STRATAFORM: A PROGRAM TO STUDY THE CREATION AND INTERPRETATION OF SEDIMENTARY STRATA ON CONTINENTAL MARGINS

By Charles A. Nittrouer and Joseph H. Kravitz

. . . a coordinated multi-investigator study of continental-margin stratigraphy.

CONTINENTAL MARGINS are complex regions of the Earth, because they are the interface between terrestrial and marine environments. Many natural processes occurring on land or in the ocean combine to influence continental margins. Commonly, these processes are accentuated on margins; for example: fluvial discharge reaches its maximum at river mouths; many physical oceanographic processes (e.g., tides, surface gravity waves) are intensified by shallowing water depths. Consequently, the processes affecting the fate of sedimentary particles are diverse and energetic, and superposition (often with nonlinear coupling) of relevant processes makes stratigraphic investigation difficult. However, such investigation is worth the effort, because the record of processes operating on continental margins is frequently preserved in the strata formed at the seabed. Therefore the history for many of the events influencing the Earth (both on land and in the ocean) can be unraveled by carefully documenting and accurately interpreting sedimentary strata on continental margins. Accomplishing this for two distinctly different study areas—northern California and New Jersey—is a general goal of the STRATAFORM program.

STRATA FORmation on Margins (STRATAFORM) was initiated in 1994 by the Office of Naval Research (Marine Geology and Geophysics) as a coordinated multi-investigator study of continental-margin stratigraphy. As stated above, a goal of the program is better *interpretation* of the high-resolution sedimentary record preserved on shelves and slopes. Another general goal is better *prediction* of strata, in space and time. For example, what data about a location are needed to predict past or future strata forming there. STRATAFORM participants are focusing their efforts on the upper ~10^2 m of the seabed (commonly representing <10^6 y). For detailed examination of these strata, knowledge is required of processes occurring on a range of scales, extending from short-term (<10^2 y, e.g., storms, floods, bioturbation) to long-term (>10^4 y, e.g., sea-level change, tectonic movements). Consequently, a broad suite of geologists and geophysicists are involved in STRATAFORM, as demonstrated by the following articles (see References). The purpose of this introduction is to describe the framework in which these scientists interact and to demonstrate some of the preliminary links among their research efforts.

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Objectives

The layering of sediment on continental margins (i.e., stratigraphy) has been studied in numerous ways. One common approach is for marine geologists to measure active processes (e.g., bottom shear stresses, benthic biological mixing, sediment accumulation rates) and relate them to strata being created. Another approach is for marine geophysicists to document stratigraphic relationships through seismic records, and from these to interpret the history of formative processes. In one case, the processes are well known and strata are predicted; in the other case, strata are well documented and processes are interpreted. We believe that interaction of these two groups can provide a more thorough understanding of stratigraphy. Geophysicists know which types of strata are commonly preserved, and can direct marine-geology studies to focus on understanding the formative processes. In return, marine geologists can provide a realistic assessment of the processes responsible for documented stratigraphic sequences. STRATAFORM has brought these two groups together with the common program objectives described below.

To Add Geological Perspective to Shelf and Slope Studies of Sediment Transport, Morphology, and Fine-Scale Stratigraphy (Time Scales <10^2 y)

Detailed knowledge of the environmental processes affecting a continental margin is available only for a century or less. New measurements of active processes usually can be used to represent this period with confidence or, at least, with explicit knowledge of limitations (e.g., natural or anthropogenic changes). Geophysical observations in northern California are directing the focus of studies relating processes to preserved strata; among many examples: the location of a distinct stratigraphic boundary between inner-shelf sands and midshelf muds, the geometry of sedimentary deposits associated with the Eel River dispersal system, the morphology of mass-movement scars and deposits on the slope, and the character of gullies associated with fluid escape from the seabed.

