Marine Seismics in Cam

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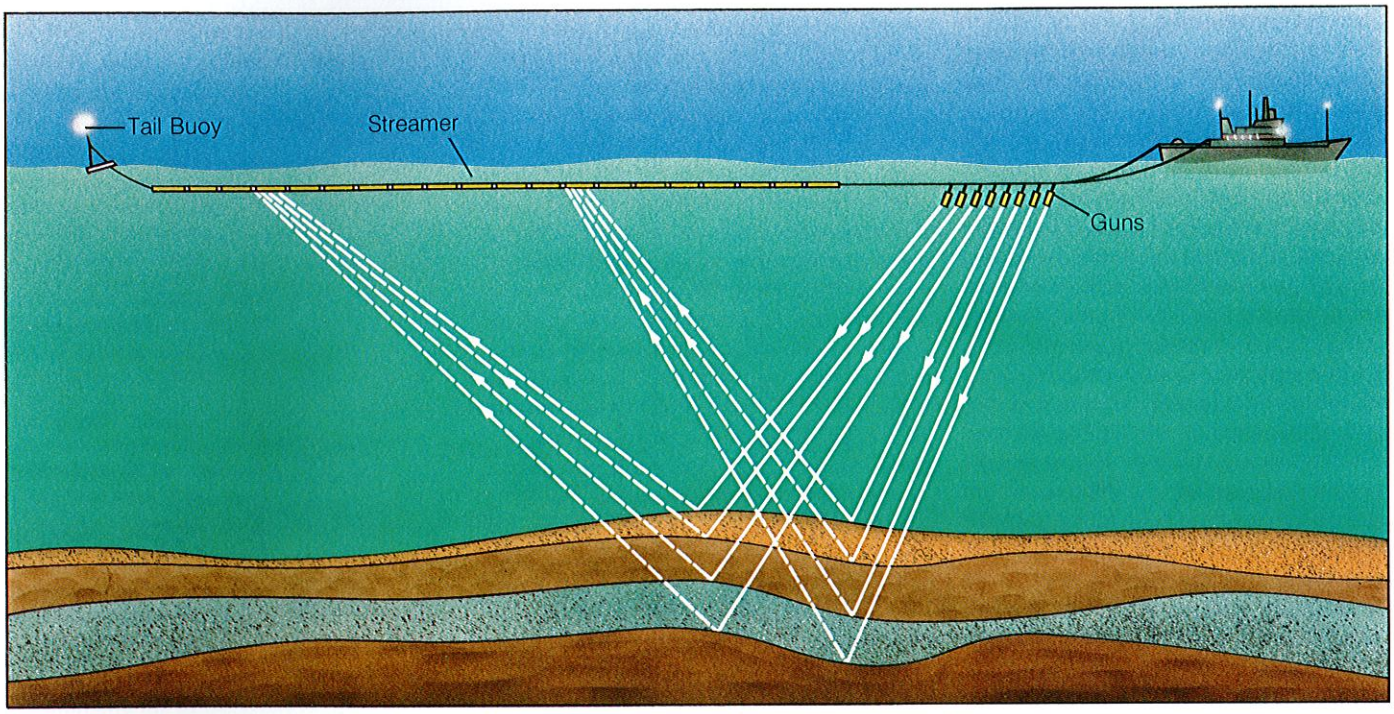

□*Marine seismic surveys involve a specially equipped vessel, about 75 meters [246 feet] long, that moves at about 5 knots [9.3 km/hr (5.75 statute miles/hr)], towing arrays of air guns and hydrophones a few meters below the water surface. A tail buoy at the end of the hydrophone array helps the seismic crew keep track of the hydrophones' locations. The cylindrical air guns vary in diameter but are about 1 meter [3.3 feet] long. As many as 40 guns may be grouped in an array, charged with compressed air, and simultaneously activated every 25 meters [82 feet] (about every 10 seconds) to produce a high-amplitude sound wave that travels through the water and reflects off the underlying rock. Reflected seismic waves detected by the hydrophones are recorded versus two-way travel time—the time it takes the seismic pulse to travel down, be reflected, and arrive at a particular hydrophone. Recordings are made on magnetic tapes each capable of holding 1.8 x 10^{18} bytes of data. The hundreds of tapes that may be generated from a single survey are then flown to processing centers where the data are used to create an image of the subsurface geologic structure. Geologists and geophysicists interpret the processed data to learn about geologic structures such as folds, faults, truncations, and erosional and depositional patterns that help identify potential hydrocarbon traps.*

Petroleum exploration continues to move offshore and with it grows the importance of marine seismics. This article introduces the basic ingredients of a two-dimensional offshore seismic survey—from navigating a vessel towing air gun and hydrophone arrays to basic signal-processing steps to interpretation on an interactive workstation. A recent 2-D nonexclusive proprietary survey in the offshore Douala Basin, Cameroon serves as a case study throughout. Subsequent articles will discuss emerging acquisition, signal-processing and interpretation techniques, and three-dimensional seismic surveys used increasingly for reservoir development.

Nonexclusive proprietary surveys (NEPS)—regional seismic surveys sold on a nonexclusive basis—are used to indicate potential structural and stratigraphic hydrocarbon traps. NEPS emerged in the 1960s to keep expensive seismic vessels in operation whenever exploration activity declined, but the intermittent and informal basis on which they were conducted frequently jeopardized their accuracy and worth. Today, high standards of quality make NEPS a profitable business venture (*above*).

