SEQUENCE STRATIGRAPHIC ANALYSIS OF EARLY AND MIDDLE MIOCENE SHELF PROGRADATION ALONG THE NEW JERSEY MARGIN

by

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ABSTRACT OF THE DISSERTATION

Sequence stratigraphic analysis of early and middle Miocene shelf progradation along the New Jersey margin

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This dissertation uses sequence stratigraphic analysis to study the early to middle Miocene growth of the New Jersey margin, particularly the connection between relative sea level change and variable sediment supply in sequence architecture and preservation. Previous studies of the New Jersey Mid Atlantic margin have concentrated either onshore through extensive coring and few seismic profiles or the outer continental shelf and slope where excellent seismic profiles but limited cores exist. The *R/V Cape Hatteras* (*CH0698*) high resolution seismic data fills the missing interval between the two databases thereby forming a tie between onshore coreholes and offshore shelf seismic profiles. Eleven candidate sequence boundaries were identified by seismic reflector termination geometries in high resolution MCS profiles and traced across the inner margin. ODP Leg 150X onshore coreholes were matched by geophysical log signatures and lithologic changes to offshore boreholes within the seismic grid. Sequence analysis at these drill sites were then matched to the seismic sequence boundaries and drill hole chronologies were used to assign ages to the intervening seismic sequences. A single land-based seismic profile reveals reflector geometries tied to lower Miocene litho- and

bio-facies at the Island Beach borehole thereby providing ground truth for seismic facies interpretations. Offshore seismic facies correlate well with paleoenvironmental interpretations of borehole lithologies.

Regional early Miocene sequences correlate globally and suggest a dominant role of global sea-level change. However sequence formation and preservation was controlled by localized sediment contribution and the wave and current regime along the New Jersey Mid Atlantic margin. Lowstand deposits were regionally restricted and point to both single and multiple sediment sources. Transgressive sediments are thin and generally below seismic resolution. Highstand deposit form a more regional sedimentary blanket and document redistribution by along shelf currents. Fluvial incision is limited and generally found far from the clinoform inflection point. No evidence suggests that sea level fell below the elevation of the clinoform inflection point thereby exposing the entire paleoshelf. Efficient cross shelf sediment transport mechanisms account for the extensive lowstand deposits seaward of this inflection point.

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No research can be done without the help of a multitude of different people. There are those who help only at select steps in the process and then there are those who shadow each and every step, always present when needed, until the ultimate conclusion. I have been lucky enough to have had many people who fit into each category who, through their deeds and comments have allowed my research to move along to its final completion. I cannot thank them enough so I just hope to apply the lessons learned and pass it on, so to speak, by offering my assistance to others as they migrate through their own research.

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Mostly though, I need to thank my main advisers, Greg Mountain and Ken Miller who gave positive input whenever asked but still allowed me to find my own way even with the numerous cul de sacs and blind alleys I stumbled upon. I never could have reached this point without their help. I know that some help was offered and supplied even though they were setting themselves further in a hole in their own research. I hope to pay them back (not really but it sure sounds good don't it). My other advisers, Martha Withjack, Bob Sheridan of Rutgers and Craig Fulthorpe from U Texas, Austin supplied further insight into my research. They all noted different possibilities that showed me all the possible routes that I needed to consider. Thanks for the time and help you invested even though your return on investment did not seem guaranteed as the years kept passing.

Most of all I need to thank family. To my parents who were nice enough to stay around for me until I finally, finally finish the project. They somehow instilled a love of learning in me. I still can't figure out how they did it though. Most of all my wife and kids made it all worthwhile. I know I came home in bad moods or always seemed to be thinking research but they allowed me my dark moments. Danie, Abby and Ryan made me realize that no matter what happened I will leave the world a better place by having them. Mostly though I need to thank my beautiful, intelligent wife Kim who put up with all my black clouds and knew just where and when to kick me onward. Finally as the famous philosopher Stymie said, "I don't know where I'm going but I'm on my way".

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Introduction

Seismic sequence stratigraphy provides a new paradigm in sedimentology and basin analysis. Since its first introduction by Payton (1977) the model, now simply termed sequence stratigraphy has continued to evolve and adapt as a research tool (see Nystuen, 1998 for a description of the developmental history of sequence stratigraphy). New investigations along both modern and ancient passive and active margins using outcrop data where exposures exists and drill cores and logs often tied to seismic data continue to provide stimulus for further model evolution. Eustasy, accommodation and sediment supply together are the forcing functions that control the geometry of basin fill. Climate variability such as glacial-interglacial cycles is one of the drivers controlling sea-level change that affects the planet as a whole. More localized accommodation and sediment supply conditions further organize the internal sedimentary architecture and whether a margin progrades or aggrades.

Analysis of seismic data drove the nascent development of seismic stratigraphy, the predecessor of sequence stratigraphy. Vail and Mitchum (1977) stated that "seismic reflections follow chronostratigraphic correlations" thereby making "stratigraphic interpretations from the geometry of seismic reflection correlation patterns". This simple statement concerning the chronostratigraphic significance of seismic reflectors allows the interpretation of deposition at different locations across a basin. Initial basin studies analyzed low resolution seismic profiles to image basin stratigraphy and history. To study basin development during discrete time intervals requires a seismic acquisition

program designed to target select depths for the best image resolution. Here the ability to differentiate small scale features comes into play.

Seismic resolution plays a major role in identifying and tracing sequence changes across a basin. Targeting specific depth intervals with higher frequency seismic sources and tighter line spacing allows more sequences to become apparent. Christie-Blick and Driscoll (1995) suggest that differentiating parasequences from true sequences can be solely a resolution question. Further problems exist in lower resolution seismic data because apparent onlap or downlap reflector terminations are probably an amalgamation of discrete surfaces (Cartwright et al., 1993). Cartwright et al. (1993) suggested that unconformities identified on low resolution seismic will not represent an isochronostratigraphic surface but will vary in time across a basin. Schlager (1993) suggested that inadequate seismic resolution can cause sedimentary facies changes to be imaged as unconformities. Detailed analysis of well logs across a basin has defined siliciclastic sequences of 100-200 kyr duration (Vail et al., 1991; Van Wagoner et al., 1990), much higher frequency than previously observed in older seismic data except near surface Pleistocene deposits. Now higher resolution seismic data has been developed that images higher frequency sequences, similar to the 100-200 kyr sequences of well log data, deeper below the surface.

Mid Atlantic Margin Investigation

Basin studies need to look at sequences in the third dimension to truly characterize the basin development (Martinsen, 1994). Modern basin studies, such as the Gulf of Mexico, show that variable conditions exist synchronously across the basin (Martinsen and Helland-Hansen, 1995). Depending on the proximity of a sediment source, a single seismic line can portray either transgressing or prograding strata. Carey et al. (1998) suggested that lateral sequence preservation relies on nearness to fluvial systems and scale of sea-level fluctuations. This, too, suggests that the different seismic profile positions could possibly image a different geometry and not sufficiently characterize basin evolution. Variable basin subsidence or sediment supply within a single basin has been shown to directly affect what depositional systems are preserved and how they change along strike (Posamentier and Allen, 1999). These studies suggest that no one single seismic profile can image the complete series of sequences present in the basin (Martinsen et al., 1995; Anderson et al., 1996).

Sequence stratigraphy invited a reevaluation of how specific basins evolved. The Mid Atlantic margin came into play as a location to evaluate the premises of sequence stratigraphy. This basin, portraying only limited localized faulting, is controlled by thermal flexural subsidence (Steckler and Watts, 1978; Kominz et al., 1998; Steckler et al. 1999) and records high sediment input and subsequent preservation. A new look at early industry seismic and well data suggested the potential of sequence stratigraphy to explain the Mid Atlantic margin evolution (Greenlee et al., 1988, 1992). The New Jersey

margin has continued to comprise a major research location to evaluate both the sequence stratigraphic model as well as identify the controlling variables in margin's development (e.g, Mountain, Miller, Blum et al., 1994; Austin, 1997; Miller et al., 1998; Austin, Christie-Blick, Malone, M.J., et al., 1998).

The nature of the Mid Atlantic margin has evolved from early rifting to its present day mature passive margin morphology (fig. I.1). Seismic studies have shown that a Jurassic carbonate buildup defined the original margin edge (Poag, 1985). Subsequently as the basin deepened Cretaceous and Paleocene clastic material and Eocene clay-rich carbonates infilled behind the Jurassic paleoshelf edge creating a ramp morphology (1:300 to 1:500 gradient, Steckler et al., 1999). Oligocene clastics prograded beneath the modern coastal plain and created a gently sloping, (~0.06^{o}, 1:1,000 gradient, Steckler et al., 1999, Pekar et al., 2003) continental shelf and moderate Oligocene depositional front atop the remnant ramp morphology (fig. I.1; Steckler et al., 1999). Miocene sedimentation built upon this existing margin morphology and by upper Miocene had reached the original Jurassic paleoshelf.

Strike variable middle and upper Miocene sequence development has been documented under the modern middle to outer shelf, New Jersey margin. Studies based on academic MCS collected in 1975 and reprocessed with a 20-30m vertical resolution (Fulthorpe and Austin, 1998) and *Ew9009* (Poulsen et al., 1998) on the outer continental shelf have found significant along-strike variability in these middle and upper Miocene sequences. Fulthorpe and Austin (1998), investigating upper Miocene sequences showed that fluvial

point sources supplied sediment irregularly along the clinoform strike as opposed to the original sequence model consisting of uniform clinoform progradation. They suggested some sediment migrated laterally due to marine shelf currents. Fulthorpe and Austin (1998) and Fulthorpe et al. (1999) further suggested that sediment supply resulted from many small fluvial sources that coalesced to form a line source landward of the clinoform. Therefore sea level did not drop below the clinoform inflection point as concluded by Greenlee et al. (1992).

Poulsen et al. (1998) studied middle and upper Miocene sequences and came to similar conclusions. Lowstand facies deposits developed as localized deltaic lobes controlled by the location of fluvial sediment disbursement. More proximal facies were sand-rich with sediment grain size minimizing laterally and basinward away from the source. Highstand facies deposits also portrayed deltaic lobe migration and thickened in regions of thinner lowstand facies. Poulsen et al. (1998) suggested depositional centers migrated through time with a corresponding accumulation pattern change. Further work by Fulthorpe et al. (1999, 2000) focused on upper Miocene sediments along the outer continental shelf used higher resolution *Oc270* seismic data and suggested that fluvial incisions were sufficiently close to mimic a line as opposed to multiple isolated point sources of sediment. Line sediment supply greatly reduces the sediment variable in basin development and allows the margin a greater possibility to develop more uniformly across the basin.

To date, no detailed investigation has examined the lateral variability of the early Miocene Mid Atlantic shelf progradation. Onshore detailed coring, specifically Ocean Drilling Program (ODP) legs 150X and 174AX, offers the best information of the regional variation of early Miocene deposition to date (Miller et al. 1994a, 1994b, 1996; Sugarman et al. 2007). Sugarman et al. (1993) used well data to document regional thickness variations of early to middle Miocene sediment deposition and preservation. Subsequent sequence stratigraphic analysis of the ODP core data subdivided the three deposits of Sugarman et al. (1993) into ten different sequences (Browning et al., 2006; Browning et al., in review). All portray lateral thickness and paleoenvironmental changes. A clearer, three-dimensional picture is needed to document margin deposition during this time interval.

Study Proposal

The main depositional center of early Miocene sediments lies under the nearshore New Jersey margin as imaged on the limited *Ew9009* and *Oc270* seismic lines that cross the area in question. This region provides the best opportunity to establish the sequence stratigraphic conditions of margin progradation in this region due to the locally thick and most nearly continuous sediment accumulation. Recently collected *CH0698* seismic data was specifically designed to image early and middle Miocene deposition. It provides an excellent opportunity to establish the relationship of early Miocene sediments at their depocenter. It forms the backbone database of this research into the circumstances that organized margin progradation in the early Miocene.

This study investigates the evidence in seismic and well data of how the New Jersey margin evolved during the early Miocene. It attempts to elucidate four topics. First, can the tenets of sequence stratigraphy be applied to the New Jersey margin to establish the general conditions of formation? Second, once the sedimentary deposits are subdivided using sequence stratigraphic criteria, can they be compared and correlated to the ODP leg 150X and 174AX core data as well as any nearby offshore well data in an internally consistent manner? That is, will the seismic reflectors defined by sequence stratigraphy correlate to the same stratigraphic horizons and boundaries at all borehole locations? This data phase will use both lithologic and downhole geophysical log data as the offshore wells contain only cuttings or limited core recovery (Hathaway et al., 1976; Ferrebee, 1981a, 1981b; Mullikin,1990). Further, can the seismic stratigraphic results enhance the interpretation of corehole data that lacks either paleontological or chemostratigraphic data substantial enough for sequence definition? Third, how do corehole paleoenvironmental interpretations match features imaged on both *CH0698* and limited land based seismic data? Fourth, what is the lateral variability of sediment thickness and sequence development and how has sea-level change, sediment supply or accommodation controlled its formation?

This research attempts to use regional and localized seismic data, core and borehole lithologic, age control and geophysical data to provide the best answers to these questions. Chapter 1 describes an initial interpretation of sequence development using the best available seismic data at the time. It consisted of several *CH0698* dip lines,

which were independently analyzed and not loop correlated. As such reflector correlation was done purely on position and number of candidate sequence boundaries. This led to the conclusion described in Chapter 1. As *CH0698* seismic data processing was completed at Lamont-Doherty Earth Observatory and analyzed (methodology and results described in Chapter 2) revisions were required. Loop correlation showed that the one for one reflector correlation of Chapter 1 needed to be updated. Chapter 2 outlines the increased number of candidate sequence boundaries that resulted from the additional data. Chapter 3 outlines the regional ramifications of the CH0698 seismic data interpretations, including number and provenance of sediment sources, regional sediment redeposition from the current and wave climate and the amount of subaerial exposure during relative sea-level lowstand.

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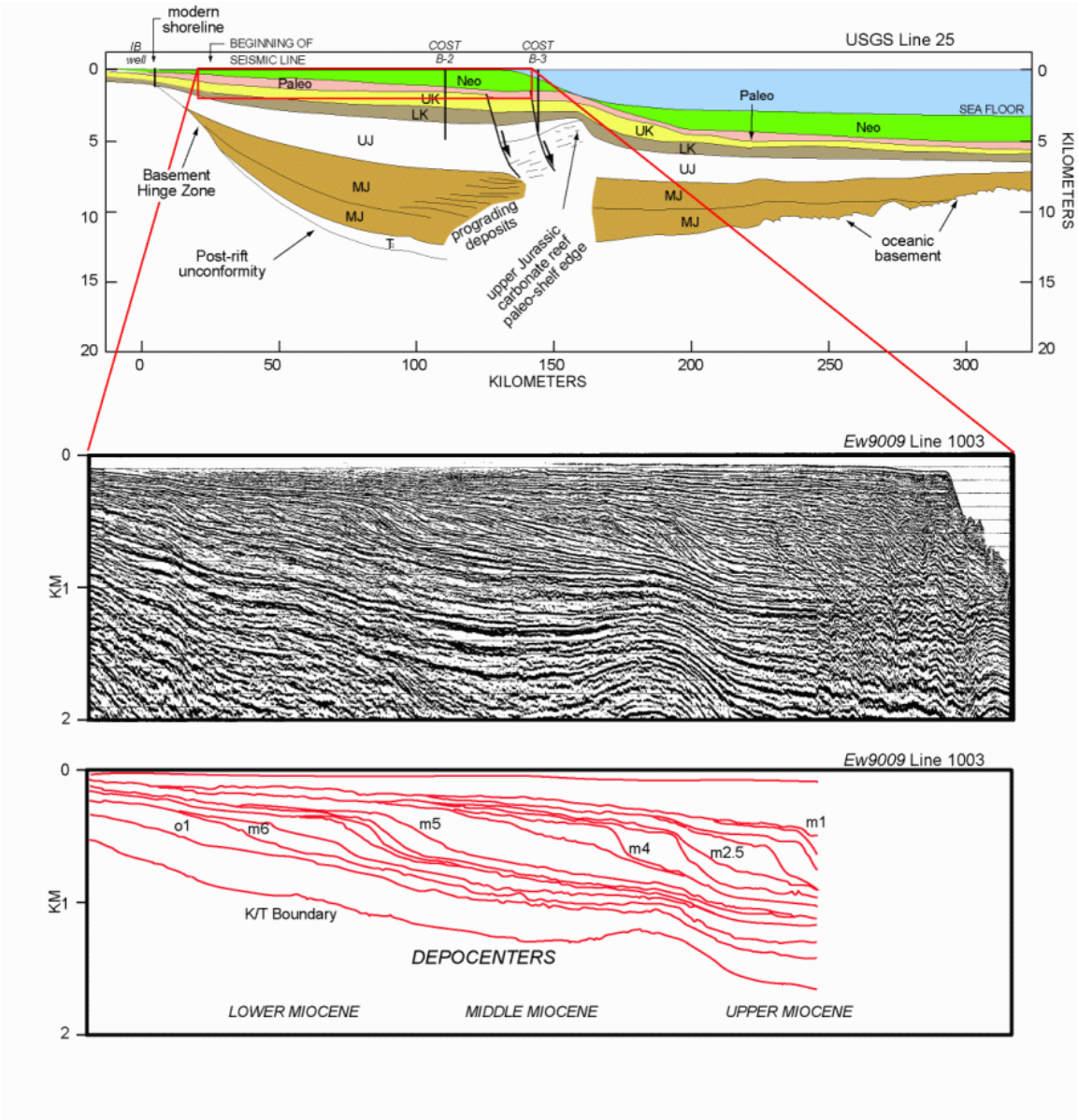

Figure I.1 a) Schematic cross-sectional interpretation of USGS Line 25 based on Grow et al., (1988) and Poag (1985) across the Baltimore Canyon trough depicting the New Jersey margin geometry. Upper Jurassic carbonate reefs built across the margin and defined the paleoshelf edge. Later deposits up to the Oligocene prograded and infilled behind these reefal deposits creating a ramp morphology (1:300, 1:500; Steckler et al., 1999). Oligocene clastics prograded atop the ramp margin and created a gentle continental shelf gradient of 1:1000 and steeper depositional front (Kominz et al., 1998, Steckler et al., 1999, Pekar et al., 2003). Sediments reoccupied the margin edge at its present location by upper Miocene. TR= Triassic, MJ = middle Jurassic, UJ = upper Jurassic, LK = lower Cretaceous, UK = upper Cretaceous, Paleo = Paleogene, Neo = Neogene. b) Seismic interpretation of *Ew9009* line 1003, which parallels *Oc270* line 529, imaging the geometry of Oligocene seismic sequence boundary (o1) and lower (m6-

m5), middle and upper Miocene seismic sequence boundaries (m4, m2.5, m1; Steckler et al., 1999). Miocene sequences prograded across the margin infill the remnant ramp morphology and created a 1:1000 gradient continental shelf. Miocene sequence clinoform inflection points steepened over time due to larger accommodation from leveling of the ramp geometry.

Chapter 1 - Correlation of offshore seismic profiles with onshore New Jersey Miocene sediments

A described in the introduction an earlier version of this chapter was published as: Monteverde, D.H., Miller, K.G., and Mountain, G.S., 2000, Correlation of offshore seismic profiles with onshore New Jersey Miocene sediments; Sedimentary Geology, v.134, p. 111-127

Abstract

We describe new seismic data from the innermost New Jersey shelf that tie offshore seismic stratigraphy directly to onshore boreholes. These first-order correlations confirm previous ones that were based on the similar ages of sequences recognized in onshore boreholes and seismic sequences identified beneath the shelf and dated on the continental slope. Profiles were collected approximately 700 m and 1500 m from boreholes at Atlantic City and Island Beach State Park, respectively, using the Lamont HiRes MCS acquisition system aboard the *R/V Cape Hatteras* in May, 1998. These data link the onshore boreholes to existing seismic grids across the outer margin and to boreholes on the continental slope. Sequence boundaries defined by age, facies, and log signature in the onshore boreholes as the base of Kw2b, Kw2a, Kw1c, and Kw0 are now conclusively tied to sequence boundaries m5s, m5.2s, m5.4s, and m6s, respectively, defined previously by seismic character beneath the inner shelf. These boundaries also appear to correspond to reflections m5, m5.2, m5.4, and m6 respectively that were dated at slope boreholes. We recognize an additional sequence beneath the modern shelf that we name m5.5s and correlate to onshore sequence boundary Kw1b. The new seismic data clearly image prograding Oligocene clinoforms beneath the inner shelf, consistent with the results from onshore boreholes. A land-based seismic profile crossing the Island

Beach borehole reveals reflector geometries that we tie to lower Miocene litho- and bio-facies in this borehole; this provides ground truth for seismic facies interpretations. This integration of core, log, and seismic character of mid-Tertiary sediments across the width of the New Jersey margin is a major step in the long-standing effort to evaluate the impact of glacioeustasy on siliciclastic sediments of a passive continental margin.

Introduction

Seismic profiles show that the New Jersey continental shelf contains a thick record of prograding clinoform wedges. First recognized by Schlee (1981) and interpreted as prograding deltas, many of the clinoformal reflections have since been documented as sequence boundaries (Greenlee et al., 1988, 1992; Greenlee and Moore, 1988) based on classic criteria of onlap, downlap, and offlap (erosional truncation and toplap) (Mitchum et al., 1977; Christie-Blick and Driscoll, 1995). Similar prograding clinoform wedges are observed in Neogene sediments of passive and active margins throughout the world (Bartek et al., 1991), indicating a common link to global climate and glacioeustatic change as recorded by global $\delta^{18}O$ variations (Miller et al., 1991a). While most of these wide-ranging clinoforms are Miocene and younger, the age of the initiation of large-scale progradation has been poorly documented and ranges from Oligocene (Greenlee et al., 1988, 1992; Bartek et al., 1991) to late Eocene (Pekar et al., 2000).

The prograding ?Oligocene-Recent clinoforms beneath the New Jersey shelf provide an opportunity to evaluate the relationships between sequences and sea-level change (Miller

and Mountain, 1994). This period of Earth history is associated with the growth and decay of large continental ice sheets recorded by global $\delta^{18}O$ variations (Miller et al., 1991). The Ocean Drilling Program (ODP) chose the New Jersey margin to drill a borehole transect from the slope to the coastal plain (fig. 1.1; Miller and Mountain, 1994) to test the relationship between sequences, sea level and $\delta\ ^{18}O$ variations. Although drilling originally targeted shelf locations where seismic facies are best imaged (Miller and Mountain, 1994), safety considerations required initial drilling on the slope (ODP Leg 150; Mountain, Miller, Blum, et al., 1994) and onshore (ODP Leg 150X; Miller et al., 1994, 1996a). In 1997, drilling edged onto the outer continental shelf (ODP Leg 174A; Austin, Christie-Blick, Malone, et al., 1998) targeting Late Neogene clinoforms (see Metzger et al., 2000).

Previous onshore studies by the New Jersey coastal plain drilling project (ODP Legs 150X and 174AX) recognized Cenozoic sequences in onshore boreholes by integrating physical evidence for erosion with age and biofacies/lithofacies changes (Miller et al., 1994, 1996a; Miller and Snyder, 1997). Studies based on seismic geometries have recognized sequences beneath the continental shelf and traced them to slope boreholes (ODP Leg 150), where they were dated as Eocene to Recent (Mountain, Miller, Blum, et al., 1994; Miller et al., 1996b). The ages of the sequences compare well onshore and offshore, and both sets correlate with deep-sea $\delta\ ^{18}O$ increases (fig. 1.2), thereby indicating glacioeustatic control on sequence development (Miller et al., 1996b, c; 1998).

Despite these efforts, there has been: 1) inadequate direct sampling of Oligocene-middle Miocene strata beneath the shelf where the record is most sensitive to sea-level change; and 2) inadequate seismic coverage in the nearshore zone, a critical region linking onshore and offshore stratigraphy. Middle Miocene sequences are best developed beneath the middle New Jersey shelf where they have been well imaged by *R/V Ewing* 9009 (*Ew9009*; Miller and Mountain, 1994) and *R/V Oceanus* 270 (*Oc270*; Austin et al., 1996) profiles (fig. 1.1), whereas lower Miocene sediments are best developed beneath the inner shelf. These lower-middle Miocene sediments have not been sampled in the optimal locations: the oldest strata sampled by Leg 174A are about 12 Ma (Austin, Christie-Blick, Malone, et al., 1998), whereas the lower-middle Miocene sections sampled onshore represent only proximal facies deposited well landward of the clinoform inflection points. Although the onshore sites sampled Oligocene-lower Miocene sediments that are relatively complete and potentially represent critical clinoformal facies, until now correlation of onshore boreholes with offshore seismic profiles has required a jump of several tens of kilometers.

We present seismic profiles that provide direct correlation between the well-sampled onshore lower to middle Miocene sections with offshore seismic profiles. This allows us to: 1) test the correlations of lower to middle Miocene onshore sequences (fig. 1.2) by tracing seismic sequences directly to onshore boreholes; 2) ground-truth Miocene seismic facies by comparison with facies interpretations derived from litho- and bio- facies studies; and 3) extend seismic facies interpretations offshore, where direct sampling awaits future drilling efforts.

Methods

Marine multichannel seismic profiles form the basis of this study, supplemented by an onshore seismic profile (fig. 1.6) published by P. Miller et al. (1996). We used reflection geometries seen in these high-resolution data to define Oligocene and lower Miocene seismic sequences that we traced through the data grid and tied into boreholes using synthetic seismograms and time-depth relationships. The seismic character of onshore and offshore sequences was directly compared to borehole lithologies and ages derived from biostratigraphic and isotopic studies (fig. 1.3, Miller et al., 1994a, 1994b, 1996).

Offshore seismic data

MCS profiles were collected aboard the *R/V Cape Hatteras* using the Lamont-Doherty Earth Observatory (LDEO) HiRes MCS system in May 1998 (*CH0698*). Unusually bad weather kept the ship in port for 5 of the scheduled 14 days of acquisition. Though with greater distance between adjacent lines than planned, we nonetheless collected 1100 kilometers of profiles that link onshore boreholes to existing profiles extending seaward to boreholes on the outermost shelf and upper slope (fig. 1.1). Three onshore boreholes were approached as close as possible: we sailed directly into Cape May inlet, collecting underway data to within ~700 m of the Leg 150X borehole (Miller et al., 1996a); we collected data while leaving Absecon inlet, 700 m from the Atlantic City borehole (fig. 1.9) (Miller et al., 1997); and we acquired an offshore strike line that at its closest

approach was 1500 m from the Island Beach borehole (fig. 1.4) (Miller et al., 1997). In addition, we acquired 3 grids of closely spaced profiles that meet the guidelines for safety assessment (JOIDES, 1994) across additional proposed drill sites (Miller et al., 1998).

The LDEO MCS system used a 150 cu-in Generator-Injector airgun towed at approximately 2 m depth. A 48-channel, 600 m solid (not oil-filled) ITI streamer was maintained at 2±0.5 m depth with a near trace source offset of zero. Ship speed, monitored by DGPS, was maintained at 4.9 kn over the seafloor to yield 12.5 m between shots at 5 sec intervals. The data were recorded with an OYO DAS-1 at a 0.5 ms sample rate; trace lengths were 2 sec. Preliminary processing has been completed on several lines and includes outside mute, velocity analysis, Normal Moveout (NMO) correction, bandpass filtering, spreading loss correction, predictive deconvolution, Stolt migration, and time-varying gain. The data are of excellent quality with vertical resolution approaching 5 m and usable acoustic imaging to approximately 1 sec of two-way traveltime.

For this study we analyzed five *CH0698* dip lines (lines 9, 11, 13, 15, 17 and 19, which links to *Oc270* line 529, Fig. 1.1) and two strike lines (lines 16 and 14, Fig. 1.1) that have been processed thus far, detailing features from Atlantic City northward. Miocene sequences generally thicken and are more numerous downdip; because of the oblique strike of Miocene strata relative to the modern coastline, Island Beach, Atlantic City, and Cape May sample progressively downdip sections. Thus, future studies of the southern portion of the dataset between Atlantic City and Cape May are expected to provide better

coverage of lower to middle Miocene strata (e.g., the Kw1c, Kw2c, and Kw-Cohansey sequences are only found at Cape May; Fig. 1.2; Miller et al., 1996a). Chapter 2 describes the sequence definition as imaged on the entire *CH0698* seismic grid.

Synthetic seismogram, depth-time relationships, and seismic borehole correlations

The wireline sonic log at the Leg 150X Island Beach borehole provides the depth-to-acoustic-traveltime conversion needed to tie firmly features in the rock record to reflections in nearby seismic profiles. Accordingly, a 50 Hz Ricker wavelet (similar to the *CH0698* seismic source) was convolved with the acoustic log to create a synthetic seismogram (J. Metzger, pers. comm.). Using the Miocene strike direction provided by Miller et al. (1997) as a guide, the synthetic seismogram was projected 1800 m northeast to cdp 9450 of *CH0698* line 14 (fig. 1.4). The data quality is good and we find a close match between the synthetic and observed seismic data for the prediction of reflection m6s. The seismic match for older stratigraphy below this is reasonable but not as close. There is no correspondence for the interval from 0 to 0.148 ms subsurface where the sonic log was run through casing. Geophysical logs from other sites aided in the correlation of the seismic boundaries. The Atlantic City Offshore Well 2 (ACOW2) borehole contained gamma ray and check shot surveys; interval velocities derived from the latter (Waldner and Hall, 1991) were recalculated as depth vs. time and compared to a depth vs. time plot derived from the Island Beach sonic log. These two datasets (fig. 1.5a) match closely, adding confidence to our depth-time correlations at the Island Beach projection to *CH0698* line 14 as well as the projections of Atlantic Margin Coring Project

borehole 6011 (AMCOR6011, Hathaway et al., 1976, 1979), ACOW2, and Atlantic City borehole data into the seismic grid.

More detailed analysis on the complete *CH0698* seismic data suggest that the synthetic seismogram created using the Island Beach sonic log convolved with a 50 Hz Ricker wave can be improved upon for a better core-seismic correlation. An 80 Hz Ricker wave would have been more appropriate, and as described in Chapter 2, the velocity function identified by semblance plot analysis and used in *CH0698* seismic data processing proved the best for time-depth comparison. Stacking velocity is uniformly slower than other data and offers the best correlations.

ACOW2 data not only allowed an evaluation of the Island Beach depth-traveltime function, but also allowed direct correlation of sequences identified in boreholes with seismic profiles. The late J. Owens (Owens et al., 1995) identified subsurface Miocene coastal plain formations based on the drill cuttings and gamma ray log character for the ACOW2 borehole. We placed the formation picks of Owens et al (1995) into the Miocene sequence terminology of Miller et al. (1997) (fig. 1.5b). We extended these correlations using gamma ray logs to the Atlantic City borehole, matching the sequence usage of Miller et al. (1994, 1996c, 1997, 1998) (fig. 1.5b). Sequence boundaries from two sites (ACOW2 and Atlantic City) were projected into seismic lines 9 (ACOW2) and 27 (Atlantic City) using the Island Beach/ACOW2 depth-time relationship. The AMCOR 6011 provided a correlation for Oligocene/Miocene sequence boundary, m6 (Pekar et al., 2000).

Land seismic and facies analysis

A high-resolution land reflection profile runs N-S (P. Miller et al., 1996), crossing within 250 m of the ODP Leg 150X Island Beach borehole (fig. 6). P. Miller et al. (1996) described data collection consisting of summed impacts from a 4.5-kg hand-held sledge hammer provided 225-425 Hz source frequencies at 5 m spacing. Walkaway noise tests provided optimum source-geophone offsets and allowed at least 180 m depth penetration. A geophone array provided 6-fold stacking after trace editing, inside mute, velocity analyses every 5 to 10 m along line, and Normal Moveout correction. Deconvolution, bandpass filtering at 150-350 Hz and time-varying gain resulted in vertical resolution that approached 1 m (P. Miller et al., 1996).

A graphic lithologic description and gamma ray log of the Miocene-Holocene section recovered at the Island Beach Leg 150X borehole was scaled to the land seismic profile published by P. Miller et al. (1996) using their stacking velocities (fig. 1.6). Lower Miocene sequence boundaries recognized by physical and log character (Miller et al., 1994; 1997) closely match seismic surfaces defined by reflector terminations (fig. 1.6). However, the sub-bottom placement of the boundary between sequences Kw1a and Kw1b remains uncertain: Miller et al. (1994) originally placed the base of the Kw1b sequence at a surface at 85 m (279 ft.). After Owens et al. (1997) noted a distinct facies overstep associated with a surface at 92.3 m (303 ft), Miller et al. (1997) moved the base of Kw1b to this level, interpreting the surface at 85 m (279 ft) as a maximum flooding

surface (MFS). Miocene age control at Island Beach is poor: the entire Kw2a sequence is simply assigned "lower East Coast Diatom Zone 2 (ECDZ2)", and Sr-isotopic ages are available only for the base of the Kw1a sequence (fig. 1.6). Age control on the upper Pleistocene to Holocene is provided by Accelerator Mass Spectrometry (AMS) ^{14}C dates (Miller et al., 1994). Sugarman and Miller (1996) and Miller et al. (1997) provide facies interpretations for this section using lithologic and paleontologic criteria.

Results

Identifying lower Miocene sequences in offshore profiles

We used seismic sequence analysis to identify several well-developed sequence boundaries in offshore data based on offlap, downlap, and onlap reflector geometries (Figs. 1.4, 1.7, 1.8). Five sequence boundaries are expressed on each of the northern *CH0698* dip lines we investigated, while an older, sixth sequence boundary appears on the two northernmost lines (fig. 1.4). Onlap and erosional truncations outline the sequence-bounding reflections seaward of the clinoform inflection point of each sequence boundary[1] (e.g., Fig. 1.7). Erosional terminations of underlying reflectors identify sequence-bounding surfaces landward of the clinoform inflection points. Select intra-sequence reflectors define systems tracts (Van Wagoner et al., 1988) as follows: a key surface (maximum flooding surface [MFS]) divides a thin interval of parallel reflectors

[1]This is the point of maximum change in slope associated with a clinoform geometry. It has been termed shelf edge (Schlee, 1981), depositional coastal break (Vail et al., 1987), shelf break (Van Wagoner et al., 1988), clinoform breakpoint (Fulthorpe and Austin, 1998; Fulthorpe et al., 1999), and clinoform inflection point (this study).

below (termed the transgressive systems tract [TST]) from a generally thicker, prograding high stand systems tract (HST) above. Lowstand systems tracts (LST) have not been identified on the seismic profiles studied so far.

Initial interpretations of systems tracts often fall prey to a dearth of data. Correlations may be inadequate without sufficient strike lines to allow detailed loop correlations of identified reflectors. This is the case here as further study after publication of the journal article (Monteverde et al., 2000) has outlined a total of eleven candidate sequence boundaries between and including m6 to m5. Initially described TST deposits proved on more detailed inspection and careful loop correlation to represent LST deposits.

We correlate 5 sequence boundaries defined on *CH0698* profiles as lower Miocene and one as Oligocene. In keeping with former nomenclature, we name the lower Miocene sequence boundaries m5s, m5.2s, m5.4s, m5.5s, and m6s. The subscript 's' for shelf, distinguishes each from the m5, etc. reflections whose ages were determined by samples from the slope, and they emphasize that we have now firmly linked these surfaces to shallow-water lithologies and ages.

Prior to the present study, there were significant uncertainties in the relationship of reflections beneath the inner shelf (e.g., m5s, m5.2s, etc.) with surfaces drilled in onshore sites (e.g., the base of Kw2b, the base of Kw2a, etc.) and reflections beneath the slope. Our study provides first-order correlations of sequence-bounding reflections beneath the

inner shelf with onshore sequence boundaries (fig. 1.4, 1.9). The agreement between the two data sets is compelling.

By dating the nearshore sequences, we provide age correlations for shelf sequence boundaries with slope reflections that are independent of seismic tracing. In particular, the lower Miocene seismic surfaces that were dated on the New Jersey slope (Miller et al., 1996) required tracing more than 100 km to the inner shelf, where they can be seismically defined as sequence boundaries. We correlate five sequence boundaries defined with *CH0698* profiles with five sampled in ODP Leg 150 boreholes, and named (from youngest to oldest) m5, m5.2, m5.4, m6, and o1 (Mountain, Miller, Blum, et al., 1994). The sixth sequence that we recognize is Oligocene; seismic resolution with available data on the slope precludes a confident recognition of Oligocene reflections that can be traced to the inner shelf (Mountain, Miller, Blum, et al., 1994).

The shelf sequence boundaries and slope reflections appear to be causally linked. Although reflections on the slope lack definitive geometric criteria of sequence boundaries, they commonly have been found associated with evidence for down slope sediment transport (Mountain, Miller, Blum, et al., 1994; Miller et al., 1998). More importantly, Miller et al. (1996, 1998) showed that these surfaces correlated with glacioeustatic variations inferred from $\delta^{18}O$ studies, implicating them as records of sea-level lowering. We suggest that as more *CH0698* lines are processed and loop-correlated through close seismic lines from existing grids, a close match will be found for lower Miocene sequence boundaries. Unambiguous tracing of slope reflections to the inner

shelf may be beyond the resolution of current data; however, we suggest that current age correlations between onshore and offshore locations leave little doubt that these physical correlations are correct.

These preliminary results offered initial first-order correlations. Detailed loop correlation of the entire *CH0698* data portrays substantial along strike variability such that five sequences on each of two side by side dip lines may not correlate directly. Further study of onshore cores also outlined a substantial increase in different sequences (Miller et al., 2001, Browning et al. 2006). The onshore cores and *CH0698* data do correlate well when considering the increased number of sequences delineated.

Correlating offshore seismic sequences to onshore sites

The Island Beach sonic log allowed us to correlate seismic sequences recognized on the *CH0698* profiles into the onshore boreholes in two ways. First, the sonic log provided the means to construct a synthetic seismogram that we compared with the point of closest approach on offshore line 14 (roughly 1500 m). Second, it confirmed the ACOW2 check shot velocity data, thereby providing further assurance that our depth-time conversions were highly reliable.

The Island Beach, ACOW2, and Atlantic City sites date the upper two seismic surfaces, m5s and m5.2s; these surfaces bracket the Kw2a sequence defined onshore (fig. 1.2). The underlying seismic boundary, m5.4s, is truncated by m5.2s seaward of Island Beach

and Atlantic City. Its location in ACOW2 indicates a correlation with the basal sequence boundary of onshore Kw1c (fig. 1.2). The only other place that Kw1c has been sampled is in the Cape May borehole; consistent with this fact, line 27/9 (fig. 1.9) shows that this sequence pinches out ~17 km downdip of Atlantic City. Sequence boundary m5.4s is provisionally correlated with slope reflection m5.4 (fig. 1.2) of Mountain, Miller, Blum, et al. (1994). The next oldest boundary, m5.5s, corresponds to the base of the Kw1b sequence (Miller et al., 1994, 1997; Sugarman and Miller, 1997; Sugarman et al., 1997). No seismic sequence has been previously recognized on the slope that correlates with this surface. However, glauconite abundance at Site 904 shows a large coeval peak (K.G. Miller, unpublished data, 1999); such peaks are commonly associated with sequence boundaries on the slope. Although this correlation is speculative at this point, we can unequivocally define a previously unrecognized seismic sequence, date it as 20.2 Ma by correlating it with Atlantic City Sr-isotopic stratigraphy (Miller et al., 1997; Sugarman et al., 1997), and correlate it with the Kw1a/Kw1b sequence recognized in boreholes.

Comparison of the synthetic seismogram with the *CH0698* high-resolution profiles allows dating of the two oldest clinoforms on the seismic grid. A sequence-bounding surface recognized on each of the *CH0698* profiles, reflection m6s, can be traced shoreward to the Island Beach (fig. 1.7), Atlantic City (fig. 1.8), and AMCOR 6011 boreholes and correlated to the Oligocene/Miocene boundary (fig. 1.2). At this time, we cannot trace this sequence boundary to the slope and tie it to Leg 150 slope boreholes, but stratigraphic placement and age make it the precise equivalent of slope reflection m6. At the Atlantic City borehole, m6s correlates with the base of onshore sequence Kw0. This

surface could be a concatenation of sequence boundaries m6s and the younger m5.6s because the Kw0 sequence is absent at Island Beach and at Atlantic City is only ~9 m thick (fig. 1.3; Miller et al., 1994a, 1994b). Surface m6 was not penetrated by ACOW2.

The oldest clinoform inflection identified in the *CH0698* grid lies beneath reflection m6s, yet above the projection of slope reflection o1 (lowermost Oligocene; Mountain et al., 1994, Miller et al., 1996, 1998) from the Island Beach site. It is only imaged on the two northern *CH0698* lines, 17 (fig. 1.4) and 19 (not shown here). The precise correlation of this sequence boundary with the onshore Oligocene sequences of Pekar et al. (1997) and Pekar et al. (2000) is not certain at present. Nevertheless, the *CH0698* data clearly image prograding Oligocene clinoformal wedges beneath the inner shelf, corroborating inferences based on the onshore coastal plain boreholes (Pekar et al., 2000).

Correlating an onshore profile to the Island Beach borehole

Three sequence boundaries identified in the Island Beach Leg 150X borehole (23.7, 55.5, and 92.3 m; 78, 182, and 303 ft) are associated with the three most prominent and continuous reflections on the P. Miller et al. (1996) profile (fig. 1.6). These sequence boundaries are associated with the bases of the upper Pleistocene-Holocene, Kw2a, and Kw1b sequences, respectively. The base of Kw1a is apparently not seismically resolved as it projects beneath 190 ms (fig. 1.6). Each of these units is described as follows.

Upper Pleistocene-Holocene sequence (mostly younger than 5.6 ka). The first reflection, identified at ~32 ms (fig. 6; P Miller et al., 1996), lies immediately below the contact between sands deposited in beach environments and sandy muds deposited in lagoonal environments; it is associated with the top of tight clay. The impedance contrast at the base is associated with a sharp lithologic change from upper Pleistocene-Holocene fluvial gravel above to Kirkwood delta front sands below. There are hints of channeling on this surface at SP 60 (fig. 1.6).

Kw2a sequence (16.5-17.8 Ma as dated at other sites). Three seismic facies in sequence Kw2a correspond to three environments of deposition inferred from borehole studies. At the base, a distinct, continuous reflection correlates with a sequence boundary in the borehole, although there is no seismic evidence at this site for this being a sequence boundary (fig. 1.6). We correlate this surface to m5.2s. Immediately above this, a moderately continuous reflection with downlap coincides with a MFS inferred from core studies. The intervening 10 ms between the sequence boundary and the MFS consists of sands deposited in nearshore environments. The overlying sections (15-20 ms thick) show several downlapping reflectors that appear to prograde to the north (fig. 1.6). These prograding lower HST sediments consist of silts deposited in prodelta environments. A thin upper section (10 ms) that caps the sequence portrays moderately continuous reflections; the associated sediments are sands deposited in delta front environments (upper HST; Fig. 1.6).

Kw1b sequence (19.5-20.1 Ma as dated at other sites). The reflection at 120 ms at the north end of the profile is recognized as a seismic sequence boundary by truncation of underlying reflections and possible channeling at SP25 and SP55 (fig. 1.6). We correlate it to m5.5s. A downlap surface at 103 ms with progradation toward the north correlates with the MFS inferred from the borehole. The intervening section shows a hummocky seismic character with somewhat discontinuous reflections; this TST is associated with sands that were possibly deposited in inner neritic environments. Above the MFS, 15 ms of somewhat discontinuous reflections associated with prodelta silts are overlain by 8 ms of chaotic reflections associated with fluvial sands. These are capped by two continuous reflections that are also associated with fluvial sands.

Kw1a (20.1-21.1 Ma as dated at other sites). There is distinct downlap on a reflection at 170 ms (fig. 1.6) with general progradation toward the north (and possible bi-directional downlap at SP55). There may be some truncation associated with this surface at SP42; however, it appears to be associated with a regression from inner neritic, slightly glauconitic sands below to estuarine/lagoonal sediments above. Therefore, we interpret it as a MFS. More data are needed to resolve the significance of this surface. Above this, there are two seismic facies separated by a reflection at 145 ms that correlates with a large gamma ray log increase. The lower facies is associated with strong downlap and discontinuous reflections; the upper facies is associated with stronger, more continuous reflections and is truncated at its top. Both are associated with sands deposited in delta front environments. Sequence boundary m5.6s/m6s is apparently not seismically resolved as it projects beneath 190 ms.

Discussion

The lower Miocene sequences identified in onshore boreholes also correlate to seismically-defined sequences in the *CH0698* data. Most of the Miocene sequences have been dated at more than one borehole (the Kw1c, Kw2c, and Kw-Cohansey are notable exceptions), lending confidence to the global correlation of the seismically and core-defined sequences (fig. 1.2). Still, some sequences identified both onshore and at slope sites do not image as seismic sequence boundaries in this initial interpretation of the *CH0698* data. Slope seismic reflection m5.6 either is not represented or is beneath the resolution of the *CH0698* data. Onshore sequence Kw0 is absent in the north at both the Island Beach and AMCOR-6011 (Miller et al., 1994; Pekar et al., 2000). Farther to the south at Atlantic City, sequence Kw0 is 10 m thick (Miller et al., 1994). Tracing the overlying Kw1a sequence boundary offshore from Atlantic City does not reveal stratal geometry indicative of a seismic sequence boundary. The thin sequence Kw0 probably prevents seismic resolution of the equivalents of slope reflections m6 (correlative to the base of Kw0) and m5.6 (correlative to the base of Kw1a; Fig. 1.2). Sequence Kw0 thickens southward to Cape May, where it is ~36 m thick (Miller et al., 1996). Seismic data from this region have not been processed, although we predict that a prominent sequence boundary equivalent to slope reflection m5.6 and the base of onshore sequence Kw1a should be present in the southern region of *CH0698* data coverage.

Confirming these correlations requires completing the analysis of *CH0698* data and detailed tracing of *Oc270* data, using the dated surfaces from slope Leg 150 and shelf/slope Leg 174A. However, the *Oc270* data may be of insufficient quality to trace unambiguously all of these sequences across the outer shelf (Craig Fulthorpe, written communication, 1999). Initial interpretations of *Oc270* line 529 (Figs. 1 and 9: N. Christie-Blick et al., pers. comm., in prep.) show a similar number and spacing of sequences as we observe in *CH0698*. These surfaces have been tentatively correlated to *Ew9009* line 1003 and traced to the slope where they were named m5, m5.2, m5.4, 5.6, and m6 and tied to Leg 150 drill sites.

One major difference between the nearshore and slope seismic interpretations requires verification. We identify sequence m5.5s on the *CH0698* profiles that appears acoustically similar to reflection m5.6 traced from the slope; however, our age correlations for these two reflections are clearly different (fig. 1.2). We believe that this age difference may be real and that m5.5s may be a slightly younger sequence boundary than m5.6. Reflector m5.5s clearly correlates with the basal Kw1b sequence boundary (i.e., it can be clearly traced to Kw1b at both Island Beach and Atlantic City); it also appears to correlate with a minor global $\delta^{18}O$ increase (Mi1aa; Fig. 1.2). Reflector m5.6 apparently correlates with the basal Kw1a onshore sequence; first-order correlation shows that m5.6 is associated with the global Mi1a $\delta^{18}O$ increase on the slope (Miller et al., 1998) (fig. 1.2). We can test the differences between these two sequences by examining as-yet unprocessed seismic profiles south of Atlantic City (fig. 1.1) and by (re)tracing reflection m5.6 from the slope to the *CH0698* seismic grid.

Conclusions

This study presents seismic data that fill the data gap between the onshore ODP Leg 150X boreholes and New Jersey shelf and slope investigations encompassing the *Ew9009* and *Oc270* seismic grids and Legs 150 and 174A boreholes. Velocity data from two boreholes were used to construct a time-depth relationship so that borehole data could be projected into the seismic grid. Limited borehole geophysical logs aided tying in two other offshore locations. Seismic stratal geometries defined six sequence boundaries on the *CH0698* seismic profiles: m5s, m5.2s, m5.4s, m5.5s, m6s, and an unnamed Oligocene sequence boundary. These seismic sequences can be definitively correlated with sequence boundaries recognized in onshore boreholes as the bases of Kw2b, Kw2a, Kw1c, Kw1b, and Kw0, respectively. Litho-, bio-, and isotope stratigraphies of onshore sequences were used to date the seismic surfaces, and these ages can be used to compare with those of seismic reflections on the slope. These nearshore/onshore sequence boundaries correlate with four of five lower Miocene reflections dated on the slope: m5, m5.2, m5.4, and m6. The surface dated as m6s is apparently a concatenation of slope reflections m6 and m5.6. A fifth surface, herein labeled m5.5s, is associated with the base of the onshore Kw1b sequence, a sequence not identified previously on the slope. The sixth surface documents that Oligocene clinoformal wedges occur in the nearshore region as predicted by Pekar et al. (1997, 2000). Land seismic data clearly image the various intra-sequence sedimentary facies documented at the Island Beach site. Future

work will carry these intra-sequence facies interpretations offshore onto the *CH0698* grid and verify the interpretation of m5.5s as a sequence distinct from m5.6.

This chapter represents early work on the analysis of lower Miocene construction of the New Jersey margin. It defined an interpretation based on the best available seismic data at the time, which consisted of several *CH0698* dip lines. No strike lines were yet processed and as such, loop correlations were not performed. Sequences defined on one line seemed to match the analysis of adjoining dip lines. The full *CH0698* seismic data, when processed, forced a revised interpretation. As described in later chapters the full data, when loop correlated showed that a similar number of sequences in adjoining dip lines did not necessarily equate to a definite correlation. Not all seismic reflectors defined as candidate sequence boundaries on one seismic line display similar geometries on all dip lines. In this way the amount of sequences identified as lower Miocene increased to eleven. Chapter 2 elucidates the methodology used in defining all lower Miocene candidate sequences.

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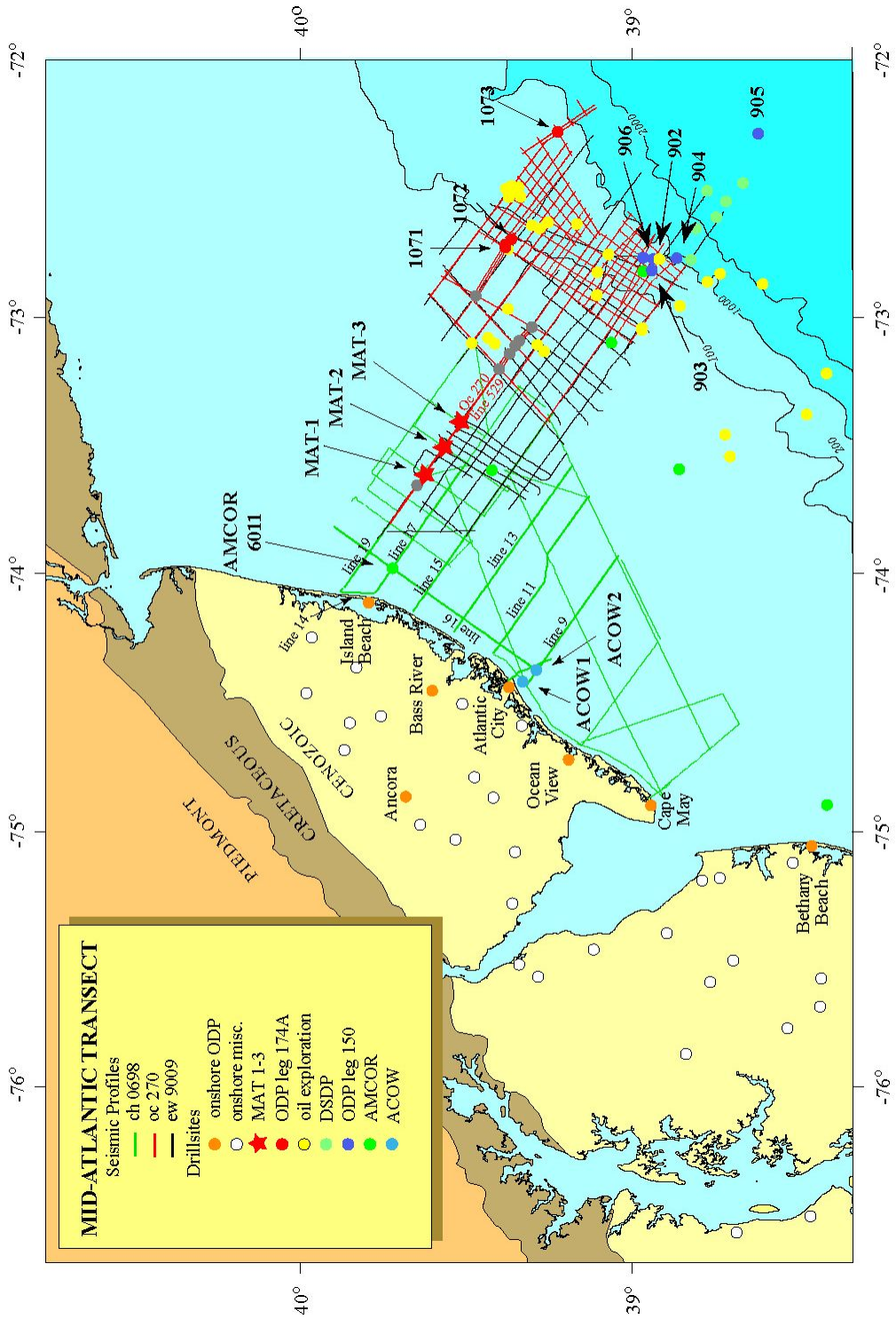

Fig. 1.1 Location map showing the location of the *CH0698*, *Oc270* and *Ew9009* seismic grids, offshore ODP Legs 150 and 174A, onshore ODP Legs 150X and 174AX and nearshore AMCOR6011 and ACOW2 sites. *CH0698* lines 9, 14, 17, 19 and 27 are used in other figures and described in the text.

