The sedimentary imprint of Pleistocene glacio-eustasy: Implications for global correlations of seismic sequences

Article in Geosphere · January 2017
DOI: 10.1130/GES01569.1

CITATIONS 0
READS 12

6 authors, including:

Cecilia M. G. Mchugh
City University of New York - Queens College
151 PUBLICATIONS 1,556 CITATIONS

Some of the authors of this publication are also working on these related projects:

- Extreme event deposits archived in the sedimentary record offshore Japan [View project]
- Earthquake-triggered remobilization of surficial sediments [View project]

All content following this page was uploaded by Cecilia M. G. Mchugh on 29 October 2017.
The user has requested enhancement of the downloaded file.
The sedimentary imprint of Pleistocene glacio-eustasy: Implications for global correlations of seismic sequences

Cecilia M. McHugh1,2, Craig S. Fulthorpe3, Koichi Hoya-nagi4, Peter Blum5, Gregory S. Mountain6, and Kenneth G. Miller4
1School of Earth and Environmental Sciences, Queens College City University of New York, Flushing, New York 11367, USA
2Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA
3Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas 78758, USA
4Department of Geology, Shinshu University, Matsumoto 390-8621, Japan
5United States Implementing Organization, Integrated Ocean Drilling Program, Texas A&M University, College Station, Texas 77845, USA
6Rutgers University, Department of Earth and Planetary Sciences and Institute of Earth, Oceans, and Atmospheric Sciences, Piscataway, New York 08854, USA

ABSTRACT

We evaluate lithofacies, chronology, and seismic sequences from the Canterbury Basin, New Zealand passive continental slope (Integrated Ocean Drilling Program [IODP] Expedition 317 Site U1352 and environs) and compare this with slope sequences from the New Jersey passive margin. Our goal is to understand continental slope sedimentation in response to glacio-eustasy and test the concepts of sequence stratigraphy. High-resolution geochemical elemental and lithostratigraphic analyses were calibrated to a chronology constructed from benthic foraminiferal oxygen isotopes for the past ~1.8 m.y. We identify lithofacies occurrences by their unique geochemical and lithologic signature and correlate them with marine isotope stages (MIS) at Milankovitch 100 k.y. (MIS 1–12) and 41 k.y. (MIS 13–63) periods. Eight seismic sequence boundaries (U13–U19) were identified from high-resolution multichannel seismic data, providing a seismic stratigraphic framework. Except for MIS 1–5 and MIS 54–55, there are 2–16 MIS stages and a comparable number of lithofacies contained within each seismic sequence, indicating that it took one to several glacio-eustatic cycles to build each seismic stratigraphic sequence. These findings support prior results obtained by the Ocean Drilling Program (ODP) Leg 174A on the New Jersey continental slope. On both margins, there is a strong correlation between seismic sequences, lithofacies, and MIS, thus linking them to glacio-eustasy. However, the correlation between MIS and seismic sequences is not one-to-one, and Pleistocene seismic sequences on the two margins are not synchronous. Local conditions, including differences in sedimentation rates and creation of accommodation space, strongly influence sediment preservation at each location, revealing that high-frequency Pleistocene seismic sequences need not correlate globally.

INTRODUCTION

The impact of past sea-level change has been preserved in the thick sediments along continental margins. Global sea-level (eustatic) change directly affects coastal plain, continental shelf, and continental slope sedimentation through shoreline migration, generating regionally extensive unconformities that bound packets of sediment known as sequences. Claims of a causal link between eustasy and the unconformity-bounded sequences that pervade continental-margin sedimentary deposits have been made since the concept of sequence stratigraphy was first presented in its current form (Mitchum et al., 1977; Vail et al., 1977; Haq et al., 1987; Posamentier et al., 1988), and it is generally agreed that glacio-eustasy is the main driver of sequence formation during the Earth’s most recent icehouse period ca. 34 Ma to present (Miller et al., 1991, 1996). During the Quaternary (past 2.55 m.y.), Milankovitch orbital cyclicity (eccentricity, obliquity, and precession) has driven large-scale changes in both Antarctic and Northern Hemisphere glaciation that are manifested as large-amplitude glacial-interglacial cycles and attendant sea-level changes (e.g., Hays et al., 1976; Imbrie et al., 1984; Lisiecki and Raymo, 2005).

It is commonly accepted that sedimentation at continental margins during the Late to Middle Pleistocene (past 800 k.y.) has been controlled by 100 k.y. cyclicity as indicated by the δ18O proxy for ice volume (Hays et al., 1976; Lisiecki and Raymo, 2005). Under ideal circumstances of sufficient accommodation and sediment supply, depositional sequences on continental margins over the past 800 k.y. would follow a sequence stratigraphic conceptual model reflecting the influence of one 100 k.y. Milankovitch cycle per seismic sequence. Such a correlation is strong for the past 125 k.y. (i.e., the last glacial-interglacial cycle), where seismic sequences on several margins have been successfully correlated to marine δ18O record across marine isotope stages (MIS) 1–5 in both tectonically active and passive margins (e.g., Hernández-Molina et al., 2000; Kolla et al., 2000; Anderson et al., 2004; Çağatay et al., 2009). On margins with very high sedimentation rates, the 100 k.y. cyclicity is punctuated by a 20 k.y. cyclicity (Hernández-Molina et al., 2000; Kolla et al., 2000; Çağatay et al., 2009). However, for sediments older than 125 k.y., such correlations are rare. One example from the Adriatic margin shows a continuous correlation between 100 k.y. Milankovitch cyclicity and seismic sequences for the past ~370 k.y., spanning MIS 1 to the top of MIS 11 (Ridente et al., 2008, 2009). Ultra-high-resolution chirp sonar was used by Ridente et al. (2008, 2009) to define the seismic stratigraphic sequences that were calibrated to a chronology constructed from oxygen isotopes. One-to-one
correlation of seismic sequences and Milankovitch cyclicity was proposed for the tectonically active Eel River Basin offshore California, using lower-resolution multichannel seismic (MCS) data, but the chronology needed to verify this correlation was poor (Burger et al., 2002; Mountain et al., 2007). In the Eel River Basin, as in most margins, individual Milankovitch-scale Pleistocene MIS eustatic cycles have not been dated. Questions therefore remain about whether Pleistocene seismic sequences defined on MCS data, commonly used in sequence stratigraphic interpretations, have any direct link to Milankovitch-scale cyclicity and, therefore, to eustasy and hence whether it is meaningful to correlate such sequences globally in both tectonically active and passive margins (Watkins and Mountain, 1990).

Passive margins along the South Island of New Zealand and the mid-Atlantic region off New Jersey were selected at a community workshop in 1988 as places where ocean drilling could determine links between glacio-eustasy and sea-level change (Watkins and Mountain, 1990). Since then, a series of experiments have been conducted at both locations to understand the influence of eustasy on continental margin sedimentation and to test sequence stratigraphic models using scientific ocean drilling. Eocene to Holocene siliciclastic sediments of the Canterbury Basin, offshore eastern South Island, New Zealand were drilled by Integrated Ocean Drilling Program (IODP) Expedition 317 (Fulthorpe et al., 2011). Siliciclastic sediments of nearly the same age offshore New Jersey were drilled during Ocean Drilling Program (ODP) Legs 150 (Mountain, 1994), 150X (Miller et al., 1994), 174A (Austin et al., 1998), 174AX (Miller et al., 1998), and IODP Expedition 313 (Mountain et al., 2010). These two settings are similar in that both are passive margins with similar tectonic and subsidence histories and both are mid-latitude margins where siliciclastic sedimentation has been affected by glacio-eustasy (Fig. 1). However, the settings are also different in significant ways. Rifting is younger (Cretaceous) in New Zealand than at the New Jersey margin (Late Triassic–Early Jurassic). In New Zealand, sediment supply was influenced by uplift of the Southern Alps, beginning in the Early Miocene, and also by oceanic currents, whereas the New Jersey margin received drainage from an eroded metamorphic terrain, and its sedimentation has been influenced by its proximity to the Laurentide Ice Sheet, particularly by glacial isostatic adjustment (e.g., Peltier, 1998).