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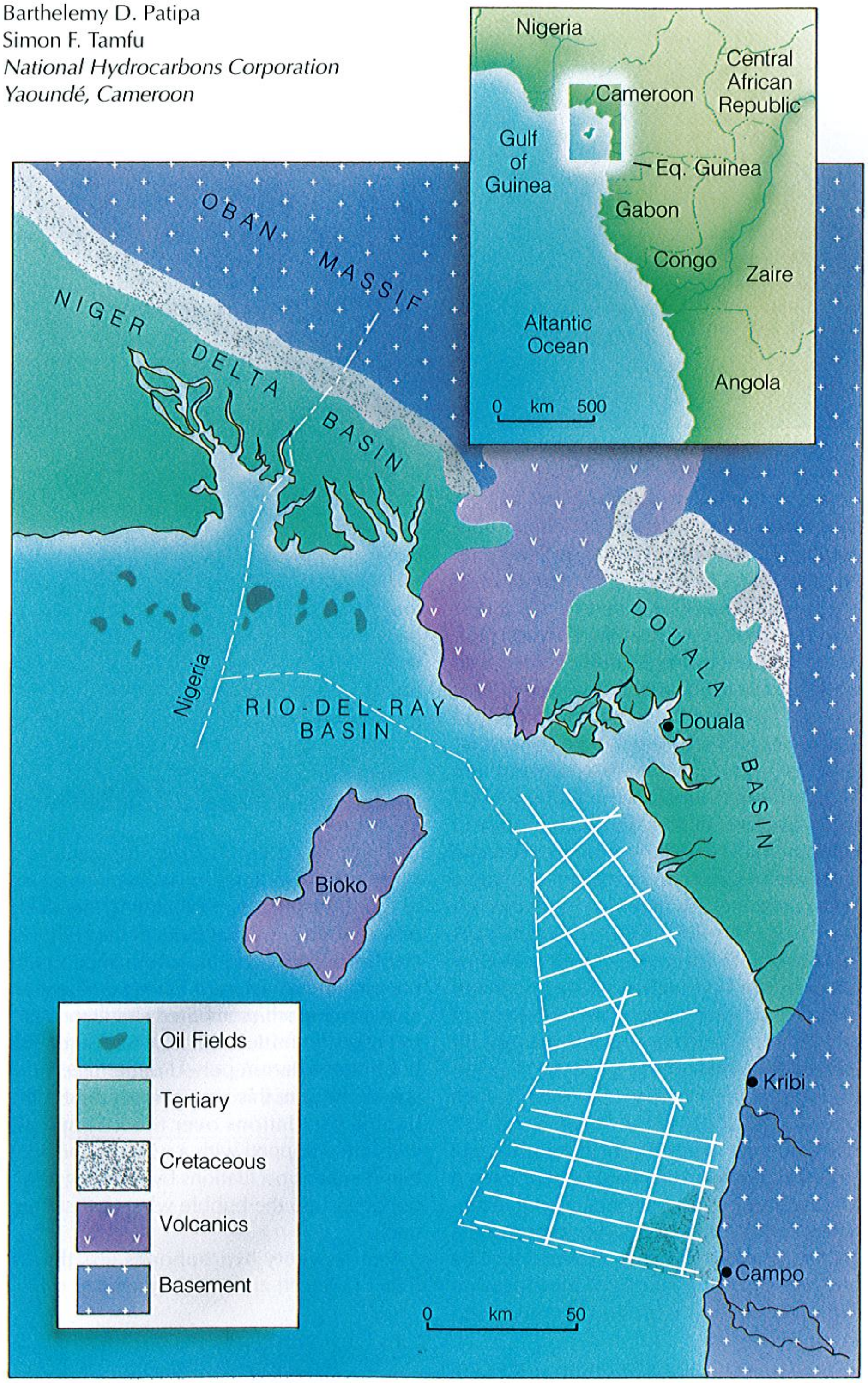
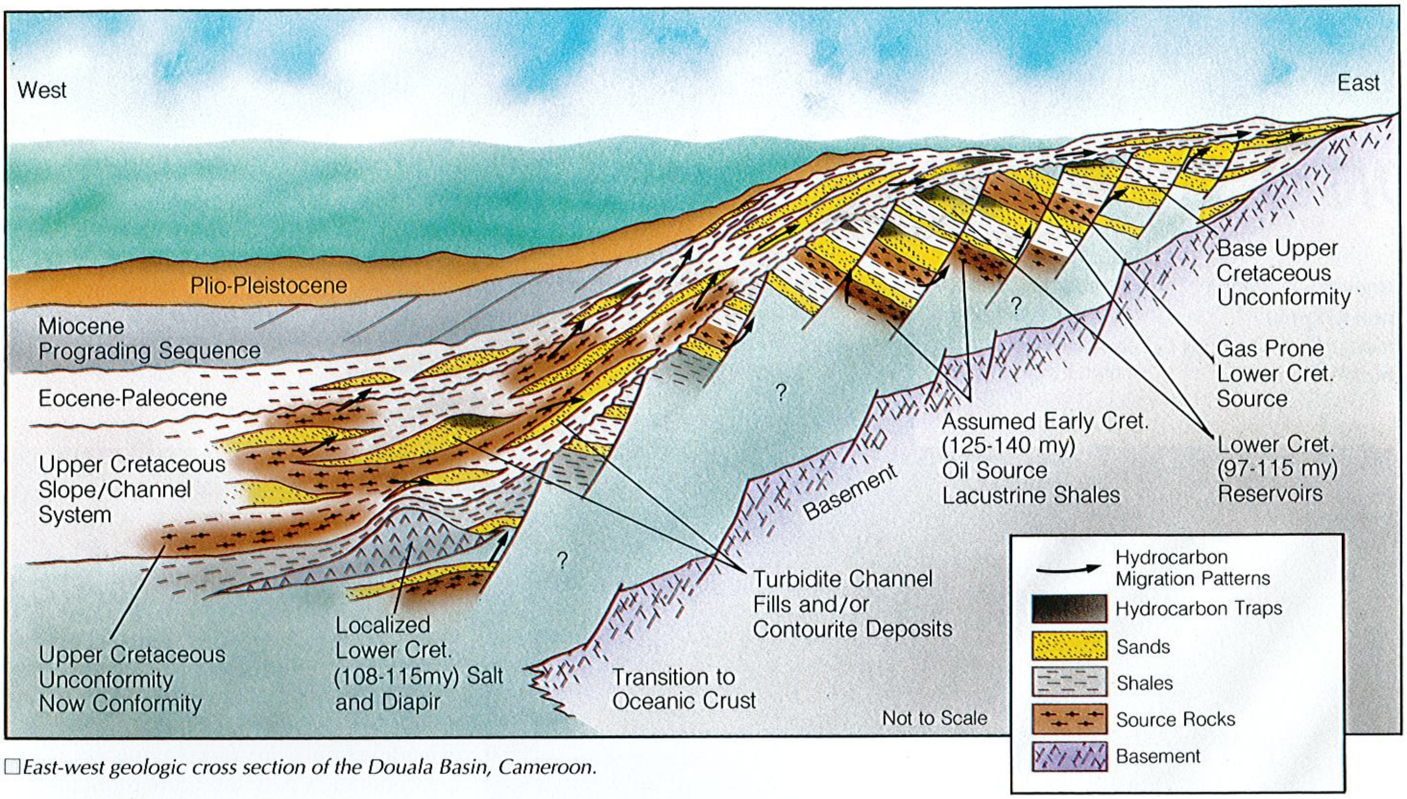


The financial risk associated with the nonexclusive sale of acquired and interpreted seismic data makes NEPS different from other oil field services. Seismic exploration companies commonly reduce this risk by arranging for governments of a potential exploration target to underwrite a portion of the survey in return for sharing profits from the NEPS' sales.

Last July, as part of a West African NEPS extending from Cameroon to Angola, GECO in cooperation with the Cameroonian government shot nearly 1,200 kilometers (km) [745 miles] of seismic lines in the offshore Douala Basin, Cameroon (*left*). The survey, which builds on older seismic surveys of poor definition, has helped change the reputation of the Douala Basin from a gas to an oil province.[1] This was accomplished by using a high density of hydrophones, a powerful source array and special processing procedures. Sharing data processing between two centers and performing the interpretation on an interactive workstation limited the project time to 6 months.

□*West African coast from Nigeria to Equatorial Guinea showing the seismic lines used in the Cameroonian nonexclusive proprietary survey (NEPS). The Cameroonian survey is part of GECO's West African NEPS extending from Cameroon to Angola.*

1. Tissot BP and Espitalié J: "L'évolution Thermique de la Matière Organique des Sédiments: Applications d'une Simulation Mathémathique," *Revue de l'Institut Français du Pétrole* 30 (1975): 743-777.
   Tissot BP, Pelet R and Ungerer PH: "Thermal History of Sedimentary Basins, Maturation Indices, and Kinetics of Oil and Gas Generation," *AAPG Bulletin* 71 (1987): 1445-1466.