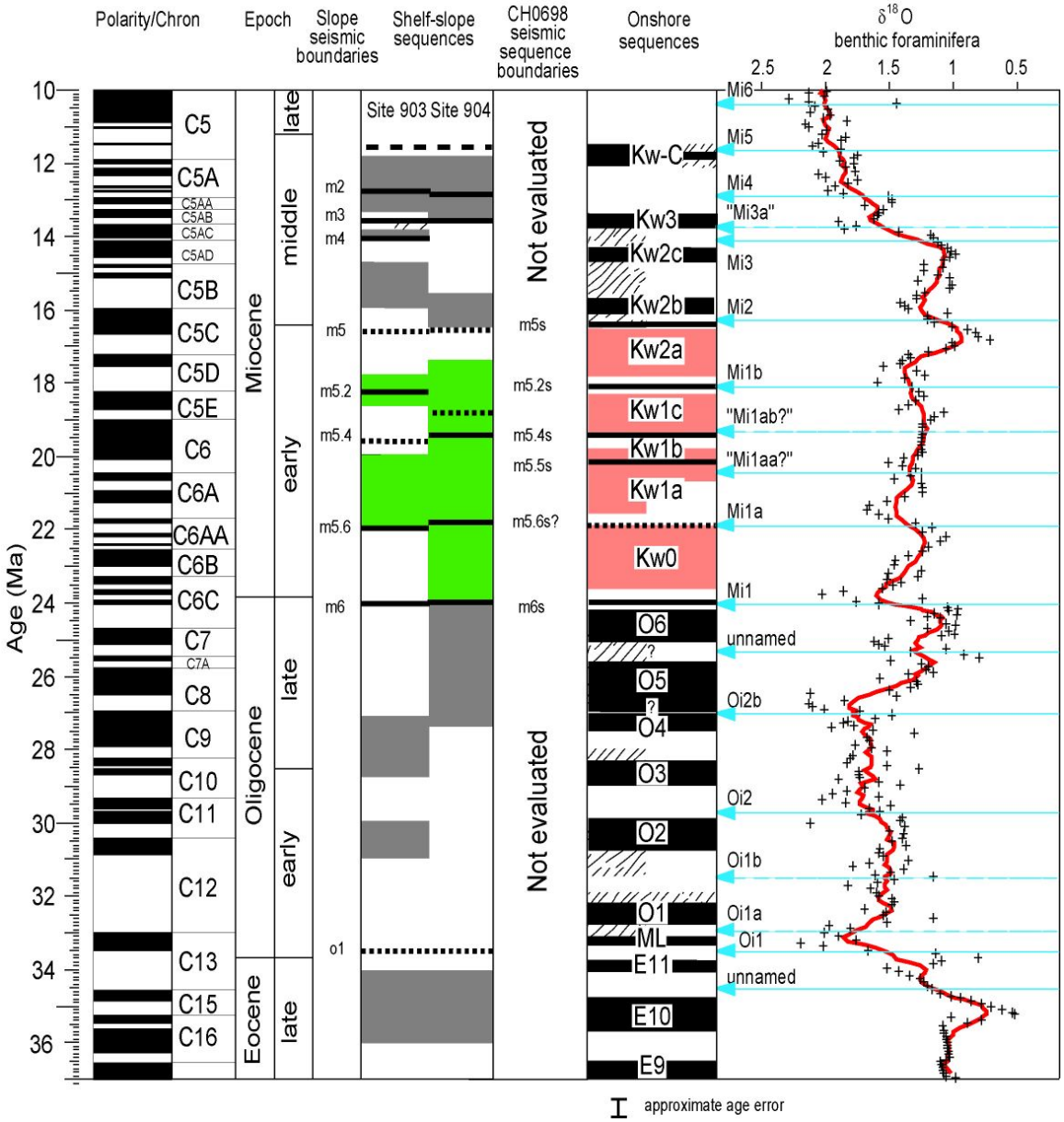

Fig. 1.2. Revised comparison of Oligocene-Miocene slope sequences, onshore sequences, oxygen isotopes, Bahamian reflections (Eberli, Swart, Malone, et al., 1997), and the inferred eustatic record of Haq et al. (1987) Modified from Miller et al. (1998).

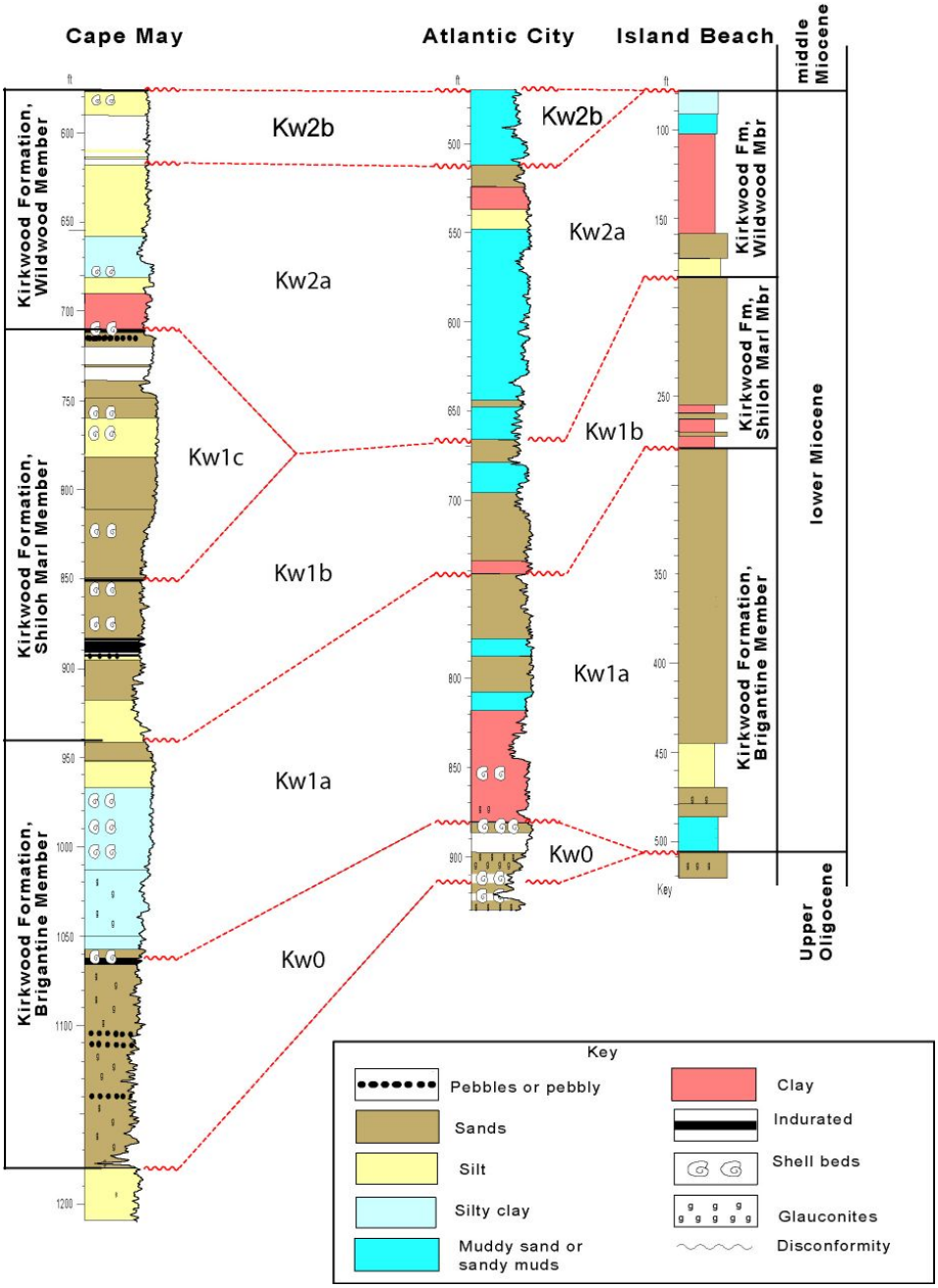

Fig. 1.3. Comparison of lithologic units, sequences, and chronostratigraphic units at Island Beach, Atlantic City, and Cape May. Abbreviations: up. = upper, lo. = lower, Mbr. = member. After Miller et al. (1997b).

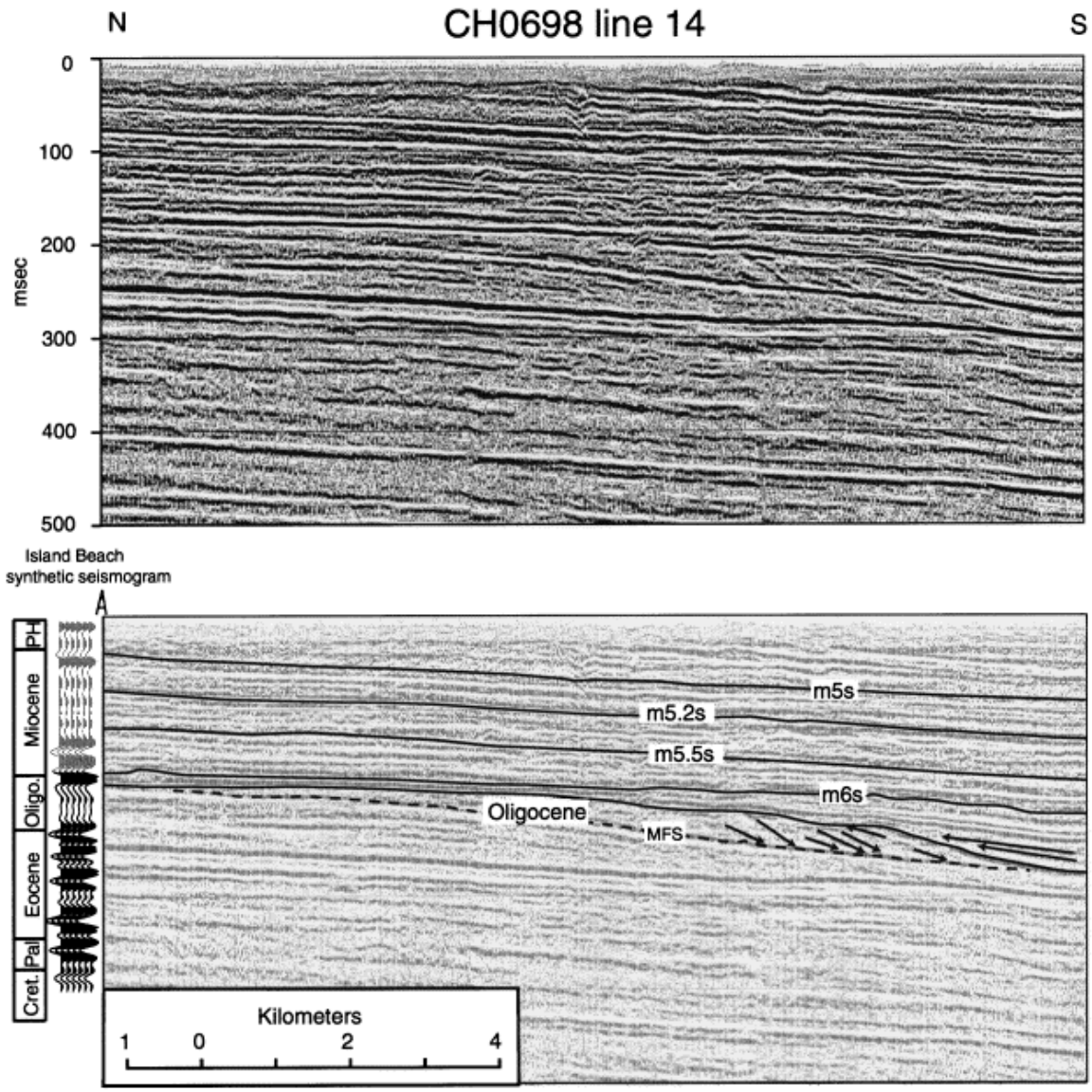

Fig. 1.4. Synthetic seismogram derived from the Island Beach acoustic log has been projected onto *CH0698* line 14 using the Miocene strike of Miller et al., (199). The upper part of the sonic log (in gray on the synthetic seismogram) was run through the casing and imaged reflectors should be disregarded. Ages depicted to the left of the synthetic seismogram result from detailed study of Island Beach borehole (PH is Pleistocene through Holocene, Miller et al., 1994a). Sequence boundaries m5s, m5.2s and m5.5s were traced around *CH0698* seismic grid and correlated to land profile near Island Beach (P. Miller et al., 1996) and sequence boundaries identified in Island Beach borehole and projected into line 14 using depth vs. time relationship. The m6s seismic sequence boundary was identified with the seismogram and agreed with data from AMCOR6011, downdip on line 17; a dip line recorded as a continuation of line 14. Seismic terminations identified a new clinoform inflection that appears below m6s, the lower Miocene-Oligocene boundary, and is dated as Oligocene by the Island Beach borehole (projected with the synthetic seismogram).

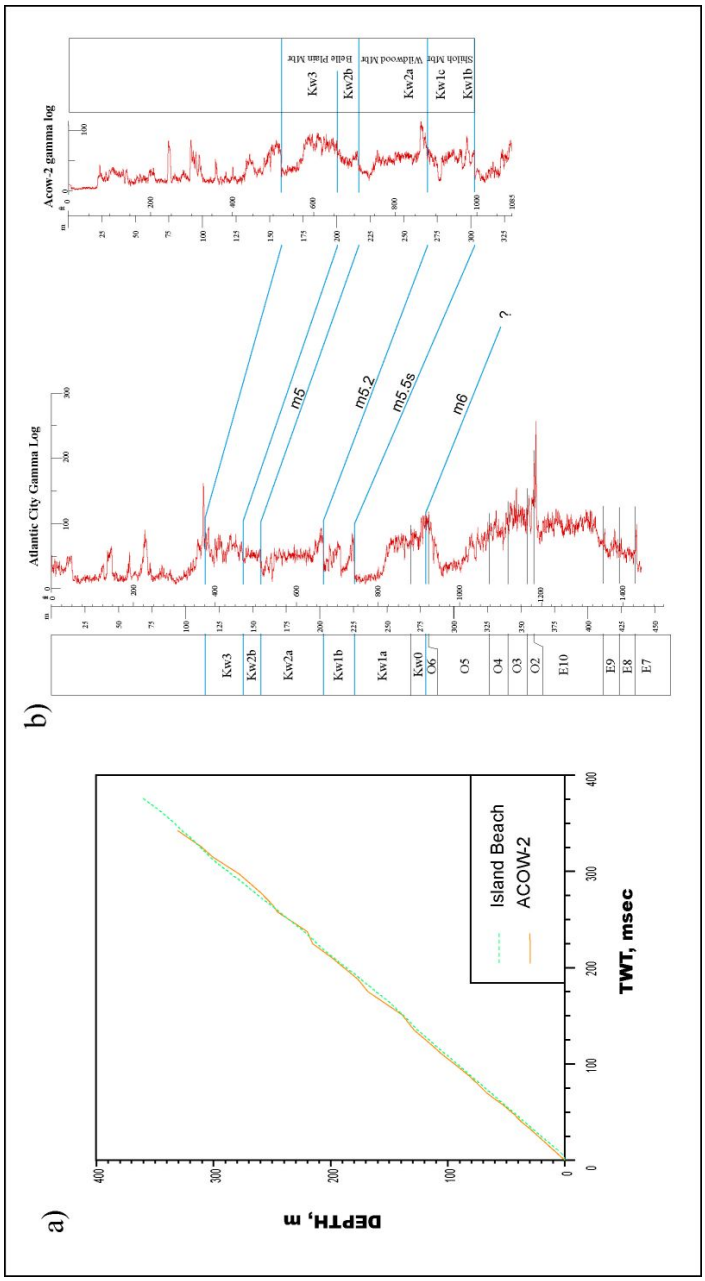

Fig. 1.5. a). Graph presents the acoustic data plotted as depth vs. two-way traveltime (TWT) from Island Beach and ACOW2. The Island Beach data derive from a downhole sonic log (Miller et al., 1994a), while check shot survey data (Waldner and Hall, 1991) recalculated from interval velocities back to depth vs. TWT supplied the information at ACOW2. b.) Graph displays correlation based on gamma logs from both Atlantic City borehole and ACOW2 well. Sequence stratigraphy at Atlantic City is based on physical and biostratigraphic criteria of drill core (Miller et al., 1997) while Owens et al (1995) used drill cuttings to define the coastal plain stratigraphic units in ACOW2. Sequence delineation used on ACOW2 units from (Miller et al., 1997).

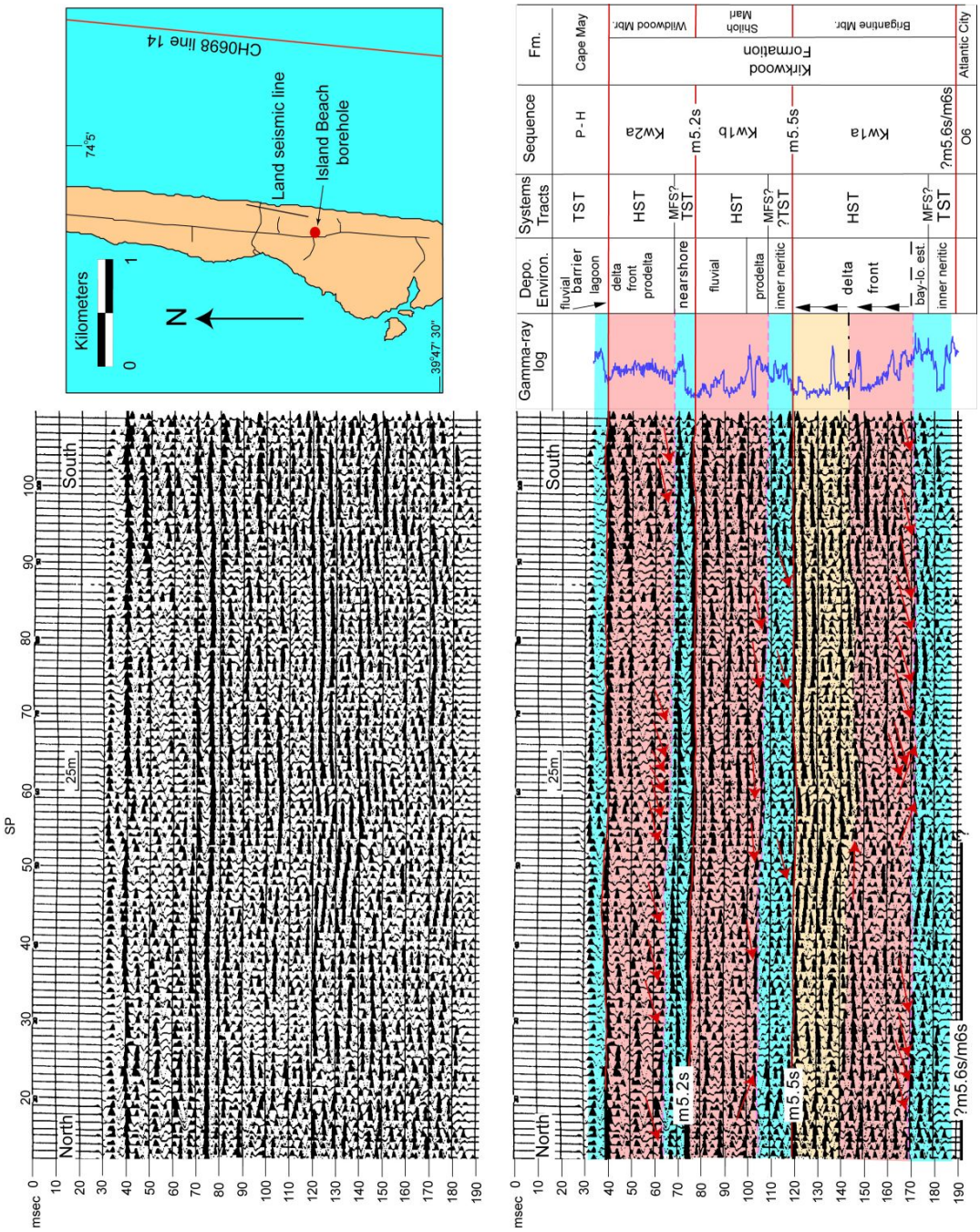

Fig. 1.6. Land seismic profile crossing the Leg 150X Island Beach site. Seismic data are after P. Miller et al. (1996). Lithology, gamma log, sequence stratigraphic interpretations, depositional environments, systems tract interpretations, and ages are derived from the Island Beach site (Miller et al., 1997a). Sequence boundaries m5.2s, m5.5s are imaged on the profile. Solid lines represent sequence boundaries, dashed lines are MFS, and dotted lines are other surfaces identified on the profiles that reside within the HST. See text for description of seismic interpretation.

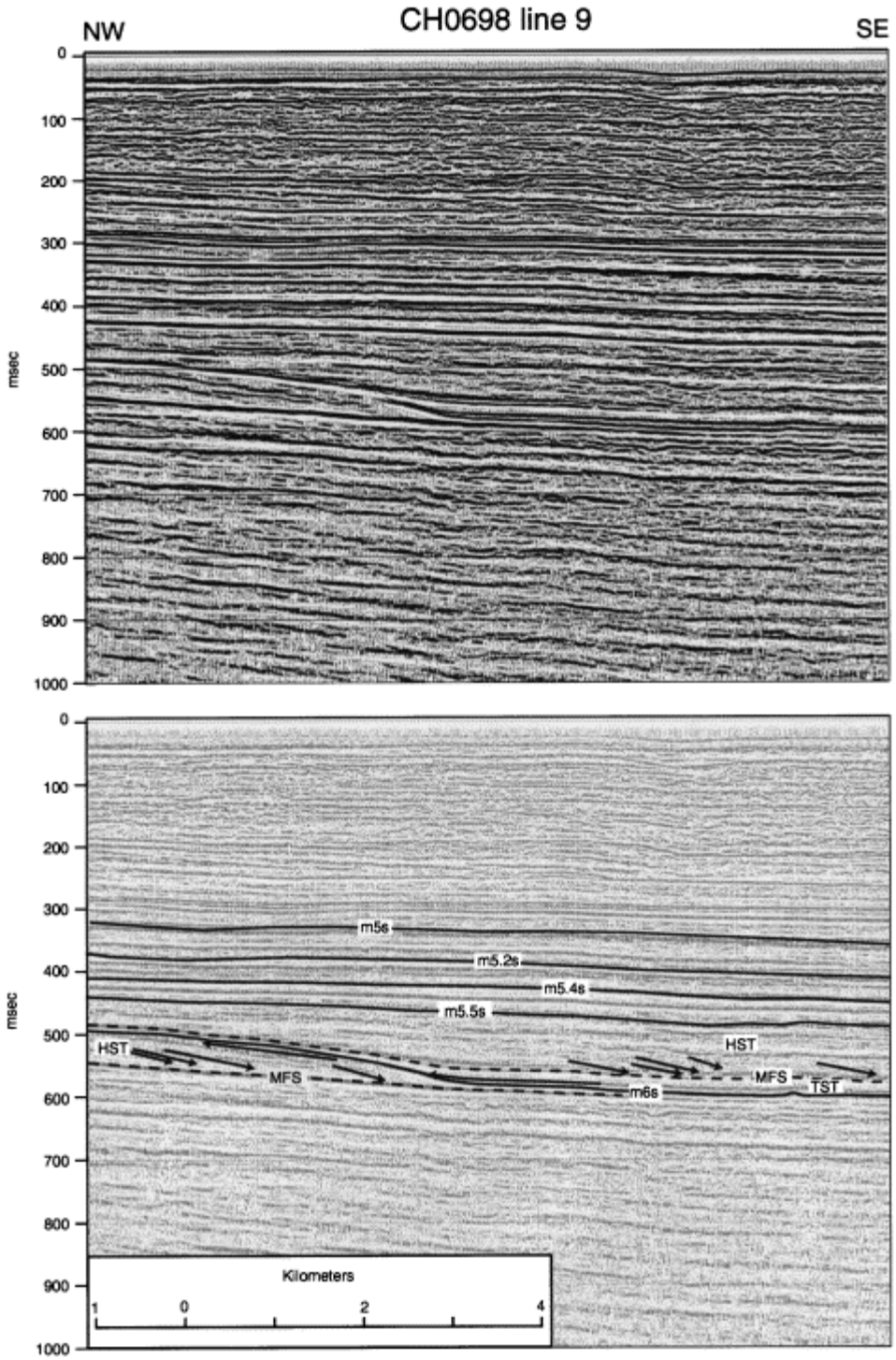

Fig. 1.7. Seismic dip profile *CH0698* line 9 shows onlap, offlap and erosional truncations used in defining the m6s seismic sequence boundary. Onlap on the m6s surface defines the Transgressive Systems Tract (TST). The maximum flooding surface (MFS, dashed line) separates the TST from the Highstand Systems Tract (HST). Offlap representing seaward sediment progradation defines the HST. Offlap beneath the m6s boundary represents Oligocene progradation.

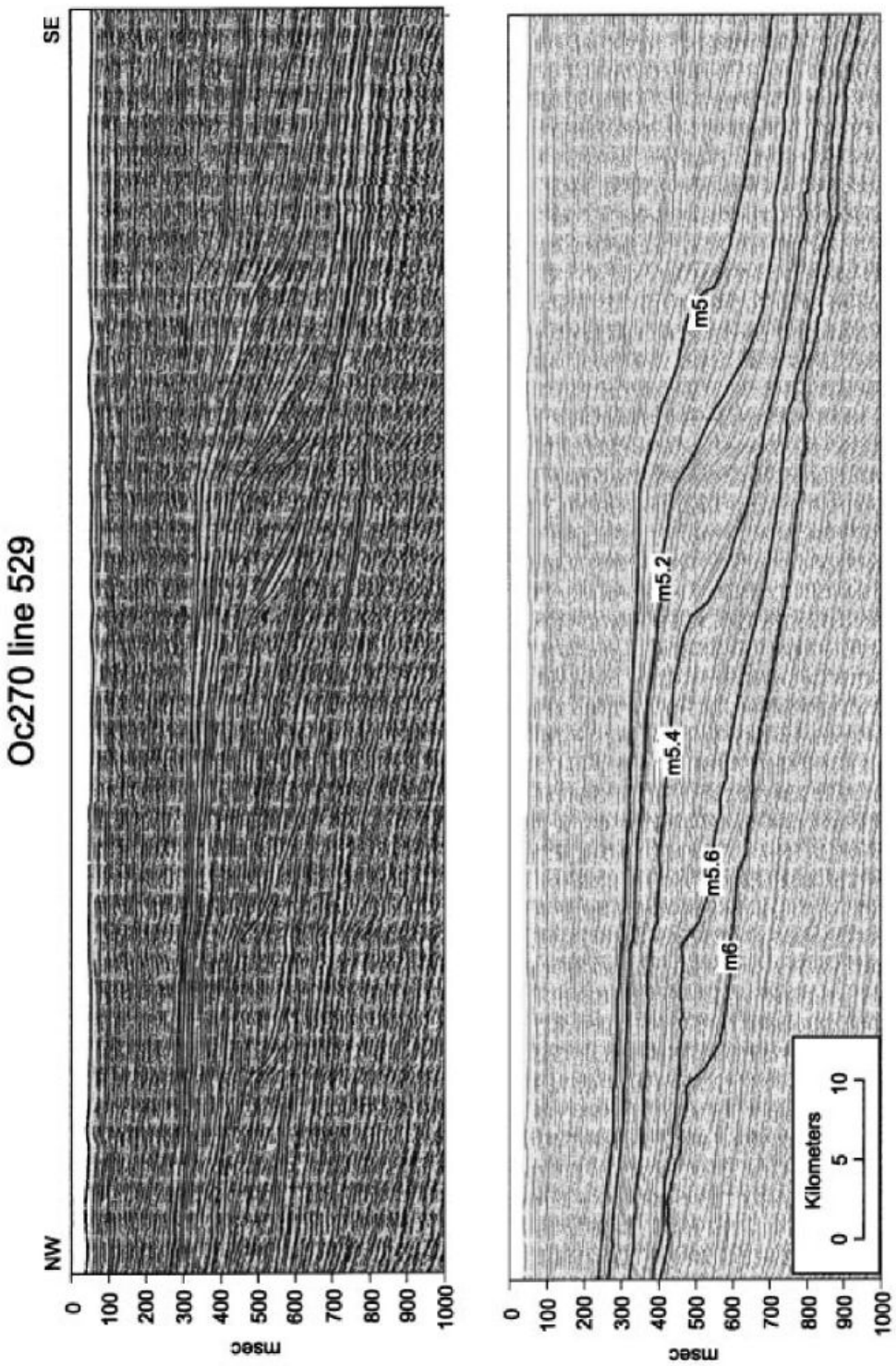

Fig. 1.8. Seismic dip profile *Oc270* line 529 depicting the lower Miocene seismic sequences boundaries m6, m5.6, m5.4, m5.2, and m5 from the interpretation of N. Christie-Blick et al., (pers. comm., in prep). Compare the spacing and morphology of these seismic boundaries to m6s, m5.5s, m5.4s, m5.2s and m5s on Fig. 1.9 from the *CH0698* data. Scale same as Fig. 1.9.

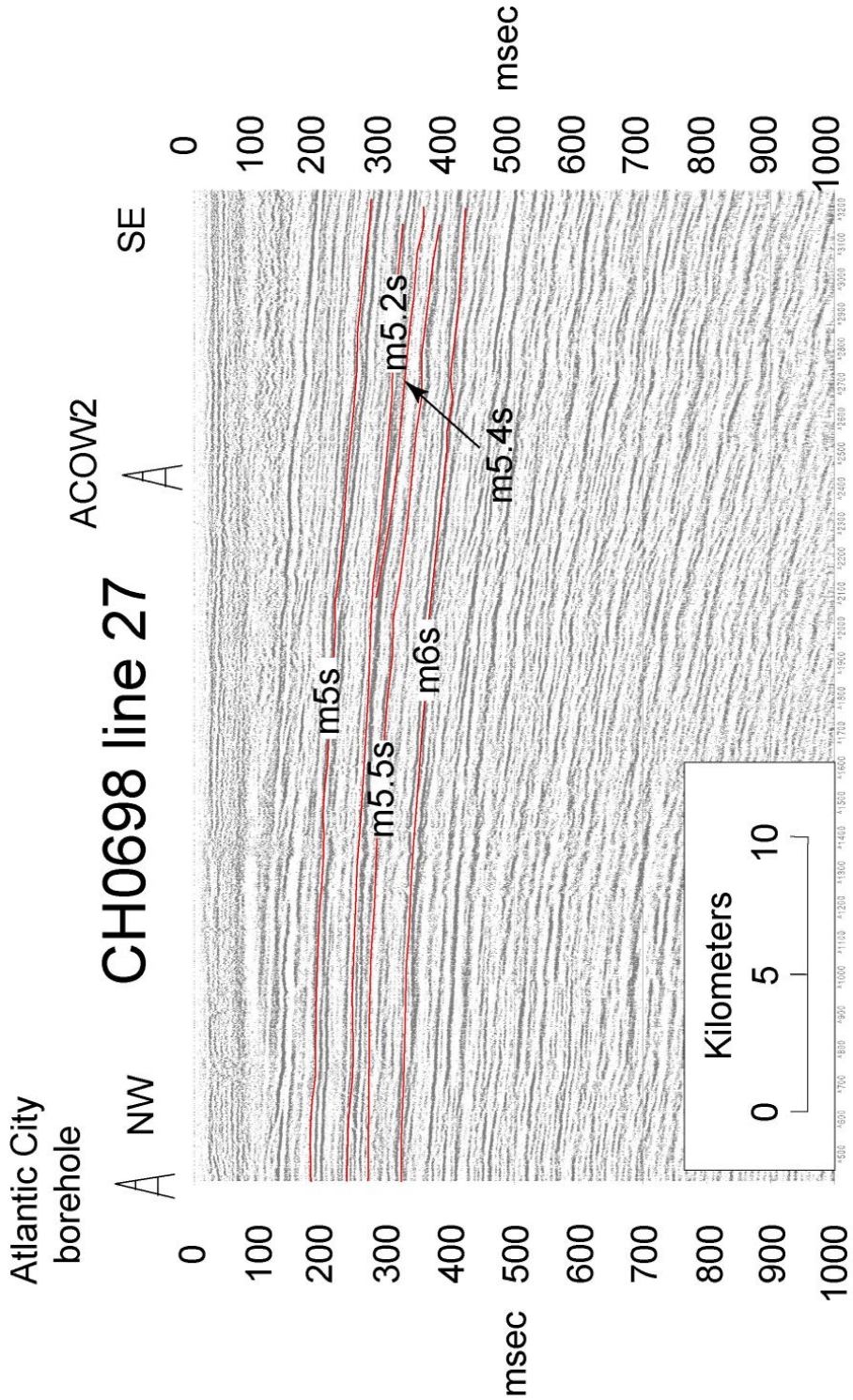

Fig. 1.9. Seismic dip profile *CH0698* line 27/9 showing the shelf defined m6s m5.5s, m5.4s, m5.2s and m5s seismic sequence boundaries. Atlantic City borehole and ACOW2 well were used in dating these seismic sequence boundaries. Compare the spacing and morphology of these seismic boundaries to m6, m5.6, m5.4, m5.2, and m5 on Fig. 1.8 from the *Oc270* line 529. Scale same as Fig. 1.8.

Chapter 2 – Identification of lower Miocene sequences on the New Jersey margin through seismic, borehole geophysics and core data

Abstract

Integration of seismic and corehole data are essential steps in studying continental margin evolution. Studies of the New Jersey Mid Atlantic margin have been ongoing through several generations of seismic and borehole data, though direct linking of onshore and offshore data has been sparse. Onshore locations have been extensively cored with few seismic profiles whereas outer shelf sections have excellent seismic profiles but limited cores. The missing interval between the two databases has been sampled by high resolution seismic data aboard the *R/V Cape Hatteras* (*CH0698*) that allows a tie between onshore coreholes and offshore shelf seismic profiles.

Analysis of 1100 km of seismic data has identified 11 candidate lower Miocene sequence boundaries, traceable through the entire seismic grid that portrays a definitive along strike variability. Lowstand and highstand facies are clearly identified while transgressive facies are rarely imaged due to minimal thickness of deposits that are below seismic resolution. Onshore ODP Leg 150X corehole data have been correlated into three offshore boreholes that have limited lithologic but good borehole geophysical data. Three ODP onshore coreholes just outside of the *CH0698* grid as well as the three boreholes within the grid have been projected into the time domain and correlated with the candidate seismic sequence boundaries. Correlations are consistent throughout the grid and allow dating of candidate seismic sequence boundaries. The correlation of seismic sequences with onshore identified sequence boundaries are as follows, (seismic surface, color – base of ODP sequence) m6, purple - Kw0, m5.8, brown – Kw1a1, m5.7,

red – Kw1a2, m5.6, dark blue – Kw1a3, m5.5, green – Kw1b1, m5.47, light blue – Kw1b2, m5.45, pink – Kw1c, m5.4, yellow – Kw2a1, m5.3, red – Kw2a2,3, m5.2, orange – Kw2b.

Introduction

The critical data analyzed in this study are recently collected marine seismic profiles traversing the New Jersey inner continental shelf (fig. 2.1). This seismic grid collected on the *R/V Cape Hatteras* (*CH0698*) was planned approximately paralleling the lower Miocene strike and dip trends and totals 1100 kilometers. Older, lower resolution seismic lines collected on the *R/V Maurice Ewing* (*Ew9009*) that traverse the New Jersey shelf are restricted in sufficient density or areal extent to clearly define the development of lower Miocene sequences in this nearshore region. More importantly, the *CH0698* grid fills the higher resolution data void between the outer shelf and slope seismic databases (fig. 2.1) (*Ew9009* and higher resolution *Oceanus* 270 (*Oc*270)) and ODP Leg 150X and 174AX onshore boreholes (Mountain, Miller, Blum, et al. 1994; Austin, Christie-Blick, Malone et al. 1998). Data collection proceeded into both the Cape May and Absecon Inlets, thereby approaching the Cape May and Atlantic City ODP Leg 150X boreholes within 700 m (fig. 2.2). Another ODP Leg 150X borehole at Island Beach still requires a 1500 m projection into the *CH0698* grid. These correlation distances between *CH0698* seismic lines and ODP coreholes are still not optimal but greatly reduce the error of the nearly 30 km jump into the *Ew9009* and *Oc270* grids.

Early results stated in the previous chapter describe the initial interpretation of the incomplete *CH0698* seismic data set. Dip line analysis showed that seismic reflector terminations outline candidate sequence boundaries that appeared to correlate to the onshore ODP coreholes. However to establish a more complete margin wide interpretation, the candidate boundaries must be connected or loop correlated throughout the entire seismic grid. The intra-sequence geometries also identified by reflector terminations help to define the sedimentary environments responsible for deposition. Identification and interpretation of systems tracts as well as possible sedimentary environments implicated by reflector geometries will shed light on the evolution of the New Jersey Mid Atlantic margin.

Seismic data require "ground truthing" to validate any scientific interpretations. Ideal methods could employ continuously cored and geophysically logged coreholes located at all seismic crossings. These cores would then be studied for age and lithologic characterization, including identification of surfaces important in model development. Lithologic data would explain downhole log response. The logs could then form a stronger comparison into older wells lacking detailed lithologic and biostratigraphic data but sampled with geophysical logs. These data would be integrated into seismic reflector and interval identification. Unfortunately ideal worlds do not exist and seismic interpreters work with a smaller "hard" database than desired. This is the case for this study. Three continuously cored land based boreholes, part of ODP Leg 150X, supply the best seismic "ground truthing" (Miller et al., 1994a, 1994b, 1997). While not located along *CH0698* line intersections, two of the boreholes, Atlantic City (Miller et al., 1994b)

and Cape May (Miller et al., 1997) lie only several hundred meters off of *CH0698* lines 27 and 99, respectively (fig. 2.2). The third Leg 150X borehole at Island Beach (Miller et al., 1994a) requires a longer jump along strike into *CH0698* into line 14. This distance increases possible errors in identifying the best correlation between the Island Beach data and an individual *CH0698* seismic CDP. Biostratigraphy and Sr-isotopic age delineation is poorest at the Island Beach borehole due to high sand content and scarcity of both micro- and macrofossils.

Three older offshore boreholes lie along the *CH0698* seismic grid but suffer from limited sampling and corresponding lithologic descriptions (fig. 2.2). Atlantic Margin Coring Project (AMCOR) (Hathaway et al., 1976) drill site, AMCOR 6011 occurs at the intersection of *CH0698* lines 16 and 17. Two other boreholes were drilled southeast of Atlantic City as part of the Atlantic City Offshore Well Program (ACOW) to investigate the presence of fresh water in deep coastal plain aquifers under marine waters. The ACOW-1 and 2 boreholes lie along *CH0698* lines 38 and 16, respectively. The limited lithologic and paleontologic material from these older wells requires the use of downhole geophysical logs correlation with the ODP Leg 150X coreholes.

A further complication in evaluating seismic interpretations arises from the quantity and quality of logs collected in the different wells. Poor borehole conditions in Atlantic City and Cape May coreholes restricted acquisition of a complete suite of geophysical logs. Only gamma and neutron porosity logs were completed at these two sites before the coreholes collapsed. Data from nearby municipal water wells containing a more

complete geophysical database supplemented correlation between the onshore and offshore wells Atlantic City, New Jersey.

Transferring the corehole lithologic and geophysical data into the seismic grid is the final requirement in data analysis. This important step requires the best time vs. depth calculations as possible. All data relating time to depth need analysis to arrive at the best outcome. The two databases can then be correlated and ages determined for the candidate seismic sequence boundaries.

Seismic data

CH0698 data used the Lamont-Doherty Earth Observatory (LDEO) HiRes multichannel seismic (MCS) system. Data gathering used a 45/45 cu-in Generator-Injector airgun towed at approximately 2 m depth. It maintained a 48-channel, 600 m solid (not oil-filled) ITI streamer at 2±0.5 m depth with a near trace source offset of zero. Ship speed, monitored by DGPS, was maintained at 4.9 knots over the seafloor to yield 12.5 m between shots at 5 sec intervals. The data were recorded with an OYO DAS-1 at a 0.5 ms sample rate; trace lengths were 2 sec. Seismic data processing included outside mute, velocity analysis, Normal Moveout (NMO) correction, bandpass filtering, spreading loss correction, predictive deconvolution, Stolt migration, and time-varying gain. The data are of excellent quality with vertical resolution approaching 5 m and usable acoustic imaging to approximately 1.2 sec of two-way traveltime. Sea floor multiples have been

sufficiently muted. However peg leg multiples are still present beneath steeper dipping reflectors and hinder the interpretation.

CH0698 seismic data were analyzed in a sequence stratigraphic framework. Geometry of seismic reflector terminations defined individual sequences according to methods outlined by Mitchum (1977), Mitchum and Vail (1977), Mitchum et al., (1977a, 1977b, 1993), Badley (1985), and Vail (1987). Typical reflector geometries of onlap, downlap, toplap, and erosional truncations outlined the sequence geometry (fig. 2.1) such as sequence boundaries, maximum flooding surfaces (MFS) as well as sedimentary packages that include Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST) and Highstand Systems Tracts (HST) and Falling Stage Systems Tracts (FSST).

The sequence boundary forming the lower surface of the depositional sequence is described by Mitchum (1977b) as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities. Van Wagoner et al, (1988, 1990) further clarified the sequence boundaries as unconformity surfaces and their corresponding correlative conformities that separate overlying younger from underlying older strata. Those authors state that unconformities are surfaces with a "significant hiatus" and subaerial erosional truncation and do not include nondeposition submarine surfaces as defined by Mitchum (1977b). Christie-Blick, (1991), Christie-Blick and Driscoll, (1995), and Myers and Milton (1996) further discuss this definition and suggest that surfaces of transgression and marine erosion that do not correlate to subaerial erosion are not sequence boundaries. Lowering of depositional base level that

initiates subaerial erosion and stream incision and/or bypass, however, does mark a sequence boundary (Vail et al, 1984, Van Wagoner et al, 1988, Christie-Blick, 1991, Christie-Blick and Driscoll, 1995).

Seismic sequence boundaries by these definitions show subaerial exposure and erosion, including incised valleys (fig. 2.1). Reflectors beneath sequence boundaries can exhibit erosional truncation, toplap or offlap (fig. 2.1). Above this surface and seaward of baselevel, onlap and downlap can occur against the clinoformal sequence boundary. This geometry represents fan deposition during a relative sea-level lowstand. Onlapping reflector terminations landward of the clinoformal sequence boundary mark rising relative sea level. A marine erosion surface marking storm wave base could form above or erode and therefore amalgamate into the sequence boundary. Taken together these geometric reflector terminations identify candidate sequence boundaries. Directly sampling above and below the identified boundaries or tying into existing corehole are necessary to ground truth the interpretation.

Initial identification of seismic sequence boundaries relied on correlation of seismic sequence surfaces m6, m5.6, m5.4, m5.2 and m5.0 traced through the *Ew9009* grid and projected on *Oc*270 line 529 (fig. I.1; N. Christie-Blick, G. Mountain and K. Miller, 1998 oral communication). *Oc*270 line 529 repeated *Ew9009* line1003 using the LDEO HiRes MCS system and has multiple crossings with the *CH0698* grid thereby allowing direct data integration. Initial interpretations of paper seismic records were reevaluated and updated using processed data on a workstation running SeisWorks®, an industry standard

program licensed to run at LDEO. Interpretation outlined candidate sequence boundaries and delineation of seismic facies. Each dip line was independently interpreted and loop correlated to maintain interpretational consistency. Loop correlation suggested that candidate boundaries did not portray similar sequence-defining characteristics on each dip profile.

Geophysical Logs

In general, gamma ray logs have proved quite beneficial in tracing lithologic and aquifer units over long distances in the New Jersey and other Atlantic coastal plain deposits (fig. 2.14; Sugarman et al., 1993, Siron and Segall, 1997). Miller et al. (1998) and Sugarman et al. (1993) have described a characteristic gamma signature constructed from core-log correlation of Miocene deltaic deposits. Rider (1990) warned of using gamma logs to characterize grain size variations due to the variable relationship between these two parameters. However, data suggest that fluvio-deltaic environments (wherein radioactive clay and quartz mixtures form a direct relationship between grain size and clay content) provide gamma logs that are especially reliable indicators of grain size variability (Rider, 1990). Analysis of Leg 150X cores shows that clays and, where present, glauconite, carry the radioactive signature observed in the gamma response across the sedimentary units deposited during the Miocene (Lanci et al., 2002; Miller et al., 1994a, 1994b, 1997). Glauconite forms a dominant constituent of Oligocene sediments, but occurs only in the lowermost Miocene sequence and only in the base (Miller et al., 1998). Heavy minerals that might contain a natural radioactivity comprise less than one percent of the Miocene

sedimentary material (J. Browning, personal communication). Therefore, conditions are generally met whereby the gamma response should mimic grain size within the Miocene New Jersey Coastal Plain.

Spontaneous potential, also called self-potential (hereafter SP) and resistivity are two downhole geophysical logs that can delineate sand and clay horizons (fig. 2.14). SP tools measure the natural potential difference between an electrode pair; one is a surface electrode, and the other is within the tool. The tool records the electrical potential that develops between the different salinity fluids within the borehole and the formation (Rider, 2002). A high negative surface charge occurring in clay layers impedes the passage of anions but allows cations to pass, which creates a positive deflection as recorded by the SP tool (Rider, 2002). Sands display a characteristic negative deflection due to the opposite effect of clay (Schlumberger, 1989). These deflection directions depend on the salinity of the borehole fluid being lower than that of the formation water (Keys, 1989). The clay and sand response will reverse if the borehole fluid is more saline than formation water. If salinities of both borehole and formation fluids are the same, no response or a straight line will be recorded by the SP tool (Keys, 1989; Schlumberger, 1989). Resistivity uses similar principles to outline sand and clay horizons. It measures the electrical potential drop between two electrodes that lie within an induced electrical current between two wider spaced electrodes within the tool, and thereby defines the normal resistivity (Ryder, 2002). Lateral resistivity configuration varies from the normal electrode configuration with the measuring electrodes beneath the two current generating electrodes (Schlumberger, 1989). Modern tools are more complex and may contain

various electrode-spacing with the wider spacing electrodes sampling deeper into the formation away from the drill disrupted zone (Keyes, 1989; Ryder, 2002). Resistivity tools include single point, short normal (16 inch spacing), long normal (64 inch spacing) and lateral logs; induction is a conductivity tool that records the reciprocal of resistivity (Ryder, 2002). Resistivity values measure both the rock resistivity or pore structure geometry, a function of the permeability pathways caused by grain size and sorting, and fluid resistivity, both formation and borehole fluids (Schlumberger, 1989). Resistivity decreases as porosity and formation water increases. If all things are taken equal, the higher the salinity of the fluid the lower the resistivity (Schlumberger, 1989).

Neutron and density logs are another set of geophysical tools that increase the interpretational ability of poorly sampled boreholes. Neutron sondes outline formation porosity by recording variations in hydrogen content through the borehole (Schlumberger, 1989). Hydrogen values should record water filled pore spaces. However, bound water in clays, such as lattice water occurring as part of the clay molecular structure and water of crystallization increases the log response and requires careful analysis (Schlumberger, 1989; Rider, 2002). Shale or clay layers will record abnormally high porosity values due to this bound water (Rider, 2002). Values diminish gradually with depth due to compaction. Rider (2002) suggests that tests in 3000 m deep boreholes showed that neutron shale values dropped very slowly as the pore waters were squeezed out while the adsorbed and interlayer water remained relatively constant. Different clay mineral assemblages do not affect the neutron log response as much as the addition of non-clay minerals such as quartz. Schlumberger (1989) suggests that using

only the neutron log for any interpretation is fraught with errors unless the uncertainties involved are considered. Density logs supply the necessary information and, in conjunction with neutron logs fully characterize the different layer lithologies and bulk density (Keys and MacCary, 1971). Density logs record the different bulk density of the various lithologies intersected in the borehole. Several different tools were used to collect density measurements in the wells included in this study. The gamma-gamma tool relies on the inverse relationship of gamma radiation attenuation and bulk density of intersected rock (Keys, 1989). Similar to most tools, the wider the spacing between the source and detector, the greater the penetration depth where material was sampled.

These different geophysical logs help to characterize and identify the different lithologies encountered during drilling (fig. 2.14). Keys (1989) characterized borehole geophysical tool response to varying lithology while Van Wagoner et al. (1990), Ryder (1996) and Posamentier and Allen (1999) portray the use of log responses to identify sequences and their associated internal geometries. Correlating the geophysical logs with detailed core analysis from the same borehole is desirable, but not always possible. Gamma logs work best in sequence correlations around the New Jersey Coastal Plain (Sugarman et al., 1993, Miller et al., 1998). Gamma data can be compared with other geophysical log data to decipher the lithological makeup and thereby the sequence systems tracts. Sugarman et al. (1993), Miller et al. (1998), and Sugarman (2001), building on idealized geophysical log responses, described the generalized lithologic variation and corresponding borehole geophysical responses in typical Miocene-aged sequences along the New Jersey margin (fig. 2.14).

DATA INTERPRETATIONS

SEISMIC DATA

Initial interpretation of *CH0698* data revealed sufficient reflector terminations that outlined both sequence boundaries and internal sequence morphology. Progradational downlapping reflector terminations proved to be best displayed in *CH0698* dip lines within progradational facies beneath sequence boundaries. These same reflectors can often portray oblique toplap terminations thereby outlining potential sequence boundaries. Lowstand downlapping surfaces were not as clearly and obviously imaged as highstand prograding deposits. Onlapping reflectors are best shown against the more steeply dipping sigmoidal candidate sequence boundaries in a lowstand position. Once these reflectors crest the sigmoidal sequence boundary, onlap was rarely in evidence. Sequences generally thin landward as gently dipping surfaces tend to amalgamate into erosional surfaces that comprise the next older boundary. Tracking these amalgamated surfaces landward proved difficult, as the individual reflectors are often discontinuous and not “hard” reflectors throughout their complete course. Overall reflector geometry suggested thin transgressive deposits, where present, and thicker highstand or regressive facies that mimicked lithologic facies observed in onshore coreholes (Miller et al, 1994a, 1994b, 1996a, 2001). Prograding reflectors greatly dominated over their transgressive counterparts. Seaward projection of seismic interpretation also proved difficult for several reasons. First data quality declines below approximately 1msec TWTT nearshore and 1.2 msec TWTT farther offshore. Identified sequence boundaries continue below

this level approaching the eastern edge of the seismic grid. Second, faulting becomes evident on the eastern margin of the grid. Seismic grid spacing was insufficient to correlate any of these small scale faults along adjoining profiles (fig. 2.3). Similar fault patterns exist in the North Sea and Lower Congo basins and are attributed to syneresis, a process related to volumetric decreases during early compaction of clay-rich sediments and oozes (Cartwright and Dewhurst, 1998; Gay et al, 2004).