To Provide Physical Constraints on Interpretation of High-Frequency Seismic Stratigraphy in the Upper ~100 m of the Seabed (Time Scales ~10^4–10^6 y)

Based on seismic profiles and boreholes, interpretations are commonly made for the sequences of environmental processes that create the observed stratigraphy. The combination of the two study areas is an attempt to add more insight to these types of interpretations. Strata are actively forming in the northern California study area, and the resulting stratigraphy is being investigated by a nested assortment of observational tools (Fig. 1). The highest resolution tools are used in direct coordination with measurements of oceanic processes, so strata interpretation is well calibrated. Different processes are dominant on different portions of the shelf and slope, allowing a range of stratigraphic signatures to be investigated. Superposition of these signatures through geological time creates the stratigraphic record, which is documented by the seismic tools with progressively greater penetration. The ultimate test is to transpose these new insights of strata interpretation to the New Jersey margin, where observations will be limited to seismic tools and boreholes (in part, through coordination with the Ocean Drilling Program, ODP).

To Develop Approaches for Obtaining Stratigraphic Insights by Interpolating Between Time Scales and by Extrapolating to Other Margins

A number of difficulties result from merging the studies described in the previous two objectives, because typically process-based studies characterize strata for a time scale shorter than seismic profiles can resolve. Smooth merger of these studies requires a modeling component. Extrapolation of insights to different margins, with different relative importance of various environmental processes, also requires modeling for accurate interpretation of stratigraphy. In addition, not all geologically relevant processes can be expected to occur (or to be observed) within the time scale of a research program; therefore laboratory simulations are required for some processes (e.g., debris flows, turbidity currents). Accurate interpolation and extrapolation are possible through mathematical/computer modeling and laboratory studies.

Organization

A tenet of STRATAFORM is that continental-margin stratigraphy is best studied from a holistic perspective. Presently, the regions of primary interest stretch from the midshelf to the midslope, and these physiographic regions are being examined in unison. Additional, but lesser, effort is given to adjacent environments landward (fluvial to inner shelf) and seaward (lower slope). To investigate these regions effectively, the STRATAFORM program has >30 principal investigators. These scientists have been organized into three primary projects, as described below.

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Shelf Sediment Dynamics and Development of Lithostratigraphy

This project is investigating the physical oceanographic processes (e.g., waves, currents) that transport sediment, and whose spatial variability leads to a divergence in sediment flux, such that material accumulates in the seabed. Particularly relevant are periods when "event" beds form during ocean storms and during river floods (with turbid plumes) in northern California. These event beds, as well as sediments deposited during more typical conditions,

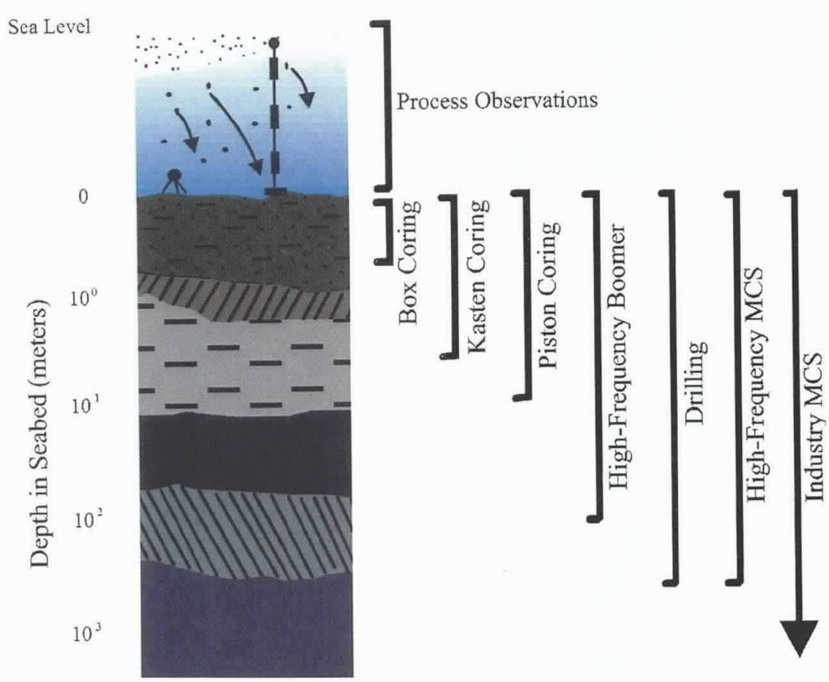

Fig. 1: A schematic representation of nested tools for STRATAFORM research—ranging from coring to MCS (multichannel seismic) devices, for progressively deeper observation of seabed strata.

