The Petroleum Potential of the Saba Bank Area, Netherlands Antilles*

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Abstract

Saba Bank is a submerged carbonate bank in the northeastern Caribbean Sea, located five kilometers southwest of the northern Lesser Antilles island of Saba. It is approximately 140 kilometers east-southeast of St. Croix, U.S. Virgin Islands. The bank is an elliptical platform 10 to 100 meters below sea level, covering approximately 2200 square kilometers. Saba Bank is part of the Netherlands Antilles, and petroleum activities on the bank are administered by Saba Bank Petroleum Resources, a company jointly owned by the central government of the Netherlands Antilles and the island governments of Saba, Sint Maarten, and Sint Eustatius.

Saba Bank is a backarc basin on the west side of the northern Lesser Antilles, a slowly moving, active margin island arc on the eastern edge of the Caribbean Plate under which Atlantic oceanic crust is being subducted.

Exploration activities, including the acquisition and interpretation of 4300 kilometers of seismic data and the drilling of two wells in the southeastern part of the bank, have defined a Tertiary basin with over 4000 meters of Recent-Eocene sedimentary fill in the eastern half of the bank and a western shelf with a thin Tertiary section underlain by a thick pre-Eocene (Cretaceous?) sedimentary sequence. The basin and shelf areas are separated by a major wrench fault with associated flower structures.

Saba Bank No. 1 tested a mid-Tertiary reef, 934 meters thick; it contained several porous, permeable intervals, but the only indications of hydrocarbons were minor gas shows. Saba Bank No. 2, on a high deeper in the basin, encountered a turbidite/deepwater fan sequence, instead of the reef. Minor gas shows during drilling and log interpretation indicated the presence of possible gas-bearing reservoirs. Geochemical studies suggest that the hydrocarbons represent migrated hydrocarbon generated from deeper, more mature source rock.

A large four-way dip closed prospect with the potential for substantial hydrocarbon reserves has been developed on the untested western shelf area of Saba Bank.

Introduction

Location

Saba Bank is a shallow-water submerged carbonate bank in the northeast Caribbean Sea five kilometers southwest of the northern Lesser Antilles island of Saba (Figures 1 and 2). It is approximately 140 kilometers east-southeast of St. Croix, U.S. Virgin Islands. As defined on published bathymetric charts, Saba Bank is a submerged elliptical platform, 10 to 100 meters below sea level, that covers approximately 2200 square kilometers (Figure 3). It is about 1000 meters above the sea floor in the vicinity of Saba Island, the only landmass in the immediate area, and is separated from the island by a 700-meter deep trough.

The Saba Bank area is part of the Netherlands Antilles, an autonomous part of the Kingdom of the Netherlands consisting of the Caribbean islands of Bonaire, Curacao, Saba, Sint Maarten and Sint Eustatius. Petroleum activities are administered by Saba Bank Resources N.V., a company jointly owned by the central government of the Netherlands Antilles located on Curacao and the island governments of Saba, Sint Maarten, and Sint Eustatius. For petroleum exploration licensing purposes the Saba Bank Area is divided into forty-three 7’30” x 3’45” blocks.

Exploration History

The presence of a relatively large shallow-water area in a geologically interesting and unexplored region led to at least eleven seismic surveys being conducted in or near the Saba Bank area by various oil companies, government agencies, and academic institutions between 1970 and 1999. Approximately 4300 kilometers of seismic data have been acquired over the Saba Bank area. They include six seismic surveys conducted on or near the Saba Bank area between 1970 and 1974 by United Geophysical (1970 and1971), the USGS (1972 Sparker survey), Weeks Natural Resources (GSI 1973 and CGG 1974) and Shell (1974 reconnaissance north and east of Saba), and four subsequent surveys acquired over Saba Bank by Weeks (1975), Fina Petroleum Sint Maarten N.V. (1980), Aladdin Petroleum Corporation (1988), and Saba Bank Resources (1999).

In December, 1974, Weeks signed an agreement with the Netherlands Antilles Government, which granted Weeks an exclusive seismic option and the right to select seven contiguous blocks of 3' 45" longitude by 7' 30" latitude. GSI subsequently shot a 500-kilometer seismic survey for Weeks in 1975. Weeks then formed an exploration group, which eventually included Amerada Hess, Anadarko, Hamilton Brothers Petroleum, Marathon, and Santa Fe Minerals, with Marathon as the operator.

In December, 1976, the Netherlands Antilles Government enacted a new petroleum law, which created Saba Bank Resources N.V., with the rights to explore and produce petroleum on the Saba Bank. A production sharing agreement between Saba Bank Resources and the Marathon group was signed on December 15, 1976.

The Marathon group spudded Saba Bank No. 1 (**SB-1**) (Figures 4, 5, and 6), the first exploratory well in the Saba Bank area, on April 6, 1977. The well was abandoned as a dry hole with minor gas shows on June 21, 1977, after reaching a total depth of 2974.7 meters. No further exploration was done, and the production sharing contract was terminated at the end of April, 1978.

On July 1, 1979, Saba Bank Resources N.V. granted Weeks Natural Resources an exclusive option to acquire nine contiguous blocks with an obligation to conduct a seismic survey and drill an exploratory well not later than June, 1982. Weeks formed a group with Fina Petroleum and Cities Service, and in January, 1980, the group signed a production sharing agreement with Saba Bank Resources N.V. The contract area was subsequently increased by an additional five blocks. The group, with Fina Petroleum Sint Maarten as operator, conducted a detailed 1708-kilometer, 48 fold seismic survey over the eastern part of Saba Bank (Figure 7), in September, 1980. Arkla Exploration Company acquired a portion of Cities Service's interest in February, 1982. The Fina group spudded the exploratory well SB-2 (**SB-2**) (Figure 7), located 15 kilometers east-northeast of SB-1, on February 22, 1982. It was abandoned as a dry hole with minor gas shows on May 25, 1982, at a total depth of 4231 meters. The group subsequently dropped the block and withdrew from the area.

In January, 1988, Saba Bank Resources N.V. granted Aladdin Petroleum Corporation an option to acquire 14 contiguous blocks with an obligation to conduct a detailed seismic survey over the blocks. During February, 1988, Western Geophysical acquired 343 kilometers of 60 fold seismic data over the western Saba Bank (Figure 8) for Aladdin in fulfillment of the seismic obligation. On October 22, 1988, Aladdin signed a production sharing agreement with Saba Resources N.V. covering 14 contiguous blocks with an obligation to drill one exploration well or re-enter and deepen the Saba Bank No.1 prior to April 28, 1990. Aladdin withdrew from the area at the end of 1990 without completing the drilling obligation.

During December, 1999, Western Geophysical acquired 205 kilometers of 120-fold infill seismic over the southwestern part of the bank on a large previously identified prospect for Saba Bank Resources N.V. (Figures 8 and 9).

Database

The presently available seismic database within the Saba Bank area consists of field tapes of a1708-kilometer 1980 Fina survey, a 343-kilometer 1988 Aladdin survey, and 205 kilometers acquired for Saba Bank Resource in late 1999. Tapes and prints of 60 kilometers of Fina data reprocessed during 1998 and of the entire Aladdin survey reprocessed in 1999 are also available. This new and reprocessed data is also available as a project in GeoQuest and Landmark formats. Paper prints of most of the older vintage seismic lines are also accessible, along with some gravity and magnetic data acquired by Fina during 1980.

Well data for SB-1 SB-2 include wireline log suites, mud logs, and operational reports, as well as various in-house and consulting reports analyzing and interpreting the biostratigraphy and geochemistry of the sediments encountered. Several consultants' reports and accompanying maps describing the prospectivity of the block are also available.

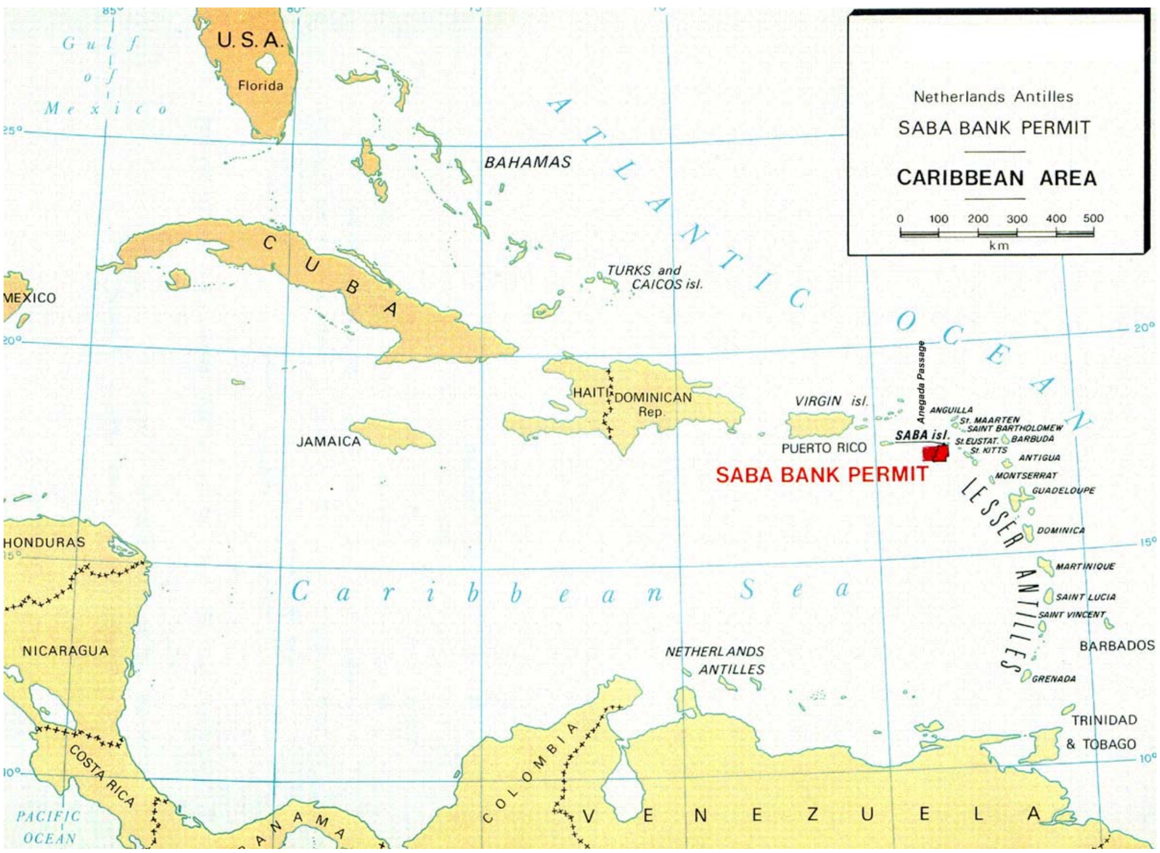

Figure 1. Location of Saba Bank, located in the northeastern Caribbean Sea near the island of Saba at the junction of the Greater Antilles and Lesser Antilles.

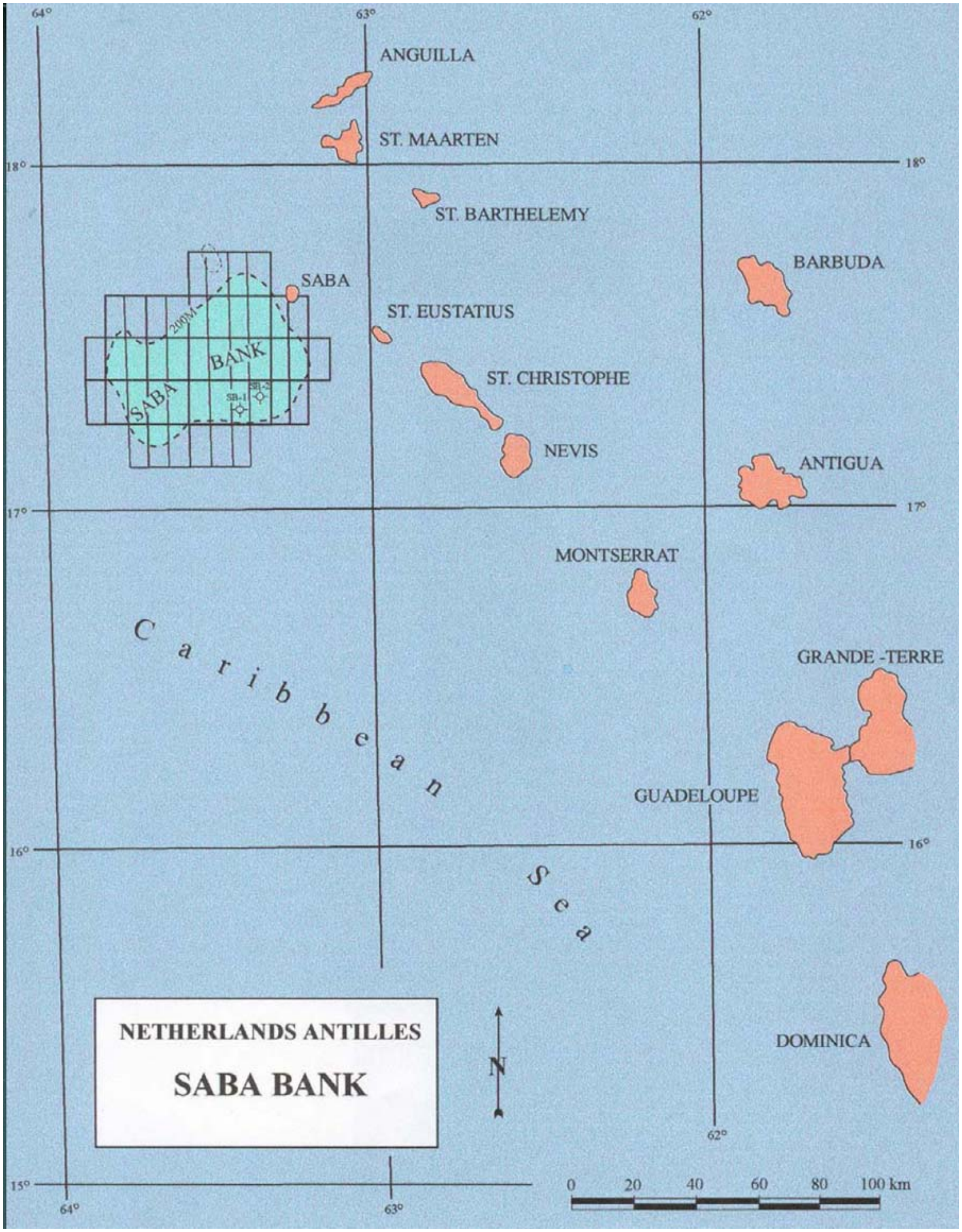

Figure 2. Carbonate bank southwest of Saba, showing area available for exploration licensing. Saba bank is the second largest carbonate bank in the world, approximately 2200 square kilometers in size, lying adjacent to the northern Lesser Antilles island of Saba.

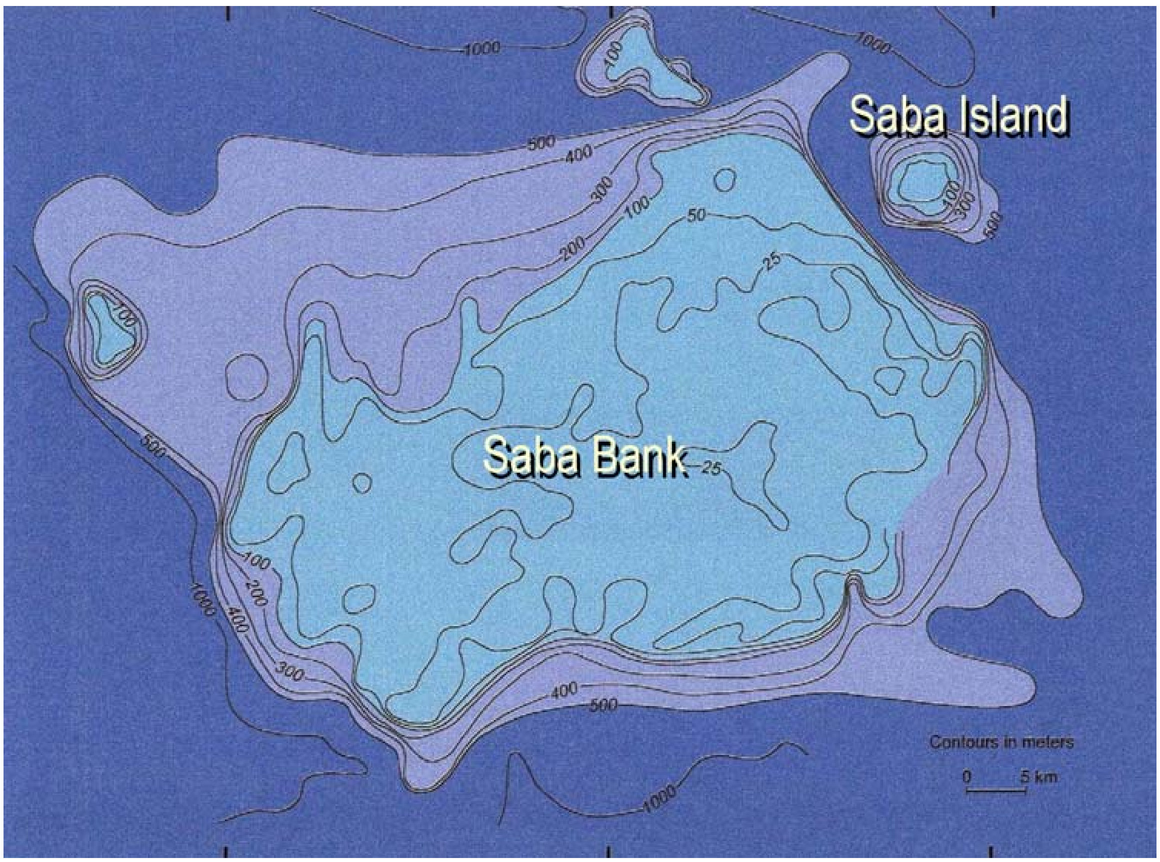

Figure 3. Bathymetric chart of Saba Bank. Water depth on this elliptical platform, ranging from 10 to 100 meters, is generally less than 50m.

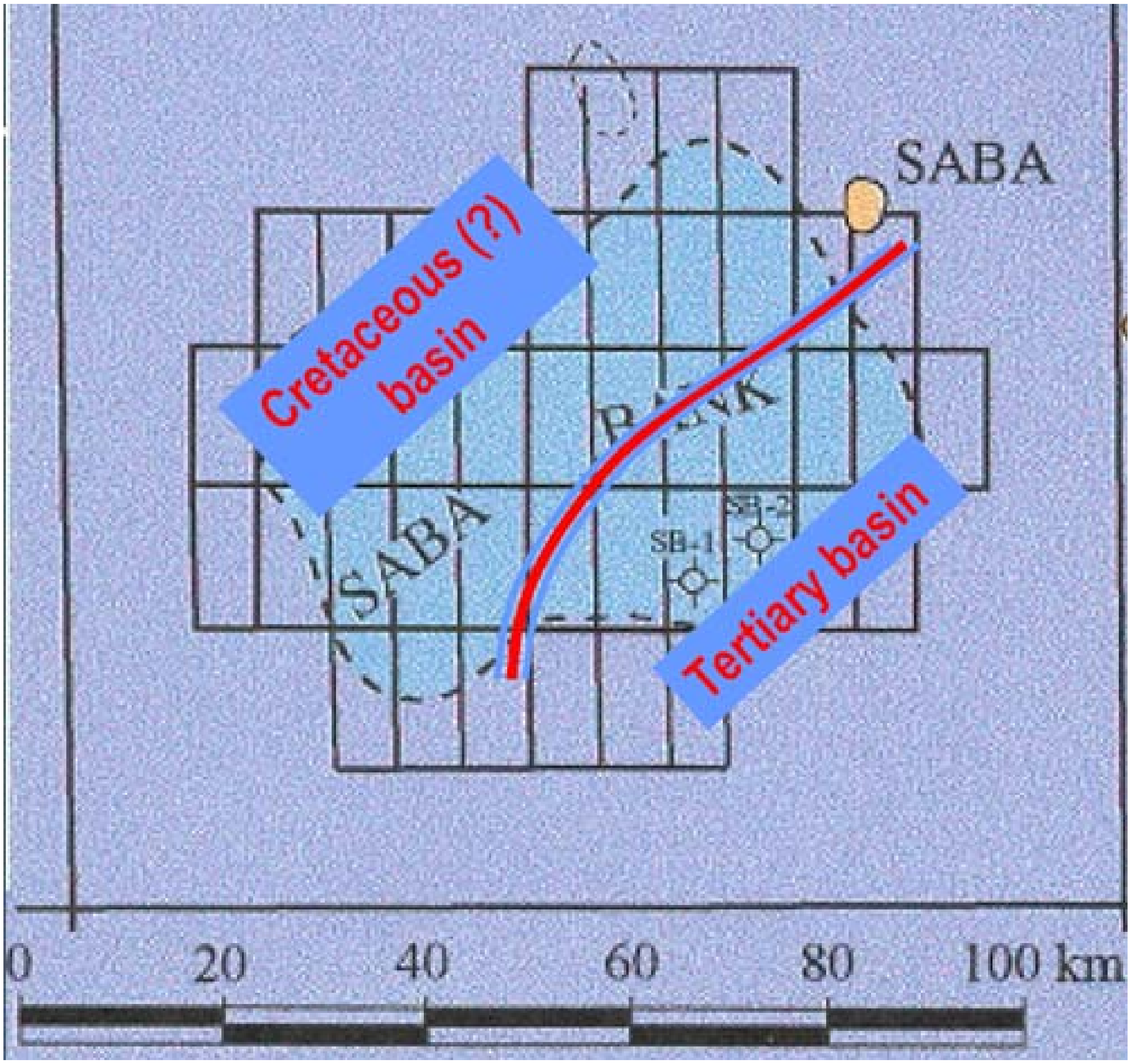

Figure 4. Generalized geologic setting of Saba Bank, showing a Tertiary basin on the east and an older, probably Cretaceous, basin on the west and north, along with locations of the two exploration wells drilled on Saba Bank. Marathon SB-1 was drilled in 1977 to 2975m, and 15 km to the northeast, Fina SB-2 was drilled in 1982 to 4231m.

