EVIDENCE OF A CARBONATE PLATFORM BENEATH GEORGES BANK

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ABSTRACT


The subsurface of the New England continental margin beneath Georges Bank contains a Jurassic and Cretaceous carbonate platform that interfingers landward into and is stratigraphically sandwiched between clastic wedges of deltaic origin. The seaward edge of the platform is a presently buried precipitous up to 5 km high wall that resembles the modern Bahama Escarpment. The platform edge and its younger cover have been sampled by submersible and dredging where they outcrop locally in submarine canyons. There is no evidence of a major vertical tectonic displacement beneath the continental slope and the ocean. Subsidence has been continuous and regional, commencing with listric faults in stretched brittle continental lithosphere and diminishing in rate with the square root of time primarily in respond to thermal cooling and flexure from the sedimentary overburden.

INTRODUCTION

The continental slope of the passive-type margin of the North Atlantic is particularly steep off New England (Emery and Uchupi, 1965). Here it is incised by numerous submarine canyons (Stetson, 1936). Some of the canyons expose the bedrock of the continental shelf and provide windows into the stratigraphic history of the margin (Uchupi et al., 1977). Seismic reflection profiles show that the present continental slope overlies a much steeper paleoslope that effectively truncates deeply buried strata beneath the shelf (Schlee et al., 1976). The buried slope resembles morphologically the modern Bahama Escarpment, except that off New England it is buttressed by the prism of continental rise sediments and at the Bahamas the escarpment is free standing. The precipitous nature of the paleoslope is a clue that the New England margin might contain an ancient carbonate platform (Austin et al., 1980). The presence of carbonates was not unexpected (Schlee, 1978) because limestones had been drilled to the north beneath the Scotian shelf.

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where they comprise the thick Abenaki Formation of Jurassic age (McIver, 1972; Jansa and Wade, 1975).

FIELD WORK

In 1977 we carried out exploration of three New England submarine canyons around the perimeter of Georges Bank in an attempt to sample the continental-margin bedrock (Ryan et al., 1978). Precise sampling was accomplished using the deep diving submersible “Alvin”. The Georges Bank sampling took place in Heezen, Oceanographer and Corsair canyons. The dive transects used canyon thalwegs to find exposures of Mesozoic strata that had been mapped previously with a dense network of seismic reflection profiles obtained by the U.S. petroleum industry (David Hanselmann, personal communication). Figure 1 shows the location of four reflection profiles that have been published and therefore are not proprietary information (Grow and Schlee, 1976; Given, 1977). Figure 1 also shows the geological column obtained by drilling the Mohawk-B-93 and Naskapi N-30 wells (Williams et al., 1974) on the southwestern Scotian shelf. The seismic stratigraphy of the Scotian margin was initially developed by Jansa and Wade (1975), revised by Given (1977) and extended southwards to Georges Bank by Wade (1977). In this paper we follow the reflector nomenclature of Wade (1977) and calibrate the seismic horizons, where possible, by the submarine canyon sampling.

RESULTS

Horizon $K_o$ corresponds to the “O” marker level of Barremian age in the Missisagua Formation beneath the Scotian shelf. This horizon can be traced southward through the Mohawk well where it corresponds to the top of the limestone-bearing Roseway Unit developed above LeHave platform. Strata of similar lithofacies to the Roseway Unit were found in Heezen Canyon (Ryan et al., 1978). They can be stratigraphically calibrated to USGS Line 4 comprising a section from 1400 to 1850 m below sea level at the shelf edge. Heezen canyon is located on the eastern side of Yarmouth Arch. The 180 m thick interval sampled and photographed at Heezen canyon contains bioclastic and algal-bearing limestones formed in high-energy environments ranging from patchreefs to beaches (Ryan et al., 1978). Beneath the Scotian shelf, open marine carbonate platform deposition begins in the Middle Jurassic with the base of the Abenaki Formation (McIver, 1972). The marine transgression is expressed by the widely distributed Scatarie Limestone Member which exhibits a conformable relationship to underlying continental and deltaic sediments of the Mohawk Formation of Jansa and Wade (1975) or the revised Mohican Formation of Wade (1977).

