INTRODUCTION

Three multichannel, common-depth-point (CDP), seismic reflection profiles (Figures 1-3) were run off Delaware's coast (Figure 4) for the Delaware Geological Survey. Their purposes were (1) to determine the depth to the unconformity (=post-rift unconformity) at the base of the nearshore submerged Coastal Plain sedimentary rocks and (2) to relate onshore with offshore geology as interpreted from the U. S. Geological Survey's network of regional seismic profiles (Figure 5). In addition, the nearshore profiles reveal considerable detail about the nature of the Neogene lithostratigraphic units and aquifers within them that supply water to the coastal communities of Delaware and Maryland (Miller, 1971; Weigle and Achmad, 1982).

SEISMIC DATA COLLECTION AND PROCESSING

Data for two of the three profiles (Figures 1 and 2), consisting of six separate lines, were collected and processed in 1976 by Digicon, Inc. under contract to the Delaware Geological Survey (DGS) with partial funding provided by the U. S. Geological Survey. The seismic source for the marine high resolution profiling consisted of two sparker arrays providing 62,000 joules of energy. The streamer cable was 800 meters long and contained 24 groups, each 33.33 meters in length; it was towed at a 3.7-meter depth, 60 meters behind the seismic source. The passband filtering applied to the field recording system was 18-248 Hz. The shot-point interval was approximately 50 meters. Three seconds of data were recorded on 24 channels. The data-processing sequence included binary gain recovery and editing, application of spherical divergence corrections plus exponential gain, 24-fold gather, velocity analysis every half mile (805 meters), normal moveout corrections, deconvolution, 24-fold CDP stack, and time variant band pass filtering. No migration was performed on the lines; therefore, Figures 1 and 2 are unmigrated sections.

Grant-Norpac, Inc. ran profile DGS-001 (Figure 3) in 1983 under contract to the DGS. The seismic source consisted of three 1,000-cubic-inch (16,387-cm^3) arrays of six air guns for a total of 3,000 cubic inches for the tuned 18-gun array that provided a nominal pressure of 2,000 psi. Air guns, separated from each other by four feet (1.2 m), were towed 90-120 feet (27-37 meters) behind the vessel. The near trace of the 120-channel, 3,000-meter-long (1.86 miles) streamer cable was 250 meters (820 feet) behind the vessel; the far trace was at 3,225 meters (10,581 feet). The group interval and shot-point interval were each 25 meters (82 feet). Six seconds of data were recorded on 120 channels. The basic data-processing sequence performed by American Resources Consultants, Inc., a subsidiary of Grant Norpac, included demultiplexing, true amplitude recovery, trace editing, datum statics, passband filtering (7.5-62.5 Hz), deconvolution, 60-fold CDP gathers, velocity analysis every 2,500 meters (8,203 feet), normal moveout corrections, first break suppression, 60-fold CDP stack, time variant band pass filtering, and 500-millisecond automatic gain control. The final migrated stack is shown in Figure 3. Note that Figures 1 and 2 are three-second records and Figure 3 is a six-second record.

SEISMIC STRATIGRAPHIC INTERPRETATIONS

Previous interpretations of portions of the Digicon profiles (Figures 1 and 2) were published by Woodruff (1977) and Weigle and Achmad (1982). Benson (1984) used interpretations of all three profiles off Delaware's coast in determining depth to pre-Mesozoic? basement. The seismic stratigraphic interpretations of Figures 1-3 emphasize correlation from the COST B-2 well of individual or selectively grouped chronostratigraphic units defined by Poag (1980, Figure 24) for that well. Seismic profiles adjacent to the well were stratigraphically correlated with those units by means of time-depth curves constructed from the sonic log of the well and velocity analyses of nearby shot points of the profiles.

