Collaborative Research: Community-Based 3D Imaging that Ties Clinoform Geometry to Facies Successions and Neogene Sea-Level Change

PROLOGUE

This resubmission has benefited from constructive input by 8 mail reviewers, a panel summary, and NSF feedback (fall 2011). In response, we amplify three issues: 1) 3D imaging will detect nearshore features (e.g., meandering rivers, estuary complexes, lagoons/barrier islands, incised shelf valleys, etc.) that can be tied to IODP Exp313 sites M27-M29; mapping these features and associated facies, which developed during a time of known glacioeustatic variation, is a key both to understanding the evolution of siliciclastic systems and quantifying eustatic changes preserved in clinoformal architecture; 2) the proposed 3D survey area is 50% larger than in our initial submission, with no increase in survey time (34 days), as a result of revised estimates of in-fill shooting and downtime based on well-known histories of weather, currents, ship traffic and marine mammal activity in the proposed study region offshore New Jersey (NJ); and 3) a robust collaboration with the aligned GeoPRISMS community, including at-sea participation and pre-and post-data acquisition workshops; all activities are designed to help educators, young investigators and students understand the value of calibrating models of stratigraphic facies successions, as well as to engage them in theoretical and hands-on learning experiences with 3D seismic acquisition/processing. The goal throughout this project will be to optimize community use of the proposed product -a 3D data volume tied to continuously cored/logged/dated siliciclastic clinoforms that evolved at a stable passive margin during a time of independently measured glacioeustatic change.

INTRODUCTION

Shoreline movements and linked shifts in nearshore processes have important societal consequences. As discussion of global warming grows from speculation to more widespread acceptance (Intergovernmental Panel on Climate Change, 1995; 2001; 2007), impacts at the land-sea divide are gaining media attention. Nonetheless, journalists, policy makers, and even earth scientists often fail to grasp that while links exist among warming, melting ice and rising sea levels, actual effects on shoreline position locally vary widely. Shoreline positions are controlled by many factors, only one of which is global sea level. For example, in Scandinavia (rising due to glacial rebound) and Venice, Italy (subsiding due to sediment compaction), shorelines are moving in opposite directions despite the current rise in global sea-level of ~3mm/yr (projections point to an increase of ≥8 mm/yr by 2100; Rahmstorf et al., 2007). Other drivers include sediment supply and wave/storm-influenced sediment dispersal/compaction, plus regional influences: lithospheric cooling, isostatic/flexural loading, and dynamic topography within the asthenosphere. On old passive margins (e.g., NJ), regional effects are small and perhaps impossible to measure, but all contribute to the complexity of assessing eustatic change through geologic time.

Preserved shallow-water sediments are divided into facies successions bounded by regional unconformities (e.g., Sloss, 1963). The difficulty of mapping these “sequences” (Vail et al., 1977) in true 3D, and deconvolving factors that generate them, have long hindered all but broad interpretations regarding their relationships to eustatic change (e.g., Haq et al., 1987). Because of the importance of coarse-grained sand bodies as reservoirs, oil companies have sought ways to anticipate distributions of sequences based on seismic data alone, often without investing in costly geologic sampling. They focus on intervals/settings that offer the highest economic returns, most recently in structurally complex deep-water settings, leaving behind less productive, Neogene shelf clinoform settings. They also generally withhold their high-quality seismic data and predictive techniques from public disclosure. The international research community shares many of the same scientific interests, but relies less on high-quality seismic data and more on samples from scientific ocean drilling to link the preserved stratigraphic record with eustasy (COSOD II, 1987; Watkins and Mountain, 1990; JOIDES, 1992; Fulthorpe et al., 2008). Such efforts have focused on assembling a global compilation of co-registered analyses of paleo-water depths, sediment compaction/age, and thermal/isostatic/flexural subsidence in shallow-water basins along continental edges. Gathering these drilling-based data has been challenging, and accompanying industry-grade seismic data remain generally unavailable. Our goal here is to augment recently drilled and logged NJ shelf successions with superb 3D seismic images to provide the interested academic community an improved understanding of the factors shaping the global sedimentary record at passive margins, including the long-term history of eustatic change. Because continental margins contain the archive from which much of the world's oil and gas is extracted, and along which ~10% of humanity lives, knowledge of the interaction of this sediment record with ongoing base-level changes serves highly relevant societal interests.

BACKGROUND

The Transect Drilling Strategy

ODP/IODP-related workshops (refs. above) and more than two decades of community-based discussions have concluded that a global set of borehole transects across multiple passive margins is required to deconvolve eustatic signals from those of local processes (Christie-Blick et al., 1990; Kominz and Pekar, 2001). Only this strategy can confirm global synchroneity of sequence boundaries and document stratigraphic responses in diverse tectonic/depositional settings. To yield a reliable measure of eustatic change between two sequences, drilling must sample an intervening sequence boundary in at least three locations: 1) the youngest topset sediments of the older sequence, close to the seaward increase in gradient (the clinoform "rollover"/paleo-shelf edge); 2) the oldest bottomset sediments of the younger sequence at the seaward toe of that same clinoform; and 3) farther seaward along the same surface, where complications of reworking are diminished and age control optimal (Fulthorpe et al., 2008). Using this approach, lateral variations in facies, paleo-water depth and age can be traced along key surfaces. With proper accounting for total subsidence, reliable elevations/dimensions of sequences at their time of deposition can be estimated to distinguish local transgressive/regressive cycles (e.g., Scandinavia vs. Venice) from eustatic changes (e.g., Steckler et al, 1999).

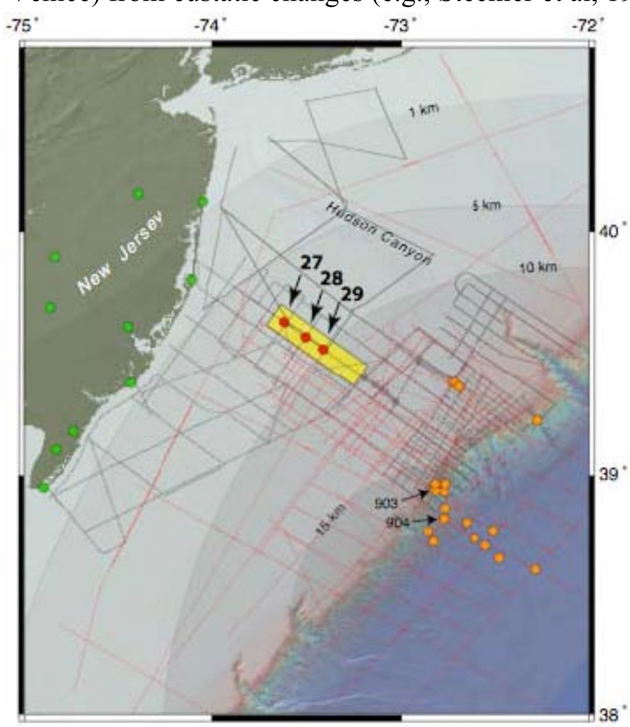

Figure 1. *Proposed 12 x 50 km 3D seismic volume (yellow rectangle) encompassing Exp313 Sites 27-29 (red circles) embedded within grids of deep-penetration, reconnaissance (dashed red lines) and higher-resolution (solid gray lines) 2D MCS profiles. Previous studies have tied these grids to scientific ocean drilling wells on the outer shelf, slope and rise (orange circles). Onshore wells (green circles) provide updip equivalents to offshore stratigraphic units (see details in the text). Depths to basement are indicated (muted gray colors/contours).*

IODP Expeditions 313 and 317 (NJ and offshore New Zealand, respectively) have followed this strategy, drilling dip-oriented transects imaged by grids of 2D MCS profiles (Mountain, Proust, McInroy et al., 2010; Fulthorpe, Hoyanagi, Blum et al., 2011). This proposal builds on the successful drilling of the first of these, termed the "Mid-Atlantic Transect" (MAT), by seeking to fill a critical gap in seismic correlation. Exp313 samples provide age/paleo-water depth/facies variations within and between sequences imaged by existing grids of 2D MCS data (Fig. 1). The 3D volume we propose to collect will provide accurately rendered, high-resolution "seismic geomorphology" linking depositional/erosional processes driving shoreline movements to known mid-Neogene base-level changes.