New Jersey margin sequence boundary nomenclature initially employed terms outlined by Miller and Mountain (1994), Mountain, Miller, Blum, et al. (1994) and Miller et al. (1996b) through analysis of *Ew9009* data (Table 2.1). These surfaces correlated to shelf sequences identified on older lower resolution data (Greeenlee et al, 1992) with the addition of several additional possible sequence boundaries (Table 2.1). These surfaces were identified by colors as used by Mountain, Miller, Blum, et al. (1994); (oldest to youngest) pink-3 (purple of this study), true blue (dark blue of this study), sand (yellow of this study), ochre (orange of this study) and green. The colors correlated to reflectors m6, m5.6, m5.4, m5.2 and m5.0 respectively (Table 2.1; Miller and Mountain, 1994). Seismic sequence surfaces m6, m5.6, m5.4, m5.2 and m5.0 investigated on ODP Leg 150 have all been tied to oxygen isotope increases suggesting a eustatic control on their development (Miller et al, 1996b). These five sequence boundaries have been tracked landward and tied to *Oc*270 line 529 at crossings with *Ew9009* seismic lines (N. Christie-Blick, G. Mountain and K. Miller, oral communication, 1998). Additional surfaces were recognized through loop correlation of dip line interpretations. New surfaces were given an m5.x demarcation between the previously noted terms, that is, a newly outlined

surface between m5.6 and m5.4 was named m5.5. An additional surface identified between m5.4 and m5.5, was named m5.45. This identification system continued until all surfaces were named and consisted, from oldest to youngest of m6, m5.8, m5.7, m5.6, m5.5, m5.47, m5.45, m5.4, m5.3, m5.2, and m5.

Initial loop correlations identified major along-strike variability of sequence-defining characteristics of the candidate sequence boundaries. These boundaries are clearly defined on select dip profiles but appear as just another reflector on other dip profiles orientated along strike. Therefore "type dip lines" were selected for each boundary where the onlap, downlap, toplap and erosional truncation terminations most clearly outline and distinguish the reflector as a sequence boundary. Intra-sequence variability also occurs that depends on lower and upper boundary morphology as well as the internal reflector terminations that define LST, TST, HST and FSST facies.

m6 purple reflector

The basal Miocene reflector (pink of Greenlee et al. 1992) carried through the *Ew9009* data (N. Christie-Blick, G. Mountain and K. Miller, oral communication, 1998) to *Oc*270 line 529 is labeled m6 (Mountain, Miller, Blum, et al. 1994) and colored purple for this study (Table 2.1). Miller et al. (1996, 1998) correlate oxygen isotope increase Mi1 with m6 thereby establishing a glacioeustatic control. These authors matched the point of steepest positive change in $\delta^{18}O$, which represents a growth of ice sheets and corresponding sea-level lowering. Miller et al. (1996, 1998) provide a best age estimate

at 23.8 Ma with a 23.6-24.0 Ma range which correlates to the Miocene-Oligocene boundary. Reflector geometries best define sequence boundary characteristics in the northern *CH0698* grid particularly north of line 9 where it clearly marks the termination of a broadly downlapping older reflector package. These Oligocene downlapping reflectors prograde both offshore on dip lines and towards the south on strike lines thereby implying a dominant source from the northwest corner of the grid.

CH0698 line 15 records the southern most defined onlapping terminations against the base of the sigmoidal m6 reflector (Fig. 2.10). Progressing to line 17 in the north (Fig. 2.11), the m6 sequence boundary shows basal reflectors that both onlap and downlap suggesting LST conditions. Overlying and ending the LST is a downlap surface that records the change to prograding reflectors of the HST. The TST is thin to absent as the overlying m5.8 reflector subparallels and locally merges with m6 landward of the m6 clinoform inflection point (CIP) where the gently seaward dipping m6 surface steepens and becomes sigmoidal shaped. Moving northward onto *Oc270* line 529 (Fig. 2.12) and *CH0698* line 21 (Fig. 2.13), a similar geometry is evident. The entire sequence has filled a slightly larger area suggesting a more proximal sediment source. The overlying m5.8 reflector marks the end of the sequence.

The development of the m6 sequence is limited southward across lines 13 to 1 (figs. 2.4-2.9), as evidenced by the proximity of the overlying m5.8 candidate sequence boundary that suggests either erosion or limited deposition of m6. However line 1 (Fig. 2.4) images a separation between boundary m6 and the overlying m5.8 sequence boundary

that continues into Cape May inlet on line 99. Limited seismic resolution outboard of the clinoform inflection point towards the eastern edge of the seismic data grid suggests that deeper water lowstand fan deposits exist. Within the *CH0698* grid line 17 best depicts the termination geometries that identify m6 as a sequence boundary (Fig. 2.11).

m5.8 brown reflector

The higher resolution *CH0698* data including *Oc*270 line 529 allowed the recognition of candidate sequence boundary m5.8 not previously identified in *Ew9009* or older, lower resolution seismic data across this region (Table 2.1, Fig. 2.12). Reflector m5.8 tends to mimic the location and internal morphology of m6. Sequence defining criteria are best displayed on *Oc*270 line 529. Adjoining dip lines 21 (Fig. 2.13) to the north and 17 (Fig. 2.11) to the south also image surface terminations identifying the sequence boundary morphology of m5.8. A thick diffuse basal reflector suggesting a LST fan deposit overlies m5.8 on line 529 (Fig. 2.12). Line 17 shows a similar though less defined reflector aligned in the same geometric orientation (Fig. 2.11). A single reflector on line 21 that both onlaps and downlaps occurs farther offshore and away from the sigmoidal m5.8 surface may also represent a LST fan deposit (Fig. 2.13).

A thickened m5.8 sequence only exists in the northern grid region. Line 21 portrays climbing, onlapping reflectors against the m5.8 clinoform inflection point (Fig. 2.13). Transgressive deposits have been removed as the sequence has been decapitated by deep erosion or possible slump evidenced by the undulating m5.47 surface. Downlapping

surface truncations indicating regressive deposits occur farther seaward. Progressing southward and away from this extensive erosion, reflectors on line 529 (Fig. 2.12) express both lowstand and highstand deposits and continue a prograding margin outboard from the m6 sequence. By line 17 (Fig. 2.11), the m5.8 sequence thins as the m5.7 surface down cuts. An onlapping and downlapping body, possibly a lowstand fan, develops on the more muted m5.8 surface. Outboard, more downlapping occurs suggestive of a regressive outbuilding. Southward from line 13 (Fig. 2.9), the m5.8 surface merges with m5.7 near to the clinoform inflection point. Outboard an apparent separation may occur between m5.8 and m5.7 suggesting deeper water deposits developed however it is uncertain whether these are lowstand, highstand or falling stage deposits. Along strike to the southwest reflector m5.7 commonly truncates or merges with m5.8 below seismic resolution in a shoreward direction. A slight thickening exists between lines 3 and 5 and suggests a limited redevelopment of the thin prograding sequence (figs. 2.5 and 2.6). Sequence thinning continues to the southern extremity of the grid.

m5.7 red reflector

Candidate sequence boundary m5.7 has only been imaged on *CH0698* grid and marks a prominent reflector throughout the seismic grid. However m5.7 only displays sequence-defining characteristics on a few northern dip profiles. Line 529 (Fig. 2.12) marks the most clearly defined reflector truncations indicative of a sequence boundary though lines 17 through 9 (figs. 2.7- 2.11) image truncations partially suggestive of sequence

boundaries. Onlap against the sigmoidal m5.7 clinoform inflection point and other more seaward bidirectional lapout truncations (onlap and downlap on the same reflector) mark the lowstand position. The appearance of limited toplap beneath m5.7 on lines 529 and 21 add to the boundary demarcation (figs. 2.12 and 2.13). These terminations identify the candidate m5.7 surface as a sequence boundary.

Sequence m5.7 displays a variable development across the *CH0698* seismic grid. Dip lines 21 and 529, where m5.7 is best characterized, exhibit a major erosional truncation by the m5.47 (light blue) reflector that decapitates the sequence (figs. 2.12 and 2.13). Limited reflector terminations suggestive of LST deposits, mostly lowstand fans, are imaged on line 529. Onlapping against the sigmoidal m5.7 surface occurs on both 21 and 529. Any TST reflectors have been either eroded or below resolution. Indications of regressive offlap suggesting HST appear near the overlying m5.6 candidate sequence boundary.

The m5.7 reflector remains a prominent surface throughout the remaining seismic lines, but with less evidence of the defining sequence boundary terminations. However the m5.7 sequence is well defined both by internal surface terminations such as downlap and offlap and the upper boundary m5.6 (dark blue) reflector truncations. Sequence m5.7 continues from line 17 to line 3 as a low relief sigmoidal feature (figs 2.5-2.11). By line 1 the sequence has shortened considerably in length and thickness (Fig. 2.4). Internal morphology, though still imagining limited truncations no longer displays sequence-defining characteristics.

m5.6 dark blue reflector

The m5.6 sequence boundary was first mapped on the outer continental shelf and slope through *Ew9009* data and sampled in ODP Leg 150 (Mountain, Miller, Blum et al. 1994). Miller et al. (1996, 1998) have suggested a glacioeustatic control on m5.6 development through correlation to oxygen isotope increase Mi1a, and have dated the surface as ranging from 21.5 to 22.5 Ma with a best estimate of ~22 Ma.

Reflector m5.6 is best identified as a sequence boundary through the middle of the *CH0698* seismic grid, from dip lines 9 to 13 (figs. 2.7-2.9). Again, basal reflectors located seaward of the candidate m5.6 clinoform inflection point terminate both as onlap and downlap, suggesting LST facies, probably a fan deposit. Onlapping reflector terminations climb the sigmoidal m5.6 surface to the clinoform inflection point and define a thick succession of LST deposits. A thin TST is imaged by onlapping reflector terminations that crest the m5.6 sequence clinoform inflection point and march landward. Progressing landward from the clinoform inflection point, both toplap and/or erosional truncation of underlying reflectors delineate the m5.6 surface as a sequence boundary. The sequence thins dramatically towards the shore away from the clinoform inflection point, due to erosion by an overlying sequence boundary. Seaward of the CIP a reflector downlaps against the LST deposits marking the change between LST to regressive deposits of the HST facies. This downlap surface, or MFS, projects above the clinoform inflection point suggesting that some TST still resides atop the gently dipping shoreward

projecting m5.6 reflector. Reflector m5.6 is truncated on lines 529 and 21 by a very irregular reflector representing an erosional surface, identified as m5.47 (light blue, figs. 2.12 and 2.13).

Reflector m5.6 begins to lose its sequence boundary definition southwestward within the grid. A subtle CIP still exists on line 5 and displays erosional truncation and toplap of reflectors from the m5.7 sequence. LST deposits, identified by onlapping and doubly terminated onlap and downlap reflectors, are imaged southward through line 3. These reflectors give an overall hummocky appearance, but a MFS is difficult to interpret. TST terminations cannot be adequately found, suggesting that they are below seismic resolution or subsequently removed. Rare reflector terminations landward of the m5.6 CIP are all regressive. HST terminations are not clear as reflector configurations are wavy to contorted. Overall the sequence has thinned on line 5 but prograded farther seaward than to the northeastern part of the grid. Dip lines 3 and 1 show the last vestiges of a partially defined CIP change into a more subtle slope increase (figs. 2.4 and 2.5). Some onlaps are still imaged suggesting a LST. Overall the reflectors are inclined seaward with an appearance of toplap. The overlying m5.5 surface also shows no clearly defined clinoform inflection point that would mark the seaward extent of thicker sequence development.

m5.5 green reflector

Surface m5.5 (green reflector) represents a newly defined candidate sequence boundary not imaged previously on other seismic data. Candidate sequence m5.5 is eroded where sampled by both *Ew9009* and *Ocs270* grids. Boundary m5.5 portrays the most characteristic reflector terminations of a sequence boundary on lines 13 through 5 (figs. 2.602.9). Here onlapping reflector terminations lie against the base of the sigmoidal m5.5 surface. However these onlapping surfaces depict a limited lowstand wedge and fan deposits. Line 13 images the best wedge formed against the base of the m5.5 clinoform (Fig. 2.9). Here, a few reflectors representing younger lowstand deposits onlap against the wedge before overtopping it and climbing the m5.5 surface. This wedge resembles a similar feature on candidate sequence boundary m5.4 on line 529 (Fig. 2.12). Onlapping reflectors climb the sigmoidal m5.5 surface on lines 11 through 5 but do not depict good downlapping terminations. Limited possibilities of small LST fan deposits at the seismic resolution threshold occur on lines 11 and 9 (figs. 2.7 and 2.8). Reflector m5.5 has rare onlapping TST deposits landward of the CIP. However, toplap truncations beneath m5.5 aid in delineating it as a sequence boundary. By lines 3 and 1, the m5.5 reflector has lost its sequence defining morphology (figs. 2.4 and 2.5). All that remains is a uniform, gently seaward dipping reflector that still suggests onlap and toplap reflector terminations. To the north erosion and surface amalgamation removed surface m5.5 on lines 21 and 529 (figs. 2.12 and 2.13).

Sequence m5.5 depositional signature only remains southwest of dip line 529 (Fig. 2.12). A thin relic landward of the line 17 CIP is all that remains while line 15 only contains a thin section with limited truncations landward of the CIP (Fig. 2.11). The best

development of the m5.5 sequence is imaged on lines 13, 11, and 9 (figs. 2.7-2.9). Lowstand deposits occur as small wedges and limited fan deposits. Atop the lowstand lies a relatively thick areally extensive deposit well marked by gently sloping to horizontal, discontinuous reflectors that both onlap the sigmoidal m5.5 clinoform and downlap and converge seaward, forming a broad wedge-shaped body. Posamentier and Allen (1993, 1999) characterized similar patterns as part of a transgressive healing phase whereby sediment reworking from wave ravinement processes transports finer grained material into deeper waters and settles past the previous clinoform inflection point position. A convex upward morphology distinguishes the healing phase wedge. Myers and Milton (1996) supplied an alternative interpretation of retrogressive slumping of the previous highstand. Retrogressive highstand deposits cap the sequence. To the southwest on lines 3 and 1 the m5.5 sequence forms a thin wedge atop the nearly planar m5.5 reflector (figs. 2.4 and 2.5). The capping m5.47 reflector outlines a gently sigmoidal trace on line 3 that changes into a more subtle oblique orientation. On these two lines the m5.5 sequence, though thinner, still images onlapping terminations capped by a semi-transparent downlapping to hummocky seismic configuration.

m5.47 light blue reflector

The seismic surface identified here as m5.47 (light blue) reflector represents the next youngest candidate sequence boundary and also was not previously identified. *Oc*270 data only detected m5.47 on line 529 where it images a planar erosional surface (Fig.

2.12). Lower resolution *Ew9009* survey traversed too far northeasterly and thereby missed where sequence boundary characteristics are most evident.

Reflector m5.47 is best established as a sequence boundary through the middle of the *CH0698* grid, similar to reflector m5.5. Dip line 15 establishes the northernmost extent of m5.47 that displays candidate sequence boundary morphology that becomes more pronounced southwestward (Fig. 2.10). By line 1, this surface has changed from a steep sigmoidal clinoform to a muted, very gently dipping clinoform inflection point displaying limited vertical change (Fig. 2.4). Between these two lines the m5.47 surface has the necessary truncations to establish it as a sequence boundary (figs. 2.5-2.9). All dip lines show erosional terminations and toplap up against m5.47. Erosion is most evident on lines 21 and 529 where an extremely undulating surface abbreviates underlying reflectors (figs. 2.12 and 2.13). By line 17, the irregular, erosional m5.47 surface has been imaged as a more planar, locally discontinuous surface (Fig. 2.11). A beginning of a more sigmoidal clinoformal surface first become evident on line 15 and continues across the southern grid extension (Fig. 2.10). Onlapping surfaces climb this sigmoidal surface and suggest lowstand deposition. Lowstand fans occur seaward of the CIP. Again, onlaps are less clear after cresting the CIP as the reflectors become discontinuous, locally hummocky and are more suggestive of regression than transgression deposition.

The m5.47 sequence is best developed best from dip lines 15 to 11 (figs. 2.8-2.10). Line 13 images the best developed lowstand facies deposit. A small wedge lies along the base of the sigmoidal clinoform (Fig. 2.9). It is overlain by a reflector configuration

suggestive of a fan deposit. These reflectors climb and onlap the m5.47 surface. Limited downlap surfaces are cut farther offshore by a possible second or parasequence lowstand deposits. It displays onlapping against the steeper oblique clinoform and terminates with downlapping seaward. However the reflections are discontinuous, low amplitude and hummocky which limits the interpretation. A flooding surface caps the lowstand and marks the change into a highstand regressive domain. Line 11 to the south reveals a lowstand fan with subtle onlapping features lying on the gently dipping m5.47 surface (Fig. 2.8). A mounded deposit lies outboard that onlaps against the fan and downlaps m5.47 forms a second lowstand fan similar to line 13 (Fig. 2.9). Line 15 portrays slightly different lowstand morphology. A lowstand wedge exists on line 15 as do some thinner lowstand fans farther seaward than line 13 (figs. 2.9 and 2.10). A downlap surface ends these lowstand deposits. No transgressive deposits are evident due to either seismic resolution or erosion and truncations by overlying reflectors. Regressive oblique to sigmoidal reflectors build out across the lowstand units ending at the m5.45 sequence boundary.

Sequence definition in the southern grid is not as clearly defined. Dip line 9 exposes a possible fan deposit outboard of the CIP characterized by generally inclined, discontinuous, low amplitude seismic facies (Fig. 2.7). Moving inboard a sigmoidal, parallel drape facies suggesting possible onlap overlies and climbs the m5.47 boundary. Other fan facies consisting of inclined, sigmoidal to locally mounded facies build farther seawards. The sequence character continues to change southward. Line 5 is too short to image much of the m5.47 sequence, but resembles the more complete exposure of line 3

and 1 (figs. 2.4-2.6). Here, discontinuous, variable amplitude, wavy facies onlaps the lower angle clinoform inflection point. This possible lowstand deposit forms an overall thick blanket deposit that can be somewhat chaotic internally. Limited downlaps and mounded structures suggestive of turbiditic material occur. Clearly defined regressive configurations are not present. Instead, a package of discontinuous surfaces portrays limited oblique to shingled downlaps and cut by the overlying m5.45 boundary. This seismic morphology suggests that line 13 is more proximal to a sediment source.

Little remains of the m5.47 sequence as imaged by northern lines 21, 529, and 17 (figs. 2.11-2.13). Erosional downcutting by the overlying m5.45 reflector has removed most evidence of the sequence on these lines. Only a thin sliver of sedimentary material remains.

m5.45 pink reflector

The m5.45 pink reflector resides between m5.47 and the overlying m5.4 surface. Surface m5.4 has been dated on the slope as approximately 19.5 Ma with an age range of 18.7-19.9 Ma (Miller et al, 1998) making m5.45 slightly older. This candidate sequence boundary was not identified previously due to similar sampling deficiencies as the underlying m5.47, consisting of a lack of sequence defining reflector terminations where crossed by both *Ew9009* and *Oc*270 lines.

Dip lines 15 through 11 most clearly image reflector truncations against a sigmoidal surface indicating m5.45 as a sequence boundary (figs. 2.8-2.10). Elsewhere within the grid, select surface geometries such as onlap against a gently sloping surface add support to this conclusion. Minor onlap is expressed on dip lines 21 and 529 where m5.45 dips gently seaward (figs. 2.12 and 2.13). Little toplap exists on these same lines due to the thin nature of the m5.47 sequence. Onlapping patterns increase in frequency at line 17 where the m5.45 surface locally steepens and begins to develop a more sigmoidal geometry (Fig. 2.11). By line 15 through 11, onlapping terminations clearly climb a steeper sigmoidal m5.45 sequence boundary reflector (figs. 2.8-2.10). Offlap and apparent erosional truncation against the base of surface m5.45 are best imaged on these lines. Line 9 shows a gentler angle of the sigmoidal sequence boundary (Fig. 2.7). Though toplap is evident here, onlap is masked as the m5.45 sequence thins dramatically against the immediately overlying m5.4 reflector. Line 5 only images landward of the m5.45 CIP though limited onlap and more common toplap is still evident (Fig. 2.6). The two southern most dip lines travel farther offshore than line 5 and once again show a similar pattern as depicted on line 9, that of a very gently sloped clinoform inflection point. Onlaps clearly can be seen on lines 3 and 1 (figs. 2.4 and 2.5).

Sequence m5.45 is most clearly developed in the northern *CH0698* grid. However the internal sequence geometry differs from the standard model here because the m5.45 surface dips gently and lacks a classic sigmoidal clinoform inflection point surface. Regressive highstand downlapping surfaces dominate to the north on line 21 (Fig. 2.13). Inboard of crossing line 22, the geometry suggests the possibility of highstand

parasequences but multiples and out of plane reflections could confuse the interpretation. A second interpretation could be related to lobe switching. These features are not evident southward on lines 529 and 17 (figs. 2.11 and 2.12). Limited onlaps occur outboard and suggest a thin lowstand deposit that the regressive body overrides as the sequence builds out across the paleoshelf. Continuing southward across lines 15 through 11, the m5.45 sequence lowstand facies thickens (figs. 2.8-2.10). Lowstand onlap exist as the m5.45 sequence boundary steepened forming a sigmoidal rollover. Transgressive deposits are either absent or below seismic resolution landward of the clinoform inflection point. Only highstand regressive downlap truncations are evident. Seaward the highstand deposits has not developed or been removed as the overlying m5.4 surface directly overlies m5.45 by line 9 (fig. 2.7). Line 9 also shows the landward joining or amalgamation of m5.45 and m5.4. Onlapping is again visible on lines 3 and 1 (figs. 2.4 and 2.5). Hints of regression again become apparent on line 1 but internal reflectors are more common as higher amplitude parallel surfaces.

m5.4 yellow reflector

Candidate sequence boundary m5.4 was first identified and labeled as “sand” on the continental shelf using *Ew9009* data (G.S. Mountain, K.G. Miller and N. Christie-Blick, unpubl. data, 1990 as recorded by Miller and Mountain, 1994). Miller et al. (1996b) estimate a best age of m5.4 as 19-20 Ma with a range of 18.4-20.6 Ma

Sequence characterization is restricted to the northern section of the grid. Line 9 is the southernmost dip profile where m5.4 shows signs of being a potential sequence boundary (Fig. 2.7). At this location, clear onlapping features climb the gentle sigmoidal m5.4 surface. Line 11 is not as clear due to a thin deposit but line 13 again picks up the onlap and downlap termination of suspected lowstand material (figs. 2.8 and 2.9). Similar surface terminations continue through the remaining northern dip lines. Toplap butting up against the m5.4 surface also become evident and supportive of the sequence boundary interpretation.

The m5.4 sequence does not appear as clear cut as most other sequences imaged by the *CH0698* seismic data. Interpretation of lowstand facies both onlapping and downlapping against the proposed m5.4 boundary suggests two younger lowstand parasequences that image erosion due to possible slope failure during low relative sea level. Line 24 images this parasequence interpretation the best (fig. 2.15). Three apparent erosional surfaces that dip southwestward towards line 529 show onlapping terminations representing individual flooding surface. The two younger erosional surfaces amalgamate to a single surface that displays an apparently slope derived erosional canyon. The canyon feature marks a slope failure during low relative sea level. The overlying flooding surface starts the next youngest LST parasequence. Line spacing is insufficient to show if this feature is connect to a “shelf” fluvial channel, though the depth of the canyon feature and lack of corresponding incised channels on surrounding lines suggests not. Therefore, headward erosion from slope failure is the most likely cause of these features. Line 21 shows a small sigmoidal surface related to the oldest lowstand parasequence (Fig. 2.13).

Onlapping surfaces dip gently to the south-southwest. No prograding deposits top these suggested falling stage deposits. Onlapping reflectors transgress up the youngest lowstand wedge on line 529 and 15 and less definitively 17 (figs. 2.10-2.12). A well-defined flooding marked by steeply dipping downlapping reflectors cap the new lowstand facies. The sequence thins dramatically by line 21 (Fig. 2.13).

m5.3 red reflector

The last newly identified reflector is m5.3 red. It lies between m5.4 and m5.2, which places the best age estimate as between 19-20 and 18.2 Ma (Miller et al, 1996b). It was not previously identified on either *Ew9009*, possibly due to lower seismic resolution, or *Oc*270. Southern dip lines from 1 to 5 portray m5.3 as just another reflector without any clearly sequence boundary definition (figs. 2.4-2.6). This exists because either a lack of deposition or, a more realistic possibility that the overall margin had already prograded past the edge of the data. However line 3 does image an incised valley containing probably lowstand facies (Fig. 2.5). Moving northward line 9 (Fig. 2.7) shows the beginning of a gently sloping clinoformal inflection point morphology that continues to develop into a candidate sequence boundary from line 11 through 21 (figs. 2.8-2.13).

Reflector geometries indicative of a sequence boundary occur through a major portion of the *CH0698* seismic grid. Toplap truncations can be observed beginning in the south on lines 5, 9, and possibly 11 (figs. 2.6-2.8). From line 13 through 21, definitive toplap of

both oblique and sigmoidal surfaces (figs. 2-9-2013). Onlapping terminations onto m5.3 exist on the northern dip lines down to line 5 (Fig. 2.6).

The m5.3 sequence is best defined in the north as margin progradation had already advanced outside the southern seismic grid from line 5 through 1 (figs. 2.4-2.6). Thin lowstand deposits onlap and lie subparallel to the gently sigmoidal sequence boundary on dip lines 9 through 13 (figs. 2.7-2.9). As with other sequences transgressive deposit are not imaged clearly. Regressive reflector downlaps build from landward of the CIP across and over the lowstand deposits. The regression thickens and progrades seaward past the underlying m5.4 CIP on lines 9 through 15, commonly as oblique reflectors (figs 2.7-2.10). The overlying m5.2 sequence boundary ends the regressive deposits, because lowstand facies appear to be all that continues into deeper waters. The m5.3 sequence is aggradational across the remaining northern dip lines. Both lowstand and regressive deposits thin, and transgressive units appear below seismic resolution or migrate rapidly landward across the planar shelf.

m5.2 orange reflector

Sequence boundary m5.2 was previously identified and used to plan the New Jersey Sea-level Transect by G.S. Mountain, K.G. Miller and N. Christie-Blick (unpubl. data, 1990 as recorded by Miller and Mountain, 1994). Like boundary m5.4, m5.2 was initially identified on the continental shelf using *Ew9009* seismic data and subsequently resampled by *Oc*270 at a higher resolution. Miller et al. (1996, 1996b) used Sr-isotopic

analysis of ODP Leg 150 cores to estimate m5.2's age as 18.2 Ma with a range of 18.0-18.4 Ma as identified on *Ew9009* data. *Ew9009* interpretations were projected to *Oc*270 data for verification before the *CH0698* data collection.

Selection of surface m5.2 as a potential sequence boundary becomes evident in the northern grid from lines 9 through 21 (figs 2.7-2.13). South of these data sediment progradation has moved out of the *CH0698* grid so that m5.2 appears as any other reflector. Toplap is evident below the m5.2 boundary northward of the underlying m5.3 clinoform inflection point on all the northern dip lines. Onlapping lowstand deposits occur over this same region further categorizing m5.2 as a sequence boundary. This surface also outlines erosional features near the toe of the sigmoidal surface on lines 11, 13 and 529 that suggests possible slope failure during lowstand (figs. 2.8, 2.9 and 2.13).

The m5.2 sequence is most complete on the northern two dip lines. The seismic data from line 11 through 21 amply defines a sequence clinoform inflection point (figs. 2.8-2.13). Lowstand facies are present on all these northern lines as defined by onlapping surface terminations climbing the clinoform inflection point and appear to thicken moving northward. Surfaces do crest the sigmoidal clinoform and continue landward indicating transgressing deposits but these appear to be restricted as surfaces inboard of the clinoform inflection point only suggest a prograding pattern. The m5.2 sequence displays a series of possible parasequences from line 9 north. Two lowstand packages can be seen that lie against the clinoform inflection point. An apparent flooding surface marks a break from onlapping to a second generation of fan deposits that portray both

onlap and downlap. This surface arrangement is clearly evident from line 15 to 529 (figs. 2.10-2.12). A subtle downlap surface overlies the younger parasequence and marks a change into a regressive package. Line 17 does not clearly image prograding deposits outboard of the CIP, but does suggest some slumping, suggested by short, discontinuous, hummocky seismic facies (Fig. 2.11). Continuing northward another parasequence caps the unit. Seaward there are hints of a forced regression deposit, which is equivalent to the falling-stage systems tract of Plint and Nummedal, 2000, Catuneau, (2002) and Coe (2002), and early LST of Posamentier and Allen (1999**)**. This uppermost attached deposit seen only on lines 21 and 529 consists of a small deposit below the clinoform inflection point marked by downlapping surface terminations (figs. 2.12 and 2.13).

m5.0 green reflector

First identified and labeled as "green bice" on the continental shelf using *Ew9009* data (G.S. Mountain, K.G., Miller and N. Christie-Blick, unpubl. data, 1990 as recorded by Miller and Mountain, 1994), surface m5.0 was also defined as a candidate sequence boundary in this study. Miller et al. (1996b) estimated a best age of m5 as ~16.9 Ma, with a range of 16.3-18.0 Ma.

Sequence defining surface terminations remains dominant in the northern grid section. Here onlapping is evident beginning low on the clinoform inflection point toe that climbs and overrides the clinoform inflection point in an inboard direction. Terminations from

beneath m5.0 are more evident from line 15 north (figs. 2.10-2.13). They develop where the underlying sequence is thicker and appear as toplap structures.

DRILL SITE DATA

AMCOR 6011

The US Geological Survey (USGS) drilled the continental shelf offshore Georgia to Massachusetts in 1976 under the auspices of the Atlantic Margin Coring Project (Hathaway et al., 1976). One of the cored sites, AMCOR 6011 lies 6 nautical miles (11 km) off Barnegat Inlet, NJ (fig. 2.2) and was selected to investigate the extent of freshwater aquifers with coastal plain sediments and the regional stratigraphy. *CH0698* seismic grid designed a line crossing over the drill location. All AMCOR 6011 coring data and downhole geophysical logs reported in Hathaway et al. (1976) were measured from Kelly bushing, 9.73 m (32 ft) above sea level and a recorded sea floor at 22.25 m (73 ft). Subsequent analysis recalculated sea floor to 0 m (0 ft). AMCOR 6011 had a total penetration of 260 m (850 ft) and bottomed out in Eocene sediments. Limited grain size and sedimentary facies analysis was performed on the AMCOR 6011 cores (Hathaway et al., 1976, Poppe, 1981). The data paucity resulted from extremely poor core recovery averaging only 23% (Hathaway et al., 1976) (fig. 2.16). Hathaway et al. (1976) and Ferrebee (1981a, 1981b) described the core and performed grain size analysis

(fig. 2.16). Geophysical well logs supply the best continuous data through the cored intervals as described below.

Poor core recovery of Miocene sediments inhibited age correlation. Abbott (1978) defined four Miocene age zones using diatom and silicoflagellate fossil assemblages from various onshore and offshore sites including AMCOR 6011. Andrews (1988) revised the Siliceous Microfossil Zones (Abbott, 1978) into the East Coast Diatom Zones (ECDZ), such that zone I of Abbott (1978) is ECDZ 1, zone II and III of Abbott (1978) equates to ECDZ 2 and zone IV of Abbott (1978) correlates to ECDZ 3 to 5 of Andrews (1988). Using these revised zonations on fossil assemblages of Abbott (1978) AMCOR 6011 contains ECDZ 1 correlating to Kw1 (Sugarman et al., 1993) between 122.7 and 127.7 m (402.5-419 ft), ECDZ 2 correlating to Kw2 (Sugarman et al., 1993) between 80.8 and 122.7 m (265-402.5 ft) and ECDZ 3-5 correlating to Kw3 (Sugarman et al., 1993) from 66.3 and 80.8 m (217.5-265 ft) (fig. 2.16). All these ECDZ assemblages correspond to early through middle Miocene ages.

More recent detailed sample analysis of AMCOR 6011 has elucidated the Oligocene-aged sedimentation and sequence stratigraphy. However this study was again restricted by poor core recovery (5-10%) spanning the Miocene-Oligocene boundary. Pekar (1999) and Pekar et al. (2000) performed limited sedimentary facies as well as biofacies and Sr-isotopic chemostratigraphic analysis on lowest most Miocene and Oligocene-aged strata. Uppermost Oligocene sediment recovered in AMCOR 6011 continues the same lithologic characteristics recovered in drill holes on the New Jersey margin. Abundant glauconite

both primary and as reworked detrital grains characterizes these deposits. With limited core recovery, Pekar (1999) was able to piece together an upper Oligocene sequence beginning in clayey glauconite sand that grades upwards into coarse quartz sand. This coarsening upwards indicating initial sea level deepening during clayey glauconite sand deposition followed by shallowing marine conditions and regression producing quartz sand deposits. Benthic foraminiferal assemblages collaborated the changing relative sea-level conditions (Pekar, 1999). Lying atop an uppermost Oligocene sequence boundary is lower Miocene fine- to medium-grained glauconitic quartz sand containing benthic foraminiferal assemblages that indicate deepening relative sea level (Pekar et al., 2003). Pekar (1999) correlated a positive gamma ray kick associated with the sequence stratigraphic boundary. Pekar et al. (2000) placed the sequence boundary at 212.4 m (697 ft). Sr-isotopic chemostratigraphic analysis of AMCOR 6011 sediments identifies the sequence boundary as the Oligocene/Miocene boundary. Kominz and Pekar (2001) and Pekar et al. (2003) discussed their dating techniques and suggested an increased age precision to $\pm$0.1 m.y. over the $\pm$ 0.6 m.y. for late Oligocene Sr-isotopic age regression (Reilly, 1996). Sr-isotopic chemostratigraphic results bracket the sequence boundary with age dates of 27.0 Ma at 222 m (728.4 ft) and 19.1-19.7 Ma at 212 m (695.6 ft) (Pekar, 1999).

USGS sampled AMCOR 6011 with geophysical borehole logs including gamma, SP, caliper, single point resistivity, and short and long normal resistivity (fig. 2.16). A sonic log was also attempted but the tool apparently lacked a good contact with the borehole wall making the data unusable (Nancy K Soderberg, written communication). Paper

downhole geophysical logs obtained from C. Wylie Poag (USGS), were scanned and digitized. The resulting curves were rectified to match the original logs. The SP and resistivity logs did not follow a predicted pattern when assuming formation fluid salinity higher than borehole fluid. A negative spontaneous potential marks sand bodies in the standard oilfield boreholes (Keys, 1989) and corresponds with elevated normal resistivity values. However in AMCOR 6011, positive SP values correlate to high normal resistivity returns. Keys (1989) and Rider (1996) indicated that SP reversals, that is, a positive response in sand layers occur when the borehole mud filtrate is more saline than the formation's natural interstitial water. Hathaway et al. (1976) and Booth (1981) stated that borehole salinity varied from 28.9 to 29.6‰ down to 52 m (170.6 ft) where salinity decreased to 1.5 to 2.2 ‰ from 79 to 196 m (259.2 to 643 ft) depth suggesting an influx of less saline formation water. Therefore the SP log interpretation must account for the more saline borehole fluid and a positive response correlating to sand horizons (fig. 2.16).

The AMCOR 6011 gamma log portrays several cycles beginning at the Oligocene-Miocene boundary identified by Pekar (1999) and Pekar et al. (2000). These data mimic those discussed by Sugarman et al. (1993) for coarsening upwards Miocene-aged deltaic sequences (fig. 2.14). Gamma cyclicity begins with a characteristic positive gamma kick that either maintains or gradually increases up section before it changes slope and begins to decline. This gamma slope change can be either gradual or rapid (Sugarman et al., 1993, Miller et al., 1998, Sugarman, 2001). Basal sediment can vary from a lag and overlying clayey sand, possibly glauconitic to clay silt. The top of the silt to clayey sand marks the maximum relative sea level for the cycle before they grade upwards into silty

clay to clayey silt of a prodelta paleoenvironment. The MFS correlates to the slope change from positive to negative in gamma (fig. 2.14). Continuing upsection coarser-grained silts to sands and finally into quartz sands record shallower relative sea level and a change into delta front and possibly delta plain paleoenvironments (fig. 2.14).

Electric logs from AMCOR6011 indicate the presence or absence of sand rich beds and substantiate interpretations based on gamma log values (fig. 2.16). SP and both short and long normal resistivity logs suggest a similar cyclicity along the same depth intervals as the gamma log (fig. 2.16). Two different patterns are discernable. One pattern indicates a basal sand-rich unit at 213 to 208 m, (699-682 ft) and 177 to 169 m (580.7-554.5 ft) (fig. 2.16, beginning at a gamma kick that grades upwards into finer material at 208 to 203 m (682.4-666 ft), and 169 to 162 m (554.5-531.5 ft). The gamma log shows a negative slope trend that displays a saw tooth pattern suggesting a sand-rich horizon with lesser interbedded clay. The MFS separates the basal sand from the finer material above in the cycle similar to the prodelta sediments following patterns outlined by Sugarman et al. (1993) and Miller et al. (1998). The basal sands represent deposition during the initial transgression. A period of nondeposition could have occurred as relative sea level continued to rise. A sharp decrease in resistivity and spontaneous potential values marks the MFS (fig. 2.16). Gamma curve either shows a sharp increase followed by gradual reduction in value or a single negative sloping trend. Thick sand-rich sediments cap the sequence 203 to 189 m (666-620.1 ft) and 162 to 156 m (531.5-511.8 ft). Positive fluctuations in both SP and normal resistivity curves agree with the gamma curve and indicate the sand-rich horizons. Gamma curves present an overall negative sloped trend

with a finer developed saw toothed pattern. Log response and increasing sediment grain size is suggestive of delta front sediments, commonly found in Miocene-aged New Jersey coastal plain sequences. Limited grain size descriptions from Hathaway et al. (1976) and Ferrebee (1981a, 1981b) are not sufficient to either support or refute this interpretation.

A sand-rich horizon also caps the second pattern but the coarser-grained sediments are missing at the base (fig. 2.16). This cycle again begins at a boundary outlined by a positive gamma kick that here is apparently overlain by finer material, possible silt and clay at 194 to 190 m (636.5-623.4 ft), and 156 to 151 m (531.5-495.4 ft) as opposed to the coarser grained material outlined above (fig. 2.16). This could indicate a condensed section with only very limited transgressive deposition. The geophysical signature mimics the material overlying the interpreted MFS noted in the first pattern described above. Here, the pattern correlates to a different gamma log response. The gamma curve portrays a short interval of a gradual positive slope before switching to a negative slope interpreted to represent an overall coarsening grain size. The change from an apparent positive to negative slope was selected as the MFS in the second geophysical cycle type. SP and resistivity logs again suggest a sand-rich horizon capping the cycle (fig. 2.16). A generally positive sloped saw toothed shape gamma log supports the coarse-grained horizon interpretation of the other logs. Again, limited grain size descriptions from Hathaway et al. (1976) and Ferrebee (1981a, 1981b) lend limited support to the above interpretation.

All the geophysical logs are muted between 137 and 99 m (449.4-324.8 ft), which allow several different interpretations (fig. 2.16). Gamma logs present a typical saw-toothed shape with a slight negative slope that appears to steepen at just below the next interpreted sequence boundary at 99 m (324.8 ft). SP data suggest a gentle positive slope up to 115 m before reversing to a negative slope that ends in a suggestion of coarser grained material (fig. 2.16). Both normal resistivity logs show little variation with an almost vertical trend before ending with an indication of coarser material between 104 and 97 m (341.2 and 318.2 ft), similar to the SP results. Hathaway et al. (1976) describe the grain size within this interval as “silt, micaceous sandy “ and “silt, sandy” while Ferrebee (1981a, 1981b) shows silt content to range from 41-78% and clay fraction accounting for approximately 21% (fig. 2.16). A tentative MFS has been interpreted at 117 m (383.9 ft) where the SP curve slope changes slightly from flat positive to flat negative. The MFS could be as high as 108 m (354.3 ft) as limited sediment descriptions show high clay and silt percentages to this depth. Above 108 m all the borehole logs suggest an increasing grain size distribution. No other material was recovered within this coarser interval (Ferrebee, 1981a, 1981b).

A second interpretation involves a possible sequence boundary at 114.5 m (375.7 ft) depth (fig. 2.16). This interpretation is based on minor inflections in the different logs. SP and normal resistivity all portray a slight coarsening-upward grain size change from 117 to 114.5 m (363.9-375.7 ft). This is followed by a grain size decrease above 114.5 m (375.7 ft). Gamma data lend some support to this interpretation. Across this same interval, 117-114.5 m (363.9-375.7 ft), gamma log values show a change in general slope

suggesting an overall grain size increase. The limited lithologic data indicates a consistent silt dominated grain size across this interval (Hathaway et al., 1976; Ferrebee, 1981a, 1981b). However the interpretation of a sequence boundary at 114.5 m (375.7 ft) and MFS at both 117 m (383.9 ft) and 108 m (354.3 ft) seems the most likely and is adopted here.

The last candidate sequence occurs between 99 and 72 m (324.8 and 236.2 ft) depth. Both gamma and SP indicate finer grained material marks the lower sediments in this sequence (fig. 2.16). These logs agree with sediment descriptions of Hathaway et al. (1976) who described sand at 99 m (324.8 ft) that fines upwards into sandy clay. The basal grain size distribution of Ferrebee (1981a, 1981b) shows gravel and sand comprising 42% with an equal percentage of silt; the remainder composed of clay. The next higher sample at 92 m (301.8 ft) establishes a finer grain size distribution where clay and silt consist of greater than 99% of the material. Log results suggest an increasing grain size across the depth interval between 84 to 81 m (275.6-265.7 ft). SP log values mark the deepest beginning of this coarsening upwards phase at 84 m (275.6 ft) while resistivity shows a deflection around 83 to 82 m (272.3 to 269 ft), which is just deeper than the gamma curve move between 82-81 m (269-265.7 ft). The MFS placement between 83 and 82 m (272.3 and 269 ft) marks the grain size change. The closest sediment size distribution sample of Ferrebee (1981a, 1981b) between 81-80 m (265.7-262.5 ft) describes the sediment as greater than 95% sand. Log signatures portray a continuation of the sand-sized material up to the selected sequence boundary at 72 m (236.2 ft). There, a major sedimentological change occurs as marked by a gamma kick a

decreased grain size distribution at 71 m (232.9 ft; Ferrebee, 1981a, 1981b). The SP and normal resistivity logs flatten out above 71 m (232.9 ft) and no longer yield useable data.

ODP Leg 150X Island Beach

A continuously cored borehole was drilled in 1993 at Island Beach State Park, (fig. 2.2) (Miller et al., 1994). It was the initial corehole of the New Jersey Coastal Plain Drilling Project (hereafter NJCPDP) and anchored the land-based section of the New Jersey Sea-Level Transect (hereafter NJSLT; Miller, 1994). NJCPDP consists of onshore Ocean Drilling Program legs 150X and 174AX. The borehole location captures the updip Miocene through Paleocene and into Upper Cretaceous sediments. It lies 12 nautical miles from a shore perpendicular offshore multi-channel seismic line collected on *Ew9009* that sampled across the continental shelf and over the shelf-slope break (Miller and Mountain, 1994). The *Ew9009* grid ties in ODP Leg 150 boreholes, drilled across the New Jersey continental slope and rise with proposed drill sites across the continental shelf. The Island Beach site (hereafter IB) is the closest ODP Leg 150X borehole to the *Ew9009* data. *Oc*270, similar resolution as *CH0698*, resampled the *Ew9009* cross shelf seismic line and tied in ODP Leg 174A boreholes located on the outer continental shelf and slope.

The Leg 150X IB borehole lies close to an older generation water well also designated as Island Beach (hereafter OIB) that was rotary drilled into metamorphic basement material in the early 1960's by the New Jersey Department of Conservation and Economic Development (Gill et al., 1963). They collected a suite of downhole geophysical logs including gamma, sonic, and normal resistivity that allow correlation to the IB site (fig. 2.17). The older well has subsequently been used in regional ground water studies (Gill et al., 1963; Clark and Paulachok, 1989; Mullikin, 1990; Barton et al., 1993; and McAuley et al., 2001).

ODP Leg 150X IB bottomed out at 372.8 m and recorded a mean core recovery of 86.7% (Miller et al., 1994). Detailed litho and biostratigraphic analysis of the core supported by limited strontium-isotopic stratigraphy allowed characterization of the Miocene sequence stratigraphy (Miller et al., 1994; Sugarman et al., 1997; Sugarman and Miller, 1997; Owens et al., 1997). The oldest Miocene sequence, correlates to Kw1a (Brigantine Member of the Kirkwood Formation) through six Sr-isotopic dates (Miller et al., 1997; Sugarman et al., 1997; Pekar, 1999). Its exact boundaries are in question as researchers chose different basal contacts (fig. 2.17; Owens et al., 1997; Miller et al., 1997). Owens et al. (1997) indicated a reworked zone of glauconite sand beginning at 154.8 m (507.9 ft) that marks the Oligocene/Miocene boundary and the basal boundary of the Kw1a sequence. Miller et al. (1997) selected the top of this sand zone at 154.1 m (505.5 ft) as the basal boundary. Limited controversy also exists on its upper bounding surface. Owens et al. (1997) suggested hard sandy clay at 92.4 m (303.1 ft) separated by an overlying massive, bioturbated fine- to medium-grained micaceous quartz sand identifies

the upper sequence boundary. Miller et al. (1997) placed the upper contact at 85 m (278.9 ft) with fine sand below and clay and fine sand alterations above that accompanies a corresponding gamma increase. The absence of either biostratigraphic or Sr-isotopic age data sheds no light on these differences. Miller et al. (1997) suggested that a MFS occurs at 144.8 m (475 ft) based on benthic foraminiferal data and lithofacies interpretation. Gamma log portrays a cyclicity of a positive kick followed by decreasing values. Miller et al. (1997) interpreted the cyclicity, which repeats 4 times as coarsening-upwards successions representing either fluvial successions or parasequences.

The second sequence correlates to Kw1b (Shiloh Marl of the Kirkwood Formation). Miller et al. (1997) suggested that the lithic change at 85 m (278.9 ft), besides being a possible sequence boundary, could also represent a MFS that separates inner neritic from prodelta sedimentary facies. Overlying clay-silt material containing diatoms and woody fragments represents fluvial lithofacies and further HST sediment progradation. Three decreasing upsection gamma cycles, similar to those in Kw1a, within the fluvial sediments are interpreted as coarsening-upwards parasequences. Both Miller et al. (1997) and Owens et al. (1997) used lithofacies analysis and selected the same upper boundary at 55.5 m (182 ft).

The youngest Miocene-aged sequence identified in IB contains East Coast Diatom Zone 2 and correlates to Kw2a, which is the Wildwood Member of the Kirkwood Formation (Miller et al., 1997). Miller et al. (1997) placed a MFS at 48.2 m (158 ft) that separates sandy silt and clayey fine quartz sand interpreted as nearshore or inner neritic lithofacies

from overlying silty clay and fine sands representing prodelta facies and sands of delta front affinity. The sequence ends at 23.8 m (78 ft) and overlain by Pleistocene-aged Cape May Formation.

Borehole geophysical data does not add much to the lithologic, biostratigraphic, and Sr-isotopic characterization of the IB borehole (fig. 2.17). Log data was collected after casing installation. The casing, down to 139.3 m (457 ft) limited density, resistivity and sonic logging tools usability. Only gamma and SP are useable through the casing. The gamma log does not portray the characteristic Miocene sequence signature as outlined by Sugarman and Miller (1997). The limited geophysical logs collected in the OIB borehole are more useful as casing was set at 42.8 m (140.4 ft). Gamma logs from both IB and OIB boreholes were matched to account for elevation differences between the two wells (fig. 2.17). Even with the additional borehole log data, only limited further interpretation is possible. IB gamma, SP and laterolog (resistivity) combined with gamma and normal resistivity from OIB maps out a candidate sequence boundary at 144.2 m. Gamma logs display a negative kick at the lithologic and Sr-isotopic boundary identified at 154.8 or 154.1 (see above discussion for boundary location) and increasing values up to 148.7 m, a possible MFS. SP shows a positive slope while resistivity, both normal and lateral logs show an initial negative slope that rotates into a vertical slope (fig. 2.17). Continuing upwards above 148.7 m resistivity has a positive increase, which coincides with a negative kick on SP. Both changes suggest increased sediment grain size upwards as also shown by the negative slope on the gamma curves. The geophysical data agrees with the lithologic description of Miller et al. (1994, 1997). I suggest that this lowest sequence

correlates to Kw0. Sr-isotopic age estimates of this sequence range from 21.4 to 22.2 Ma, which correlate to Kw0 as outlined by Sugarman et al. (1997).

ODP Leg 150X Atlantic City

A second borehole of ODP Leg 150X was drilled in 1993 at the Atlantic City Coast Guard Station (fig. 2.2, hereafter AC) (Miller et al., 1994). Target horizons ranged from middle Miocene through Eocene, all sampled within the 443 m penetration. Total recovery over the length of the core was 67%, less than at IB. Recovery across the 166 m of Miocene-aged Kirkwood Formation (113-279 m), using the upper contact as defined by de Verteuil (1997), into Oligocene-aged sediment was higher at 75.8% (Miller et al., 1994) (fig. 2.18). An abundance of shelly material allowed a detailed Sr-isotopic age chronology that greatly aided in regional sequence correlation (Sugarman et al., 1997; Miller et al., 1997).

Difficulty with the drill string limited borehole geophysical data collection to only gamma and neutron porosity, logged entirely through the drill pipe. The present study investigated the New Jersey borehole geophysical database in effort to supplement the borehole geophysical data in AC. A water well drilled by the Atlantic City Municipal Utilities Authority (hereafter ACMUA) (New Jersey State Permit 36-26186) in October

2002 proved sufficiently close to correlate to AC through similar gamma log patterns (fig. 2.18). This allows a better correlation with several offshore wells that contain a more complete geophysical log suite but limited lithologic information. Select sequences can be seen to thin or thicken between the two Atlantic City wells (fig. 2.18).

ACMUA was rotary drilled and geophysically logged for gamma, SP, and single point resistance (fig. 2.18). An onsite geotechnical consultant described the cuttings. Gamma log data for ACMUA was collected every 0.1 ft., which created an extremely data intensive, jagged graph when plotted on the reduced figure size. Therefore, the data were smoothed by calculating a 5-point running average in which the smoothed point occurs in the middle of the 0.5 ft averaged interval (fig. 2.18). SP and single point resistance curves did not require this extra step due to their original smooth curve shape and larger sampling intervals.

Miller et al. (1994, 1997) described six different Kirkwood sequences using lithofacies, biostratigraphic, Sr-isotopic and gamma log data within the AC borehole (fig. 2.18). Of these, ACMUA sampled the youngest four completely and bottomed out in the top of the second oldest. The oldest Miocene-aged sequence (not reached in ACMUA) Kw0, occurs as a thin, 7 m thick sequence in AC. Miller et al. (1997) described basal glauconitic sand containing benthic foraminifers indicating inner to middle neritic paleowater depths. Drilling only recovered 4.1% of the upper 3.7 m of the sequence making any lithologic call questionable so Miller et al. (1997) classified the entire interval as representing a transgressive phase suggesting a fining upwards lithology.

Borehole geophysical data seems to support this interpretation (fig. 2.18). No well-defined gamma kick marks the sequence base as commonly seen on the New Jersey margin. Instead a high gamma value interval, probably correlating to the glauconite content in the upper Oligocene traverses the contact into the Kw0. Gamma values decrease upwards through Kw0 to its upper sequence boundary. These gamma values agree with the clay beds within the overlying Kw1a sequence. Neutron data also suggest a clay rich interval for the upper section of Kw0 within the AC borehole. Sr-isotopic age control dates the sequence at 23.8 to 22.2 Ma (Sugarman et al., 1997: Miller et al., 1994, 1997).

