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Lithostratigraphic-Seismic Evaluation of Hydrocarbon Potential, North Carolina Coastal and Continental Margins: Interim Report, Year 2

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ABSTRACT

Geological and geophysical review of 19 wells, 14 synthetic seismograms, and 153 miles of 12-fold CDPS seismic data, recorded to four seconds, indicates that the coastal margin of North Carolina in the Pamlico-Albemarle-Croatan sound area is underlain by sequences of non-marine, deltaic, and shelf sediments that rest on a faulted Paleozoic crystalline basement.

Variability in the middle and upper Mesozoic sedimentary section corresponds to probable erosional relief on the crystalline basement. Only rarely do faults extend from the crystalline basement well into the overlying sedimentary section. Rather, erosional relief on the basement surface caused sediments to by-pass topographically higher areas. The resulting distribution of shalier and sandier sections is reflected in structures formed by differential compaction. Further, such redistribution of the sediments has caused significant variation in seismic velocities across the area, so that considerable velocity control is essential to successful geologic interpretation. By the end of Cretaceous time such basement control of sedimentation had largely disappeared.

Cenozoic sedimentation was controlled by interaction between sediment supply, eustatic sea-level fluctuations, shelf subsidence, and the lateral shifting of the Gulf Stream, as indicated in a study of largely offshore seismic data by Popenoe (1985). This pattern is also evident on the lines investigated in this study.

INTRODUCTION

Geological review of well-log data and geophysical review of newly acquired regional seismic profiles and synthetic seismograms indicate considerable variability and complexity in the subsurface geology of the Pamlico-Albemarle-Croatan Sound areas of the eastern coastal margin of North Carolina. This area is shown in Figure 1, as are the locations of seismic lines, wells, and synthetic seismograms used. Data used in this report are listed in the Appendices.

As indicated on Figure 1, the study area is located in the Albemarle Embayment, one of several broad strucural basins with axes that are oriented approximately perpendicular to the Atlantic margin and that are found along the continental border.

In the regional cross-section (Figure 2), the area has been projected approximately into a section interpreted by Grow (1981, p. 3-13) from geophysical data. The cross-section traverses the Carolina Platform and Trough to the southeast, perpendicular to the trend of the continental margin. It illustrates the broad regional relationship of the crust and overlying sediments, which are quite similar to those in the area studied.

The North Carolina coastal plain is underlain by a seaward-thickening wedge of primarily clastic sediments that range in age from Triassic-Jurassic to Recent. The older rocks lie unconformably upon an erosion surface developed on Paleozoic crystalline rocks that were fractured by rifting associated with the opening of the Atlantic Ocean in Triassic-Jurassic times (Figure 2, after Grow, 1981). The rifted basins are filled with sediments. A continuous sedimentary cover, largely unaffected by basement faulting, was developed by late Jurassic time - mid-Cretaceous time and covers the rifted basins. Sedimentation has continued to the present day. The stratigraphic record that developed shows successive periods of onlap westward over the crystalline rocks (Figure 2), punctuated by times of uplift, sea-level fluctuation, and erosion.

PREVIOUS WORK

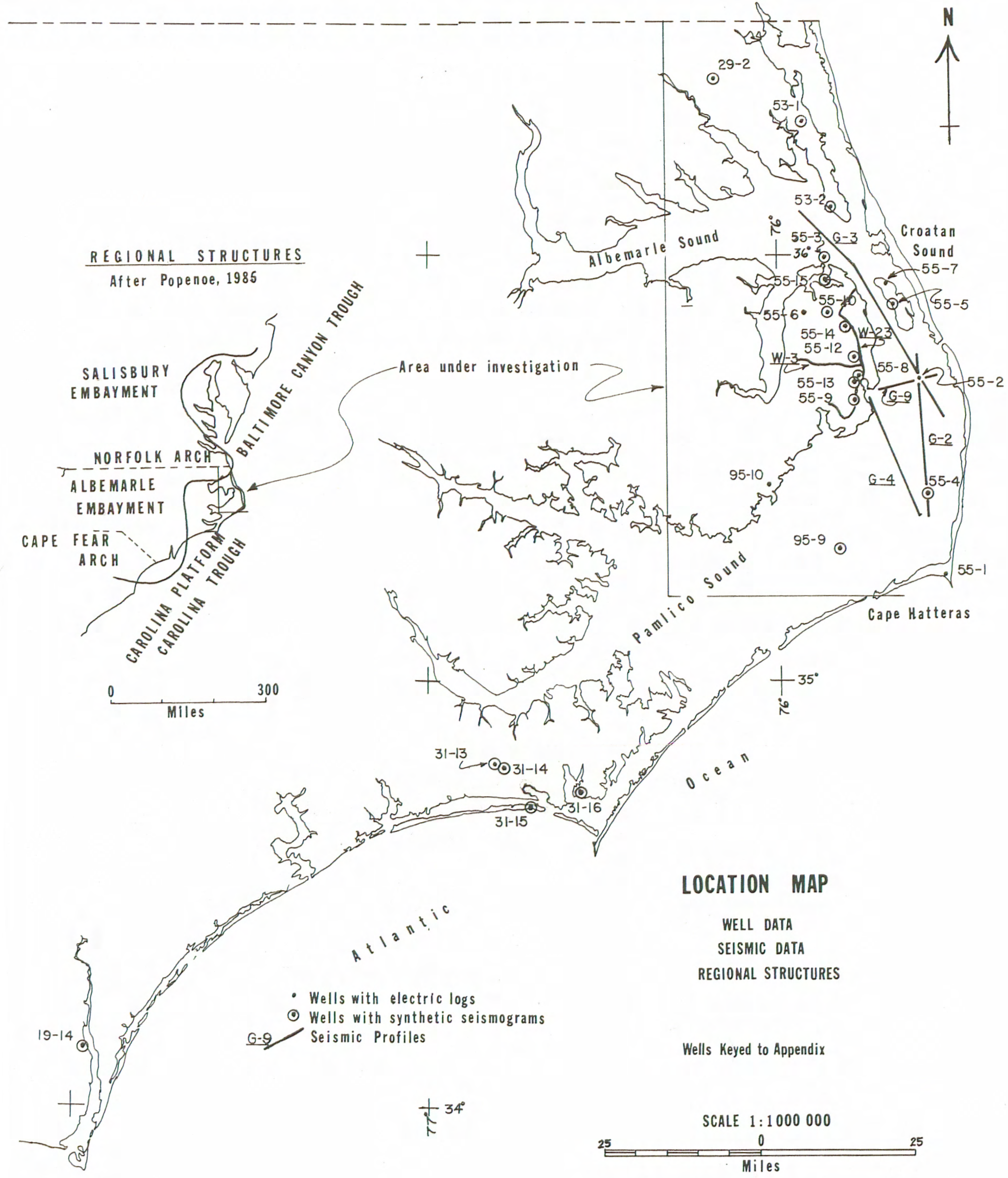
Initially, subsurface lithostratigraphic units were extrapolated from more detailed work and abundant data in the Gulf of Mexico to the North Carolina coastal areas through the study of such pioneer wells as the Standard of New Jersey #1 NC Hatteras Light (Spangler, 1950).

Two regional studies, the extensive compilation of regional subsurface data by Brown, et al. (1972) and the recent volume edited by Poag (1985), which has provided the modern regional synthesis for the Atlantic continental margin, have been most helpful in this investigation.

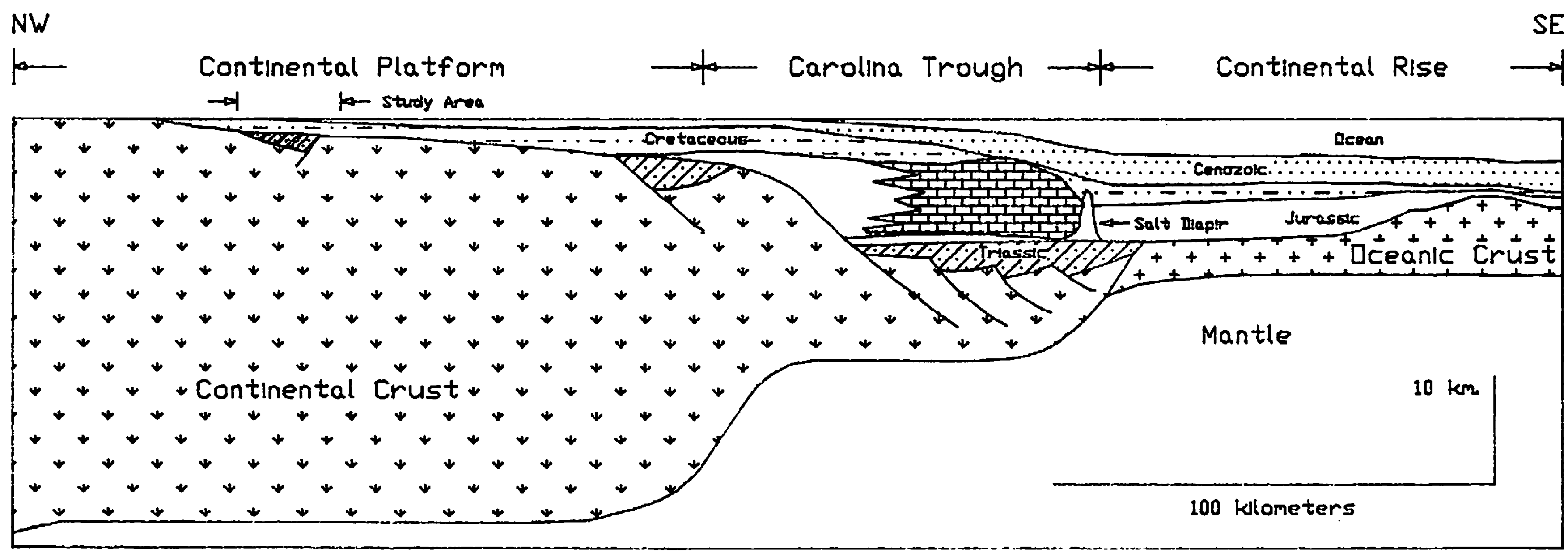
Brown, et al. (1972) established a series of subsurface units. Available regional micropaleontology of the time and well-log correlations were used to establish these units, but, as noted by Poag (1985, p. 257), the units were based on limited paleontologic data and do not represent true chronostratigraphic units for the Atlantic Coast as they are defined today. Nevertheless, the work provides a useful compilation of data and a framework from which to begin a more detailed review of portions of the stratigraphic section of the coastal plain.