East-west geologic cross section of the Douala Basin, Cameroon.

The Douala Basin

Spanning 18,000 km² [6,950 square miles], of which 11,000 km² [4,247 square miles] are offshore, the Douala Basin lies in the Gulf of Guinea as the northern extension of the Gabon Basin, a vast salt basin that extends from southern Cameroon to Angola (*above*). The Douala Basin formed during an early rift phase of the South Atlantic Ocean, when a triple junction of tectonic plates occurred at what is now the Niger Delta. Two arms, radiating northwest and south, developed through the Mesozoic (250 million to 65 million years ago) to eventually form the western coast of Africa. The third arm, trending northeast, became inactive.

From the Late Jurassic (135 million years ago) to the Late Cretaceous (97 million years ago), a thick series of nonmarine clastic sediments was deposited. Near the end of this period, the southern half of the Douala Basin developed massive evaporites, a possible northern extension of the evaporites in Gabon. From the beginning of the Upper Cretaceous (97 million years ago) to the present, open marine conditions have dominated with the opening of the South Atlantic. Shales and sandstones form a westward prograding sediment prism.

Source rocks occur in the Lower Cretaceous (135 million to 97 million years ago) pre-salt sequence and also the Upper Cretaceous (97 million to 65 million years ago). Reservoir rocks are found in the Lower Cretaceous pre-salt sequence as alluvial and fluvial deposits, and in the Upper Cretaceous as channel fills and submarine fans. Porosities of 16 to 25 percent have been recorded in Cretaceous sandstones. Some Tertiary channel fills may also have reservoir qualities. Possible hydrocarbon traps include Lower Cretaceous sands sealed by salt or by the base of the Cretaceous unconformity and Upper Cretaceous sandstones in salt-induced structures or in channel fill stratigraphic traps.

Data Acquisition

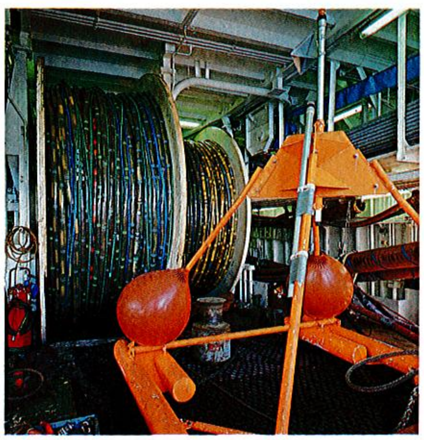
Since no amount of signal processing can coax useful information out of poor data, a successful seismic survey begins with accurate data acquisition. First, the paths that the boat will follow during the survey must be planned, in this case by Cameroonian explorers familiar with local geology and existing wells.

Next, source and hydrophone arrays are selected according to the known geology of the area. Large air guns produce lower frequency signals with good penetration for deep surveys, but the higher frequency signals produced by small guns may be preferred for resolving faults or thinly layered beds. A single air gun creates seismic energy that travels in all directions, but a combination of air guns can focus the seismic energy. The width of a gun array is adjusted to minimize side-to-side projection of seismic energy while the length is adjusted to focus energy downward rather than forward or backward.

When an air gun is fired, it produces a bubble that oscillates in size while moving to the surface. Each oscillation generates a new seismic pulse that reduces the ability to resolve the original pulse. To dampen bubble oscillations, air guns having different air chamber capacities are fired simultaneously to boost the initial signal pulse. Since the bubble oscillation period depends on the size of the gun, this arrangement dilutes the bubble oscillations over time. Larger air guns are equipped with a wave-shaping kit that dampens oscillations by inserting additional air into the bubble when it first contracts.

Ten to twenty hydrophones less than 1 meter [3.3 feet] apart are arranged in subarrays on a streamer cable. The hydrophone responses from one subarray are combined into a single seismic trace to reduce noise produced by the cable passing through the water. As many as 240 such subarrays each producing a seismic trace may be connected along a cable to form the streamer. The cable comprises oil-filled sections for buoyancy plus the wiring for hydrophones (*below*). The streamer should be equally buoyant along its length, a condition achieved by adjusting the oil in the cable sections or wrapping them in 0.5-meter (1.65-foot) lead sleeves weighing 2 kilograms (4.4 pounds) apiece.

Streamers are submerged 8 to 10 meters (26.2 to 32.8 feet) below the surface to reduce wave-generated noise. Pressure-sensitive hydrofoils, or "birds," are spaced evenly along the streamer to control depth. To monitor streamer position, a tail buoy is placed at the end of the streamer. Deviation of the streamer from the true seismic line is called feathering and, to preserve the integrity of the acquired data, it must not typically exceed 8 degrees. Finally, waterbreak devices placed near the beginning of the streamer monitor the offset distance between the near hydrophone subarray and the source array, a crucial parameter in signal processing.



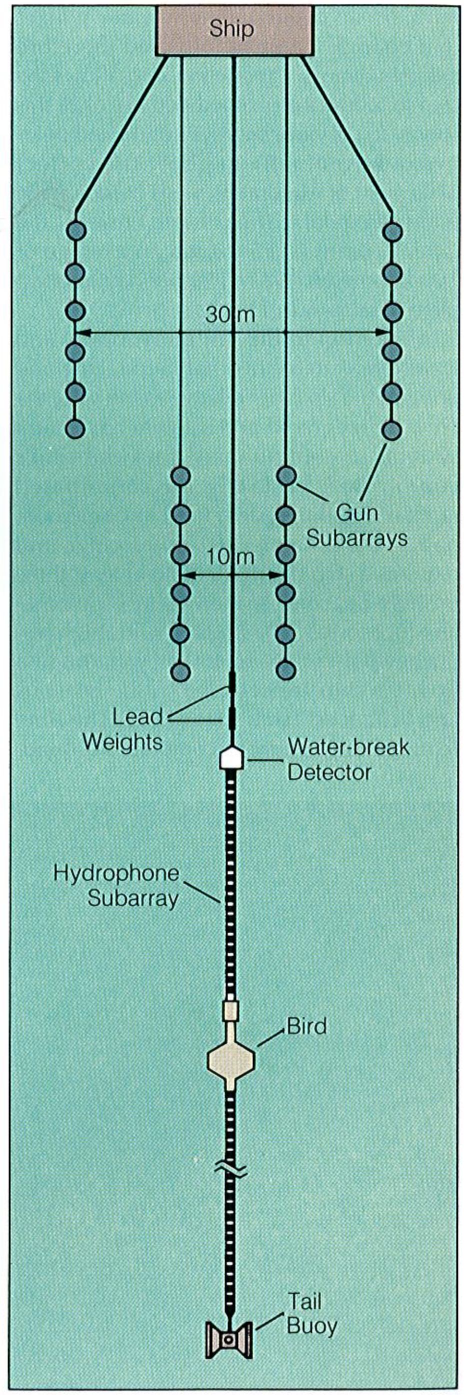
□Coiled streamer cable with hydrophones ready for a survey. The streamer cable is filled with oil to control its buoyancy. In the foreground is the tail buoy used to monitor streamer position.