Evolution of the "Mid-Atlantic Transect" (MAT)

The NJ margin has long been recognized as a leading candidate for the study of eustatic change and its impact on the sediment record because of: 1) smooth thermal subsidence since Triassic-Early Jurassic rifting (Watts and Steckler, 1979); 2) substantial sediment supply since the mid-Oligocene (Poag, 1985), when high-latitude glaciations provide an independent measure of eustatic forcing (Miller et al., 1998;

Zachos et al., 2001; Pekar et al., 2002; Pekar and Christie-Blick, 2008); 3) optimal geochronologic control as a result of a mid-latitude setting; and 4) accessibility/wealth of supporting information (Fig. 1).

In support of the transect drilling approach, multiple 2D MCS grids have been collected since 1990 to locate potential drill sites (Fig. 1). The first was a reconnaissance grid of 120-channel, 1350 in.^{3} air-gun array profiles across shelf wells spot-cored by the U.S. Geological Survey and industry (Hathaway et al., 1976; Scholle, 1977; Libby-French, 1984). Roughly two dozen unconformity bounded, post-Eocene sequences across the shelf/upper slope were traced areally using these data. ODP Leg 150, restricted to the slope/rise, recovered sediments documenting 22 early Eocene-middle Pleistocene ("Ice House") seismic surfaces (Mountain, Miller, Blum, et al., 1994; Miller et al., 1996). In most cases, seismic sequence boundaries matched to Leg 150 boreholes showed little/no time missing across them. Coarse-grained deposits that fined upwards from the bases of many sequences were interpreted as sediments transported basinward during sea-level lowstands. The scientific community understood that Leg 150 samples were from paleo-water depths too deep to yield insight into eustatic amplitudes and their role in shaping facies successions, but shelf drilling required was not at that time deemed safe.

To attempt to remedy the need for shallow-water control, Coastal Plain drilling was begun to complement the deep-water data (Miller et al., 1994). Oligocene – mid-Miocene sequence boundaries onshore (Fig. 1) were found to correlate well with $\delta^{18}O$ increases derived from deep-ocean sampling, confirming that they formed during times of most rapid global sea-level falls (Fig. 2). Furthermore, sequence ages compared well with the Haq et al. (1987) eustatic chart (see also Miller et al., 1996, 1998).

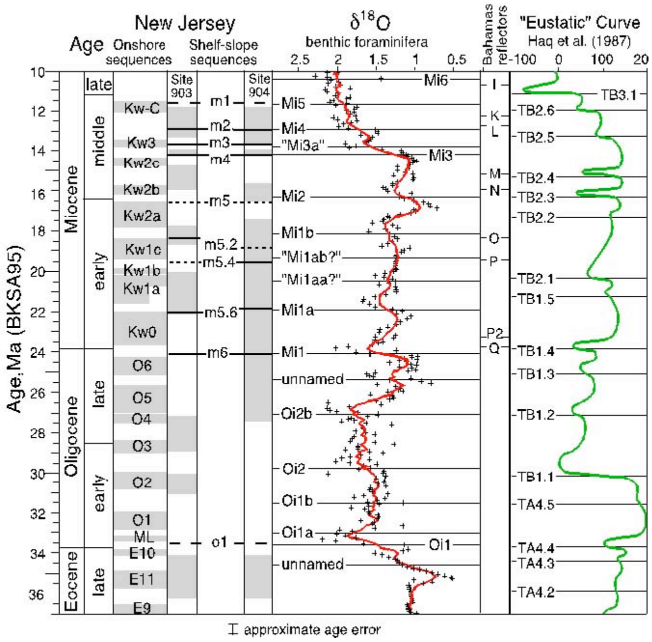

Figure 2. *Correlation chart of the NJ margin, late Eocene-late middle Miocene. Onshore sequences (19 total, gray=recovered, white=hiatus) were sampled at 6 sites. Shelf sequence boundaries (10 total, o1-m1) were defined in MCS profiles (see Fig. 1) and traced to the slope. Depositional sequences at ODP slope sites 903/904 (gray=recovered, white=hiatus; Fig 1) are tied to the magnetic reversal time scale (Berggren et al, 1995) and the global $\delta^{18}O$ curve. Ice volume increases are inferred from $\delta^{18}O$-matched hiatuses in the updip/onshore record and slope sequence boundaries. A global sea level curve inferred from coastal onlap and other means (Haq et al., 1987) is at far right. While these correlations appear robust, the critical missing piece for understanding the evolution of the siliciclastic sedimentary record during a time of known eustatic change is spatial correlation of 3D seismic images (crucial for identifying/tracking shorelines and related shallow-water features) with well-sampled drillsites, such as Sites 27-29 (Fig. 1).*

The Coastal Plain effort showed that: 1) sequence boundary ages could be determined to better than ±0.5 myr, thereby providing the chronologic control needed to track eustasy for the past 42 myr (Miller et al., 1996, 1998); 2) stratal surfaces are the primary cause of margin seismic reflections (Mountain, Miller, Blum, et al., 1994); 3) middle Eocene-Miocene sequence boundaries correlate with globally recognized $\delta^{18}O$ increases, linking their formation to glacioeustatic falls (Miller et al., 1996, 1998); 4) through correlation with Leg 166 (Bahamas) drilling, siliciclastic and carbonate margins yield correlatable and in some cases comparable records of inferred sea-level change (Miller et al., 1998; Eberli, Swart, and Malone, et al., 1997); and 5) several amplitude estimates of ~20-85 m for my-duration sea-level variations exist that agree with estimates based on $\delta^{18}O$ changes (Kominz et al., 1998, 2003).

Nonetheless, onshore/slope drilling on the NJ margin cannot alone constrain late Paleogene-Neogene eustasy. Onshore wells are too far updip to recover lowstand sediments and, without seismic profiles, they lack the complementary sequence architecture needed to understand facies distributions within clinoform packages. Furthermore, neither onshore nor deep-water drilling can sample paleo-shelves/clinoform rollovers that are among the most sensitive features to post-Oligocene sea-level change. The full range of known/expected “Ice House” sea-level variations cannot be addressed without drilling on the shelf.

To prepare for shelf drilling, 2D MCS profiles across the shelf/uppermost slope were collected (Fig. 1; Austin et al., 1996). These featured two aspects required for safety: high-resolution (shallowly-towed, short-offset GI gun/streamer geometry, 12.5 m shot spacing, 1 ms sampling, ~5 m vertical resolution) and dense spacing (150 m) around locations of proposed drill sites. Such data quality and density were deemed necessary to avoid drilling into pockets of shallow, pressurized gas. These data increased the resolution and number of mappable sequences (Fulthorpe et al., 1999, 2000; Fulthorpe and Austin, 2008). Unfortunately, because the *JOIDES Resolution* generally employs open-hole drilling, ODP denied all proposed sites except two that "twinned" the COST B-2 stratigraphic test well, to ensure the absence of gas (Scholle, 1977). Consequently, ODP Leg 174A drilled Sites 1071 and 1072 on the outer shelf ~.75 and 3.5 km from B-2 (Fig. 1; Austin, Christie-Blick, Malone, et al., 1998). Loose sands and drill-ship heave resulted in limited recovery to the extent that bounding surfaces could not be sampled/dated with the desired precision. Nonetheless, observed prograding clinoformal seismic sequences were confirmed as being bracketed by unconformities that formed during sea-level falls. Other contributions included: 1) water depths during late-middle Miocene-Pleistocene lowstands were close to zero ~100 km seaward of the modern shoreline; 2) inferred fluvial incisions (restricted to topsets) suggest that ambient sea-level never fell below rollovers; and 3) benthic forams indicate that maximum highstand water depths were ~50-100 m, constraining sea-level amplitudes once the effects of accumulation, compaction and loading are taken into account.

Leg 174A results also showed that a drilling platform immune to heave and a drill rig with closed-circulation were needed to provide both the flexibility in site selection and high core recovery required to meet long-standing MAT objectives. This suggested that drilling beneath the inner shelf, where ~30 m water depths permitted use of a self-propelled jack-up rig (“mission-specific platform”) planted on the seafloor, was essential. To serve safety constraints, a second 2D MCS grid was completed landward of previous surveys, again with ~5 m vertical resolution and narrow line spacing (Fig. 1; Monteverde et al, 2008). Sites were selected following the transect strategy; imaging focused on early Neogene clinoforms on the inner-middle shelf.