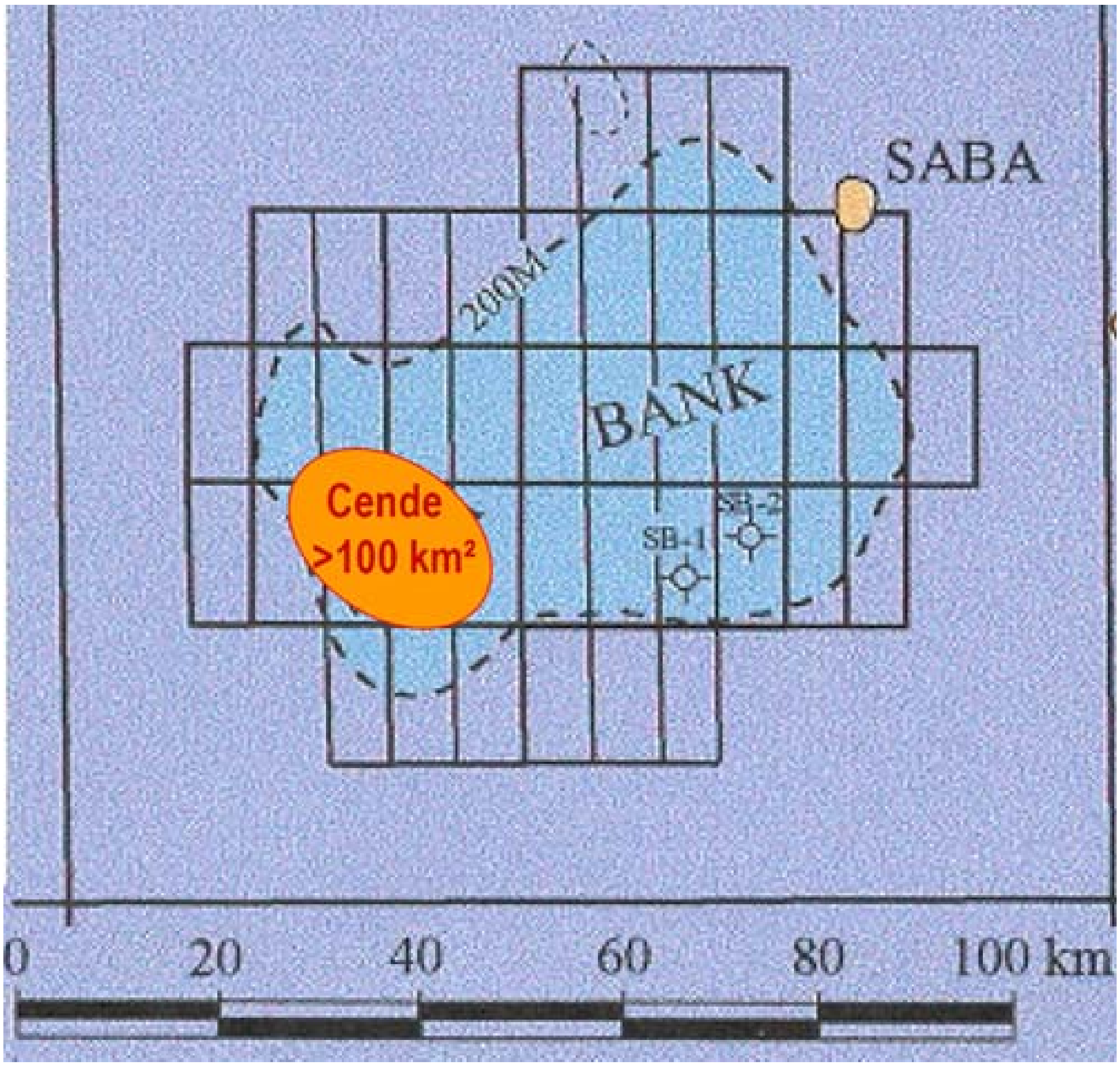

Figure 5. Location of the Cende Prospect in the Cretaceous basin with an area of four-way dip closure that is 100-200 square kilometers.

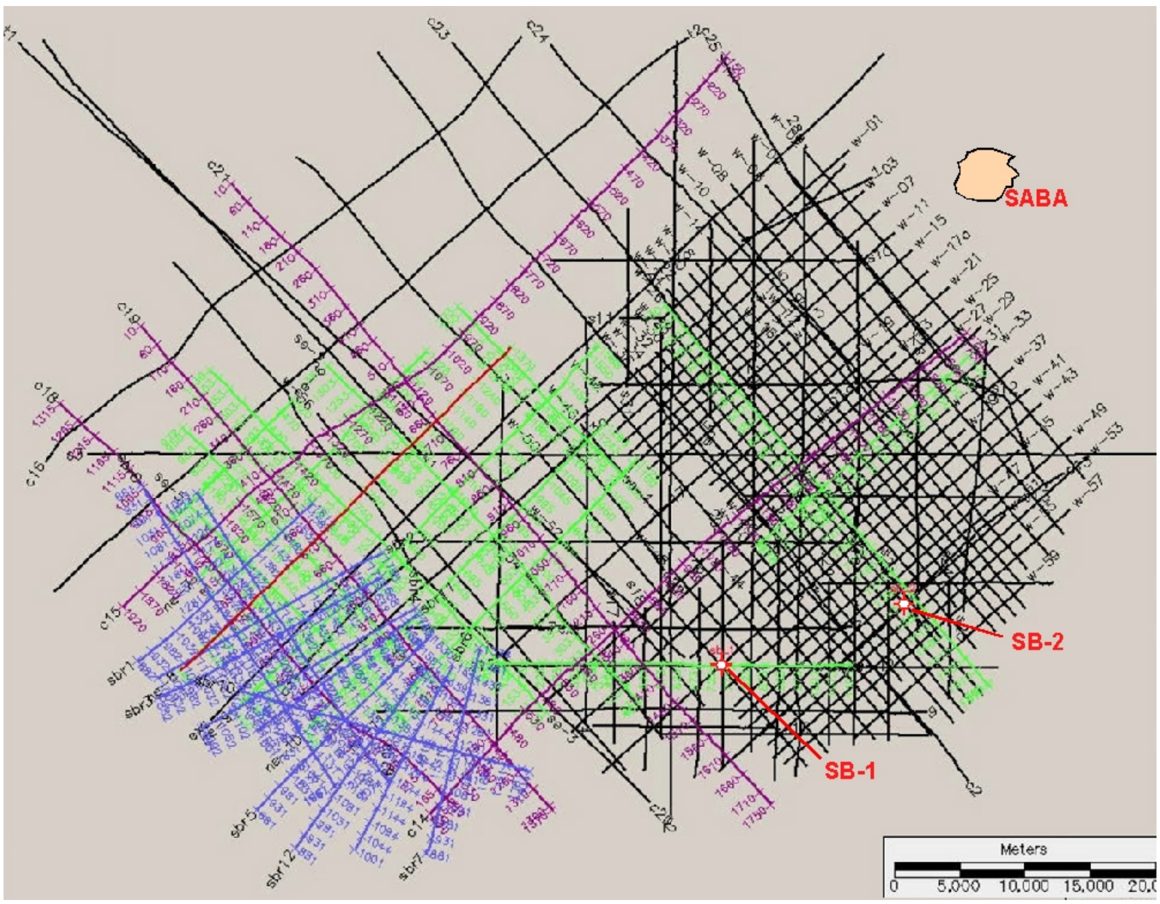

Figure 6. Seismic coverage map. Several vintages of seismic data totaling some 4300km have been acquired in the area.

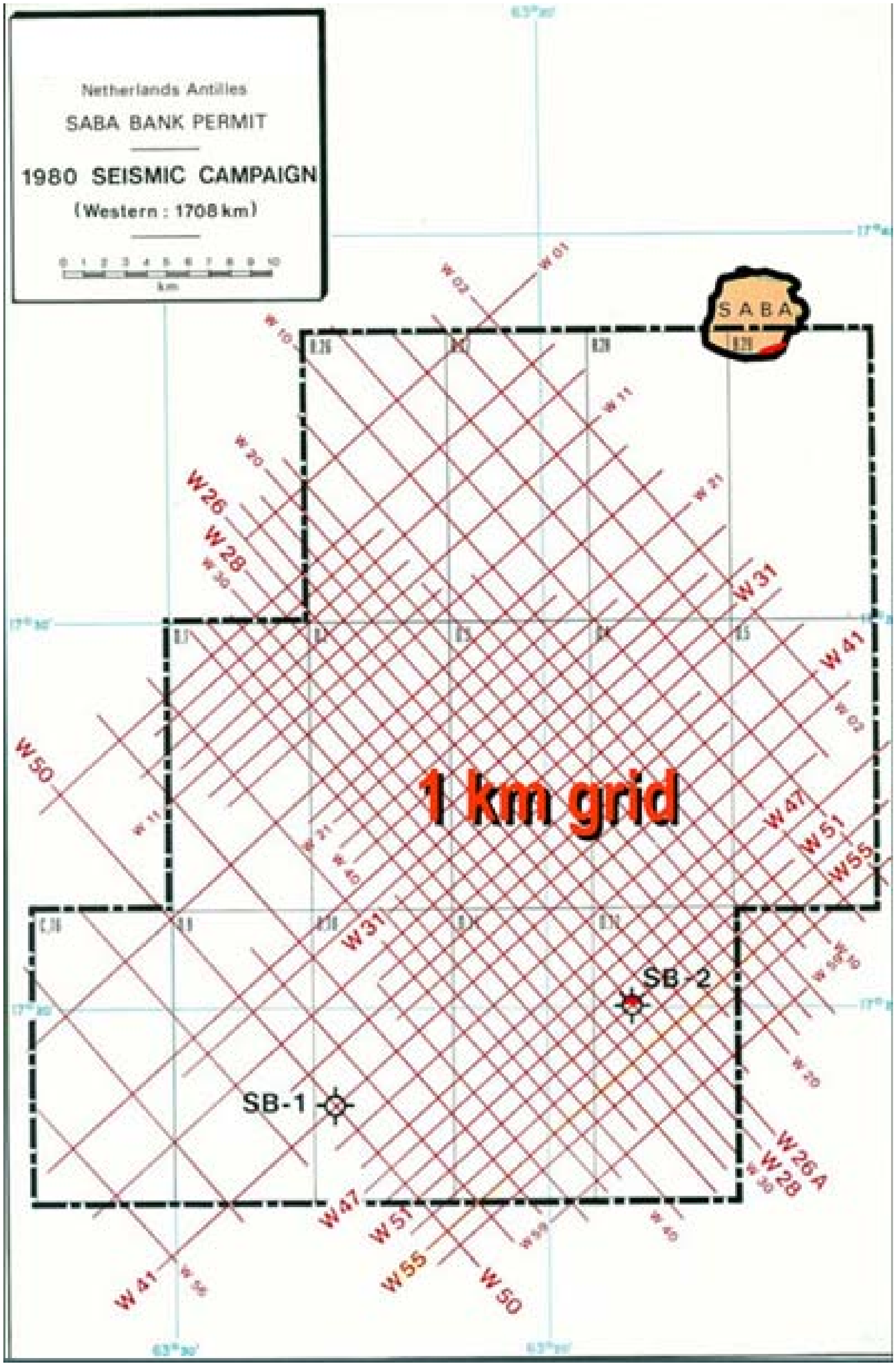

Figure 7. Map of seismic coverage (1708 km) acquired by Fina in 1980 in eastern part of the Saba Bank.

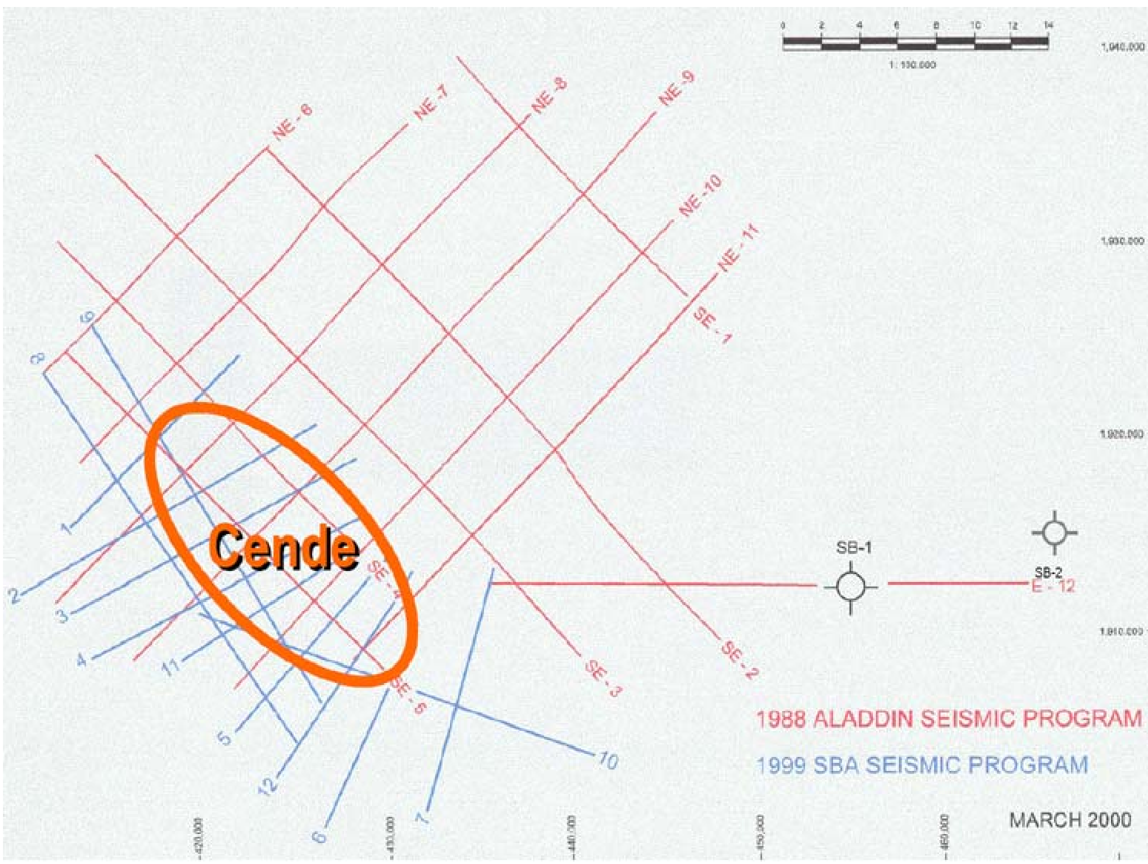

Figure 8. Map of seismic coverage (343 km) acquired by Aladdin in 1988 (in red) and acquired by Saba Bank Resources in 1999-2000 (205 km, in blue) in area of Cende prospect. The 2-D grid over the prospect is generally less than 2 km.

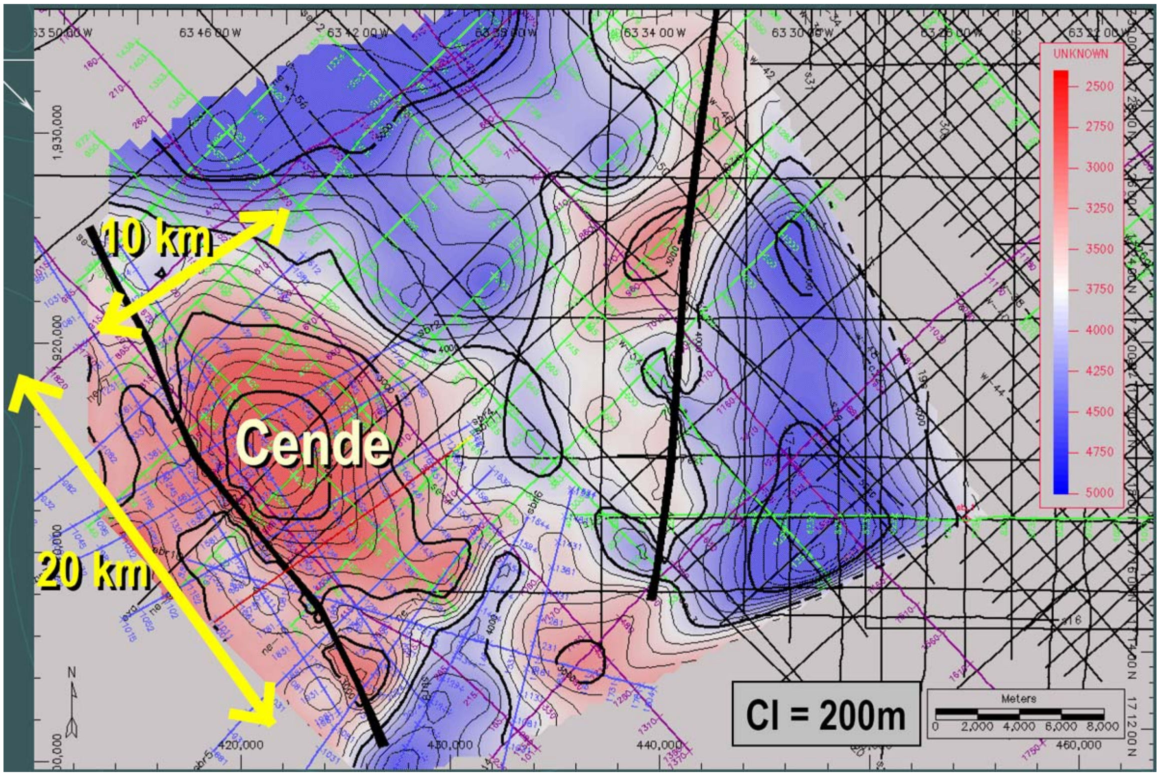

Figure 9. Cretaceous formline depth map, showing closed structure (~20 x 10 km) over Cende prospect.

Geologic Setting

Regional Setting

Saba Bank is a backarc basin on the west side of the northern Lesser Antilles, a slowly moving, active margin island arc on the eastern edge of the Caribbean plate under which Atlantic oceanic crust is being subducted at a rate of about 2.2 centimeters per year.

The present northern Lesser Antilles are formed by a double volcanic arc that coalesces to the south near Martinique (Figures 1, 10, and 11) to form a single row of islands in the southern Lesser Antilles. The islands and islets of the outer arc, often referred to as the "Limestone Caribbees", are composed of middle Eocene to Oligocene volcanics and questionable Miocene intrusives capped with middle Eocene to Pleistocene carbonates (Maury et al, 1990). There are no Neogene volcanic centers in the outer arc. The northern inner arc, often referred to as the "Volcanic Caribbees", is made up of young volcanic islands, including Saba Island, in which volcanism was initiated during latest Miocene or Pliocene and continues today (Figure 11), and by an extinct volcanic ridge extending 120 kilometers northward from Saba Island to the Anegada passage (Figure 1). The two arcs are separated by an intra-arc trough, the Kallinago Depression, which extends from north of Guadeloupe to the Anegada Passage. It varies in depth from 600 meters to about 2000 meters at its north end. The forearc complex of the northern Lesser Antilles near Saba Bank is much narrower than farther south.

Fina's SB-2 encountered nearly 4000 meters of middle Eocene to Recent sediments overlying Eocene andesite. The andesite is approximately the same age as the earliest volcanics identified in the Lesser Antilles outer arc to the northeast. The Tertiary sediments were deposited in a highly asymmetric backarc basin resembling a half graben with the eastern steep basin flank controlled by a large down-to-the-west fault system just west of St. Eustatius. Seismic data indicate the Tertiary section thickens to the southeast into the Grenada Trough, the basin that separates the Antilles Island arc system on the east from the Cretaceous Aves ridge on the west (Figure 11).

Seismic and airborne gravity data indicate the Eocene andesites encountered in both of the Saba Bank wells are underlain by a thick sedimentary section which appears to thicken to the west. Reworked Paleocene spores and Cretaceous coaly material identified in SB-1 indicate that the pre-volcanic section may consist of Paleocene to middle-Eocene-age sediments overlying an Upper Cretaceous and older sedimentary sequence. The presence of sediments that predate the middle Eocene outer Lesser Antilles volcanic arc suggests the Saba Bank area occupied a backarc or interarc position in an older island arc system which may have included Avis Ridge, St Croix, Puerto Rico and Hispanola during Cretaceous and earliest Tertiary time.

Plate Tectonic History

In order to develop a coherent geologic model for Saba Bank it is necessary to examine the geologic history of the northern Lesser Antilles within the framework of the tectonic development of the Caribbean Plate. Within the last decade a number of syntheses for the plate tectonic history of the Caribbean have been published. While there remain numerous unresolved details, there appears to be general agreement among the leading researchers for a plate history involving a single Great Caribbean island arc system (Burke, 1988), also referred to as a continuous Mesozoic Arc (Bouysse, 1988), which was initiated in the Pacific during Cretaceous time and migrated into the Atlantic.

