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Early Miocene sequence development across the New Jersey margin

Donald H. Monteverde,*‡ Gregory S. Mountain*† and Kenneth G. Miller*

*Department of Geological Sciences, Rutgers University, Piscataway, NJ, USA
†Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA
‡New Jersey Geological Survey, Trenton, NJ, USA

ABSTRACT

Sequence stratigraphy provides an understanding of the interplay between eustasy, sediment supply and accommodation in the sedimentary construction of passive margins. We used this approach to follow the early to middle Miocene growth of the New Jersey margin and analyse the connection between relative changes of sea level and variable sediment supply. Eleven candidate sequence boundaries were traced in high-resolution multi-channel seismic 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. We conclude that the regional and global correlation of early Miocene sequences suggests 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 distribution of highstand deposits, by contrast, documents redistribution by along shelf currents. We find no evidence that sea level fell below the elevation of the clinoform rollover, 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). Although 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 & 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 & James (1993) and Christie-Blick & 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 & Helland-Hansen, 1995). For example, previous studies of the New Jersey margin (Metzger *et al.*, 2000; Pekar *et al.*, 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 modelled (e.g. Steckler & Watts, 1978; Kominz *et al.*, 1998; Van Sickel *et al.*, 2004), although 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 two-dimensional (2D) or 3D view is needed either through closely spaced well logs, (van Wagoner *et al.*, 1990) seismic profiles, or a combination of both.

Correspondence: Donald H. Monteverde, Department of Geological Sciences, Rutgers University, Piscataway, NJ 08854, USA. E-mail: dmonte@rci.rutgers.edu

The earliest multi-channel 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 Palaeogene and Neogene sequences (Poag & Schlee, 1984; Poag, 1985a, b; Poag & Ward, 1987; Greenlee & 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 *et al.*, 1987; Ocean Drilling Programme (ODP) Legs 150, Mountain *et al.*, 1994; Ocean Drilling Programme (ODP) Legs 174A, Austin *et al.*, 1998).

Although 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 *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 & 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 depocentres.

We describe early Miocene sequence development as imaged on a regional seismic grid across the current nearshore and offshore New Jersey margin (Fig. 1). Candidate boundaries are tied to onshore ODP coreholes (Miller *et al.*, 1994a, b, 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 we examined. The extent of subaerial margin exposure during relative sea-level fall is analysed.

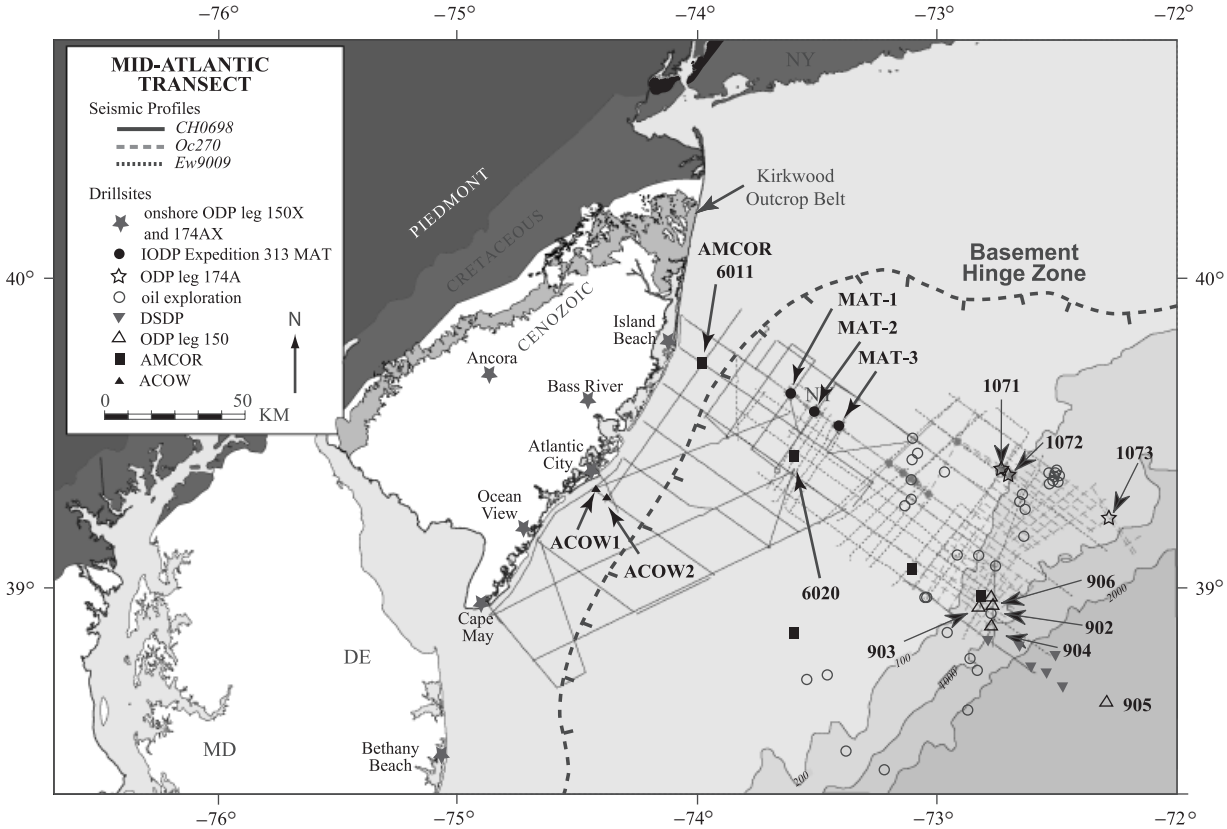

Fig. 1. Locality map of the New Jersey margin showing the extent of previous seismic surveys including *Ew9009* and *Oc270*. Offshore drilling programs shown include ODP Legs 150 and 174A that reached Miocene sediments. Data used in this study include the *CH0698* seismic grid, onshore ODP Legs 150X 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).