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are subsequently reworked by biological and physical processes, which lead to postdepositional modifications of strata. After some degree of modification, continual sediment deposition buries strata below the zone of active reworking. This project is investigating the net imprint created by sediment transport, deposition, mixing, and burial to form a long-term ($>10^2$ y) stratigraphic record.

Slope Geological Processes and Resultant Geomorphology

The northern California shelf (Fig. 2) is relatively narrow (~20 km), so some sediment is able to escape beyond the shelf break to the slope. This project is interested in the fluxes and mechanisms for sediment reaching the open (noncanyon) continental slope from external sources. Subsequent to deposition, sediments on slopes are influenced by gravitational movements (e.g., slides, slumps, debris flows, turbidity currents) that remobilize the seabed and transport material within and out of the slope. Evidence of such processes is being identified from stratigraphic and geotechnical studies. Erosional and depositional features (slide scars, gullies, slump deposits) result and affect the morphologic character of slopes, as evidenced for both New Jersey and northern California. Gravitational processes have recurrence intervals too long for a research project; therefore the mechanisms themselves are being investigated in special laboratory flumes. Together, these studies provide insight into slope processes and their resultant stratigraphy and morphology.

Stratigraphic Sequences Resulting from Shelf and Slope Sedimentation

The processes acting on continental shelves and slopes do so with spatial and temporal heterogeneities that create a complex stratigraphic record. This project seeks to understand the meaning of that record, specifically by determining the geological identities of seismic reflectors, sequence boundaries, and intervening sequences. A nested assortment of seismic techniques is being utilized with a range of penetration depth and stratigraphic resolution (Fig. 1). In most cases, this work creates two-dimensional profiles, but where important structures are identified, three-dimensional observations are obtained. The seismic studies interface with process studies in northern California and with ODP drill holes in New Jersey. This drilling will be performed in 1997 and represents the first time ODP has ventured onto the continental shelf. Together, seismic and drill-hole data will provide input to stratigraphic models attempting to explain the architecture of reflecting surfaces and associated strata.

Cross-Cutting Groups

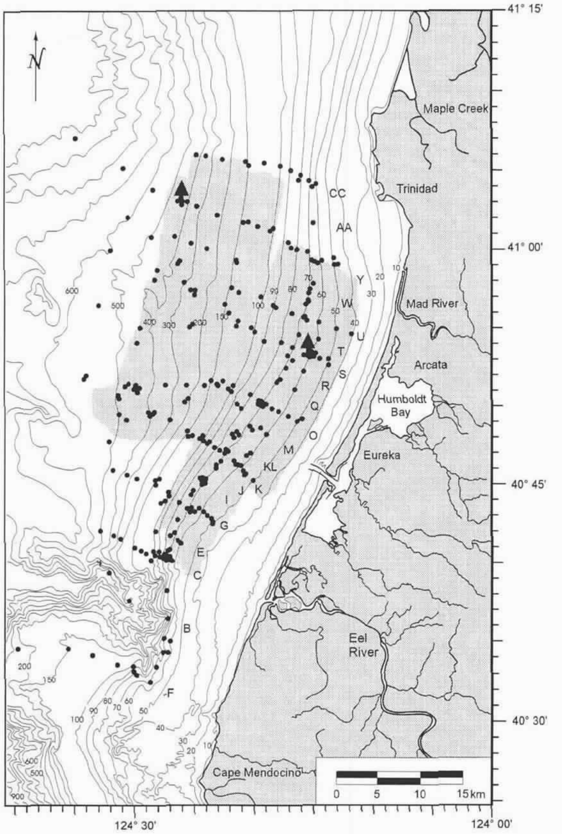
In addition to these three projects, STRATAFORM contains numerous cross-cutting groups that guarantee interaction among the projects. A group of scientists is sampling the seabed with a range of tools, from box corers to piston corers and ultimately to drill rigs. The modeling efforts within STRATAFORM are coordinated among the three projects and include overlapping stratigraphic models extending from vertical scales of centimeters to hundreds of meters. An especially important cross-cutting group is responsible for a long-term observation effort in northern California, which will provide continuous physical and sedimentological data over a 5-y period from both the continental shelf and slope. This is the type of input that is needed for longer-term modeling extrapolations.