IODP Expedition 313 – Neogene Clinoforms Continuously Cored and Logged

Exp313 drilled/logged 3 sites, (M)27-29, in 35 of water 45-65 km offshore NJ in 2009 (Figs. 1 and 3; Mountain, Proust, McInroy et al., 2010). Goals were to: 1) identify surfaces representing late Paleogene-Neogene base-level changes and compare their ages with sea-level variations implied by the $\delta^{18}O$ glacioeustatic global proxy (Fig. 2); 2) estimate corresponding amplitudes/rates/mechanisms of sea-level change during this “Icehouse” time; and 3) evaluate/improve models predicting lithofacies successions, depositional environments and seismic architecture in response to such sea-level changes and other processes that imprint the shallow-water record. Exp313 collected 1311 m of very good-excellent quality cores with 80% recovery. The deepest hole penetrated 757 mbsf to upper Eocene sediments. Slim-line logs included spectral gamma ray, resistivity, magnetic susceptibility, sonic and acoustic televiewer. Porewater chemistry profiles were generated; uncontaminated sediments were also frozen for microbiologic studies.

Downhole logs, multi-sensor track measurements of unsplit cores, and physical properties of discrete samples, aided by vertical seismic profile measurements at each site, provided core-log-seismic ties with preliminary depth uncertainties of ±5 m or less (Mountain, Proust, McInroy et al., 2010). Excellent synthetic seismograms provide support for core-log-seismic correlation within specific intervals (Mountain and Monteverde., in review). Studies by the Exp313 Scientific Party (over 2 dozen papers representing scientific results are due for submission to *Geosphere* by Aug 4, 2012) link strata to 16 seismically mapped (Figs. 1, 4) regional surfaces/unconformities. The three sites sampled topsets, foresets and toesets of multiple stacked clinoforms. Litho-and biofacies have been correlated along key seismic surfaces to yield mutually consistent depositional histories, although, as will be described, nagging

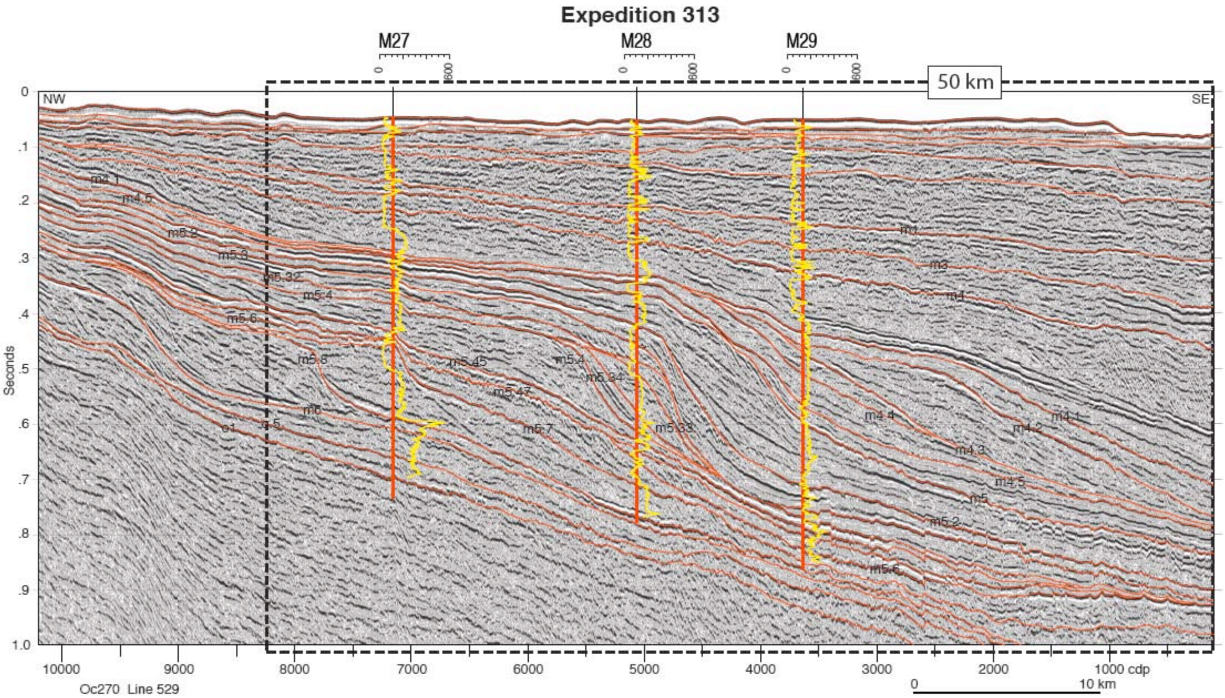

Figure 3. Oc270 line 529 through Exp313 sites M27-29 and the area we propose for a 12x50 km 3D seismic volume (dotted rectangle is the long dimension of that survey; Fig. 1). Gamma ray logs, converted to travel-time with velocities developed for Exp313, are shown in yellow. Early Oligocene -mid-Miocene sequences o1 to m4.1 have been continuously cored/logged and correlated across an existing 2D grid of seismic data on the inner shelf (Monteverde et al., 2008; Figs. 1, 4). As good as the resulting correlations appear to be, ambiguities fundamental to understanding the link between sea-level change and sequence evolution, notably the recognition of diagnostic shorelines and related shallow-water features (fluvial incisions, point bars, estuary complexes, etc.), remain and will not be fully resolved without 3D imaging encompassing these drill sites.

uncertainties remain that cannot be resolved with existing seismic coverage. Excellent paleontologic zonations (based on coccolithophores, dinocysts, diatoms and limited planktonic foraminifera), plus Sr-isotopic ages, are revealing a nearly continuous record of 0.5-2 myr sea-level cycles in the 22-12 Ma interval. Older and younger strata outside this age range have also been sampled, but were not present at all sites. Facies and benthic foram assemblages implying paleo-water depth changes of 60-80 m have been found in topset beds within transgressive-regressive cycles. Initial 2-D backstripping suggests that these paleobathymetric changes are the result of eustatic variations of ~1/2 this magnitude (Mountain and Steckler, 2011; Steckler et al, in review). Ongoing shorebased studies, involving correlation/backstripping of additional surfaces to recover original geometries, should improve eustatic amplitude estimates within the targeted time interval.

However, despite Exp313 successes, made possible by excellent core recovery with ties to logs and mapped sequences (Mountain, Proust, McInroy et al., 2010), uncertainties regarding sequence evolution and relationships with eustatic change remain: 1) If topset strata become subaerially exposed during lowstands, why are no shoreline features, and so few incised valleys, recognized on existing 2D seismic data in the Exp313 region (Fig. 4)? 2) What is the source of debris flow deposits found in Exp313 cores seaward of clinoform rollovers, during what stage(s) of the sea-level cycle are they likely to have formed, and why is there no seismic geomorphologic evidence of sediment transport from either up-dip or along-strike sources on the 2D data? 3) How are prograding Oligocene -mid-Miocene clinoforms influenced by initiation of the globally important mid-Miocene climate transition? Despite progress in sampling these clinoforms, one key element, encompassing spatial imaging, is missing. The clinoform rollover (i.e., paleo-shelf edge) is the key imaging location, because landward shoreline trajectories shift, and the growth and development of incisions in response to sea-level change can be observed seismically. Drilling calibrates those trajectories, but only spatial imaging can both recognize and document them through time.

We must know more about detailed processes and depositional environments at/near rollovers, especially volumes/timing of sediment bypass to clinoform slopes. Lateral variability along shorelines is also crucially important, so we must document changes in processes/depositional environments in both dip and strike directions, to the extent that resources allow.

In summary, the "MAT" has been a long-term effort, culminating in Exp313, involving repeated 2D seismics at a range of frequencies to carry out iterative drillsite targeting (using successive sampling technologies) to address the Neogene geologic history at an old passive margin. One crucial piece remains – to integrate calibrated shallow-water facies with 3D images of architecture/geomorphology.