The next oldest sequence, Kw1a, was completely sampled and yielded a Sr-isotopic age estimate at 21.7-20.1 Ma in AC (Sugarman et al., 1997: Miller et al., 1994, 1997), but was only partly recovered in ACMUA (fig. 2.18). Geophysically, this represents the more characteristic New Jersey Miocene sequence. Though lacking an initial gamma kick, the log portrays elevated counts correlated to the lower clay rich horizons of the TST and lower HST (hereafter lHST; Miller et al. 1994, 1997). Values decrease corresponding to the upper sand rich layers of the upper HST (hereafter uHST; Miller et al. 1994, 1997). The neutron log mimics this same trend (fig. 2.18). Miller et al. (1997) placed the division between the lHST and uHST at 246.9 m, which is higher than suggested on the geophysical logs. Solely using gamma and neutron the lithic change appears approximately 3 m lower in the hole. However, this does not match the cored sediments across the same interval. ACMUA amply mirrors the increasing grain size of the upper section of KW1a with SP and resistivity logs. The SP log response in

ACMUA, a consistent positive correlation with resistivity suggests less saline formation fluid and more saline borehole fluid (fig. 2.18). This would account for the opposite correlation between the two logs. However salinities were not recorded. Resistivity and SP appear to mark the grain size transition from finer to coarser grained within Kw1a better than the neutron log.

Miller et al. (1994, 1997) characterized the Kw1b sequence as containing two parasequences according to lithologic and log response data (fig. 2.18). ACMUA logs mimic the same change as seen in AC. All the logs portray the parasequences as thin sediment packages; that is, they have a basal gamma kick, which corresponds to an apparent grain size decrease (fig. 2.18). Neutron, SP, and resistivity logs from ACMUA portray a fine-grained unit above both the basal sequence boundary and the flooding surface marking the upper parasequence. The log curves all grade upwards and indicate coarsening upwards sediment grain size. Thus a similar expression occurs for both the sequence boundary and the flooding surfaces. The two parasequences recovered in AC are approximately equal thickness while the lower parasequences in ACMUA is quite a bit thinner than the upper one (fig. 2.18). The upper ACMUA parasequence as identified in the borehole logs suggests a thin, finer grained unit, either silt or clay dominated, that divides the coarser grained unit into a lower and upper sand horizon. This division is not clear on the AC data. Four AC Sr-isotopic age dates range from 20.2 to 20.0 Ma for sequence Kw1b in AC.

The thickest lower Miocene sequence in AC and ACMUA lies above the Kw1b. Borehole logs correlate well and outline the lithic changes identified by Miller et al. (1994, 1997) for this Kw2a sequence. As with most Miocene sequences, a positive gamma kick marks its basal boundary (fig. 2.18). Gamma from both wells as well as AC neutron portray either a slight negative increase upsection or a vertical slope (suggesting no grain size variability) through this clay dominated interval recovered in core. SP and resistivity show an opposite increase through this same horizon before presenting an increase indicating a coarser grained interval. Gamma logs supply a similar indication of increasing grain size. Core recovery was limited through this interval but recovered sediments include a fine sand bed containing shells overlain by a few thin clay horizons within a poor recovery interval that is capped by a coarse sand layer. SP, resistivity, and neutron logs image one or two thin clay rich horizons within an overall coarser grained dominated sedimentary package (fig. 2.18). The Kw2a sequence at AC contains a thin TST bounded by a MFS interpreted within the increasingly negative gamma log trend just below the long, uniform vertically sloped interval. Nine Sr-isotopic age dates place the Kw2a sequence at AC between 16.6 and 17.8 Ma. A single date of 19.9 Ma just below the lower sequence boundary was probably burrowed up from the underlying Kw1b sequence (Miller et al., 1994b). Likewise a 16.0 Ma age date just below the upper sequence boundary was mixed from overlying sediments.

The younger Kw2b sequence lies above the Kw2a sequence at AC. A gamma kick is evident at the Kw2b basal sequence boundary (fig. 2.18). Miller et al. (1994, 1997) described a fining upwards sequence that changes from basal clayey silt to silty clay that

resides above a possible MFS. The sequence ends in a clay horizon. Miller et al. (1997) suggested a truncation of the sequence due to the absence of a characteristic HST sand horizon. Therefore the entire cored interval might just represent the TST, but they outline a possible MFS and limited HST interval. All the logs from both wells show little variation in signature throughout this thin, 13 m sequence (fig. 2.18). ACMUA SP, resistivity, neutron, and AC gamma logs show a minor inflection reflecting a coarsening-upwards trend in the uppermost 2 meters below the upper sequence boundary. However this grain sized material was not recovered in the core. Four Sr-isotopic age dates bracket the Kw2b sequence from 15.5 to 16.0 Ma.

ACOW-1

The U.S Geological Survey commenced an investigation in 1984 to study the extension of onshore, deep fresh-water aquifers out into the marine environment offshore Atlantic City, New Jersey. They drilled two wells in the Atlantic City Offshore Wells program, ACOW-1 and ACOW-2 (discussed below), 3.1 km (1.9 mi) and 9.35 km (5.8 mi) offshore respectively (fig. 2.2). ACOW 1 was drilled in July 1985 by Warren George, Inc., Jersey City, NJ in water 9.75 m (32 ft) deep using a jack-up barge. The borehole was drilled using a rotary bit and only collected three split spoon cores and eight pitcher-type cores. Geophysical logs were recorded using the drill deck as datum 17.98 m (59 ft) above sea floor. Mullikin (1990) recorded lithologic descriptions as measured from sea floor. A data report was not published but subsequent aquifer studies by Clark and

Paulachok (1989), Barton et al. (1993), and McAuley et al. (2001) used borehole data. The current analysis recalculated log depths to sea floor as 0 m (0 ft).

Lithologic descriptions are limited and recorded in Mullikin (1990). Average grain size, subordinate accessory mineralogy, color, and presence of paleontological material were recorded for 3.1 m (10 ft) intervals from drill cuttings. Several intervals have no recorded lithologic characteristics. No record was encountered of core descriptions or the current location of core material. Mullikin (1990) supplied the lithologic data used in fig. 2.19. Clay dominates the lower and middle Miocene stratigraphic interval from bottom of the borehole to 95 m. Though clay dominates, the subordinate grain size varies from silty and sandy clay up to clayey silt. Less frequent clayey through silty sand into sand occurs between 165 - 170 m and between 245 - 260 m (fig. 2.19) (Mullikin, 1990).

Age designations are also limited for ACOW-1 to only two Sr-isotopic age dates. Sugarman et al. (1993) calculated two Sr-isotopic ages of 13.1 and 13.3 Ma at 114 and 129 m, respectively, from core material and the drill shoe, which give accurate depth delineation. These two ages correlate with Kw3 sequence of Sugarman et al. (1993). Select grab samples that contain shell material were analyzed but they appear to be mixed material due to the nature of the rotary drilling method. They are inconsistent and not used for age discrimination.

Downhole geophysical logs include gamma, neutron porosity, resistivity single point, short and long normal resistivity, SP, fluid resistivity, gamma-gamma and temperature

(fig. 2.19). Data were recorded as analog paper copies that required digitizing. Several logs portrayed insufficient variability to be used in interpretation. These logs included SP, plotted with too coarse a scale, and single point resistivity. Several studies (Owens and other, 1998; McAuley et al., 2001; Sugarman, 2001) used gamma logs to correlate ACOW-1 into the AC borehole, part of ODP Leg 150X (Miller et al., 1994). McAuley et al. (2001) and Sugarman (2001) also interpreted the gamma logs into aquifer units as defined by Zapecza (1989). Sugarman (2001) correlated several aquifer units directly to sequences as defined by Miller et al. (1998). Sequence definition on the gamma log starts with a basal positive kick that gradually decreases upsection that mimics the general trends described by Sugarman et al. (1993) (fig. 2.14).

Sequence definition used gamma log correlation to the Atlantic City borehole (fig. 2.19) as well as comparison to previous interpretations of Owens and other (1998), McAuley et al. (2001), and Sugarman (2001). Other borehole logs were compared to either AC or the ACMUA water well depending on the log. The Kw1a sequence forms the oldest sequence encountered in ACOW-1. Only a gamma log sampled this sequence and the log profile mimics the AC log. ACOW-1 log sampling stopped near the base of the sequence and did not delineate whether the basal unit sampled is the basal sequence boundary or the MFS as seen in AC. Gamma log values suggest a finer grained lower section corresponding to the lHST, which grades upwards into the coarser grained unit of the uHST at approximately 280 m. Resistivity, which only sampled the upper section of the sequence, also suggests a coarser grained unit. Drill cuttings showing a lower clay zone overlain by silty sand to sand collaborate the log interpretation. Two intervals of 6

and 9 m within that depth have no lithologic description. A positive gamma kick and resistivity change marks the upper sequence boundary at 255.2 m.

The Kw1b sequence from 255.2-229.3 m occurs next and portrays parasequences similar to those encountered in AC (Miller et al., 1994, 1998). Both gamma and resistivity suggest a lower fine-grained unit that grades into a coarser-grained unit lay above the sequence boundary (fig. 2.19). Parasequence boundaries occur at 246.5 and 239.5 m. Logs suggest a thicker finer grained section and thinner coarser grained sediment within the lower parasequence. Lithologic data portrays this parasequence as clayey silt. The upper parasequence of silty clay displays a very thin, fine unit dominated by thick coarser sediment defined by gamma as opposed to equal thickness of fine and coarse units as defined by resistivity. Again, as in AC and ACMUA the pattern of the parasequences mimics the lower sequence boundary layers. The upper sequence boundary rests at 229.3 m.

A thick Kw2a sequence occurs next atop Kw1b from 229.3-181 m (fig. 2.19). The Kw2a sequence at ACOW-1 mimics the AC and ACMUA log response. ACOW-1 borehole contains a thin TST with two possible MFS surfaces. Logs and lithic description do not clearly define the MFS surface. A surface at 225.5 m was chosen based on a break in the resistivity and slight change on the gamma log. Above this surface, logs show a rather consistent lithologic expression continuing upwards to approximately 190 m, which agrees with the lithologic description of silty clay. A thin coarser unit described as silty sand and sand that mirrors the gamma and resistivity logs tops the sequence at 181 m.

Neutron log also shows a slight increase suggesting higher porosity due to coarser grain size (fig. 2.19).

The Kw2b sequence proves to be the least defined sequence by logging criteria in this borehole, similar to AC and ACMUA. Gamma shows a slight basal kick that slowly decreases upsection to a smaller kick at 168 m that defines the sequence. Neutron log signature is fairly flat while resistivity continues to decrease from the underlying Kw2a until it begins to flatten out at 178.5 m and maintains a uniform value through the upper section of the sequence (fig. 2.19). Above 178.5 m the resistivity log loses detail, which could be caused by borehole fluid salinity equal to formation salinity. Lithology varies only slightly from clay above the basal boundary up to 173.8 m. The overlying unit coarsens only up to silty clay.

The youngest sequence for this study is the Kw3 sequence. Overall, gamma log character of Kw3 at ACOW-1 parallels that of AC and AMUA but expresses a thicker, more uniform upper coarse section (fig. 2.19). AC and ACMUA express three gamma cycles of upwards increasing values followed by decreasing values. ACOW-1 only delineates two such cycles with the lower switch from increasing to decreasing values marking the MFS. The lower cycle is subordinate to the upper and within the upper cycle, the decreasing values, suggesting coarser lithologies dominates over the increasing gamma values, indicating clay rich layers. ACOW-1 lithologic data parallels the overall AC lithologic character, that of clay rich lower section that changes into a coarser layer. ACOW-1 ends in a fine layer while AC has no recovery in the interval. Sugarman et al.

(1993) listed two Sr-isotopic dates for this sequence, 13.3 and 13.1 Ma at 147 and 135 m, respectively. A slight positive kick marks the upper sequence boundary, as opposed to the strong positive kick at the AC well (fig. 2.19).

ACOW-2

The second well drilled in the US Geological Survey Atlantic City Offshore Wells program, ACOW-2 spudded in 9.35 km (5.8 mi) offshore, farther offshore and downdip from ACOW-1 (fig. 2.2). Drilling on a jack-up barge occurred in 13.1 m (43 ft) deep water in September 1985 by Warren George, Inc., Jersey City, NJ. Like ACOW-1, this borehole was drilled using a rotary bit with seven pitcher-type cores collected. Geophysical logs were recorded using the drill deck as datum 21.34 m (70 ft) above sea floor. Mullikin (1990) recorded lithologic descriptions as measured from sea floor. The current analysis recalculated sea floor to 0 m (0 ft) on all log data.

Similar lithologic descriptions and parameters recorded for ACOW-1 are also described for ACOW-2 (Mullikin, 1990). Overall, the ACOW-2 hole recovered coarser material but in a similar lithologic pattern as the more landward ACOW-1. Clayey silt through sand dominates the lower and middle Miocene stratigraphic interval from bottom of the borehole to 202 m (662.7 ft). Above this, clay to silty clay continues up to 146 m (479 ft; Fig. 2.19) (Mullikin, 1990). Younger material not studied here coarsens dramatically from 146 m to the borehole top and ranges from sand to gravel with occasional silt interbeds and corresponds to middle Miocene to Holocene.

Limited age data for ACOW-2 aids in delineating sequences. No consistent Sr-isotopic age data exist due to sample mixing, commonly observed in uncased rotary cuttings. Owens (unpublished data) recorded five paleontological ages; two horizons at 241 and 247 m (790.7 and 810.4 ft respectively) contain samples representing ECDZ 2 while the remaining three samples at 201, 187 and 174 m (659.4, 613.5 and 570.9 ft respectively) are ECDZ 6(?) using correlations of Andrews, (1978, 1987, 1988). These samples probably come from pitcher-type cores or the drill shoe similar to the Sr-isotopic dating of Sugarman et al. (1993) on ACOW-1 because they are the only depth controlled samples from an otherwise rotary drilled borehole. These two age zones, ECDZ 2 and 6 correlate with sequences Kw2 and Kw3 respectively.

The basal sequence above the 332 m (189.2 ft) total depth encountered during drilling correlates to the uHST of Kw1a of AC. Both gamma and resistivity suggest a coarser grained unit upwards to the upper sequence boundary at 303 m (994.1 ft) marked by a positive gamma kick (fig. 2.19). Mullikin (1990) did not describe lithologic samples corresponding to this depth, but lists his deepest unit, clay, between 304.8 and 306.3 m (1000 and 1005 ft respectively).

The Kw1b sequence of Miller et al. (1995) occurs at 299-276.5 m. Here, as to the west of ACOW1, the sequence can be subdivided. Gamma, neutron, and resistivity logs (fig. 2.19) portray a thin coarsening upwards layer that tops out at 299 m (981 ft). A similar overlying coarsening upwards unit continues to 294 m (964.6 ft). Mullikin (1990)

characterized the lower unit as clay and the overlying unit as clay changing upwards into silt. These two sediment packages correlate to the parasequences bounded by flooding surfaces observed in AC (Miller et al., 1994, 1997), ACMUA and ACOW-1 (fig. 2.19). The upper part of Kw1b coarsens upward from silty sand into sand. Geophysical logs indicate a slowly coarsening upwards package before reaching the thin, coarsest unit marking the sequence top. The upper boundary lies at 276.5 m (907.2 ft) and correlates to a positive gamma kick, again following the sequence model of Sugarman et al. (1993) (fig. 2.14).

The thickest sequence encountered in the well lies above sequence Kw1b and correlates to sequence Kw2a in the AC well. Owens (unpublished data) dated this interval as ECDZ-2 which Sugarman et al. (1993) used to establish the Kw2 sequence and later subdivided into Kw2a and Kw2b. Logs delineate an overall fining upwards interval corresponding to rising relative sea level until 264.7 m (868.4 ft), which agrees with the limited lithologic descriptions of silty clay overlain by clay to 264.7 m. This in turn is overlain by sandy silt marking a sharp break in gamma and the probably location of the MFS. Lithology returns to a thick clay-rich interval with corresponding gamma, neutron porosity and resistivity portraying fairly continuous straight vertical slopes until 228 m (748 ft) (fig. 2.19). A slight coarsening upward trend begins at 245 m (803.8 ft) as observed in both gamma and resistivity. A corresponding lithologic change from clay to silt does not occur until 241 m (790.7 ft) but due to widely spaced samples, the actual contact might be deeper. Silt continues upwards until 228 m (748 ft). Here, a sand interval occurs as seen in ACOW-1 and to a less developed extent in ACMUA and AC

(fig. 2.19). This corresponds to the uHST of the Kw2a sequence. Resistivity suggests a finer interval here but it could be the inverse due to a fresh water lens and a more saline borehole fluid. The upper sequence boundary occurs at 216.7 m (711 ft) as defined by the characteristic positive gamma kick (fig. 2.19).

Sequence Kw2b lies atop Kw2a in this borehole similar to the wells to the west. Clayey silt to clay suggesting rising relative sea level forms the TST of this sequence. A change in the geophysical log character marks the MFS where the sediment type returns from clay back to clayey silt above 212 m (295.5 ft) (fig. 2.19). Silt continues to dominate upwards to the overlying sequence boundary at 203 m (666 ft). Geophysical logs do not clearly define this sequence boundary (fig. 2.19).

The next sequence mimics the characteristics of Kw3 in all the boreholes to the west. Owens (unpublished data) recorded three separate horizons with diatoms representing ECDZ-6(?) of Andrews (1978) corresponding to Kw3 of Sugarman et al. (1993). Gamma logs indicate a fining upwards section to 188.5 m (618.4 ft) to the suggested MFS location. Some spikes in gamma and neutron porosity suggest a thin slightly coarser interval just below the MFS (fig. 2.19). A proposed interbedded clay and silt interval not described in drill cuttings probably continues upward to 177 m (580.7 ft) where the geophysical logs and lithologic descriptions indicate a coarser unit, though only as coarse as silty clay, corresponding to the HST. In ACOW-2, Kw3 continues to its upper boundary at 159 m (521.6 ft).

ODP Leg 150X Cape May

The southernmost cored borehole of ODP Leg 150X was drilled in Cape May, New Jersey (CM) on the US Coast Guard Receiving Station, Sewell Point, 783 m (2569 ft) west of the Cape May Inlet (fig. 2.2). It was the last of three continuously cored boreholes comprising ODP Leg150X. Target horizons were middle Miocene through Eocene (Miller et al., 1996). The corehole was drilled in March and April 1994 to a total depth of 457.2 m (1500 ft). Recovery was good with a median of 75%, while the cumulative average over the 184 m (604 ft) middle and lower Miocene section in question was 68.55% (Miller et al., 1996). Biostratigraphy and Sr-isotopic age estimates dated the different horizons and allowed regional correlation with other cored boreholes.

As at the AC location, hole conditions limited geophysical log collection in Cape May. Only logs that sampled through the drill pipe could be acquired, therefore restricting logging to gamma and neutron porosity (fig. 2.20). To facilitate log interpretation a search of the New Jersey Geological Survey well database located a proximal well containing a more complete log suite. This well, drilled at the Coast Guard Engineering Center (CGEC) on the northern side of Cape May Inlet in August 1989 (TD - 275.2 m, 903 ft) contains SP, both short and long normal resistivity, and a lateral log (fig. 2.20). Unfortunately the well did not penetrate the entire lower Miocene so a complete correlation with Cape May could not be made. The USGS logged the well shortly after drilling ended (logs on file at the NJGS, Trenton, NJ). The well is 1483.2 m (4,866 ft) north of the inlet, slightly off strike from the Cape May well.

`The oldest Miocene sequence encountered at Cape May is Kw0. Core recovery indicates that sand dominates the sequence. Neutron porosity displays a near vertical gradient indicating little change through the unit (fig. 2.20). A single positive gamma kick occurs at the lower boundary before returning to previous values. Miller et al. (1996, 1997) suggested that the presence of detrital glauconite both above and below the boundary accounts for the subdued gamma signature. Miller et al. (1997) placed the MFS at 354.3 m (1162 ft) marked by a positive gamma spike that separates deeper water benthic foraminifera biofacies from overlying shallower water facies of the HST (fig. 2.20). The HST is subdivided at 343 m (1125 ft) into a lHST and uHST based on a lower clay silt content and grain size increase upsection. Glauconite occurs upsection through the TST and into the lHST. Gamma logs display a slope change through the HST while neutron porosity spikes at the upper contact.

The Kw1a forms the overlying sequence. Detrital glauconite disguises the gamma signature similar to Kw0 (fig. 2.20). The 1.2 m (3.9 ft) TST identified by Miller et al. (1997) contains glauconite rich sands and clays up to the MFS at 322.6 m (1058.4 ft). Thick silt clay marks the lHST and shows a decreasing gamma upsection in traversing from silt to clay, opposite of what is expected. The curve is influenced by a decreasing glauconite content upsection before reaching the glauconite-free clay. Above 306 m (1003.9 ft), the gamma log displays a more representative grain size curve without the glauconite present (fig. 2.20). An uHST containing coarsening-upwards quartz rich sand continues to the upper boundary at 287.7 m (942 ft). Browning et al. (2006) subdivided

the Kw1a into three sequences with the upper two, Kw1a2 and Kw1a3 occurring here. They placed the boundary separating Kw1a2 from Kw1a3 at 306.5 m (1005.6 ft) coincident with a small gamma kick separating Sr-isotopic ages of 20.2 and 20.6 Ma. This boundary serves well as a sequence bounding surface as gamma showing a positive slope of the silty sediments follows the log pattern of a sequence described by Sugarman et al. (1993) and Miller et al. (1998), and Sugarman (2001). Higher upsection gamma switches to negative slope indicative of the increasing grain size of the sands recovered in core (fig. 2.20). The slope switch suggests the Kw1a3 sequence MFS.

The Kw1b sequence presents a generally sand rich unit showing a general coarsening-upwards trend throughout the sequence. Miller et al. (1997) recorded fine sands grading into silty clays and moderate gamma values through the TST. They placed the MFS at a strong positive gamma peak that decreases upwards through the lHST but still remains higher than the underlying TST (fig. 2.20). Shelly sands comprise the uHST (Miller et al., 1996). Miller et al. (1997) identified three coarsening-upwards parasequences or fluvial facies successions based on repetitive decreasing gamma log cycles (mistakenly described as increasing values). An indurated zone was encountered at 272.3 to 270.4 m (893-887 ft) and described as a possible flooding surface (Miller et al., 1997) but could represent a sequence boundary. Gamma and neutron logs show slope changes at this interval that represent sediment grain size change (fig. 2.20). If this is a separate sequence coarse sediments dominated and therefore could represent a truncated section. The only two Sr-isotopic age estimates for this interval lie above the indurated zone and record an age of 19.9 Ma (Miller et al., 1997).

Kw1c forms the next youngest sequence and was first identified in this borehole. It also forms the first sequence completely sampled in the bottom of the CGEC well. A change from medium quartz sand topped by a strong positive gamma kick and overlain by sandy clay marks the Kw1c lower sequence boundary (fig. 2.20). SP, resistivity and gamma log responses amply portray the fine grained material above the sequence boundary that begins to coarsen-upwards to the MFS as correlated to Cape May well. All logs display a coarsening upwards trend through the lHST as identified by Miller et al. (1997).

Above the lHST-uHST contact at 247 m (810 ft), CM gamma log values remain flat with a small positive spike at 231.8 to 232 m (760.2-760.9 ft). Miller et al. (1997) indicated this surface, corresponding to a shell bed that overlies an indurated zone at 232.9 m (764 ft), is a flooding surface similar to features described by Kidwell (1989, 1991) as opposed to a possible unconformity (Miller et al., 1996). Foraminiferal data support an upward shallowing from middle neritic to near-shore to bay environments. However Miller et al. (1997) showed a shallowing at CM just below this surface (fig. 2.20, their fig. 7), which could indicate the indurated zone at 232.9 m (764 ft) as an unconformity. Resistivity, SP, and porosity curves suggest a grain size decrease beginning directly above this point (fig. 2.20). Core recovery above this point was extremely poor however logs within this zone suggest a possible flooding surface at 225 m (738.2 ft). Medium sand dominates the lithologic material with limited interbedded fines above this MFS. The sequence ends at 216 m (708.66 ft) corresponding to a gamma spike and major resistivity log change in CGEC and a more subdued change in Cape May.

The question becomes whether this truly is another sequence within a zone previously identified solely as Kw1c. Browning et al. (2006) described a time equivalent sequence from the Leg 174AX Bethany Beach, Delaware corehole just across the Delaware Bay. This C4 sequence yields an age estimate of 18.4 to 18.0 Ma, which agrees with the single Sr isotopic age of 18.4 Ma from Cape May. Similar gamma log signatures reinforce this interpretation. Benthic foraminiferal biofacies also suggest a deepening followed by a gradual shallowing (fig. 2.21, Miller et al. 1997). This interpretation requires further analysis of regional borehole logs on the Cape May peninsula.

The overlying Kw2a sequence was initially described as a classic sequence displaying expected facies association of deepening upwards TST overlain by shallowing upwards HST (Miller et al., 1996, 1997). Browning et al. (2006) have since subdivided the Kw2a into three different sequences, with the younger two (Kw2a2 and Kw2a3) occurring in the Leg 150X Cape May corehole. The MFS was originally placed at 207.3 m (680 ft), just below a gamma and neutron kick at CM and corresponding major deflections in resistivity at CGEC. Miller et al. (1996) described lithologic characteristics that compare the indurated surface at 207.3 m (680 ft) with sequence boundaries lower in the Cape May well. They stated that the surface is either a disconformity or a flooding surface. Subsequently these downhole geophysical signatures were used to separate Kw2a2 below 207.3 m (680 ft) from Kw2a3 (Browning et al., 2006). Logs of Kw2a2 display characteristic trends of Miocene-aged sequences (Miller, 1997; Sugarman, 2001) and accompany a coarsening-upwards lithology. The MFS for Kw2a2 is suggested to be at

210 m (689 ft) (Browning et al., 2006) where a gamma slope change from positive to negative and accompanied change in neutron, SP and resistivity at CGEC. The Kw2a3 sequence presents a similar but more subdued log signature (fig. 2.20). The TST contains laminated clays to a MFS at 199 m (652.9 ft) that is overlain by medium grained sands. Sands continued up to a log spike coincident with interbedded sand and sandy clay horizons (Miller et al., 1996). CGEC SP and resistivity logs amply point out the thin clay interbeds. The overlying sequence boundary occurs at 187.5 m (615 ft) within a poorly recovered interval.

The final sequence sampled at CM is Kw2b. CGEC downhole logs display characteristic trends of Miocene sequences. The Cape May logs are less definitive, but a MFS is suggested at ~185 m (607 ft). Logs suggest a thin basal sand layer and overlying silt/clay up to the MFS. CGEC logs portray a coarsening upwards package of lithologies with few clay interbeds. The upper sequence boundary occurs at 175.6 m (576 ft) that marks the beginning of Kw2c.

WELL PROJECTION INTO THE SEISMIC GRID

The projection of well data into a seismic grid requires an accurate time depth function. Three different types of velocity data were investigated for this study. Sonic logs collected in the two Island Beach wells (IB and OIB) and ODP Leg 174AX Oceanview corehole located between Cape May and Atlantic City (fig. 2.2) yielded different results.

Island Beach wells were quite similar while the Oceanview sonic was considerably slower (fig. 2.22). The Oceanview sonic log suffered from both small and large channel skips on both the descending and ascending log data. A composite sonic log was created as the channel skips on both sonic logs occurred at different depth intervals. Check shot surveys on the two ACOW wells (Waldner and Hall, 1991) provided the second velocity data set. These data overlapped with the IB wells to approximately 140 m (459.3 ft) where they began to slow in relation to the IB velocities. The last velocity data derives from semblance plot analysis performed on *CH0698* data to construct the seismic velocity functions for subsequent seismic data processing. Stacking velocity is uniformly slower than other data except for the Oceanview sonic. Geophysical logs were recalculated into the time domain using all three data sources. The resulting gamma logs, now in the time domain were hung at appropriate "elevations", offshore wells were projected on seismically identified seafloor while onshore wells were placed at their respective time elevations. The stacking velocity proved to consistently have the best correlations between log-identified surfaces in drill holes and the seismic data. Other velocity files would show a good correspondence on one or two surfaces within several wells but were not consistent throughout the entire database. Therefore the same stacking velocity data served both the seismic processing as well as the time-depth conversion.

Analysis of the seismic information identified eleven individual candidate sequence boundaries based on reflector truncations and seismic facies. These sequences, named for the color of their basal boundary proceed from oldest to youngest as purple, brown, red 1,

dark blue, green1, light blue, pink, yellow, red 2, orange and green2 (Table 2.1). The upper boundary marking the top of the green2 sequence lies outside the dominant portion of the *CH0698* grid and therefore has not been adequately characterized. Borehole lithologic, biostratigraphic and isotopic data as well as downhole geophysical data allows comparison and alignment of the borehole delineated sequences as described by Miller et al. (1998) and Browning et al. (2006) with candidate seismic sequences identified in the *CH0698* grid.

Borehole-derived sequence boundaries generally match well with seismically identified and traced sequence boundaries. Reflector characteristics used to identify seismic sequence properties are best displayed offshore where deposition and sediment accumulation is thickest. These surfaces were looped through the grid and towards the onshore and nearshore boreholes. Tracing surfaces shoreward through the seismic grid produced overall sequence thinning and local surface amalgamation. The study then tracked the candidate boundaries into the wells, where sedimentation is markedly thinner. Tracking candidate sequence boundary landward toward the ODP coreholes proved difficult because the reflectors lost continuity and at times reflector intensity. Therefore correlation between well information and seismic interpretation is not necessarily hard and fast. It can only be truly tested by drilling offshore. However, the best interpretation developed from comparing all information and selecting the most consistent both lithologically seismically and regionally.

Another problem exists as initial borehole analysis (Miller et al. 1994a, 1994b, 1996, 1997a, 1997b, 1998) only identified six lower Miocene sequences while the seismic data indicates ten. The sequence boundary amalgamation described above does not alleviate this problem. Recent drilling and analysis of the ODP Leg 174AX Oceanview borehole has subdivided the Kw1a sequence into three higher order sequences labeled Kw1a1, Kw1a2, and Kw1a3 from oldest to youngest (Miller et al., 2001). Browning et al. (2006) performed more detailed reanalysis of other ODP Legs 150X and 174AX wells and maintained a single Kw1b sequence but further subdivided Kw2a into three separate sequences, that of Kw2a1, Kw2a2 and Kw2a3 from oldest to youngest. These additional borehole sequences in conjunction with seismic surface tracking allow a better correlation between borehole and seismic sequences. However, comparisons require a reevaluation or refinement of previously identified borehole delineations.

CH0698 candidate seismic sequences including their local amalgamation as they trace landward have been correlated to corehole-identified sequences as described in Browning et al. (2006) and dated according to the refined ages of Miller et al. (2001) and Browning et al. (2006) (Table 2.1). The basal Miocene sequence Kw0 equates to the purple seismic sequence. The subdivisions of next youngest sequence Kw1a into Kw1a1, Kw1a2 and Kw1a3, from oldest to youngest, correspond to brown, red and dark blue seismic sequences. Continuing upward and younger, seismic data suggests that the Kw1b sequence can be subdivided into the Kw1b1 and Kw1b2 sequences and correlated to green and light blue. This new sequence division lies on previously identified flooding surfaces in the Atlantic City and Cape May coreholes. The Kw1c sequence equates to

the pink seismic sequence. The Kw2 sequence accounts for the remaining three seismic sequences. Kw2 is divided into Kw2a and Kw2b. Kw2a is further subdivided into Kw2a1, which corresponding to yellow and Kw2a2 and Kw2a3 are both represented by the red seismic sequence (Browning et al., 2006). The final and youngest sequence involved Kw2b correlates to the orange seismic sequence. The green2 candidate sequence boundary forms the upper boundary of Kw2b.

The AMCOR 6011 hole lies at the crossing of *CH0698* lines 17 and 16 (fig. 2.2). Line 17 was used for correlation as being a dip line, it continues shoreward merging with line 14, parallel to the coastline and containing the projected Island Beach borehole, the closest cored borehole. The lithologic change observed in the AMCOR 6011 geophysical logs inhibited direct correlation to Island Beach (Miller et al. 1998) without the seismic connection. AMCOR 6011 downhole geophysical data correlates quite well with seismically characterized sequence boundaries (fig. 2.23). The Oligocene/Miocene boundary identified by Pekar (1999) matches the basal boundary of the purple sequence, which correlates to Kw0. This correlation is slightly older than the 19.8-19.7 Ma age recorded by Pekar (1999), Pekar et al. (2000, 2003), and Kominz and Pekar (2001). This age discrepancy could relate to extremely poor core recovery or burrowing down of shell fragments. Progressing upwards, the next five log-identified sequence boundaries match the seismic picks, from lowest to highest, brown, green, pink, yellow and orange seismic sequences. This suggests these five sequences correlate to Kw1a1, Kw1b1, Kw1c, Kw2a1 and Kw2b respectively. These correlations do match the limited biostratigraphic data in the well.

Island Beach well was projected 1500 m along stratigraphic strike into *CH0698* line 14 at CDP 9550 (fig. 2.24). The Kw1a sequence is the oldest recorded sequence in the borehole (Miller et al. 1997). However, the Sr isotopic ages correlate with Kw0, which was first encountered in the Cape May borehole, a subsequently drilled site. This correlates with the purple seismic reflector on line 14. The brown seismic sequence correlates with the upper section of the Kw1a borehole sequence and dates it as Kw1a1. No other age data exists until the very top of the well (Miller et al., 1994). The upper boundary of Kw1a has been identified at two different depths by different researchers; Owens et al. (1997) placed the upper contact at 92.4 m (303.2 ft) while Miller et al. (1997) placed it at 85 m (278.9 ft). These two boundaries could both be correct as they correlate to the green seismic reflector and the interval represents Kw1b1. A re-designation of the age in Island Beach is necessary to account for the pink seismic sequence lying above the green sequence. The borehole sequence was originally correlated as Kw1b, but without age constraints. Correlating this sequence with Kw1c is therefore reasonable. The yellow sequence lies above pink along this seismic line (fig. 2.24). The boundary occurs within the new Kw1c sequence, but a possibility occurs of another sequence boundary at 70 m (229.7 ft) as subtly indicated by borehole logs and lithic descriptions. It would fit the boundary between pink and yellow, making the upper part of the originally classified Kw1b actually Kw2a1. The highest sequence identified as Kw2a actually correlates to Kw2b according to the seismic orange sequence. Therefore the lower Miocene seismic sequences from oldest to youngest in the Island Beach well are Kw0, Kw1a1, Kw1b1, Kw1c, Kw2a1 and Kw2b.

Moving to the south, the Atlantic City, ACOW-1 and ACOW-2 wells offer the next opportunity for well seismic integration. The best projection places all three wells into *CH0698* line 27 (fig. 2.25), which enters Absecon Inlet. The placement affords the opportunity to investigate seismic, lithologic and log character changes on moving offshore down an approximate dip line. The interplay of seaward thickening sequences and landward surface amalgamation appears in both line 27 and also the three projected boreholes.

Beginning at the AC well, the borehole sequence boundaries match well the seismic sequences (fig. 2.25). Changes in lithology from clay to sand rich sediments represent the strongest reflectors as expected. The basal Kw0 sequence, marking the lowermost Miocene, does not match with the purple reflector as expected. Kw0 occurs within the basal section of the red seismic sequence while the purple sequence appears just 15 msec below. The Kw1a sequence from the borehole matches with the red sequence and therefore should be Kw1a2. Its upper boundary agrees with the basal green boundary so suggested to be Kw1b1 sequence. The Kw1b identified in the Atlantic City well has two parasequences (Miller et al., 1997) although the borehole geophysics suggests the possibility of a third. The boundary between the second and third parasequences correlates with the light blue seismic boundary. This suggests that instead of parasequences, they seismically are identified as sequences and correlate to Kw1b1 and Kw1b2. A strong reflector marks the contact between the two lower parasequences described in the borehole (Miller et al., 1997). The upper boundary correlates with the

yellow seismic reflector. Therefore, the borehole Kw2a correlates to Kw2a1. The Orange reflector resides above yellow and agrees with the Kw2a-Kw2b boundary in the Atlantic City well.

Traversing toward the offshore along *CH0698* line 27 the sequences begin to slightly thicken and shows other changes. Several other sequences that were amalgamated in Atlantic City begin to split and become more evident as individual sequences. Green and dark blue surface splits revealing both sequences just west of ACOW-1 (fig. 2.25). A similar splitting occurs between ACOW-1 and 2 where the upper red sequence also becomes apparent. ACOW-1 shows the same sequence arrangement as Atlantic City. The only change is the appearance of the dark blue reflector correlating to Kw1a3 of Miller et al. (2001) and Browning et al. (2006). There is a spike in the ACOW-1 gamma log but due to its limited thickness it was insufficient to outline as a sequence with the data at hand. A slight misalignment is present between the orange sequence and Kw2b as identified by borehole geophysical logs. They have similar thickness in TWTT but are off by an individual reflector.

Moving toward the offshore ACOW-2 continues with the individual sequence thickening. Borehole sequence boundaries agree in time with the seismically identified boundaries, like the other wells to the west (fig. 2.25). Again the dark blue unit corresponding to Kw1a3 is not well represented in the borehole geophysics. The logs give a hint of this sequence but it only would have been picked after knowing that it should be there. The Kw1b sequence continues the subdivision as seen in Atlantic City and ACOW-1. Three

parasequences/sequences were chosen based on the logs. However they do not match the green-light blue boundary observed in seismic. Again, analysis after the fact might have selected a boundary by log characteristics. ACOW-2 contains the Kw1b1 and Kw1b2 sequences. Moving upwards the upper light blue contact matches the Kw1b-Kw2a borehole boundary. The sharp positive gamma spike described as a possible MFS in sequence Kw2a forms a strong reflector. It appears within the yellow sequence therefore correlating to Kw2a1. An upper red seismic sequence matches with the interpreted uHST of Kw2a. Unfortunately the red unit representing Kw2a2-3 had dramatically thinned here so a log signal association is not noticeable. Borehole sequence Kw2b again tallies with the upper and lower boundary of the orange seismic reflector.

The final borehole used in seismic tying, Cape May lies in the southwestern corner of the seismic grid on line 99, which enters the Cape May Inlet (fig. 2.26). The borehole projection places the well just west of the seismic line thereby making a direct correlation into seismic data more difficult. Borehole sequence Kw0 matches with the purple, brown and lowermost red sequences. Purple correlates from the basal Kw0 up to the contact of lHST and uHST. Brown appears to represent the medium sands covering the basal uHST and may represent Kw1a1. The basal red seismic sequence correlates with the clayey sand that coarsens upwards into fine sands in the remaining uHST. Borehole sequence Kw1a equates to red and dark blue seismic sequences. The red and blue contact correlates well to the contact between Kw1a2 and Kw1a3 of Browning et al. (2006). The Kw1b sequence similarly compares well with the corresponding green and light blue

seismic sequences. The borehole defined Kw1b1 and Kw1b2 sequence boundary also agrees well with the green and light blue seismically defined surface.

Sequence Kw1c was defined in this borehole (Miller et al., 1996, 1997), so this well allows the only direct correlation into the *CH0698* grid. Its basal contact fits the location of the pink seismic sequence, but the upper beds of Kw1c correlate with the yellow sequence. However yellow's lower reflector boundary fits the location of the C4 sequence. Yellow's upper reflector boundary matches the lower Kw2a unconformity. Regionally, the yellow sequence traces well into Kw2a (Atlantic City wells). The C4 sequence is best developed in Delaware and thins northward into Cape May. It has not been defined as a sequence along the New Jersey coastal plain. Therefore the best correlation would be yellow as Kw2a1.

The remaining borehole sequences are subdivisions of the Kw2 sequence first defined by Sugarman et al. (1993). Borehole sequence Kw2a can be subdivided into two separate sequences that correlate to Kw2a2 and Kw2a3 of Browning et al. (2006). The upper red seismic sequence covers this interval and equals Kw2a2 and Kw2a3 (fig. 2.26). The youngest sequence is Kw2b that elsewhere within the grid has matched the orange seismic sequence. This correlation also fits here.

CONCLUSION

Seismic and borehole data needs to be integrated in order to understand the evolution of continental margin growth. The New Jersey Mid Atlantic margin is no exception. Detailed analysis on the outer continental margin using higher resolution seismic data has begun to elucidate the margin history (Austin et al. 1998, Fulthorpe and Austin, 1998, Fulthorpe et al. 1999, Metzger et al, 2000 for example). This study has continued the process in the inner continental margin. Complete analysis of the *CH0698* seismic grid outlines 11 sequence boundaries that are the main target horizons for the IODP Expedition 313 New Jersey Margin. They have been tracked throughout the seismic grid. Along strike variability is evident in all candidate sequences throughout the seismic grid. LST are most evident where sedimentation was thickest and unfortunately the farthest away from any drill holes. LST deposits thin along strike and are not present on every seismic line. TST are rarely identified suggesting that these deposits are below seismic resolution. HST dominates the seismic data landward of the clinoform inflection points.

Dating of candidate seismic sequence boundaries required correlation with ODP Leg 150X coreholes (Miller et al., 1994a, 1994b, 1997). Supplemental borehole information from AMCOR6011 and ACOW1 and 2 aided the seismic interpretation. ACOW wells correlated to the ODP Leg 150X Atlantic City corehole and allowed the best comparison and dating of corehole identified sequence boundaries with those of the seismic. Limited lithologic and biostratigraphic analysis of AMCOR6011 (Pekar, 1999) supplemented with borehole geophysical interpretation showed a strong sequence correlation with the seismic data.

Seismic sequences Greenlee et al. 1992	Seismic sequences Mountain, et al. 1990	Seismic sequences Miller et al. 1996	Seismic sequences This study	Sequences Browning et al 2006	Sequence age (Ma) Browning (pers comm..)
Green	Green	m5- Kw2b	Green – m5		~16.9 slope ~15.6 shelf
	Ochre	m5.2 – Kw2a	Orange – m5.2	Kw2b	15.7-16.1
			Red – m5,3	Kw2a2-2a3	16.9-17.1 17.1-17.2
	Sand	m5.4 – Kw1c	Yellow – m5.4	Kw2a1	17.2-17.8
			Pink – m5.45	Kw1c	19.4-19.5
			Lt Blue – m5.47	Kw1b2	19.7- 19.9
			Green – m5.5	Kwb1	20.0-20.1
Blue	blue	m5.6 – Kw1a,b	Dark Blue – m5.6	Kw1a3	20.2-20.3
	Pink3	m6 – Kw0	Red – m5.7	Kw1a2	20.3-20.4
			Brown – m5.8	Kw1a1	20.4-21.9
			Purple – m6	Kw0	23.6-24.2

Table 2.1. Correlation of seismic surfaces from seismic data of different resolution. Greenlee et al. (1992) studied low resolution data, Mountain et al. (1990) investigated Ew9009 which Miller et al. (1996) renamed and correlated to select Kirkwood sequences drilled on land. Further subdivision of sequences by Browning et al. (2006) found after drilling ODP Leg 174AX. Approximate ages of each Kirkwood sequence is from Browning (personal communication)

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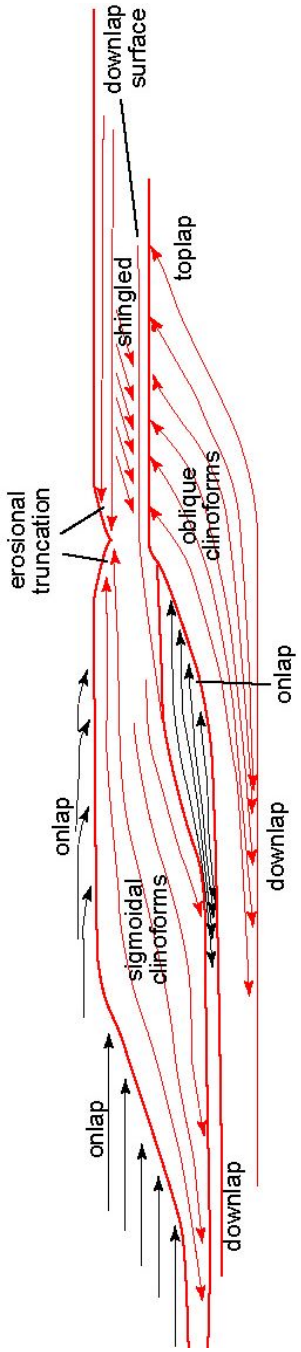


Figure 2.1. Types of seismic reflector terminations and patterns. Modified from Coe and Church (2003) and Mitchum et al., (1977b)

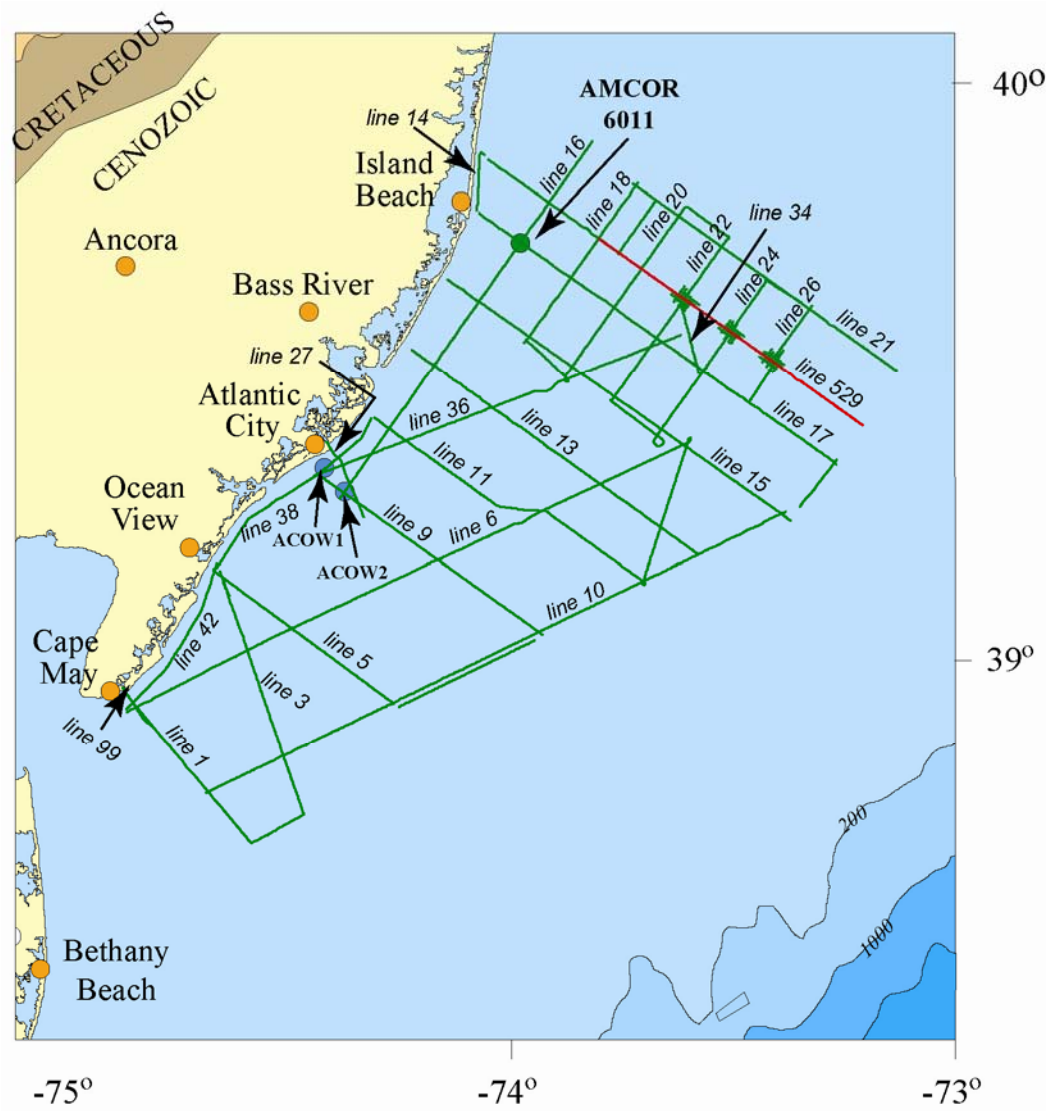


Figure 2.2. Location map of *CH0698* seismic lines in relation to ODP Leg 150X coreholes at Island Beach, Atlantic City and Cape May, and offshore wells AMCOR6011, ACOW1 and ACOW2. Also shown is *Oc270* line 529

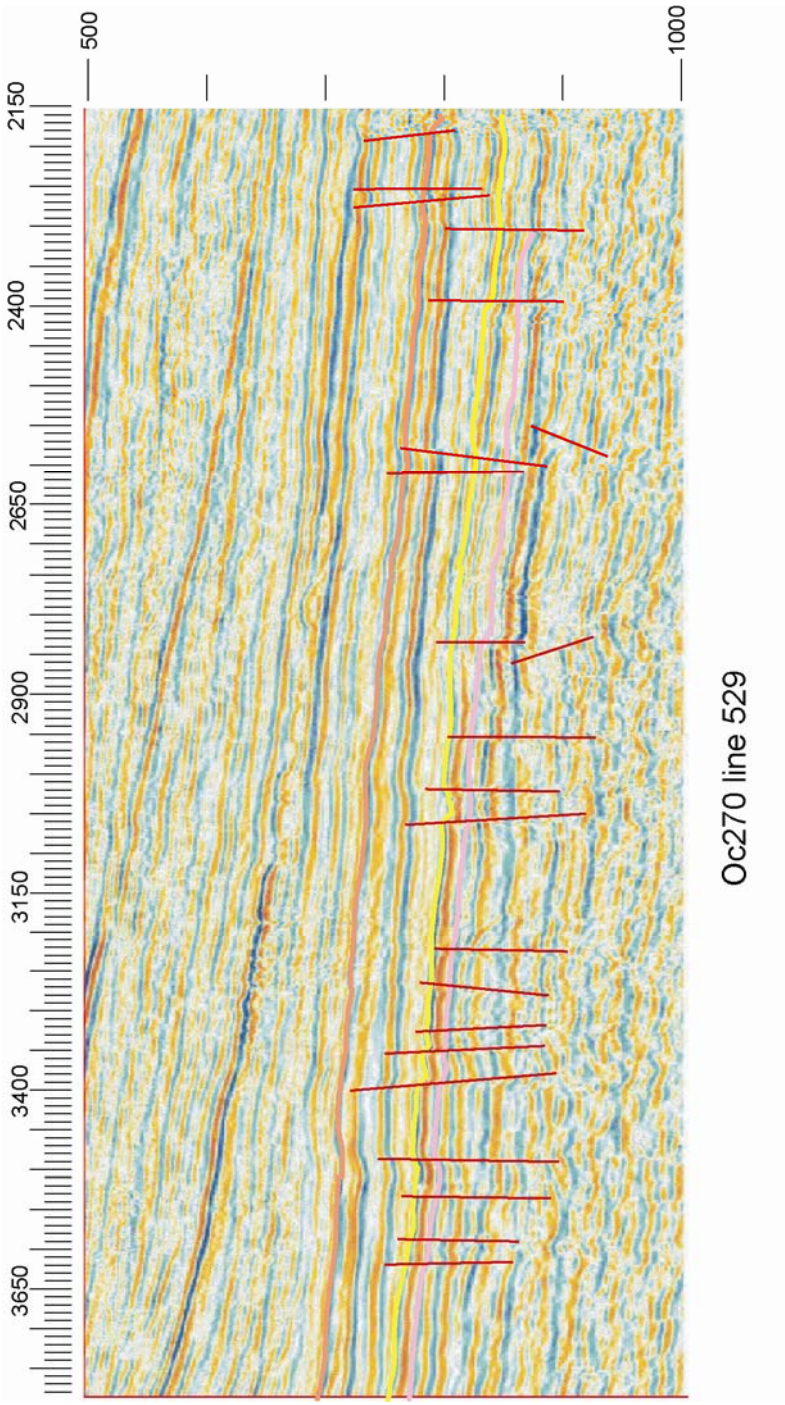


Figure 2.3 Example of faulting (red lines) on Oc270 line 529. Faulted material comprises fine grained sediment deposited in deeper water environments.