Poag (1985), summarized stratigraphic and paleontologic work of the past 15 years in the context of the modern understanding of oceanic evolution, global sea level changes, and deep marine processes.

The report from the N. C. Geological Survey to the MMS/AASG for Year 1 (Hoffman, et al., 1985) outlined much of the earlier work of Brown, et al. (1972), as well as a summary of possible lithostratigraphic units proposed for this area. Included was a structural synthesis that continued the hypothesis of Brown, et al. (1972) that patterns of sedimentation were directly controlled by basement faults. As indicated in this current


N
REGIONAL STRUCTURES
After Popenoe, 1985
SALISBURY EMBAYMENT
BALTIMORE CANYON TROUGH
NORFOLK ARCH
ALBEMARLE EMBAYMENT
CAPE FEAR ARCH
CAROLINA PLATFORM
CAROLINA TROUGH
0
300
Miles
Area under investigation
Albemarle Sound
Croatan Sound
Pamlico Sound
Cape Hatteras
Atlantic Ocean
29-2
53-1
53-2
55-3
G-3
36°
76°
55-15
55-7
55-10
55-5
55-6
55-14
W-23
55-12
W-3
55-8
55-2
55-13
55-9
G-9
G-2
95-10
G-4
55-4
95-9
55-1
35°
76°
31-13
31-14
31-16
31-15
19-14
34°
77°
LOCATION MAP
WELL DATA
SEISMIC DATA
REGIONAL STRUCTURES
Wells with electric logs
Wells with synthetic seismograms
G-9 Seismic Profiles
Wells Keyed to Appendix
SCALE 1:1000 000
25
0
25
Miles

DIAGRAMMATIC REGIONAL CROSS-SECTION
ATLANTIC MARGIN, NORTH AND SOUTH CAROLINA



Modified from a cross-section based on U. S. G. S. seismic line 32, gravity data, and magnetic data, as interpreted by Grow, 1981.

FIGURE 2

investigation and in Poag (1985, p. 256-257), the probable influence of regional basement faults on the sedimentary section is minimal much above the lower part of the Cretaceous (Almy, 1986).

Hoffman, et al.(1985) also presented an initial analysis of the first of the synthetic seismograms which indicated that useful correlations between wells and the seismic profiles could be made, that distinctive reflectors were present across the study area, and that reflector character might be variable.

DATA FOR THIS STUDY

Well logs for 19 wells in the area were reviewed. For 14 of these, sonic logs were available, and Chevron USA provided synthetic seismograms for these. Additionally, seismic profiles from Cities Service were interpreted, using available well logs and synthetic seismograms. All these data are available in the repository of the N. C. Geological Survey in Raleigh, N. C.

Other sources of information included a brief review of cores and cuttings available in the repository of the N. C. Geological Survey, as well as the literature cited above. The multi-taxonomic microfaunal and microfloral data from cuttings and cores that would enable the detailed fluctuations of sea-level and environment to be determined, as has been done in studies of other areas or regionally, were unavailable at the time of completion of this report.

Data and Methods in Stratigraphic Studies:

In the stratigraphic studies, correlations were established between the wells by use of the electrical logs primarily. Other logging services were checked if available. These were then compared to data in the literature that would provide some time control. Correlations used in mapping and on the seismic sections are shown in Plates 5, 6, and 7. All elevations are referenced to sea level unless otherwise noted.

All correlation points are not shown, but correlations are good to excellent between most wells, except Blair #1 Ballance (poor quality gamma-ray/neutron). The Mobil #2 State of North Carolina well drilled in the southern portion of Pamlico Sound (Figure 1), has served as the reference well for this study because of its complete suite of wireline services and its termination in crystalline basement.

Horizons for mapping or for limits on stratigraphic intervals were named for correlation points in the Mobil #2 NC well. The principal ones are the following: Crystalline Basement; M2-6600; M2-4420; M2-3950; M2-3810; M2-3175; Top Cretaceous. This method was used because of the current uncertainties in the chronostratigraphic-lithostratigraphic status of the correlations of Brown, et al. (1972) relative to newer correlations currently being developed (Poag, 1985, p. 257). The correlation points used in this study are correlated with Brown et al. (1972) and with Owens and Gohn (1985) in Figure 3 and discussed later in this section.

Similarly, Mobil #1 State of North Carolina served as a reference point for the northern part of the Albemarle Embayment. Other key wells for stratigraphic correlation were the E. F. Blair #1 Marshall Collins and the Cities Service #1 Westvaco-Stumpy Point. Because of its extreme downdip position, and because of the availability of cores for study, the Esso #1 State of North Carolina-Hatteras Light well was useful. Structure maps (Plates 1, 2, 3, and 4) that are a part of this report were constructed from these correlation supplemented by depth determinations made from the reconnaissance seismic data.

From well data, large depositional units were established for the Cretaceous and correlated to the literature. These units were based on electric log character and the literature and are shown in Figure 3.

STRATIGRAPHIC SUBDIVISIONS OF CRETACEOUS ROCKS IN MOBIL 2 NC

SERIES: EUROPEAN	SERIES: GULF COAST	STAGE: EUROPEAN	STAGE: GULF COAST	UNITS OF BROWN et al. 1972	UNITS OF OWENS & GOHN, 1985	DEPOSITIONAL UNITS IN THIS PAPER
UPPER CRETACEOUS	GULF	MAESTRICHTIAN	NAVARROAN	A	6	5 SHELF
UPPER CRETACEOUS	GULF	CAMPANIAN	TAYLORAN	B	5	5 SHELF
UPPER CRETACEOUS	GULF	CAMPANIAN	TAYLORAN	B	4	5 SHELF
UPPER CRETACEOUS	GULF	SANTONIAN	AUSTINIAN	C	3	4 DELTAIC
UPPER CRETACEOUS	GULF	CONIACIAN	AUSTINIAN	C	3	4 DELTAIC
UPPER CRETACEOUS	GULF	TURONIAN	EAGLEFORDIAN	D	2	3 SHELF
UPPER CRETACEOUS	GULF	CENOMANIAN	EAGLEFORDIAN	D	2	3 SHELF
UPPER CRETACEOUS	GULF	CENOMANIAN	WOODBINIAN	E	1	3 SHELF
UPPER CRETACEOUS	COMANCHE	CENOMANIAN	WASHITAN	F	1	2 DELTAIC
LOWER CRETACEOUS	COMANCHE	ALBIAN	WASHITAN	F	1	2 DELTAIC
LOWER CRETACEOUS	COMANCHE	ALBIAN	FREDERICKS-BURGIAN	F	1	2 DELTAIC
LOWER CRETACEOUS	COAHUILAN	ALBIAN	TRINITIAN	G	1	2 DELTAIC / 1 NONMARINE
LOWER CRETACEOUS	COAHUILAN	APTIAN	TRINITIAN / NUEVO LEONIAN	H	1	1 NONMARINE
LOWER CRETACEOUS	COAHUILAN	BARREMIAN	NUEVO LEONIAN	H	1	1 NONMARINE
LOWER CRETACEOUS	COAHUILAN	HAUTERVIAN	NUEVO LEONIAN	H	1	1 NONMARINE
LOWER CRETACEOUS	COAHUILAN	VALANGINIAN	DURANGOAN	H	1	1 NONMARINE
LOWER CRETACEOUS	COAHUILAN	BERRIASIAN	DURANGOAN	H	1	1 NONMARINE

VARIATIONS IN FACIES WITH TIME OWENS & GOHN 1985

MOBIL 2 NC ELECTRIC LOG SHOWING CORRELATIONS

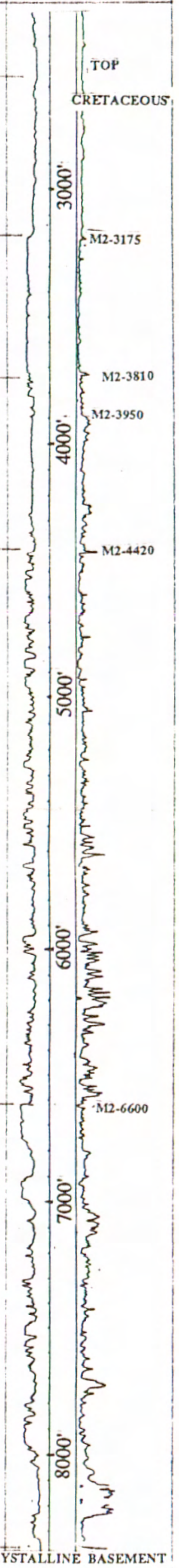


FIGURE 3

After Owens and Gohn, 1985

Limited review of some cuttings and of the cores from the well at Hatteras Light added to the review of well logs. Also, correlations over longer distances in the area were aided by the seismic lines and the synthetic seismograms.

Paleontologic data:

Paleontologic data was available from the report by Brown, et al. (1972), and from isolated references in the literature. Additionally some limited sampling, focussed primarily on Unit F (upper part of Depositional Sequence 1, Owens and Gohn, 1985) or Unit 2 of this report, was carried out by the North Carolina Geological Survey in 1985 and 1986. As indicated in Owens and Gohn, (1985, Figures 2-3 and 2-4), Unit F of Brown, et al. (1972) is primarily Late Albian-Early Cenomanian inage. The ages from all sources agree closely and include information from foraminiferal, ostracode, and palynological sources. A systematic modern review of microfloral and microfaunal materials for the wells of the Albemarle Embayment and for the other wells of the North Carolina coastal plain is essential.

Data and Methods in Seismic Studies:

Cities Service Oil Co. contributed 153 miles of 12-fold CDPS data recorded to 4 seconds. The data is 1970-71 vintage and was shot with airgun for inland waters and VibroSeis for land data. The data came to the N. C. Geological Survey processed, including deconvolution. Statics corrections in general are appropriately applied, although some lines show areas where additional corrections could be made. Most of these are obvious and pose no problem in interpretation. Data shallower than 0.4 seconds two-way time are not recorded. However, extensive work by Popenoe (1985) and others in the shallow section above 1.0 second two-way time provide coverage in the area studied for the shallow section. The profiles used in this study reach well below the top of crystalline basement, provide good regional coverage for the Albemarle Embayment, and tie to wells discussed above.