Horizon $J_4$ correlates with the Scatarie Member and is considered to be Callovian in age (Williams et al., 1974). Horizon $K_a$ is Albian–Aptian in age in the Shell Naskapi well. Over much of the Scotian margin and Georges Bank Horizon $K_a$ is an erosional hiatus. Horizon $K_a$ is correlated at the shelf
Fig. 1. Acoustic and lithostratigraphic correlation along the New England and paleogene/Neogene age unconformity; Horizon $K_w$ = the Campanian-age Wyan carbonate stringer; Horizon $K_{m}$ = the prominent Barremian age "C" marker layer corresponds to the top of the carbonate-rich Roseway Formation; Horizon $J$ = also shown are the locations of multi-channel seismic reflection profiles and Oceanographer Canyon samples were obtained by the DSRV "Alvin". Hecsen Canyon Georges Bank depocenter. On the structural high, elastic deposition is significant.
in Nova Scotia margins. Reflecter nomenclature is adapted from Wade (1977). Horizon A = a
indot chalk; Horizon K_P = The Turonian-age Petrel limestone; Horizon K_A = an Albian/Aptian-age
level of Givien (1977), that locally on structural highs such as the Yarmouth Arch and Laffave Platform
is the Berriasian-age upper contact of the Abenaki Formation.

The level in these profiles corresponding to the selected acoustic reflectors. The Heezen and Oceanogra-
pher Canyon is along the axis of the unitly reduced and unconformities are common.
Fig. 4. A breakaway planview and cross sections of Georges Bank projected onto two n Yarmouth Arch north of Hooe Canyon and is a literal translation of interpretation p Schles (1976). The reflection nomenclature is adopted from Wade (1977) and is the 4 Quaternary glacial errors. Horizon Jm is a Palaeocene age transition to carbonate mudstone Jm = Bathonian-age beginning of carbonate platform deposition and marks the real be the stratigraphic equivalent of the Argo Formation in the Scotia Basin and which pro on structural highs. The Roman numerals are major pulses of dolusic sedimentation at hatched grid corresponds to tracts offered for lease sale in 1979 by the U.S. Departe nature of the seaward edge of the carbonate platform.
two multi-channel seismic profiles located in Fig. 1 (inset). U.S.G.S. Line #4 (foreground) crosses
tion published by Wade (1977). Small numbers are interval velocities in km/sec from Grow and
is the same one used in Figs. 1, 2, 4 and 5. Horizon G = a Neogene erosion surface beneath the
sandstone equivalent to the Mississippian Member of the Abanaki Formation in the Scotian Basin; Horizon
real beginning of open-marine sedimentation; Horizon S = Sinemurian-age flowing salt layer which is
rich produces diapiric anticlines in the axis of the Georges Bank depocenter. The salt is thin or absent
don at times when the sediment supply overwhelmed subsidence and eustatic sea-level rise. Pine
Department of Interior. G-1 and G-2 are deep stratigraphic test boreholes. Note the precipitous
edge to a depth of 1080 m on USGS Line 1 and is calibrated by samples from “Alvin” dive 784 in Oceanographer Canyon recovered from 1500 to 1580 m. The seismic calibrations at Heezen Canyon are illustrated in Fig. 2. The entire section from Horizon J to Horizon $K_o$ is exposed in outcrop both in the thalweg and on the southwest wall. At Heezen Canyon there is a major disconformity between the Roseway Unit equivalent and the overlying Middle Eocene chalks. These chalks have no equivalent beneath the Scotian margin, but they are similar to Middle Eocene chalks drilled at DSDP site 108 on the lower slope adjacent to New Jersey (Hollister, Ewing et al., 1972) and recovered in allochthonous position as large olistoliths in Hudson Canyon. The cliffs of Eocene chalks are illustrated in Fig. 3 based on videotape reconstruction of “Alvin” dive 783.

Horizon $K_p$ corresponds to the Petrel Limestone Member of the Dawson Canyon Formation beneath the Scotian shelf. This horizon can be traced to a level at 750 m near the shelf edge on USGS Line 1 and has been calibrated by the dredging of Turonian-age marls in Oceanographer Canyon (Thompson et al., 1980).