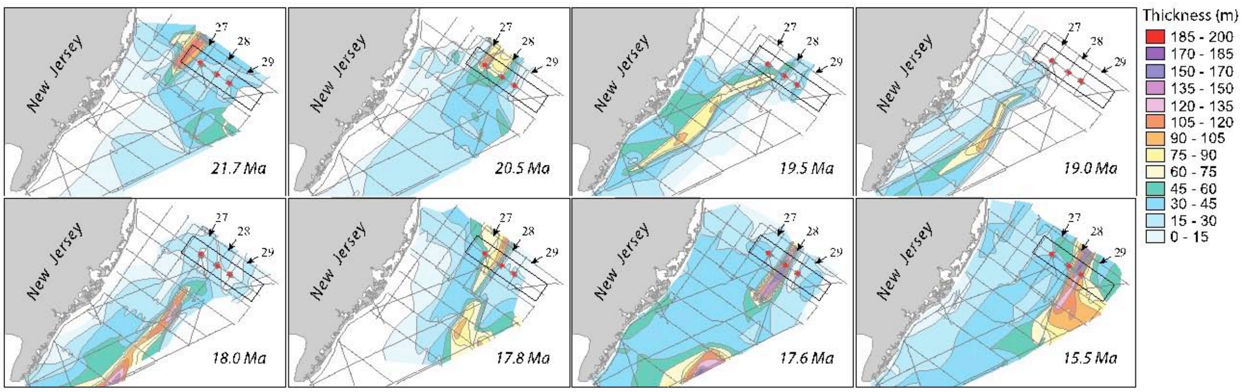

Figure 4. *Isopachs of 8 early to middle Miocene sequences offshore NJ (legend at right; after Monteverde et al., 2008; basal age of sequences from Browning et al., in review). The proposed 12 x 50 km 3D MCS volume encompassing Exp313 Sites M27-M29 (red circles) is outlined in black. Seismic sequences have been identified using 2D MCS profiles (Figs. 1, 3), tied to ODP drill sites on the outer shelf and slope (see Fig. 1), and correlated to hiatuses in ODP onshore wells (Figs. 1, 2). Note seaward progradation of Miocene sediments through time, plus progression from a northern sediment buildup (21.7 Ma), followed by a southern buildup (18.0 Ma), then returning to a northern buildup (15.5 Ma) suggesting both time-varying sources of sediment and margin-parallel redistribution. This complex evolution challenges the reliability of understanding sequence development using only sparse, primarily dip-oriented 2D profiles. The proposed 3D volume will image stratal features within both the thickest parts of some sequences and along the thinner perimeters of others.*

RESEARCH GOALS of the PROPOSED WORK

Provide Community Access to a Calibrated (by Exp 313 Drilling) 3D Seismic Volume

Integration of 3D images with Exp313 drilling results will couple the highest quality cores from this passive margin with unparalleled definition of seismic facies character and spatial geometry where they are needed, near rollovers/paleo-shelf edges most sensitive to changes in base-level during the Ice House. Such an integration will advance sea-level science, while providing unprecedented insights into impacts of migrating shorelines during rising sea level, such as we are experiencing today (see Broader Impacts). Future breakthroughs in the marine geosciences will rely on spatial imaging of the subsurface that can only be achieved with 3D technology. Since its appearance in the early 1970's (Walton, 1972), commercial 3D surveying has grown at such a rate that by 1999 it had eclipsed 2D profiling in terms of worldwide dollar value of acquisition (Liner, 1999). However, despite clear science advantages, its use by academia has followed slowly due to high costs of acquisition and processing.

NSF addressed this issue by convening the 2010 workshop *Challenges and Opportunities in Academic Marine Seismology* (http://www.steveholbrook.com/mlsoc/workshop_report.pdf) to encourage the academic research community to explore ways of increasing access to 3D data. A major recommendation comprised three parts: 1) generate "community" 3D surveys using the *Langseth*, the first academic 3D seismic vessel, 2) hire private companies to process 3D data to an initial interpretable volume within 6 months post-cruise, and 3) release 3D volumes for general use in follow-on, PI-driven interpretation projects. Our proposal follows this model, while being driven by MAT's enduring scientific goals.

Capitalize on the Fundamental Advantages of 3D Seismic Data

The power of 3D seismic volumes is their ability to elucidate both sedimentary processes and paleoenvironments, through assessments of "seismic geomorphology". Sedimentary basin fill is inherently 3D at all spatial scales. Traditional 2D surveys can document basin-scale (tens of km) three-dimensionality, but cannot differentiate km-scale (and less) morphologies, e.g., estuary complexes, shelf channels, upper slope canyons, etc., that are keys to defining shallow-water processes and paleoenvironments, which in turn can be used to determine shifting shoreline positions through time and hence constrain paleo-sea level changes. Individual profiles may image such features, but mapping them between profiles kilometers apart is possible only in a generalized fashion (see Fig. 4). Whereas commercial 3D data can meet academic research needs on some margins, such data are lacking off NJ.

A common misconception exists that 2D and 3D reflection data differ only in image presentation, i.e., that 2D surveying produces a cross section, while 3D surveying produces a volume. In truth, what can be extracted from 3D data far exceeds this conspicuous dimensional component. 2D images are also fundamentally hampered by "cylindrical ambiguity" and "viewpoint limitation". Cylindrical ambiguity means that 2D data lack information necessary to establish cross-profile positioning; there is no way to know true locations of reflections that "appear" to lie beneath the survey track, but which originate from somewhere to one (either) side of the profile plane. Viewpoint limitation means that only reflecting surfaces facing the profile plane can be imaged; all others, including those directly below with even modest cross-profile dips, remain invisible. Maximum reflector dips beneath the inner NJ shelf are small (<8°; Figs. 3, 4), so cross-profile mis-positioning of reflections is not as large as in geologic areas with more steeply dipping features. However, for the two-way travel time range of highest interest (0-0.8 s; Fig. 3), and the corresponding average velocity range (1.6-1.8 km/s), the expected maximum cross-profile mis-positioning of events on existing profiles is 35-100 m, which is as large or larger than incised valleys and related shoreline-related features we hope to observe. 3D acquisition and processing will virtually eliminate these problems.

Another challenge using 2D data for stratigraphic interpretations is caused by streamer cable side-drift/feathering (Renick, 1974; Levin, 1983). During 2D acquisition, cross-currents cause average feathering of ~10° (Yilmaz, 2001). As a result, 2D profiling becomes a limited-swath 3D survey to one side of profile track. Processing such marine survey data using standard 2D imaging procedures (as has been done to the present) creates spurious discontinuities/wipeouts in reflection events (Nedimovic et al., 2003). Currents offshore NJ vary in both strength and direction (Butman et al., 2003), so they must have caused 5-10° streamer feathering when existing 2D data were collected (Fig. 3); this is confirmed by records of visual sightings of tail buoys. Such feathering has detracted from reflection event continuity in all 2D profiles offshore NJ. Unfortunately, past feathering effects cannot be corrected because streamer navigation was not utilized during all of those 2D surveys.

Exploit the Unique Tools Associated with 3D Imaging

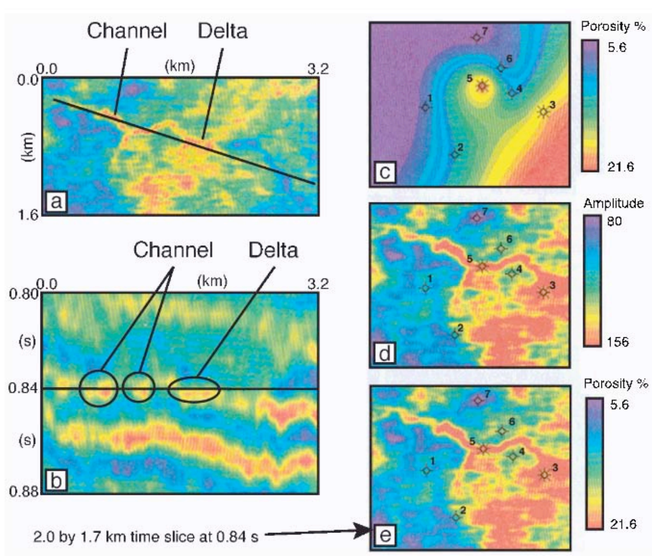

Figure 5. *(a, b) Channel systems (from the Gulf of Mexico) in 2D and 3D and (c, d, e) integrating seismic and well data to extract porosity. a-b: While a map view (a) of an amplitude slice at 840 ms two-way travel-time provides a clear image of a channel and (associated) delta, little can be inferred about this system from a cross-sectional image (b) carefully chosen to cross the channel twice and the delta once. (c): Gridded porosity map at the reservoir level (840 ms, see a), based upon samples from 7 drilled holes. (d): Time slice at the same level as in (c). Note the level of detail of sratigraphic features. (e): Seismic-guided porosity map formed by integrating seismic and well data. If 3D seismic data had been collected before drilling, 5 dry holes (1, 2, 4, 6, 7) would not have been drilled. Figure adapted from Liner (1999).*

The growing use of 3D seismic techniques has led to significant advances in stratigraphic studies. Small but important "process" features like incised channels, difficult to document using 2D data, stand out in maps derived using 3D data (Figs. 5, 6). However, stratigraphic interpretation benefits not only from a 3D view of the subsurface, but also from the ability to extract quantities called "seismic attributes" from 3D volumes. Both pre-stack and post-stack attributes will be needed from the proposed 3D volume to extract the maximum information for ongoing stratigraphic interpretations of the NJ margin.