In Cameroon, the sources were positioned in four subarrays, each containing six guns evenly spaced over 18.5 meters [61 feet], the leading two separated by 30 meters [98.4 feet] and the trailing two separated by 10 meters [32.8 feet] (*below right*). One hundred forty-five meters [475.6 feet] behind the sources, hydrophones arranged in 240 subarrays of 20 were spaced in 12.5-meter [41-foot] segments along the cable to form a 3,000-meter [9,840-foot] streamer. This yields a higher hydrophone density, and hence greater resolution than previous seismic surveys conducted in the region, which used only 96 groups of 15 hydrophones spaced 25 meters [82 feet] apart to form 2,400-meter [7,872-foot] streamers.

Before reflected seismic waves are recorded on magnetic tape, they are converted from analog to digital signals by measuring the incoming signals at discrete time intervals. The reciprocal of the sampling interval is the sampling frequency and one half is the so-called Nyquist frequency. The Nyquist frequency represents the highest frequency that can be defined accurately by a given sampling interval. Previous seismic data were sampled every 4 milliseconds (ms) corresponding to a Nyquist frequency of 125 Hertz (Hz). The GECO data, sampled every 2 ms, have a Nyquist frequency of 250 Hz. The highest frequency actually recorded in either case, however, is less than the Nyquist frequency because of analog filters applied to remove noise from the traces. Because desirable seismic information occurs at frequencies up to at least 100 Hz, the 64-Hz high-cut filter applied to the previous seismic data attenuated important information but the 180-Hz high-cut filter applied to the Douala Basin data did not.

Navigation

It takes a day to set up the streamers and ensure that the guns fire properly, the hydrophones work and produce traces and that the cable is free of disruptive electrical noise. Prior to the survey, GECO frequently tests different gun arrays to determine the best one—higher frequency sources for fine resolution or lower frequency sources for greater depth penetration. Once the survey begins, the seismic crew works around the clock monitoring the position of the streamers and tracking the coordinates of the ship, an especially challenging task in cross cur-

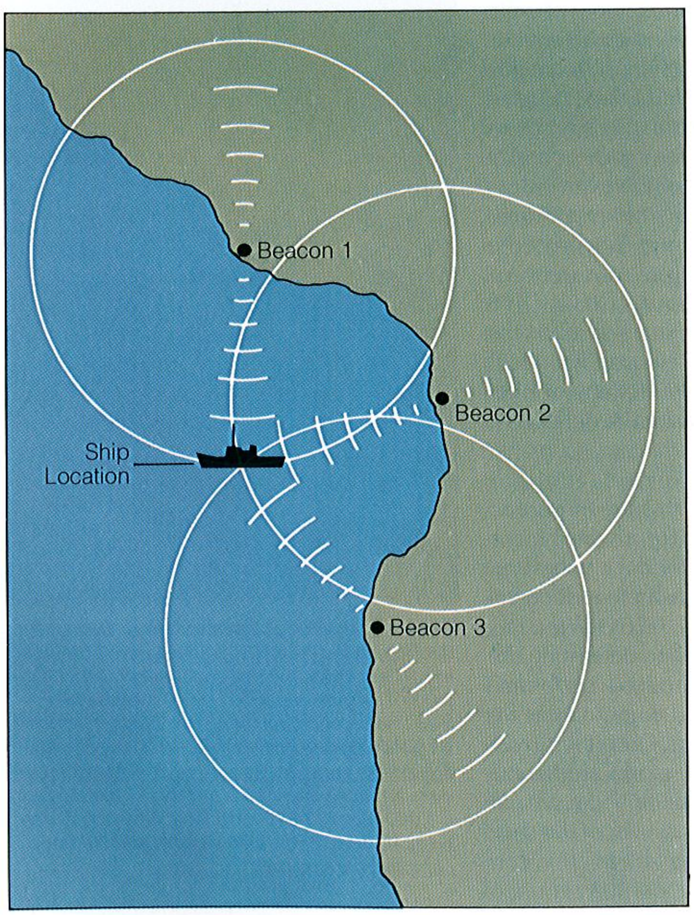


□Layout of source and hydrophone subarrays for the Douala Basin survey. Sources were positioned in two subarrays, the first containing two parallel pairs of six guns separated by 30 meters [98.4 feet], the second containing two parallel pairs of six guns separated by 10 meters [32.8 feet]. Behind the guns, 240 groups of 20 hydrophones were arranged every 12.5 meters [41 feet] to form a 3,000-meter [9,840-foot] long streamer. Water-break devices, birds, lead weights and tail buoy complete the streamer.

rents, ocean swells and fresh water influxes that change water salinity and therefore cable buoyancy. Precise tracking allows the ship to follow the planned grid, to relate this survey to previous surveys conducted nearby, and eventually to allow the correct placement of exploration wells based on the interpreted data. The seismic crew for the Douala Basin NEPS logged an average of 109 kilometers [68 miles] per day to complete the survey in 11 days.

In addition to the tail buoy, birds, and water-break detectors that help locate and position the streamer relative to the ship, the crew utilizes radio and satellite navigation systems to continuously track the ship's coordinates. SYLEDIS,[2] the shore-based radio navigation system used in Cameroon, has a 100-kilometer [62-mile] range and requires a ship tranmsitter and at least three onshore beacons, spaced 10 to 15 kilometers [6.2 to 9.3 miles] apart. Ultrahigh frequency pulses (400 to 450 megahertz) sent from the ship are detected by the beacons and broadcast back to the ship. The time required for a signal to complete its round-trip determines the ship-beacon distance. The intersection of arcs representing distances between the ship and the beacons determines the ship's location within an accuracy of 5 to 10 meters [16.4 to 32.8 feet] (*below*). Factors that may affect the operation of SYLEDIS are the shape of the shoreline, elevation of the onshore beacons, broad-leafed trees near the beacon that deflect signals, and interference from nearby vessels or aircraft. Other shore-based navigation systems that sacrifice accuracy for increased range compare the phase difference between arriving signals from different beacons. Throughout the survey, a shipboard computer records all navigation data to optimize the ship's position with respect to the seismic line.

As a navigational backup in Cameroon and to establish coordinates for onshore beacons, GECO tapped the NAVSTAR Global Positioning System (GPS)[3], a four-satellite navigation system that functions only a few hours a day. Like SYLEDIS, GPS relies on measurement of travel times, in this case the time for a signal emitted from the satellite to reach the ship's receiver. Four satellite passes are needed to fix the ship's three-dimensional coordinates. The accuracy of GPS is 10 to 20 meters [32.8 to 65.6 feet]. A second satellite navigation system called Transit[4] is sometimes tapped, but has inaccuracies of 100 to 150 meters [328 to 487.5 feet]. To calculate a position with Transit, an onboard receiver measures the Doppler effect, or frequency shift, detected in signals emitted by a satellite with known trajectory.