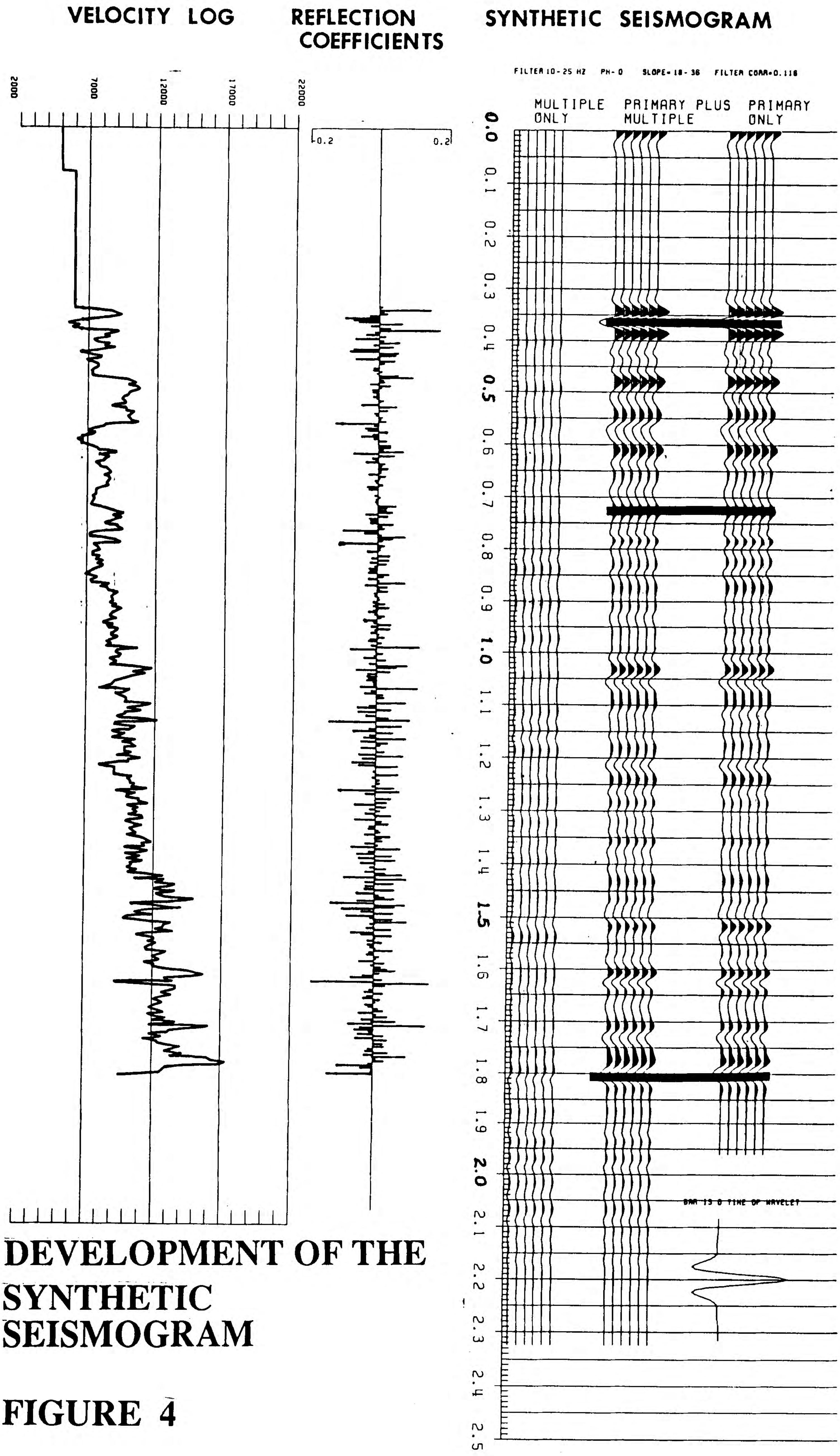
Fourteen of the wells in the area under study have sonic logs available and these with others along the rest of the Coastal Plain were converted to synthetic seismograms for the North Carolina Geological Survey and for the geology program at Guilford College by Chevron Oil Company. Earlier synthetic seismograms had been developed for three wells in the study area by King and Costain (1982). Agreement between the two sets is good to excellent.

Briefly, the data from the sonic logs is converted to a velocity log and then reflection coefficients are determined and plotted against depth. These are convolved with an appropriate signal, and a simulated seismogram, as if shot at the well site, is produced (Figure 4). Additionally, velocity information and time-depth charts, are produced. For this project, Chevron USA provided synthetic seismograms at three standard phase angles (0 and 90 degrees and at minimum phase) and at four frequency ranges (10-25hz., 10-30hz., 10-40hz., 10-50hz.) for each phase angle for each well. Those at O degrees phase angle and 10-30 or 10-40 hz. were most useful on these seismic profiles.

The synthetic seismogram for a well was then compared to the actual seismic section, and with stratigraphic horizons superimposed on the well trace, specific correlations to specific reflections recorded on the seismic profile can be identified (Figure 5). In the case of the synthetic seismograms developed for this project, correlation between seismic profile and synthetic seismogram was good to excellent in the vicinity of the well. Variability in the rock section commonly precluded application of the synthetic seismogram results or the time-depth curves for more than a few miles from the well (Figure 6).

In developing the synthetic seismograms, velocities for the sedimentary section behind casing, and therefore not logged, had to be assumed. Velocities of 5,000 ft/sec. were assumed for the first 1,000 feet and 6,000 ft./sec. for the remainder of the unlogged portion of the hole, to the bottom of surface casing. Indirect evidence suggests that in