Table 1. Miocene sequences on the New Jersey margin determined from both seismic and borehole data

Seismic sequences (Greenlee *et al.*, 1992)	Seismic sequences (Mountain *et al.*, 1994)	Seismic sequences (Miller *et al.*, 1996a)	Seismic sequences (this study)	Sequences from coreholes (Browning *et al.*, 2006)	Sequence age (Ma)	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	16.9–17.1	Ocean View
				Kw2a3	17.1-17.2	
	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	Dk 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

Early work of Greenlee *et al.* (1992) used low-resolution data and described two early Miocene sequences. Mountain *et al.* (1990) analysed *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.* (1994). This study outlined 11 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).

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, b; Poag *et al.*, 1987; Mountain *et al.*, 1994; Austin *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 & 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 & 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 & 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 Palaeogene and Neogene stratigraphy in the modern mid- to outer shelf and slope (Fig. 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 centres beneath the current inner shelf (Table 1, Mountain *et al.*, 1994). Seismic interpretation confirmed four sequences of Greenlee & 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 & Mountain, 1994; Mountain *et al.*, 1994). These borehole locales were chosen to calibrate the seismically identified sequence boundaries in a distal setting where known palaeoenvironmental conditions held the promise of high sedimentary and biostratigraphic preservation potential (Miller & Mountain, 1994; Mountain *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. 1). This dip line, constructed from several aligned dip profiles (*Oc270* lines 29, 129, 229, 329, 429 and 529) resampled industry data described by Greenlee & 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 & Mountain, 1994). *Oc270* grid also traversed the ODP Leg 150 sites thereby improving sequence correlation across the outer shelf slope (Fig. 1; Fulthorpe *et al.*, 1999, 2000). *Oc270* guided the next generation of Mid-Atlantic Drilling Transect drilling during ODP Leg 174A (Fig. 1). This ODP leg sampled Late Miocene through Pleistocene sediments

beneath the modern outer shelf and slope (Christie-Blick & Austin, 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 centres were imaged on *Ew9009* and *Oc270* data (Fig. 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. 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 m 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 s; sample rate was 1 ms on *Oc270* and 0.5 ms 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 s 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 analysed in a sequence stratigraphic framework. Geometry of seismic reflector terminations defined individual sequences according to methods outlined by Mitchum (1977), Mitchum & Vail (1977), Mitchum *et al.*, (1977a, b, 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 labelled by colour, from oldest to youngest as pink-3, blue, sand, ochre and green (Table 1) as listed in Miller & Mountain (1994). When more detailed analysis revealed additional mappable surfaces these sequence boundaries were changed to an α-numeric designation from oldest to youngest as m6, m5.6, m5.4, m5.2 and m5, respectively (Table 1; Mountain *et al.*, 1994). Surface m6 was correlated to the Miocene–Oligocene boundary (Mountain *et al.*, 1994; N. Christie-Blick, G. S. Mountain and K. G. Miller, pers. comm.). *Ew9009* grid lines lie mostly on the current outer shelf where middle Miocene to Pleistocene sequences are best developed (Fig. 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 rollover (Fig. 2). The clinoform rollover 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 & Austin, 1998; Fulthorpe *et al.*, 1999), and clinoform rollover (this study). At these locations seismic terminations characteristic of falling stage, lowstand and highstand facies are best developed. Away from these depocentres 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 (Figs 2 and 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 centre where continuous parallel reflectors mark deeper water sediments and

