lain by the oolitic grainstones of the Mississippian St. Louis Formation. Three distinct Chappel facies can be identified: the bank core, flank, and interbank facies. The bank core is composed of crinoid-fenestrate bryozoan mudstones and wackestones; the flank consists of crinoid-bryozoan grainstones and packstones; and the interbank consists of argillaceous sponge spicule mudstones with minor crinoid and bryozoan debris. Chert is a major constituent of the interbank facies but decreases in amount toward the bank core.

Bank growth began in a low-energy environment with the mechanical accumulation of lime mud which was baffled and trapped by crinoids and fenestrate bryozoan. Once the bank core reached wave-base, the crinoid-bryozoan mudstones and wackestones were reworked and redeposited as the crinoid-bryozoan grainstones and packstones of the flank facies. The extensive development of the flank facies, compared with bank core development, indicates that the top of the bank remained at or near wave-base for an extended period of time.

Porosity development in the Chappel banks is secondary and results from dolomitization of the micritic bank core, fracturing and leaching. Although the crinoid-bryozoan grainstones of the flank facies were originally porous, primary intergranular porosity is now absent because of epitaxial cementation.

The Chappel banks can be located in the subsurface by using isopach maps which help identify interval thickening within the Chappel. In addition, thinning, shown by the isopach intervals on horizons immediately overlying the Chappel Formation, can also be used to delineate the presence of these bank deposits.

In subsurface exploration, the bank facies can be differentiated from the interbank facies by petrographic analysis and by noting the more "massive" and also lower gamma ray log response. The lower gamma ray log response is caused by a lack of argillaceous material in the bank facies.

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## Late Eocene to Early Oligocene Calcareous Nannoplankton Biostratigraphy and Biogeography

The extinction of *Discoaster barbadiensis* and *D. saipanesis*, the last representatives of the highly successful low- and mid-latitude group of Paleogene rosette-shaped discoasters, close to the Eocene-Oligocene boundary, has been unfortunately seen by some as evidence of a major extinction "event" in the calcareous nannoplankton. These extinctions (and a few others that occur at about the same time) should be more properly viewed against the larger background of calcareous plankton biostratigraphy and paleobiogeography.

A compilation of DSDP Paleogene calcareous nannoplankton data from low, middle, and high latitudes shows maximum diversity values (ca 120 species) during the middle Eocene (NP14-15) and minimum diversity values (ca 37 species) in the early Oligocene (NP22). The approximately 70% reduction in diversity occurs over an interval of approximately 7 m.y. in a stepwise fashion with the most abrupt reduction (~50%) occurring between the late middle Eocene (NP16) and the early late Eocene (NP18). A further reduction of about 20% occurs across the Eocene-Oligocene boundary (NP18 to NP22), and the values for the remainder of the Oligocene (NP23-25) stabilized at about 50+ species.

A quantitative investigation has been made of late Eocene-early Oligocene calcareous nannoplankton assemblages at 4 DSDP sites in the North (Site 292, 16°N) and South (Site 277, 52°S) Pacific, Indian (Site 219, 9°N) and South Atlantic (Site 363, 20°S) Oceans. An equatorward migration of high latitude floral assemblages occurred during the late Eocene and early Oligocene. This migration was initiated in the late middle Eocene (NP16-17) and the replacement of a tropical flora (dominated by discoasters and *Reticulofenestra reticulata*) by mid-high latitude assemblages (dominated by reticulofenestrids, *R. bisecta, R. hesslandi, R. umbilica, R. hampdenensis*) was not completed until the early Oligocene (NP22; see Figure 1). The extinction of the rosette-shaped discoasters and *R. reticulata* is related to the late Eocene-early Oligocene isotopic cooling event but does not reflect its maximum. These species became extinct when sea surface temperatures reached a threshold value below which they could not survive.