MOBIL #2 NC



DEVELOPMENT OF THE SYNTHETIC SEISMOGRAM

FIGURE 4

CORRELATION OF THE SYNTHETIC SEISMOGRAM WITH THE SEISMIC PROFILE

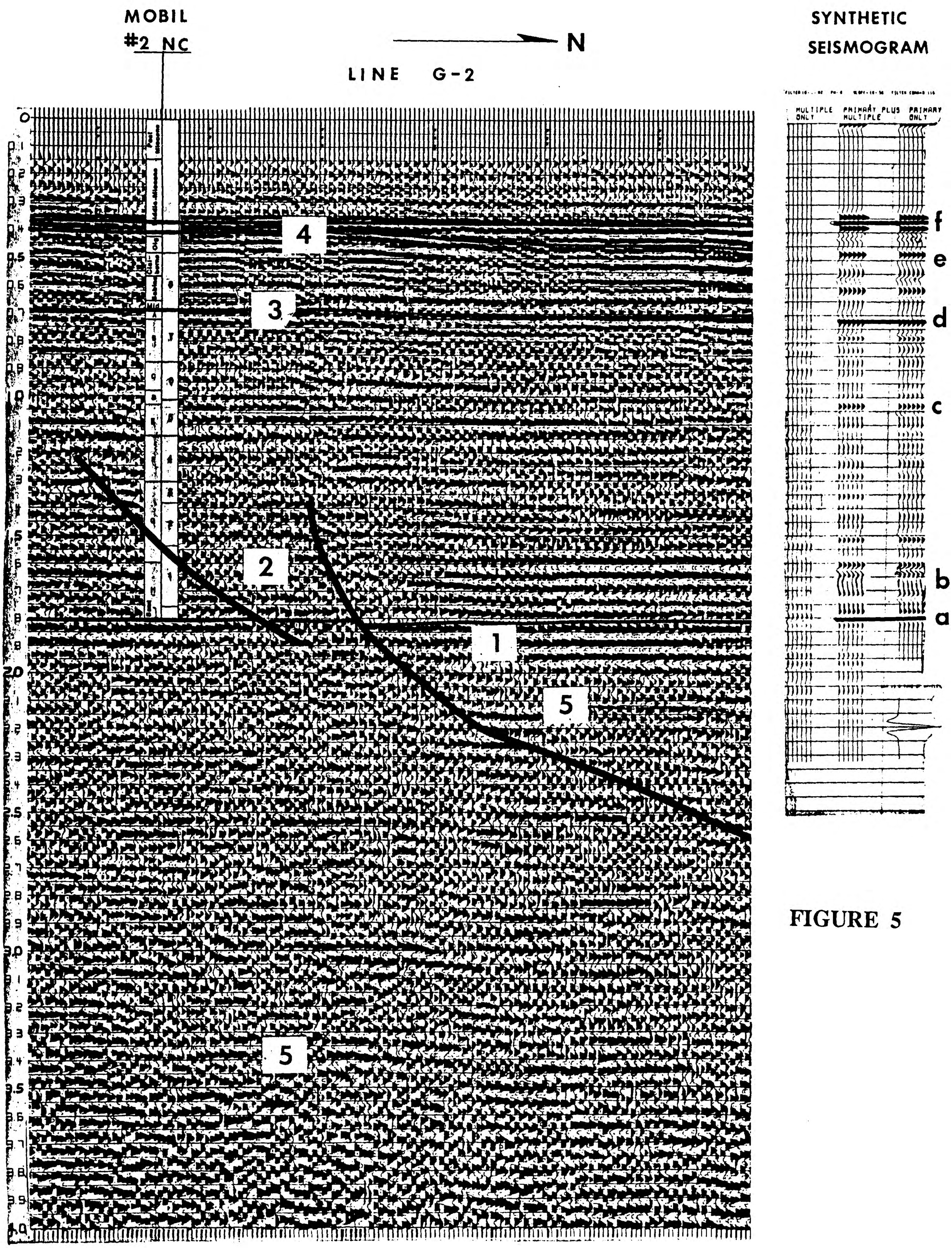


FIGURE 5

COMPARISON OF SYNTHETIC SEISMOGRAMS

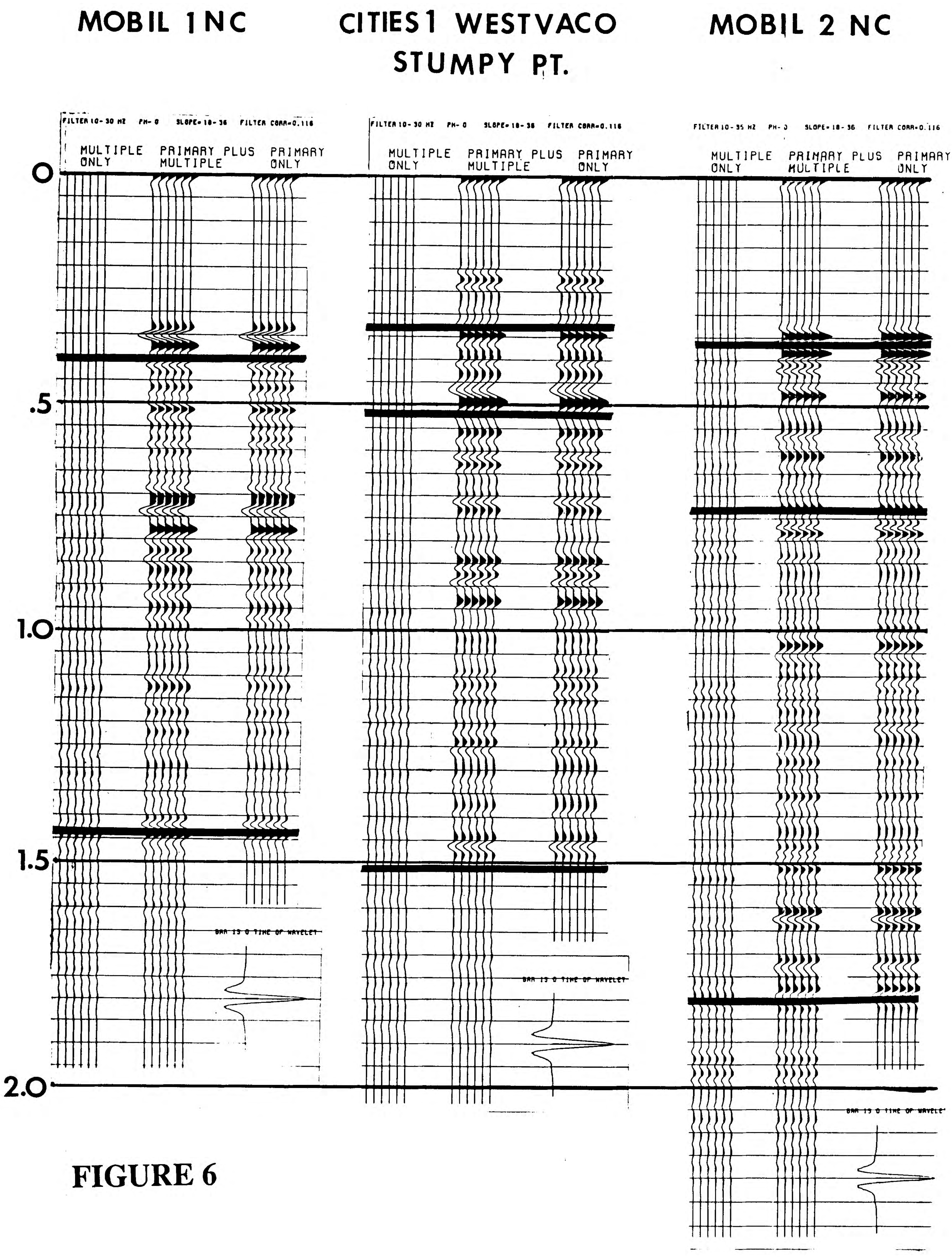


FIGURE 6

general these velocities were suitable to slightly high over the area studied, but that no local anomalies or mis-ties were introduced by these assumptions.

STRATIGRAPHIC STUDIES

Considerable work on the shallower section has been done both stratigraphically and seismically. As seismic data in this study was focussed on deeper targets and as more questions on the stratigraphic sequence exist there, this study focussed on the Cretaceous rocks.

Depositional Units:

The stratigraphic section has been divided into several related packets or units by earlier workers, with the boundaries of the packets being unconformities (Brown, et al. 1972; Owens and Gohn, 1985; Poag, 1985; Popenoe, 1985). The Tertiary has been variously divided into two to eleven units, and the Cretaceous into five to eight units. Additionally, Haq, et al. (1987) in presenting the sequence stratigraphy of the Tertiary and Cretaceous, has defined 37 depositional sequences or cycles for the Cretaceous and 43 for the Tertiary. Because of the current shifts in meaning for the word "sequence", it has generally been avoided in this report, unless the word is being used directly as a cited author wished to use it (e. g., Owens and Gohn, 1985) or unless the stratigraphic units being described meet the definition of Vail, et al. (1977).

The emphasis of this study as mentioned above is on the Cretaceous section in the Albemarle embayment of the eastern North Carolina Coastal Plain. The principal reasons for concentrating on the Cretaceous sequence are the abundance of deep data in the new seismic profiles, the incomplete Tertiary section represented on the geophysical data in hand for the project, and the existence of a recent detailed review and interpretation of the Tertiary by Poag (1985) and Popenoe (1985).

For this study, the Cretaceous and older Mesozoic section within the Albemarle embayment was subdivided into five lithologic units (Figure 3). This is a modification of the depositional sequences given by Owens and Gohn (1985), and is based primarily on the overall lithologic character of the sediments as they appear on logs from the 19 wells used, as well as earlier work by Brown, et al., (1972). These subdivisions are also supported by the stratigraphic position of the most continuous mappable seismic reflectors indicated by correlations with the seismic profiles and the synthetic seismograms. From oldest to youngest,the five units are as follows (Figure 3):

1) A pre-Aptian unit of sands and limestones or shales, which is largely non-marine at the base.

2) A thick unit of alternating discontinuous sands and shales that represent a deltaic or pro-deltaic facies.

3) A thin unit of shelf deposits with a few well developed limestones.

4) A thin unit of sands and shales, largely deltaic.

5) A fine-grained, glauconitic, marly unit that represents shelf deposits.

In general, in developing the stratigraphic correlations in this study, well-log correlations derived from spontaneous potential and resistivity logs and their equivalents were found to be consistent and clearly developed, from log to log. Only at the Top of Cretaceous and within the Albian-Cenomanian Unit F of Brown, et al. (1972) are correlations difficult. In this study a somewhat more consistent pattern of correlations has been developed than that provided in Brown, et al. (1972), with the differences being found at the top of Unit A, at the boundary between Units C and D, rarely at the correlation for the top of Unit E, and at the contact between Units F and G.

With respect to Owens and Gohn (1985), the depositional units developed in this study differ in two ways. First, a consistent change in sedimentation occurs at the base of the Unit G of Brown, et al. (1972) at the top of a thick, massive sand unit that thins updip. This occurs at approximately the upper part of the Aptian series and is a significant feature on the well-logs in the area. The interval from the bottom of the stratigraphic section to this point is marked by largely non-marine deposits and limestones with shales that gradually give way to more marine sediments. Above this massive sand, the rocks are deltaic to prodeltaic in nature with rapidly alternating shales and sand bodies that have minimal horizontal continuity. The sands become more abundant upwards to an abrupt break that marks the top of Unit F of Brown, et al. (1972), and a shift to shelf sedimentation marked by thin, sandy limestones and shales of Unit E. The shales of Unit F may have calcareous breaks with large moldic pelecypods present in some core samples in the Esso #1 Hatteras Light well. This upper interval coincides with most of Unit G and all of Unit F of Brown et al. (1972) and is the second depositional unit of this study. Both of these units are included in the first depositional sequence of Owens and Gohn (1985).

The third unit in this study coincides with the uppermost part of Sequence 1 of Owens and Gohn (1985) and with the calcareous shelf sediments of Unit E of Brown, et al. (1972). Unit D of Brown et al., (1972) coincides with the second sequence of Owens and Gohn (1985), and their third sequence incorporates most of Unit C of Brown, et al. (1972). The upper part of Unit C and the lower half of Unit B of Brown, et al. (1972) is equivalent to the fourth sequence of Owens and Gohn (1985). The upper half of Unit B and the basal part of Unit A is equivalent to the fifth sequence of Owens and Gohn, and the rest of Unit A is equivalent to their sixth sequence. For this study, however, log character clearly shows the deltaic, and possibly regressive, nature of Units C and D of Brown et al. (1972) as the sand section becomes better developed towards the top part of Unit C. Units A and B are similar in log and lithologic character and in seismic response; they have not been differentiated in this report because of inadequatepaleontological data. They consist of glauconitic, marly sands and shales that represent shelf deposits.

In summary, the five lithologic subdivisions of the Cretaceous used in this report are based on Owens and Gohn (1985), Brown, et al. (1972), log analysis for the current study, and seismic character as indicated on the synthetic seismograms and the seismic profiles. Modification of the regional work by Owens and Gohn (1985) has occurred where obvious log breaks coincided with seismic character change, and stratigraphic character suggested a break in deposition or a reversal in transgressive-regressive direction. Paleontologic data to support these modifications is not available from modern integrated micropaleontological studies.

Tertiary stratigraphic units may be grouped into two larger units - a lower Tertiary unit representing outer shelf conditions which consists of upper Paleocene rocks and the Eocene arenaceous clastic limestones with some minor Oligocene units, and an upper unit that is predominantly shallow shelf and arenaceous, especially in the Miocene and Pliocene. A thin Pleistocene series is developed above these Tertiary units.

SEISMIC STUDIES

Geophysical review of 153 miles of 12-fold CDPS seismic data, recorded to 4 seconds two-way time, and the analysis of 14 synthetic seismograms suggest that the stratigraphic section under the coastal plain of North Carolina has the following seismic characteristics:

1) Seismic velocities increase generally with depth to the same rock unit, and they vary horizontally at the same depth or within the same rock unit. In any given direction, variation in seismic velocity is sufficient to require a great deal of control for successful understanding of spatial geometry.

2) Fairly continuous reflectors are developed well enough to be used across the area of study.

3) Faulting is developed primarily in Paleozoic crystalline rocks and rarely extends more than a short distance into the overlying lower portion of the ?Jurassic-Cretaceous sedimentary section.