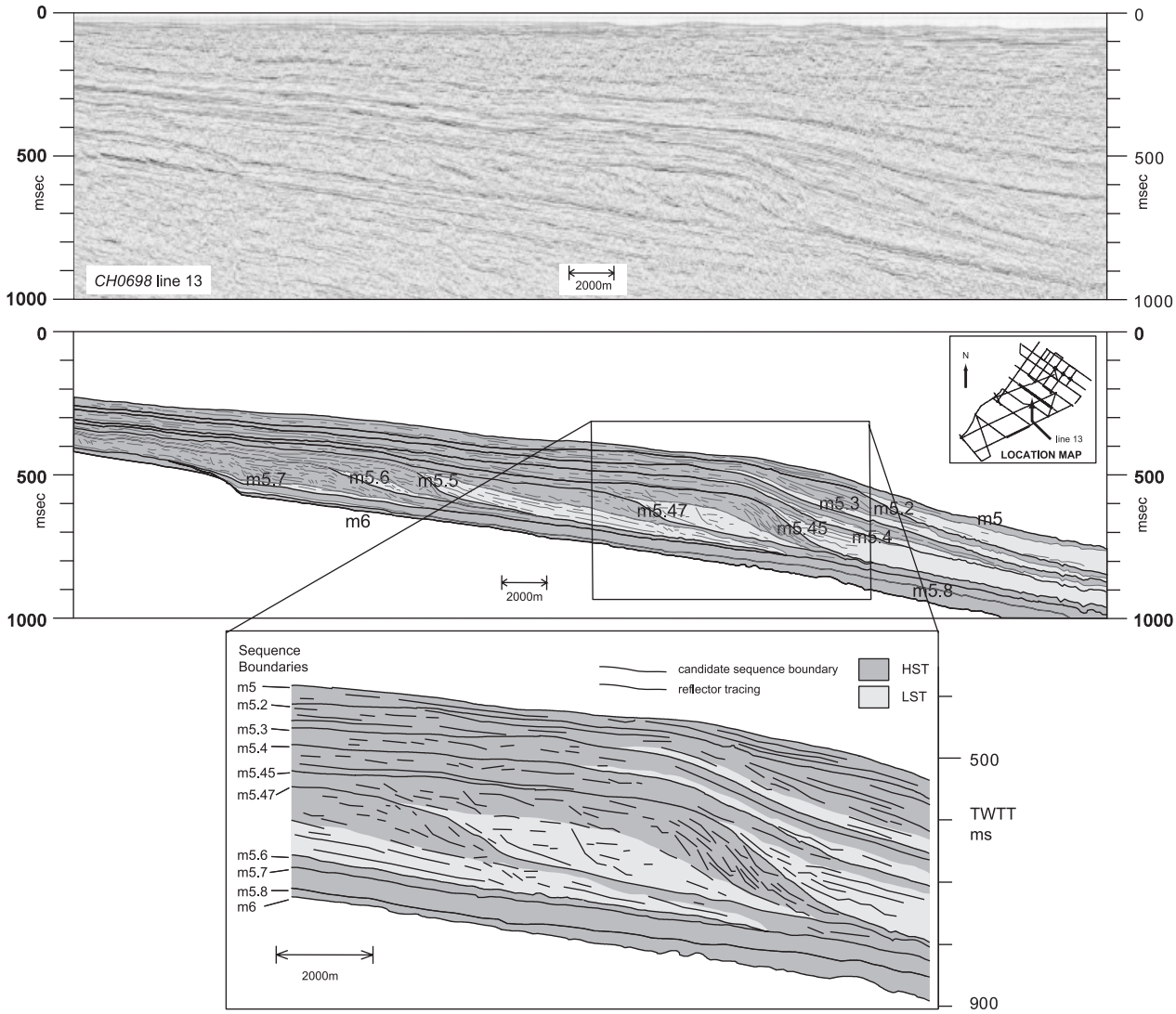

Fig. 2. Example of seismic reflectors on *CH0698* line 13 outlining both highstand and lowstand facies deposits in different shades of gray. Transgressive deposits are generally below seismic resolution and not shown. Location map shows position of line 13 within the *CH0698* data grid.

fine-grained deposition would be expected. Numerous small-scale normal faults are imaged in this section. Cartwright & 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 *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 rollover 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 palaeoshelf (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, b, 1997, 2001) (Fig. 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