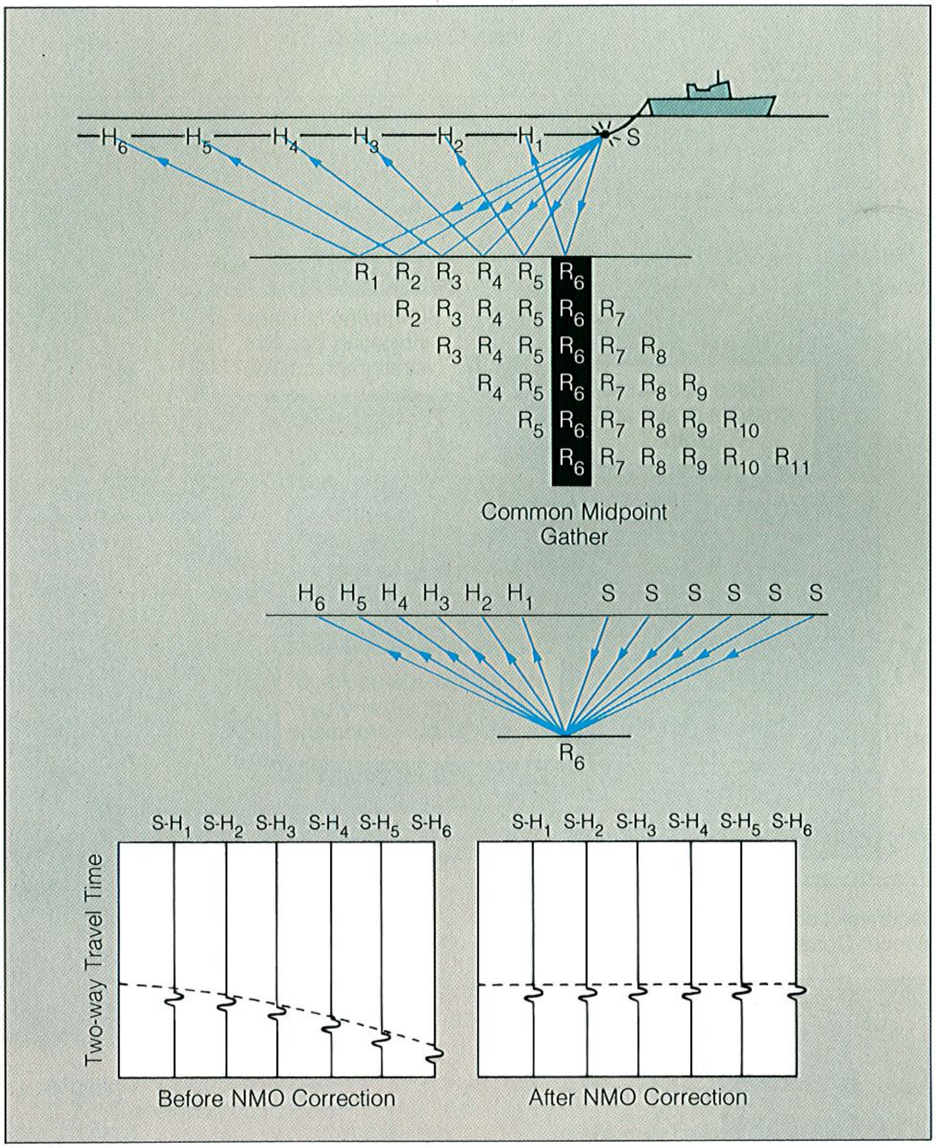
A shore-based radio navigation system. Ultrahigh frequency signals (400 to 450 megaHertz) emitted from the ship are received at onshore beacons and rebroadcast. The time required for the signal to return to the ship gives the ship-beacon distance. The intersection of arcs representing distances between the ship and beacons fixes the ship's position. At least three beacons are needed to achieve an accuracy of 5 to 10 meters (16.4 to 32.8 feet).

Processing Seismic Data

Following the processing performed on GECO's seismic survey of the Douala Basin, which occurred at centers in Dubai and London to shorten the procedure to 12 weeks, shows how seismic data are prepared for interpreters. Once seismic signals are recorded, the processors remove artifacts from the data and improve their signal-to-noise ratio.[5] Two kinds of noise plague seismic recordings: coherent noise generated by sources, and incoherent (or random) noise generated by wave action, marine life and other boats. Some of this noise can be attenuated by adjusting the spacing of hydrophone subarrays and the gun array, and by applying filters during recording. Remaining noise and artifacts, such as multiple reflections between beds, must be attenuated during processing.

Processing begins with editing the traces to mute or remove those with unusually high noise and correct those with reversed polarity. Next, a source signature compensation, or designature, is applied. This compensates for the signal of the air gun array, which although carefully arranged and tested, does not produce an "ideal" signal containing equal components of all frequencies. Processors generate a mathematical operator that converts the actual seismic source signature into a more ideal pulse. Then, the operator is applied to shape the data into the response of this more desirable signal passing through the earth.

Because some signal processing steps are time-consuming and therefore costly, the initial volume of recorded data is frequently reduced early by summing adjacent traces. This halves the volume of data—from 240 to 120 traces in the case of the Douala Basin NEPS—and increases the signal-to-noise ratio. Two-dimensional filters, also known as velocity filters or frequency-wavenumber (*f-k*) filters, reject noise events with known velocities such as ground roll[6] in land seismics and towing noise in marine seismics.



□*Common midpoint gather. As the ship towing source and hydrophone arrays navigates a seismic line, different source-receiver combinations reflect off the same midpoint. Once the traces from these different combinations have been adjusted for differences in offsets—the normal moveout (NMO) correction—the signals can be added, or stacked, to improve the signal-to-noise ratio.*

Another important step is deconvolution, which compensates for the filter characteristics of the earth.[7] Deconvolution involves designing and applying filters that are the inverse of the "earth filter." They remove multiple reflections from the data and convert waveforms filtered by the earth into simpler pulses.

The next and most important improvement in signal-to-noise ratio comes from stacking, or combining, reflections off the same midpoint from different source-receiver distances, called offsets (*above*). As the source-receiver offset increases for a common midpoint, so does the length of the travel path and therefore the travel time. In stacking, this increment in travel time with offset—the normal moveout (NMO)—must be accounted for.

NMO corrections are determined by comparing the stack output using a range of average velocities for the subsurface rock. From these comparisons, the optimum stacking velocity for any point on the seismic line can be found. The NMO corrections, or time shifts, are applied to the traces to simulate having all the sources and receivers coincident (zero offset). The corrected traces can then be stacked. Because the NMO correction assumes horizontal layers (dipping layers cause the NMO-derived velocity to be anomalously high),