The main objective of this study is to assess the correlation between the sedimentary record and seismic stratigraphic sequences resolvable on relatively high-resolution MCS profiles for both the Canterbury Basin and New Jersey margins, focusing on Pleistocene glacio-eustatic fluctuations. For this purpose, the lithostratigraphy from Canterbury Basin slope Site U1352 (340 m water depth) is correlated to interpreted seismic sequences and to an age model derived from a benthic foraminiferal δ¹⁸O record at Site U1352 (Fulthorpe et al., 2011; Hoyanagi et al., 2014). We compared the Canterbury Basin with a similar slope site on the New Jersey margin (ODP Leg 174A Site 1073 at 640 m water depth (McHugh and Olson, 2002; Mountain et al., 2007). Prior studies of Site 1073, based on benthic foraminiferal δ¹⁸O records and seismic sequences, revealed variability in sedimentation patterns and that the correlation between seismic sequences and glacio-eustasy is complex for the Middle to Late Pleistocene (McHugh and Olson, 2002; Mountain et al., 2007).

### GEOLOGIC BACKGROUND

#### Canterbury Basin

The eastern margin of the South Island of New Zealand, including the Canterbury Basin, rifted from Antarctica during the Late Cretaceous (Weaver et al., 1994). It acted as a simple passive margin until the Late Eocene when convergence between the Australasian and Pacific plates began to influence the region, leading to the formation of the Alpine fault at ca. 23 Ma (King, 2000; Fig. 1). The basin has since experienced high rates of Neogene sediment input from the uplifting Southern Alps, and has consequently preserved a high-frequency (0.1–0.5 m.y. periods), seismically resolvable record of depositional sequences (Fulthorpe and Carter, 1988; Browne and Naish, 2003; Lu and Fulthorpe, 2004). At present, water depths shallower than 300 m are influenced by the northward-flowing Southland Current and deeper than 900 m by the southward-flowing Antarctic Circumpolar Current (Morris et al., 2001; Fig. 1A). Similar currents likely influenced the formation of sediment drifts throughout much of the Neogene (Fulthorpe and Carter, 1991; Lu et al., 2003). Termination of drift development (ca. 3.25 Ma; Carter et al., 2004a, 2004b) may have been related to initiation of Late Pliocene to Pleistocene high-amplitude eustasy, which could have enhanced downslope processes relative to sediment re-distribution by along-strike transport, by bringing fluvial sources and/or paleoshorelines closer to the shelf edge (Fulthorpe and Carter, 1991; Lu et al., 2003; Carter et al., 2004a, 2004b). Alternatively, the climatic transition may have directly caused changes in regional oceanographic circulation.

High-resolution MCS profiles were used to interpret 19 Middle Miocene to Recent clinoformal seismic sequence boundaries (U1–19; Fig. 2) (Lu and Fulthorpe, 2004). Two larger (~1–2 m.y. duration) seismic sequences are defined based on seismic architecture and facies (Fulthorpe et al., 2011). Upper Miocene–Lower Pliocene seismic sequence boundaries (~U10 and below) feature smooth, onlapped paleoshelves and rounded rollover, or cliniform breaks. In contrast, Middle Pliocene to Pleistocene seismic sequence boundaries (above U10, ca 3.6 Ma) display eroded and incised, downlapped paleoshelves and more pronounced rollovers with oblique reflection geometries. We interpret this contrast was the result of larger eustatic amplitudes in the Plio-Pleistocene compared to earlier times.

#### New Jersey Margin

The U.S. middle Atlantic margin (New Jersey–Delaware-Maryland) is a classic passive margin studied through extensive seismic imaging and on-
Figure 1. The two study areas with overview maps on left and close-up maps with seismic line tracks and drill sites on right. (A) The Canterbury Basin is offshore from the South Island, New Zealand and influenced by both the Southland Front and a gyre related to the Subantarctic Front. The Alpine fault, a transform boundary that accommodates motion between the Australasian and Pacific plates is 200 km from the drill sites in Canterbury Basin. Sediments shed from the rising Alps have contributed significantly to the offshore sedimentation (left). Multichannel seismic (MCS) grid that formed the basis for IODP Expedition 317, showing location of drill sites (right). Modified after Fulthorpe et al. (2011). (B) The New Jersey margin has been extensively surveyed for sea-level studies (left, right). Modified after Mountain et al. (2010).
Figure 2. Multichannel seismic lines for the Canterbury Basin drill transect. Multichannel seismic line EW00-01-66 (A) and its interpretation (B) after Lu and Fulthorpe (2004) across the shelf and slope showing seismic sequence boundaries U1–U19 and location of drilled sites U1351, U1353, and U1354. Multichannel seismic line EW00-01-60 (C) and its interpretation (D) modified after Fulthorpe et al. (2011), across the slope showing seismic sequence boundaries U4–U19 and MP (Marshall paraconformity) and location of drilled Site U1352.
shore and offshore drilling. As a result, it is considered a “type margin” for studies of eustasy and seismic stratigraphy (Fig. 1). Accommodation primarily resulted from thermal subsidence and loading of the continental shelf and slope (Komíz et al., 1998). Other contributing factors include changes in sediment supply due to increased continental erosion caused by uplift of the Appalachian Mountains during the Miocene (Pazzaglia, 1993) and long-term changes in sea level and climate (Miller et al., 1996). Rifting began in the Late Triassic (Sheridan et al., 1988) and seafloor spreading in the Early to Middle Jurassic (Sheridan et al., 1983), followed by thermal subsidence, sediment loading, and flexure (Watts and Steckler, 1979; Reynolds et al., 1991; Komíz et al., 1998). A major change from carbonate- to siliciclastic-dominated sedimentation occurred from the late Middle Eocene to the earliest Oligocene in response to global cooling (Miller et al., 1996). Cenozoic sedimentation rates varied from low during the carbonate-dominated times (~13 m/m.y.) to high in the Late Oligocene and Middle Miocene (30–100 m/m.y.) to moderate-high (10–100 m/m.y.) during the Miocene to Pleistocene period (Miller et al., 1996; Steckler et al., 1999).

The New Jersey margin differs from the New Zealand margin in that sediment supply was relatively lower during the Miocene to the Early Pleistocene, though rates exceeded 100–240 m/m.y. on the shelf and slope at these times (Mountain et al., 1994, 1996; Browning et al., 2013). This was related to low relief in the New Jersey hinterland, where rivers drained eroded metamorphic and igneous terrains; although Appalachian Mountain rejuvenation during relief in the New Jersey hinterland, where rivers drained eroded metamorphic terrains; although Appalachian Mountain rejuvenation during the Miocene yielded significant input (Poa and Sevon, 1989; Pazzaglia, 1993; Steckler et al., 1999; Mountain et al., 2007). During the Quaternary, sediment was reworked across a wide, low-gradient shelf by systems of braided channels during glacial stages and longshore currents during interglacial cycles (Goff et al., 2005; Nordfjord et al., 2005; Mountain et al., 2007). In contrast, high rates of sediment supply (up to 750 cm/k.y.) reached the New Jersey upper slope during the initial deglaciations in the Middle and Late Pleistocene (Christensen et al., 1996; McHugh and Olson, 2002). This high influx of sediment was related to the proximity (~200 km) of the study area to the southern margin of the Laurentide Ice Sheet.

An extensive network of seismic profiles was collected on the New Jersey margin by oil companies and the U.S. Geological Survey in the 1970s (Greenlee et al., 1992) and by academia in the 1980s and 1990s (e.g., Austin et al., 1996; Monteverde et al., 2000). The high-resolution MCS data collected by academia and used for ODP site selection is of similar resolution to the Canterbury Basin MCS data, facilitating comparison of seismic sequence stratigraphies in both locations. These data have allowed interpretation of seismic sequence boundaries from the Eocene to the Holocene. Four Early to Late Pleistocene to Recent sequences (Fig. 3) have been interpreted along the outer shelf (Mountain et al., 2007) and dated by correlation to benthic foraminiferal δ18O record at upper-slope Site 1073 (McHugh and Olson, 2002; Mountain et al., 2007). These sequences have been named Yellow, Green, Blue, and Purple, and their bases are marked by seismic sequence boundaries p4, p3, p2, and p1, respectively (Mountain et al., 2001, 2007; Fig. 3).