Horizon $K_w$ corresponds to the Wyandot Formation of Campanian age in the Shell Naskapi well. Horizon $K_w$ is correlated to eastern Georges Bank.
using the stratigraphic position of Lower Maastrichtian calcareous mudstone recovered by "Alvin" in Corsair Canyon (Ryan et al., 1978) and the Maastrichtian and Campanian calcareous mudstones cored and dredged from a depth of 415–680 m in Oceanographer Canyon (Thompson et al., 1980).

Horizon A denotes a widespread Paleogene–Neogene unconformity which corresponds in the deep North American basin to reflector $A_u$ of Tucholke and Mountain (1979). Beneath Georges Bank the unconformity separates Maastrichtian and Eocene strata from Miocene strata and the young glacial cover. Beneath the continental rise, reflector $A_u$ generally separates Middle
or Upper Eocene sediments from Miocene sediments. There are several deep seismic horizons beneath Georges Bank which have no outcrops. We have correlated these units following Wade (1977) based purely on geophysical criteria. Horizon $J_m$ beneath the Scotian shelf corresponds to the base of the Mohawk Formation, or the Mohican equivalent. It is Bathonian in age. Horizon $S$ is the top of the flowing salt layer corresponding to the Argo Formation. Horizon $B$ is the acoustic basement.

**INTERPRETATION**

The seismic horizons discussed in the text are identified on USGS Lines 1 and 4 in Fig.4*, and Line 5 in Fig.5. Figure 4 is a three-dimensional break-away diagram showing the geological interpretation of Line 1 and the geophysical interpretation of Line 4 as projected onto true depth profiles. Figure 5 is a travel-time section of Line 5. The geological interpretation of Line 1 is based on the canyon sampling for horizons $K_o$ and younger, and on the analysis of reflector continuity, amplitude, geometry and coherence for the older horizons. Horizons $J$, $J_J$, $J_m$, and $S$ were traced and cross-tied between Lines 5 and 4 using the proprietary reflection profiles. They can be calibrated with geological formations at the stratigraphic boreholes G-1 and G-2 (Amato and Simonis, 1980), following the recent leasing of tracks for commercial exploration.

Reverberant acoustic units have been interpreted to correspond to platform limestones. Beneath Georges Bank, the limestones are sandwiched between Horizon $J_m$ at the base and Horizon $K_o$ at the top. Above Horizon $K_o$ and below Horizon $K_p$ there is a draped apron of sediment containing laterally discontinuous low-amplitude reflectors. This draped unit correlates with quartz- and mica-bearing sandstones with intercalated conglomerates, sampled in Oceanographer Canyon both by “Alvin” (Ryan et al., 1978) and by dredging (L-DGO unpublished data). On Line 5 (Fig.5) the seaward progradation of this apron is most clearly illustrated. Four major pulses of deltaic sedimentation have been identified and they are labelled with Roman numbers in Fig.4.

*Phase I is the alluvial—fluvial infilling of basement grabens during the presalt break-up stage of the margin. Phase I is recognized as the Eurydice Formation beneath the Scotian shelf (Jansa and Wade, 1975).

*Phase II corresponds to the Middle Jurassic progradation of the developing shelf basin prior to the first extensive marine transgression. During Phase II, both the New England and Scotian margin were dominantly subaerial, reflecting a rapid supply of immature gravels, sands and muds from the local erosion of faulted and tilted basement blocks, tectonically disturbed during the continental break-up.

*Phase III corresponds to an Upper Jurassic regression whose nearshore facies is expressed in the Mich Mac Formation of the Scotian basin. During Phase III, carbonate deposition is interpreted to have continued uninterrupted along the outer shelf.

*Fig.4 on pp. 217–218.
Phase IV corresponds to the Middle Cretaceous renewal of clastic supply, expressed by the Logan Canyon Formation on the Scotian shelf, and by the Hatteras Formation in the North American Basin (Tucholke and Mountain, 1979). The transition from limestone to non-calcareous shales in the deep North Atlantic takes place around Barremian time, and is marked by Horizon \( J_m \).