Post-stack seismic attributes result from image manipulation (Liner, 1999; Fig. 5). For NJ, the most useful post-stack attributes are instantaneous amplitude, phase, frequency and Q (1/attenuation). When applied to 3D volumes, these attributes can be powerful indicators of lithologic variations, event continuity, fracturing and absorption. The most useful 2D attributes for delineating channels are coherency, edge detection, directional gradient (e.g., "curvature", Fig. 6) and shaded relief.

While 3D surveys provide more accurate and useful information than 2D seismic imaging (Fig. 5c-e), the most complete geologic information is extracted by combining 3D images with drilling/logging. Such a combined approach allows for detailed analysis of geometry, lithology, porosity, fluid saturation and anisotropy of buried sediments and associated depositional/erosional systems (e.g., complex fluvial channel systems; Fig. 6) and their geometric relationships with Neogene rollovers sampled by Exp313.

An excellent example of the value of 3D data is provided by ongoing research into the upper Oligocene-Recent clinoformal stratigraphy of the Northern Carnarvon Basin (NCB), Australian Northwest Shelf (NWS) (Liu et al., 2011; Sanchez et al., 2012a, b). Middle Miocene-Pliocene siliciclastic sediments represent a long-lived (~8 my) break in otherwise carbonate-dominated shelf sedimentation. Available commercial 3D volumes have enabled a profound new interpretation of these prograding siliciclastics as 27 shelf-/shelf-edge delta lobes (Fig. 7). Only through true 3D mapping has it been possible to correlate individual clinoform sets with these lobate, complex deltaic morphologies. Long-term (cumulative) progradation of this delta system and subsequent backstepping correlate with long-term sea-level fall and rise during the late middle-late Miocene. This observed siliciclastic influx correlates with other coeval increases in siliciclastic sediment supply worldwide, including offshore NJ and a prospective depocenter in the Gulf of Mexico (see text below).

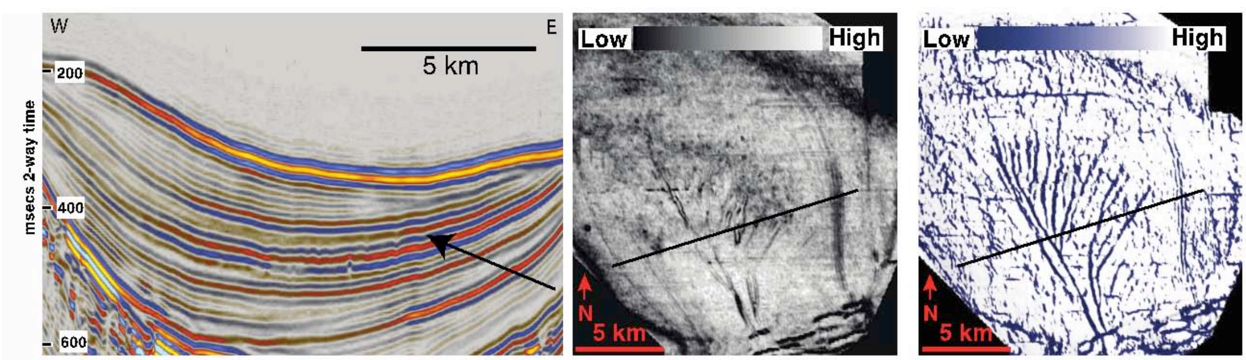

Figure 6. *Visualization and interpretation of paleo-channels in 2D (left) and 3D (center, right) seismic data. Left: Strike-oriented 2D seismic reflection profile from the Gulf of Mexico showing subtle undulations in one imaged stratal horizon (indicated by the black arrow) which are produced by slope channels. However, this could not be confirmed using the 2D representation by itself. Center/right: Seismic attribute (travel-time) slices produced along the same horizon extracted from a conventional 3D volume, the center view showing "coherence" and the right view highlighting "most-negative curvature". Identifying complex channel features and tracking them spatially is straightforward using the 3D volume, but challenging if not impossible to achieve using 2D control alone, even if the 2D grid is dense, as is true for some of the grids on the NJ margin (Figs. 1, 4). From Lozano and Marfurt, 2008.*

In addition, 3D mapping in the NCB has yielded important insights into the relationships between clinoformal sequence boundaries and sea-level change, particularly: 1) complex spatial acoustic evidence of karst topography (indicative of shelf exposure) along some horizons, and 2) step-like, vertical offsets up to 65 m high, downward toward the basin on the outer paleo-shelves (near rollovers) of two early-middle Miocene sequence boundaries. These have been interpreted as rarely preserved examples of wave-cut terraces or sea cliffs (Liu et al., 2011). All of these features represent direct evidence of paleo-sea level and shoreline location, which can only be interpreted with 3D data.

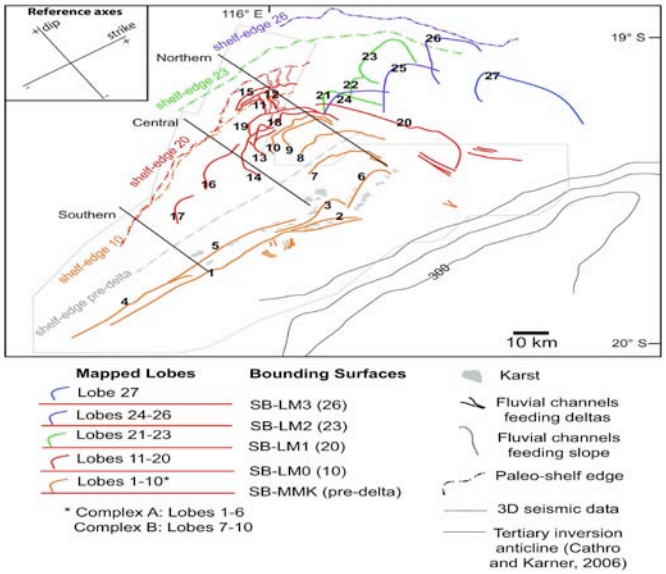

Figure 7. *Delta lobes and positions of paleo-shelf edges at the ends of deltaic progradation pulses in the Northern Carnarvon Basin (NCB), Australian Northwest Shelf (NWS; Sanchez et al., 2012 a, b). The outline of each lobe corresponds to the rollover of the upper bounding unconformity of the mapped clinoform set representing that lobe. Interpreted fluvial channels within the siliciclastic interval are shown in colors correlative with their presumed associated delta lobe. Interpreted karst features, indicative of paleo-shelf exposure (i.e., sea-level low stand), also underlie lobes 1-6. This interpretation of clinoform sets as a spatially complex set of prograding delta lobes was only possible through mapping within a 3D seismic volume (outline of the volume shown in the figure, thin grey line).*

Tie 3D Volume to Exp 313 Results to Resolve Ambiguities of Neogene Stratigraphic Evolution

Seismic morphologies similar to those of the NWS, containing imprints of changing sea level and other factors that control shallow-water sedimentary processes, are present on the NJ margin (Fulthorpe and Austin, 1998; Nordfjord et al., 2005). The 3D MCS volume we propose to collect will focus on resolving the origin of such features critical to understanding the relationships between sea-level change and sequence development. In particular, we will focus on shallow-water features near and at paleo-shorelines: fluvial channels, point bars and estuary complexes (Nordfjord et al., 2005). MCS line 529 (Fig. 3) runs through the center of our proposed survey area and ties the three Exp313 sites. Below, we use that image to frame three working hypotheses that can be tested by combining a 3D volume with Exp313 results. These hypotheses/related goals agree with components of the Eastern North American Margin (ENAM) component of the GeoPRISMS Draft Implementation Plan (http://www.geoprisms.org/enam.html).