### Slope Processes

Canterbury Basin Site U1352 and New Jersey margin Site 1073 were drilled on the upper slope, at 340 and 640 m of water depth, respectively (Figs. 2 and 3). An additional slope Site 903 was drilled in the New Jersey upper slope at 444 m by ODP Leg 150 (Mountain et al., 1994; Christensen et al., 1996). Site 903 had high Pleistocene sedimentation rates of 66 cm/k.y. and recorded numer-
ous glacial-interglacial cycles but also showed evidence of erosion (e.g., the last glacial cycle has been eroded; Christensen et al., 1996). In the Canterbury Basin, the Site U1352 location was chosen because it lacked evidence of channel-canyon incision and pelagic fossils are more abundant than beneath the shelf, providing better age control (Fulthorpe et al., 2011). New Jersey Site 1073 was selected because seismic data showed an especially thick and relatively complete sedimentary section, distal from submarine canyon drainage, in addition to the possibility of obtaining good age control (Austin et al., 1998). As a result of interactions between accommodation space and sediment supply, upper slopes on passive margins can be depositional, erosional, or undergo sediment bypass (Galloway, 1998). Both Canterbury and New Jersey slopes are optimal locations because they had been well supplied with sediment and had accommodation space to form seaward prograding clinoforms (e.g., Swift and Thorne, 1991; Lu and Fulthorpe, 2004). Although there is evidence of erosion, both settings have provided a sedimentation record from which we can extract their geologic history.

### METHODS

A multi-proxy approach using X-ray fluorescence (XRF) geochemical analyses, grain-size variability, and calcium carbonate percentages was employed in the study of sediments from the Canterbury Basin. High-resolution XRF measurements were made using a nondestructive AvaaTech scanning instrument at a sampling interval of 5 cm. The data were filtered with a 5 pt moving average, and both elemental areas and ratios were studied. Analyses of grain-size variability (1000 µm to 1 µm fraction) were conducted every 3 m using a Sedigraph. Calcium carbonate weight percent analyses were obtained at 3 m spacing with a coulometer. These analyses were used for the identification of lithofacies (Figs. 4 and 5), which were in turn correlated to a benthic foraminiferal δ18O record developed by Hovanagi et al. (2014) and to Pleistocene seismic sequence boundaries U19–U13 (Figs. 6–8; Tables 1 and 2).

Similar analyses (grain-size variability, calcium carbonate, and opal weight percent) were conducted for the New Jersey margin and also used for identification of sedimentary facies (McHugh and Olson, 2002). The New Jersey margin sediments were then correlated to a δ18O scale through radiocarbon ages, nanoplankton biostratigraphy, and magnetostratigraphy (Fig. 9; Table 3; McHugh and Olson, 2002).

We use seismic stratigraphic concepts and terms as defined by Mitchum et al. (1977) in which a seismic depositional sequence is defined by genetically related packages of sediment bounded above and below by unconformities or sequence boundaries. These genetically related packages are further classified into lowstand, transgressive, and highstand systems tracts related in turn to the cycle of relative sea level presumed to be responsible for each seismic sequence. Multichannel seismic (MCS) profiles, collected with a relatively high-frequency source for MCS (100–500 Hz) were used in this study (Lu and Fulthorpe, 2004). Based on the peak frequencies, vertical resolution is ~5 m of two-way travel time. Hole conditions prevented a vertical seismic profile (VSP, or “check-shot survey”) that measures in situ seismic velocities, and also limited the depth and quality of sonic and density logs. Consequently, core-seismic correlations were developed using a velocity-depth function derived prior to the expedition from check shot and sonic log data at the Clipper exploration well located 10 km from the Expedition 317 Site U1352 (Fulthorpe et al., 2011). Synthetic seismograms were evaluated against this velocity-depth function (Polat, 2012), as was a third approach based on compaction characteristics and porosity trends together with Site U1352 lithologic information on the amounts of sand, silt, and clay (Brusova, 2011). All methods gave consistent travel time–depth conversions, with a maximum discrepancy between the three methods of less than 10 m particularly in the upper 500 m at Site U1352, which is the focus of this paper. The seismic data on the complementary New Jersey margin was based on a single GI air gun used on the R/V Oceanus 270 and was collected at 50–250 Hz with an ~5 m vertical resolution. The stacking velocities were converted to interval velocities and linked to lithofacies boundaries in cores and logs at Sites 903 and 1073. These resulted in calculated depths that were within 5% of the depth of the likely stratigraphic surfaces that generated the reflections at both sites; synthetic seismograms have not been generated at any of the New Jersey slope sites.

### RESULTS FOR CANTERBURY BASIN

#### Sedimentology and Geochemistry

The dominant upper-slope lithology at Site U1352 is mud and sandy mud with minor sand (Fulthorpe et al., 2011). These lithofacies tend to be arranged in packages, or facies successions, ~10–60 m thick (Figs. 4 and 5). We have defined these packages based on grain-size variability, sedimentary structures, elemental composition, and calcium carbonate percentages (Figs. 4 and 5). From the base upwards, the lithofacies successions consist of as many as four distinct lithofacies and sedimentary environments. The lowermost facies overlies a sharp basal contact that separates greenish-gray calcareous muddy sand overlying gray mud, or thinly bedded sand and mud below (Figs. 4 and 5). The basal contacts tend to be lightly to heavily bioturbated; discrete burrows can be tracked for 1 m beneath the contact. The heavily bioturbated basal contact or surface, here defined as Type 1, is similar to a firm ground. A firm ground has been defined as a stiff but uncemented surface that resulted from erosion of the overlying softer sediment layers (Savrda et al., 2001; Droser et al., 2002). These surfaces are at the sediment water interface and heavily bioturbated.

The basal lithofacies (facies A, Type 1 contact; Table 1) above the heavily bioturbated contact is ~1–5 m thick and consists of greenish-gray muddy sand and sandy mud containing abundant shells and shell fragments up to 3 cm long. Geochronologically, the greenish-gray muddy sand and/or sandy mud of facies A is best expressed by a sharp upward increase in Ca and Sr count
Figure 4. Site U1352 correlation of X-ray fluorescence elemental analyses ratios, calcium carbonate percentages, grain-size variability, and lithostratigraphy. The lithologic column is based on the stacking of lithofacies successions. Horizontal, solid, blue lines correlate basal contacts of the lithofacies successions associated with a firm ground (Type 1 contact). Increases in Ca/Ti, Ca/Sr, CaCO$_3$, and sand occur above the contact. Horizontal, dashed blue lines indicate similar characteristics except that there is slight or no bioturbation associated with the sharp Type 2 basal contact.
Figure 5. Lithology and photos of cores from Site U1352 showing variability in the stacking patterns of lithofacies successions. (A) The most commonly preserved lithofacies succession: the basal contact, defined as Type 1, is sharp. Below the contact bioturbation can extend down for 1m. The sediment above is composed of muddy green sand or sandy mud with abundant shells and shell fragments (facies A). Above the shelly muddy sand, the sediment fines to silt and contains fewer shells (facies B). The uppermost part of the sedimentary package fines upwards into gray mud (facies C). (B) The main difference between the stacking of lithofacies on Figures 5A and 5B is that on 5B the basal contact, defined as Type 2, although sharp, is not associated with bioturbation or only slightly bioturbated, and the sand above contains fewer shells and fragments. (C) Example of a complete lithofacies succession that coarsens upwards. Above facies A, B and C are interbeds of fine sand and silt (facies D). (D) The main difference between the lithofacies on Figures 5D and 5A is that facies A on Figure 5D has been cemented and is here defined as facies E. This stacking pattern occurs below 450 m.
rates, as well as in the Ca/Sr ratio (Figs. 4 and 5). These sharp increases in Ca and Sr also correlate with upward increases in calcium carbonate weight percent measurements obtained through wet chemistry. Similarly, facies A, Type 2 contact (Figs. 4 and 5; Table 1) is also manifested as green sand or muddy sand >1 m thick but contains fewer shells and fragments. The Type 2 contact differs from Type 1 in that it is slightly or most commonly non-bioturbated.

Overlying facies A, facies B is typically 5–10 m thick and consists of green, muddy, fine sand to silt containing rare shells and shell fragments grading upwards into gray mud. The Ca/Sr ratio and CaCO$_3$ both gradually decrease upwards within facies B, and the sediment becomes silt dominated (Figs. 4 and 5). Facies B differs from facies A in that it is fine grained and rarely contains shells and fragments.

