling Break (ft/hr)	Sample Description (mud log)	Total Gas b.g	Total Gas int.	Chromato-graph	Cuttings Gas	Sidewall Cores Depth (feet)	Sidewall Cores Ø (percent)	Sidewall Cores K	Sidewall Cores O_p	Sidewall Cores O_b	Sidewall Cores G_b	Porosity Logs Ø (percent)
7,835-7,880	60-70	Sand, hard to unconsolidated	45	345	C_{1-2-3}	100	7,846	30	6	0	0	2	35+
							7,847	30	4	0	0	3	
							7,848	31	4	0	0	2	
8,310-8,340	60-80	Sandstone, hard to unconsolidated	30	40	C_1	30	8,310	33	14	0	0	9	
							8,318	31	40	0	0	12	35
8,640-8,750	60-100	Sand, slightly unconsolidated	12	40	C_1	28		--------no data-------					35
9,935-9,960	40-100	Siltstone, sandy, soft, slightly calcareous	2	2	C_1	1	9,926	25	50	0	0	6	29
							9,931	30	420	0	0	4	
13,120-13,180	10-15	Sandstone, very hard calcareous, and consolidated	3	14	C_{1-2}	12		--------no data-------					9
15,400 15,420	10-30	Sandstone, hard, tr. por., tr. organic matl., slight mineral flu., blue-white cut	2	3	C_{1-2-3}	6		--------no data-------					11
17,240-17,280	8-17	Limestone, hard	3	6	C_{1-2-3}	4		--------no data-------					12(?)

b.g. - background
int. - interval
Ø - porosity
K - permeability in millidarcies
O_p - oil, pore (percent)
O_b - oil, bulk (percent)
G_b - gas, bulk (percent)
$C_{1-2-3-4}$, etc. - carbon chains

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