Depths in meters below sea level were derived from interval velocities calculated, using the Dix equation (Dix, 1955), from two-way travel times and root mean square stacking velocities at selected locations for the following contacts: (1) upper Oligocene?-lower Miocene/Paleocene-Eocene (base of Neogene), (2) Paleocene-Eocene/Coniacian-Maastrichtian (base of the Paleogene), (3) Berriasian/Tithonian (base of Cretaceous), (4) post-rift unconformity (base of Jurassic-age drift sequence), and (5) base of interpreted synrift? rocks of Late Triassic?-Early Jurassic? age (top of pre-Mesozoic? basement). The depths are shown in Figures 1-3, and interval velocities of the units bounded by the contacts are given in Table 1.

Depth calculations for portions of the seismic profiles are generally in good agreement with the data of Brown, Miller, and Swain (1972) for three deep Coastal Plain drill holes (Figure 4). Table 2 lists estimates of two-way travel times, calculated from interval velocity data of Table 1, to the following contacts picked by those authors for the three holes: (1) Neogene/Paleogene, (2) Paleogene/Cretaceous, (3) a contact probably not far above the Cretaceous/Jurassic contact, namely, the one between their Cretaceous Unit G and Cretaceous and Late Jurassic? Unit H, and (4) the base of Jurassic? Unit I, the post-rift unconformity. The times are compatible with those for the same unit-contacts on nearby portions of the offshore profiles. However, as noted in the discussion of the drift sequence to follow, there is not good agreement with some of the chronostratigraphic contacts in the subsurface Potomac Group reported by Hansen (1982, 1984) in deep drill holes of the Delmarva Peninsula.

Pre-Mesozoic? Basement, Synrift? Rocks, Post-Rift Unconformity

Benson and Doyle (in press) mapped early Mesozoic-age rift basins buried beneath the sedimentary rocks of the United States middle Atlantic Coastal Plain and its offshore extension into the Baltimore Canyon trough. The bulk of the synrift fill of the basins is interpreted as nonmarine sedimentary rocks derived from erosion of adjacent fault-block-bounded highlands underlain by pre-Mesozoic-age rocks. As described by Ratcliffe and Burton (1985), the basin and range structure probably was controlled by reactivation of Paleozoic thrusts, ramps, and antithetic faults in the pre-Mesozoic basement. Sediments were deposited in the basins during the Late Triassic-Early Jurassic rifting stage prior to continental breakup and subsequent separation and drifting of North America from northwest Africa in Middle Jurassic time. As drifting began, the margins of both continents began to subside, and the erosion surface called the post-rift unconformity (Grow *et al.*, 1983), which truncates both pre-Mesozoic basement and synrift rocks, was onlapped in a progressively landward direction by the marine to marginal marine sedimentary rocks of the drift sequence.

On profile DGS-001 (Figure 3), the post-rift unconformity is easily recognized as it is onlapped by the overlying drift sequence. Because the Digicon profiles of Figures 1 and 2 were generated from a high-resolution seismic survey with a lower (sparker) energy source, the post-rift unconformity is not as apparent as in Figure 3. This is probably because the sparker data have reverberation noise interfering with primary events to the extent that the primary events are nearly totally obscured in the deeper parts of the lines (H. E. Bowman, personal communication). Nevertheless, it was possible to define the post-rift unconformity on the profiles of Figures 1 and 2. On lines DGS-3 and DGS-2 there is a strong reflection between about 1.45-1.7 seconds which strongly resembles the unconformity represented by the reflector on line DGS-001 (Figure 3). With a fair degree of confidence, the reflector of Figure 1 was traced downdip and offshore to where it extends below the 3-second record of Figure 2. On the nearshore end of profile USGS 10, where it intersects line GD-1 of Figure 2, the unconformity is interpreted at 3.4 seconds.