4) Basement topography has moderate relief developed primarily by erosion around probable intrusive bodies and along relief associated with faults in the Paleozoic basement.

5) Although patterns in interval velocity maps indicate possible basement control of sedimentation during the Cretaceous, patterns of faulting associated with rifting found in the basement do not parallel the variations in interval velocity.

Interpretation of synthetic seismograms:

Review of the synthetic seismograms for the 14 wells for which they were developed indicate that the sedimentary section under study produces the following distinctive seismic events:

a) A distinctive broad trough at the sedimentary contact with the crystalline basement.

b) A single, moderately strong reflection at a persistent sand at the base of the Aptian section.

c) A single strong reflection on the top of a thin Cenomanian limestone.

d) A single strong reflection just beneath the top of Cretaceous.

e) A single strong peak at the top of the middle Eocene (Claibornian) limestone.

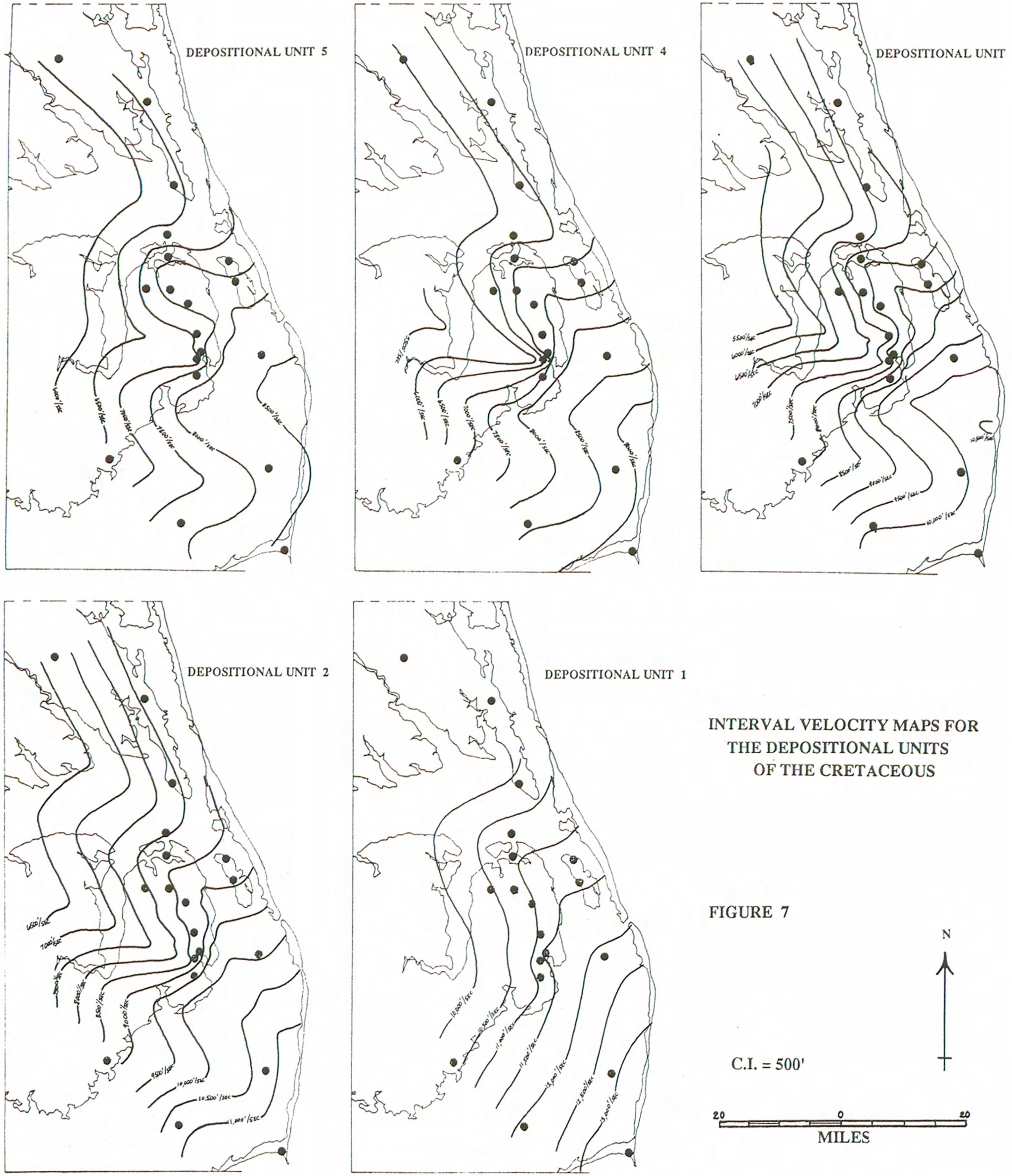
f) A strong doublet associated with the limestone in the lower part of the middle Miocene.

g) Multiple reflections developed from reflectors in the Eocene, Oligocene, and Miocene sediments and from the surface of the crystalline basement. Multiple attenuation was attempted in processing and was generally successful except in the areas of the profile where minimal signal was being generated, especially within the crystalline basement below the basement reflection. There, the automatic gain feature built up the faint multiple reflections in the absence of other signal. However, the synthetic seismogram had a separate seismogram for multiples only that enabled the interpreter to sort multiples, throughout the profile, from desired signal.

These are illustrated in Figure 4, with the data from the Mobil #2 State of North Carolina well. They have also been discussed in more detail in Hoffman, et al. (1985).

Using the data that accompanies the synthetic seismograms, interval velocities for each of the depositional sequences outlined in the section on stratigraphy and the average velocity values to each of the horizons for which structure maps are presented were calculated, plotted, and contoured. These maps are on file and available in the offices of the N.C. Geological Survey, Raleigh, NC.

Both sets of maps show considerable variation in seismic velocity for all horizons considered across the area studied. As the interval velocity maps contain no approximation of surface velocities (as the average velocity values must), they are the best indicator of such variation (Figure 7). In general, from interval to interval, southeastward plunging trends of low velocity alternate with northwest-trending high velocity zones across the mapped area. At first it was thought that these would represent basement blocks displaced by faulting, but investigation of the seismic profiles indicates no such correlation - in fact, most of the faults do not extend above the basement. There is a



INTERVAL VELOCITY MAPS FOR THE DEPOSITIONAL UNITS OF THE CRETACEOUS

FIGURE 7

C.I. = 500'

correlation between velocities and thickness of the interval and possible lithology that suggests that the controls on velocity may be partially explained by differential compaction over persistent basement high areas developed by erosion before deposition of the Mesozoic sediments.

Analysis of Time-Depth Data and Interval Velocities:

The Stumpy Point area offers an unusually good opportunity for observing the relationships that exist between time data from seismic reflection surveys, depth data from subsurface well control, and interval velocity data from sonic logs. Seismic line W-23 trends generally north-south through the Stumpy Point area, although the line follows a road which is anything but straight. There is on line W-23 a very noticeable structural anomaly at basement depth. The structural elements appear to include: (1) a change in character of basement lithologies (an intrusive body?); (2) topographic relief on the nonconformity between crystalline basement and overlying sediments; (3) faulting which extends upward from the basement, cutting Jurassic and possibly even lowermost Cretaceous rocks; and (4) segments of relatively steep dip in the oldest part of the sedimentary section. This structural feature has attracted the attention of explorationists, as is indicated by the presence of three oil and gas tests along the three-mile stretch of line W-23 which contains the anomaly.

All three of these wells, the Cities Service #1 Westvaco, the Gentles #3 Westvaco, and the Rapp #1 Laverne Twiford, have sonic logs which have been digitized as a part of this study. Time-depth charts have been prepared on 10-foot depth intervals as an intermediate step in the construction of synthetic seismograms. Using these time-depth charts, two-way reflection times were computed to seven correlative horizons in each of the three wells. The top of Eocene and the top of crystalline basement (which was not reached in the #1 Twiford well) were included, along with the five depositional units identified for mapping purposes in this study. Average transmission velocites were also computed in each well for each of the six intervals defined by these seven horizons. The resulting time, depth, and interval velocity data for these three wells are summarized in cross-section form in Figures 8 and 9.

Figure 8 compares the actual structural gradients in feet with the reflection arrival times predicted by the sonic log data. Note that the predicted gradients in reflection times differ significantly from the actual structural conditions. The Gentles #1 Westvaco well is structurally the highest on all horizons. The structural gradients to the north and south of this well increase with depth from less than five feet per mile at the top of Eocene to as much as 150 feet per mile on the basement. The predicted gradients in reflection times agree with the structural conditions only at the top of the Cretaceous. Above that depth the cross-section shows a 10 millisecond dip from north to south. Below the top of the Cretaceous the cross-section exhibits between 37 and 42 milliseconds of north dip. Finally, below -3300 feet the time gradients are all toward, rather than away from the Gentles well. That is, the direction of the predicted time gradients is exactly opposite to that of the structural dips. This striking discrepancy in time and depth gradients indicates the presence of important velocity variations among these three wells.

Figure 9, which compares structural gradients with interval velocities, shows at most horizons that interval velocities are slowest in the structurally highest well, the Gentles #1 Westvaco. This, of course, accounts for the reversal, illustrated in Figure 8, of predicted time gradients as compared to structural gradients. The relatively low velocities found in the Gentles well probably reflect topographically controlled lithologic differences formed during periods of deltaic and prodeltaic deposition. Reflection seismic data reveal the presence of a topographic high on the faulted and eroded basement, and the persistence of subtle seabottom relief above this feature is indicated by stratigraphic thinning found throughout the sedimentary section in the Gentles well.