The lithologic variability within the uppermost 10–50 m of the sediments at Site U1352 is interpreted as facies C and D. Geochemically, facies C and D are characterized by an upward increase in the count rates of K, Si, Al, Fe, and Ti. These elemental enrichments are interpreted as terrigenous in origin and are at the expense of the calcium carbonate content (Figs. 4 and 5). Sediments fine upwards in facies C into gray mud that can be up to 30 m thick. Facies D differs from facies C in that the upper part of the lithofacies coarsens upwards and is composed of amalgamations of thinly (1–5 cm) interbedded gray sand and mud (Figs. 4 and 5).

Facies E is present below 450 m. Facies E is equivalent to facies A in its stacking position at the base of the lithofacies succession and above a bioturbated contact. The main difference between the two is that the green sandy mud and muddy sand that formed facies A has been partly cemented in facies E, and there are no shells or fragments present.

The calcium carbonate content measured by coulometry and the Ca, Sr, and Ca/Sr trends measured by XRF are highest where the sandy mud contains shells and shell fragments (facies A, B, and E) and lowest toward the top of the sedimentary sequence at Site U1352, where K, Si, Al, Fe, and Ti increase (facies C and D).

**Lithofacies Interpretation**

The lithofacies successions at Site U1352 can be tied to the seismic sequences (Figs. 5 and 6) and related to sea-level cycles using a sequence stratigraphic framework. We interpret the basal facies A, above the bioturbated contact. The main difference between the two is that the green sandy mud and muddy sand that formed facies A has been partly cemented in facies E, and there are no shells or fragments present.

The calcium carbonate content measured by coulometry and the Ca, Sr, and Ca/Sr trends measured by XRF are highest where the sandy mud contains shells and shell fragments (facies A, B, and E) and lowest toward the top of the sedimentary sequence at Site U1352, where K, Si, Al, Fe, and Ti increase (facies C and D).
Figure 7. Correlation of the lithology to seismic sequence boundaries, the oxygen-isotope record calibrated with nanoplankton biostratigraphy, and paleomagnetics to the LR04 stack. The shaded orange areas indicate nannofossil datums, and the orange line correlates these datums with the oxygen-isotope record and the LR04 stack. The solid turquoise lines correlate the lithology with seismic sequence boundaries, the oxygen-isotope record, and the LR04 stack. Ages every 0.1 Ma are noted to the right of the LR04 stack. The dotted turquoise lines correlate the lithology with the oxygen-isotope record. There is also a good correlation between these basal contacts (mainly Type 2) and glacial-interglacial transitions revealing that deposition of lithofacies was driven by eustasy. Dinarès-Turell and Tinto (2014) showed reverse polarity that correlates with the Brunhes/Matuyama transition at 250 mbsf. The record below 250 mbsf, although depicted as reverse, is not as reliable. VPDB—Vienna PeeDee belemnite; XRF—X-ray fluorescence.

modified after Hoya et al., 2014
A is nearly always found above the seismically defined sequence boundary, which likely represents multiple erosional intervals and an unconformable surface formed during a sea-level lowering (Figs. 4–6). Benthic foraminifera indicate deposition of the Pleistocene section in outer shelf to upper bathyal paleodepth (100 to over 200 m based on *Globocassidulina* and *Trifarina*), with extensive reworking of shallow water (subtidal to inner neritic; e.g., *Elphidium*) taxa (Fulthorpe et al., 2011). We interpret the erosional surfaces as due to downslope processes, particularly turbidity currents, during intervals of sea-level lowering. The shell-rich facies A could be either a transported deposit downshelf processes, particularly turbidity currents, during intervals of sea-level lowering. The shell-rich facies A could be either a transported deposit downslope or reworked shell fragments and concentrations of foraminifera or repre-

Figure 8. Pleistocene age-depth plot showing a mean sedimentation rate of 27.8 cm/k.y. at Site U1352. The solid lines correlate depth, age, seismic sequence boundary, and marine isotope stages (MIS). The dashed lines correlate the depth and age to MIS. The black dots mark the points from where the ages were determined and are connected with a thin black line. The stair-step look of the accumulation history reveals significant reductions in sedimentation or hiatuses (H). These discontinuities in the record are consistent with the lithology that revealed that lithofacies successions are incomplete especially toward the top where facies D is generally missing. Facies D is associated with uppermost regressive phase equivalent of either the highstand system tract (HST) or a falling stage system tract (FSST). The bottom axis shows the age and MIS correlation with the LR04 stack (Lisiecki and Raymo, 2005). The solid turquoise lines link the age and MIS with H and seismic sequence boundaries.

sent in situ outer-shelf transgressive shell meadows, a region with abundant marine life. Given the present water depths of 340 m, we favor the former based on frequent to abundant *Elphidium* noted in several of the shelly intervals (e.g., 151–156 m, 189 m, and 208 m; Fulthorpe et al., 2011). Another possibility is that facies A accumulated from 100 to over 200 m water depth and that during glacio-eustatic falls of ~120 m, the sediments may have been exposed, subjected to direct wave action and then transgressed. In this case, the erosional basal contacts would be a ravinement surface and overlain by increasingly deeper sediments. This is a strong possibility for the shelf Sites U1353, U1354, and U1351 drilled in 85, 113, and 122 m of water depth, respec-
<table>
<thead>
<tr>
<th>Core number</th>
<th>Top of core depth (mbsf)</th>
<th>Contact and sequence boundary depth (mbsf)</th>
<th>Facies A: sand bed thickness (cm) per core</th>
<th>Facies A: sandy mud bed thickness (cm) per core</th>
<th>Type of basal contact</th>
<th>Type 1* or Type 2† basal contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>55.7</td>
<td>64</td>
<td>151</td>
<td>0</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>64.2</td>
<td>N.A.</td>
<td>5</td>
<td>0</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>9</td>
<td>74.7</td>
<td>N.A.</td>
<td>25</td>
<td>14</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>10</td>
<td>84.2</td>
<td>94</td>
<td>86</td>
<td>60</td>
<td>Sharp; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>94.0</td>
<td>98.5</td>
<td>88</td>
<td>40</td>
<td>Sharp; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>103.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>13</td>
<td>112.7</td>
<td>113</td>
<td>0</td>
<td>100</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>14</td>
<td>122.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>15</td>
<td>131.7</td>
<td>N.A.</td>
<td>0</td>
<td>4</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>16</td>
<td>141.2</td>
<td>148</td>
<td>140</td>
<td>28</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>150.7</td>
<td>155</td>
<td>92</td>
<td>173</td>
<td>Sharp; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>18</td>
<td>156.2</td>
<td>160</td>
<td>150</td>
<td>160</td>
<td>Sharp; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>165.7</td>
<td>N.A.</td>
<td>3</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>20</td>
<td>174.7</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>21</td>
<td>180.4</td>
<td>N.A.</td>
<td>3</td>
<td>66</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>22</td>
<td>189.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>23</td>
<td>198.7</td>
<td>200</td>
<td>210</td>
<td>0</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>208.2</td>
<td>210</td>
<td>120</td>
<td>100</td>
<td>Sharp; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>217.7</td>
<td>N.A.</td>
<td>27</td>
<td>7</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>26</td>
<td>227.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>27</td>
<td>236.7</td>
<td>246</td>
<td>88</td>
<td>45</td>
<td>Sharp</td>
<td>N.A.</td>
</tr>
<tr>
<td>28</td>
<td>246.2</td>
<td>250</td>
<td>141</td>
<td>0</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>29</td>
<td>251.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>30</td>
<td>257.7</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>31</td>
<td>267.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>32</td>
<td>272.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>33</td>
<td>282.0</td>
<td>282</td>
<td>361</td>
<td>0</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>34</td>
<td>288.2</td>
<td>N.A.</td>
<td>0</td>
<td>7</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>35</td>
<td>292.9</td>
<td>293</td>
<td>0</td>
<td>99</td>
<td>Sharp</td>
<td>2</td>
</tr>
<tr>
<td>36</td>
<td>295.3</td>
<td>N.A.</td>
<td>0</td>
<td>37</td>
<td>Gradational</td>
<td>N.A.</td>
</tr>
<tr>
<td>37</td>
<td>297.0</td>
<td>298</td>
<td>87</td>
<td>47</td>
<td>Gradational</td>
<td>2</td>
</tr>
<tr>
<td>38</td>
<td>302.6</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>39</td>
<td>312.2</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>40</td>
<td>321.9</td>
<td>330</td>
<td>0</td>
<td>107</td>
<td>Diffuse; burrowing</td>
<td>2</td>
</tr>
<tr>
<td>41</td>
<td>331.5</td>
<td>N.A.</td>
<td>30</td>
<td>0</td>
<td>Gradual; burrows</td>
<td>2</td>
</tr>
<tr>
<td>42</td>
<td>341.1</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>Diffuse; gradual</td>
<td>9</td>
</tr>
<tr>
<td>43</td>
<td>350.7</td>
<td>360</td>
<td>0</td>
<td>267</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>44</td>
<td>360.4</td>
<td>N.A.</td>
<td>62</td>
<td>0</td>
<td>Gradational</td>
<td>N.A.</td>
</tr>
<tr>
<td>45</td>
<td>370.0</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>46</td>
<td>379.6</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>47</td>
<td>389.2</td>
<td>395</td>
<td>100</td>
<td>45</td>
<td>Gradational; slight burrowing</td>
<td>2</td>
</tr>
<tr>
<td>48</td>
<td>398.7</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>49</td>
<td>408.3</td>
<td>N.A.</td>
<td>33</td>
<td>0</td>
<td>Gradational</td>
<td>N.A.</td>
</tr>
<tr>
<td>50</td>
<td>417.9</td>
<td>N.A.</td>
<td>0</td>
<td>15</td>
<td>Gradational; diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>51</td>
<td>427.5</td>
<td>428</td>
<td>68</td>
<td>98</td>
<td>Sharp</td>
<td>2</td>
</tr>
<tr>
<td>52</td>
<td>437.1</td>
<td>N.A.</td>
<td>0</td>
<td>0</td>
<td>None</td>
<td>N.A.</td>
</tr>
<tr>
<td>53</td>
<td>446.7</td>
<td>453</td>
<td>643</td>
<td>0</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>54</td>
<td>456.3</td>
<td>N.A.</td>
<td>255</td>
<td>135</td>
<td>Sharp; gradiental</td>
<td>N.A.</td>
</tr>
<tr>
<td>55</td>
<td>465.9</td>
<td>N.A.</td>
<td>196</td>
<td>199</td>
<td>Sharp; gradiental</td>
<td>N.A.</td>
</tr>
<tr>
<td>56</td>
<td>475.5</td>
<td>482</td>
<td>400</td>
<td>153</td>
<td>Sharp; heavy burrowing</td>
<td>1</td>
</tr>
<tr>
<td>57</td>
<td>485.1</td>
<td>N.A.</td>
<td>30</td>
<td>40</td>
<td>Gradational; cements</td>
<td>N.A.</td>
</tr>
<tr>
<td>58</td>
<td>494.7</td>
<td>N.A.</td>
<td>0</td>
<td>73</td>
<td>Diffuse</td>
<td>N.A.</td>
</tr>
<tr>
<td>59</td>
<td>504.3</td>
<td>N.A.</td>
<td>28</td>
<td>0</td>
<td>Gradual</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