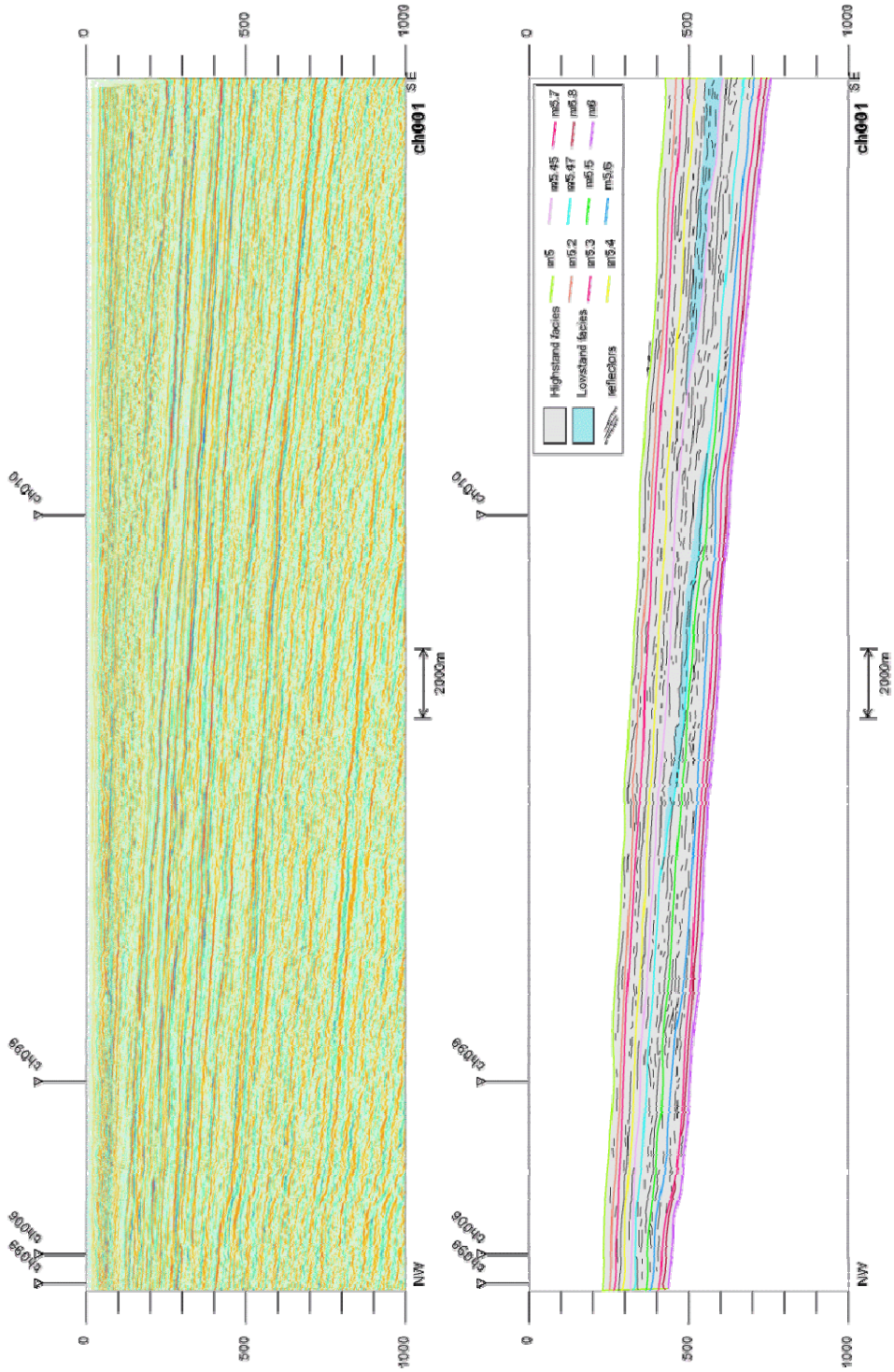


Figure 2.4 Seismic interpretation of *CH0698* Line 1

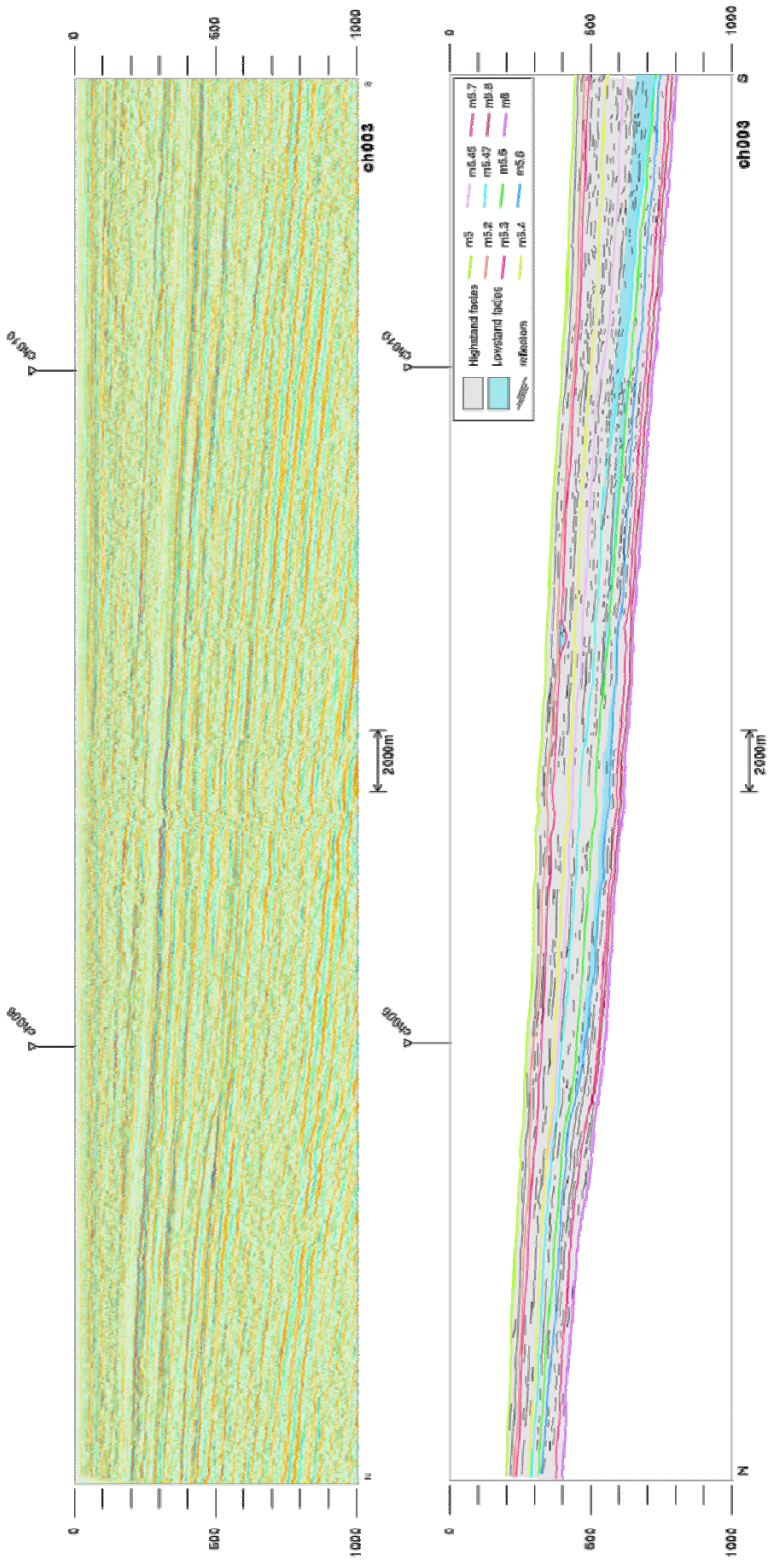


Figure 2.5 Seismic interpretation of *CH0698* Line 3

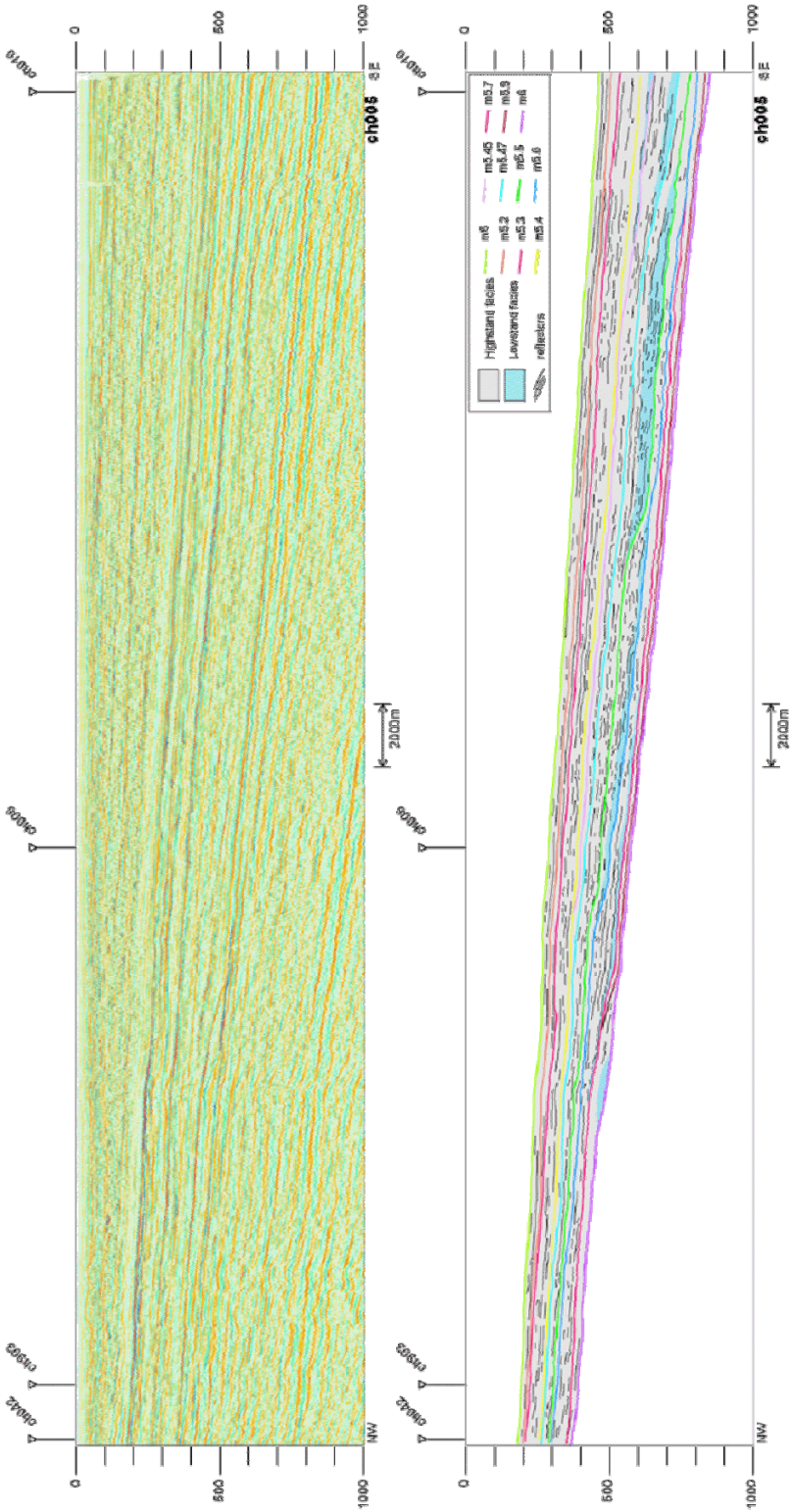


Figure 2.6 Seismic interpretation of *CH0698* Line 5

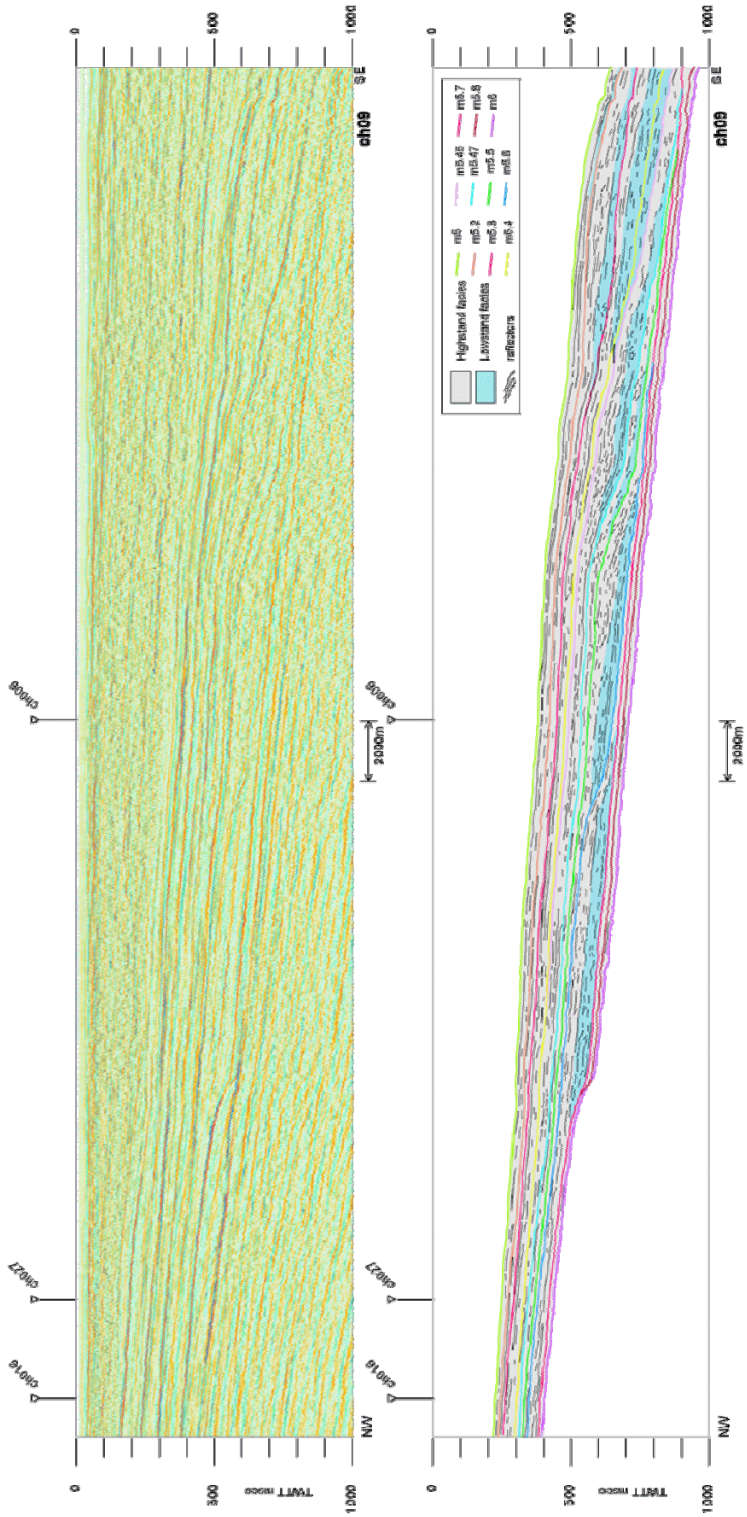


Figure 2.7 Seismic interpretation of *CH0698* Line 9

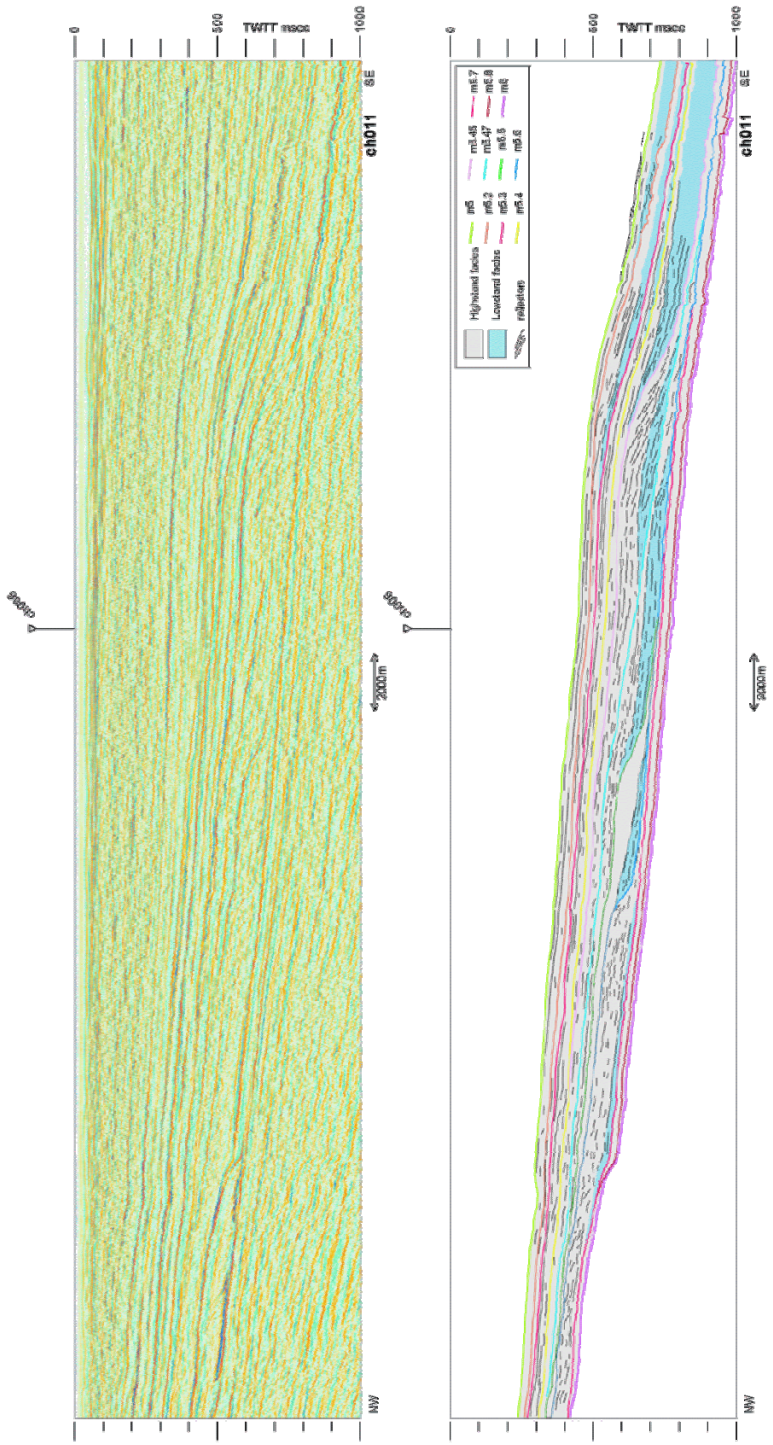


Figure 2.8 Seismic interpretation of *CH0698* Line 11

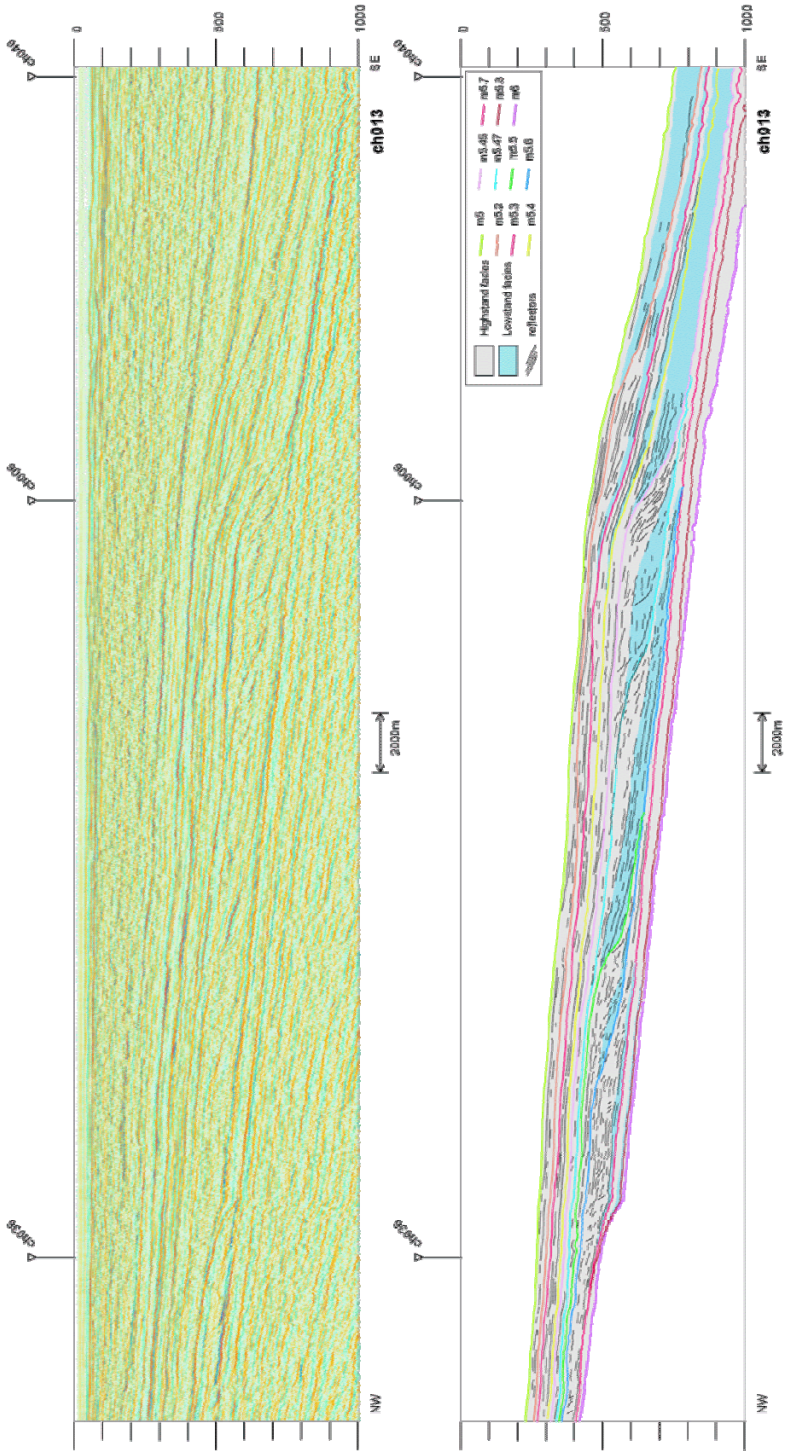


Figure 2.9 Seismic interpretation of *CH0698* Line 13

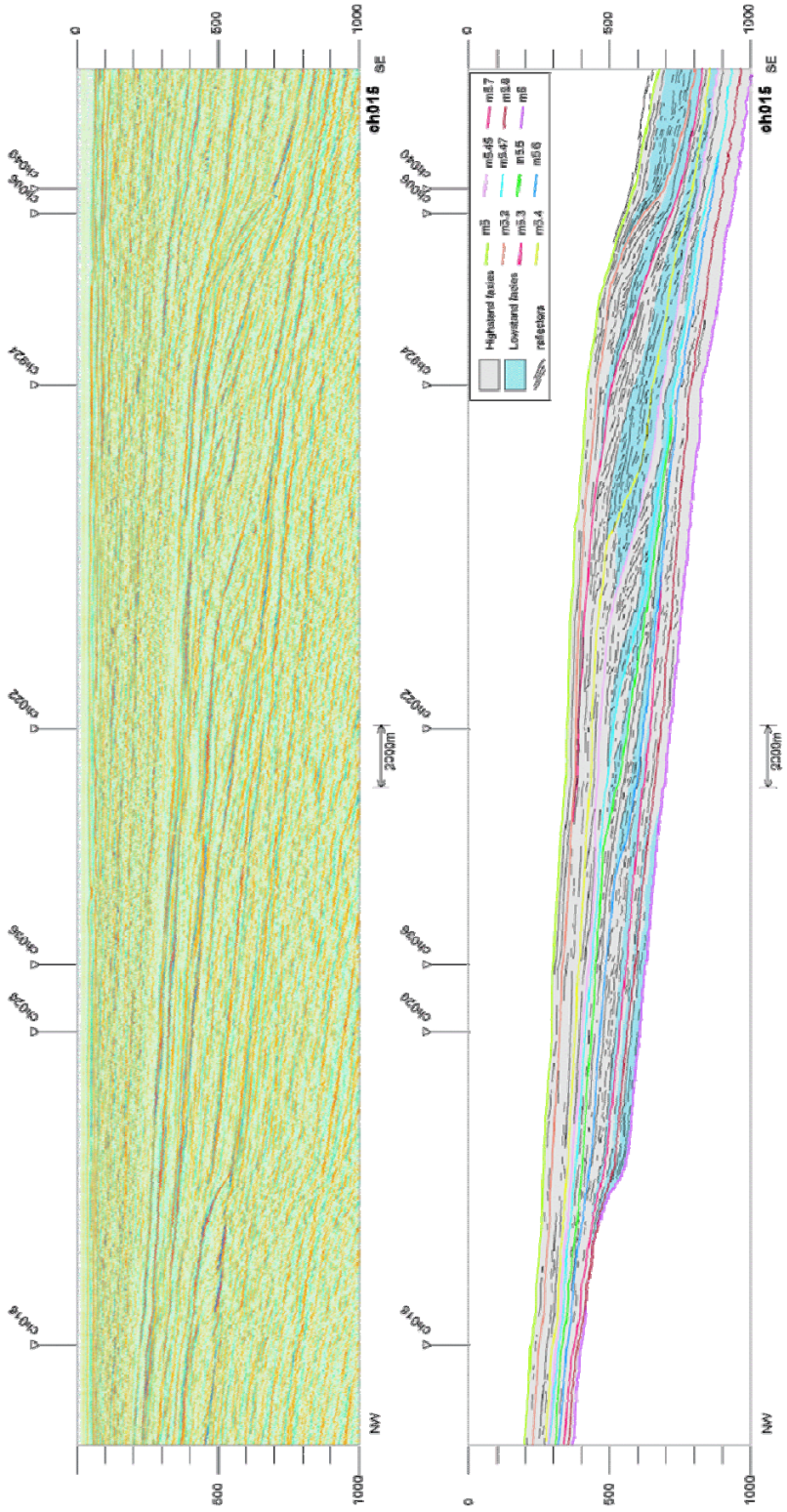


Figure 2.10 Seismic interpretation of *CH0698* Line 15

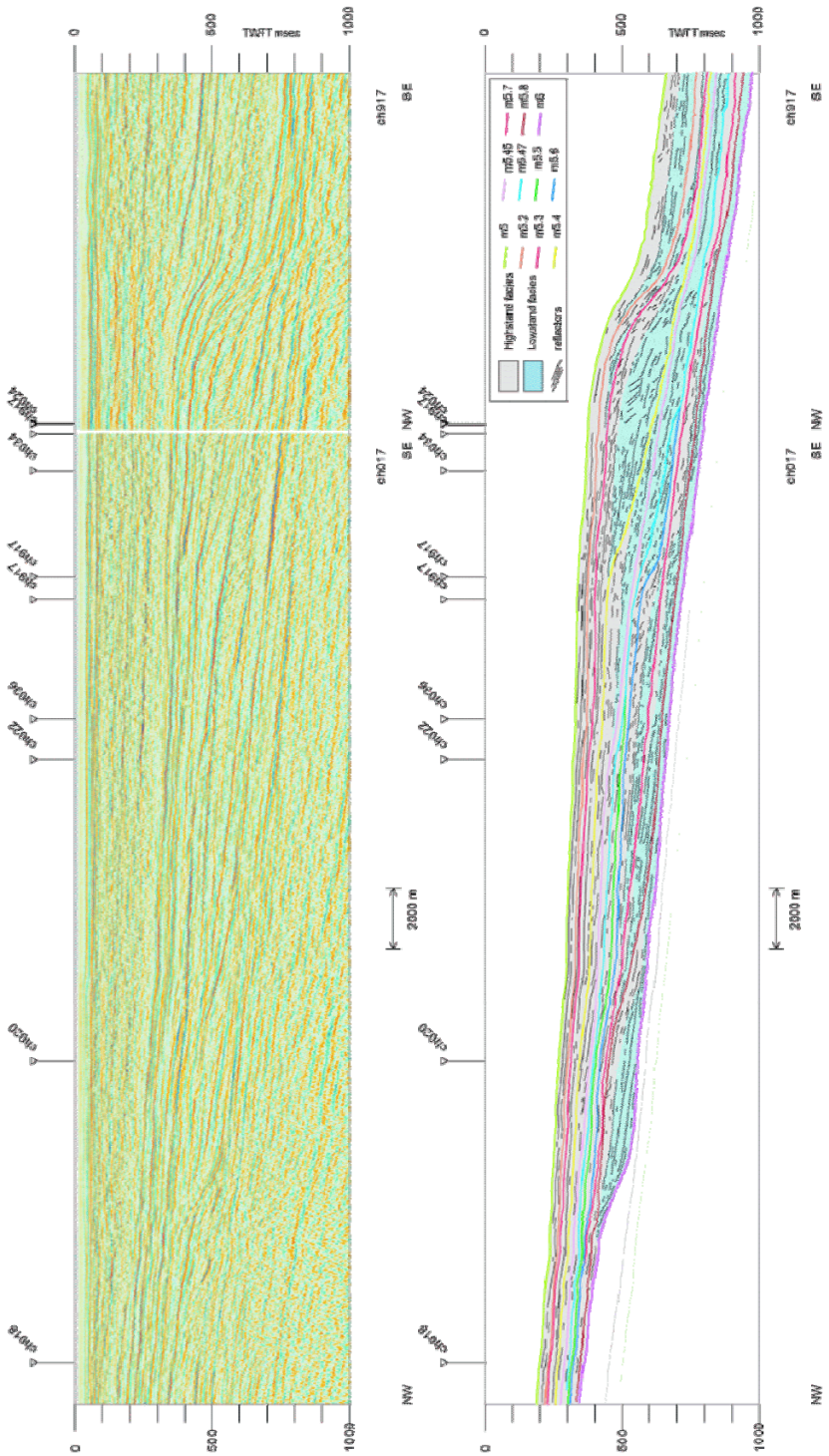


Figure 2.11 Seismic interpretation of *CH0698* Line 17

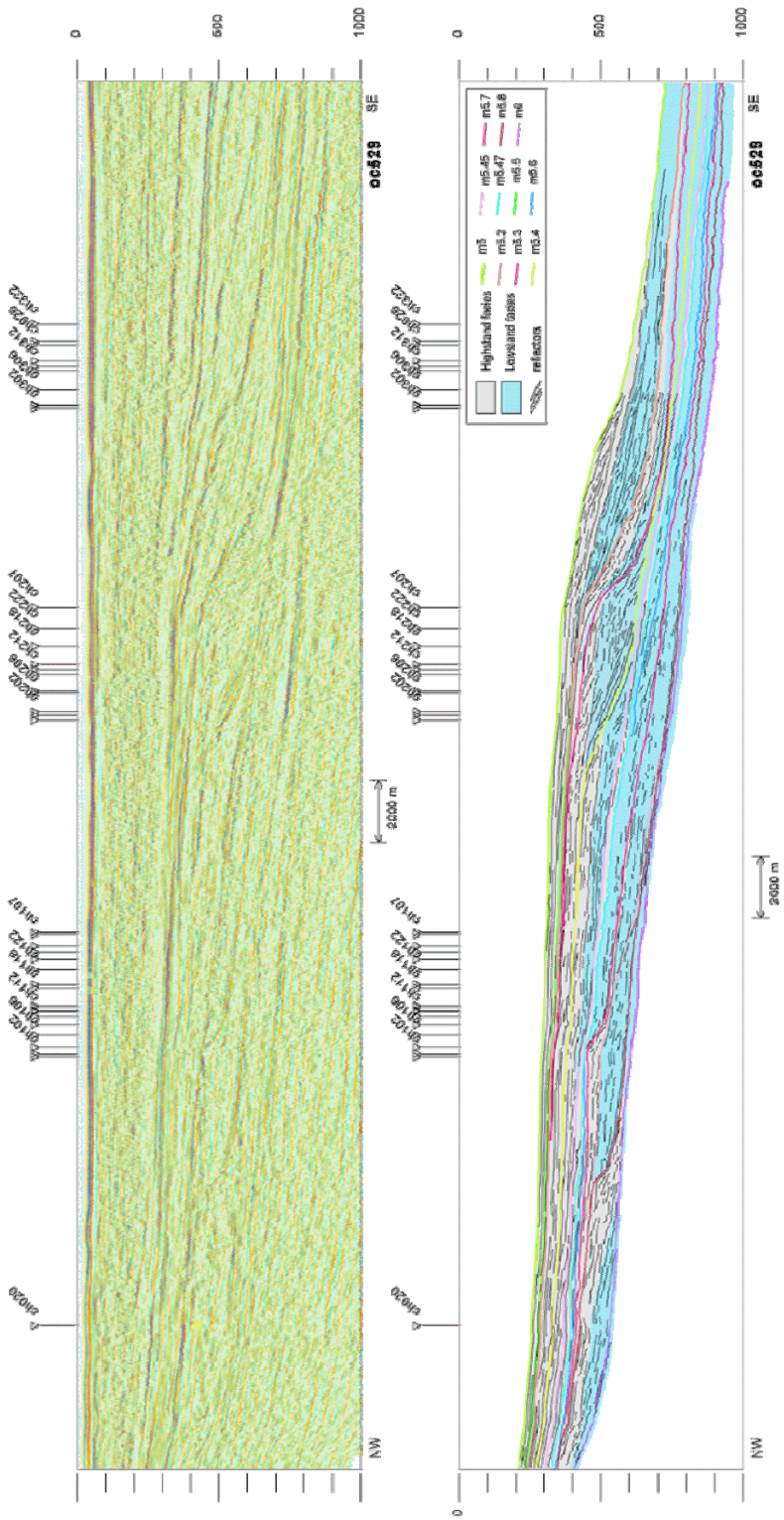
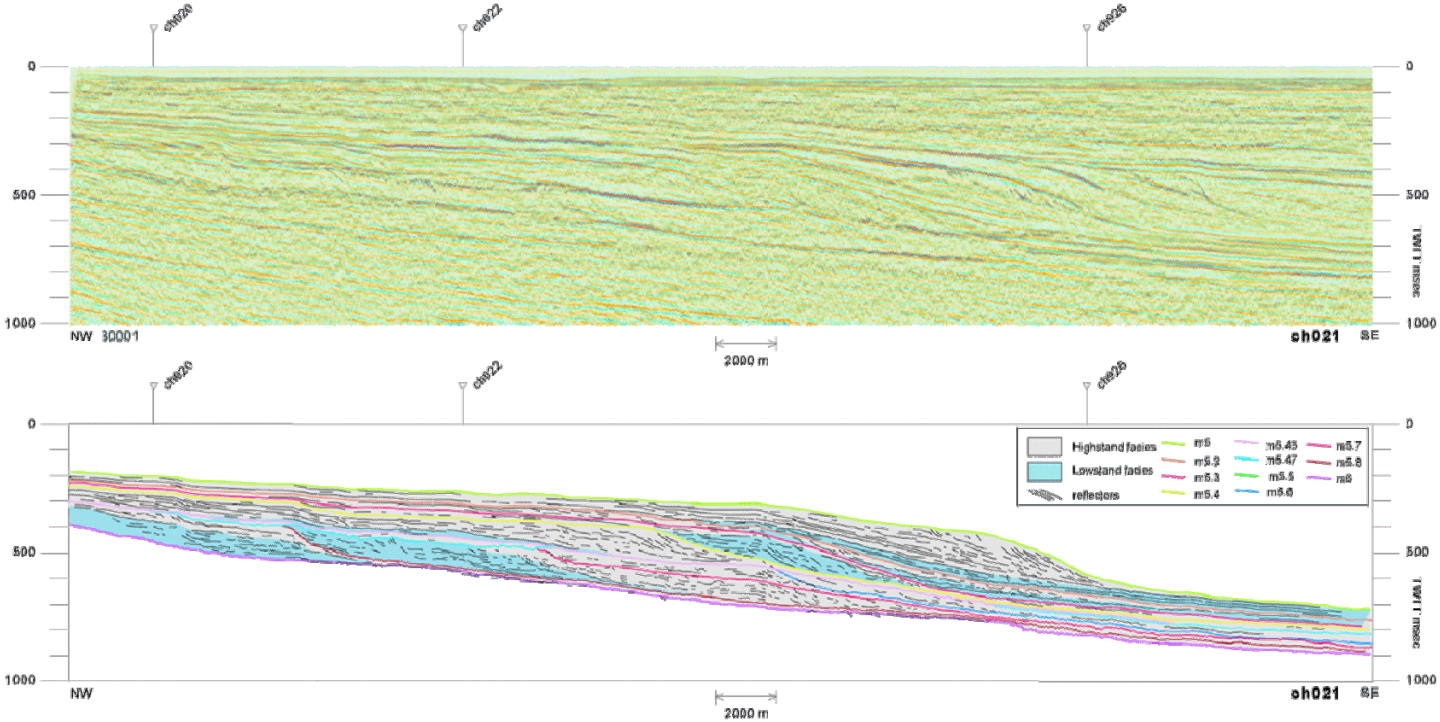


Figure 2.12 Seismic interpretation of *Oc270* Line 529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m5.4
m5.45
m5.47
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m5.7
m5.8
m6
NW
2000 m
ch021
SE

Figure 2.13 Seismic interpretation of *CH0698* Line 21

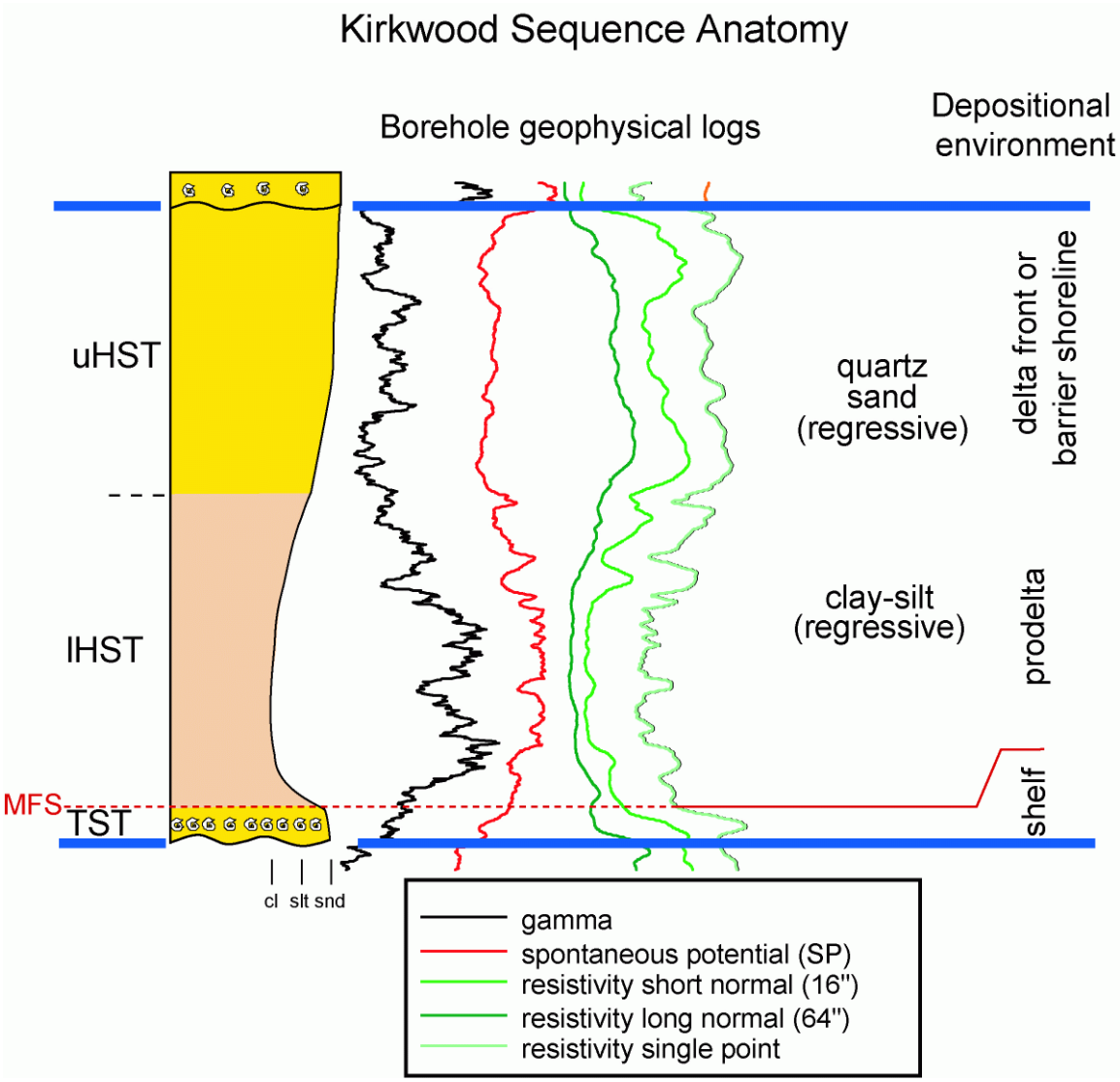

Figure 2.14. These are the characteristics of a lower Miocene Kirkwood sequence along the New Jersey margin. Deltas supply sediment to the margin. TST are generally very thin and dominated by HST deposits. The sequence displays a coarsening upwards sequence as the delta progrades. Gamma logs have a characteristic pattern controlled by the sediment type.

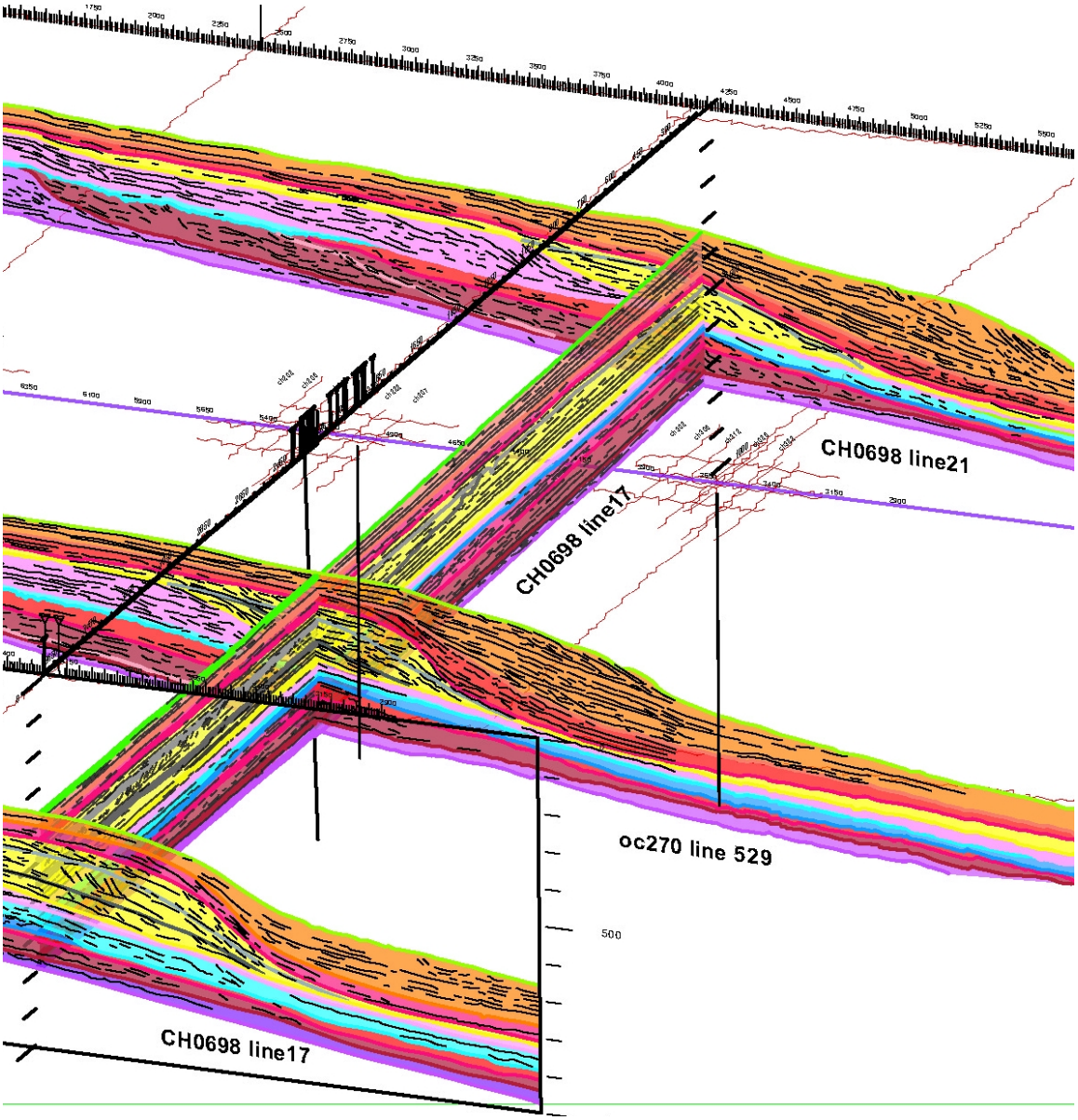

Figure 2.15. Seismic interpretation of intersection lines CH0698 lines 21, 17 and 24 and Oc270 line 529. Depicts possible lowstand parasequences within m5.4 (yellow sequence). Flooding surfaces are marked by black and gray continuous lines within the yellow sequence. Parasequences prograde to the southwest along the strike line. Slumping is evident within the lowstand facies deposits.

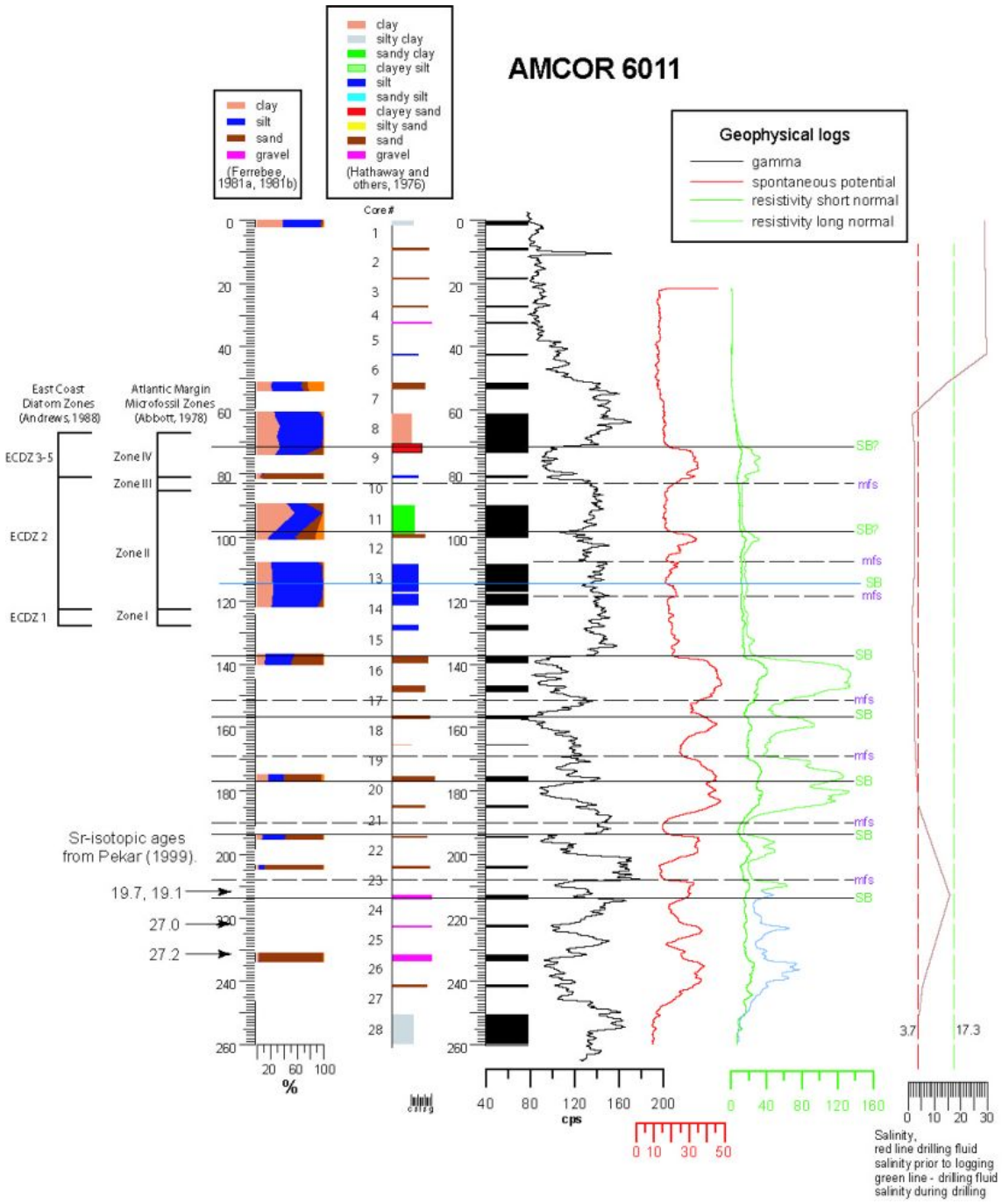

Figure 2.16. Lithologic and log data for AMCOR 6011 are depicted here. Lithologic data is form Hathaway et al. (1976) and Ferrebee et al (1981a, 1981b). Paleontologic data is form Abbott (1988) and Sr-isotopic ages are from Pekar (1999).

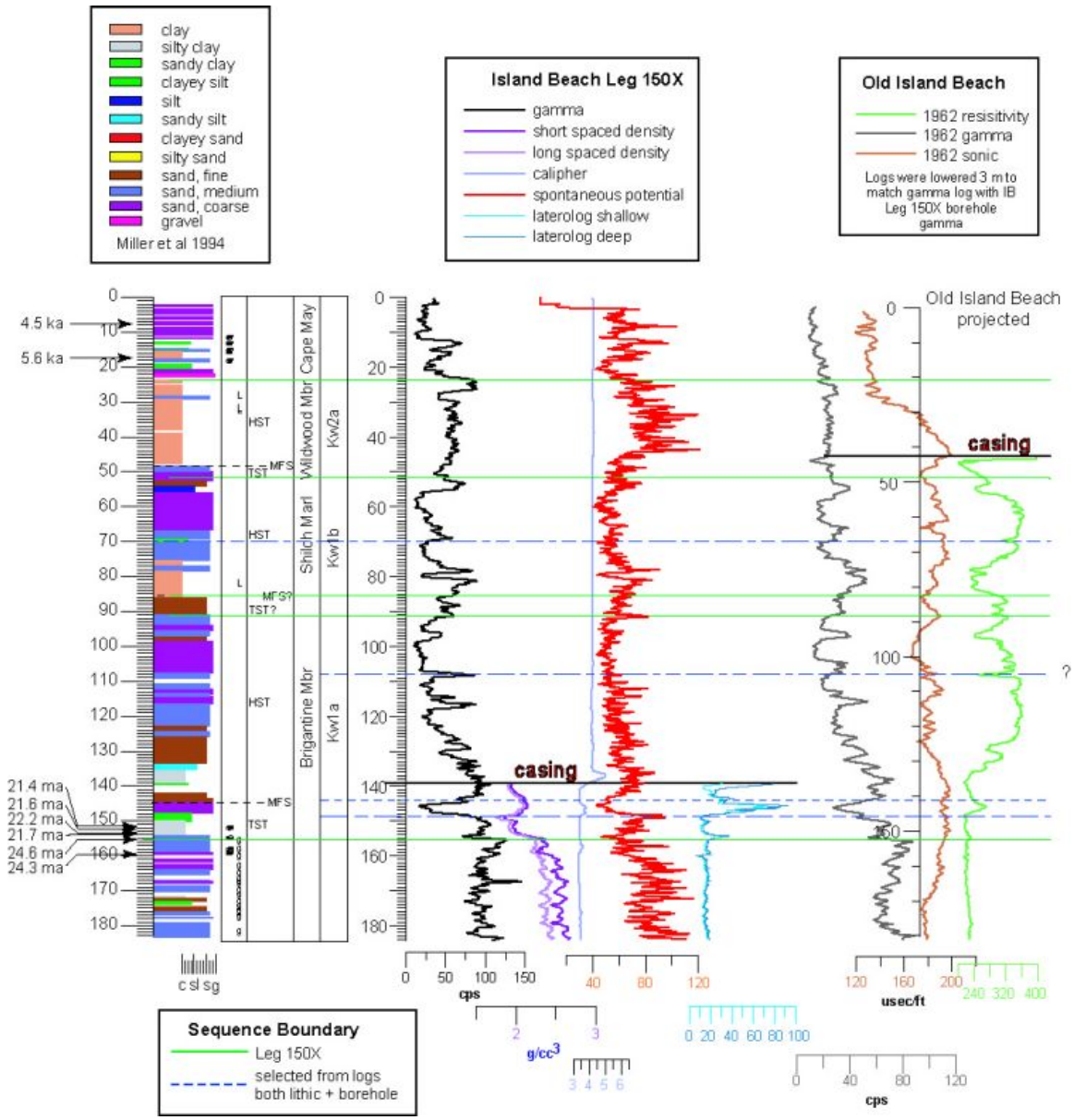

Figure 2.17. Lithologic and log data for ODP Leg 150X Island Beach site. Lithologic and Sr-isotopic age data are from Miller et al (1994). Sequence identification is from Miller et al. (1994) and Owens et al (1997). The Old Island Beach well has been projected to the IB well by gamma correlation.