Study Areas

The two study areas were chosen for special opportunities they each provide, and also to allow contrasts between a collision and a trailing-edge margin. The northern California study area (between Cape Mendocino and Trinidad Head; Fig. 2) receives fluvial sediment that reaches the shelf and slope, so modern strata formation can be investigated. The New Jersey study area (Fig. 3) is a wider margin with classic stratigraphic sequences that will be drilled in 1997, so ancient strata can be well studied.

The primary fluvial source of sediment to the northern California study area is the Eel River, which has a mean sediment discharge $>10^7$ t/y. The Mad River also enters the study area but supplies an order of magnitude less sediment. Together, they produce deposits of sand on the inner shelf, which, in a seaward direction, grade to mud at ~50 m water depth. The dominant direction of sediment transport is northward, and a Holocene deposit ~10 m thick has formed on the shelf. Some of the sediment is reaching the slope, and the Eel Canyon (located south of the Eel River mouth) was a significant conduit in the geological past. The present phase of STRATAFORM is focusing north of the Eel Canyon on the open slope, where most of the modern sediment accumulates. The combination of rapid sedimentation and frequent earthquake activity causes slope deposits to fail, and evidence of mass movement (e.g., slumps, debris flows) is well documented. Therefore, a range of shelf and slope sedimentary processes is active on the Eel margin, and the impact on strata can be evaluated directly.

The New Jersey margin is an important stratigraphic counterpoint to the northern California margin. The New Jersey margin is presently sediment starved, because most fluvial input is trapped in river-mouth estuaries (Hudson, Delaware) or lagoons (behind barrier islands). The shelf surface is a layer of sand (with some mud in local depressions) formed by shoreline retreat during the Holocene sea-level rise, and subsequently deformed by storms. However, below the relict (or palimpsest) surface is a rich record of sedimentation that is >15 km thick. The Quaternary and Ter-



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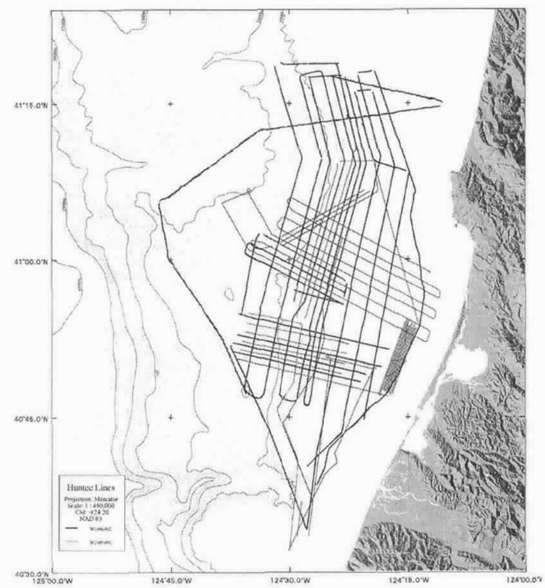