In fact, the reflections along seismic line W- 23 across the Stumpy Point structure (shotpoints 310 through 370) do not follow the gradients predicted by the sonic logs of

Comparison of Gradients Depths and Reflection Times

Stumpy Point, NC

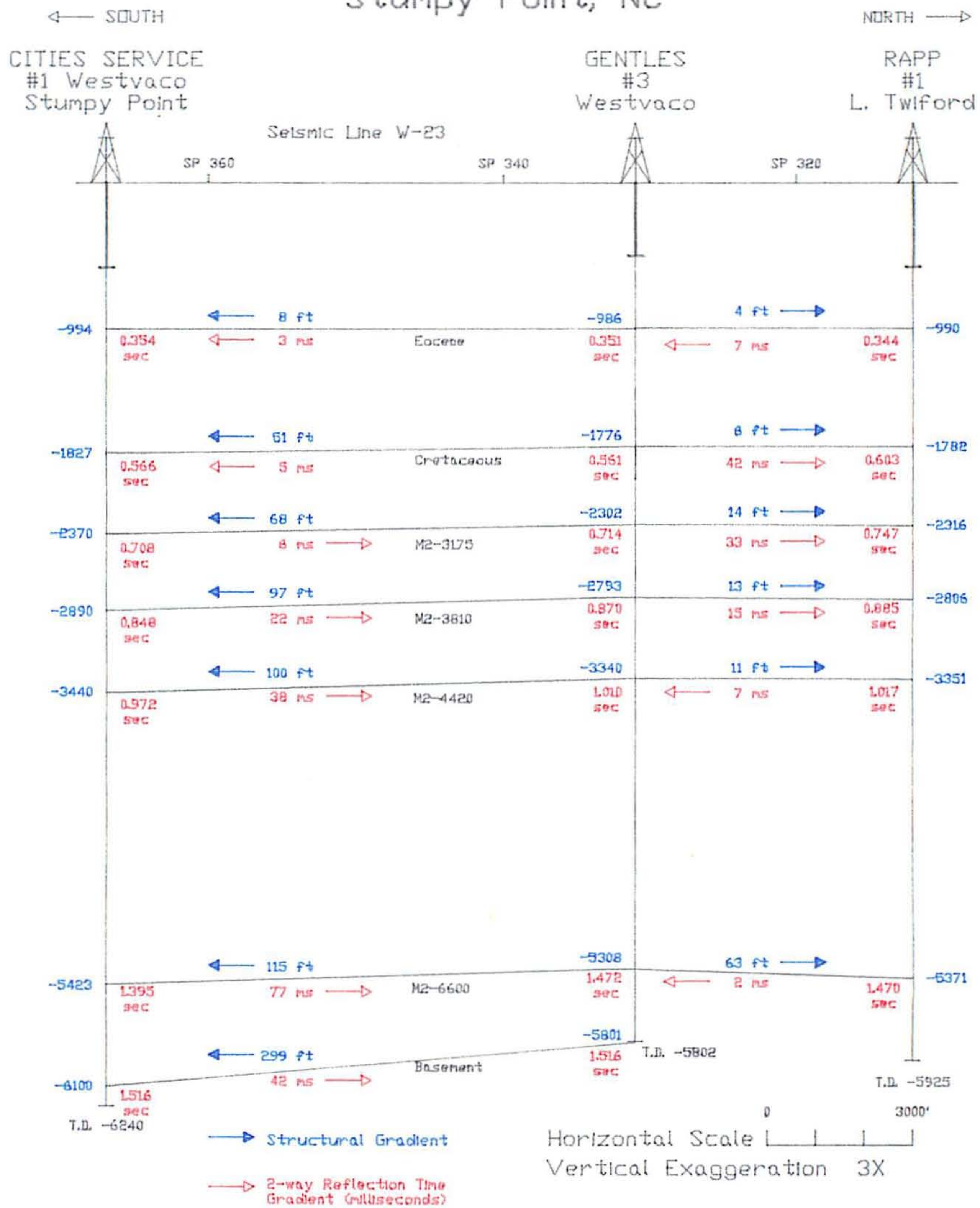


FIGURE 8

Comparison of Gradients
Depths and Interval Velocities
Stumpy Point, NC

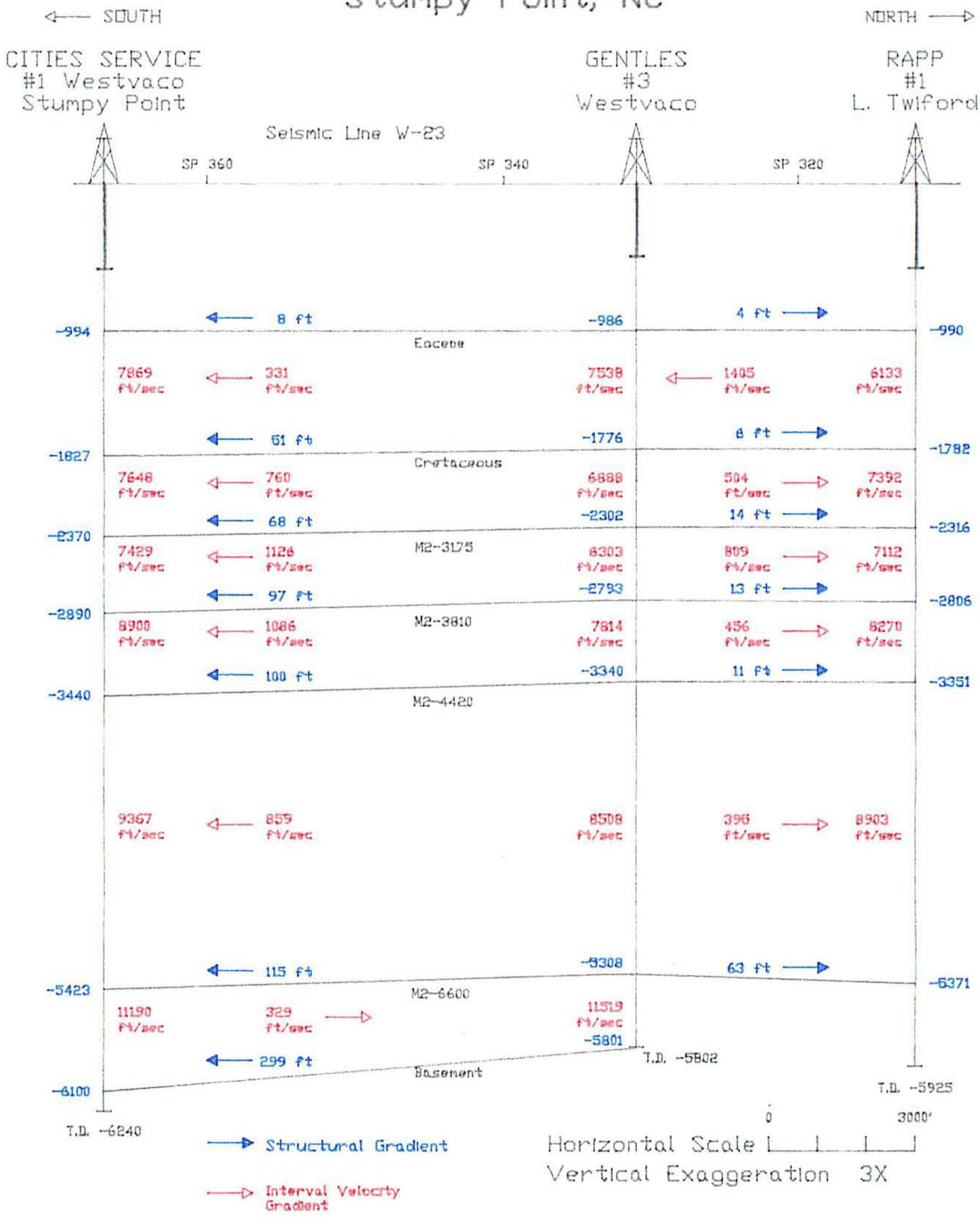


FIGURE 9

the nearby wells. It appears that either one or more of the sonic logs was calibrated inaccurately or the seismic processing methods used on this line compensated somehow for the indicated velocity variations. The break-up of the data in the first 0.3 seconds in the vicinity of the Gentles #1 Westvaco well suggests that some large static corrections were made. If sufficiently large, such corrections could fully compensate for the low velocities found in the Gentles well and achieve the results seen on the processed records. Another possibility has to do with the geometry of the W-23 line in plan view. In the Stumpy Point area the road which the line follows makes two sweeping turns, forming an S- shaped track. In 1972, when these lines were shot, standard stacking techniques neither allowed for nor compensated for crooked lines. Information on cable geometries (i.e., were they laid out in line or en echelon) as well as stacking methods would be relevant here. A third explanation for the failure of the W-23 line to agree with sonic log data is that a variable velocity function may have been used along the seismic line. Unfortunately, very little information is available concerning the exact processing techniques and parameters employed on these lines, and there is no reliable way to choose among these several speculative expanations of the fact that the processed seismic line W-23 disagrees with predictions derived from sonic log data.

The above analysis of time and depth relationships in the Stumpy Point area raises some important issues for the current investigation. First, the conditions at Stumpy Point make it clear that velocity variations can be sufficiently large to seriously affect structural interpretations if velocity data are either ignored or unavailable. But important variations in interval velocities are not restricted to Stumpy Point and seismic line W- 23. Indeed, interval velocity maps on all five of the depositional units between top of Cretaceous and basement show a wide range of values across the entire study area, with contours of equal interval velocity diverging significantly from the regional direction of structural strike.

Second, it seems likely that the seismic profiles used in this investigation have been processed in a manner intended to compensate, at least partially, for local changes in velocity. The likelihood that specialized processing is responsible for the difficulty of correlating the Stumpy Point wells to the W-23 seismic section understandably introduces some ambiguity and doubt into the more regional interpretations using these seismic profiles. While there is no way to know the extent of such compensatory processing, it is logical to assume that these techniques were used most often to resolve local anomalies, and need not be considered as important in a regional interpretaion.

Interpretation of Seismic Profiles:

In reviewing the seismic profiles, there are specific structures that can be illustrated by specific examples from the profiles. Otherwise, the general structural configuration of the rocks in this area are summarized on the four structural subsurface maps drawn on the Crystalline Basement, the M2-6600 Horizon, the M2-3950 Horizon, and the Top Cretaceous, presented in Plates 1-4, respectively.

With respect to the Paleozoic crystalline basement, the following features may be observed:

1) The basement reflector is quite reliably present and distinctive over most of the area. Where the reflector appears to break up, the surface has apparently been faulted and the relief produced has been filled with sediments deposited before the development of the Post-Rift Unconformity. Lines G-2, G-4, and W-23 show some of these effects (Figures 10 and 11).