*Type 1 = Facies A thicker than 1 m, contact sharp with heavy burrowing up to 1 m below contact.
*Type 2 = Facies A thicker than 1 m, contact sharp with no burrowing or slight (few cm below).

Type 1 is always associated with facies A thicker >1 m, a sharp contact and heavy burrowing (1 m). Type 2 is associated with facies A thicker >1 m, a sharp contact with no or slight (few cm) burrowing. Seismic sequence boundaries depths are highlighted in bold.
Gradual decrease in Ca/Sr and CaCO₃ contrast to facies A, facies B has rare shell fragments. The sediments show a truncation surface (MFS) in shelf successions. Within a sequence stratigraphic depositional environment framework, facies B is interpreted as a condensed interval forming surface (MFS) in shelf successions. Within a sequence stratigraphic depositional environment framework, facies B is interpreted as a condensed interval. Facies B is composed of sediment that fines upward from sand to silt. In contrast to facies A, facies B has rare shell fragments. The sediments show a gradual decrease in Ca/Sr and CaCO₃ content. We interpret this muddy sediment as a time of maximum water depths, equivalent to the maximum flooding surface (MFS) in shelf successions. Within a sequence stratigraphic depositional environment framework, facies B is interpreted as a condensed interval (Loutit et al., 1988).

Facies C is in the top of the lithofacies successions. Facies C is composed of mud with increasing Ti, K, and Fe, interpreted as an increasing proportion of sediment derived from terrigenous sources. The Ca/Sr ratios, as well as the fact that the site was drilled at 340 m of water depth, are interpreted as an increasing proportion of mud with increasing Ti, K, and Fe, interpreted as an increasing proportion of sediment derived from terrigenous sources.

As an early lowstand system tract (eLST) that accumulated at the start of the next relative sea-level fall as defined by Posamentier and Allen (1999). Because for the most part the lithofacies succession lacks deposits of the uppermost regressive phase, facies C is also truncated, and the lithofacies succession fines upwards. The truncation could be due to frequent erosive episodes that are common in upper-slope settings (e.g., McHugh and Olson, 2002; McHugh et al., 2002).

Coarser-grained amalgamated, thinly bedded sand-mud sequences of facies D are interpreted as stacked turbidites deposited as regressive, coarsening-upward sediments of the lowstand system tracts (LST) that were preserved on the slope. Facies D is mainly preserved in the upper 50 m of Site U1352 and is characterized by the lowest Ca/Ti and Ca/Sr ratios and calcium carbonate measured at Site U1352. Above facies D, there is 1 m of green Holocene sand of facies A.

Finally, facies E is equivalent to facies A, but due to the downhole depth at which it occurs (deeper than 450 m), has been cemented and lacks the shell and shell fragments typical of facies A.

The upper and basal contacts of the lithofacies successions that correlate with seismic sequence boundaries likely represent multiple erosional intervals and an unconformable surface and are interpreted as having been formed during lowstands of sea level. This firm ground surface as previously described is commonly associated with burrowing and subsequent marine flooding events (Svarda et al., 2001; Droser et al., 2002).

**Lithofacies Succession Correlation to the Oxygen-Isotope Record and Seismic Sequence Boundaries**

Hoyanagi et al. (2014) derived a chronology from δ¹⁸O record generated for Site U1352. The δ¹⁸O record was calibrated to marine isotope stages of Lisiecki and Raymo (2005) by nannoplankton biostratigraphy and paleomagnetics (Fig. 12).
Figure 9. New Jersey slope Ocean Drilling Program (ODP) Site 1073. (A) Oxygen-isotope record calibrated to SPECMAP by nannoplankton biostratigraphy, $^14$C, and paleomagnetics for Pleistocene sediment. The oxygen-isotope record was correlated to seismic sequence boundaries: p1, p2, p3, and p4 encompassing sequences purple, blue, green, and yellow (Mountain and Monteverde, 2000). The lithology of Site 1073 is more complex than that of Canterbury Basin having preserved more mass-wasting and gravity flow deposits. The sediments deposited during interglacial cycles are mainly composed of mud. Modified after McHugh and Olson (2002). (B) Depth age plot showing a fairly continuous sedimentation record for the Middle Pleistocene but very discontinuous for the Late Pleistocene with much higher sedimentation rates (up to 750 cm/k.y.) and extensive hiatuses (for example, marine isotope stages [MIS] 5e, 6, and 7 are missing).
This chronology permits correlation of the lithofacies successions to seismic sequences and to global records of ice volume and Milankovitch cyclicity (Figs. 6–8). These data also allow for correlations of the lithology, oxygen isotopes, and stratigraphies from other margins (Figs. 9 and 10). The Type 1 basal contact of the lithofacies succession characterized by a heavily bioturbated surface or firm ground with green sand with abundant shells above correlates with the transition from glacial to interglacial in the δ¹⁸O record (Fig. 7). This association has been documented between MIS 6–5, 12–11, 16–15, 22–21, 53–52, 58–57, and 62–61. The slightly or non-bioturbated Type 2 contact correlates with MIS 6–8. These data also allow for correlations of the lithology, oxygen isotopes, and stratigraphies from other margins (Fig. 6). Uncertainties in both the depths of seismic reflectors and the depths of the sediment cores are of the order of several to up to 10 m. However, within this range of uncertainty, one key finding of this study is that, except for U15, seismic sequence boundaries are always associated with firm grounds that characterize Type 1 basal contacts of lithofacies successions. The discontinuities represented by these contacts are clear in the sedimentation record (Fig. 8). Facies A, Type 2 basal contacts, are also present at glacial-interglacial transitions but generally do not correlate with seismic sequence boundaries (Table 1).