Early Mesozoic rift basins were interpreted as present on all three profiles, but they are not readily apparent. In general, the fairly continuous, subparallel reflectors below the post-rift unconformity represent synrift? rocks. The boundary between those reflectors and pre-Mesozoic basement was arbitrarily picked where they either end against or onlap a series of less continuous reflectors that may have a different attitude. Also, the post-rift unconformity, synrift? rocks, and pre-Mesozoic basement are shown on interpretations of lines USGS 10, USGS 37, and D-102 (Benson and Doyle, in press) where they intersect the profiles of Figures 2 and 3 (Figure 5). On those lines, the rift basins are more apparent and were interpreted with a higher level of confidence (Benson and Doyle, in press). Average interval velocities of the synrift? rocks (Table 1) of Figures 1-3 plot on or close to the Jurassic-Triassic line on Faust's (1951, Figure 3) plot of sedimentary rock velocity versus depth for each geologic age. However, interval velocities for pre-Mesozoic? basement, which could only be determined for profile DGS-001 (Table 1), are too low. They plot on the Jurassic-Triassic line (as extended beyond the end of Faust's diagram) rather than on the lines for the Paleozoic systems as expected. According to H. E. Bowman (personal communication) the low velocities may be due to one or more of the following: (1) spread length was too short, (2) root mean square velocities were improperly picked (multiples?), (3) problems in data processing (lingering reverberations).

On profile DGS-001 (Figure 3) fairly continuous groups of reflectors within pre-Mesozoic? basement dip in a seaward direction. These may represent the attitude of stratification of relatively undeformed Paleozoic? sedimentary rocks, Paleozoic-age thrust sheets, or, possibly, thrust faults reactivated as low-angle detachment surfaces during early Mesozoic rifting. A fairly continuous set of reflectors extends from about 3 seconds on the northwest end of DGS-001 to about 5.3 seconds on the southeast end. This may be a detachment surface, and the interpretation shown in Figure 3 suggests that bounding faults of the rift basins end where they intersect that surface.

Faults inferred from offset reflectors are shown only in Figure 3 because the high-resolution records of the unmigrated profiles of Figures 1 and 2 do not reveal the same degree of detail in the section beneath and immediately above the post-rift unconformity. The inferred faults primarily offset reflectors in the synrift? and pre-Mesozoic? basement. Presumably, they include both reactivated Paleozoic faults as well as faults generated during early Mesozoic rifting. Also, the few faults that extend into the overlying lower drift sequence (Upper Jurassic) were those rift-stage faults that remained active along the hinge zone of the Baltimore Canyon trough as the U. S. Atlantic continental margin rapidly subsided during deposition of the early drift sequence.

Drift Sequence

The drift sequence that onlaps the post-rift unconformity is no older than Middle Jurassic (Bajocian?-Bathonian?) in far offshore regions (Benson and Doyle, in press). As shown in Figures 1-3 it is probably no older than Oxfordian-Kimmeridgian in nearshore regions. The bulk of the sequence, the Upper Jurassic through lower Cenomanian, is represented in Coastal Plain drill holes (Figure 4) by the nonmarine, fluvio-deltaic, interbedded sands and silt/clays of the Potomac Group (Hansen, 1982, 1984). Seismic reflections in this interval tend to be discontinuous, but in some places their greater degree of continuity probably reflects periods of marine sedimentation. The chronostratigraphic correlations in this interval (Figures 1-3) do not agree well with age determinations of the Potomac Group based on palynological studies of samples from Delmarva Peninsula drill holes (Hansen, 1984). H. J. Hansen (personal communication) points out that the available evidence onshore does not support an Aptian unit five times as thick as the Albian unit as shown in Figure 2. Also, in the Bethards No. 1 well (Figure 4) the available palynological evidence indicates that rocks of Early Cretaceous age occur to a depth of at least 6,500 feet (1,980 meters), suggesting that the Jurassic/Cretaceous contact shown in Figure 2 is probably too high. On the other hand, we are confident of our seismic correlation of this contact from the COST B-2 well along three different routes of seismic profiles (Figure 5). Unfortunately, the problem may never be resolved because no other fossil groups with better zonal resolution are present in the Potomac Group rocks penetrated by onshore drill holes.

The Upper Cretaceous through Paleogene section in Delaware consists predominantly of fine-grained marine sediments deposited in waters that approached bathyal depths during peak transgressions (Benson, Jordan, and Spoljaric, 1985). Reflections representing this interval are generally more continuous than those of the preceding sequence.