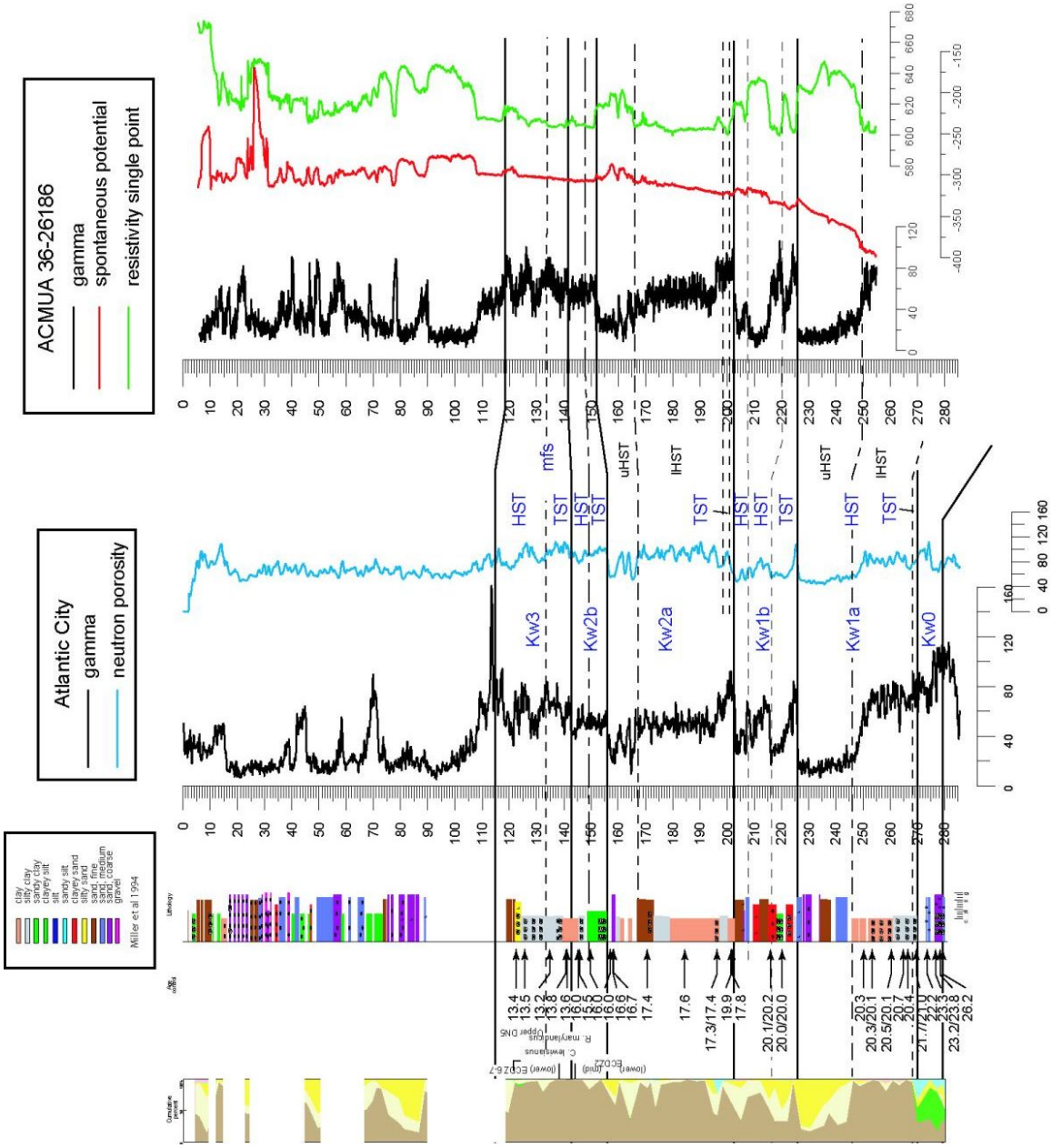

Figure 2.18. Lithologic and log data are for ODP Leg 150X Atlantic City corehole. Lithologic and Sr-isotopic age data as well as sequence identification are from Miller et al (1996a). Sequence interpretations have been projected into the nearby municipal well ACMUA 36-26186. ACMUA has a more complete log suite and allows better correlation into offshore wells (ACOW 1 and 2).

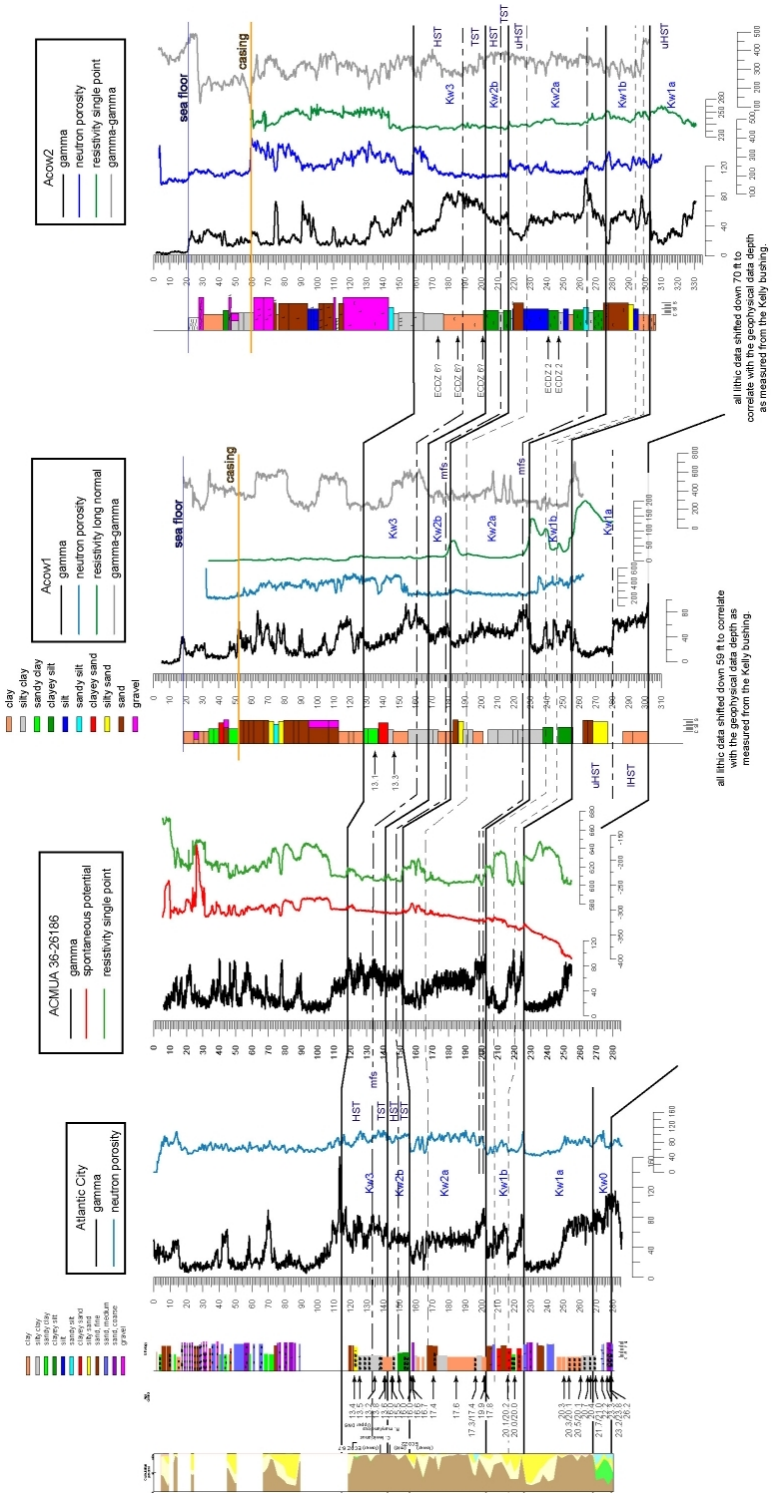

Figure 2.19. Correlation of the AC and ACMUA wells with the ACOW 1 and 2 boreholes

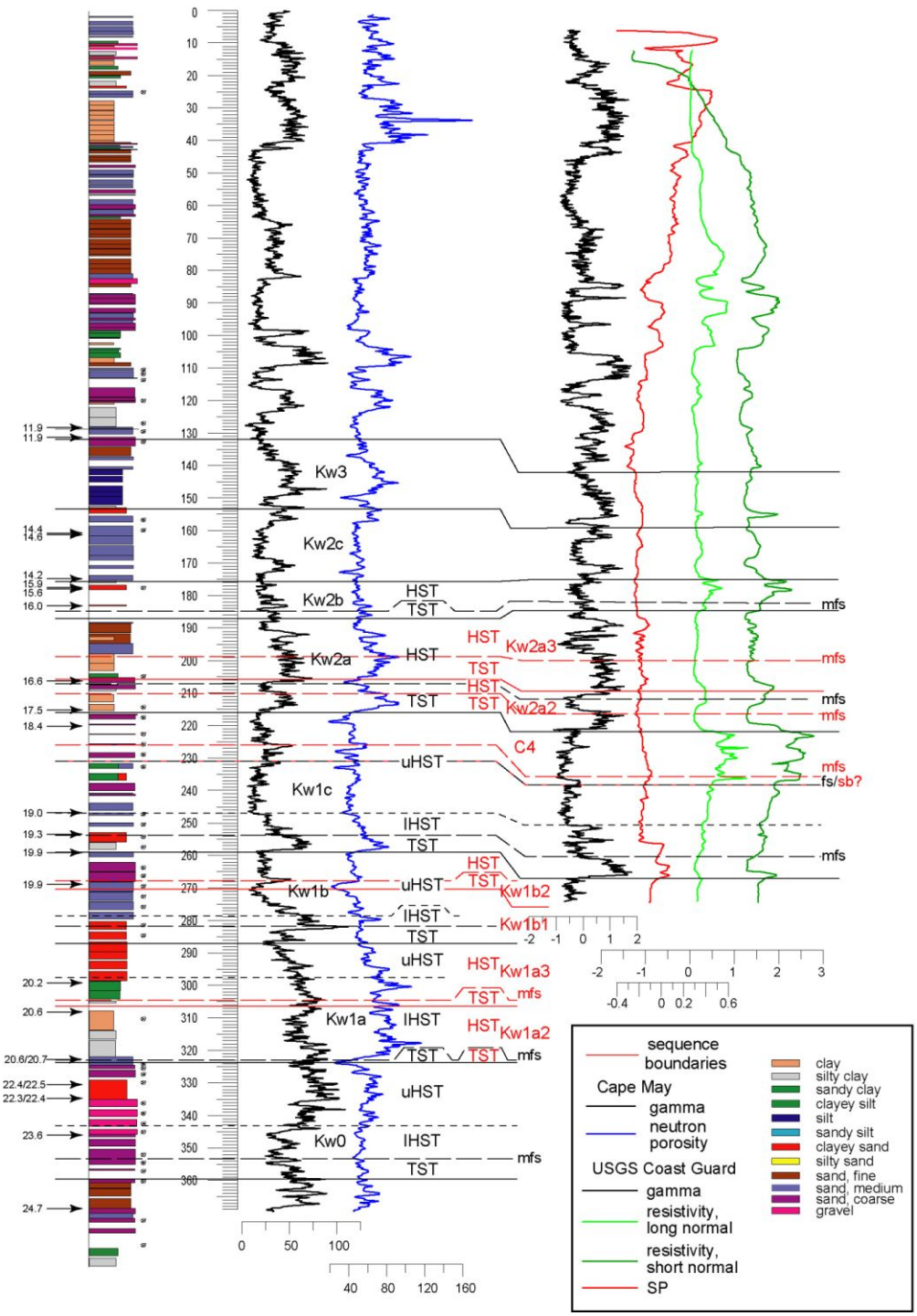

Figure 2.20. Lithologic and log data of Miocene sediment in the ODP Leg 150X Came May well. Lithologic and Sr-isotopic age data as well as sequence identification are from Miller et al (1996b). A near by Coast Guard borehole will a more complete suite of logs has been correlation to CM.

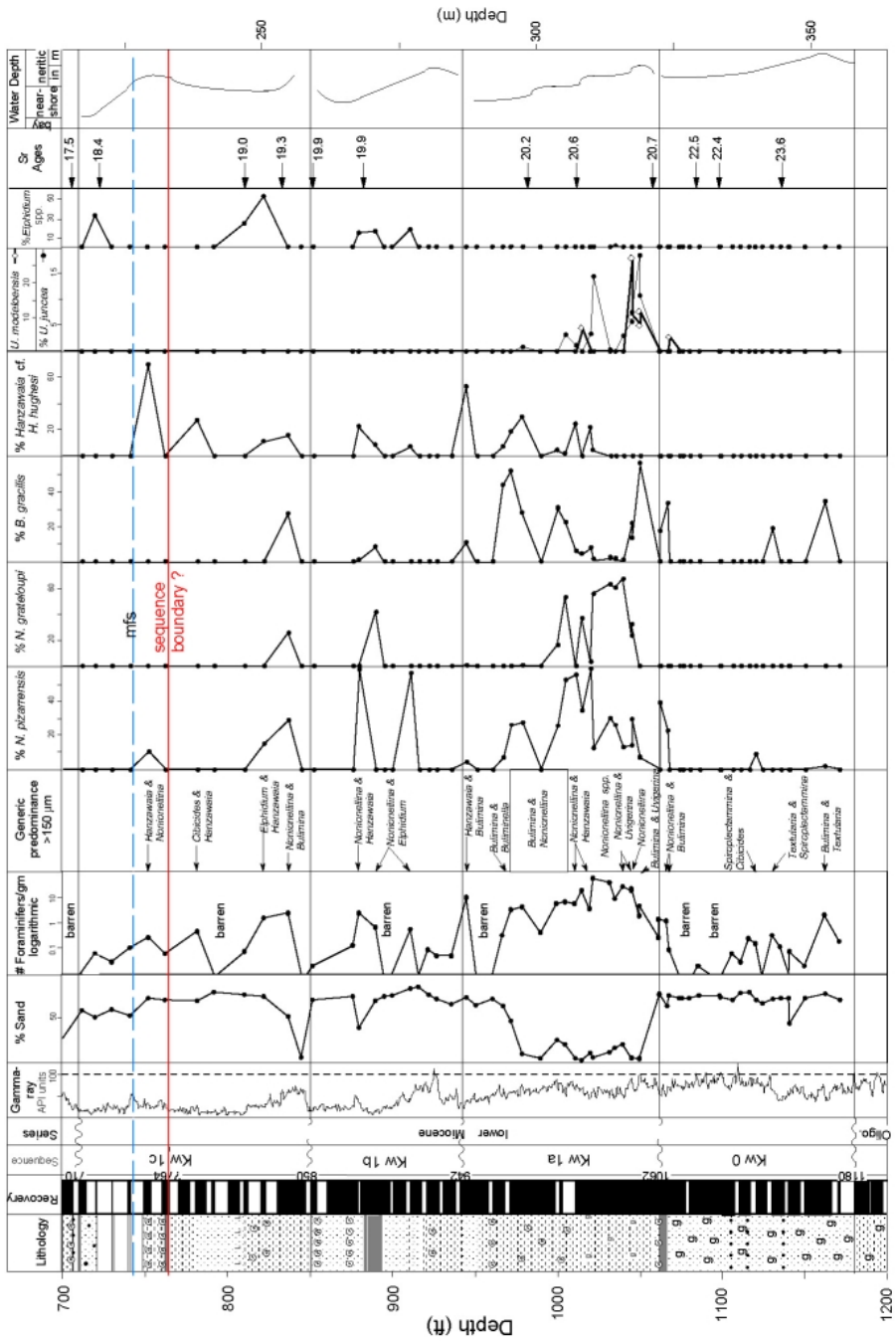

Figure 2.21. Benthic foraminiferal biofacies results from lower part of Cape May borehole from Miller et al (1997). Red solid line outlines possible sequence boundary, dashed blue line represents the suggested mfs. Modified from Miller et al. (1997).

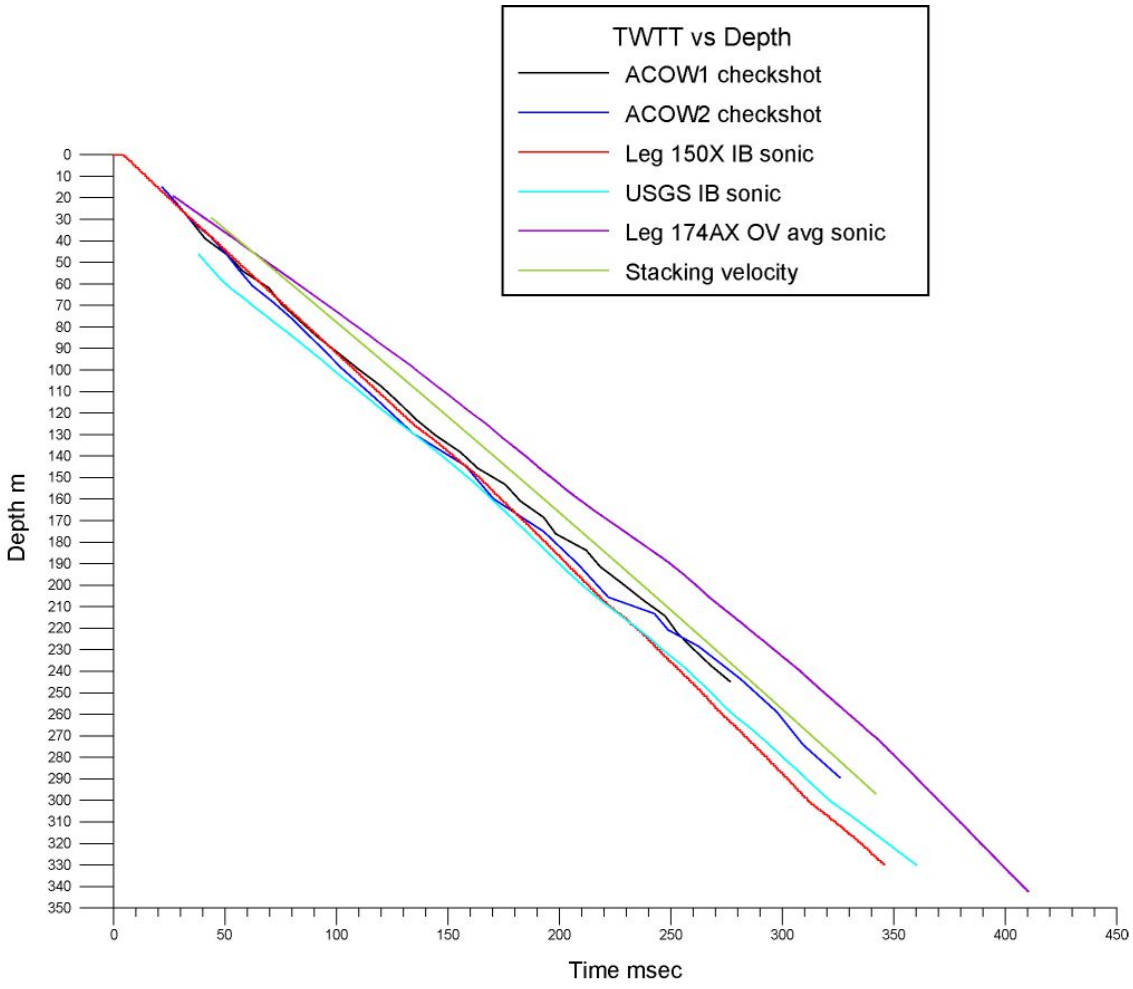

Figure 2.22. Seismic velocity data from several different sources analyzed to calculate the best time-depth function to allow an accurate projection of well log data into the time domain. Stacking velocity from CH0698 velocity analysis proved to be the best

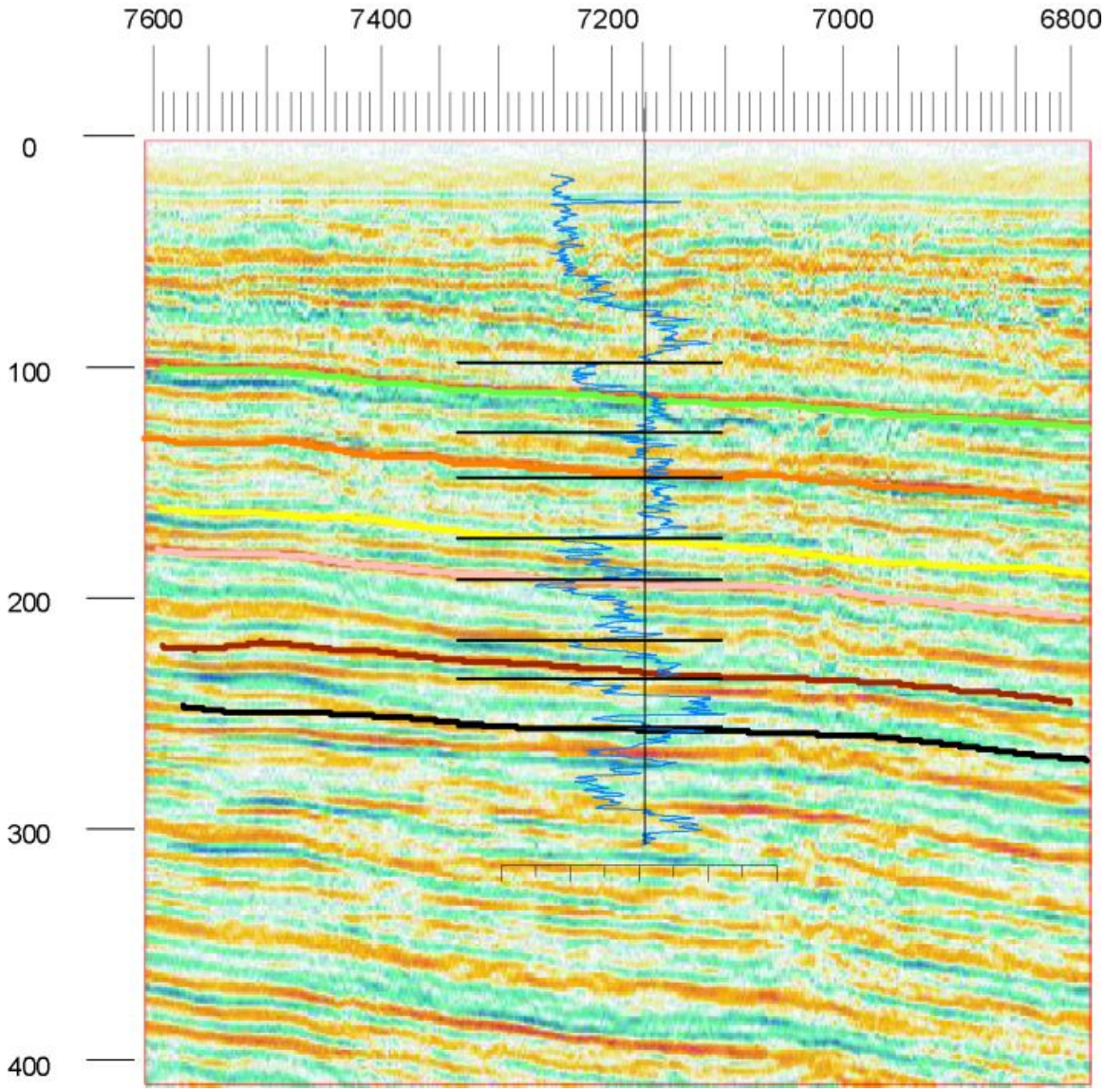

Figure 2.23. Projection of AMCOR 6011 gamma log into the time domain at the intersection of CH0698 line 17 (shown above) and line 16 is depicted. Sequence boundaries identified on the seismic data are shown according to their colors.

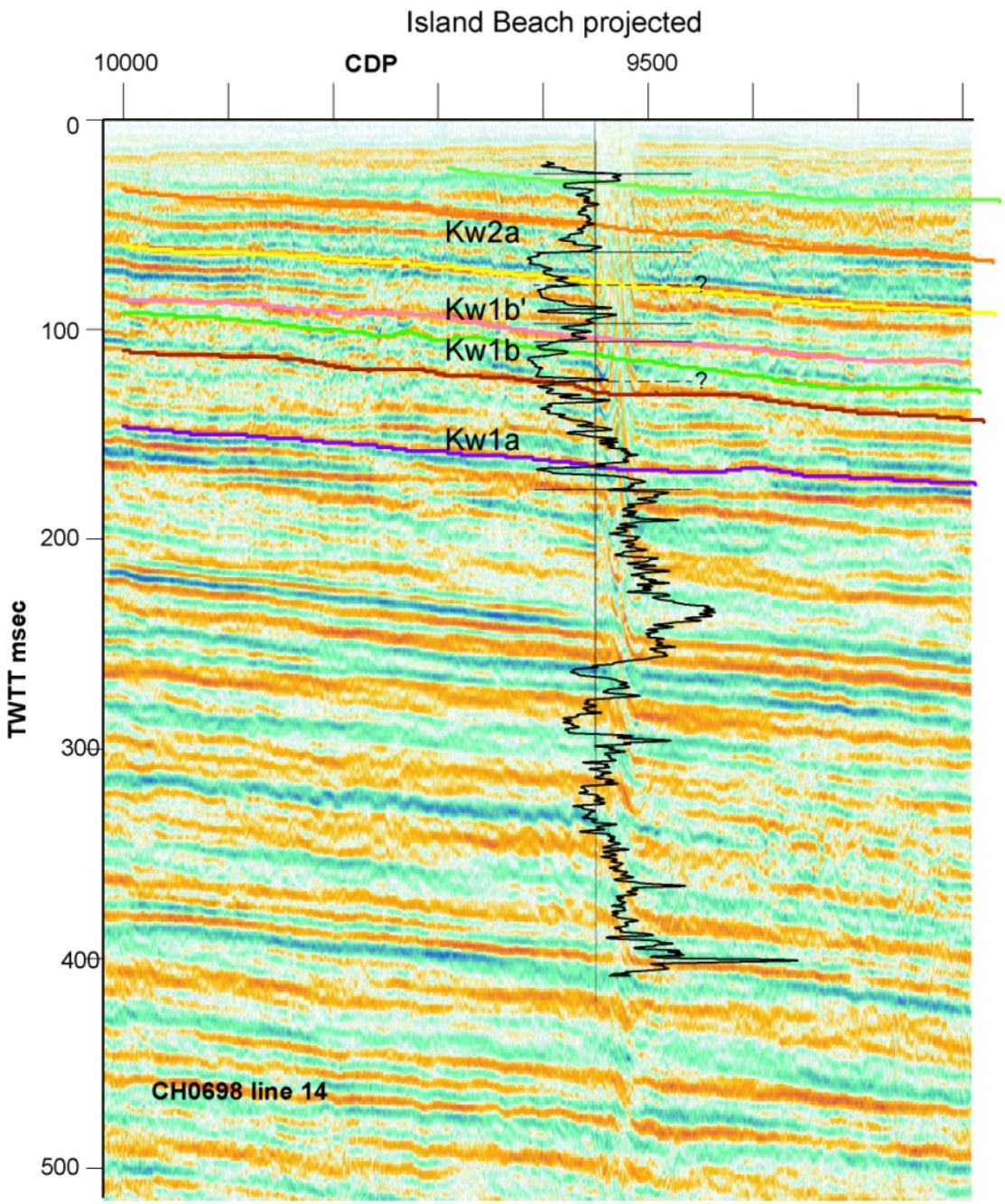

Figure 2.24. The IB gamma log has been moved into the time domain and projected along strike into CH0698 line 14. Sequence boundaries identified on the seismic data are shown according to their colors.

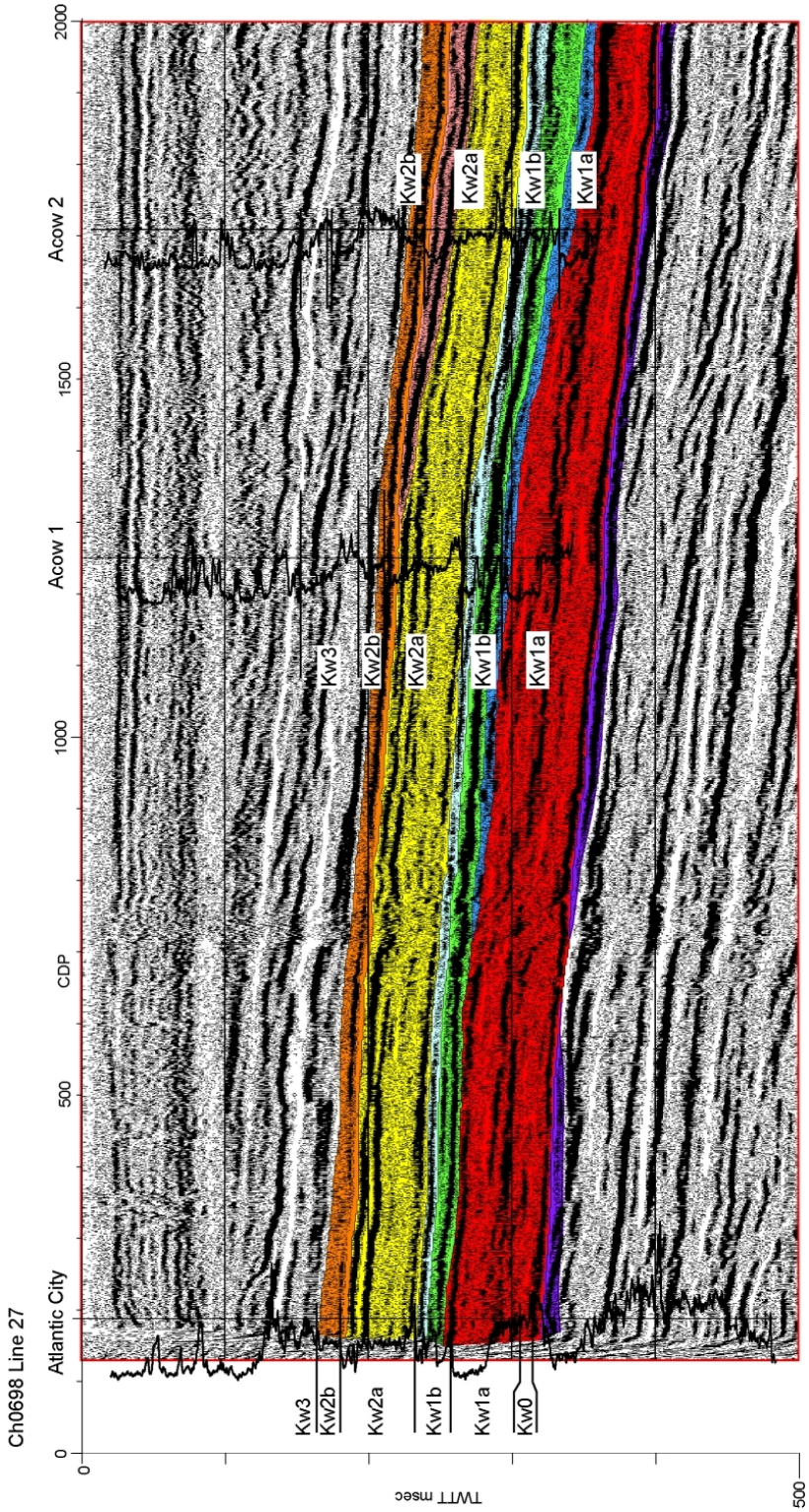

Figure 2.25. CH0698 line 27 is shown along with gamma logs for AC and ACOW wells 1 and 2. Sequence boundaries identified on the seismic data are shown according to their colors.

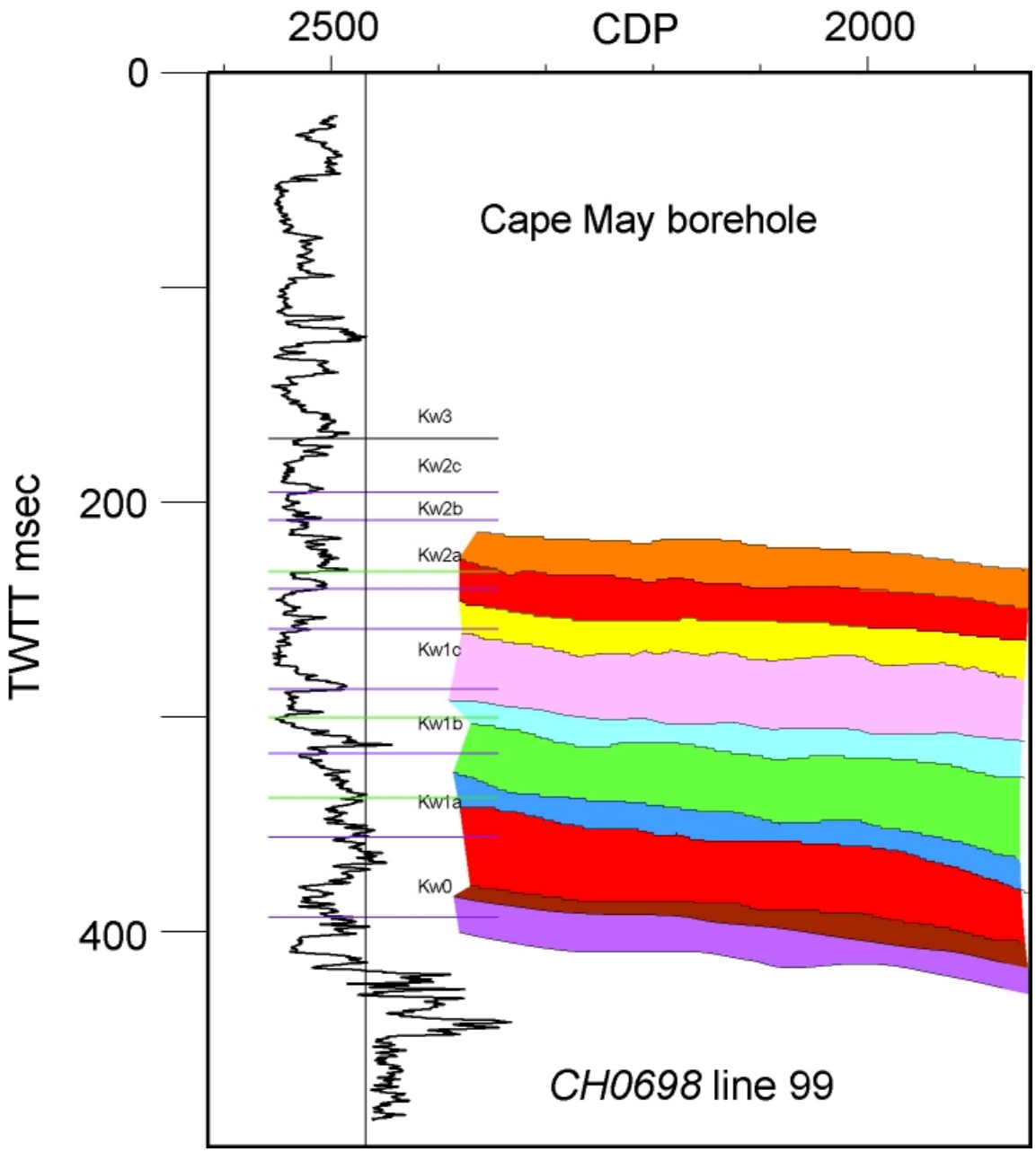

Figure 2.26. Seismic sequence interpretation has been carried to CH0698 line 99 which was collected entering Cape May inlet. The CM gamma log has been projected into the seismic line. However it falls just west of the end of line 99. Sequence boundaries identified on the seismic data are shown according to their colors.

Chapter 3 - Early Miocene growth of the New Jersey margin

A described in the introduction an earlier version of this chapter was published as:

Abstract

Sequence stratigraphy provides an understanding of the interplay between eustasy, sediment supply and accommodation in the sedimentary construction of passive margins. This study used sequence stratigraphic principles to follow the early to middle Miocene growth of the New Jersey margin and analyze the connection between relative changes of sea level and variable sediment supply. Eleven candidate sequence boundaries were traced in high resolution MCS profiles across the inner margin and matched to geophysical log signatures and lithologic changes in ODP Leg 150X onshore coreholes. Chronologies at these drill sites were then used to assign ages to the intervening seismic sequences. This study concludes that the regional and global correlations of early Miocene sequences suggest a dominant role of global sea-level change but margin progradation was controlled by localized sediment contribution and that local conditions played a large role in sequence formation and preservation. Lowstand deposits were regionally restricted and their locations point to both single and multiple sediment sources. The location of highstand deposits, by contrast, documents redistribution by along shelf currents. There is no evidence that sea level fell below the elevation of the clinoform inflection point, and the existence of extensive lowstand deposits seaward of this inflection point indicates efficient cross shelf sediment transport mechanisms despite the apparent lack of well-developed fluvial drainage.

Introduction

Reconstructing sea-level changes requires multiple techniques of investigation on multiple margins. Global (eustatic) sea-level fluctuations were primarily driven by global changes in ice volume during the Miocene epoch (23.8-5.3 Ma: Miller et al., 1996a, 1998). Though oxygen isotope variations reflect these glacioeustatic fluctuations, $\delta^{18}O$ is an imperfect recorder of ice-volume changes due to the additional effects of temperature and local salinity variations. Continental margin sediments (particularly along passive margins) also yield records of sea-level changes and the erosion and depositional patterns in sequences. Climate changes are also contained within these sediments as suggested by dramatic increases in Miocene sediment supply on this margin (Poag and Sevon, 1989, Pazzaglia, 1993) as well as globally (Bartek et al., 1991).

Sequences are unconformably bounded units initiated during baselevel lowerings by either tectonism or global sea-level falls (Vail et al., 1977, Christie-Blick et al., 1990). Vail et al. (1977) showed that sequences are the building blocks of the stratigraphic record. Posamentier and James (1993) and Christie-Blick and Driscoll (1995) suggested that sequence stratigraphy is not a rigid discipline to be forced on all sedimentary basins. There are no set rules requiring the occurrence of all systems tracts of specific geometry and thickness on all seismic profiles. Local conditions must be considered in defining internal stratal patterns (Martinsen, 1994, Martinsen and Helland-Hansen, 1995). For example, previous studies of the New Jersey margin (Metzger and others, 2000; Pekar

and others, 2001) highlighted variations on the standard model and concluded that Lowstand Systems Tract (LST) deposits were absent from the coastal plain (see summary in Browning et al., this volume).

Passive margins record changes in tectonic subsidence, sediment supply and sea level. Tectonism on passive margins is generally dominated by passive thermal subsidence that can be modeled (e.g., Steckler and Watts, 1978; Kominz et al., 1998; Van Sickel et al., 2004), though local variations need to be identified by evaluation of the distribution of sequences in coreholes or seismic profiles. In general, changes in sediment supply cannot cause baselevel lowering (Christie-Blick et al., 1990), but they can affect sequence preservation (e.g., Browning et al., 2006), thickness variations and within sequences facies changes (e.g., Posamentier et al., 1988). To evaluate sedimentation effects, a 2D or 3D view is needed either through closely spaced well logs, (van Wagoner et al., 1990) seismic profiles, or a combination of both.

The earliest multichannel seismic (MCS) profiles collected across the New Jersey shelf (Grow et al., 1979; Schlee, 1981) showed this is an excellent location to examine sequences and document the factors that control their development in a siliciclastic-dominated, prograding passive margin. These seismic data comprised widely spaced profiles using low frequency sources designed to image rift-stage sediments 10+ km below the seabed, and were not ideal for resolving details within the much shallower Cenozoic section. Later studies, some of which incorporated commercial seismic data, outlined suspected Paleogene and Neogene sequences (Poag and Schlee, 1984; Poag,

1985; Poag and Ward, 1987; Greenlee and Moore, 1988, Greenlee et al., 1988, 1992). Based in part on these analyses, but more significantly on research-based higher-resolution MCS profiles, several drilling expeditions attempted to establish correlations between sequence evolution, facies succession and sea-level change (Deep Sea Drilling Project (DSDP) Leg 95, Poag, C. W., Watts, A. B., et al., 1987; Ocean Drilling Program (ODP) Legs 150, Mountain, G.S., Miller, K.G., Blum, P., et al., 1994; Ocean Drilling Program (ODP) Legs 174A, Austin, Christie-Blick, Malone et al., 1998).

Though the New Jersey margin has been intensely studied, there have been few comprehensive reports on the 2D and 3D distribution of Miocene facies from seismic profiles. Mountain, Miller, Blum et al. (1994) used regional seismic data to provide a limited interpretation of margin development. They used the latter data to propose a drilling transect from the coastal plain to the slope that would evaluate how changes in eustasy, sediment supply and accommodation controlled sequence and margin construction through time. Scientific investigation of this transect using seismic data includes Fulthorpe and Austin (1998) and Fulthorpe et al. (1999) who studied the regional development of middle and upper Miocene sequences beneath the outer continental shelf. Poulsen et al. (1998) investigated middle Miocene sequence formation and noted a strike parallel variability in thickness and internal morphology. To date, analysis of lower Miocene sequences has been restricted to coreholes in updip and downdip locations far from their corresponding depocenters.

This study describes early Miocene sequence development as imaged on a regional seismic grid across the current nearshore and offshore New Jersey margin (fig. 3.1). Candidate boundaries are tied to onshore ODP coreholes (Miller et al., 1994a, 1994b, 1996b) to establish a sequence chronology. Seismic data interpretation depicts distinct along-strike variability in sequence development. Several isolated sediment sources and subsequent sediment redistribution due to wave climate and alongshore currents account for variations in depositional pattern among the several sequences examined. The extent of subaerial margin exposure during relative sea-level fall is analyzed.

Regional Geology

Shelf, slope and rise boreholes drilled by both industry and research scientists determined the general composition and age of seismic horizons on the New Jersey margin (Hathaway et al. 1976, 1979; Scholle 1980; Libby-French, 1981; Poag, 1985a, 1985b, Poag et al. 1987, Poag, C. W., Watts, A. B., et al., 1987, Mountain, G.S., Miller, K.G., Blum, P., et al., 1994; Austin, Christie-Blick, Malone et al., 1998). These studies identified Oligocene and lower Miocene sediments beneath the inner shelf but were hampered by low core recovery and thin deposits (Poag, 1985a). A thicker middle Miocene assemblage was identified beneath the middle and outer shelf (Poag, 1985a). Poag (1985b) and Poag and Mountain (1987) outlined separate upper Oligocene to middle Miocene seismic sequences across the slope and rise. Seismic resolution did not allow further differentiation within these deposits. Greenlee and Moore (1988) and Greenlee et al. (1988, 1992) used commercial well information and proprietary industry

seismic data to date lower Miocene seismic sequences. These authors used sequence stratigraphic criteria outlined in Payton (1977) to define four Oligocene, four lower Miocene and four middle Miocene sequences. Greenlee and Moore (1988) and Greenlee et al. (1988, 1992) concluded that lower Miocene sequences are thin units that depict limited progradation past Oligocene clinoforms. However, rapid margin progradation dominates the middle Miocene owing to significantly increased siliciclastic sediment supply.

Seismic data collected in 1990 (cruise 9009 of the R/V Ewing *Ew9009*; vertical resolution of 15 m) traversed the New Jersey margin and concentrated on imaging Paleogene and Neogene stratigraphy in the modern mid- to outer shelf and slope (fig. 3.1). Only a few lines crossed the nearshore region thereby restricting the ability to clearly define lower Miocene sequence development. *Ew9009* data outlined five lower Miocene sequence boundaries with their main depositional centers beneath the current inner shelf (table 1, Mountain, Miller, Blum et al. 1994). Seismic interpretation confirmed four sequences of Greenlee and Moore (1988) and Greenlee et al. (1988) as well as defined an additional sequence (G.S. Mountain, K.G. Miller and N. Christie-Blick, unpubl. data). Fulthorpe et al. (1996) used *Ew9009* and single-channel seismic (SCS) to map upper Oligocene to upper Miocene sequences along the modern shelf-slope break. *Ew9009* guided ODP Leg 150 on the current slope and rise (fig.1; Miller and Mountain, 1994, Mountain, Miller, Blum et al. 1994). These borehole locales were chosen to calibrate the seismically identified sequence boundaries in a distal setting where known paleoenvironmental conditions held the promise of high sedimentary and

biostratigraphic preservation potential (Miller and Mountain, 1994; Mountain, Miller, Blum et al., 1994).

R/V Oceanus collected higher resolution seismic data *(Oc270)* in 1995 over the same region as *Ew9009*, including a single shelf dip line that traversed nearly the entire shelf (fig. 3.1). This dip line, constructed from several aligned dip profiles (*Oc270* lines 29, 129, 229, 329, 429, 529) resampled industry data described by Greenlee and Moore (1988), Greenlee et al. (1992) as well as *Ew9009* line 1003. Line 1003 and the *Oc270* "29" line series image proposed drill sites of the Mid Atlantic Drilling Transect (Miller and Mountain, 1994). *Oc270* grid also traversed the ODP Leg 150 sites thereby improving sequence correlation across the outer shelf slope (fig. 3.1; Fulthorpe et al., 1999, 2000). *Oc270* guided the next generation of Mid Atlantic Drilling Transect drilling during ODP Leg 174A (fig. 3.1). This ODP leg sampled Late Miocene through Pleistocene sediments beneath the modern outer shelf and slope (Christie-Blick, Austin et al., 1998). Leg 174A sites on the modern outer continental shelf resulted in poor recovery and hole collapse owing to high sand content. Sediments older than upper Miocene were not sampled.

Marine seismic profiles traversing the modern New Jersey inner continental shelf currently supply the best images of lower Miocene shelf progradation across the Mid Atlantic margin. The seismic grid of approximately 1100 km collected on the *R/V Cape Hatteras* (*CH0698*) in 1998 crossed the inner continental shelf where lower Miocene depositional centers were imaged on *Ew9009* and *Oc270* data (fig. 3.1). The *R/V Cape*

Hatteras seismic grid forms the basis of this study. Data collection proceeded into both the Cape May and Absecon inlets thereby approaching ODP Leg 150X boreholes at Cape May and Atlantic City, NJ within 700 m. ODP Leg 150X borehole at Island Beach supplies the final core-seismic integration but still requires a 1500 m projection into the *CH0698* grid. These correlation distances between *CH0698* seismic lines and ODP coreholes are still not optimal but they greatly reduce the chance of erroneous correlations in the nearly 30 km jump into the *Ew*9009 and *Oc270* grids. Dip line *Oc270* line 529 covering the proposed IODP Expedition 313 drill sites was included in our study (fig. 3.1).

Seismic data

Seismic data acquisition on *R/V Oceanus 270* and *R/V Cape Hatteras 0698* comprised a 48-channel, 600 m streamer towed at 2 or 4 m depths (depending on sea state), a single 45/105 cu in generator-injector airgun towed at 2 meters depth and fired roughly every 12.5 m along shiptrack while maintaining a ship speed of roughly 4.9 kn over the ground. The data were recorded with an OYO DAS-1 with trace lengths of 2 sec; sample rate was 1 msec on *Oc270* and 0.5 msec on *CH0698*. Seismic data processing included outside mute, velocity analysis, Normal Moveout (NMO) correction, bandpass filtering, spreading loss correction, predictive deconvolution, Stolt migration, and time-varying gain. The data are of excellent quality with vertical resolution approaching 5 m and usable acoustic imaging to approximately 1.3 sec of two-way traveltime. Sea floor

multiples have been sufficiently suppressed. However peg leg multiples beneath steeper dipping reflectors hinder interpretation.

Seismic data interpretation involved two stages. Initial interpretation was performed on paper copies of processed data, but was superseded by interpretations on computer workstations using Landmark's Seisworks 2D software. All data were analyzed in a sequence stratigraphic framework. Geometry of seismic reflector terminations defined individual sequences according to methods outlined by Mitchum (1977), Mitchum and Vail (1977), Mitchum et al., (1977a, 1977b, 1993), Badley (1985), and Vail (1987). Typical reflector geometries of onlap, downlap, toplap, and erosional truncations outlined the classic sequence features such as sequence boundaries, and maximum flooding surfaces (MFS).

Seismic Sequences

Analysis of *CH0698* and *Oc270* seismic data built on earlier analysis of *Ew9009* profiles. Initial interpretation of *Ew9009* outlined five lower and lower middle Miocene sequences (G.S. Mountain, K.G. Miller and N. Christie-Blick, unpubl. data). Following procedures of Greenlee et al. (1992) these reflectors were labeled by color, from oldest to youngest as pink-3, Blue, sand, ochre and Green (table 1) as listed in Miller and Mountain (1994). When more detailed analysis revealed additional mappable surfaces these sequence boundaries were changed to an alphanumeric designation from oldest to youngest as m6, m5.6, m5.4, m5.2 and m5 respectively (table 1; Mountain, Miller, Blum et al. 1994).

Surface m6 was correlated to the Miocene-Oligocene boundary (Mountain, Miller, Blum et al. 1994; Christie-Blick, Mountain and Miller, personal communication). *Ew9009* grid lines lie mostly on the current outer shelf where middle Miocene to Pleistocene sequences are best developed (fig. 3.1). Only an areally limited grid occurs on the inner shelf where Oligocene and lower Miocene deposits are thickest. *Ew9009* interpretations and reflector designations were matched and transferred to *Oc270* line 529 (N. Christie-Blick, G.S. Mountain and K.G. Miller, unpubl. data). *CH0698* grid crossing *Oc270* line 529 specifically targeted Oligocene through lower Miocene deposition off the New Jersey coast creating a more regional seismic coverage and therefore offers a more complete representation of early Miocene shelf progradation.

Candidate sequence boundaries are best defined where sediments are thickest immediately seaward of the preceding clinoform inflection point (fig. 3.2). The clinoform inflection point is the location of maximum change in slope associated with clinoform geometry. It has been termed shelf edge (Schlee, 1981), depositional coastal break (Vail et al., 1977), shelf break (Van Wagoner et al., 1988), clinoform breakpoint (Fulthorpe and Austin, 1998; Fulthorpe et al., 1999), and clinoform inflection point (this study). At these locations seismic terminations characteristic of falling stage, lowstand and highstand facies are best developed. Away from these depocenters the seismic expression of sequence boundaries within the *CH0698* seismic grid becomes discontinuous and harder to track. Sequence boundaries may be truncated, amalgamated, or simply appear to merge in profiles because they are below seismic resolution (fig. 3.2 and 3.3). This creates the problem that not all sequence boundaries

project landward and will not necessarily be intercepted in all drill locations. Small scale incised valleys that average 540 m wide with an approximate 10 m deep thalweg are evident on most candidate boundaries on *CH0698* data. Seismic resolution and grid line spacing prohibits detailed tracing of the valleys. Surface amalgamation also occurs seaward of the depositional center where continuous parallel reflectors mark deeper water sediments and fine grained deposition would be expected. Numerous small-scale normal faults are imaged in this section. Cartwright and Dewhurst (1998) and Gay et al., (2004) described similar fault morphologies in fine grained sediments in the North Sea and Congo Basin, respectively and ascribed it to syneresis, a process related to volumetric decrease during early compaction of clay-rich sediments and oozes.