2) Surface relief on the crystalline basement is also developed over intrusive bodies within the crystalline complex. Such relief is well illustrated on Line W-23 (Figure 10) where considerable well control is concentrated. The attractiveness of such basement relief as a drilling target is quite clear at this point. However, extensive velocity control was necessary to aid in understanding the structures here, as discussed above. Relief is estimated at 250 feet or more.

FIGURE 10

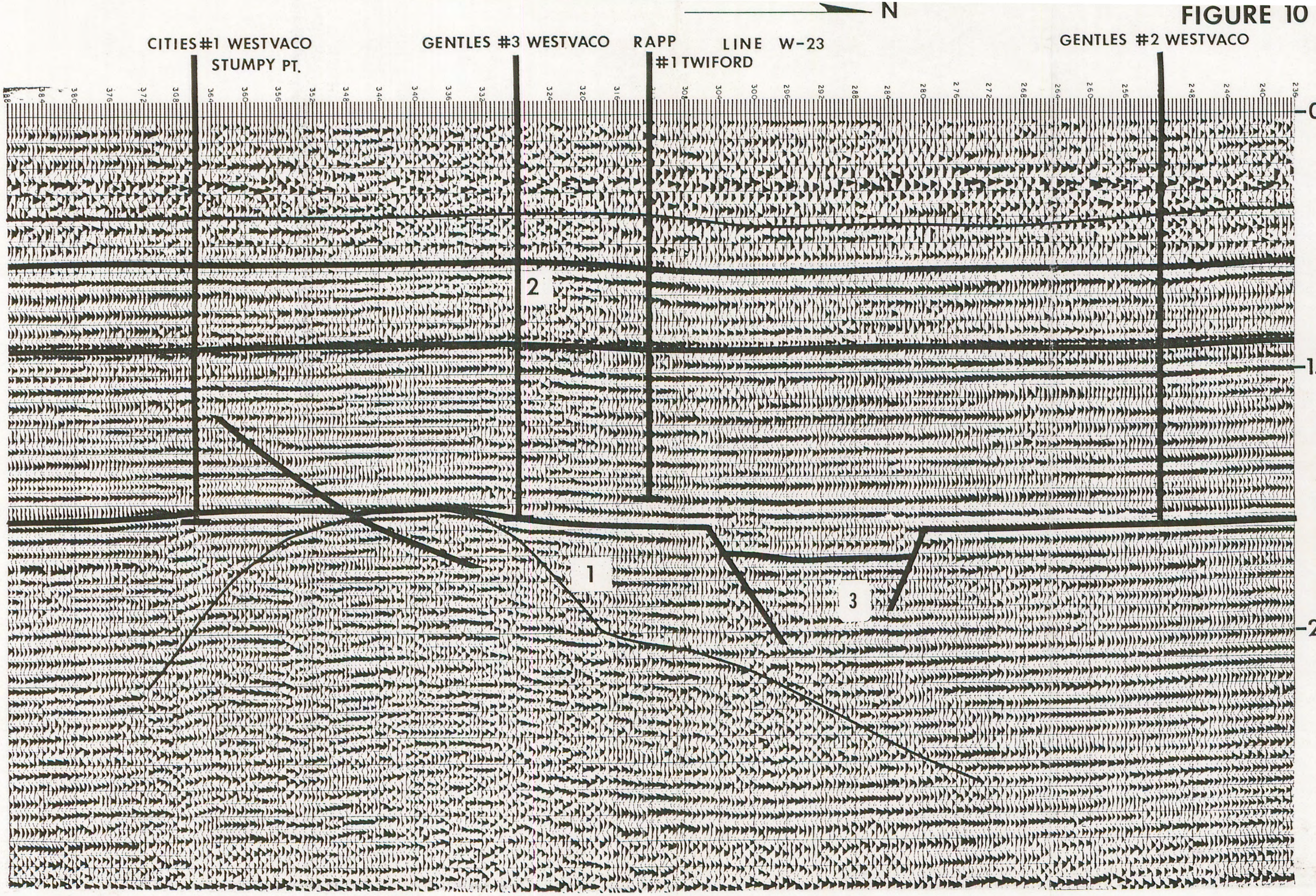
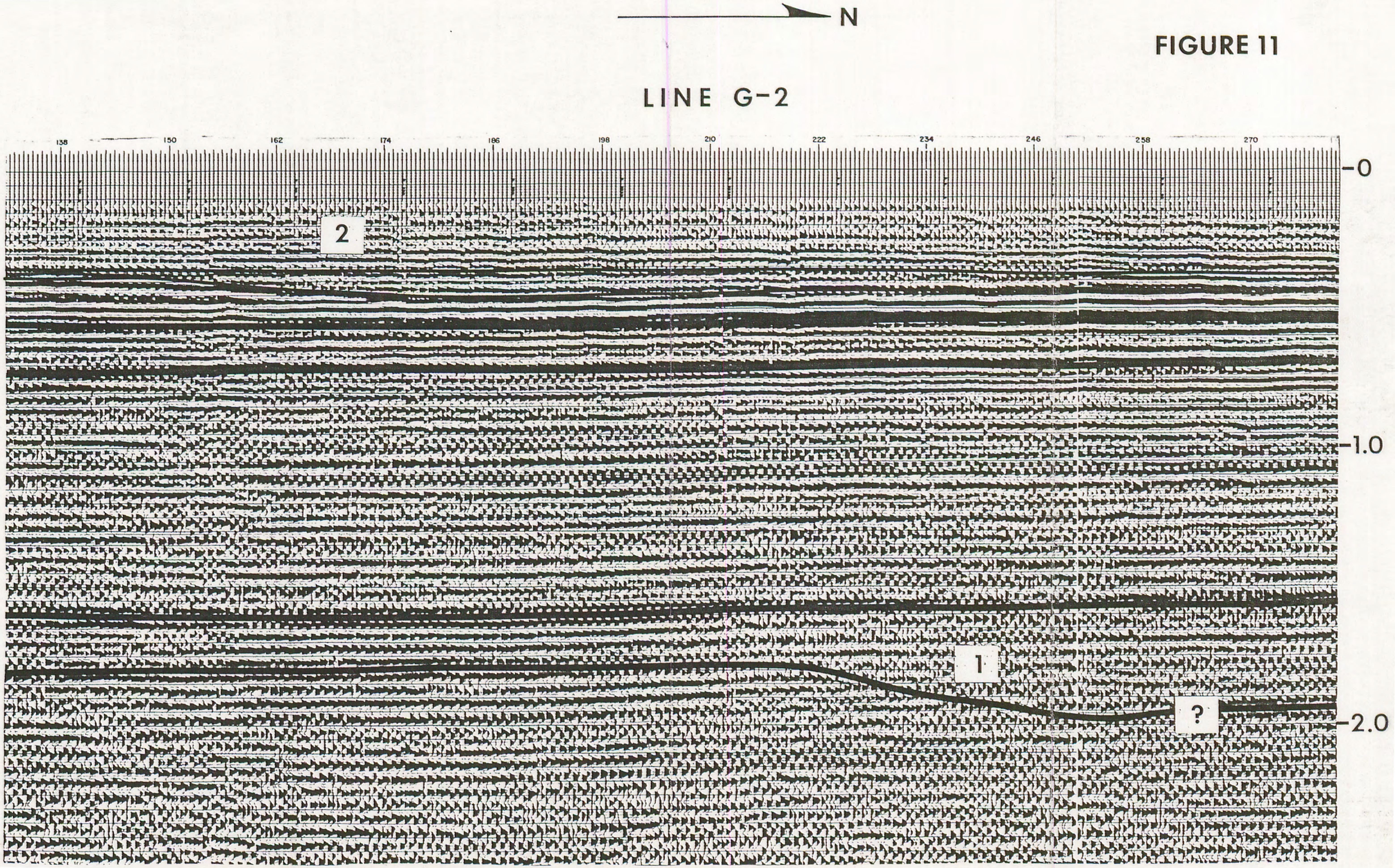

N
CITIES #1 WESTVACO
STUMPY PT.
GENTLES #3 WESTVACO
RAPP
#1 TWIFORD
LINE W-23
GENTLES #2 WESTVACO
0
1.0
2.0
1
2
3

FIGURE 11

LINE G-2



Gravity and magnetic data also possibly support an intrusive body at this location and at locations to the north within the area of study (Watkins, et al., 1985). Here erosional relief is positive.

3) Most faults are pre-Cretaceous and extensional, displacing only the surface of the crystalline basement. Approximately 1000-1500 feet of relief are created on these faults, but the basins created are filled with non-marine, coarse clastic materials and undergo little or no compaction over time. As a result the relief developed is not reflected in the overlying younger stratigraphic section. A few faults cut the overlying Cretaceous section, but those disappear near the base of the Aptian sedimentary section (Figures 5, 10, and 11).

Within the sedimentary section the following features are seen:

1) Though somewhat variable in seismic character, the Tertiary-Cretaceous boundary is persistent in the seismic profiles and is unconformable, with erosional relief, in the area of study. The unconformity is supported by well-log correlations and paleontological data.

2) A sequence of strongly progradational sediments, with a northward component to the progradation, is present in the Miocene section (Line G-2; Figure 5 and 11). This has been noted by Popenoe (1985) in a regional, offshore study. He attributes these structures to erosional reworking of sediments on the prograding Atlantic continental shelf by the Gulf Stream.

Four structural maps were developed from the seismic profiles and the well logs. Because of the high velocity gradients and variability in seismic velocities from well to well, average velocity maps were developed from the data associated with the synthetic seismograms, and the interpolated values transferred to the seismic profiles at the appropriate shot points that were to be used in the structure maps. Horizons were then timed at the selected shot point intervals, and the appropriate velocities were used for the conversion of time to depth. For an area as variable as this one, it is almost essential to have as complete an understanding of velocity variation as is possible.

STRUCTURAL MAPS ON SELECTED HORIZONS

Using the methods described above, structural geological maps were constructed from seismic and well data on the following stratigraphic horizons:

1) Pre-Mesozoic Crystalline Basement, Plate 1.

2) Top of the M2-6600' Sand, Plate 2. Top Depositional Unit 1 of this report, basal sand of Unit G of Brown, et al. (1972). This sand was called the "M2-6600' Sand" in the process of assembling this study because of its occurrence at 6600 feet in the Mobil #2 State of North Carolina well.