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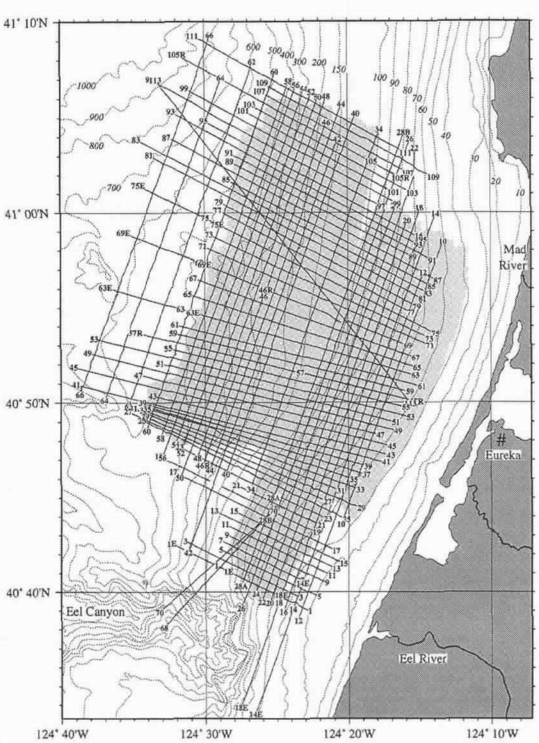

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*Fig. 2: The study area in northern California. (**A**) Core locations sampled to date are shown by black dots; at most locations, numerous replicate box cores were obtained. Longer kasten and piston cores will be collected in the future. The 2 triangles show the locations of the shelf and slope sites for long-term observations (~5 y). The letters on the landward side identify transects frequently sampled. (**B**) Track lines for high-resolution Huntec boomer surveys during 1995 (thin lines) and 1996 (thick lines). (**C**) Track lines for high-resolution MCS (multichannel seismic) operations in summer 1996. The gray shading in **A** and **C** indicates the region of swath mapping (see Goff* et al., *1996, this issue).*

tiary strata in the upper ~10^2 m contain clinoform features and other evidence of margin aggradation and progradation. In addition, this long-term record has been impacted by subsidence, compaction, and repeated sea-level changes. These processes produce sequences of strata typical of many margins worldwide, and better interpretation of the New Jersey record would provide valuable new insights of global significance.

Some Examples of Coordinated Research

The STRATAFORM program is divided into three 2-y increments. The first phase (1995–1996) is just ending, and some initial results can be used to demonstrate the benefits of interactive research.

River Plumes and Flood Deposits

STRATAFORM was fortunate to experience a substantial flood (~30-y recurrence interval) of the Eel River during the first year of operation (Wheatcroft *et al.,* 1996, this issue). This created a deposit on the shelf clearly defined by observations of sedimentary fabric, grain size, porosity, and both stable and radioisotopes. The fate of this deposit will be followed for the duration of STRATAFORM. Among the modifying processes will be bioturbation by the benthic community that is recolonizing the deposit. In addition, physical processes (bottom currents and surface gravity waves) create very energetic near-bed conditions in this study area (Wiberg *et al.,* 1996, this issue), which have been observed to advect sediment (directly from the Eel River?) as well as to rework the seabed. A major storm (~5-y recurrence interval) occurred during the second year of STRATAFORM, after boundary-layer sensing systems were deployed and the preexisting flood deposit was well characterized. Rapid-response teams cored the flood deposit during and immediately after the storm event and can relate modifications directly to boundary-layer physical processes. In addition to following the evolution of a flood deposit, the origin of the deposit will be investigated by a sediment plume study. This research will examine the fate of fluvial particles from the Eel River, which flocculate and sink as they are advected northward.