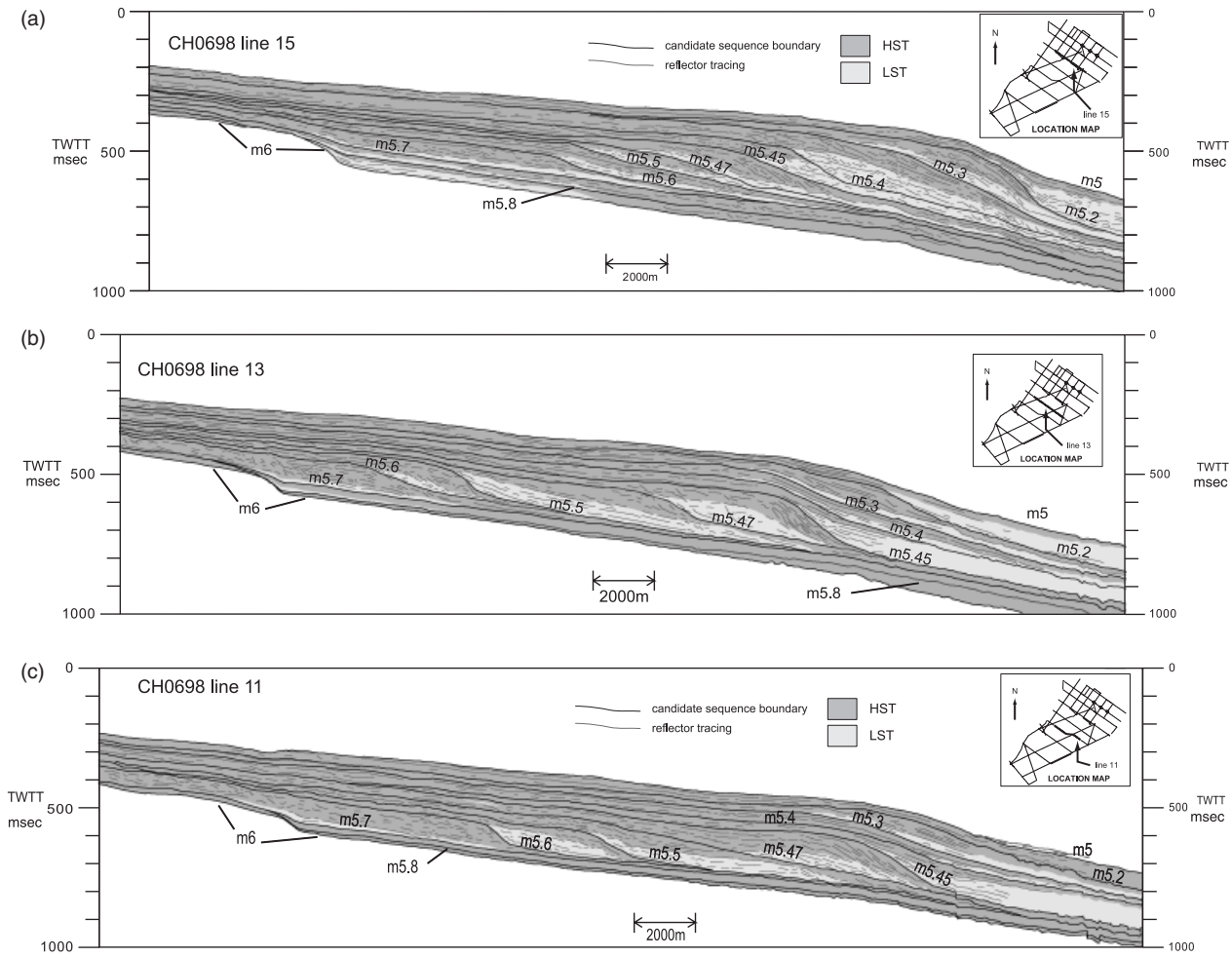

Fig. 3. Three successive dip profiles within the *CH0698* grid portraying significant along strike variability within individual sequences. The seismic sections are, in the north, lines 15, 13 and 11 in the central grid section. Candidate sequence boundaries can be seen to erode, amalgamate or join, 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.

boundaries. A gently sloping, ~0.06°, 1 : 1000 gradient (Steckler *et al.*, 1999; Pekar *et al.*, 2003) Oligocene palaeoshelf allowed relative sea-level rise to rapidly migrate across the shelf. Miocene sediments prograded past the Oligocene palaeoshelf edge and infilled an Eocene ramp margin (1 : 500 gradient).

Isphording & 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. 1). The Alloway Clay was mapped in the south and described as representing a middle neritic palaeoenvironment. 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 & 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 & Lodding (1969) and Isphording (1970) represented the generally nearshore deposits suggesting the lateral extent of marine incursion during the early and middle Miocene. The palaeoshelf/coastal plain was approximately 110 km wide when measured from the western outcrop belt (Fig. 1; Owens *et al.*, 1998) to the lower Miocene clinoform rollover observed in *CH0698* seismic data. The rapid, relative sea-level rise across this low-gradient shelf limited the deposition of transgressive sands.

Highstand Systems Tract (HST) deposits identified by prograding, downlapping reflector terminations dominate the areal extent of the seismic sequences. Distance to the underlying clinoform rollover 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 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 rollover. 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 rollover 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 palaeoshelf (Fig. 2).

Lowstand (LST) deposits are restricted to seaward of the clinoform rollover of the underlying sequence. Seismic resolution restricts any interpretation of valley fill on the palaeoshelf as either lowstand and/or transgressive facies. Rare larger incised valleys contain reflectors showing oblique onlap. Ashley & 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 & Sheridan, 1994). Reflector geometry on *CH0698* data do not definitively support nor contradict the interpretation of Ashley & Sheridan (1994). Lowstand facies contain reflectors that both onlap the clinoform front and downlap farther offshore (Mitchum *et al.*, 1977b; Sangree & 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 (possible fans?) typically developed farther seaward. Broad wedge-like bodies occur atop mounded 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. 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 (Figs 1 and 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. 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, whereas the remaining three samples at 201, 187 and 174 m are ECDZ 6(?) using correlations of Abbott (1978) and Andrews, (1987, 1988) (Fig. 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. 1). Hathaway *et al.* (1976) describes a 23% average core recovery within this hole. However, Abbott (1978) was able to supply palaeontological 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. 4) (Miller *et al.*, 1994a, b, 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, b, 1996b) (Fig. 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, Kwla, Kwlb, Kwlc, Kw2a and Kw2b; 24.2–15.6 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