The δ¹⁸O record was correlated to seismic sequences U13–U19 identified by Lu and Fulthorpe (2004) at 68, 142, 195, 249, 428, 448, and 500 mbsf are very close in depth with the base of lithologic successions and Type 1 contacts identified at 64, 148, 200, 248, 453, and 482 mbsf (Fig. 6). Uncertainties in both the depths of seismic reflectors and the depths of the sediment cores are of the order of several to up to 10 m. However, within this range of uncertainty, one key finding of this study is that, except for U15, seismic sequence boundaries are always associated with firm grounds that characterize Type 1 basal contacts of lithofacies successions. The discontinuities represented by these contacts are clear in the sedimentation record (Fig. 8). Facies A, Type 2 basal contacts, are also present at glacial-interglacial transitions but generally do not correlate with seismic sequence boundaries (Table 1).

The δ¹⁸O record was correlated to seismic sequences U13–U19 identified by Lu and Fulthorpe (2004) at 68, 142, 195, 249, 428, 448, and 500 mbsf are very close in depth with the base of lithologic successions and Type 1 contacts identified at 64, 148, 200, 248, 453, and 482 mbsf (Fig. 6). Uncertainties in both the depths of seismic reflectors and the depths of the sediment cores are of the order of several to up to 10 m. However, within this range of uncertainty, one key finding of this study is that, except for U15, seismic sequence boundaries are always associated with firm grounds that characterize Type 1 basal contacts of lithofacies successions. The discontinuities represented by these contacts are clear in the sedimentation record (Fig. 8). Facies A, Type 2 basal contacts, are also present at glacial-interglacial transitions but generally do not correlate with seismic sequence boundaries (Table 1).

Figure 10. Synthesis of results from Canterbury Basin (Site 1352) and the New Jersey slope (Site 1073). Light blue represents sediments deposited during glacial cycles and white represents sediments deposited during interglacial cycles. Also noted are sequence boundaries and their respective ages for each margin revealing that most seismic sequence boundaries preferentially resolved by multichannel seismic (MCS) data on each margin don’t form at a consistent time with respect to isotopic stages within a margin and their ages are not synchronous between margins. Note that seismic sequence boundary p1 at Site 1073 corresponds to a 120 ka gap spanning 128–248 k.y. (Mountain et al., 2001). MIS—marine isotope stages.
tionship exists between what is preserved in the lithology and what is imaged in the seismic profiles and interpreted as a seismic stratigraphic sequence.

Seismic sequences older than ca. 0.8 Ma contain highly variable numbers of glacio-eustatic cycles, and their correlation to patterns in lithofacies variation becomes tenuous. This change coincides with the transition from 100 k.y. to 40 k.y. dominance, and we would not generally expect seismic profiles to resolve such lower-amplitude and high-frequency 40 k.y. Milankovitch cycles. The corresponding lithofacies successions are not well developed and are primarily dominated by a strong CaCO₃ signal and reduced terrigenous influence (Figs. 4 and 7). The seismic sequence U15 to U16 contains 11 glacial-interglacial stages (MIS 53–22), whereas the Early Pleistocene sequences U14 to U15 and U13 to U14 only contain two and three glacial-interglacial cycles (MIS 57–54 and MIS 63–58), respectively. A sharp unconformity with a hiatus from 2.78 to 1.73 Ma was documented at the Plio-Pleistocene boundary (Hoyanagi et al., 2014).

**DISCUSSION**

Much has been learned in the past 30 years as a result of scientific ocean drilling about the sedimentary response to eustasy and the role of eustatic fluctuations in the formation of seismic sequences (Miller et al., 1994; Mountain et al., 1994; Austin et al., 1998; Miller et al., 1998; Mountain et al., 2010; Fulthorpe et al., 2011). Our results expand on these findings. We first discuss the results from Canterbury Basin IODP Expedition 317 and then compare them with those of New Jersey margin IODP Leg 174A. Comparisons between these Northern and Southern Hemisphere passive margins are feasible because the MCS seismic acquisition systems and resolutions were similar in both locations (Lu and Fulthorpe, 2004; Mountain et al., 2007). In addition, an oxygen-isotope chronology was developed for each margin (McHugh and Olson, 2002; Mountain et al., 2007; Hoyanagi et al., 2014; Table 3). Therefore the lithology in each case can be integrated with seismic data and correlated to an age model. The concepts learned can be applied to other settings.

**Slope Sedimentary Response to Glacio-Eustasy and Link to Seismic Sequences**

One of the most interesting results of IODP Expedition 317 and this study was the identification of predictable and repetitive slope lithofacies successions with their stacking patterns driven by glacio-eustasy. This stacking of lithofacies is repetitive and predictable in its sedimentary and geochemical characteristics but shows variability in its preservation. Our analyses reveal that the composition and color of the sediments are associated with distinct parts of glacial and interglacial cycles. The green (carbonate-rich) sand to silt is associated with interglacial cycles while gray mud was deposited during glacial cycles. But the record is not continuous, and significant hiatuses were documented likely due to nondeposition, erosion, or sediment bypass. Such reductions in sedimentation are associated with the regressive phase of each glacial cycle. Only the most recent glacial-interglacial interval contains >30 m of turbidites and coarser grain size at the top of Site U1352 representative of the MIS 2 regressive phase of the sea-level cycle. Otherwise, most lithofacies successions fine upwards (Fig. 5).

It is not surprising to find a complex response of continental slope sedimentation to eustatic forcing. Interestingly, the most severe glaciations associated with, for example, MIS 12 and MIS 16 have left a thin (<10 m) sedimentary record in the upper-slope sites. This indicates that during these glacial stages there were high-amplitude eustatic fluctuations and most of the lowstand sediment was likely transported to the deeper basin. The sediments preserved during MIS 2, mainly stacked turbidites, give us a glimpse of the types of sediments that could have been either eroded or bypassed the slope. The low δ¹⁸O values reflect the fact that the peak of glaciation must correlate with the most pronounced sea-level lowstand, and it is likely that during this time, the sediments were not preserved in the upper slope but rather transported seawards. The predictable stacking of lithofacies permits to link the depositional environment with the δ¹³C record for a more robust interpretation overcoming the fact that parts of the δ¹³C record such as high values during peak glaciations may be missing.

Slope processes consist of a competition between hemipelagic settling and mass flows (slides, slumps, debris flows, and turbidity currents). Slope sedimentation can be linked to both sea-level change and sediment supply, with spatial and temporal variability occurring in both interglacial cycles and glacial cycles. On the modern New Jersey slope, surface samples show a largely in situ benthic biofacies (Miller and Lohmann, 1982) with visual observations of largely hemipelagic drape and sporadic turbidity-current activity in some canyon thalwegs; in contrast, the last glaciation shows considerable evidence of widespread transport across the slope (McHugh et al., 1993; Pratson et al., 2007; Miller et al., 2014). The interplay between depositional and erosional slope processes results in complex preservation of the eustatic signal in water depths greater than ~120–140 m (i.e., below the lowest lowerings of Pleistocene sea level).

The slope record appears to be most incomplete during major glaciations (MIS 22, 16, 12, and perhaps 8 at ca. 850, 650, 450, and 275 ka, respectively; Fig. 8). It is interesting that the most severe of the glaciations (MIS 12, 16, and 22), where severity is read from the Lisiecki and Raymo (2005) stack are associated with the greatest evidence for hiatuses (Fig. 8). We cannot determine the extent of hiatuses given our chronology; but through correlation with the lithofacies, we can deduce that the late lowstand deposits are commonly missing. An exception is for the last glacial-interglacial MIS 5–2, where facies A, B, C, and D were identified. Green sand of facies A is Holocene in age and was deposited above the stacked turbidites of facies D that were deposited during MIS 2.