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A Full-Margin Sediment Budget

The discharge of sediment from the Eel River is relatively well constrained by U.S. Geological Survey river gauges and rating curves, which provide a record ~80 y long. With a very small delta plain, almost all sediment reaches the ocean. The bulk of the sediment (>80%) is silt and clay, and its accumulation on the adjacent shelf is being documented over various time scales (Wheatcroft *et al.,* 1996, this issue). ^{210}Pb geochronology is ideal for providing a record of accumulation on the same scale as the discharge record (~1 century). Accumulation rates on the shelf vary spatially, but are commonly >5 mm y^{-1} on the mid-shelf (60–100 m water depth) and decrease offshore. On the northern portion of the adjacent slope, accumulation rates are typically 1–4 mm y^{-1} (Syvitski *et al.,* 1996, this issue). Together, shelf and slope studies should allow derivation of a full-margin sediment budget, which will reveal much about processes affecting the fate of particles. For example, the 1995 flood deposit on the shelf accounts for only ~25% of the flood sediment discharged by the Eel River. The remaining ~75% was broadcast widely on the margin. ^{7}Be is a natural radioisotope (53-day half life) closely tied to recent fluvial particulate discharge, and was identified on the slope soon after the river flood. The export of sediment by river plumes and by storm resuspension on the shelf is being investigated through comparison of long-term observations on the shelf and slope as part of STRATAFORM.

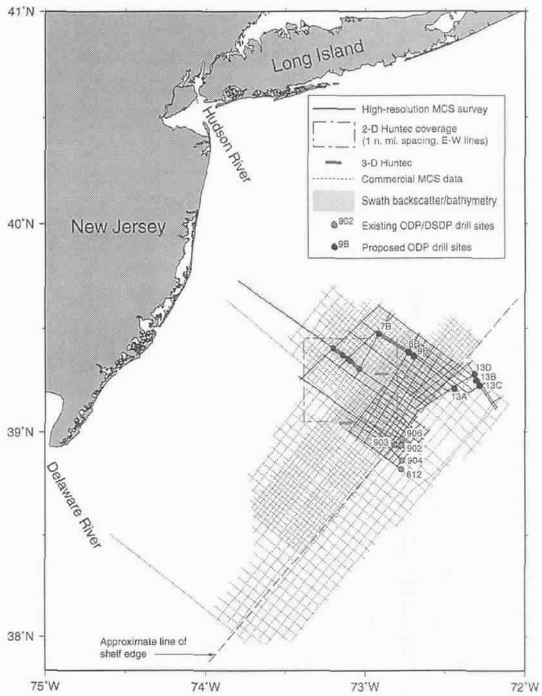

Fig. 3: Compilation of STRATAFORM-related data collected from the study area in New Jersey.

Formation of Slope Gullies

The origin of morphological features on continental margins is another important consideration of STRATAFORM. Gullies are small linear depressions (a few meters deep) extending down the gradient of continental slopes. These are observed on the New Jersey slope and are believed to represent failure features that are early stages in the formation of submarine canyons (Pratson *et al.,* 1996, this issue). Northern California reveals a variety of slope gullies (Goff *et al.,* 1996, this issue). In the southern portion of the study area, they are large and associated with the Humboldt slide. In the north (where active accumulation has been measured), they are smaller and have a similar appearance to New Jersey gullies, but their upper terminations are not failure features. In addition, the traces of the gullies in seismic profiles can be followed tens of meters into the underlying seabed, further supporting their participation in accretion of the slope. In some cases, gullies are aligned with pock marks; sediment in and near the gullies is probably unstable due to gas charging. Therefore the northern California gullies may be maintained as local depressions by erosive gravity flows (e.g., turbidity currents), as hypothesized for the New Jersey slope, but in northern California the same gravity flows also may be responsible for distributing sediment that leads to the upward growth of the overall seabed.

Erosion and Deposition Resulting from Mass Movement

The conditions found on the northern California margin (e.g., rapid sediment accumulation, a gas-charged seabed, frequent earthquake activity) are ideal for causing large-scale slope failure and mass movement (Pratson *et al.*, 1996, this issue). Observations of geotechnical properties reveal variable strength for the seabed and help delineate areas of the slope prone to future failures. Much information about the development of slope morphology can be learned from a past slide that created a large amphitheater-shaped scar, and the series of deposits at its base (Goff *et al.*, 1996, this issue). Slump blocks and pressure ridges form a series of contour-parallel topographic highs at the base. The exposure of underlying (consolidated) strata in the slide scar is obvious from seismic profiles (Austin *et al.*, 1996, this issue; Syvitski *et al.*, 1996, this issue). Large gullies have developed in this region and appear to be funneling sediment to form secondary turbidite deposits at the base of the scar. Therefore slope failure can lead to spatially and temporally varying sequences of positive and negative morphological features.