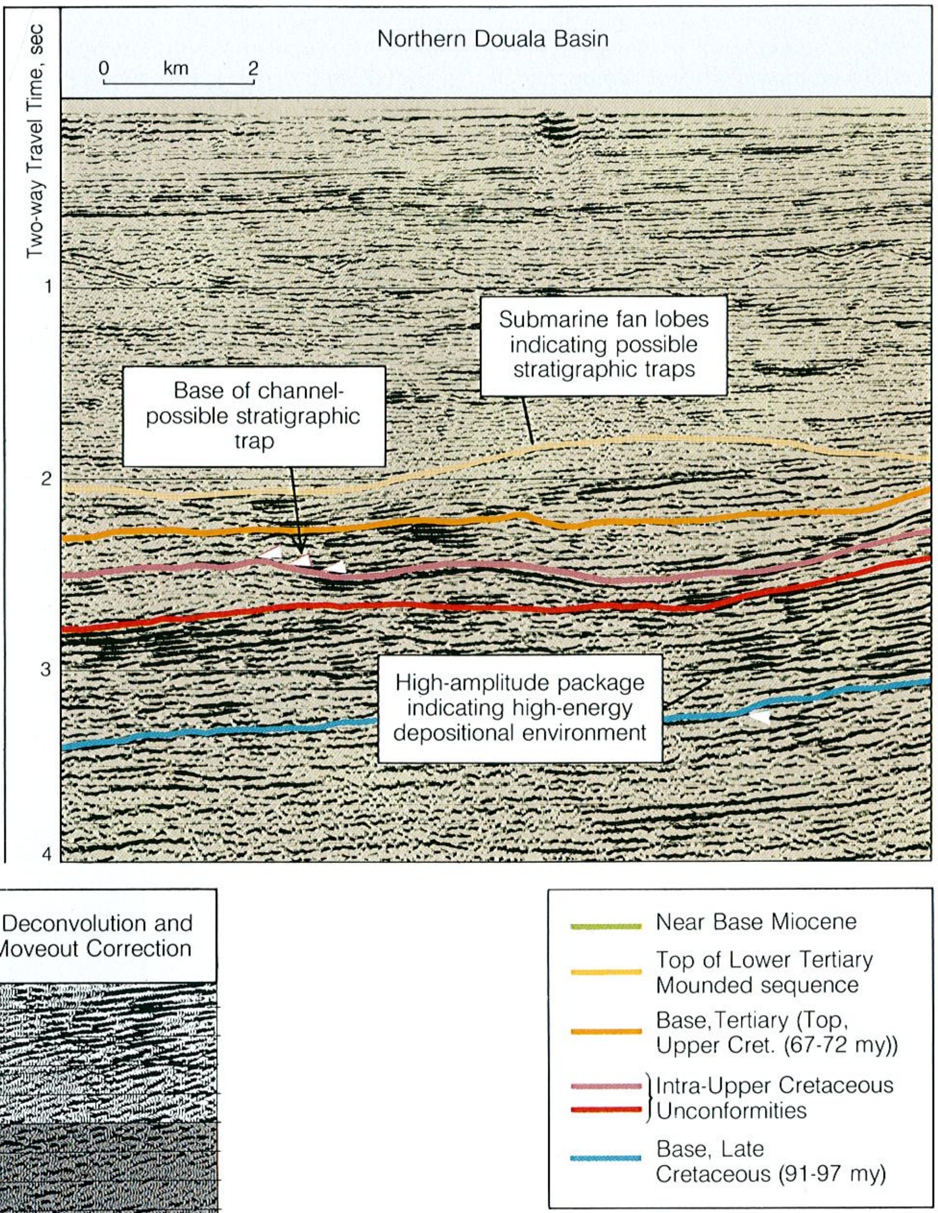
2. Mark of Sercel-France
3. Operated by the United States Department of Defense.
4. Developed by the US Navy in 1960, Transit will eventually be replaced by GPS.
5. For a detailed discussion of signal processing: Hatton L, Worthington MH and Makin J: *Seismic Data Processing: Theory and Practice.* London: Blackwell Scientific Publications, 1986.
   Yilmaz Ö: *Seismic Data Processing.* Tulsa, Oklahoma: Society of Exploration Geophysicists, 1987.
6. Ground roll refers to low-frequency, low-velocity surface waves that obscure reflections on seismic records.
7. For a detailed discussion of deconvolution: Ziolkowski A: *Deconvolution.* Boston: International Human Resources Development Corporation, 1984.
8. Berg LE: "Pre Stack Partial Migration," presented at the 1984 SEG 54th Annual Meeting, Atlanta, December 2-6.

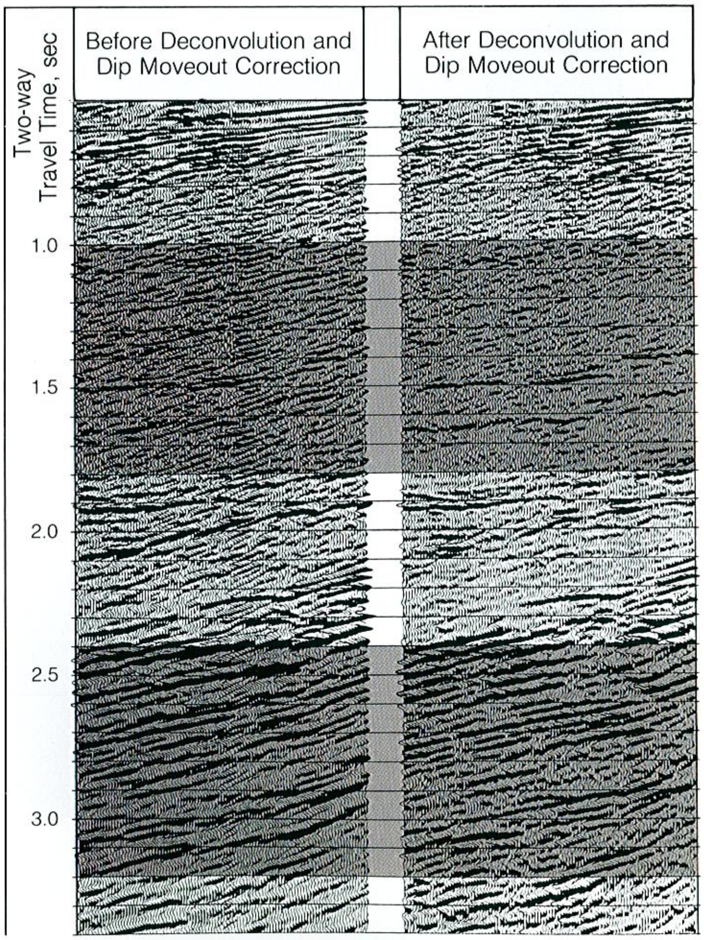
GECO developed a dip moveout correction that must be applied before stacking to correct for dip.[8] A comparison of processed seismic sections with and without dip moveout correction, also known as partial prestack migration, and deconvolution shows their dramatic impact on resolution (*below*).

The last major processing activity is migration, which moves dipping reflectors to their true postions (*below right*). This step is necessary because reflections on a stacked seismic trace appear to be directly below the midpoint of the source-receiver offset regardless of the true position of the reflecting surface. The final product of all the processing is seismic sections, vertical slices through the earth providing a window on the subsurface geology.

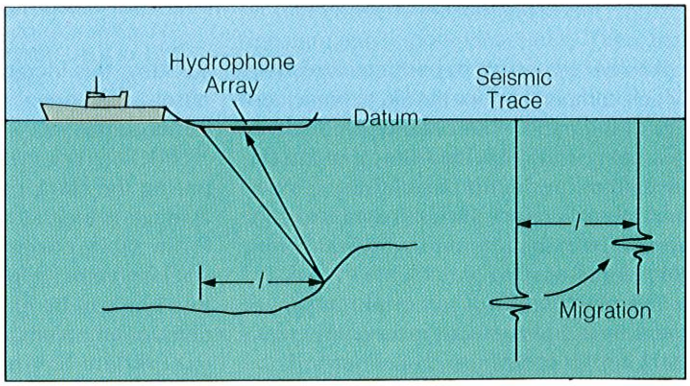
Interpretation: Oil in the Douala Basin?