***1**) What are the spatial/temporal relationships between sea-level low stands and areas of paleo-shelf exposure adjacent to/landward of clinoform rollovers? Linked hypothesis: low stand paleo-shelf exposure has increased since the Oligocene, probably in response to increasing eustatic amplitudes (Fig. 2), resulting in an increasing number of fluvial incisions both up-section and seaward across the NJ margin.*

Seismic sequences, when first defined, were classified according to the nature of their basal boundaries (Mitchum et al., 1977). While terminology has since been refined, a fundamental observation remains valid: some sequences begin with valleys cut into the top of the underlying sequence, while others have no such incisions, and begin instead with apparently conformable deposition onto beds of the preexisting shelf/uppermost slope. The former incised, "Type 1", sequence boundaries have been inferred to indicate a larger and/or more rapid fall in base-level than the latter, "Type 2", boundaries. Judging from existing 2D MCS data off NJ (Fig. 1), incised valleys appear to be scarce in paleo-shelf strata landward of rollovers, suggesting that Type 2 boundaries dominate the early Miocene within the proposed survey area (Fig. 3). Similarly, a lack of lobate low stand fans seaward of clinoform toes (Figs. 3, 4; see below) supports the hypothesis that Type 1 systems are minor to nonexistent in this lower Miocene section. Nonetheless, there is seismic evidence (at ~cdp 4000, between m5 and m4.5, Fig. 3) of a shelf-edge delta and erosional truncation of foresets, suggesting base level at m5 time was very close to, if not below, the elevation of adjacent topsets. In addition, landward of all Exp313 sites (Fig. 1), isolated incisions ~100 m wide and 510 m deep are observed seismically, but none can be connected with existing data coverage (Fig. 4;

Monteverde et al., 2008). Possible explanations include: 1) incised valleys are well-preserved/present, but existing 2D profiles do not cross them (unlikely); 2) such valleys were removed by ravinement during transgressions (possible, but unlikely due to the lack of core-based evidence for accompanying hiatuses between sequences in Exp313 samples); or 3) such valleys are present, but too small/widely spaced to be resolved by existing 2D coverage (very likely). This third possibility is supported by interpretations of dense, ultra-high resolution single-channel (2D/3D CHIRP geophysical profiles) of the NJ shelf 60 km to the southeast, which confirm that complex dendritic, incised fluvial systems formed during the latest Pleistocene (Davies et al., 1992; Duncan et al., 2001; Nordfjord et al., 2005). Incised valleys are crucial paleo-water depth indicators at sequence boundaries, independent of benthic foraminiferal successions. We are confident that if incised valleys exist within lower Miocene sediments around Exp313 sites, and seaward toward correlative rollovers, they will be detected using 3D images along with related morphologic enhancement techniques (Figs. 5, 6). Mapping these incisions will constrain shoreline positions through time, improve estimates of eustatic amplitudes, and enable sequence architecture/seismic geomorphologic techniques to predict facies distributions calibrated by Exp313.

While pre-middle Miocene shelf exposure near Exp313 sites is difficult to detect with existing 2D data, this is not true of younger intervals sampled by Exp313 above reflector m4.1 (Fig. 3). Spot coring at irregular surfaces corresponding to sequence boundaries m1, m3 and m4 at sites M27 and M29 recovered shallow water sands, and in several cases ~1 m of paleosol (Mountain, Proust, McInroy, et al., 2010). These surfaces can be traced seismically to clinoforms on the mid-shelf 25 km seaward of M29, but the proposed 3D imaging will not extend seaward to those younger clinoforms. Nonetheless, several hundred meters of largely discontinuous reflectors above m4.1 (Fig. 3) are virtually certain to be resolved with 3D techniques to a degree rarely seen, providing seismic expression of nearshore and coastal plain facies tied to Exp313 cores and logs.

Using the proposed 3D volume, seismic evidence for paleo-shelf exposures and proximity of fluvial sources to paleo-shelf edges/rollovers can be mapped, along with shelf/uppermost slope delta architecture (if it exists; Fig. 7), within any of the eight sequences constrained by Exp 313 results (Fig. 3). Community-based efforts can then document any enhanced fluvial contributions to observed clinoform progradation during a known time interval of long-term eustatic fall and increasing glacioeustatic amplitudes. Seismic attribute analyses, e.g., coherence displays (Fig. 6, center), offer exciting opportunities to locate/map incised valleys/canyons at sequence boundaries, to calibrate sand distribution in shallow shelf intervals/topsets, clinoform front/toe and basinal settings, and to investigate facies-dependent bedding characteristics calibrated by Exp 313. The higher fold and improved source to be used for the proposed 3D survey (see below) will also provide enhanced multiple suppression and thereby produce sharper definition of sequence boundaries (e.g., Fig. 4), a task that is especially challenging along the mid-Atlantic shelf because of highly reflective and parallel layering of interbedded muds and sands in the Neogene section (e.g., Austin, Christie-Blick et al., 1998)

2) *What are the mechanisms of sediment transport seaward of clinoform rollovers, and how do they fit into the sequence stratigraphic model? Linked hypothesis: During shelf progradation, the evolution of clinoform front morphology is a complex response to changes in gradient, sediment source geometry (point-vs. line-source), and basinward redeposition by sediment gravity flows/turbidity currents.*

Despite the lack of seismic evidence for inner-shelf incisions along the tops of Oligocene-middle Miocene sequences (Fig. 4), mass-transport deposits on slopes were encountered by Exp313 (Fig. 8). The classic model of siliciclastic sequence development includes submarine fans seaward of clinoform toes (Van Wagoner et al., 1988; Posamentier and Vail, 1988), presumed to represent sediment by-pass/basinward transport of mostly coarse-grained material during times of rapid sea-level fall. However, there is little evidence of such lobate depocenters in Oligocene-Miocene sections beneath the NJ shelf (Figs. 3, 4; Greenlee et al., 1992; Poulsen et al., 1998). In their place beneath the inner shelf there are well-defined deposits less than a few km seaward of rollovers that accumulated as units 10's-100's of m thick on ~2° clinoform slope gradients (Fig. 3). All pinch out landward and thin seaward, where most become seismically indistinguishable from underlying strong reflectors at slope toes. Each extends for 10's of km along-strike. These sediments have been termed “slope apron deposits”; Exp313 results have shown that they comprise glauconitic sands and mature quartz grains up to gravel size, all presumably shed from edges of adjacent clinoform tops (Fig. 8). The Exp313 team is using both litho-and seismic stratigraphic features of several of these deposits where they occur within a single sequence. The goal is to identify criteria that divide them into separate depositional units, but because they represent rapidly deposited, reworked material, such subdivisions will be difficult or impossible to establish with the existing 2D data. We will also be able to determine how slope apron deposition relates to timing of eustatic change(s), a goal at the heart of understanding clinoform evolution. A 3D volume is required to do this work.

In addition to resolving internal structures of slope aprons, the 3D volume will also detect failure scars/transport lanes that directed mass flows basinward (Fig. 8). The volume will also document spatial/temporal connections to shelf-crossing incised valleys immediately landward of rollovers. One important objective is to determine the degree to which observed incised features served as conduits for sediment originating landward of the rollover, as opposed to more local slope redistributions, such as headward erosion, gravitational creep, slumping and/or debris flow mechanisms, all of which originated seaward of rollovers. Ties between continuously sampled cores and 3D images make this possible.

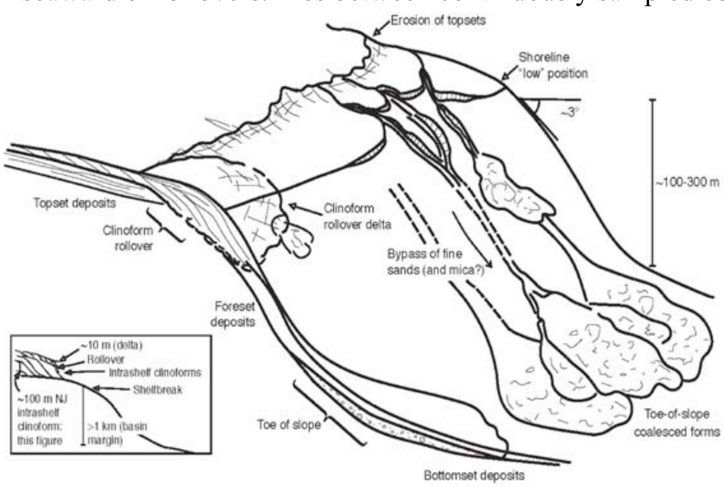

Figure 8. *Conceptual model developed during Exp313 to explain regular occurrences of poorly sorted, stratified, glauconite-rich coarse sand/gravels in cores taken near the tops of clinoform slopes. Multiple channels and/or regressive shorefaces at clinoform rollovers are presumed to erode into/entrain older topset deposits. These sediments are remobilized and transported down the clinoform slope as debris flows and turbidity currents to form aprons close to the toe of slope (Mountain, Proust, McInroy et al., 2010). The 3D volume will vastly improve images of clinoform rollovers, where these sediment movements take place in response to base-level changes.*