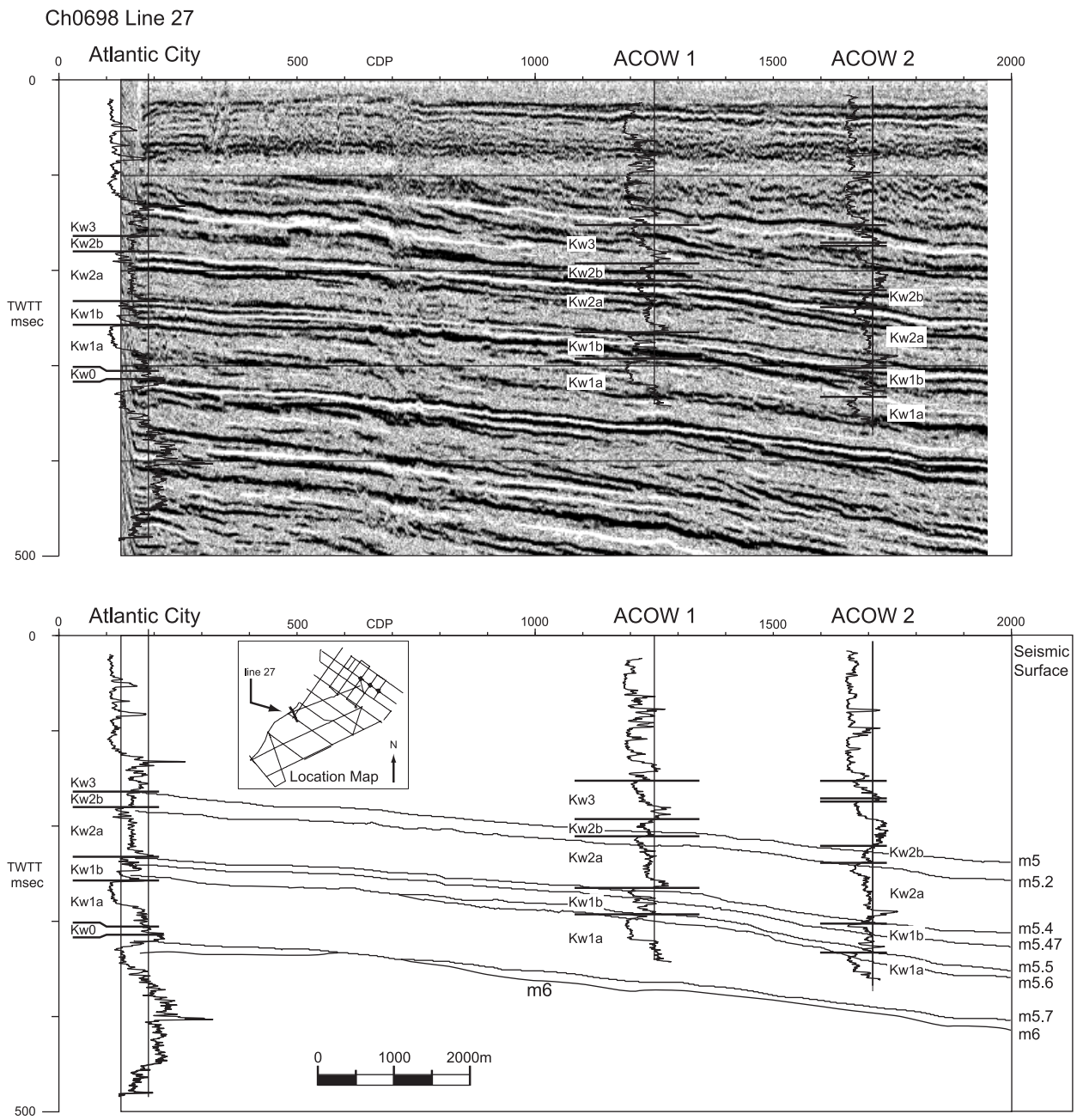

Fig. 4. Integration of ODP Leg 150X Atlantic City corehole and ACOW 1 and 2 boreholes into *CH0698* line 27. Onshore sequences were identified by litho and biostratigraphic data in the AC corehole (Miller *et al.*, 1994b). Sequences were characterized to their corresponding log signatures and compared to good geophysical logs for the rotary-drilled boreholes ACOW 1 and 2, which had limited litho and biostratigraphic recovery.

(Miller *et al.*, 2001; Sugarman *et al.*, 2007) supplied sufficient information to redefine the six sequences into 10.

These onshore and offshore drill holes supply sufficient information to date and correlate the *CH0698* seismic sequences (Table 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 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 whereas the present analysis suggests an association with the top of Kw2b. 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 (Figs 3, 5 and 6). Sequences and

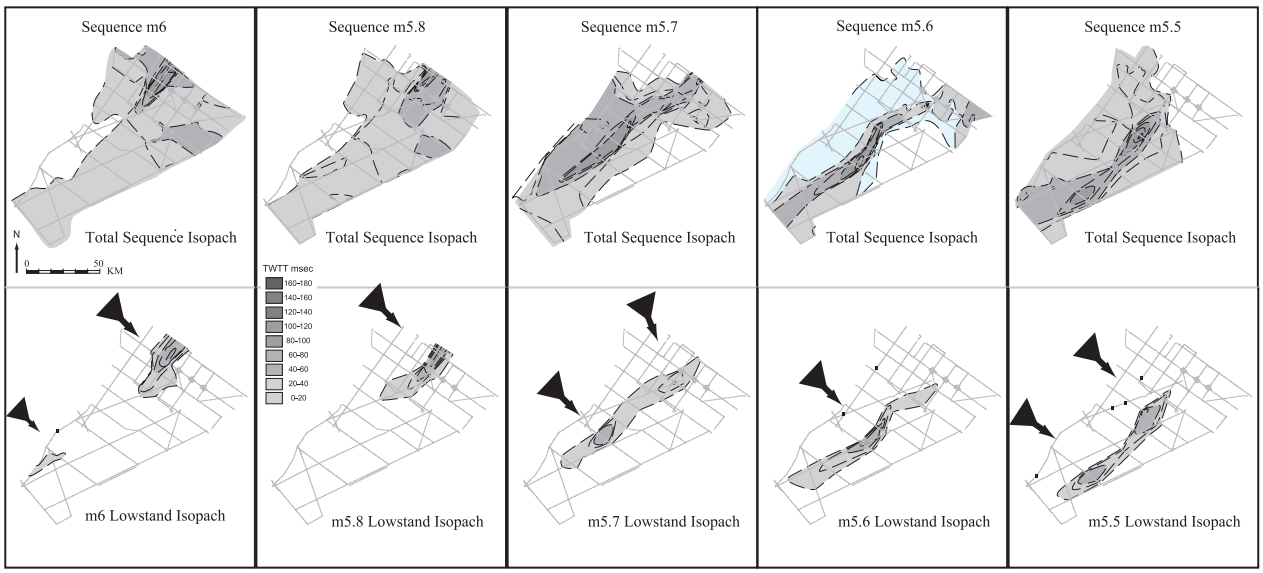

Fig. 5. Isopach map of the five oldest seismic sequences identified on *CH0698* data. Sequences are identified by the basal reflector and from oldest to youngest consist of m6, m5.8, m5.7, m.5.6 and m5.5. Isopachs of total sequence thickness are shown above their corresponding lowstand isopachs. Units 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 palaeoshelf.