The Caribbean did not exist prior to the Late Triassic-Jurassic breakup of the Pangean supercontinent. By Early Cretaceous time a Proto-Caribbean Ocean had developed with oceanic crust being created along northeast-trending spreading axes as North America, South America and Africa drifted apart. A Proto-Greater Antilles island arc formed in the Pacific Ocean at the eastern edge of the Farallon plate subduction zone in the widening gap between North and South America. The polarity of the subduction zone beneath the Proto-Greater Antilles island arc changed from east-dipping to west-dipping as the Farallon Plate began to intrude between North and South America. The Proto-Caribbean oceanic crust was subducted beneath the Greater Antilles island arc as the plate moved eastward. By Late Cretaceous (Campanian) time Cuba, Puerto Rico, and Aves Ridge (including the Saba Bank area) formed the eastward advancing active island arc (Figure10). The Caribbean Plate continued to advance to the northeast during the

Paleocene. The Grenada Basin began to form at this time, probably by backarc spreading. By middle Eocene time it was probably fully opened, and the Aves Ridge was no longer part of the active island arc. During the remainder of the Cenozoic, the Lesser Antilles formed the eastward-migrating volcanic island arc along which the Atlantic oceanic crust was being subducted.

Today the Lesser Antilles remains a slowly moving active margin island arc on the eastern edge of the Caribbean plate (Figure 11). Because of the low rate of convergence, volcanism and seismic activity are presently relatively subdued (Bouysse, 1984).

Within the framework of the overall plate tectonic history, the Lesser Antilles have experienced a complex history which is not well understood, but they have probably been part of an active volcanic arc since Early Cretaceous time (Bouysse, 1988). Their pre-middle Eocene history is not well known because of lack of outcrops. The oldest known rocks are uppermost Jurassic to Lower Cretaceous volcanics reported from La Desirade Island; they may represent early stages in the development of the Great Arc. Upper Cretaceous volcanics have been dredged from the midslope of the Anguilla and Antigua platforms and Cretaceous granodiorite and volcanic fragments have been dredged from the Aves Swell. Other pre-middle Eocene data are limited, but the Lesser Antilles were probably part of an arc system that included what is now the Aves Swell as well as the Greater Antilles until mid-Eocene time when the Grenada basin formed and left the Aves Swell as an inactive remnant arc west of the Cenozoic Lesser Antilles volcanic island arc. At about the same time the Lesser Antilles volcanic arc was separated from the Greater Antilles arc.

As noted earlier, the present northern Lesser Antilles are a double volcanic arc composed of an inactive Eocene-Oligocene outer arc formed by the islands and islets of Marie-Galante, Grande-Terre of Guadeloupe, Antigua, St. Barthelemy, St. Maarten, Tintamarre, Anguilla, Dog and Sombrero, and an active Neogene inner arc consisting of the islands of Dominica, les Saintes, Basse-Terre of Guadeloupe, Montserrat, Redonda, Nevis, St. Kitts, St. Eustatius, and Saba. It has been suggested that this westward shift of magmatism to the northern Volcanic Caribbees during the latest Miocene or Pliocene was induced by the subduction of ridges that flank old transform faults in the Atlantic oceanic crust (Bouysse, 1984; Westbrook and McCann, 1986). This may have produced a flattening of the angle of subduction of the lithosphere because of the buoyant effect of the ridges, or a narrowing of the forearc by displacement/erosion of part of the forearc by the ridges.

Paleogeographic Evolution

Saba Bank presently is a backarc basin on the west side of the active northern Volcanic Caribbes island arc platform. Data from SB-1 and SB-2 along with records from several seismic acquisition programs give the most complete record of the post-Late Eocene geology in the northern Lesser Antilles from which to interpret the local paleogeography. Seismic records over the Bank show that there is a significant pre-late Eocene stratigraphic sequence present, which, on regional considerations, may include Upper

Cretaceous to middle Eocene sediments, but there is little direct evidence to describe the pre-late Eocene paleogeography of Saba Bank.

Late Cretaceous

As noted in the section of plate tectonic history, Jurassic to Lower Cretaceous volcanic units have been identified on La Deseride Island, and Upper Cretaceous volcanic rocks have been dredged from steep escarpments located east of Antigua, Barbuda and Anguilla, and from the Aves Swell. They strongly suggest that both the northern Lesser Antilles and the Aves Swell were part of a Mesozoic volcanic island arc that was initiated in the Pacific and was intruding into the Caribbean by Late Cretaceous time (Figure 10). The southern Lesser Antilles volcanic arc may not have existed prior to the Eocene so that by Late Cretaceous time the northern Lesser Antilles-Aves Ridge volcanic arc was impinging on the northwest margin of South America (Figure 10).

While the stratigraphic evidence necessary to define the paleogeography of Saba Bank during Late Cretaceous time is sparse, scattered dredge hauls suggest extensive shallow-water platform areas were present within the volcanic island arc. Dredging along the northern slope of the Anguilla platform during the French Arcante 3 cruise recovered volcanic tuffs and marls from depths between 4100 and 2500 meters containing radiolarians and also planktonic foraminifera and nannofossils with a Late Cretaceous age range of 86 to 65 Ma. Some reworking of neritic biogenic components appears to have occurred, indicating the existence of a shallow platform at that time. An Arcante 3 dredge haul from the northern part of the Aves Swell (Loro Seamount) recovered Upper Cretaceous shallow-water tuffaceous limestones. Bouysse et al (1985) conclude from dredging results, bathymetric mapping, and seismic surveys that the numerous seamounts and ridges present on the Aves Swell are the remnants of volcanic islands in the Cretaceous volcanic island arc. Pindell's (1991) model for the formation of the Grenada Basin (Figure 11) places Saba Bank in a backarc position.

St. Croix Island, 150 kilometers to the west-northwest of Saba Bank, has over 10,000 meters of strongly deformed Upper Cretaceous deepwater calcareous turbidites and volcaniclastics. They were deposited in a deep-water basin from a northerly volcanic arc source and appear to be unrelated to Upper Cretaceous sediments of the Aves Swell/Lesser Antilles island arc.

Analyses of kerogens in SB-1 by Marathon revealed considerable reworked Cretaceous coaly material in the upper Eocene-middle Miocene volcaniclastic sequence. The character of the material indicates it was sourced from an exposed Cretaceous deltaic source that had undergone considerably less deformation than the St. Croix section. Robertson Research reported reworked Cretaceous calcareous nannofossils from the equivalent, but deeper water section in SB-2. The relationship of Saba Bank -1 and SB-2 suggests the Late Cretaceous sediment source was to the west or northwest of the wells.

Paleocene

The only known outcrop of Paleocene rocks in the Lesser Antilles is on Anguilla island where uppermost Danian to Thanetian pelagic marly limestones and black shales completely devoid of volcanic elements crop out at Crocus Bay. They indicate that a pause in volcanic activity occurred approximately between 65 and 58 Ma; i.e., during most of Paleocene time. The lack of volcanism is probably related to the opening of the Grenada Basin during the Paleocene by backarc spreading. Some authors, in studies of backarc spreading in the western Pacific arc-backarc complex, have suggested that periods of backarc spreading are accompanied by a marked weakening or by quiescence of arc volcanism.

Dredge hauls east of Grande-Terre de Guadeloupe and west of Sombrero Island recovered Paleocene to Eocene platform limestones and shallow-marine limestone and greywacke, respectively. DSDP holes 30 and 148 drilled on the Aves Swell recovered reworked Paleocene microfauna. Reworked Paleocene spores were also found in a sidewall sample from 2795 meters in SB-1.

With no apparent volcanic activity during the Paleocene and only the very limited geologic data described above we can only speculate that the Aves Swell/Lesser Antilles area was a dormant island arc magmatic platform with eroding island landmasses surrounded by inter-island carbonate platforms and deeper basins. Plate II is a representation of what the paleogeography of Saba Bank and the northern Lesser Antilles may have been like during the late Paleocene

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Middle-Late Eocene

Outcrops on the islands of the Limestone Caribbees, extensive dredge hauls, and the results of SB-1 and SB-2 provide considerably more data from middle Eocene and younger rocks than is available for the older section. During middle and late Eocene time most of Saba Bank area was located on a backarc carbonate platform. The southeastern part of the bank was in deeper water of the northern end of the backarc Grenada Basin. Dredge hauls from the Aves Swell indicate Saba Bank formed part of what was a much more extensive shallow-marine backarc platform or series of inter-island platforms developed on the flanks of and over the tops of the extinct Cretaceous volcanic islands, perhaps similarly to those presently surrounding the Limestone Caribbees. By early Eocene time volcanic activity had been initiated in the Lesser Antilles outer volcanic island arc well to the east of Saba Bank at St. Maarten Island, and by the middle Eocene, St. Barthelemy Island was also the site of shallow submarine volcanism. Volcanic activity appears to have increased during the late Eocene with Anguilla, Dog, and Sombrero Islands probably also sites of active volcanism.

SB-1 encountered a thick mid- to late Eocene reefal carbonate unit that grew on a shallow-marine carbonate shelf. SB-2, drilled to the east-northeast off the shelf edge, encountered neritic to bathyal slope submarine sands, pelagic shales, and fine-grained turbidites in the equivalent section. They were deposited in the northernmost part of the

Grenada Basin. The carbonate and clastic sections can be correlated to the middle part of the Point-Blanche Formation on St. Maarten.

Oligocene

Volcanic activity continued in the Lesser Antilles outer arc during early Oligocene time. St. Maarten, St. Barthelemy, and Antigua were all sites of volcanism in the northern Lesser Antilles, and Martinique and the Grenadines were active in the southern Lesser Antilles. Volcanism ceased in the northern Lesser Antilles in mid-Oligocene time (30 Ma) and did not resume until the late Miocene (10 Ma) when it shifted to the Inner Arc. A volcaniclastic section was deposited in the eastern Saba Bank area in an inner shelf to upper slope environment. The sands and silts encountered in both SB-1 and SB-2 form an eastward prograding fluvial deltaic sequence containing significant quantities of volcanoclastic material. At SB-2, turbidites were initially deposited in a fore-reef trough which the fluvial deltaic system eventually prograded across. The previously noted reworked Cretaceous coaly material in both SB-1 and SB-2, and reworked Paleocene spores in SB-1 indicate erosion of exposed older rocks to the west or northwest of the wells, possibly from the western part of Saba Bank and adjacent areas.

Other than Oligocene corals and limestones recovered in a dredge haul southeast of Aves Island, there are very little Oligocene data available for Aves Swell. It was the site of extensive late Eocene and early Miocene shallow-marine carbonate platform deposition, and there is no reason to believe that conditions were any different during the intervening Oligocene.

Early Miocene

There is no evidence of volcanic activity in the northern Lesser Antilles outer arc during early Miocene time, but volcanism continued in Martinique and other islands in the southern part of the arc. Dredging results on the northern outer arc magmatic platform indicate deeper water conditions, with pelagic marls and tuffs being widely deposited. Shallow-water carbonates may have been developed on the platforms of the dormant volcanoes.

Deposition of the fluvial deltaic volcaniclastic sequence continued on the eastern Saba Bank, while erosion of older sediments probably continued on the western part of the bank and adjoining areas to the west or northwest. Dredging results indicate shallow to open marine carbonate deposition continued on the Aves Swell.

Late Miocene-Pliocene

The inner volcanic arc of the northern Lesser Antilles developed during late Miocene-Pliocene, and parts of it have remained active during historic time. An intra-arc basin, the Kallinago Depression, developed to the east of the northern volcanic arc, between it and the now inactive outer arc. Westward tilting of the northern Lesser Antilles magmatic arc complex occurred during mid-Miocene, resulting in major subsidence on the Aves Swell.

The westward tilting was also responsible for subsidence of the Saba Bank and adjacent areas that had been a source of clastic sediments during the Oligocene and early Miocene. Saba Bank became the site of carbonate deposition that kept pace with the rate of subsidence so that it remained a shallow-water carbonate platform while deeper water pelagic clays, mudstones and calcareous oozes were deposited on the Aves Swell.

Large shallow-marine carbonate platforms developed on the northern Lesser Antilles magmatic arc around the extinct volcanoes, which probably provided limited sources for volcaniclastic sediments. Deeper water pelagic marls and tuffaceous marls were deposited in the interplatform area and between the volcanic islands of the active inner arc.

Structure

Saba Bank is a highly asymmetric backarc basin on the west side of the slowly moving Lesser Antilles island arc. It is essentially a half graben with the eastern steep basin flank controlled by a large down-to-the-west normal fault system just west of St Eustatius (Figure 1).

A major northeast-trending, down-to-the-southeast fault divides Saba Bank into a western platform area characterized by a thin Tertiary section unconformably overlying a thick pre-Eocene (Cretaceous?) sequence and an eastern area with a thick Tertiary sedimentary section overlying Eocene volcanics and an older (Cretaceous?) sequence (see Figure 24). The Tertiary section in the eastern area thickens to the southeast into the Genada Trough. Reworked Late Cretaceous kerogen in SB-1 indicates the down-to-the southeast fault has been active since at least late Eocene time. Interpretation of the seismic data reprocessed during 1999 clearly shows a complexly faulted flower structure indicating that at least the latest movement on the fault has been wrenching and that significant lateral movement may have occurred.

Angular unconformities seen on the reprocessed seismic data show that the area west of the flower structure (the “western block”) was uplifted and eroded at least twice prior to deposition of the middle Miocene-upper Pliocene Upper Carbonate Unit. The detailed pre-Eocene structural history is obscure, but it is apparent that a large fault block developed in the southwestern corner of the Bank. That corner of the fault block was tilted upward and was eroded to form an almost flat surface. The western and southwestern edges of the western block are controlled by a large down-to-the-west fault.

The structure of the eastern Tertiary basin fill is typical of a subsiding shelf-shelf edge trough with numerous down-to-the-basin and antithetic normal faults. The structure of the pre-Eocene is obscured by its greater depth and the presence of a volcanic section, but the reprocessed data indicate extensive half grabens and tilted fault blocks are present in what appears to be a continuation of the thick pre-Eocene section to the west.

Stratigraphy

SB-1 and SB-2 encountered a thick Tertiary sedimentary section composed of carbonate and clastic sequences with some pyroclastic intercalations resting on porphyritic andesite. In each of the wells the section overlying the andesites has been divided into three major stratigraphic units (Figures 12, 13, 14, 15 16, and 17). They are: an Upper Carbonate Unit, a Fluvio-Deltaic (Fina) or Volcaniclastic Unit (Marathon), and a Lower Carbonate Unit in SB-1 and its Channel-Turbidite Unit equivalent in SB-2.

Analyses of seismic data after the drilling of the two wells indicate a thick sedimentary section is present beneath the andesites. A number of seismic lines have fair to good quality reflections below the volcanics with dips that are unconformable with the overlying sequences (see Figure 26). According to Warner et al. (1989), a depth interpretation of airborne magnetic data flown by Aladdin Petroleum Corporation over the SB-2 location during 1982 indicates basement is between 6100 and 6700 meters below sea bottom; correspondingly, there is a 1500- to 2400-meter sedimentary section below the andesite at that location. Seismic data indicate the pre-volcanic sediments may thicken to the west.

The stratigraphy of the post-volcanic units has been summarized by Robertson Research (1984), a summary of which is presented below.

Upper Carbonate Unit (e.g., Figures 14, 16)

The uppermost unit encountered in SB-1 is an 1110-meter carbonate sequence composed of translucent to pale yellow, crystalline to micro- crystalline limestones with sugary texture, and white bioclatic limestone with micritic cement. The lower portion of the unit is more argillaceous and contains cryptocrystalline light green limestones and light brown, hard, brittle microcrystalline sucrosic dolomites. Fossils are abundant throughout the unit with numerous shell and coral fragments, algae, and foraminifera. Porosity generally varies from 10 - 25 percent.

SB-2 well encountered a thicker Upper Carbonate Unit (1429 meters) with similar lithology. Lost circulation was common while drilling the Upper Carbonate Unit. As a consequence, no samples were recovered from the lowermost part of the unit in either well, and its lower boundary is placed from wireline log and seismic data.

Planktonic foraminifera give a middle Miocene to early Pliocene age for the Upper Carbonate Unit. The fossil data indicate deposition at shallow depths within a reef complex that was dominated by lithothaminoid algae throughout most of its development.

The Upper Carbonate Unit is at least in part equivalent to the Kingshill Limestone that crops out on St. Croix Island and is similar to limestones of the same age exposed on St. Maarten, St. Barthelemy, and Anguilla Islands.

Fluvial-Deltaic Unit (Volcaniclastic Middle Series) (e.g., Figures 14, 16)

SB-1 encountered a 755-meter clastic sequence immediately beneath the Upper Carbonate Unit. It consists primarily of interbedded siltstones, claystones, and tuffaceous, very fine grained to silty sandstones with conglomerates and rare thin marine limestones. Marathon referred to this sequence as the Volcaniclastic Series. The sandstones and some conglomerates have fair to excellent porosity. Foraminiferal assemblages indicate an inner shelf environment down to a depth of 1554 meters.

The interval between 1554 meters and 1920 meters is mostly mudstone with interbedded siltstone, some fine-grained sandstones, and rare thin limestones. The mudstones contain foraminiferal assemblages indicating initial deposition in an upper slope environment that shallowed with time to outer, and then inner shelf environments. The volcaniclastic series has been age-dated as late Eocene to middle Miocene.

SB-2 encountered a 1486-meter sequence of fluvial-deltaic sediments beneath the Upper Carbonate Unit, which Fina named the Fluvial-Delta Sequence. Robertson Research (1984) has divided the unit into two sections as follows:

The Upper Section (1480-2256 meters) is mainly composed of dark green, firm claystones grading to pale green, slightly calcareous siltstones, with some beds of white silty limestones and red to brown claystones, in the upper part. The unit becomes increasingly sandy with depth.

Microfossils are rare at the top of the interval where very poor assemblages of benthonic rotalid foraminifera occur. Below 1770 meters *Miogypsina, Elphidium,*and a few ostracods are recognized. The unit ranges in age from late Oligocene to early Miocene. The sediments were deposited in an inner neritic environment.

On the basis of log correlation, seismic reflections,and age control, this upper section in SB-2 has been correlated with a series of tuffaceous claystones containing thin calcareous intercalations, sandstones, and sandy conglomerates encountered from 1167 to 1562 meters in SB-1; it was also deposited in an inner neritic environment.

In the Lower Section (2256-2967 meters), the lithology from the top down to 2930 meters is quite similar to the overlying section, except that it is less sandy and siltstones become more abundant. Some patches of black organic matter are also present. Seismically, the Lower Section is characterized by southeasterly prograding sequences.

A middle to late Oligocene age has been assigned to this section based mainly on good calcareous nannofossil assemblages. Benthonic foraminifera indicate an open marine, probably middle neritic environment was predominant, but the intermittent occurrence of nannofossils also suggests fluctuating conditions. This sequence in SB-2 is tentatively correlated with the section of interbedded claystones and tuffaceous, very fine grained to silty sandstones encountered in SB-1 from 1556-1685 meters, where slightly shallower inner to middle neritic conditions are indicated.

Lower Carbonate Unit (Figure 14)

SB-1 encountered a thick carbonate unit beneath the Volcaniclastic Series (at 1922 meters), which Marathon referred to as the Lower Carbonate Unit. Labofina S.A. describes the 934-meter Lower Carbonate Unit as alternations of micritic to microsparitic limestone, dense to slightly porous, containing bioclasts; biomicrites and biosparites to biomicrosparites, locally recrystallized, having very good vuggy and intergranular porosity; and thin clayey laminations. Poorly sorted, bioclastic fractions composed mainly of very abundant debris of encrusting coralline algae do not exceed 50%. Large sized bioclastic debris is mainly coral encrusted by coralline algae, which are abundant and present everywhere in this unit. Less numerous are echinoderm debris, echinoid spines, pelecypods, microgastropods, ostracods, and foraminifera.

Study of conventional core material, sidewall cores and wireline logs indicate substantial intervals of porous and permeable rock with porosities from 11 to 25%.

The Lower Carbonate unit is separated from the underlying volcanic sequence by a 12-meter weathered zone of undetermined age. Based on the predominant larger benthonic foraminifera assemblages, the age of the Lower Carbonate Unit was determined to be middle to late Eocene and is partially time-equivalent to a silty section drilled in SB-2 from 3367 to 4032 meters.

A shallow, shelf marine environment is indicated for the Lower Carbonate Unit. The presence of reef building organisms such as coralline algae and corals, associated with large benthic foraminifera, indicates a reef facies. However, the common presence in cores of algal grains rather than large crusting or branching colonies may suggest a back reef shelf environment.

Channel-Turbidite Unit (Figure 16)

SB-2 did not encounter the Lower Carbonate Unit beneath the Fluvial-Delta unit as expected, but instead penetrated a 1065-meter clastic unit which Fina termed the Turbidite Sequence and which Robertson Research has named the Channel-Turbidite Unit. They divided it into two sections as follows:

The Upper Section (2967-3367 meters) of the Channel-Turbidite Unit is a thick series of siltstones, claystones, and clayey siltstones. An age from late Eocene to early Oligocene has been assigned this section even though the position of the Oligocene/Eocene boundary cannot be precisely defined.