**Comparison of Canterbury Basin and New Jersey Margins**

Canterbury Basin is not the only margin at which lowstand deposits are patchy or missing from shelf and upper-slope settings. Latest Pleistocene low-
stand deposits are missing on the inner-middle continental shelf of the New Jersey, Virginia, and North Carolina margins, and at ODP Site 903 on the New Jersey upper slope (Christensen et al., 1996; Mallinson et al., 2010; Miller et al., 2012, 2014). On the New Jersey shelf, lowstand (MIS 2) and transgressive deposits (early MIS 1) are primarily found as incised valley fills in channels (Goff et al., 2005; Nordfjord et al., 2005; Christensen et al., 2013). In contrast to the Canterbury Basin and New Jersey ODP Site 903 slope sites where mass-transport deposits were rarely preserved, Pleistocene mass-transport deposits (mainly slumps and debris flows) and few turbidites were preserved at New Jersey upper-slope ODP Site 1073. Differences in sediment preservation between ODP Sites 1073, 903, and IODP U1352 slope sites are possibly related to their location. Site 1073 is located ~200 km from the southeastern terminus of the Laurentide Ice Sheet (Teller, 1987) where sedimentation rates were greater in the Late Pleistocene, while ODP Site 903 was more distal from the Laurentide Ice Sheet terminus and mainly influenced by rivers draining the New Jersey coastal plain (Fig. 1B). Ice sheets did not reach sea level in the Canterbury Basin (Putnam et al., 2013).

It is clear from these comparisons that the parts of the eustatic cycle that are preserved are determined to a great extent by rates of sediment supply, erosion, and creation of accommodation in both shelf and slope settings. Sedimentation rates were high, averaging 28 cm/k.y., during the Pleistocene on the Canterbury Basin shelf and slope (Hoyanagi et al., 2014), but they were even higher for the Late Pleistocene near Site 1073 reaching >750 cm/k.y. (McHugh and Olson, 2002). This created conditions locally favorable to the preservation of lowstand deposits in the vicinity of Site 1073, but not for Canterbury Basin Site U1352.

Comparison of the lithofacies contained in the seismic sequences of the New Jersey margin and in those of the Canterbury Basin reveals that the stacking and preservation of the New Jersey lithofacies is less predictable in that it contains more mass-wasting deposits and therefore is more difficult to interpret within a glacio-eustatic context than that of Canterbury Basin. This is because the correlation between the stacking of lithofacies and seismic sequences is irregular and also punctuated by erosion (Fig. 9). In both the Canterbury Basin and New Jersey, seismic sequences also do not correlate with MIS stages on a one-to-one basis. For example, sequence Blue off New Jersey (beneath sequence Purple) is composed entirely of sediment deposited during MIS 8 (~300–250 k.y.); sequence Green (beneath sequence Blue) was formed during MIS 9, 10, and 11 (~330–460 k.y.); and the oldest sequence, Yellow, during MIS 12–20 (460–755 k.y.; Fig. 9; Table 3; McHugh and Olson, 2002). When compared to other margins, there are similarities in the stacking of lithofacies in Canterbury Basin and the sedimentary sequence described for the Gulf of Lion by Sierro et al. (2009) for the last deglaciation. In both cases, a thin veneer of sand with coarse-grained skeletal material extends from the shelf to the upper slope. In Canterbury Basin, a finer-grained, calcareous-rich deposit (facies B) overlays a very thin sand layer (facies A) in the slope. This deposit or interval of condensation, as in the Gulf of Lion, is likely derived from the slow accumulation of pelagic sediment. In both settings, the calcareous-rich sand and silt overlay terrigenous-derived sediments deposited during the previous sea-level lowstand. This is not the case for the New Jersey margin in which higher rates of sedimentation have been associated with both glacial cycles and interglacial cycles. A main difference is related to the proximity of Site 1073 to the southeastern terminus of the Laurentide Ice Sheet and the Hudson Valley that likely provided a large supply of sediment once the terminal moraines were breached during the early stages of deglaciation (see below).

**Is Global Correlation of Pleistocene MCS Sequences Possible?**

The oxygen-isotope record reveals that in both continental margins the formation of seismic sequences defined using MCS data is complex. For example, in the Canterbury Basin, all except one Pleistocene seismic sequence boundary, correlate with a Type 1 lithofacies succession basal contact, which in turn correlates with the transition from glacial to interglacial periods in the oxygen-isotope record. The seismic sequence boundaries therefore record eustatic change and are not, for example, artifacts associated with limited resolution or seismic interference. However, there is a lack of one-to-one correlation between seismic sequences and individual 100 k.y. cycles during the period of high-amplitude Pleistocene glacio-eustatic fluctuations. This is documented for sequences U19–U16 in the Canterbury Basin and Purple, Blue, Green, and Yellow sequences on the New Jersey margin (Fig. 10). Furthermore, seismic sequences on each margin encompass different groups of MIS. In Canterbury Basin, the last glacial-interglacial sequence above seismic sequence boundary U19 was preserved (MIS 5 and 2). In contrast, on the New Jersey margin, seismic sequence boundary p1 at Site 1073 corresponds to a 120 k.y. gap spanning 128–248 ka, and part of MIS 5 is missing (Mountain et al., 2001). Two factors are considered to explain this mismatch: (1) rates of sediment supply and accommodation space creation; and (2) loss of seismic resolution with depth.

Sediment supply, proximity to ice sheets, and rivers, and oceanographic conditions such as local currents (long-shore drift, tides, and surface circulation) are major controls on seismic sequence architecture and evolution and must contribute to selective preservation of seismic sequence boundaries locally. As mentioned earlier, there are large differences in sedimentation rates between the Canterbury and New Jersey margins. Pleistocene sedimentation rates in the Canterbury Basin average 28 cm/k.y. (Fig. 8). In contrast, sedimentation rates at the New Jersey margin increase from 62 cm/k.y. in the Early to Middle Pleistocene (MIS 18–12) to 750 cm/k.y. during MIS 2 with great variability in between (McHugh and Olson, 2002; Mountain et al., 2007). There is also variability in the types of preserved sediments (debris flows, slumps, and turbidites) and evidence for large hiatuses in Site 1073 in New Jersey. As in New Jersey, the sedimentary record of Canterbury Basin contains many discontinuities. However, the Canterbury Basin lithofacies are stacked in predictable successions. Such patterns are less clear on the New Jersey slope. The Canterbury Basin facies permit a stronger correlation to glacio-eustasy and a better understanding of how and when sediment is preserved within both
glacio-eustatic cycles and seismic sequences. These comparisons of the Canterbury Basin and the New Jersey margin reveal that differences in the lithostratigraphy and sediment preservation can lead to seismic sequence boundaries and intervening sequences being discontinuous and locally absent. For example, discontinuities appear to have reduced or cut out portions of MIS 8, 16, and 22 in Canterbury Basin, resulting in truncations and thin lithofacies successions that are below seismic resolution.

Insufficient seismic resolution is expected for the older part of the Pleistocene record in Canterbury Basin, where the 40 k.y. Milankovitch-scale cyclicity dominated. Indeed, our results show that, in this older part of the Pleistocene, multiple glacio-eustatic fluctuations (up to 11) were recorded within seismic sequences. But our results also show that only two glacial-interglacial stages are contained in an even older early Pleistocene seismic stratigraphic sequence. Therefore, poor seismic resolution is unlikely to be the primary cause for poor correspondence between glacio-eustatic cycles and seismic sequences.

We suggest that it is more likely that the presence of incomplete lithofacies successions is the primary cause of the lack of one-to-one correlation with seismically defined sequence boundaries in the older 41 k.y. world, with seismic resolution playing a subordinate role. Our results also indicate that there should be a closer relationship between lithofacies successions and what it is imaged by seismic profiles during high-amplitude Pleistocene 100 k.y. eustatic fluctuations where distinct lithologic successions are thick, e.g., the upper 250 m of Site U1352 (Fig. 4). Our findings about the relation between the lithology and what is recorded in a seismic stratigraphic sequence are consistent with Miller et al. (2013) results based on Oligocene to Miocene sequences from the New Jersey Continental Shelf. Miller et al. (2013) showed that seismic sequence boundaries correspond with lithologic changes or unconformities that create impedance contrasts. We also identified a correspondence between “firm grounds” and seismic sequence boundaries most likely caused by impedance contrasts.