3) M2-3950 Horizon, Plate 3. Thin Cenomanian Limestone (Top Sequence 1 of Owens and Gohn, 1985; Top Unit E of Brown, et al. 1972; middle part of Depositonal Unit 3 of this report). This unit was called the M2-3950 horizon for purposes of this study because of its development at 3950 feet in the Mobil #2 State of North Carolina well.

4) Top Cretaceous, Plate 4. This is a noticeable unconformity both in well correlations and on the seismic profiles.

In constructing these maps, depth determinations were made from the seismic profiles every 60 shot-points or less as needed. The up and downthrown edges of faults were also chosen where needed. Average velocity maps were used to convert times to depths because of the extreme variability in velocities. The density of sonic data permitted this to be done on a reasonable basis.

In general the maps show the following structural features: (1) a persistent structural high near the Mobil #2 NC well; (2) a re-entrant to the northwest near the mouth of Albemarle Sound - Roanoke Island, and another south of Stumpy Point; and (3) faulting that rifts the basement, but only mildly affects the overlying Post-Rift sediments. By mid-Aptian time the faults have all but disappeared in the sedimentary section.

The map on Paleozoic crystalline basement shows extensional faulting oriented northeast-southwest and a series of structural highs that trend northwest-southeast upon which the faulting is superimposed. Had the map been drawn on the Post-Rift Unconformity, the fault traces would have shown, but little or no relief would be present across the faults. However, the gentle structural noses, plunging southeastward, would still be present.

The map on the M2-6600 horizon, top of Depositional Unit 1 of this report (mid-Aptian) shows a few small faults and the persistence of the features listed above.

The structural map on the Cenomanian limestone (M2-3950) shows the same features with less relief than the deeper horizons. There are no faults.

The Top of Cretaceous map shows less relief that the previous maps and the persistent structural trends are somewhat reduced in their impact by the presence of an erosional surface.

Popenoe (1985) suggested that the Aurora Embayment first developed in Tertiary time, and that the Cape Lookout High formed as an erosional remnant as the Gulf Stream migrated across the Hatteras portion of the continental shelf throughout Tertiary time. Evidence from these seismic profiles suggest that the inshore portion of these structures have had a longer life than that and that they represent persistent basement relief, projected through the section by differential sedimentation and differential compaction of the sediments deposited in the associated low areas. Additionally, the erosion by the Gulf Stream may have contributed to the development of the Cape Lookout High, as suggestedby Popenoe (1985) and sedimentary deposition by the Gulf Stream may have created a bypass area that became the Aurora Embayment in Tertiary time, but the fundamental position and nature of these structures is not entirely based on Tertiary erosion and sedimentation. Rather these processes have enhanced or continued the existence of features already present since the early Mesozoic.

HYDROCARBON POTENTIAL

This study has necessarily been a review of data released and available to the public by industry. Further, the data sets are not totally modern, and do not include all the data that is available. However, the following possibilities may be considerered in developing exploration programs for this area:

1) Flanks of resistant topographic highs on the crystalline basement may possibly be prospective. Certainly the example at Stumpy Point, though not productive, is a typical example of a stratigraphic-structural prospect that is possible in the area. The available velocity control provides other leads, not all of which have been tested.

2) The broad high near the Mobil 2 NC well may have some further potential.

3) Should tests in the exposed onshore rift basins prove productive, further investigation of the buried rift systems suggested by this study in the crystalline basement, below the Post-Rift Unconformity, would be warranted.

4) Depositional Unit 2 offers possibilities, because of the interbedded nature of the sands and shales of which it is composed, and because it represents relatively rapid marine deposition.

5) Depositional Unit 1 may offer a few moderately attractive targets for exploration for similar reasons.

Hydrocarbon potential is not as great in the area studied, as further offshore, because much of the section is thin and in an updip position and because maturation of the organic material may not have taken place.

However, this study has provided an understanding of the variations in seimic velocities and indicated one possible relationship to the stratigraphic record, the association with older topographic relief. The seismic framework offered here should lead to better interpretations of the seismic data available and to improved interpretations of new data when it is acquired.

CONCLUSIONS

Availability of seismic data recorded to depths well below crystalline basement, of velocity information at a data density to give good control over a variable sedimentary section, and of new concepts in stratigraphy that integrate seismic control and paleontology into identifiable global sea level events has made a review of the subsurface data of the eastern portion of the North Carolina Coastal Plain (Albemarle Embayment) feasible. Specifically this study has indicated the following:

1) Lithostratigraphic units initially established by Brown, et al. (1972), are generally usable with minor refinement in the subsurface of North Carolina - they coincide with easily identifiable breaks in lithology and in log character.

2) Systematic and detailed micropaleontological work is needed for the wells in North Carolina, across all the subfields of the discipline, especially as the sedimentary section in large part located in the shoreward portion of the continental margin.

3) Data associated with the synthetic seismograms permitted the development of interval velocity maps and average velocity maps. These tools permitted the control of velocity variations and presentation of more accurate structural maps.

4) Basement faulting does not persist much above the Post-Rift Unconformity.

5) Topographic relief developed upon the crystalline basement by erosion persists through much of the sedimentary section in the Cretaceous and possibly influences structural elements in the Tertiary section.

6) The trend of the basement faults is northeast-southwest, and that of the basement erosional remnants is northwest- southeast.

7) The prograding Miocene deposits, observed on the inshore seismic profiles reviewed in this report, show a northward component of progradaton. As this component cannot be easily given a deltaic origin off lands to the northwest, the solution suggested by Popenoe (1985) from his offshore data is feasible. Popenoe (1985) observed such progradation and ascribed it to the erosional and depositional activities of the Gulf Stream in the Tertiary.

8) A portion of the Cape Lookout High and the Aurora Embayment appear to be older features than Tertiary. Rather they seem to have persisted into the Tertiary from earlier Cretaceous times. Their current location and size may

have been reduced or augmented by Tertiary erosional activities of the Gulf Stream, as postulated by Popenoe (1985).

9) Hydrocarbon exploration in this area will be risky because of the thin updip section, but it is enhanced by the excellent control of complexly varying seismic velocity in the sedimentary section. Some modest prospect targets do exist, notably in the areas of high velocity gradients and in the areas of the deeper rifts. Both are high risk.

The reconnaissance seismic data has permitted us to see continuous segments of the Mesozoic sedimentary section in the inland waters of North Carolina and to begin to unravel small portion of the complex large scale sedimentary system of the Atlantic margin in some detail. Additional seismic and paleontological data would permit a greater understanding of tectonic and eustatic sea level control of sedimentation and geologic history of this portion of the Atlantic margin. A more controlled approach to resource development and a better understanding of earth processes and history will be the result.

ACKNOWLEDGEMENTS

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APPENDIX 1

INVENTORY OF WELLS USED IN THIS REPORT

OPERATOR/ LEASEHOLD	Well Number (API)
E.F. BLAIR	
Ballance #1	32-95-10
Marshall Collins #1	32-55- 5
Twiford	32-53- 1
West Virginia Pulp and Paper Co.	32-55- 6
Weyerhaeuser #1	32-29- 2
F.W. CARR	
Atlantic Beach #1	32-31-15
Int'l. Paper Trader #1	32-31-14
J.E. Elliott #1	32-31-13
Samon #1	32-31-16
CITGO (Cities Serv)	
1st Colony Farms #1	32-55-14
1st Colony Farms #2-A	32-55-15
Westvaco, South Lake #2	32-55-10
Westvaco, #1 Stumpy Point	32-55- 9
COLONIAL OIL AND GAS	
Rabon #1	32-19-14
A. GENTLES	
Westvaco, #2 Pamlico Sound	32-55-12
Westvaco, #3 Pamlico Sound	32-55-13
MOBIL (Socony)	
N.C. #1	32-55- 3
N.C. #2	32-55- 4
N.C. #3	32-95- 9
RAPP OIL	
Kellogg #1	32-53- 2
Laverne Twiford #1	32-55- 8
Etheridge #1	32-55- 7
STANDARD OF N. J.	
N.C. #1 Hatteras Light	32-55- 1
N.C. #2 Pamlico Sound	32-55- 2

APPENDIX 2

INVENTORY OF SYNTHETIC SEISMOGRAMS USED IN THIS REPORT

OPERATOR/ LEASEHOLD	FILM	DATA* SOURCE	PHASE ANGLE
E.F. BLAIR			
Marshall Collins #1	*	V	0
	*	V	Min.
	*	V	90
Twiford #1	*	V	0
	*	V	Min.
	*	V	90
Weyerhauser #1	*	V	0
	*	V	Min.
	*	V	90
F.W. CARR			
Atlantic Beach #1	*	V	0
	*	V	Min.
		V	90
Int'l. Paper Trader #1	*	V	0
J.E. Elliott	*	V	0
	*	V	90
		V	Min.
Samon	*	V	0
		V	90
		V	Min.
CHEVRON			
V.R. Groce #1	*	V	0
	*	V,D	0
CITGO (Cities Serv)			
1st Colony Farms #1	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	0
	*	V,D	90
1st Colony Farms #2-A	*	V	0
		V	Min.
		V	90
	*	V,D	0
	*	V,D	Min.
	*	V,D	90

APPENDIX 2 *(continued)*

Westvaco, South Lake #2	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	0
	*	V,D	Min.
	*	V,D	90
Westvaco, #1 Stumpy Point	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	Min.
	*	V,D	90
		V,D	0
COLONIAL OIL AND GAS			
Rabon #1		V (time-depth chart only)	
A. GENTLE			
Westvaco, #2 Pamlico Sound	*	V	0
	*	V,D	0
Westvaco, #3 Pamlico Sound	*	V	0
MOBIL (Socony)			
N.C. #1	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	0
	*	V,D	Min.
	*	V,D	90
N.C. #2	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	0
	*	V,D	Min.
	*	V,D	90
N.C. #3	*	V	0
	*	V	Min.
	*	V	90
	*	V,D	0
	*	V,D	Min.
	*	V,D	90
RAPP OIL			
Kellogg #1	*	V	0
		V	Min.
		V	90
Laverne Twiford #1	*	V	0

*V = Velocity from sonic or borehole-compensated sonic log.
*D = Density available from borehole-compensated formation density log.