In SB-1, a late Eocene to early Oligocene age has also been assigned to the interval between 1685 meters and the top of the Lower Carbonate Unit. This interval consists mostly of claystones with some interbedded, very fine-grained sandstones. The sequence has also been interpreted as having been deposited in a shallowing-upward, middle neritic to upper bathyal environment. As in SB-2, the section is characterized by an increase of planktonic foraminifera with depth. It is considered the equivalent of the Upper Channel-Turbidite Unit in SB-2 (see Figure 24).

The Lower Section (3367-4032 meters) is primarily a sequence of silty claystones and argillaceous siltstones. Several sandstones with low to moderate porosity were reported between 3829 and 3840 meters and between 3937 and 3969 meters. They represent the only significant reservoir development in this unit.

Sedimentological evidence from cores at 3421-3428 and 3786-3795 meters strongly suggests the presence of an outer submarine fan sequence with pelagic shales and fine-grained turbidites. The sandstones and siltstones are usually graded.

Planktonic foraminifera and calcareous nannofossils date the unit as not older than late Eocene. Foraminiferal faunas indicate deposition in an outer neritic to bathyal slope environment. The top of this section in SB-2 is considered the time equivalent of the top of the Lower Carbonate sequence in SB-1. The base of the unit is separated from the volcanic unit by a 57-meter interval of either weathered volcanic rock or sedimentary rocks containing abundant volcanic fragments. According to Robertson Research, the lower section of the Channel-Turbidite Unit and the SB-1 Lower Carbonate Unit can be correlated with the upper Eocene Point-Blanche Formation that is exposed on St. Maarten Island.

Volcanic Unit (Figures 14, 16)

SB-1 encountered a volcanic unit from 2856 to 2975 meters (T.D.). As described from a conventional core at the base of the drilled section, the rock is a gray-green andesite porphyritic unit with dark green millimetric phenocrysts, euhedral to subhedral hornblende and indistinct white battens of plagioclases, coated in a microlitic goundmass composed primarily of plagioclases. Streaks of hematite and small millimetric accumulations of pyrite are scattered in the rock. Potassium/Argon radiometric dating of hornblende by Geochron USA for Marathon dated the andesite encountered at 2865 meters in SB-1 as 64.5 Ma, or earliest Paleocene.

SB-2 also penetrated an andesite. The top of the unit is somewhat ambiguous, but Fina picked it at 4032 meters on a velocity increase on the sonic log. However, gamma ray readings increase sharply at 3974 meters and remain high to 4032 meters. The lithology of the 3975-4032-meter interval could be either weathered volcanic rocks or sedimentary rocks containing frequent to abundant volcanic fragments. The volcanic section continues to 4231 meters (T.D.). According to Robertson Research (1984), the andesites in the two wells are probably equivalent even though some macroscopic differences are evident in cores as well as in microscopic studies and laboratory analyses. Whole rock Potassium /Argon dating by Robertson Research determined the age of the andesite encountered at 3927 meters in SB-2 to be 38.4 Ma. The Universite Libre de Bruxelles dated samples supplied by Fina of the SB-2 andesite as 34.4 Ma and the SB-1 andesite as 37.3 Ma using the Potassium/Argon whole rock method. With a margin of error of 3.7 to 1.4 m.y., the dates are all late Eocene.

Marathon interpreted the andesite in SB-1 as a near surface intrusion and/or part of a volcanic feeder system. Neither well penetrated the base of the andesite, but seismic data strongly suggest the presence of a thick sedimentary section beneath the volcanic unit. Thus it is unlikely the andesite originated as oceanic crust. It is more likely related to a regional magmatic pulse. Igneous rocks outcropping on St. Maarten Island have been dated from 28 to 32 Ma.

Pre-Volcanic Sequence (Figures 14, 16, and 17)

The age of the pre-volcanic sequence is uncertain. Marathon dated the andesite encountered at 2865 meters in SB-1 as earliest Paleocene. The radiometric analyses Fina had done on both the SB-1 and SB-2 andesites dates both rock units as late Eocene. If the age dating done for Fina is correct, the pre-volcanic section could consist of Paleocene to middle Eocene age sediments overlying Upper Cretaceous and older sediments.

During the Late Cretaceous, Saba Bank is thought to have occupied a backarc position on the Aves Swell volcanic arc that was part of the Greater Antilles volcanic arc that also included Cuba, Hispanola, Puerto Rico, and St. Croix Island. As noted earlier, scattered dredge hauls over the Aves Swell suggest extensive shallow-water platform areas were present during the Late Cretaceous. St. Croix Island has over 10,000 meters of strongly deformed Upper Cretaceous calcareous turbidites and volcaniclastics that were deposited in a deep-water basin and appear to be unrelated to the Upper Cretaceous sediments of the Aves Swell. Puerto Rico also has thick sequences of Cretaceous and Early Tertiary volcanic, volcaniclastic and calcareous rocks. The strata include shales, sandstones, and rare limestones deposited as turbidites, shelf sediments, and reefs, suggesting the magmatic arc platform was topographically complex.

Analyses of kerogens in SB-1 by Marathon revealed considerable reworked Cretaceous coaly material in the upper Eocene-middle Miocene volcaniclasitic sequence. The character of the material indicates it was sourced from exposed deltaic sediments. Thermal maturation indices within the oil window indicate the deltaic rocks have undergone considerably less deformation than the St. Croix sequence. Marathon biostratigraphic studies also report the presence of reworked Cretaceous fossils in the Tertiary volcaniclastic section, and Robertson Research found similar reworked Cretaceous fossils in SB-2. The relationship of the two wells along with dipmeter data from SB-2 indicate the exposed Cretaceous deltaic sequence supplying sediments to the volcaniclastic sequence was located to the west or northwest of the wells, possibly in the western Saba Bank platform area.

The sediment source for the indicated Cretaceous deltaic sediments may have been the southern Yucatan block with which the Greater Antilles arc collided during Late Cretaceous time (Figure 10).

It is possible that the Saba Bank pre-volcanic sequence also contains Paleocene sediments. Reworked Paleocene spores were found in a sidewall sample from 2795 meters in SB-1. Bouysse (1988) reports the presence of Paleocene (uppermost Danian to Thantian) pelagic marly limestones and black shales completely devoid of volcanics on Anguilla Island. As noted in the section on paleogeography, dredge hauls in the Lesser Antilles have recovered Paleocene shallow-marine limestone and greywacke while DSDP holes 30 and 148 drilled on the Aves Swell recovered reworked Paleocene microfauna. Because of the probable exposure of Cretaceous sediments to the west, Paleocene sediments, if present, would probably be limited to the eastern part of Saba Bank.

Figure 10. Caribbean Plate in Late Cretaceous, when Saba Bank lay in a backarc position, east of known Cretaceous basins and north of the Aves Ridge (after Montgomery and Pessagno, 1999).

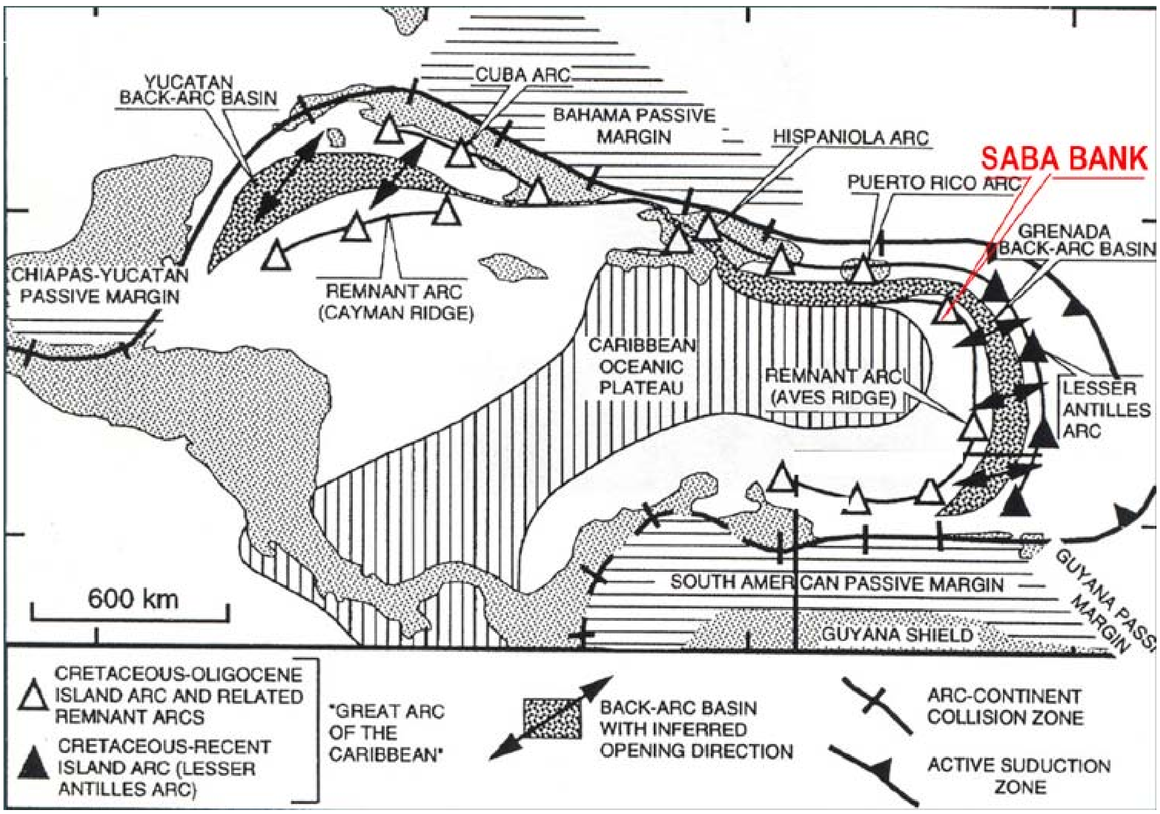


Figure 11. Caribbean Plate at present, with the backarc Saba Bank behind a slowly-moving active-margin-island arc on the eastern edge of the Caribbean Plate, under which Atlantic oceanic crust is being subducted (after Babb and Mann, 1999).

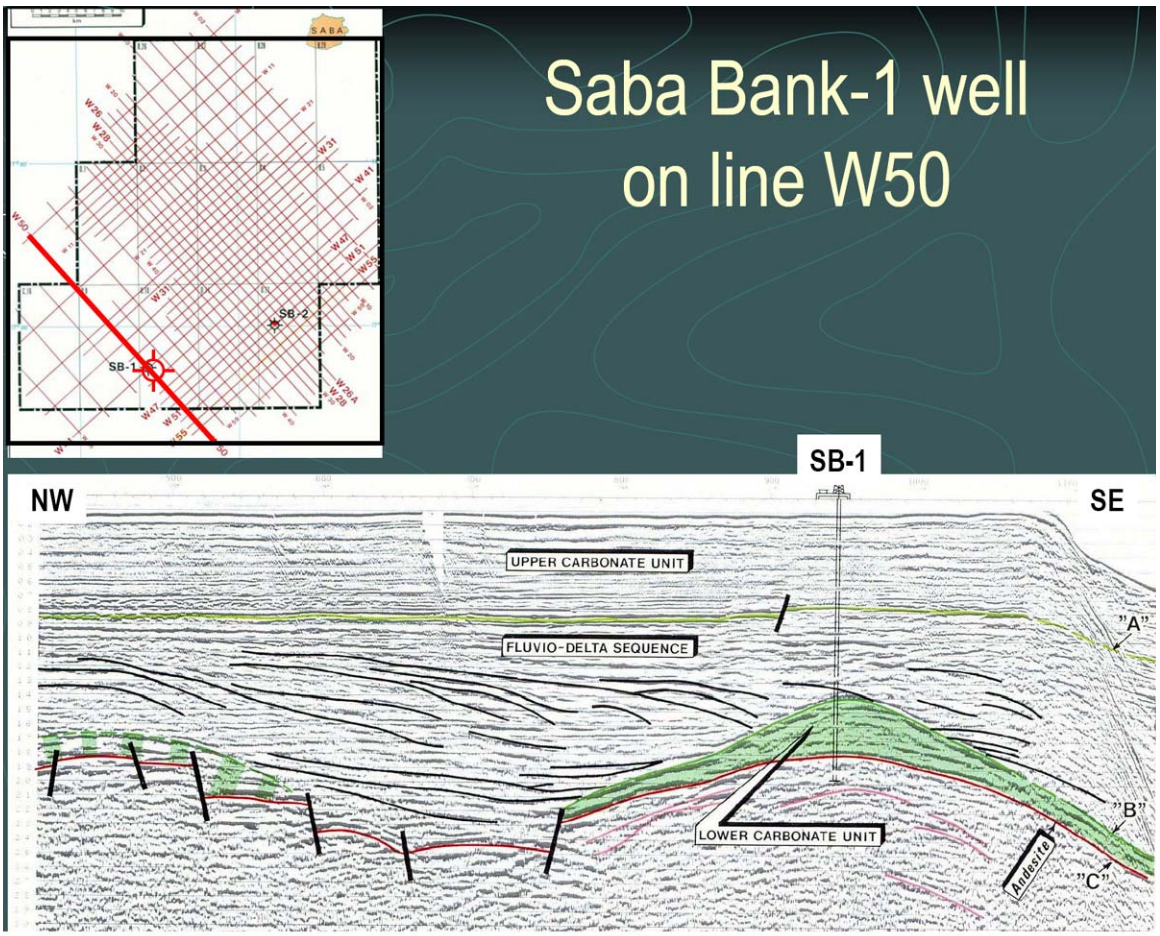


Figure 12. Stratigraphic section, as shown on dip-oriented seismic line W50 and in well SB-1, with an Upper Carbonate Unit overlying a Fluvio-delta Sequence that onlaps, abuts, and overlies a Lower Carbonate Unit, which in turn overlies andesite.

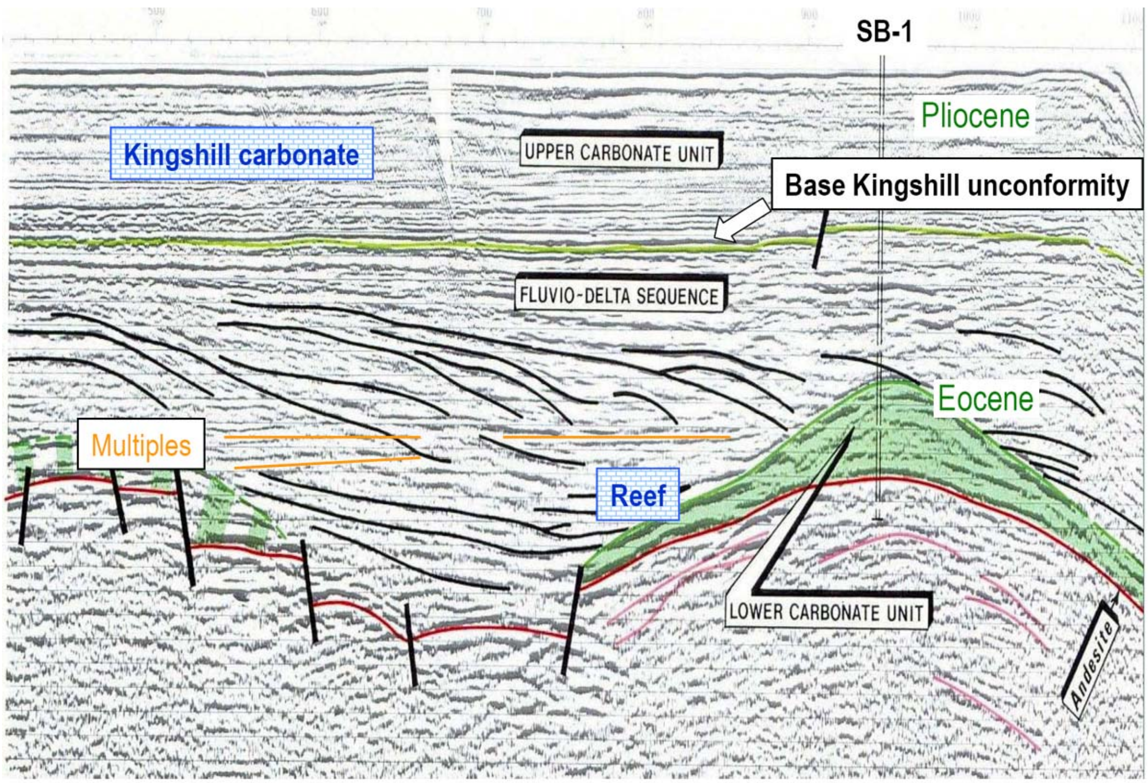


Figure 13. Seismic line W-50 and SB-1, showing Fina-designated ages of the Upper Carbonate Unit, or Kingshill Carbonate (Pliocene) and the Fluvio-deltaic Sequence (Eocene to Pliocene), along with base Kingshill unconformity. The Lower Carbonate Unit is regarded as reefal.

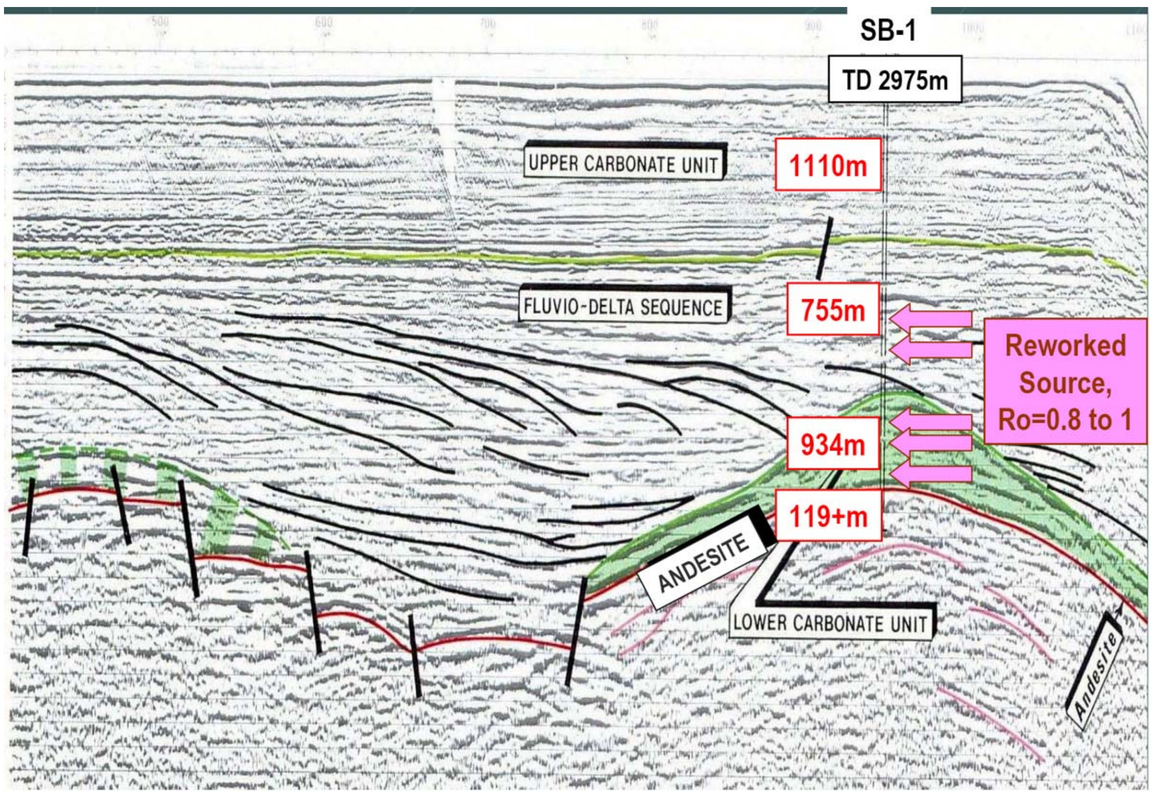


Figure 14. Well SB-1 on seismic line W-50, with positions of source-rock samples. The organic matter, considered reworked Cretaceous material, is oil-mature (Ro=0.8-1.0).