Most studies that focused on the last glacial-interglacial cycle MIS 1–5 have been successful in obtaining a good correlation between that glacio-eustatic cycle and seismic sequences (e.g., Hernández-Molina et al., 2000; Kolla et al., 2000; Anderson et al., 2004; Çağatay et al., 2009). Ridet et al. (2008, 2009) were able to do even better using a higher-frequency system combined with good age control to document one-to-one correlation between seismic stratigraphy and glacio-eustatic cycles for the past ~370 k.y. However, most studies either lack age control, seismic resolution, or both. Villasenor et al. (2014) used X-ray diffraction mineralogy to study Pleistocene shelf sediments recovered during Expedition 317 and suggested that sediment dynamics were the key factor in sediment preservation along the shelf within the 100 k.y. eustatic cycles. However, based on Expedition 317 shipboard chronology, this study was unable to demonstrate a strong link between sedimentation and the global record. Browne and Naish (2003) used a higher-resolution, 3.5 kHz subbottom profiler to document seven sequences within the upper 100 m in the Canterbury Basin but were unable to date the sequences.

Our detailed results based on two IODP expeditions indicate that both the Canterbury and New Jersey seismic sequences demonstrably correlate with the MIS record and are therefore of eustatic origin. However, our findings also reveal that most seismic sequence boundaries preferentially resolved by MCS data on each margin cannot be correlated between margins at the MIS level due to large sediment preservation gaps and great differences in accumulation rates. The evidence from the Canterbury Basin and New Jersey margins suggests that seismic correlations between margins are difficult because the ages of most seismic sequence boundaries are not synchronous between margins, that seismic sequence boundaries preferentially resolved by MCS data on each margin cannot be correlated one-to-one with MIS, and that more than one MIS glacial-interglacial stage are preserved within a seismic stratigraphic sequence.

CONCLUSIONS

Pleistocene sediments recovered from Canterbury Basin, New Zealand slope Site U1352 contain a predictable stacking of lithofacies successions that, when correlated with the global benthic foraminifera δ18O stack, document lithofacies preservation during glacial-interglacial cycles. Within a seismic sequence stratigraphic context, green sand (facies A) was deposited above a firm ground interpreted as an erosional surface overlain by a lag deposit corresponding to the deeper-water equivalent of a transgressive systems tract (TST). Overlying green silt (facies B) is associated with the maximum flooding surface representing increasing water depth in shelf successions and part of a condensed interval on the slope. Gray mud of facies C is interpreted as an early LST that accumulated at the start of the next relative sea-level fall. The coarser-grained amalgamated, thinly bedded sand-mud sequences of facies D are interpreted as stacked turbidites deposited as regressive, coarsening-upward sediments of the late LST. However, facies D is missing from most lithofacies successions except for MIS 2. The stair-step appearance of the depth-age plot reveals significant reductions in sedimentation rate or hiatuses, and it is likely that facies D has been either removed by erosion or that these lowstand sediments have bypassed the upper slope.

Comparisons between the Canterbury Basin and New Jersey margin are possible due to similarities in tectonic and geomorphic settings, MCS seismic acquisition systems and resolution, and an oxygen-isotope chronology that was developed for each margin. These comparisons reveal that the formation of seismic sequences is driven by eustasy, but that there is a lack of one-to-one correlation between seismic stratigraphic sequences and individual 100 k.y. cycles during high-amplitude Pleistocene glacio-eustatic fluctuations. These differences were documented on the slope by this study and on the shelf by previous studies for each margin and in between margins. We suggest that variability in sedimentation rates and accommodation space appears to be a key factor in controlling which MIS glacio-eustatic lowstands are preferentially recorded as seismic sequence boundaries during the period of high-amplitude
PlIOCene glacio-eustatic fluctuations. Therefore, high-frequency Pleistocene seismic sequences defined using MCS data may not correlate globally even though they are demonstrably driven by glacio-eustasy.

ACKNOWLEDGMENTS
We are grateful to the captain, officers, and crew of the RV JOIDES Resolution and to the IODP technical staff of Expedition 317. We also acknowledge the Expedition 317 Scientific party for their contributions during and after the Leg. This work was supported by the United States Science Support Program (USSSP) award T317A470 and Post-Expedition Activity funding part of USSSP (McHugh and Fulthorpe) and National Science Foundation (OCE14-63759 to Miller). We acknowledge Kristi Tinto for scientific advice, the staff of the XRF Core Scanning facility at the IODP Gulf Coast Repository, and Queens College students Katherine Mishkin, Diana Morgan, Jennifer Rios, and Yolanda Chow for their support in the laboratory. We are grateful to two anonymous reviewers that helped improve the manuscript.

REFERENCES CITED


Lu, H., and Fulthorpe, C.S., 2004, Controls on sequence stratigraphy of a middle Miocene to Re-
cent, current-swept, passive margin: offshore Canterbury Basin, New Zealand: Geological

Lu, H., Fulthorpe, C.S., and Mann, P., 2003, Three-dimensional architecture of shelf-building sedi-
ment drifts in the offshore Canterbury Basin, New Zealand: Marine Geology, v. 193, p. 19–47,

the Hatteras region of the Atlantic passive margin, USA: Marine Geology, v. 268, p. 16–33, doi:
10.1016/j.margeo.2009.10.007.

McHugh, C.M.G., and Olson, H.C., 2002, Pleistocene chronology of continental margin sedimen-
tation: New insights into traditional models, New Jersey: Marine Geology, v. 185, p. 389–411,

McHugh, C.M.G., Ryan, W.B.F., and Schreiber, B.C., 1993, The role of diagenesis in exfoliation

McHugh, C.B.G., Damuth, J.E., and Mountain, G.S., 2002, Cenozoic mass-transport facies and
their correlation with relative sea-level change, New Jersey continental margin: Marine Geol-


Miller, K.G., Barrera, E., Olsson, R.K., Sugarnan, P.J., and Savin, S.M., 1991, Does ice drive Maas-
tricia clayey eustacy?: Geology, no. 27, p. 793–786.

Drilling Program, Proceedings of the Ocean Drilling Program, Initial Reports, v. 150, p. 5–35,

Miller, K.G., and Lohmann, G.P., 1994, Island Beach Site Report: College Station, Texas, Ocean
Drilling Program, Proceedings of the Ocean Drilling Program, Initial Reports, v. 150, p. 40–63,


Norford, S., Goff, J.A., Austin, J.A., Jr., and Sommerfield, C.K., 2005, Seismic geomorphology of

Pazzaglia, F.J., 1993, Striatigraphy, petrography, and correlation of the late Cenozoic middle Atlantic
coastal plain deposits: Implications for late-stage passive margin geologic evolution: Geolog-

Peltier, W.R., 1986, Postglacial variations in the level of the sea: Implications for climate dynamics

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in postrift Mesozoic and
Cenozoic sediments of the middle United Atlantic continental margin: Geomorphology,

Polat, F.O., 2012, Core-seismic correlation and sequence stratigraphy at IODP Expedition 317 drill-
sites, Canterbury Basin, New Zealand [M.S. thesis]: University of Texas at Austin, 82 p.

Posamentier, H.W., and Allen, G.P., 1999, Siliciclastic Sequence Stratigraphy: Concepts and Appli-

Posamentier, H.W., Jersey, M.T., and Vali, P.R., 1988, Eustatic controls on clastic deposition A Con-
ceptual framework, in Sea-Level Changes: An Integrated Approach: SEPM (Society for Sedimi-

T.G., 2007, The impact of floods and storms on the acoustic reflectivity of the inner continental
csr.2006.12.018.

records and sequence archi-

Ridente, D., Trincardi, F., Piva, A., Asioli, A., and Cattaneo, A., 2008, Sedimentary response to cli-
mate drifts in the offshore Canterbury Basin, New Zealand: Marine Geology, v. 193, p. 19–47,

during Milanovitch cyclicity: Evidence from shallow-marine O°C records and sequence archi-

Savrda, C., Krawin, H., McCarthy, F.M.G., McHugh, C.M.G., Olsson, H.C., and Mountain, G., 2001,
Ichnofabrics of a Pleistocene slope succession, New Jersey margin: Relations to climate and
Research Paper

McHugh et al. | Sediments, Pleistocene glacio-eustasy, oxygen isotopes, and seismic sequences

GEOSPHERE | Volume 13 | Number 5

20