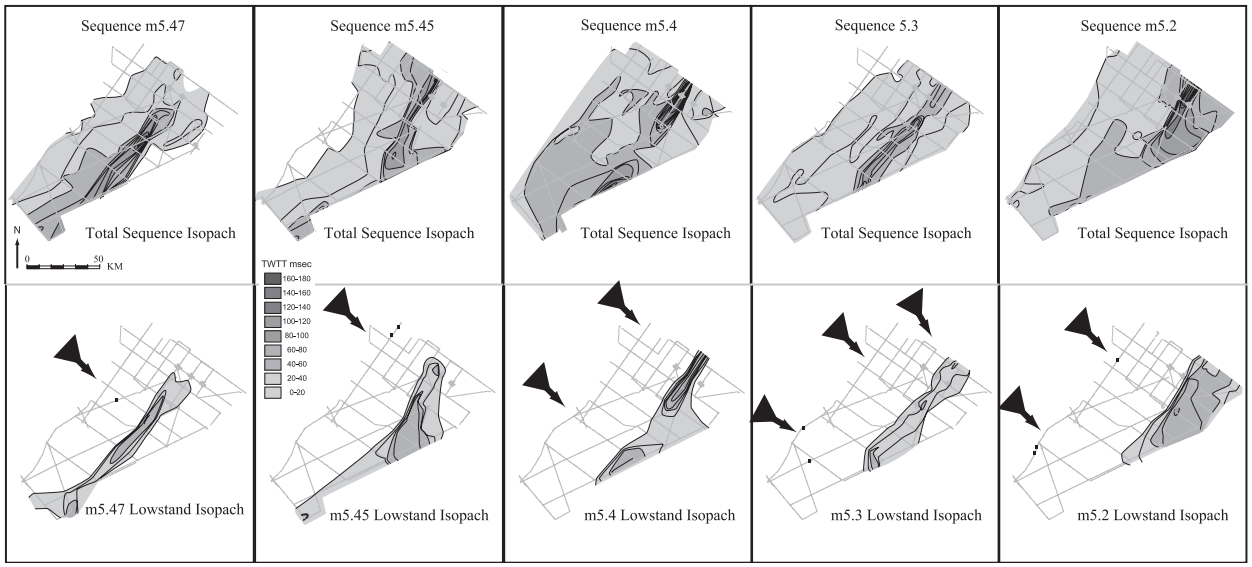

Fig. 6. Isopach map of the next five (youngest) seismic sequences identified on *CH0698* data. Sequences are identified by the basal reflector and from oldest to youngest are m5.47, m5.45, m5.4, m.5.3 and m5.2. Isopachs of total sequence thickness (in msec of two-way traveltime) are shown above their 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 palaeoshelf.

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 rollover 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 & Sohl, 1969; Sugarman *et al.*, 1993; Browning *et al.*, this volume). Use of the term 'deltaic' to describe deposition in these palaeoshelf environments is further supported by increasingly shallow lowstand palaeowater depth estimates for this margin, as discussed below (see also Pekar *et al.*, 2003). Sugarman *et al.* (1993) studied lower and middle Miocene sequence deposition patterns under the modern coastal plain and recorded an initial depocentre south of

Island Beach that migrated southward near Cape May through time (Fig. 1). Not surprisingly, seismic sequence isopachs also display changing deltaic depositional centres (Figs 5 and 6). Lowstand facies isopachs further substantiate and locate the approximate sediment inputs that dominated margin growth during low relative sea level (Figs 5 and 6). Isopachs suggest two main foci of sedimentation: one, from the north to NW and restricted to the northeastern section of the *CH0698* grid and a second and larger depocentre 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 depocentre that builds seaward into a slight promontory (Fig. 5). A subordinate m6 lowstand occurs near Cape May indicating a secondary sediment source (Fig. 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 (Fig. 5). Both sequences merge with the m5.7 sequence towards the SW. It is uncertain whether m5.7 amalgamates with m6 and m5.8 because of low sedimentation in the SW or because of an increased removal from transgressive ravinement or shelf current-controlled redeposition. Allen & 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 & Sheridan, 1994; Cattaneo & 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 (Figs 5 and 6). Isopachs depict margin-parallel, linear to slightly arcuate depocentres across the central section of the grid. Lowstands suggest that sequences m5.7 and m5.5 have two separate sediment inputs whereas sequences m5.6 and m5.47 present a dispersed, single source (Figs 5 and 6). Sequence m5.7 has limited connection between the two separate lowstand facies whereas 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 (Figs 5 and 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 SW. 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, SW-trending depositional front (Fig. 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 (Figs 5 and 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. 6). Only m5.4 suggests multiple separate sediment sources during lowstand deposition (Fig. 6). By the time of sequence m5.3 the clinoform rollover 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. Lowstands facies are restricted to mounded (fan?) and wedge-like bodies at the clinoform fronts. *CH0698* seismic resolution limits identification of TST and LST incised valley fills. Highstand deltaic sediments blanket the palaeoshelf, downlap onto the underlying sequence boundary, and prograde to the preceding clinoform rollover (Fig. 3). Once deposition filled the accommodation on the palaeoshelf the foci of highstand sedimentation migrated seaward of the clinoform rollover 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 rollover.

The US Mid-Atlantic margin has long been categorized as storm-dominated. 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 kilometres offshore. Both sand and mud are resuspended by occasional storm waves and carried farther offshore. Swift (1970) and Swift *et al.*, (1986a, b) 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.

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 rollover. Here, marine erosion removed sediment that was then redeposited seaward of the clinoform rollover (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 & Driscoll (1997) and Driscoll & 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 rollover and shoreline positions coincide (Karner & Driscoll, 1997; Driscoll & 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 & 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 palaeo 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, b, 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, b, 1997).