Research on sediment transport pathways using 2D data has been unable to provide definitive models of shelf/slope/basin connectivity on this or any continental margin. In the sequence stratigraphic model, fans and laterally extensive onlap depend on stable point sources of sediment (e.g., Karner and Driscoll, 1997). But even middle-late Miocene sequence boundaries that display evidence of paleo-shelf exposure are not associated with lobate lowstand accumulations basinward of clinoform toes, based on available 2D profiles (e.g., Fulthorpe et al., 2000). Perhaps such deposits were instead transported farther basinward to the continental rise and/or laterally along the margin, as probably occurred in the Miocene on Australia’s NWS (Cathro et al., 2003). Lowstand fans are also absent in paleo-shelf settings of the Canterbury Basin, New Zealand, where influences of along-strike currents are unequivocal (Lu et al., 2003; Lu and Fulthorpe, 2004). Morphologic elements of paleo-slope incisions, i.e., canyons and rills, on the mid-Atlantic and other margins remain unclear with available (2D) seismic control. Pleistocene and modern canyons are large (up to 300 m deep and 2-5 km wide), closely spaced (2-10 km), and the Hudson and Delaware canyons off the east coast of the U.S. are clearly linked to river systems that have retreated westward during the Holocene sea-level rise. In contrast, middle-late Miocene canyons are both less deeply incised and less common and do not appear to be directly linked to paleo-shelf incisions, suggesting that they are not directly related to fluvial sources (Fulthorpe et al., 1999; Fulthorpe et al., 2000). Fulthorpe et al. (1999) have advanced the hypothesis that observed paleo-shelf-edge linearity results from along-strike sediment transport by waves and currents, which mutes the influence of individual fluvial point sources to form a line-source of sediment delivery to clinoform fronts (see also Fulthorpe and Austin, 2008). Individual fluvial sources apparently did not deliver sufficient sediment to overcome along-strike forcing to produce lobate depocenters (see Fig. 7), even though some fluvial incisions appear similar in width and depth to the Pleistocene Hudson and Delaware shelf channels (Fulthorpe et al., 1999). Shelf and slope incisions cannot be observed on the NCB/NWS, despite 3D imaging (Fig. 7). A lack of prominent point sources on the Miocene NJ margin (Fulthorpe et al., 1999; Pekar et al., 2003) may account for differences between NJ sequences and the standard sequence model (e.g., presence of slope aprons and absence of lobate fans). However, none of these inferences can be confirmed using only the available 2D seismic control. The only way that process-based links between sediment sources and observed/sampled NJ Oligocene-Miocene clinoforms can be established, and their relationship to sea-level cycles defined, is by 3D imaging encompassing Exp313 sites (Figs. 3-4).

Similarly, canyons cut into clinoform slopes do not appear to be linked to those incising more gently dipping surfaces basinward of clinoform toes, suggesting that different submarine erosional processes may be associated with observed changes in gradient. This may result from different "regime variables" controlling sedimentation patterns (Swift and Thorne, 1991; Fulthorpe et al., 2000). Along the modern shelf edge offshore NJ, incisions up to 140 m deep can occur even on low gradients basinward of clino-form toes, most likely due to fluid escape processes (Dugan and Flemings, 2000). 3D imaging along clinoform slopes in this project can test for this process of slope failure in the early -mid-Miocene.

3) *What was the sedimentary process response to the global mid-Miocene climatic (and tectonic) transition? Linked hypothesis: Changes in the rate of sediment input to the NJ margin during the mid-Miocene, as evidenced by mapping clinoforms bracketed by sequence boundaries, are linked to globally significant changes in the relative intensity of margin erosion.*

Many continental margins reveal mid-Miocene influxes of siliciclastic sediments (Molnar, 2004). In addition to NJ (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996; Steckler et al., 1999), other well-constrained examples of this pattern include the Gulf of Mexico (Galloway et al., 2000; Galloway, 2008), Canterbury Basin (Lu et al., 2005), NCB (Cathro et al., 2003; Sanchez et al., 2012a, b), the Angola margin (Lavier et al., 2001), and the Maltese Islands margin (John et al., 2003). Age estimates for this influx range from 15-12 Ma. The NCB case (Fig. 7) is striking, because the observed siliciclastic increase occurred at a preexisting carbonate margin. In the Canterbury Basin, the mid-Miocene sediment increase is not linked to known tectonism in the proximal Southern Alps; the only notable increase in sedimentation rate that coincides with tectonism is much later, during a well-defined period of increasing convergence rates at the Alpine Fault (Lu et al., 2005). This global pattern of mid-Miocene sediment influxes has been linked to global cooling following the mid-Miocene $\delta^{18}O$ peak. One possible mechanism is that the post -mid-Miocene global sea-level fall may have led to increased shelf erosion everywhere. However, reconstructed paleobathymetric profiles on the NJ margin suggest that the amount of sediment required for the observed progradation, estimated as a 20-fold increase in flux, exceeds that available from paleo-shelf erosion alone (Steckler et al., 1999). Other proposed mechanisms include changes in precipitation and in the amplitude/frequency of late Cenozoic climate change (Molnar, 2001; 2004).

However, climate may not have been the only driver of mid-Miocene sediment influx. Tectonic uplift of the hinterland may also have contributed (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996). Potter and Szatmari (2009) have united climatic and tectonic mechanisms for Miocene sedimentation by hypothesizing a global increase in middle-late Miocene tectonic activity driven by accelerated upwelling at two "superplumes" below the Pacific and Africa plates, which may also have produced far-field uplift of passive margins such as NJ. In their scenario, tectonic activity drove the coeval climatic transitions, through opening/closing key gateways and changing the oceanic circulation to trigger global cooling. The same Appalachian uplift that provided sediment to NJ has also been proposed as the origin of voluminous mid-Miocene sediments in the deep Gulf of Mexico (Jackson et al, 2011). These sediments were delivered by the paleo-Tennessee River, which discharged into the northeastern Gulf prior to its capture by the Mississippi (Galloway et al., 2000; Galloway, 2008). In spite of the large volumes of sandy sediment delivered to the Gulf basin, coeval updip slope canyons have not been identified, in marked contrast to the Pleistocene depositional episode (Galloway et al., 2000; Galloway, 2008). These Gulf of Mexico Miocene sediments are now targets of intensive hydrocarbon exploration, so understanding processes of middle Miocene sediment delivery from shelf to basin is economically as well as academically important.

The middle-late Miocene was a critical period in which climatic/tectonic processes combined to influence sedimentation globally. One of the long-term goals off NJ is to evaluate sedimentary response to these Miocene changes that influenced hinterland capability to provide sediment to the margin. Our proposed 3D survey will target initiation of the mid-Miocene sediment influx by imaging the transition between steep, slowly prograding Oligocene to mid-Miocene clinoforms drilled during Exp313 (Fig. 3), to more gently dipping, but more rapidly progradating features deposited later in the Miocene. Seismic geomorphology derived using the 3D volume will allow us to map temporal changes in shelf channel geometrical parameters (e.g., width, depth, sinuosity, gradient) to deduce changing sediment transport capacities from the hinterland through time, while slope morphologies, including the presence/absence of incised valley/canyons, will provide insights into processes involved in sediment bypassing to deep water (Fig. 8). In addition, correlation with the well-dated mid-Miocene sequences in the Gulf of Mexico, sourced from the same hinterland, will enable the timing of the influx in each basin to be compared.

WORK PLAN

Early-middle Miocene sequences clearly vary along-strike (Fig. 4), but a 3D volume long enough (perhaps ~100 km) to image all mapped variability is cost prohibitive. Instead, we propose to collect a 50 (dip) x 12 (strike) km volume encompassing all Exp 313 sites (Fig. 1), which has sampled ~12 sequences (Fig. 3). Some will be imaged along depocenter axes, others along peripheries, so we should image the full suite of potential shelf/slope, process-related seismic geomorphologies. Only one boundary (m5.6) will be missed. Fig. 3 shows that the volume proposed will image at least eight Miocene clinoform rollovers; these paleo-shelf edges record primary depositional processes associated with base-level change.

We have prepared a 2-year budget for acquisition/initial commercial processing of the volume (Fig.1). The data will be acquired on *Langseth*; processing will be done by a commercial company to pre-stack time-migrated (PSTM) shot gathers and 3D image volume (see quote in "Other Supplementary Documents"). The 12 km survey width optimizes turn efficiency and allows full data acquisition to be completed in two 6-km wide ‘racetracks’. The 50 km dip-length enables imaging of early Miocene topsets landward of Site M27 to middle Miocene toe-of-clinoform morphologies basinward of Site M29 (Fig. 3).