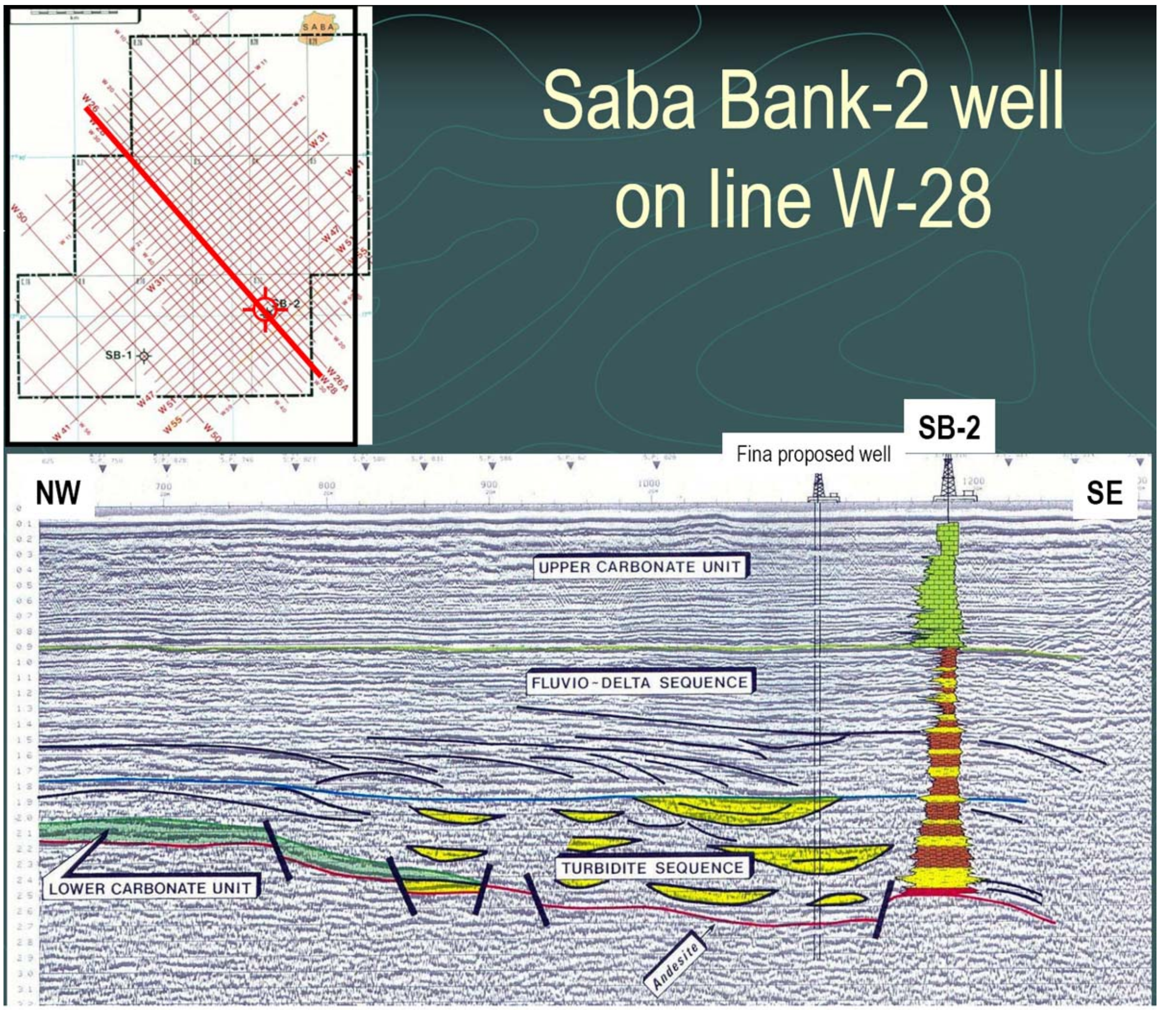


Figure 15. Seismic line W-28 and well SB-2, showing four major units above the andesite—Upper Carbonate Unit, Fluvio-delta Sequence, Turbidite Sequence, and Lower Carbonate Unit.

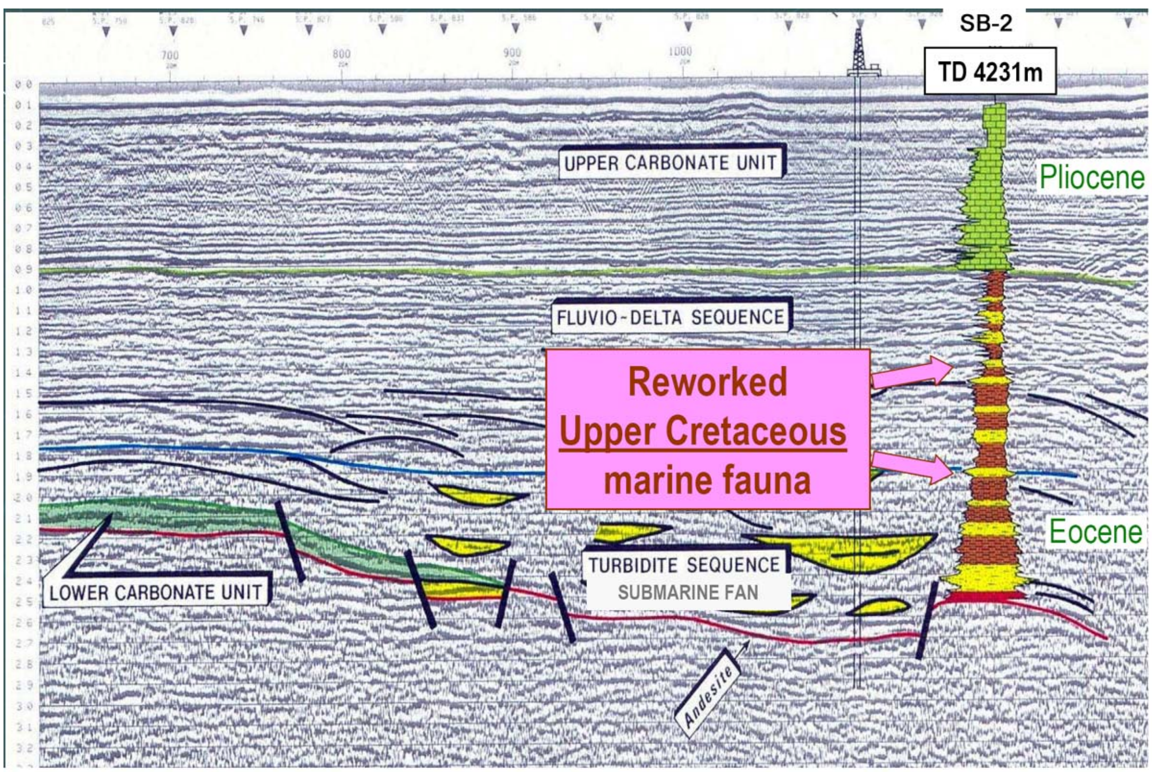


Figure 16. Seismic line W-28 and well SB-2, showing Fina-designated ages and positions in the well of reworked Late Cretaceous marine fauna (calcareous nannofossils).

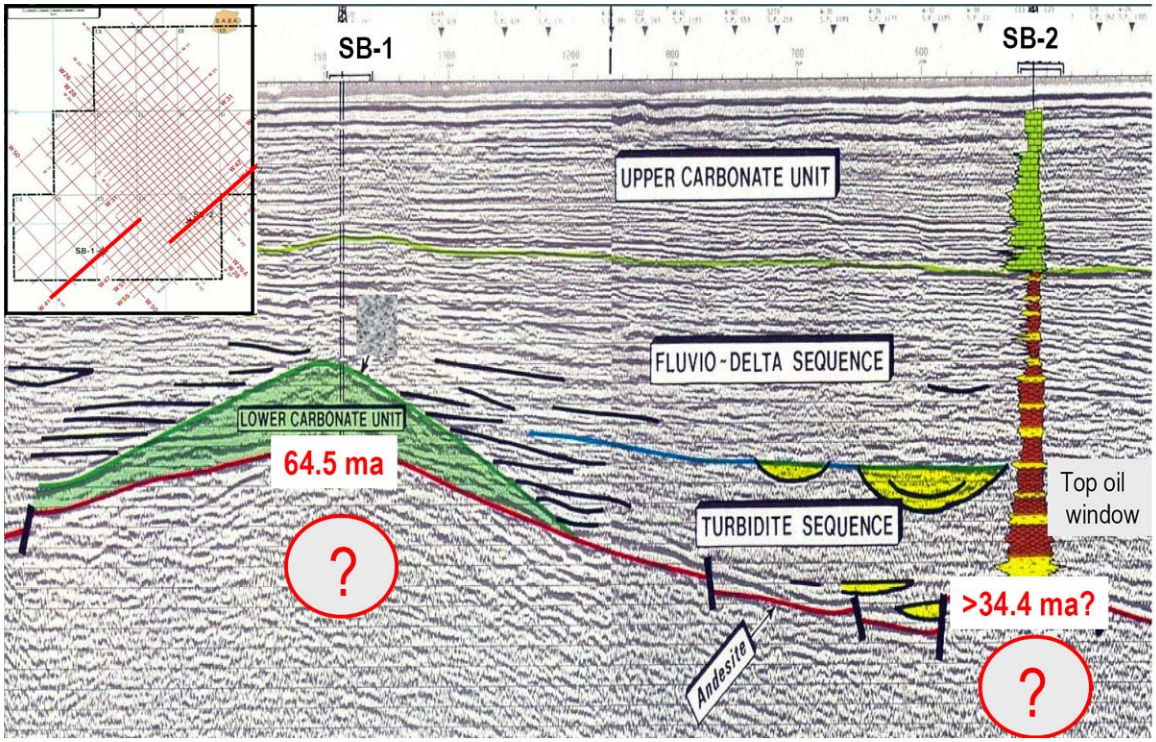


Figure 17. Segments of two seismic lines and wells SB-1 and SB-2, with correlation of the stratigraphic sections between the wells and age dates of andesite encountered at TD in both wells. Above the andesite there was reefal development on the paleohigh and deposition of turbidites in the paleolow.

Petroleum Geology

Well Results

SB-1

SB-1 was drilled by Marathon and partners on the southeast part of the Saba Bank to test the hydrocarbon potential of a well defined seismic anomaly thought to be a mid-Tertiary reef (Figures 13 and 14). The well was spudded on April 16, 1977, and was plugged and abandoned June 21, 1997, as a dry hole at a total depth of 2974.7 meters in andesite. The well penetrated a series of carbonate and clastic sediments dated Pliocene to Eocene overlying the andesite. The objective reef carbonate section, which was encountered at 1922 meters, was 934 meters thick.

The reef section contains several intervals of porous and permeable carbonates with porosities in the 20-25% range, but the only indications of hydrocarbons are minor gas shows between 2140 and 2380 meters. No other oil or gas shows were encountered in the well. Electric log interpretation indicates all potential reservoir rocks are wet. No drill stem tests were made.

Kerogen analyses indicate the thermal maturity of the penetrated section is low. Data indicate that samples near the bottom of the well are approaching the oil generation zone, but are not thermally mature enough for generation.

SB-2

The presence of what were thought to be good, but immature source rocks in SB-1, along with good reservoir intervals within the Lower Carbonate Unit suggested that a carbonate buildup located deeper in the basin within the oil window would likely contain producible hydrocarbons. This led the Fina group to drill SB-2 on a relatively well defined seismic anomaly located on a basement high deeper in the basin (Figures 17 and 18). It was expected that the well would encounter a carbonate buildup with associated reservoir facies.

SB-2 was spudded on February 22, 1982, and was plugged and abandoned as a dry hole on May 25, 1982, at a total depth of 4231 meters. As expected, the well did penetrate a sequence of Pliocene to Eocene age sediments overlying what has been dated as late Eocene andesite; however the objective carbonate facies were not present. The Lower Carbonate Unit facies equivalent penetrated by SB-2 is a series of claystones, argillaceous siltstones to silty claystones with subordinate sandstones having low to moderate log porosity. The unit has been interpreted by Robertson Research as a turbidite/deep sea fan sequence.

No significant hydrocarbon shows were encountered while drilling. Minor gas shows were encountered in sandstones and siltstones between 3800 and 3975 meters and log interpretation indicated the presence of possible gas-bearing reservoirs that were subsequently evaluated by testing through a 7-inch liner. Two intervals were tested: 3936.7-3946.8 meters and 3961.4-3970 meters. No liquid hydrocarbons were recovered, but a small amount of gas with a C_1-C_5 composition was recovered from the drill collars. Fina has suggested that severe mud losses while drilling the section may have resulted in extensive formation damage and that the test is inconclusive.

Source Rock Potential and Geochemistry (Figures 19-22)

Geochemistry of SB-1

In 1977 Marathon Oil's Denver Research Center made geochemical analyses on nine composite samples from SB-1 between 387 meters and 2837 meters. The analyses include total organic carbon (TOC), percent carbonate carbon, qualitative analysis of extracts, and kerogen maturity based on organic matter coloration.

Although TOC values were generally low, bitumen extracts yielded total hydrocarbons of 239-593 ppm. As no evidence for contamination by mud additives such as crude or diesel oil was found, Marathon interpreted these data as indicating that good, but immature oil source rocks occur in both mudstones and carbonates in a sequence at around 2840 meters (composite sample 8) on the basis of higher total organic carbon (1.3%) and 593 ppm hydrocarbons. They note that the hydrocarbons appear to be immature, based on hydrocarbon distributions seen in gas chromatographs of the saturate hydrocarbon fractions. Shallower samples were also reported as potentially good source rocks on the basis of total hydrocarbons although TOC values were low.

Robertson Research's interpretation of these data (1984) is that not enough analyses were done to give an accurate assessment of the hydrocarbon-generating potential of the penetrated section. On the basis of the data that are available, they believe that most, if not all, of the extractable hydrocarbons in the samples represent migrated hydrocarbons and not indigenous material. Yields and composition of source rock extracts from Robertson Research's 1984 report are given in Table 1. Organic richness is very low in most samples and conventional assessment of source bed quality based on organic richness (TOC) would classify most of the samples as nonsource (<0.5% TOC) to marginal (0.5-1.0% TOC) sources. They rate one interval (2453-2600 meters) with 1.3% organic carbon as good source. Rock-Eval pyrolysis data presented by Robertson Research have very low hydrogen indices for the tested samples and suggest they are gas prone.

Kerogen maturation studies by Marathon based on spore and cuticle coloration indicate the thermal maturity of the penetrated section is low. The data indicate that the samples near the bottom of the well are approaching the oil generation zone, but are not thermally mature enough for generation to have occurred.

During the course of the kerogen maturation evaluations, Marathon noted older reworked organic material in several samples. A sidewall core at 1679 meters contained much fungal material and many pieces of light brown cuticle with a color indicating thermal maturity (Ro=0.8%), as well as fusinite and wood fragments. G. K. Guennel, who conducted the study, stated that he considered this material to be reworked from older, more mature rocks, probably from a Cretaceous coal seam. He noted similar, but not as abundant, material in a sidewall core at 1538 meters. A ditch sample from 2390-2399 meters also contained abundant fungal material, wood, and fusinite along with a suite of medium brown Mesozoic spores (Ro=1.0%), probably associated with the fungal material. Guennel again suggested a Cretaceous coal or lignite might have been one of the sources for some of the organic material in this sample. Ditch samples from 2582-2591 and 2737-2246 meters also contain similar reworked fungal and coaly material.

In summary, the geochemical data from SB-1 indicate that significant quantities of extractable hydrocarbons are present in the samples throughout the entire sedimentary section. However, the low TOC values and low maturity (<0.6% Ro equivalent) of these samples strongly suggest that the hydrocarbons present are migrated rather than indigenous. The implication is that, although SB-1 probably does not contain good, mature source rocks, there is a good possibility of more deeply buried, thermally mature petroleum source rock facies in the area.

Geochemistry of SB-2

Geochemical studies on cuttings, sidewall, and conventional cores from SB-2 were conducted by both Labofina in Brussels (82 samples) and Robertson Research in Houston (12 samples) in order to determine TOC, thermal maturity, and source rock quality.

Vitrinite reflectance values indicate that SB-2 reached the mature zone for oil generation. The top of the oil window is located between 2760 meters (Ro=0.55%) and 3100 meters (Ro=0.62%). Most of the samples analyzed are low in organic carbon (<0.5% TOC) and are rated as non-sources, with the exception of a few intervals between 2899 to 3423 meters and in core material at 2788 meters, where some samples rated as marginal source rocks. The organic matter that is present is primarily humic Type III, which is generally gas-prone. Data from Rock-Eval Pyrolysis give low Hydrogen Indices and high Oxygen Indices, also indicative of gas-prone organic material. Some sapropelic organic material was also recognized, but the concentrations are minimal.

Bottom hole temperatures derived from wireline logs give a geothermal gradient of 3.3^{o}C/100 meters from 1520-4185 meters. This gradient is lower than the SB-1 geothermal gradient, which is 3.8^{o}C/100 meters.

The lack of significant source rocks in the generally deeper water sediments encountered in SB-2, along with the presence of abundant thermally mature, reworked Upper Cretaceous organic material in SB-1 and reworked Upper Cretaceous marine fauna in SB-2, strongly suggest the possibility that the migrated hydrocarbons in SB-1 were sourced from the underlying Upper Cretaceous rocks.

Regional Geochemical Considerations

A review of Caribbean hydrocarbon source rock data strongly suggests that early Late Cretaceous rocks are the most likely source for hydrocarbons on Saba Bank. The Tertiary basin in the east, where SB-1 and SB-2 are present, shows immature source and/or unlikely sourcing (Figure 19). According to Pindell (1991, 1995), rocks of this age, which he terms "medial" Cretaceous, are the most significant hydrocarbon source rocks for the two primary suites of rock that occur in the Caribbean region. These source rocks for the highly prolific Proto-Caribbean autochthonous suite of Jurassic, Cretaceous, and Cenozoic passive margin sediments deposited along the rifted margins of North and South America are well documented while their role as source rocks of the allochthonous suite of the Caribbean Plate are less well known and their hydrocarbon potential has yet to be realized. Pindell postulates the Caribbean Plate medial Cretaceous source rocks were deposited in the eastern Pacific realm during an oceanic anoxic event, similar to roughly contemporaneous events in the Atlantic and Proto-Caribbean, prior to the relative eastward migration of the plate into the present Caribbean region. Supporting evidence are reported TOC concentrations of up to 4.2% from Upper Cretaceous anoxic shales interbedded with limestone from D.S.D.P. site 146 in the deepwater Venezuelan Basin (Edgar et al., 1973), and the occurrence of Upper Cretaceous source rocks with reported TOC values of up to 7% in Puerto Rico.

Robertson Research (1984) performed geochemical analyses on a limited number of outcropping sediments from St. Martin and St. Barthelemy Islands on the Anguilla Platform, St. Croix, and Puerto Rico, and on several samples from three wells in Puerto Rico. Saba Bank Resources had samples from Anguilla Island analyzed for source rock potential. In addition, nearly 100 outcrop samples from Puerto Rico were collected and analyzed for source rock potential by J. A. Hayes for an M.S. thesis (1985) at Stanford University; the study was subsequently published (Hayes et al., 1986).

The four outcrop samples Robertson Research analyzed for source-rock potential from the Eocene St. Bartholomew Formation on St. Barthelemy Island were found to have very low organic carbon content, ranging from 0.03 to 0.09% TOC. Maturity data from vitrinite reflectance analysis performed on one sample indicates that it is overmature with a Ro of 1.86%. Only one sample from the upper Eocene Pointe Blanche Formation on St. Martin Island was analyzed. It contained 0.17% TOC and was classified as a nonsource.

Saba Bank Resources had eight outcrop samples from the Paleocene section at Crocus Bay on Anguilla Island analyzed by DGSI in 1996. The total organic content was very low (0.04-0.21%); correspondingly, no additional work was done.

Thirteen Cretaceous outcrop samples from the Late Cretaceous Caledonia Formation of St. Croix were analyzed by Robertson Research to determine their hydrocarbon-generating potential. All of the samples, except one, were too organically lean to be considered potential hydrocarbon source rocks. The exception contains 0.56% TOC, but maturity data determined by pyrolysis and vitrinite reflectance indicate it is well beyond the oil-generating stage with an Ro>3.2%. Kerogen typing indicates that large quantities of oil-generating components are present and that this rock probably represents a marginal spent source bed.

There are two confirmed reports of minor oil occurrences in the rocks of the Older Series in the south-central part of Puerto Rico. Robertson Research analyzed four samples from pre-middle Tertiary outcrops and three probable pre-middle Tertiary samples from Kewanee Oil company CPR-1 for source-rock potential. Three of the outcrop samples rated as non-source rocks on the basis of organic richness (0.06-0.16% TOC) as did the CPR-1 samples (0.14-0.28% TOC). The fourth outcrop sample, from an Upper Cretaceous mudstone, had 1.29% TOC but was thermally overmature for oil generation (Ro=2.05%). Visual kerogen examination indicates that a large quantity of oil-generating amorphous kerogen is present in the sample. Robertson also analyzed a limited number of middle to Upper Tertiary age samples from the Kewanee CPR-1, 2, 3 and 4 wells for source-rock potential. Some samples have over 1% TOC, but all contained primarily terrestrial dry-gas generating organic matter and were generally thermally immature.

Nearly 100 samples were collected by J. A. Hayes (Hayes et al., 1986) from outcrops located throughout Puerto Rico of the Cretaceous-Early Tertiary volcanic, volcaniclastic, and calcareous strata composing the sediments deposited on the Late Jurassic-Early Cretaceous magmatic arc platform and from the Kewanee CPR-1 and 3 wells. Sampling concentrated on organic-rich Cretaceous strata, but some Lower Tertiary units were also sampled. Rock types analyzed included chert, calcareous and non-calcareous shale, and limestone. The samples were analyzed for total organic content, thermal maturity (vitrinite reflectance), and visual kerogen identification with reflected light. If the samples displayed Ro<2.0%, thermal alteration index (TAI) was measured and kerogen types were identified. Rock-Eval pyrolysis was conducted on samples with sufficient kerogens and Ro<2.0%.

Total Organic Carbon in the majority of the Puerto Rico samples is less than 3.0%, but ranges to 7%, with Upper Cretaceous limestones having the highest values (Figure 20). Kerogen identification by reflected light was successful on 62 of the samples. Of these, 24 (39%) contained enough amorphous organic matter and exinite to plot in the oil and gas producing field (Figure 21), 12 (19%) of the samples plot in the wet gas and condensate field and 26 (42%) plot in the dry gas field. Rocks younger than Eocene are in general immature to marginally mature. Rocks of Eocene age (limited sampling) are mature to overmature; Upper Cretaceous rocks are slightly less mature, and Middle Cretaceous rocks are mature to greatly overmature. A plot of Rock-Eval pyrolysis derived Hydrogen Index vs. Oxygen Index data on a modified van Krevelen diagram (Figure 22) shows that the majority of the samples are in the fields of types II and III kerogen; i.e., those that are oil- and gas-prone or gas-prone.