A major regional unconformity separates the Paleogene from the Neogene (Jordan and Smith, 1983; Benson, Jordan, and Spoljaric, 1985). The subaerially exposed erosion surface was transgressed by the predominantly marine Chesapeake Group sediments of late Oligocene?-Miocene age. The seismic stratigraphic signature of this sequence is characterized on most offshore seismic profiles by a series of prograding clinoforms. Clinoforms downlapping on the Paleogene/Neogene unconformity are shown clearly on lines DS-5 and DGS-1 of Figure 1.

The Calvert, Choptank, and St. Marys? formations comprise the bulk of the Chesapeake Group. Their contacts are identified on the high resolution profiles of Figures 1 and 2. Table 3 gives information on depths to formation contacts in shallow drill holes Ni31-07 near Lewes, Delaware and WorAh-6 near Ocean City, Maryland. Two-way travel times estimated for these depths were used in locating corresponding reflector-contacts on the seismic profiles.

Detailed seismic stratigraphy of the Chesapeake Group and overlying Columbia Group (Pleistocene) cannot be adequately shown at the scales of Figures 1-3. Study of full-scale seismic sections indicates that the Chesapeake Group unconformably overlies the Eocene. Within the Chesapeake Group, several unconformities of probable regional extent are indicated, and cut-and-fill features are common, especially on the landward ends of the profiles. Reflections are more continuous and subparallel in the seaward direction, indicating deeper water environments characterized by less reworking and erosion.

Detailed seismic stratigraphic interpretations of the full-scale seismic profiles by Andres (1986) show a minimum of two depositional sequences in the post-Choptank part of the Chesapeake Group. In the upper sequence three subsequences were identified, but the sequence and subsequence contacts do not correlate with those of the lithostratigraphic units identified in onshore drill holes.

The section identified as Manokin is a composite unit that includes the Manokin and Bethany formations as defined by Andres (1986). The Manokin formation is a newly recognized, informal lithostratigraphic unit that corresponds to the section referred to as the Manokin aquifer by Rasmussen and Slaughter (1955). The Bethany formation is another, newly recognized, informal lithostratigraphic unit that includes the Pocomoke and Ocean City aquifers and the upper and lower confining beds as defined by Weigle (1974). Details of the lithologies and subsurface distribution of the Manokin and Bethany formations are reported by Andres (1986). The section identified as Columbia is a composite unit that includes the Columbia Group as defined by Jordan (1962), late Wisconsinan valley fill deposits, and Holocene shelf deposits. The resolution of the seismic reflection data is not sufficient to differentiate between these units.

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Principal responsibilities for seismic stratigraphic interpretations of the profiles lie with: Benson for pre-Mesozoic? basement, synrift? rocks, and post-rift unconformity; Benson and Roberts for reflectors defining chronostratigraphic units correlated from the COST B-2 well; Andres and Woodruff for the Chesapeake and Columbia groups. Former Delaware Geological Survey Research Associate Richard V. Smith first identified the post-rift unconformity on the Digicon profiles at or near its position shown in Figures 1 and 2.

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Table 1. Interval velocities.

	NEOGENE			PALEOGENE		
	Range m/sec	Mean m/sec	S.D. m/sec	Range m/sec	Mean m/sec	S.D. m/sec
Profile of Figure 1	1735-1882	1821	±38	1950-2200	2094	± 62
Profile of Figure 2	1814-1884	1858	±26	2032-2460	2246	±163
Profile of Figure 3	1722-1927	1895	±58	2150-2460	2268	± 82
All three profiles	1722-1927	1844	±48	1950-2460	2193	±130

	CRETACEOUS			JURASSIC		
	Range m/sec	Mean m/sec	S.D. m/sec	Range m/sec	Mean m/sec	S.D. m/sec
Profile of Figure 1	2493-2813	2635	± 87	2809-3422	3233	±185
Profile of Figure 2	2700-2922	2841	± 82	3460-3802	3629	±140
Profile of Figure 3	2626-3049	2877	±135	3519-4504	3930	±322
All three profiles	2493-3049	2772	±154	2809-4504	3578	±392