Eleven candidate sequence boundaries were identified within the *CH0698* grid. These include five previously selected boundaries on *Ew9009* data (N. Christie-Blick, G.S. Mountain and K.G. Miller, unpubl. data). Surfaces originally defined as m6, m5.6, m5.4, m5.2 and m5 (Mountain, Miller, Blum et al. 1994) are consistent throughout the *CH0698* grid (table 1). Newly identified candidate sequence boundaries lie between these reflectors and are named consistent with position. New boundaries include, from oldest to youngest, m5.8, m5.7, m5.5, m5.47, m5.45, and m5.3 (table 1). Sequences are named according to their basal reflector boundary, such that sequence m5.5 lies on reflector m5.5 and may be truncated by several different younger reflectors according to regional surface truncation and/or amalgamation.

Seismic facies definition allowed discrimination of internal stratal geometries that helped define systems tracts boundaries. Transgressive facies defined by onlap landward of the clinoform inflection point are rarely evident due to thin onlapping deposits that are generally below seismic resolution. Miller et al. (1998) characterized Miocene sequences, based on cores collected on the early Miocene paleoshelf (now beneath the modern coastal plain) as beginning with a thin Transgressive Systems Tract (TST). Results from ODP onshore core locations (Miller et al., 1994a, 1994b, 1997, 2001) (fig. 3.1) show that lower Miocene TST's average 6 m in thickness, approximately equal to *CH0698* seismic resolution. *Oc270* line 529 records the best example of TST deposits. TST sediments prograde rapidly as suggested by middle neritic clays encountered in cores (Miller et al., 1997) commonly overlying sequence boundaries. A gently sloping, ~0.06^{o}, 1:1,000 gradient (Steckler et al., 1999, Pekar et al., 2003) Oligocene paleoshelf allowed relative sea-level rise to rapidly migrate across the shelf. Miocene sediments prograded past the Oligocene paleoshelf edge and infilled an Eocene ramp margin (1:500 gradient).

Isphording and Lodding (1969) and Isphording (1970) described the lower and middle Miocene Kirkwood Formation in the outcrop belt as composed of three different members that grade into each other along strike (fig. 3.1). The Alloway Clay was mapped in the south and described as representing a middle neritic paleoenvironment. In the north the Asbury Park Member represents transitional marine environments. Gradational between and overlying these two members is the Grenloch Sand Member, an interbedded sand unit deposited in nearshore environments that marks a change from

transgression to regression. Miller et al. (1997) and Sugarman and Miller (1997) both noted the inability to correlate these facies either in outcrop, due to poor remaining exposures, or in downdip wells. However the deposits described by Isphording and Lodding (1969) and Isphording (1970) represented the generally nearshore deposits suggesting the lateral extent of marine incursion during the early and middle Miocene. The paleoshelf/coastal plain was approximately 110 km wide when measured from the western outcrop belt (fig. 3.1; Owens et al., 1998) to the lower Miocene clinoform inflection point observed in *CH0698* seismic data. The rapid, relative sea-level rise across this low gradient shelf limited the deposition of transgressive sands.

Highstand (HST) deposits identified by prograding, downlapping reflector terminations dominate the areal extent of the seismic sequences. Distance to the underlying clinoform inflection point controls the arrangement of HSTs in the following ways. More landward regions contain a thin, discontinuous, oblique downlapping basal unit that due to inadequate seismic resolution typically contains an unresolvable Maximum Flooding Surface (MFS) that commonly merges with the sequence boundary within seismic resolution. Continuous to discontinuous parallel reflectors overly these downlaps and continue seaward of the clinoform inflection point. These parallel reflectors continue up to or are cut by the next overlying sequence boundary. Hummocky reflector patterns occur locally within these prograding units. Seaward of the clinoform inflection point downlapping reflector terminations, both oblique and sigmoidal, are more evident and delineate the MFS atop the lowstand deposits. Downlaps dip more steeply and form

thicker depositional units at these locations due to higher accommodation than across the paleoshelf (fig. 3.2).

Lowstand (LST) deposits are restricted to seaward of the clinoform inflection point of the underlying sequence. Seismic resolution restricts any interpretation of valley fill on the paleoshelf as either lowstand and/or transgressive facies. Rare larger incised valleys contain reflectors showing oblique onlap. Ashley and Sheridan (1994) identified similar reflector geometries in Pleistocene incised valley fills interpreted to develop during transgression. A thin lowstand lag deposit mantles the incised valley in their Pleistocene examples (Ashley and Sheridan, 1994). Reflector geometry on *CH0698* data do not definitively support nor contradict the interpretation of Ashley and Sheridan (1994). Lowstand facies contain reflectors that both onlap the clinoform front and downlap farther offshore (Mitchum et al., 1977b, Sangree and Widmier, 1977). Several different depositional geometries characterize the lowstand facies within the *CH0698* grid. Thin onlapping and downlapping reflectors capped by a high amplitude reflector commonly occur at the clinoform base. Other lowstand bodies display a subtle mound morphology typically developed farther seaward. Broad wedge-like bodies occur atop both mound-like units and onlap the clinoform front. Seaward from the clinoforms the basal reflectors can display hummocky reflector patterns. Continuous to discontinuous parallel reflectors within the wedge overlie older reflectors and onlap the clinoform front and either downlap past the hummocks or project out of the seismic grid. Locally overlying sequence boundaries can truncate the lowstand facies reflectors (fig. 3.2).

Sequence Chronology

Deciphering the chronology of the candidate sequence boundaries relies on correlation to onshore coreholes and to a lesser extent three boreholes resident within the seismic grid. Two rotary drilled holes ACOW 1 and 2, drilled by US Geological Survey offshore Atlantic City currently within the *CH0698* grid have limited lithological descriptions (Mullikin, 1990) and fossil and/or Sr-isotopic age determinations (fig. 3.1 and 3.4). Sugarman et al.(1993) listed two Sr ages for ACOW 1 of 13.1 and 13.3 Ma at 114 and 129 m, respectively, from core material and the drill shoe, which give accurate depth delineation (fig. 3.4). Owens (unpublished data) used diatom and silicoflagellate fossil assemblages from five horizons to supply limited dating on the ACOW 2 borehole. This analysis included two horizons at 241 and 247 m that contain East Coast Diatom Zone (ECDZ) 2 assemblages, while the remaining three samples at 201, 187 and 174 m are ECDZ 6(?) using correlations of Abbot (1978) and Andrews, (1987, 1988) (fig. 3.4). Sugarman et al. (1993) used Sr-isotopic age estimates to date the different ECDZ zones thereby allowing a better chronostratigraphic correlation into onshore ODP coreholes.

Atlantic Margin Coring Project hole 6011 (AMCOR 6011) drilled by the USGS in 1976 (Hathaway et al., 1976, Poppe, 1981) is the only corehole that intercepts the lower Miocene and Oligocene sediments within the *CH0698* seismic grid (fig. 3.1). Hathaway et al. (1976) describes a 23% average core recovery within this hole. However, Abbott (1978) was able to supply paleontological age information for AMCOR 6011 using diatom and silicoflagellate fossil assemblages. Andrews (1988) subsequently redefined

these ages into the East Coast Diatom Zones and outlined ECDZ 1, ECDZ 2 and ECDZ 3-5 in three different horizons within AMCOR 6011 cores. This only allows a general chronostratigraphic division of the drilled material and correlation with more accurately dated sequences onshore. Across the Oligocene/Miocene boundary, core recovery in AMCOR6011 is further reduced to approximately 5-10% (Hathaway et al., 1976) thereby restricting the ability to date the sediment and establish correlations to *CH0698* seismic sequence boundaries. However, Pekar (1999) was able to approximate the Oligocene/Miocene boundary within AMCOR6011 through Sr isotopic ages of shell material. All three of these offshore holes, ACOW1, 2 and AMCOR 6011 have high-quality downhole geophysical logs that can be used to validate sequence interpretation as well as provide age constraints on seismic data. When used with the limited geochronological information, the logs allow direct correlation with well dated, higher resolution ODP Leg 150X onshore coreholes (fig. 3.4) (Miller et al., 1994a, 1994b, 1996b).

Geophysical logs collected in the offshore wells display similar log patterns to those collected in onshore coreholes, thereby suggesting similar sedimentation patterns and sequence development. These data indicate the offshore wells contain a basal fine-grained sediment similar to the clay silt of the TST described in the onshore ODP coreholes (Miller et al., 1994a, 1994b, 1996b) (fig. 3.4). Log patterns above the TST in the HST in the ODP wells mimic those in the offshore. The pattern of grain size within sequences coarsening upwards from overall silt into sand therefore continues offshore.

Analysis of ODP onshore coreholes drilled at Island Beach, Atlantic City and Cape May established a detailed geochronology of six different lower and lower middle Miocene sequences (Kw0, Kw1a, Kw1b, Kw1c, Kw2a, Kw2b; 24.2 to 15.6 Myr, table 1; Sugarman et al., 1997; Miller et al., 1998). Each sequence begins with a basal unconformity covered by a thin TST and a thicker HST. Sr-isotopic stratigraphy using the timescale of Berggren et al. (1995) shows a strong chronostratigraphic correlation between sequences sampled in ODP onshore and offshore legs (Miller et al., 1991, 1996b, 1998). Miller et al. (1991, 1996a, 1998) has shown that glacioeustatic changes correlate to the development of sequences in the coastal plain. de Verteuil (1997) used palynological data to outline seven sequences at the ODP Leg 150X Atlantic City corehole. ODP Leg 174AX coreholes at Ocean View and Cape May Zoo (Miller et al., 2001, Sugarman et al., 2007) supplied sufficient information to redefine the six sequences into ten.

These onshore and offshore drill holes supply sufficient information to date and correlate the *CH0698* seismic sequences (table 3.1). Miller et al. (1998) correlated onshore Miocene sequences with seismic sequence boundaries (m6, m5.6, m5.4, m5.2 and m5) on *Ew9009*. *CH0698* core-seismic integration (table 3.1) further refines these associations with the benefit of an increased number of both sequences and seismic surfaces. An interpretational difference exists on surface m5 as Miller et al. (1998) correlated it with the base of onshore sequence Kw2b while the present analysis suggests an association with the top of Kw2b. The total amount of time recorded by the seismic sequences varies on each seismic line due to along strike variability (figs. 3.7 and 3.8). Wherever a

sequence is not interpreted on a seismic line a hiatus or missing time interval occurs. Coring and logging during proposed IODP Expedition 313 is designed to resolve inconsistencies of this type and establish the extent to which there are relationships between facies and seismic character in siliciclastic systems.

Along-Strike Variability

The thickness of lower Miocene sediments varies along the New Jersey margin, making it impossible to detect all sequences on all profiles (fig. 3.3, 3.5 and 3.6). Sequences and their defining boundaries can be resolved where thick accumulation contains recognizable reflector terminations against underlying surfaces and provide evidence of base-level fall. But there are areas in which sediments seaward of the underlying clinoform inflection point thin laterally to reveal basal downlap in the along-strike as well as the seaward direction. At these locations sequences are too thin to resolve the reflector geometry and as a result dip lines through these areas fail to detect the complete succession of sequences seen elsewhere.

Miocene sedimentation in the New Jersey coastal plain was dominated by deltaic deposition (e.g., Owens and Sohl, 1969; Sugarman et al., 1993; Browning et al., in review). Sugarman et al. (1993) studied lower and middle Miocene sequence deposition patterns under the modern coastal plain and recorded an initial depocenter south of Island Beach that migrated southward near Cape May through time (fig. 3.1). Not surprisingly, seismic sequence isopachs also display changing deltaic depositional centers (fig. 3.5 and

3.6). Lowstand facies isopachs further substantiate and locate the approximate sediment inputs that dominated margin growth during low relative sea level (fig. 3.5 and 3.6). Isopachs suggest two main foci of sedimentation: one, from the north to northwest and restricted to the northeastern section of the *CH0698* grid and a second and larger depocenter from a western provenance disbursing sediment across the south and central grid. Lowstand facies of the m6 and m5.8 sequences are dominated by a northeastern depocenter that builds seaward into a slight promontory (fig. 3.5). A subordinate m6 lowstand occurs near Cape May indicating a secondary sediment source (fig. 3.5). The well-defined linear lowstand deposits indicate sediment reworking probably due to wave activity. The distribution of m6 and m5.8 highstand facies portrays a limited amount of progradation seaward of the lowstand, accompanied by a significant amount of lateral deposition (figs 3.5). Both sequences merge with the m5.7 sequence towards the southwest. It is uncertain whether m5.7 amalgamates with m6 and m5.8 because of low sedimentation in the southwest or because of an increased removal from transgressive ravinement or shelf current controlled redeposition. Allen and Posamentier (1993) indicated that landward of the shoreline two stages of ravinement occur: (1) an initial tidal and (2) subsequent wave ravinement surface as sea level rises and migrates across the region. Sediments deposited in ~10 m water depth, equal to fair-weather wave base commonly undergo marine erosion and subsequent redeposition during transgression (Ashley and Sheridan, 1994, Cattaneo and Steel, 2003). These erosional processes could account for the removal and redeposition of a significant amount of sediment.

Sequences m5.7, m5.6, m5.5 and m5.47 portray a more regionally uniform cross shelf progradation (fig. 3.5 and 3.6). Isopachs depict margin-parallel, linear to slightly arcuate depocenters across the central section of the grid. Lowstands suggest that sequences m5.7 and m5.5 have two separate sediment inputs while sequences m5.6 and m5.47 present a dispersed, single source (fig. 3.5 and 3.6). Sequence m5.7 has limited connection between the two separate lowstand facies while the two sediment inputs of sequence m5.5 are more closely spaced and show a higher degree of overlap. A more linear lowstand that mimics the overall sequence deposition occurs for sequences m5.6 and m5.47 (fig. 3.5 and 3.6). Both lowstand facies could represent a single, dominant sediment source with subsequent along-strike current modification that redistributed the sediment. Lowstand isopachs hint of a possible redistribution towards the southwest. Alternatively, sediment may have been supplied by several smaller sources, approaching a line source morphology originating over a wider area. Later alongshore current modifying lowstand sediment distribution of sequences m5.6 and m5.47 cannot be ruled out.

Sequences m5.7, m5.6, and m5.5 prograded to approximately link with the promontory constructed by sequences m6 and m5.8, thereby developing a more linear, southwest trending depositional front (fig. 3.5). Dominant deposition migrated to the central and southern section of the grid during construction of the three younger sequences m5.7, m5.6, and m5.5. By the time of sequence m5.47 the central part of the deltaic depositional front had prograded farther eastward to the edge of the *CH0698* grid such that it remains the youngest sequence completely imaged with the grid (fig. 3.5 and 3.6).

The four youngest sequences examined in this study (m5.45, m5.4, m5.3 and m5.2, table 1) display fairly uniform deltaic progradation (fig. 3.6). Only m5.4 suggests multiple separate sediment sources during lowstand deposition (fig. 3.6). By the time of sequence m5.3 the clinoform inflection point had built seaward of the southern half of the *CH0698* grid and is no longer imaged. The northern half of the grid, by contrast, covers all the major features of the m5.3 and m5.2 sequences.

Regressive highstand sediments form the most areally extensive deposits within the *CH0698* grid. Lowstand~~s~~ facies are restricted to mound and wedge bodies at the clinoform fronts. 'The resolution of CH0698 seismic data (roughly 5-10 m vertical and 100-150 m lateral) limits the ability to detect incised valleys. Highstand deltaic sediments blanket the paleoshelf, downlap onto the underlying sequence boundary, and prograde to the preceding clinoform inflection point (fig. 3.3). Once deposition filled the accommodation on the paleoshelf the foci of highstand sedimentation migrated seaward of the clinoform inflection point where accommodation was greater. However, highstand facies display a greater along margin sediment redistribution than imaged in lowstand facies. The along-margin currents allow highstand sediments to blanket the region landward of the clinoform inflection point.

Deposition along the US Mid-Atlantic margin has long been categorized as storm-dominated. Beardsley and Boicourt (1981) described a southwest directed, counterclockwise eddy along the Mid Atlantic Bight maintained in part by the

northeasterly flow of the Gulf Stream. Stronger alongshore currents related to the eddy develop in the nearshore as opposed to mid to outer shelf locations. Byrnes et al., (2004) determined that along-shelf currents are dominated by wind processes and account for ~70% of total current energy. Cross shelf currents are lower and have a mean flow direction onshore within the modern transgressive regime. The main sediment migration controlled by shelf currents is from north to south based on an analysis of data from 1843 to 1891 and from 1934 to 1977 (Byrnes et al., 2004). Snedden et al., (1994) and Haynes and Nairn (2004) explained late Pleistocene/Holocene sand bodies now oriented NE-SW along the inner shelf developed as the result of waves approaching from the NE that move sediment south along the New Jersey coastline. Overeem et al., (2005) modeled this late Pleistocene and Holocene sedimentary deposition and stated that storm climate strongly controlled grain size estimates. The strong storm and marine current regime is responsible for the dominant sediment redistribution along the New Jersey coastline. Pleistocene and Holocene data show a consistent alongshore sediment migration controlled by intermittent, large nor'easter storms (Swift 1970; Swift et al., 1986a, 1986b; Beardsley and Boicourt 1981; Byrnes et al., 2004; Haynes and Nairn 2004) Both sand and mud are resuspended by occasional storm waves and carried farther offshore. Moore (1969) argued that sand drops out of fluvial plumes and becomes reworked by nearshore, margin-parallel currents. Mud remains in suspension longer, but is eventually deposited several kilometers offshore. Swift (1970) and Swift et al., (1986a, 1986b) stressed a more dominant influence of storms along the Mid-Atlantic margin, claiming that sand is constantly redistributed southwestward along the margin by diffusive and advective processes.

Miocene deltaic sedimentation along the New Jersey margin was strongly influenced by a storm waves. While early work characterized deltas as either sediment-, tide- or wave-dominated (Coleman and Wright, 1975; Galloway 1975), recent studies have shown that this subdivision is too simple as it overlooks individual delta lobes that experience different controlling factors that vary through time (Rodriguez et al., 2000; Bhattacharya and Giosan, 2003; Porebski and Steel, 2003, 2006; Swenson et al., 2005). Isopachs prepared in this present study show limited progradation; Miocene deposition more commonly linear, shore parallel deposits similar to deltas controlled by a strong wave climate (Rodriguez et al., 2000; Bhattacharya and Giosan, 2003; Correggiari et al., 2005). However it should be noted the difficulty in differentiating wave-influenced deltas from shoreface deposits (Bhattacharya and Giosan, 2003) as New Jersey has been described as controlled by deltaic deposition (Sugarman et al., 1993; Miller et al., 1997, 1998; Browning et al., 2006, in press) and Delaware by shoreface processes (Miller et al., 2003; Browning et al., 2006).

Pekar et al. (2003) suggested that wave conditions during the Oligocene were similar to those on the modern Mid-Atlantic shelf, characterized by efficient sediment dispersal due to along-shelf currents. These workers also suggested that once sea level dropped through 90 m, across-shelf processes led to sediments bypassing-the clinoform inflection point. Here marine erosion removed sediment that was then redeposited seaward of the clinoform inflection point (Pekar et al., 2003). Suspected Oligocene sequences imaged

on *CH0698* data prograde both eastward as well as southwestward, lending support to this proposed process of across- and along-shelf sediment movement.

Karner and Driscoll (1997) and Driscoll and Karner (1999) studied the effect of advective-diffusive sediment transport on deltaic sedimentation. They suggested that at high energy margins where storms govern sediment movement, shore-parallel currents dominate other processes of cross shelf sediment transport such as floods and storms. Basinward sediment transport dominates during sea-level fall because of the high advection to diffusion ratios. Along strike variability should be greater when clinoform inflection point and shoreline positions coincide (Karner and Driscoll, 1997; Driscoll and Karner, 1999). *CH0698* data suggest point sources of deltaic sediments throughout the Oligocene-Miocene were dispersed by shelf currents moving parallel to the shoreline, consistent with this model.

Lithologic characterization of sequences

Lower Miocene lithologic successions in New Jersey coastal plain sequences (Miller et al., 1998) compare well with offshore seismic reflector characteristics. Sugarman and Miller (1997) and Miller et al. (1998) described a pattern for Miocene sequences in ODP Leg 150X and 174AX coreholes that is dominantly controlled by deltaic sedimentation. Sequence boundaries and transgressive ravinement surfaces are amalgamated and lowstand facies are absent, with a few notable exceptions. A basal shelly bed including sand and rare glauconite sand commonly overlies the sequence boundary transgressive

ravinement composite surface. The basal thin TST deposits are commonly reworked as a result of storm and inner neritic wave conditions, but as indicators of paleo water depths increase, clay-sized sediment begins to accumulate. Terrigenous input coarsening from clay to silt offers the first evidence of prograding deltaic sediments. The onset of these prodelta regressive sediments marks the MFS. Miller et al.(1994a, 1994b, 1997) identify the prodelta sediments as the lower HST (lHST). Sediment continues to coarsen as the delta progrades across the shelf. Quartz sand then dominates and varies from medium to coarse grained, marking the migration of the delta front and defining the upper HST (uHST) (Miller et al., 1994a, 1994b, 1997).

Offshore geophysical logs display characteristics similar to onshore corehole logs, suggesting similar sedimentation patterns and sequence development. High values of natural gamma rays across the Miocene sedimentary units indicate clays and, where present, glauconite as shown in Leg 150X cores (Miller et al., 1994a, 1994b, 1997; Lanci et al., 2002). Glauconite is a dominant constituent of Oligocene sediments, but occurs only in the lowermost Miocene sequence Kw0 and only in the base of that sequence (Miller et al., 1998). Heavy minerals that might contain a natural radioactivity comprise less than one percent of the Miocene sedimentary material (J. Browning, personal communication). Therefore, the gamma response should mimic grain size within the Miocene New Jersey Coastal Plain. A gamma spike commonly marks the sequence boundary, recording the change from quartz sand below to clay rich sediment above (Miller et al., 1994a, 1994b, 1996b) (fig. 3.4). Log patterns of Leg 150X coreholes document the MFS and lHST and uHST pattern (fig. 3.4). Offshore logs in ACOW 1 and

2 and AMCOR6011 boreholes mimic this pattern in several different log responses. These mutual log signatures suggest that the deltaic successions sampled in the ODP onshore coreholes continues offshore.

Lower Miocene sequences on the New Jersey margin have not been sampled at their thickest locations immediately seaward of their clinoform inflection point (fig. 3.1, 3.5 and 3.6). While not thoroughly sampled, middle Miocene sequences, by contrast, have been seismically imaged and logged at industry wells on the middle and outer shelf (fig. 3.1). The middle Miocene was a time of increased regional siliciclastic sedimentation due to hinterland uplift and global cooling (Poag and Sevon, 1989). As a result, thick lowstand wedges controlled by localized fluvial input built depocenters that thin along strike. Industry wells penetrated several of these sequences, and using *Ew9009* profiles that crossed these wells, Poulsen et al. (1998) examined the log response in both LST and HST. They concluded that the depocenters comprised great thicknesses of sand, while the thinner margins were mud-rich at the base and coarsened upwards to sands. Vertical resolution in the *Ew9009* data was insufficient for resolving TSTs at these locations. Overlying sequences step seaward in a progressively prograding succession to the current shelf slope break. McHugh et al. (2002) documented rare late Miocene prodelta facies on the upper slope, consistent with increased sediment supply during the upper Miocene. Fulthorpe and Austin (1998) noted that middle and upper Miocene sequences also advanced in a southeastward direction. They suggested two alternative explanations; either 1) widely distributed, low gradient fluvial systems that delivered sediment to the margin at the clinoform inflection point migrated south with time, or 2) sediment delivery

occurred landward of the clinoform inflection point and was subsequently redistributed by shelf sediment processes sufficient to obscure evidence of sediment point sources.

Sediment sources

Previous studies have found some evidence of fluvial deposits across the New York-Washington DC corridor that correlate to lower Miocene marine sequences. Pazzaglia (1993) and Pazzaglia and Gardner (1993) have described the Bryn Mawr Formation, a fluvial terrace deposit that crosses Maryland, Delaware and Pennsylvania and consists of three separate cycles ranging from late Oligocene to late Miocene. Each cycle represents a third-order (1-10 My) marine transgressive event. The late Oligocene cycle contained sediments from paleo-Hudson and Susquehanna rivers disbursing quartzose braid plains across a broad arcuate coastline (Pazzaglia, 1993). The Bryn Mawr second phase represents further aggradation during the late early and middle Miocene and correlates to Kirkwood Formation deposits (fig. 3.1). Stanford (1993) and Stanford et al., (2001) showed that the oldest remnant fluvial sediments in New Jersey are upper Miocene, though rising sea-level between the late Oligocene and middle Miocene was responsible for an upland erosion surface formed in the New Jersey Piedmont. This eroded material comprising the Beacon Hill Gravel was redeposited by rivers flowing south towards Atlantic City and into the marine environment at approximately 10 Ma (Stanford, written communication). Subsequent Bridgeton (8 Ma) and Pennsauken (5-2 Ma) fluvial systems flowed across the southern third of New Jersey with small stream systems disbursing eastward from the northern coastal plain (Stanford, written communication).

Therefore, late Miocene through Pliocene fluvial systems showed considerable lateral migration across the New Jersey coastal plain and changing sediment entry into the marine environment (Stanford et al., 2001).

Fluvial deposits incising lower Miocene sequence boundaries associated with lowstands have not yet been recorded in coreholes on the New Jersey coastal plain. Non-marine deposits do occur within the uHST of the Kw1b in the Island Beach (Owens et al., 1997; Miller et al., 1997b) and Atlantic City boreholes (Miller et al., 1997). Liu et al. (1997) used paleoenvironmental reconstructions based on foraminiferal biostratigraphy to suggest that the Island Beach sediments represent estuarine conditions. Other non-marine deposits encountered in Island Beach and Atlantic City coreholes represent prograding delta plain sediments. No seismic data exist that image lower Miocene incised valley sediments beneath the New Jersey coastal plain.

CH0698 data image possible incised valleys formed by rivers that transported sediment across the exposed coastal plain (fig. 3.5 and 3.6). None of these erosional features can be connected between adjacent profiles. It's possible that due to the 12.5 km seismic grid spacing few incised valleys would be detectable as anything other than the isolated features observed.

Submarine erosion enhanced by low accommodation could further account for the limited occurrences of incised valleys. Marine erosion during transgression can remove enough sediment to erase a stream channel or reduce its size below seismic resolution. As

previously stated, the New Jersey margin has long been considered a wave-dominated coastline (Swift 1970, Swift et al., 1986a, 1986b). Pekar et al., (2003) and Browning et al. (2006) described –it as wave-dominated from the Oligocene through the Miocene. Areas of large storm waves can create wave ravinement surfaces at 30 m water depth, but fair-weather wave base is more common (Ashley and Sheridan, 1994, Cattaneo and Steel, 2003). Catuneanu (2002) denoted as much as 10-20 m of substrate erosion caused by wave scour during transgression. More recently Goff et al. (2005) described up to 10 m of marine erosion at water depths >40 m on the New Jersey outer shelf due to unidirectional bottom currents concentrated on ridge and swale morphology. CH0698 data do not have the seismic resolution to detect similar features several hundred meters sub-seafloor, and data on current direction during the early Miocene is lacking. Therefore it is premature to evaluate the potential for this type of deep water erosion for the early Miocene

The landward merging of sequence boundary within the *CH0698* grid suggests low accommodation and therefore less sediment preservation in the updip/landward direction. Klitgord et al. (1988) have identified a basement hinge zone along the U.S. Atlantic margin that is related to Mesozoic rifting and that differentiates normal continental crust from extended continental crust. It separates accommodation controlled by thermal flexural subsidence (on the landward side) from accommodation enhanced by increased subsidence (on the seaward side). This hinge zone bisects the *CH0698* grid, generally separating the lower Miocene paleoshelf from the lowstand depositional centers farther offshore (fig. 3.1). Cattaneo and Steel (2003) argued that high accommodation and high

sediment influx can result in especially thick preservation of coastal plain material between sequence boundaries and transgressive ravinement surfaces. Such a pattern would increase incised valley preservation as well.

Multiple sediment sources implicated in *CH0698* data could correlate to "ancient Hudson" and "ancient Delaware" fluvial sources of Poag and Sevon (1989). Pazzaglia (1993) suggests that a paleo-Hudson and paleo-Delaware dominated the New Jersey margin beginning in the Pliocene-early Pleistocene and that the Susquehanna River was a dominant source during the late Oligocene-late Miocene. Stanford et al. (2001) supports the age of the paleo-Hudson as Pliocene-early Pleistocene or older but with certainty of its location decreasing as one goes back in time.

Shelf exposure

An unresolved debate concerns the paleowater depth of clinoform inflection points: are they ever shallow enough during cycles of sea-level change for sediments to bypass entirely and be deposited directly on the seaward front of clinoforms and beyond? Posamentier et al., (1988) and Posamentier and Vail (1988) initially described shoreface deposits that migrate to and below the clinoform inflection point due to a relative drop in sea level. Subsequently various authors (e.g., Hunt and Tucker, 1992, Plint and Nummedal, 2000) described a separate systems track which compares to the "lowstand fan" of Posamentier et al. (1988) (Catuneau, 2006). The history of these various sequence models is amply described by Nystuen (1998). It is expected that a relative sea-

level fall below the paleoshelf edge would have accentuated fluvial channel incision cutting the clinoform inflection point and proximal sections of the paleocontinental shelf. Incision would have migrated landward by headward erosion, cutting through knick points (Catuneau, 2006) as relative sea level remained below the clinoform inflection point. Channel incision would have developed across the entire exposed continental shelf as the river systems graded to the new sea level and fluvial channels would have delivered sediment directly to the paleoslope and possibly linked with previously formed submarine canyons.

Previous studies on the Mid-Atlantic margin have investigated the extent of sea level fall during sequence development. Steckler et al. (1999) used modeling to calculate the true elevation of major Cenozoic sequence boundaries across the New Jersey margin. Applying 2-D backstripping techniques on *Ew9009* line 1003, they reconstructed the margin from late Eocene to late Miocene and documented a change from a carbonate ramp to mature shelf-slope morphology. Their results suggest that early and middle Miocene clinoform inflection points remained covered by 60-127 m of seawater and were never subaerially exposed. *Ew9009* seismic resolution and the limited grid size covering lower Miocene sequences hinders identification of small incised channels that could substantiate the position of lowest relative sea level for each sequence. Kominz and Pekar (2001) used ODP Leg 150X borehole and other regional well information in a 2-D backstripping of onshore Oligocene and lower Miocene (Kw0) sequences. They, too, found that the clinoform inflection point was not exposed during sequence unconformity

development. Pekar et al. (2003) suggested that during the middle to late Oligocene, the clinoform inflection point was never covered by less than 20±10 m water depth.

Seismic studies of middle and upper Miocene sequences offer disparate results concerning the debate about paleowater depth of clinoform inflection. Poulsen et al. (1998) noted the *Ew9009* resolution was not sufficient to clearly image incised valleys. They described two possibilities to explain lateral migration of highstand sediments by lobe switching that correlate to variable degrees of relative sea-level fall. An autocyclic process has relative sea level stabilized at the paleoshelf edge. Under these conditions the delta progrades and lowers the fluvial gradient by lengthening the river course. Channel avulsion creates a new shorter, steeper fluvial channel that would supply sediment more efficiently to the slope. The relative sea level falls below the shelf in the allocyclic mechanism of Poulsen et al. (1998). This fall forces channel incision across the clinoform inflection point. Transgressive ravinement could have removed evidence of channel incision. Both models explain the lateral migration of highstand in relation to lowstand sediments. However, the allocyclic model would expose the clinoform inflection point while the autocyclic model would have relative sea level at the clinoform inflection point. Fulthorpe et al. (1999) investigated shelf exposure during lowstands using *Oc270* data. Thirteen sequences were defined by seismic reflector terminations. Their grid covers ODP Leg 150 coreholes that supplied age constraint of the middle and late Miocene sequences. Incised valleys, noted across the Miocene shelf to the break point, supply sediment directly to the slope. However due to limited incision depths on the paleoshelf, Fulthorpe et al. (1999) suggested that relative sea level fell just to and not

over the clinoform inflection point. McHugh et al. (2002) showed delta progradation reached the upper slope during late Miocene. This progradation is associated with m0.3 to p6 sequences of Mountain et al. (1994).

Metzger et al. (2000) correlated *Oc270* seismic profiles with ODP Leg 174A coreholes in a study of upper Miocene and Pliocene sequence development. Seismic sequence m0.5 (> 8.6 Ma) contains marginal marine sediments ~2.5 km landward of the clinoform inflection point (Austin, Christie-Blick, Malone et al., 1998). Metzger et al. (2000) suggested that the base of m0.5 was possibly exposed during the sea-level low. The surface was further modified by wave activity during the formation of the transgressive ravinement surface **(**Metzger et al., 2000). This upper Miocene sequence records a depositional history driven by increased accommodation, in contrast to the processes controlling lower and middle Miocene sequences on the inner Mid Atlantic margin described previously. Lowstand deposits at this outer shelf location are absent while a thick TST unit exists. This differs from the older sequence characterized by well developed lowstand facies and transgressive units absent or below seismic resolution.

Evidence from seismic images of Pleistocene fluvial channels also portray sea level approaching the clinoform inflection point (Nordfjord et al., 2005). A dendritic channel morphology was imaged to 90 m water depth marking a paleoshoreline and processes responsible for deposition of a succeeding offlapping wedge. Nordfjord et al. (2005) described their “R” reflector as paleo-seafloor and noted an inflection point or rollover that was identified as the shelf edge during a sea-level fall at ~35-22 ka. Deposition of

the offlapping wedge occurred seaward of the clinoform inflection point. Incised valleys were reworked and truncated by tides and wave action during subsequent sea-level rise.

Profiles from *CH0698* have been examined for indication of paleowater depths at clinoform inflection points. The only data suggesting sea level reached the clinoform inflection point occurs on *Oc270* line 529 where a small shelf edge delta formed immediately seaward of the clinoform inflection point of sequence m5.4 (fig. 3.9). The delta is imaged only on a single dip line where it shows a progradation no longer than approximately1.8 km. Lowstand facies of the m5.4 sequence on line 529 are suggested by reflectors onlapping the delta's base. *CH0698* data images two lowstand parasequences that prograde from the north towards the southeast through line 529. On strike parallel seismic lines these parasequences show basal slump morphologies that are overlain by parallel reflectors. Only the parallel reflectors are imaged on line 529 (fig. 3.9). A small river with limited incision could supply the sediment for this delta. The shelf edge delta just below the clinoform inflection point suggests that sea level remained at this level as this delta prograded. Evidence of continued sea-level fall during this time is lacking. If relative sea level just reached the clinoform inflection point, fluvial incision would be minimal (Emery and Myers, 1996). No fluvial channels are imaged close to or associated with the delta. Further evidence, if it exists, is probably at a scale below the lateral and vertical resolution of these profiles (roughly 150 m and 5m, respectively) or has been missed by the nominal 12.5 km line spacing.

Additional erosional features incise the m5.47 sequence boundary near the northern limit of the CH0698 grid (figs. 3.9-3.12); some are deep enough to cut into older clinoform inflection points as well. The incisions comprise an interconnected set of channels or gullies that end in a planar surface that dips roughly 0.8° SE. Erosion into the m5.47 surface continues at least 16 km along strike and 8-20 km down dip (figs 3.9-3.11), ending near the m5.47 lowstand deposit (figs. 8 and 9; figs. 3.9-3.11). The *CH0698* grid does not extend far enough to the NE to determine the full extent of this erosional surface.

This erosion can be interpreted as either a large incised valley or as a submarine sediment failure surface. The areal extent of the erosion would make it the largest subaerial valley within the grid and would signify a dramatic drop below the clinoform inflection point of relative sea level m5.47 clinoform inflection point. However there is no supporting evidence of such a large sea level drop at this time. A sea-level drop over the clinoform inflection point would enhance the fluvial gradient causing increased incision across the entire exposed paleoshelf. There is no evidence within the *CH0698* seismic grid of any channel downcutting approaching this projected drop in relative sea level. Furthermore, while a few other surfaces examined in this study show possible incision, none have areal distribution as large as this. While tide- and wave- erosion during transgression could have obscured or removed evidence of deep incision, sediment failure provides an alternate explanation. Though sediment failures are more common in continental slope environments (Hampton and Lee, 1996; Mulder and Cochonat, 1996; Masson et al., 2006) there is substantial evidence of failures related to deltas on continental shelves

(Prior and Coleman, 1981; Coleman and Prior, 1982; Schwab and Lee, 1988; Hampton and Lee, 1996; Papatheodorou and Ferentinos, 1997; Correggiari et al., 2001; Trincardi et al., 2004) and estuarine environments (Rossetti and Santos, 2003). The gentle slope gradient observed in the *CH0698* data does not rule out this mechanism; failures are known to occur even with gradients $<1^{o}$ (Prior and Coleman, 1981; Mulder and Cochonat, 1996; Papatheodorou and Ferentinos, 1997; Lykousis et al., 2002; Masson et al., 2006) and as low as 0.01^{o} along the Mississippi (Hampton and Lee, 1996). Correggiari et al. (2001) and Trincardi et al. (2004) record sediment failure horizons as either along unconformities or downlap surfaces such as a maximum flooding surface. McHugh et al. (2002) also noted mass-transport material resting on sequence boundaries and other prominent stratal surfaces of upper Oligocene to upper Miocene sequences on the New Jersey continental slope and rise.

Sediment failure commonly follows any of several possible trigger mechanisms. Two that are commonly cited are: 1) a period of high sedimentation that creates an under compacted layer and a build up of pore pressure that leads to a corresponding decreased shear strength; and 2), or a build up of free gas that leads to an overpressured and weak horizon (Hampton and Lee, 1996; Schwab et al., 1996; Laberg and Vorren, 2000; Trincardi et al., 2004; Masson et al., 2006). Coleman and Prior (1982) indicated that the rapid sedimentation is usually associated with river-dominated deltas. However, deltas deposited under the influence of a strong storm climate (as is thought to be the case for the Miocene New Jersey coast line) typically rework sediment and thereby reduce pore pressure buildup suggesting this mechanism may be less likely than in other, high-

sedimentation areas. Correggiari et al. (2001) and Trincardi et al. (2004) studied the wave-influenced Po delta and described soft sediment and failure structures related to a build up of free gas in subaqueous deltas in the Adriatic. CH0698 seismic data does image dewatering structures related to polygonal faulting on the New Jersey margin (fig. 2.3).

Several triggers to sediment failure are recognized: seismic shaking (Lewis, 1971; Hampton and Lee, 1996; Papatheodorou and Ferentinos, 1997; Laberg and Vorren, 2000; Biscontin et al., 2004; Masson et al., 2006), storm wave loading (Schwab and Lee, 1988; Hampton and Lee, 1996; Schwab et al., 1996) and rapid isostatic rebound (Lysa et al;, 2004). Hampton and Lee (1966) noted that no single factor alone can account as the cause of sediment failure and that a combination of factors is more likely. The Mid Atlantic margin is not seismically active though rare faults are evident within the *CH0698* data. Storm wave loading is a more likely sediment flow triggering mechanism over seismic shaking for the current study area.

In contrast to the incised valley interpretation to the incised m5.47 surface, a sediment failure interpretation provides ambiguous insight into the time or magnitude of sea-level change. Galloway (1998) noted that failures can occur during either low or high relative sea level, though storm wave loading would have more effect during a relative lowstand; destruction of oil field infrastructure down to 100 m below the seabed has been recorded for the hurricanes in the Gulf of Mexico (Hampton and Lee, 1996).

Incised valleys on CH0698 data approach within ~12 km of the corresponding clinoform inflection point position. This yields a relative maximum water depth of ~12 m across the 1;1000 gradient paleoshelf which is considerably less than the 60-127 m water depth in Steckler et al., (1999) but approximates 20±10 m water depth of Pekar et al. (2003) for the Oligocene. Taken into consideration with other regional seismic studies proposing that sea level approached but did not fall below the clinoform inflection point**,** it seems reasonable that similar conditions existed during the early Miocene. However it must be stated that *CH0698* data only indicate this for the one sequence m5.4.

If relative sea-level fall did not reach the paleoshelf-slope break, mechanisms other than transport through incised river valleys must be invoked to explain LSTs seaward of the previous clinoform. Sediment bypass can be accomplished with unincised fluvial systems (Catuneau, 2006), and lowstand deposits could develop by enhanced cross shelf sediment deposition during falling relative sea-level (Karner and Driscoll, 1997; Driscoll and Karner, 1999).

CH0698 data suggest that early Miocene sea-level may not have reached the clinoform inflection point except on sequence boundary m5.4. The absence of channel incision at of near the generally smooth clinoform inflection point offers that relative sea level did not fall below the clinoform inflection point. It should be noted that the transgressive ravinement surface could have beveled any shallow incised valleys. It is important to note that the *CH0698* seismic grid spacing inhibits the ability to effectively image all possible incised valleys. The dearth of submarine canyons imaged on the paleoslope as

well as only rare mass wasting deposits encountered downdip in ODP Leg 150 coreholes (McHugh et al., 2002) adds to the interpretation of only partial shelf exposure during lower Miocene relative sea-level fall. Only the small shelf edge delta on sequence m5.4 offers evidence of relative sea-level fall at the clinoform inflection point.

Conclusions

Higher resolution seismic data across the New Jersey shelf correlated to ODP coreholes allowed a more regional depiction of margin growth than was previously possible (Mountain, Miller, Blum et al., 1994; Fulthorpe and Austin, 1998; Fulthorpe et al. 1999, Austin, Christie-Blick et al., 1998; Metzger et al., 2000). These previous studies documented margin development under high siliciclastic sediment supply during the middle and late Miocene.

The *CH0698* seismic grid images the major lower Miocene sequences and offers the clearest understanding of their development currently available. Reflector mapping has outlined eleven candidate sequence boundaries that suggest considerable along strike variability. Lowstand deposits are associated with each sequence boundary. However**,** the lowstands did not develop uniformly along clinoform fronts but instead formed local depocenters as evidenced by lowstand isopach maps. This pattern suggests the position of primary sediment input and allows for the inference of fluvial input history. Beginning at the Oligocene Miocene boundary a northern sediment source (possibly related to a paleo-Hudson river) controlled the formation of the m6 and m5.8 sequences.

The location of the next younger sequence, m5.7**,** indicates a subsequent reduction of this northern source and the appearance of one from the south, possibly a precursor to the modern Susquehanna River. The paleo-Susquehanna controlled deposition of the following m5.6 sequence. Delivery of sedimentary material changed again as two active depocenters developed during m5.5 deposition. Position of fluvial supply continued to vary through formation of the following m5.47, m5.45, m5.4, m5.3 and m5.2 sequences. Along strike redistribution occurred at various time to dominate over cross shelf deposition. The size and distribution of lowstand deposits support Karner and Driscoll (1997) and Driscoll and Karner (1999) who propose that cross shelf sediment dispersal is highest during times of falling relative sea level.

Our study of *CH0698* profiles did not detect any valley incision that approached a lower to middle Miocene clinoform inflection point, suggesting that relative sea-level fall never fell below the depositional front. Although transgressive ravinement could have removed traces of incision, it is likely this process would have planed a sharper break at the clinoform inflection point than is observed in profiles. A single shelf edge delta developed on m5.4 sequence boundary does show that relative sea level did reach the clinoform front at least once.

The lower and middle Miocene sequences discussed have not been drilled at the offshore locations needed to evaluate their complete significance. While the succession and inferred age and facies of these ten seismic sequences compare well with the lower Miocene sequences sampled in the onshore coreholes, no offshore data yet exist to

establish these correlations with certainty. Drilling a transect of holes across the lower Miocene fronts and correlating the results to seismic profiles offers the best opportunity to determine the extent of relative sea-level fall. IODP Expedition 313 should supply the necessary information to evaluate this problem.

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Seismic sequences Greenlee et al.(1992)	Seismic sequences Mountain, et al. (1990)	Seismic sequences Miller et al. (1996)	Seismic sequences This study	Sequences Browning et al. (2006)	Sequence age (Ma) Browning (pers comm..)	ODP Leg 150X, 174AX
Green	Green	m5-Kw2b	Green – m5	Kw2c	~15.6 shelf	
	Ochre	m5.2 – Kw2a	Orange – m5.2	Kw2b	15.7-16.1	Ocean View
			Red – m5.3	Kw2a3 Kw2a3	16.9-17.1 17.1-17.2	Ocean View
	Sand	m5.4 – Kw1c	Yellow – m5.4	Kw2a1	17.2-17.8	Ocean View
			Pink – m5.45	Kw1c	18.8-19.0	Cape May Zoo
			Lt blue – m5.47	Kw1b2*	19.7- 19.9	Atlantic City
			Green – m5.5	Kwb1*	20.0-20.1	Atlantic City
Blue	blue	m5.6 – Kw1a,b	Dark blue – 5.6	Kw1a3	20.2-20.3	Ocean View
			Red – m5.7	Kw1a2	20.3-20.4	Ocean View
			Brown – m5.8	Kw1a1	20.4-20.5	Ocean View
	Pink3	m6 – Kw0	Purple – m6	Kw0	22.0-23.5	Cape May

Table 3.1 Miocene sequences on the New Jersey margin determined from both seismic and borehole data. Early work of Greenlee et al. (1992) used low resolution data and described two early Miocene sequences. Mountain et al. (1990) analyzed *Ew9009* data and described five seismic sequences. Miller et al. (1996a) jump correlated sequences identified in onshore ODP Leg 150X core data into the *Ew9009* seismic analysis of Mountain et al. (1990). This study outlined eleven candidate sequence boundaries that have been traced onshore and correlated sequences described in ODP Legs 150X and 174AX (Browning et al., 2006). Note ODP Leg 150X and 174AX references correspond as follows: Atlantic City – Miller et al. (1994b), Cape May – Miller et al. (1996b), Ocean View - Miller et al. (2001), Cape May Zoo – Sugarman et al. (2007). Sugarman et al. (1997) supplied some Sr-isotopic age dates. * Miller et al. (1994b, 1997) do not separate two sequences within Kw1b but considered them as parasequences. Ages were estimated for sequences Kw1b1 and Kw1b2 by correlating geophysical log depth to aged depth plot in Miller et al. (1997).

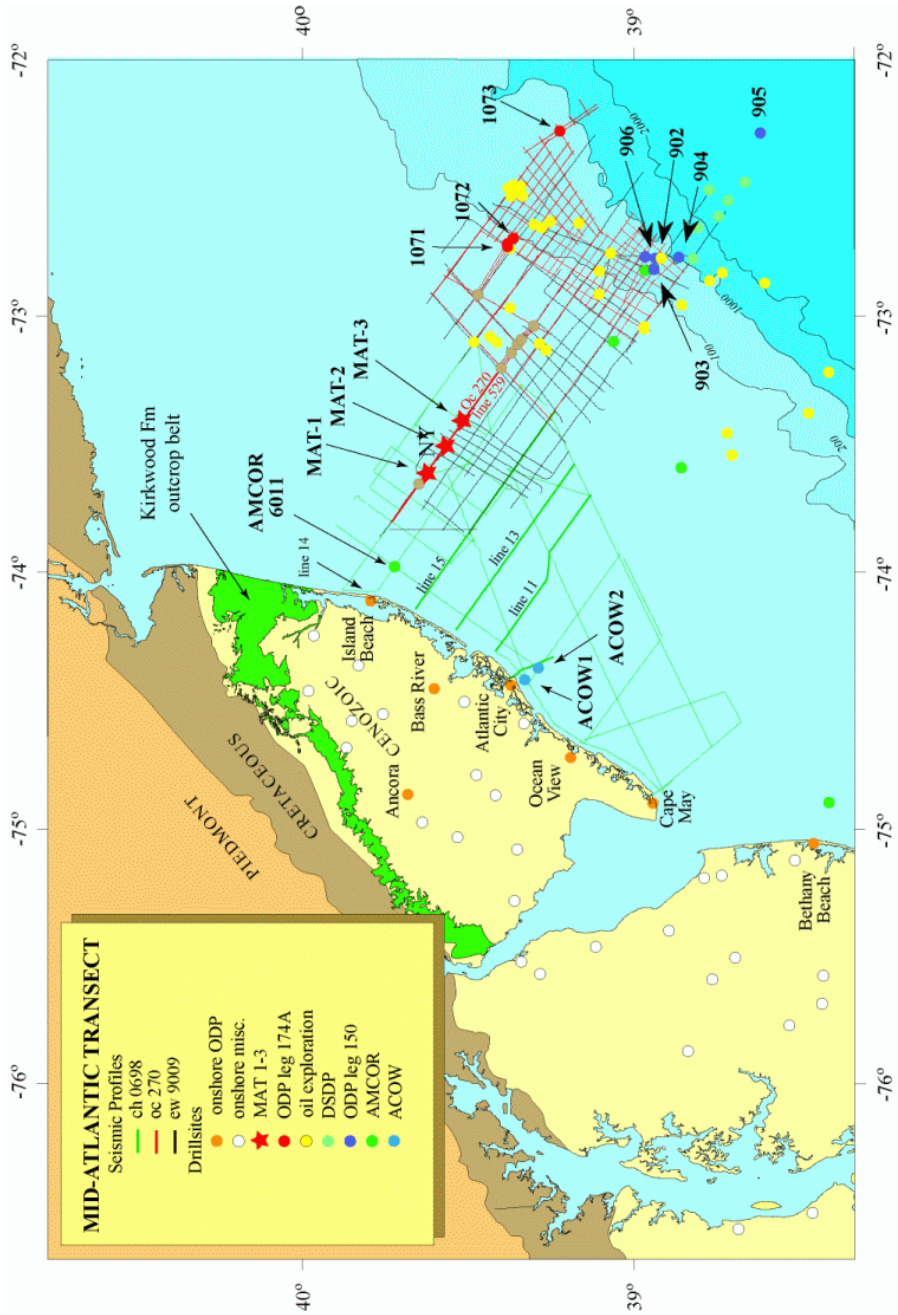

Figure 3.1 Locality map of the New Jersey margin showing the extent of previous seismic surveys including *Ew9009* and *Oc270*. Offshore drilling programs shown include ODP Legs 150 and 174A that reached Miocene sediments. Data used in this study include the *CH0698* seismic grid, onshore ODP Legs 150X and 174AX as well as ACOW1 and 2 and AMCOR6011. Basement hinge zone separates normal continental crust to the west from extended crust and increased subsidence to the east (Klitgord et al., 1988).