In summary, a significant percentage of the Cretaceous rocks sampled on Puerto Rico have moderate to fair source rock potential based on their TOC content, maturity, and kerogen type. The majority contain kerogen that is prone to gas generation; however, a few formations, particularly limestones, contain good amounts of oil- and gas-generative kerogen.

Summary of Geochemical Studies

In the limited areas of the northeast Caribbean where geochemical data are available, the Tertiary sedimentary section generally contains poor petroleum source rocks. In samples from the Saba Bank wells, outcrop samples on Anguilla, St. Maarten, and St. Barthelemy Islands on the Anguilla Platform, and outcrop and well samples on Puerto Rico, total organic carbon values are universally low; the kerogens that are present are generally gas-prone; and the post-Eocene section is immature for oil generation. Eocene sediments reach maturity in SB-1, and they are overmature on St. Maarten and St. Barthelemy Islands. On Puerto Rico the limited number of Eocene age rocks analyzed were mature to overmature. The only Paleocene rocks analyzed for source rock potential are on Anguilla, where they have very low TOC values and are rated as non-source rock.

The high bitumen extract yields in SB-1 are believed to be migrated hydrocarbons generated from deeper, more mature source rocks. The occurrence of abundant reworked mature Cretaceous organic material in that well suggests the source of the migrated hydrocarbons is the underlying Cretaceous source rocks. Saba Bank was part of the Greater Antilles Magmatic Arc until early or mid-Eocene time and shared a common Cretaceous history with Puerto Rico. The studies of source rocks on Puerto Rico described by Hayes et al (1986) demonstrate that fair to moderate quality source rocks capable of generating both oil and gas are present in the Cretaceous sediments deposited on the magmatic arc platform. There is no reason to believe that similar source rocks are not present in the thick pre-volcanic sequence underlying Saba Bank.

Reservoir Geology

The results from SB-1 and SB-2 confirm the presence of good to excellent reservoirs throughout the post-andesite Tertiary section. The Upper Limestone Unit is reported by Fina to have good porosity with visual estimates of 10-25%. No permeability data are available, but the extensive lost circulation that occurred in SB-1 and to a lesser extent in the No. 2 well indicates high permeability zones.

Marathon reported that sandstones and some conglomerates in the Volcaniclastic Middle Series (Fluvio-Deltaic Unit) in SB-1 include intervals with fair to excellent porosity and adequate permeability. The equivalent section in SB-2 is less sandy, and most of the sands that are present have a high clay content and low porosity. Occasional thin sands in the lower part of the sequence have 10-25% computed log porosity.

The 934-meter Lower Carbonate Unit in SB-1 is composed of dense to slightly porous micritic to microsparitic limestone, biomicrites and biosparites to biomicrosparites having very good vuggy and intergranular porosity, and thin clayey laminations. Study of conventional core material, sidewall cores, and wireline logs indicate substantial intervals of porous and permeable rock, with porosities from 11 to 25%. Marathon's Denver Research Center described scattered occurrences of solution-enlarged primary interparticle porosity, supplemented by moldic porosity, which ranges up to 35-40%.

The Channel-Turbidite Unit encountered in SB-2 contains a basin-plain outer submarine fan sequence deposited by turbidity currents. Porosities in the fine-grained sand units are low, however, and are generally less than 10%.

The most promising remaining prospects are in the pre-andesite sequence with Cretaceous reservoirs as the primary target. There are no data on the type or quality of Cretaceous reservoirs. The reworked Cretaceous coaly material encountered in both Saba Bank wells suggests the presence of marginal marine deltaic sediments that would be expected to have significant sand bodies with good reservoir quality.

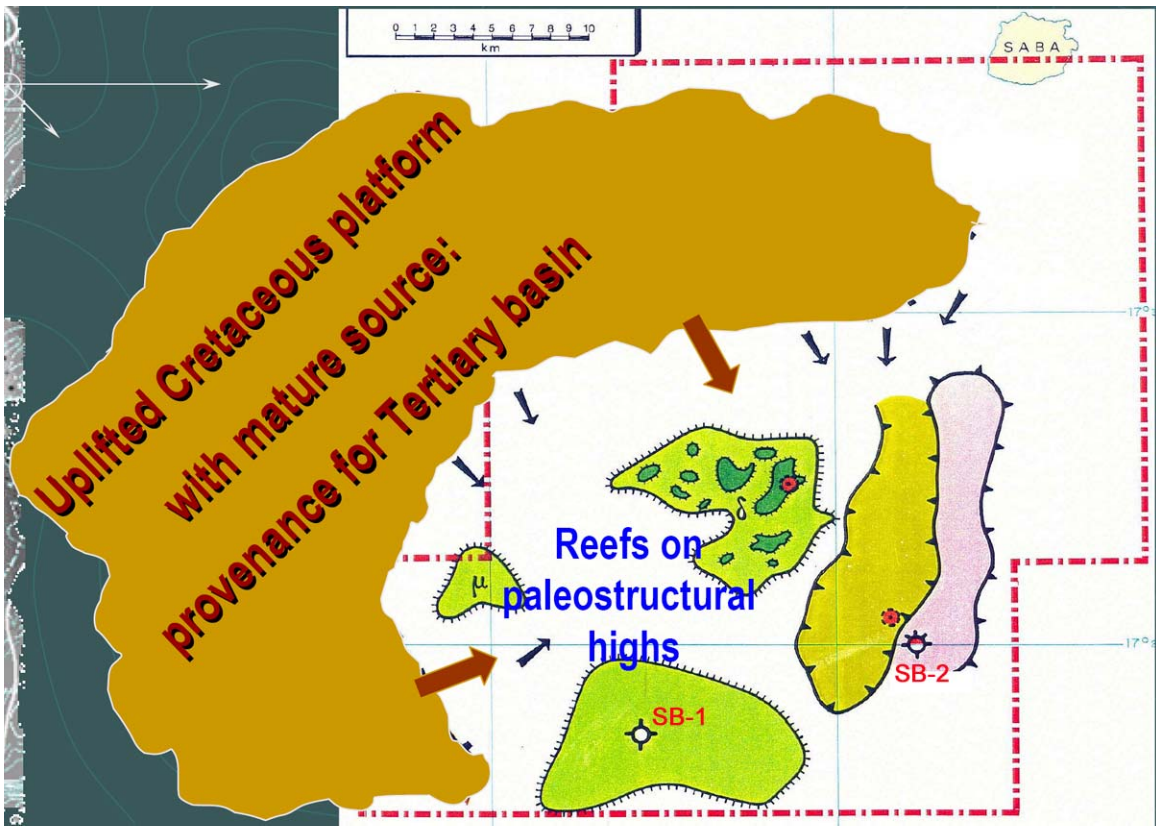


Figure 18. Paleogeography of Saba Bank area during Eocene, with areas of reef development and submarine-fan deposition. Interpretation by Fina.

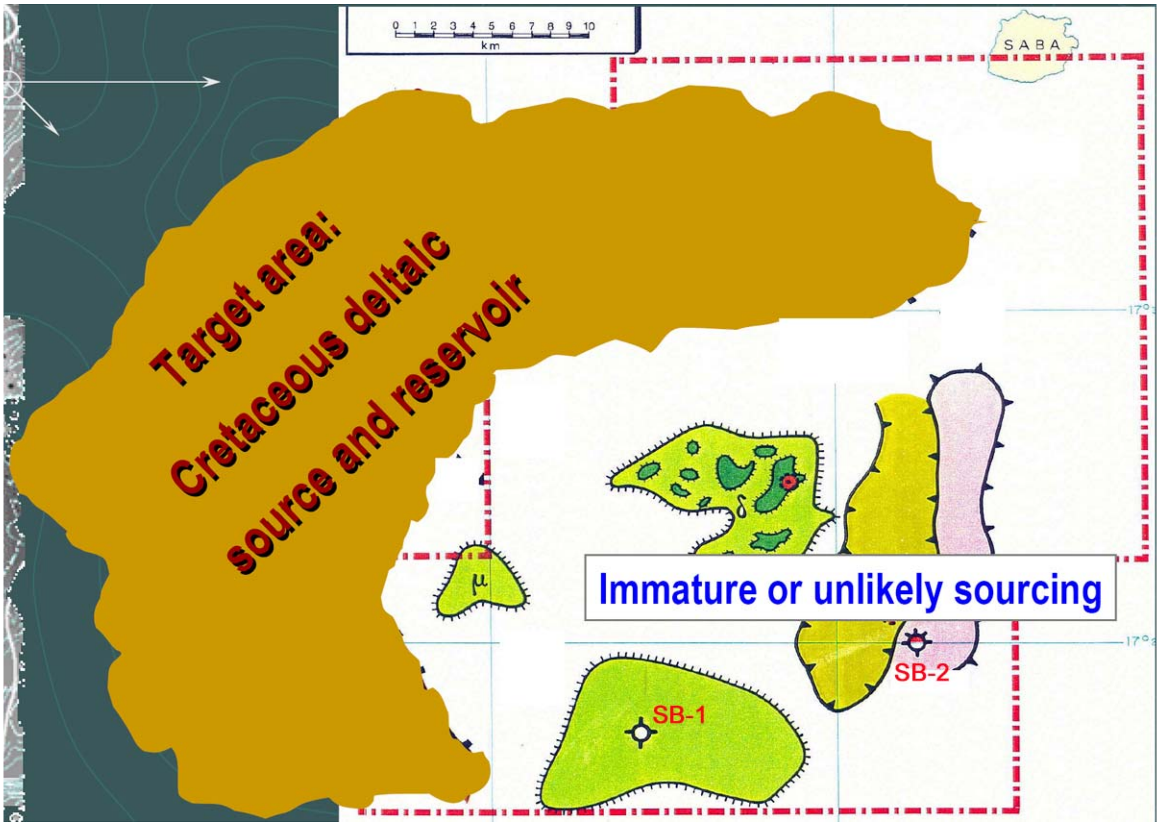


Figure 19. Hydrocarbon potential, with the Cretaceous deltaic source and reservoir rocks as the logical hydrocarbon play in the area; Tertiary basin requires Cretaceous source and migration inasmuch as Tertiary sediments are characterized by immature and/or unlikely source.

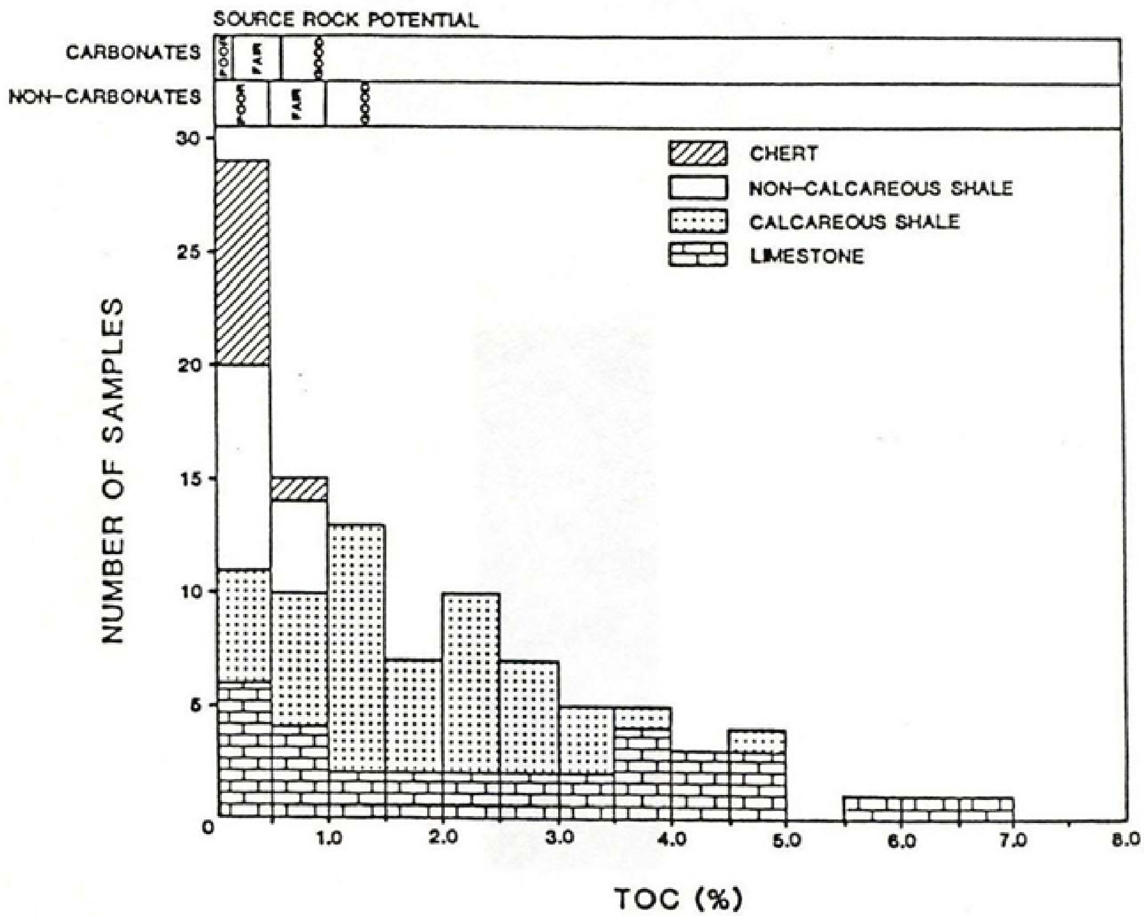


Figure 20. Total Organic Carbon from Puerto Rican source rocks. TOC values range as high as 7% (after Hayes et al., 1986). Figures 10 and 11 show location of Puerto Rico in relation to Saba Bank.

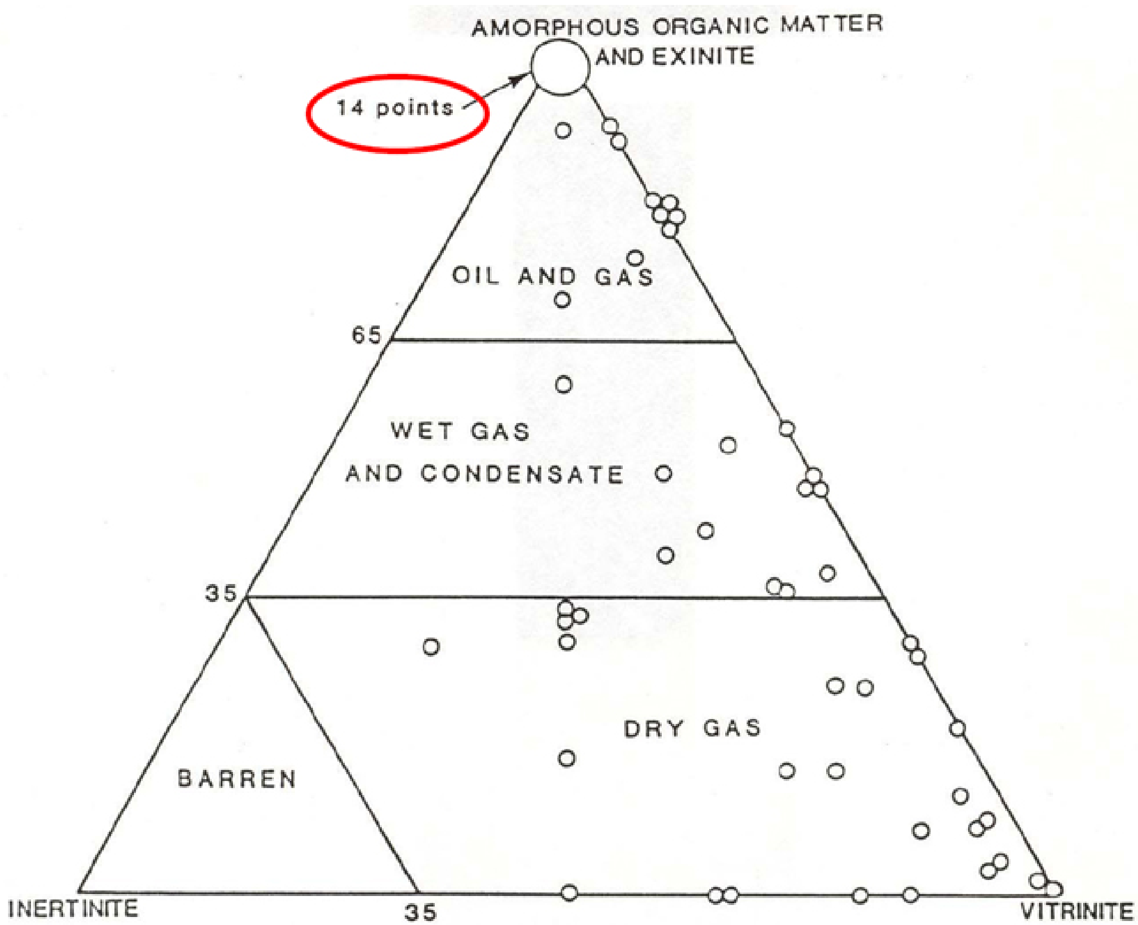


Figure 21. Van Krevelen diagram for Puerto Rican source material, indicating reasonably good hydrogen indices for the source rocks (after Hayes et al., 1986).

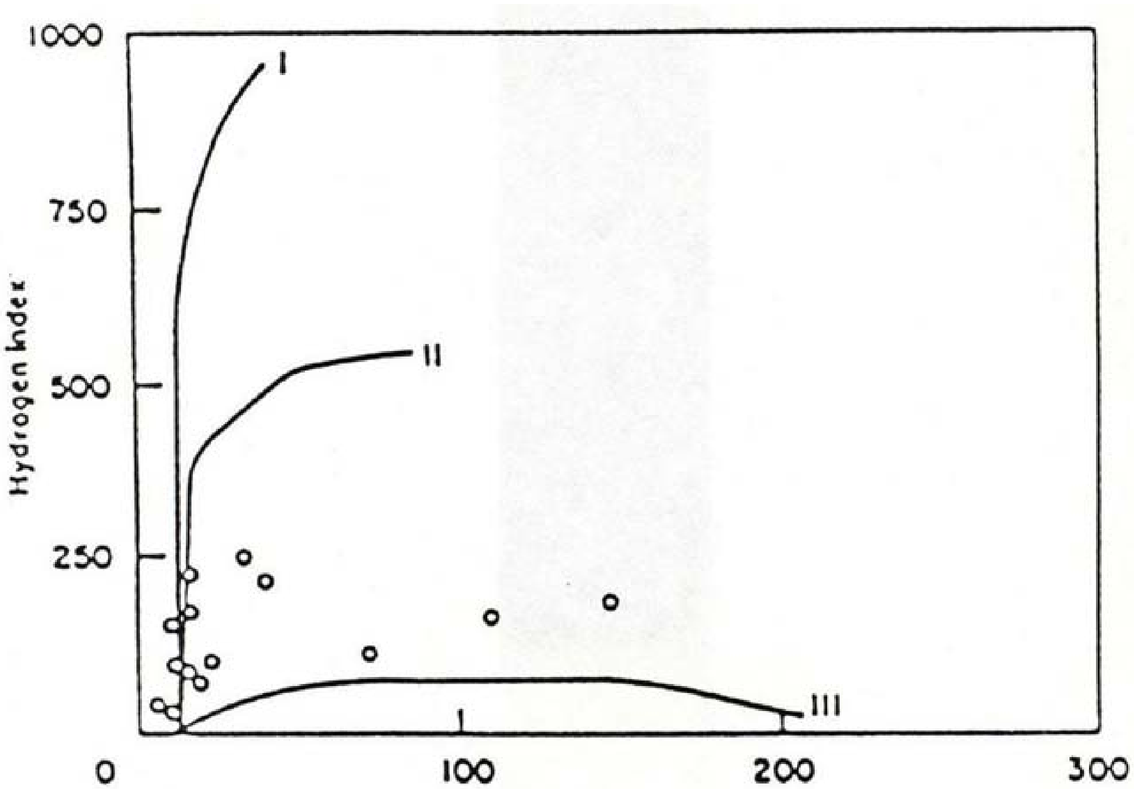


Figure 22. Kerogen types in Puerto Rican source rocks, ranging from dry-gas prone to oil prone (after Hayes et al., 1986).

Depth Meters	Extract PPM	Saturates	Aromatics Percentage	NSO + Asphaltines
442	309	56.0	19.7	24.3
1266	401	61.6	25.2	13.2
1434	548	47.1	28.3	24.6
1646	365	31.8	33.4	34.8
1829	410	37.3	30.7	32.0
2044	435	34.6	28.8	24.6
2283	464	28.0	39.0	33.0
2527	658	39.3	35.0	25.7
2719	732	51.2	29.8	19.0

Table 1. Composition of source rock extracts, SB-1.

Seismic Programs and Interpretation

Focus

The overall focus of the Saba Bank evaluation has been on the potential of the untested pre-Eocene (Upper Cretaceous?) sediments. The major geophysical emphasis has involved the reprocessing and interpretation of selected Petrofina seismic lines and all of the Aladdin lines, and the acquisition, processing, and interpretation of 205 kilometers of infill data acquired in late 1999. The input data and results of these projects follow.