	SYNRIFT? ROCKS			PRE-MESOZOIC? BASEMENT		
	Range m/sec	Mean m/sec	S.D. m/sec	Range m/sec	Mean m/sec	S.D. m/sec
Profile of Figure 1	3582-4227	3801	±196	—	—	—
Profile of Figure 2	3989-4276	4133	±144	—	—	—
Profile of Figure 3	3703-4744	4363	±290	4002-4926	4481	±225
All three profiles	3582-4744	4119	±358	—	—	—

Table 2.
Estimated two-way travel times to selected contacts of Brown, Miller, and Swain (1972) in three deep Coastal Plain drill holes (Figure 4).

	Dickinson No. 1	MD Esso No. 1	Bethards No. 1
NEOGENE			
Depth below sea level of base (m)	319	504	365
Thickness of unit (m)	319	504	365
1/ Interval velocity (m/sec)	1844	1844	1844
Two-way travel time of unit (sec)	0.35	0.55	0.40
Two-way travel time to contact (sec)	0.35	0.55	0.40
PALEOGENE			
Depth below sea level of base (m)	591	630	489
Thickness of unit (m)	272	126	124
1/ Interval velocity (m/sec)	2193	2193	2193
Two-way travel time of unit (sec)	0.25	0.11	0.11
Two-way travel time to contact (sec)	0.60	0.66	0.51
CRETACEOUS, UNITS A-G			
Depth below sea level of top of unit H (m)	1384	1554	1387
Thickness of unit (m)	793	924	898
1/ Interval velocity (m/sec)	2772	2772	2772
Two-way travel time of unit (sec)	0.57	0.67	0.65
Two-way travel time to contact (sec)	1.17	1.33	1.16
CRETACEOUS AND LATE JURASSIC?, UNITS H and I			
Depth below sea level of post-rift unconformity (m)	1938	>2346	1984
Thickness of unit (m)	554	> 792	597
2/ Interval velocity (m/sec)	3200	3200	3200
Two-way travel time of unit (sec)	0.35	>0.50	0.37
Two-way travel time to contact (sec)	1.52	>1.83	1.53

1/ Average interval velocity of all three profiles (Table 1).
2/ Average of interval velocities for five shot points closest to drill holes.

Table 3.
Estimated two-way travel times to contacts of Chesapeake Group formations in two Coastal Plain drill holes.

	Ni31-7	WorAh-6
TOP OF ST. MARYS? FM		
Depth below sea level (m)	75	147
Thickness of overlying unit (m)	75	147
1/ Interval velocity of overlying unit (m/sec)	1804	1821
Two-way travel time of overlying unit (sec)	0.08	0.16
Two-way travel time to contact (sec)	0.08	0.16
TOP OF CHOPTANK FM.		
Depth below sea level (m)	102	205
Thickness of overlying unit (m)	27	58
1/ Interval velocity of overlying unit (m/sec)	1804	1821
Two-way travel time of overlying unit (sec)	0.03	0.06
Two-way travel time to contact (sec)	0.11	0.22
TOP OF CALVERT FM.		
Depth below sea level (m)	202	309
Thickness of overlying unit (m)	100	104
1/ Interval velocity of overlying unit (m/sec)	1804	1821
Two-way travel time of overlying unit (sec)	0.11	0.11
Two-way travel time to contact (sec)	0.22	0.33
BASE OF CALVERT FM.		
Depth below sea level (m)	299	>368
Thickness of overlying unit (m)	97	> 59
1/ Interval velocity of overlying unit (m/sec)	1804	1821
Two-way travel time of overlying unit (sec)	0.11	>0.06
Two-way travel time to contact (sec)	0.33	>0.39

1/ Average of interval velocities for DGS-3, SPN 326, and DGS-2, SPN 341 and 197 for drill hole Ni31-7; average of interval velocities for DS-5, SPN 213 and 261 for drill hole WorAh-6.