Interpreters of the Douala Basin sections aim to establish the area's geologic history and stratigraphy. The bottom line, however, is to assess the likelihood that hydrocarbons were generated in the basin and subsequently trapped.[9]

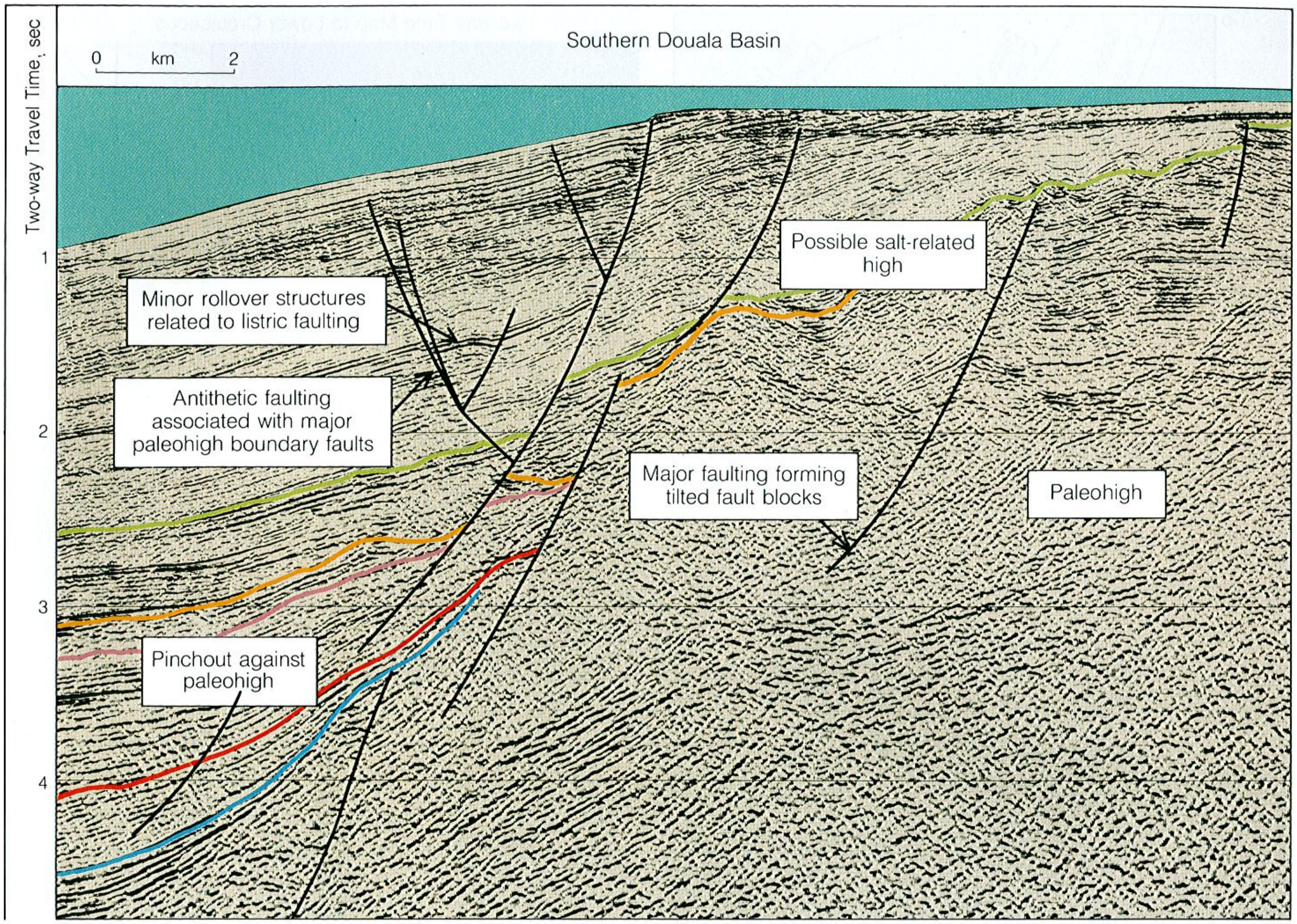




□*Comparison of Douala Basin seismic data before and after dip moveout correction and deconvolution. At about 1.5 seconds, reverberations obscuring the reflections on the left are reduced on the right. The right panel also shows improved resolution and continuity from 2.4 to 3.2 seconds.*



□*Migration adjusts the location of events on the seismic trace to account for dipping reflectors.*



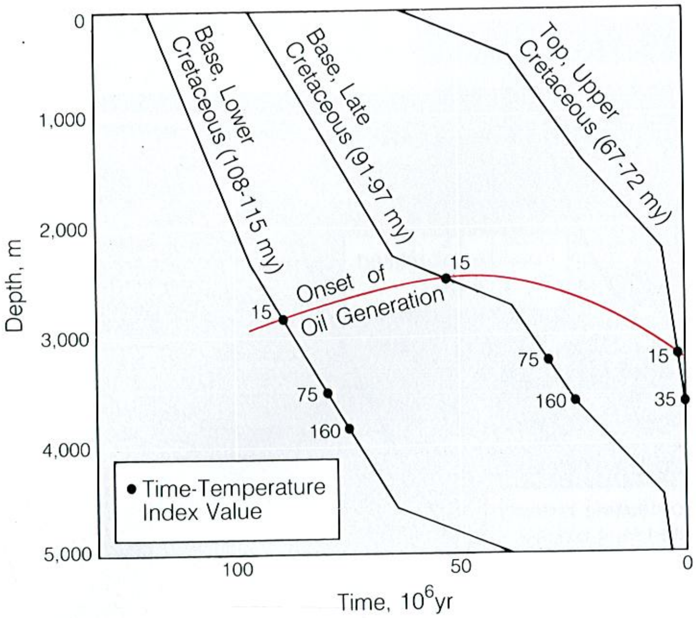
□*Interpreted seismic sections of the northern Douala Basin (above left) and southern Douala Basin. The colored horizons mark the boundaries of depositional sequences. These unconformities are identified on the seismic section by terminations (arrows) of reflectors above and below the unconformities. In the northern Douala Basin, stratigraphic traps dominate the section with submarine fan lobes in the Lower Tertiary mounds and an Upper Cretaceous unconformity forming the base of a channel. In the southern Douala Basin, structural traps are evident, ranging from a salt-related high, minor rollover structures associated with listric faulting and an Upper Cretaceous pinchout against a paleohigh.*

GECO interpreters begin their work during processing when they advise the processors of geologic features to expect on the seismic traces. Then with the resulting seismic sections in hand, they identify and date geologic unconformities, which separate depositional sequences and provide the key to understanding the basin's structural evolution (*above*). Dating the horizons involves combining all well data including biostratigraphical, petrophysical and geochemical information. After dating the structures, interpreters concentrate on identifying the lithology and sedimentology of the depostional sequences.