Seismic Acquisition

Petrofina commissioned Western Geophysical to acquire a seismic grid over the eastern half of Saba Bank in September of 1980. Acquisition parameters for this survey included firing 8 Aquapulse source guns at intervals of 25 meters into 96 receiver groups spread over a 2400-meter streamer cable and recording data at 2-millisecond intervals on DFS V instruments. These parameters resulted in 48-fold stack. The effort was the state of the art at the time, but it was designed for an objective shallower than 2500 meters. Subsequent drilling and seismic interpretation have proved the effort to be inadequate for the currently understood target; but much of the problem can be overcome with a longer cable.

Western also recorded the data shot for Aladdin in February 1988. Better acquisition tools were available by that time, and a conventional recording system and survey design were employed. Western used 18 airguns popping at 26.7-meter intervals into a 3300-meter cable with 120 receiver groups, resulting in 60- fold stack. A more advanced Litton LRS-16 system recorded the data at 2-millisecond intervals. The longer cable, higher fold, additional groups, and more powerful source allowed better records from greater depths and subsequent better evaluation of normal moveout velocities.

Seismic Reprocessing Basics

Every tool in the processor's kit has been improved significantly since the original processing was performed. Some improvements are due simply to more powerful computers, and others are a result of new and better algorithms. The key steps in the reprocessing that differentiated it from earlier efforts included deterministic designature, FK filtering, tau-p deconvolution, automated velocity analysis, and radon transform demultiple. However, the two most important are post-stack procedures: migration and the FK demultiple program.

The lack of migration on the original Petrofina data combines with inadequate multiple attenuation to make it uninterpretable in many places. Recognizing the problem, Petrofina later used various multiple elimination schemes without success. While the newer Aladdin data set is better, the original attempt at processing was so poor as to be almost totally useless to the interpreter. Understanding the source of the problems, plus using great care in each step of the pre-stack processing, allowed the migration and FK demultiple algorithms to make the data interpretable.

Petrofina Data Reprocessing

In the first phase of reprocessing, Western Geophysical of Denver worked on three of the seismic profiles (60 kilometers) acquired for Petrofina in 1980. The principal objectives were to determine if the data could be improved enough to warrant further reprocessing, and to obtain more information about the local geology. Western was successful in improving the interpretability of the data, but many multiples remain on the sections and they continue to hinder geological understanding. Based upon what was learned in the subsequent reprocessing of the Aladdin data, it should be possible to improve the Petrofina data more. However, it will be impossible to equal the quality of the newer Aladdin data due to the deeper geological target in the Petrofina area and to certain limitations in the recording parameters of the older data.

The improved multiple attenuation allowed better resolution of the pre-Eocene (Upper Cretaceous?) reflectors. This targeted zone, which on most original seismic lines appeared to be crystalline basement, is now seen to be composed of probable clastic sediments. After reprocessing of the three lines in this initial effort, it was apparent that there was a change in dip between these deeper events and the overlying sediments. The newly visible deep area was originally interpreted as half-grabens which could act as important hydrocarbon source areas for the known Tertiary reservoirs.

Aladdin Data Reprocessing

Sterling Seismic and Western Geophysical both attempted reprocessing of five of the lines acquired for Aladdin Petroleum (134 kilometers). Sterling made remarkable improvements in the data; after considerable assistance and time, Western improved the data somewhat. While the old sections showed little more than flat reflectors and seemed to indicate shallow basement and little petroleum potential, the results from both processors show geology that is consistent with the expectations for the area.

The presence of a very thick sedimentary sequence of apparent Cretaceous age is quite encouraging. Therefore, the field tapes for the remaining seven Aladdin seismic lines were requested and obtained (209 kilometers). Sterling reprocessed this data, again with promising results.

It is important to note that Western Geophysical was not content with the results they achieved in reprocessing the first five lines. On their own initiative, they tested a new post-stack multiple attenuation technique on line E-12. This is the key line in the data set; it is the only one of the newer profiles that connects the eastern area of Saba Bank to the western area. That is important because the wells were drilled in the eastern area, and the Aladdin data was shot in the western area, where the pre-Eocene reflections are much shallower and the data quality is much higher. Line E-12 crosses the poorly understood boundary between these areas, which had never been satisfactorily imaged by any processing flow. Western's reprocessing cleared the picture sufficiently to allow a new geological theory: the boundary zone is probably a wrench fault.

When Western Geophysical was shown the importance of their successful independent trial on E-12, they agreed to perform additional processing on two more lines at no cost and with additional interpreter input. This work, which came at the very end of the project, confirmed the existing deep interpretation and added more detail to the visible structures. There was little doubt that performing the same multiple attenuation technique on the other twelve reprocessed profiles would be similarly successful.

Western's poststack F-K demultiple program is used to attenuate specific residual multiple energy, either water bottom or interbed, having constant and uniform dip. This is precisely the problem in the Saba Bank area: the shallow Kingshill carbonate material is flat and it generates flat multiples from within and from its contact with the dipping clastic sediments below. Western employed the F-K technique as a supplement to the conventional pre-stack demultiple routines, Parabolic Radon transform and Tau-P deconvolution. The F-K technique requires accurate knowledge and identification of the multiple energy; in this case the interpreter worked with the analyst to digitize the base Kingshill event. While the resulting improvement was sometimes dramatic, the reprocessing was still able only to transform uninterpretable data into fair quality data. Structural "ties" were impossible, so it was feasible only to make a formline structure map within the pre-Eocene (Figure 9).

Acquisition of New Seismic

Because of the potential that became visible on the seismic reprocessing, Saba Bank Resources N.V. decided in late 1999 to acquire new seismic. Ten lines were planned to detail a large rollover prospect in the southwestern portion of Saba Bank and to evaluate further a lead immediately to the east. A total of twelve lines totaling approximately 205 kilometers were recorded, including two new lines added when rapid processing indicated that the eastern lead was valid (Figure 23).

The *MV Western Inlet* acquired the new 2-D seismic data with a 6000-meter cable and a 25-meter shot interval, resulting in 120 fold. Acquisition began on December 28 and was completed on January 1, 2000. The field data were improved from the older vintages, largely because of the longer offsets used. The processing flow at Western for the new data was similar to that for the Aladdin data.

When the processing of the new seismic data was completed, the Saba Bank interpretation project was converted to digital format. This involved digitizing the old base maps, adding the new seismic base locations, and loading the final seismic processing and reprocessing. Some of the 1970s vintage seismic data is also marginally useful, and it could be scanned and added to the database in the future.

Interpretation

Previous interpretations of the Saba Bank area had shown no faults with other than normal displacement. Such a picture is unlikely in the regional setting of the Northeast Caribbean. Once the complex faulting of the flower structure could be seen on one seismic line, it was possible to interpret it on even the original Fina processing from more than twenty years ago. The current interpretation shows this line of demarcation trending almost north-south, dividing Saba Bank into two equal-sized but economically different geological regimes.

The character of the reworked material found in the two Saba Bank wells suggests that it was sourced from an exposed Cretaceous deltaic sequence located on what is now the platform area of western Saba Bank, or from a landmass farther to the west. The reprocessed seismic corroborates this interpretation, as it shows that the area west of the flower structure was uplifted and eroded at least twice. The angular unconformities marking these times are visible on several seismic lines (e.g., Figures 24, 25, 26, 27, and 28).

The western half of Saba Bank is the more tantalizing because of depth: not only is the bank itself shallow enough for drilling by a jackup rig, but the objective section is much shallower than in the eastern portion. The probable Cretaceous sediments are only about 1000 meters from the surface, and the section is at least 6000 meters thick.

During the complex structural history of the pre-Eocene, a large fault block developed in the southwestern corner of the Bank. That corner of the fault block was tilted and eroded to almost a flat surface; it apparently served as the provenance of the reworked sediments to the east. Structure maps (e.g., Figure 9) indicate that this prospect has about 28 square kilometers of four-way dip structural closure and at least 157 square kilometers of three-way dip closure against a bank edge down-to-the-southwest normal fault.

Although the eastern half of the Bank also is characterized by shallow water, the depth to base Eocene increases rapidly to the east and south before the dip becomes gentle. The two Saba Bank wells are located in a moderately thick Tertiary basin. Because the Cretaceous lies below the andesite penetrated in the wells, the drilling depth east of the wells would be greater than 4000 meters. With the benefit of the Aladdin reprocessing, it can now be seen that the deeper areas, which were initially interpreted as small half-grabens, are actually much more extensive. It would appear that these are continuations of the thick pre-Eocene section in the west, so they should be similarly prospective geologically. Economic adjustments should be made for drilling depth and increased potential for gas.

Prospect Evaluation and Reserve Potential

The prospects and leads on Saba Bank can be divided into two groups: prospects and leads in the eastern Tertiary basin and pre-Eocene (Cretaceous?) prospects in the western platform area. The focus of the seismic reprocessing and interpretation made for the current assessment of the petroleum prospects of the Saba Bank area has been on the pre-Eocene section. Because of limitations in the recording parameters, it has not been possible to enhance the Petrofina data sufficiently to allow mapping of prospects beneath the thick Tertiary section in the eastern part of the Bank, although it is apparent that a thick pre-Eocene section is present. Reprocessing of the Aladdin data over the western platform area, however, has resulted in significant improvement in imaging of the pre-Eocene section and the recognition of a major wrench-fault separating the platform and Tertiary basin areas as well as the presence of large tilted fault blocks on the platform. Acquisition of 205 kilometers of new seismic allowed confirmation of these large prospects.

Eastern Tertiary Basin

Petrofina mapped a number of untested prospects and leads in the Tertiary section of the eastern basin after reinterpretation of their seismic data following the drilling of SB-2. They recognized both carbonate and channel/turbidite/deep sea fan prospects.

Carbonate Buildups

In addition to the carbonate buildup tested by SB-1, Petrofina identified carbonate buildups and associated reef facies in two other areas, designated by the Greek letters δ and μ in Figure 18. The mapped boundaries of these features do not represent the true limits of the carbonate developments but indicate the tentative limits of the geophysical event associated with the reef buildups.

The δ prospect is a structural and stratigraphic trap. The prospective reservoirs are likely to be carbonate reservoirs similar to that encountered in the Lower Carbonate Unit in SB-1, as well as Cretaceous clastic reservoirs similar to those in the western Saba Bank. Marine mudstones at the top and inter-reef facies should provide a good seal.

The Tertiary reef appears to have grown on a local high developed on a tilted, north-dipping pre-Eocene fault block. The hydrocarbon source is thought to be in the underlying pre-Eocene section that is believed to have generated the migrated hydrocarbons encountered in SB-1. According to Fina, the δ prospect has 15,600 acres of areal closure and could reservoir from 450 to 700 million barrels of recoverable reserves.

Petrofina estimated possible recoverable reserves of 87 to 130 million barrels of oil for the μ prospect. It is located in a faulted area, however, and the presence of an effective seal is questionable making it a higher risk prospect than δ.

Channel/Turbidite/Deep Sea Fan Prospects

Analysis of cores in the lower section of SB-2 indicate that the shales, siltstones, and sandstones were deposited in the outer fan environment of a basin plain and that the sands were deposited by turbidity flow. Petrofina’s post-drilling seismic review shows that SB-2 was drilled on a paleo-ridge to the east of a north-south trending trough located between it and the δ prospect (Figure 18). Hummocky, chaotic, discontinuous seismic reflections indicative of channels, mounds, and associated turbidite facies occur in the trough (Figure 15). The paleo-ridge acted as a barrier partially preventing eastward turbidite flow, resulting in north-south oriented assemblages of stacked sands. The distal facies encountered in SB-2 had poor reservoir quality, but a drill stem test in the interval did recover minor quantities of C_1 to C_{5+} gas components, indicating migration of liquid hydrocarbons has taken place and suggesting that the trough is prospective for hydrocarbon accumulations in the turbidite sequence. The prospect area is 10 to 15 kilometers long and 3 to 4 kilometers wide. Petrofina estimated potential minimum recoverable oil reserves in this area to be 300 to 400 million barrels.

Several seismic lines suggest similar leads may also be present between SB-1 and the δ prospect.

Western Platform Area

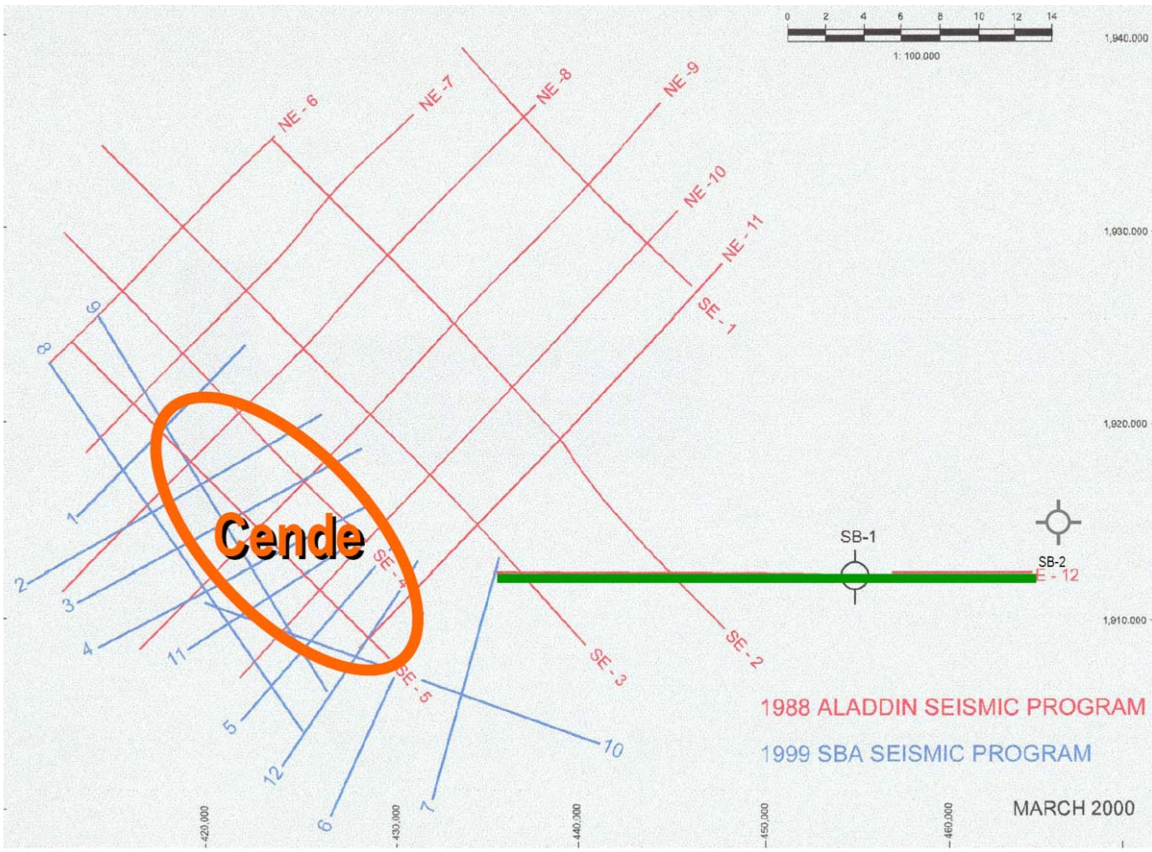
The untested Western Platform area presents the best opportunity on the Saba Bank for a major hydrocarbon discovery. The Tertiary section is thin and unconformably overlies a very thick pre-Eocene section which, based on the reworked material in SB-1 and SB-2, is probably Cretaceous in age. The pre-Eocene section contains at least one prospect capable of containing a giant oil or gas field.

As noted above, a very large pre-Eocene fault block has been mapped in the southwestern corner of the Bank (Figures 9, 29, 30, 31, 32, 33, 34, and 35). The prospect has approximately 28 square kilometers (approximately 7,000 acres) of four-way dip closure with 1200 meters of vertical closure, and 157 kilometers (approximately 38,800 acres) of three-way dip closure with 3700 meters of vertical closure against a down-to-the-southwest normal fault. The crest of the pre-Eocene section is at a depth of about 1000 meters and the section is at least 6000 meters thick. Water depth is approximately 40 meters.

There is no direct evidence to indicate the nature and quality of prospective reservoirs in the pre-Eocene section. However, the character of the reworked Cretaceous age materials recovered from SB-1 and SB-2 indicates they were derived from an unmetamorphosed deltaic sequence, probably located in the platform area. The nature of the pre-Eocene seismic reflectors also suggests a clastic sequence is present.

Significant quantities of migrated hydrocarbons occur in SB-1 and C_1 to C_{5+} gas components were recovered in a SB-2 DST. The lack of significant Tertiary source rocks in either of the wells, along with the general lack of good Tertiary petroleum source rocks in the northeast Caribbean, strongly suggest migration from a pre-Eocene source. Regional considerations indicate Upper Cretaceous sediments are the most likely source rocks.

Potential reserves are very high. A 100-foot net oil pay section could easily result in a recoverable reserve greater than 500 million barrels.



the units described from SB-1and an interpreted major wrench fault.

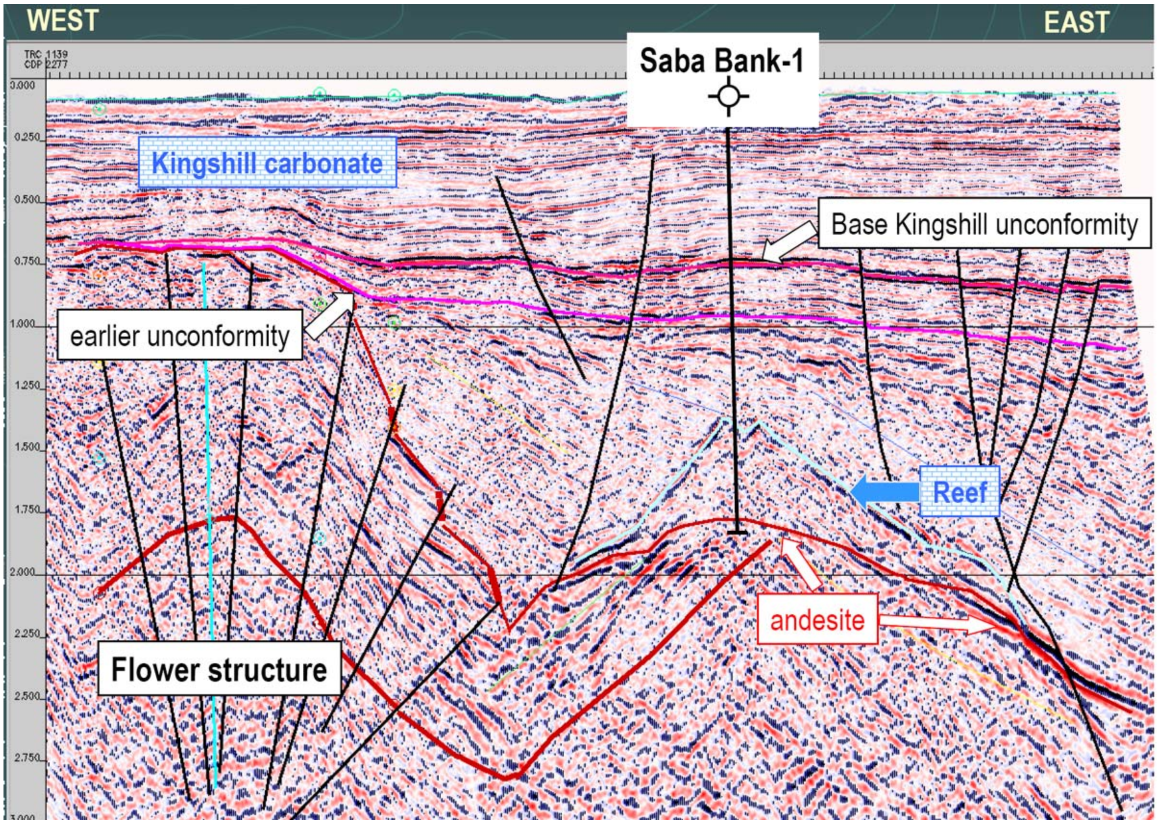


Figure 26. Interpreted seismic line E-12, with Kingshill carbonate, base Kingshill unconformity, earlier unconformity and erosion of flower structure, reef, and andesite of Early Tertiary age.