We will focus on imaging the upper 1 s two-way travel time; we expect to achieve vertical resolution of 5 m or better and horizontal resolution of 15 m or better. We will record with 1 ms sampling to a travel-time depth of 4 s to image diffractions necessary for proper migration. These constraints dictate a shallow, high frequency source array and a recording design that minimizes spatial aliasing. We expect in-line dips to be <4°, and cross-line dips to be <8°, the latter along inward-facing walls of incised valleys. To reduce aliasing of diffractions that will arise from lateral discontinuities and pinchouts, we plan to collect data with a nominal bin size of 6.25 m in-line and 18.75 m cross-line. *Langseth* will tow four 3-km streamers spaced 75 m apart to provide the necessary range of source-receiver offsets required for complete imaging to a maximum estimated target depth of 5-6 km.

We estimate cruise duration based on industry acquisition standards (e.g., 30% downtime and infill) prior *Langseth* 3D projects, consultations with the Chief Sci. Officer on *Langseth*, and use of industry acquisition planning software. We anticipate leaving from/returning to Newark, NJ, a ~80 nmi transit to/from the survey area (Fig. 1). Setup/deployment/streamer ballasting should take 3 days; gear retrieval and transit at the end will be 1 day. *Langseth* will use two flip-flopping gun arrays designed for high-resolution surveying, resulting in eight CMP lines spaced at 18.75 m for each sail line. The 12 kmwide area will be covered with 80 sail lines. Total shiptime dock-to-dock is 34 days.

Data acquisition will result in 5 terabytes of field data. PGS (see quote in "Other Supplementary Documents") has responded with a detailed work plan at a competitive cost. Their approach comprises 27 processing steps leading to various 3D PSTM shot gathers and data volumes; these will provide the community with interpretable reflection results and material for follow-on data analysis proposals. The data will be processed at 2 ms sampling rate unless the records show signal above 250 Hz, in which case the processing will proceed at 1 ms. Estimated data processing time is 5 mo. Two 1-week visits to the PGS facility by two co-PIs are budgeted to participate in and oversee the data preparation. Following a post-cruise workshop for the interested community of users (see UTIG Budget and Justification), we will upload delivered results to UTIG's Academic Science Portal of the Marine Geoscience Data System, and will also upload raw data/navigation to LDEO's Seismic Reflection Data Management System.

This is a collaborative effort between PIs with decades of experience collecting, processing and analyzing marine seismic data along continental margins, and in particular NJ. One has recently completed a successful 2-month cruise as a Co-PI aboard *Langseth* collecting multi-streamer 2D data. His experience planning and executing that campaign (that included 6 volunteer watch-standers onboard to gain scientific experience) is valuable for the proposed project. Post-cruise, he will provide primary oversight of the commercial processing; he will make two 5-day trips to the processing facility in Houston. He will be joined on both trips by a second Co-PI. G.Mountain (GM) has participated in every 2D MCS acquisition survey comprising the MAT. In his role as Exp313 Co-Chief, GM is in touch with Expedition-based research that will both augment and benefit from results of the proposed 3D volume. Three CoPIs are professors at their respective institutions with years of teaching experience that can be applied to educational aspects of pre- and post-cruise workshops and the at-sea experience of volunteer watch-standers. One brings lengthy experience in applying sequence stratigraphic principles at the outcrop scale, which tied to the Exp313 wells is what the proposed 3D imagery will closely rival. The team bring decades of experience in using both 2D and 3D MCS and ultra high-resolution acoustic tools (CHIRP, boomer, swath bathymetry) to the study of sediment transport on passive margins. With ONR support, they have studied the latest Pleistocene- Holocene stratigraphic succession of the NJ shelf for 25 yrs. Furthermore, two have analyzed 3D data volumes on the NW Australian continental margin, and three have have been ODP/IODP Co-Chiefs in continental shelf drilling efforts. All co-PIs will help run shorebased workshops pre- and post-data acquisition, and 4 will sail aboard *Langseth* and participate in the instruction of volunteer watch-standers in the theory and practice of seismic acquisition, processing and interpretation. In addition to their instructional duties, three will stand 8-hr watches each day at sea while another will oversee data QC and be on-call to troubleshoot acquisition-related problems.

The 3D, pre-stack time migrated data volume will be delivered from the processing company to UTIG, to be loaded onto a 3D visualization workstation. The co-PIs will convene a data appraisal, first-look interpretation workshop at UTIG for the interested scientific community shortly thereafter. Research themes identified will initiate sub-groups to focus on developing important research goals. Workshop products are TBD, but the intent is clear: 1) to debut the 3D data to interested researchers, 2) to task those present with developing strategies for achieving realistic goals using the 3D volume, and 3) to rapidly link a wide community of potential researchers to the 3D data by making it publically available at the close of the workshop (see the "Data Management Plan").

INTELLECTUAL MERIT

The NJ margin is among the best siliciclastic passive margins for elucidating the timing/amplitude of eustatic change over millions of years, and for examining quantitatively the link between sea-level change and the stratigraphic record. Consequently, this margin has been a key location in all long-range plans of scientific ocean drilling since it was first identified by COSOD II (1987). While Exp313 continuously cored/logged boreholes within shallow-water facies, and has recovered complete stratigraphic information, 3D seismic imaging is needed to put that sampled record in a spatially accurate, stratigraphically meaningful context. The 29 researchers of the Exp313 scientific party are an especially valuable knowledge base of the mid-Cenozoic evolution of the NJ shelf; they and other scientists involved in research of the MAT represent a large body of experts for whom the proposed seismic geomorphology will be a tremendous asset. 3D imagery will allow them to map sequences around Exp313 sites, including shoreline positions and flanking diagnostic shallow-water features (e.g., fluvial incisions, estuary complexes, point bars). The long-term objectives remain to: 1) determine the amplitude and timing of global sea-level changes during the "Ice House" 2) establish the impact of base-level changes on the preserved stratigraphic record; and 3) improve understanding of the response of shorelines/nearshore environments to changes in global sea level, a societally relevant topic today.

BROADER IMPACTS

The team of co-PIs envisions 3 phases of robust interaction with the user community before, during and after 3D acquisition aboard *Langseth*: 1) A pre-acquisition workshop to acquaint interested participants with the project (an announcement of opportunity was placed [May 2012; see 'Other Suppl. Docs.'] on the GeoPRISMS and Consortium for Ocean Leadership [COL] websites; additional announcements will follow funding) will be held at Rutgers prior to data acquisition. The scientific value of 3D data will be displayed, the history of research on the NJ margin will be highlighted, and plans for data acquisition will be laid out. Discussions will aim at reaching a consensus concerning acquisition details and processing features of the community data volume by a commercial company. 2) Community interaction during acquisition will be primarily the hands-on participation of students/young scientists aboard *Langseth* (~12 bunks are available for volunteers [see 'Mentoring Plan']). The survey area is <40 nmi from Atlantic City, so rotation of more than one group is possible by at-sea transfer, enabling a variety of education/outreach activities with perhaps occasional live satellite feeds showing the deployment/recovery of seismic gear, etc. 3) A post-acquisition workshop at UTIG will focus on avenues for community analysis/interpretation of the processed 3D volume, once that volume is available ~5 mo post-acquisition.

The Rutgers Geology Museum has previously hosted exhibits of scientific drilling in the Coastal Plain, focusing on the K/Pg boundary core obtained at Bass River, NJ (ODP Leg 174AX; Olsson et al., 1997). We will prepare similar exhibits/talks to highlight the integration of 3D seismic with drilling. We expect that 3D images will become integral to IODP outreach, along with Exp313 results. We will showcase NJ margin results for the European Union (which funded Exp313 drilling/logging costs through IODP), for ICDP (which funded some drilling costs), the COL (responsible for logging/data management) and IODP-MI (which managed Exp313). We will provide the IODP Data Bank, and, if asked, the ECORD/ESO Drilling Operator, with 3D image data. LDEO/UTIG have an ongoing collaboration through NSF to archive marine seismic data. We will make the commercially processed 3D data available to this facility, with the expectation that they will become an enduring demonstration of how 3D imaging can improve understanding of passive margin stratigraphic evolution.

A final note about societal relevance. The proposed 3D volume, tied to cored and logged drillsites, will provide a valuable opportunity to understand better the causes of an increase in mid-Neogene deposition at many passive margins around the globe (e.g., Bartek et al., 1991.). The same Appalachian hinterland that was the source of the sedimentary record offshore NJ, and concentrated on by the MAT, fed a similar pulse of sediments into the Gulf of Mexico. Consequently, increasing knowledge of the evolution of the NJ shelf may help to improve exploration strategies in the Gulf, a proven hydrocarbon province.

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