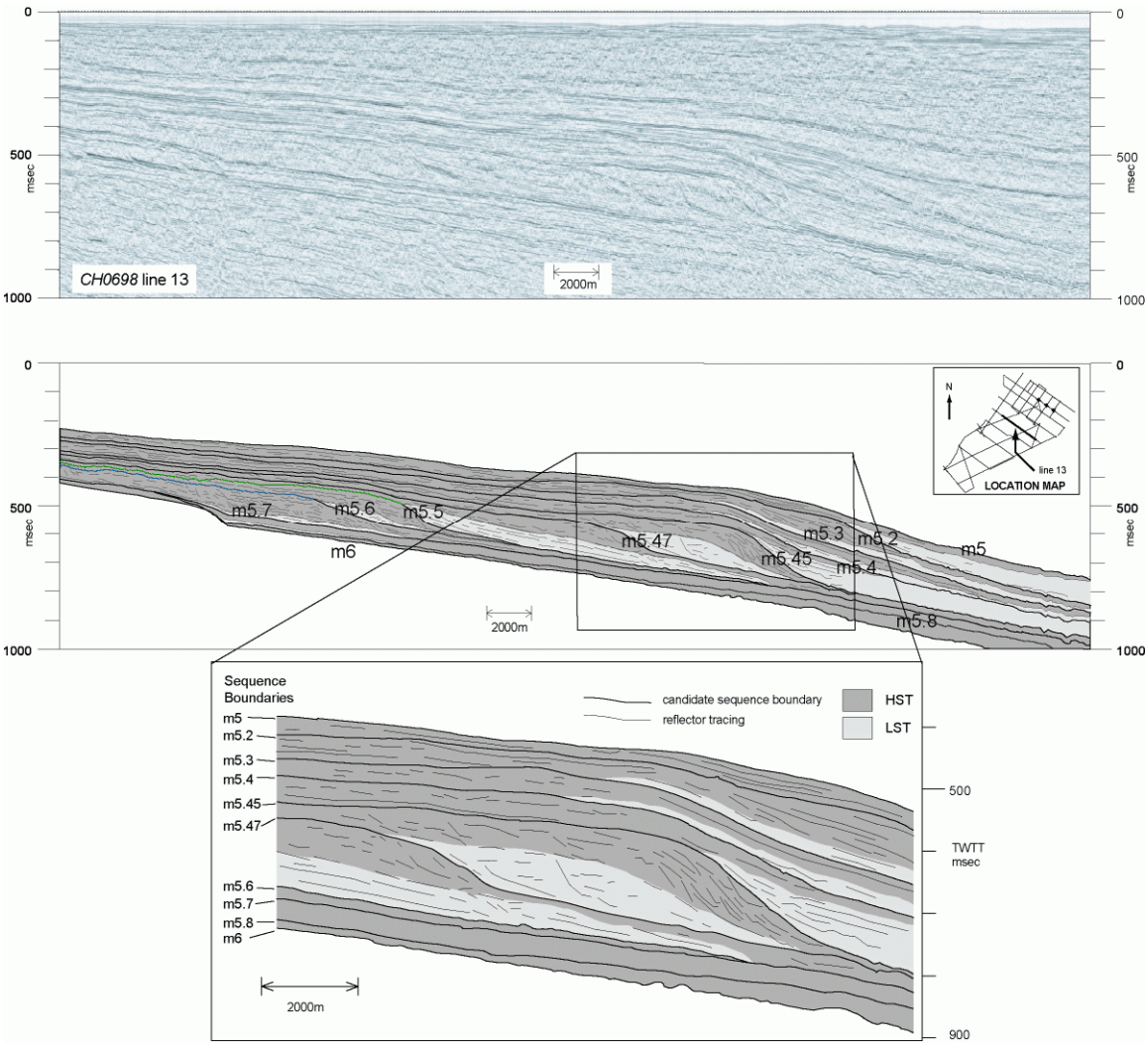

Figure 3.2. Example of seismic reflectors on *CH0698* line 13 outlining both highstand and lowstand facies deposits in different shades of gray. Transgressive deposits are generally below seismic resolution and not shown. Location map shows position of line 13 within the *CH0698* data grid.

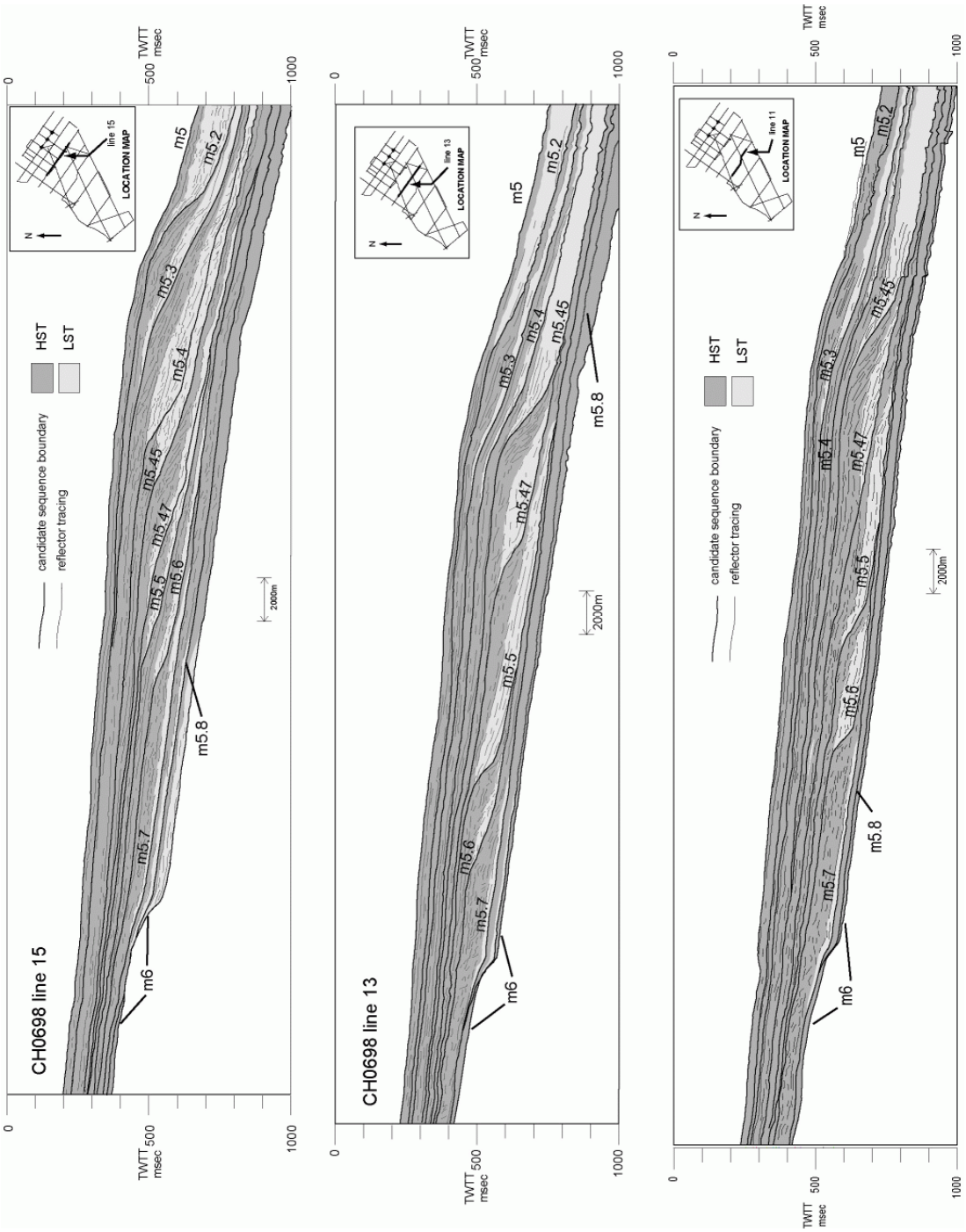

Figure 3.3. Three successive dip profiles within the *CH0698* grid are depicted that portray significant along strike variability within individual sequences. The seismic sections are, in the north, lines 15, 13 and 11 in the central grid section. Candidate sequence boundaries can be seen to erode, amalgamate or join, within seismic resolution with overlying boundaries. Sequences are named for the basal reflector. Only highstand and lowstand facies are clearly imaged within seismic resolution, a. *CH0698* line 15, b. *CH0698* line 13, c. *CH0698* line 11

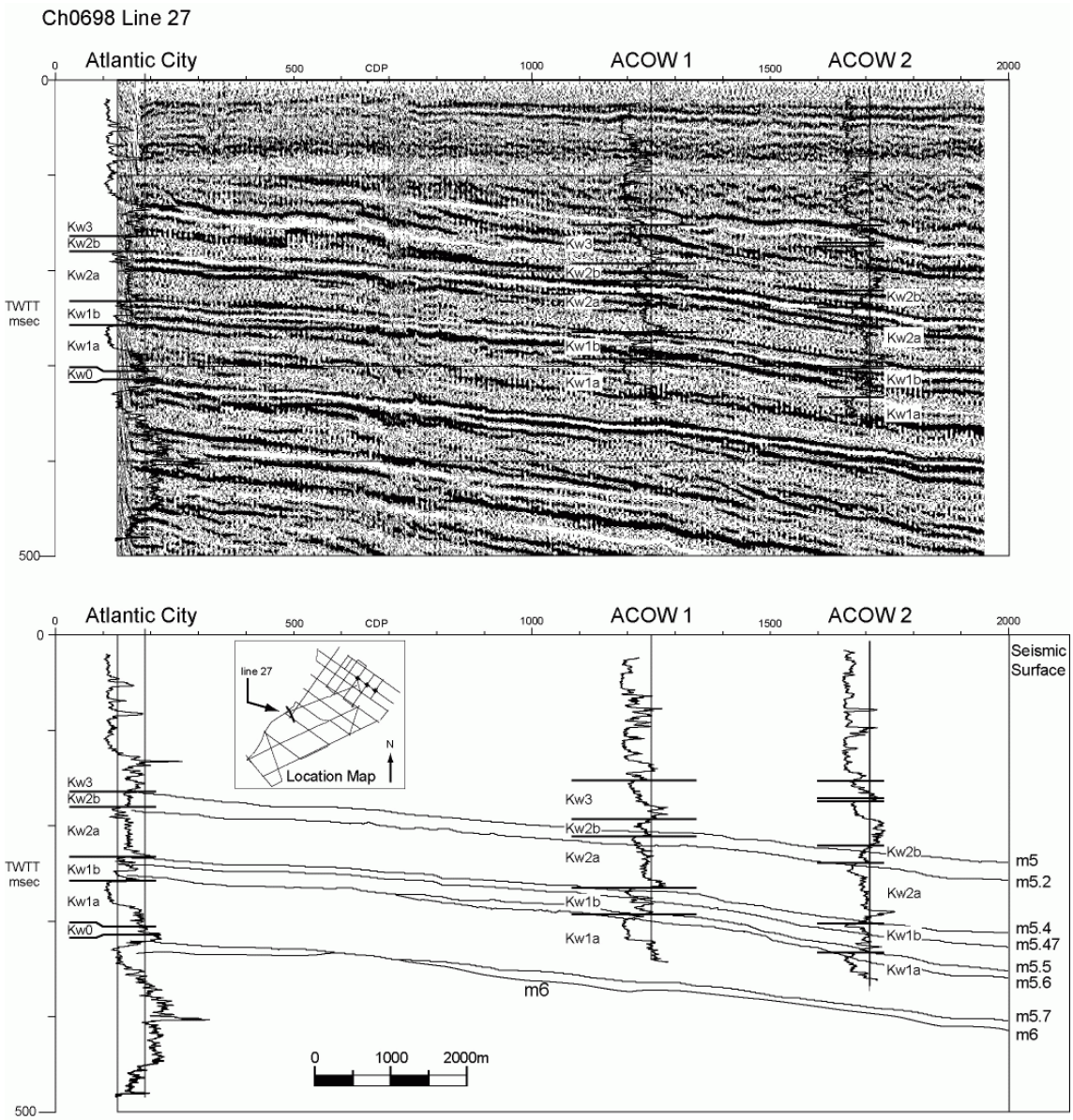

Figure 3.4. Integration of ODP Leg 150X Atlantic City corehole and ACOW 1 and 2 boreholes into *CH0698* line 27. Onshore sequences were identified by litho and biostratigraphic data in the AC corehole (Miller et al. 1994b). Sequences were characterized to their corresponding log signatures and compared to good geophysical logs for the rotary-drilled boreholes ACOW 1 and 2, which had limited litho and biostratigraphic recovery.

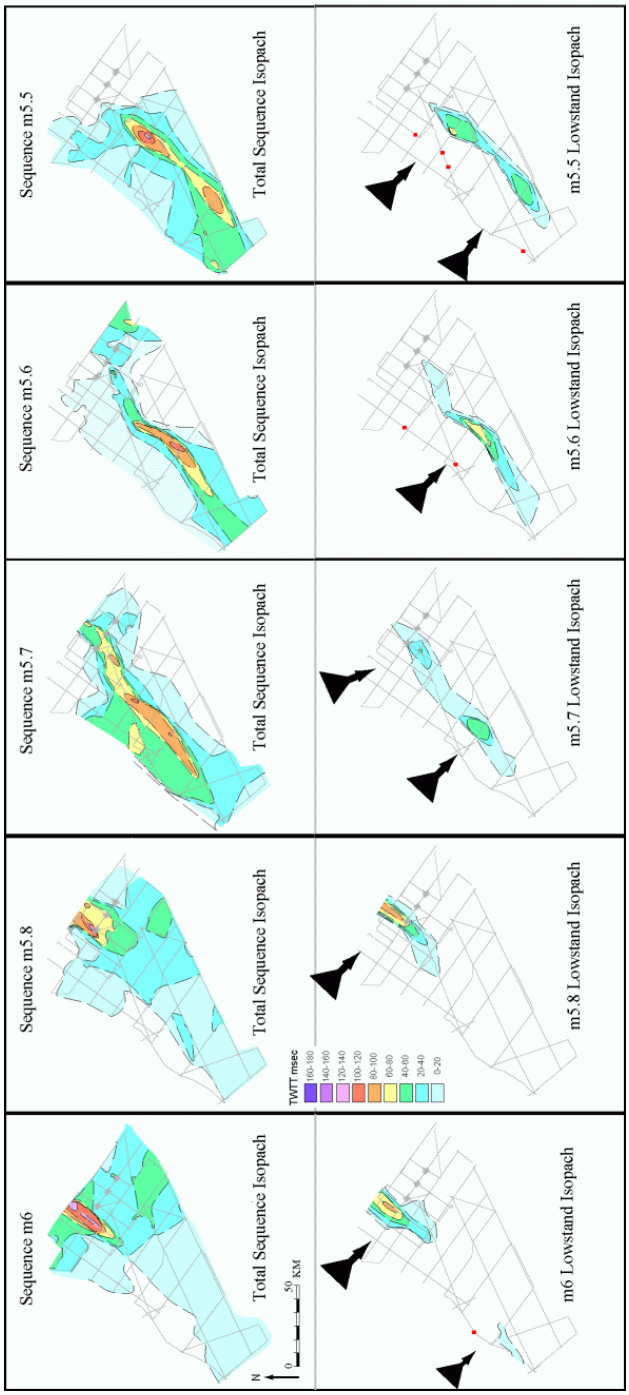

Figure 3.5. Isopach map of the five oldest seismic sequences identified on *CH0698* data. Sequences are identified by the basal reflector and from oldest to youngest consist of m6, m5.8, m5.7, m.5.6 and m5.5. Isopachs of total sequence thickness are shown above their corresponding lowstand isopachs. Units of isopachs are in TWTT msec. Red squares show locations of suspected incised valleys. Black arrows represent general direction of fluvial channels. Along margin currents redistributed sediment in a southwestward direction as the deltas prograded across the paleoshelf.

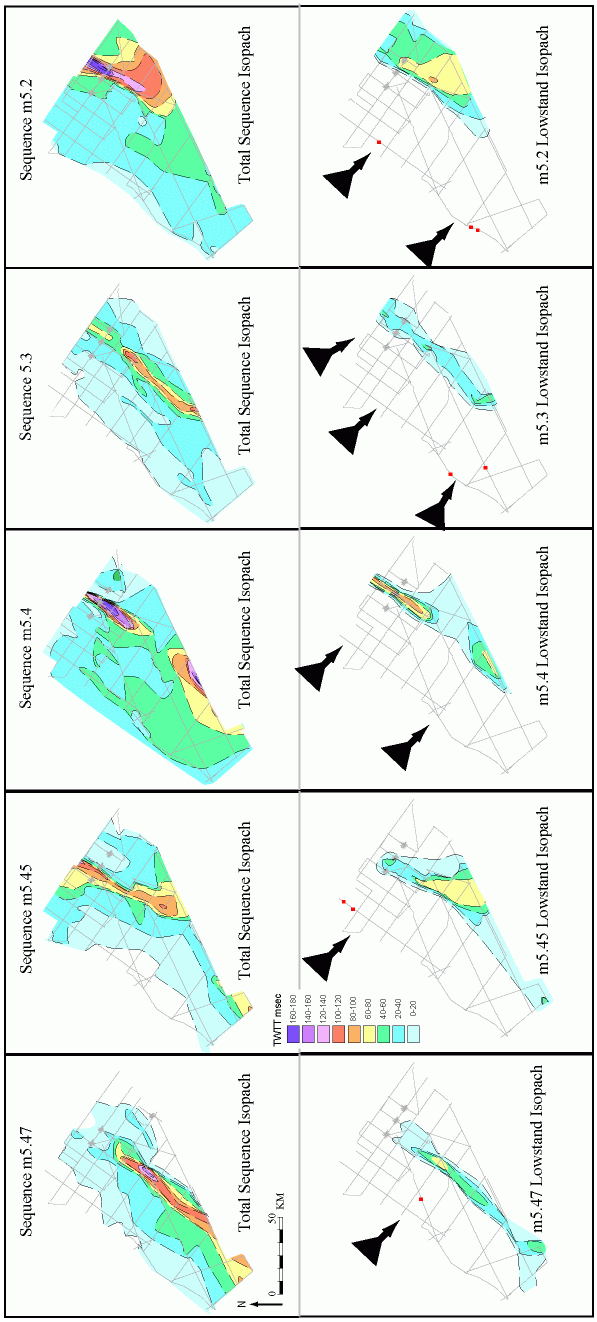

Figure 3.6. Isopach map of the next five (youngest) seismic sequences identified on *CH0698* data. Sequences are identified by the basal reflector and from oldest to youngest are m5.47, m5.45, m5.4, m.5.3 and m5.2. Isopachs of total sequence thickness (in msec of two-way traveltime) are shown above their corresponding lowstand isopachs. Red squares show locations of suspected incised valleys. Black arrows represent general direction of fluvial channels. Along margin currents redistributed sediment in a southwestward direction as the deltas prograded across the paleoshelf.

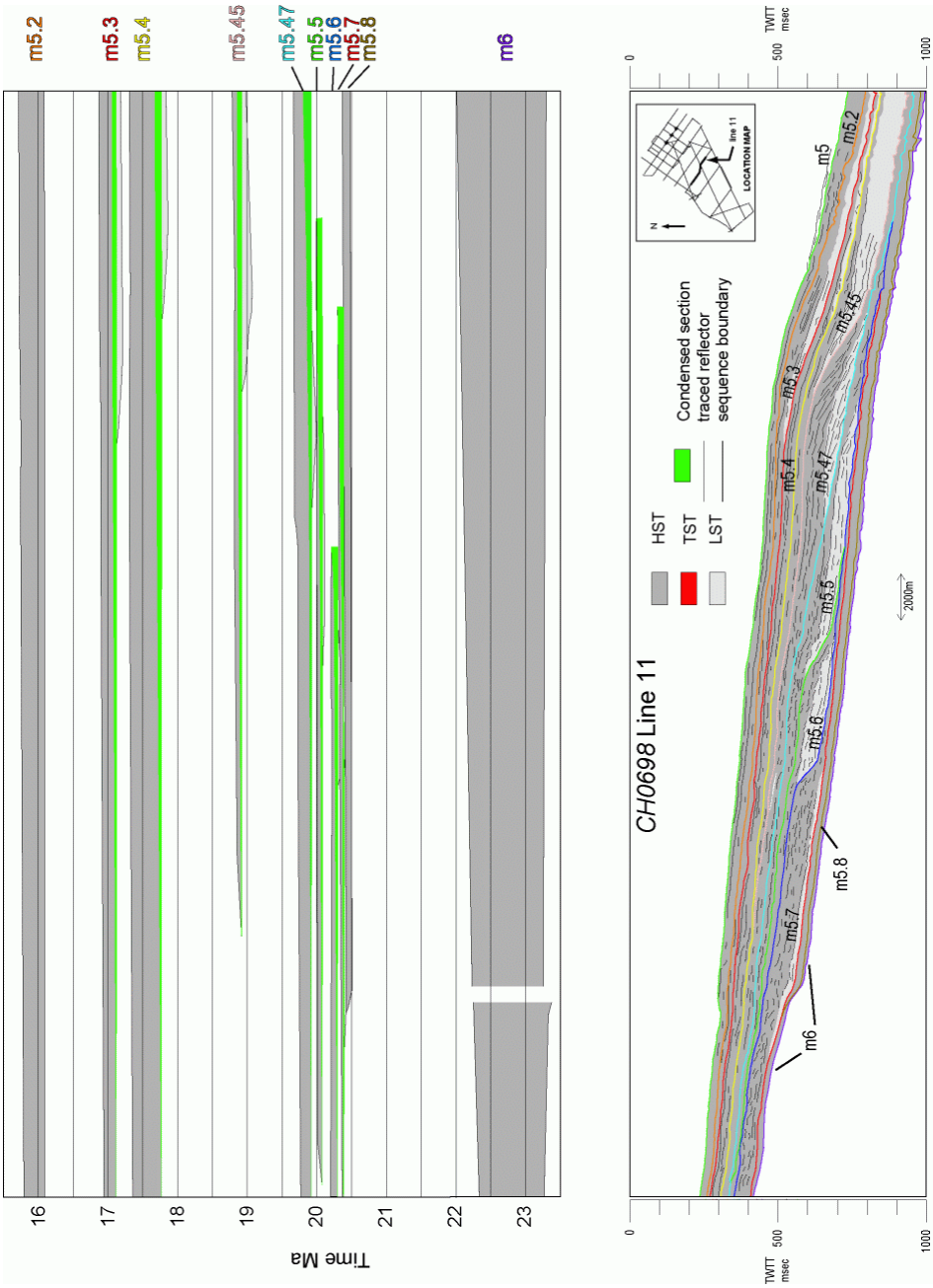

Figure 3.7 Wheeler diagram of *CH0698* line 11 shows the amount of time represented by the lower Miocene seismic sequence stratigraphy. Age range of each sequence is given in table 3.1. Line 11 depicts mostly HST deposits as it is located south of the main northern depositional center and within the central depositional center. More time is represented on line 11 than line 529 (fig. 3.8) as no sequences are missing here.

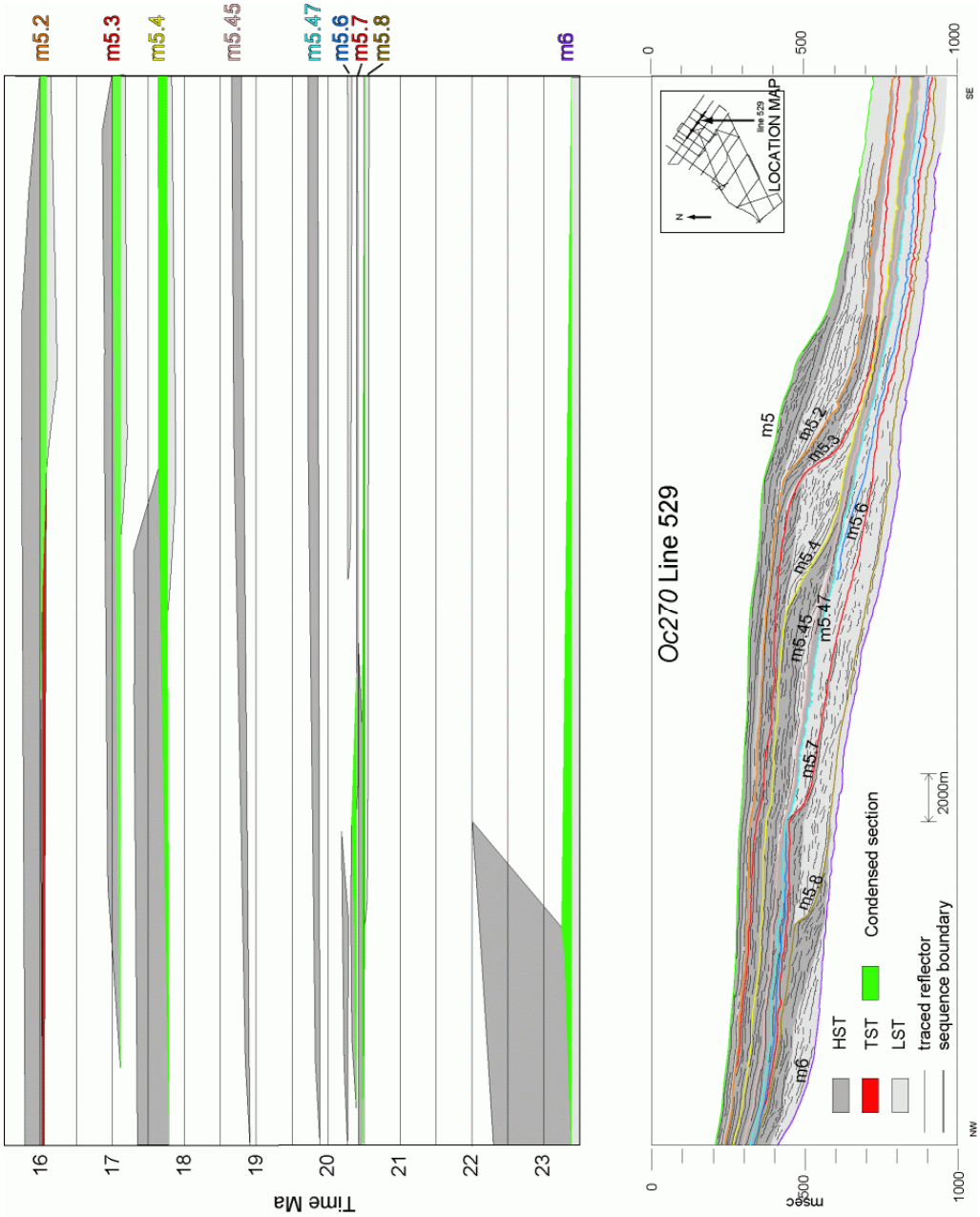

Figure 3.8 Wheeler diagram of *Oc270* line 529 shows the amount of time represented by the lower Miocene seismic sequence stratigraphy. Age range of each sequence is given in table 3.1. Line 529 lies within the main northern depositional center and displays an extensive LST and HST deposits. Sequence m5.5 does not project onto line 529, within seismic resolution.

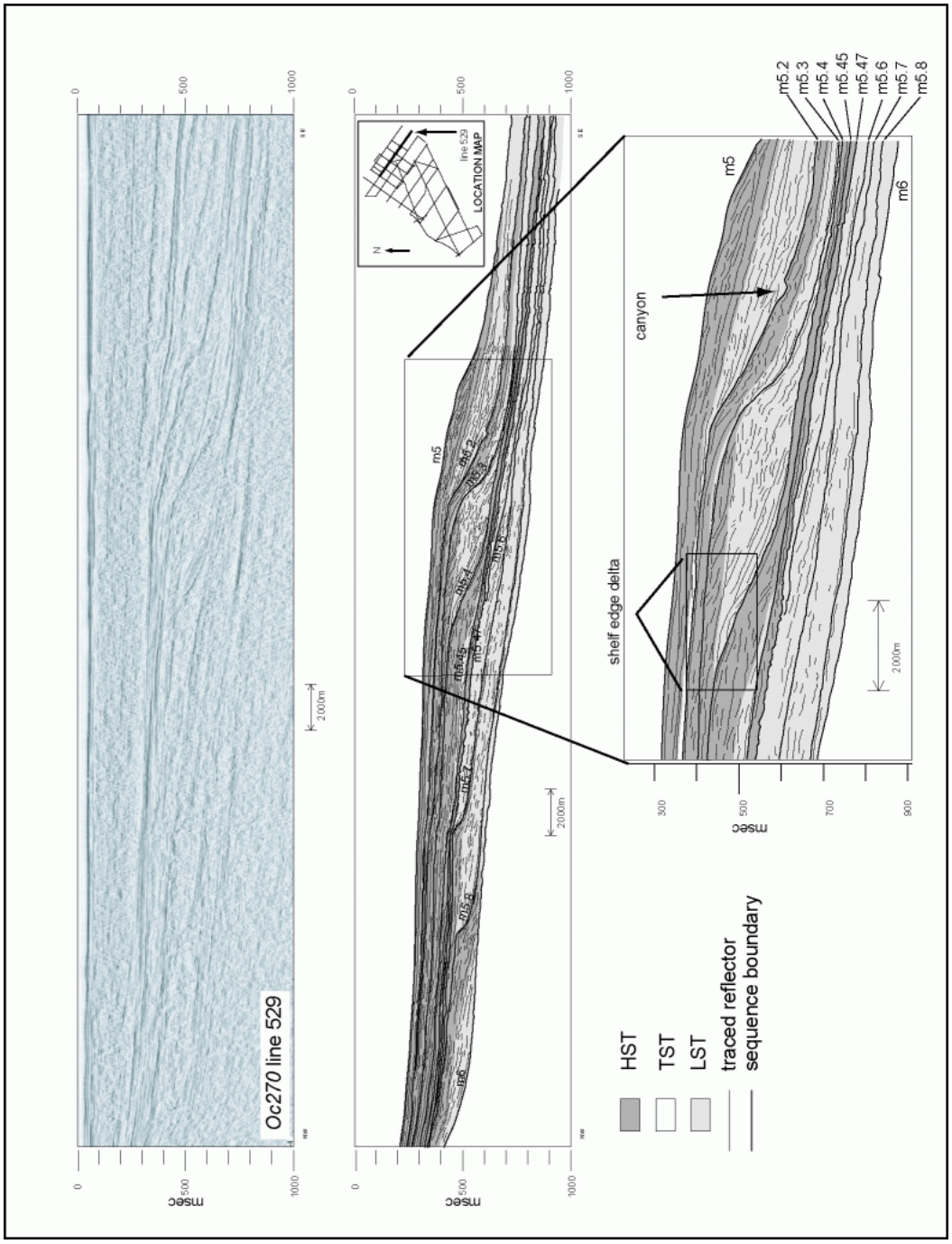

Figure 3.9. *Oc270* line 529 images a shelf edge delta just below the clinoform inflection point of sequence m5.4. This small delta is only imaged on a single line. The location of the delta top at the clinoform inflection point suggests that sea level may have reached this point. However no incised valleys related to the delta are evident on proximal lines. *CH0698* line spacing does reduce the opportunity to image associated valley incision. A canyon cut along the steeper clinoform front cuts reflector m5.2. Reflector m5.47 shows a highly channelized morphology with a slope gradient of ~0.8^{o}

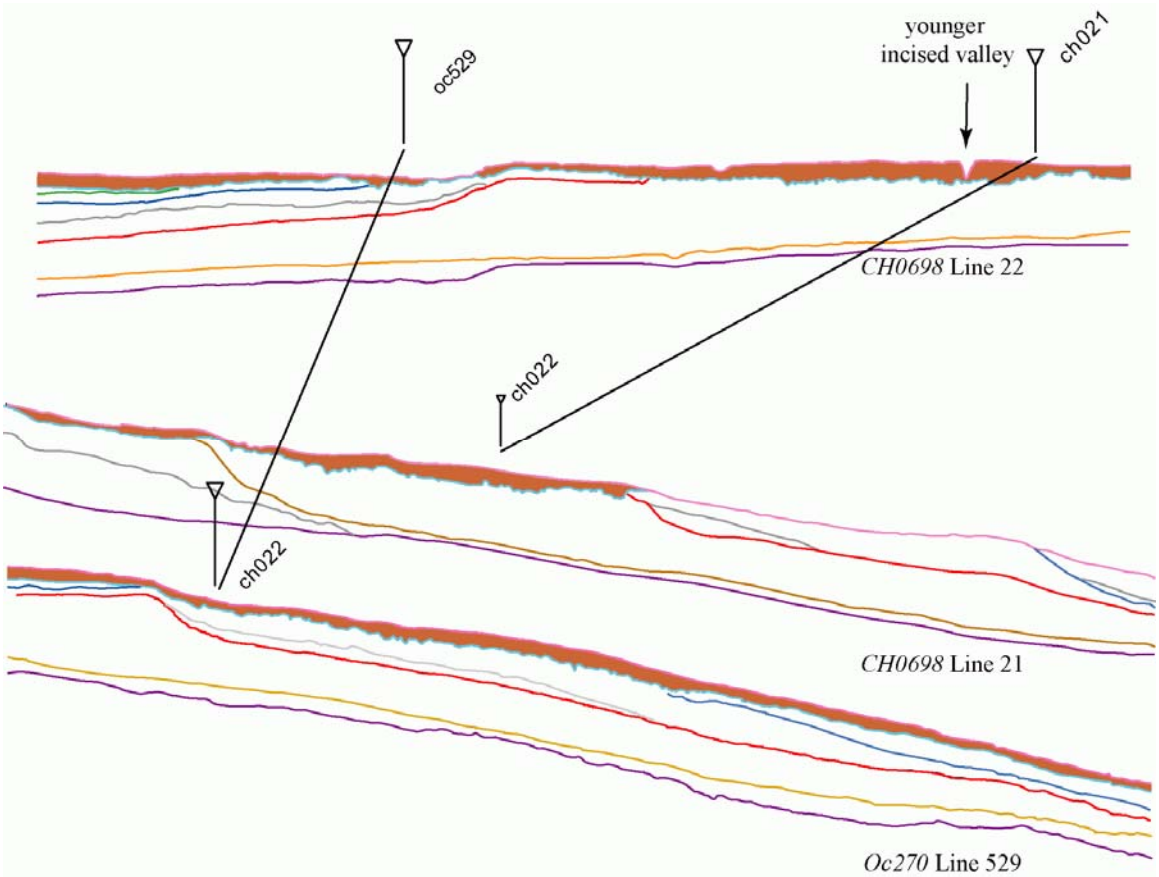

Figure 3.10 Expression of m5.47 erosion surface is displayed on dip lines 21 and 529 and strike line 22. The brown colored polygon depicts the thickness of the m5.47 sequence. Flagged lines show the intersection of respective lines. . Slope gradient of erosion surface as measured on line 529 = ~0.8^{o}.

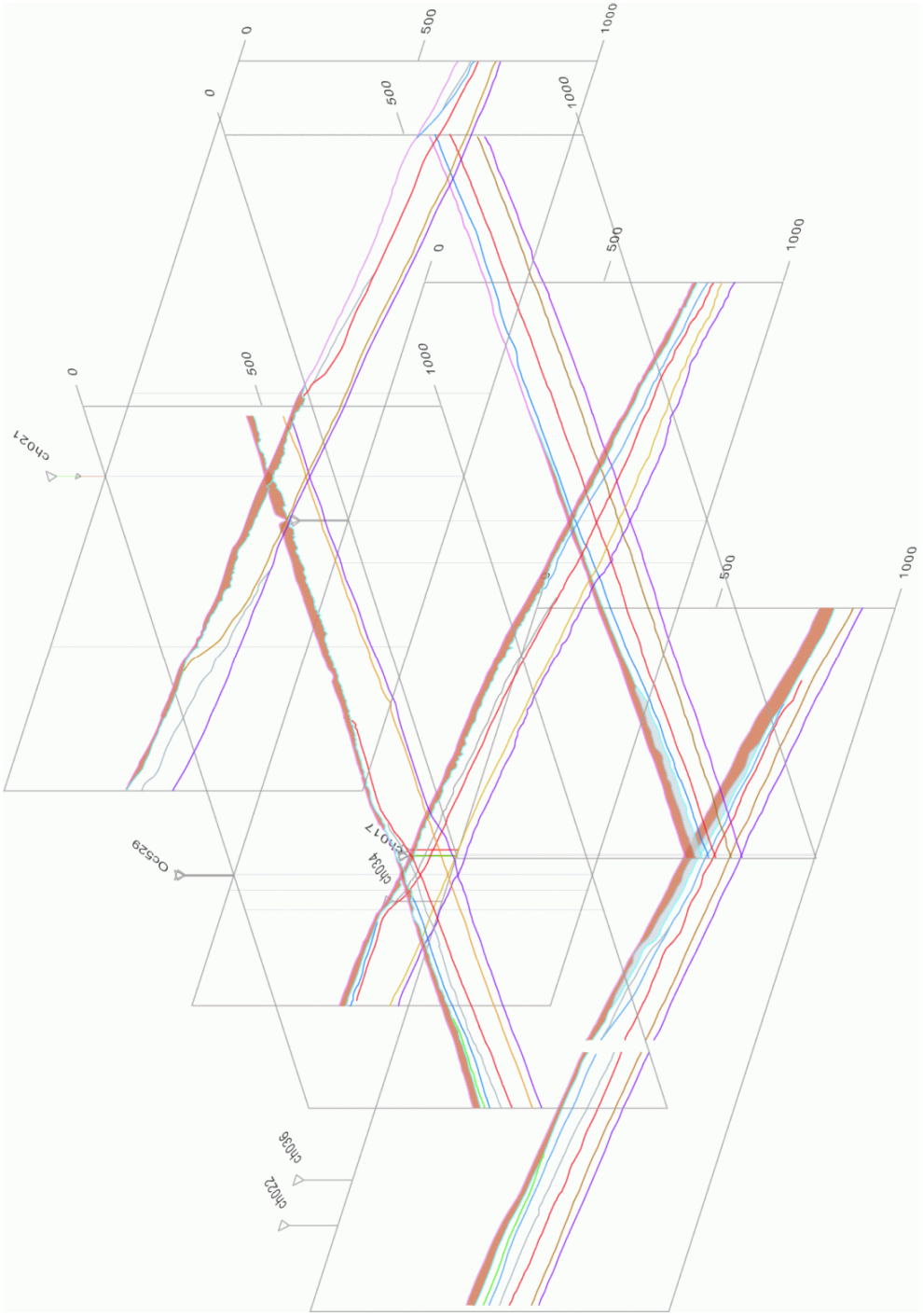

Figure 3.11 Fence diagram shows the extent of the m5.47 erosive surface. It continues to the edge of the *CH0698* grid so the total regional extent is unknown.

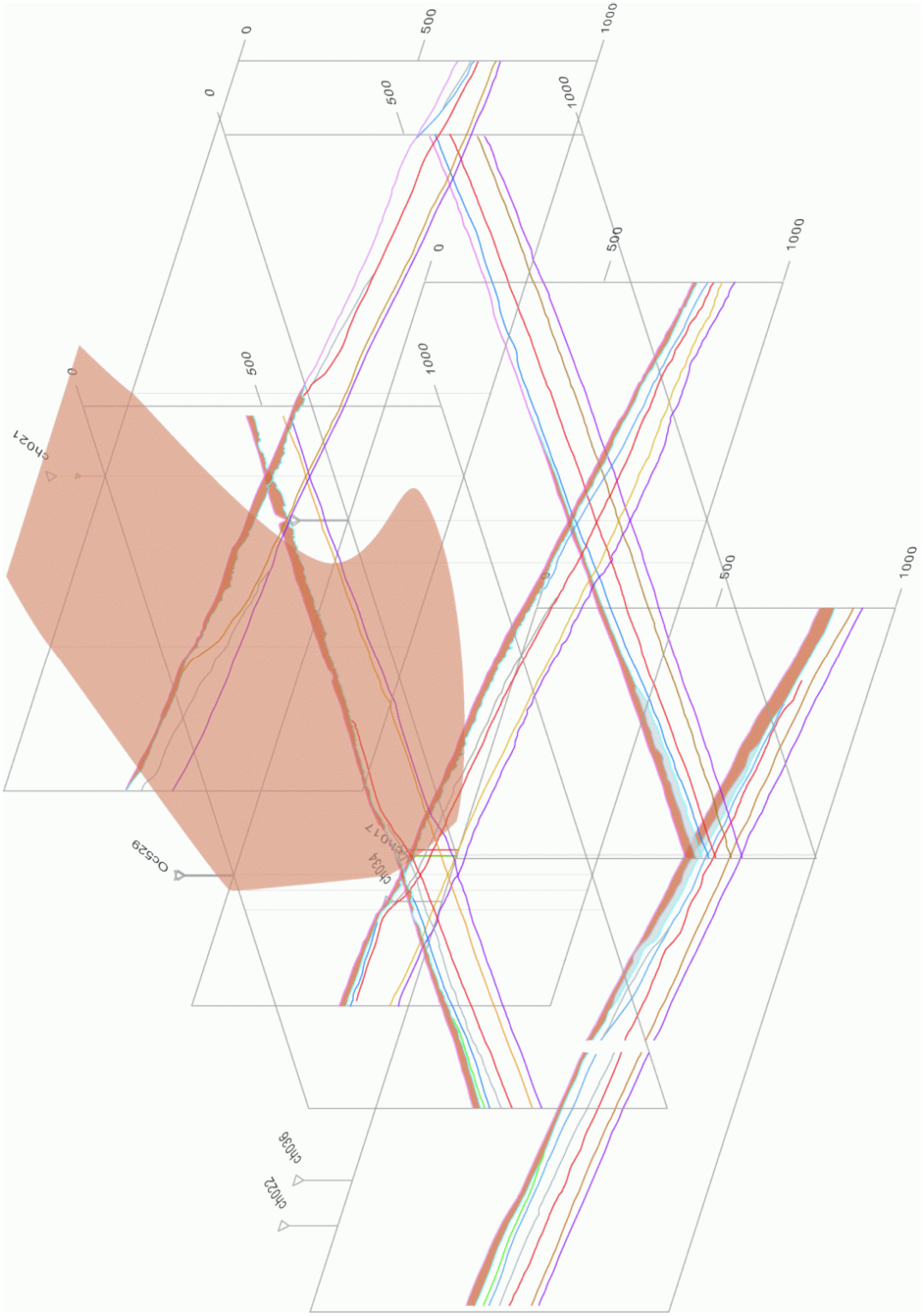

Figure 3.12 Fence diagram shows the extent of the m5.47 erosive surface within the CH 0698 grid. Polygon drape depicts the regional extent of the erosive surface in the study area.

Future work and conclusions

This study has added substantial information to our understanding of Miocene margin progradation. However more work is needed to answer some remaining questions. First and foremost, the seismic interpretation needs to be verified. A detailed coring program with a full suite of geophysical logs is necessary to validate the age and facies successions associated with the candidate sequence boundaries identified in this study. Lithologic descriptions of recovered core material would allow an understanding of the exact nature of the reflector geometries. Fortunately this large data hole will soon be filled if the IODP New Jersey Shallow Shelf Expedition proposal comes to fruition. This drilling Expedition 313, planned as part of the New Jersey Transect has already been proposed by G.S Mountain, K.G. Miller, N. Christie-Blick, P.J. Sugarman and C.S. Fulthorpe. If final contracts can be signed, drilling should commence in 2008.

Expedition 313 was designed to study how sea-level change influences sedimentary architecture. The three proposed coreholes were selected to sample sequences at multiple locations at and on either side of their clinoformal inflection points. Part of the *CH0698* seismic grid was designed to fill a tightly spaced hazards grid in preparations for the future drilling. Unfortunately, a detailed seismic grid did not yet exist in the nearshore area when the transect and these Expedition 313 in particular were sited. The amount of along strike variability in sedimentary deposition shown by the *CH0698* seismic grid would probably have influenced the selection of possible other locations to further characterize the factors controlling sequence architecture. Still, these drill holes will add

a wealth of new data that will check the interpretations and advance understanding of the seismic geometries.

Several other questions arise from this study. One question concerns the influence of local subsidence in sequence architecture. In particular, sequences in the northern grid section appear to have an increased accommodation than in the southern grid. Seismic data suggests that northern sequence geometries appear to be thicker and shorter while they are thinner and prograded farther in the south. This needs to be documented more fully than as a simple visual estimation. Monteverde et al. (2001) suggested the location of the basement hinge zone separating relatively intact continental crust on the west from extended crust on the east (Klitgord et al., 1988) could account for this apparent accommodation difference. The hinge zone lies east of the southern grid and moves north and west such that the northern sequence depositional centers lie to the east. Could subsidence be increased within the extended continental crust east of the hinge zone as compared to the relatively pristine crust to the west? Pekar et al (2003) engaged the hinge zone to explain thermal subsidence related accommodation and its relationship to Oligocene sequence development.

A second question concerns the lateral variability of the lower Miocene margin growth. Some seismic data already exists that could shed light on the more northern regions. The New York harbor lies at a vertex of the Mid Atlantic margin with depositional strike in New Jersey trending north-northeast and a more easterly trend along Long Island. How has this change in strike controlled both fluvial sediment input and corresponding

sequence development? Seismic data collected on the *R/V Endeavor* during cruise 370 covers some of this region but spacing is quite broad. Also south of the CH0698 grid a question arises as to the difference between the deltaic controlled sequences of the New Jersey promontory and more shoreface dominated sedimentation of the Salisbury Embayment. ODP Leg 174AX at Bethany Beach, DE (Miller et al. 2003) suggested that the deltaic paleoenvironmental model of New Jersey has been replaced by a shoreface model. More recent drilling in Virginia will further explain how Miocene shelf progradation varied from north to south. A well log collection and interpretation from rotary drilled domestic and municipal wells between core holes would ameliorate our data gap. However more seismic data are needed to understand how the controlling factors of accommodation, eustasy and regional sediment supply control the Miocene margin development away from the New Jersey region investigated in this study.

Conclusions

This study investigated the sequence architecture developed during early Miocene growth of the New Jersey Mid Atlantic margin. The main objectives of the study are to:

1) Identify and characterize stratigraphic sequences along the New Jersey nearshore imaged on the recently acquired CH0698 seismic grid using criteria originally developed by the Exxon Production Research Company and modified by subsequent researchers,
2) Define sequences in the offshore boreholes AMCOR6011, and ACOW 1 and 2 using geophysical logs; compare the sequences to those defined by lithologic, biostratigraphic and chronologic criteria in ODP Leg 150X boreholes at Island

Beach, Atlantic City and Cape May; project dated stratigraphic sequences into the nearshore seismic grid and date seismic candidate sequence boundaries.

3) Analyze the three dimensional nature of early and middle Miocene sequence development along the New Jersey Mid Atlantic margin in view of sea-level change, sediment supply and accommodation.

I identified candidate sequence boundaries through analysis of seismic reflector terminations following the methods originally defined in Payton (1977). The original prediction was to find and characterize the five sequences, from oldest to youngest m6, m5.6, m5.4, m5.2 and m5 encountered in drilling both onshore (Miller et al. 1994a, 1994b, 1996) and offshore (Mountain et al. 1994). Initial interpretations before complete data processing of all lines seemed to validate the original hypothesis. However careful looping of reflectors through the complete grid resulted in a considerable variability in the geometry of the candidate boundaries such that they did not match from line to line. It led to an increased number of sequence boundaries that culminated in eleven. Minor incised valleys were noted on all sequence defined surfaces. The valleys were small and generally limited to the western part of the grid. Boundaries were also seen to thin dramatically and amalgamate within seismic resolution in three directions, landward, seaward and laterally.

A strong degree of along strike variability is evident in the data. No single line showed all sequences. Sigmoidal sequence boundaries and associated surface geometries, well defined in one region changed laterally to more gently dipping surfaces with limited

reflector terminations of onlap, downlap and erosion truncation. The seismically defined sequences portrayed a picture dominated by localized development of lowstand depositional centers and highstand deposits that thinned laterally. The question became how these eleven boundaries linked to the five identified in onshore coreholes.

Land based seismic data used by P Miller et al. (1996) to study coastal plain hydrostratigraphy crossed ODP Leg 150X corehole at Island Beach. It portrayed seismic reflector terminations that characterized sequence boundaries as well as systems tracts. A comparison between the seismic and core data showed a good correlation of boundaries. Paleoenvironmental interpretation of the different sedimentary units observed in the core matched seismic reflector terminations showing that seismic data can accurately image sedimentary depositional features.

Miller et al. (1997) identified five early Miocene sequences in ODP Leg 150X coreholes. These sequences correlated to the lower and middle Miocene Kirkwood Formation and were designated from oldest to youngest Kw0, Kw1a, Kw1b, Kw1c and Kw2a. Deltaic sedimentation dominated Kirkwood deposition. All Kirkwood sequences were not evident in all coreholes due to a dominance of sand and limited biostratigraphic and Sr chemostratigraphic results. Subsequent drilling of ODP Leg 174AX (Miller et al., 2001, Browning et al., 2006) identified more sequences within the original Kw1a and Kw2a which they denoted as Kw1a1, Kw1a2, Kw1a3, Kw2a1, Kw2a2, and Kw2a3, oldest to youngest. How these new sequences fit into the original sequences defined in leg 150X

was unanswered due to the previously described absence of datable material in the older coreholes.

Validation of seismically defined sequence boundaries requires a correlation with the drill hole data. Three additional boreholes in the nearshore regional, used to design the *CH0698* seismic grid offer the best opportunity for direct correlation of core against seismic. These boreholes consisting of AMCOR 6011 and ACOW 1 and 2 were either rotary drilled or cored with low recovery so geophysical logs were used. Geophysical logs were used to outline proposed sequences in the offshore boreholes as outlined by Sugarman and Miller (1997). Sequence interpretations with then compared to sequences identified in leg 150X coreholes by geophysical log correlation. Atlantic City and Cape May coreholes had limited geophysical logs so nearby boreholes with a more complete geophysical suite of logs were employed to allow a more direct comparison with the offshore wells. Gamma logs are the most effective in correlating between wells in the New Jersey Coastal Plain, while resistivity and SP aid in defining sand horizons. The AC, and ACOW 1 and 2 wells lie proximal to CH0698 line 27 and offer the opportunity to correlate between wells and then into the seismic grid. Sequence boundary identification within the two databases correlated well. Downlapping reflectors agreed with prodelta and delta front deposits from cores. This pattern of good correlation continued into the remaining holes and seismic with Island Beach and line 14, Cape May and line 99 and AMCOR 6011 and line 17-16 crossing. A consistent correlation exists such that candidate sequence boundaries defined in the *CH0698* grid match onshore identified sequence boundaries match as follows, (seismic surface + color – base of ODP

sequence) m6 + purple - Kw0, m5.8 + brown – Kw1a1, m5.7 + red – Kw1a2, m5.6 + dark blue – Kw1a3, m5.5 + green – Kw1b1, m5.47 + light blue – Kw1b2, m5.45 + pink – Kw1c, m5.4 + yellow – Kw2a1, m5.3 + red – Kw2a2 and Kw2a3, m5.2 + orange – Kw2b. This correlation predicts the sequences originally identified in leg 150X where insufficient data hindered age dating of sequences. A discrepancy exists between this correlation and that proposed by Miller et al. (1998). They correlate m5 to the base of the Kw2b boundary while I match the base of Kw2b to m5.2. Future drilling should solve this difference in interpretations.

The final stage of the dissertation evaluated the signature of sediment supply, relative sea level and marine sediment transport recorded in the sequence architecture and preservation. As previously stated the *CH0698* sequences show a marked lateral variability in sequence geometry and sediment thickness distribution. Isopach maps of both lowstand facies and total sequence thickness outline the along strike differences. Lowstand deposits are well imaged on *CH0698* data, limited in areal extent and suggest isolated sediment supply. Their restricted regional extent suggest that individual larger point sources or an accumulation of smaller sources disbursing sediment in one localized region brought sediment to the margin. The location of these fluvial systems changed with time from a northwestern to a western source. The dominant source varied in time with duo sources present often. Lowstands developed linear deposits possibly suggesting some sediment redistribution along strike possibly due to shore parallel currents which have been active often during the growth of the New Jersey Mid Atlantic margin. Isopachs of lowstands indicate that a southward current dominated during this time.

Highstand sediments were deposited more regionally. They generally account for all sedimentation, within seismic resolution landward of the CIP. Highstand sedimentation formed in a broader area though their dominant depositional centers approximated those of lowstand facies. Movement of fluvial systems across the shelf apparent occurred after transgressions probably due to erosion and infilling of previous channels. The margin did not grow as a line source but prograded by the accumulation of sediment supplied by variable fluvial systems in different places at different times.

A final question involves the degree of margin exposure during low relative sea level. The majority of incised valleys are resident on the western part of the grid. No valleys were imaged near or at the CIP as would be expected if relative sea level dropped below the CIP. Steckler et al. (1999) has suggested that sea level was over 60 m deep at the CIP during formation of these sequence boundaries. They propose that sequence boundary geometry as imaged on *Ew9009* data is more indicative of a shelf - slope interface thane a shoreface. No evidence exists on *CH0698* data to refute this model.

Shelf current dynamics, both as along and cross shelf flow patterns controlled the distribution of sediment in the marine environment. Cross shelf currents carried sediments over the CIP during lowstand conditions. Sediment redistribution of lowstand material may have occurred during relative sea-level low or during rise. As relative sea level increased, transgressive ravinement surfaces formed and merged or became the sequence boundary within seismic resolution. Transgressive deposits are too thin to be

imaged on the *CH0698* data. During highstand conditions sediment migrated on the shelf under along and cross shelf currents. Margin parallel currents appear to have dominated though shore perpendicular sediment movement was still active.

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