| Sites | Age | *Reticulofenestra reticulata* | *Reticulofenestra bisecta; R. hesslandii; R. umbilica* s. l. (%) | *Reticulofenestra* gr. *R. hampdenensis* (%) |
|---|---|---|---|---|
| 219 | early Oligocene NP21-22 | | ≈ 25°/° | 0°/° |
| (≈9°N) | late Eocene NP18-NP19 | up to 30°/° LAD at the E/O boundary | 5°/° | 0°/° |
| 292 | early Oligocene NP21-22 | | ≈ 25°/° | ≈ 5°/° |
| (≈16°N) | late Eocene NP18-NP19-20 | ~ 15°/° LAD well below the E/O boundary | 12°/° | 0°/° |
| 363 | early Oligocene NP21-22 | | very poor recovery | |
| (≈20°S) | late Eocene NP18-NP19-20 | LAD in the late middle Eocene | ≈ 25°/° | ≈ 10°/° |
| 277 | early Oligocene NP21-22 | | ≈ 17°/° | ≈ 45°/° |
| (≈52°S) | late Eocene NP18-NP19-20 | | ≈ 30°/° | ≈ 30°/° |

Migrations of species of *Reticulofenestra* from high latitudes toward low latitudes during late Eocene/early Oligocene interval. *R. reticulata* is a warm-water taxa, whereas *R. bisecta*, *R. hesslandii*, *R. umbilica*, and *R. hampdenensis* are cold-water taxa. As percentages show, the proportions of these latter forms increase at lower latitudes through late Eocene/early Oligocene, as intensity of the isotopic cooling increases.

Isotopic records on benthic and planktonic foraminifera from the same sites (Keigwin, work in progress) show a strong parallelism between climatic changes (sharp cooling in the late middle Eocene, at the Eocene-Oligocene boundary, maximum cooling within the earliest Oligocene) and calcareous nannoplankton migrations. The extinctions of the *Reticulofenestra umbilica* group and equilibrium within the floral migration patterns in the calcareous nannoplankton coincide with the maximum isotopic cooling event in the earliest Oligocene. Our data indicate that extinctions among the calcareous nannoplankton occurred in sequential, step-like manner over a several million year interval. They may best be explained as reflecting the gradual but clearly defined trend towards decreasing temperature values during the late Eocene to early Oligocene.

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## Use of Synthetic Sonic Logs Derived from Seismic Data in Interpretation of Stratigraphic Variation in Cretaceous Carbonates of North Field Area, Qatar

This study uses geologic and synthetic sonic sections to evaluate the hydrocarbon potential of the Lower and middle Cretaceous Thamama Group carbonates of the Mishrif, Nahr Umr, Shuaiba, and Kharaib Formations in the North field, Qatar. The North field area, a regional high throughout Lower and middle Cretaceous time, is documented by depositional thinning and by higher energy carbonate facies development. Oil and gas accumulations are found on the crestal portions of this paleohigh in structural/stratigraphic traps.

The synthetic sonic program produces a series of synthetic sonic logs from real seismic traces. It is a powerful addition to the conventional seismic section because it monitors additional parameters of seismic continuity and rock properties in what otherwise is a relatively structureless subsurface carbonate terrain.

Detailed studies of seven regional synthetic sonic lines across the North field area indicate that significant decreases in interval velocities occur in all of the studied carbonate reservoir formations. Three factors affect the interval velocities on both a regional and local basis. These are (1) variation of carbonate facies- higher energy wackestone/packstone and possibly grainstones flanked by predominantly mudstones, (2) secondary porosity developed near the top of unconformity surfaces, and (3) the existence of hydrocarbons in the reservoir.

Many local lateral and vertical variations in interval velocities were noted on the synthetic sonic sections that would have otherwise been undetected, such as areas of tight or porous reservoir development, permeability barriers, and subtle faulting. In these studied formations, there are many examples of low interval velocity zones that are known to contain hydrocarbons whereas equivalent higher interval velocity zones on the seismic sections at other well site locations do not contain hydrocarbons. In many places, these variations are of sufficient magnitude to be mapped as intraformational permeability barriers. These variations were useful in explaining the occurrence of different oil-water and gas-water contacts within the same formation that could not be explained solely on structural criteria.

It can be concluded from this field study of the North field, Qatar, that the synthetic sonic technique is a particularly useful exploration tool in carbonate reservoir environments because it is able to delineate areas of higher exploration potential. The geologist can use these data in areas of known well control to project carbonate reservoir variation in areas where log or petrographic information is not available.