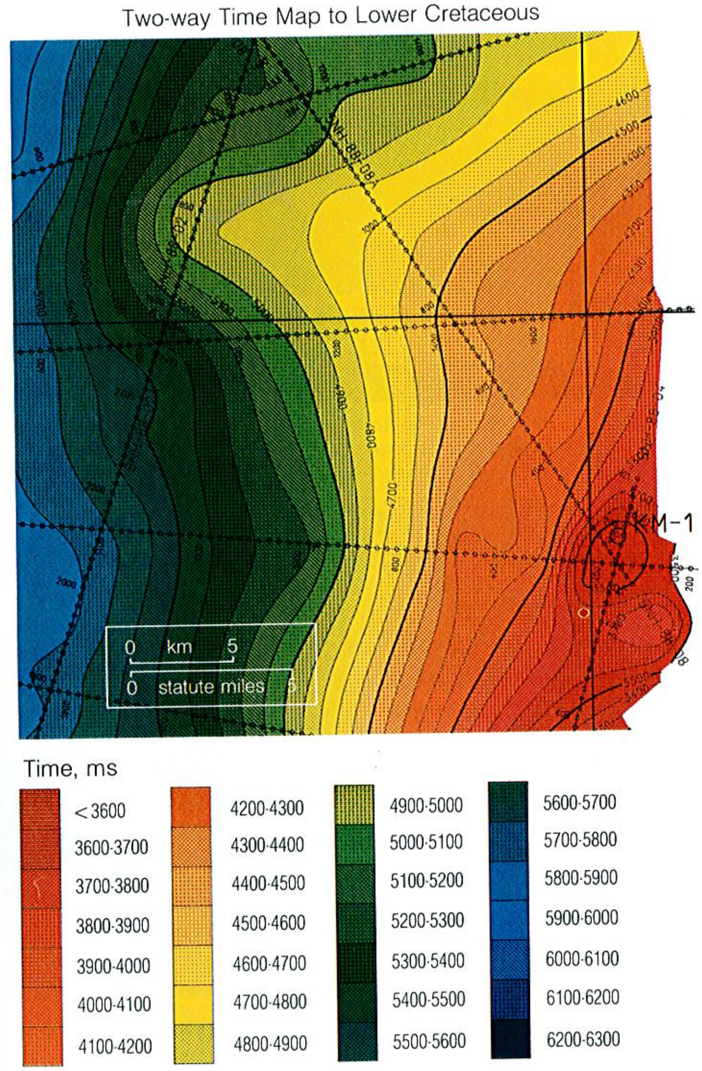
For hydrocarbon rock to be present there has to be source rock. Interpreters estimate the maturity of potential source rock using burial history curves,[10] which are derived from well data or estimated directly from interpreted seismic data (*next page, top*). (See also "The Earth's Heat," *page 54*.) These plots of age versus depth for particular formation tops allow interpreters to estimate the thermal history of rock layers. A Time-Temperature Index (TTI) accounts for the amount of time a horizon has spent at particular depths, assuming a constant geothermal gradient, taken in this region to be 35°C/km [29°F/1,000 ft]. A TTI of 15 represents the onset of oil generation and 75 the peak of oil generation; values above 160 indicate "cooked hydrocarbons" and dry gas. In the Douala Basin, a TTI of 35 for the top of the Upper Cretaceous (67 to 72 million years) is reached at a depth of 3,600 meters (11,808 feet) corresponding to an approximate two-way travel time of 2.3 seconds on the seismic section of the northern Douala Basin (*top, far left*).

After determining that the Douala Basin's thermal history favors oil generation, the

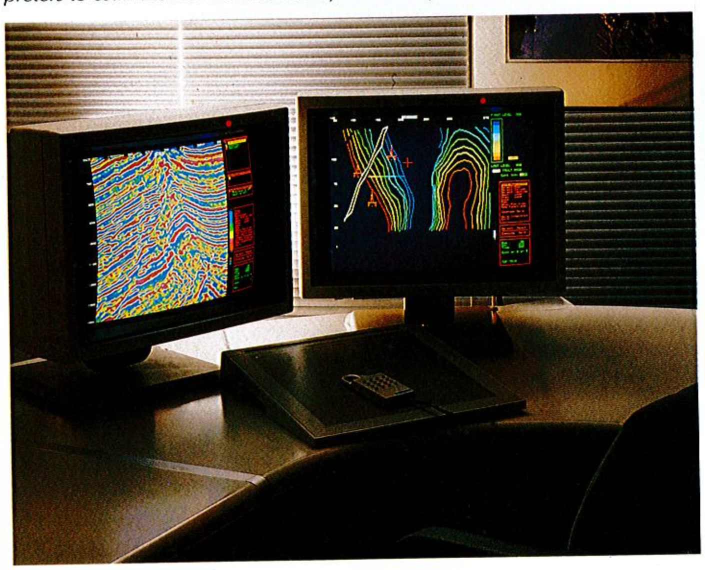
9. For a detailed discussion of seismic interpretation: Badley ME: *Practical Seismic Interpretation.* Boston: International Human Resources Development Corporation, 1985.
10. Waples DW: "Time and Temperature in Petroleum Formation: Application of Lopatin's Method to Petroleum Exploration," *AAPG Bulletin* 64 (1980): 916-926.



□*Burial history curve used to assess the maturity of potential source rocks. These plots of age versus depth for particular formation tops allow interpreters to estimate the thermal history of rock layers.*



□*Two-way travel time map to the Upper Cretaceous for the Douala Basin. The roughly circular contour (right) constitutes possible closure and may be a hydrocarbon trap, but an additional seismic survey with finer grid spacing is needed to further investigate its potential.*



□*Charisma-II interactive workstation. The left screen displays the seismic data while the right one shows a contour map. Following reflection horizons from line to line, posting two-way travel time values and contouring is at least four times faster on the workstation than by hand. To aid interpretation, Charisma workstations can also emphasize certain attributes of seismic data such as instantaneous phase or frequency.*

next step is to hunt for structural and stratigraphic traps. Using the available grid of seismic lines and the corresponding seismic sections, interpreters follow a reflection horizon from seismic line to seismic line, posting values for the two-way travel time, and contouring the travel-time values. Any horizon showing closure on the contour map is a candidate for trapping hydrocarbons (*above right*).

Following horizons from line to line, posting two-way travel time values by hand and contouring them is a painstaking process. Cutting the time this takes by a factor of four is GECO's Charisma-II‡ interactive interpretation workstation. This system can hold all seismic sections from two- or three- dimensional surveys in one database displaying the sections on one screen and displaying contour maps on a second screen (*above left*).[11] As the interpreter follows a particular horizon on the seismic section with a cursor, the color-coded contour map for that horizon is constructed simultaneously on the other screen. When the interpretation is complete, the system can produce a color hard copy of the map. The Charisma-II workstation can also display different seismic attributes such as instantaneous phase or frequency, which allows interpreters to resolve stratigraphic details, and time-thickness maps, which show the horizontal and vertical extent of particular seismic sequences.

The Douala Basin NEPS indicates good prospects for oil discoveries, and so far a significant number of oil companies have purchased the data in preparation for acquiring blocks. Additional seismic surveys with finer grid spacing are needed to resolve many of the hydrocarbon leads established in the Douala Basin NEPS. GECO is also reprocessing selected lines from previous seismic surveys to enhance their interpretability and tying them to their own database. The Cameroonian government, meanwhile, is finalizing licensing agreements.

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11. Miller PF: "GECO's Interactive Interpretation Work Station," presented at the Canadian Society of Exploration Geophysicists 1983 National Convention, Calgary, April 26-28.

‡ Mark of GECO