Offshore geophysical logs display characteristics similar to onshore corehole logs, suggesting similar sedimentation patterns and sequence development. High values of natural γ-rays across the Miocene sedimentary units indicate clays and, where present, glauconite as shown in Leg 150X cores (Miller *et al.*, 1994a, b, 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 $<1\%$ of the Miocene sedimentary material (J. Browning, pers. comm.). Therefore, the γ response should mimic grain size within the Miocene New Jersey Coastal Plain. A γ spike commonly marks the sequence boundary, recording the change from quartz sand below to clay rich sediment above (Miller *et al.*, 1994a, b, 1996b) (Fig. 4). Log patterns of Leg 150X coreholes document the MFS and lHST and uHST pattern (Fig. 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 rollover (Figs 1, 5 and 6). Although not thoroughly sampled, middle Miocene sequences, by contrast, have been seismically imaged and logged at industry wells on the middle and outer shelf (Fig. 1). The middle Miocene was a time of increased regional siliciclastic sedimentation due to hinterland uplift and global cooling (Poag & Sevon, 1989). As a result, thick lowstand wedges controlled by localized fluvial input built depocentres 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 depocentres comprised great thicknesses of sand, whereas 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 & 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 rollover migrated south with time, or (2) sediment delivery occurred landward of the clinoform rollover 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 & Gardner (1993, 1994) 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 Myr) marine transgressive event. The late Oligocene cycle contained sediments from palaeo-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. 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 (S. D. Stanford, written comm.). 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 (S. D. Stanford, written comm.). 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. Nonmarine deposits do occur within the uHST of the Kwlb in the Island Beach (Miller *et al.*, 1997; Owens *et al.*, 1997) and Atlantic City boreholes (Miller *et al.*, 1997). Liu *et al.* (1997) used palaeoenvironmental reconstructions based on foraminiferal biostratigraphy to suggest that the Island Beach sediments represent estuarine conditions. Other nonmarine 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 (Figs 5 and 6). None of these erosional features can be connected between adjacent profiles. It is possible that due to the ~12.5 km seismic grid spacing few incised valleys would be detectable as anything other than the isolated features we observe.

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, b). 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 & Sheridan, 1994; Cattaneo & 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 metres subseafloor, and data on current direction during the early Miocene are 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 boundaries 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 US 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 palaeoshelf from the lowstand depositional centres farther offshore (Fig. 1). Cattaneo & 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 & Sevon (1989). Pazzaglia (1993) suggests that a palaeo-Hudson and palaeo-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 palaeo-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 palaeowater depth of clinoform rollovers: 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 & Vail (1988) initially described shoreface deposits that migrate to and below the clinoform rollover due to a relative drop in sea level. Subsequently, various authors (e.g. Hunt & Tucker, 1992; Plint & Nummedal, 2000) described a separate systems track which compares to the 'lowstand fan' of Posamentier *et al.* (1988) (Catuneanu, 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 palaeoshelf edge would have accentuated fluvial channel incision cutting the clinoform rollover and proximal sections of the palaeocontinental shelf. Incision would have migrated landward by headward erosion, cutting through knick points (Catuneanu, 2006) as relative sea level remained below the clinoform rollover. 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 palaeoslope 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 modelling to calculate the true elevation of major Cenozoic sequence boundaries across the New Jersey margin. Applying 2D 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 rollovers remained covered by 60–127 m of seawater and were never subareally 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 & Pekar (2001) used ODP Leg 150X borehole and other regional well information in a 2D backstripping of onshore Oligocene and lower Miocene (Kw0) sequences. They, too, found that the clinoform rollover was not exposed during sequence unconformity development. Pekar *et al.* (2003) suggested that during the middle to late Oligocene, the rollover was never covered by $<20 \pm 10$ m water depth.

Seismic studies of middle and upper Miocene sequences offer disparate results concerning the debate about palaeowater 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 palaeoshelf 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. Relative sea level falls below the shelf in the second, allocyclic mechanism of Poulsen *et al.* (1998). This fall forces channel incision across the clinoform rollover. 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 rollover whereas the autocyclic model would have relative sea level at the rollover. 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 palaeoshelf, Fulthorpe *et al.* (1999) suggested that relative sea level fell just to and not over the clinoform rollover. McHugh *et al.* (2002) showed delta progradation reached the upper slope during late Miocene. This progradation is associated with m0.3–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 $\sim$2.5 km landward of the clinoform rollover (Austin *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 whereas 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 rollover (Nordfjord *et al.*, 2005). A dendritic channel morphology was imaged to 90 m water depth marking a palaeoshoreline and processes responsible for deposition of a succeeding offlapping wedge. Nordfjord *et al.* (2005) described their 'R' reflector as palaeo-seafloor and noted an inflection point or rollover that was identified as the shelf edge during a sea-level fall at $\sim$35–22 ka. Deposition of the offlapping wedge occurred seaward of the rollover. 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 palaeowater depths at clinoform rollovers. The only data suggesting sea level reached the clinoform rollover occurs on *Oc270* line 529 where a small shelf-edge delta formed immediately seaward of the clinoform rollover of sequence m5.4 (Fig. 7). The delta is imaged only on a single dip line where it shows a progradation no longer than approximately 1.8 km. Lowstand facies of the m5.4 sequence on line 529 are suggested by reflectors onlapping the delta's base. *CH0698* data image two lowstand parasequences that prograde from the north towards the SE 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. 7). A small river with limited incision could supply the sediment for this delta. The shelf edge delta just below the clinoform rollover 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 rollover, fluvial incision would be minimal (Emery & 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 and 5 m, respectively) or has been missed by the nominal 12.5 km line spacing.