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## Analysis of Hydrocarbon Potential of Outer Continental Shelf, Slope, and Rise of the Niger Delta, Nigeria, from Seismic and Geological Data

Whereas hydrocarbon potential studies of most parts of the Nigerian sedimentary regions have been documented, no similar assessment has yet been made for the outer continental shelf (OCS), slope, and rise of the Niger delta. The shelf, slope, and rise of the delta are frontier areas in which no wells have been drilled to date.

For this broad evaluation of hydrocarbon potential of the deep-water Niger delta, six published seismic sections were reviewed in conjunction with available geological information and geophysical data.

On the basis of an assumed average velocity of 2.0 km/sec, the seismic data indicate a sedimentary thickness of about 2 km (1.3 mi) in the deeper portions of the rise. This thickness increases shoreward to more than 3 km (1.9 mi) at the foot of the continental slope and 5 to 7 km (3 to 4.3 mi) beneath the outer continental shelf.

The distal relationship of the OCS, shelf, and rise to the sedimentary discharge of the Niger delta have made these areas of essentially deep-water marine sediments. With the high organic carbon content commonly associated with these areas, the thick shales in this distal deltaic environment would be very rich in kerogen. Coarse-grained clastics are identifiable on the seismic sections by their distinct and continuous reflection character. These potential reservoirs are common and widespread on the shelf and rise. The reservoir rocks occur as deep-sea fans, turbidites, canyon fills, and as onlap fills between diapiric intrusions, and are enclosed by shale, thus providing favorable conditions for the formation of stratigraphic traps. The diapirism in the slope and outer shelf provides favorable conditions for structural traps.

The tectonic origin of the Niger delta area implies a history of initially high geothermal gradients which decreased with time as the margin moved farther away from the Mid-Atlantic Ridge. The geothermal gradient map of the Niger delta indicates higher values for the OCS relative to the onshore and shallow-water areas where rapid sedimentation has depressed the geothermal gradients. The general increase of geothermal gradients toward the mid-ocean ridges would also provide gradients much higher than the 1.8°F/100 ft of the shallow shelf and probably approaching the 3.0°F/100 ft of the Anambra basin region. These gradient ranges are sufficient to mature the kerogen of the oldest shale source rocks (more than 40 m.y.) and to generate hydrocarbons within even the thinnest (2 km, 1.2 mi) sediment observed. In the areas of thin sediment, hydrocarbon potential would be appreciably increased in the vicinity of oceanic fracture zones where geothermal gradients are locally high. The hydrocarbon potential increases shoreward as sedimentary thickness increases and is very significant in the upper rise, the slope, and the OCS.

The decline in giant field discoveries in the Niger delta is a pointer to the depletion of Nigeria's onshore and shallow-water oil reserves. The continuing increase in world oil demand in the face of dwindling reserves and the steady improvement in deep-water drilling technology combine to make future petroleum exploration and production economically promising in Nigeria's high-potential deep-water frontier.

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## Reflection Seismogram in a Solid Layered Earth

Current approaches to seismic data processing and interpretation ignore the change in reflection coefficient with incident angle. The justification is typically based on fluid earth models or models in which the ratio of compressional velocity to shear velocity ($C_p/C_s$) is assumed constant. In clastic basins, normal incidence reflectivity is low, and variations in $C_p/C_s$ can be significant. Under these conditions the change in reflection coefficient with incident angle can be very significant. Replacement of the plane wave normal incidence synthetic seismogram with the point source solid earth synthetic seismogram is likely to lead to important changes in our approach to acquisition, processing, and interpretation of seismic reflection data.

The accompanying figure shows a sample solid earth synthetic seismogram. In this example, a change from brine to gas produces a dim spot on the near traces, a bright spot on the far traces, and a polarity reversal on the stacked section. The CDP stacked trace should be different from our conventional normal incidence synthetic seismogram.

In general, in a clastic basin, we might expect to see a different set of rocks emplasized on partial stacks from different offset ranges. The sensitivity of our solid earth synthetic seismogram to changes in Poisson's ratio is such that we suggest that conventional reflection data in clastic basins should permit the extraction of band-limited shear impedance logs as well as compressional impedance logs. Attempts to work only with the CDP stacked data should yield a "hybrid impedance log;" a mix-