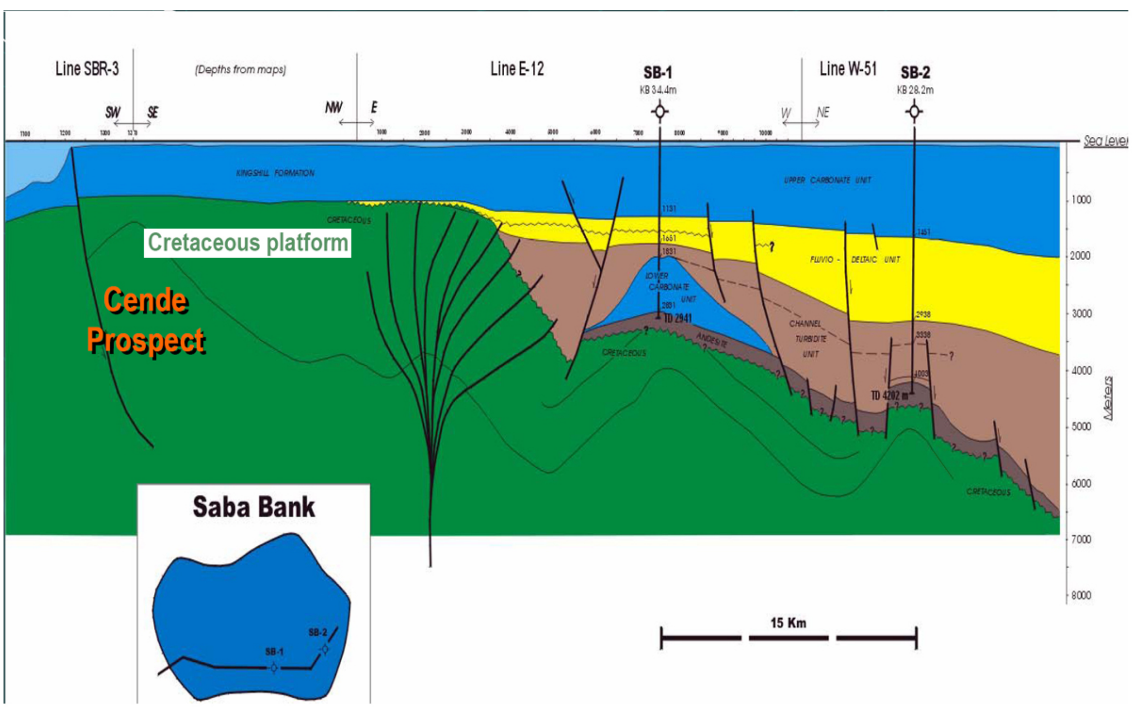


Figure 27. Geoseismic section across Saba Bank and Cretaceous platform to the west, where Cende Prospect is located.

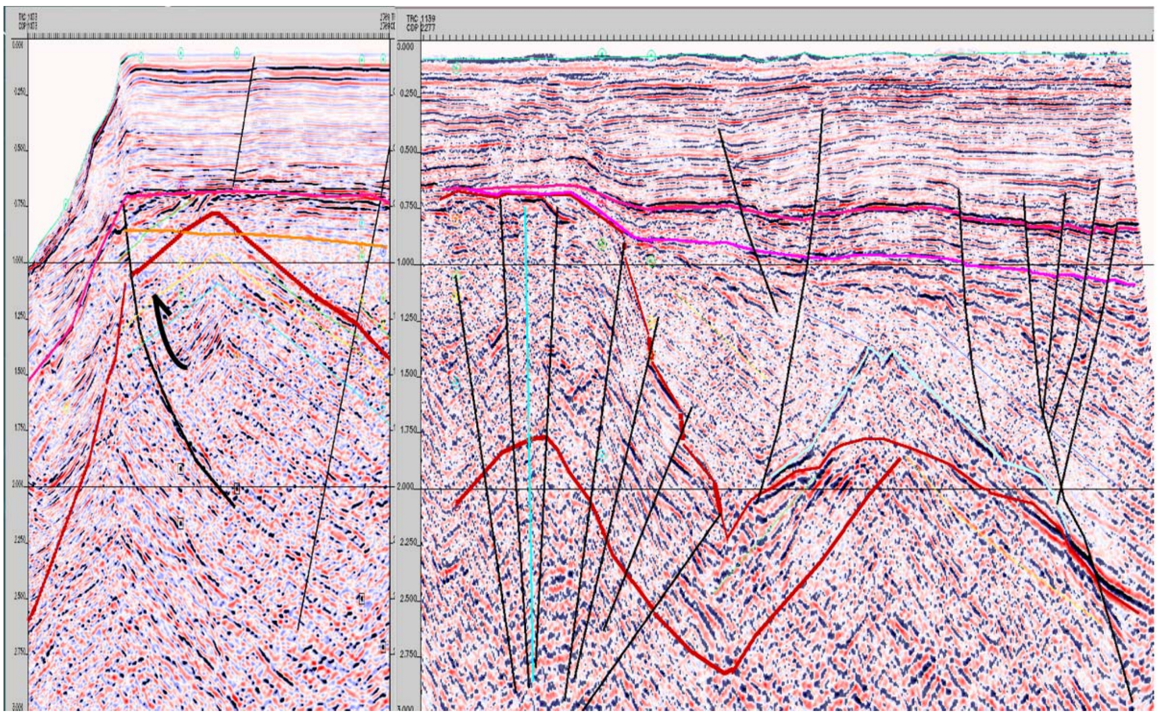


Figure 28. Interpreted seismic lines SBR-3 and E-12, corresponding to the geoseismic section (Figure 27). Cende Prospect on the left at a time of <1 second.

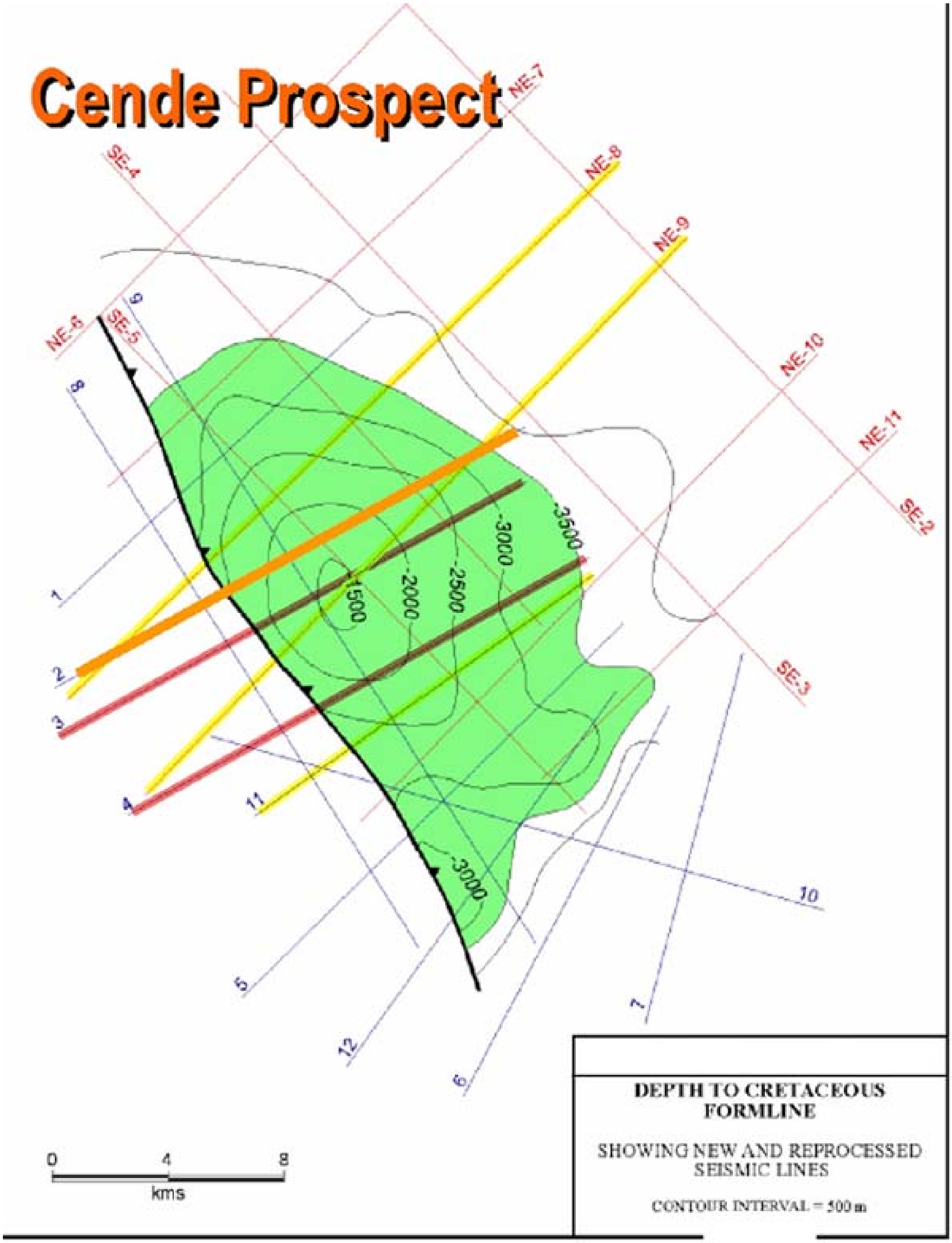


Figure 29 . Location map of seismic lines across Cende Prospect, highlighting SBR-2, SBR-3, SBR-4, SBR-11, NE-9, and NE-8.

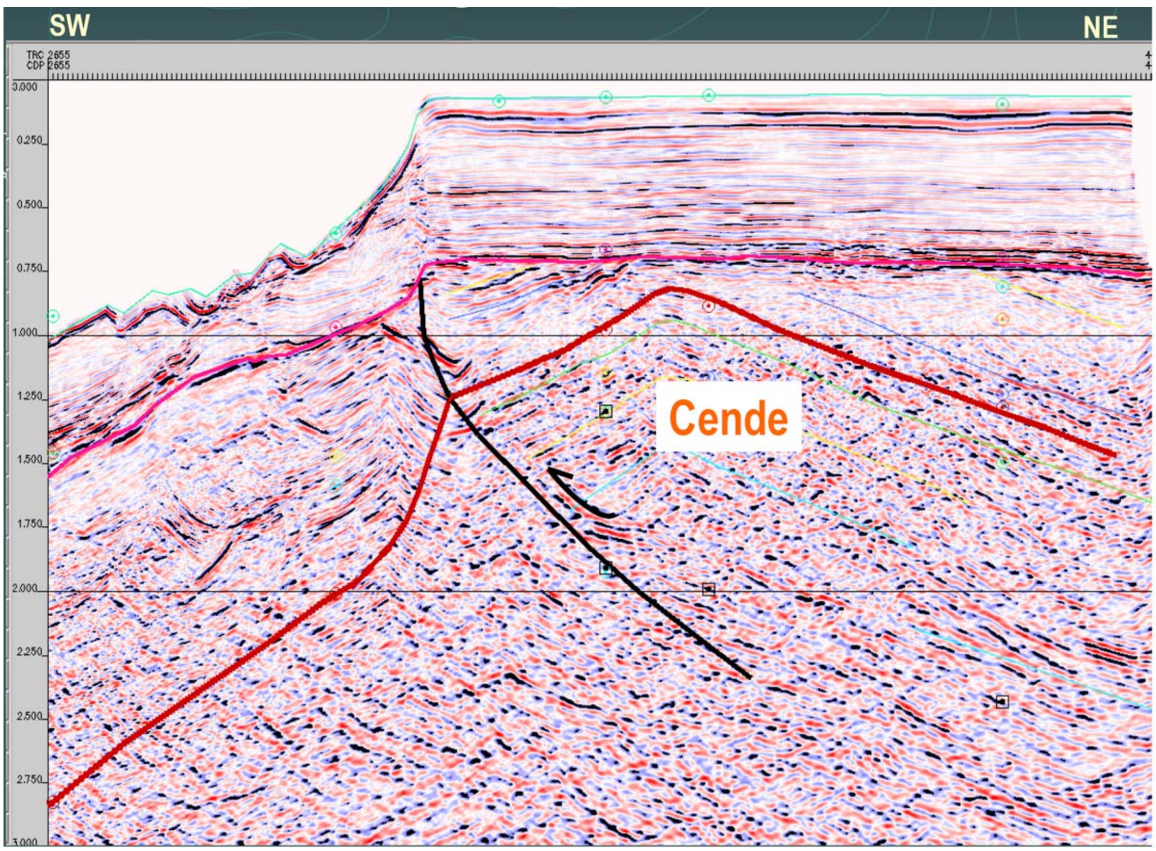


Figure 30. Interpreted seismic line SBR-2. Note that the fault seems to control the edge of Saba Bank. across the heart of Cende prospect.

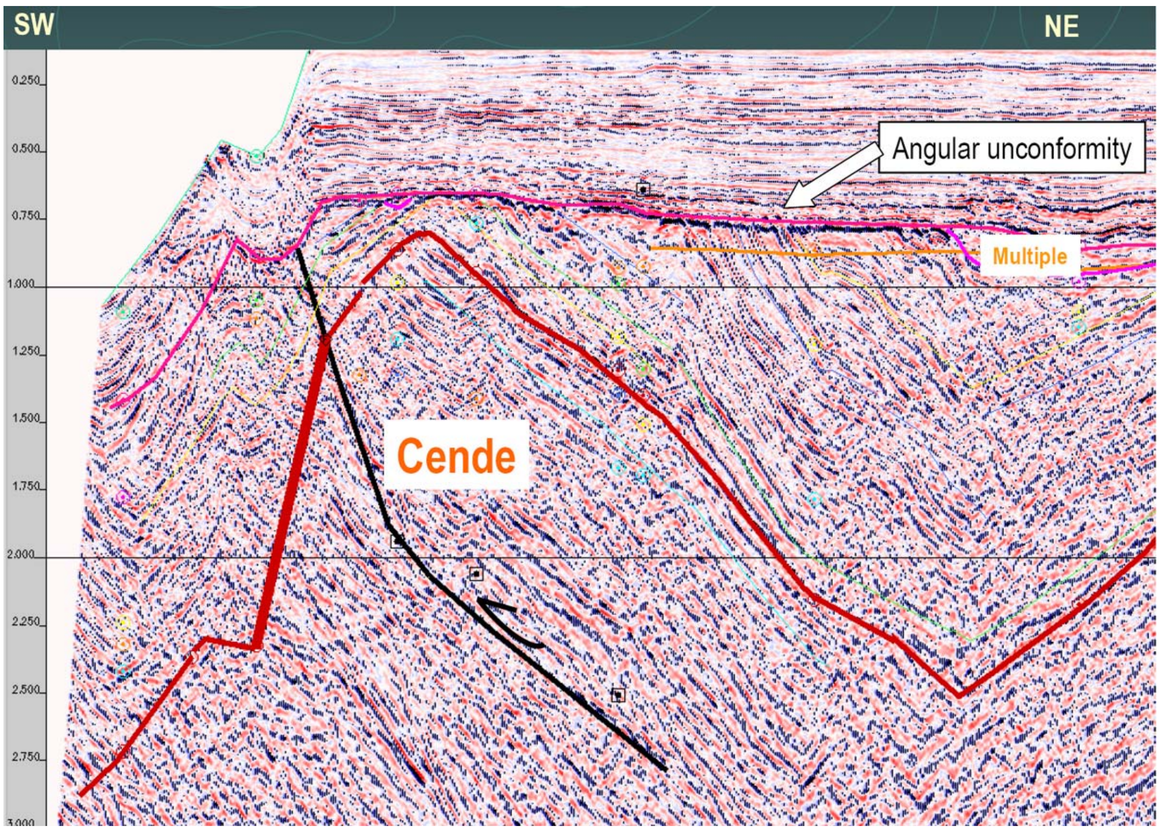


Figure 33. Interpreted seismic line NE-9, from the Aladdin 1988 survey, across Cende prospect, illustrating quite well the amount of dip closure and the unconformity. The thickness of the section has been confirmed by gravity and magnetic data.

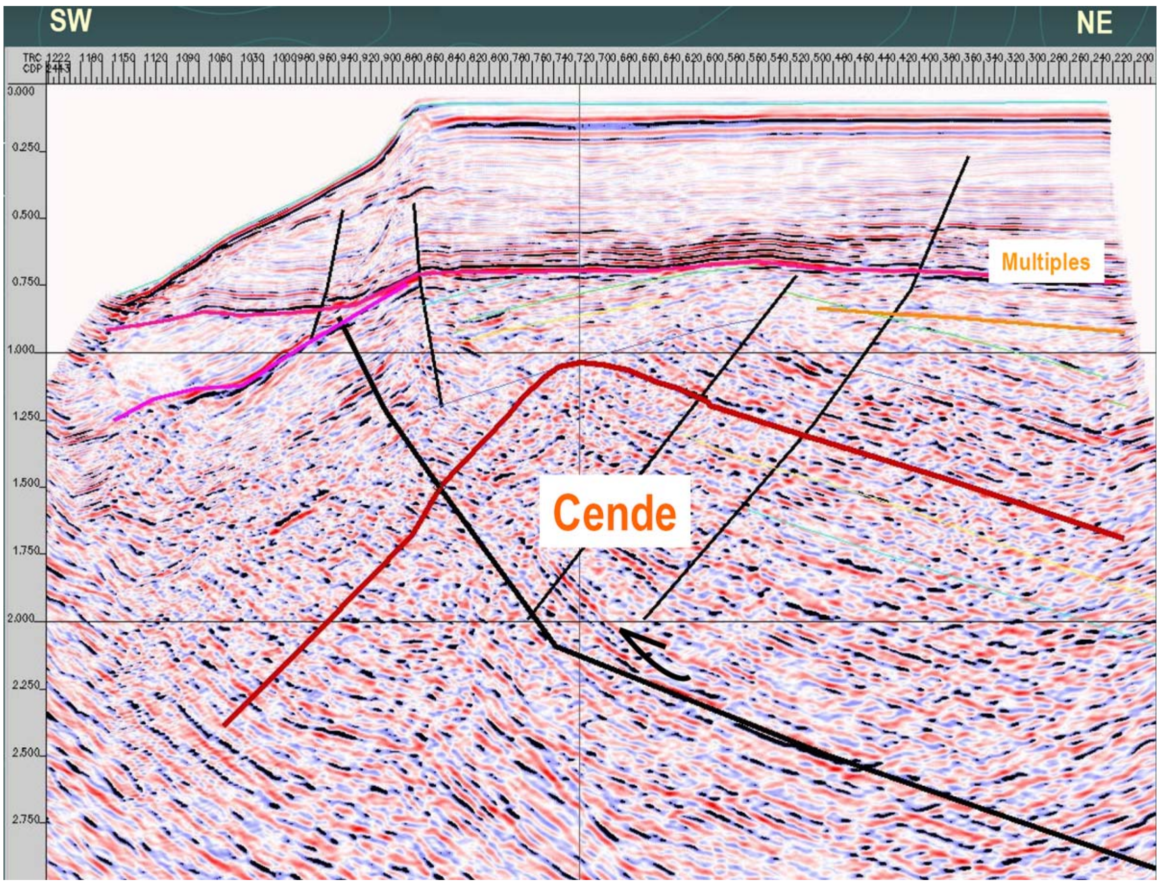


Figure 34. Interpreted seismic line SBR-11 across Cende prospect, with some shallow multiples.

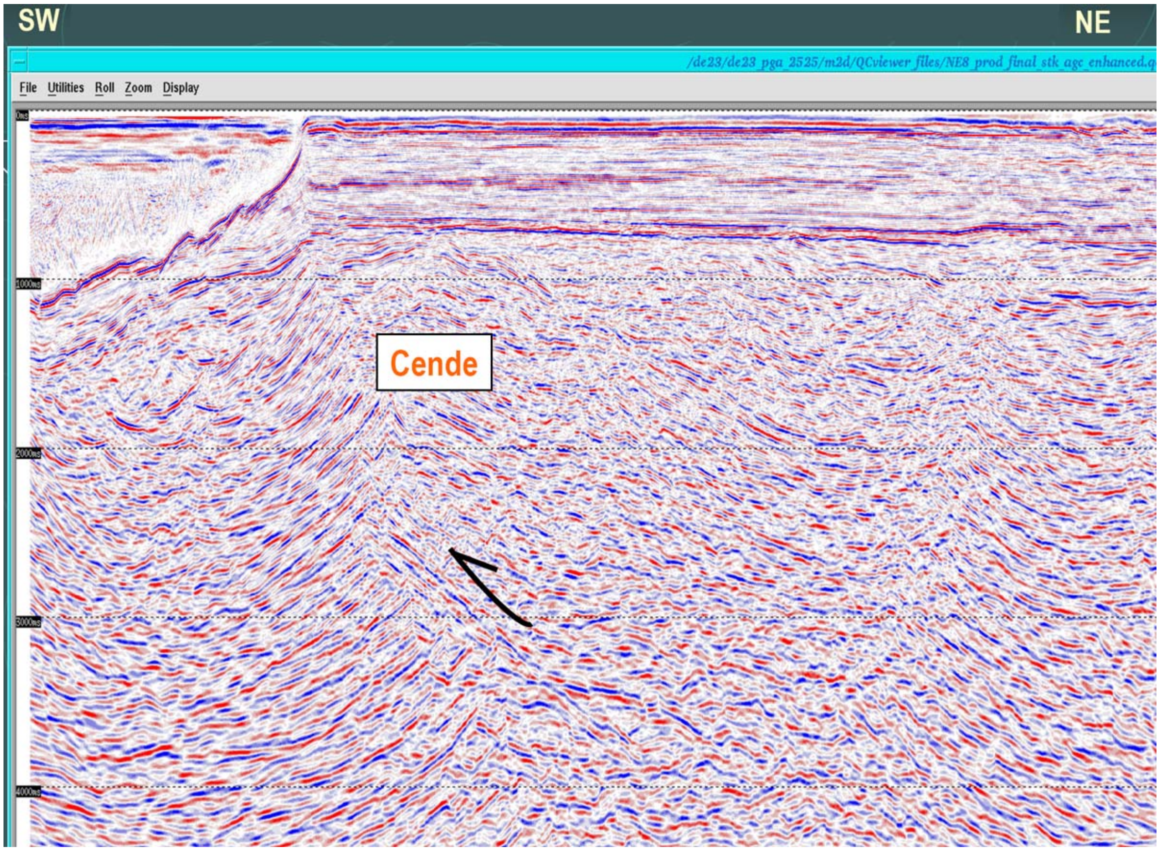


Figure 35. Reprocessed seismic line NE-8 across Cende prospect; showing the location of the fault, which controls the bank edge, and the strong dip reversal over Cende Prospect.

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