Incised valleys on CH0698 data approach within $\sim$12 km of the corresponding rollover position. This yields

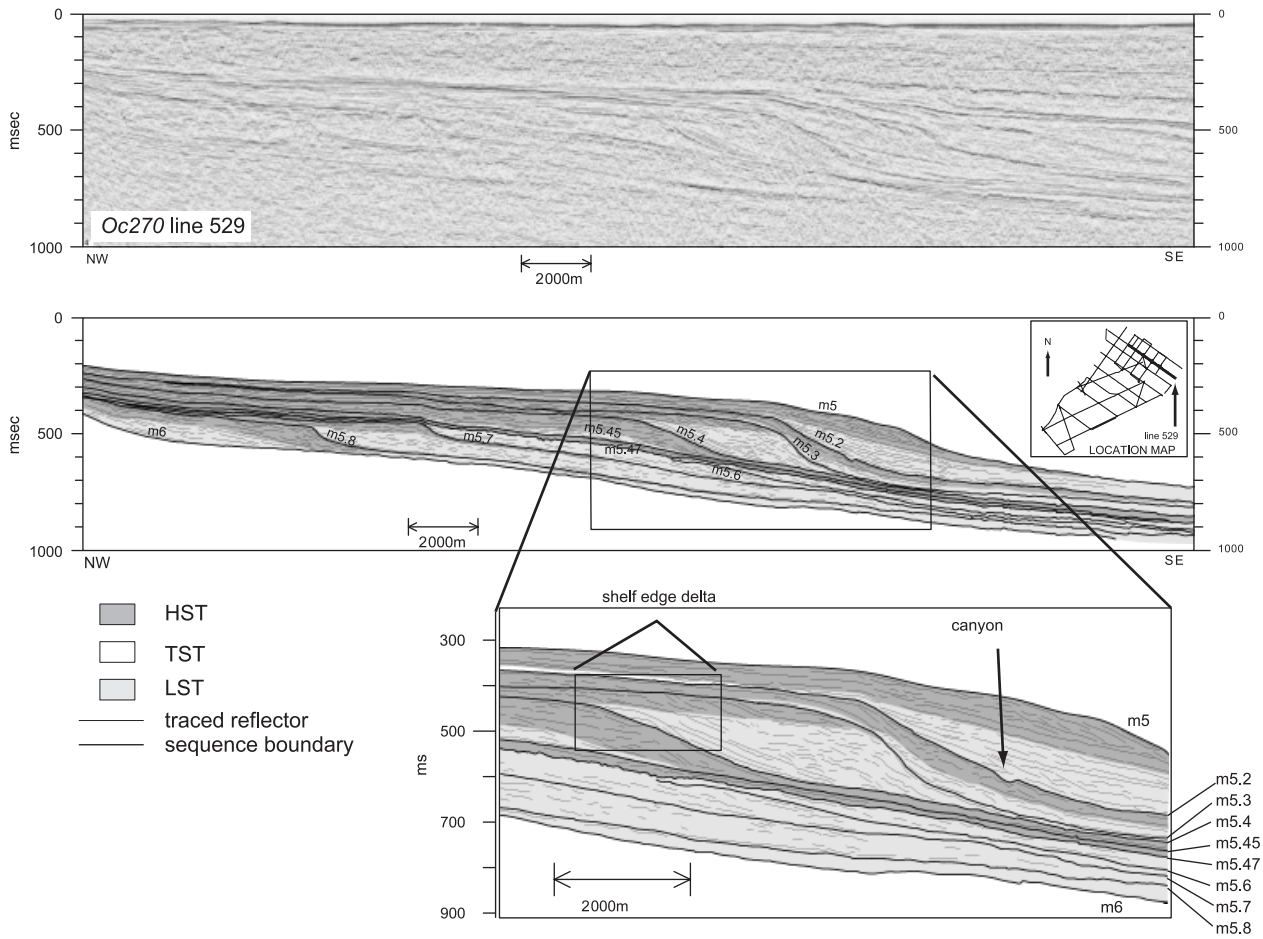

Fig. 7. *Oc270* line 529 images a shelf edge delta just below the clinoform rollover of sequence m5.4. This small delta is only imaged on a single line. The location of the delta top at the clinoform rollover suggests that sea level may have reached this point. However no incised valleys related to the 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.

a relative maximum water depth of ~12 m across the 1 : 1000 gradient palaeoshelf which is considerably < 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 rollover, 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 palaeoshelf-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 (Catuneanu, 2006), and lowstand deposits could develop by enhanced cross shelf sediment deposition during falling relative sea-level (Karner & Driscoll, 1997; Driscoll & Karner, 1999).

CH0698 data suggest that early Miocene sea level may not have reached the clinoform rollover except on sequence boundary m5.4. The absence of channel incision at of near the generally smooth clinoform rollover suggests that relative sea level did not fall below the clinoform rollover. 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 palaeoslope 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 rollover.

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 *et al.*, 1994; Austin *et al.*, 1998; Fulthorpe & Austin, 1998; Fulthorpe *et al.* 1999; 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 11 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 depocentres 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 palaeo-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 palaeo-Susquehanna controlled deposition of the following m5.6 sequence. Delivery of sedimentary material changed again as two active depocentres 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 & Driscoll (1997) and Driscoll & 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 rollover, 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 rollover 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, we have discussed have not been drilled at the offshore locations needed to evaluate their complete significance. Although the succession and inferred age and facies of these 10 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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