The Perfect Isochronal Surface

Studies of continental-margin stratigraphy often attempt to reconstruct past conditions, when now-buried strata were at the surface of the seabed. For example, a process of "backstripping" allows overlying strata to be removed, and adjustments made for sediment compaction and isostatic subsidence, so that an old surface of a continental margin can be restored. These surfaces can be very important for evaluating past processes, for example: ancient clinoforms (Miocene age) are indicated by past surfaces created from seismic data on the New Jersey shelf (Austin *et al.*, 1996, this issue). Comparison of these surfaces gives information about migration of fluvial sediment sources, development of submarine canyons, and much more. Internal seismic reflectors can be imperfect indicators of past seabed surfaces, because of complexities associated with substrate response to acoustic signals. The only perfect example of an isochronal surface is the seafloor today. And for this reason, a great effort has been expended by STRATAFORM in both study areas to document the modern seafloor (Goff *et al.*, 1996, this issue) in order to obtain detailed statistical characterizations (Steckler *et al.*, 1996, this issue).

Interpretation of Stratigraphic Sequences

The seismic observations being undertaken by STRATAFORM are providing information about the architecture of strata on continental margins (Austin *et al.*, 1996, this issue). On the largest vertical scale of interest ($\sim 10^2$ m), the packages of sediment are related as recognizable sequences that respond to environmental changes on the land (e.g., sediment supply), in the ocean (e.g., sediment transport), and under the margin (e.g., sediment compaction, subsidence). Sea-level change is an especially important factor that can cause recognizable sequences to repeat themselves. Numerical models are a critical means for examining the myriad combinations of processes impacting the stratigraphic record (Steckler *et al.*, 1996, this issue). With proper calibration from process-oriented studies, numerical models can provide a wider range of conditions than can be observed in the field or scaled in the lab.

Making Laminae into Sequences

To develop mathematical formulations that can build the stratigraphic record from centimeters to hundreds of meters, a nested set of numerical models is being developed. This starts with a one-dimensional sediment-transport model (soon to become 2-dimensional) that relates water-column flow to seabed resuspension (Wiberg *et al.*, 1996, this issue). A special benefit of STRATAFORM is the ability to incorporate data regarding the seabed response (e.g., event-bed thickness, grain-size grading), and long-term water-column conditions (from the shelf and slope long-term observations). Separate models address the preservation of event beds (Steckler *et al.*, 1996, this issue). On longer time scales, the STRATAFORM models consider factors such as climatic changes in storm occurrence, sea-level fluctuations, and vertical movements of the seabed (due to tectonics, compaction, and isostasy). Ultimately, the models for strata formation will be tested for their ability to predict and interpret continental-margin stratigraphy.

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Future STRATAFORM Studies

The results and plans presented above reflect work during the first two years of the program. As we now end the second year, a new phase of work begins. In some cases, this will bring entirely new research efforts, such as a plume study in northern California and interactions associated with ODP drilling in New Jersey. In other cases, ongoing work will be modified: laboratory models will be adjusted specifically to evaluate evolution of the Humboldt slide, and field sampling in northern California will switch emphasis from spatial distribution of surficial strata (box cores) to historical variation of deeper strata (kasten and piston cores). Some work will continue unchanged, as

. . . pursuing a better understanding of the creation and interpretation of sedimentary strata . . .

with the long-term observations on the northern California shelf and slope. STRATAFORM research in the future will continue to follow the program objectives described previously in this article, pursuing a better understanding of the creation and interpretation of sedimentary strata on continental margins.

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