Phase V is characterized by the advancement of Upper Neogene and Quaternary glacial debris across the bank, to be later reworked by tidal currents during intervals of submergence.

On all seismic lines across Georges Bank the strata below Horizon \( K_o \) terminate seaward on a precipitous slope that has regional gradients steeper than 30°. On Lines 1 and 5 the outer edge of the inferred carbonate platform has been bevelled by an erosional surface. Horizon A onlaps against the precipitous buried slope at a stratigraphical level near the top of the Jurassic. It appears that the seaward edge of the Jurassic strata was exposed in a subaqueous environment in Berriasian time.

The high-standing slope may have resembled the actual modern Bahama Escarpment. We infer from the Bahama study (Freeman-Lynde et al., this volume) that the platform edge steepens itself by mechanical defacement.
processes. In Heezen Canyon, the exposed Berriasian to Barremian limestones are horizontally bedded and obviously have been truncated by erosion. The truncation surfaces can be detected with migration processing of CDP reflection profiles. The truncation surface in Heezen Canyon is shown in Fig. 2 where it descends beneath Middle Eocene and younger canyon fill.

DISCUSSION

The origin of steep and truncated edges of carbonate platforms is controversial. In Mesozoic platforms in Alpine-type mountains the abrupt transition from shallow to deep carbonate facies has been traditionally explained in two ways. One hypothesis is that the bank was truncated by normal down-to-basin faulting during the formative stages of the continental margin. The second hypothesis is that platform edges are tectonically removed in the thrusting that emplaces the platform fragments in the orogenic belts. The Georges Bank buried escarpment and the modern Bahama Escarpment are both in the pre-mountain building phase, and yet have truncated edges. Reflection Line 5 (Fig. 5) shows one of the best examples of the narrow transition between continental crust beneath the shelf and slope and the oceanic crust beneath the rise (Folger et al., 1979). There is no indication on any of the reflection profiles that the pre-Horizon K, Jurassic sediments have been down-faulted between the shelf and the ocean basin. Line 5 shows progradational foreslope deposits of Lower Jurassic age which have formed in an attempt to build the margin outward over pre-existing basement relief. There is no evidence to support a tectonic origin for the truncated edge of the carbonate platform.

In fact, the tectonic activity involving the break-up stretching and tilting of the continental basement seems to be short-lived. The relief produced by the observed listric faulting is for the most part buried and fossilized by the salt layer. Younger faulting has produced only minor offsets of a few hundred meters maximum (see Line 4, Fig. 6) and this faulting could be in response to flowing, dissolution and collapse of underlying salt and evaporites.

The major tectonic expression is the large amount of vertical subsidence illustrated in Fig. 6. The subsidence commenced at the time of the salt deposition and was linear in relation to the square root of elapsed time for the first 60–70 m.y. The subsidence has proceeded at faster rates where the crust has been thinned the most and the net subsidence has been the greatest (i.e., the center of the depocenter near Line 1). Subsidence has proceeded at the lowest rate where basement is presently shallow (i.e., the Yarmouth Arch near Line 4).

The subsidence curves are compatible with the crustal attenuation model of McKenzie (1978) and confirm that where the crustal stretching has been less extensive, the onset of subsidence has been delayed. The subsidence curves are indicative that the vertical movements are in response to thermal contraction and broad regional flexure from the sediment overburden (Steckler and Watts, 1978).
Fig. 6. Subsidence curves for a selected shot point location near the edge of Georges Bank for each of the three U.S.G.S. reflection profiles. The square root of elapsed time since the onset of rifting at 195 m.y. is plotted against the cumulative sediment thickness without correction for compaction. The straight lines for the first 60 m.y. indicate thermal cooling of a stretched lithosphere where the maximum stretching has occurred near Line #1 and the minimum stretching near Line #4. Selected samples from Oceanographer Canyon (784-2) and Heezen Canyon (783-8, 11 and 12) are shown indicating that the Mesozoic materials recovered are from in place at the expected stratigraphic level for regional subsidence. The mid-Eocene sample 783-12 departs from the subsidence curve because the chalk was deposited in a water depth approaching 1 km.

Using the geothermal gradients measured by the stratigraphic drilling on both Georges Bank and the Scotian shelf, it is possible to calculate the present temperatures in the subsurface. Since more than half of the sediment section accumulated after the first 70 m.y. of cooling, it is likely that the present temperatures in the Middle and Upper Jurassic marine section are the highest they have ever been. Figure 7 illustrates the temperatures that have been calculated for three selected locations near the shelf edge and two locations on the slope and rise. The temperatures have been plotted against formation age revealing that beneath Georges Bank the Cretaceous and overlying deposits are insufficiently heated to generate oil and gas from in situ source material. The main oil and gas zone aligns with the Middle and Upper Jurassic carbonate section. Only beneath the rise where the post-Horizon A section is thick do the temperatures in the Cretaceous deltaic aprons reach an oil-generating potential. If thermal maturation has proceeded in the carbonate section, it is likely that the hydrocarbons in the regions between Heezen and Oceanographer Canyons might have been lost out of the truncated escarpment in pre-Horizon A time. Line 5 (Fig. 5) shows the most optimistic entrapment possibility, except that here the barrier-reef complex has probably been removed by the observed erosion of horizon Ko.
Fig. 7. Calculated sub-surface temperatures for selected locations at the seaward extremity of Georges Bank on the three U.S.G.S. seismic lines. In addition, two curves are plotted for a continental-slope and upper-rise location on Line #5. For a given stratigraphic level the highest temperatures occur beneath the rise because of the large Neogene overburden, and the lowest temperatures occur beneath the slope because of erosional mass-wasting. The thermal regime of the main oil and gas zone aligns with the Callovian (Horizon Jₙ) to Berremian (Horizon Kₒ) strata belonging to the carbonate platform facies.

The loss of hydrocarbons by continental-margin erosion has significant economic implications. The canyon sampling by submersible and dredging documents at least three major phases of erosion of the New England slope (Fig. 8). These episodes are: (1) pre-Lower Maastrichtian, post-Albian/Aptian; (2) pre-Middle Eocene, post-Late Maastrichtian; (3) pre-Neogene, post-Late Eocene. These three phases have been observed on the Bahama Escarpment (Freeman-Lynde et al., this volume) but the correlation might be a coincidence.

A fourth pre-Aptian, post-Berriasian phase is observed in the reflection profiles. The reflection profiles also indicate that the Turonian through Campanian interval may have multiple erosional events. Persistence of erosion suggests that submarine canyon formation was already an active process in Mesozoic time, as was the mechanical defacement of high-standing carbonate escarpments. Therefore, the flushing of hydrocarbons has had several opportunities to take place.

SUMMARY AND CONCLUSIONS

The seismic stratigraphy of the Scotian shelf can be extended to and calibrated at Georges Bank. The New England margin contains a 3 km thick
Fig. 8. Depth distribution of in situ "Alvin" samples from Oceanographer Canyon. The occurrence of younger slope-facies rocks at deeper levels than older slope-facies rocks is indicative of former canyon fill deposits. At least three periods of canyon excavation are suggested, the oldest being in the pre-Maastrichtian Upper Cretaceous.

Middle, Upper Jurassic and lowermost Cretaceous carbonate platform along its outer perimeter. An equivalent of the Roseway Unit beneath the southwestern Scotian shelf has been discovered and sampled at Heezen Canyon. The landward side of the New England shelf has been dominated by clastic deposition encompassing long periods of continental and deltaic environments.

The carbonate platform has sufficient subsurface temperatures near its seaward edge to maturate oil and gas in the presence of adequate source rocks. The seaward truncation of the platform may have permitted any hydrocarbons generated to be flushed. Erosion of the slope has been active in Mesozoic times and is not just a phenomenon related to Late Neogene climatic deterioration. There is evidence that the erosion has been episodic, and the timing may coincide with Atlantic paleo-oceanographic events. In the Lower Cretaceous the New England margin contained a steep ocean-facing escarpment analogous to the present Bahama perimeter. Both the ancient and modern escarpments are created by mechanical defacement mechanisms.
and have little tectonic significance. The principal tectonic process has been one of thermal contraction and crustal flexure from sediment loading.

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